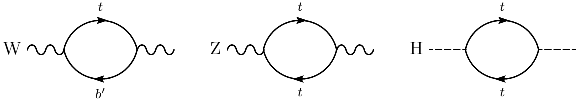
Precision mass measurements with the CMS experiment

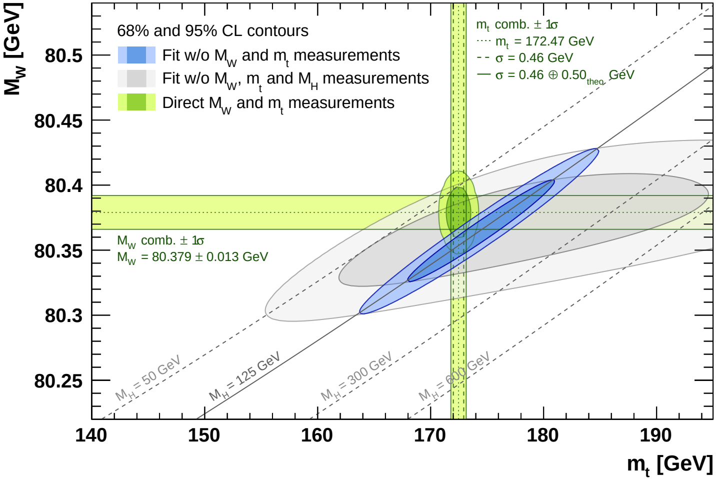
Markus Seidel

Jan 9, 2023

Heavy particle masses in the Standard Model

- Masses of top quark, and W, Z and H bosons related via loop corrections

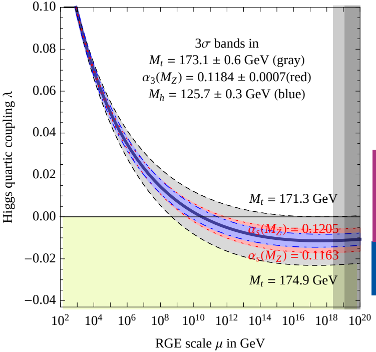




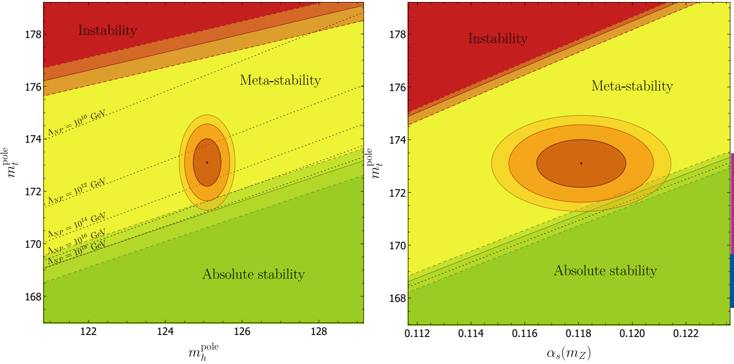
arXiv 1803.01853

Vacuum stability

- Evolution of H^4 sensitive to m_t and α_s, negative values → EW vacuum unstable



arXiv 1205.6497

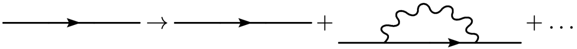


arXiv 1707.08124

- arXiv 1707.08124 : *"the first complete calculation of the lifetime of our universe: 10^139 years. With 95% confidence, we expect our universe to last more than 10^58 years."*
  dotted lines = scale at which New Physics could stabilize the SM
  - Calculated with $m_t^{\text{pole}} = m_t^{\text{MC}} = 173.1 \pm 0.6\,\text{GeV}$ (Tevatron + LHC Run 1)
- Latest result: $\tau_{\text{EW}} \sim 10^{983^{+1410}_{-430}}$ years arXiv 2108.09315
  - Using recent global averages $m_H = 125.1\,\text{GeV}$, $m_t = 172.4\,\text{GeV}$

Top mass definition

- Pole mass absorbs quantum corrections to fermion propagator



$$\frac{i}{\not{p} - m_0} \quad \to \quad \frac{i}{\not{p} - \underbrace{m_0}_{\text{'bare' mass}} - \underbrace{\delta m_0}_{\text{divergent}} - \underbrace{\Sigma'\left(m_0\right)}_{\text{finite}}} := \frac{i}{\not{p} - m^{\text{pole}}}$$

- m^{pole} = particle mass in isolation but no free quarks → renormalon ambiguity
- Short-distance mass schemes do not (fully) absorb finite terms
  → scale-dependence of mass parameter, e.g. $\overline{\text{MS}}\ \bar{m}_t\left(\bar{m}_t\right), m_t^{\text{MSR}}\left(R\right)$

Most m_t measurements rely on MC, mass scheme under discussion:

- arXiv 1405.4781 $m_t^{\text{pole}} - m_t^{\text{MC}} = 0.05^{+0.32}_{-0.62}\left(\text{MC} \to \text{MSR}\right) \pm 0.50\left(\overline{\text{MS}} \to \text{pole}\right)$ GeV
  → 0.8 GeV additional uncertainty!
- arXiv 1801.04826 MC authors: MC implements pole mass.
  → Just need to make sure that shower and hadronization uncertainties are correct?

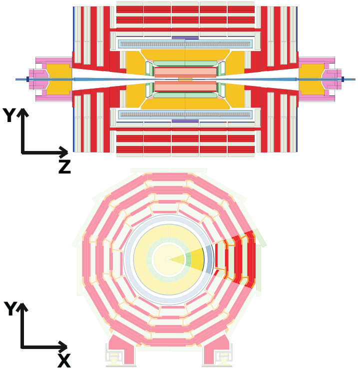
Outline

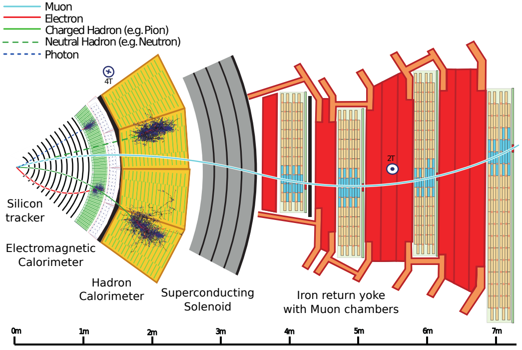
Experimental conditions

LHC + CMS

Compact Muon Solenoid experiment

CMS JINST





Dimensions

- Length: 29 m
- Diameter: 15 m
- Weight: 14 000 t

Sub systems

- Silicon pixel + strip tracker
- EM and hadronic calorimeter
- Solenoid magnet (3.8 T)
- Muon chambers

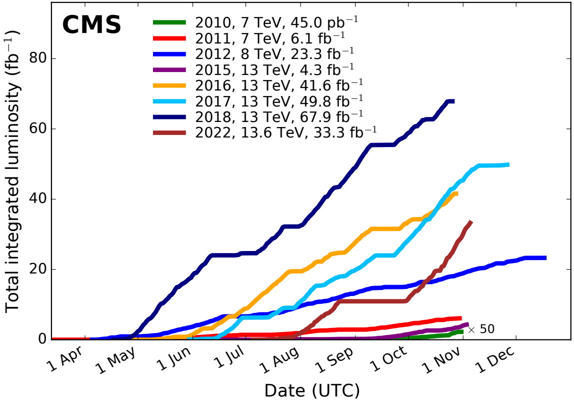
Excellent LHC performance

CMS LumiPublicResults

- Huge number of heavy particles produced at CMS
- For example, top quark pair production:

  $$N_{t\bar{t}} = \underset{\text{integrated lumi}}{\mathcal{L}_{\text{int}}} \times \underset{\text{production xsec}}{\sigma_{t\bar{t}}}$$

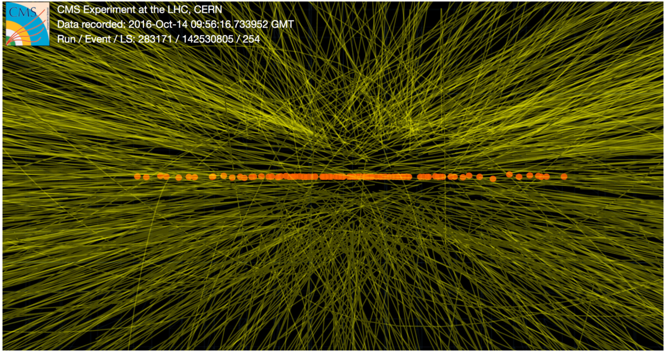
- Run 1 (2010–2012)
  $\rightarrow N_{t\bar{t}} = 7\text{M}$ at 7 and 8 TeV
- Run 2 (2015–2018)
  $\rightarrow N_{t\bar{t}} = 136\text{M}$ at 13 TeV
- Run 3 (started 2022)
  $\rightarrow N_{t\bar{t}} = 32\text{M}$ at 13.6 TeV

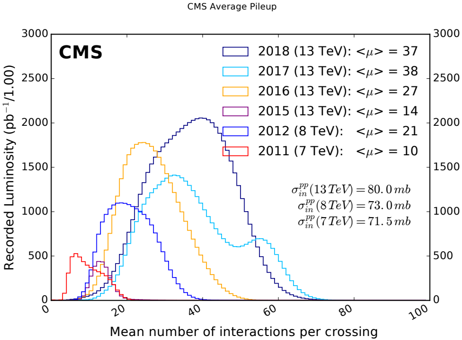


"Pileup"

