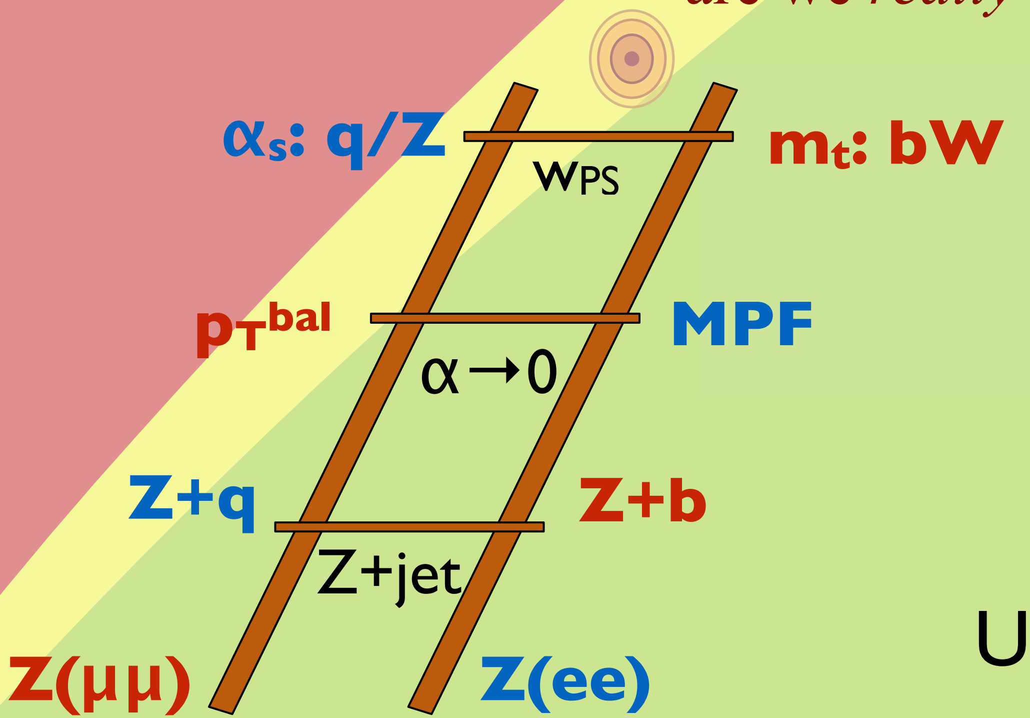
Climbing the ladder: from Z(ll) to m_t and α_s

are we *really* here?



Feb 11, 2010

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U. Helsinki and HIP

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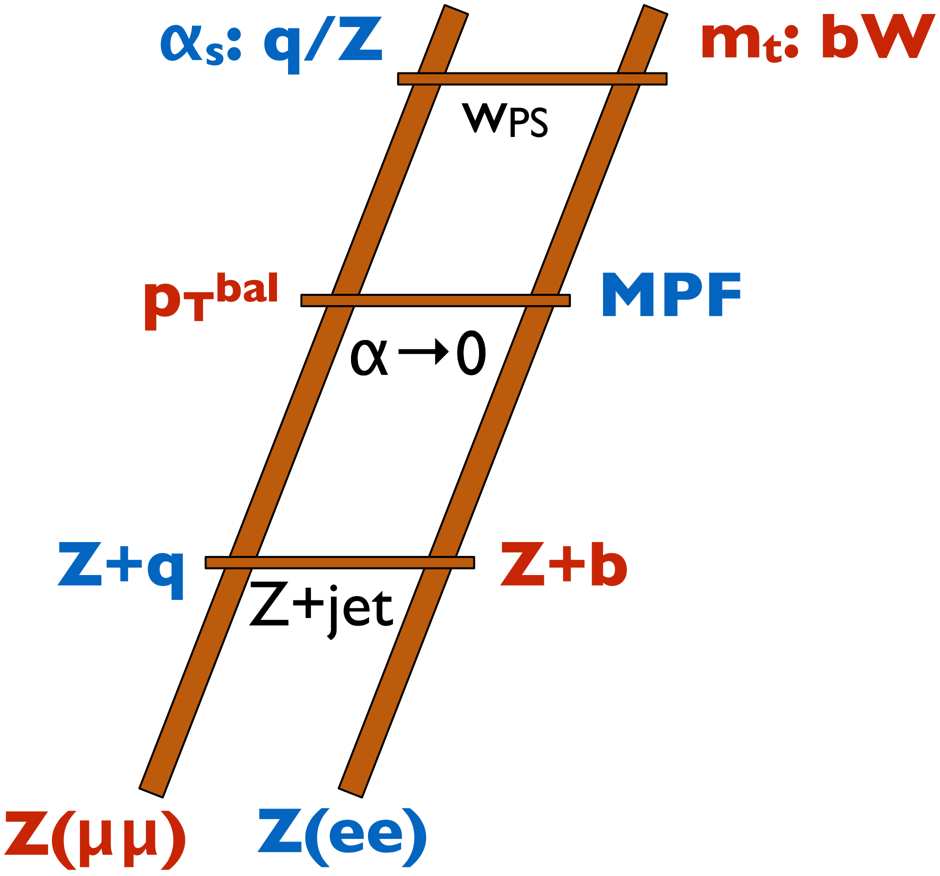
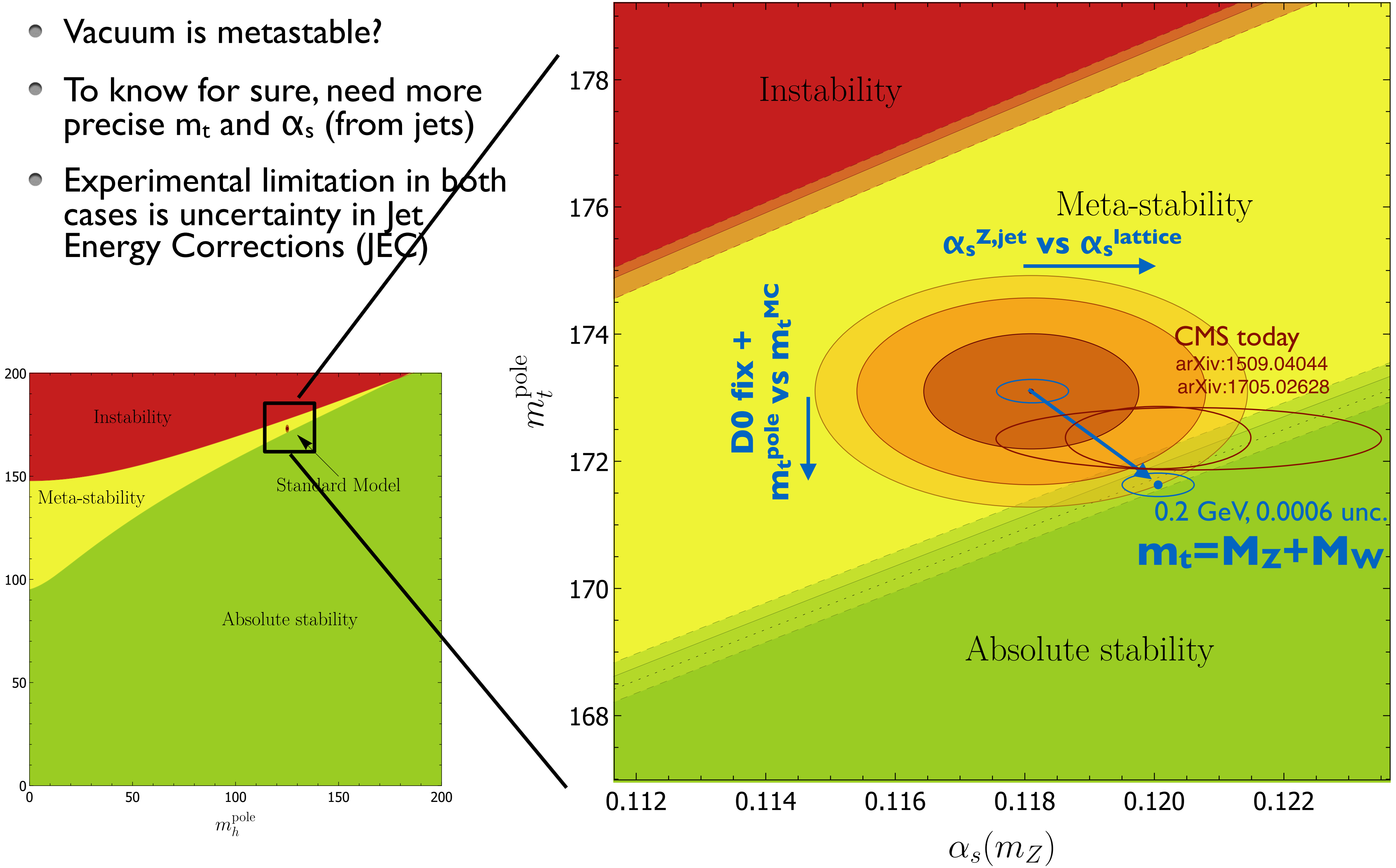


Caveat: I'm a CMS experimentalist, and as such not allowed to show unpublished results on data. To facilitate concrete discussion I will show results on representative stand-alone MC only.

LHC precision frontier

- Vacuum is metastable?
- To know for sure, need more precise m_t and α_s (from jets)
- Experimental limitation in both cases is uncertainty in Jet Energy Corrections (JEC)

