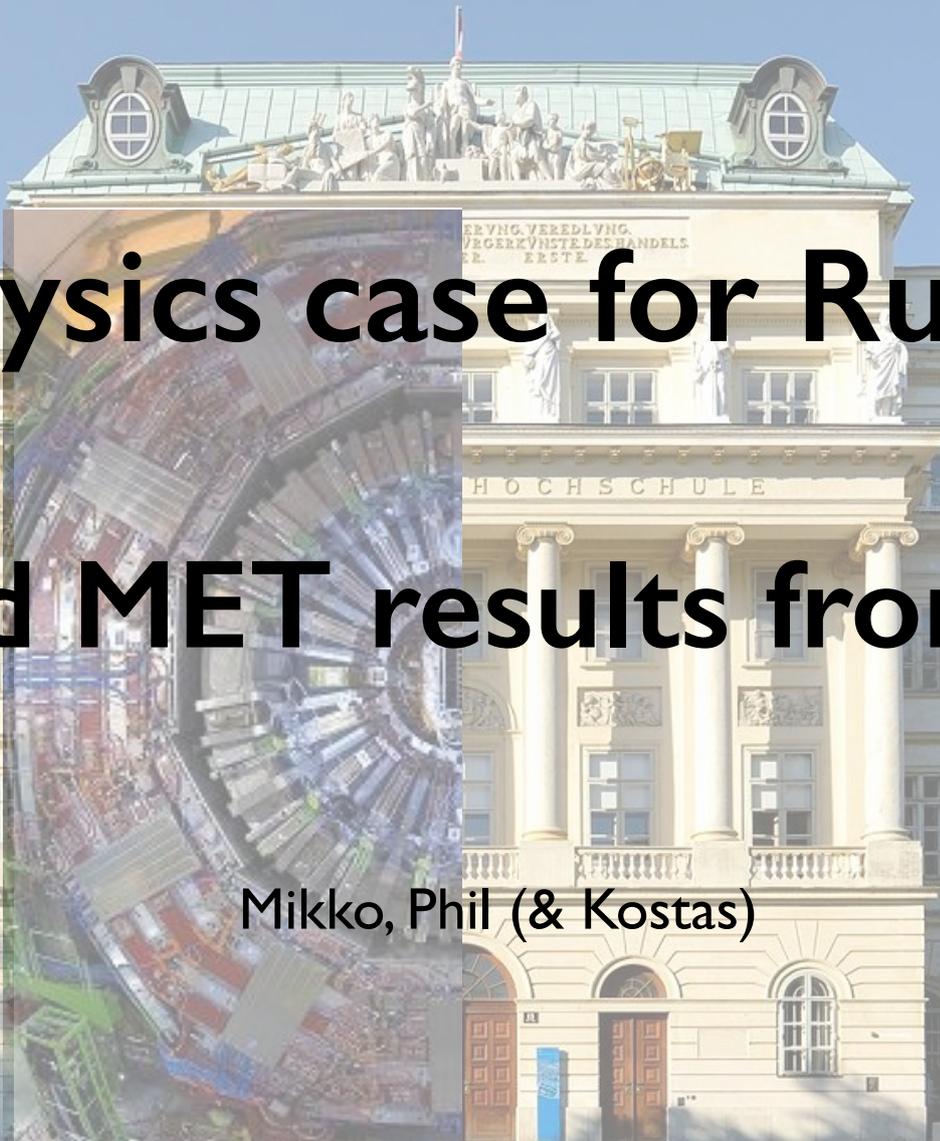


## Physics case for Run II

# Jet and MET results from CMS

Mikko, Phil (& Kostas)



- The encompassing theme of Run I was the Higgs
- From first data to discovery to precision measurements
- An incredible whirlwind tour in three years of data-taking
- Everything so far matches well with SM predictions
- Need to keep looking closer

Combined  
 $\mu = 1.00 \pm 0.13$

$H \rightarrow bb$  tagged  
 $\mu = 0.93 \pm 0.49$

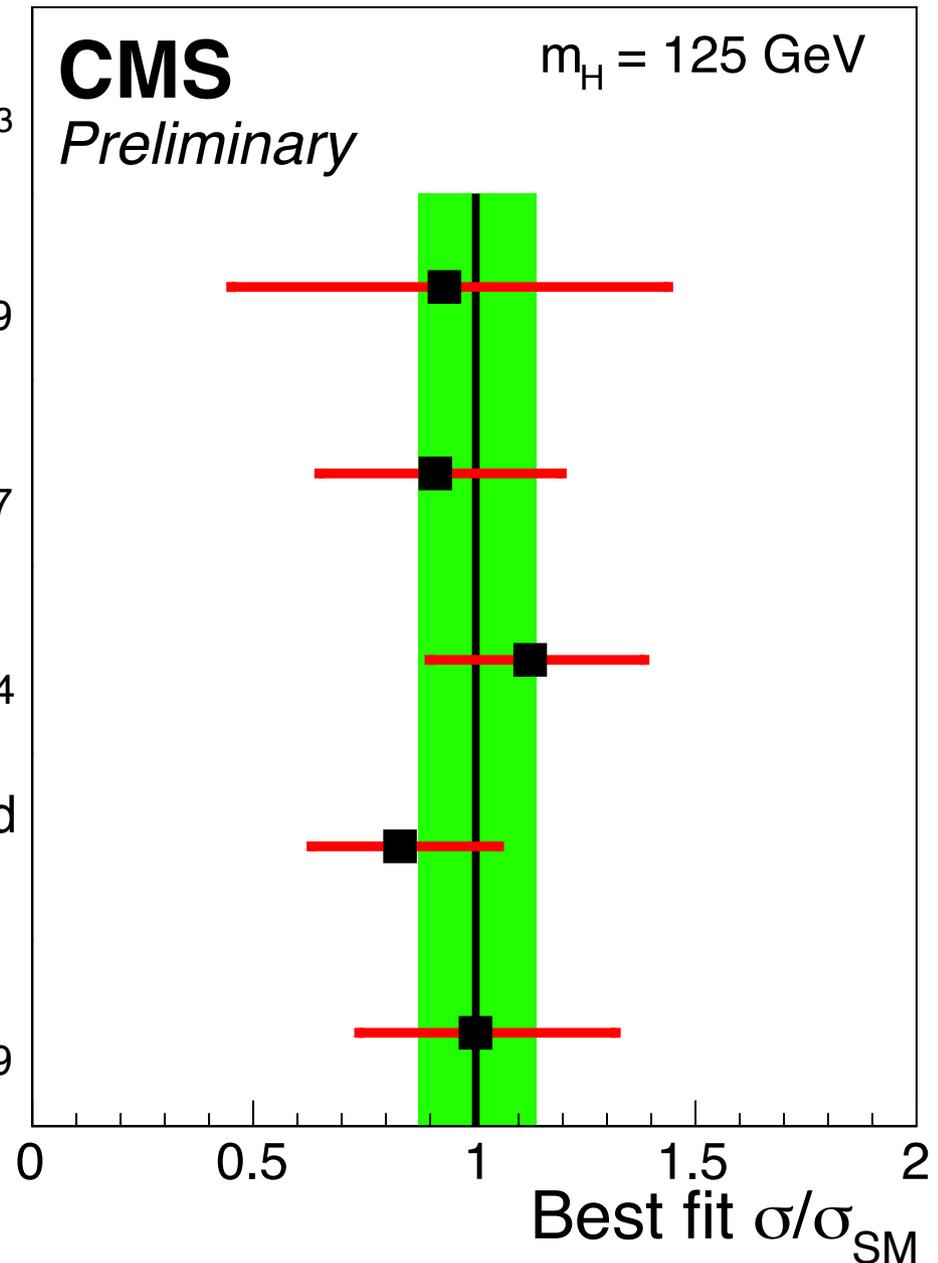
$H \rightarrow \tau\tau$  tagged  
 $\mu = 0.91 \pm 0.27$

$H \rightarrow \gamma\gamma$  tagged  
 $\mu = 1.13 \pm 0.24$

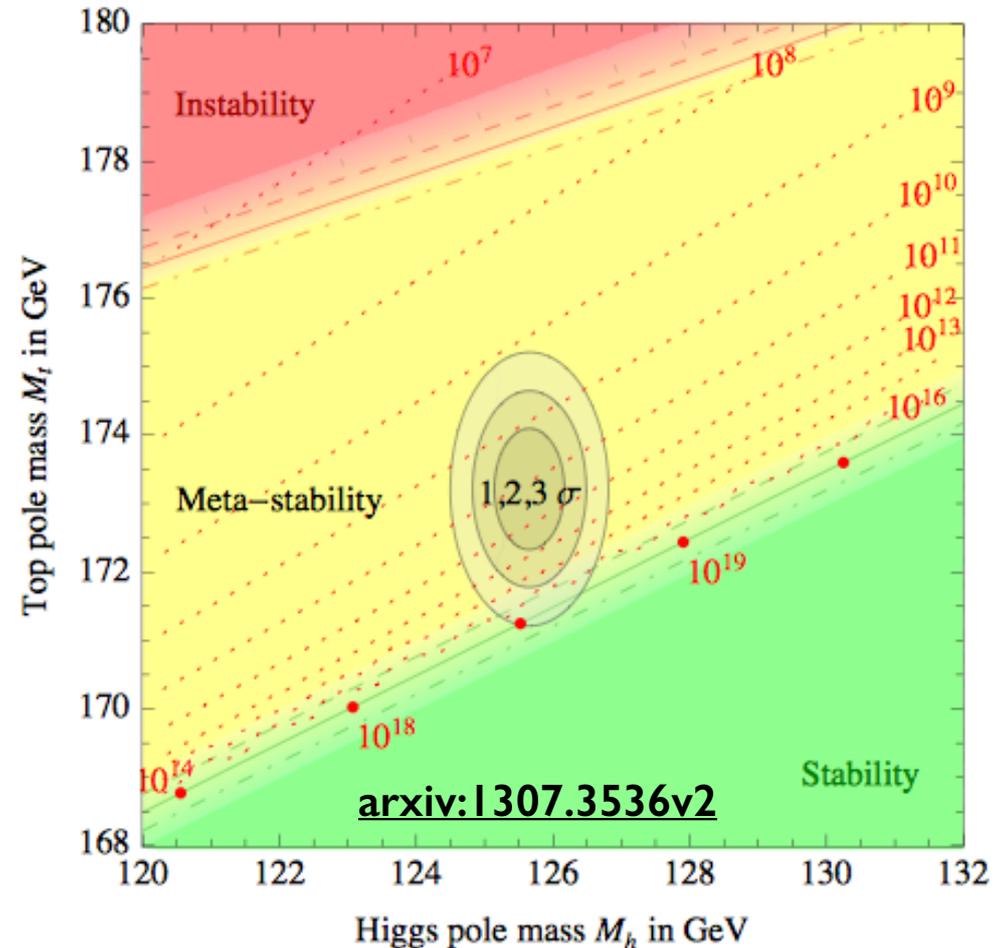
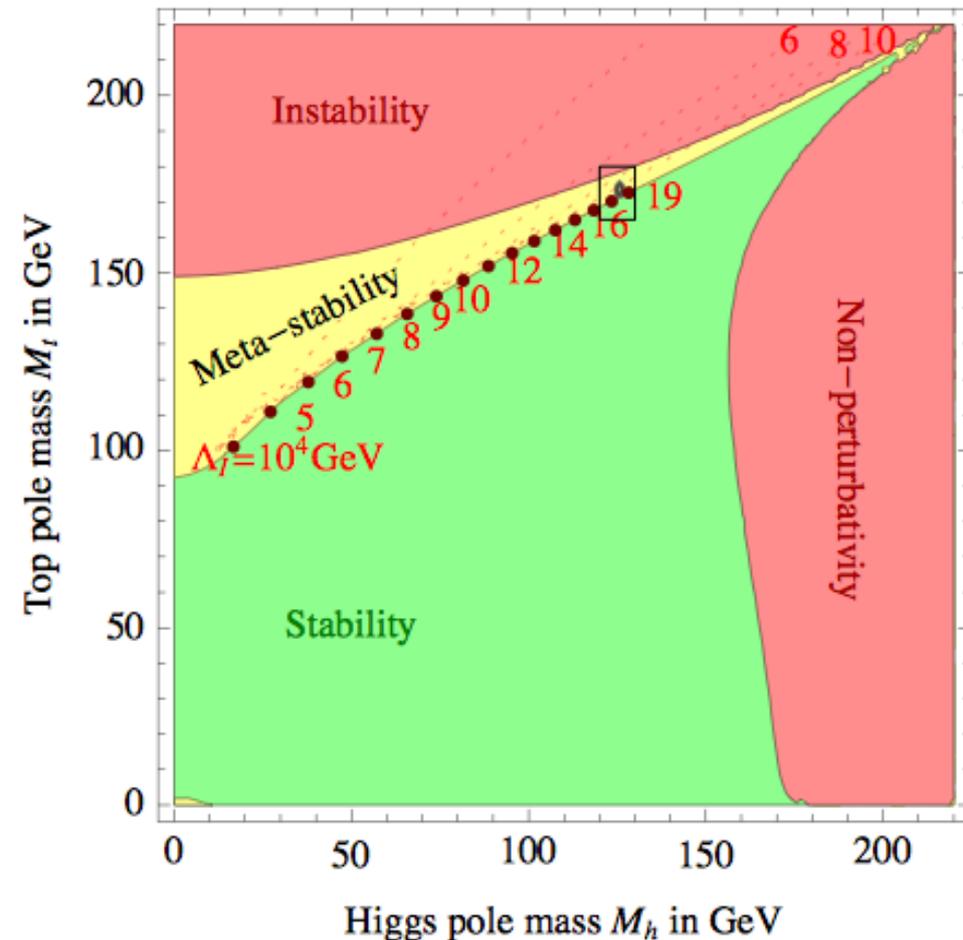
$H \rightarrow WW$  tagged  
 $\mu = 0.83 \pm 0.21$

$H \rightarrow ZZ$  tagged  
 $\mu = 1.00 \pm 0.29$

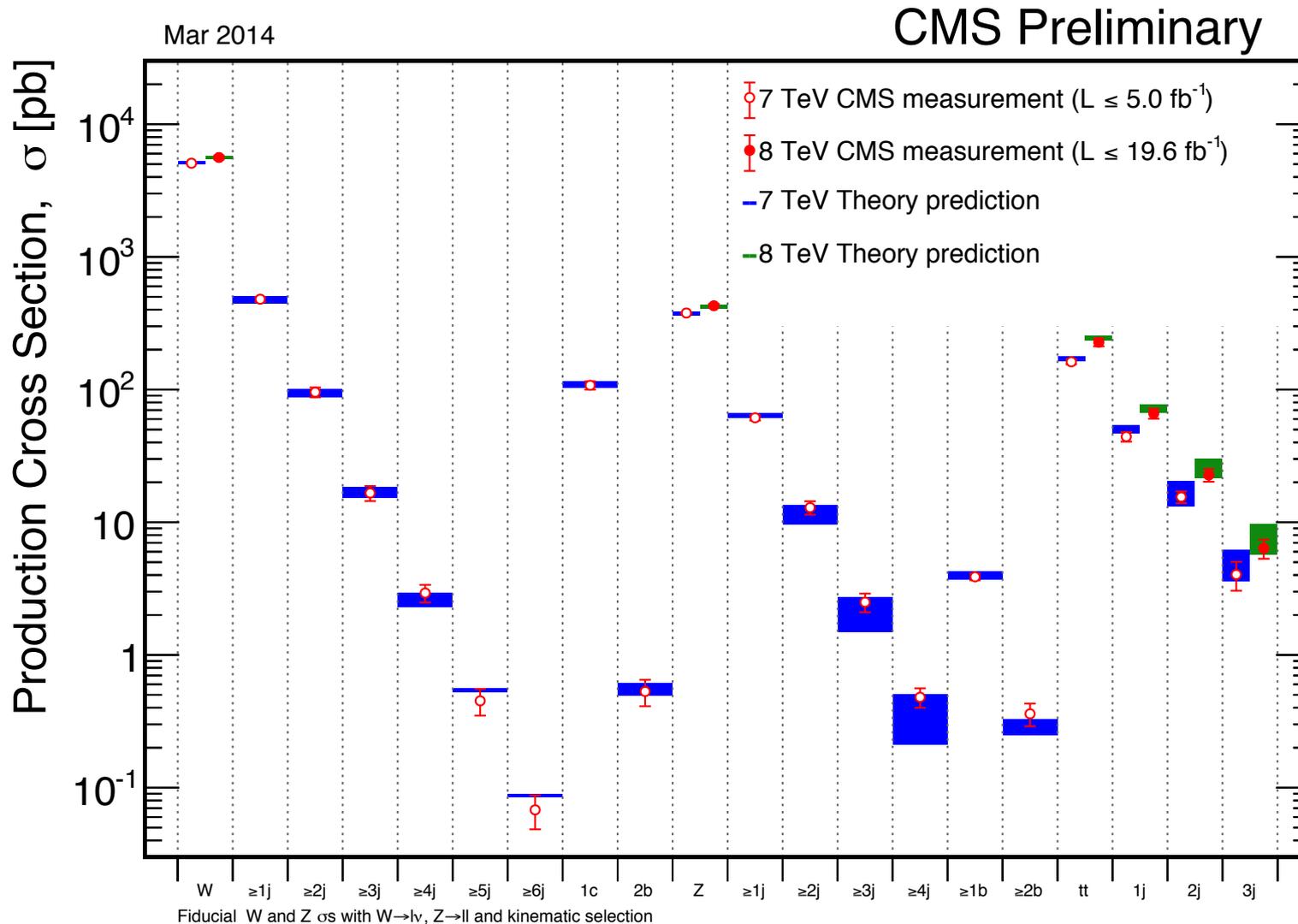
19.7 fb<sup>-1</sup> (8 TeV) + 5.1 fb<sup>-1</sup> (7 TeV)



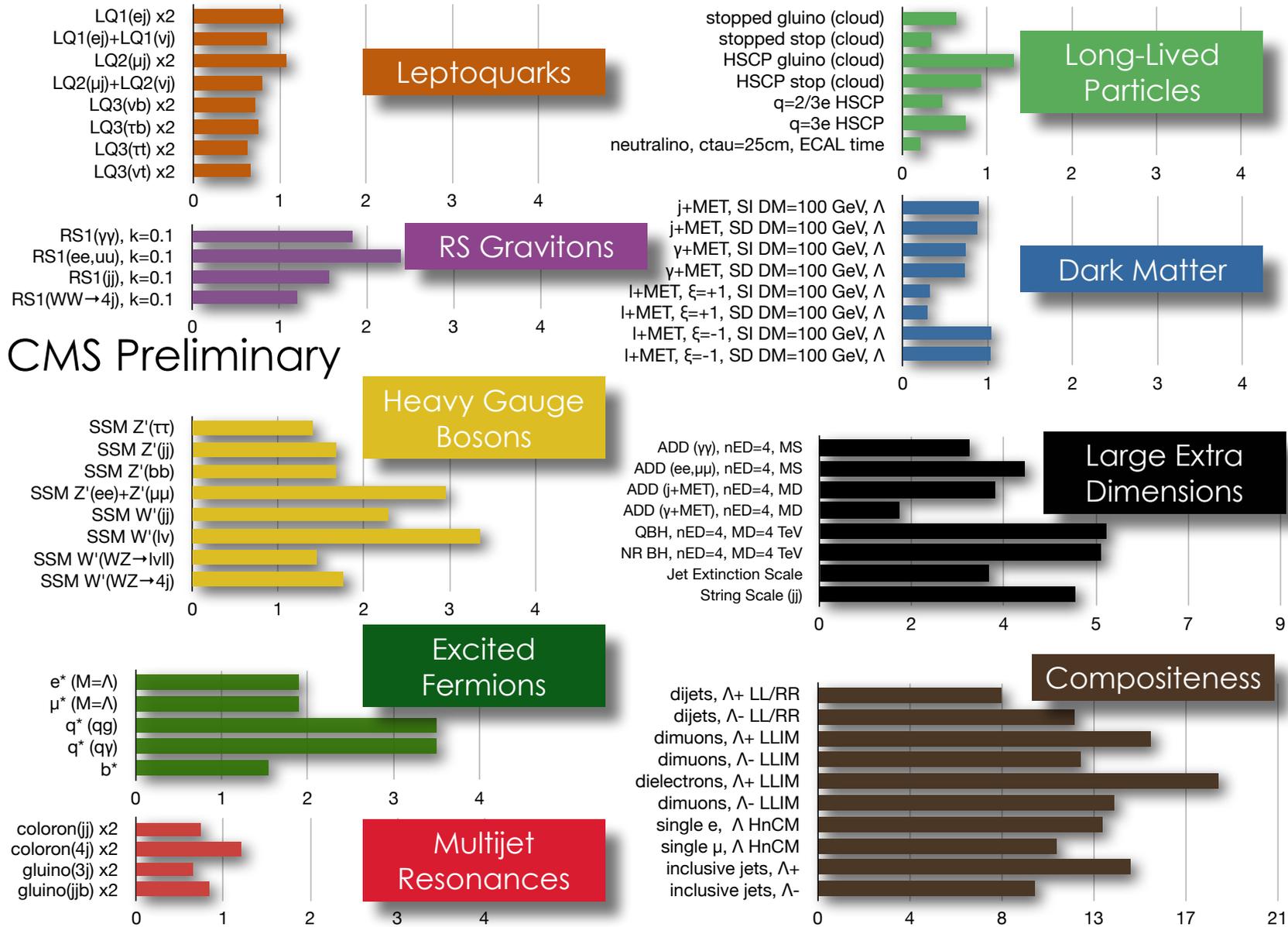
- A particularly interesting result from Run I is SM vacuum meta-stability
- This could be telling something fundamental, or hint at new physics
- The critical parameter here is the top quark pole mass  $M_t$ 
  - experimental precision of  $M_t$  relies heavily on precision JES, per flavor



- Standard Model Physics gave us the first incarnations of Stairway to Heaven (or Hell)
  - ▶ lots of jets and MET on the steps !
- This is the bread and butter of Run I+II; JEC, JER, MET, pileupID needed



- Lots of exotic models were rules out, but nothing new bagged yet



CMS Preliminary

- Whether you buy into it or not, the big dash at start of Run II is SUSY (again)
- This requires quick turn-around for MET tails scanning and JEC derivation

*SATOR/ROTAS merged by TWISTOR STRING THEORY*

<b>S</b>	<b>A</b>	<b>T</b>	<b>O</b>	<b>R</b> <sup>6</sup>
<b>A</b>	<b>R</b> <sup>5</sup>	<b>E</b>	<b>P</b>	<b>O</b>
<b>T</b>	<b>E</b>	<b>N</b>	<b>E</b>	<b>T</b>
<b>O</b>	<b>P</b>	<b>E</b>	<b>R</b> <sup>5</sup>	<b>A</b>
<b>R</b> <sup>6</sup>	<b>O</b>	<b>T</b>	<b>A</b>	<b>S</b>

**Public Domain\***

**N** CP3/1  
re: supertwistors  
N is the # of supersymmetries  
N = 2255 **S**  
thus 5 symmetries

'M<sup>6</sup>' (4) permutations  
**M** = **E** = **W** = **E**

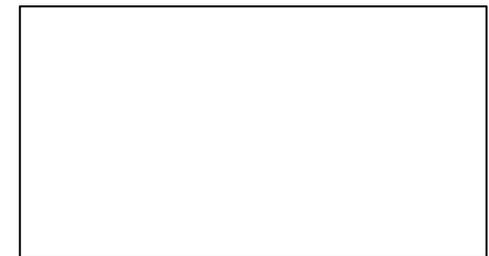
\* M<sup>6</sup> subspace of RP<sup>5</sup> cannot be locally separated  
Minkowski Space + Time 3+1 | however it is possible in twistor space

**T** 4D complex Weyl Spinor  
TWISTOR SPACE

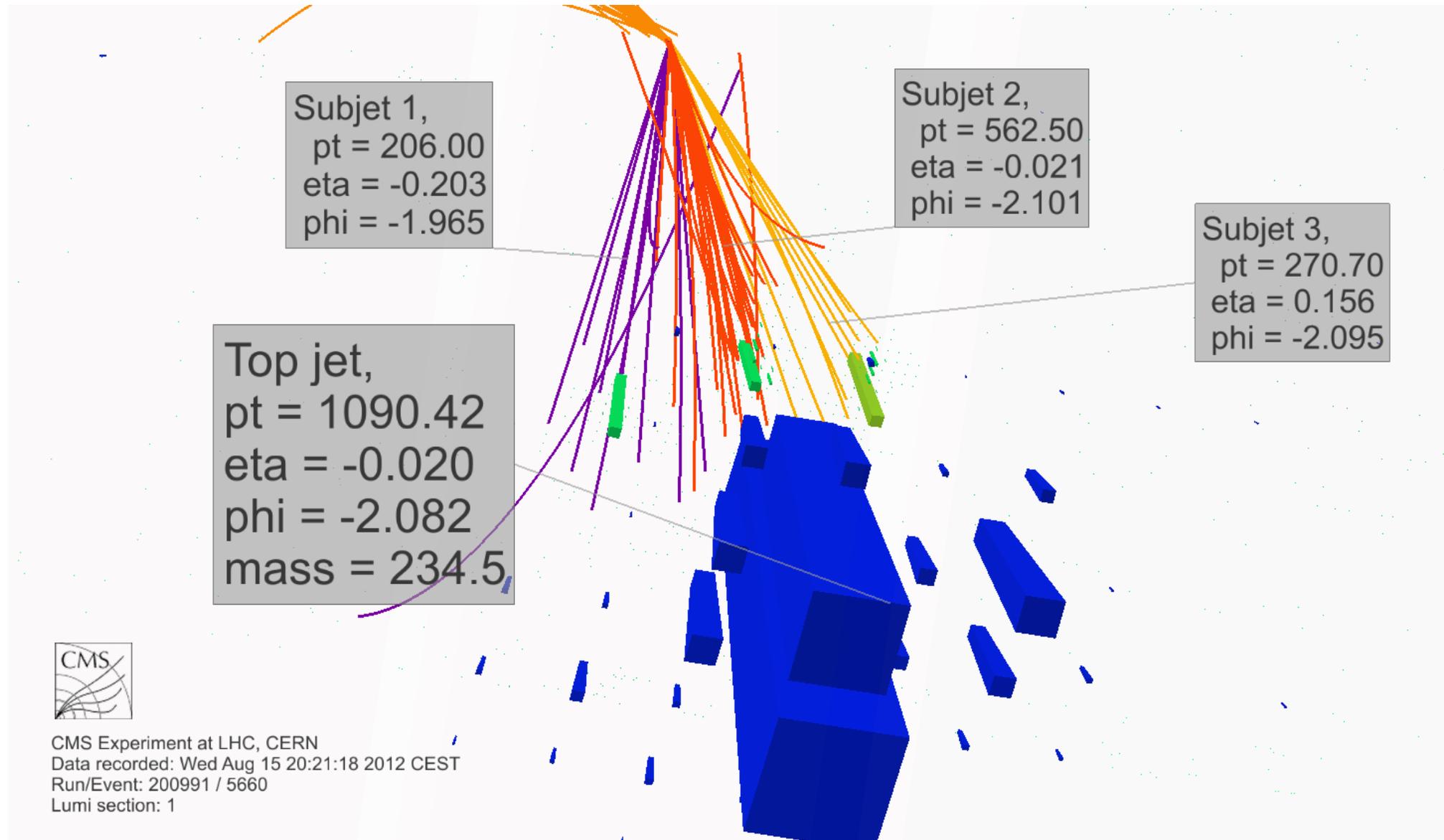
**P** **N** **P** is a subspace of PT-5 Real Dimensions

