

An experimentalist's pursuit for the meaning of m_t and α_s



are we *really* here?

Feb 27, 2019

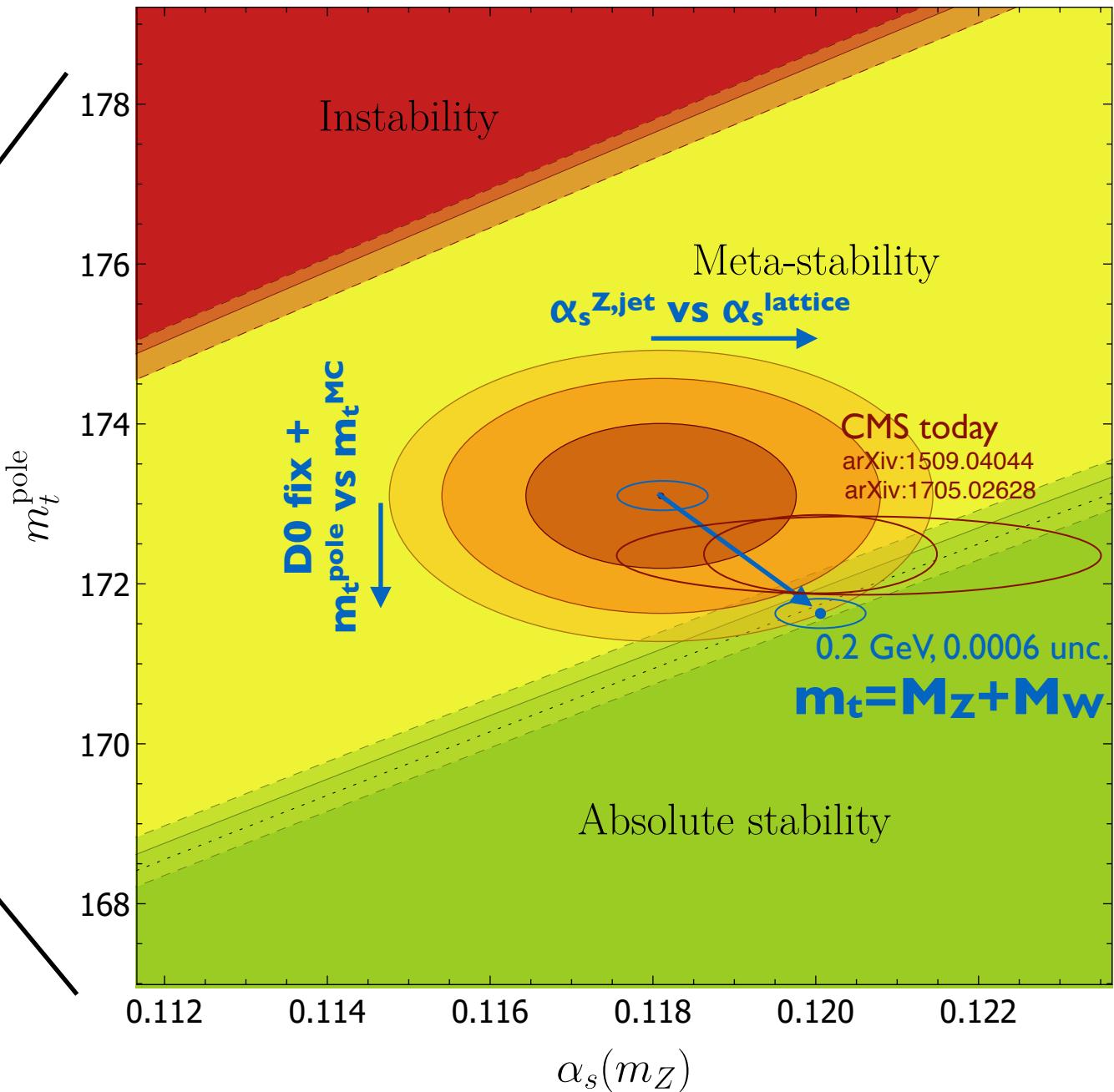
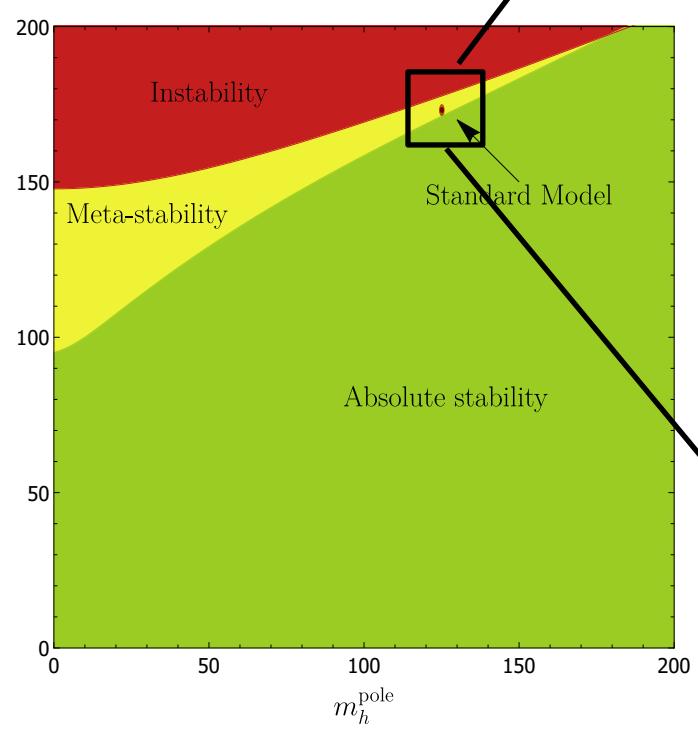
Mikko Voutilainen, U. Helsinki and HIP

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 - ▷ 13 TeV dilepton
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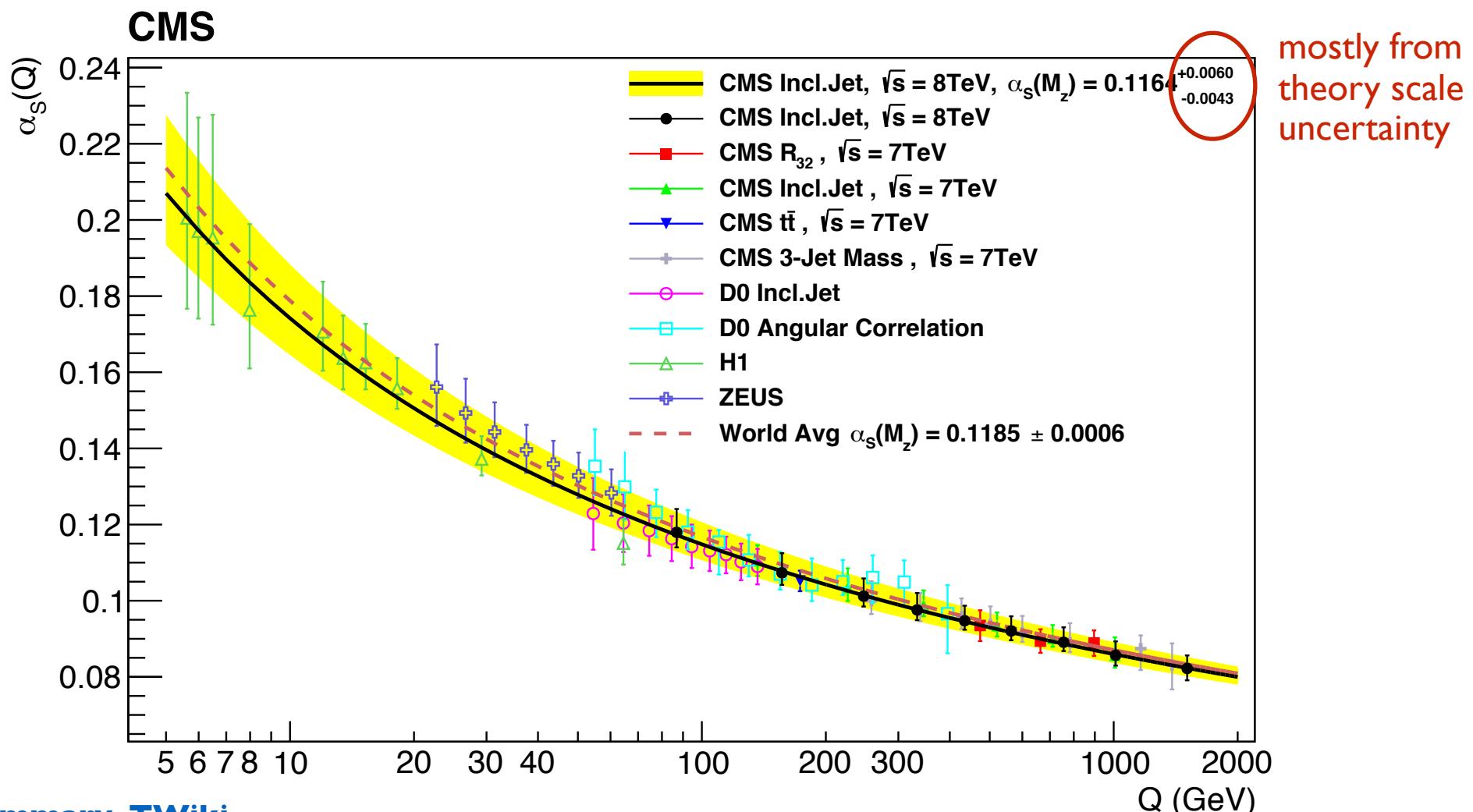
LHC precision frontier

- 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)



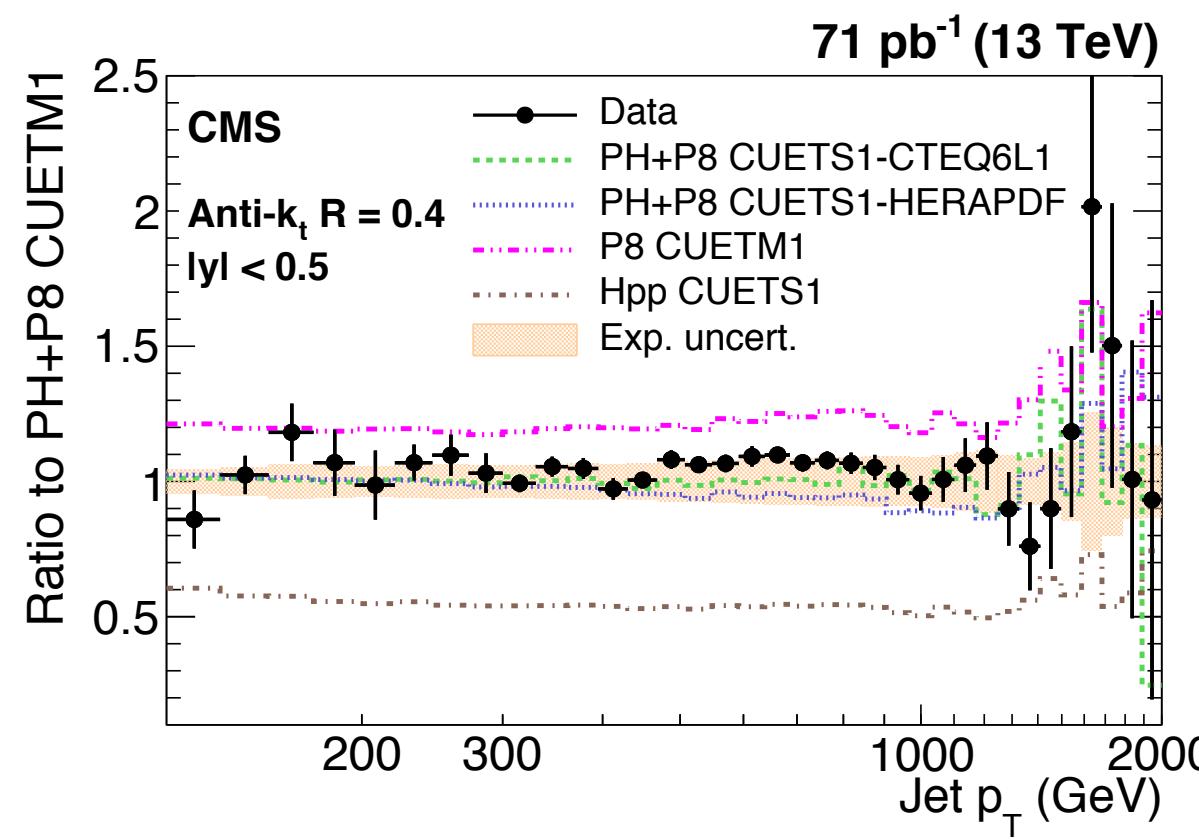
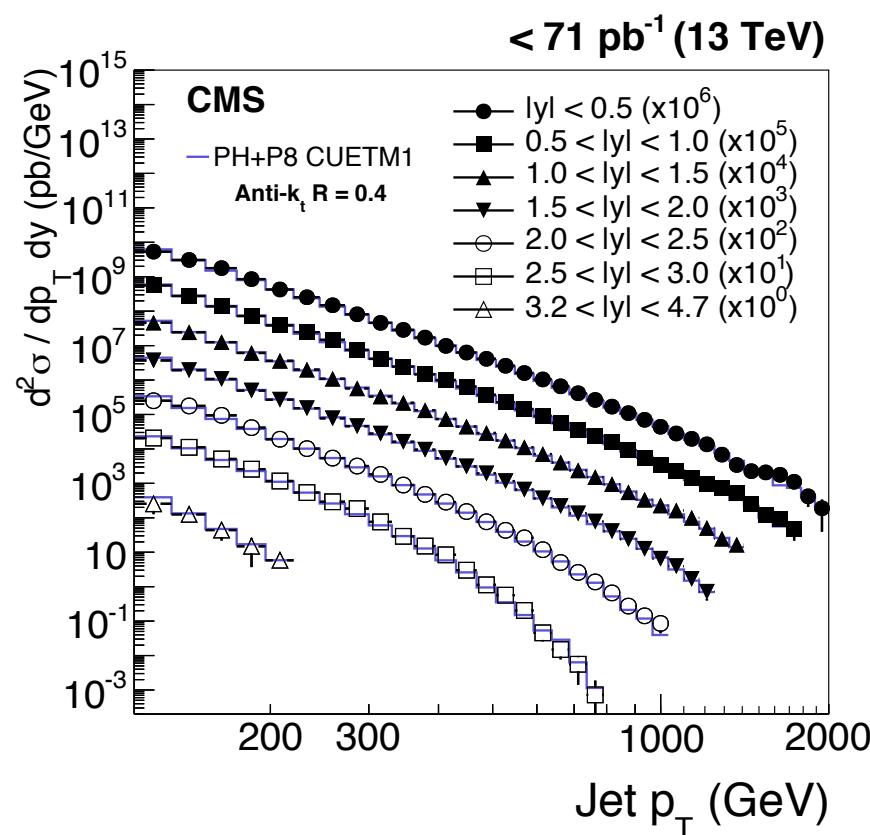
Measurement of α_s