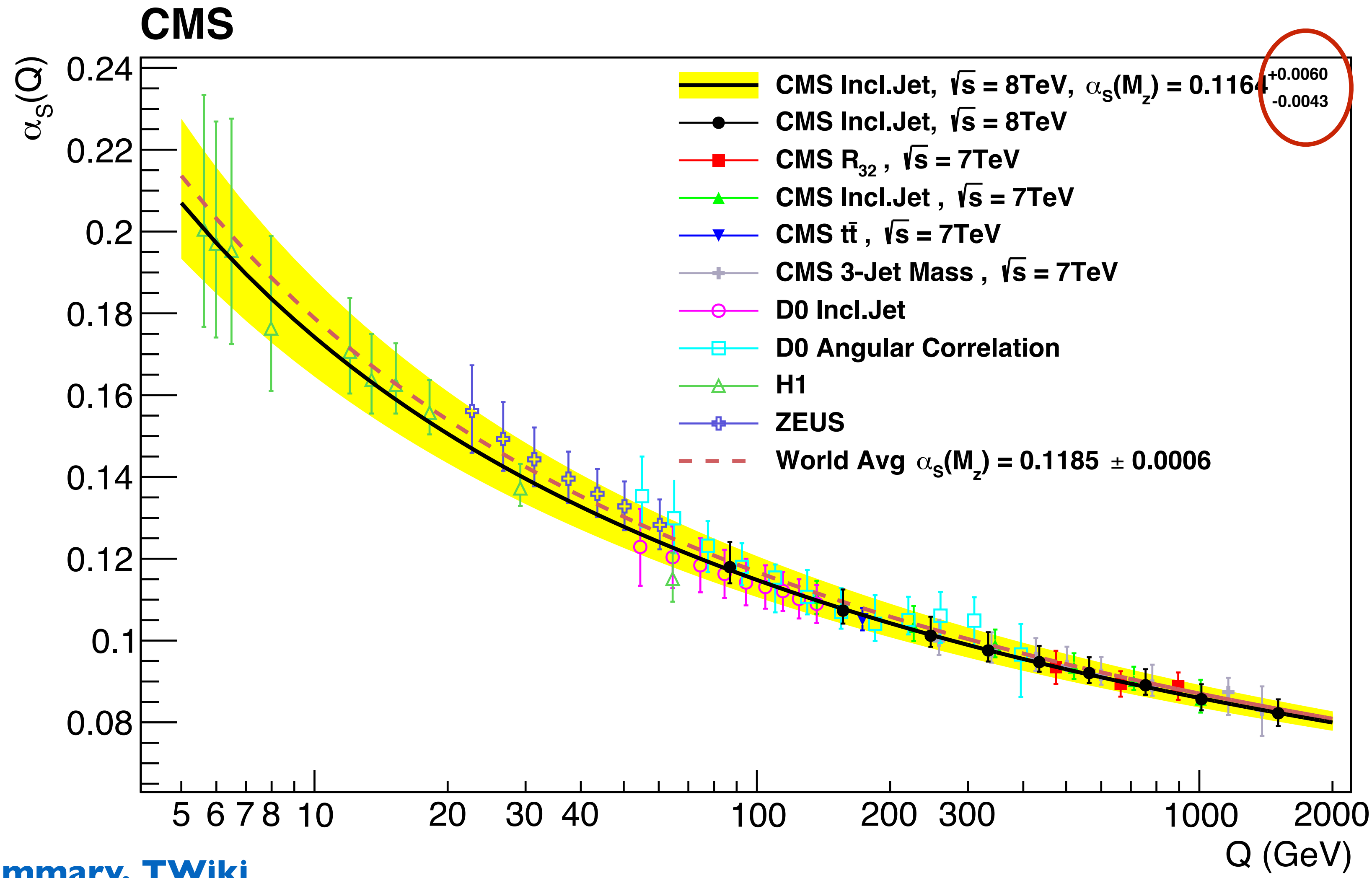


A. Andreassen, W. Frost, M. Schwartz, arXiv:1707.08124

Schwartz et al., arXiv:1707.08124

Measurement of α_s

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



mostly from theory scale uncertainty

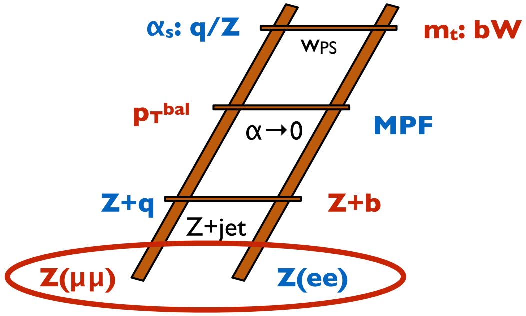
CMS summary, TWiki

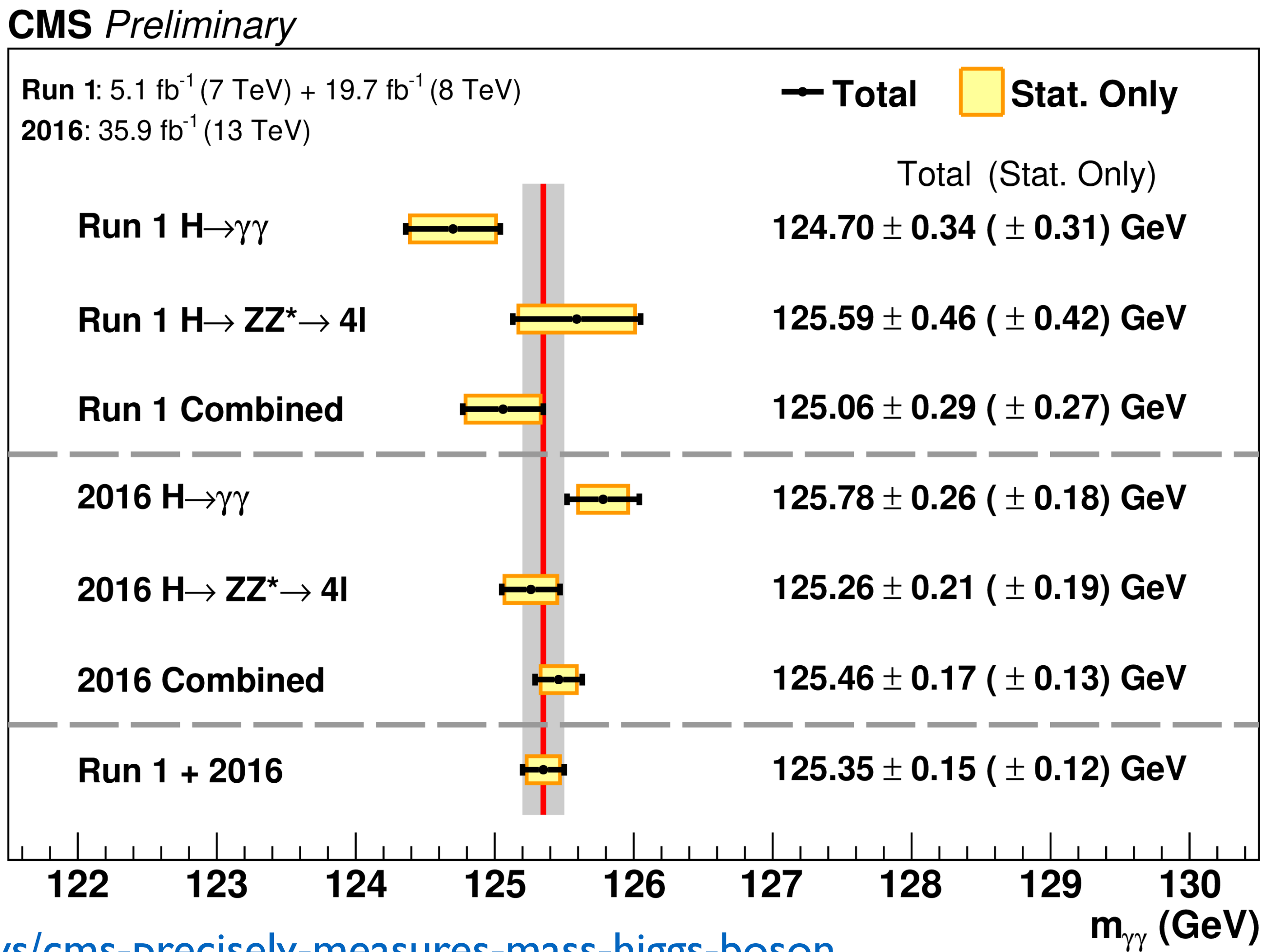
Experimental pre-requisites

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

Lepton reconstruction

- Start calibration ladder from Z(ll)
- Leptons (e,μ) calibrated with m_Z wrt LEP
- Precision far **better than 0.10%**
  - case in point: Δm_H=0.12%, still mostly statistics (syst. 0.07%)





https://cms.cern/news/cms-precisely-measures-mass-higgs-boson

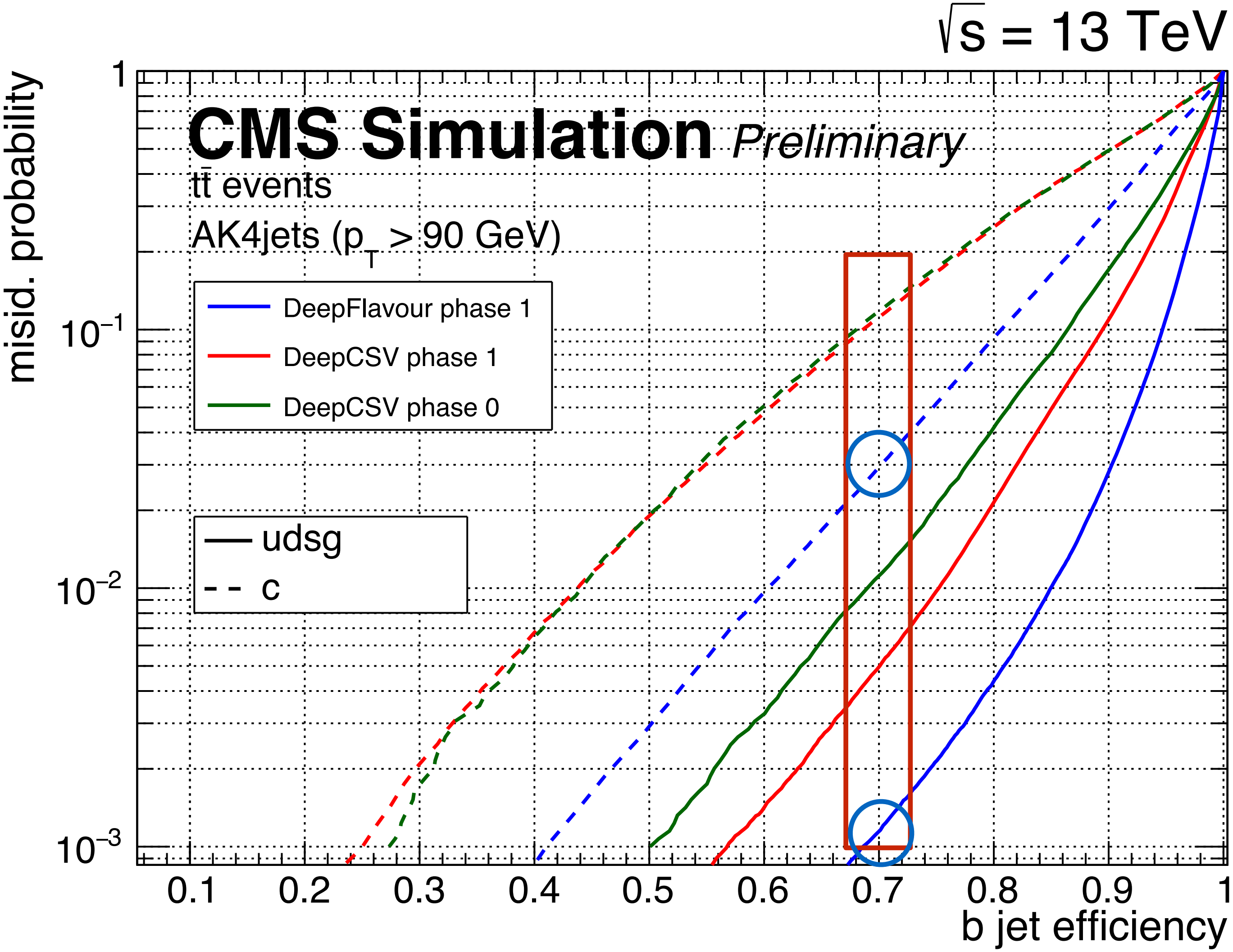
b-tagging

- 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%**

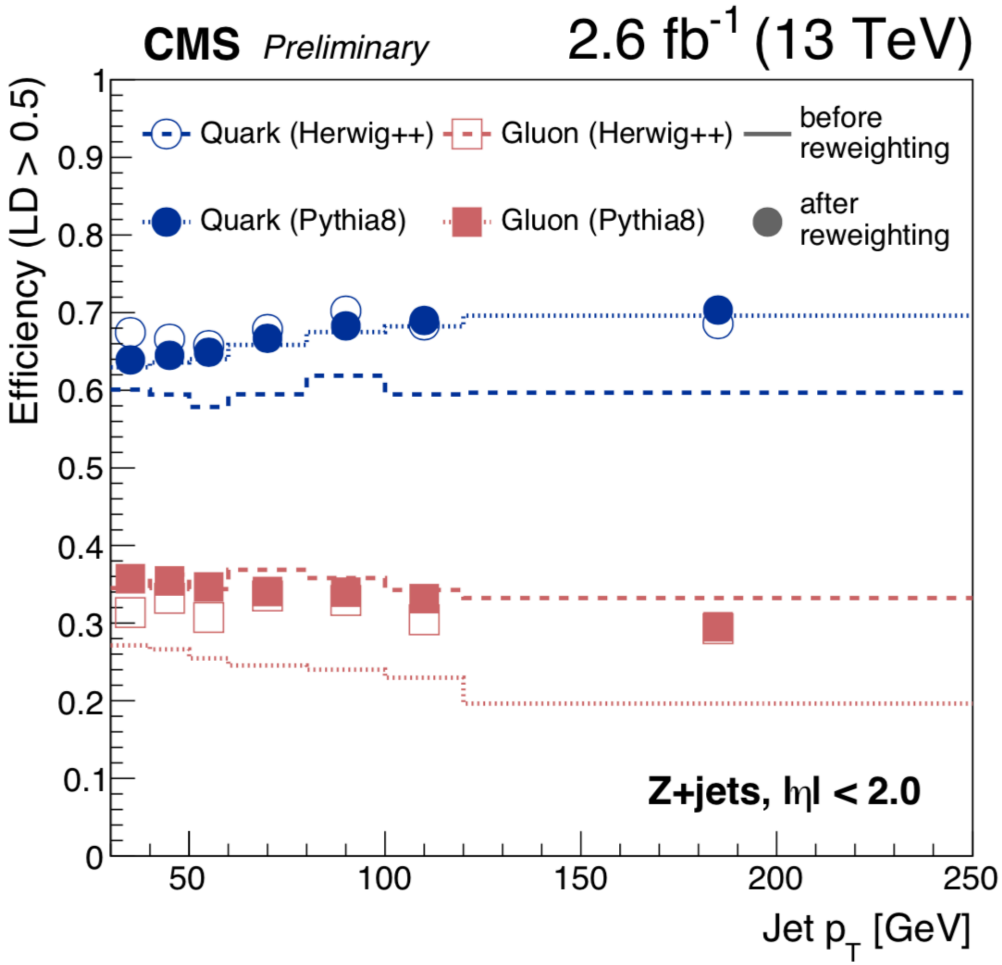
- By-product: deep methods can now also reasonably tag charm quarks vs b and udsg

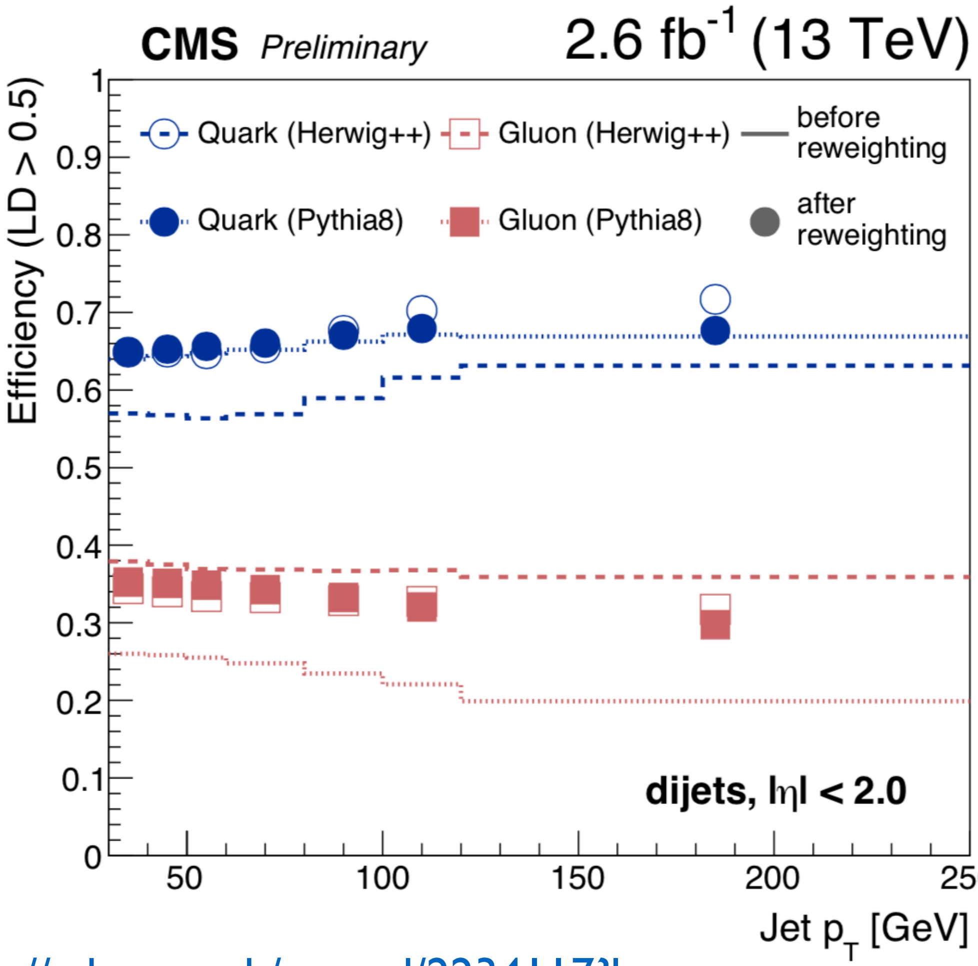


https://twiki.cern.ch/twiki/bin/view/CMSPublic/BTV13TeV2017FIRST2018

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 (σ_2)
- Quark/gluon efficiencies in data extracted by comparing Z+jet and dijet QGL shapes
- Pythia8 and Herwig++ bit agree after reweighing: **quark eff. ~0.7, gluon eff. ~0.3**

