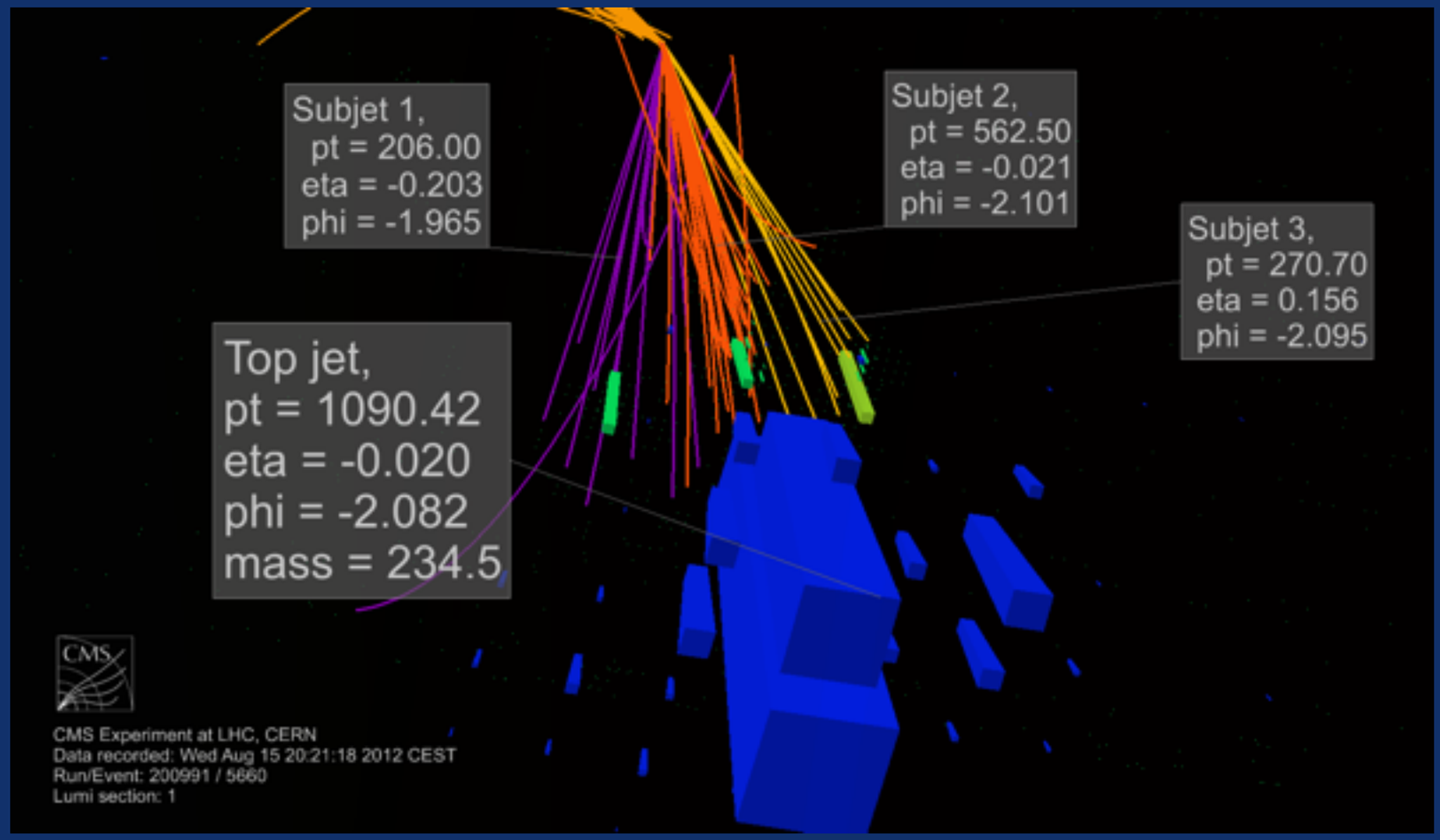
CMS Jet Substructure and Pileup Mitigation



International Center for Theoretical Sciences
Tata Institute For Fundamental Research

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(State University of New York at Buffalo)

24 Jan 2017

Disclaimers

- I had a complete “idiot moment” and didn’t realize until Saturday that this was supposed to be a CMS summary, not an overall summary (oops)
  - Rewrote talk since then entirely

- For lack of time:
  - Will focus on substructure-based taggers and algorithms
  - Lots of underlying PU mitigation at the hardware and reconstruction levels, but don’t have time to discuss

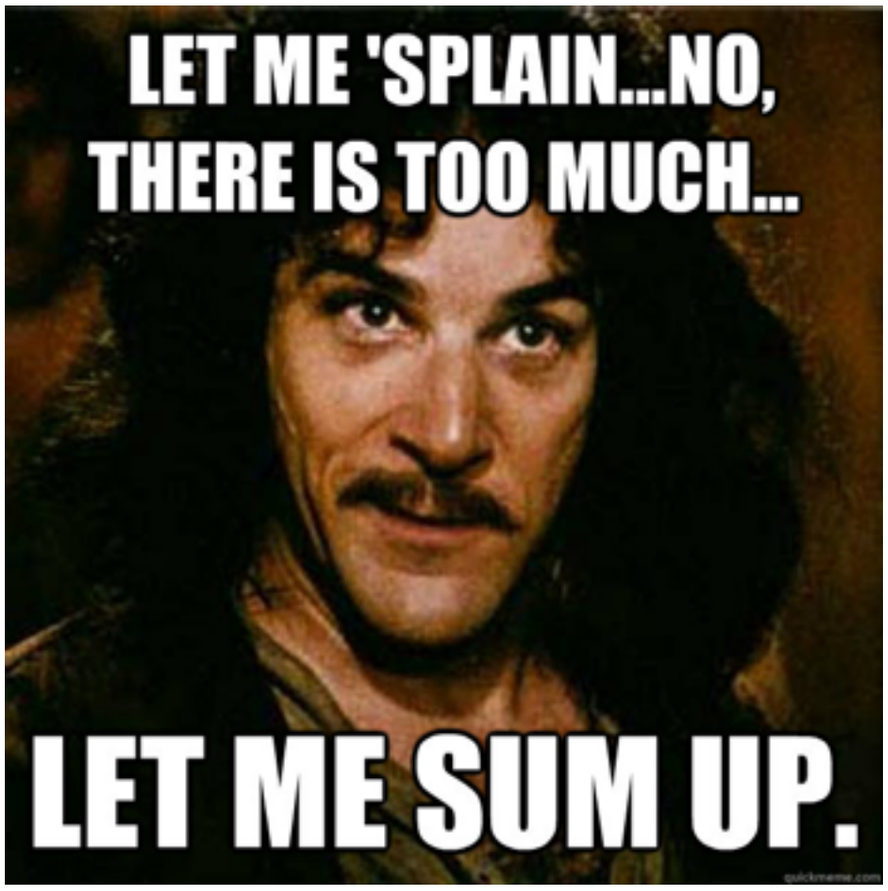
- See Devdatta’s talk for applications!

- Jet substructure and Pileup go hand-in-hand : both have contributions by integrating the entire jet area
  - The historical development here is interesting and apparently in line with everyone else’s talk, so here we go!

Outline

- Brief History
- Where are we?
- Where do we want to go?

All About That Boost



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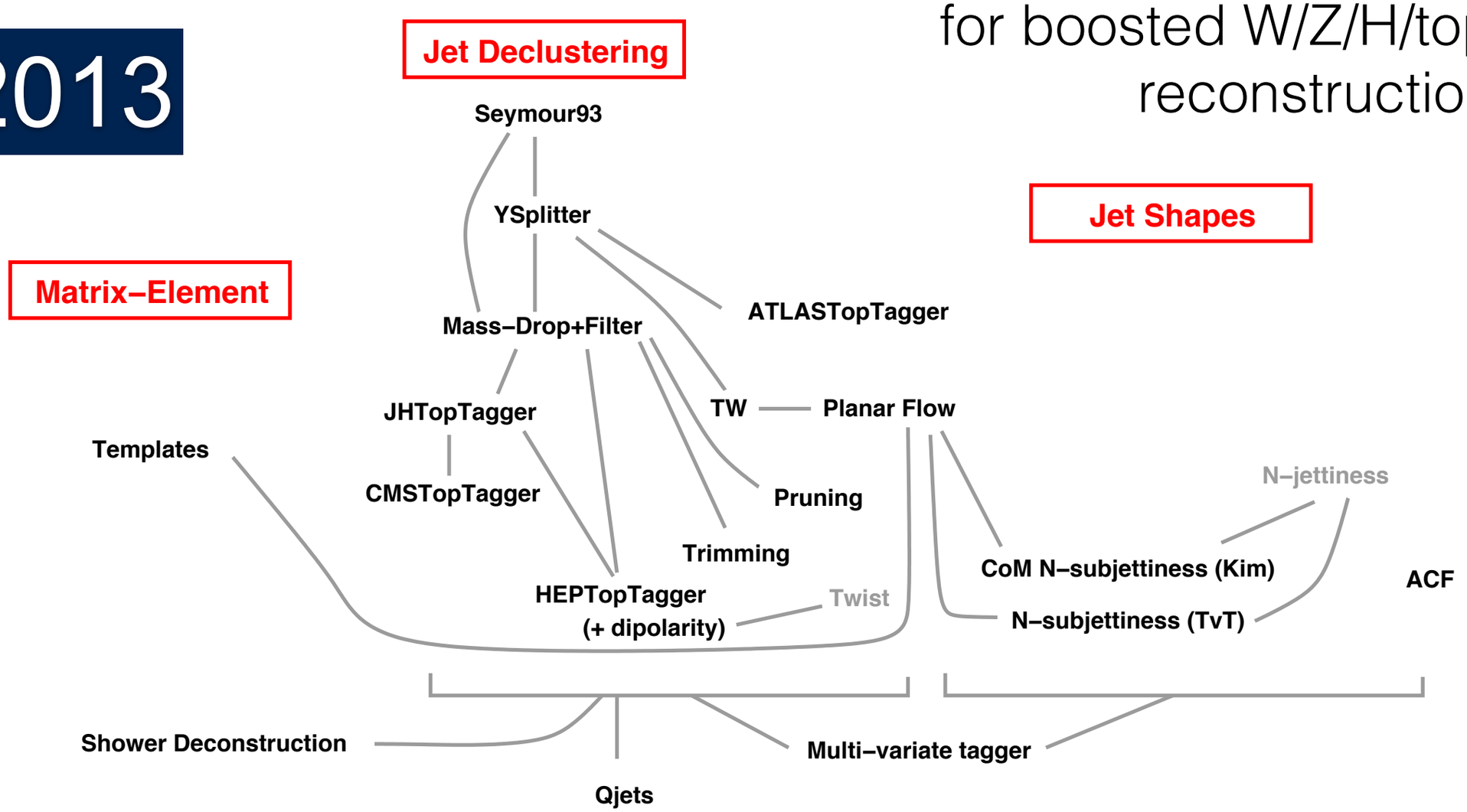
- This list is by no means exhaustive
- If you can read this, you have passed your eye exam. Congratulations.

‘Bout That Boost

Very active research field

Some of the tools developed for boosted W/Z/H/top reconstruction

2013



apologies for omitted taggers, arguable links, etc.

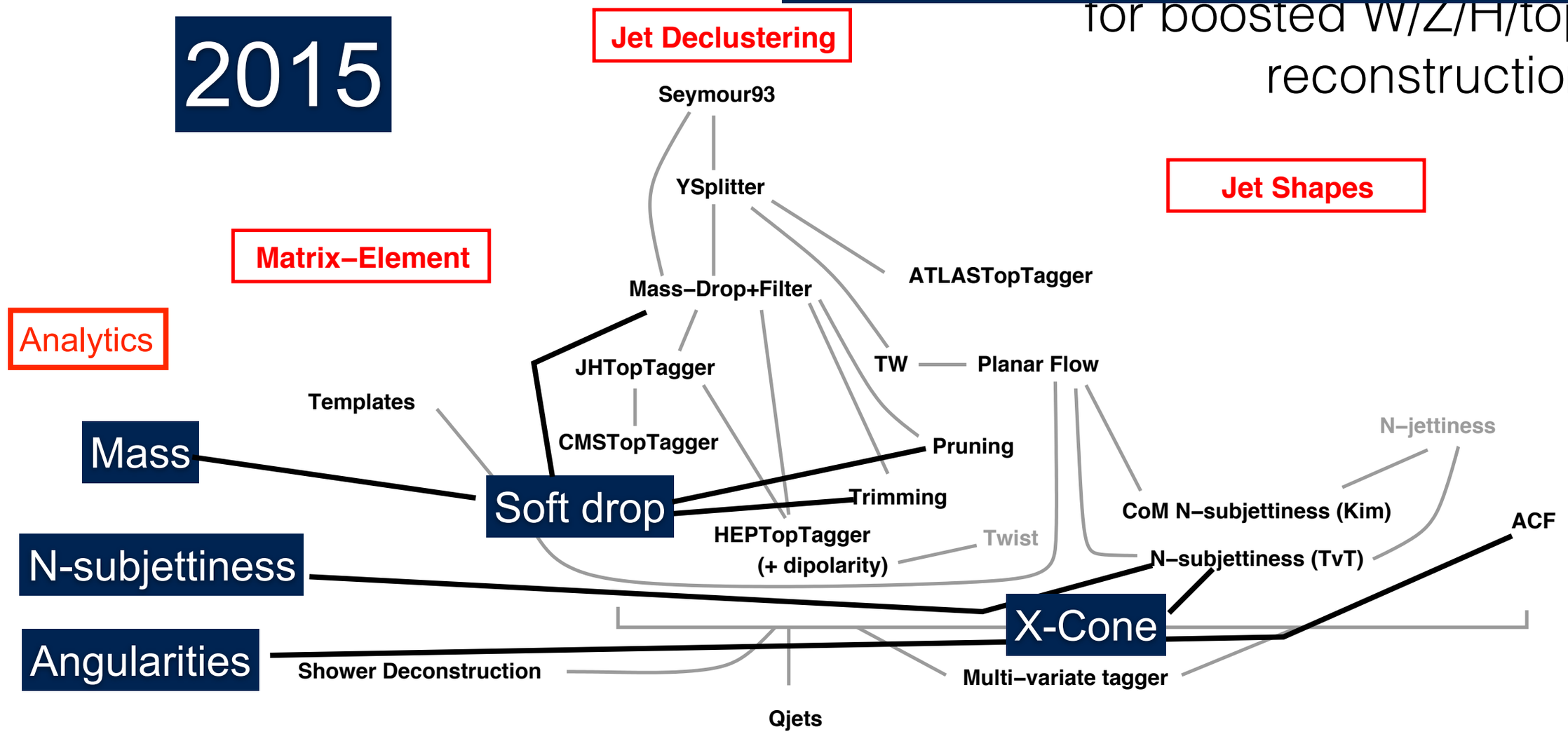
‘Bout That Boost

Very active research field

And growing!

for boosted W/Z/H/top reconstruction

2015



apologies for omitted taggers, arguable links, etc.

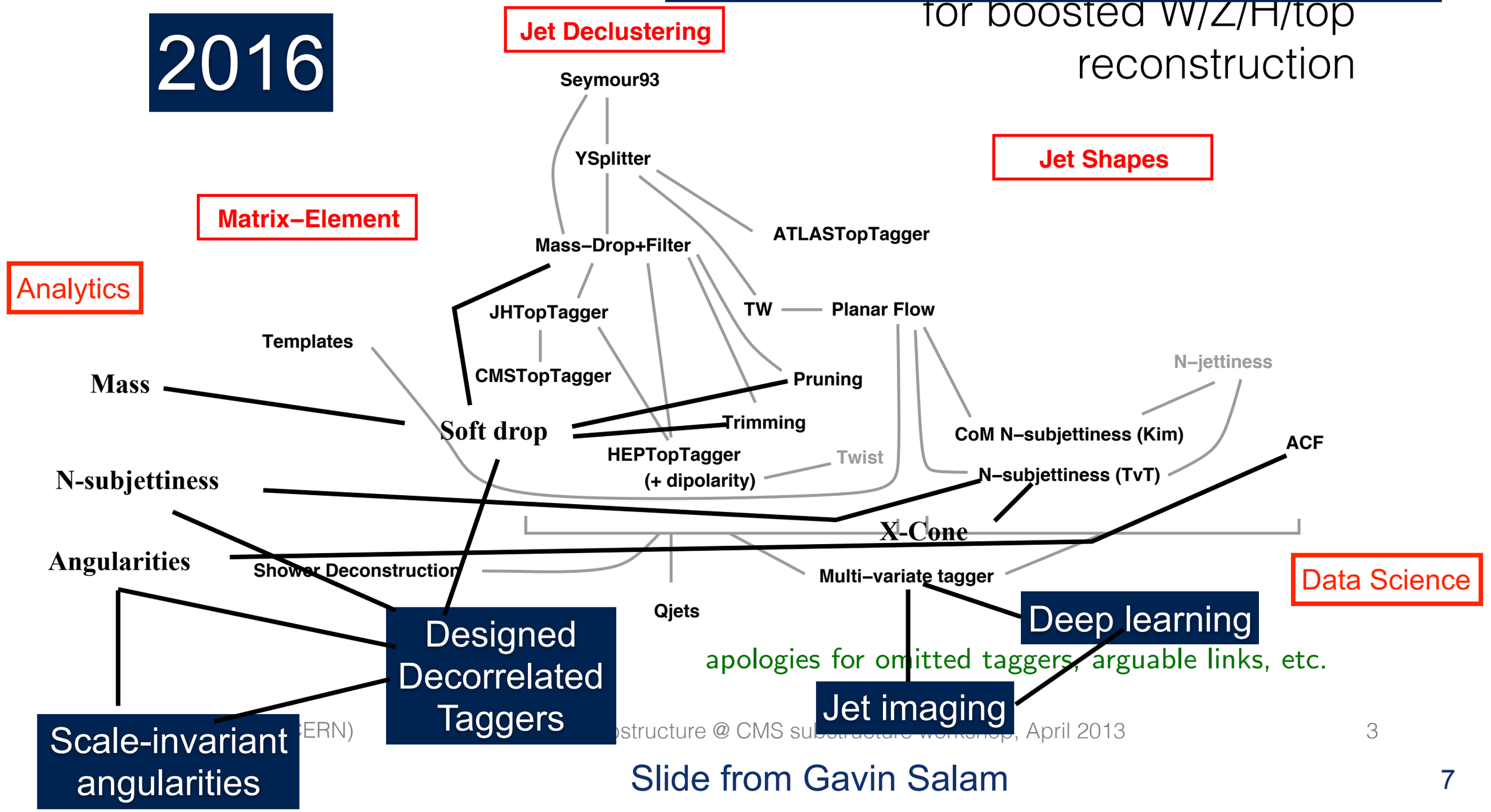
‘Bout That Boost

Very active research field

And growing still!

for boosted W/Z/H/top reconstruction

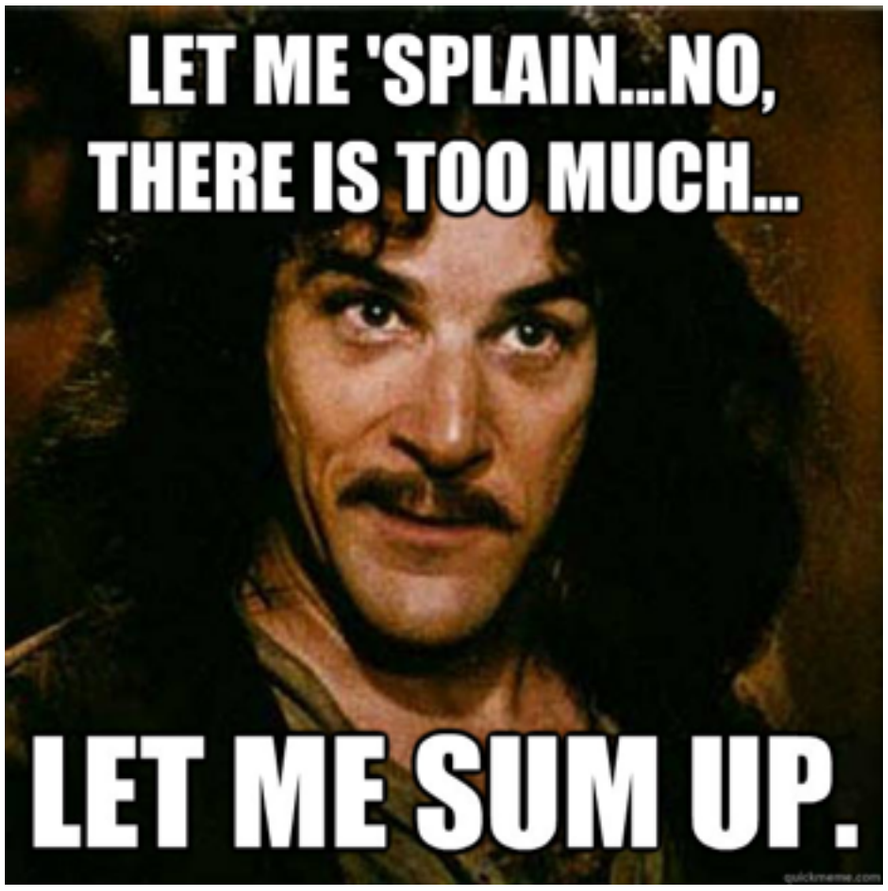
2016



apologies for omitted taggers, arguable links, etc.

Slide from Gavin Salam

All About That Pileup



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- Ellis, Vermilion, Walsh, Phys. Rev. D 80 (2009) 051501
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- CMS-PFT-10-002
- CMS-JME-13-005
- CMS-JME-14-001
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- Cacciari, Salam, Soyez, CERN-PH-TH-2014-052
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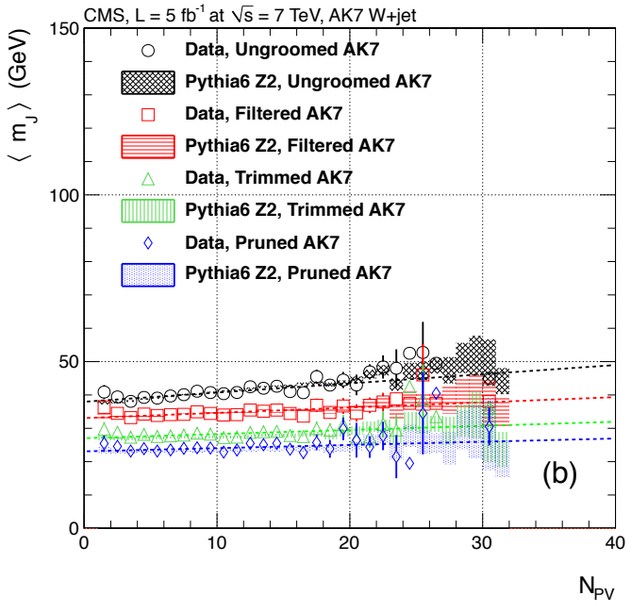
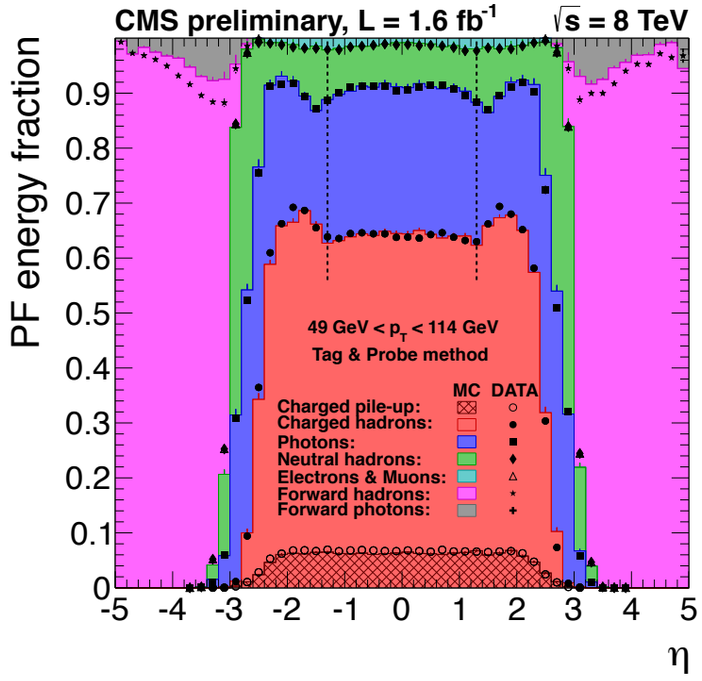
- Cacciari, Salam, Soyez, Eur.Phys.J. C75 (2015) 59