**P** ↔ **T** is a 3D complex manifold corresponding to projective twistor space

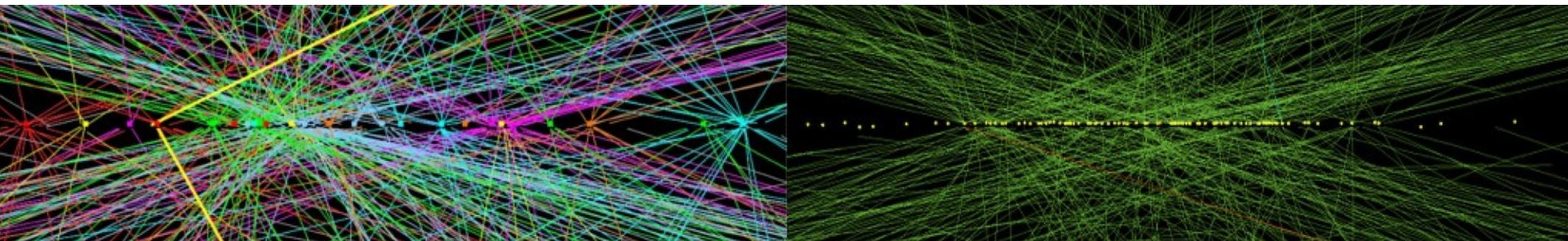
**RP<sup>5</sup>** Real 5D projective representation corresponds to **P<sup>6</sup>** under scalar multiplication = The CODE 11258



- Many new models predict heavy particles decaying to boosted tops or vector bosons
- Getting these in the bag requires delving into jet substructure; this is forte of JMAR

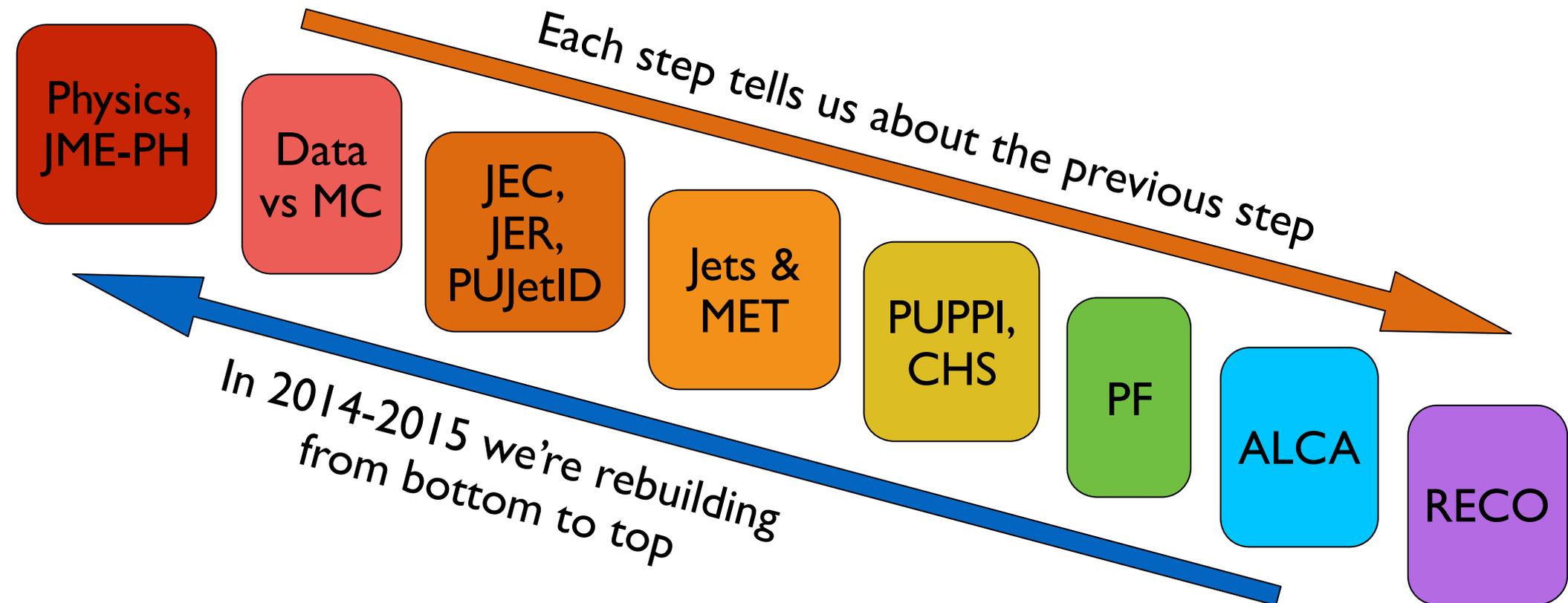


- The challenge, as you've all heard, is high pileup



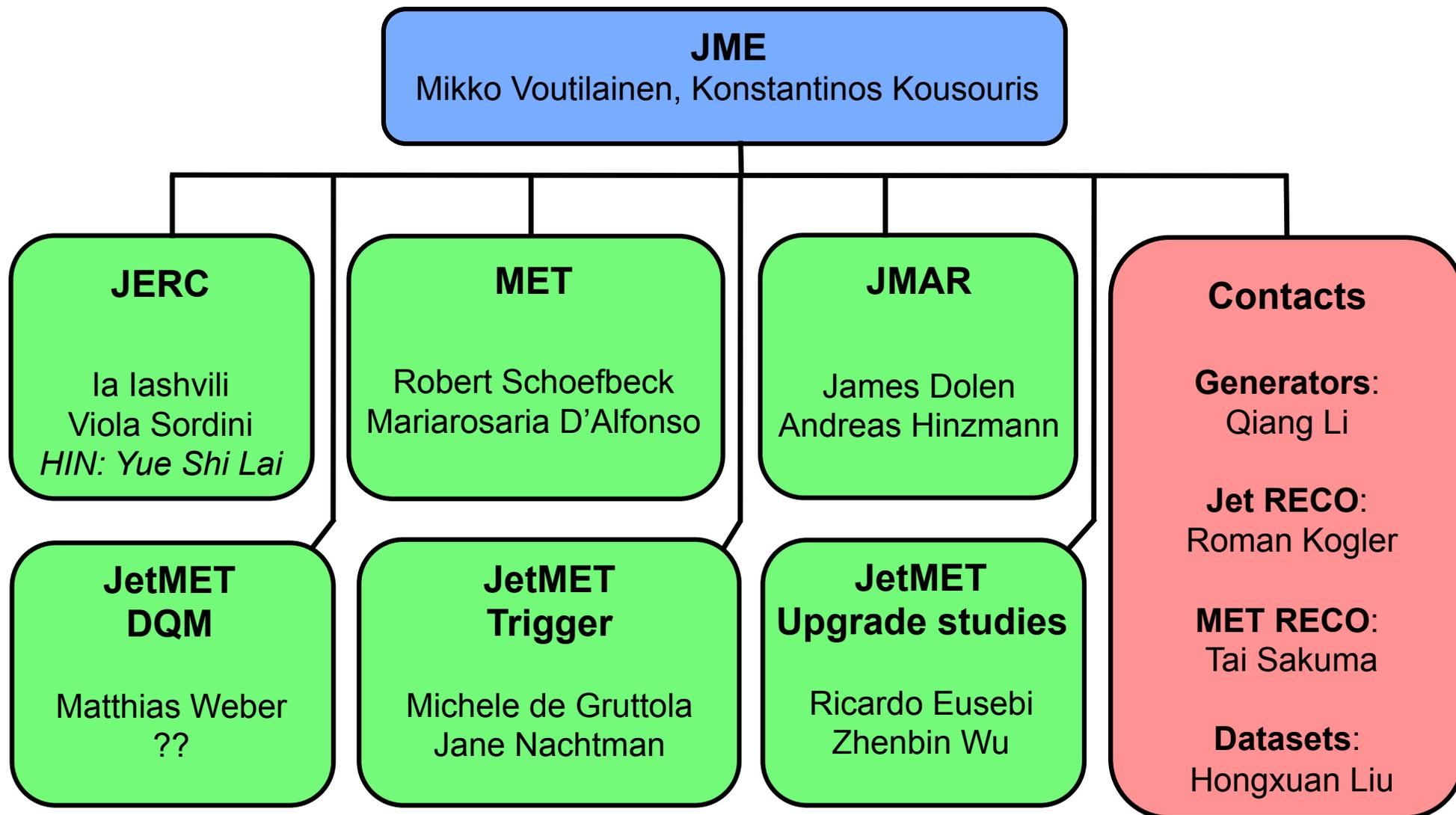
- This is true, but we already have pretty good handles on it
- “*Pileup at 40 is a solved problem*” — Gavin Salam, during a pileup workshop [1]
- Nevertheless, need to carefully commission new tools with data for all our methods
- [1] <https://indico.cern.ch/event/306155/>

- Not entirely in the hands of JetMET, but can we, after 1.5 years of shutdown
  - ▶ understand all the changes to our software (new 25 ns algorithms in particular)
  - ▶ have low-level detector alignment and calibration at pre-shutdown levels (ECAL, HCAL, tracker)
  - ▶ smoothly swap generators (Pythia 8 with new CMS tune replacing Pythia 6 Z2\*)
  - ▶ start with a new cone size (R=0.4 and R=0.8 replacing R=0.5 and R=0.7)
  - ▶ commission new tools (PUPPI to succeed PF+CHS)
- Important to estimate impact of each => **benchmarks!**



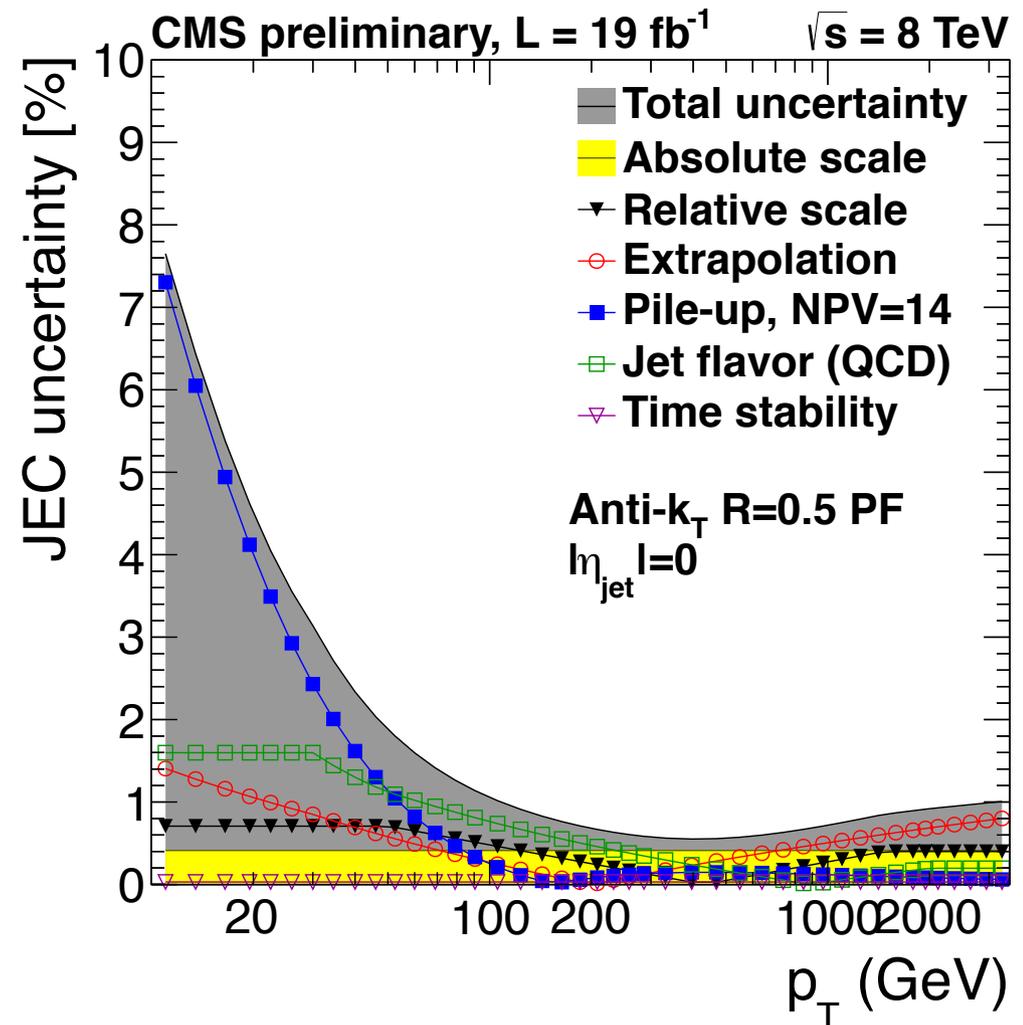
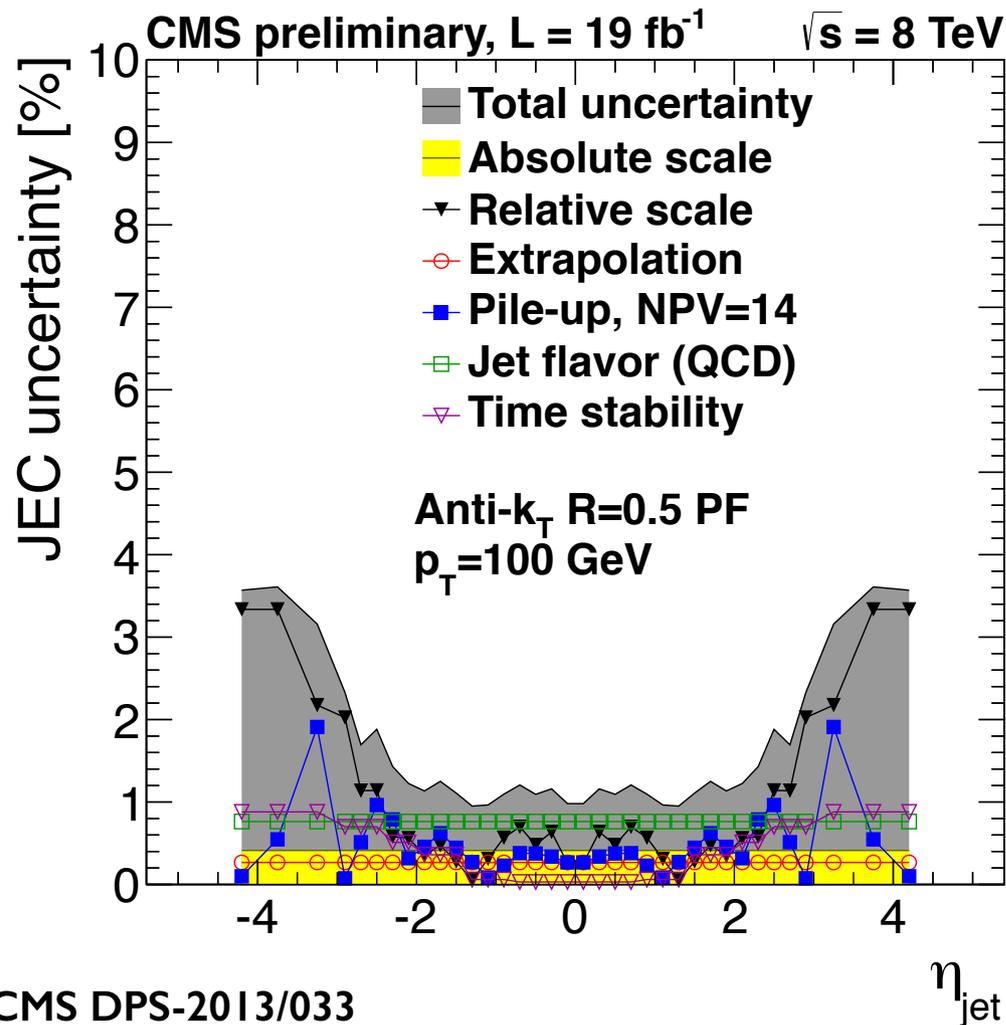


## JetMET Organization Chart for 2015

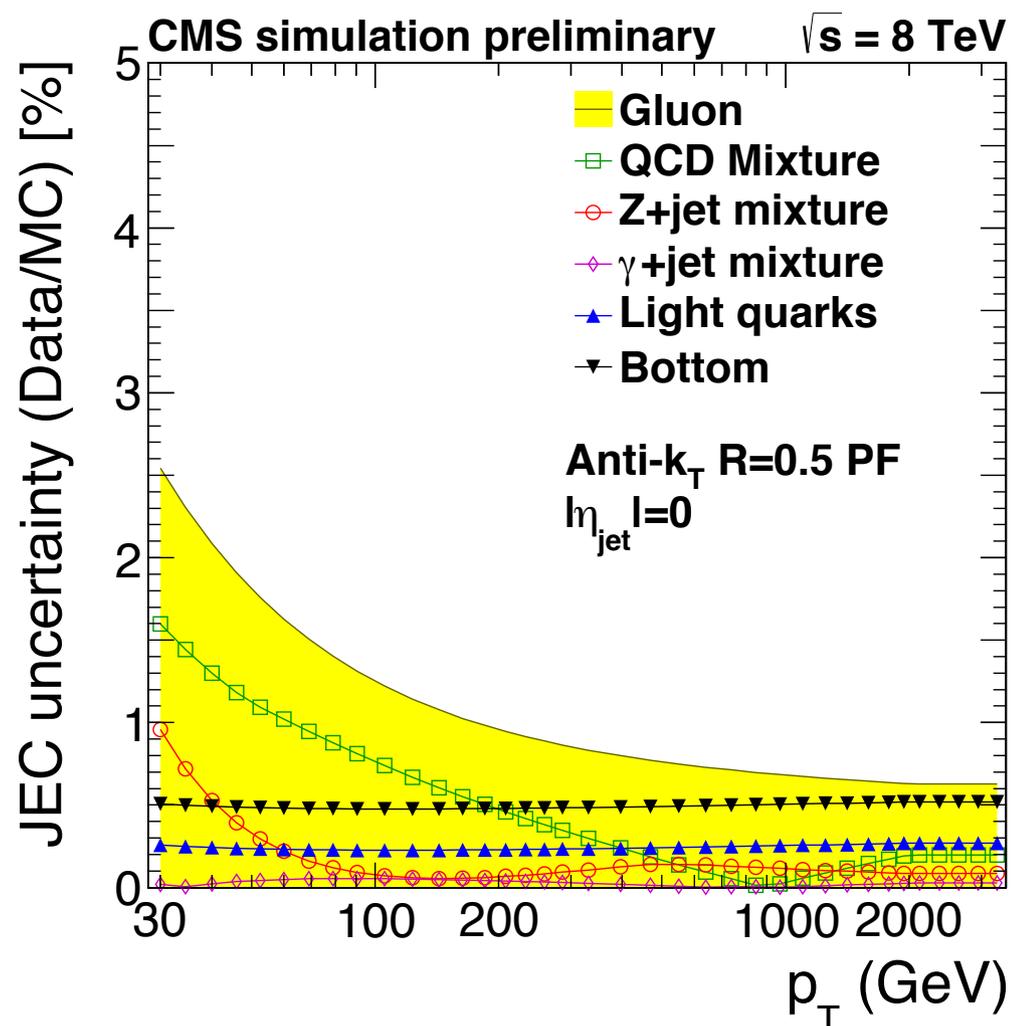
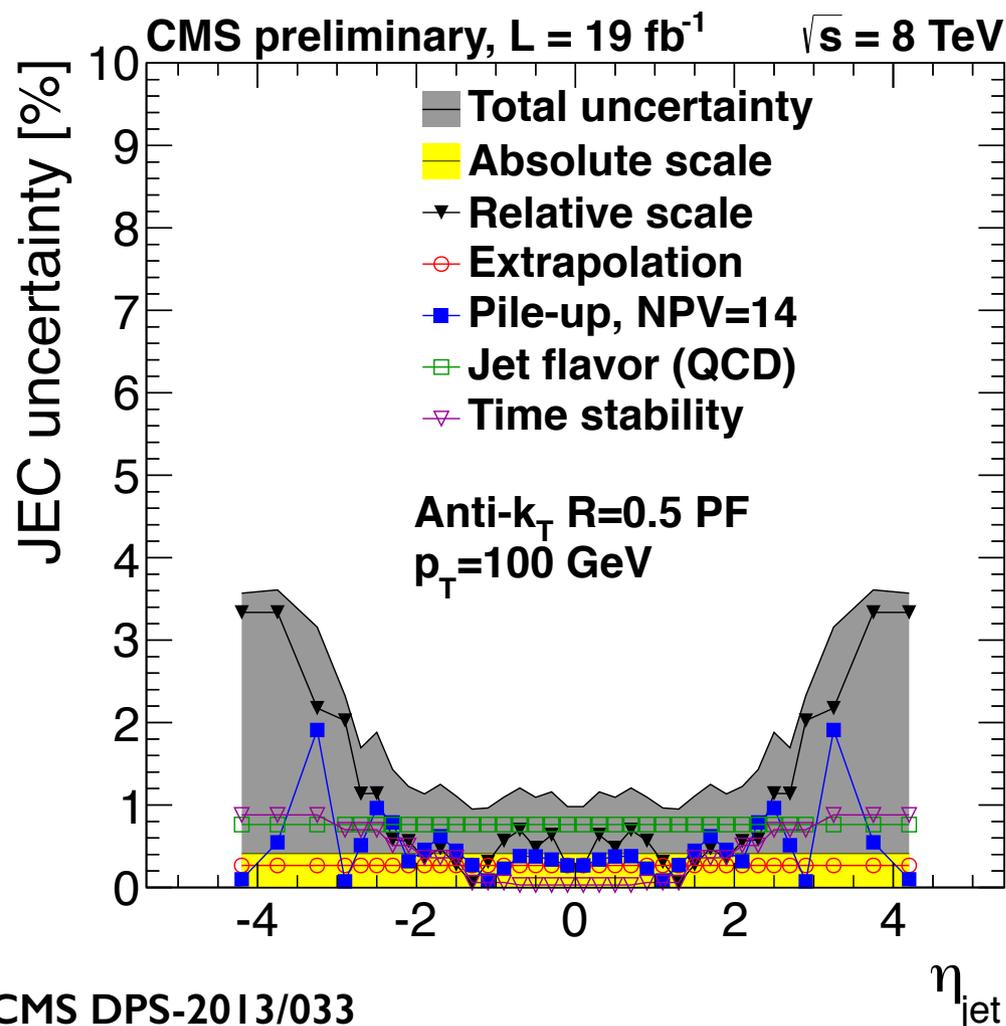


- Jet energy scale (Hartmut Stadie, 15:55)
  - ▶ DPS note on JES+JER with various cone sizes
  - ▶ PAS on Z+b (JME-13-001) and CMS/ATLAS combination (JME-14-003) underway
  - ▶ JES benchmark paper (JME-13-004) underway
- Missing ET (Brian Calvert, 14:15)
  - ▶ MET benchmark paper (JME-13-003) just submitted
- JMAR (Gregor Kasieczka on taggers, 14:55)
  - ▶ PAS on pileup removal algorithms (JME-14-001)
  - ▶ PAS on V tagging observables and correlations (JME-14-002)
  - ▶ DPS note on Top tagging
  - ▶ arXiv paper on PUPPI
- Upgrade (Kerstin Hoepfner, 16:35)
- Physics highlights:
  - ▶  $m_t$ ,  $\alpha_s$ , limits, Higgs properties, boosted ttbar, WW
  
- Today we will talk about already public results, internal results discussed tomorrow

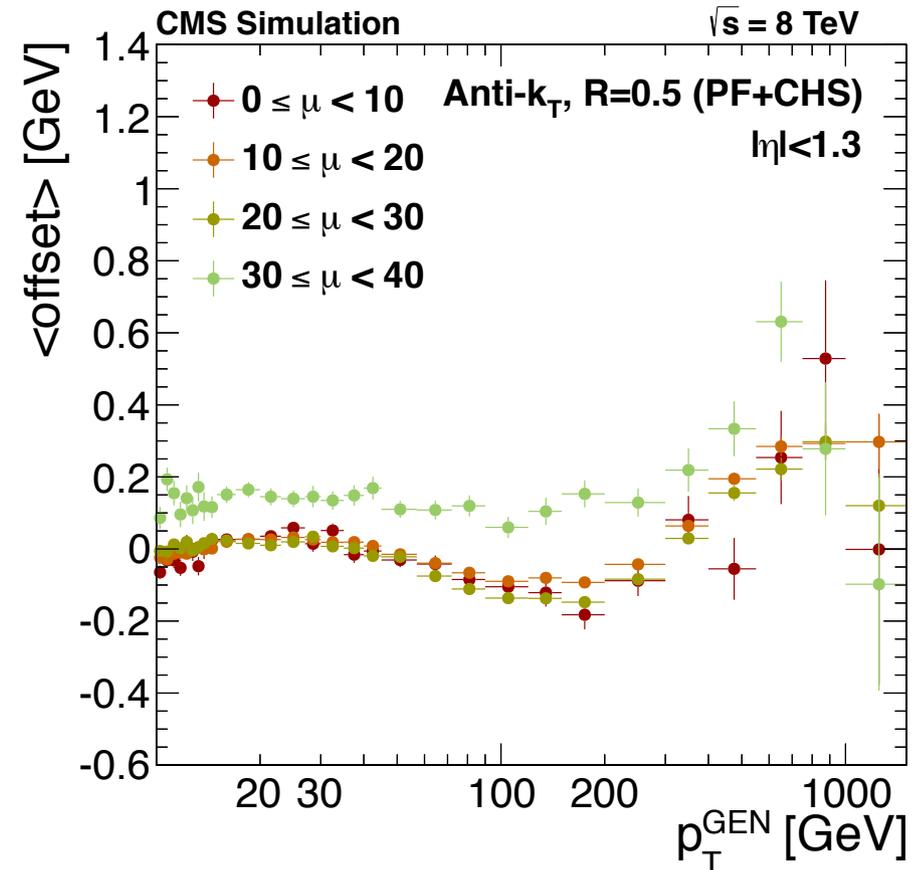
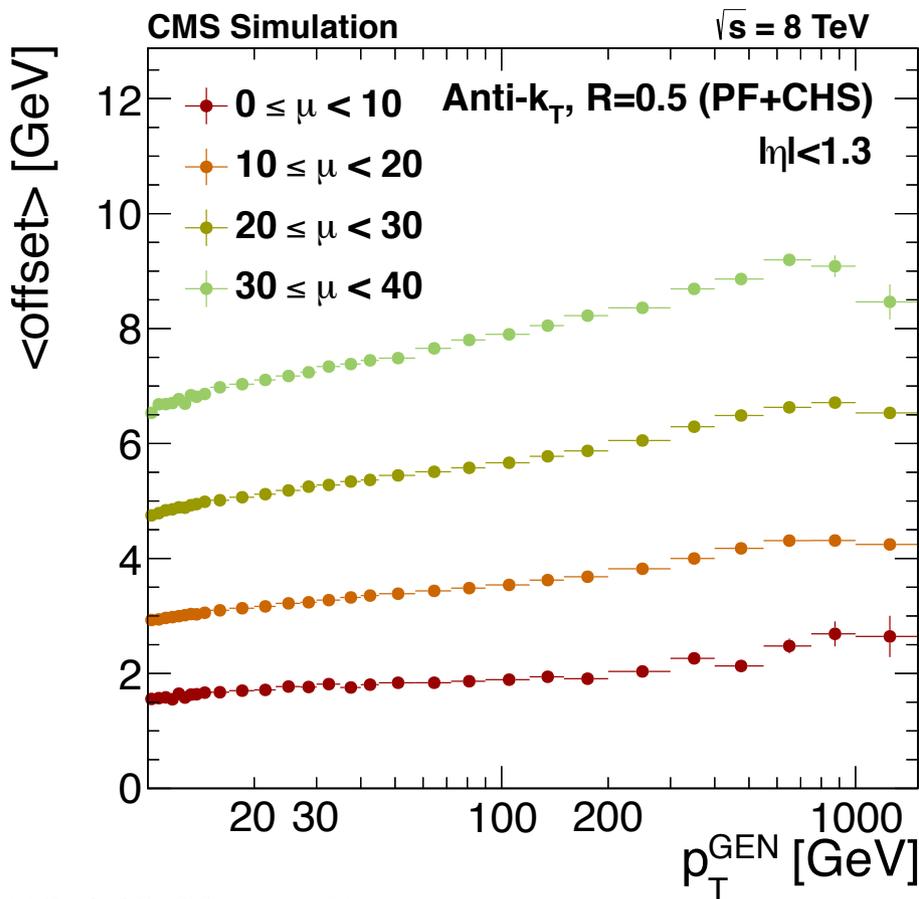
- JEC group has steadily decreased systematics, now down to  $\sim 0.6\%$  at best
- Continuous improvements in pileup handling compensated by increase in total pileup