CMS LumiPublicResults

- High instantaneous luminosity → multiple pp interactions per bunch crossing



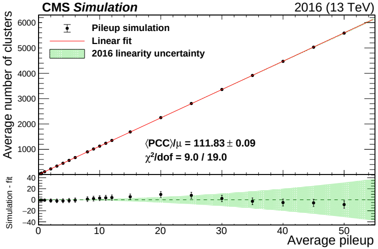


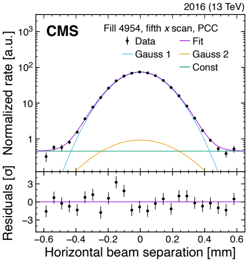
- Tracking copes well: tracks assigned to distinct interaction vertices
  - CMS Phase-2 upgrades for High-Lumi LHC will include timing capabilities → 4D vertexing
- Calorimeters: energy deposits overlap and cannot be distinguished

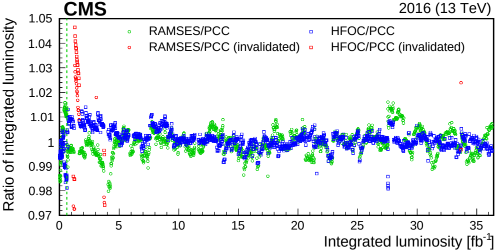
Luminosity measurement

CMS LUM-17-003

- Precise knowledge of luminosity essential for absolute cross section measurements





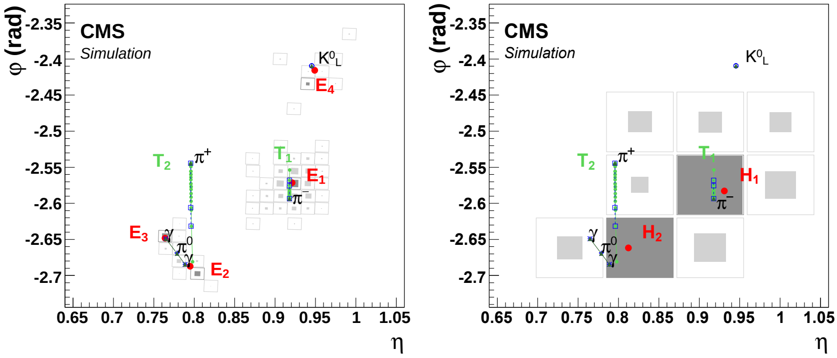


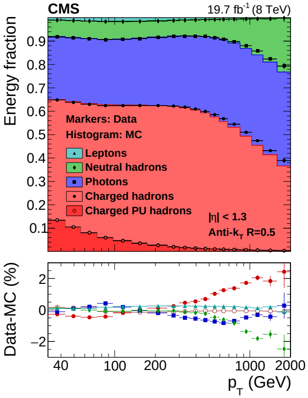
- Different methods: pixel cluster counting, vertex counting, HF occupancy, radiation monitors, muon counting (calibrated to PCC)
- Calibration using beam-separation (vdM) scans, largest uncertainties: differences between measured and predicted beam positions, x-y correlation, pp em interactions
- Integrated lumi: stability and linearity over time as main uncertainties
- Final precision 1.2 – 2.5%, depending on year

CMS PAS-LUM-17-004 CMS PAS-LUM-18-002

Particle flow reconstruction

CMS PRF-14-001





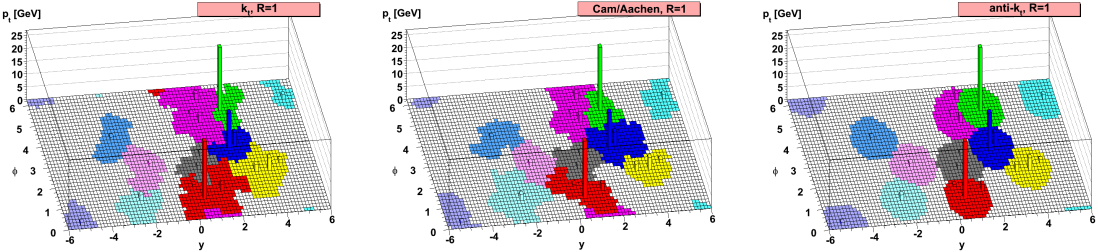
- PF algorithm keeps all tracks, and removes their energy from calorimeter towers
- Charged hadron subtraction (CHS) removes tracks not from primary vertex
- PUPPI algorithm weighs down neutral clusters not close to PV tracks arXiv 1407.6013

Jet clustering

arXiv 0802.1189

- Sequential cluster algorithms defined by the two quantities

$$d_{ij} = \min\left(p_{\mathrm{T},i}^{2k}, p_{\mathrm{T},j}^{2k}\right)\frac{\Delta_{ij}^2}{R^2},\ d_{iB} = p_{\mathrm{T},i}^{2k}$$

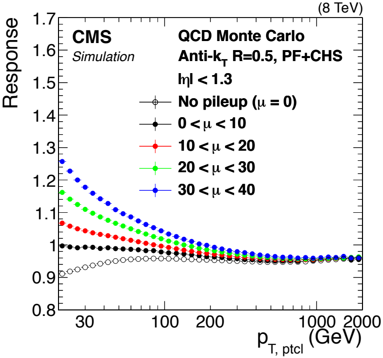


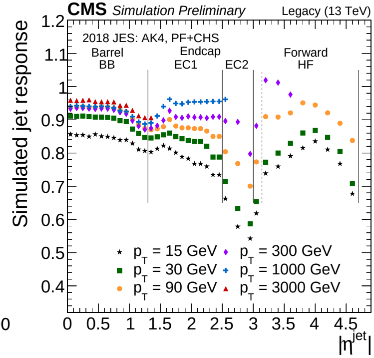
- Behavior controlled by parameter $k = \begin{cases} 1 & \text{Durham } k_t \\ 0 & \text{Cambridge/Aachen} \\ -1 & \text{anti} - k_t \rightarrow \text{default algorithm, with } R = 0.4 \end{cases}$

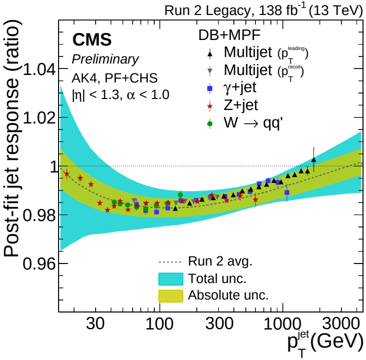
  → different sensitivity to soft particles (soft emissions, pileup, underlying event)

Jet energy calibration

CMS JME-13-004 CMS DP-2021/033



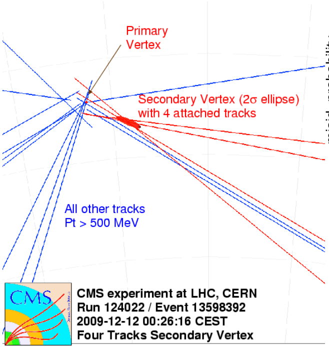


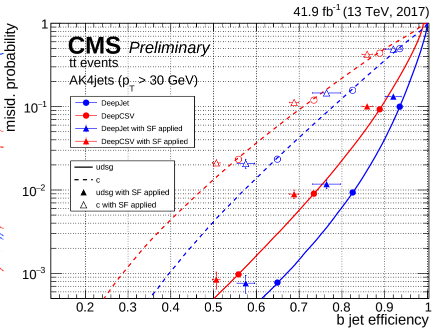


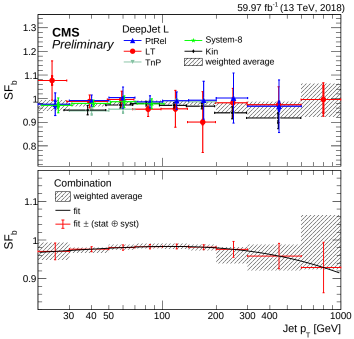
- L1Pileup correction subtracts median energy density $\rho\times$jet area
- L2Response correction as function of jet p_T/η, based on MC p_T^{reco}/p_T^{gen}
- L2Residual correction for remaining response differences in data
  - relative η calibration with dijet events
  - absolute calibration with γ/Z+jet events
- CMS Run 2 jet energy scale at level of 1%

B jet identification

CMS BTV-16-002 CMS DP-2018/058 CMS DP-2021/004



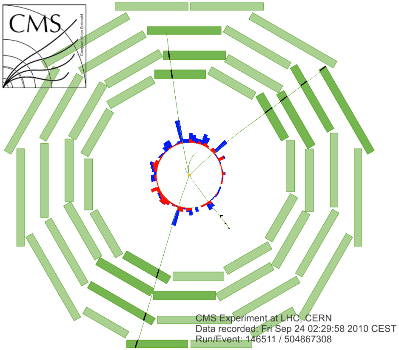


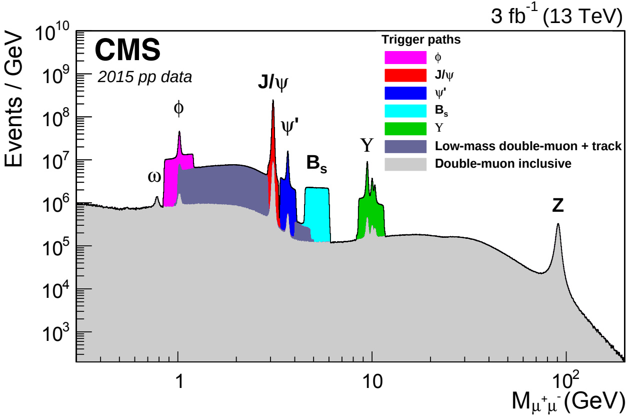


- B jets identified by secondary vertices and track properties (e.g. impact parameter)
- ML-based algorithms > 80% efficient for medium working point (1% light-jet mistag rate)
- Data/MC scale factors determined in multijet and $t\bar{t}$ events, slight decrease in efficiency