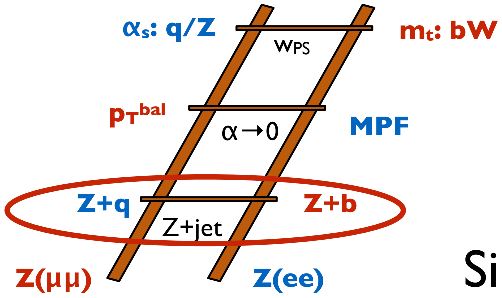


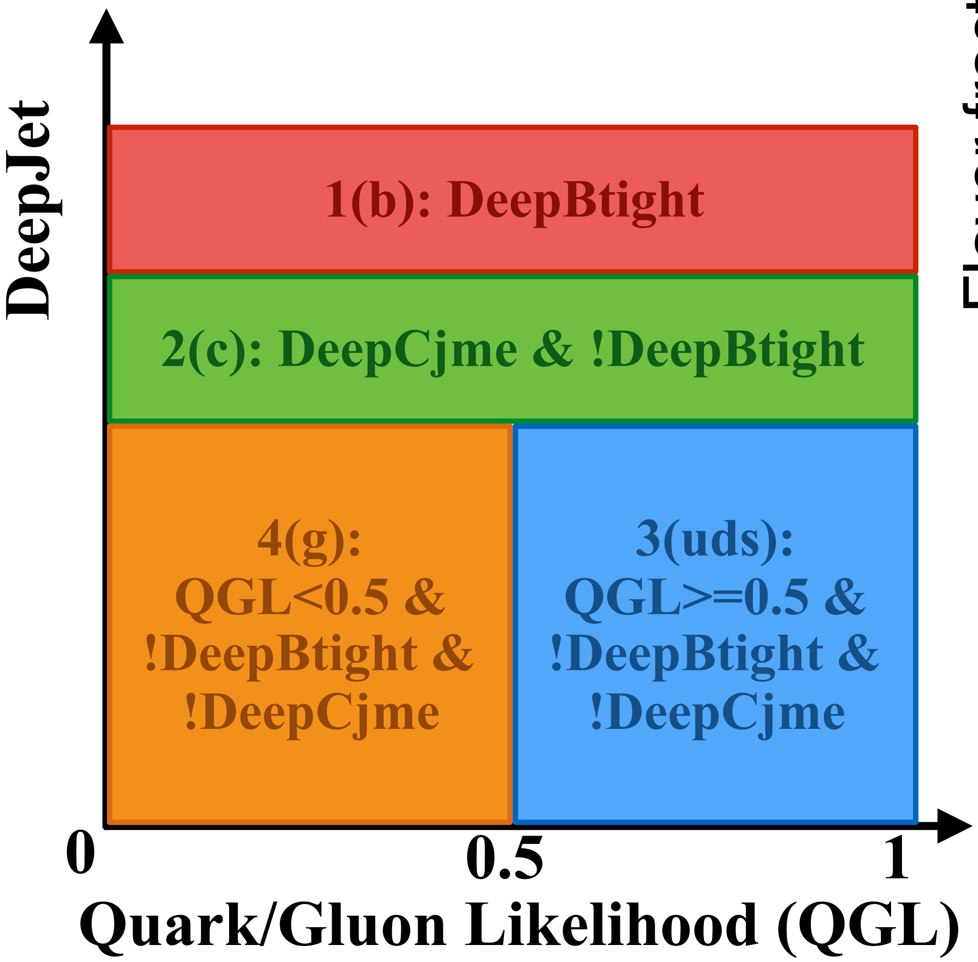


https://cds.cern.ch/record/2234117?ln=en

Flavor-tagging in Z+jet

- 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



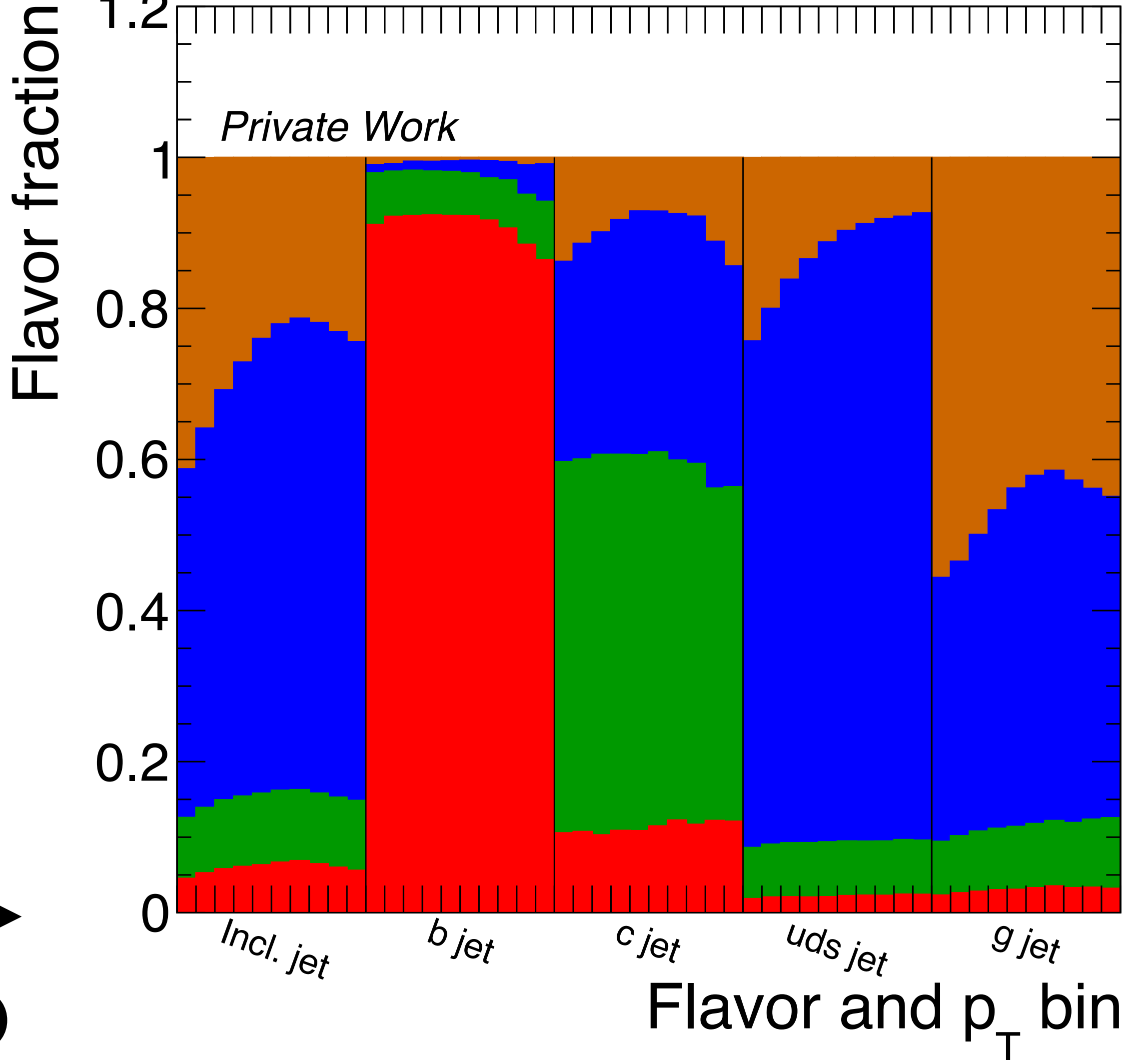


1(b): DeepBtight

2(c): DeepCjme & !DeepBtight

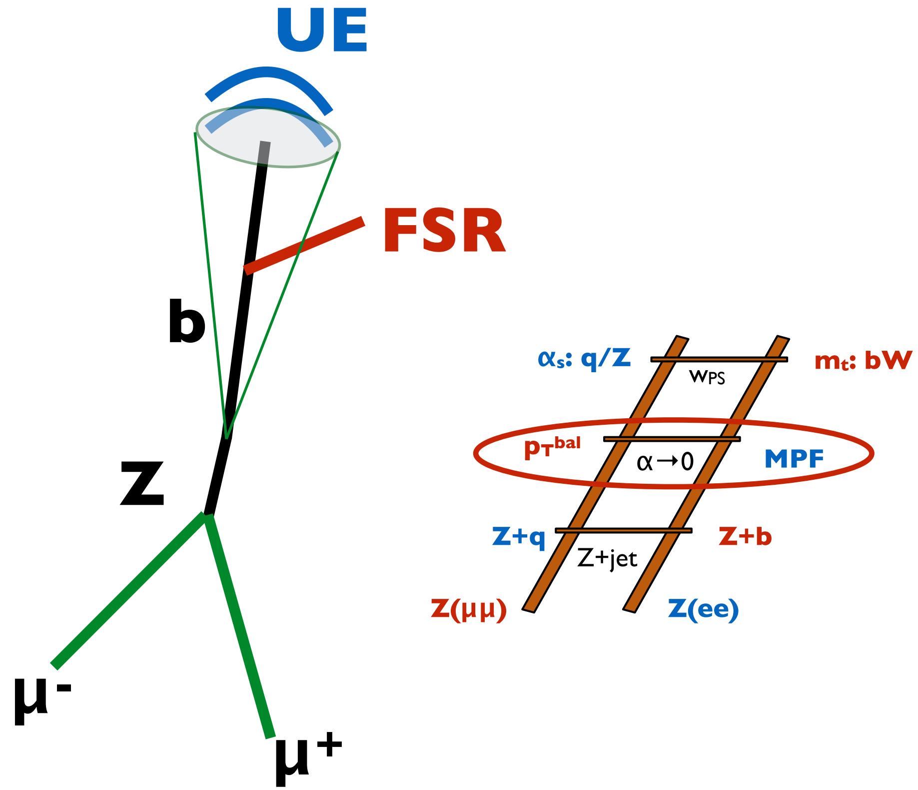
4(g): QGL<0.5 & !DeepBtight & !DeepCjme

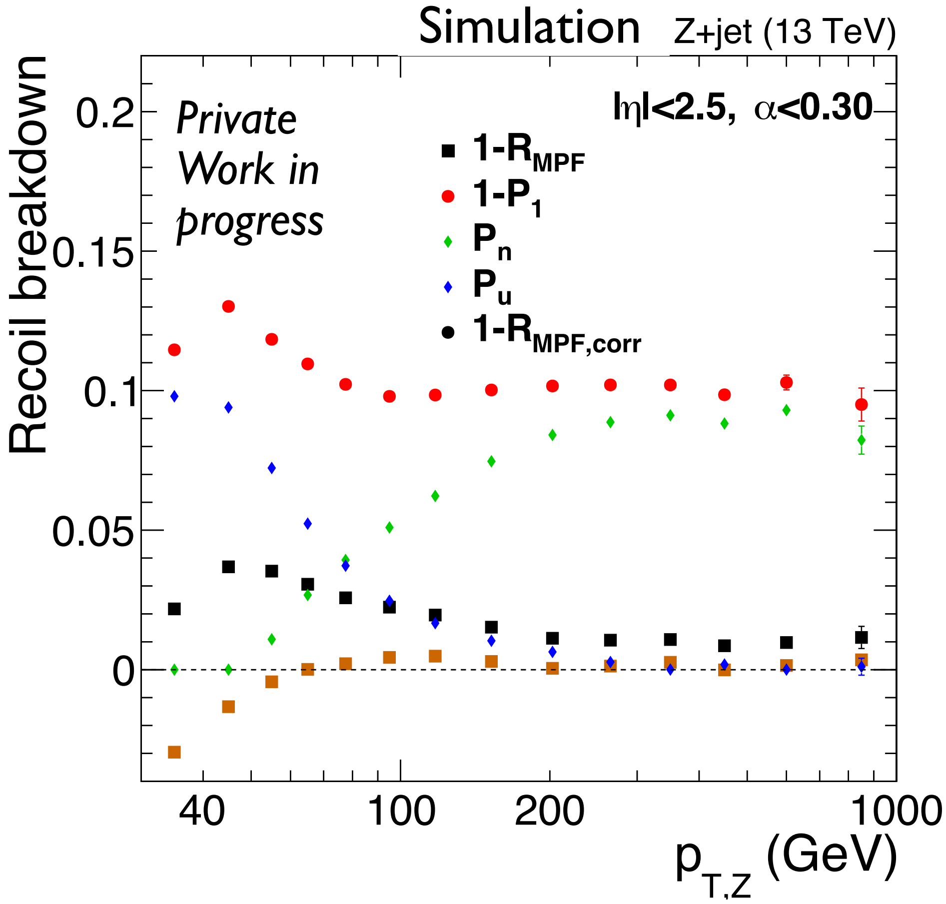
3(uds): QGL>=0.5 & !DeepBtight & !DeepCjme



Missing-E_T projection fraction

- 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 :
  - **$P_l = R_l f_l$**: leading jet (b) — R_l calibrated up to data/MC difference (aka p_T^{bal} method)
  - $P_n = R_n f_n$: subleading jets (2..n) of **$p_T > 15$ GeV** — R_n calibrated up to residual (gluon) flavor
  - $P_u = R_u f_u$: unclustered particles — R_u not calibrated
- Two identities:
  - **$R_{MPF} = P_l + P_n + P_u$** (aka MPF method)
  - $1 = f_l + f_n + f_u$ (momentum conservation)