- 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



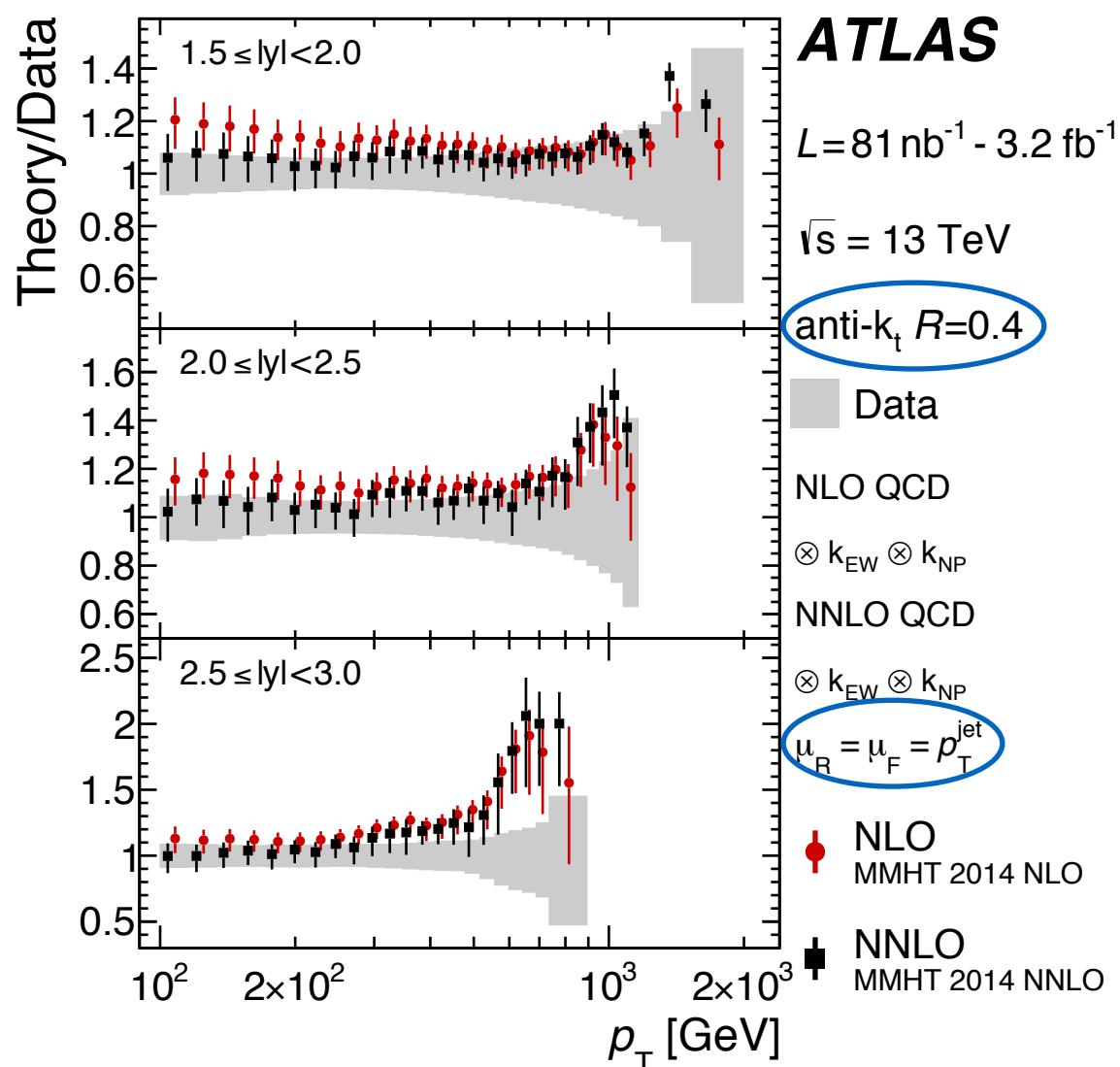
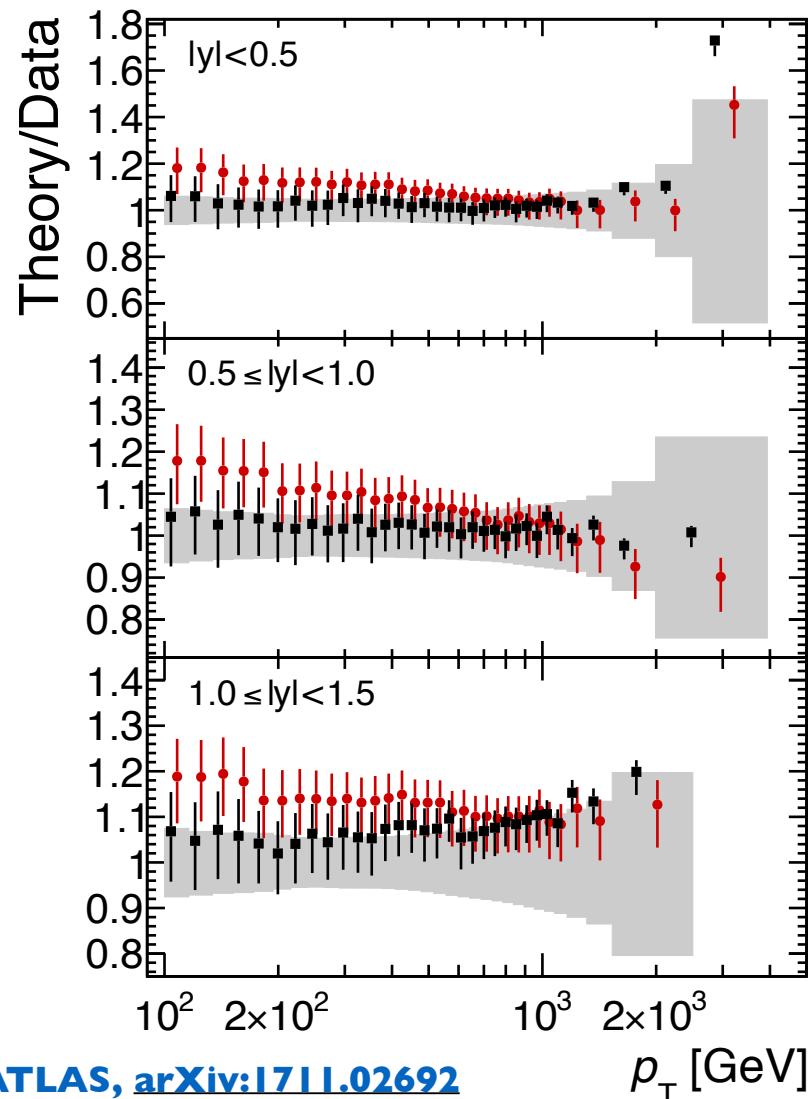
Inclusive jets — first Run II

- Inclusive jet cross section is the baseline jet measurement
 - ▷ Feeds into multiple other ratio measurements, has to be made particularly robust
- Commonly used in global PDF and α_s fits to constrain high x gluons
 - ▷ Well modelled by NLO+PS (Powheg+P8) even for small $R=0.4$ cone, but by NLO only for $R=0.7$



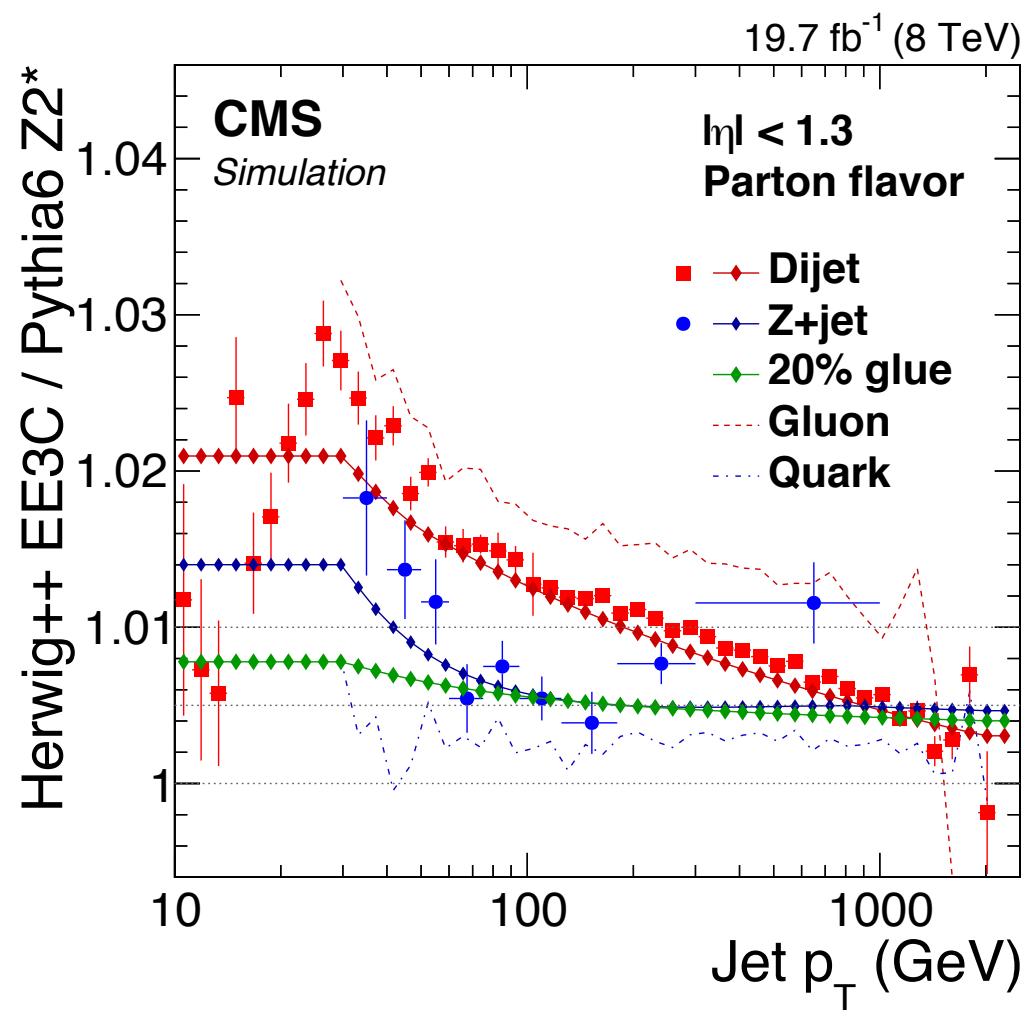
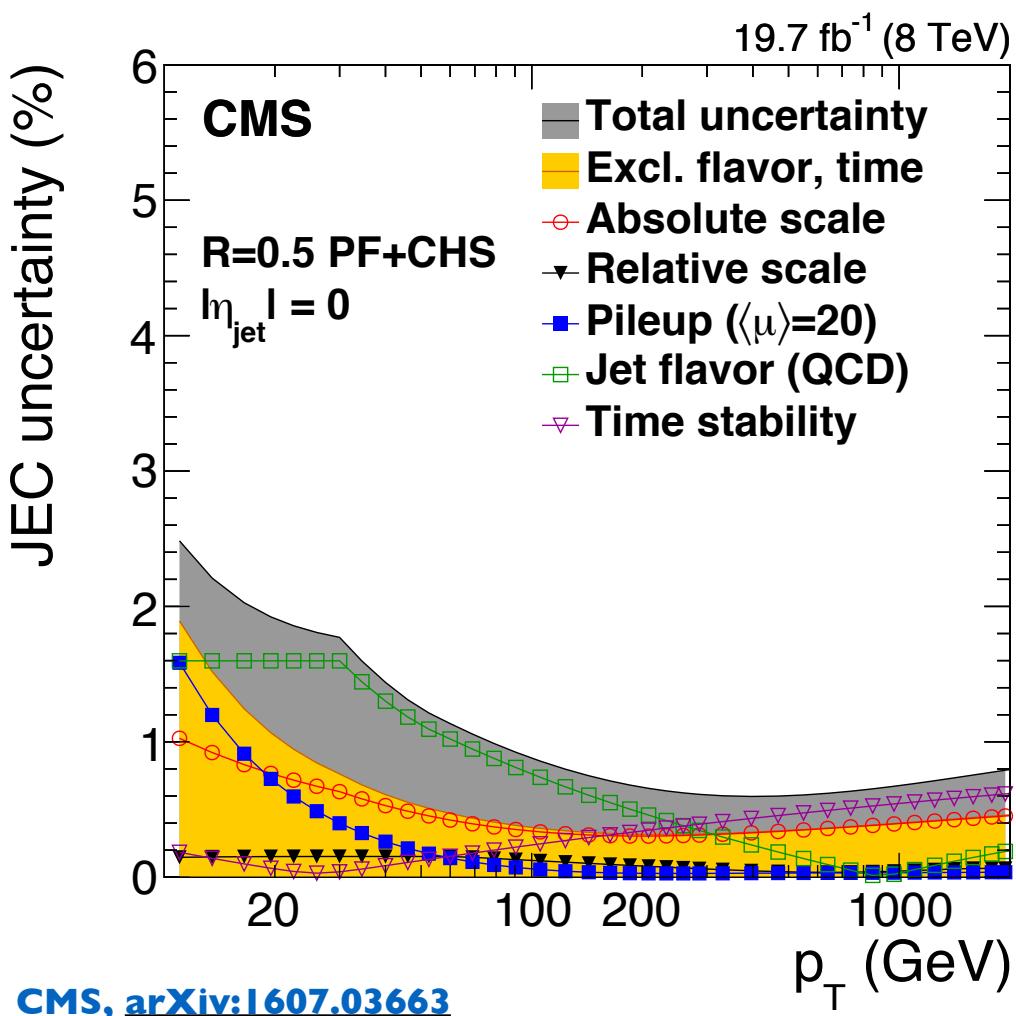
Inclusive jets — full Run II

- Full Run II data set will have up to x2000 more integrated luminosity (**here ATLAS x50**)
- Target smaller systematic uncertainties than Run I: better JEC from more $Z(\rightarrow \mu\mu) + \text{jet}$
- Detailed comparisons of NNLO ($\mu = p_{T,\text{jet}}$ or $\mu = p_{T,\text{max}}$), NLO+NLL and NLO+PS