Muon reconstruction

CMS MUO-16-001



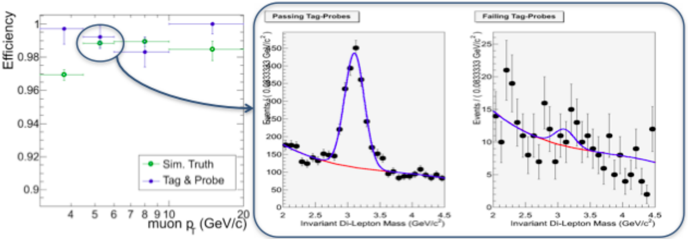


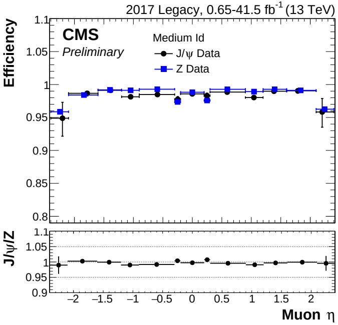
- Muons reconstructed from both inner tracker and muon system
- Identification criteria using track quality, need to be compatible with primary vertex
- Trigger paths targeting specific resonances

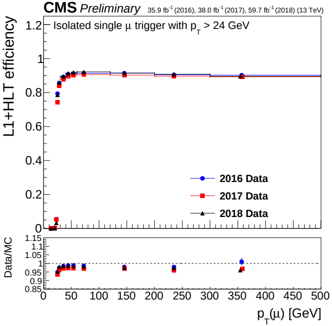
Muon efficiencies

CMS MUO-16-001 CMS DP-2020/040

- Muon efficiencies determined using tag&probe method in J/Ψ or $Z \to \mu\mu$ events
- Select muon pairs, with tag (probe) muon fulfilling tight (loose) selection criteria
- Fit resonance shape in categories of passing/failing probe criteria $\to \varepsilon = N_{\text{pass}}/(N_{\text{pass}} + N_{\text{fail}})$

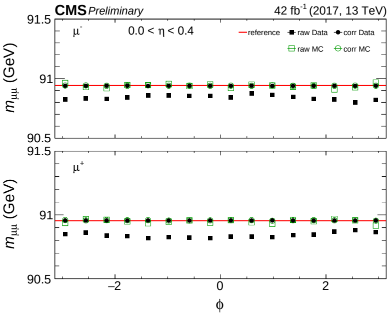


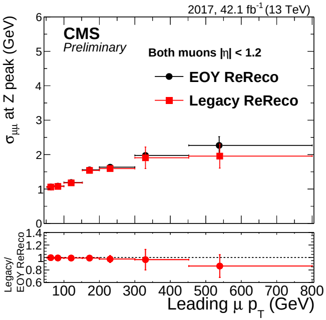


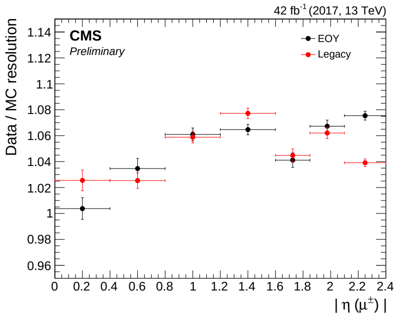


Muon calibration

CMS DP-2020/040



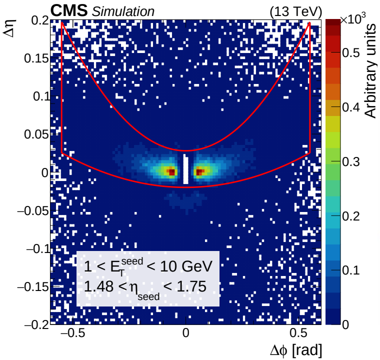


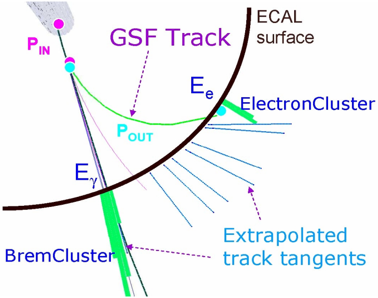


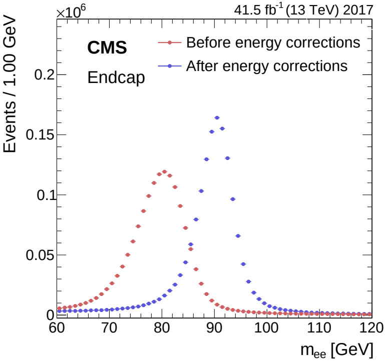
- Momentum calibration usually from line shape in $Z \to \mu\mu$ events
  - correcting both response (0.2%) and resolution (up to 8%)
  - hard limit from Z mass uncertainty: 2.3e-5
  - shift from mass-dependent width scheme: 3.7e-4
- J/Ψ: mass uncertainty: 1.9e-6, difference Pythia 8 vs PDG: 6.5e-6
- Target precision for W mass: 1e-4

Electrons

CMS EGM-17-001

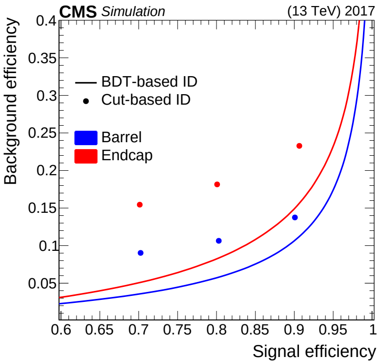


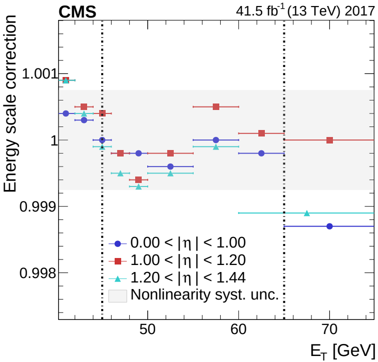


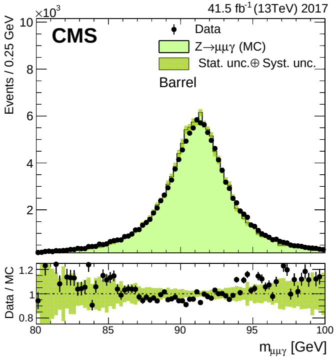


- Recover bremsstrahlung: "mustache" supercluster, "GSF" tracking algorithm, supercluster refinement (additional conversion and bremsstrahlung clusters)
- ID criteria include SC-to-track matching, HCAL/ECAL energy, isolation
- Energy regression using BDT based on shower shape and PU density (up to $\sim 8\%$)
- Efficiencies and calibration from $Z \to ee$ events, precision 0.1% (0.3%) in barrel (endcap)

Photons CMS EGM-17-001



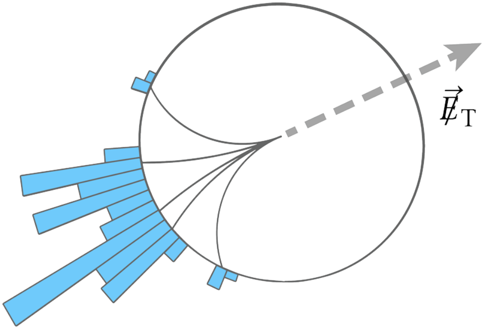


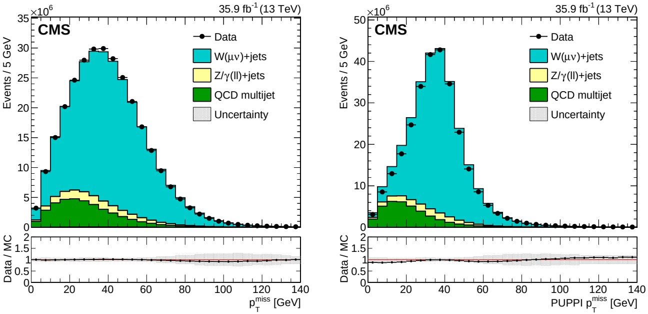


- Photons identified by [shower shape, H/E energy, isolation]$^{\mathrm{ID}}$, and electron (track) veto
- E_{T}/η-dependent corrections for $H \to \gamma\gamma$ derived from $Z \to ee$ events, precision 0.05–0.1 (0.1–0.3)% for photons in EB (EE)
- Validation of energy scale with $Z \to \mu\mu\gamma$ events → within 0.1% of $Z \to ee$