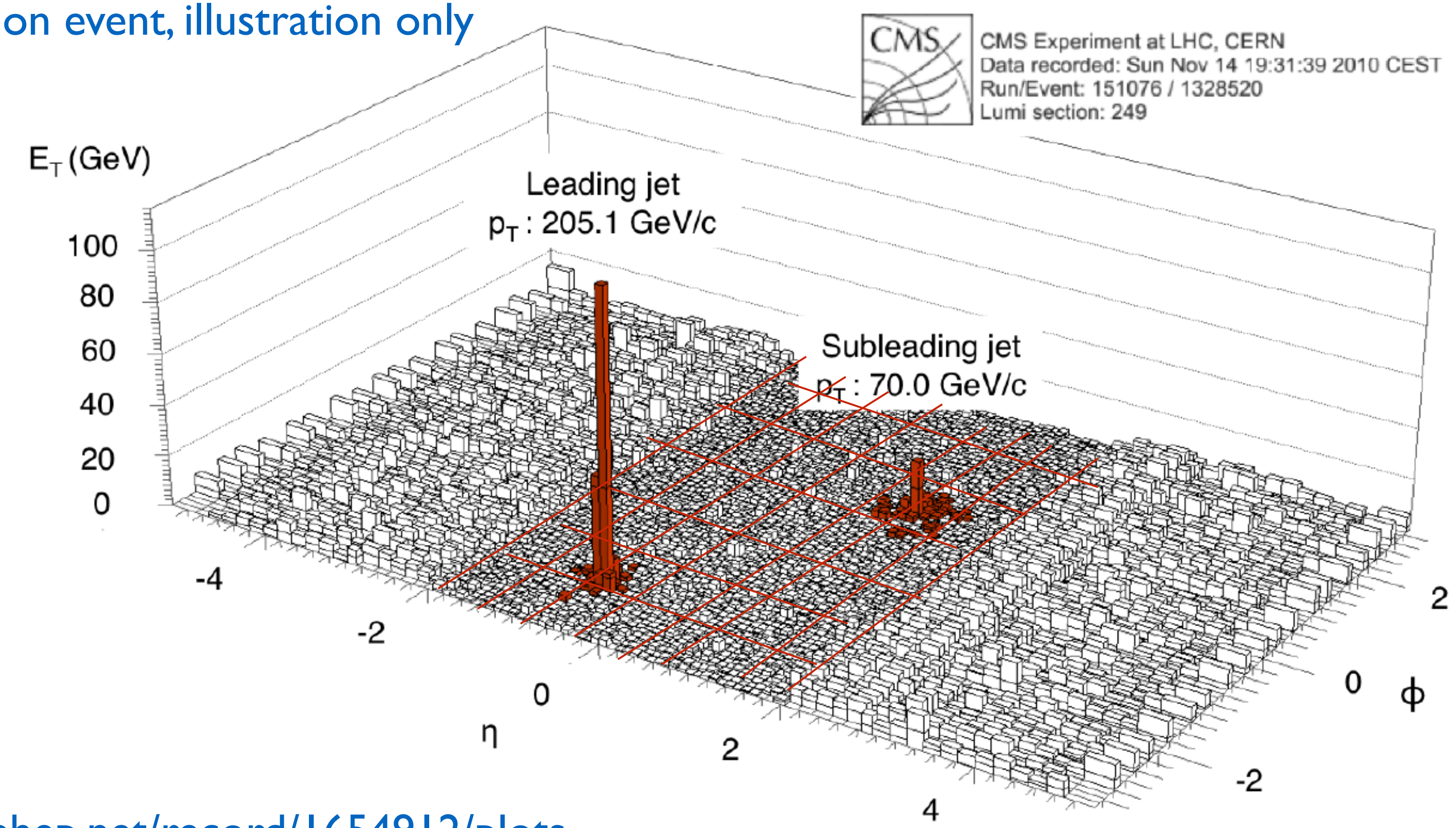
Controlling leading biases

- Underlying event: genRho
- Jet flavor response: toyPF
- Final/initial state radiation: α and w_{PS}

genRho

- 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 $N_{PU}>10$

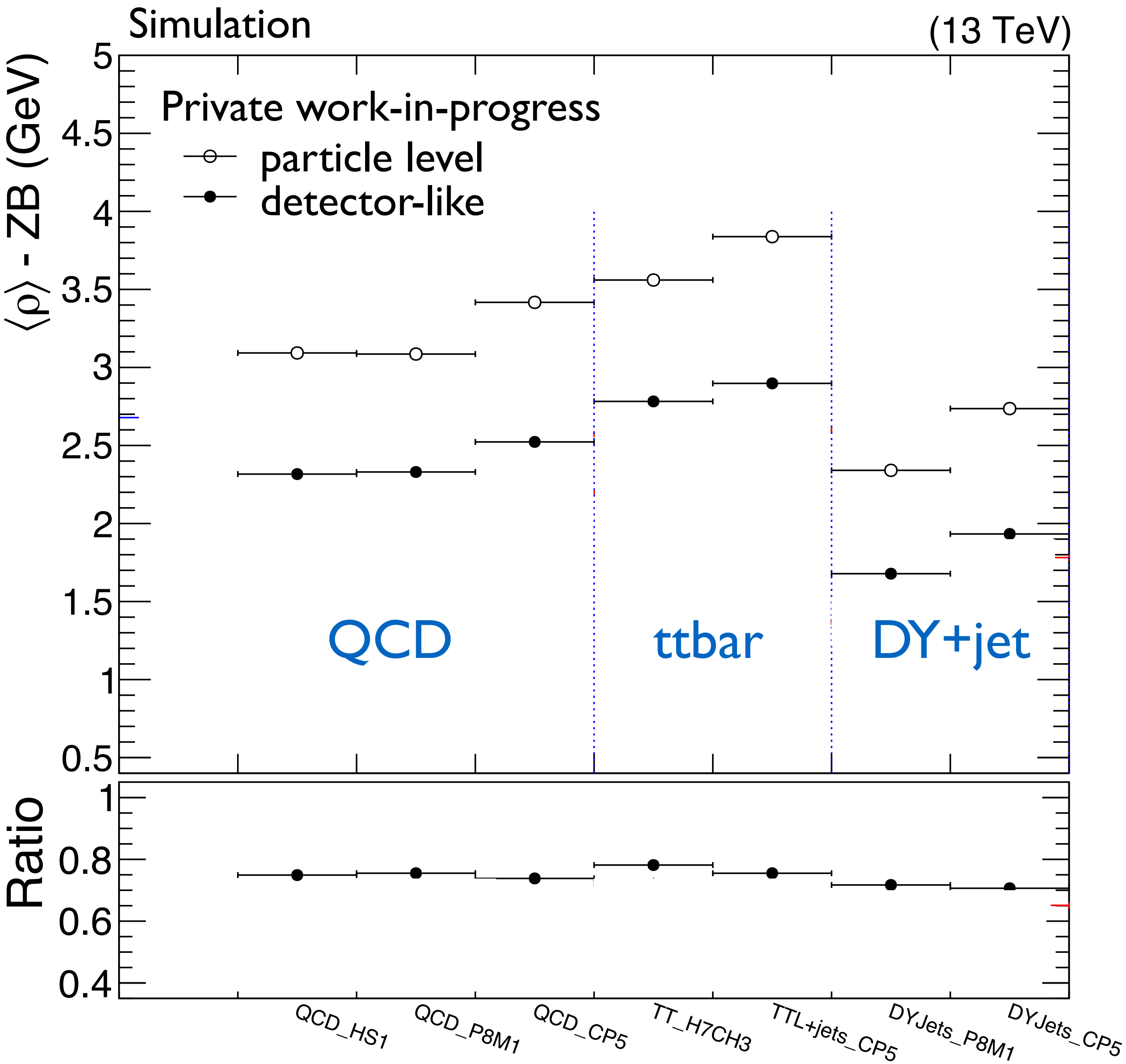
Heavy ion event, illustration only



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

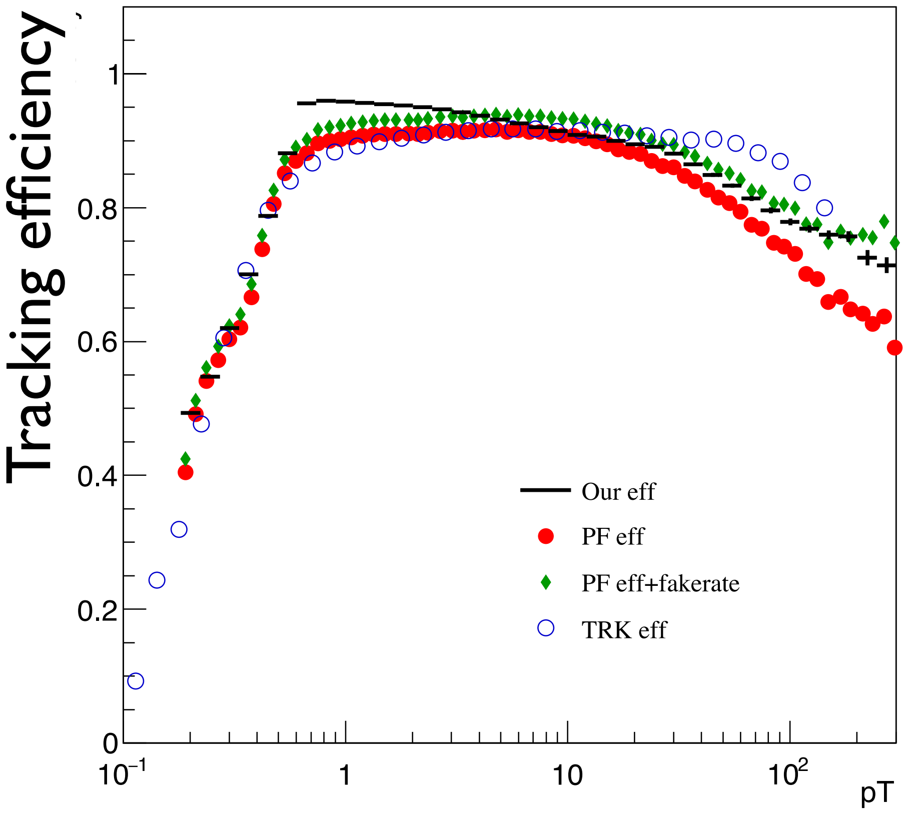
Underlying event

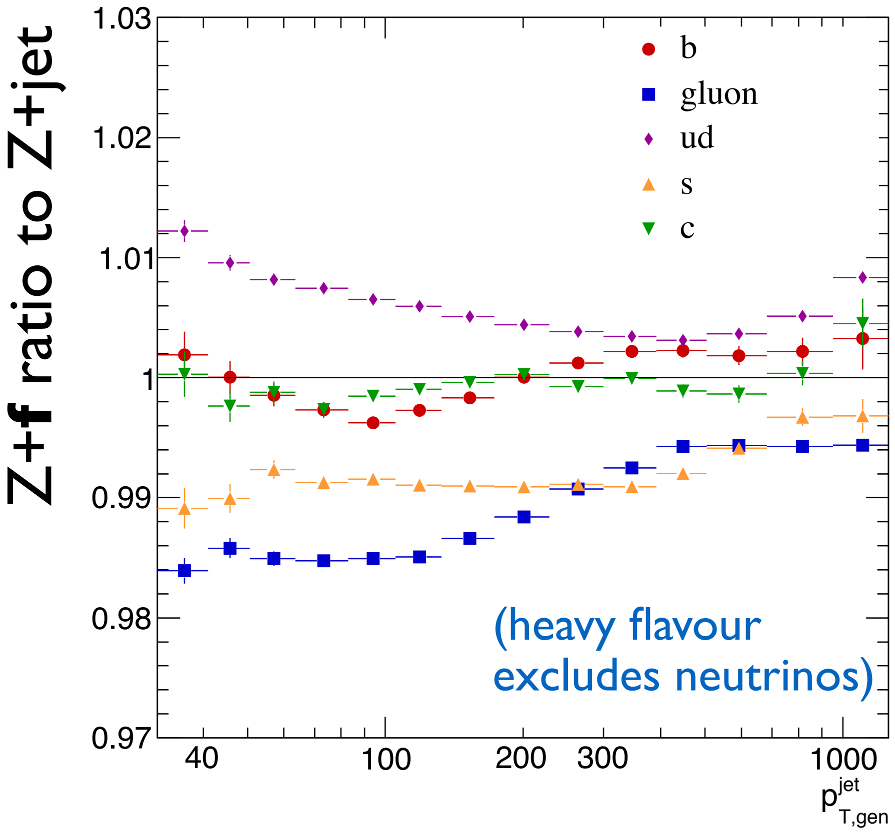
- Scanning a number of generators, tunes and final states for UE
- Detector-like level applies cuts of $p_T>0.3$ GeV on charged particles and photons, $p_T>3$ GeV on neutral hadrons
  - ratio to particle level is effective response of UE
- CMS and ATLAS pileup offset corrections are based on ρ so easy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



toyPF

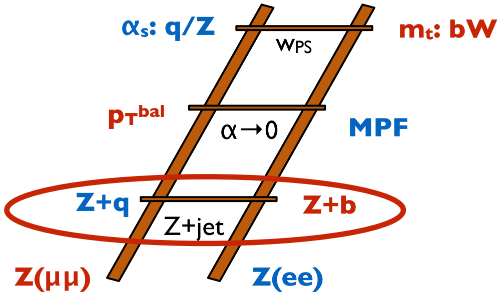
- Understand jet response from first principles by approximating particle flow (PF)
  - $p_{T,raw} = \Sigma_i R_i(p_{T,i})\ p_{T,i}$
    - ☐ $R_i(p_{T,i})=1$, if $p_{T,i}>0.3$, else zero (for photon)
    - ☐ $R_i(p_{T,i})=1$, if $p_{T,i}>0.3$, else zero (for charged with tracking)
    - ☐ $R_i(p_{T,i})=c*(1-a*p_T^{m-1})$ (for hadron without tracking)
  - parameterise tracking efficiency + fakes from CMS papers
  - apply PF hadron calibration and reconstruction thresholds on overlapping neutrals