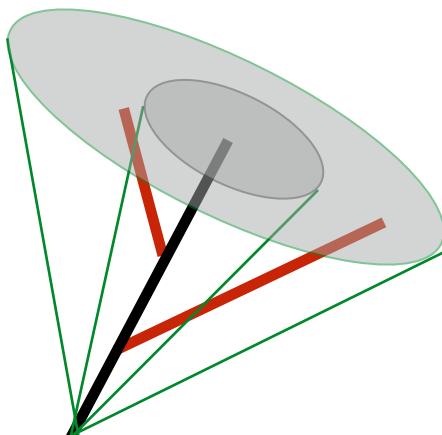
Gluon jet response

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



Radius scan

- Ratio of jet cross sections with different R is sensitive to higher order corrections
 - Ratio of LO xsec is 1
 - Ratio of NLO xsec is LO
 - Ratio of NNLO xsec is NLO
 - Progressively more FSR out of R=0.5 into R=0.7 => roughly $(1/2)^n$ convergence

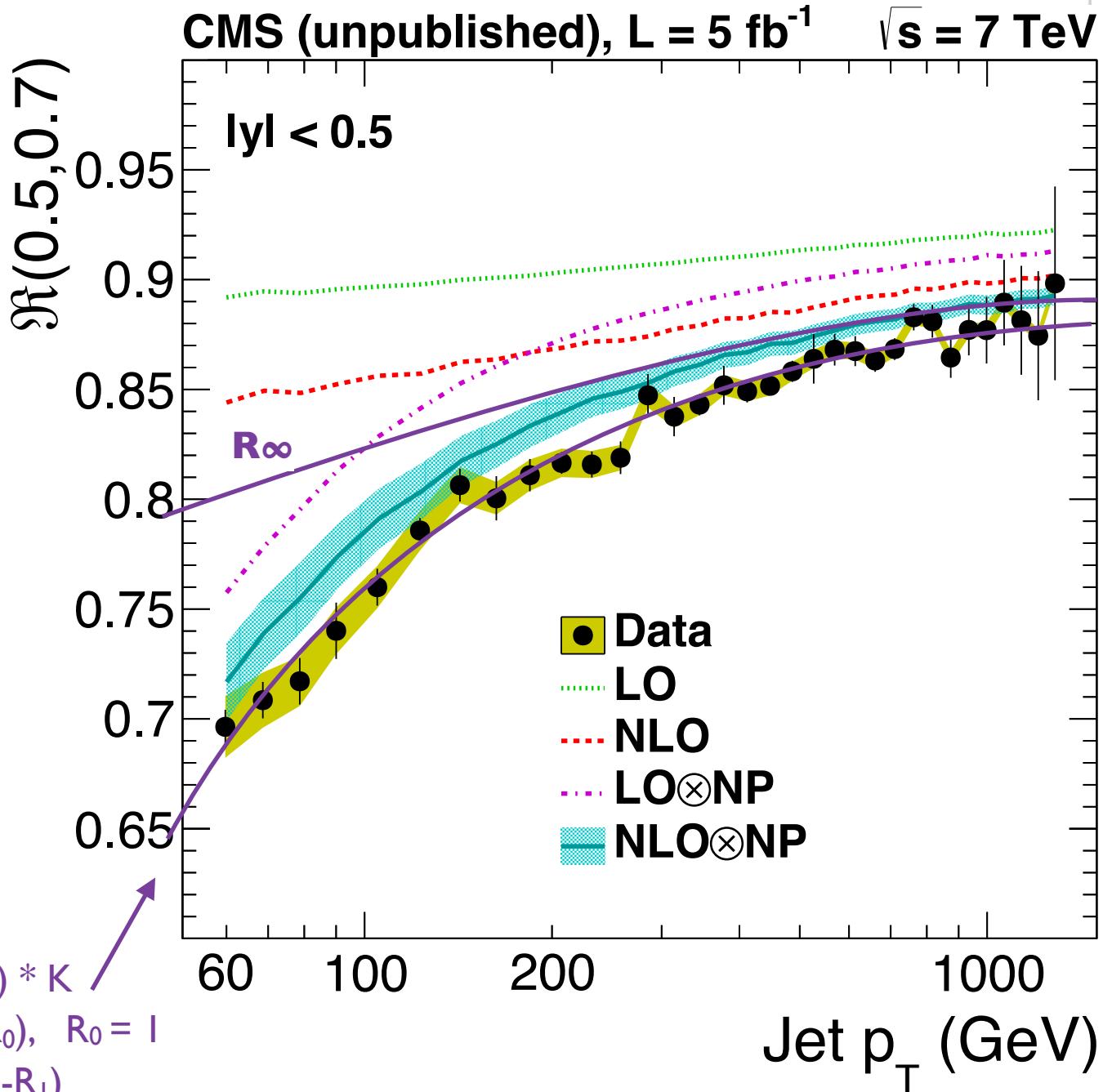


Induction:

$$R_n - R_{n-1} = (R_{n-1} - R_{n-2}) * K$$

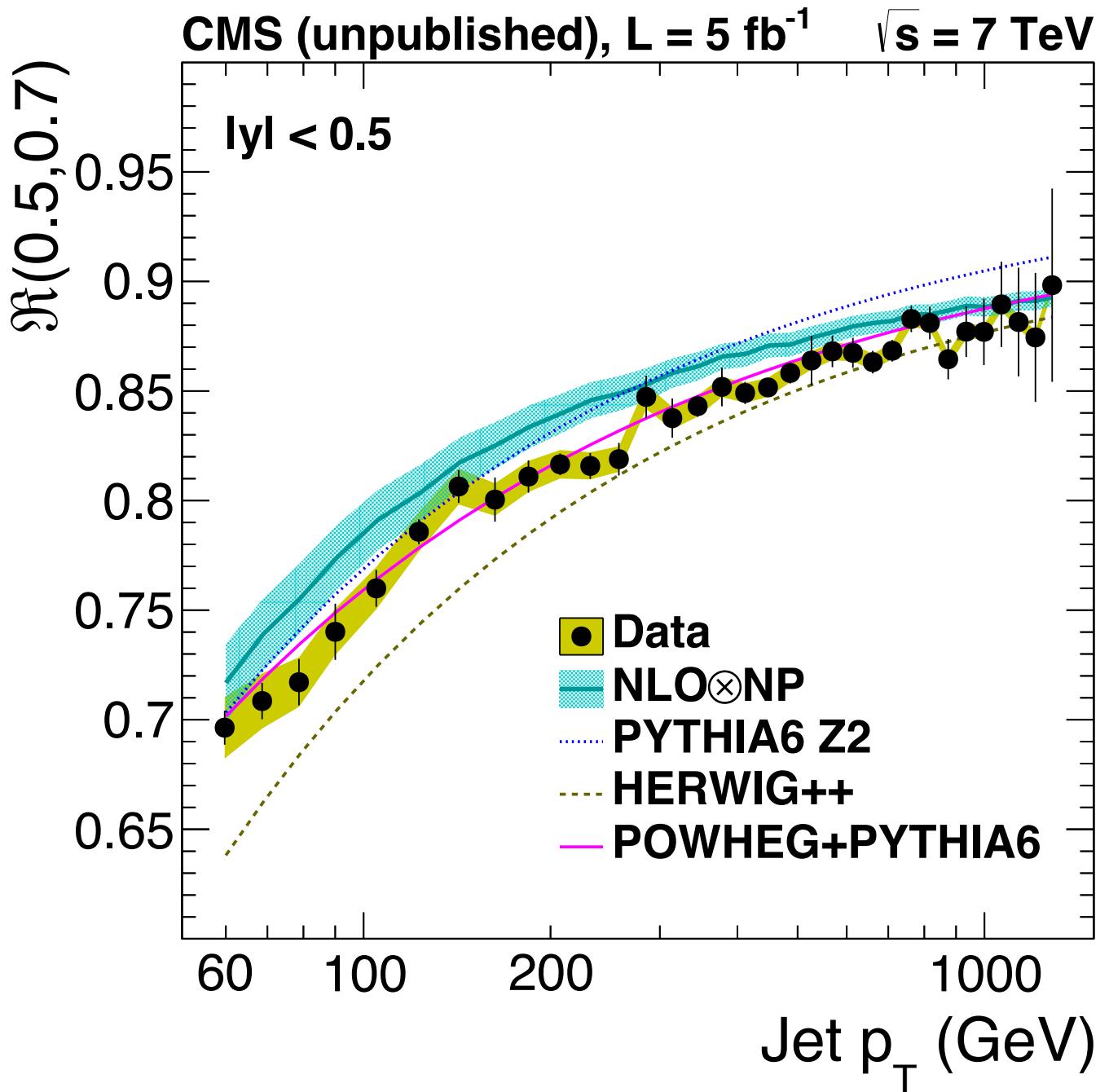
$$K = (R_2 - R_1) / (R_1 - R_0), \quad R_0 = 1$$

CMS, arXiv:1406.4080, $R_\infty = 1 - 1/(1-K) * (R_0 - R_1)$



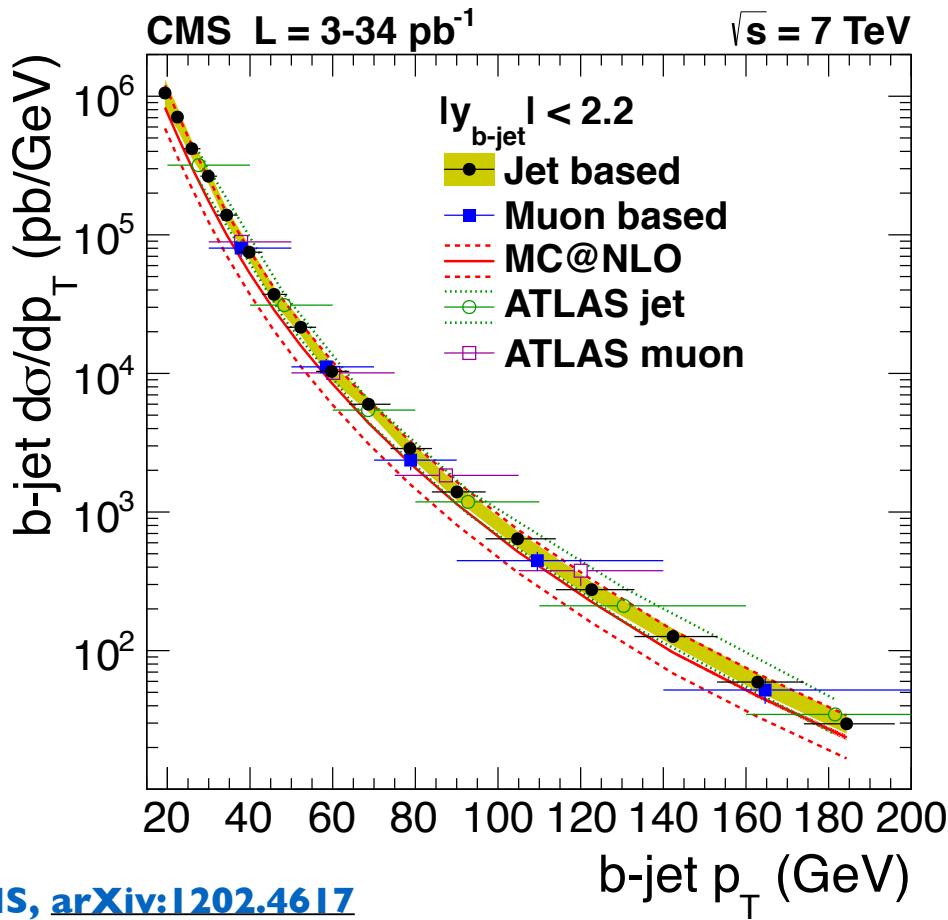
Radius scan

- (N)LO+PS (Powheg+P6) agrees with data
 - ▷ PS approximates all-orders, although P6 and H++ differ
 - ▷ MC models include NP, but with some tuning involved
- Even state-of-the-art NNLO xsec would not be sufficient for $R=0.5$ and $R=0.7$ simultaneously
 - ▷ Need all-orders resummation
 - ▷ and non-perturbative corrections at low p_T
- To be repeated at 13 TeV, with more R and more MC



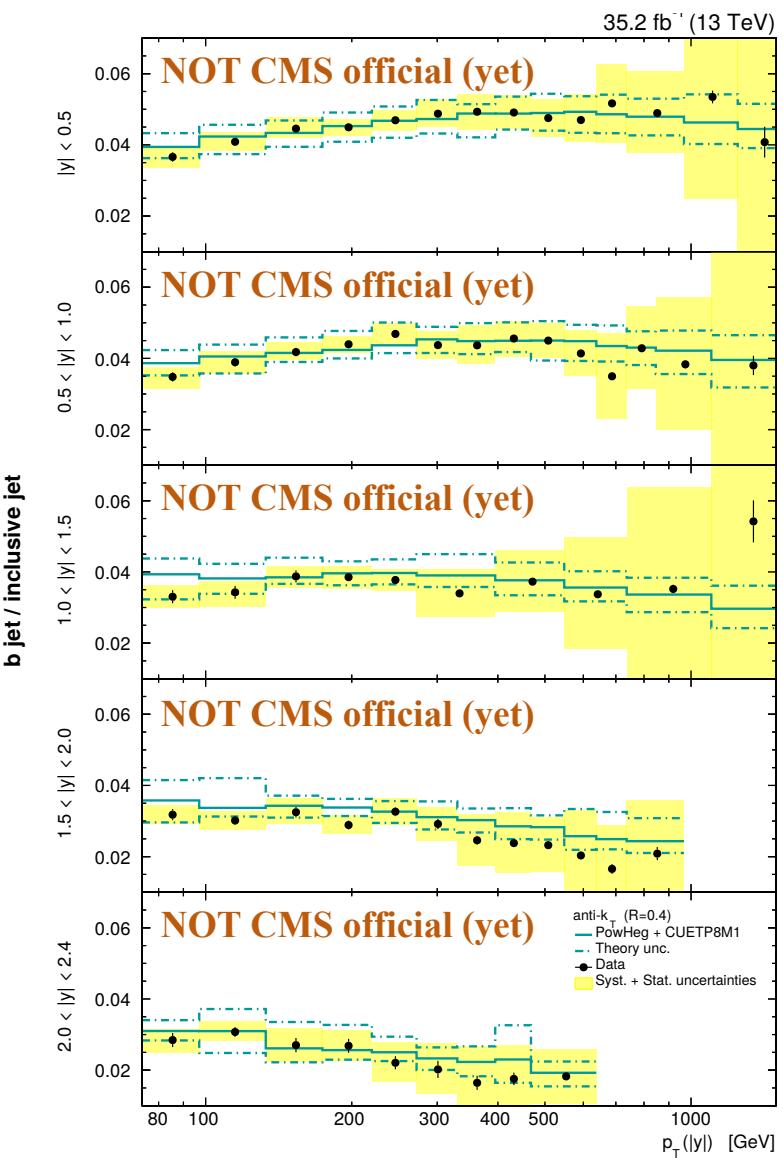
Inclusive b jets

- Ratio of b jets to inclusive jets cancels out experimental and theoretical uncertainties
- Leading exp. uncertainties b-tagging efficiency and b-jet energy scale (bJES)
- Care needed for fiducial xsec: what jet R, include ν / μ or not (ATLAS vs “jet” vs “μ”)