‘Bout That Pileup

- Run 1 : Set the baseline



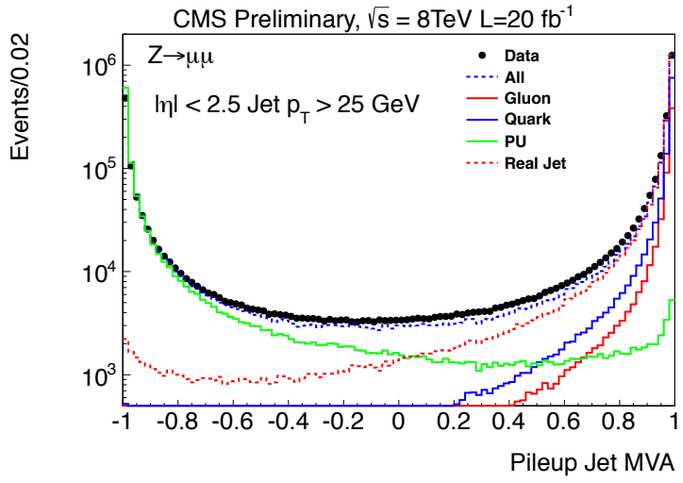


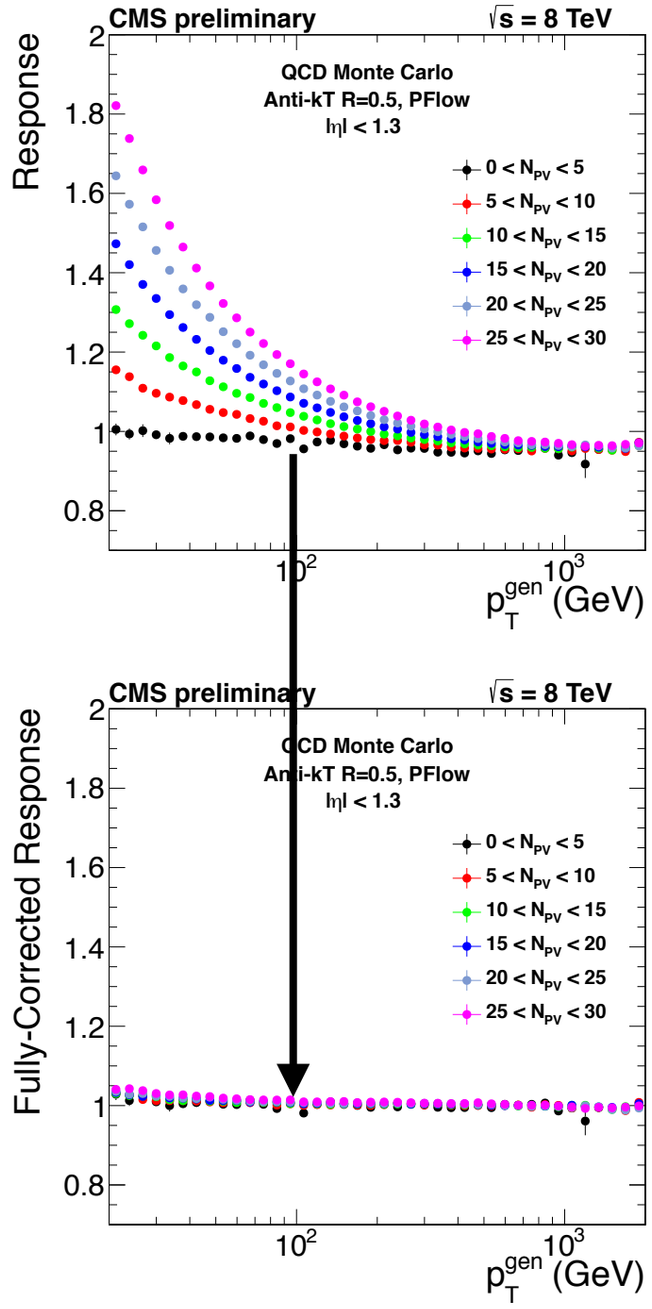
Grooming

Removal of PU tracks (CHS, JVF)

$\rho \times A$

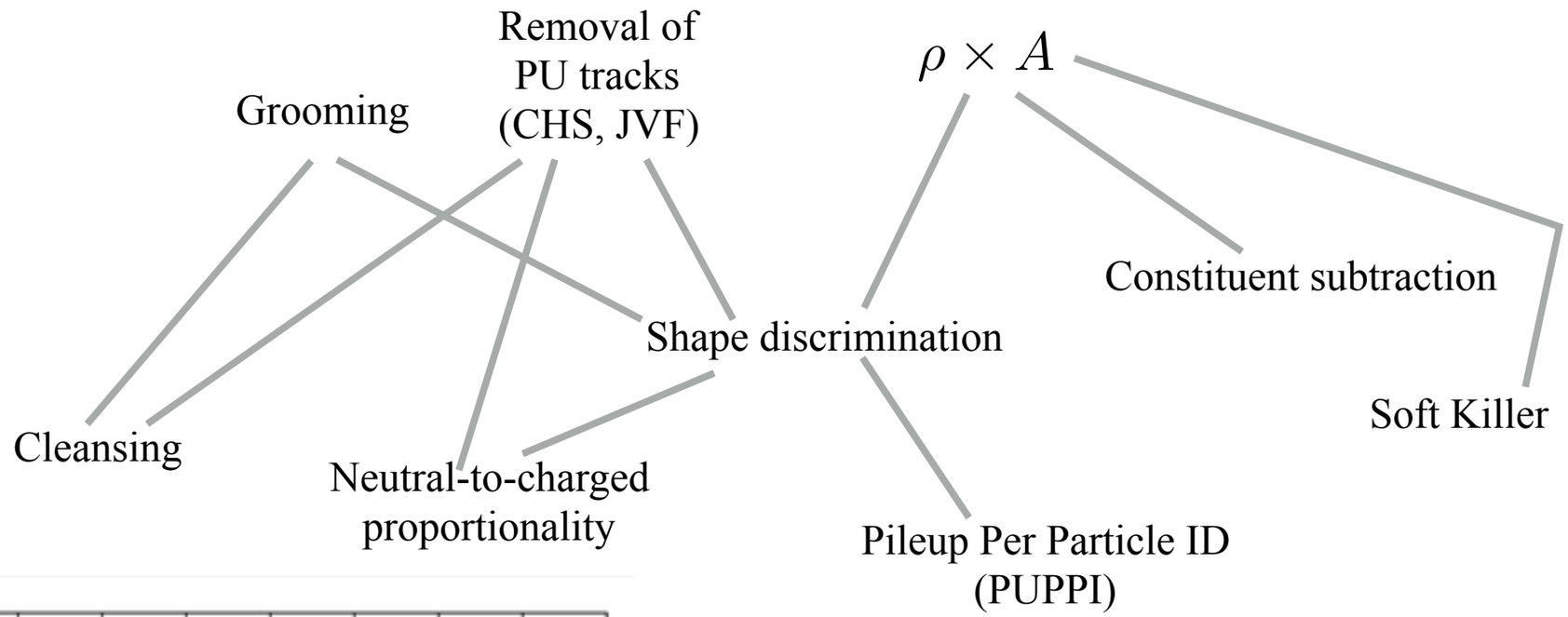
Shape discrimination

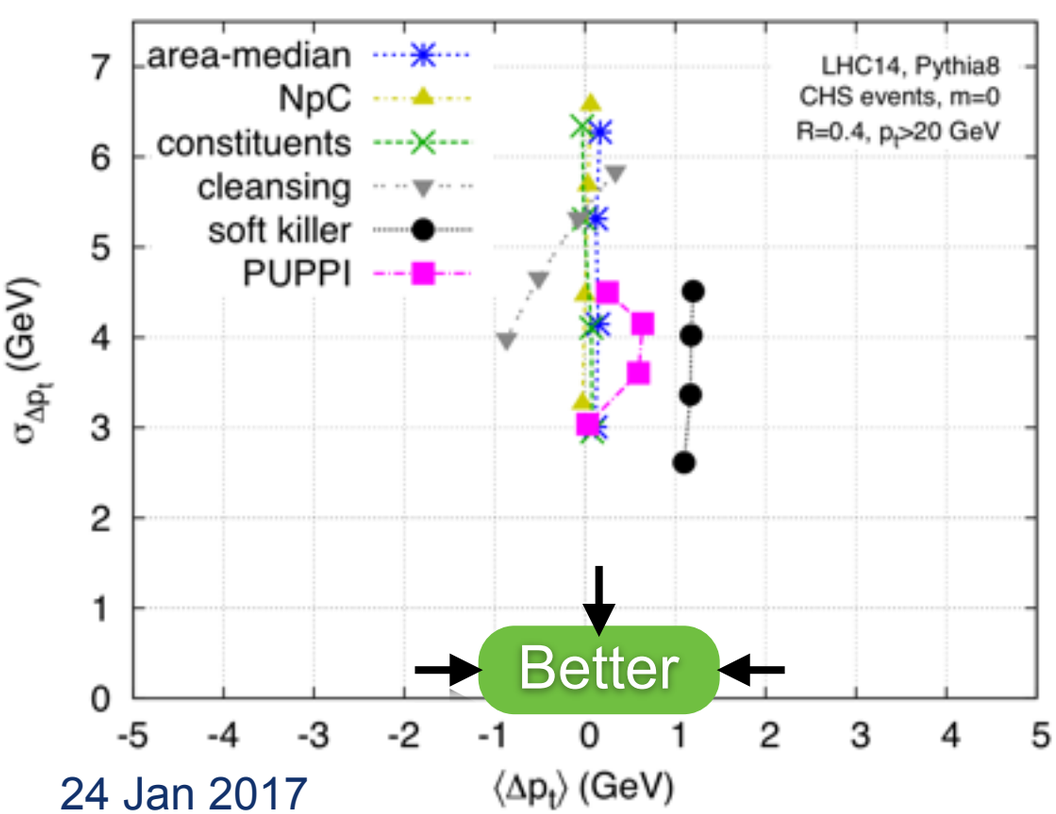




‘Bout That Pileup

- Run 2 : Kick it up a notch





From pileup mitigation workshop at CERN

Pre-LHC

- Experiment:
  - Relatively unsophisticated (cone algorithms and offset corrections) compared to today's technologies
  - "Get jets. Pileup bad."

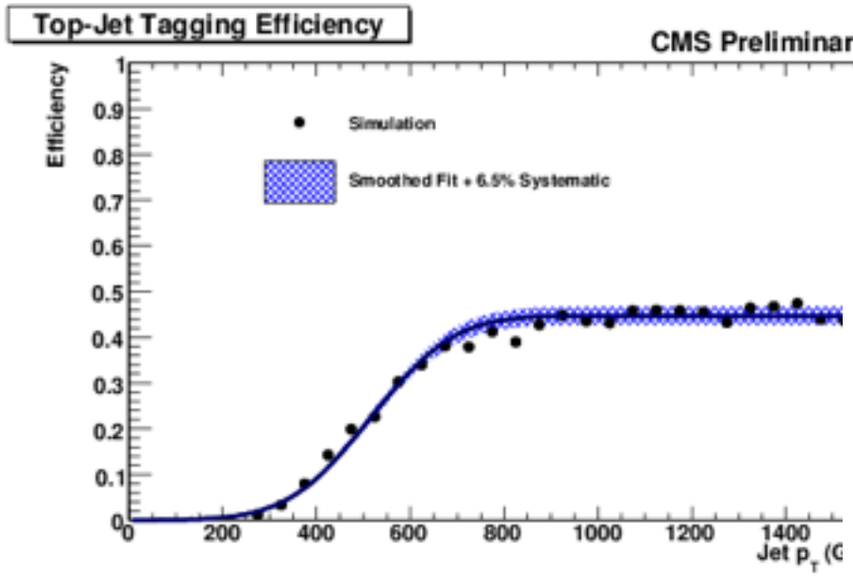
(I jest about jets before LHC, of course… many nice results!)

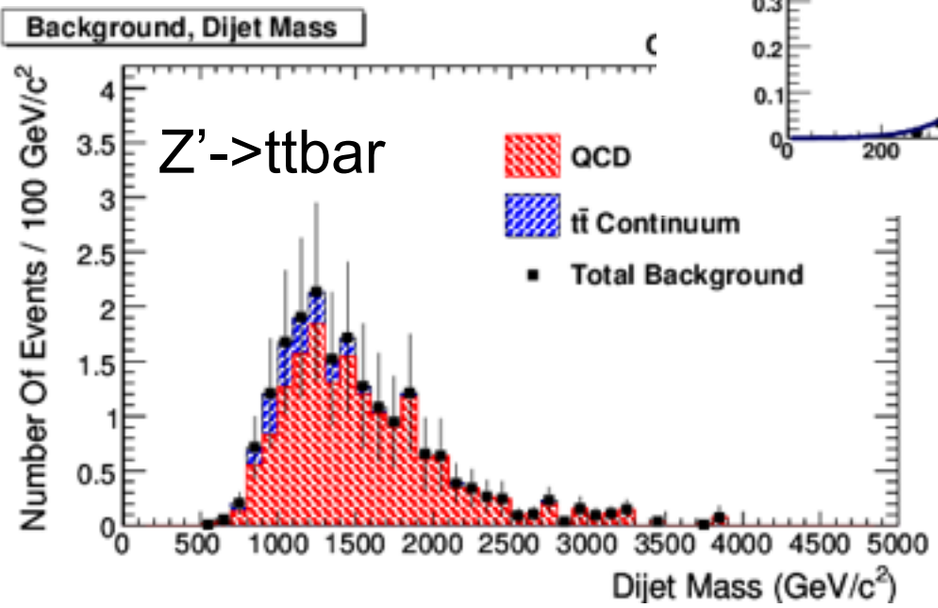
- Theory: See Steve's talk, Tilman's Talk

History : 2009

Tagging, Substructure, and Algos

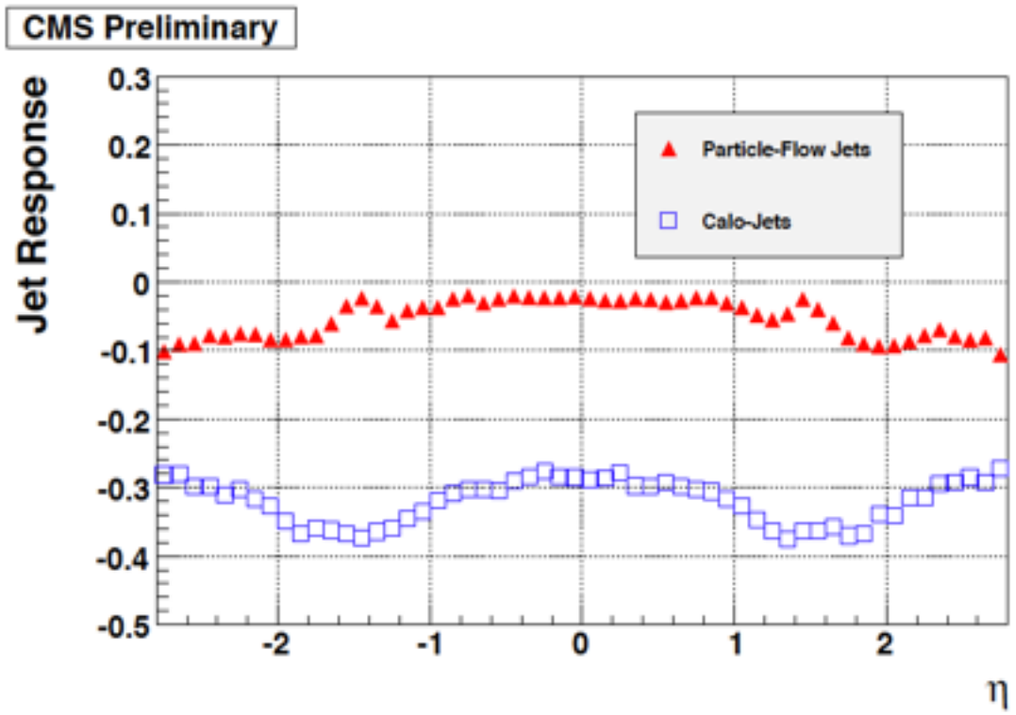
- Anti-kt investigated
- Top tagging :
  - CMS/JHU top tagger (EXO-09-006, JME-09-001)





Pileup Mitigation

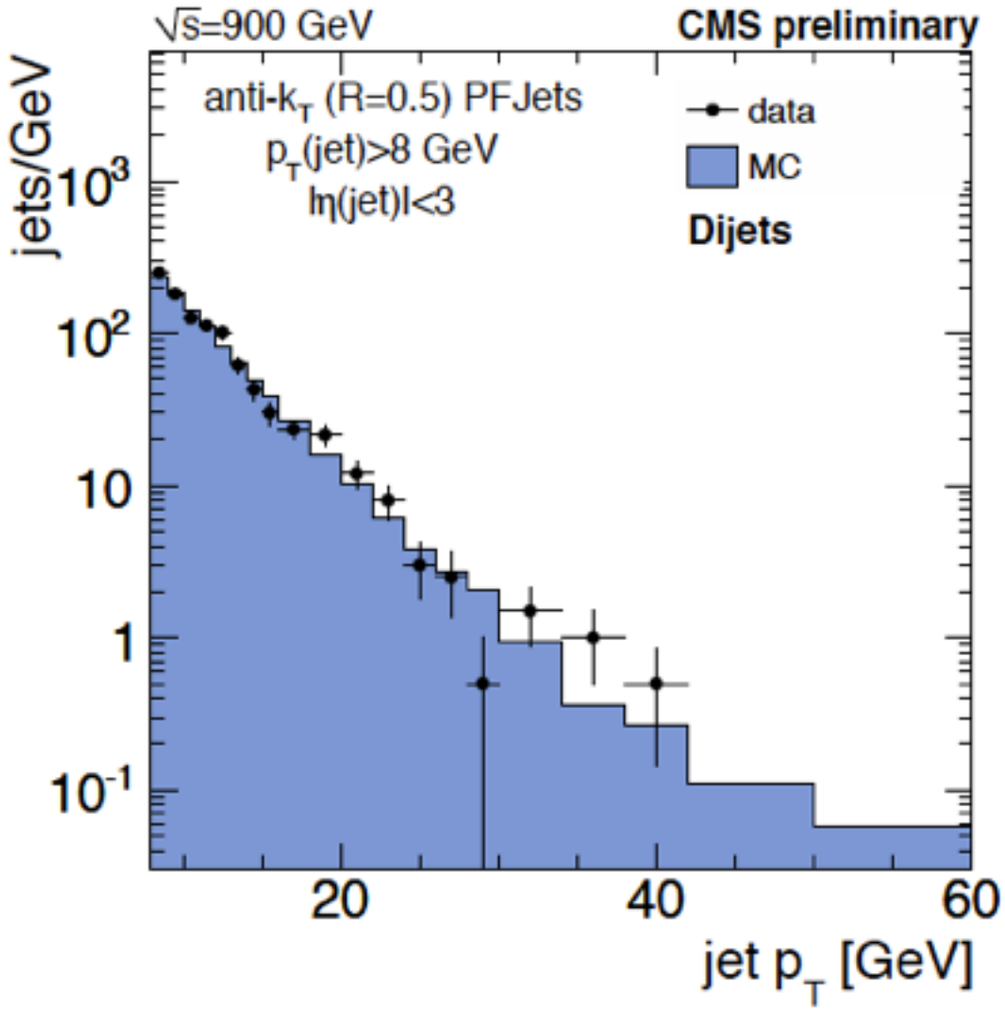
- "Offset" correction on iterative cone jets (JME-09-003)
- Particle flow document released (PFT-09-001)



History : 2010

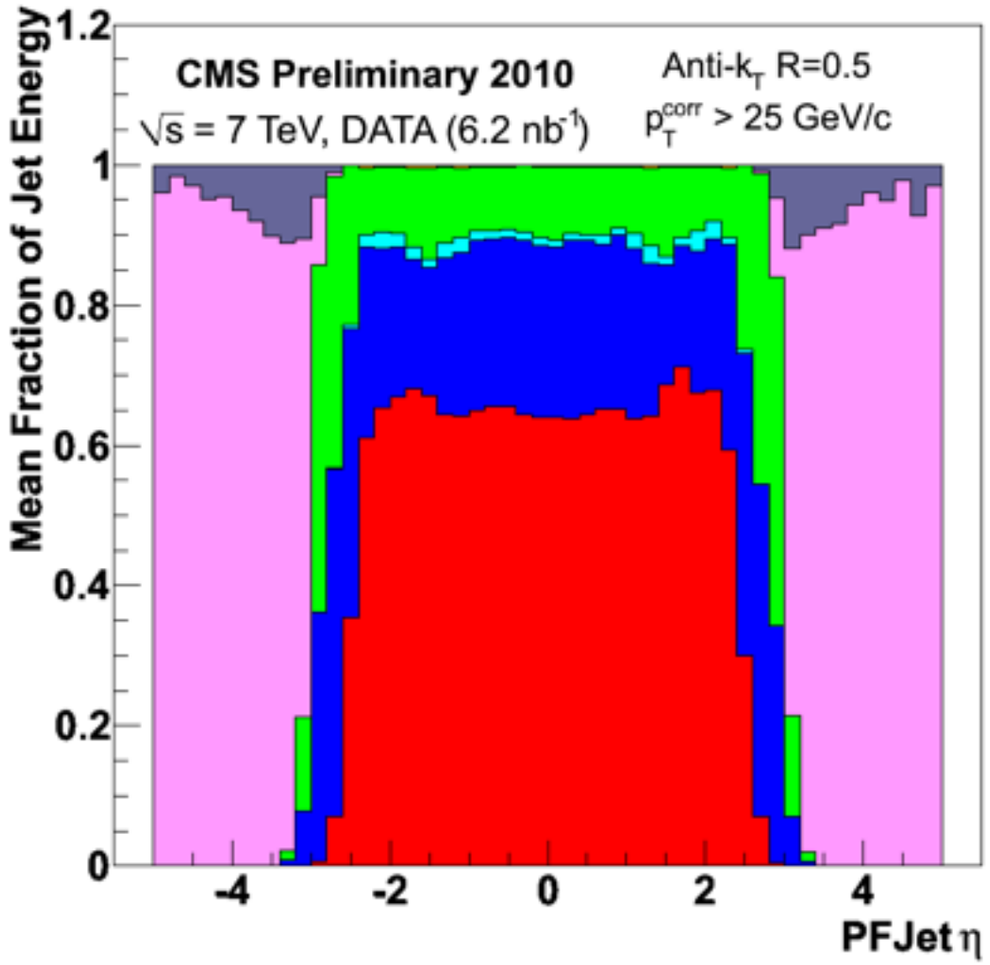
Tagging, Substructure, and Algos

- Anti-kT adopted, data commissioning (JME-10-001)



Pileup Mitigation

- Particle flow data commissioning (PFT-10-001, JME-10-001)
- Median pt / area method first tried (QCD-10-005)



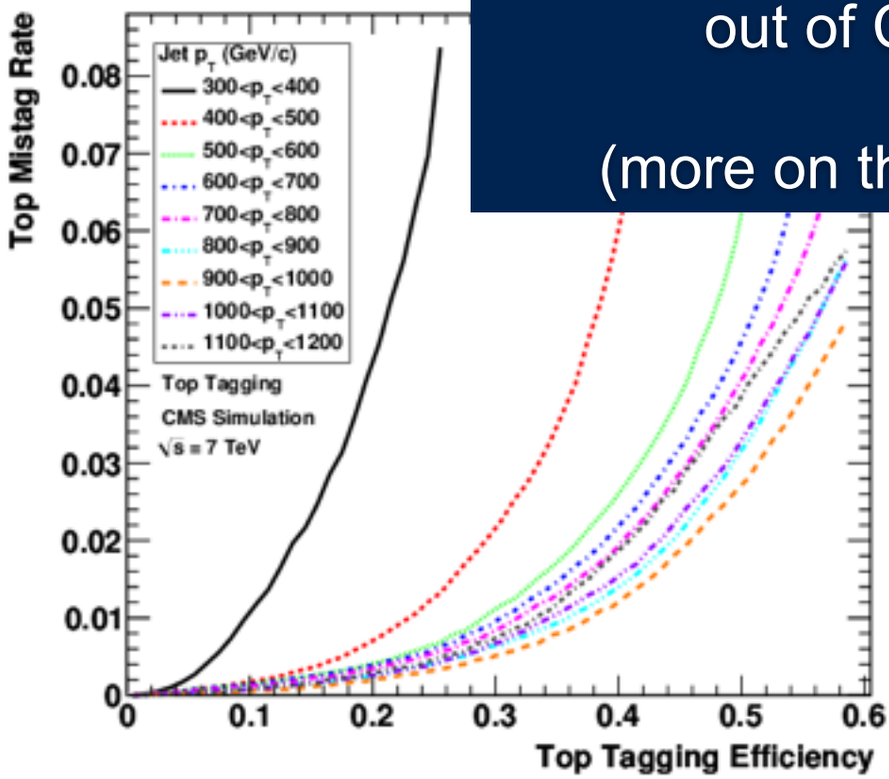
History : 2011

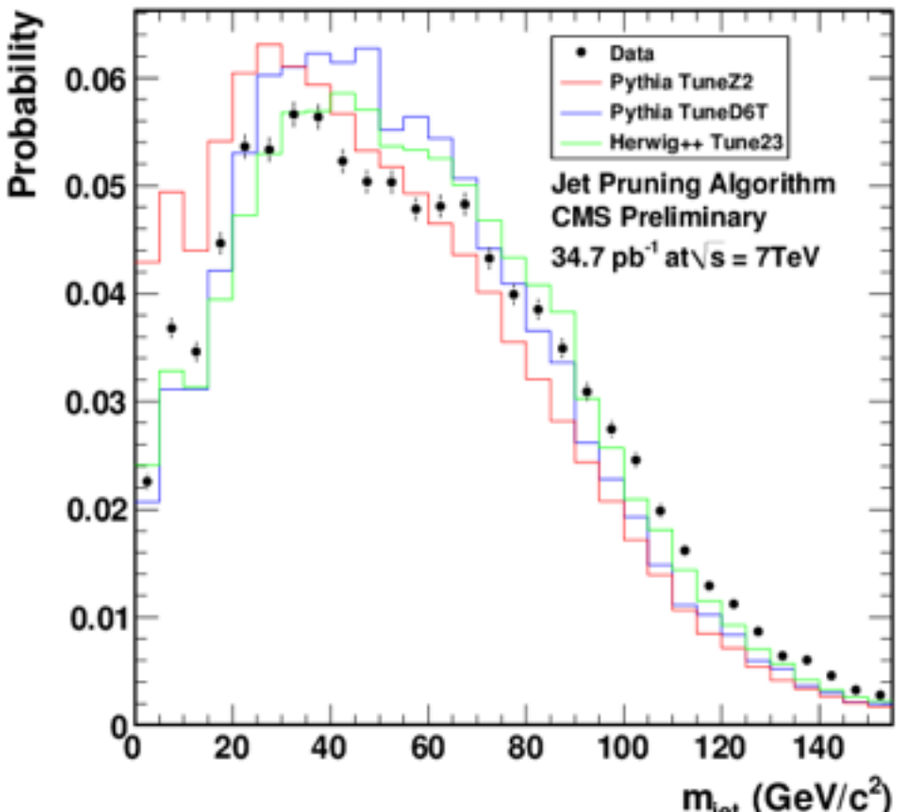
Tagging, Substructure, and Algos

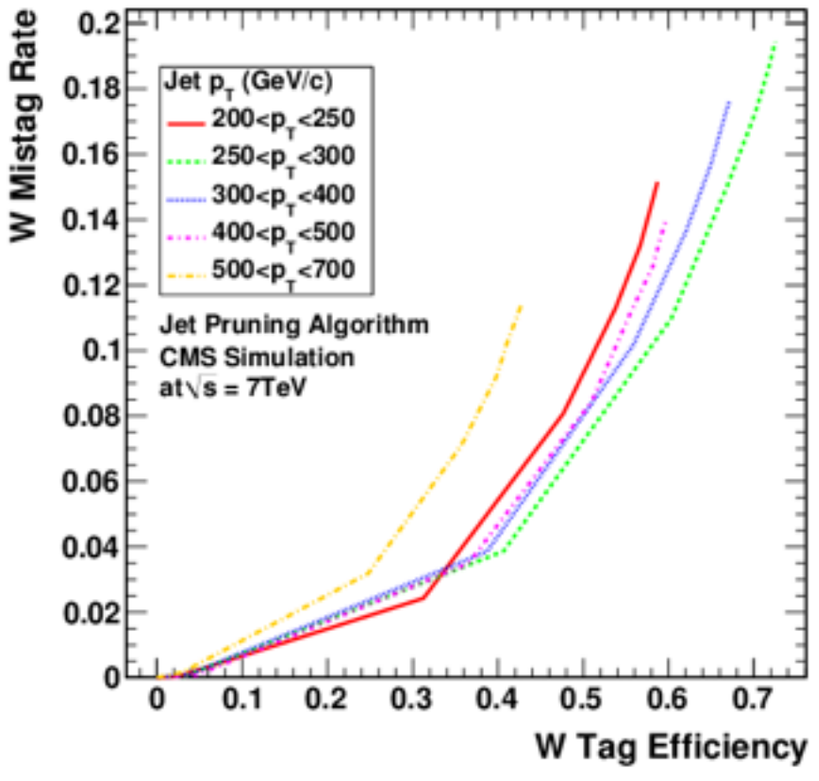
First of a nauseating stream of ROC curves coming out of CMS