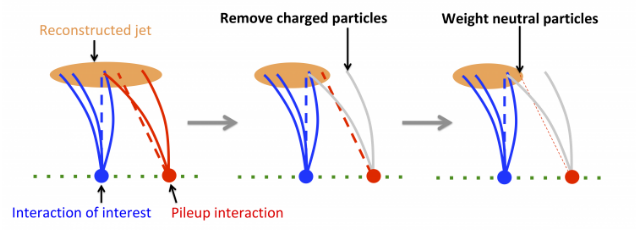
Missing transverse momentum

CMS JME-17-001 CMS JME-18-001



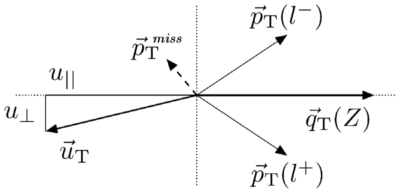


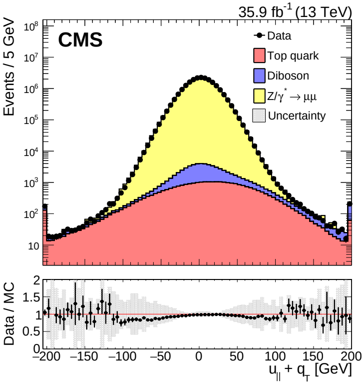
- $p_{\mathrm{T}}^{\mathrm{miss}} =$ negative vector $\vec{p}_{\mathrm{T}}$ sum of all visible final-state particles $\rightsquigarrow \sum p_{\mathrm{T}}^{\nu}$
- PUPPI algorithm tries to remove PF candidates that are likely from PU $\rightarrow$ improved resolution

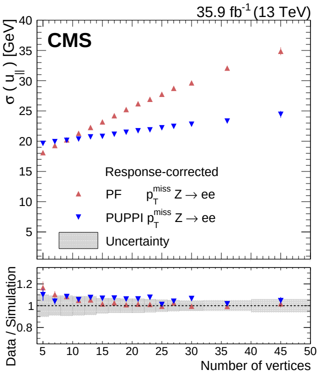


p_T^{miss} calibration

CMS JME-17-001 CMS JME-18-001







- Calibration of hadronic recoil $\vec{u}_T$ in γ or $Z \to \ell\ell$ events
- PUPPI → improved resolution and pileup resilience
- PF resolution limit for PU=0 around 10 GeV, fundamental limit from acceptance: 5 GeV
- Ongoing work on DNN algorithms to further improve p_T^{miss} resolution

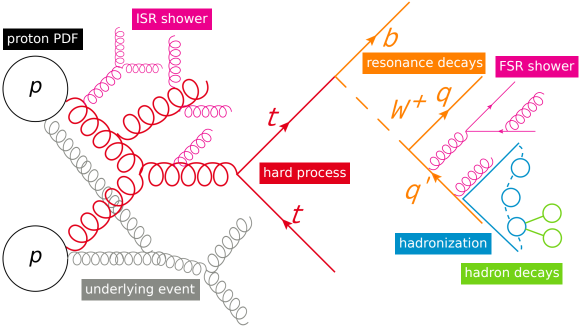
MC modeling and uncertainties

using the example of $t\bar{t}$ production

Overview MC event generation

- Measurements at the LHC rely on accurate modeling of the known physics processes
- Many stages in event generation handled by general-purpose MC generators (GPMC)

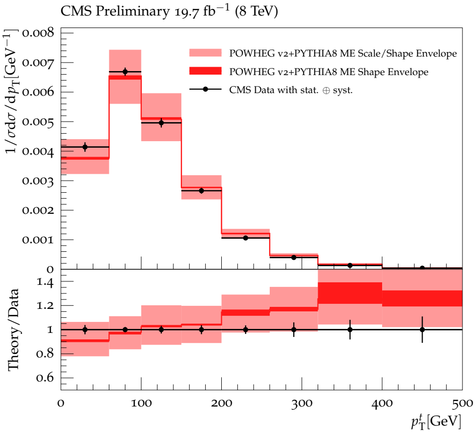
1. **Proton PDF** NNPDF, CTEQ et al.
2. **Hard process** **Resonance decay**
   GPMC or dedicated ME generators
   → MG5-aMCatNLO, Powheg
3. **Parton shower** GPMC
4. **Underlying event** **CR** GPMC
5. **Hadronization** GPMC
6. **Hadron decays** GPMC, EvtGen

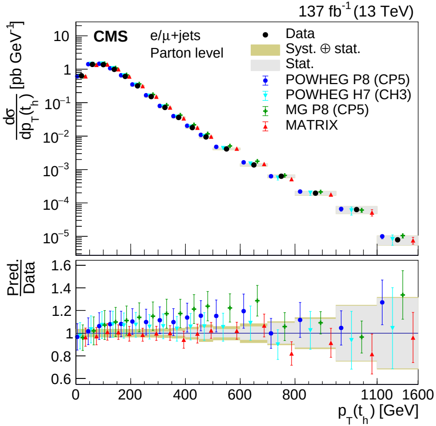


- Most widely used GPMC at the LHC are Pythia 8, Herwig 7, Sherpa 2 arXiv 1101.2599
- Dozens of model parameters to be tuned to experimental data from LEP/SLD and LHC
- Multiple Pythia 8 tunes created and used by ATLAS and CMS
- Tools: Rivet, Professor, Apprentice, MCNNTUNES

ME generators and scale uncertainties

CMS TOP-15-011 CMS TOP-20-001

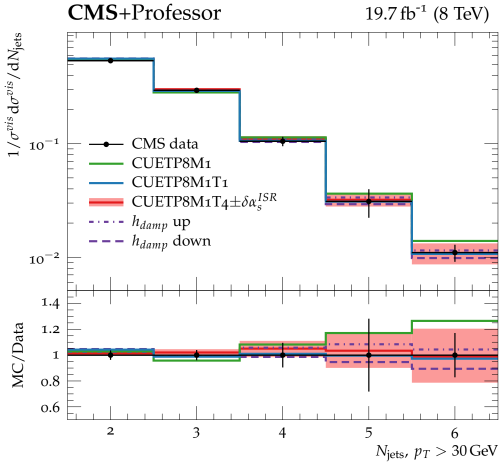


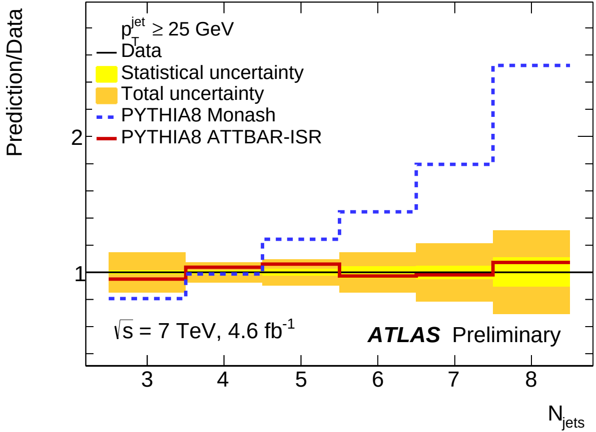


- Powheg ($t\bar{t}$@NLO): top p_T shape not covered by μ_R, μ_F 7-point variations
  - could cover data bins are uncorrelated – in practice: top p_T uncertainty
- MG5_aMCatNLO ($t\bar{t} + 2$ jets@NLO): similar agreement
- Need NNLO calculation, available now in MiNNLO+PS arXiv 2112.12135

Tuning radiation using $t\bar{t}$ data

CMS TOP-12-041 ATLAS PUB-2015-007



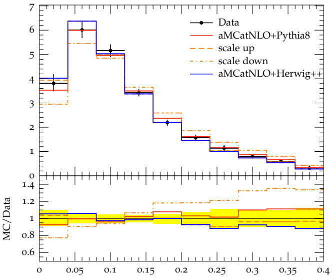


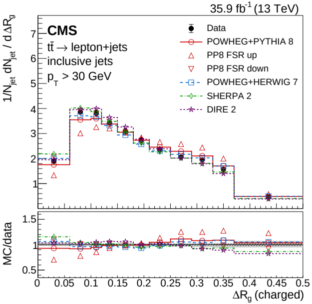
- Jet multiplicity predicted by Pythia8 default/Monash tune is too high → tune α_s^{ISR} to data, finding significantly lower values
- default $\alpha_s^{\text{ISR}} = 0.1365$, CMS $\alpha_s^{\text{ISR}} = 0.1108$, ATLAS $\alpha_s^{\text{ISR}} = 0.121$
- Run 2: CMS GEN-17-001 CP5 $\alpha_s^{\text{ISR}} = 0.118$ ATLAS PUB-2014-021 A14: $\alpha_s^{\text{ISR}} = 0.125$