CMS, arXiv:1202.4617

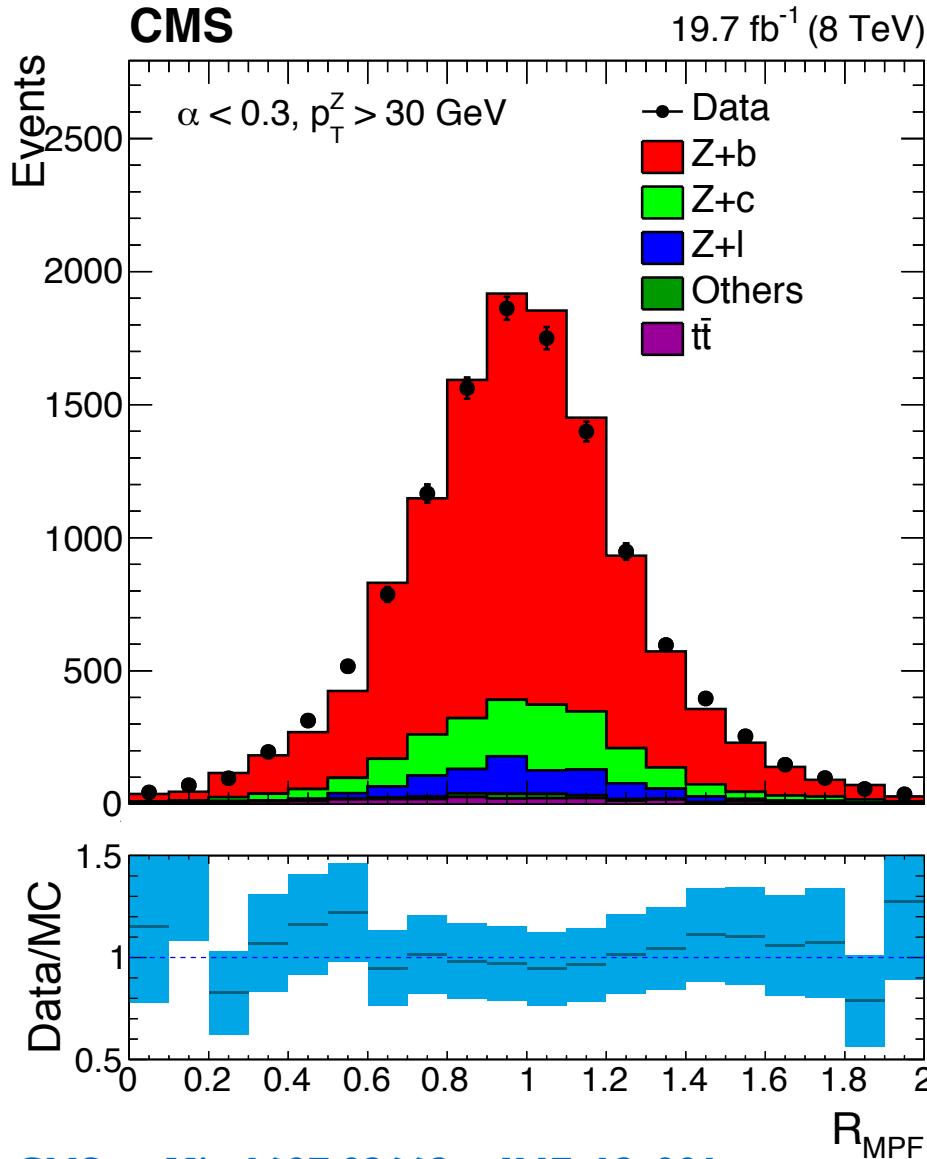
- **I3 TeV: CERN-THESIS-2018-069** (NLOxPS, Powheg+P8 good)



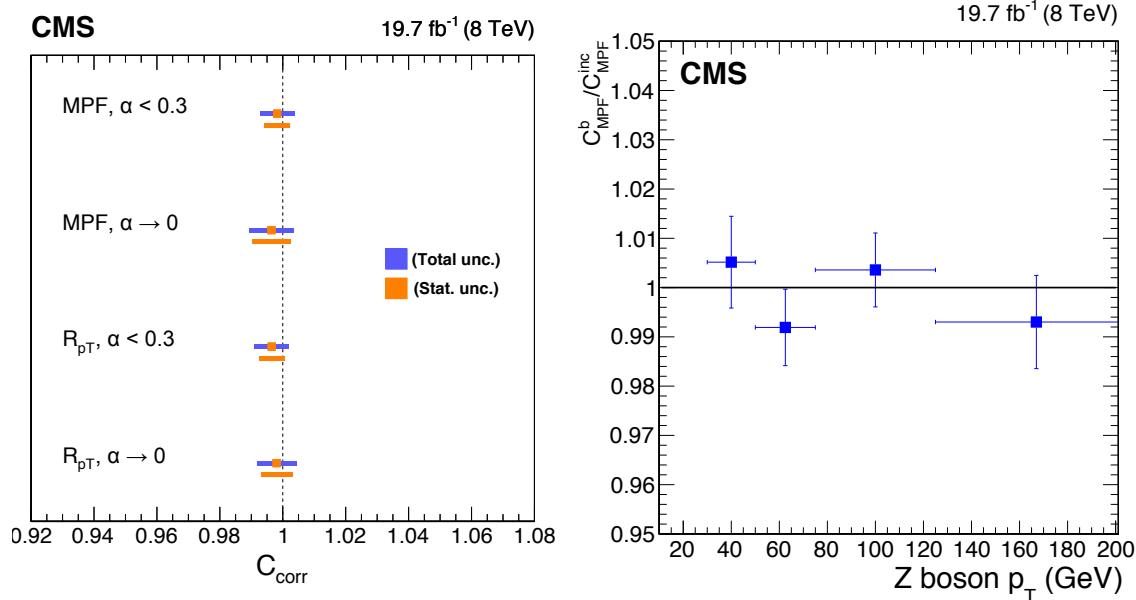
b-jet scale with Z+b

$$C_{\text{corr}}(\text{MG+P6Z2*}) = 0.998 \pm 0.005$$

$$C_{\text{corr}}(\text{H}++) = 1.006 \pm 0.007$$

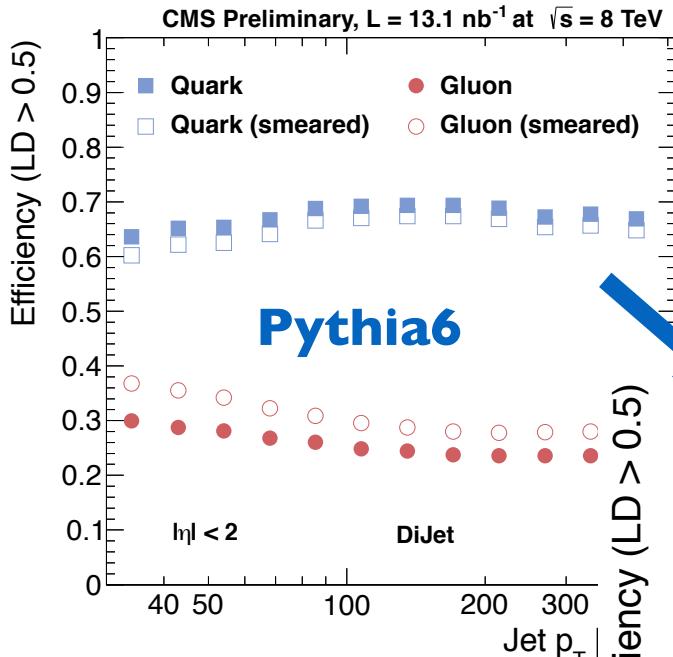


- Z+b relatively pure sample of b jets
- Double ratio wrt Z+jet data/MC, multiple balancing methods
 - ▷ stat. unc. 0.4%, reducible to 0.15% in Run II
 - ▷ syst. uncertainty 0.4%, mostly from vs (CMS reference is particle jet without ν) => reducible to ~0.15%
- MG+Pythia / Herwig differ by 0.2% for Z+jet, from 20% gluons in reference Z+jet
 - ▷ H++ stat. unc. ~0.6%, inconclusive for Z+b



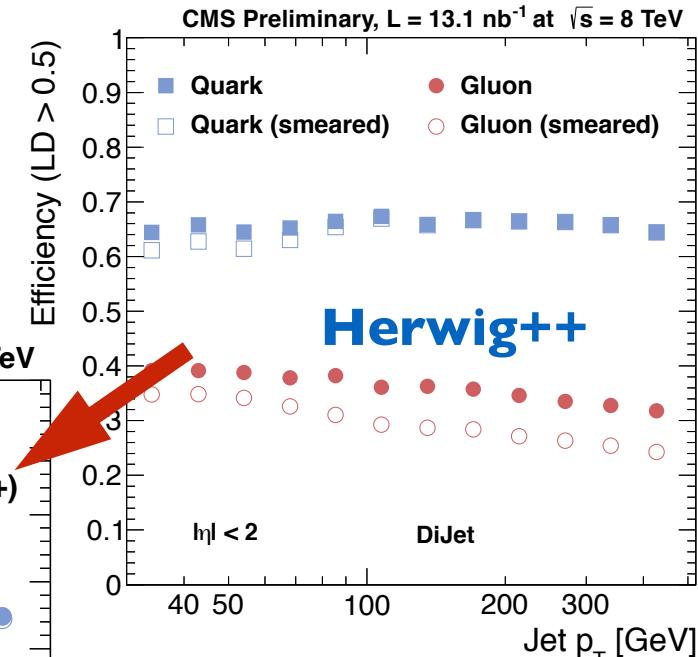
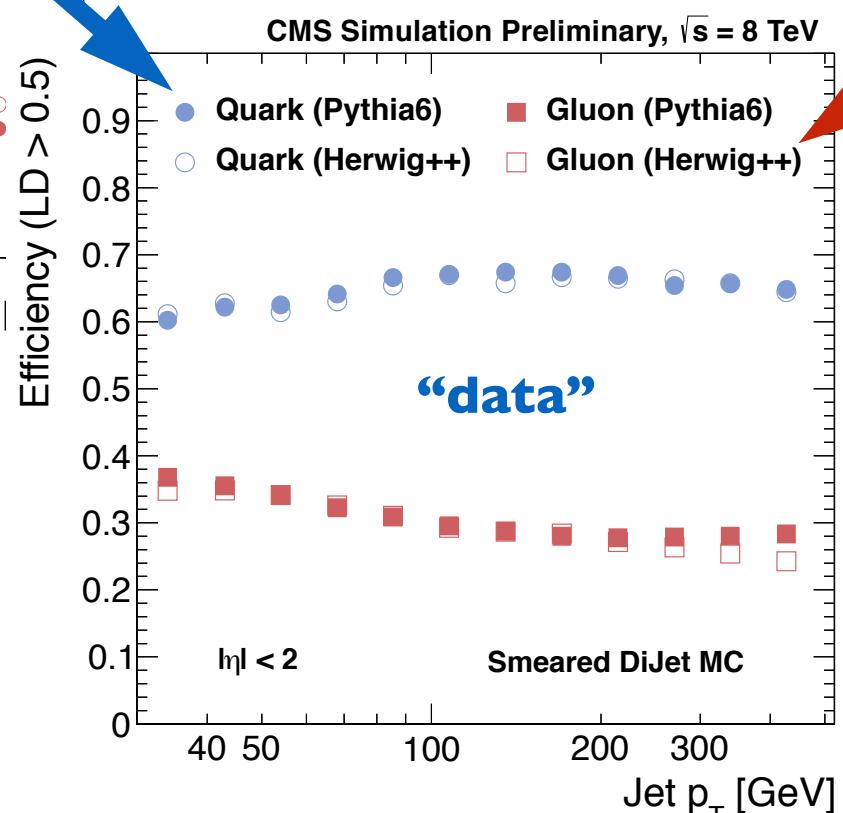
Quark/gluon likelihood

- Jet uncertainties in Run I largely boiled down to gluon (quark) fragmentation model
- Pythia6 and Herwig++ in particularly bad agreement on gluon jet modelling