(more on that later)

- Top and W tagging fully developed, commissioned in data(JME-10-013)
  - Top tagger : still CMS/JHU tagger
  - W tagger: jet pruning

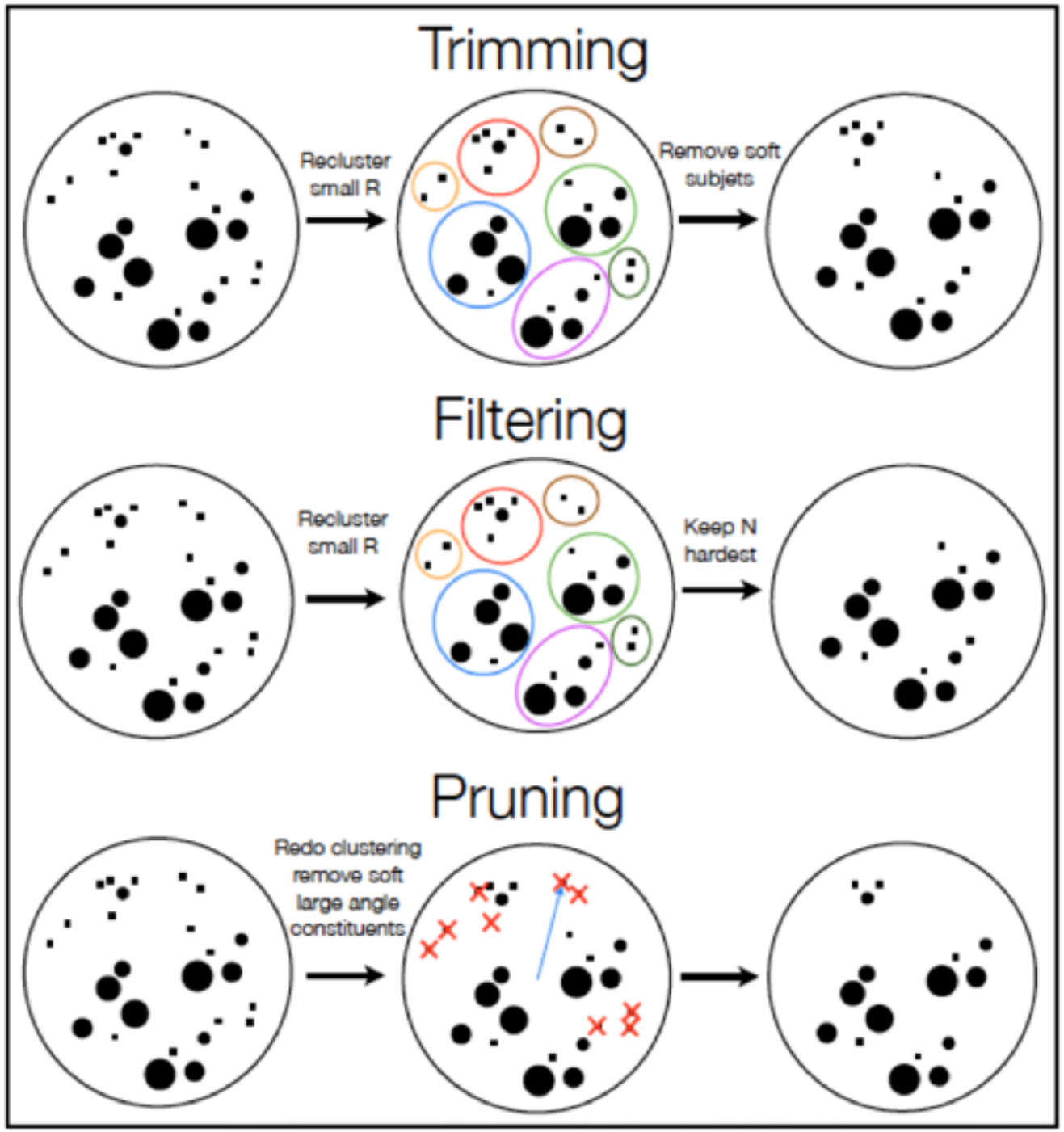






History : 2011

Grooming



CA
rfilt = 0.2
pt frac = 0.03

KT
rfilt = 0.3
nfilt = 3

CA
zcut = 0.1
alpha=0.5

J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam, Phys. Rev. Lett. 100 (2008) 242001

S. D. Ellis, C. K. Vermilion and J. R. Walsh, Phys. Rev. D 81 (2010) 094023

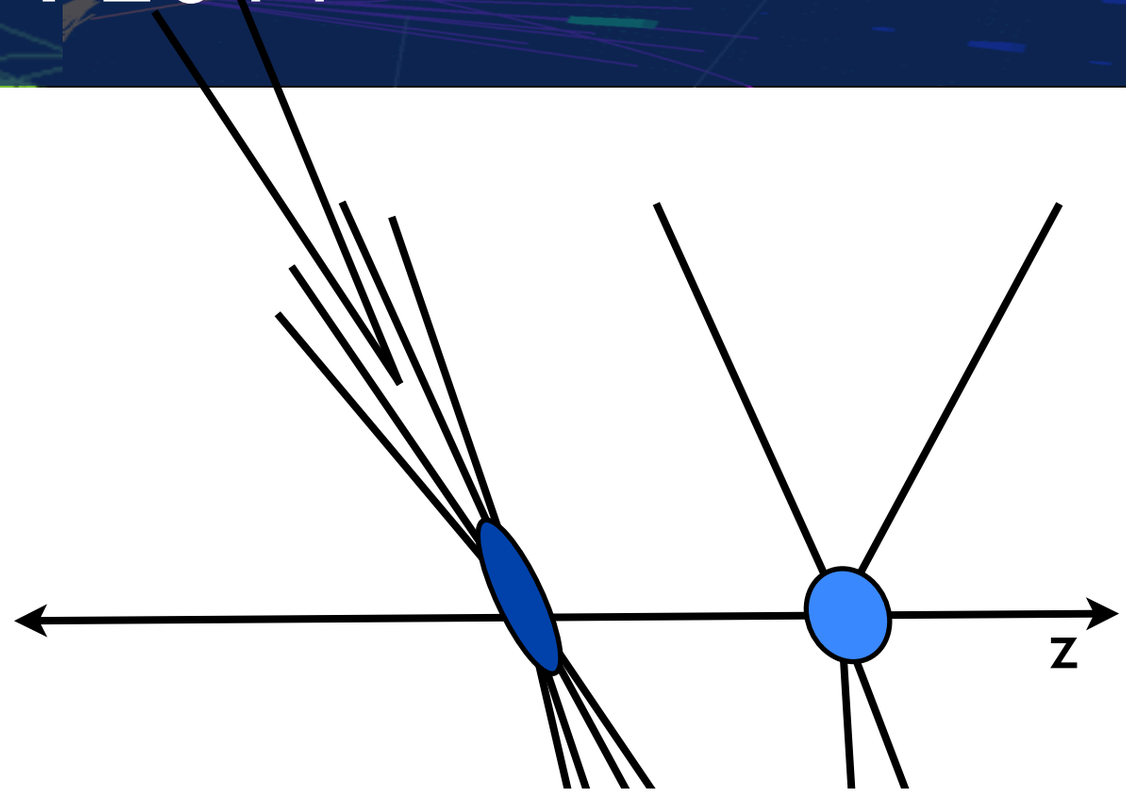
S. D. Ellis, C. K. Vermilion and J. R. Walsh, Phys. Rev. D 80 (2009) 051501

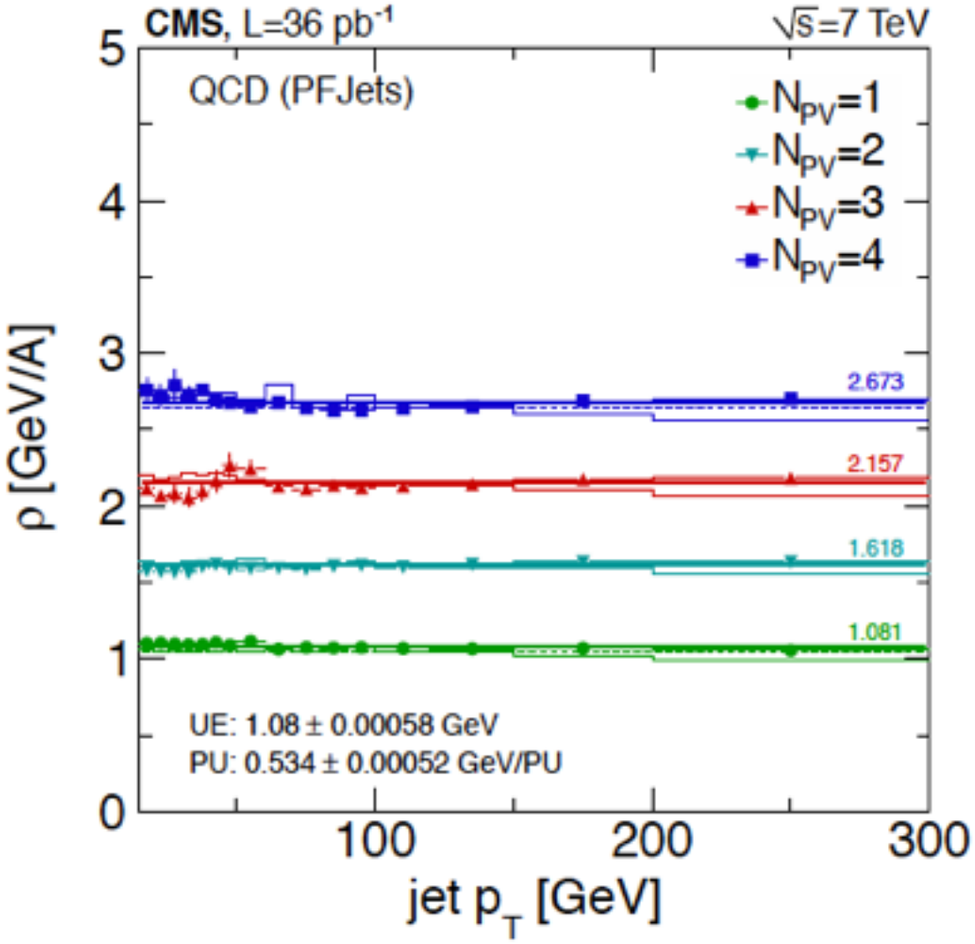
D. Krohn, J. Thaler and L. -T. Wang, JHEP 1002 (2010) 084

History : 2011

Pileup Mitigation

- Particle flow fully commissioned
  - Sub-leading PV charged hadrons identified and removed (Charged Hadron Subtraction) deployed
- Jet variables
  - Sub-leading PV charged hadron fraction (β^*)
- Median pt / area method deployed in most analyses
- JINST 6 (2011) 11002 aka JME-10-011

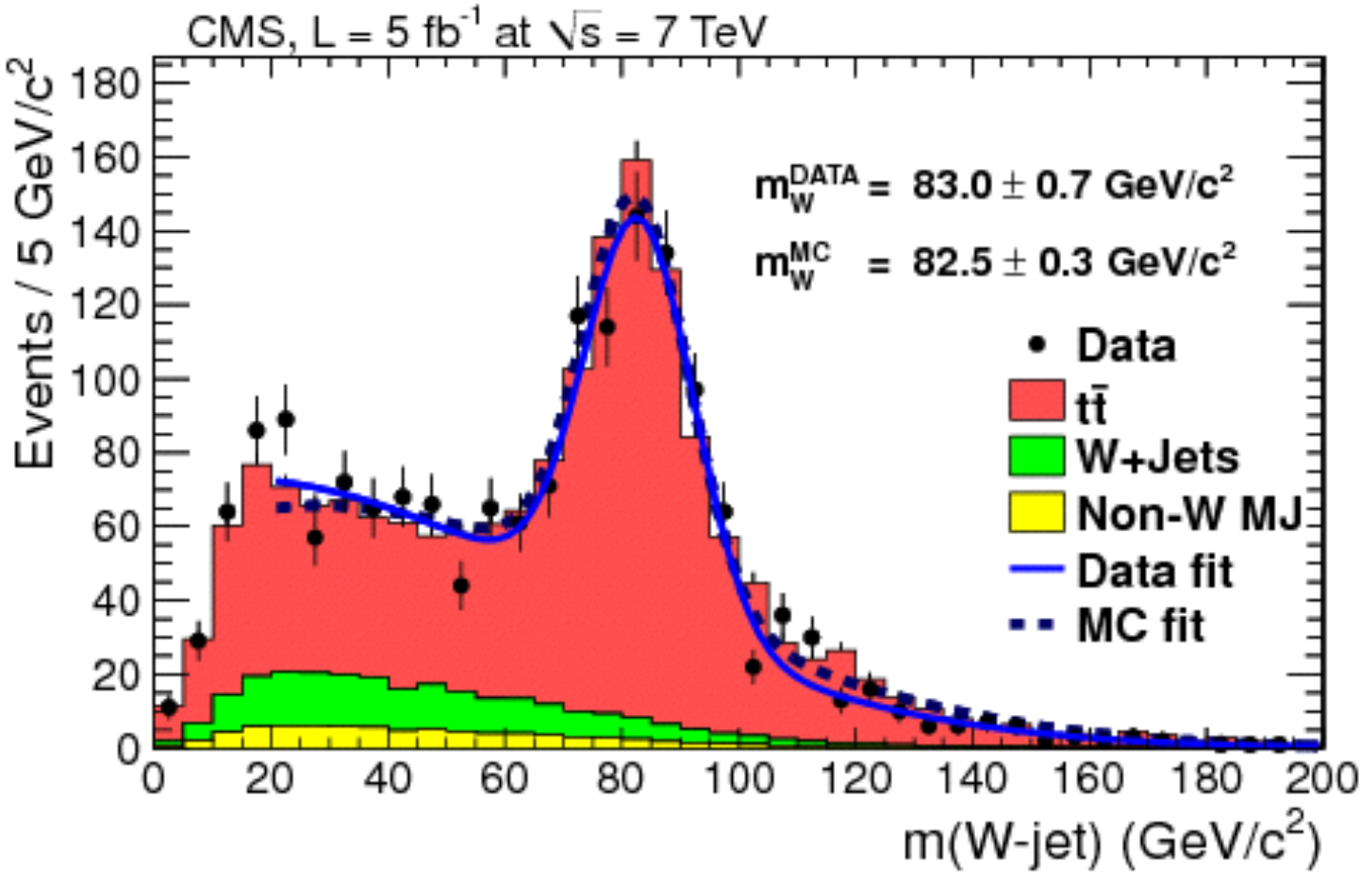




History : 2011

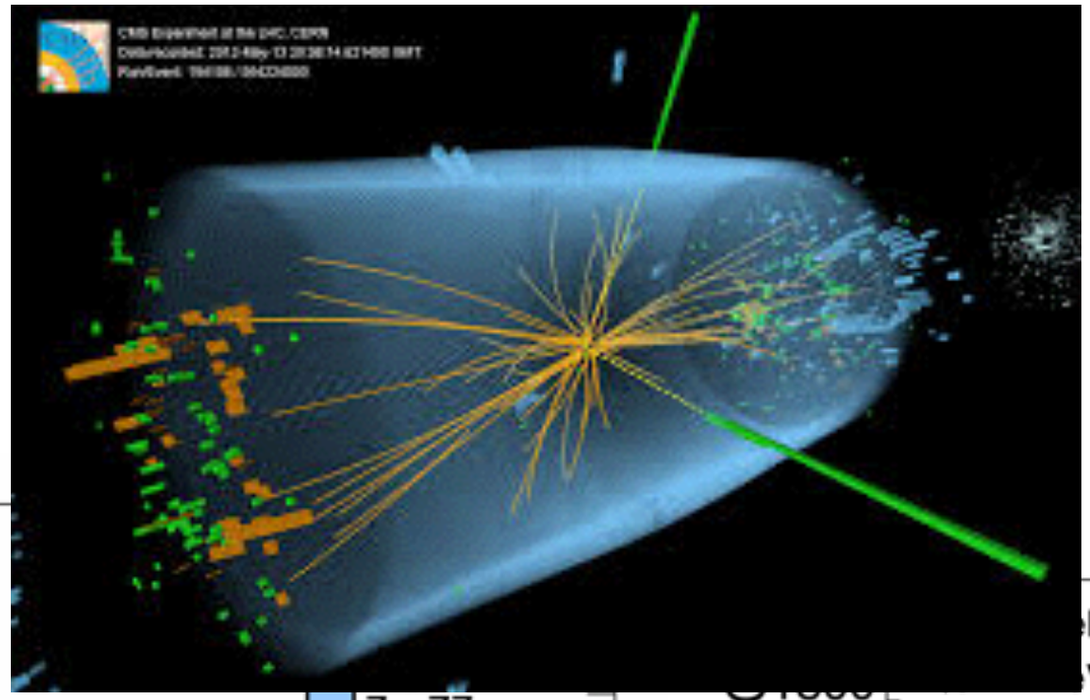
- First publication with substructure at CMS (JHEP 1209 (2012) 029 aka EXO-11-006)

- Made “type 1” (CMS/JHU tagger, fully merged) and “type 2” taggers (pruning based, W merged), CHS, with area-based pileup correction