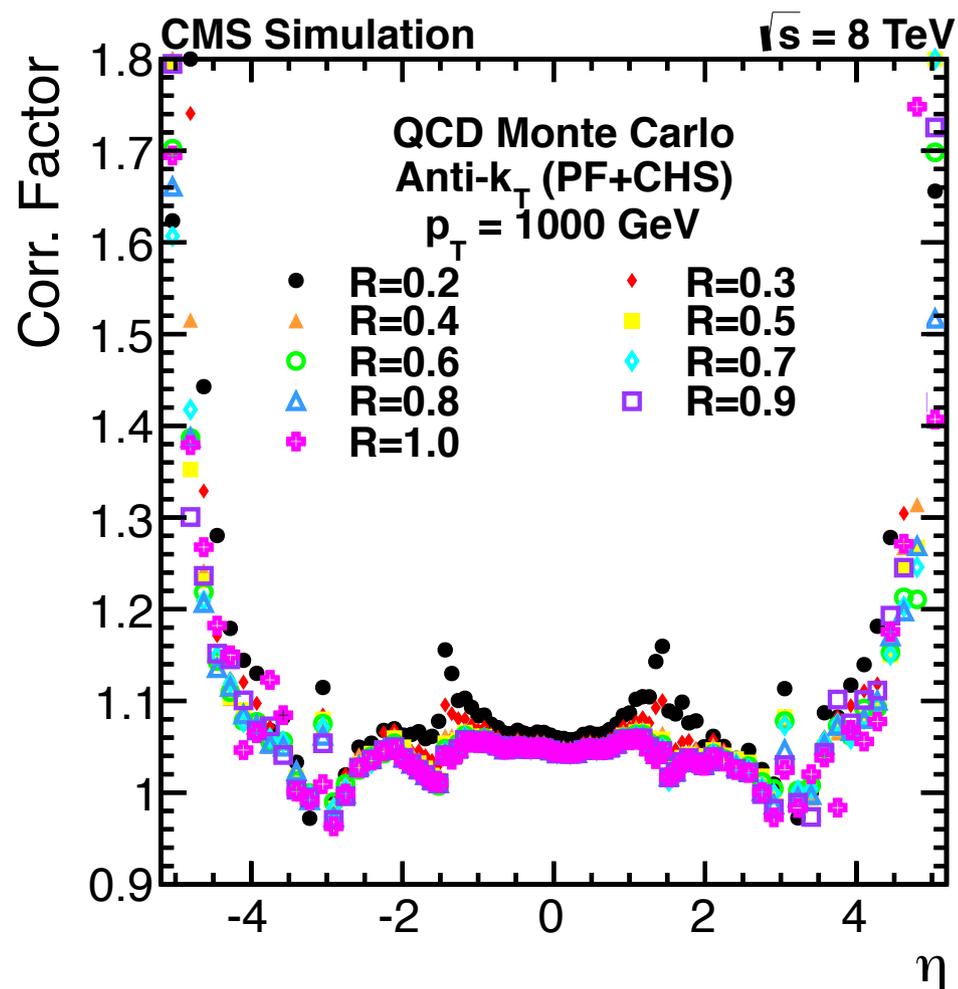
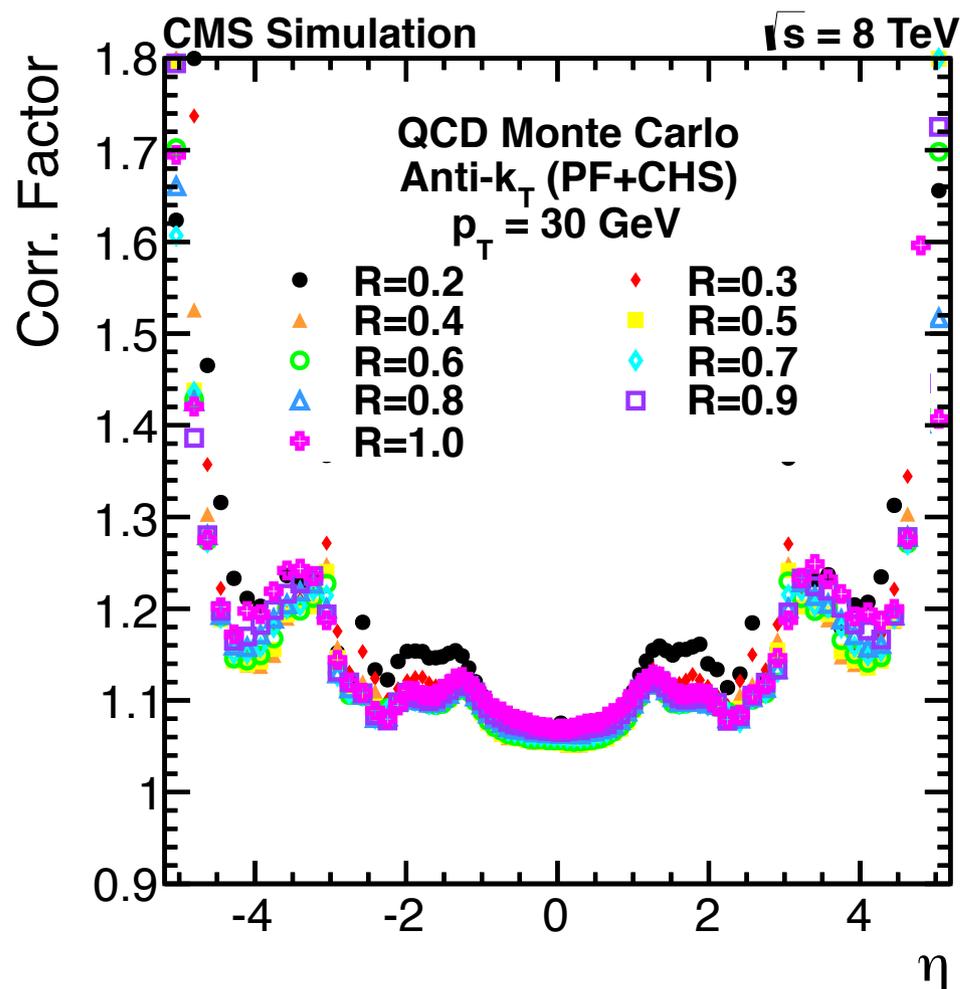
- Flavor systematics of particular interest in mid- $p_T$  range
- Most likely the part of JEC systematics most strongly correlated with ATLAS
  - ▶ Systematics from Pythia6 / Herwig++ differences, propagated through data-based JEC chain



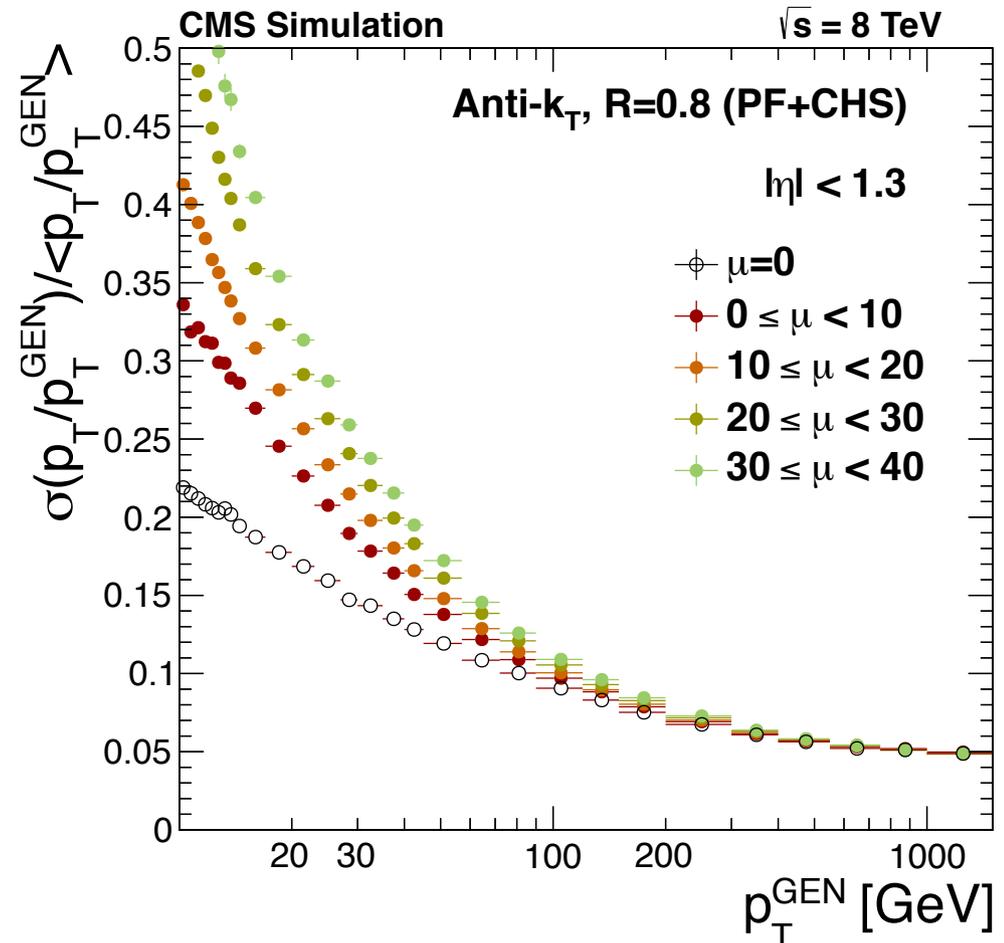
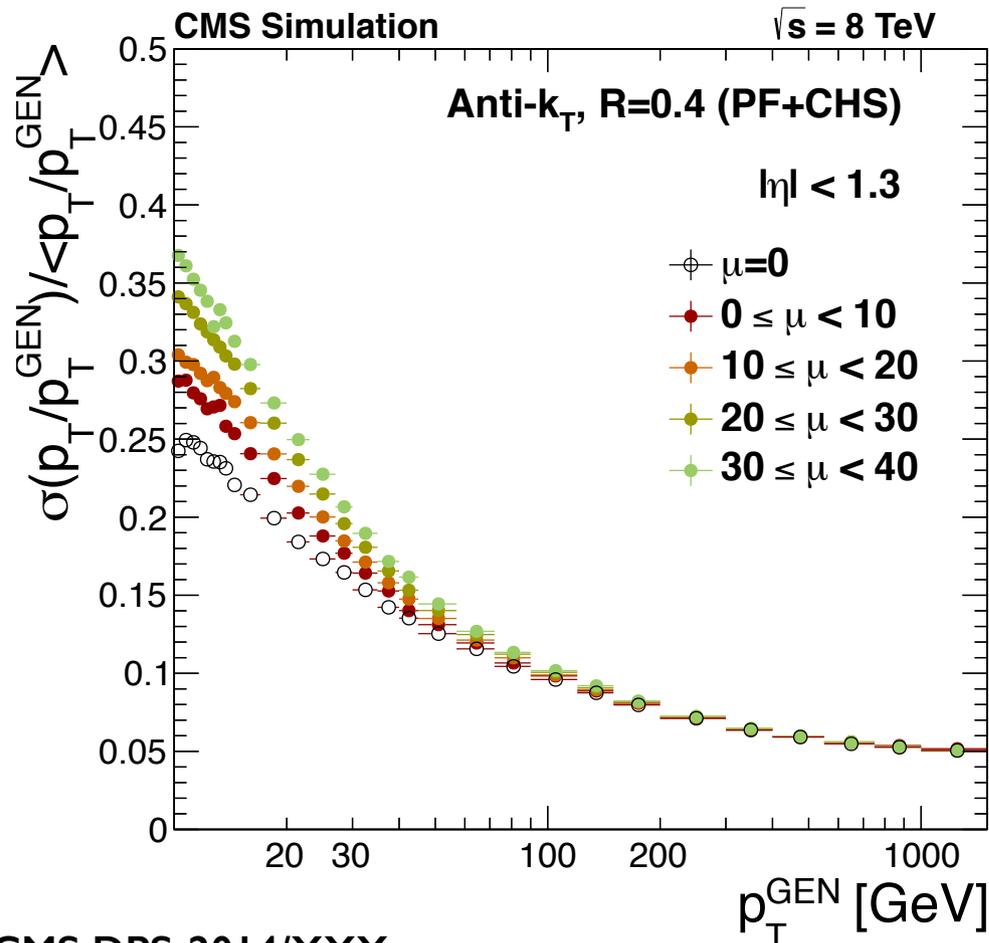
- One of our important observations since the 2010 JINST paper has been that while  $\langle \text{offset} \rangle$  is quite linear with  $\mu$ , it is also affected by the real energy from jets
- $\langle \text{Offset} \rangle$  derived by comparing same jets and events reconstructed with and without PU:
  - ▶  $\langle \text{offset} \rangle = \langle p_{T,\text{jet}}(\text{event w/ PU}) - p_{T,\text{jet}}(\text{event w/o PU}) \rangle$
- By deriving offset vs  $p_T$  from MC truth for each  $R_{\text{cone}}$  we reduce this effect to  $<0.2 \text{ GeV}$



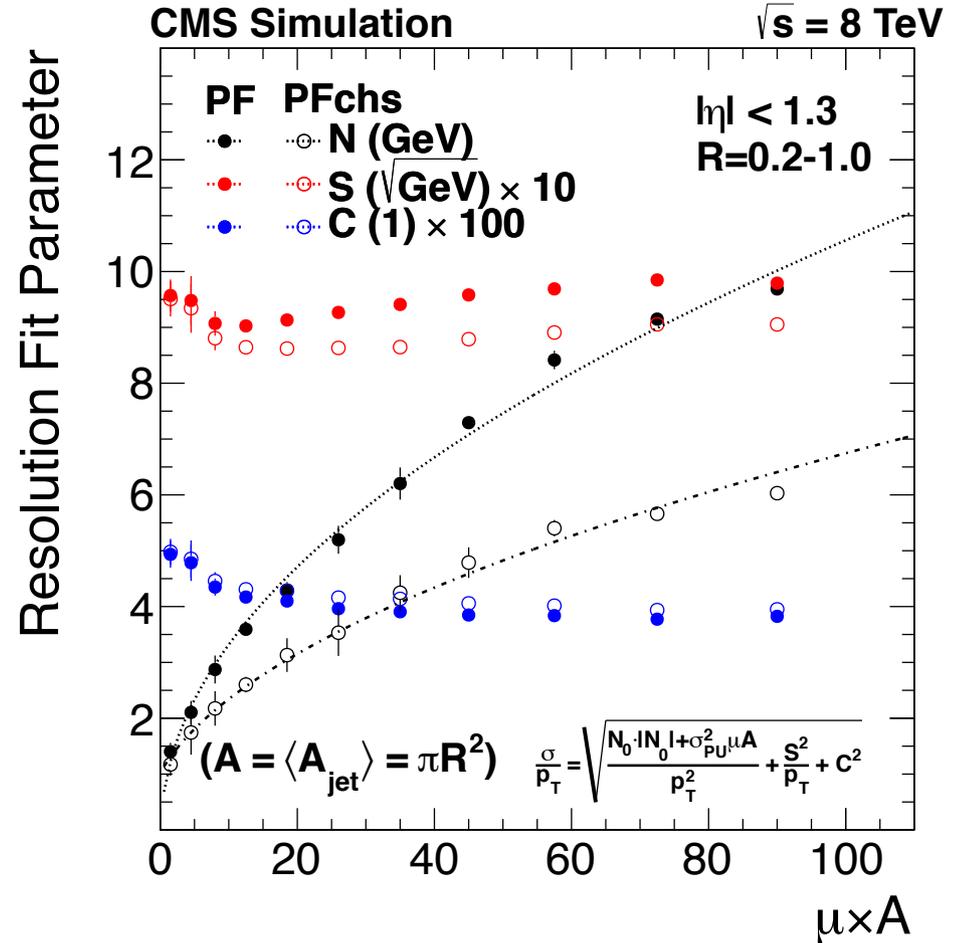
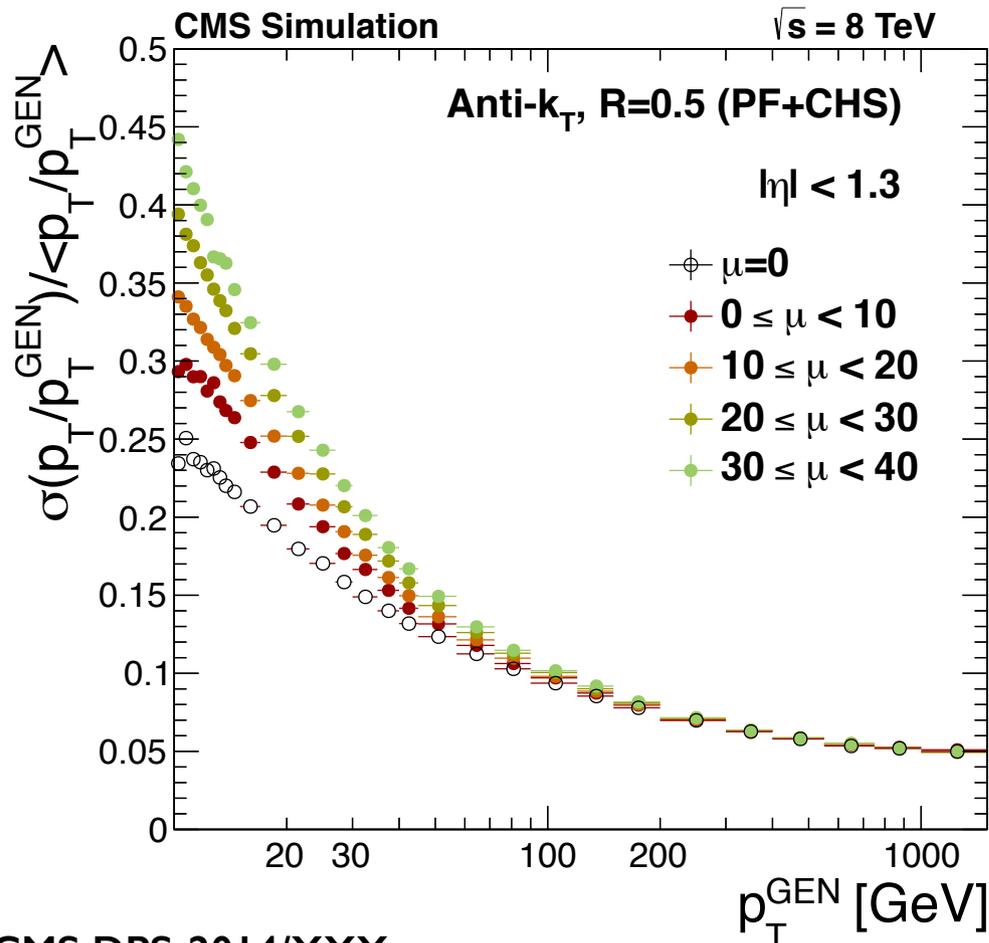
- JES quite independent of  $R_{\text{cone}}$  after accounting for  $R_{\text{cone}}$  dependence in offset
- Exception are very small cone sizes  $R \leq 0.2$ , and maybe  $R=0.3$ 
  - $R_{\text{cone}} < 0.3$  similar to subjet size, which increases out-of-cone effects



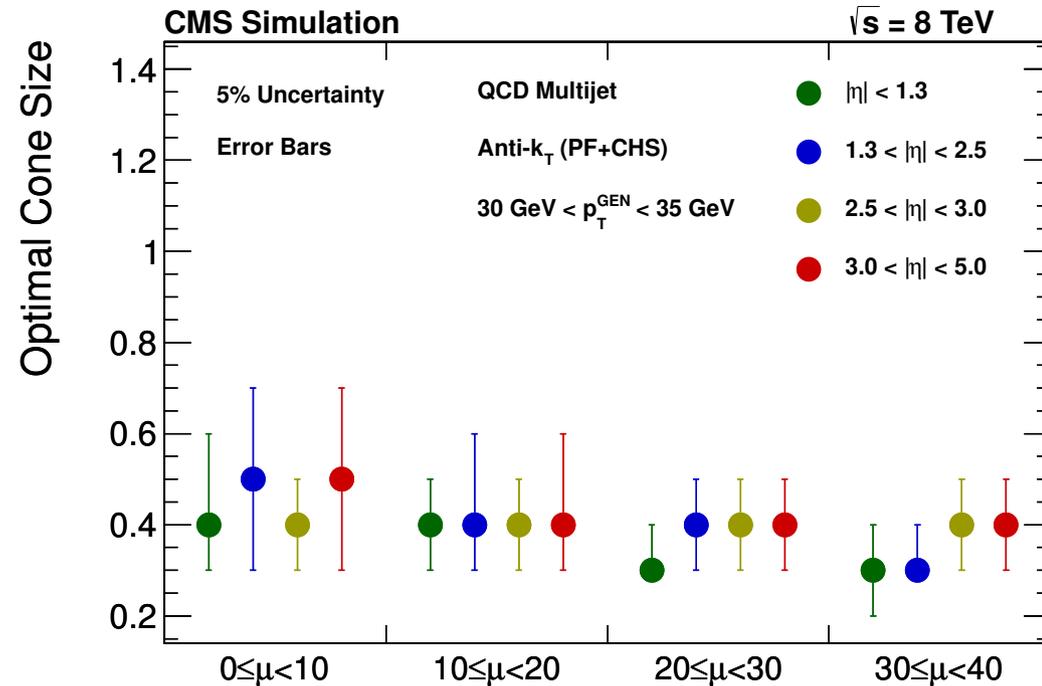
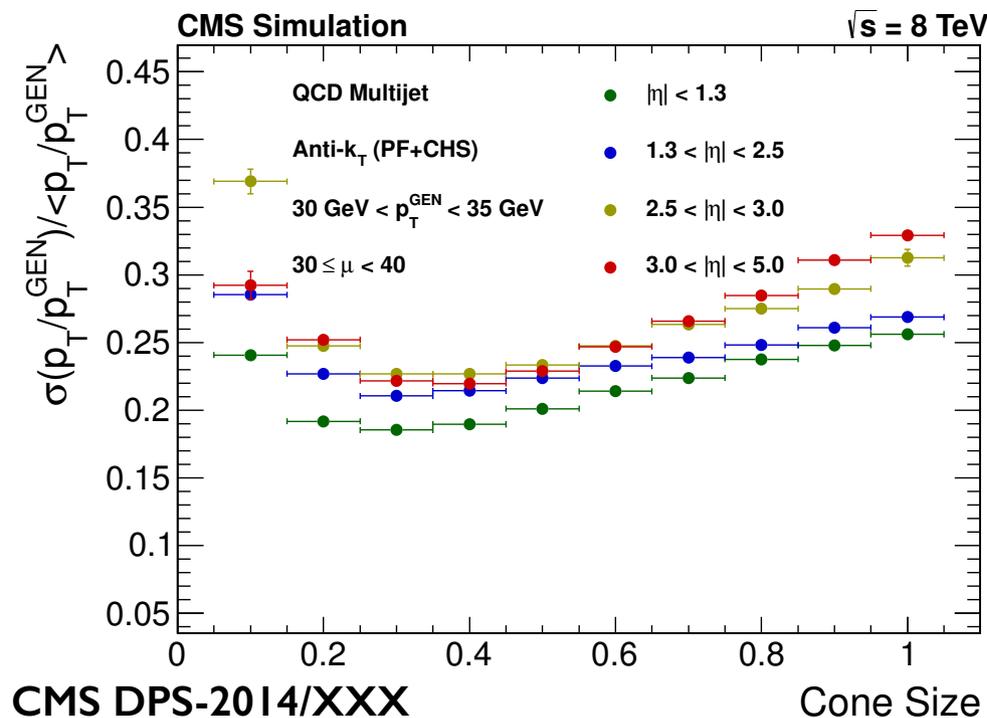
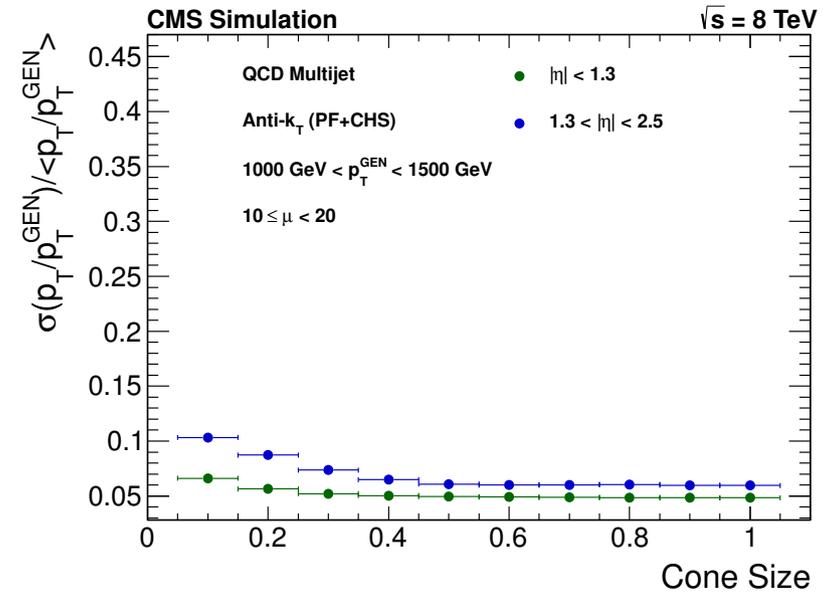
- As expected, smaller cone sizes are less sensitive to smearing from pileup
- Otherwise larger cones have slightly better JER for no pileup conditions