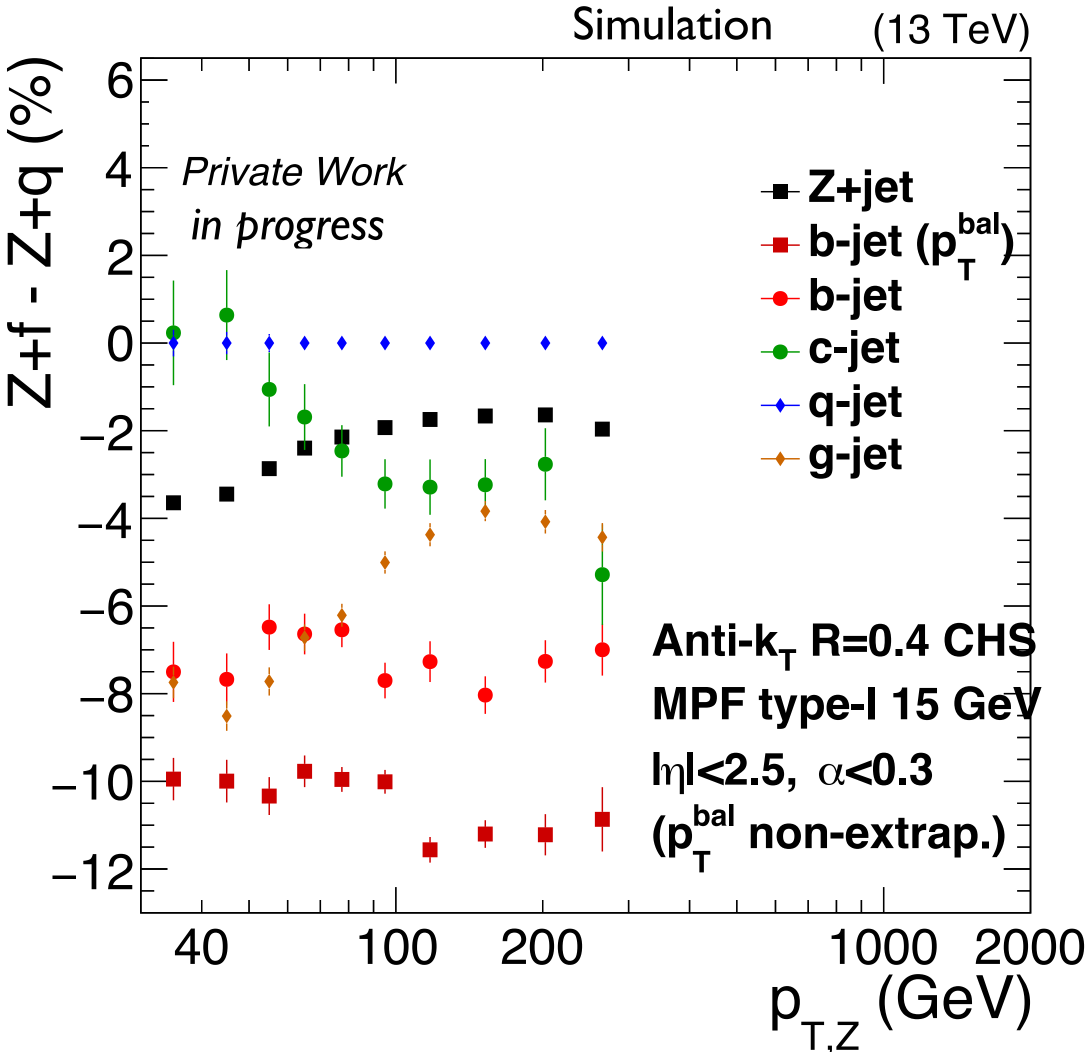




Flavor responses

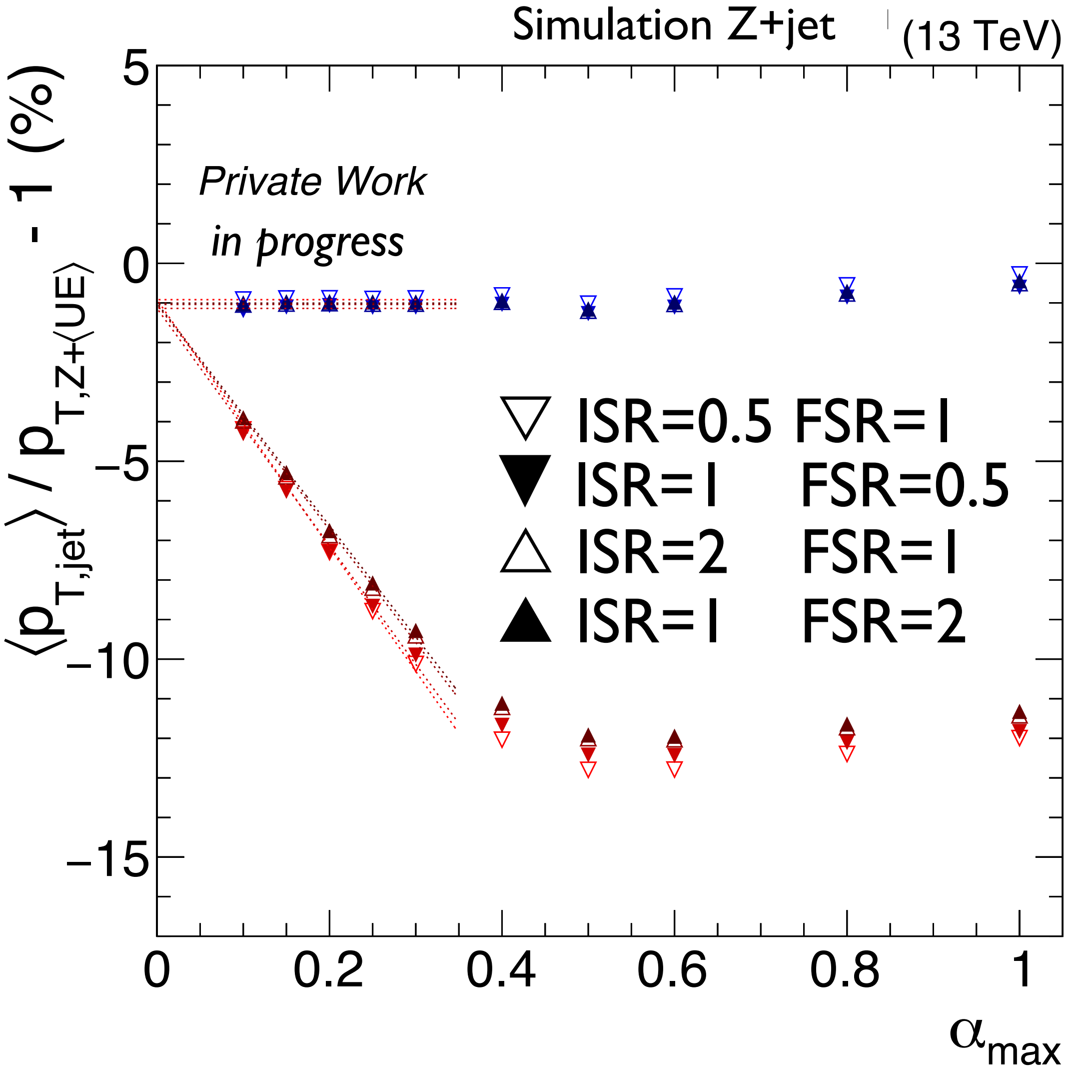
- Goal is to use toyPF to understand data/MC differences in flavour response in Z+f vs Z+q at 0.1% level
  - high statistical precision with few events, more precise than FullSim
  - stand-alone mode allows to scan more MC generator tunes quickly
  - fewer knobs so maybe more transparent

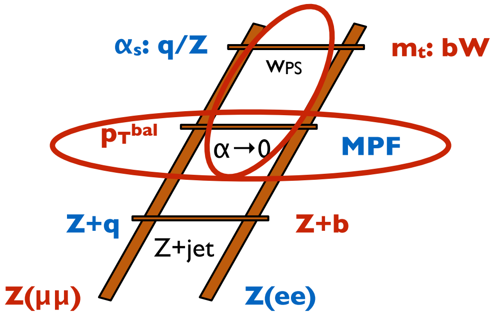




α extrapolation, w_{PS}

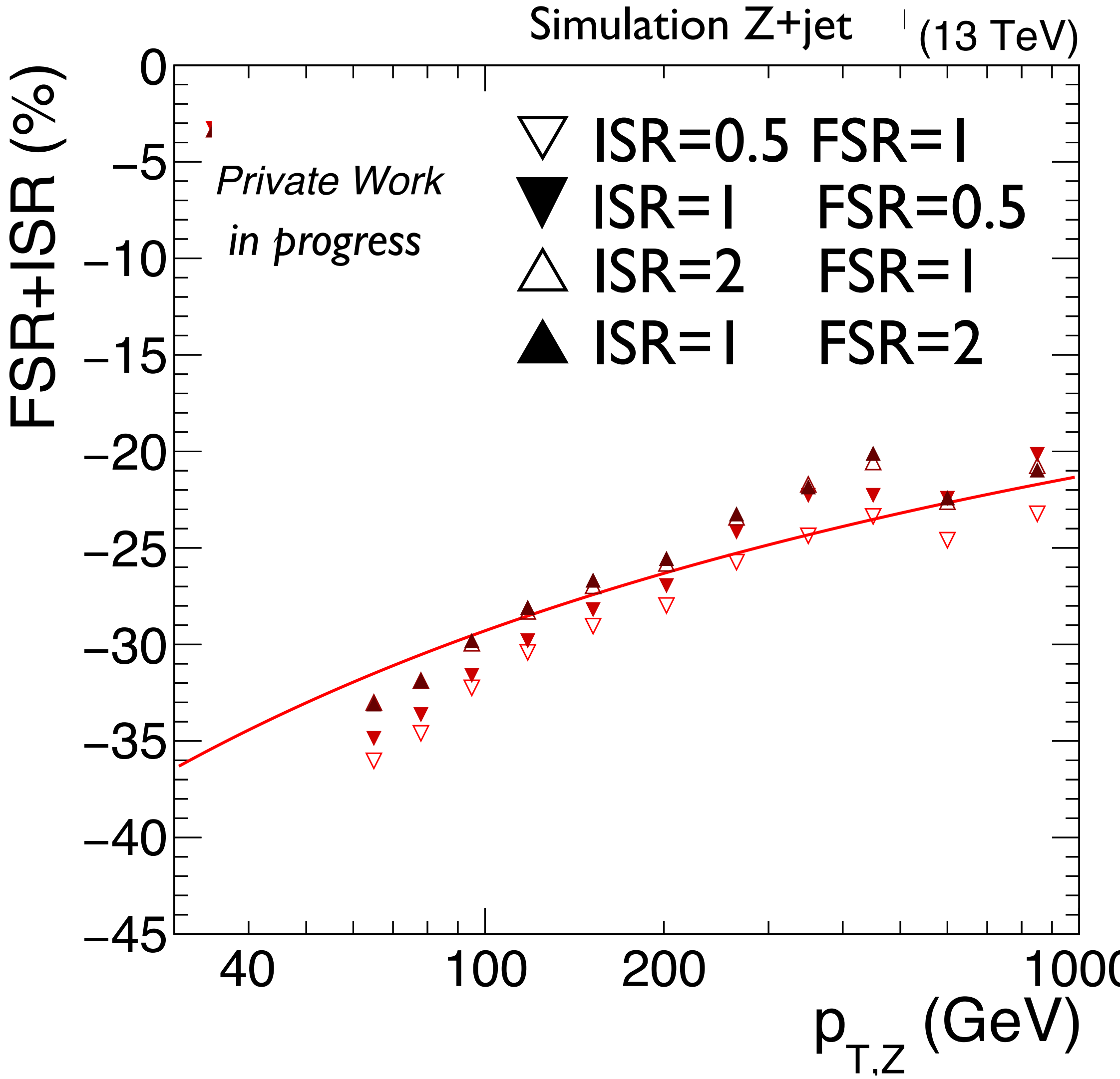
- Pythia provides a set of event weights w_{PS} to vary $\boldsymbol{\alpha}_{S,ISR}$ and $\boldsymbol{\alpha}_{S,FSR}$ in parton shower
    - latest processing messed up the weights relative to nominal, but relative spread ok
    - future iterations split weights by process (gg>gg, gg>qq, qg, qq)
- Sensitivity controlled by cutting on additional jets: $\alpha = p_{T,jet2} / p_{T,Z}$
    - Limit α→0 used for jet energy corrections
    - MPF is stable at all α 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 α cut should be **proportional to $\boldsymbol{\alpha_s}$**

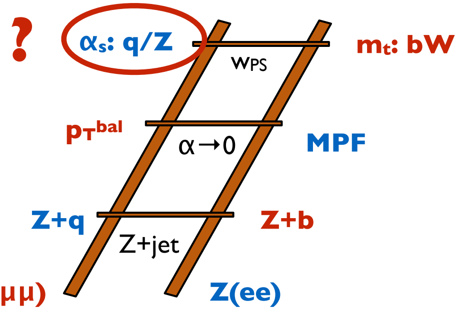




FSR+ISR vs $p_{T,Z}$

- Combined fit of MPF and p_T^{bal} vs $p_{T,Z}$ enables to extract α_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.