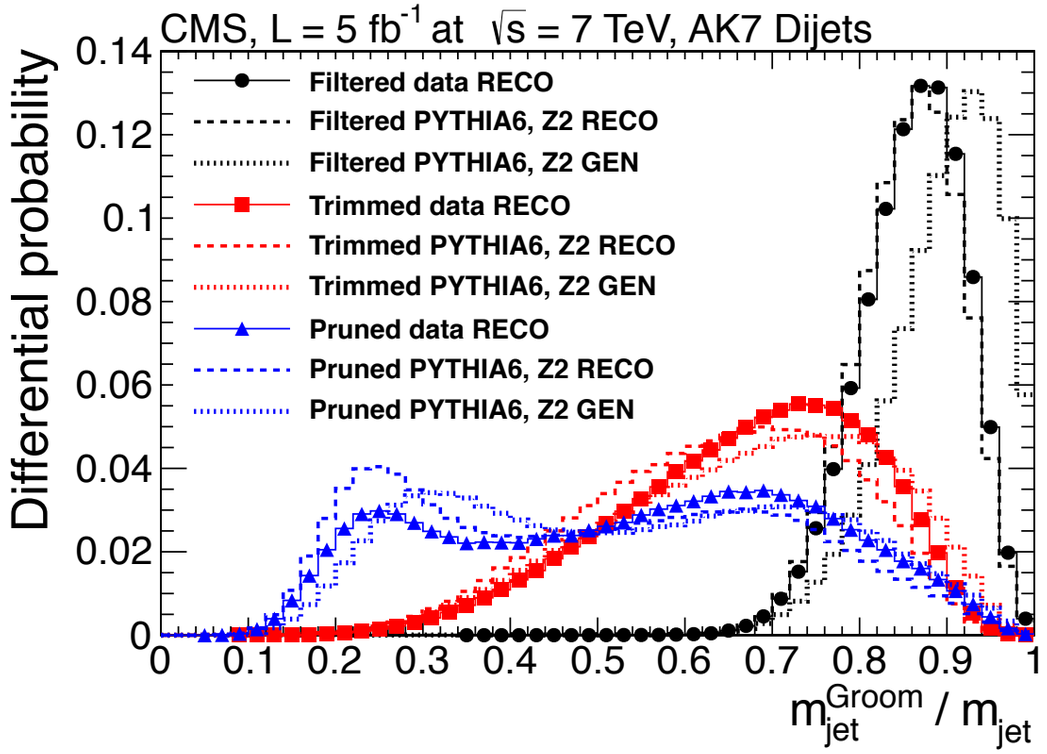
History : 2012

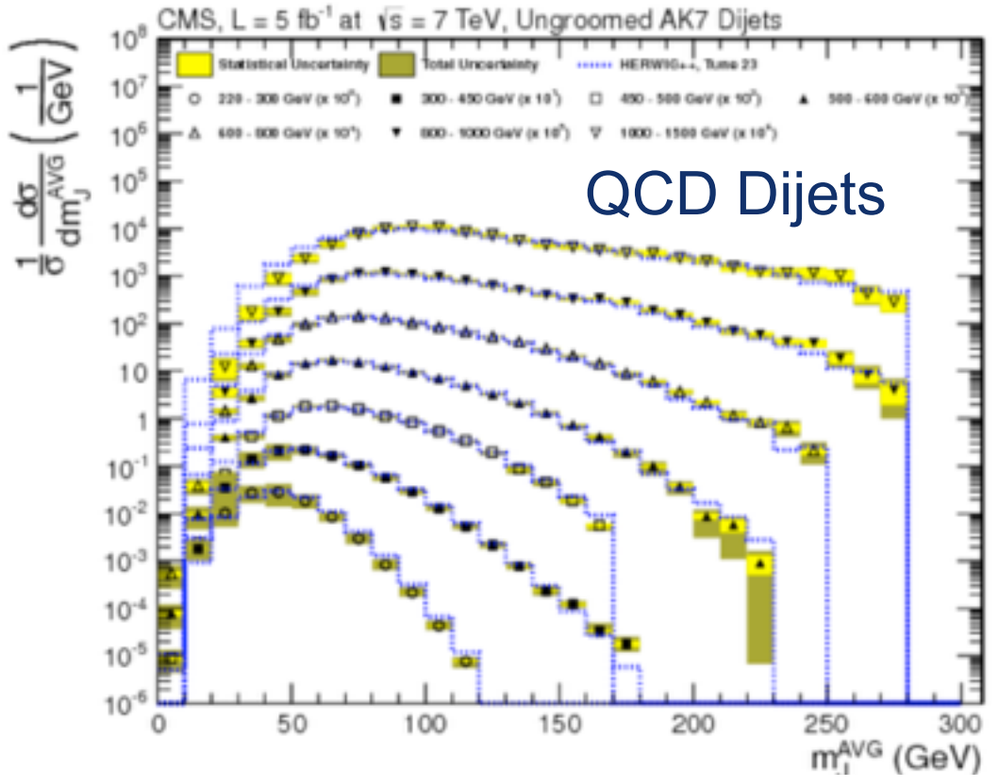
- And oh yeah…

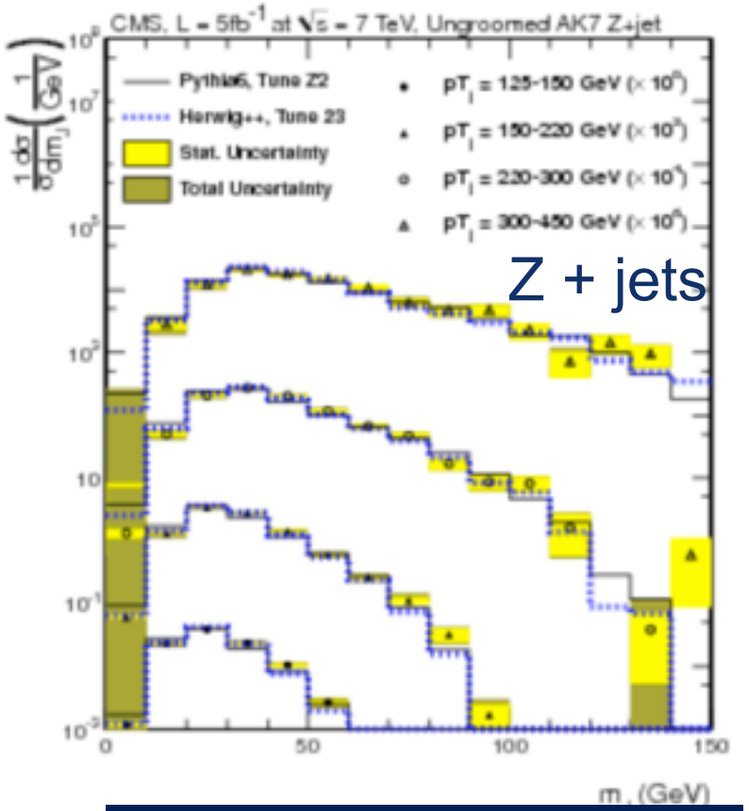


History : 2012

- Jet mass measured at CMS
  - Measured pruned, trimmed, filtered jets







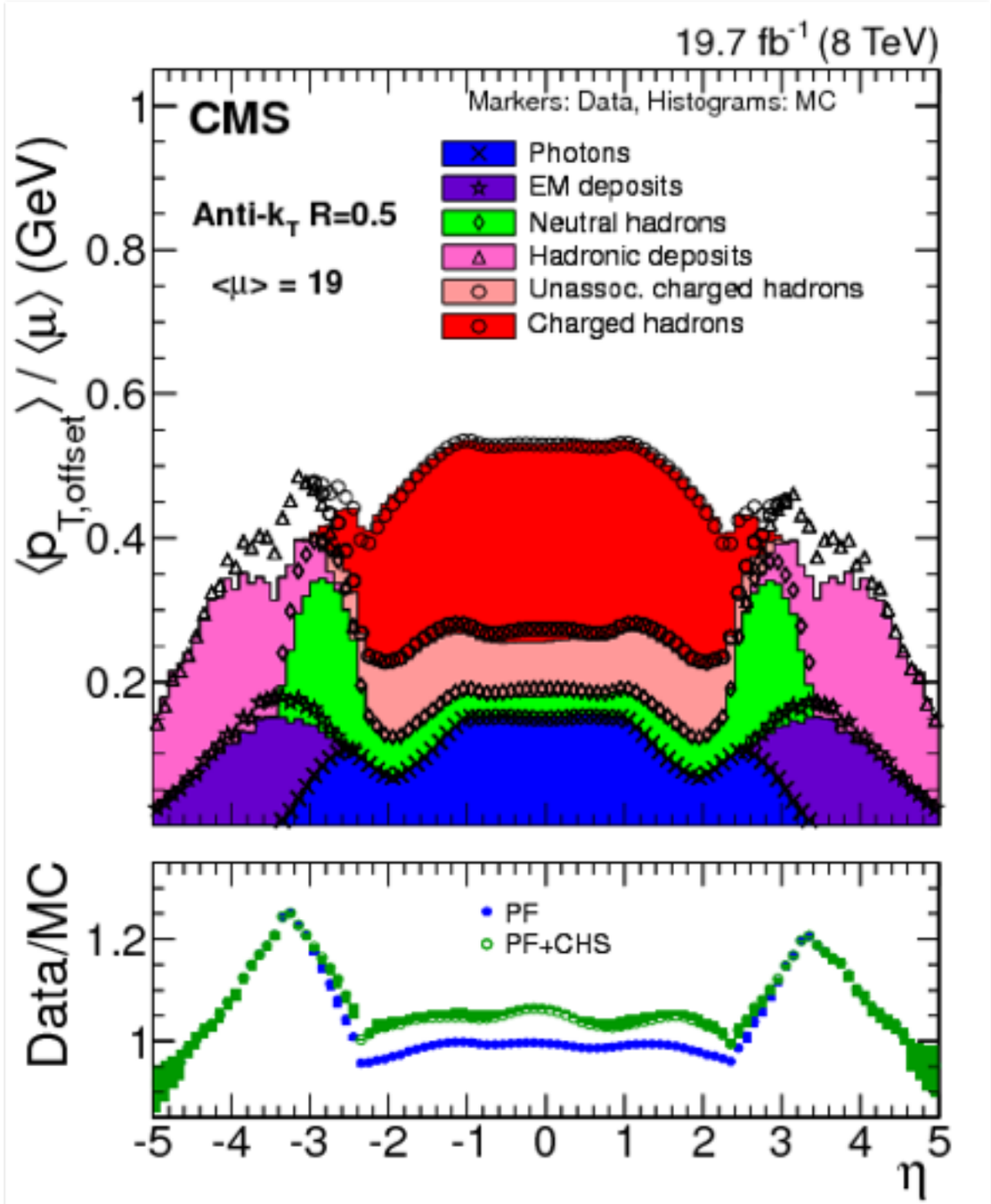
Overall good agreement with MC, but no analytic prediction! (more on that later)

JHEP 1305 (2013) 090

History : 2012

Pileup Mitigation

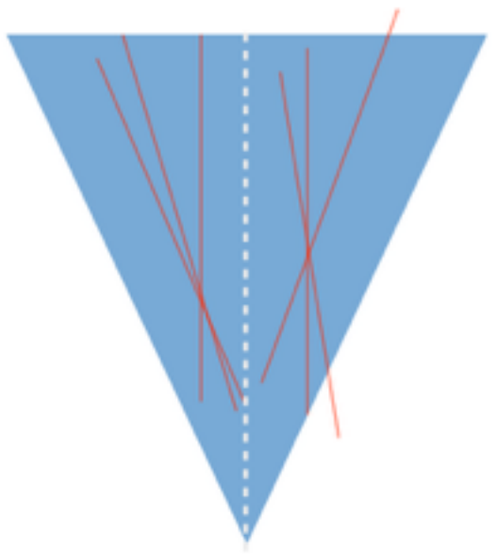
- Final Jet calibrations and corrections, include CHS and pt/area methods

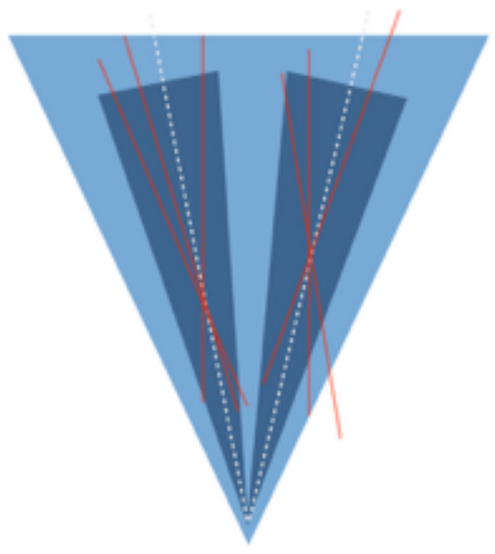


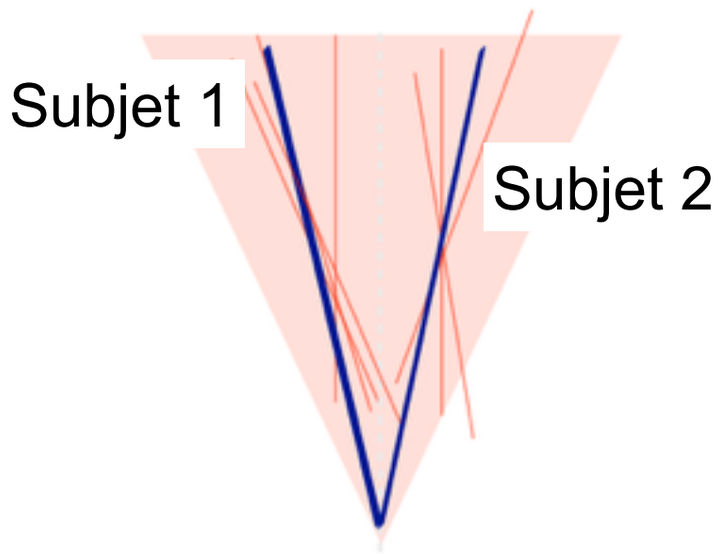
Final Run 1 paper not submitted until 2016

History : 2012

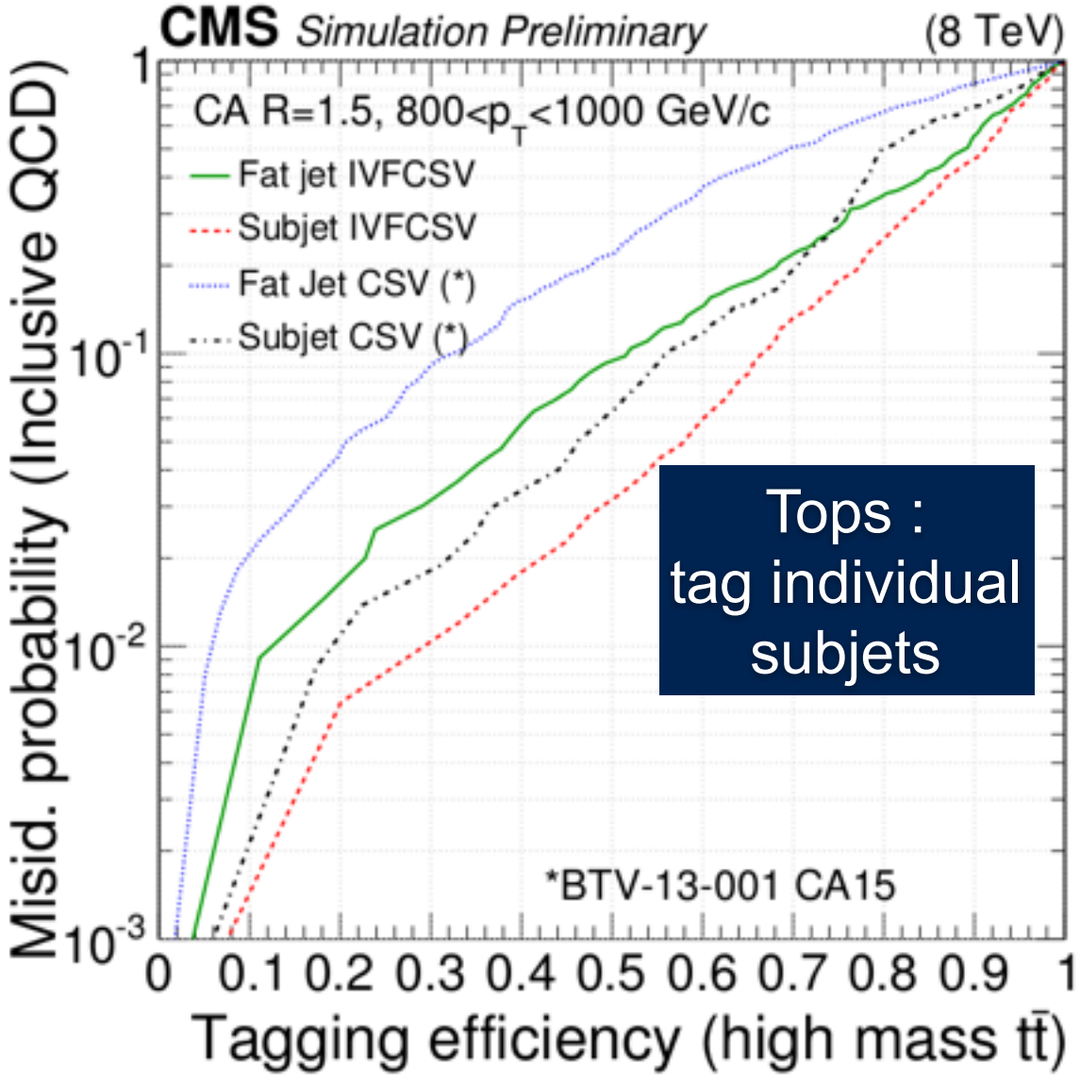
- B-tagging in Boosted Topologies : BTV-13-001
- Approaches :
  - tagging individual subjets : “Subjet CSV”
    - Combined Secondary Vertex tagger on subjets
  - tagging two b-subjets nearby (H->bb) : “Subjet IVF”
    - Iterative Vertex Finder for nearby b-subjets

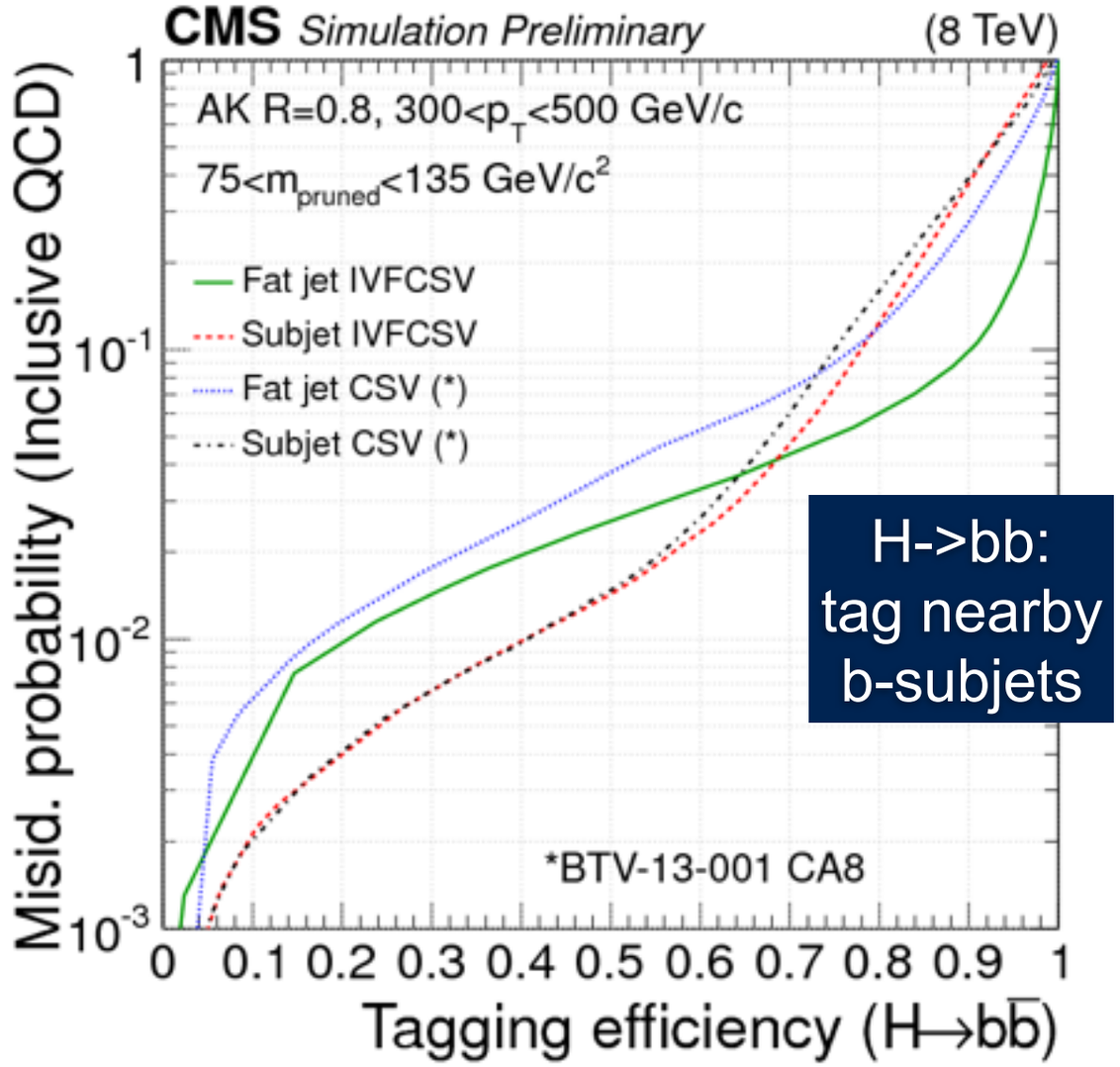






History : 2012

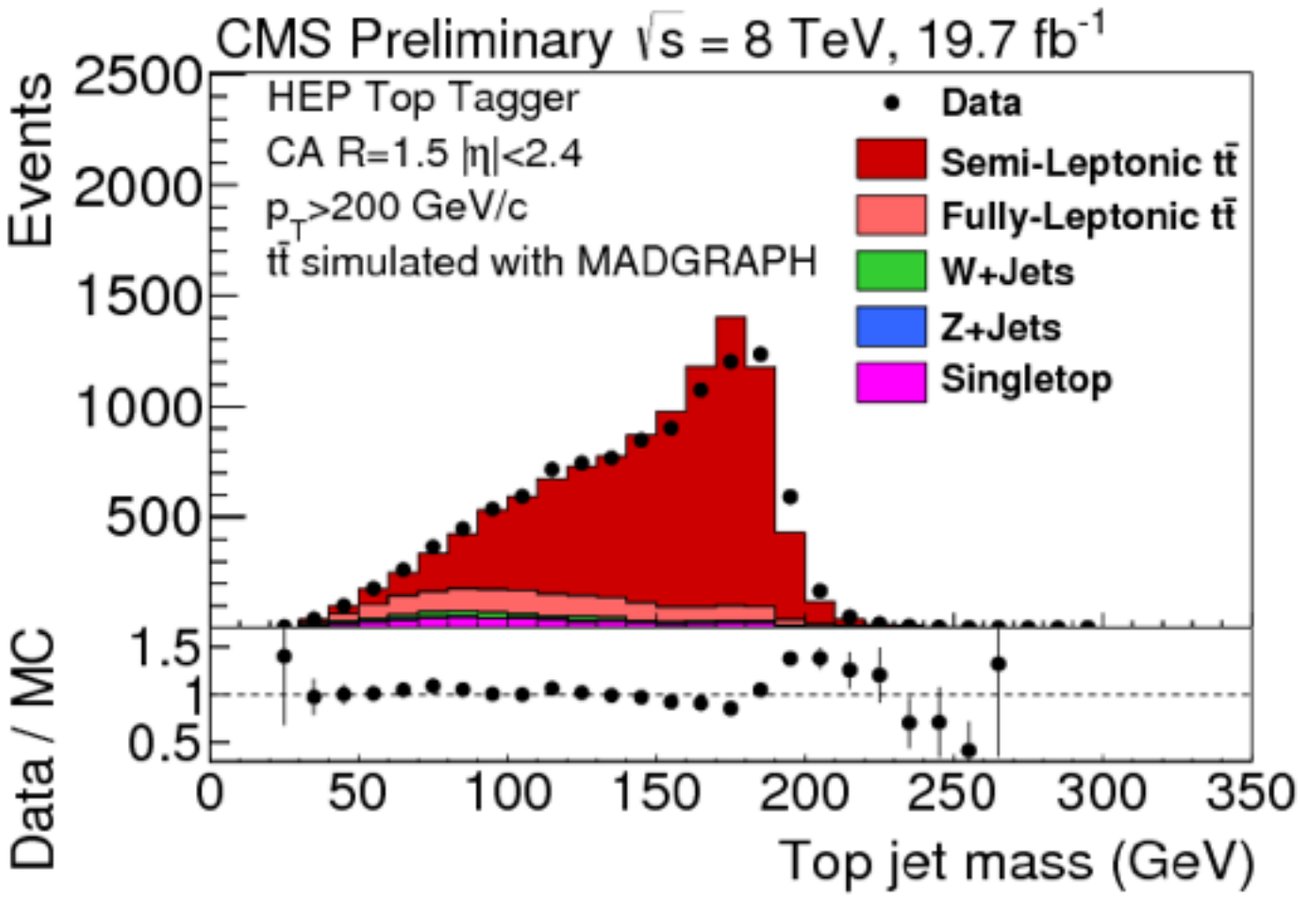


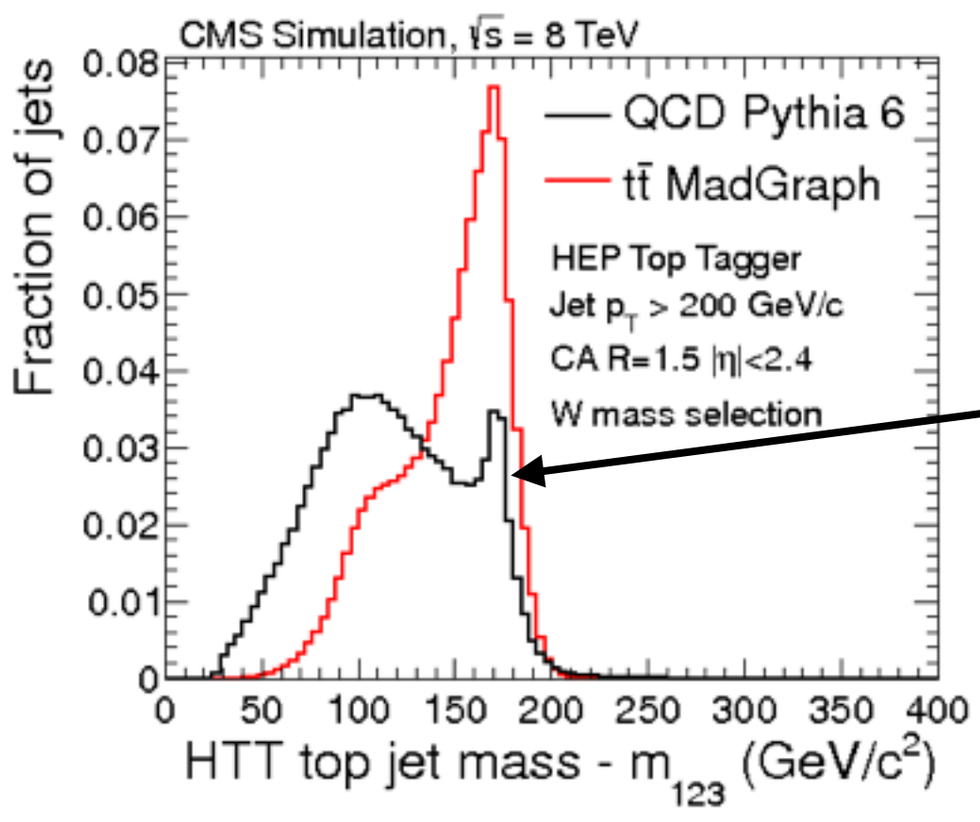


History : 2013

Tagging, Substructure, and Algos

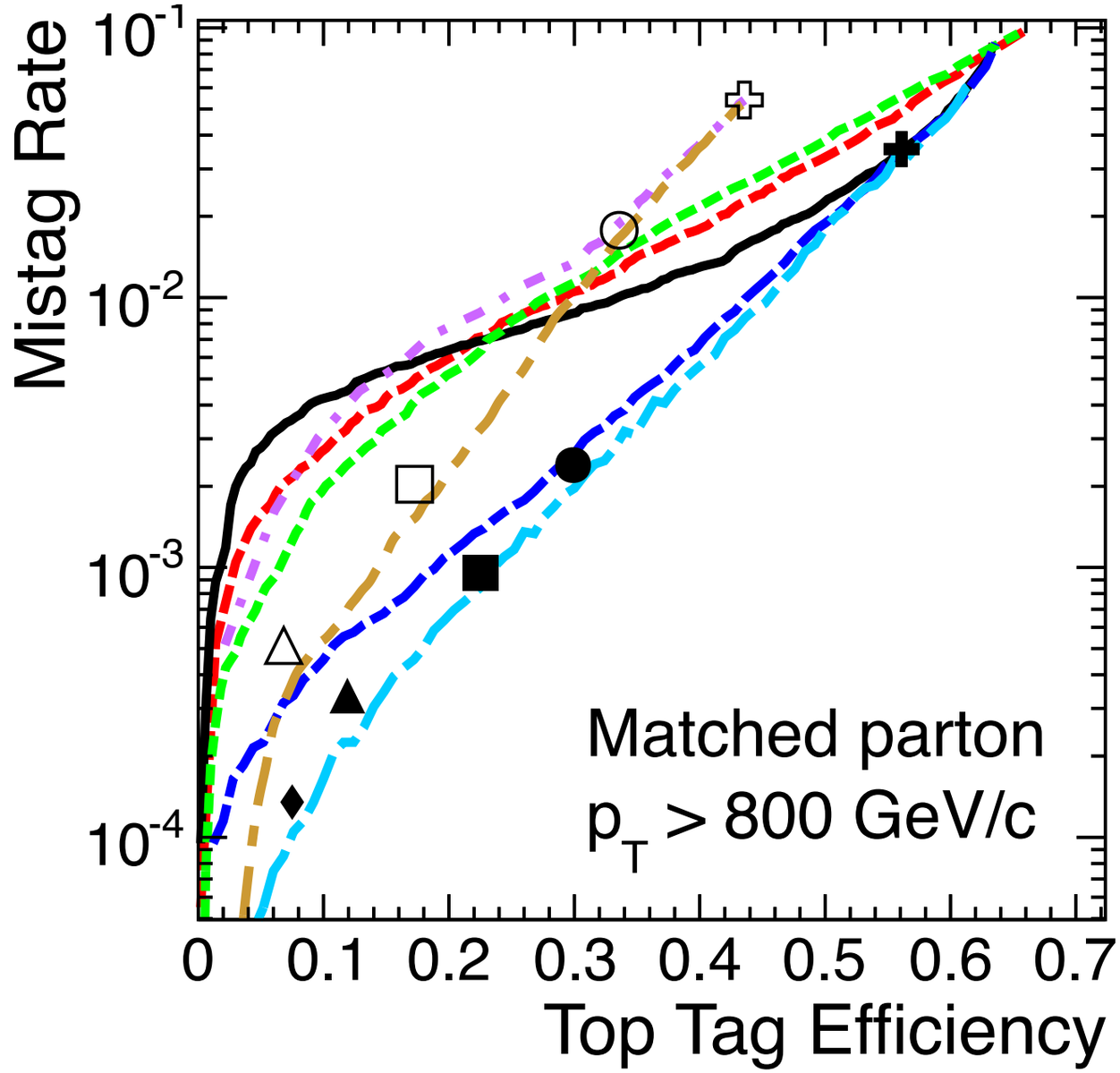
- Top Tagging:
  - HEPTopTagger (v1)
  - Updated CMS top tagger including n-subjettiness
  - Both add subjet b-tagging





Hmmm… what's that thingy?
More later.