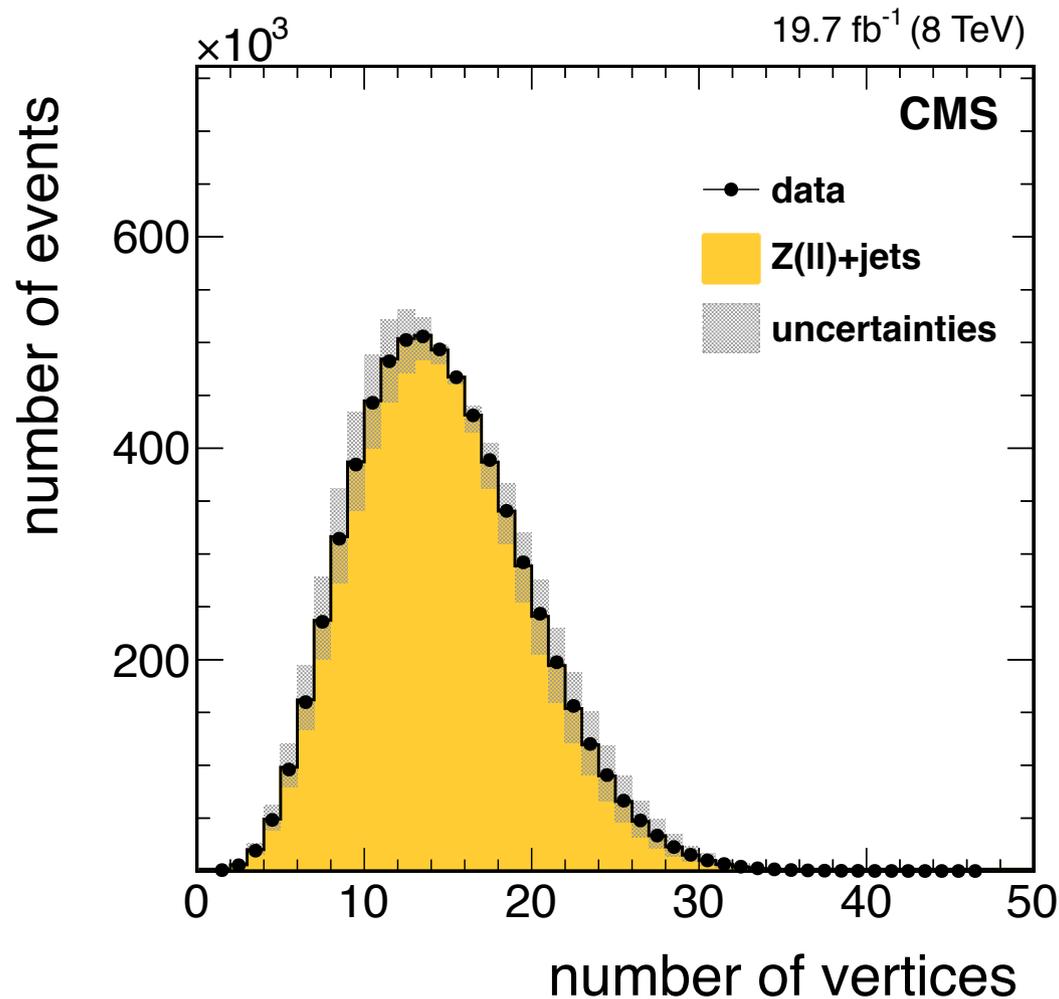
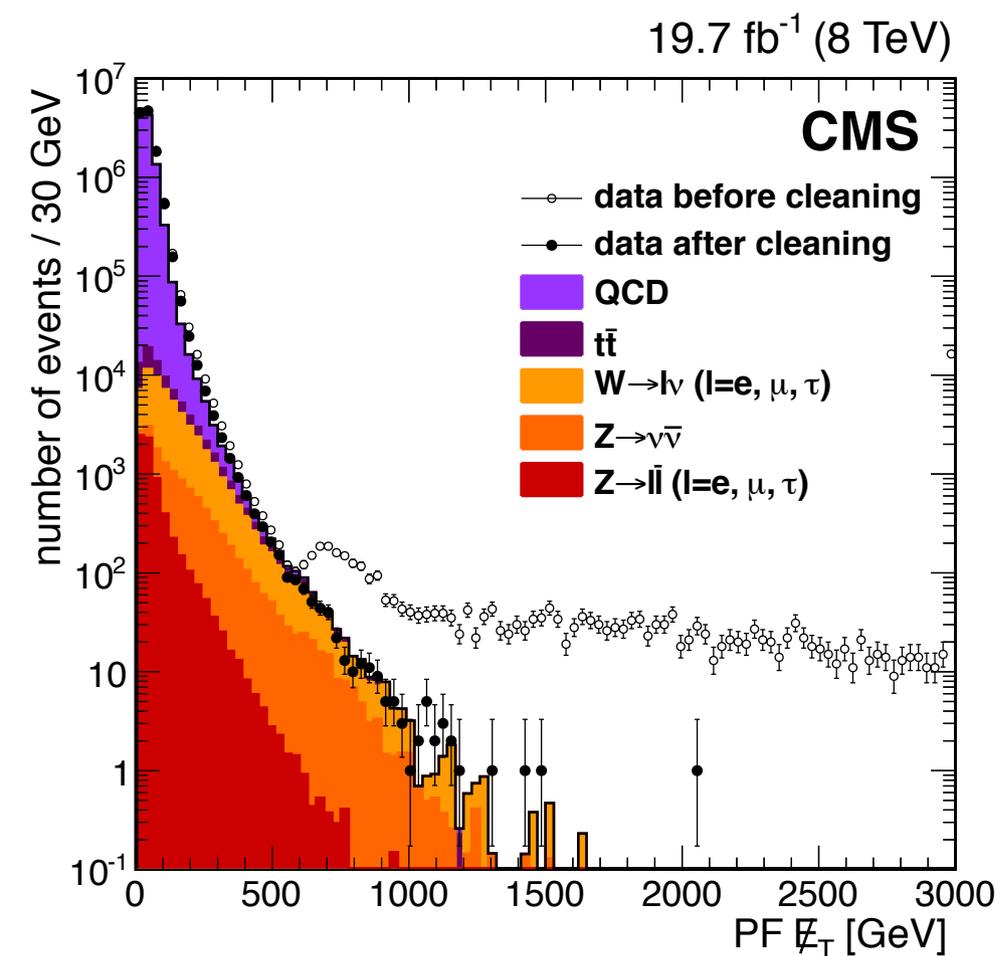
- By scanning JER vs  $\mu$  and  $A_{\text{jet}}$  we found universal  $\sqrt{\mu} A_{\text{jet}}$  scaling of the noise term N
  - small deviations only for very small  $R_{\text{cone}}$  (error bars show max. differences for  $R=0.2-1.0$ )
- Noise term further reduced by application of CHS
- Stochastic (S) and constant (C) terms relatively independent of  $\mu$  and  $R_{\text{cone}}$



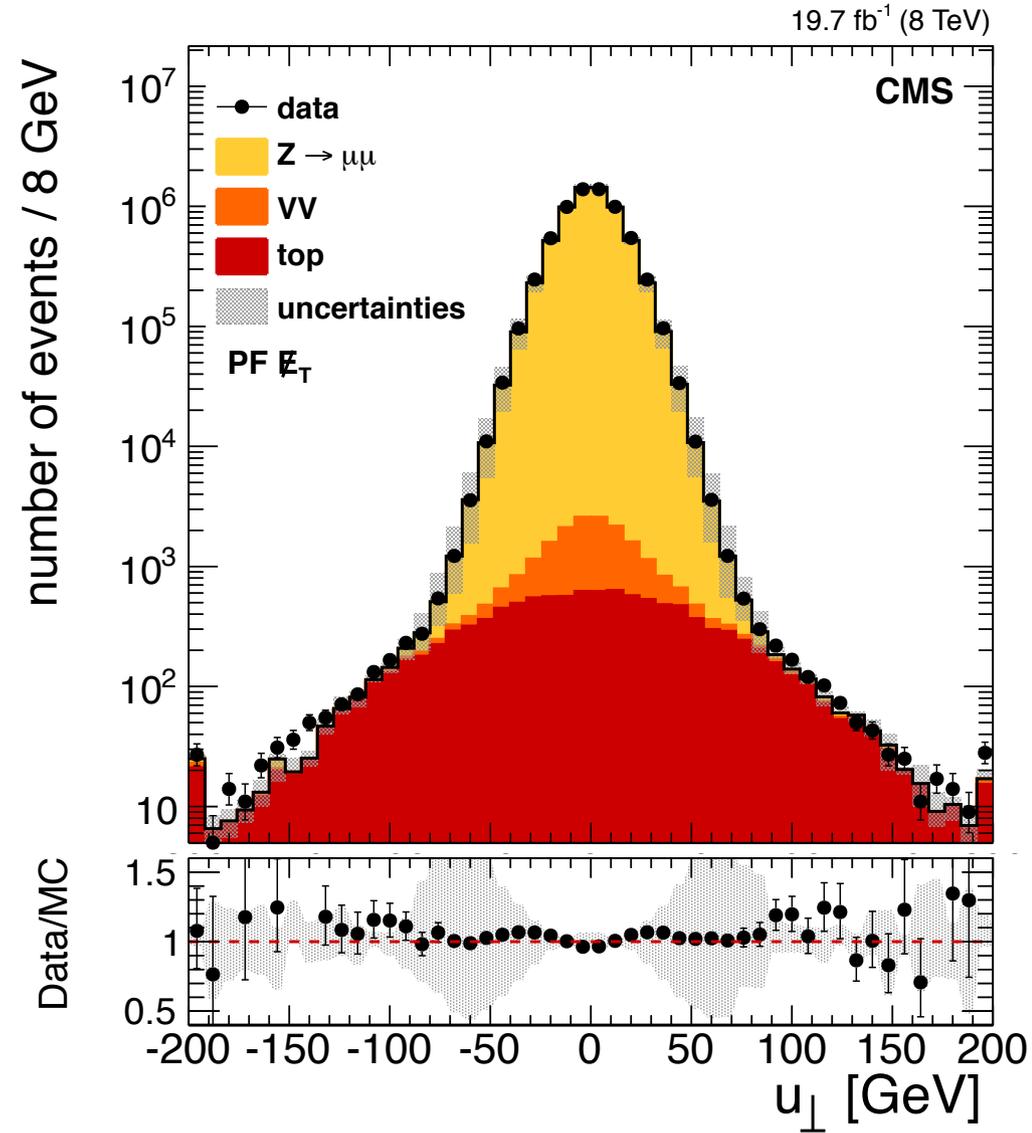
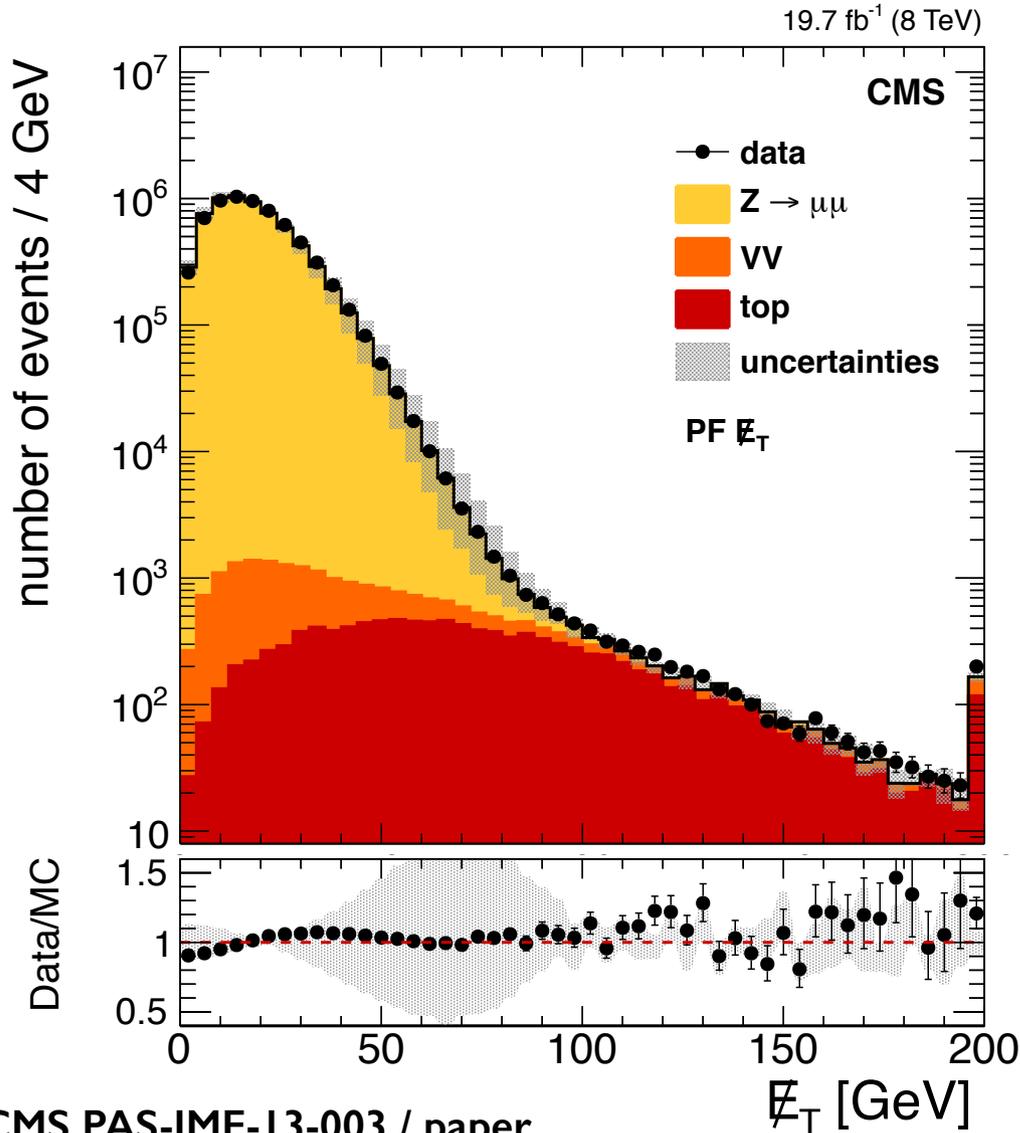
- From detector effects (JEC, JER) perspective,  $R_{\text{cone}}=0.4$  optimal for high PU, low  $p_T$
- At high  $p_T$  + low PU anyway less sensitive to  $R_{\text{cone}}$
- Physics arguments (e.g.  $W$  mass) favor  $R_{\text{cone}}=0.4$  for most analyses and  $R_{\text{cone}} \gg 0.4$  for substructure and gluon jets (QCD) at high  $p_T$ 
  - Anti- $k_T$   $R=0.8$  seems reasonable choice for the latter



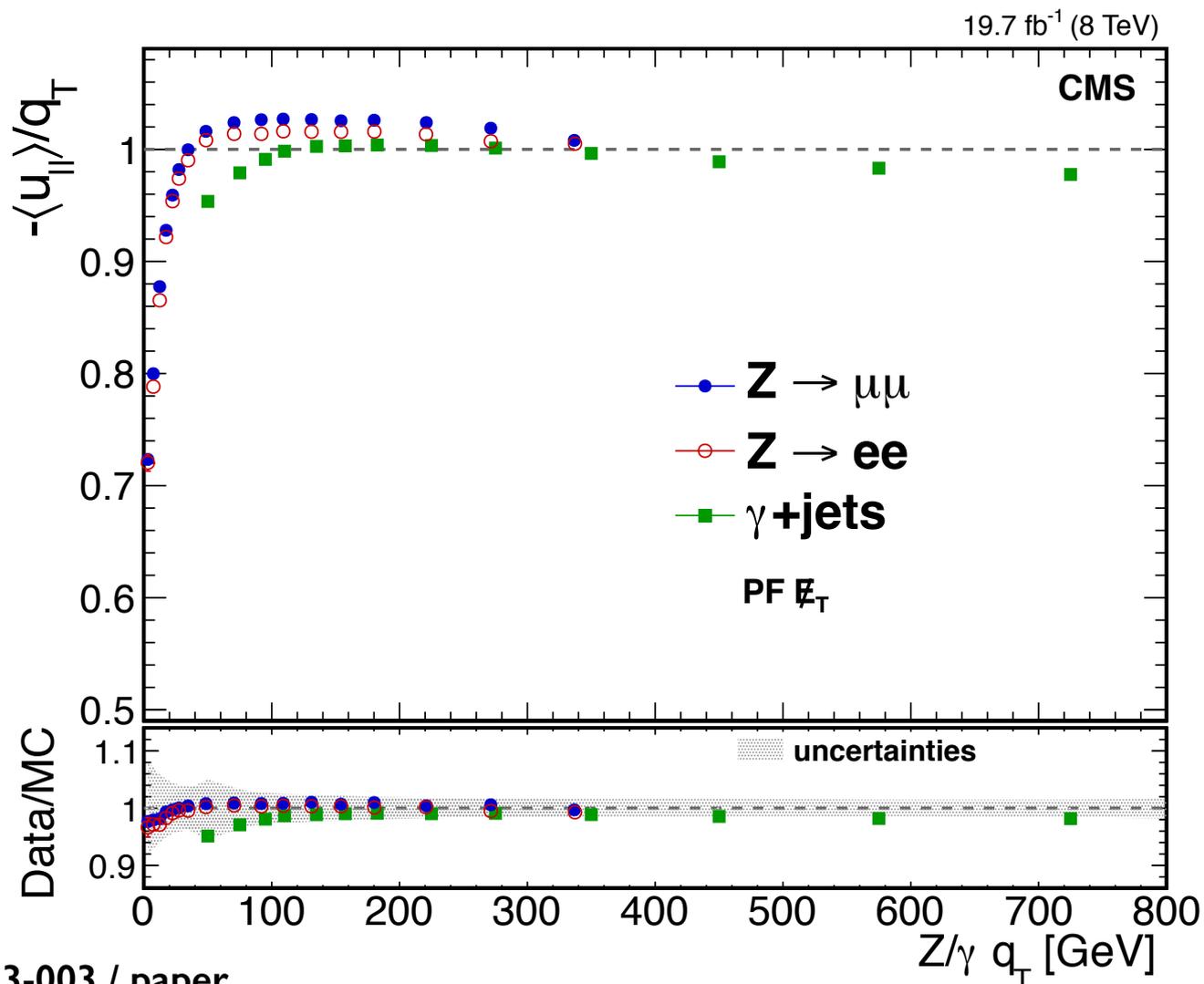
- Important pre-requisites for MET will be (a) good cleaning, and (b) good modelling of PU
  - ▶ We did a good job on cleaning in 2011, as documented in the MET paper; keep it up!
- PU modeling based on CMS tune of Pythia 6 (Z2, Z2\*), which is used for PU mixing
  - ▶ Poisson mean  $\mu$  in MC then reweighed to data based in instantaneous luminosity measurement



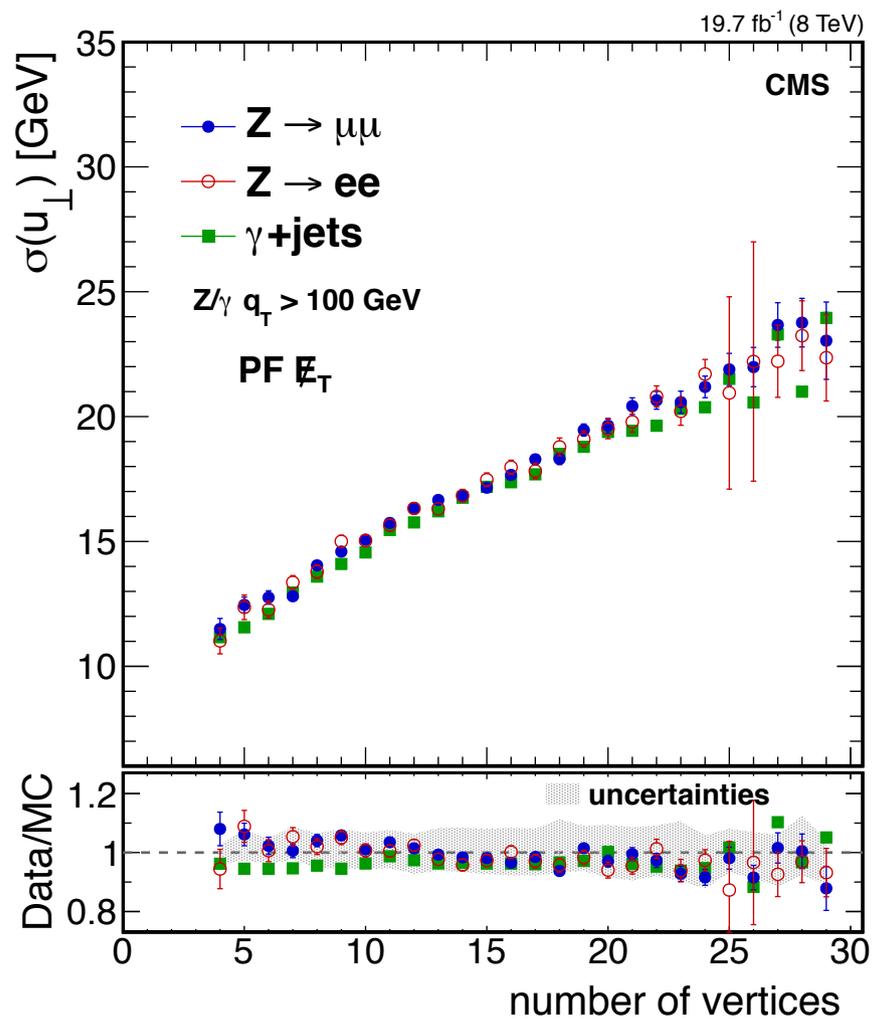
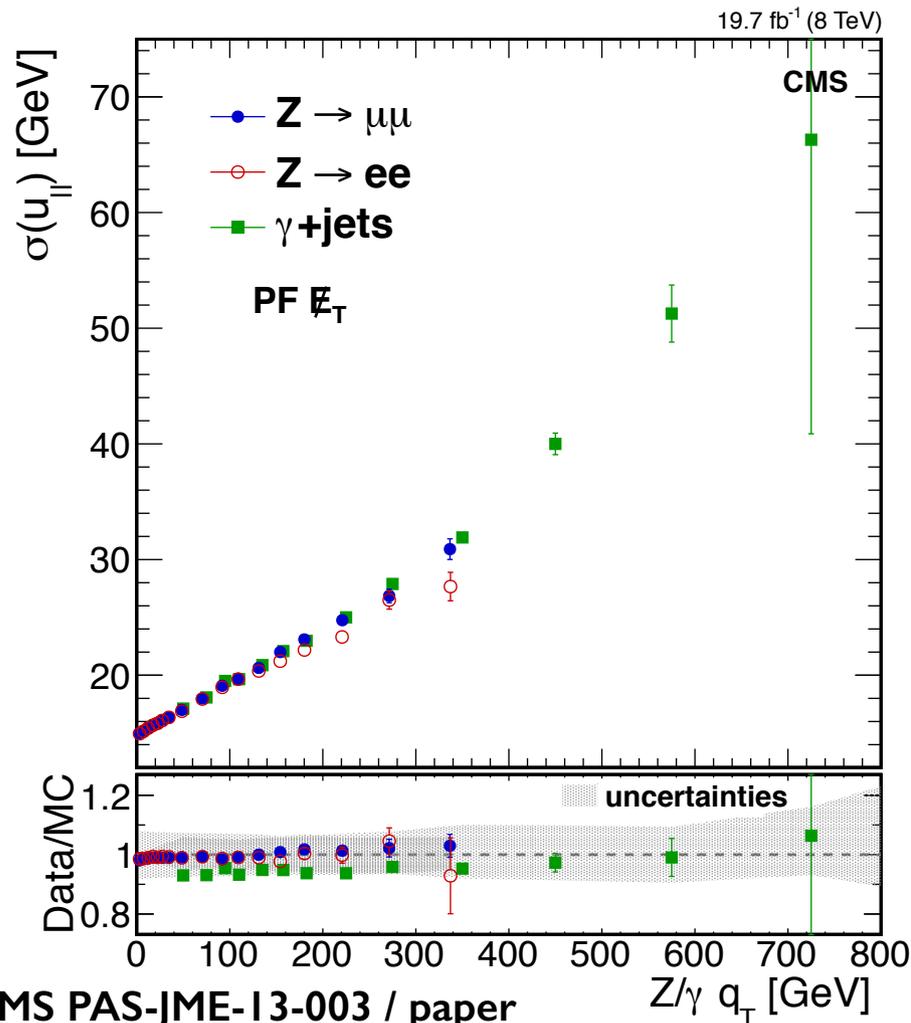
- MET is sensitive to JER, whose uncertainties dominate MET tails in no-MET events
- JER oversmearing applied to MC, resulting in good agreement in clean Zmm events



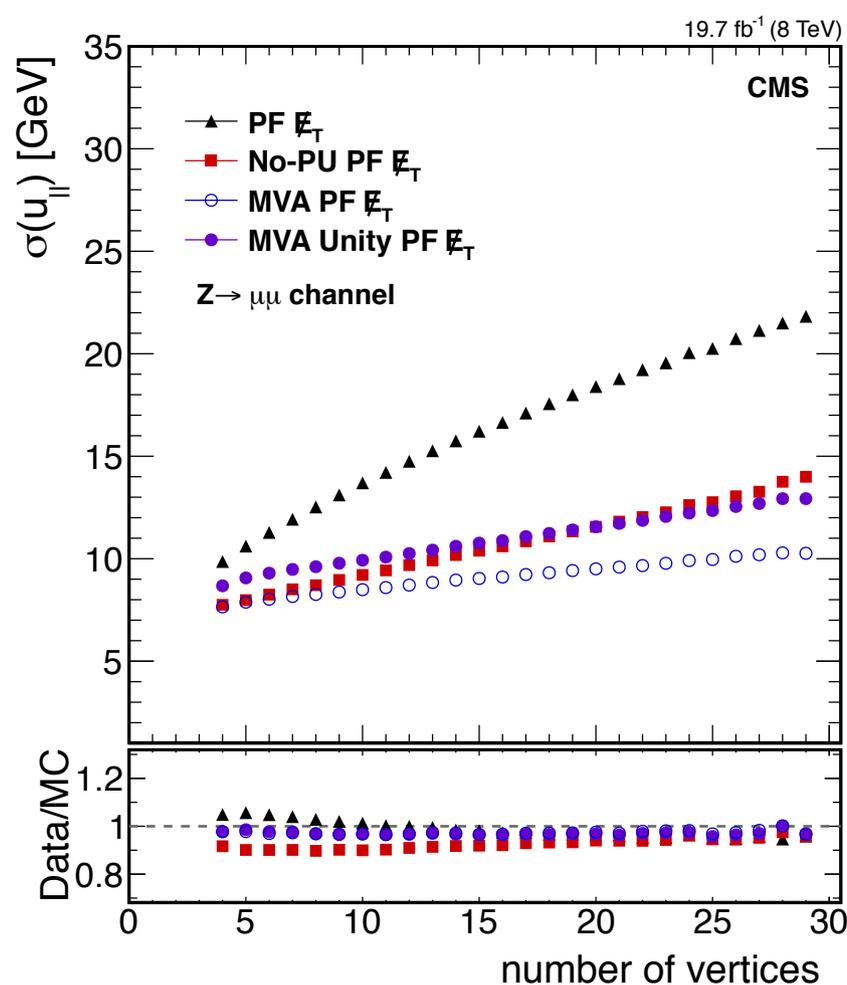
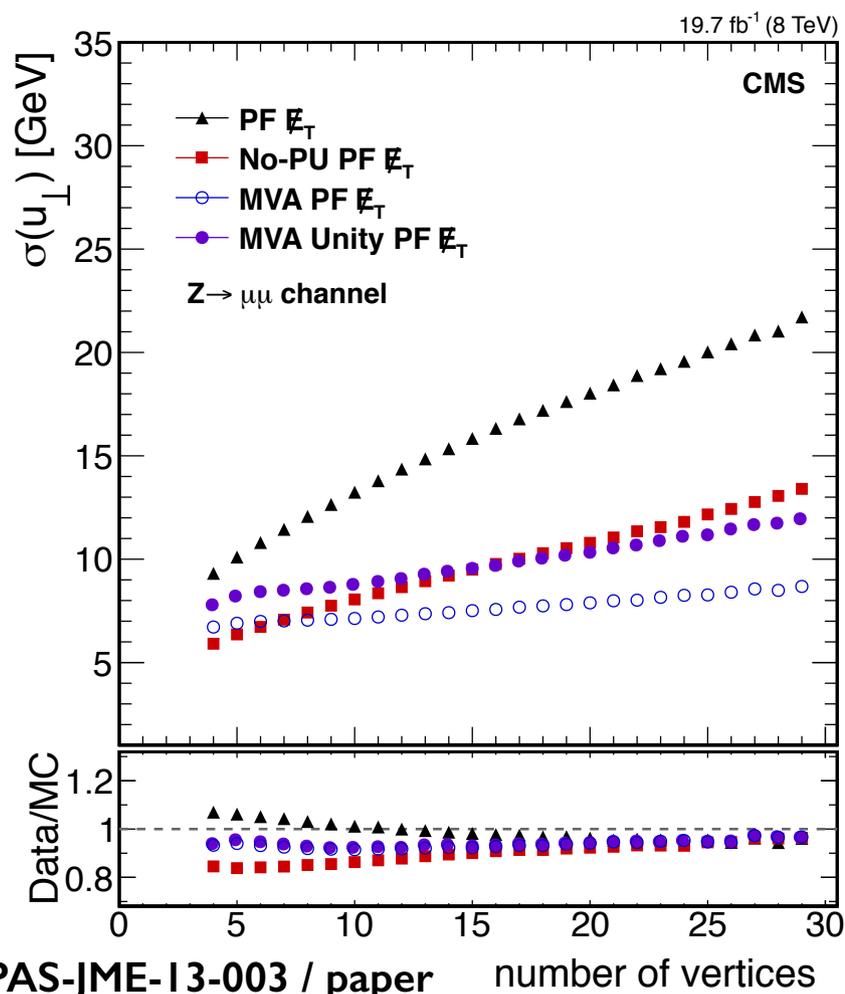
- MET scale relatively unproblematic with easy-going muons
  - ▶ (difference from one due to quark vs gluon JES; Z+jet have more quarks than QCD)
- More of a challenge with electrons and photons due to footprint effects etc.