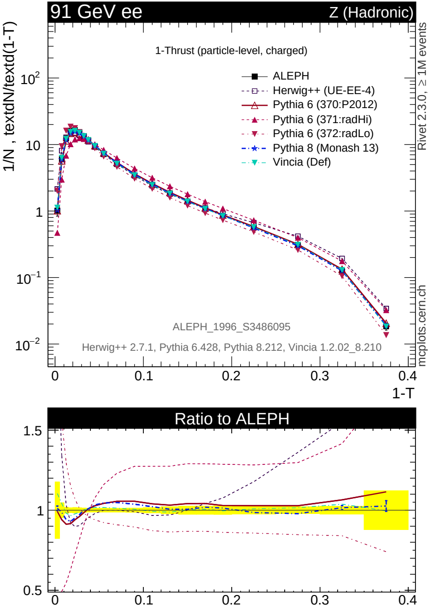
Radiation in decays

ALEPH ATLAS STDM-2011-48 ATLAS PUB-2015-007 CMS TOP-17-013

- FSR tuned to LEP event shapes, Thrust:
  - $T \rightarrow 1$: “pencil”, $T \rightarrow 1/2$: isotropic event
  - ME corrections $Z \rightarrow qqg$
  - Pythia 8 default: $\alpha_s^{\text{FSR}} = 0.1365$
- Jet shape measurements in $t\bar{t}$
  - ME corrections $t \rightarrow bWg$ and $W \rightarrow qqg$
  - α_s^{FSR} from b jet 0.127 – 0.130, need higher-order corrections for consistency

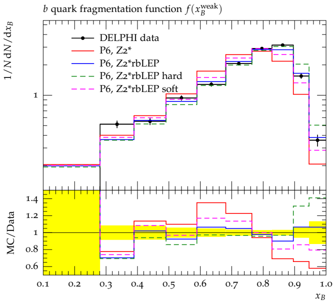


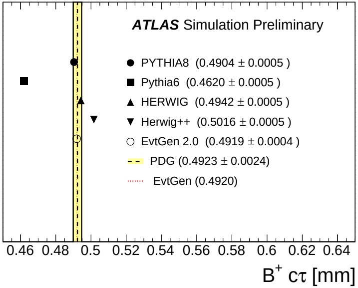


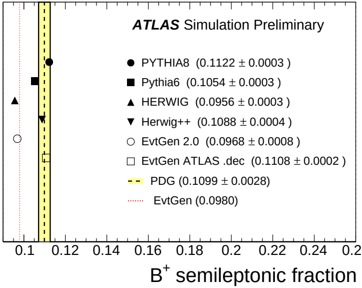


B fragmentation and decays

arXiv 1102.4748 MS ATLAS PUB-2014-008 ATLAS PUB-2016-004



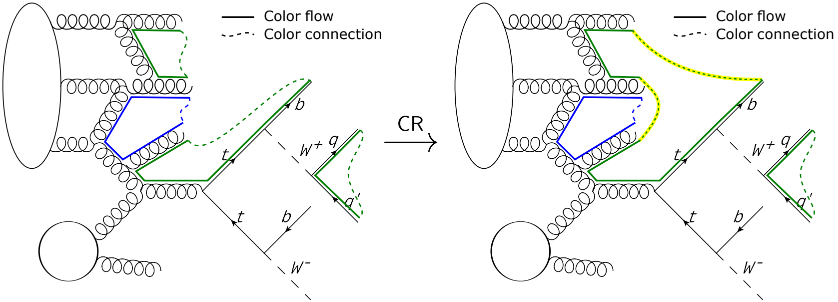


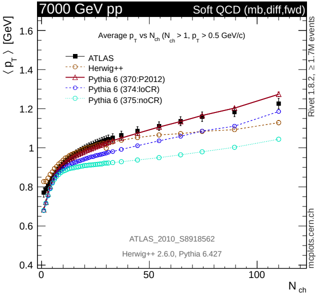


- B fragmentation function tuned to LEP data, $x_B = E_B/E_{\text{beam}}$
  - Significant impact on alternative top mass measurement using B hadron p_T
  - Recent measurements from LHC with track jet as reference, to be checked if they are precise enough CMS PAS-TOP-18-012 ATLAS STDM-2018-52 ATLAS TOPQ-2017-19
- Lifetime of B hadrons: impact on b-tag efficiencies
- Branching ratio $B \to \ell\nu X$: determines neutrino fraction in b jets → response

Color reconnection

- Color reconnection reconfigures color strings after parton shower
- Typically minimizes total string length but can also force random reconnections
- Improves description of $\langle p_T \rangle$ vs. N_{ch} in minimum-bias



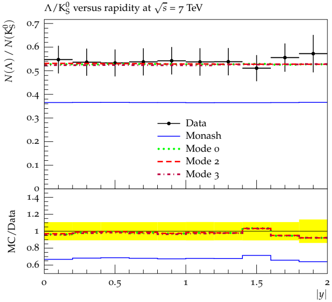


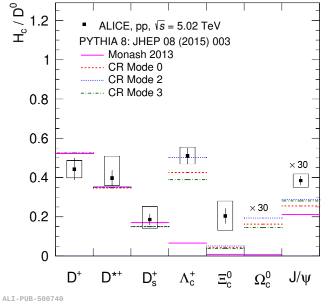
- 8 TeV: Pythia 6, Perugia2011 vs. Perugia2011noCR tunes, top decay products in CR
- 13 TeV: Pythia 8
  - PartonLevel:earlyResDec = on/**off**, by default decay products do not participate in CR
  - New CR models: QCD-inspired/CR1 arXiv 1505.01681 gluon-move/CR2 arXiv 1407.6653

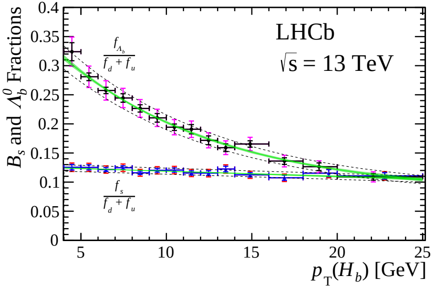
Color reconnection and baryon enhancement

- Hadronization model tuned to LEP data, including amount of baryons
- Observed enhancement of strange, charm, and bottom baryons in pp collisions:

CMS QCD-10-007 ALICE arXiv 2105.06335 arXiv 2106.08278 LHCb arXiv 1902.06794

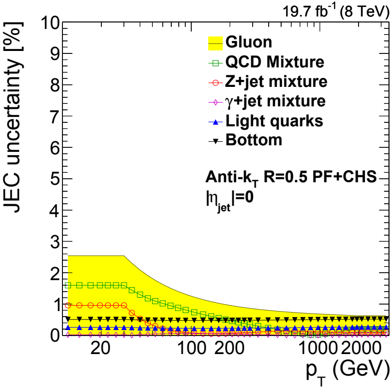


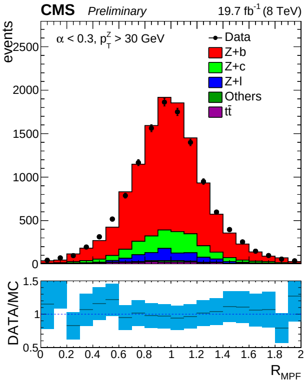


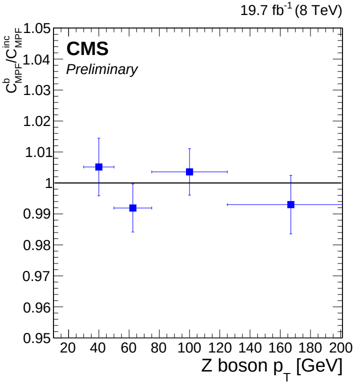


- New QCD-inspired CR model able to describe these distributions arXiv 1505.01681
  → need to include them in the tuning, as done by the authors' Mode 0/2/3 tunes
- Baryon fraction influences jet energy response ATLAS PUB-2022-021 ATLAS ETM-2022-005
- Need more measurements: enhancements also in jets and resonance decays?

Parton shower algorithm: Pythia vs. Herwig





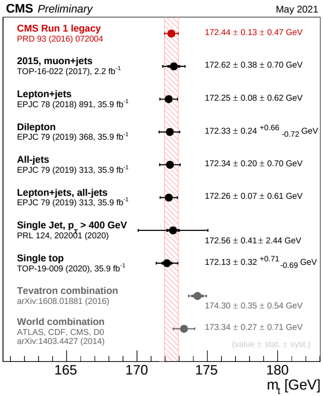


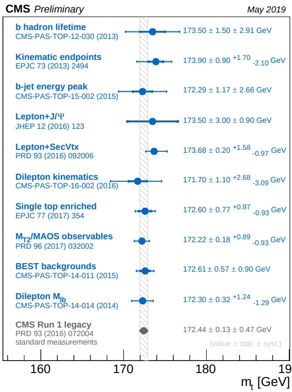
- Full comparison: changes matching, parton shower, MEC, hadronization, underlying event
- Consider Pythia 6 vs. Herwig++ jet response difference (GenJet→Jet)
  - Response depends on particle multiplicity, p_T spectrum, and type
  - 0.5% uncertainty on b jet response → leading uncertainty in top mass measurements
- CMS PAS-JME-13-001 Direct measurement of b jet response using $Z + b$ events (0.6%)
- Revise recipe for upcoming parton showers with higher accurcay (PanScales, Vincia, ...)