History : 2013

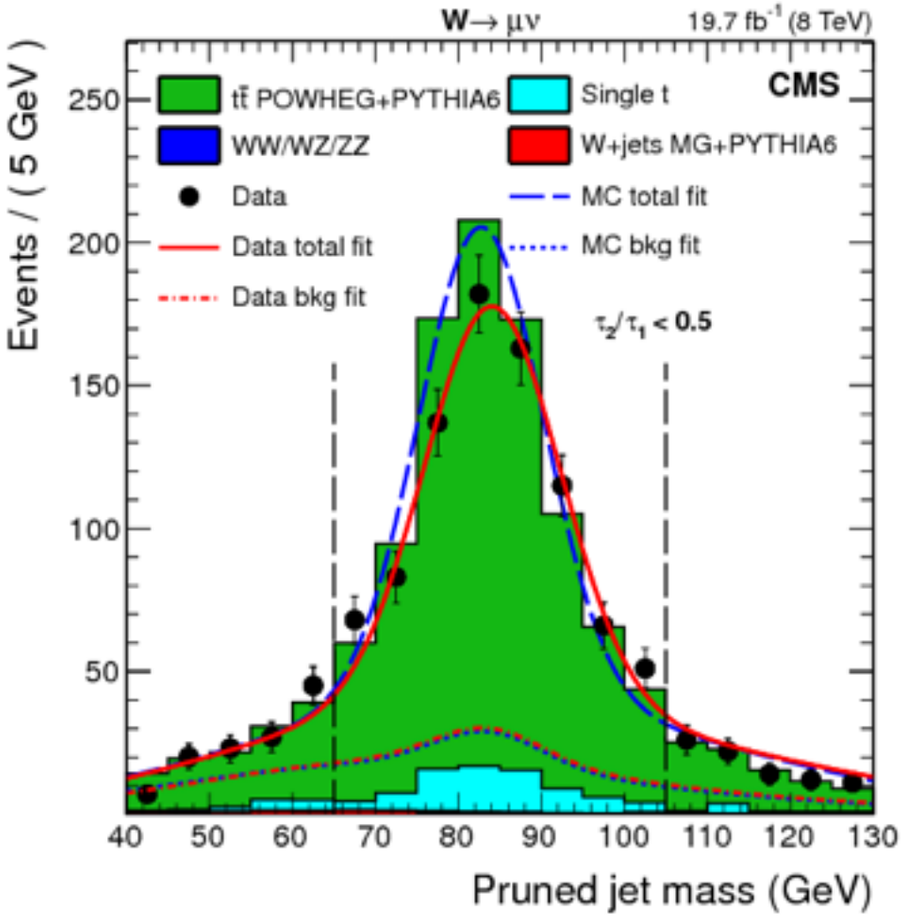


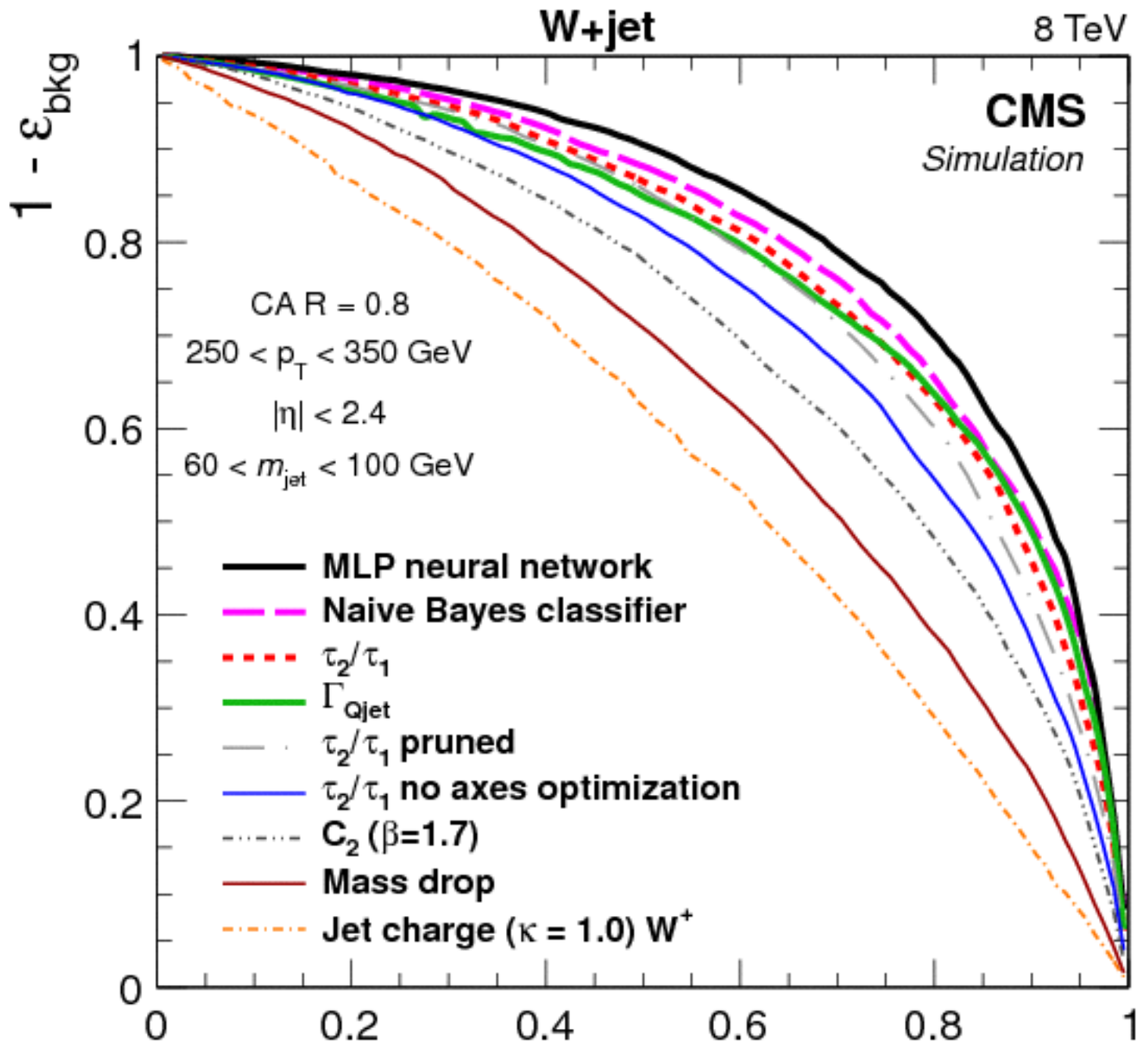
- CMS Top Tagger
- subjet b-tag
- N-subjettiness ratio τ_3/τ_2
- CMS + subjet b-tag
- CMS + τ_3/τ_2 + subjet b-tag
- HEP Top Tagger
- HEP + τ_3/τ_2 + subjet b-tag

CMS WP0	HEP WP0
CMS Comb. WP1	HEP Comb. WP1
CMS Comb. WP2	HEP Comb. WP2
CMS Comb. WP3	HEP Comb. WP3
CMS Comb. WP4	

History : 2013

- W tagging : JHEP 1412 (2014) 017 aka JME-13-006
  - Lots studied
  - Baseline : Pruning + n-subjettiness
  - Best single variable : Q-jets volatility



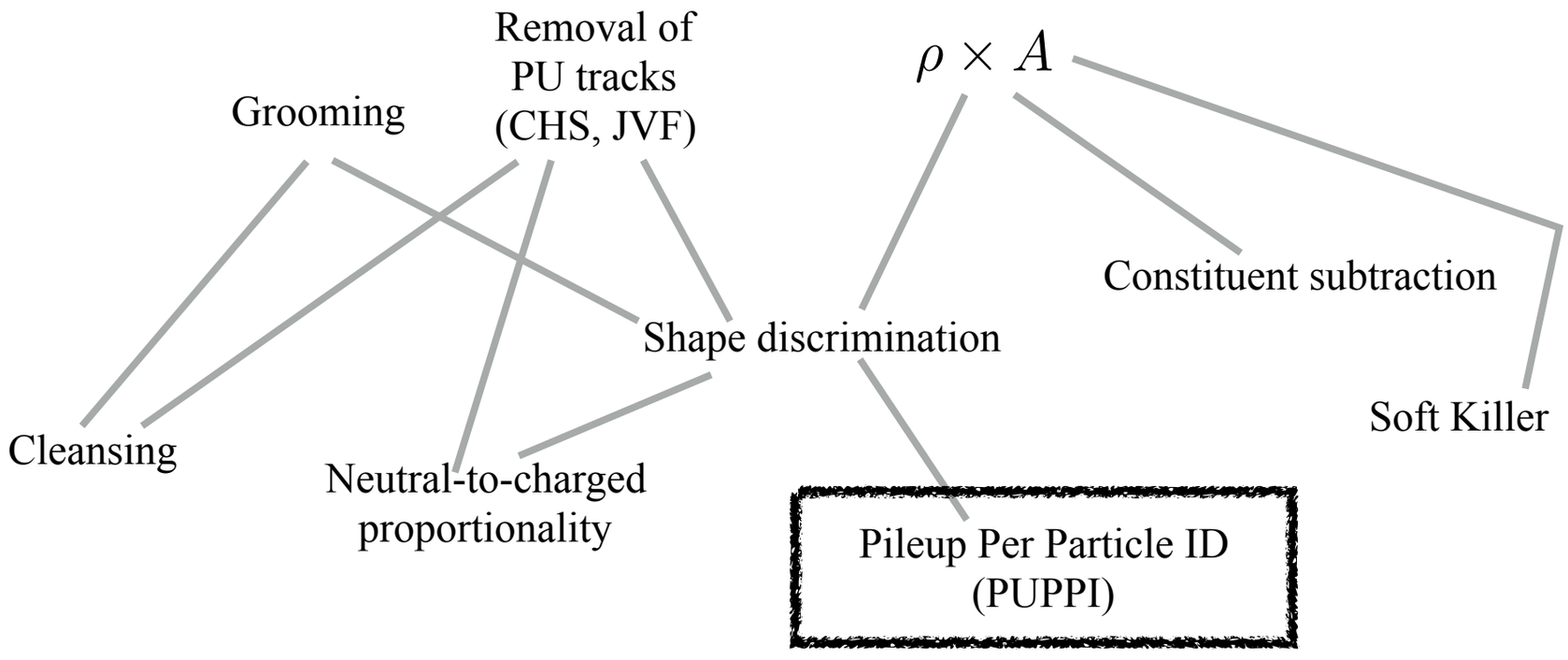


Boy, did we get GOOD at making ROC curves!

History : 2014

Pileup

- Saw huge expansion of available tools
- Investigated a lot
  - Cleansing
  - Constituent subtraction
  - Soft killer
- Talk about one briefly in particular : PUPPI



History : 2014

– Pile Up Per Particle Identification

- Establishes “guilt by association” for pileup
  - Examine charged tracks around neutrals, if they satisfy metric below, classify also as pileup

$$\alpha_i = \log \sum_{j \in \text{event}} \xi_{ij} \times \Theta(R_{\min} \leq \Delta R_{ij} \leq R_0),$$

$$\text{where } \xi_{ij} = \frac{p_{Tj}}{\Delta R_{ij}}.$$

Charged :

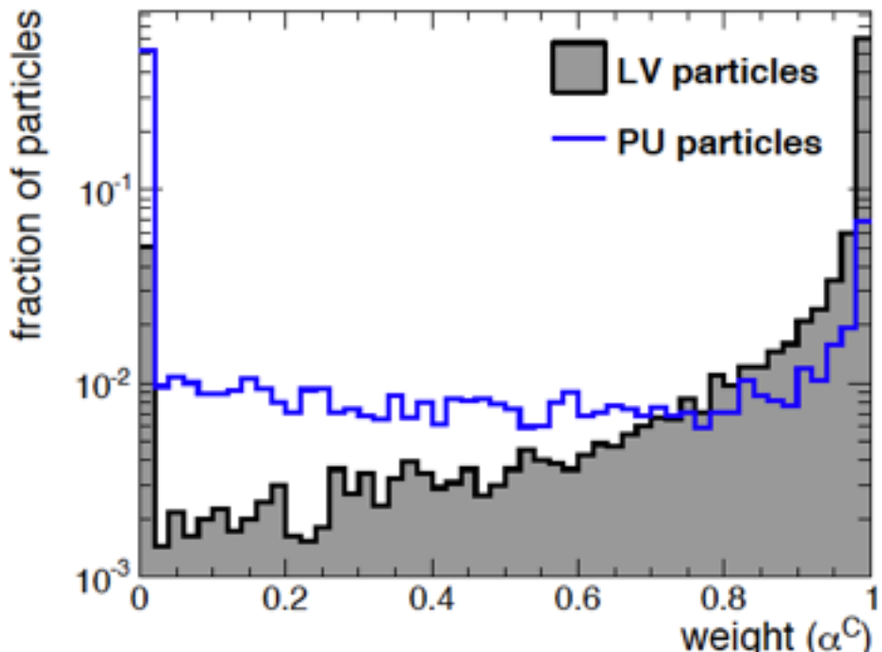
$$\alpha_i^C = \log \sum_{j \in \text{Ch,LV}} \xi_{ij}\, \Theta(R_{\min} \leq \Delta R_{ij} \leq R_0),$$

Forward :

$$\alpha_i^F = \log \sum_{j \in \text{event}} \xi_{ij}\, \Theta(R_{\min} \leq \Delta R_{ij} \leq R_0).$$

- Sample charged particles in event, get distributions for alpha for leading vertex and others
- Determine chi-squared weight to assign probability

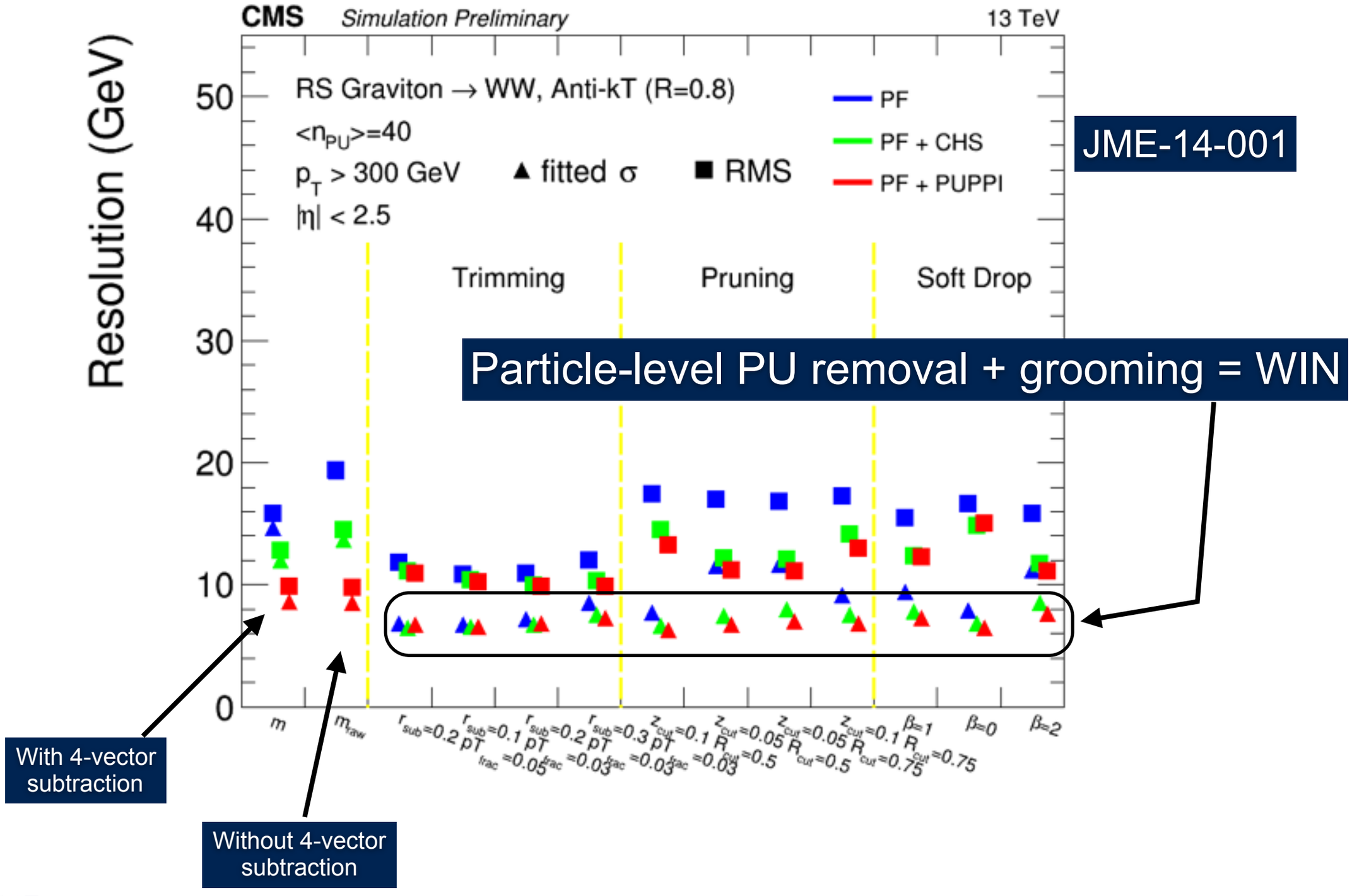
$$\chi_i^2 = \Theta(\alpha_i - \bar{\alpha}_{\text{PU}}) \times \frac{(\alpha_i - \bar{\alpha}_{\text{PU}})^2}{\sigma_{\text{PU}}^2},$$



History : 2014

- Compare mass resolution

Pileup

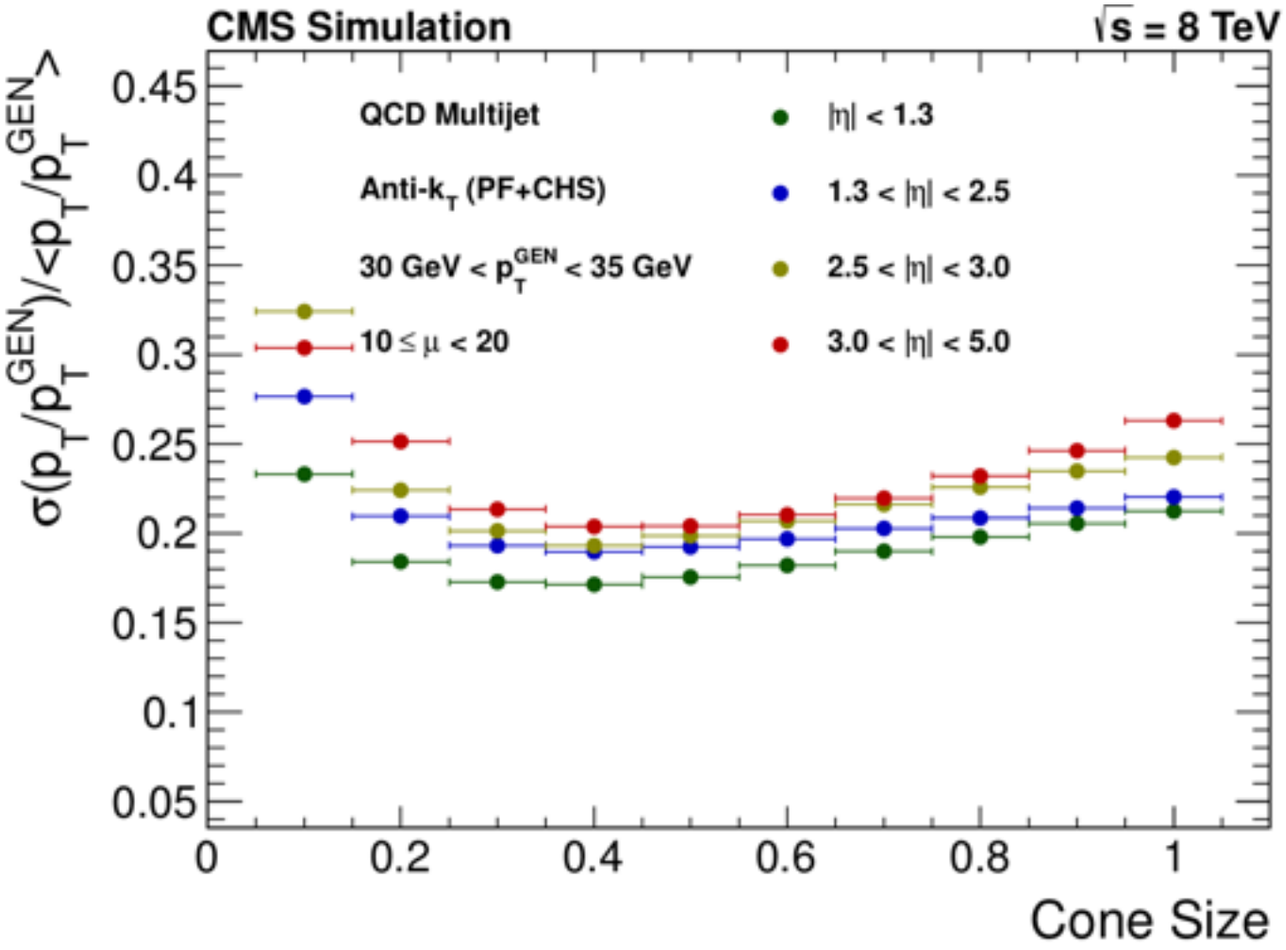


JME-14-001

History : 2014

- Other news in jet algorithms :
  CMS switches to anti-kt
  R = 0.4, same as ATLAS
  - Immense pain, huge amounts of time, and caused much displeasure from the community
  - Most people now had a photo of me on their dartboards for a while
  - Now go tell ATLAS to add R = 0.8 to their analyses, because we will never, ever, ever, evereverever do this again.

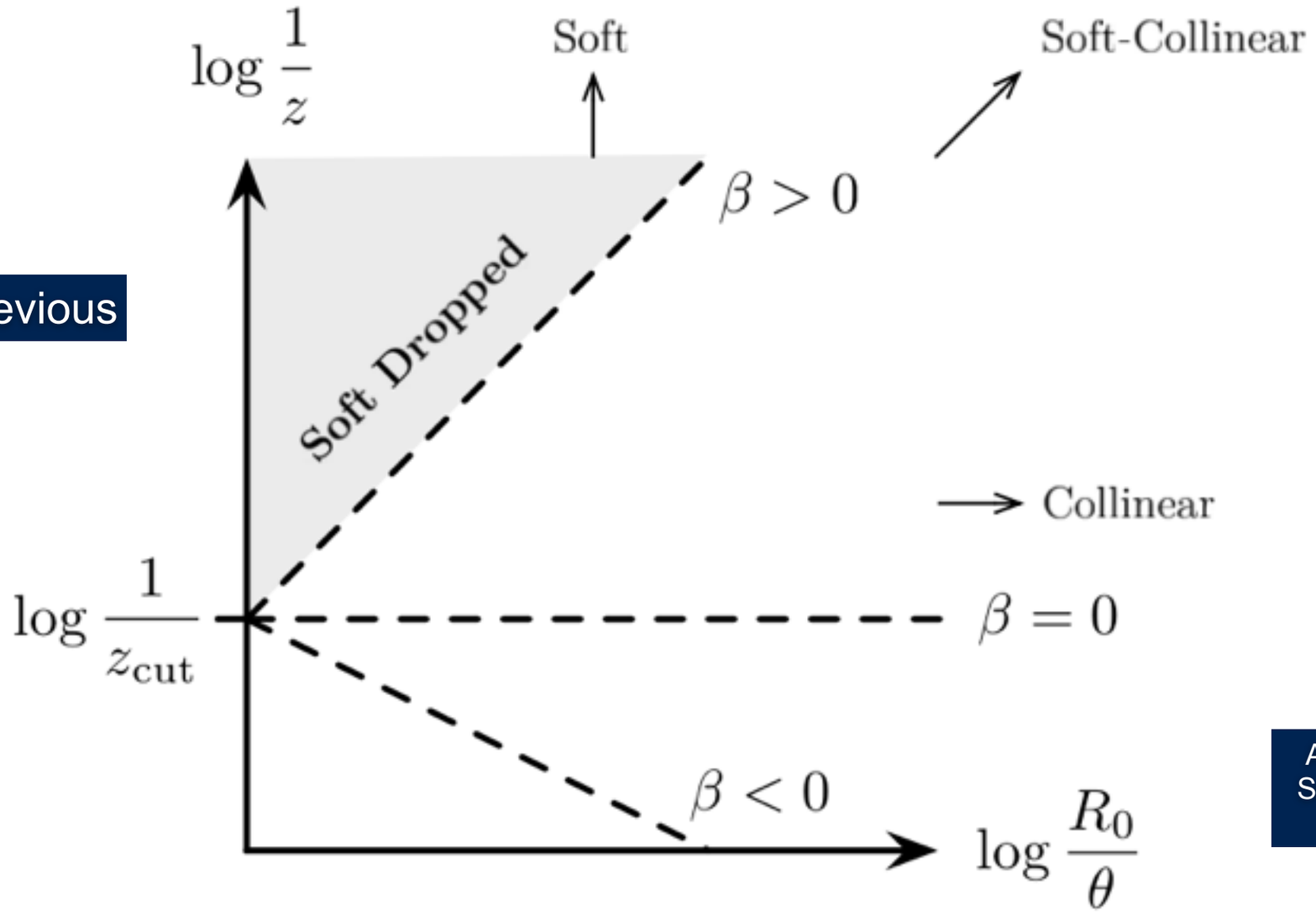
1 Year of Alexx Perloff's life



History : 2014

- Understanding gained from jet analytics even gives new and better ways to groom and tag!