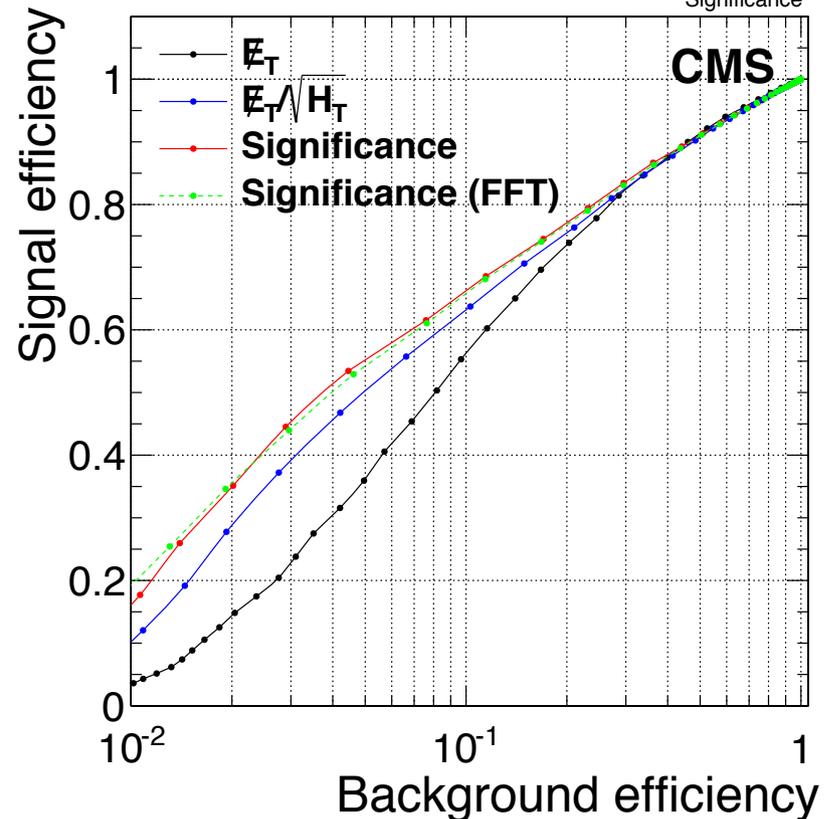
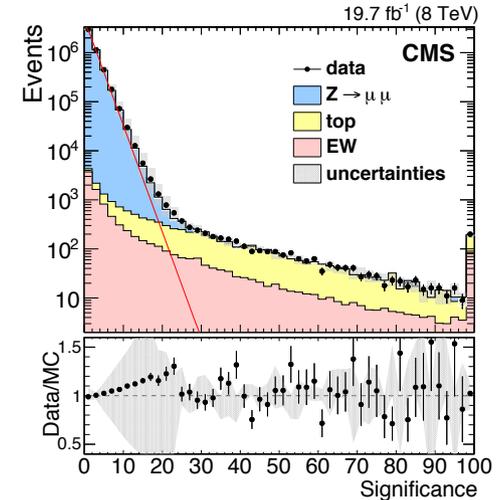
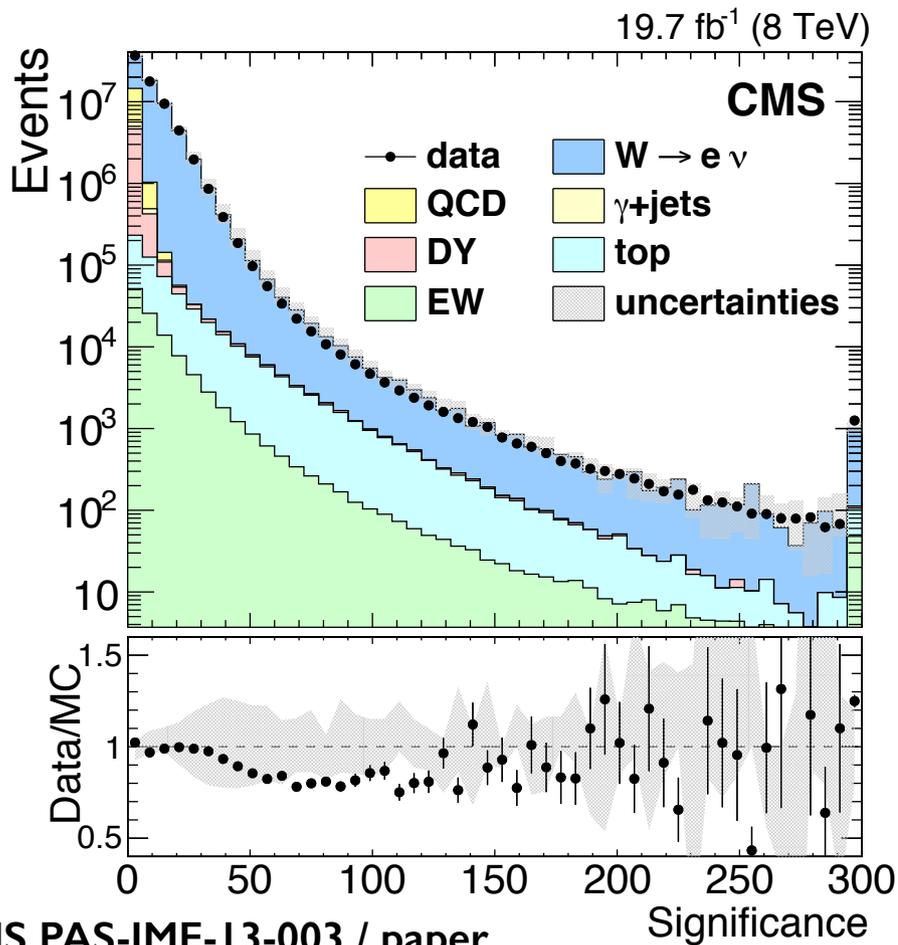
- MET resolution well understood as sum of hard component and diffuse PU background
  - ▶ hard component scales as  $(\sqrt{q_T \times S}) \otimes (C \times q_T)$
  - ▶ soft component scales as  $(\sqrt{\mu \times \sigma_{PU}}) \otimes \sigma_c$ 
    - PU adds about 3.3-3.6 GeV per interaction in quadrature



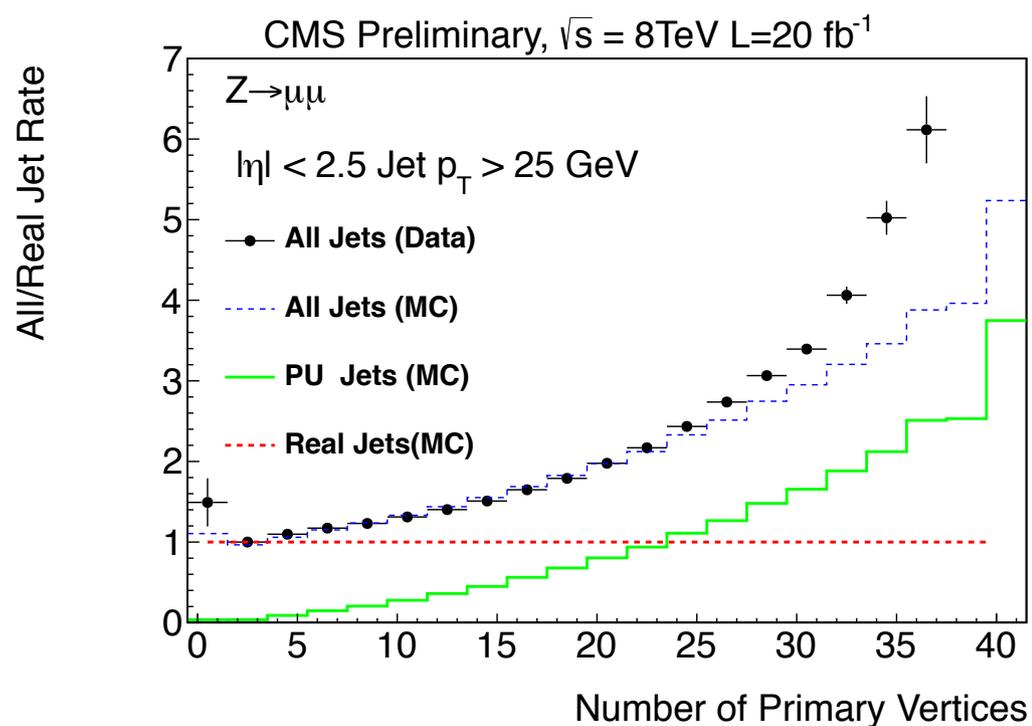
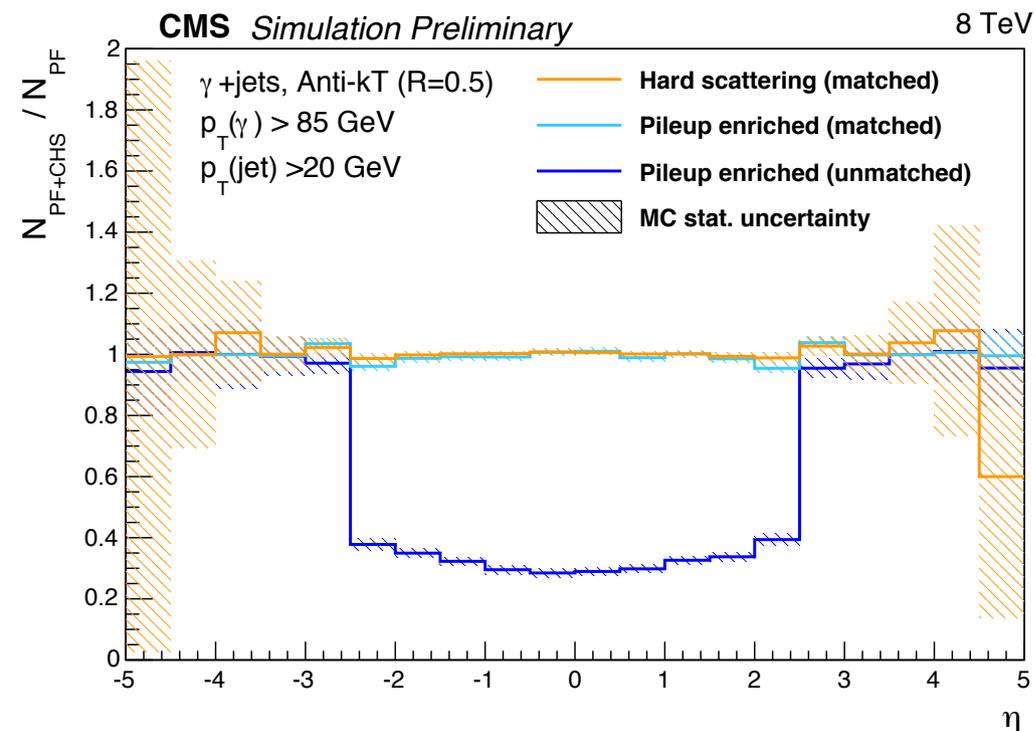
- More advanced techniques have been developed to reduce MET degradation with PU:
  - ▶ No-PU MET: particles not clearly from HS are scaled down by  $SF=HS/(HS+PU)$  from tracks
  - ▶ MVA MET: multivariate analysis of different particle categories to optimise MET resolution
  - ▶ MVA Unity MET: as above, but with target to also retain MET response close to unity
- MET resolution gains very significant, data/MC agreement reasonable



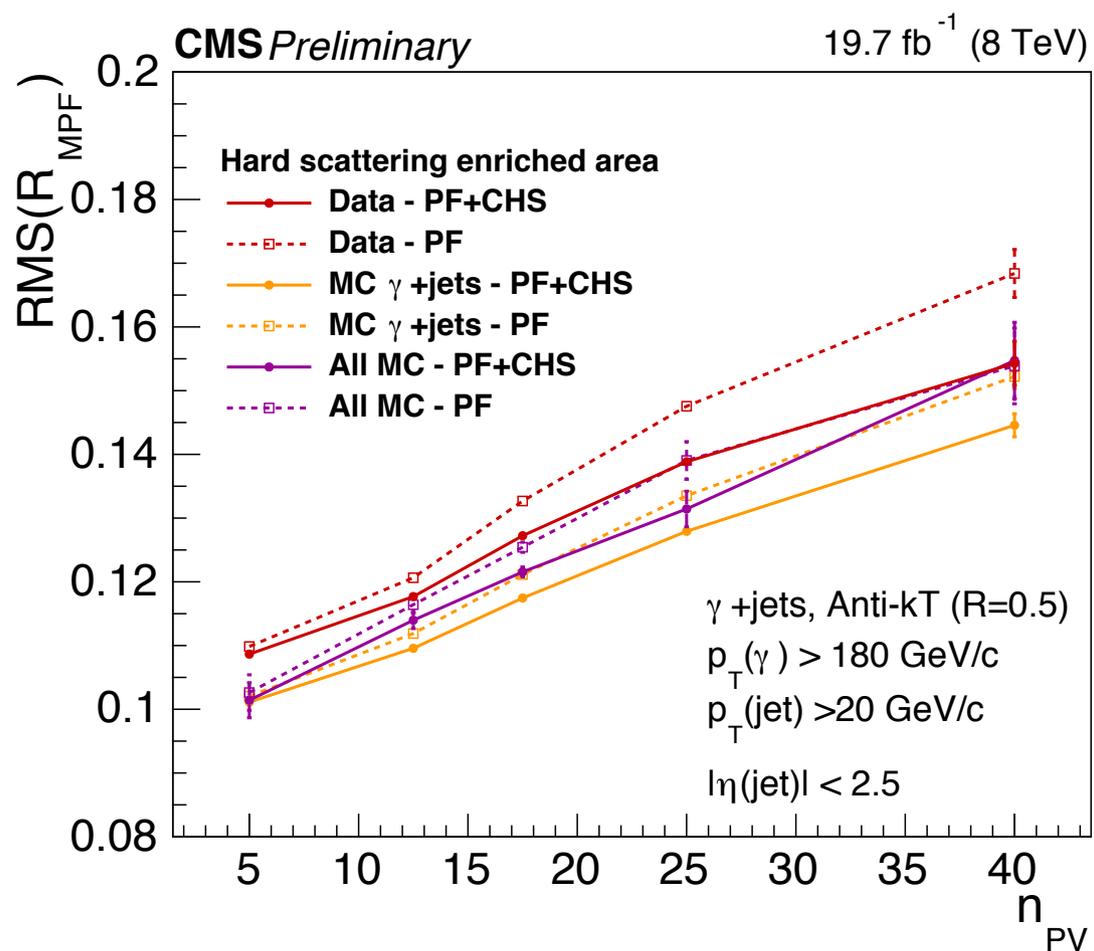
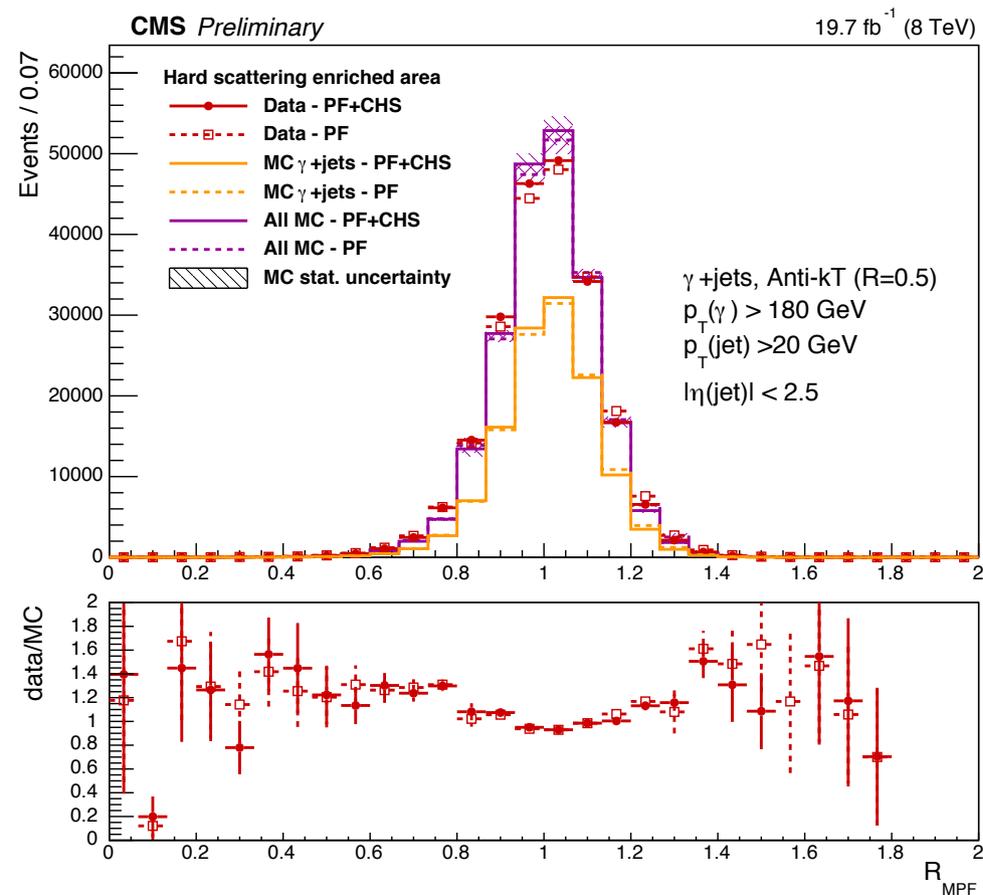
- MET significance benefits from event topology and object resolutions (jets, unclustered) to improve S/B of MET cuts
- Commissioned in data and working well; latest upgrades include non-Gaussian tails folded with FFT
- Future developments to incorporate advanced MET types



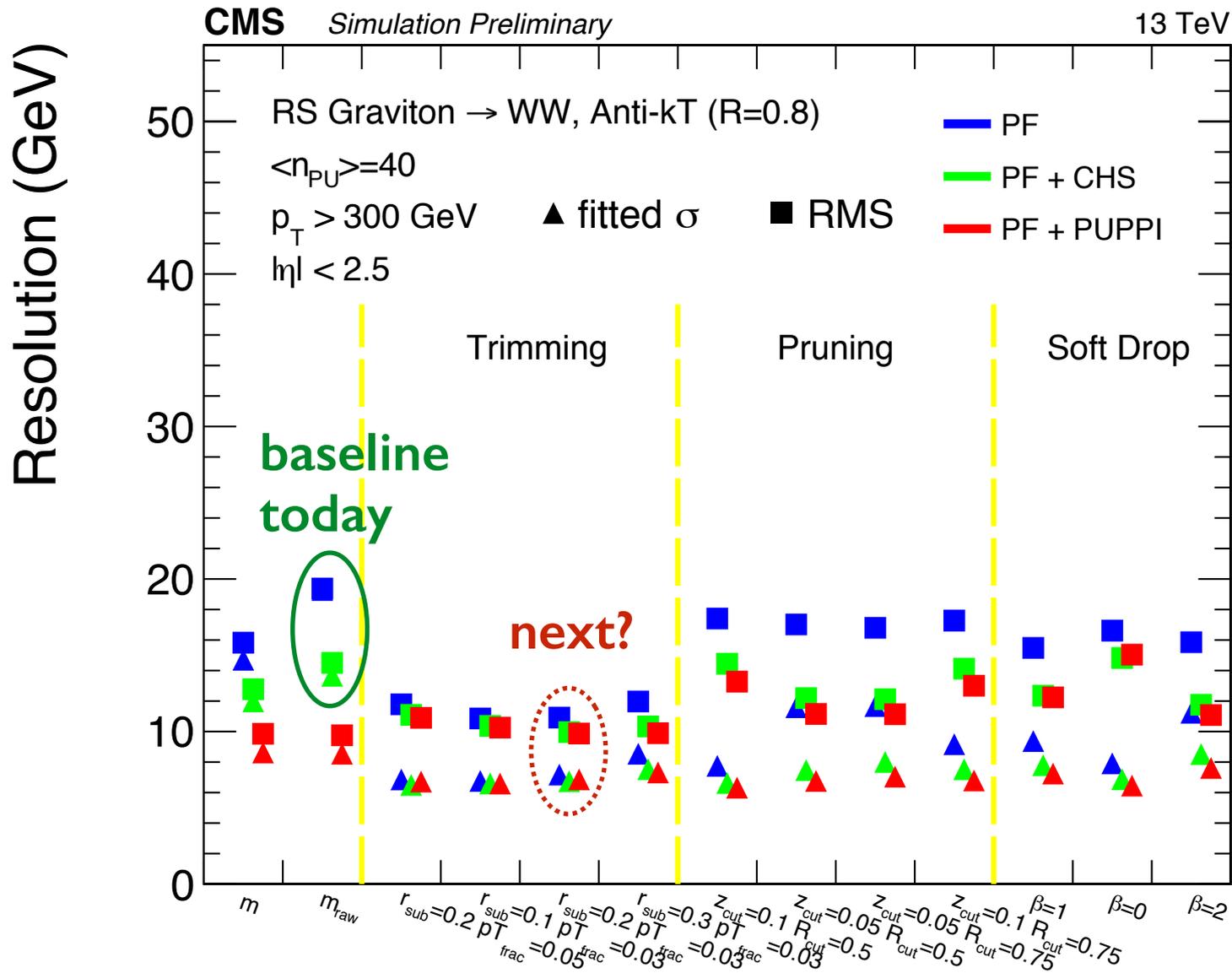
- Heavy lifting to combat out-of-time PU relies on DPGs, but JetMET can work from PF up
- Current work horses Charged Hadron Subtraction (CHS) and PileUpJetID
  - ▶ CHS only works within tracker coverage, PUJetID needed in the forward region
  - ▶ Typical PU efficiencies 15% (30% CHS only) at  $|\eta| < 2.5$ , 50% at  $|\eta| > 2.5$ , for  $p_T > 20$  GeV
  - ▶ Corresponding signal efficiencies 99% to 75-95%



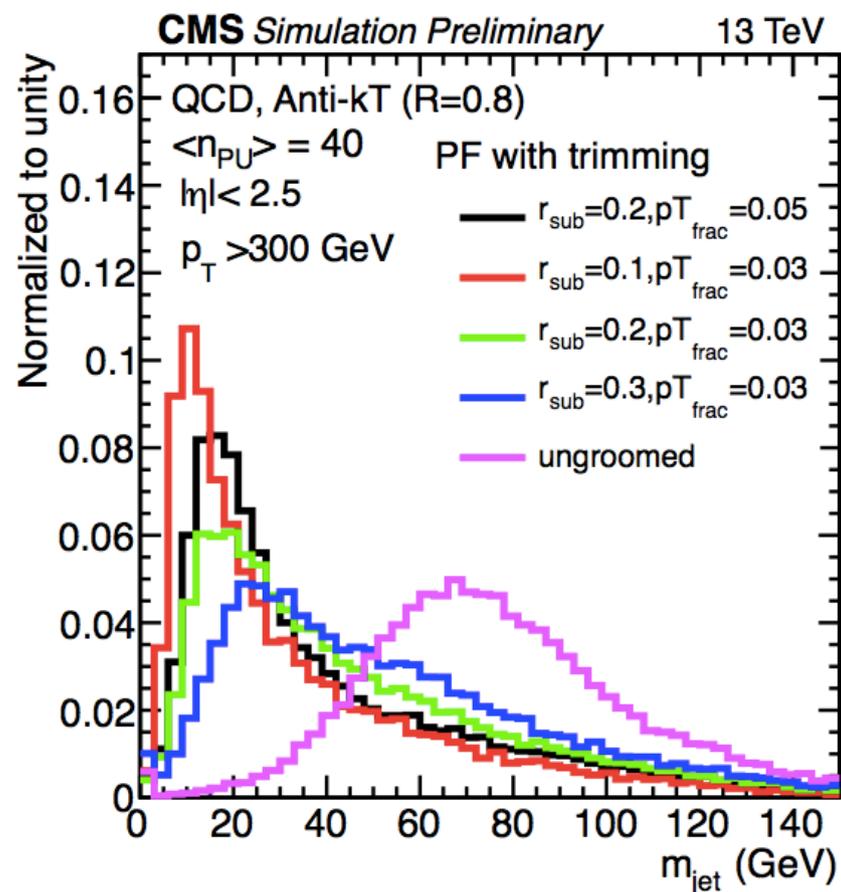
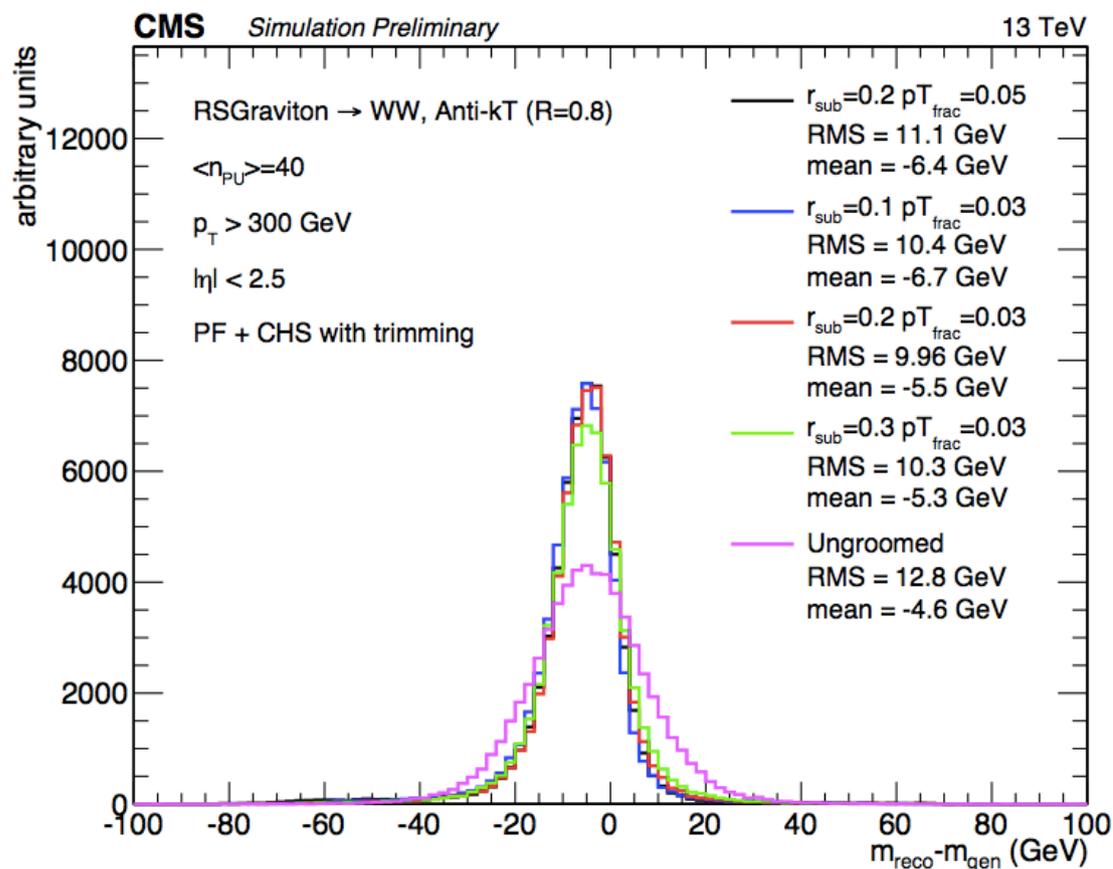
- CHS shows benefits in jet  $p_T$  resolution (JER), more clearly at high pileup
- Similar improvements in angular ( $\eta$ ,  $\phi$ ) resolutions