Pythia6 overestimates
quark/gluon differences

Smearing Pythia6 and
Herwig++ to dijet and Z+jet
data improves agreement

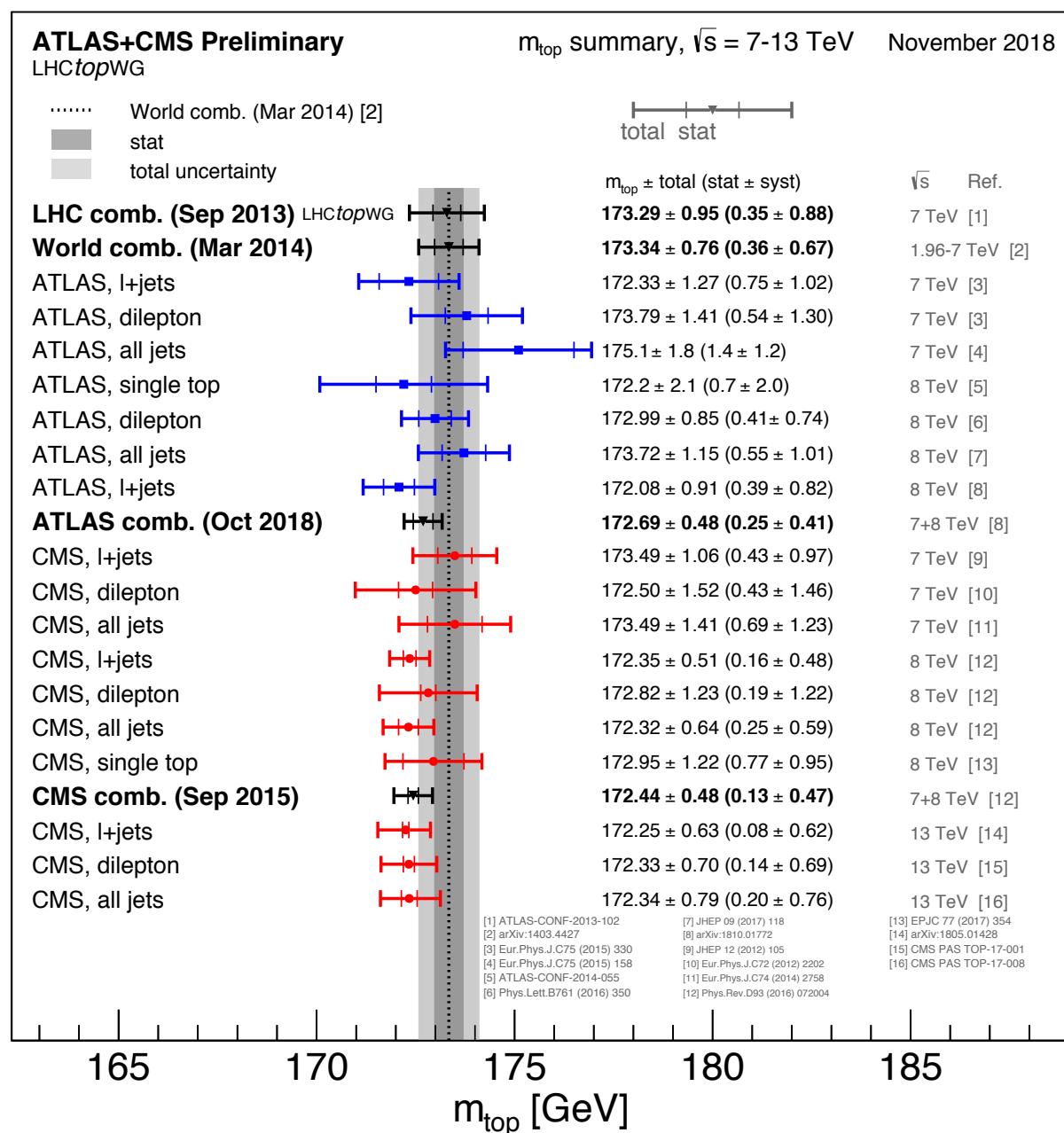


Herwig++ underestimates
quark/gluon differences

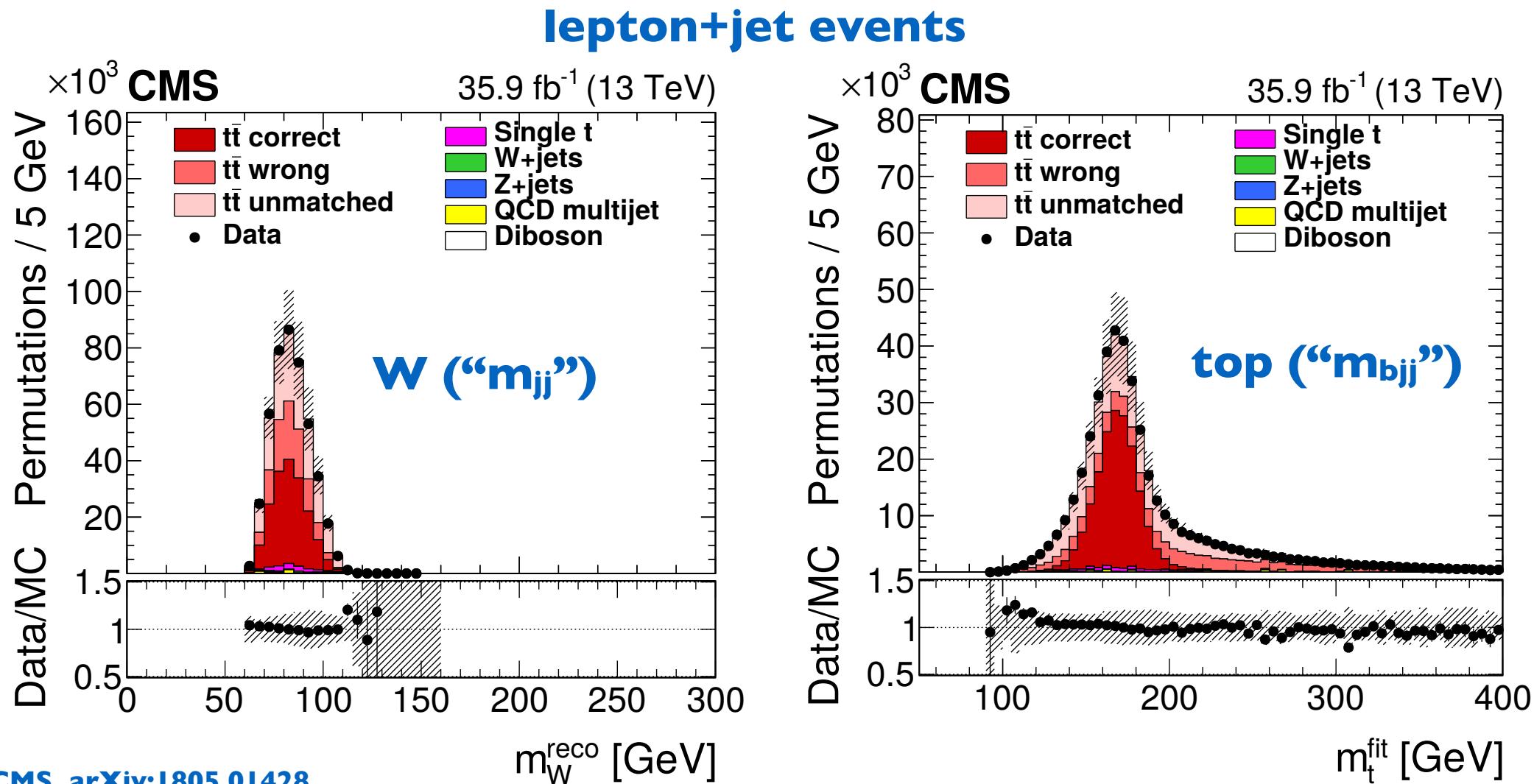
To be fully revisited in Run II
(Pythia8, Herwig7)

Top quark mass

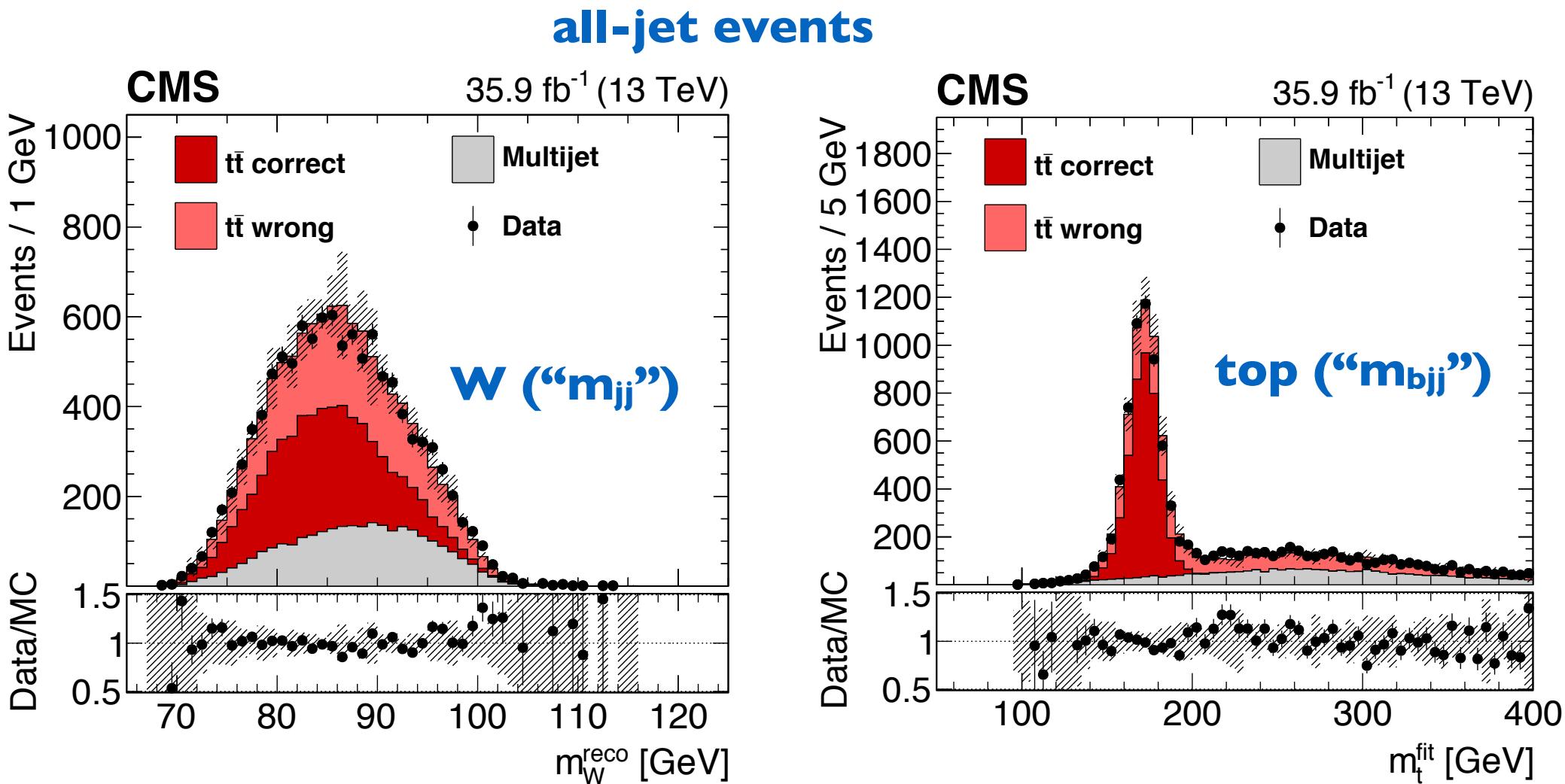
- Precision driven by kinematic reconstruction of top quark mass in lepton+jet events
- Mass extracted by varying m_t^{gen} in MC to fit m_t^{kin} to data
 - ▷ roughly mass of sum of b-jet and two light jet four-vectors
- Key technique is 2D fit using $m_{jj} = m_w^{\text{PDG}}$ to extract jet energy scale factor JSF
 - ▷ In-situ constraint on light jet scale R_q , but still leaves bJES R_b/R_q
 - ▷ Also partly removes biases from FSR and UE
- ATLAS 3D fit also extracts bJES R_b/R_q using $R_{bq} = p_{T,b}/p_{T,jj}$
 - ▷ Should still have partial biases from FSR and UE



- Lepton+jet, dilepton and all-jets at 13 TeV consistent with each other to 90 MeV
 - ▷ also consistent with Run I to better than 200 MeV
- Consistency is there, but large correlated uncertainty from bJES, FSR and UE



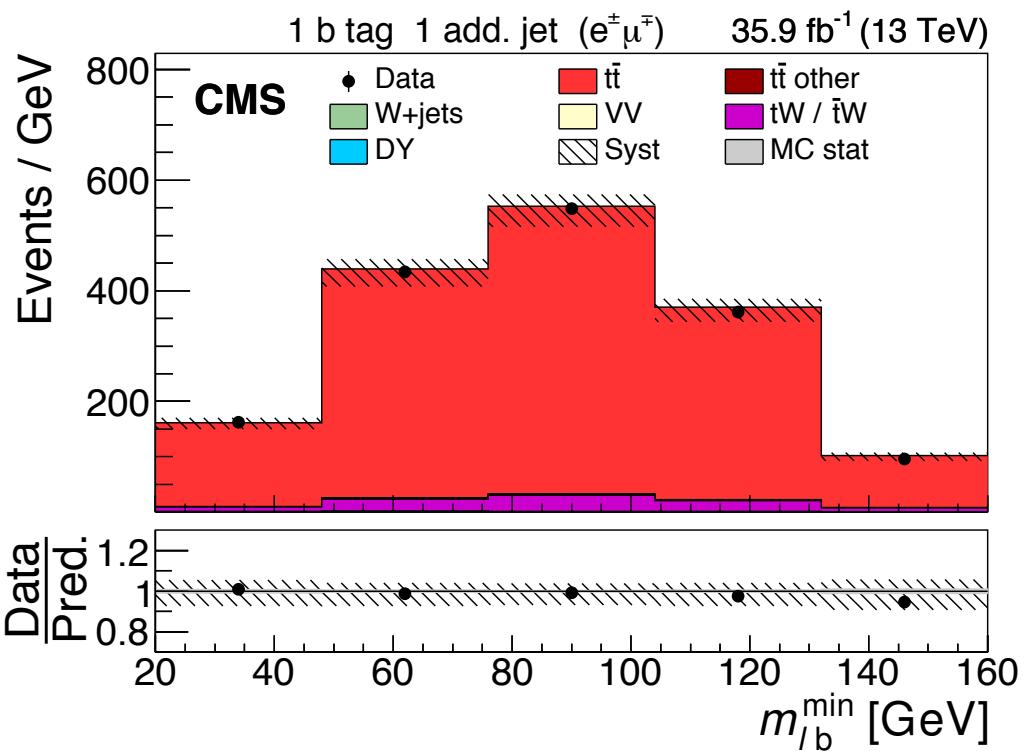
- Lepton+jet and all-jets correlated on bJES, FSR, UE due to m_W constraint
 - m_W absorbs part of FSR, UE, and modifies bJES: R_b/R_{Z+jet} to R_b/R_q