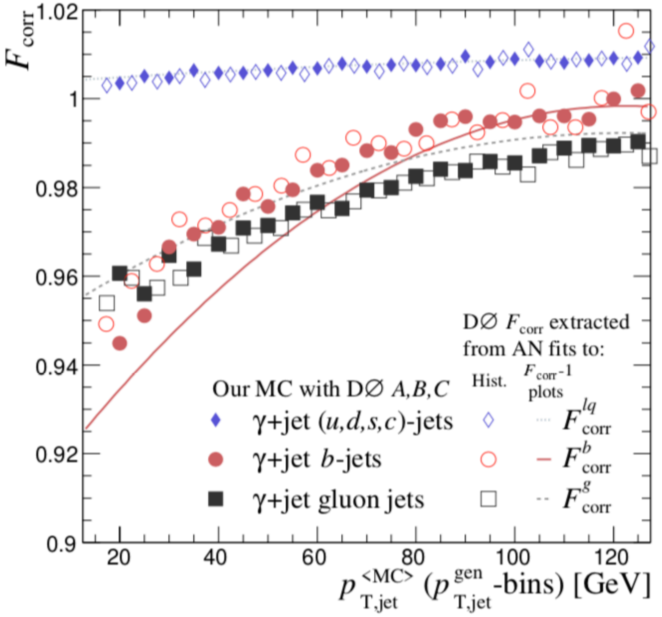


- **Application of “re-bJES” on D0 m_t**
  - Shift in bJES
  - Shift in m_t

Shift in bJES

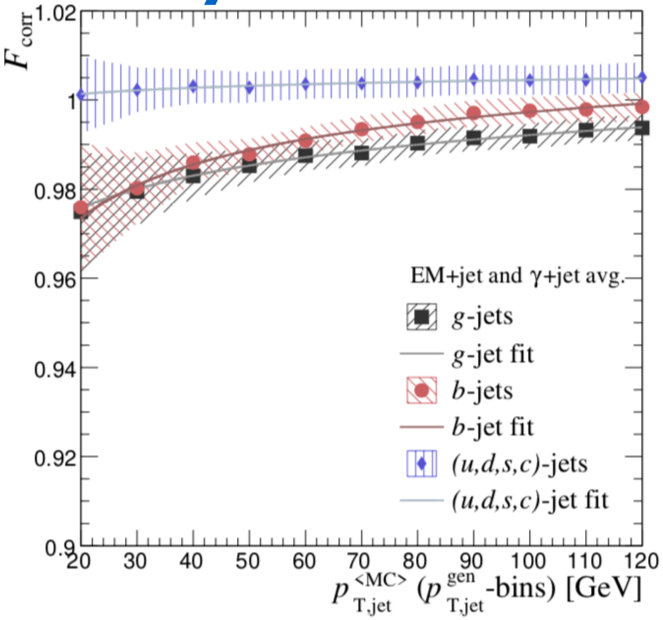
- Possible shift in D0 bJES thoroughly documented in MSc thesis of Toni Mäkelä
  - https://aaltodoc.aalto.fi/handle/123456789/39024
  - 1) could reproduce D0 results with their parameters
  - 2) our Pythia6 fit suggested different global minimum with smaller flavor correction
  - 3) our Herwig7 fit suggested yet different global minimum with even smaller flavor correction
- D0 used p_T^{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

D0 reproduction



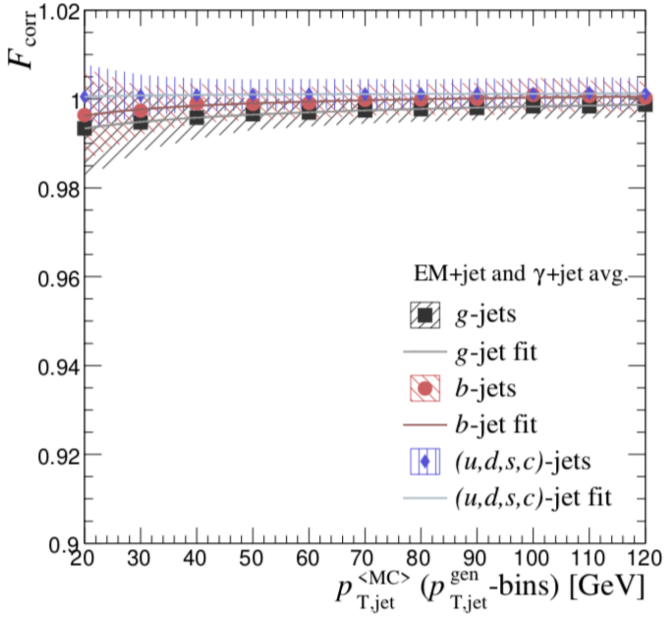
(d) $F_{corr} = F/\langle F\rangle_{\gamma+jet}$ (IIb1)

Pythia6 refit



(b) Run IIb1

Herwig7 refit

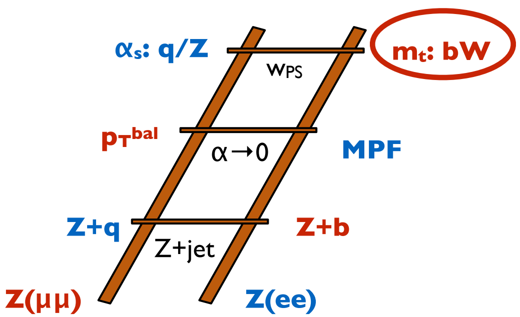


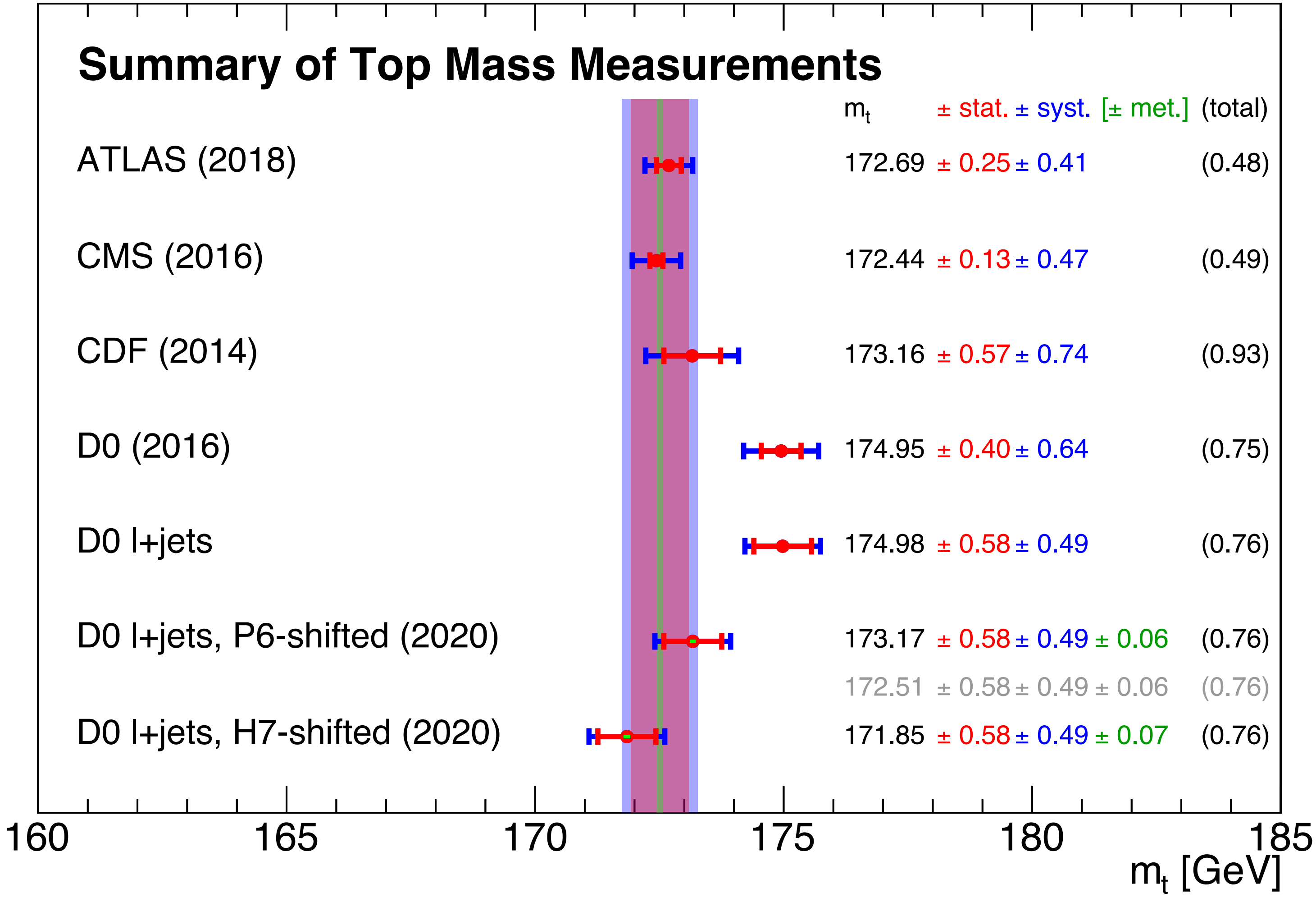
(b) Run IIb1

Shift in m_t

- Hannu Siikonen carefully reverse engineered D0 l+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

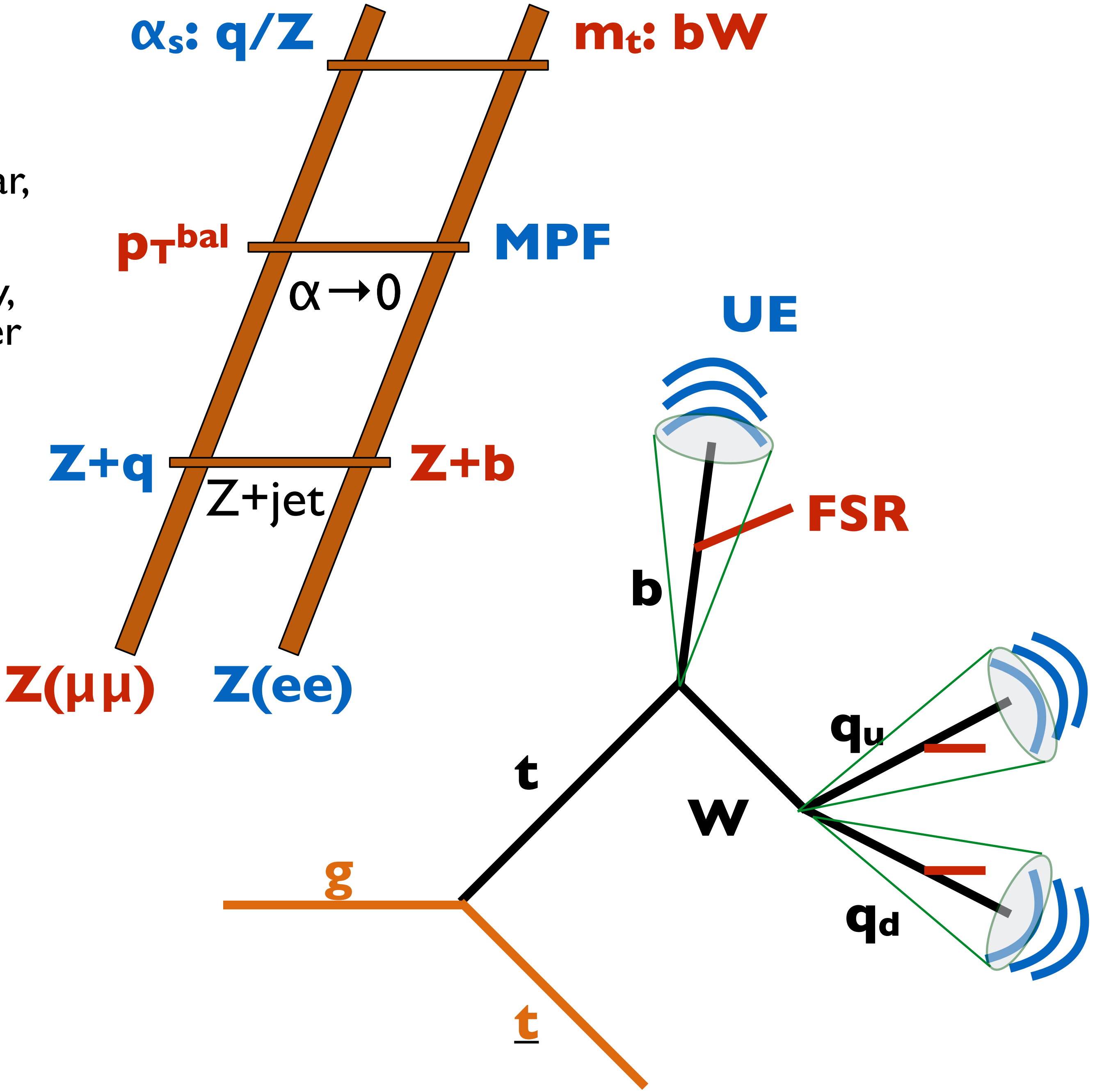
- Then do better on CMS

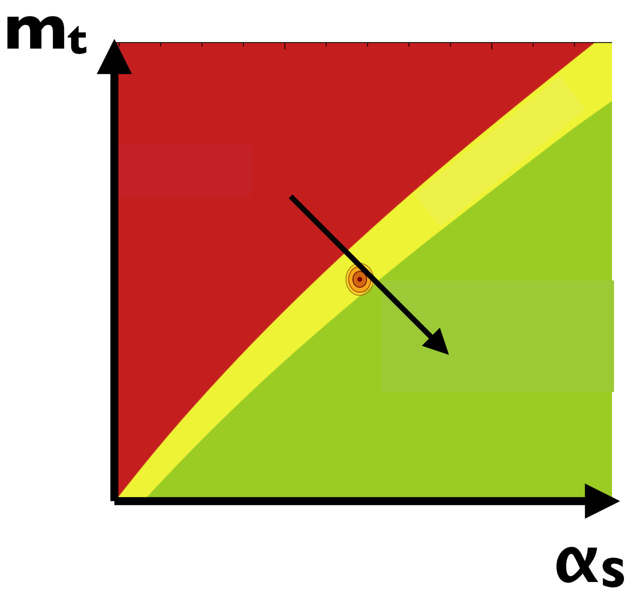




Summary

- m_t and α_s largest uncertainties for SM vacuum stability
- Need robust calibration ladder starting from Z(μμ)+jet to ttbar, *preferably backed by solid theory*
- Evaluating each step individually, and in connection to each other