- Next generation of pileup mitigation will rely more on PileUp Per Particle ID (PUPPI) and various jet grooming techniques (trimming, pruning, filtering, soft drop)



- Primary motivation is reducing hard-to-model non-perturbative QCD radiation
  - ▶ improves mass resolution on hadronic resonances, reduces QCD jet backgrounds
- Grooming is also powerful in reducing effective jet area and reducing sensitivity to PU
  - ▶ more important for large cone sizes, without strong experimental PU mitigation (e.g. PUPPI)

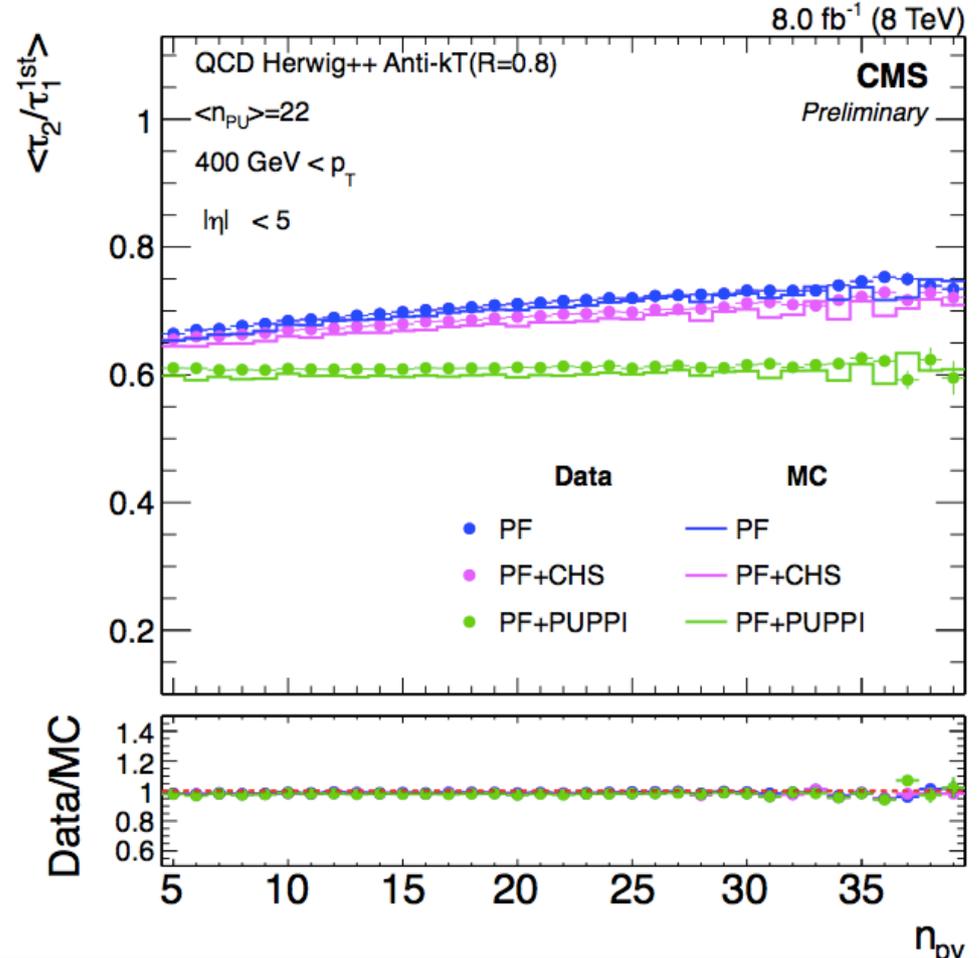
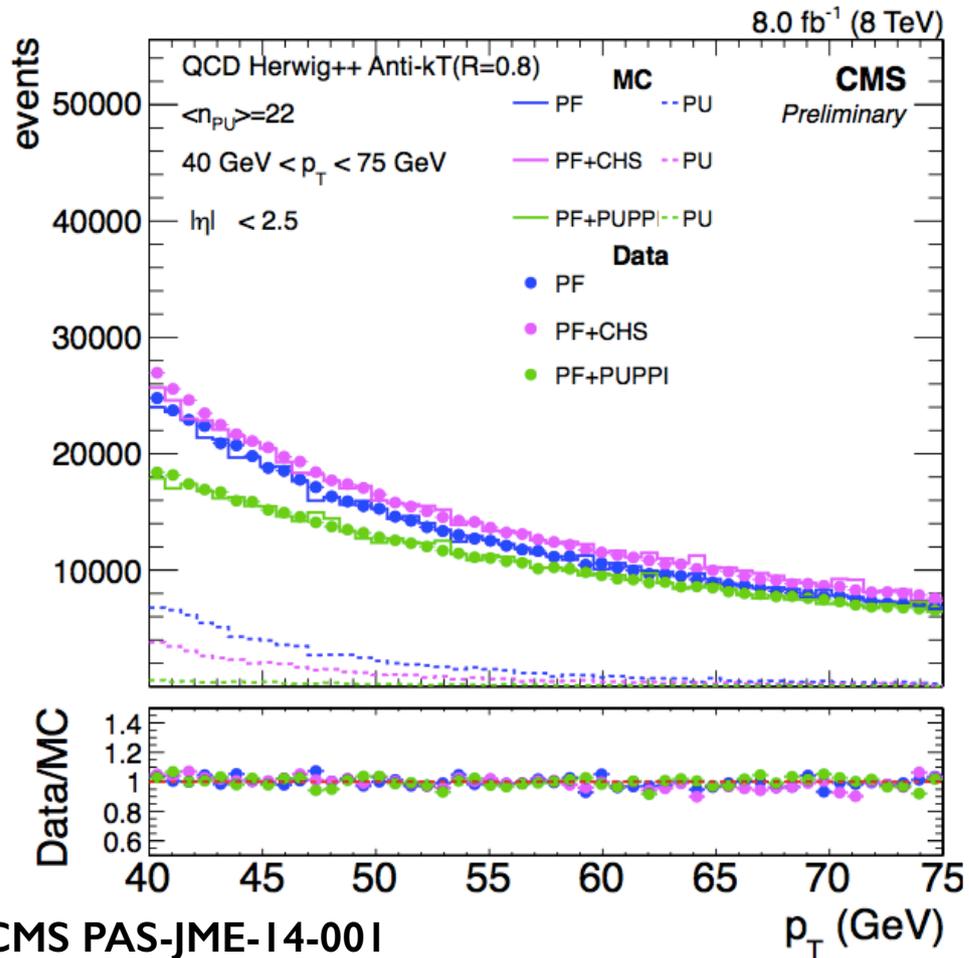




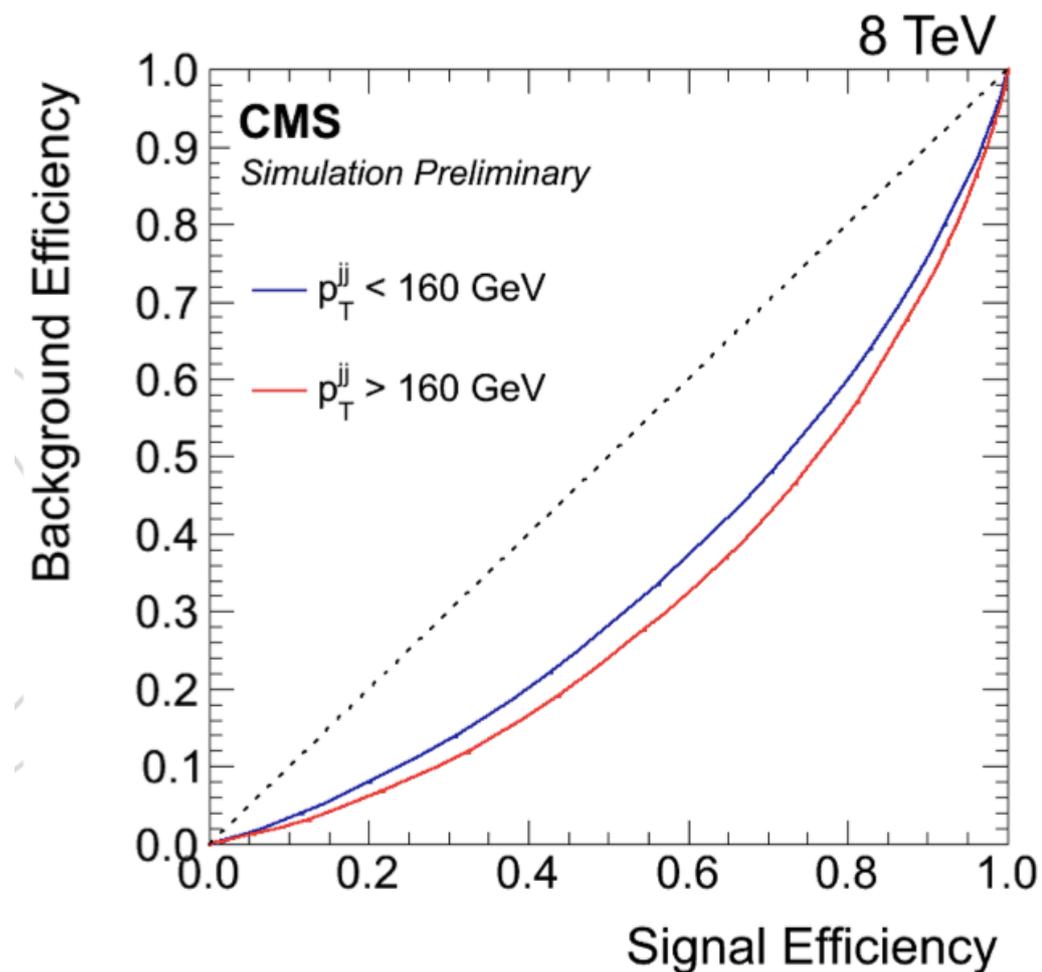
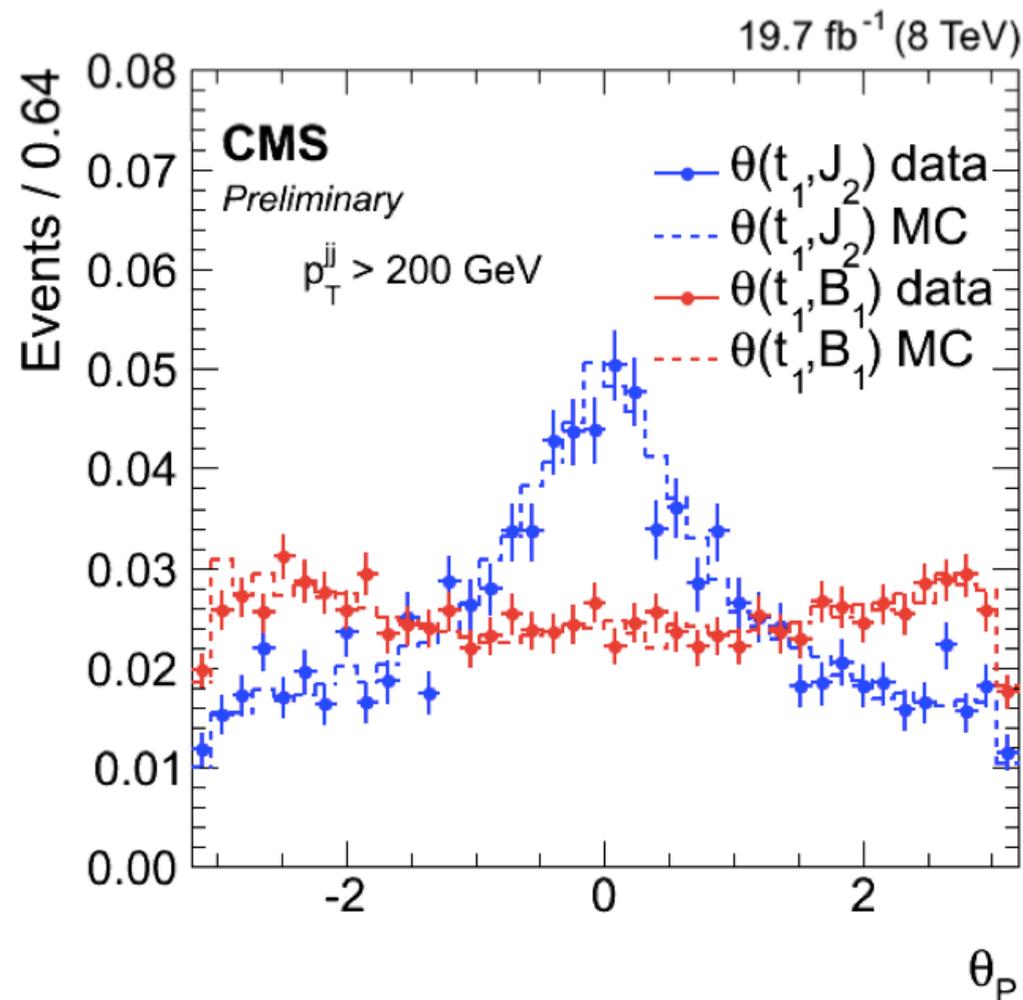
# PUPPI



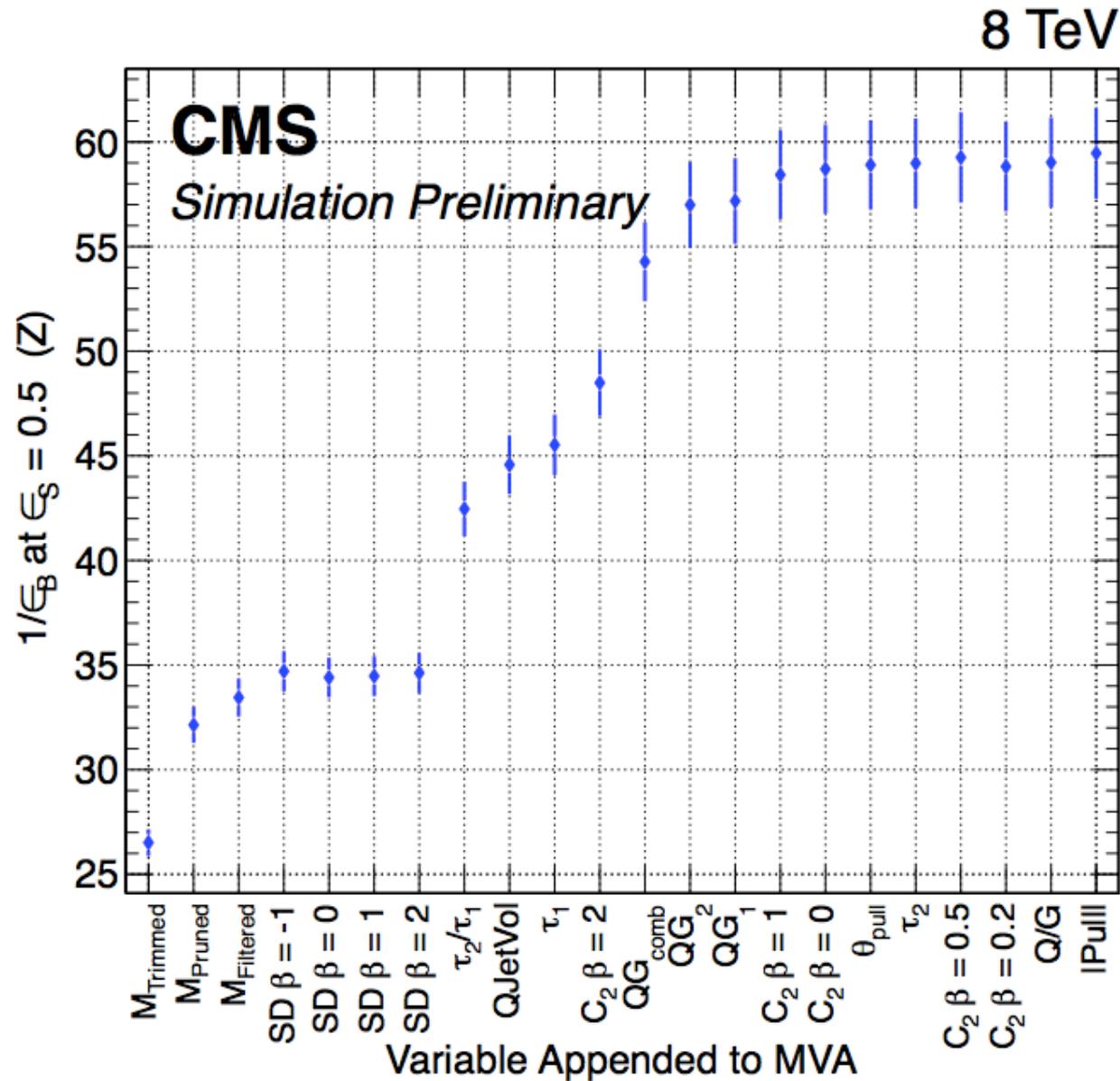
- PileUp Per Particle ID takes Particle Flow one step further (but does not require PF)
- Combines tracking/vertexing with information on local energy deposits
- Algorithm described on [arXiv:hep-ph/1407.6013](https://arxiv.org/abs/1407.6013)
- Reduces PU jet rates and makes jet observables (mass, subjettiness etc.) insensitive to PU



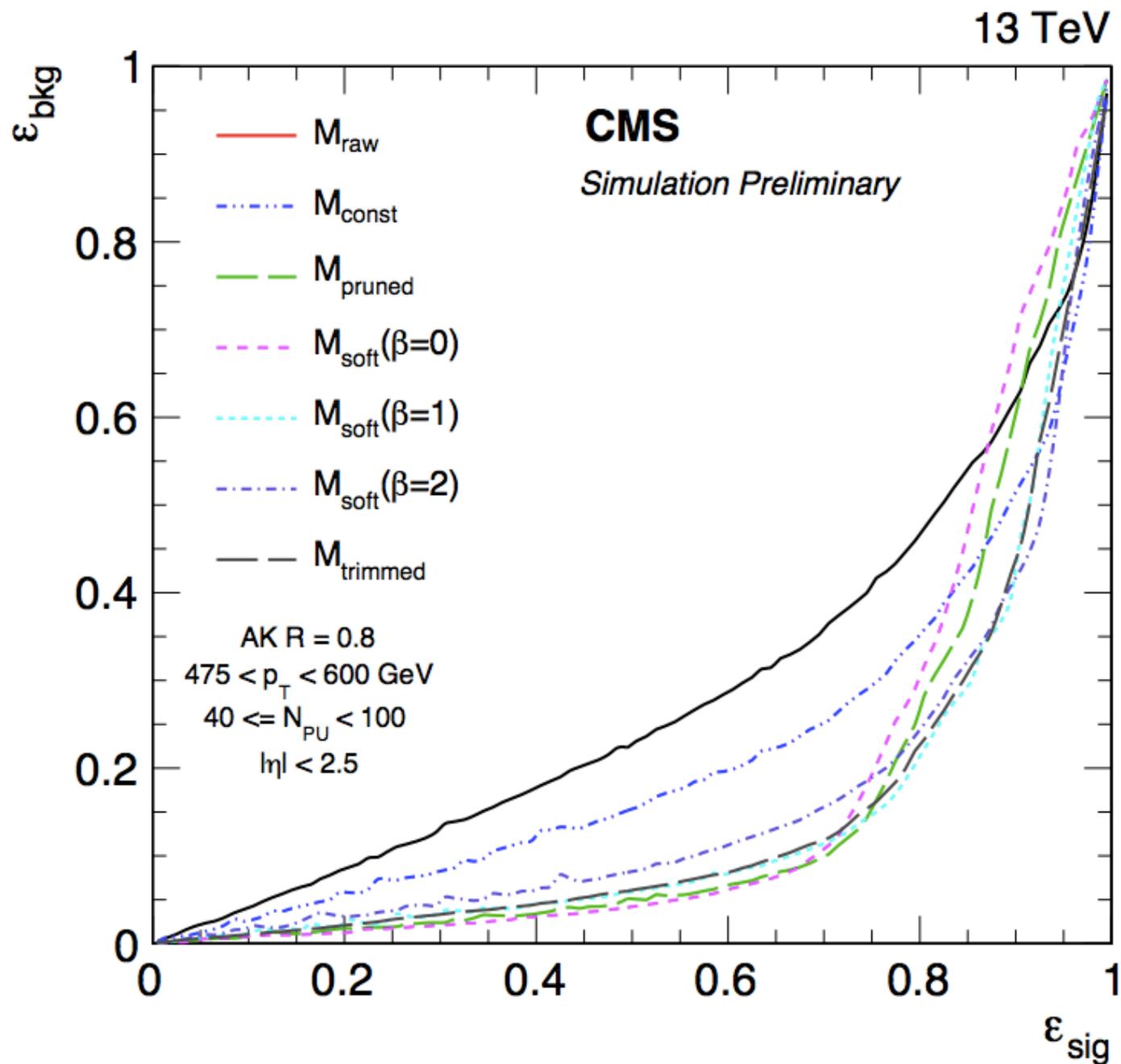
- W tagging for resolved jets based on Quark/Gluon likelihood, dijet charge and pull angle
- Pull angle is a new tool on market: weak discrimination alone, but helps in combinations



- For unresolved jets, best discrimination is with groomed jet mass ( $B \sim 10\%$  vs  $S \sim 90\%$ )
- Of other variables, N-subjettiness  $\tau_1/\tau_2$  and Qjet volatility best
- Energy correlation functions  $C_2^\beta$  and subjet Quark/Gluon likelihood (QGL) also add discrimination
- Many variables still needed for ultimate performance

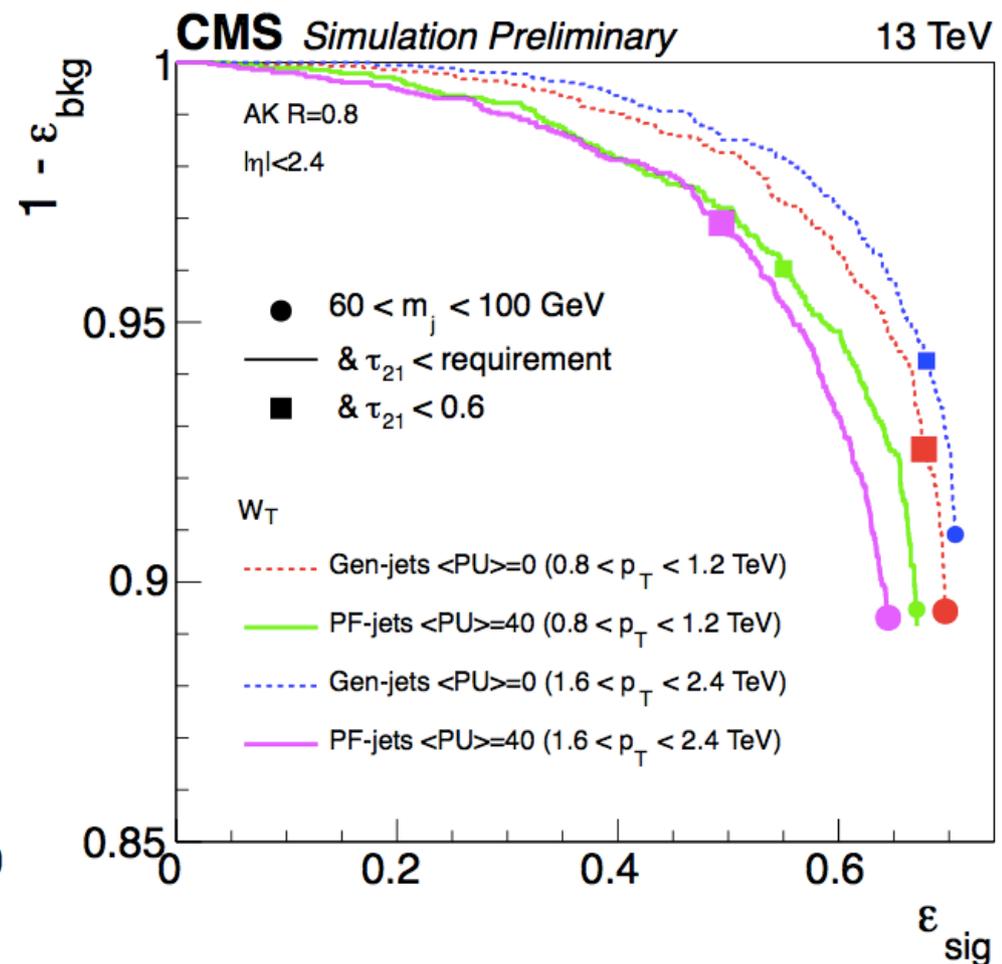
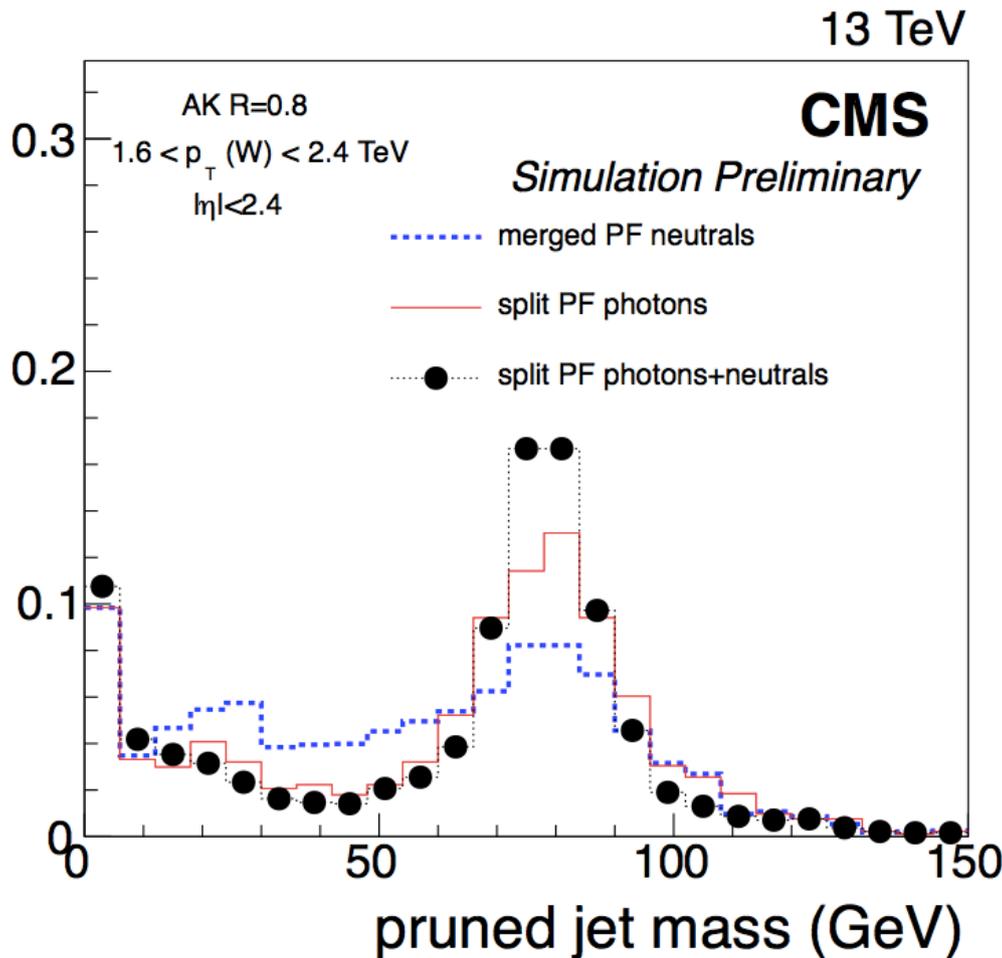