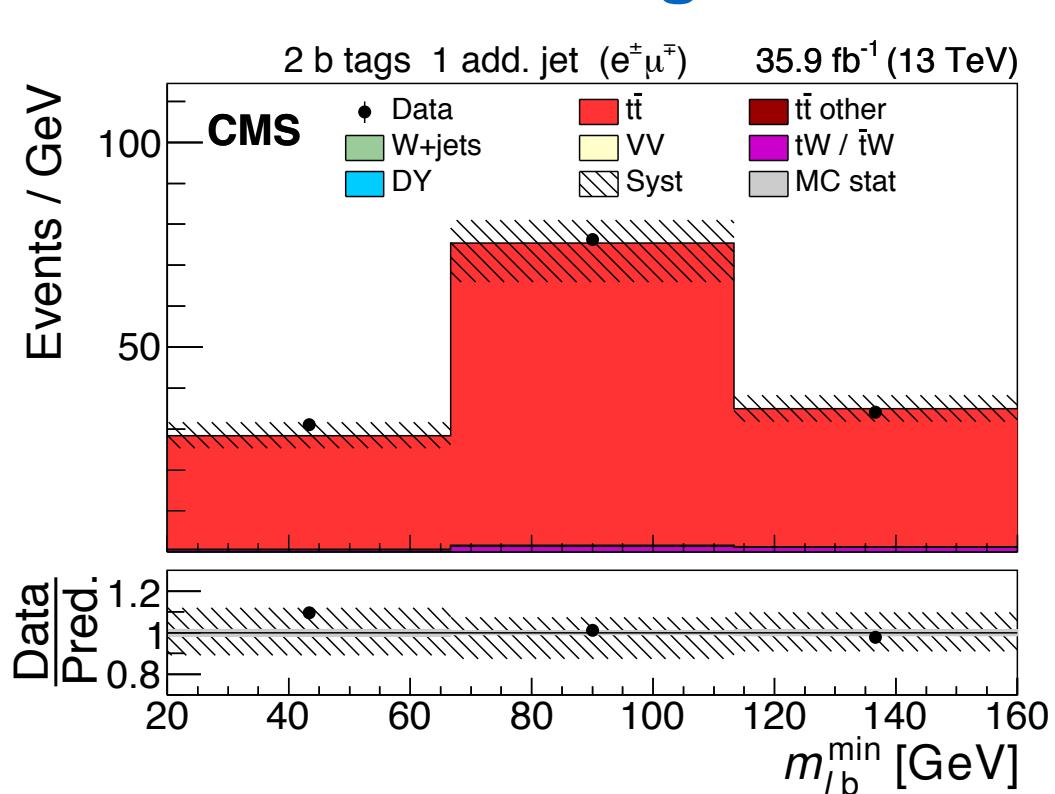
- Dilepton only partially correlated to lepton+jet and all-jets (no $m_{jj}=m_W$ mass constraint)
 - ▷ measured from simultaneous fit to cross section and mass parameter (w/ m_{lb}^{\min} on $e^\pm\mu^\mp$)
 - ▷ cross-checked with m_{lb} in events with at least one b tagged jet (171.92 GeV vs 172.33 GeV)

dilepton events

1 b tag

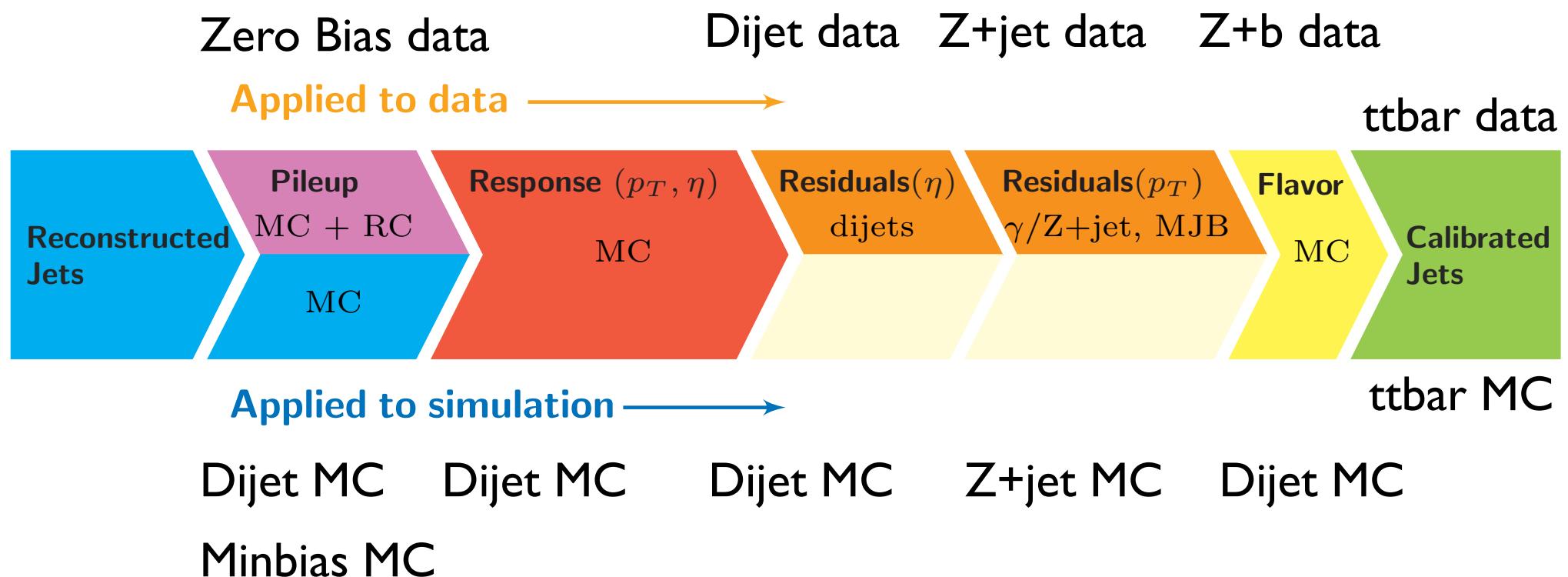


2 b tags



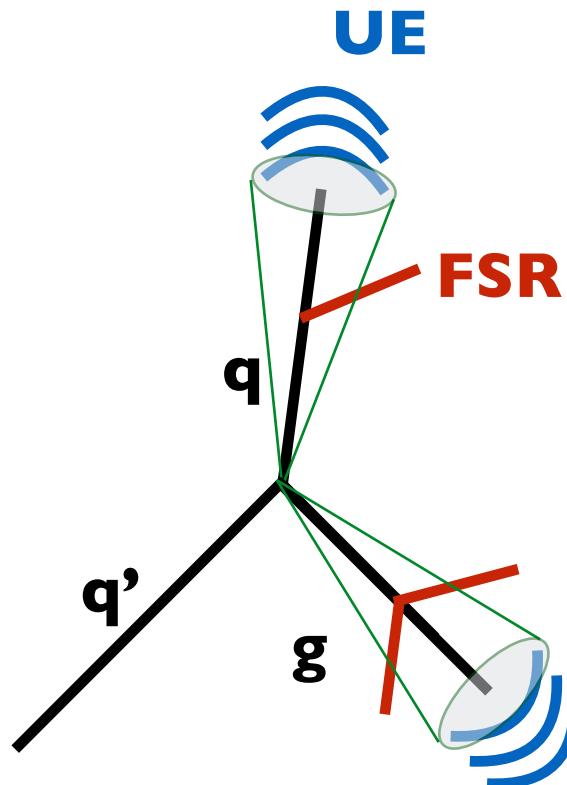
Model building

- Our Helsinki team is aiming to build a coherent model of dijet, Z+jet and ttbar events
- Dijet and Z+jet events form the baseline for jet calibration
- Aim to unify definitions of Final State Radiation (FSR), Underlying Event (UE), and b-jet energy scale R_b to keep same precision for ttbar events



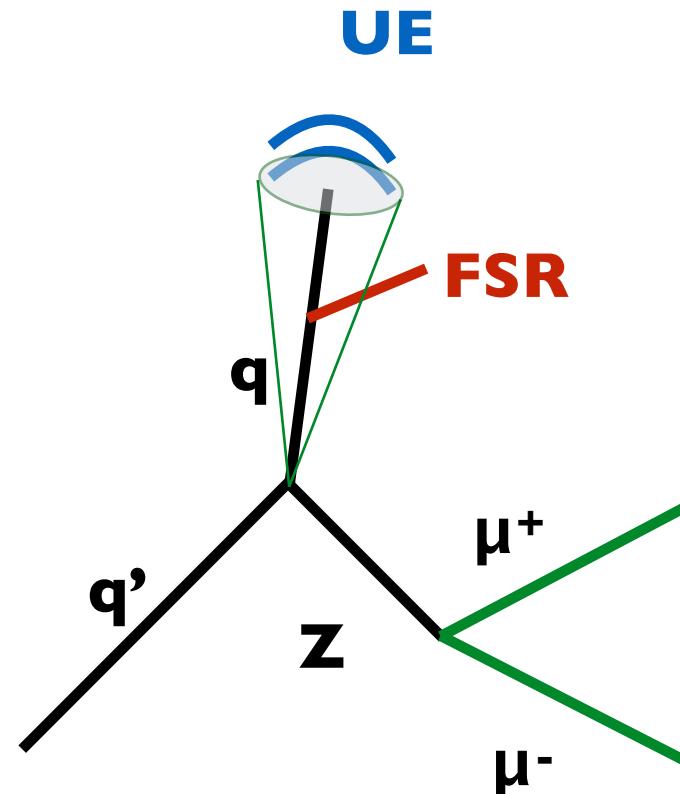
Dijet model

- At $p_T \sim 100$ GeV, inclusive jets typically form a transversally balanced gg or qg dijet system
 - ▷ although often longitudinally $|\eta_q| > |\eta_g|$
- Measured underlying event (UE) is around 2 GeV per unit area ($\sim \times 3$ at particle level)
- Final state radiation (FSR) out of jet cone is a few percent and proportional to cut on maximum p_T of additional jets, aka “ α ”
 - ▷ Also proportional to parton type (g: $C_A=3$, q: $C_F=4/3$, b= C_F + dead cone effect) and α_s
 - ▷ And in inverse relation to the jet cone size R



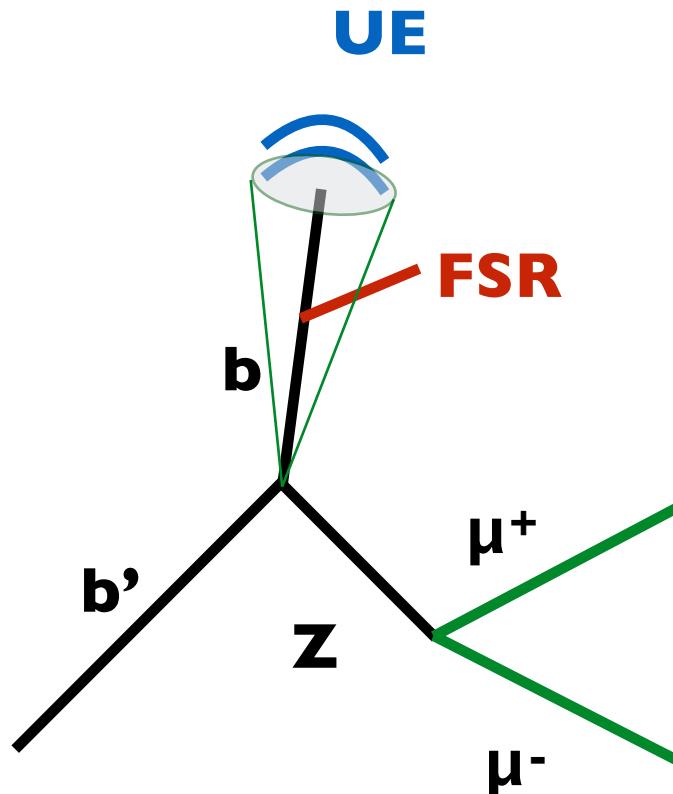
Z+jet model

- At $p_T \sim 100$ GeV, Z+jet is typically from qg interaction, so opposing jet is light quark
- Measured underlying event (UE) is around 1.3 GeV per unit area ($\sim (C_F + C_A)/2C_A$)
- FSR is less than in dijets, due to higher fraction of quark jets
- Z boson directly probes p_T at parton level, as muons do not radiate strongly, and their track reconstruction is insensitive to UE



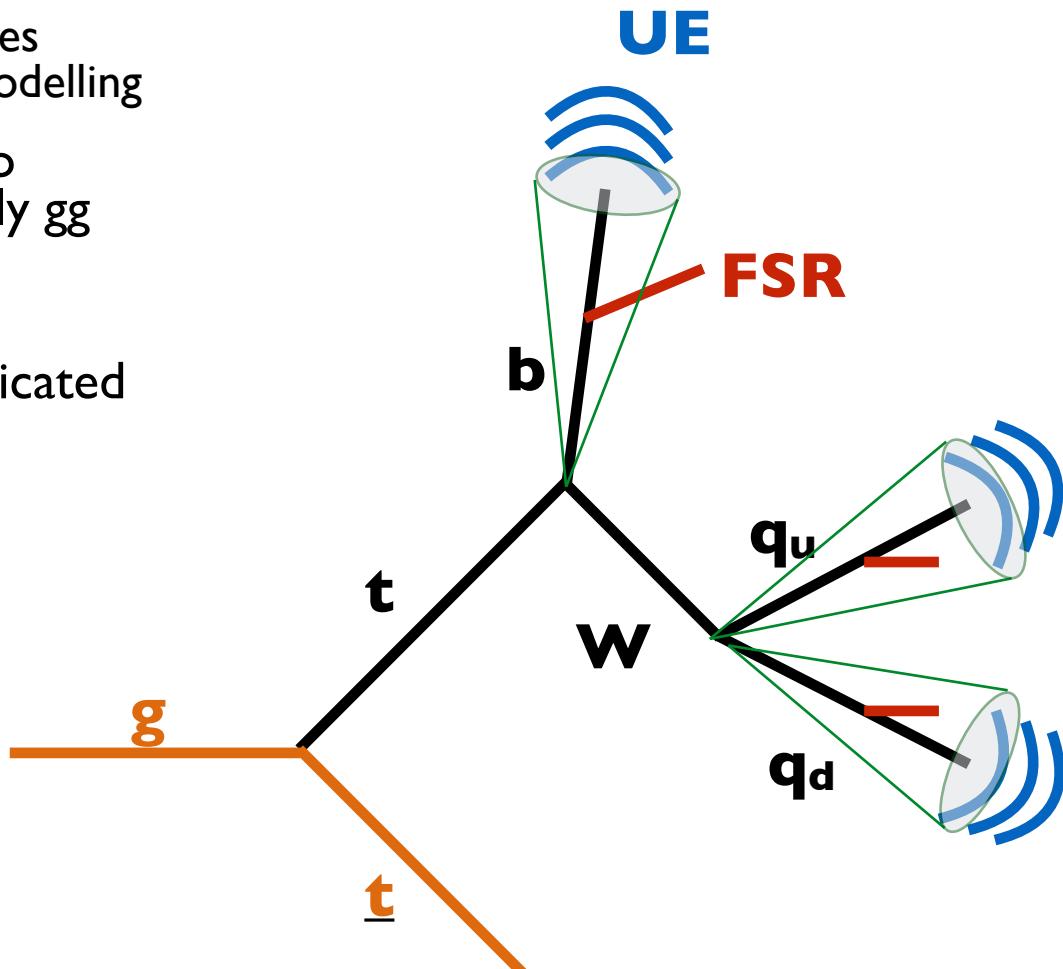
Z+b model

- At $p_T \sim 100$ GeV, Z+b is typically from bg interaction, so opposing jet is b quark
- Measured underlying event (UE) is essentially same as in Z+jet events
- FSR is very similar to light quarks, although potentially different due to dead cone effect