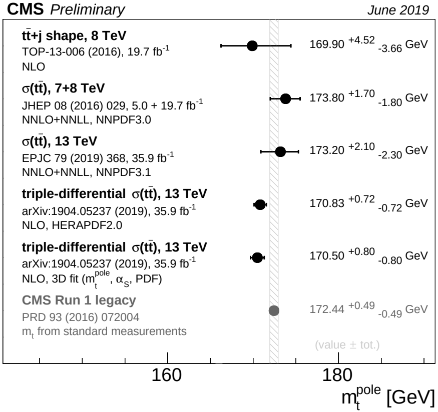
Top mass measurements

CMS top mass measurements

CMS TOP publications







Direct measurements

- Most precise
- Bound to mass definition of MC

Alternative measurements

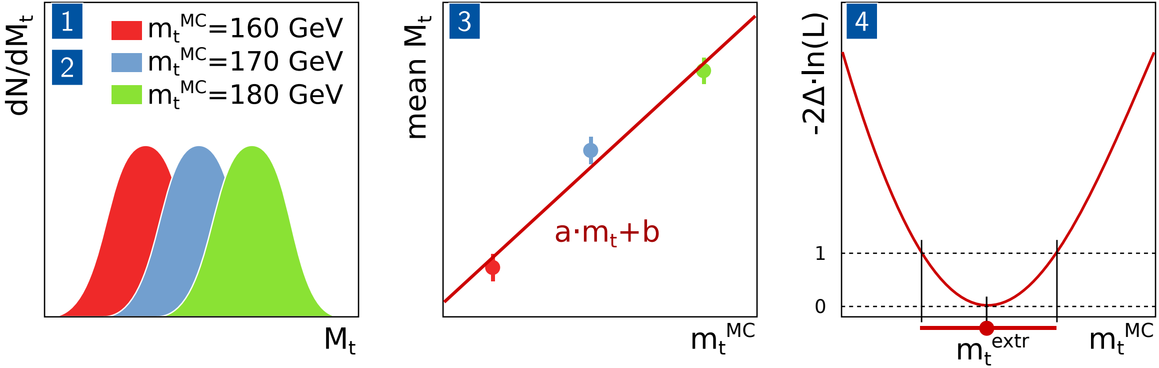
- Different observables
- E.g., reduce JES at cost of large b frag uncertainty

Pole mass measurements

- Straightforward from $\sigma_{t\bar{t}}$
- Others often missing resummation corrections

Prescription for direct mass measurements

1. Select $t\bar{t}$ events – high integrated luminosity, efficient b-tag algorithms
2. Construct estimator M_t for top mass
3. Parametrize dN/dM_t in terms of m_t^{MC}
4. Perform maximum likelihood fit. Calibration and uncertainties on MC, final result on data

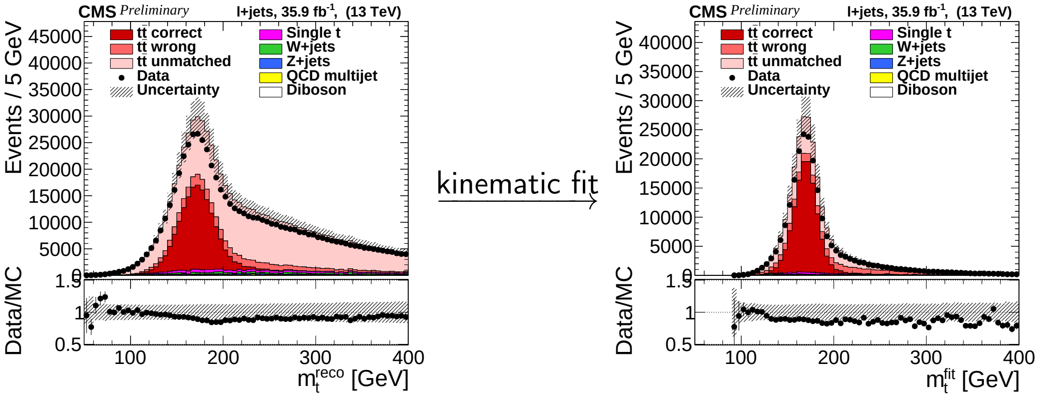


- Extensions: multi-dimensional fits, ideogram method, matrix-element method

Top-quark mass using profile likelihood approach at 13 TeV

CMS PAS-TOP-20-008

- Select events with 1 high-p_T e/μ and 4 jets (2 DeepJet b tags)
- Jet-parton assignment for hadronic ($t \to bqq$) and leptonic ($t \to b\ell\nu$) top quarks $\to$ kinematic fit to $t\bar{t}$ hypothesis ($m_W = 80.4$ GeV, $m_t = m_{\bar{t}}$)
- Require $P_{\text{gof}} > 0.2$, keep best jet-parton assignment per event

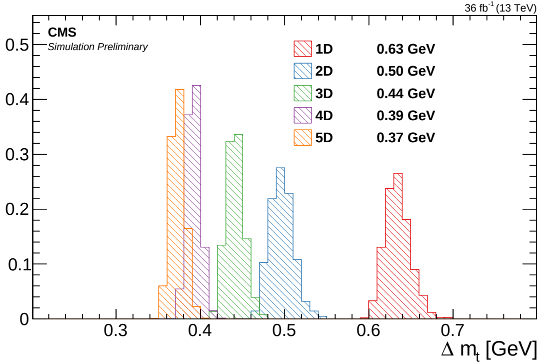


Top-quark mass using profile likelihood approach at 13 TeV

CMS PAS-TOP-20-008

- Perform profile-likelihood fit to 5 observables, systematic uncertainties treated as nuisance parameters and constrained

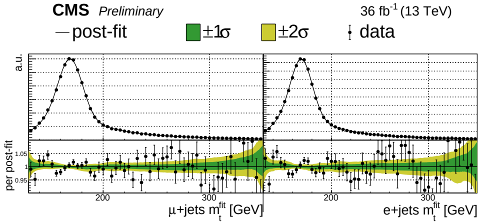
	histogram	set label				
observable	category	1D	2D	3D	4D	5D
$m_{\mathrm{t}}^{\mathrm{fit}}$	$P_{\mathrm{gof}} \geq 0.2$	x	x	x	x	x
$m_{\mathrm{W}}^{\mathrm{reco}}$	$P_{\mathrm{gof}} \geq 0.2$		x	x	x	x
$m_{\ell\mathrm{b}}^{\mathrm{reco}}$	$P_{\mathrm{gof}} < 0.2$			x	x	x
$m_{\ell\mathrm{b}}^{\mathrm{reco}} / m_{\mathrm{t}}^{\mathrm{fit}}$	$P_{\mathrm{gof}} \geq 0.2$				x	x
$R_{\mathrm{bq}}^{\mathrm{reco}}$	$P_{\mathrm{gof}} \geq 0.2$					x

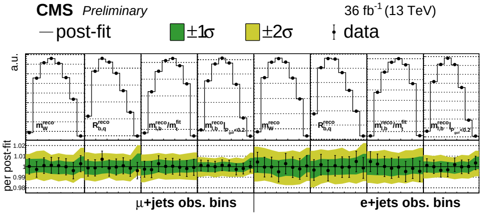


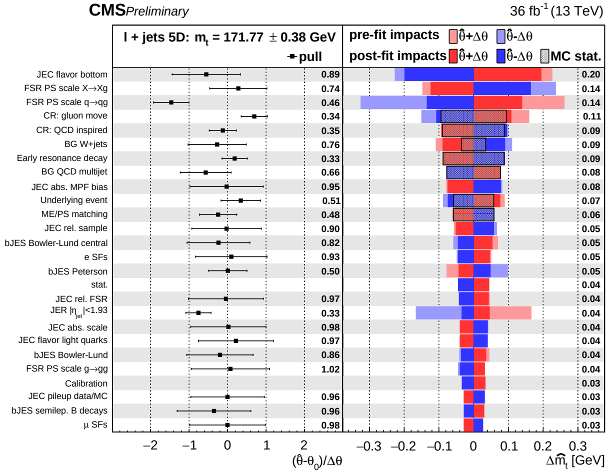
- 2D: constrain jet energy scale from W mass
  - corresponds to Run 1 legacy measurement CMS TOP-14-022
- 3D: m_t information from events failing kinematic fit
- 4/5D: observables sensitive to b-jet energy scale

Top-quark mass using profile likelihood approach at 13 TeV

CMS PAS-TOP-20-008





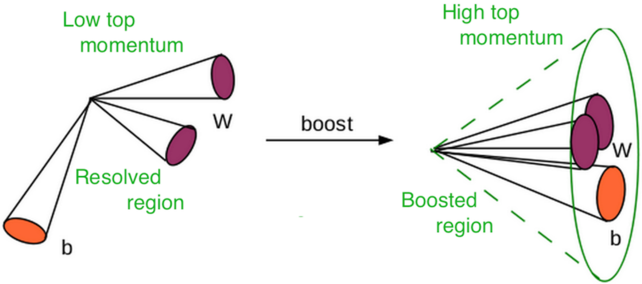


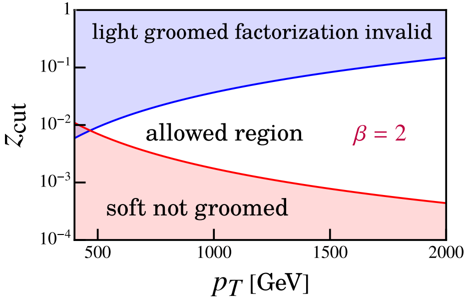
- Constraining components of (b) jet energy scale and FSR modeling
- Result of 5D fit is most precise single measurement to date! $\rightarrow m_t = 171.77 \pm 0.38\,\mathrm{GeV}$