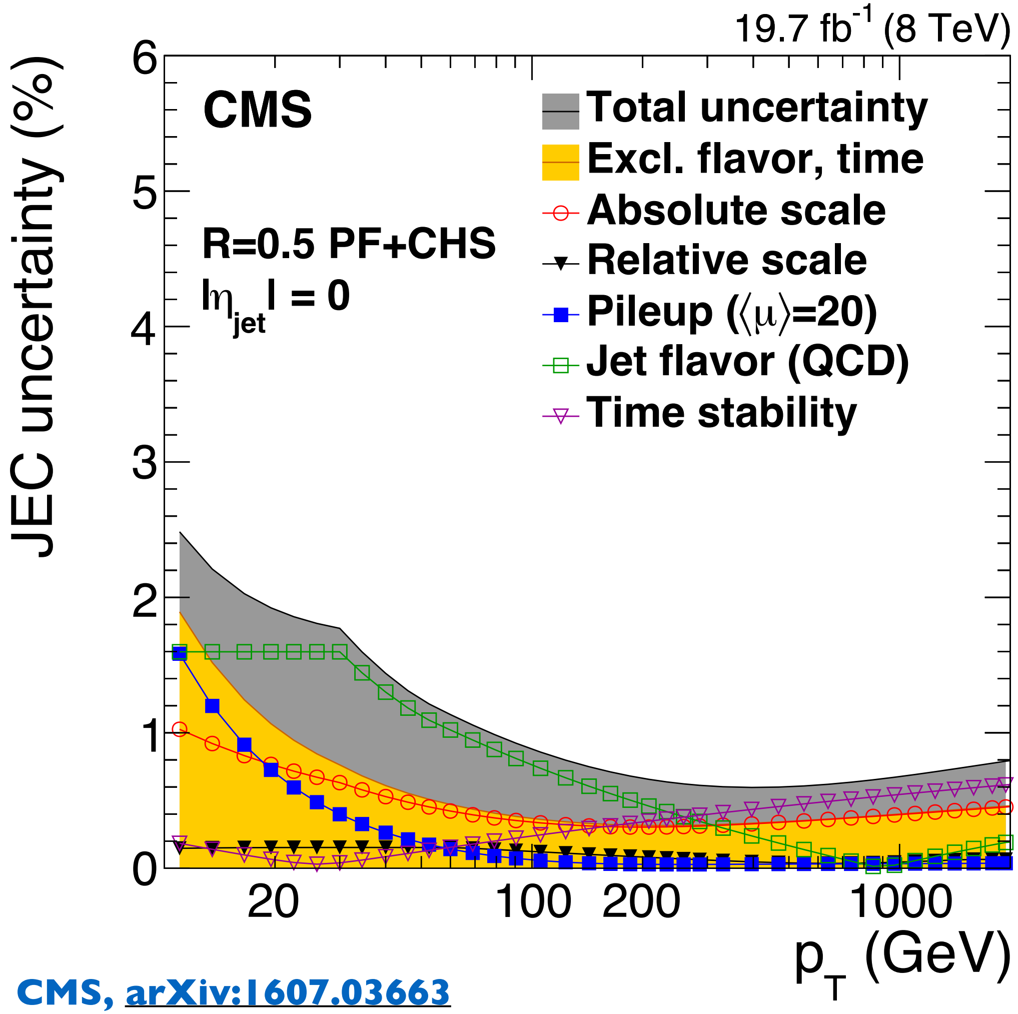


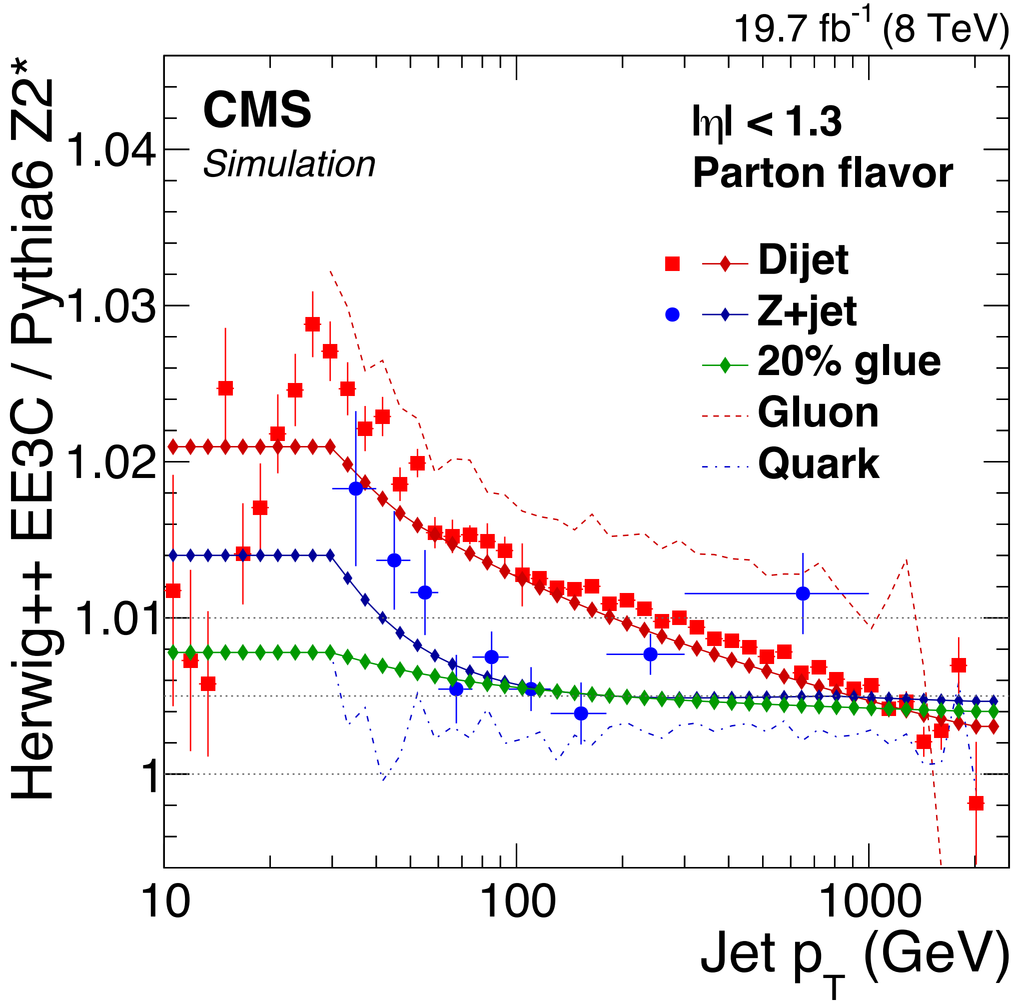


Backup slides

Gluon jet response

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

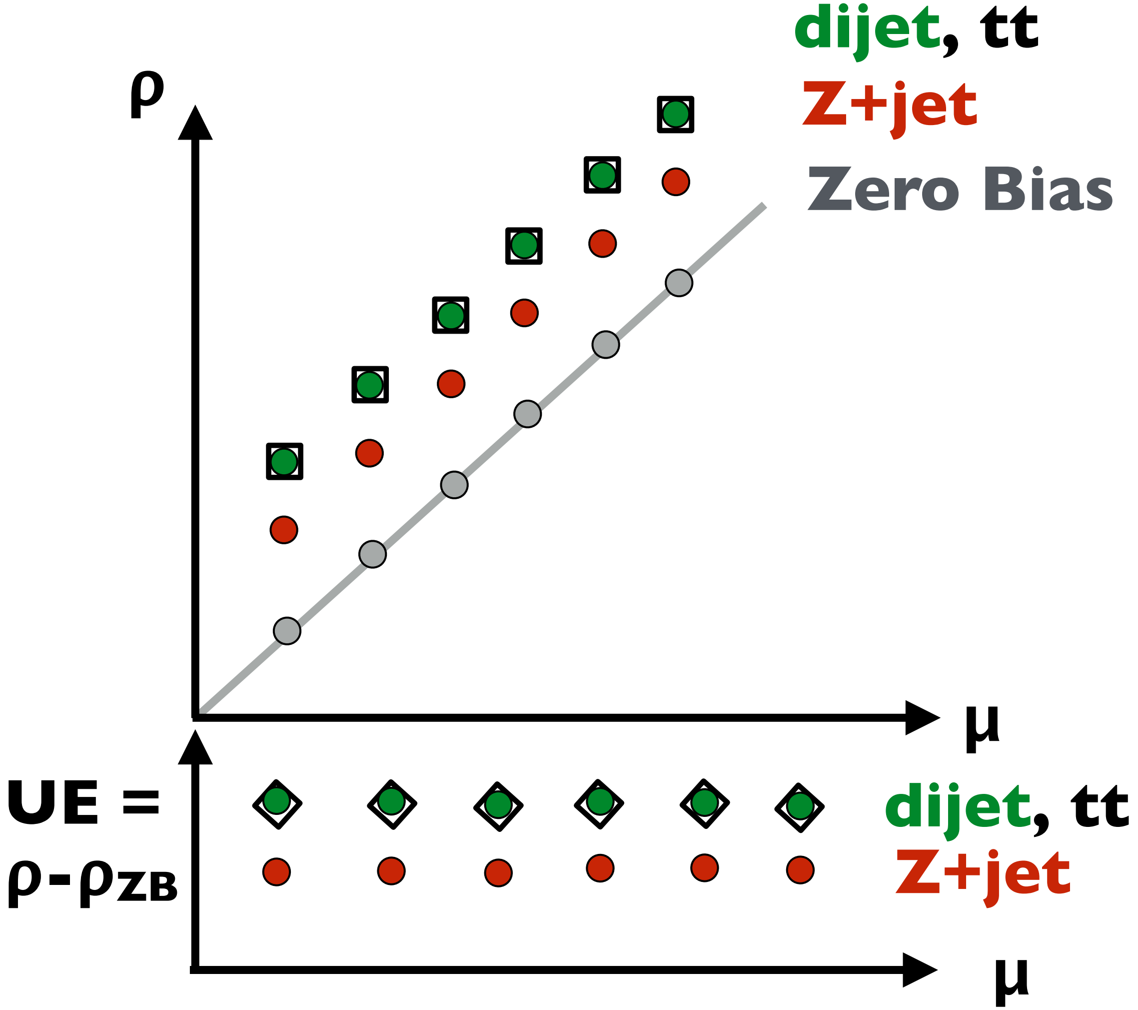




CMS, arXiv:1607.03663

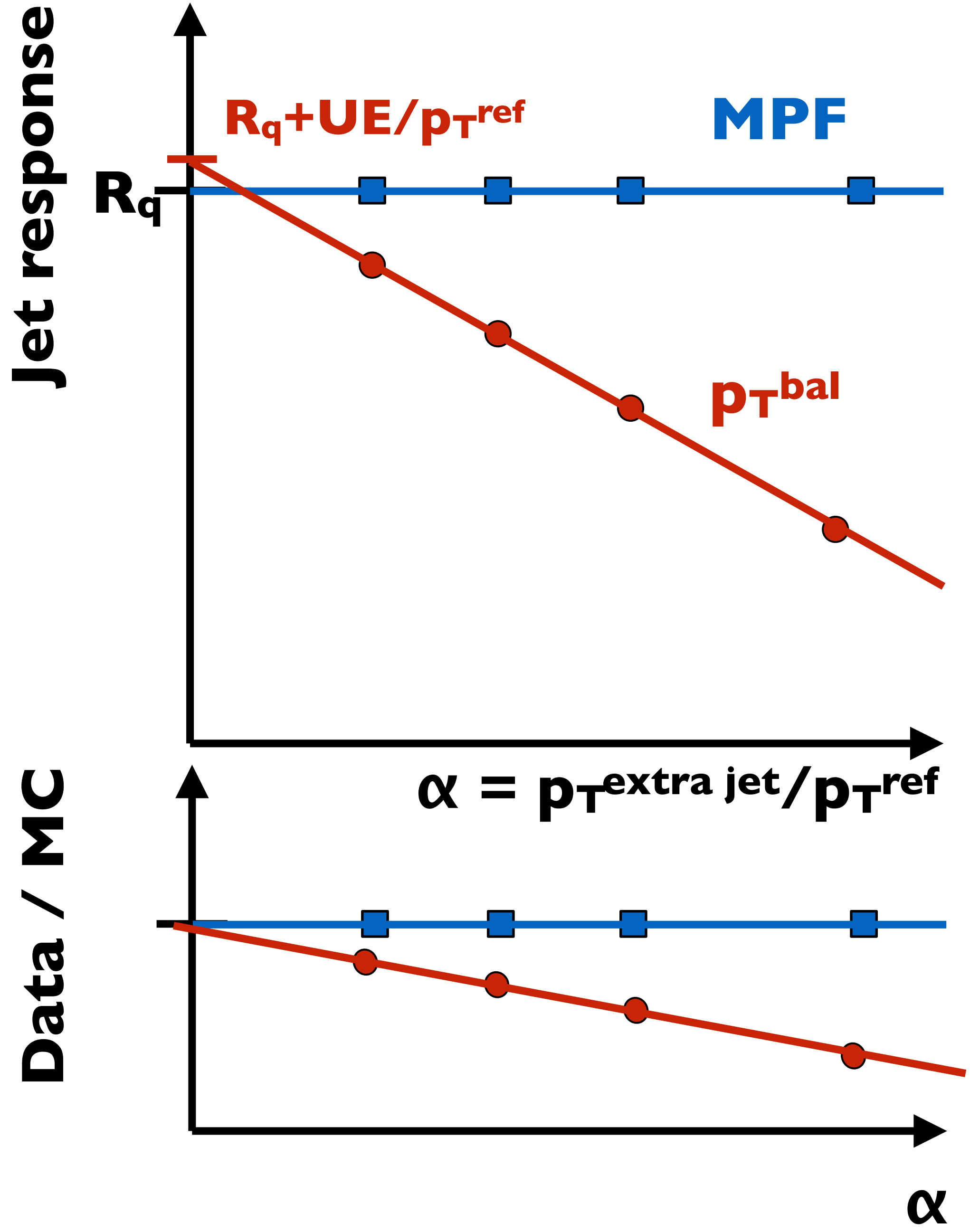
Constraints on UE

- FastJet (GridMedianEstimator) energy density ρ is a proxy of UE
  - Pileup factorized out by comparing to Zero Bias data as a function of average number of pileup (μ)
- Very minimal dependence on event scale (e.g. jet p_T, Z p_T) above p_T>10—20 GeV
- Slight dependence on μ possible from non-linear calorimeter scale
- Present work: defining ρ for particle level MC, as it is designed to work better with pileup