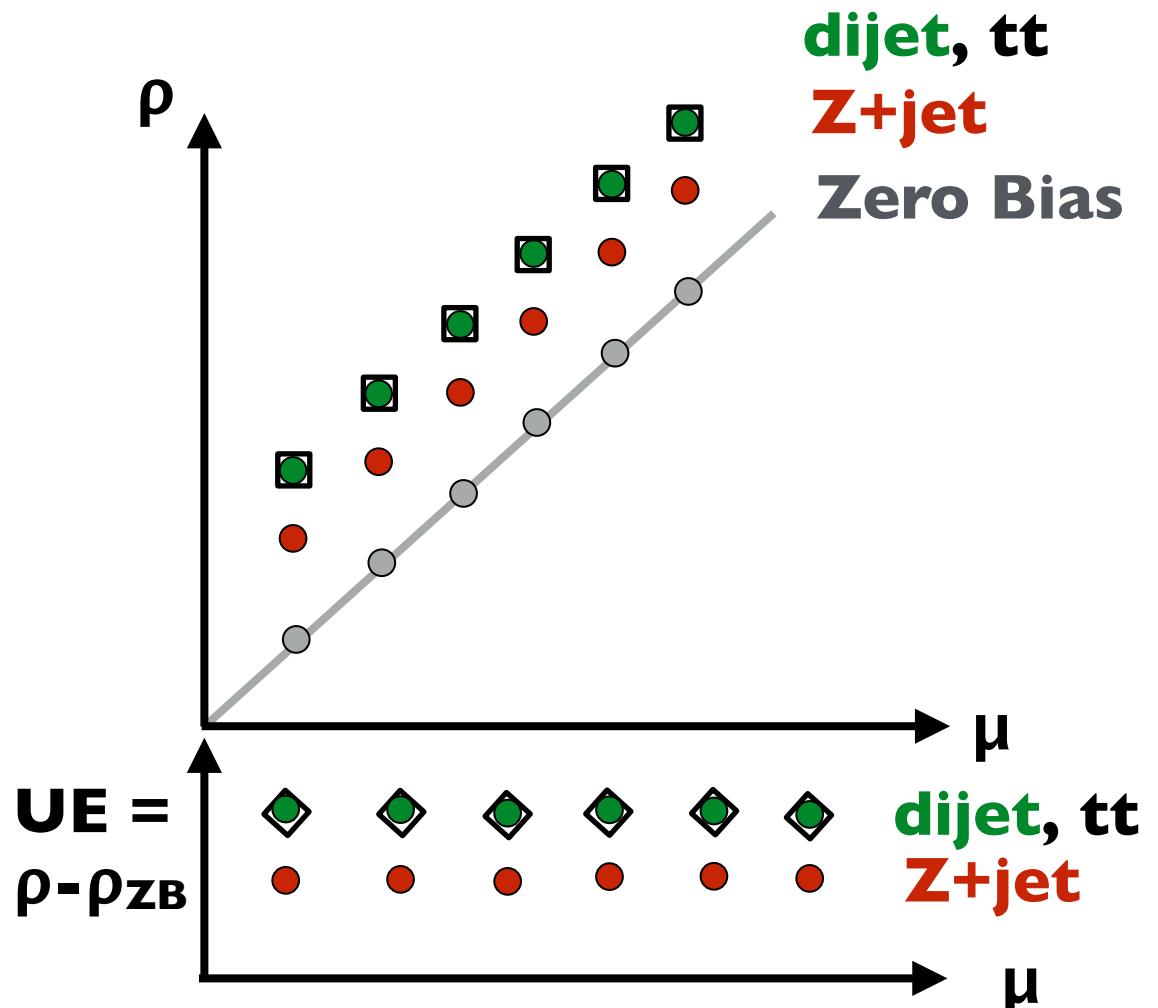
Top model

- Top decay bears similarities to $Z+b$ production, with Z replaced by $W(q_u q_d)$
 - ▷ Hadronic W reconstruction provides independent test of UE and FSR modelling
- Underlying event is very similar to dijets, as initial state in both usually gg
- FSR is similar to $Z+b$
- Transverse plane structure complicated by $t\bar{t}$ pair production



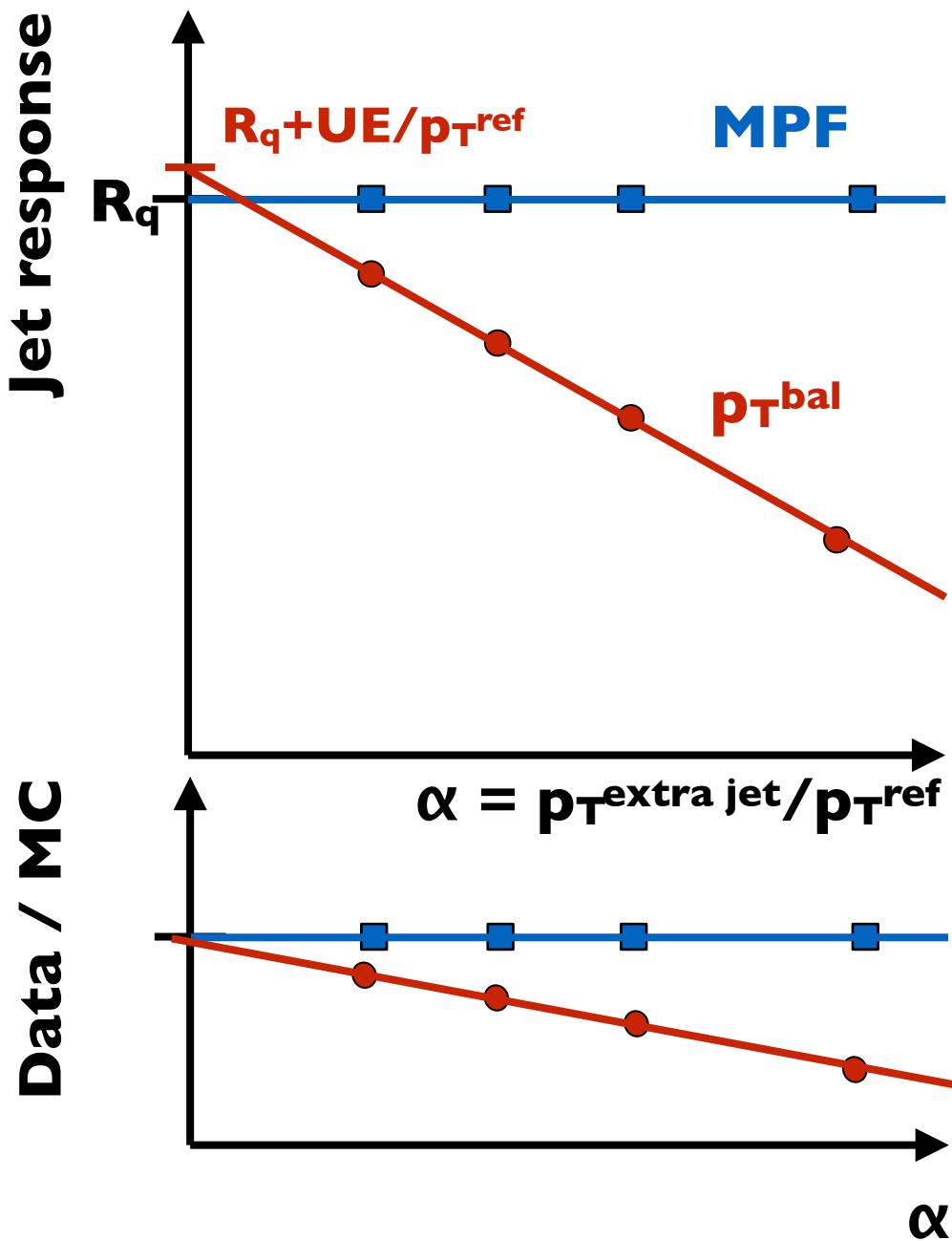
Constraints on UE

- 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



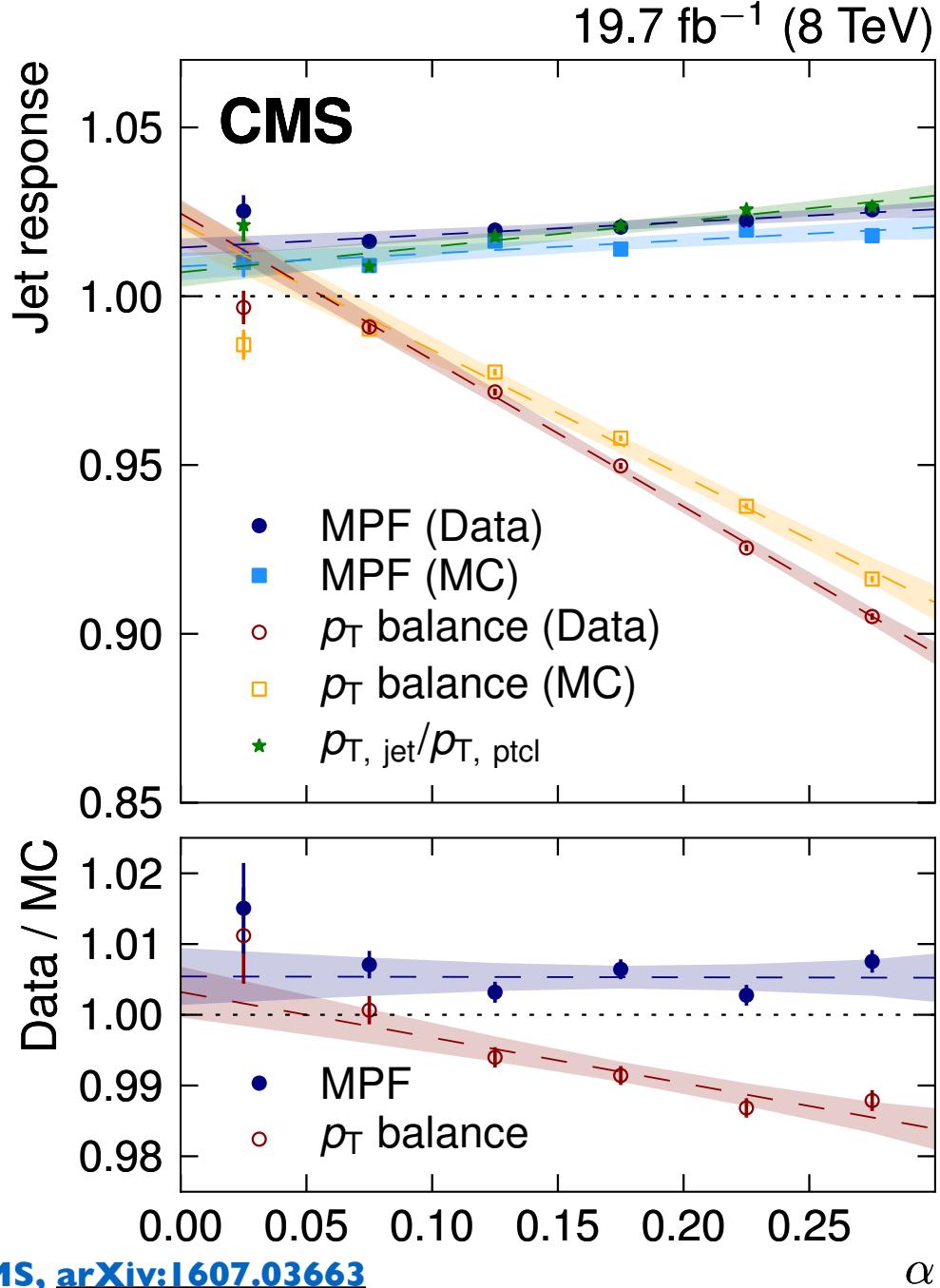
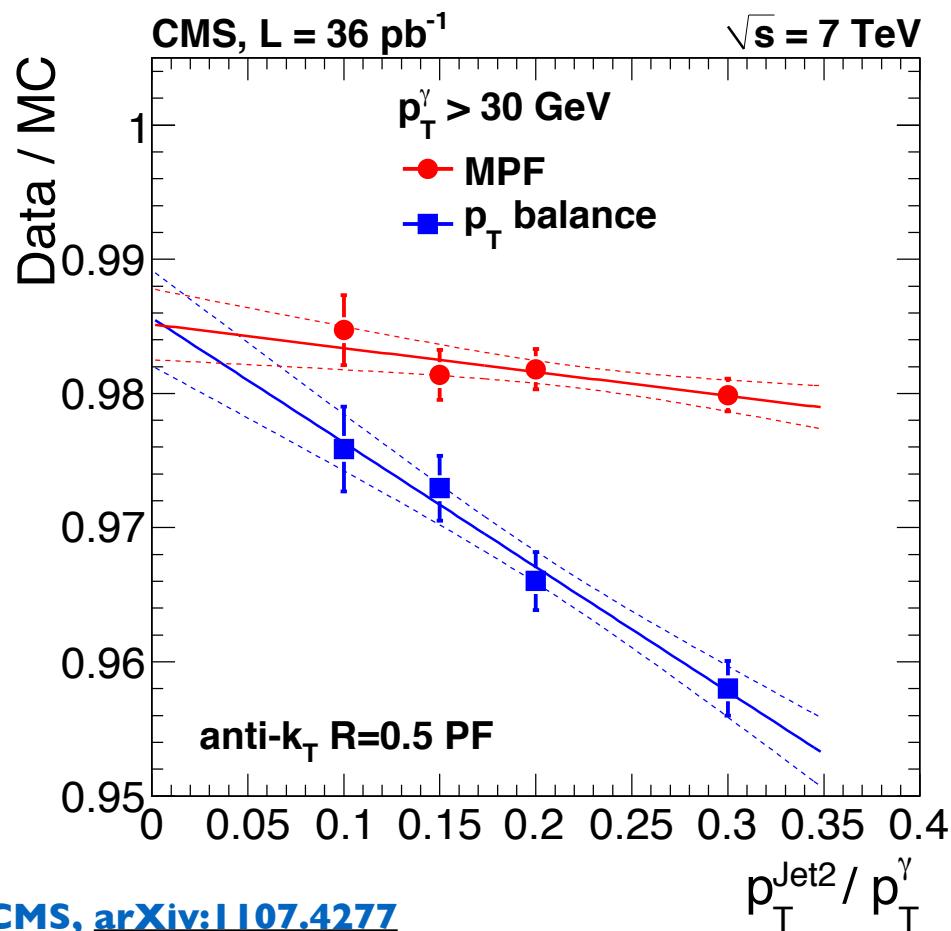
Constraints on FSR