Note : y-axis now 1/previous



A. Larkoski, S. Marzani, G. Soyez, J. Thaler,JHEP 1405 (2014) 146

Soft drop : “simple” behavior in this plane, with tunable parameter for many algorithms!

History : 2014

- Soft drop :
  - Undo last stage of C/A clustering, label subjets j1,j2
  - If :

$$\frac{min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

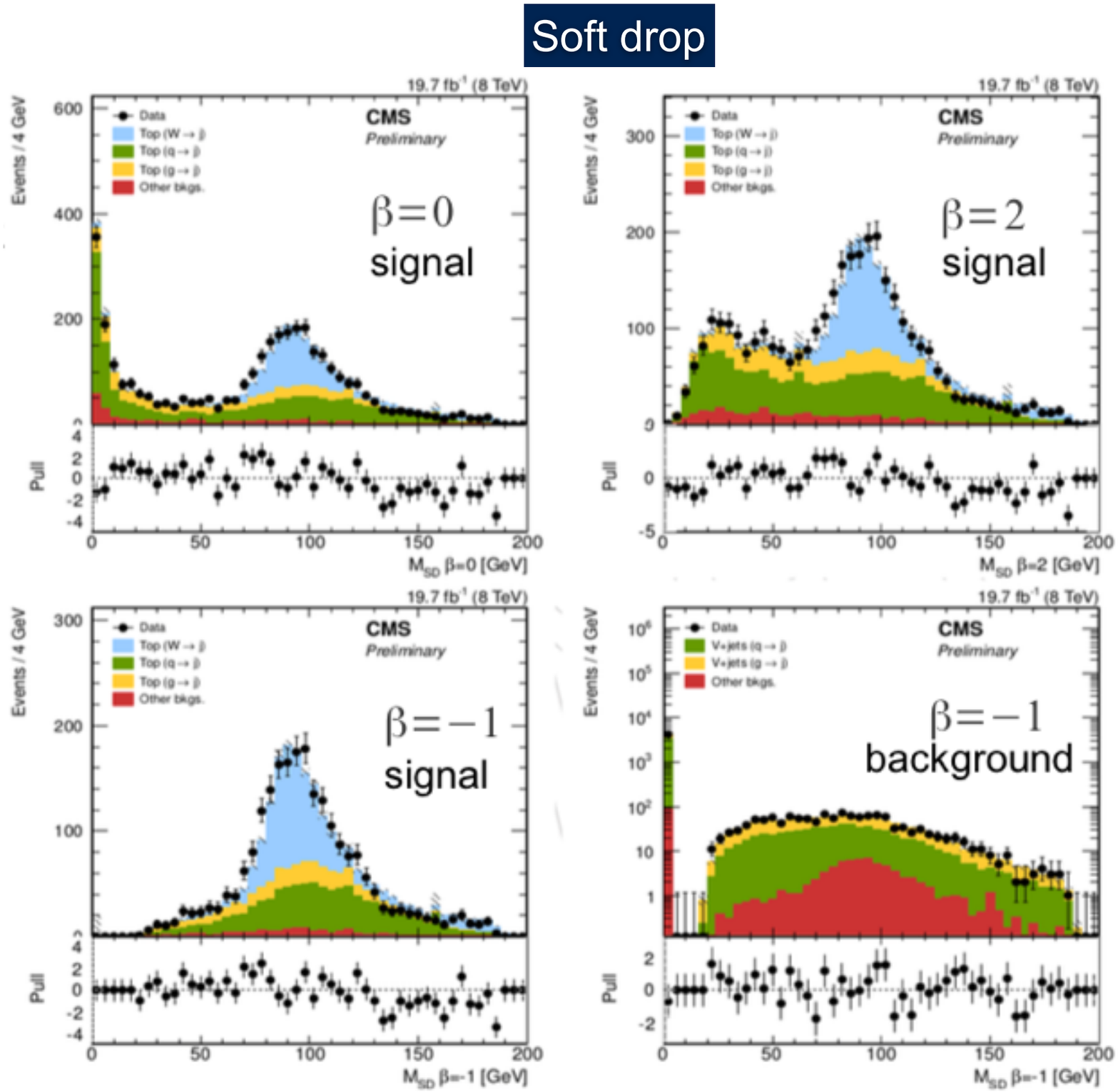
    then j is soft dropped
    else redefine j to be the harder, and iterate

  - Recovers (modified) mass drop BDRS tagger for beta=0
    - This case always removes soft radiation entirely (hence the name)

History : 2014

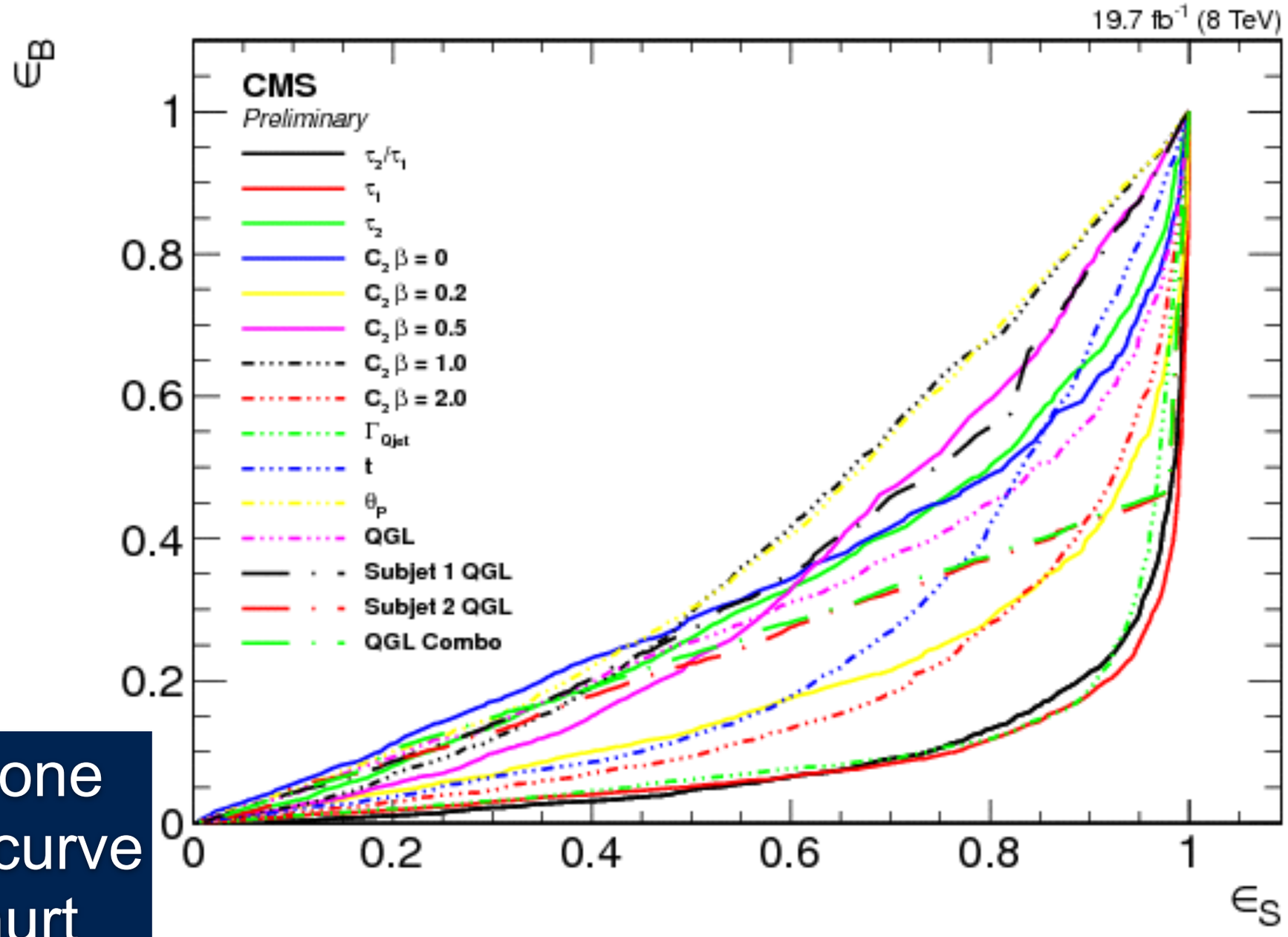
- Soft drop: First tests in data done with Run 1 data (JME-14-002)

Soft drop



History : 2014

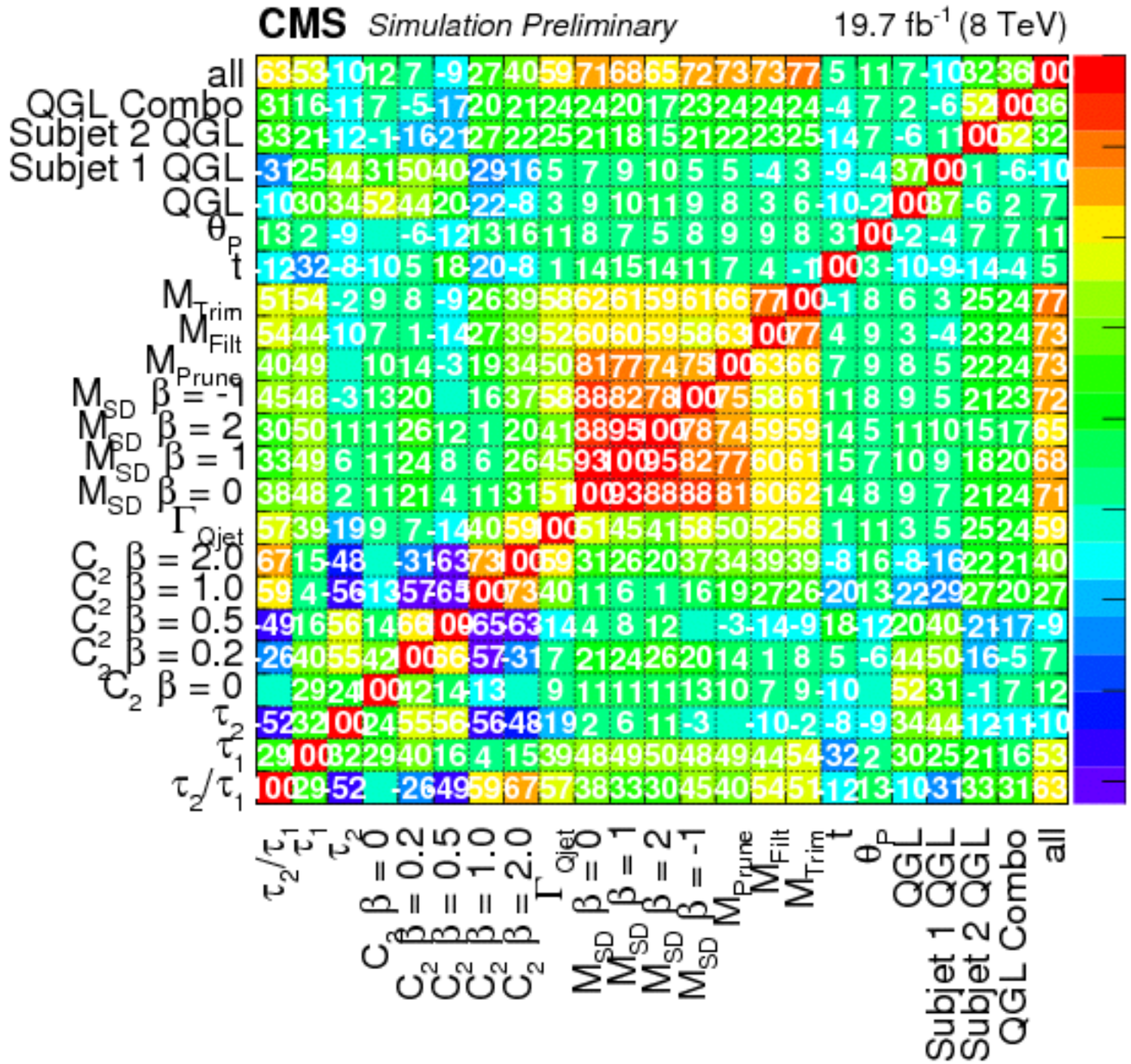
- ROC curves for single variables in W tagging
- Best performance : Qjet volatility and tau21



I suppose one more ROC curve couldn't hurt

History : 2014

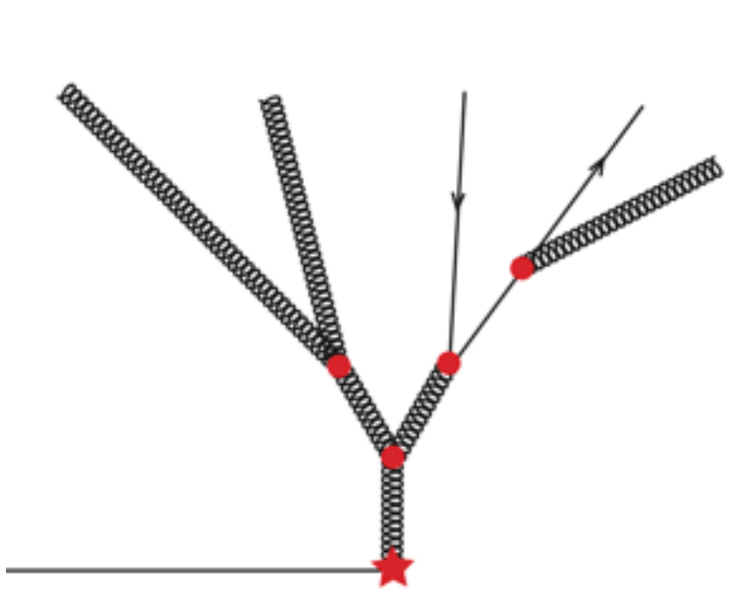
- Also understanding correlations between various tools
- Obviously groomed masses highly correlated, but not 100%
- Other variables correlated with masses also (n-subjettiness, angularities)
- Name of the game : ADDING information while MAINTAINING systematics

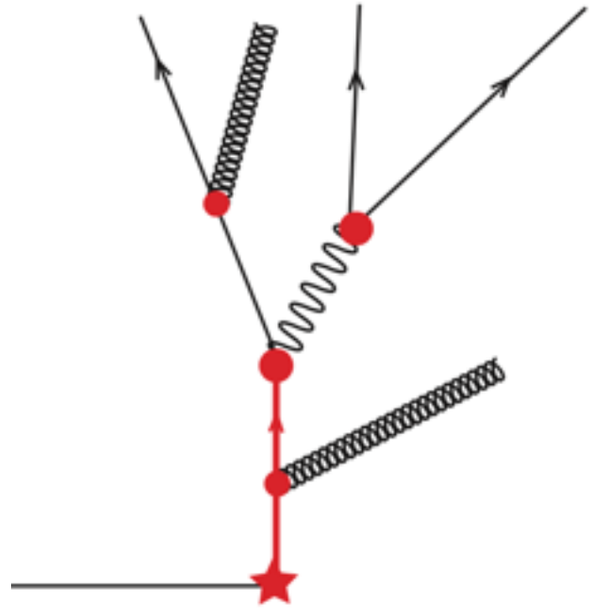


Nontrivial!

History : 2015

- Shower deconstruction :
  - Make “microjets” out of CA jet constituents
  - Keep at most 9 microjets with pt > ptmin
    - Approximate probability for observed particles to satisfy a “signal-like” shower, or a “background-like” shower
    - Construct likelihood and compa[illegible]