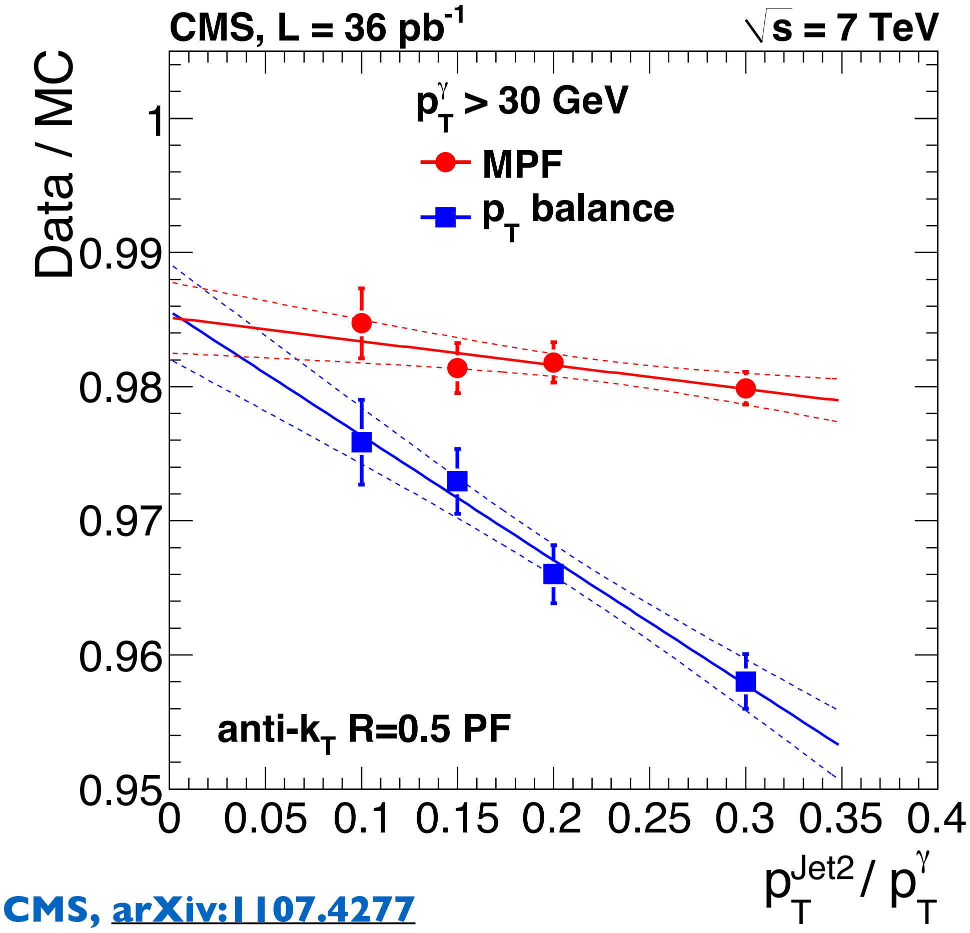
Constraints on FSR

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

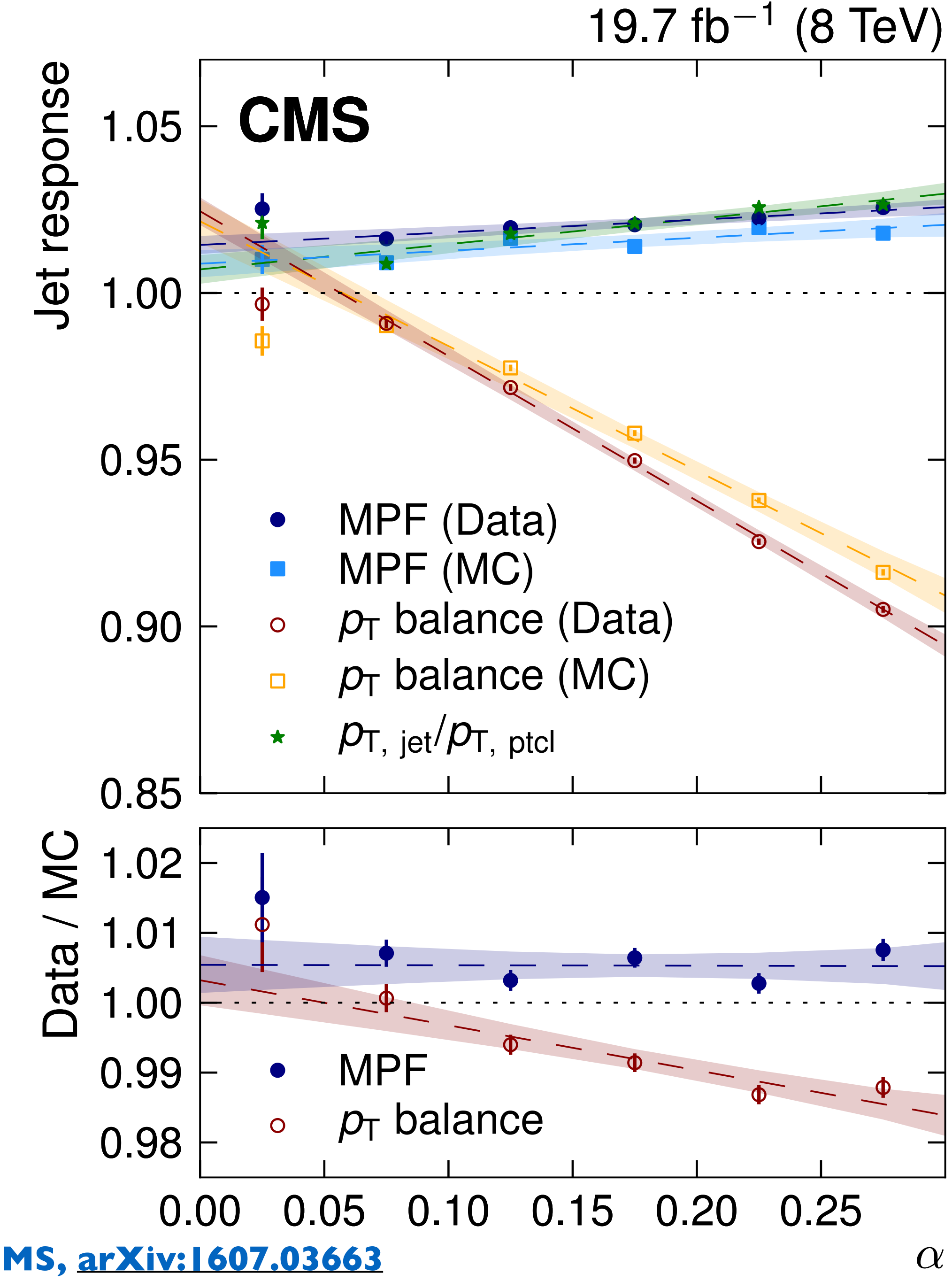


Constraints on FSR

- 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



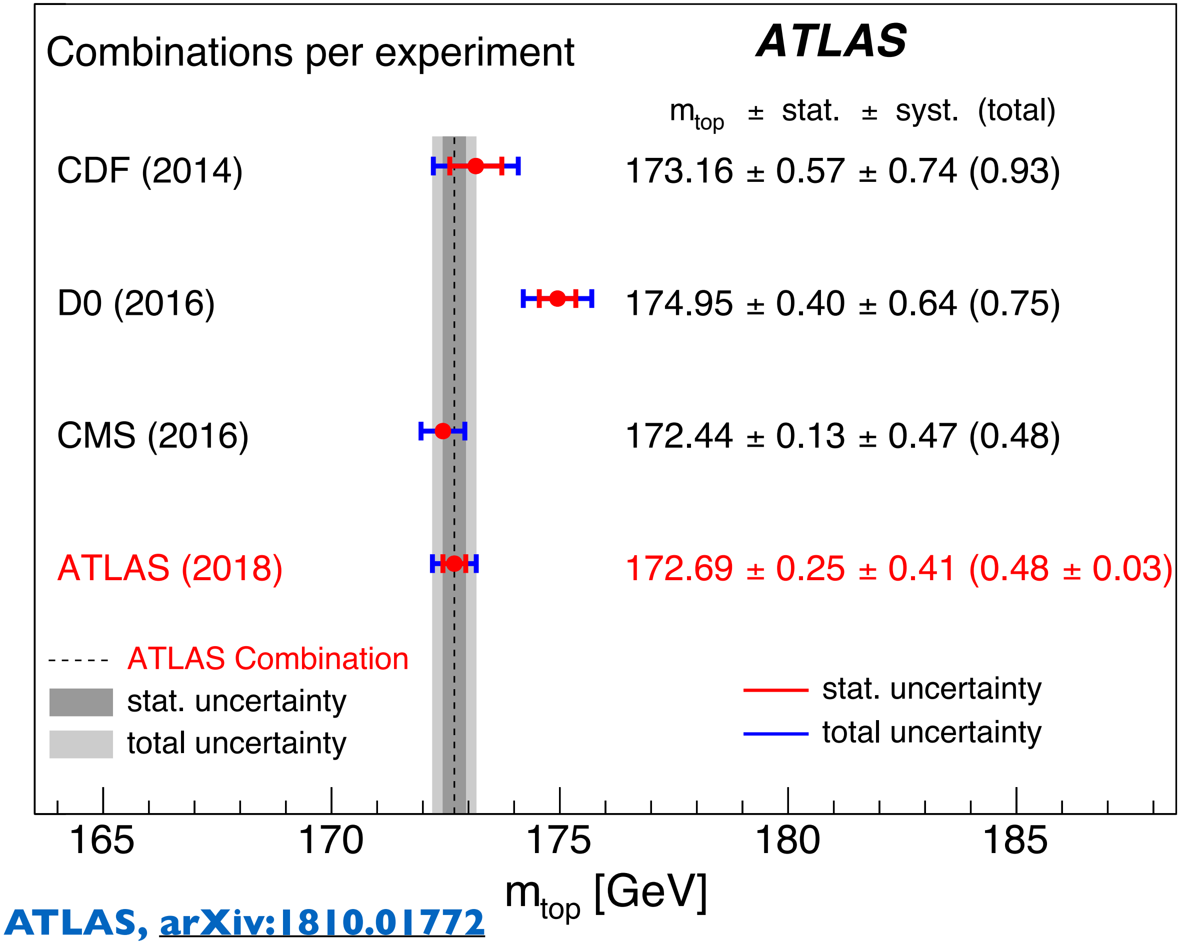
CMS, arXiv:1107.4277

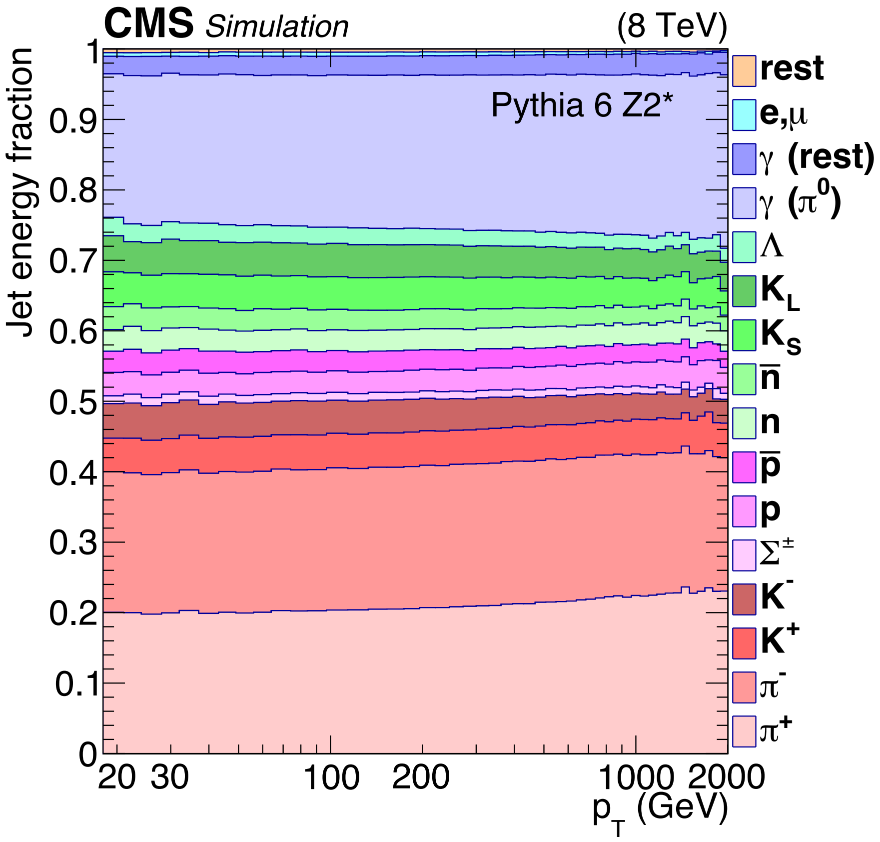


CMS, arXiv:1607.03663

Constraints on bJES

- Besides Z+b, can use jet fragmentation and single particle response to predict R_b
  - Main idea: $\boldsymbol{R_{jet} = \Sigma_i f_i * R_i(E_i)}$, 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^{bal} method to estimate R_{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)





ATLAS, arXiv:1810.01772

CMS, arXiv:1607.03663