- 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: $R_{\text{add'l}} \sim R_{\text{jet}1} \Rightarrow R_{\text{MPF}} \sim R_{\text{jet}1}$
 - ▷ p_T^{bal} : $R_{\text{add'l}} = 0 \Rightarrow R_{pT\text{bal}} \ll R_{\text{jet}1}$



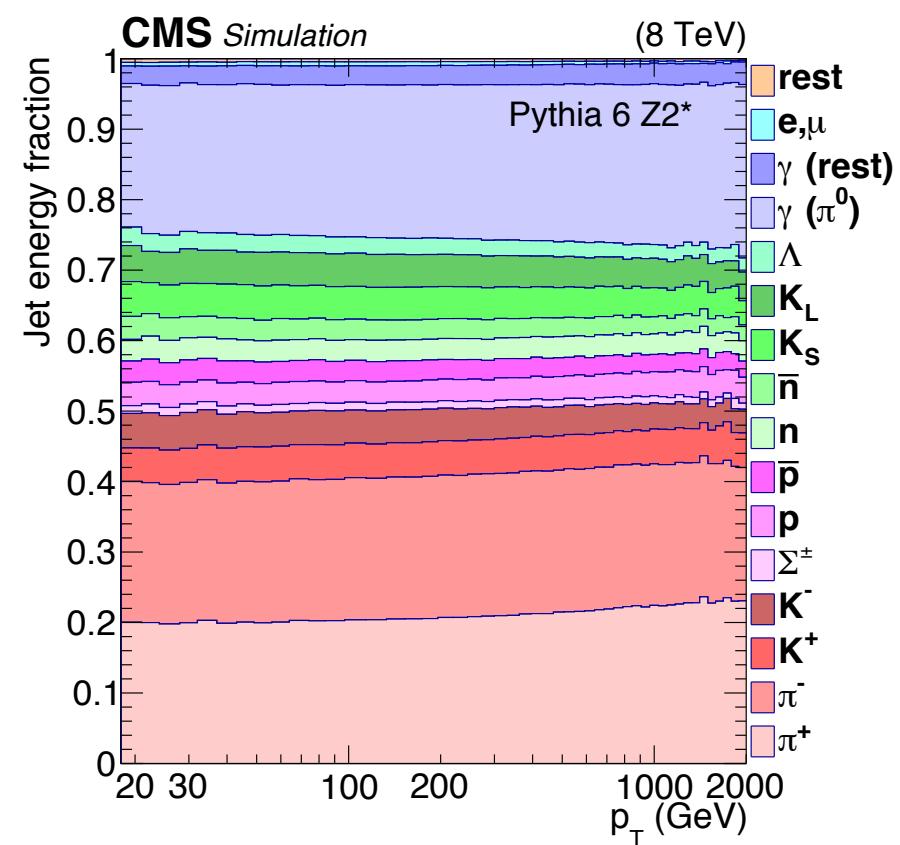
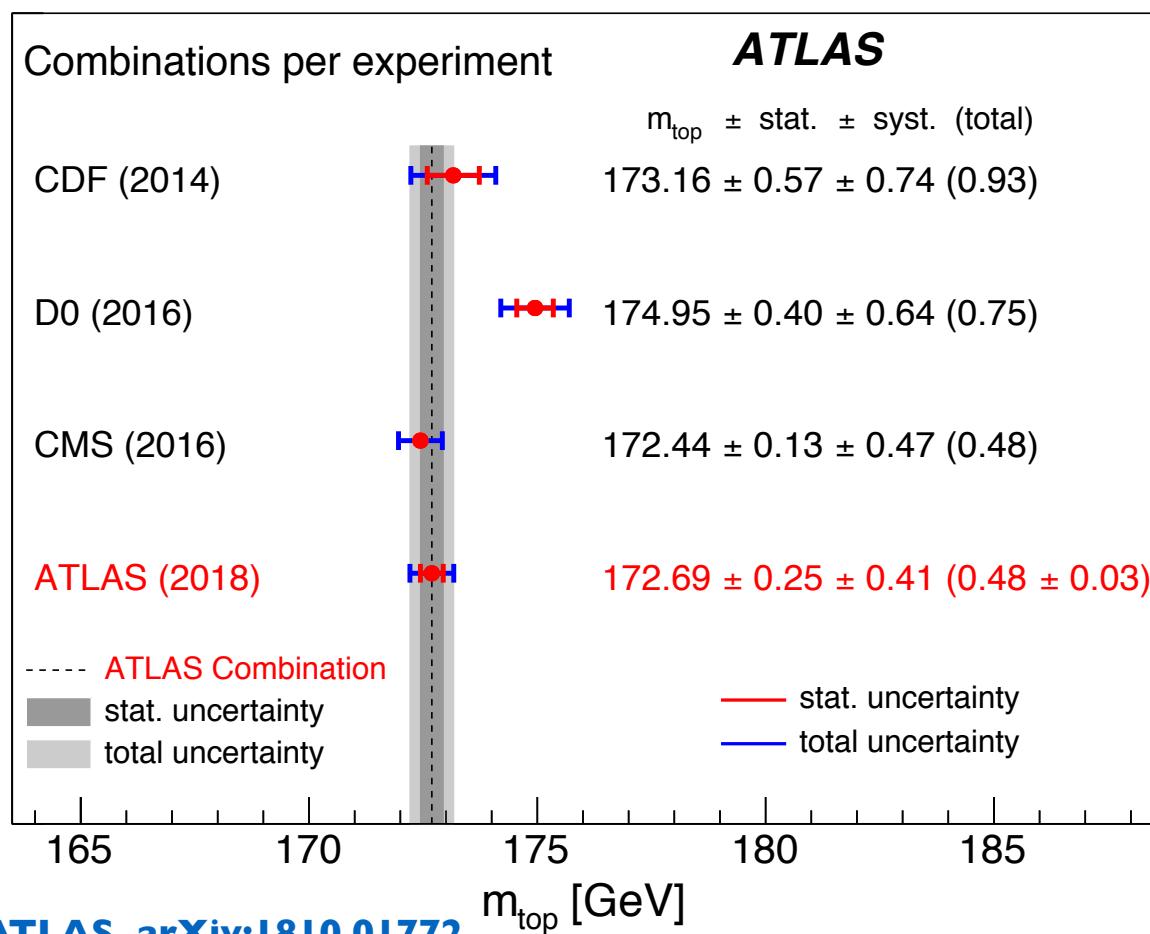
Constraints on FSR

- 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



Constraints on bJES

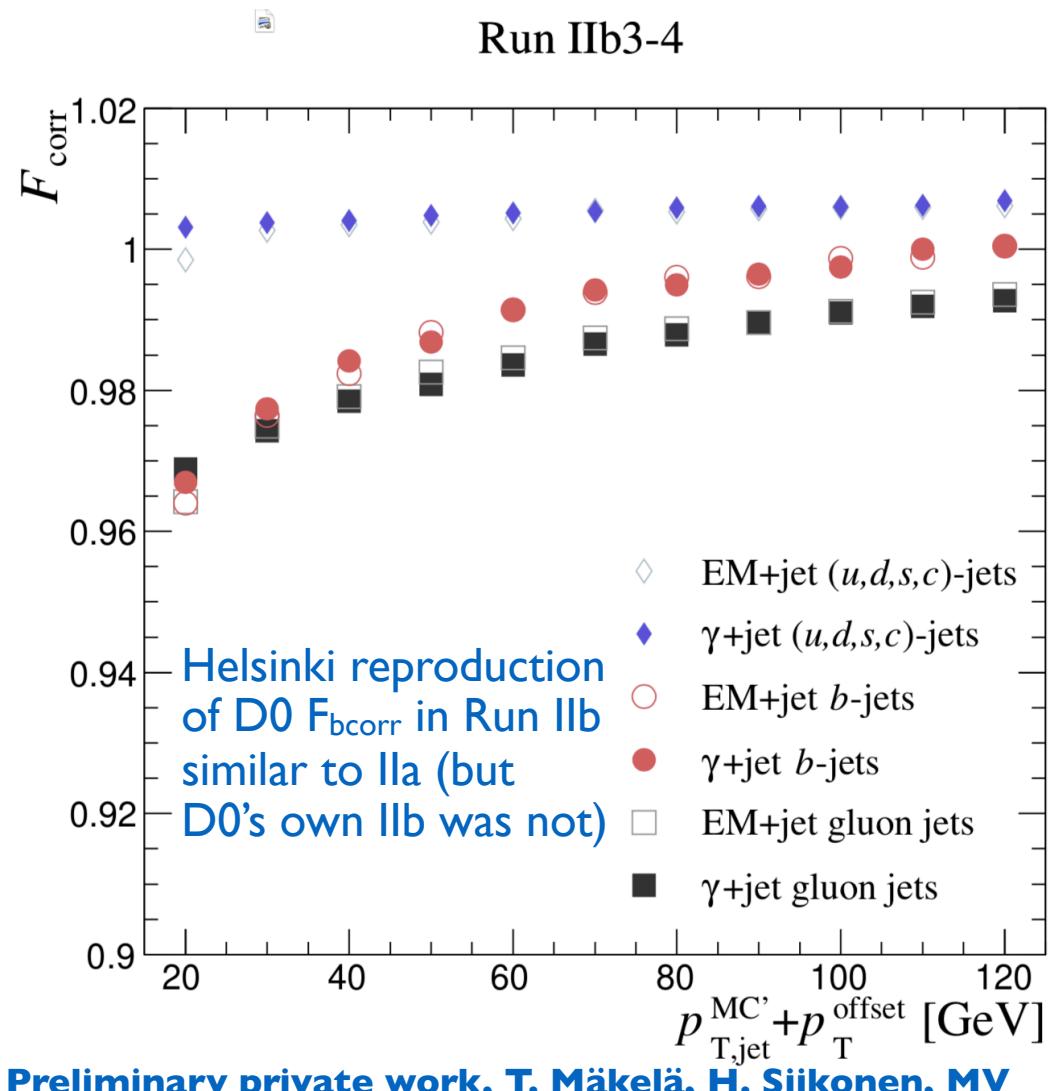
- Besides $Z+b$, can use jet fragmentation and single particle response to predict R_b
 - ▷ Main idea: $R_{jet} = \sum_i f_i * R_i(E_i)$, where f_i energy fraction, R_i single particle response to be fitted
- Method pioneered by D0, but two known caveats:
 - ▷ Input data uses p_T^{bal} method to estimate 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)



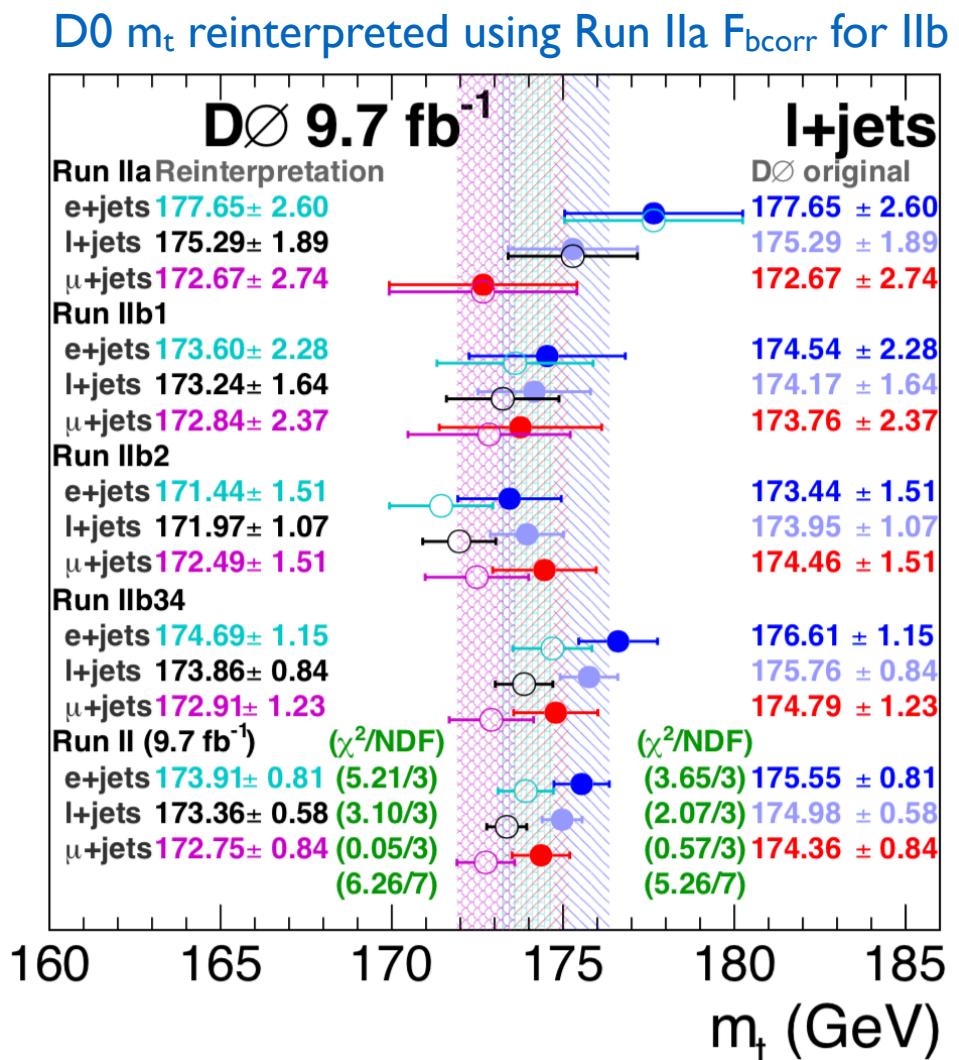
CMS, arXiv:1607.03663

D0 bJES & m_t reproduction

- Helsinki group working on reproducing D0 (or not...) and improving method for CMS
- So far evidence that Run IIb F_{bcorr} may have been unstable, and m_t should have been lower
- Also observe reinterpreted μ +jet being more stable than e +jet



Preliminary private work, T. Mäkelä, H. Siikonen, MV



Summary

- The m_t and α_s largest uncertainties for SM vacuum stability
- Best constrained at the LHC by measurements with many jets
- Running down the experimental chain leads to FSR, UE and bJES/gJES (b and gluon fragmentation)
- Need robust calibration ladder starting from $Z(\mu\mu) + \text{jet}$ to $t\bar{t}$ bar, *preferably backed by solid theory*