Top-quark mass in boosted top decays

arXiv 1708.02586 ATLAS PUB-2021-034

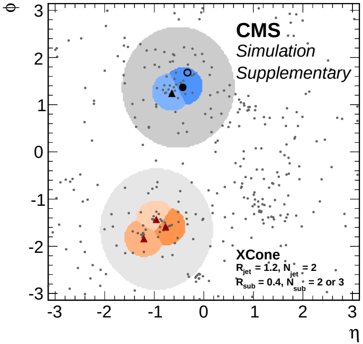
- Complementary phase space: measure m_t using boosted top quarks
- SCET calculations of top mass peak for $p_\mathrm{T} > 750\,\mathrm{GeV}$
- Estimated $\Delta^\mathrm{MSR} = m_t^\mathrm{MC} - m_t^\mathrm{MSR}(1\,\mathrm{GeV}) = 80^{+350}_{-400}\,\mathrm{MeV}$

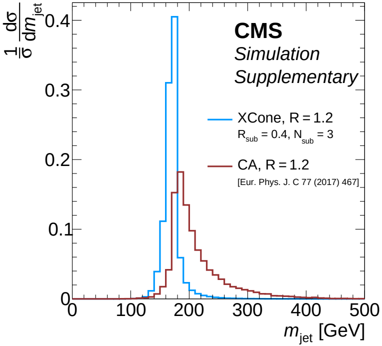


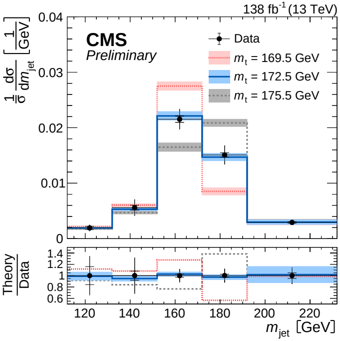


Top-quark mass in boosted top decays

CMS TOP-19-005 CMS TOP-21-012







- Events with high-p_T lepton, $p_T^{miss} > 50\,\text{GeV}$, ≥ 1 b jet
- XCone jet with $p_T > 400\,\text{GeV}$, improved resolution wrt CA jet
- Constrained jet energy scale from hadronic W subjets
- Unfolded jet mass distribution to particle level, Rivet for 2012+2016 analyses
- Extracted top mass for $p_T > 400\,\text{GeV}$: $m_t = 172.76 \pm 0.81\,\text{GeV}$

Top pole mass from cross section

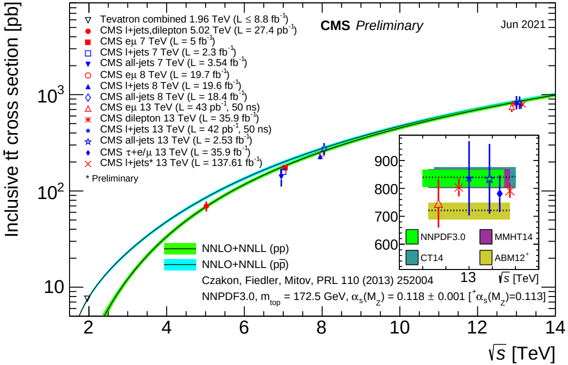
CMS TOP-13-004 CMS TOP-17-001

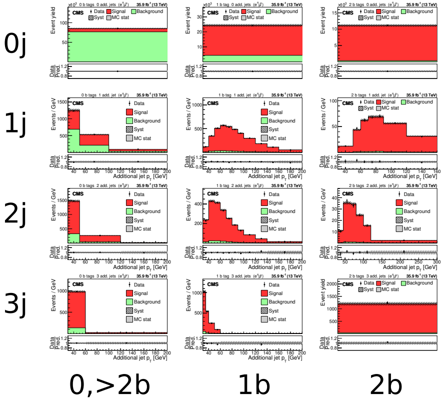
- Most precise $\sigma_{t\bar{t}}$ in dilepton channel (ee, $\mu\mu$, eμ): 2 leptons, 2 neutrinos, 2 b jets
- Cross section extracted from fit over b and additional light jet categories, largest uncertainties from lepton efficiencies and luminosity

$$\sigma_{t\bar{t}}^{7\text{ TeV}} = 173.6 \pm 2.1\ (\text{stat})^{+4.5}_{-4.0}\ (\text{syst}) \pm 3.8\ (\text{lumi})\ \text{pb} \quad \left({}^{+3.6}_{-3.5}\,\%\right)$$

$$\sigma_{t\bar{t}}^{8\text{ TeV}} = 244.9 \pm 1.4\ (\text{stat})^{+6.3}_{-5.5}\ (\text{syst}) \pm 6.4\ (\text{lumi})\ \text{pb} \quad \left({}^{+3.7}_{-3.5}\,\%\right)$$

$$\sigma_{t\bar{t}}^{13\text{ TeV}} = 803 \pm 2\ (\text{stat}) \pm 25\ (\text{syst}) \pm 20\ (\text{lumi})\ \text{pb} \quad (\pm 4.0\%)$$

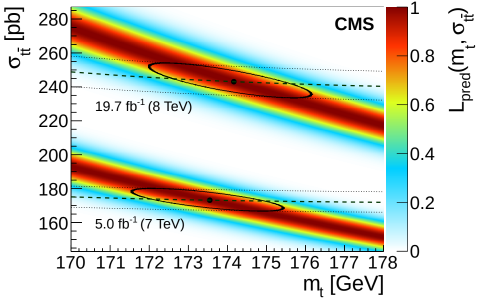


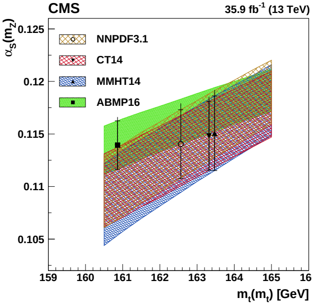


Top pole mass from cross section

CMS TOP-13-004 CMS TOP-17-001

- Measured and predicted $\sigma_{t\bar{t}}$ have different dependence on m_t
- m_t from intersection with the prediction





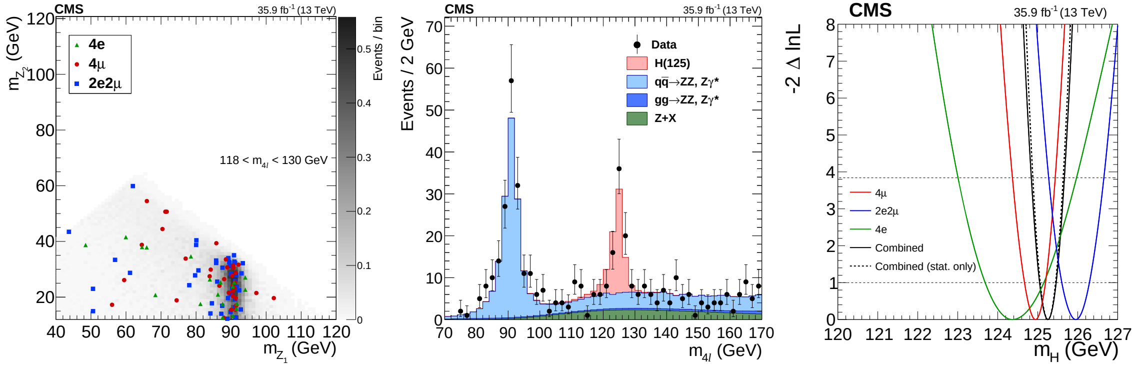
	7 TeV	8 TeV	7 + 8 TeV	13 TeV
NNPDF3.x	$173.5^{+1.9}_{-2.0}$	$174.2^{+2.0}_{-2.2}$	$173.8^{+1.7}_{-1.8}$	173.2 ± 1.9 (fit + PDF + α_s) $^{+0.9}_{-1.3}$ (scale)
MMHT14	$173.9^{+2.0}_{-2.1}$	$174.4^{+2.1}_{-2.3}$	$174.1^{+1.8}_{-2.0}$	173.6 ± 1.9 (fit + PDF + α_s) $^{+0.9}_{-1.4}$ (scale)
CT14	$174.1^{+2.2}_{-2.4}$	$174.6^{+2.3}_{-2.5}$	$174.3^{+2.1}_{-2.2}$	173.7 ± 2.0 (fit + PDF + α_s) $^{+0.9}_{-1.4}$ (scale)
ABMP16				169.9 ± 1.8 (fit + PDF + α_s) $^{+0.8}_{-1.2}$ (scale)

- Most precise result with NNPDF3.0 at 7+8 TeV: $m_t = 173.8^{+1.7}_{-1.8}$ GeV
- 3 GeV downward shift with ABMP16, enveloping direct measurements