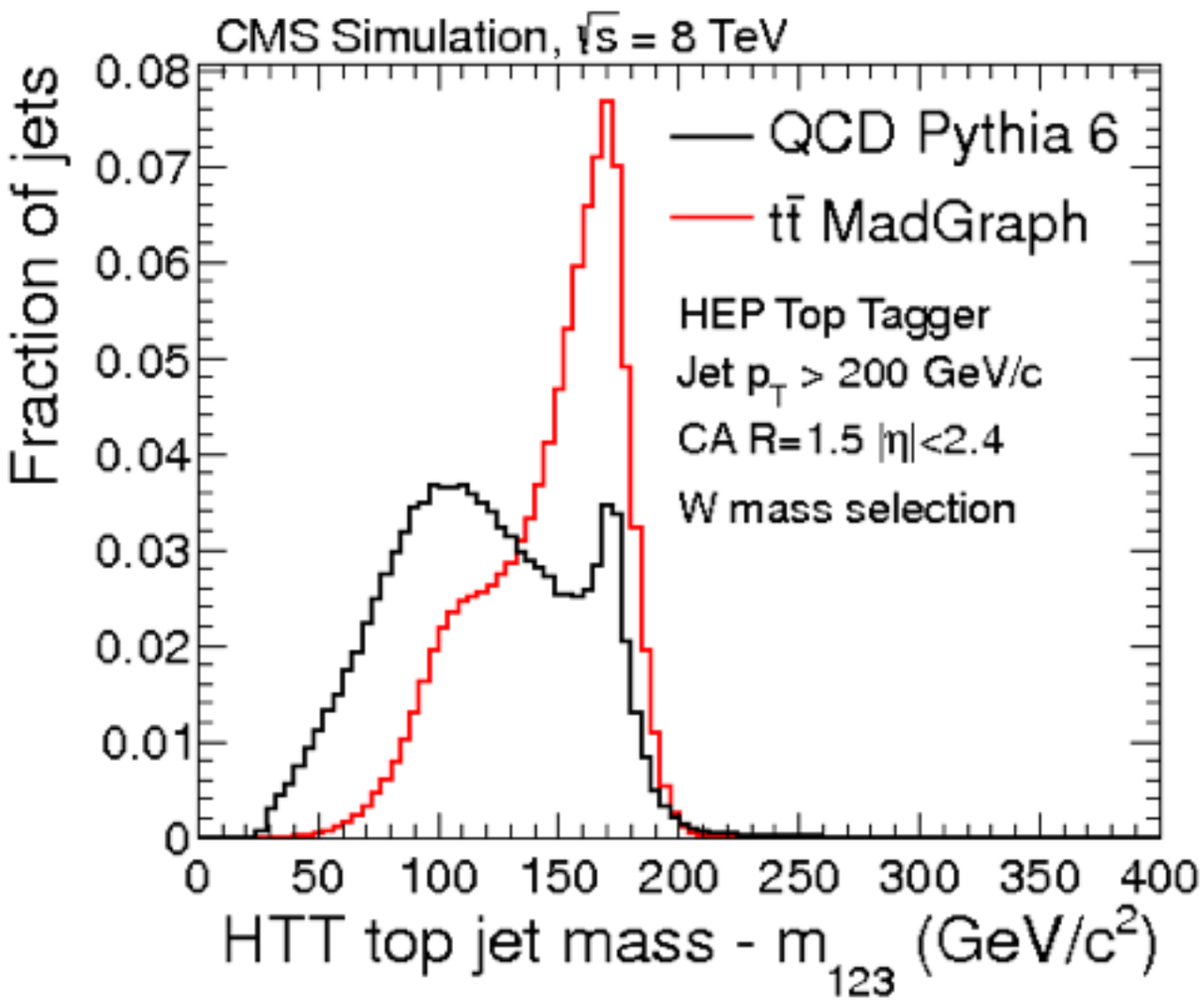


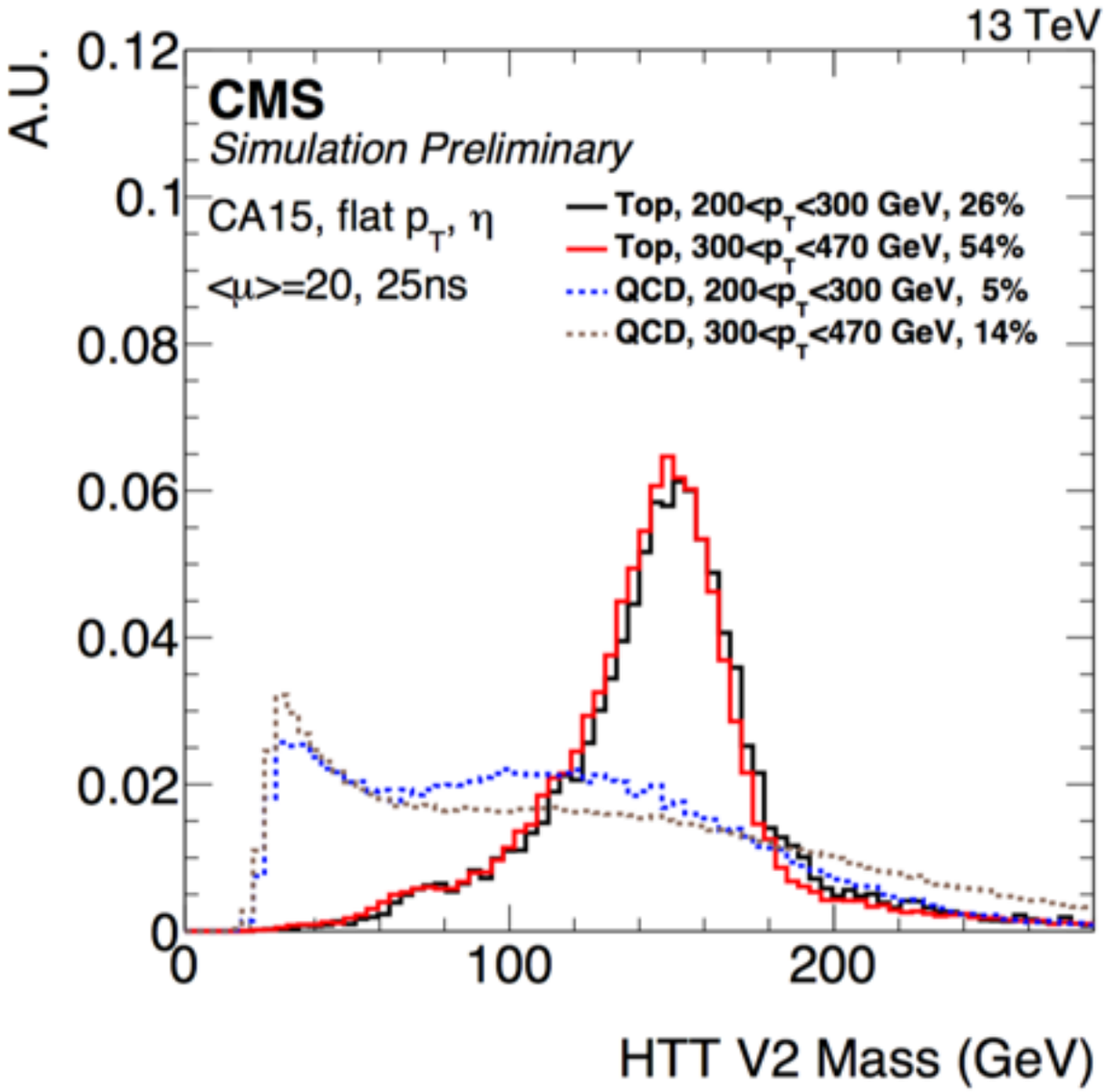


Soper and Spannowsky :
Phys.Rev. D84 (2011) 074002

History : 2015

- HEPTopTagger V1 —> V2

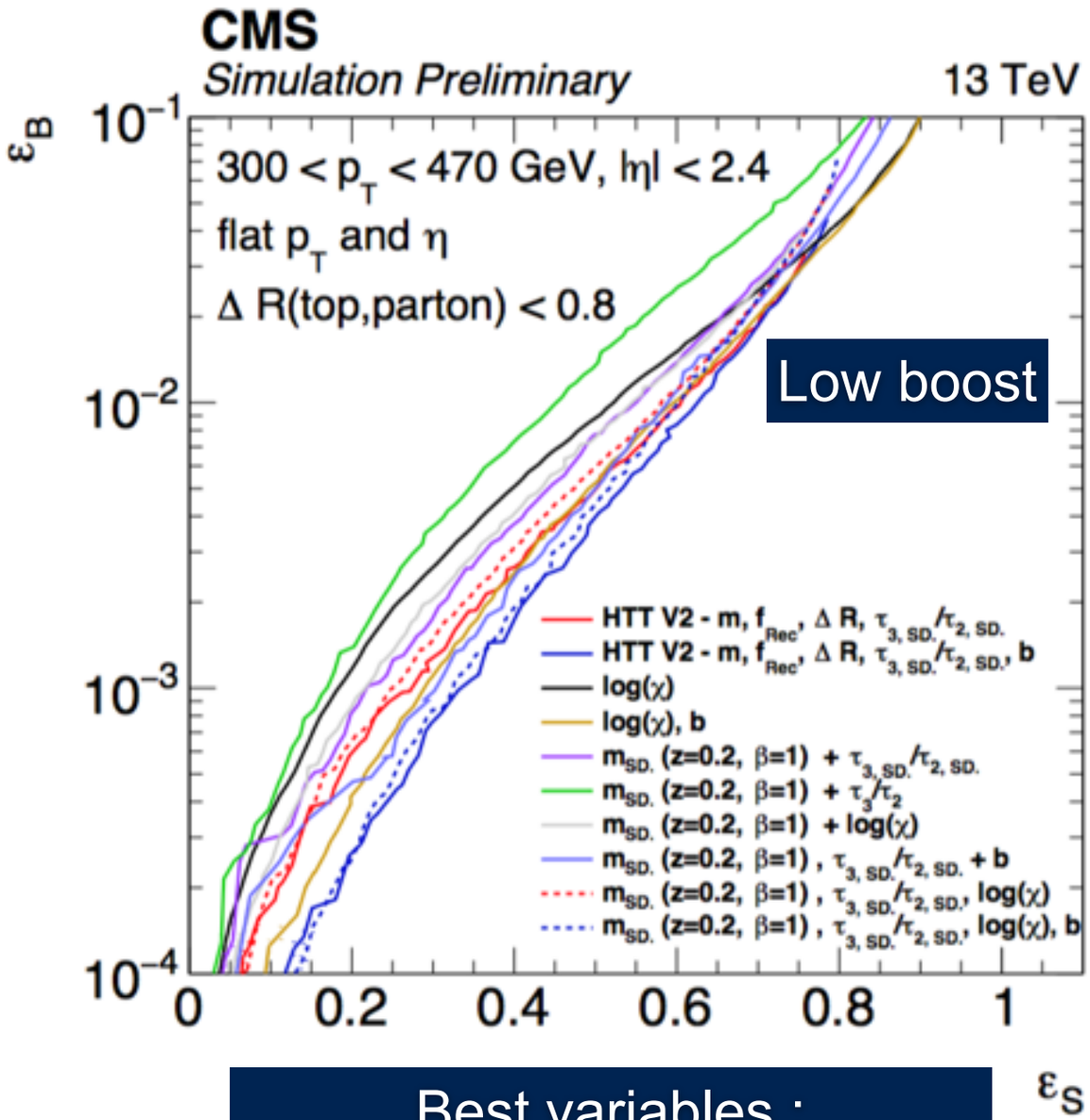




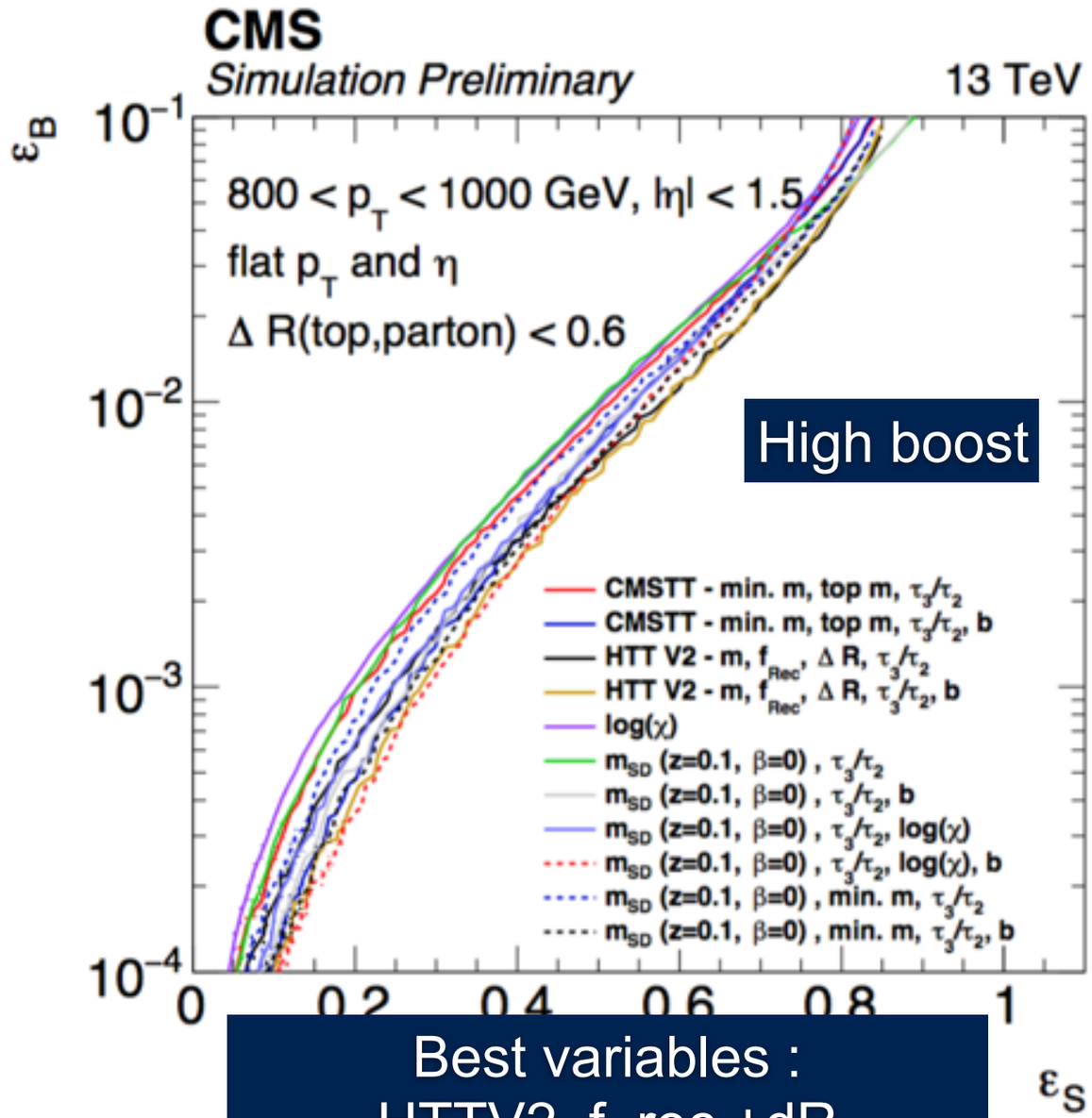
- Smoother behavior, little bump at top mass in bkg is gone

History : 2015

- Single-variable ROC curves



Best variables :
soft drop mass beta=1, tau32



Best variables :
HTTV2, f_rec +dR
comparable but simpler:
soft drop mass beta=0, tau32

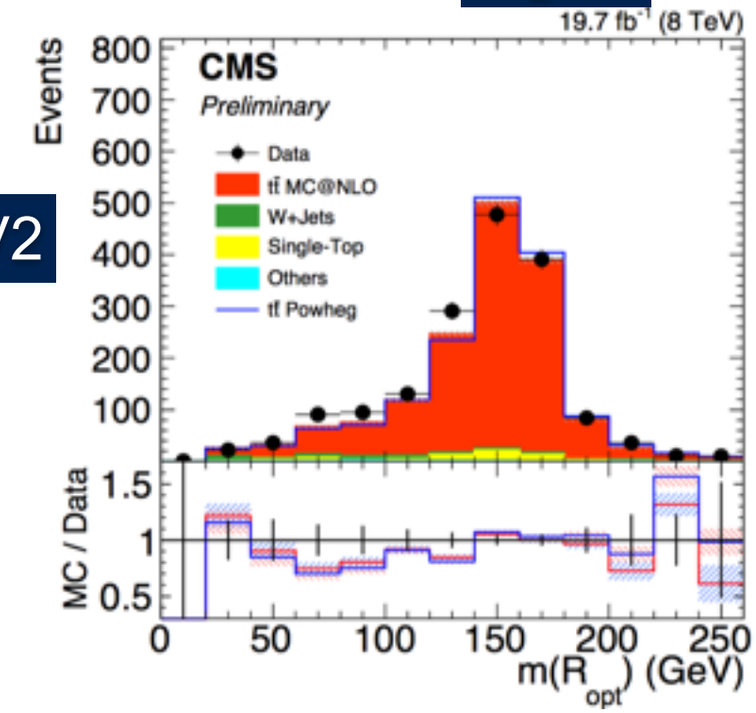
2 Annnddddd, more ROC curves. Again.

History : 2015

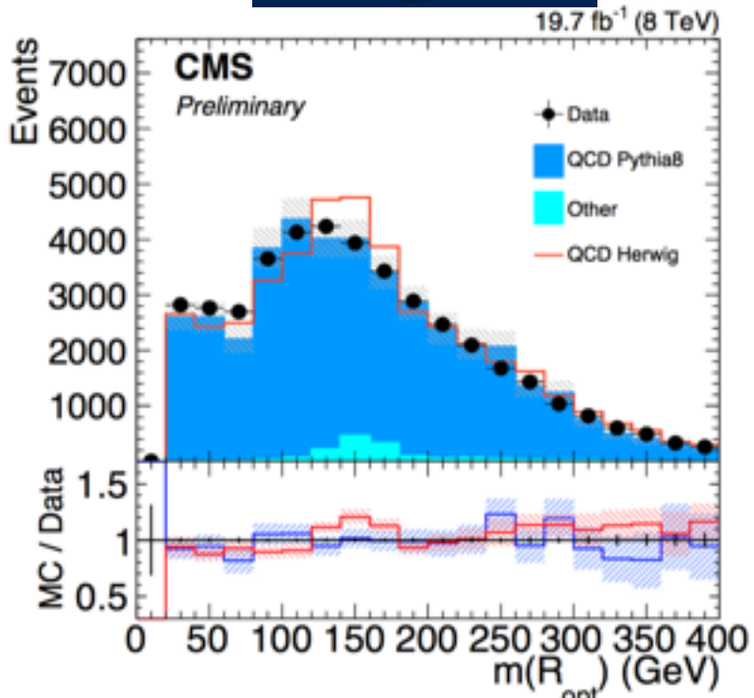
- Why not use HTTV2?
  - Background shape is a bit more complicated
  - More on that later!

HTTV2

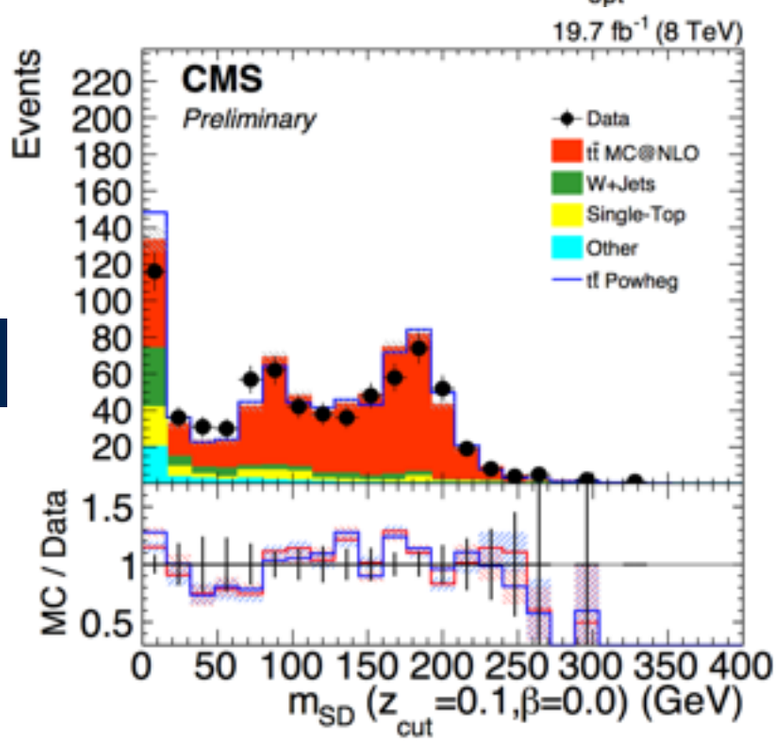
Signal

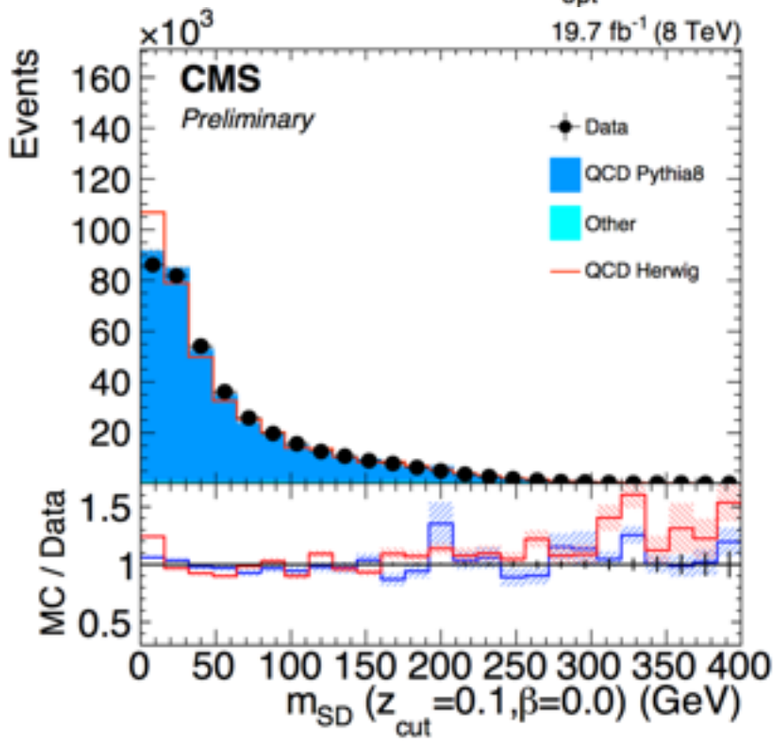


Background



Soft Drop Mass





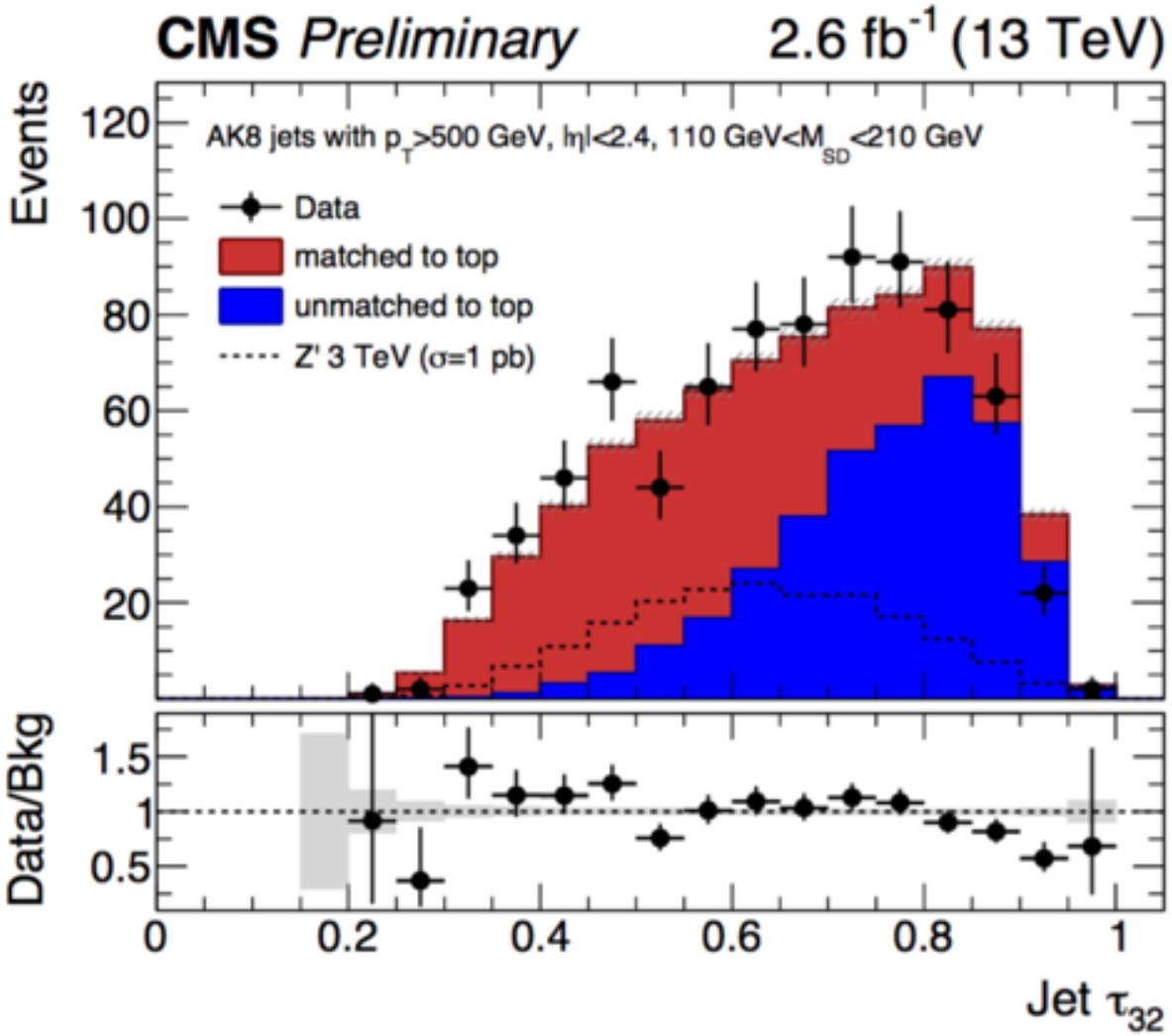
There. All caught up.

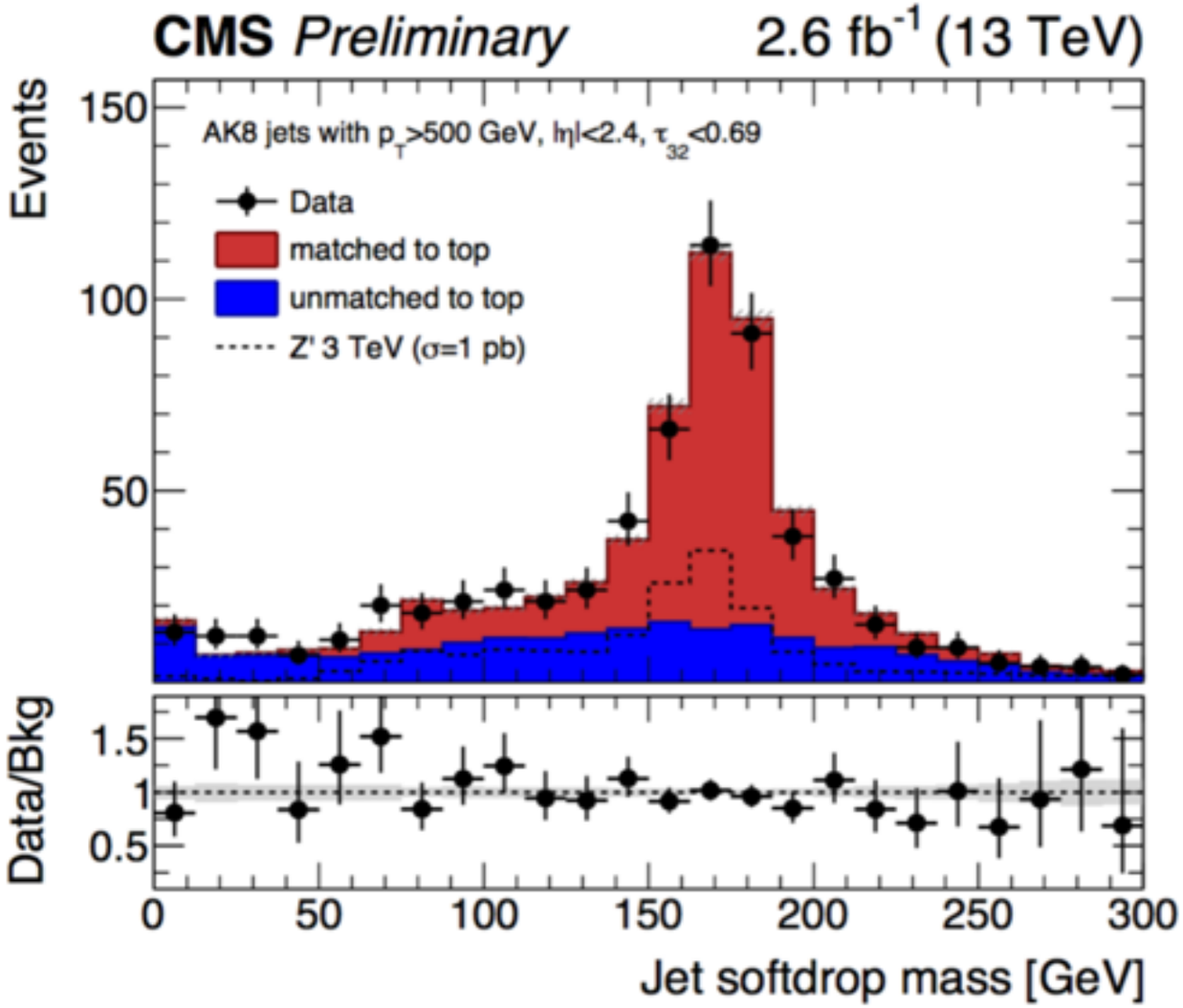
Outline

- Brief History
- Where are we?
- Where do we want to go?

Where Are We : Top Tagging

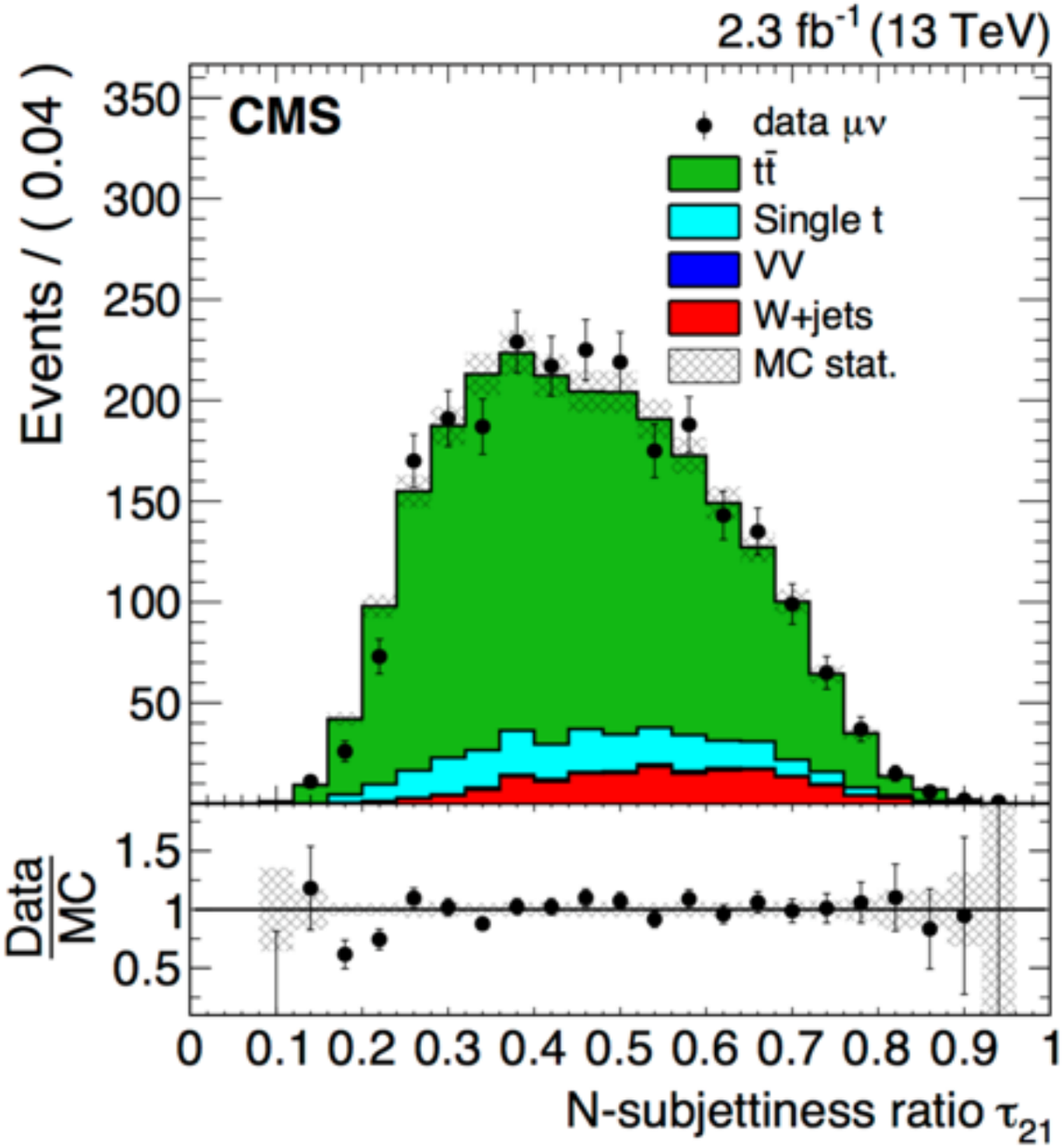
- Low-pt tagger : soft drop mass (beta=1) + tau32, with subjet b-tagging
- High-pt tagger : soft drop mass (beta=0) + tau32, with subjet b-tagging