- With MVA reweighing input variables, we can keep high performance at high pileup
- Softdrop with various beta shows best performance
  - agrees with pruning for  $\beta=0$ , trimming for  $\beta=1$
  - strong support from theory community



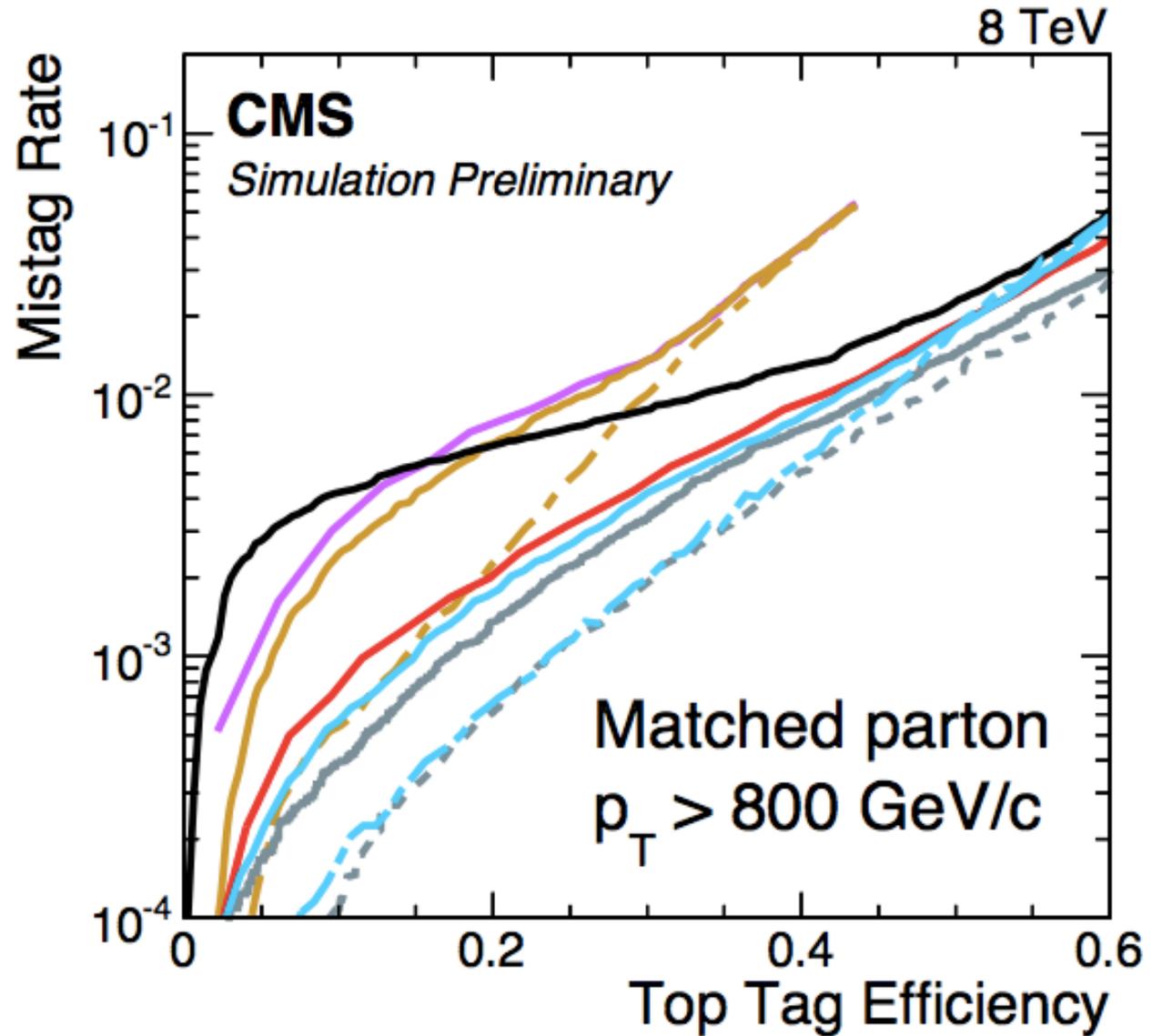
- We've not seen the limits of our detector performance yet:
- With improvements to PF neutral clustering in high  $p_T$  jets, W-tag efficiently up to 2.4 TeV

Normalized Distribution

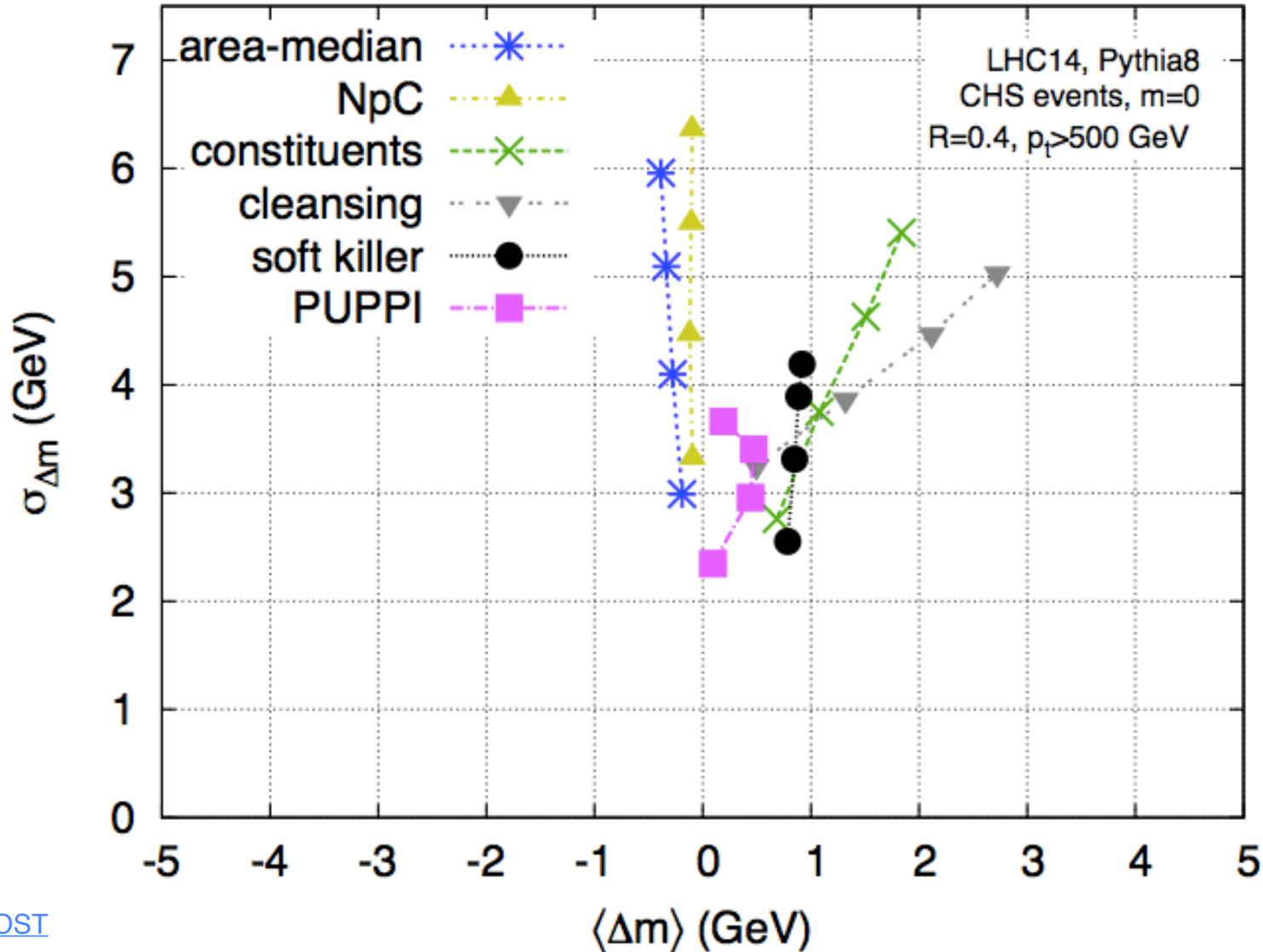


- CMS top tagger performance compares favourably to other taggers on the market

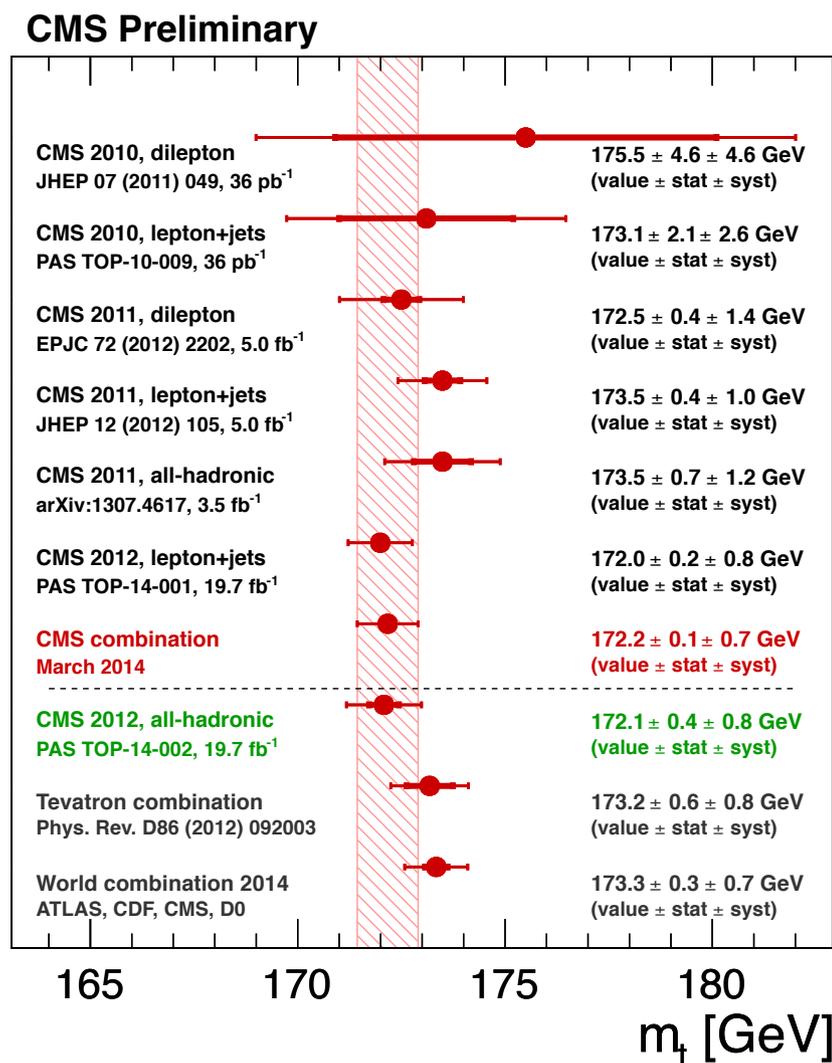
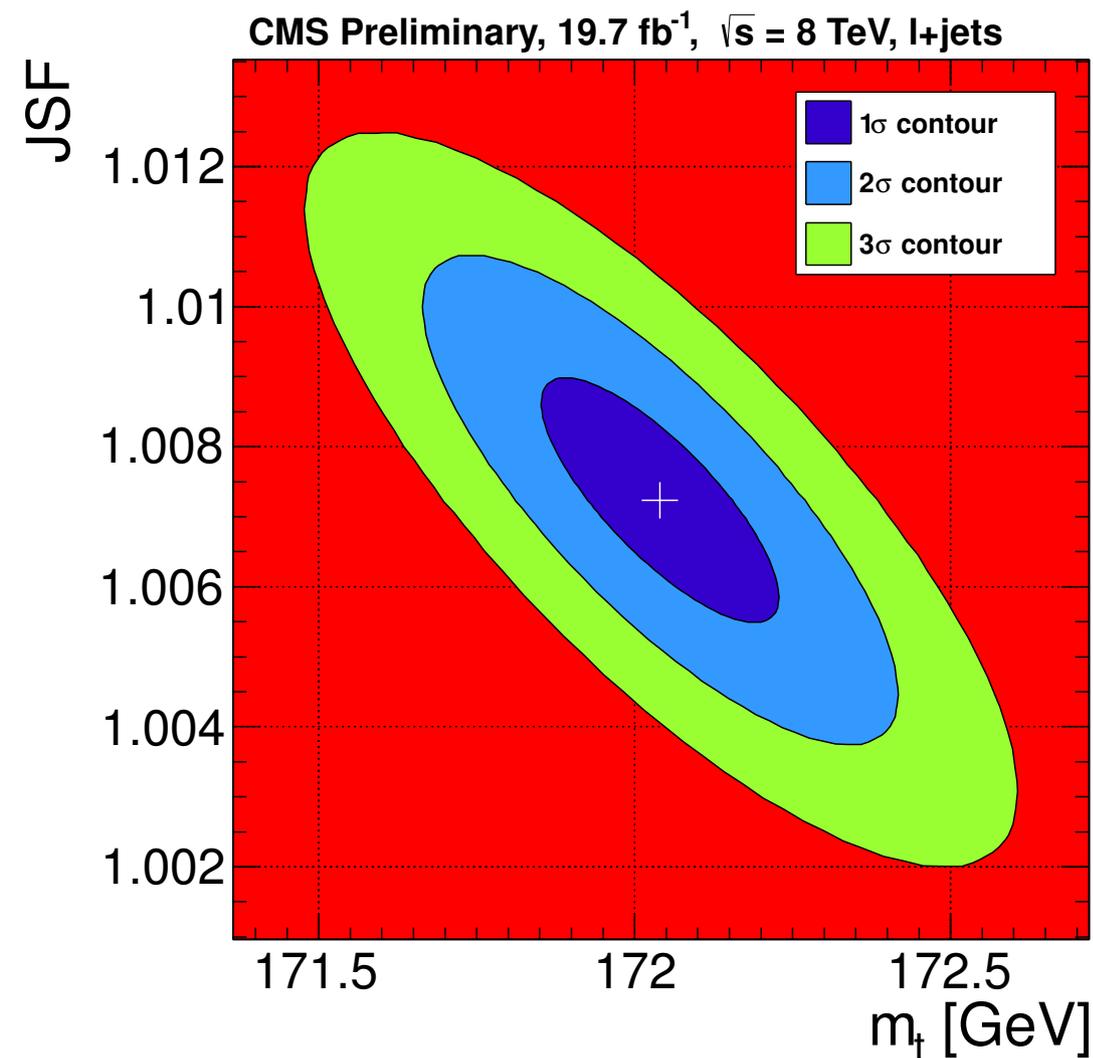
- HEP Top Tagger
- HEP +  $\tau_3/\tau_2$
- - HEP +  $\tau_3/\tau_2$  + sub. b-tag
- MultiR HEP Top Tagger
- CMS Top Tagger
- CMS Top Tagger +  $\tau_3/\tau_2$
- - CMS Top Tagger +  $\tau_3/\tau_2$  + subjet b-tag
- Shower Deconstruction CA8
- - Shower Deconstruction CA8 + subjet b-tag



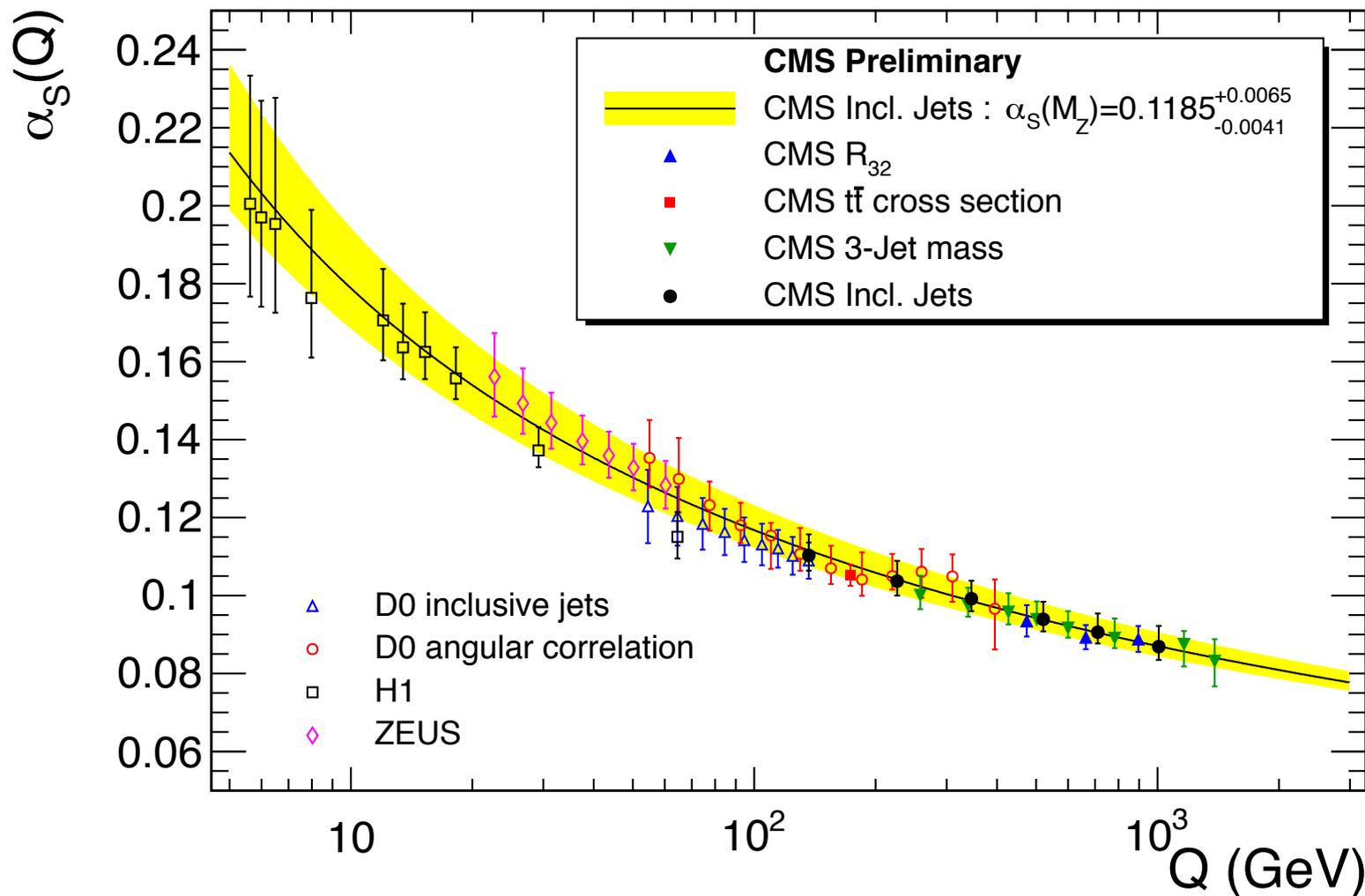
- Lot's of performance gain to be had with PUPPI and extended tracking coverage
- We can handle very high pileup (plot is 14 TeV with 30, 60, 100 going up to 140 PU)



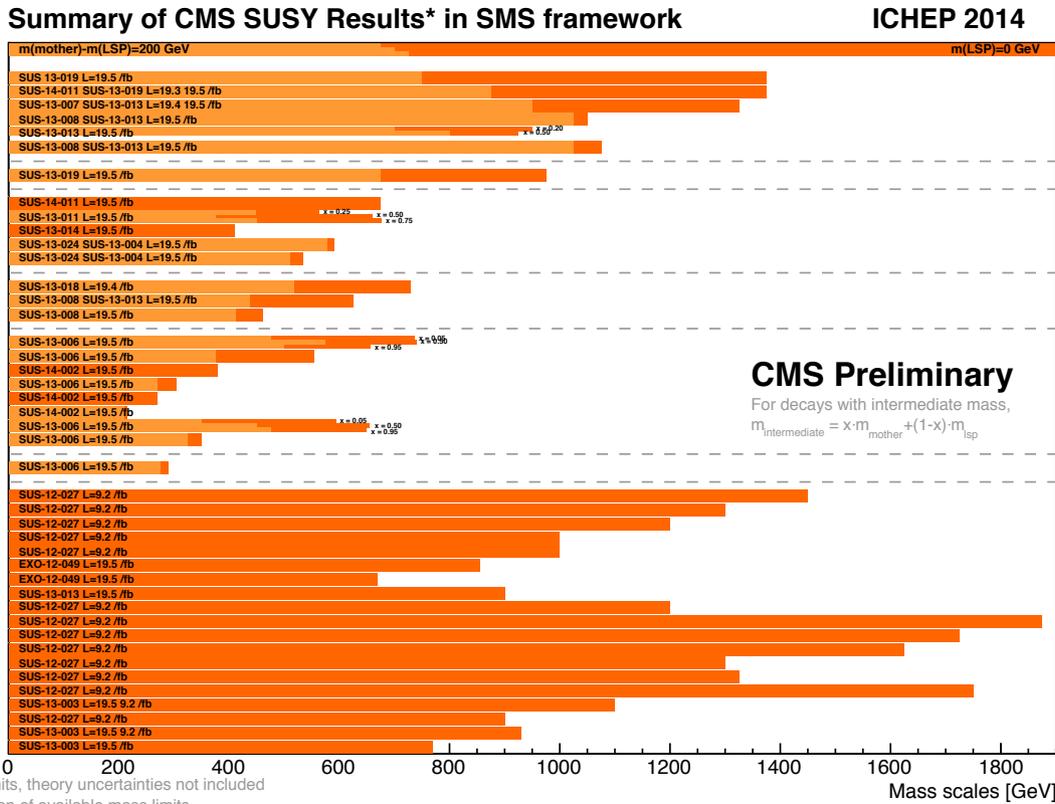
- CMS has done great progress toward passing Tevatron in top quark mass precision
  - ▶ watch out for an interesting duel at Top 2014 in September!
- Need to keep in close contact with Top group on JES topics



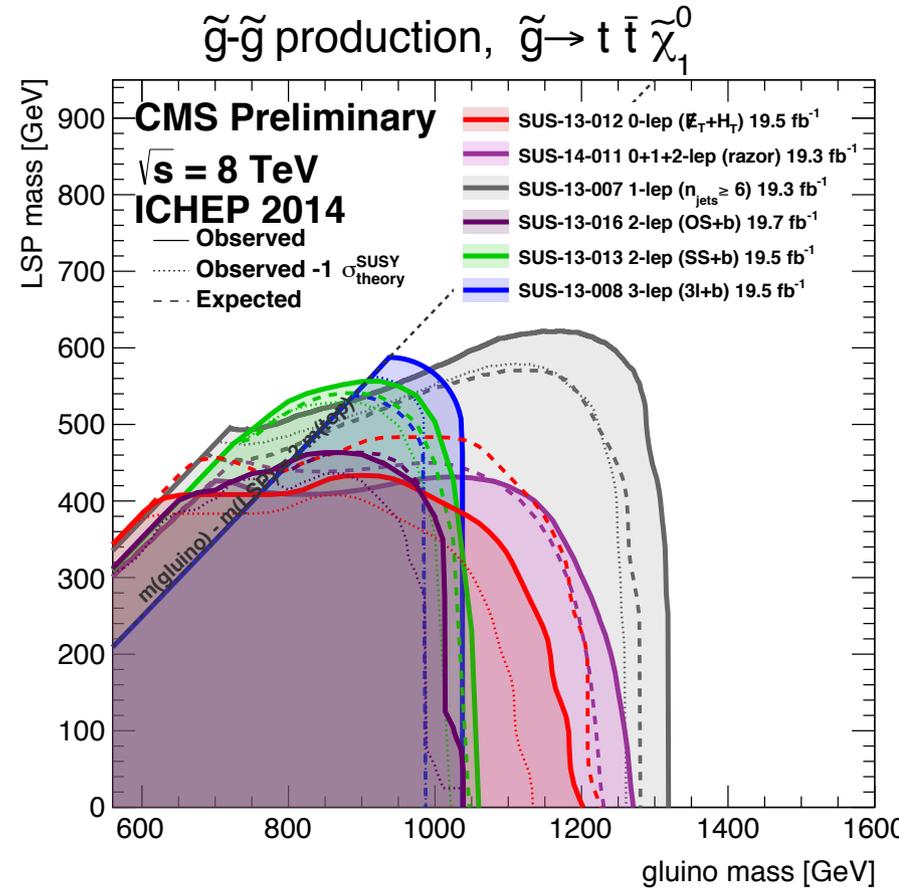
- Strong coupling is a fundamental parameter of the standard model
  - jet measurements probe  $\alpha_s$  at the highest scale to date
- By far the leading systematic for jets is JES
  - close communications between SMP-J and JEC critical for success