Higgs mass measurements

Higgs mass measurement $H \to 4\ell$

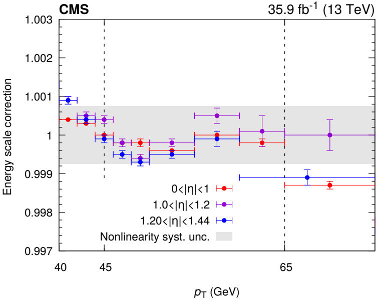
CMS HIG-16-041

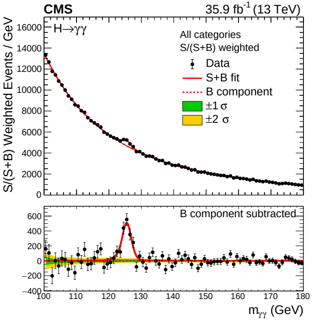


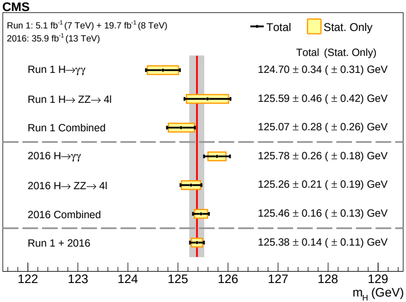
- Selecting $H \to ZZ \to 4\ell$ events, cuts on $Z_1 Z_2$ to suppress $ZZ/Z\gamma^*$
- Custom lepton corrections from Z and J/Ψ down to very low p_T, mass scale uncertainty 0.04/0.3/0.1% for $4\mu/4e/2e2\mu$ channels
- Extracted mass limited by statistics: $m_H = 125.26 \pm 0.20\ (\text{stat}) \pm 0.08\ (\text{syst})$ GeV

Higgs mass measurement $H \to \gamma\gamma$ and combination

CMS HIG-19-004



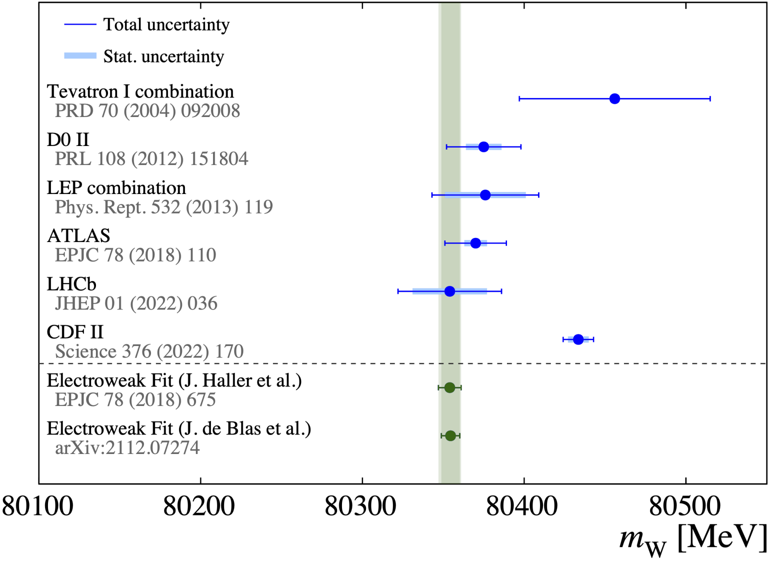




- $Z \to ee$ calibration, E_{T} dependence, γ/e difference, all at level of 0.1%
- Scaling cuts $p_{\mathrm{T}}^{\gamma 1} > m_{\gamma\gamma}/3$ and $p_{\mathrm{T}}^{\gamma 2} > m_{\gamma\gamma}/4$ to avoid distortion of low $m_{\gamma\gamma}$
- Choice of background function (exp, pol, power) → discrete nuisance parameter
- Extracted mass: $m_H = 125.26 \pm 0.18\ (\mathrm{stat}) \pm 0.18\ (\mathrm{syst})\ \mathrm{GeV}$
- Combination with Run 1 and 4ℓ: $m_H = 125.38 \pm 0.11\ (\mathrm{stat}) \pm 0.08\ (\mathrm{syst})\ \mathrm{GeV}$

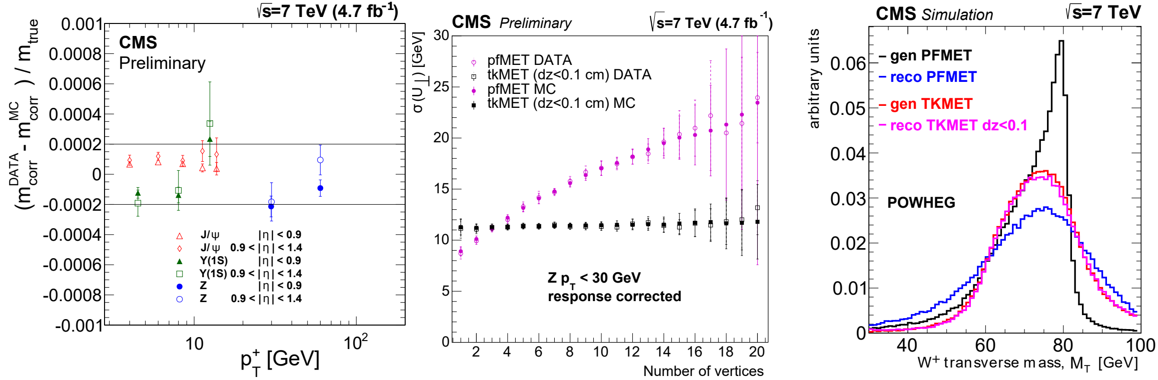
W mass measurements

W mass measurements



W-like measurement of Z boson mass

CMS PAS-SMP-14-007



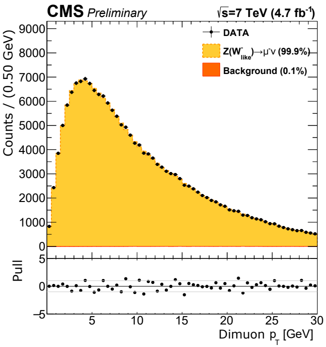
- Muon calibration at level of 2e-4 using J/Ψ and $Y(1S)$, corrected curvature $k = 1/p_T$

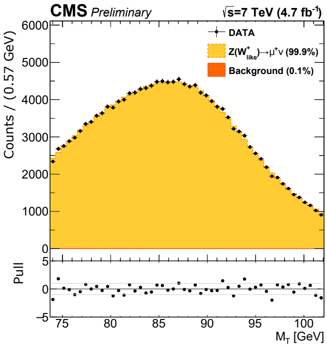
$$k^c = \underset{\text{magnetic field}}{(A-1)\,k} + \underset{\text{misalignment}}{qM} + \underset{\text{energy loss}}{k/(1+k\epsilon\sin\theta)}$$

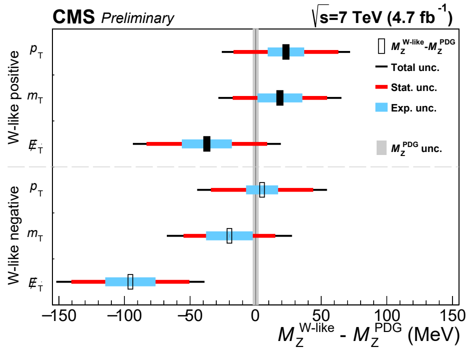
- p_T^{miss} reconstructed from tracks, captures only 40% of recoil but stable against PU, better resolution for transverse mass Jacobian peak

W-like measurement of Z boson mass

CMS PAS-SMP-14-007



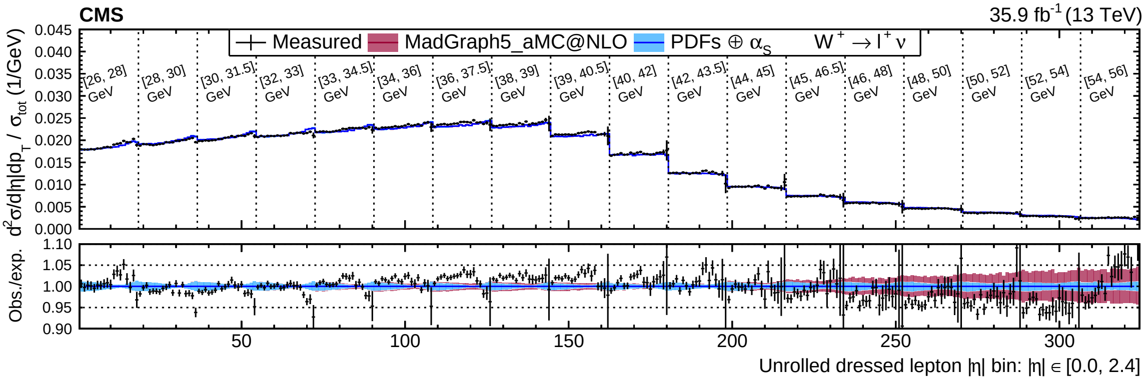




- Boson p_T distribution reweighted to data, no uncertainty considered
- Large QED (Powheg EW on/off) and statistical uncertainties
- Fit ±charge triggered samples separately → good agreement with each other and PDG

Lepton distributions from W helicity measurement

CMS SMP-18-012



- Unfolded lepton p_T/η distributions, demonstrated constraints on PDF eigenvectors, why not use for m_W?
- Lepton calibration was not at desired level for m_W yet
- Not a complete model for theory uncertainties, would result in overfitting

Summary

Rich program of precision mass measurements at CMS

- Top mass uncertainty down to 380 MeV
    - with question marks regarding theoretical interpretation though
- Higgs mass uncertainty down to 140 MeV
    - limited by statistics, full-Run 2 yet to come
- W mass work in progress :o)