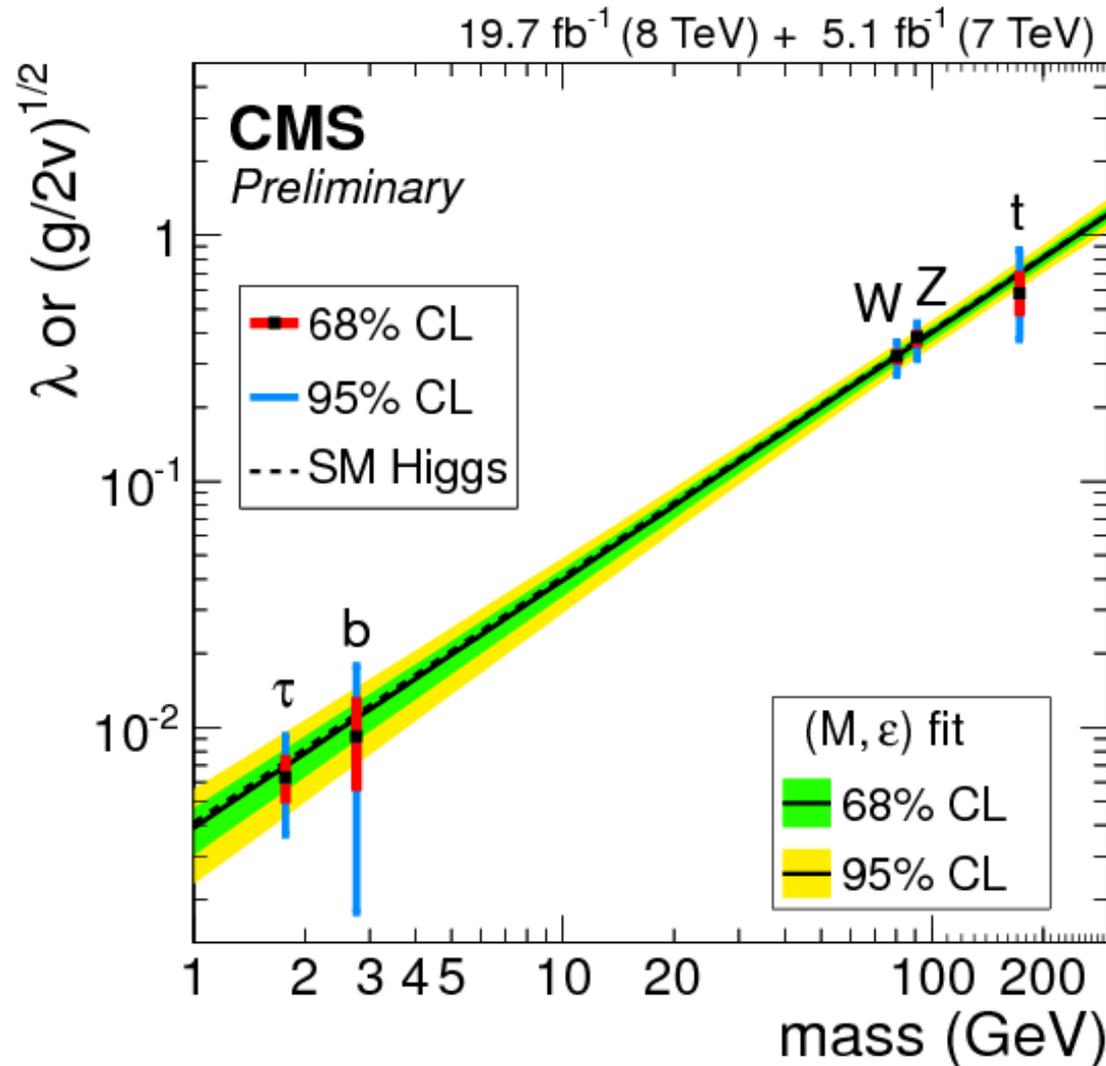
- Already ruled out a large swathe of parameter space for SUSY and EXO
- More to cover in Run II; often need understanding of MET bulk and tails
- ▶ oftentimes lots of jets as well



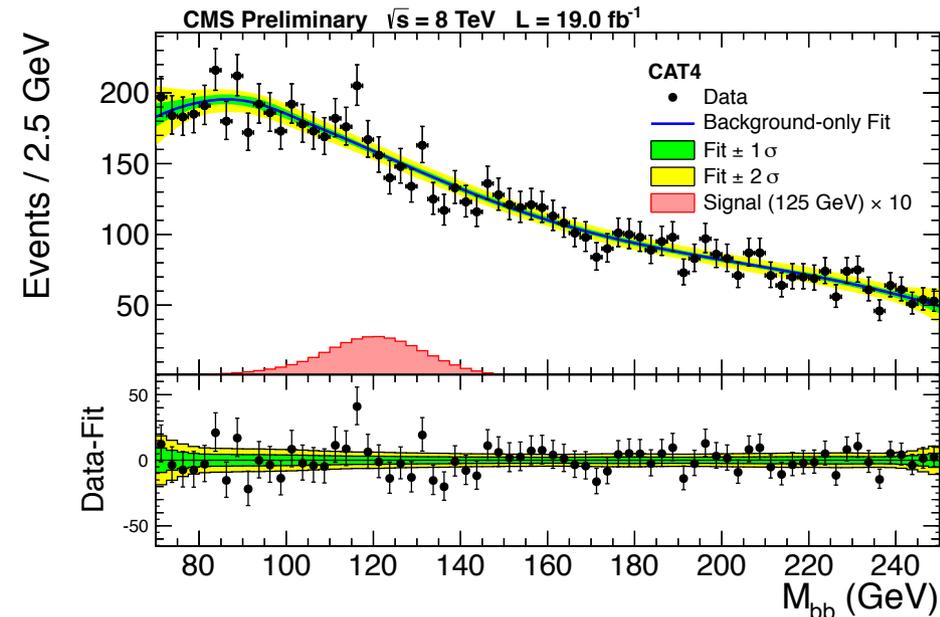
\*Observed limits, theory uncertainties not included  
Only a selection of available mass limits  
Probe \*up to\* the quoted mass limit



- Higgs discovery is what marked Run I, but Run II Higgs studies are precision measurements
- PUJetID and QGL input for vector boson fusion (VBF) modes
- Substructure techniques interesting for boosted Higgs ( $H \rightarrow bb$ ) in future

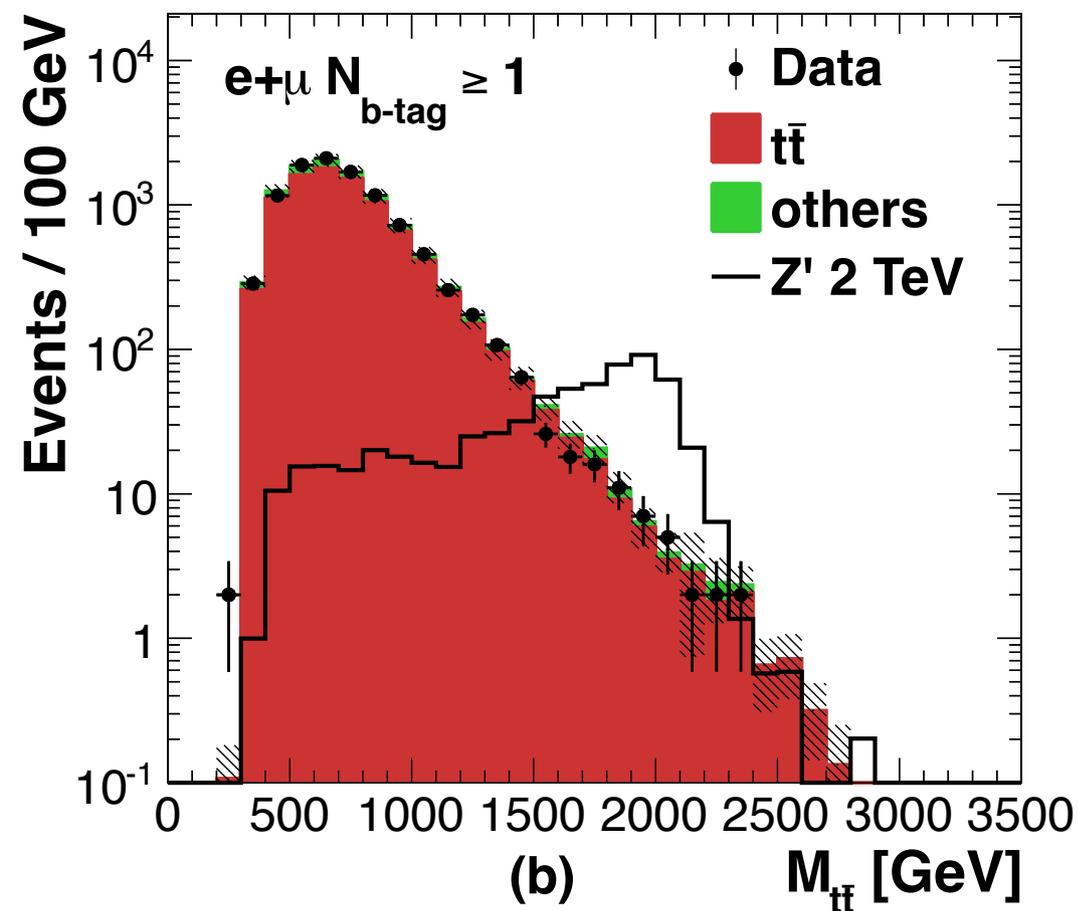


- VBF,  $H \rightarrow bb$  uses QGL and PUJetID; substructure techniques should come in Run II (Kostas's analysis)

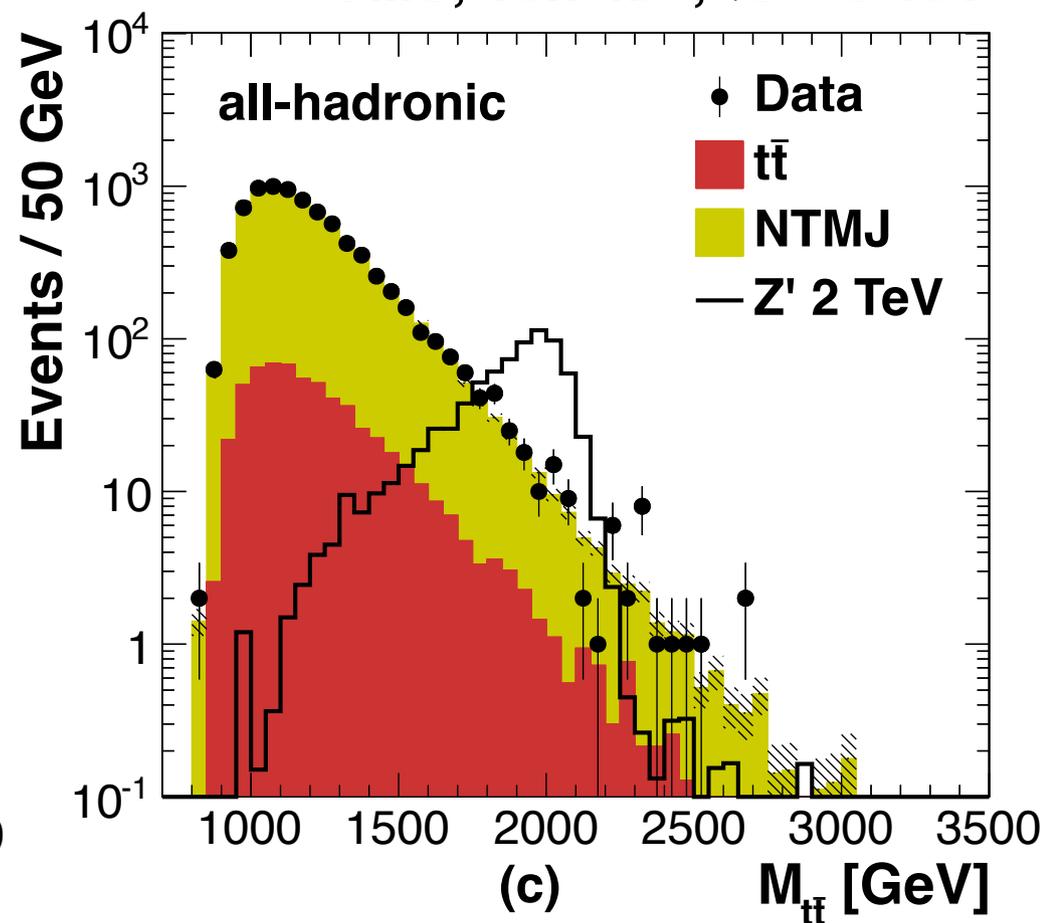


- B2G flagship analysis on boosted tops is a good use case of V and t-tagging
- These kinds of analysis will be the main drive at the start of Run II

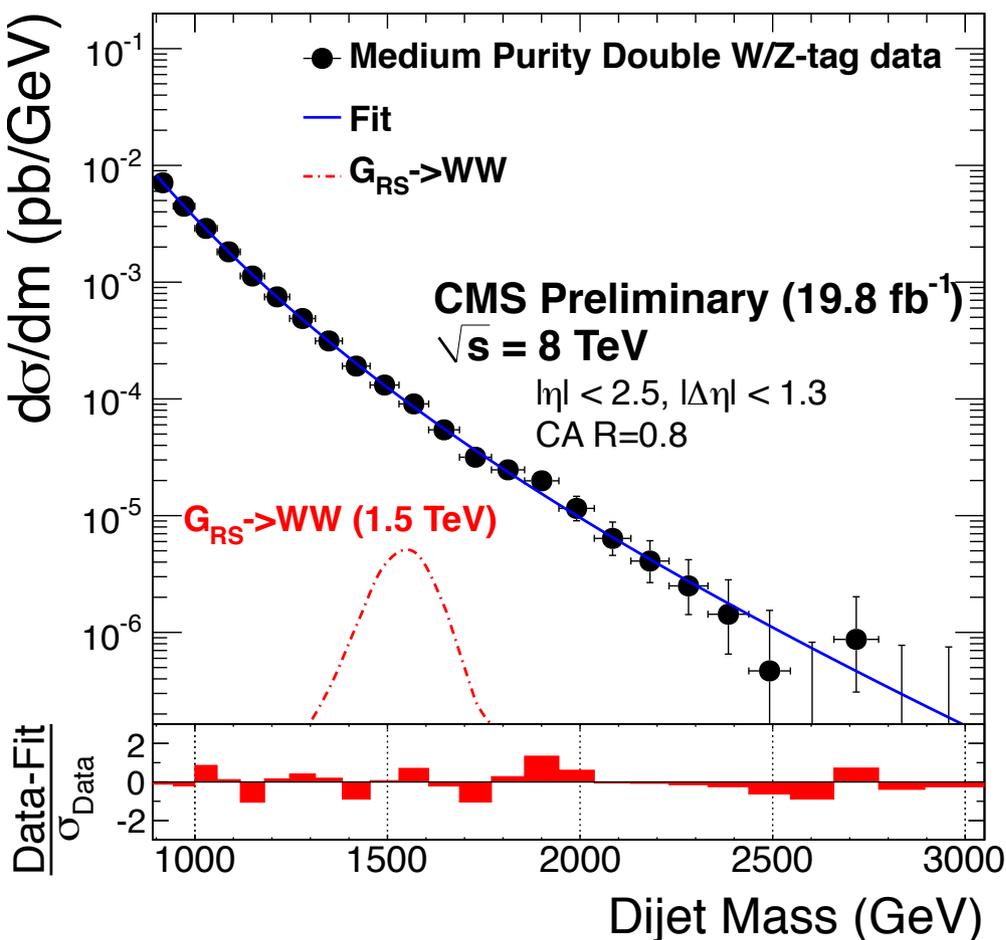
CMS,  $19.7 \text{ fb}^{-1}$ ,  $\sqrt{s} = 8 \text{ TeV}$



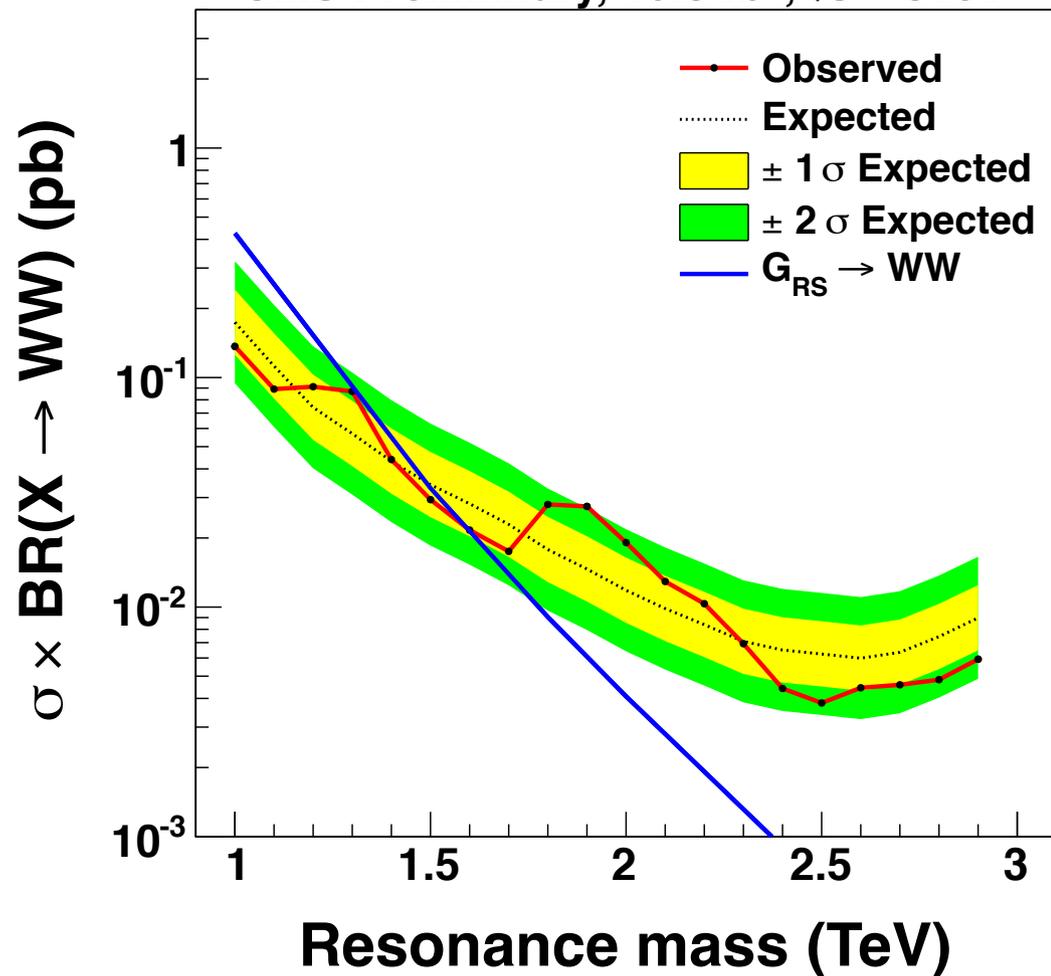
CMS,  $19.7 \text{ fb}^{-1}$ ,  $\sqrt{s} = 8 \text{ TeV}$



- This analysis looks for a Randall-Sundrum graviton decaying into a pair of Ws
- 20 fb<sup>-1</sup> left us with a cliffhanger at 2 TeV, to be continued in Run II
- Also looking forward to results from our colleagues across B40



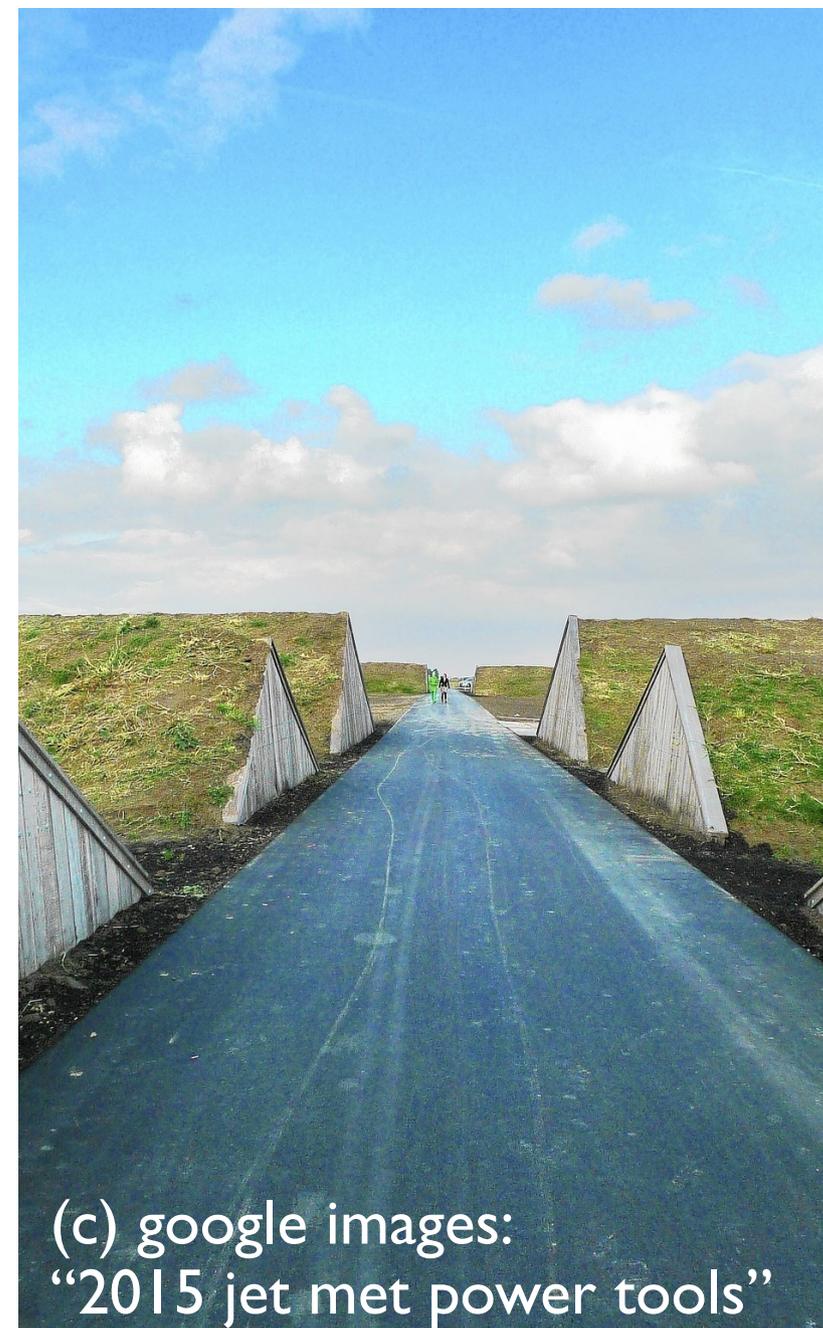
CMS Preliminary, 19.8 fb<sup>-1</sup>,  $\sqrt{s} = 8$  TeV





- It has been a year of
  - ▶ great progress on jet algorithms front
  - ▶ benchmark MET performance paper
  - ▶ steady improvements in JERC
  - ▶ important upgrade studies
- We're now looking toward Run II for
  - ▶ finding or not finding SUSY
  - ▶ investigating vacuum meta-stability with TOP
  - ▶ doing a new round of bread and butter SMP
  - ▶ ...and searching for the unexpected (EXO, B2G)
- Our power tools:
  - ▶ PF PUPPI, grooming, V+t tagging
  - ▶ PUJetID, Quark/Gluon Likelihood
  - ▶ Missing- $E_T$  (projection fraction and significance)

*Remember to act locally, think globally!*



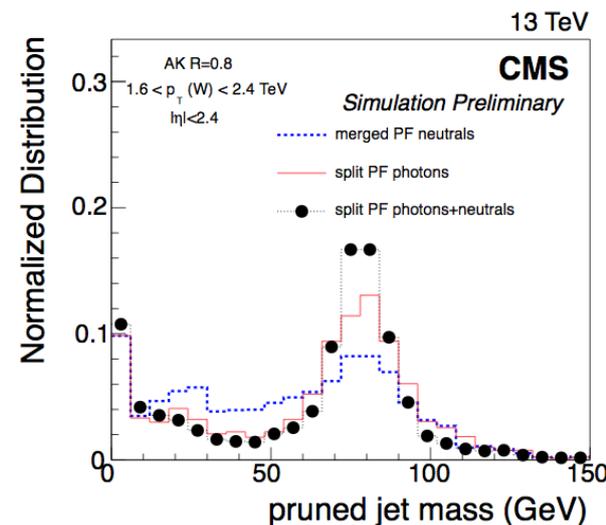
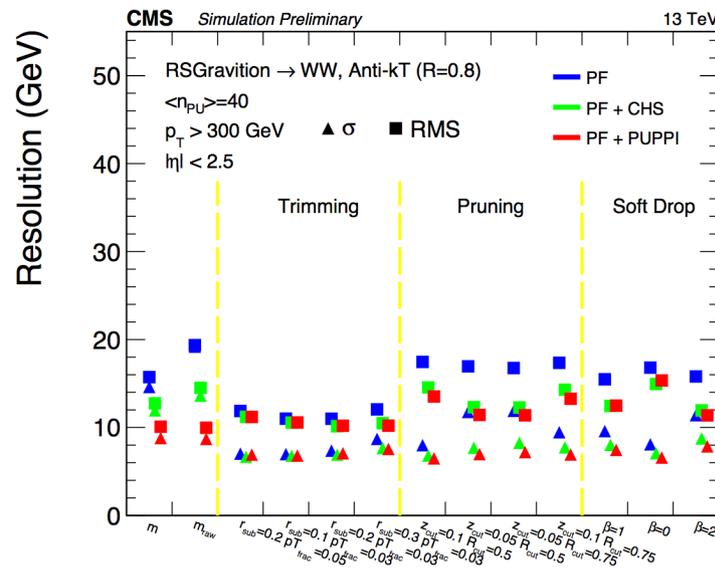
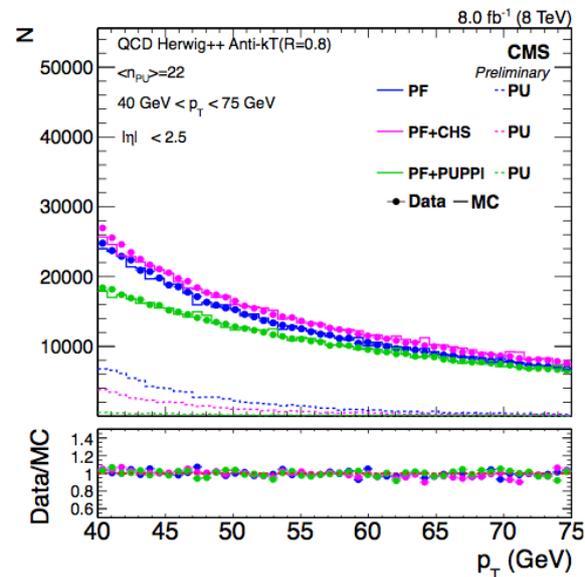
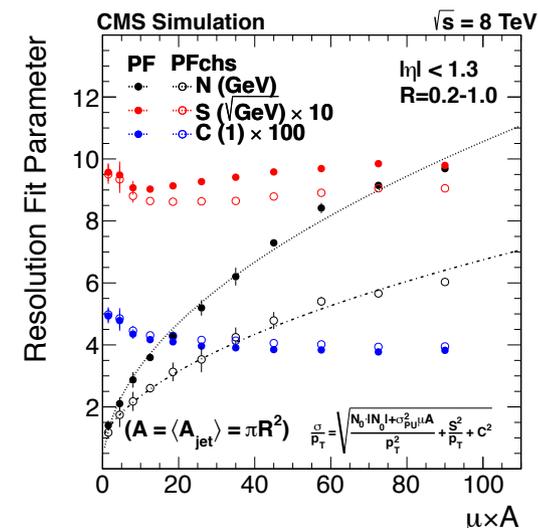
(c) google images:  
“2015 jet met power tools”



# Backup slides



- We had 2 PASEs, 2 DPS Notes approved for BOOST
  - ▶ JME-14-001: Pileup Removal Algorithms (CHS & PUPPI) [\[CADI\]](#)
  - ▶ JME-14-002: V Tagging Observables and Correlations (correlations, high  $p_T$  improvements) [\[CADI\]](#)
  - ▶ DPS Jet Energy Corrections for Multiple Cone Sizes [\[link to WGM\]](#) [\[TWiki\]](#)
  - ▶ DPS Boosted Top Jet Tagging at CMS [\[link to WGM\]](#)
- Very tight approval schedule, but no compromises on physics
  - ▶ Some very cool stuff coming out!
- We should have a very good showing in BOOST this year
  - ▶ Big thanks to authors, ARCs, and Phil for their hard work!



- To a good approximation all can be combined into a simple  $\sqrt{\text{sum } E_T}$  scaling
  - scale factor measured as about  $0.60 \text{ GeV}^{1/2}$ , consistent between different samples, data and MC