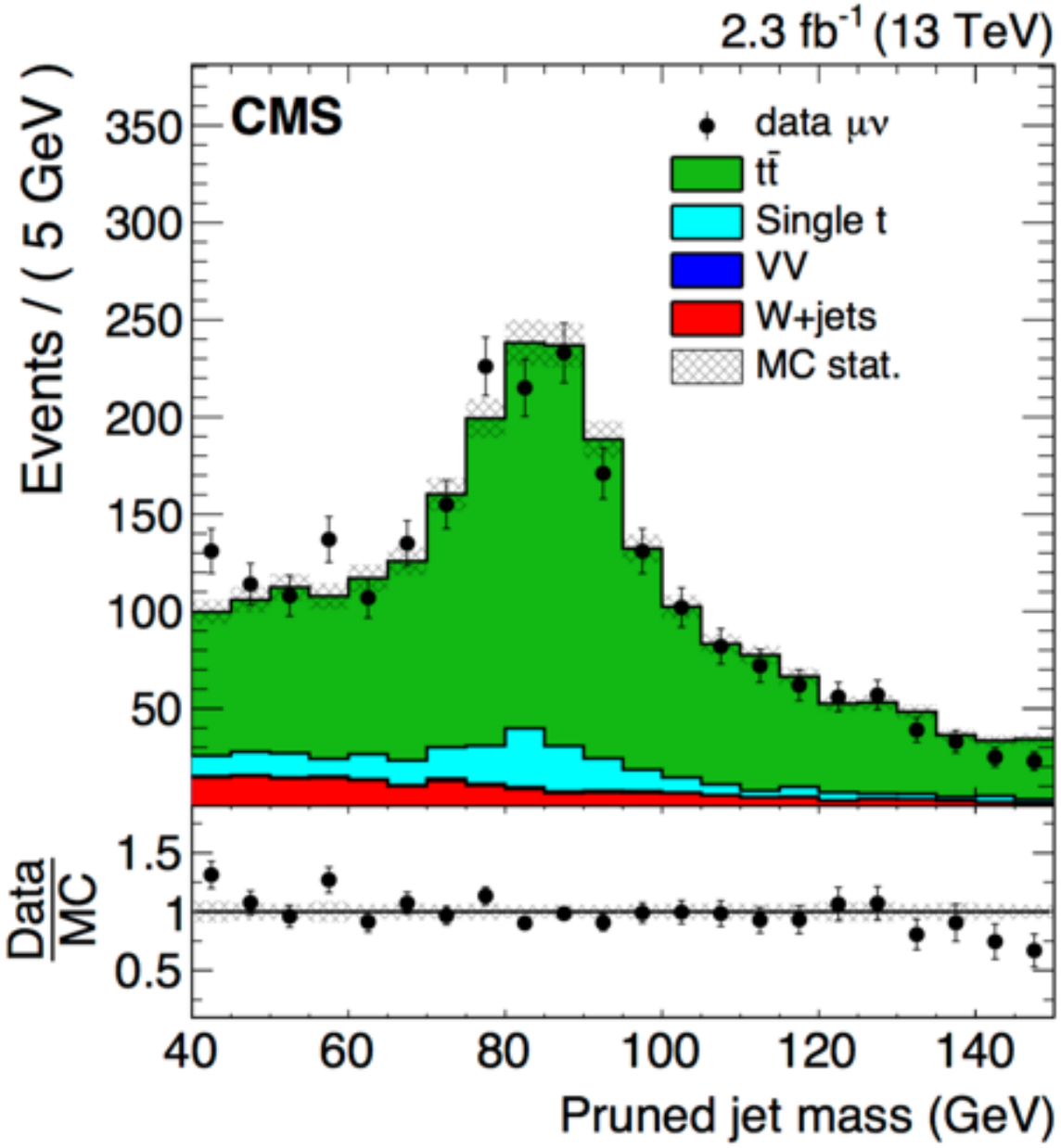




Where Are We : W Tagging

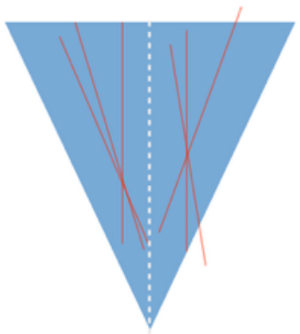
- Current tagger : jet pruning with tau21

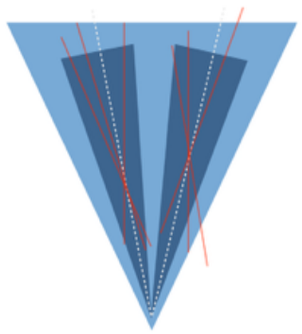


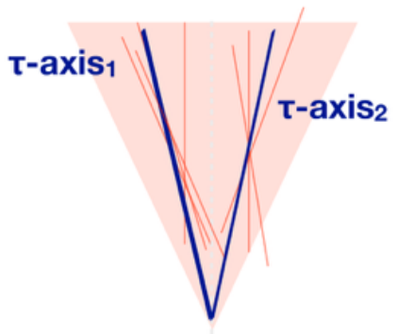


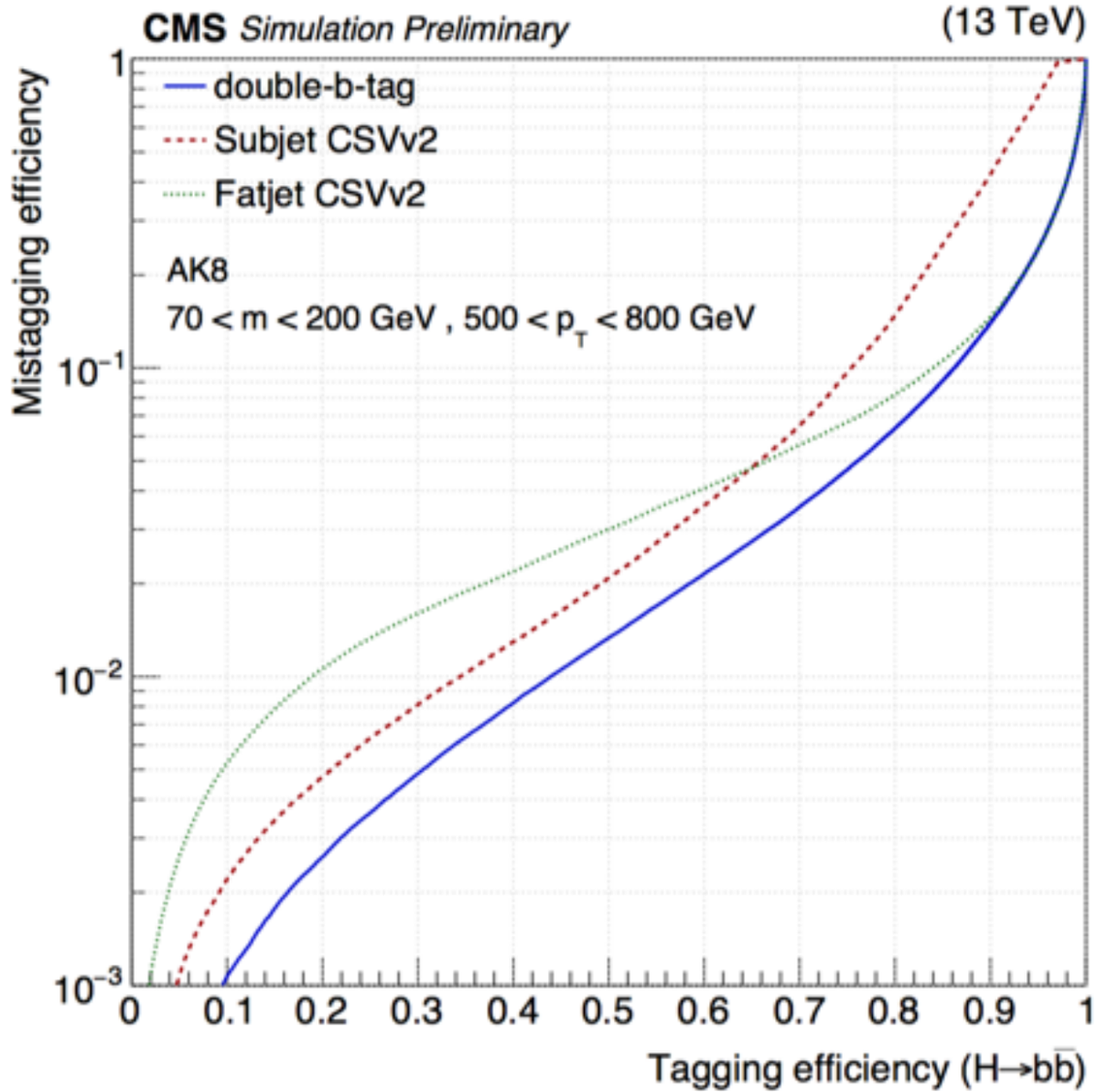
Where Are We : H Tagging

- Development of dedicated H->bb tagger (BTV-15-002)
  - Look at axes defined by n-subjettiness
  - Use MVA on variables associated with this
  - Excellent improvement everywhere!





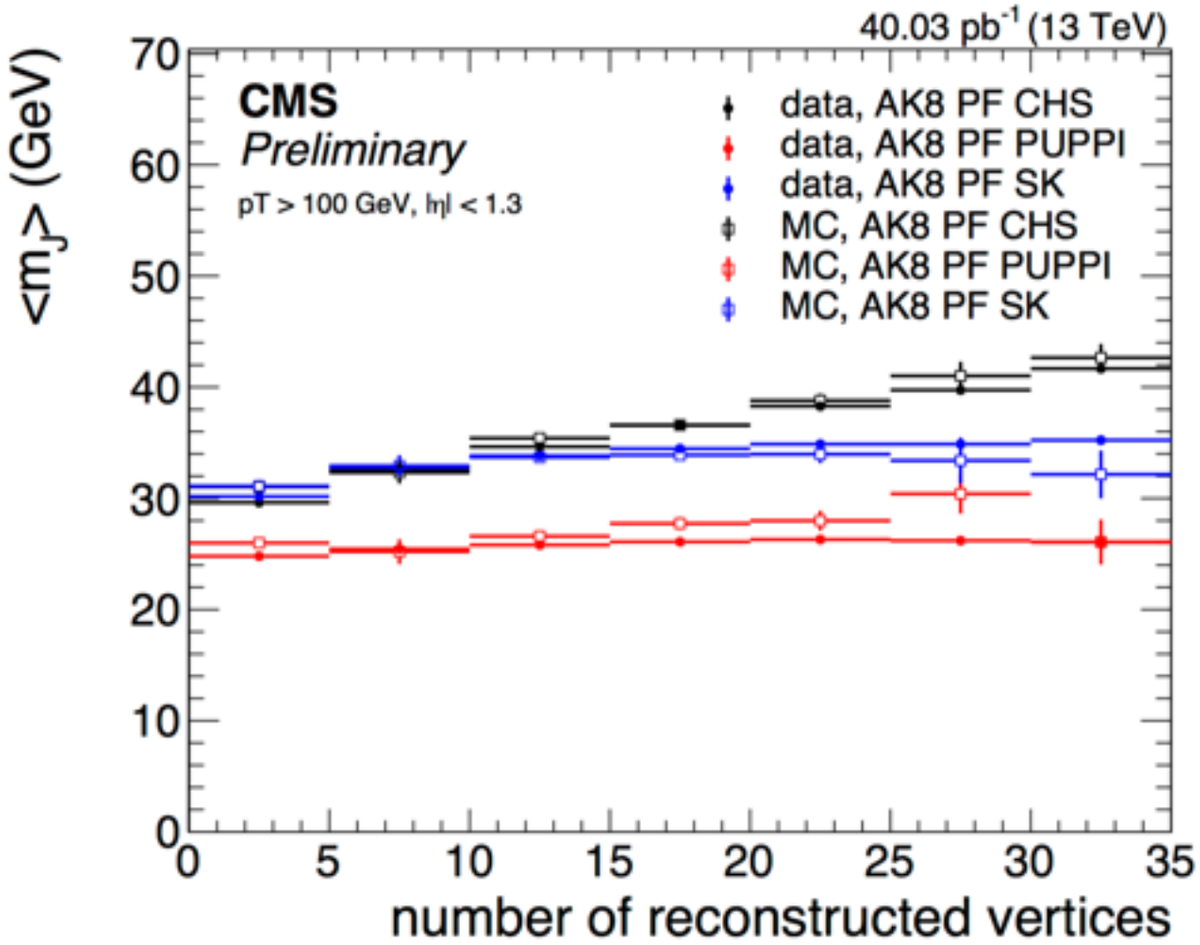




Where Are We : Pileup

- Many improvements for Run 2 under the hood with hardware and software changes
- Also coming are phase 1 upgrades and dramatic phase 2 upgrades
  - Won't talk about any of that

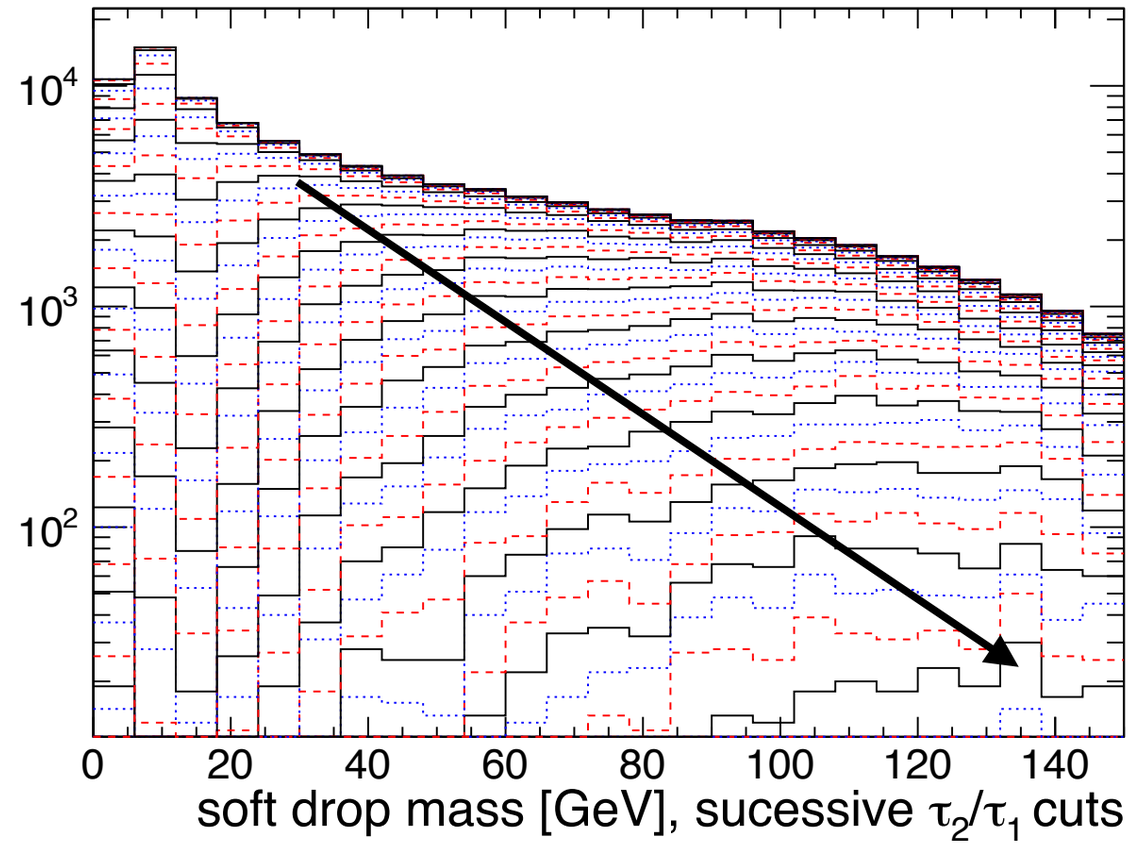
CMS-DP-2015-034



- Status of pileup mitigation algorithms :
  - CHS : alive, but not as performant as PUPPI for substructure
  - PUPPI : performing very well

Where are we?

- Lots of technologies
- Comparable performances
- Nontrivial correlations
- Nontrivial background sculpting
  - Correlations with mass bring background into signal region!
- What's an analyst to do?



Outline

- Brief History
- Where are we?
- Where do we want to go?

If I see another ROC curve I think I may be sick.

Jet Analytics

- First need to understand jet mass

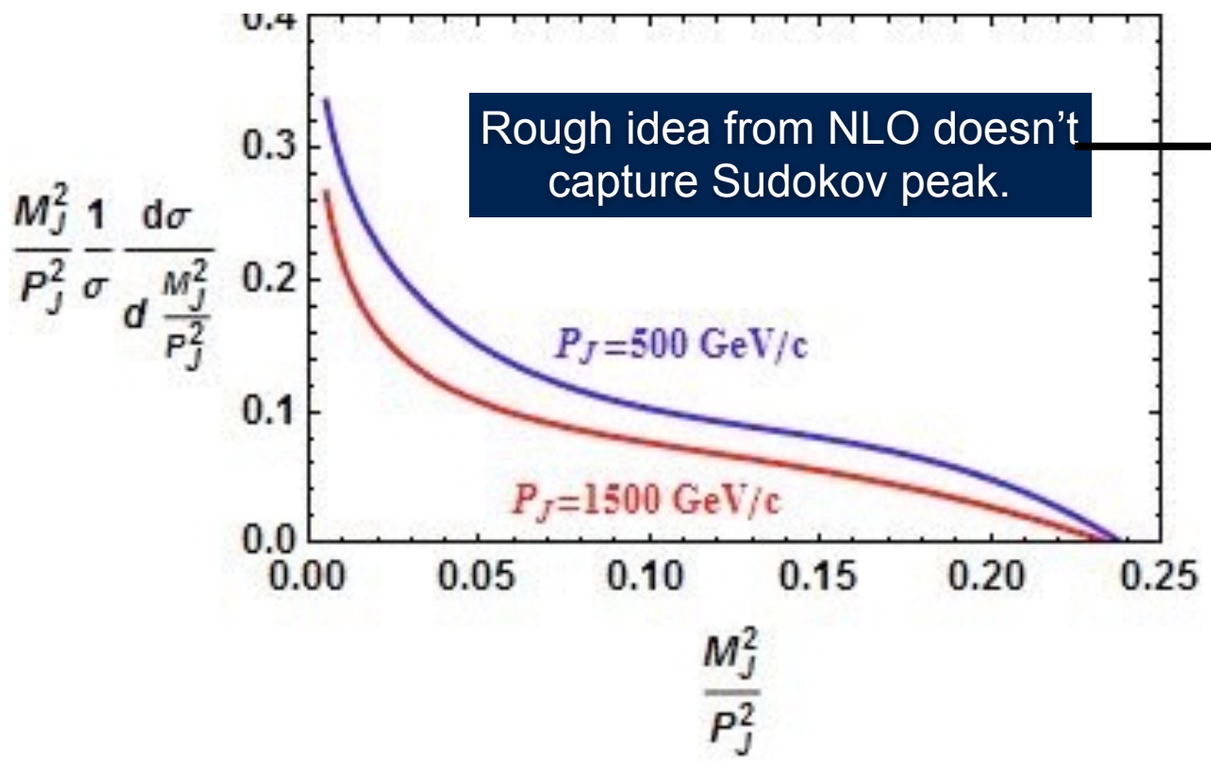
At NLO :

Finite-size effects from cutoff

Scales ~linearly with momentum

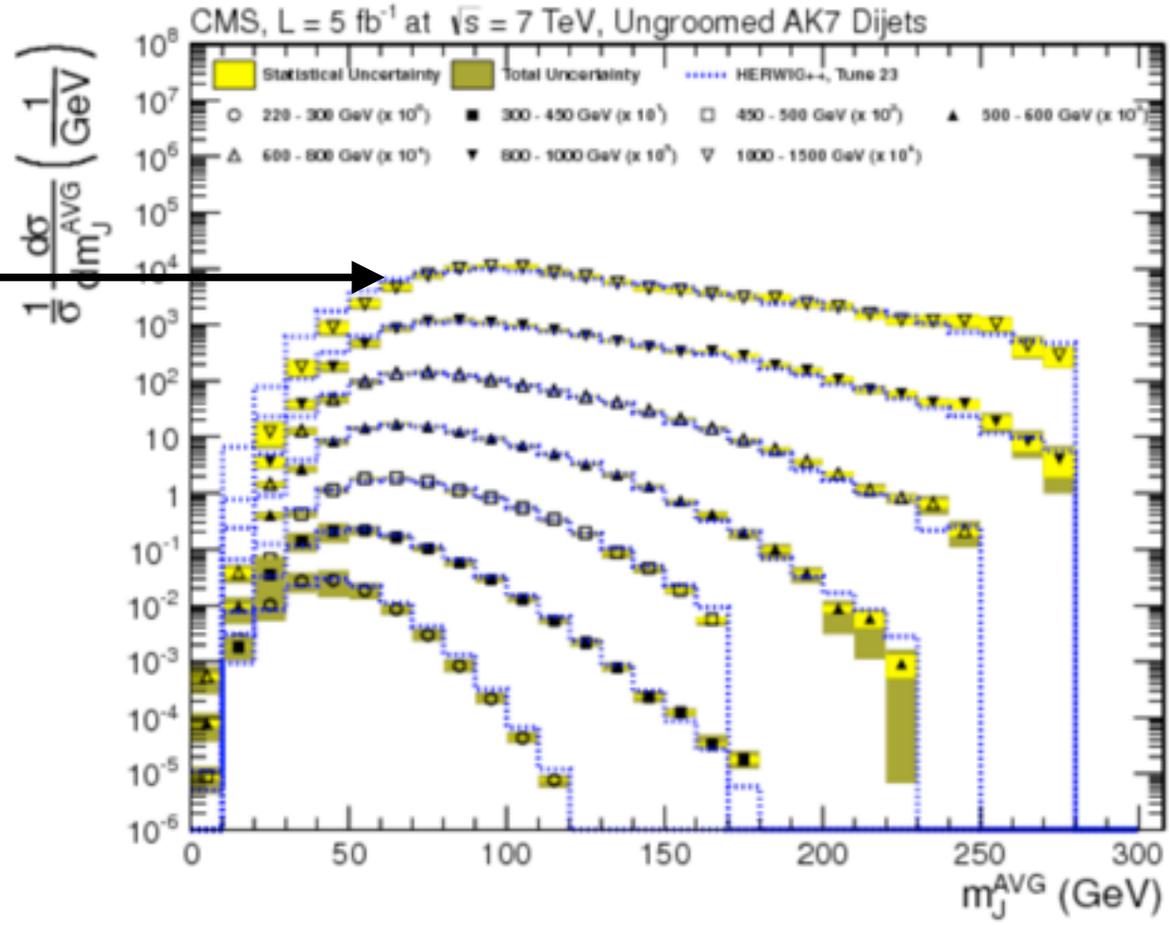
Log. divergence at low mass

$$\left\langle M_J^2 \right\rangle_{NLO} \simeq \overline{C} \left(\frac{p_J}{\sqrt{s}} \right) \alpha_s \left(\frac{p_J}{2} \right) p_J^2 R^2,$$



Rough idea from NLO doesn't capture Sudokov peak.

Good prediction of jet data from MC



S.D. Ellis, J. Huston, K. Hatakeyama, P. Loch, M. Tonnesmann, Prog.Part.Nucl.Phys. 60 (2008) 484-551

JHEP 1305 (2013) 090

Jet Analytics

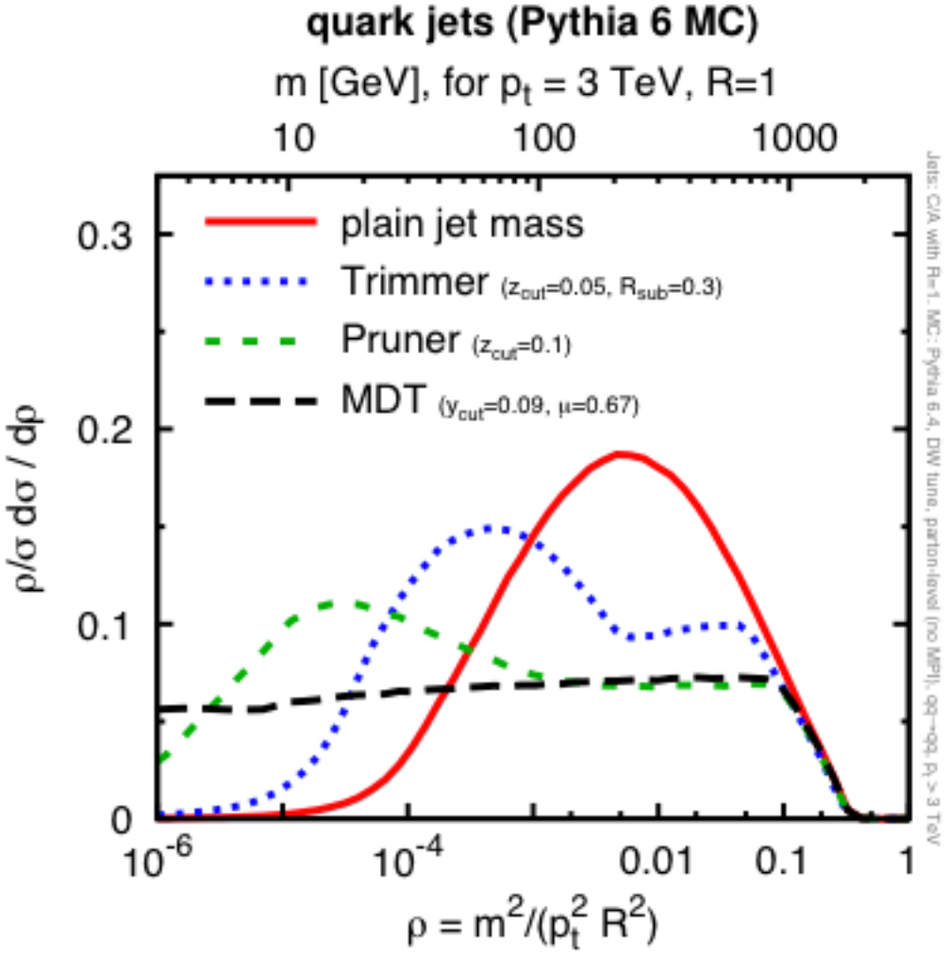
- First need to understand jet mass

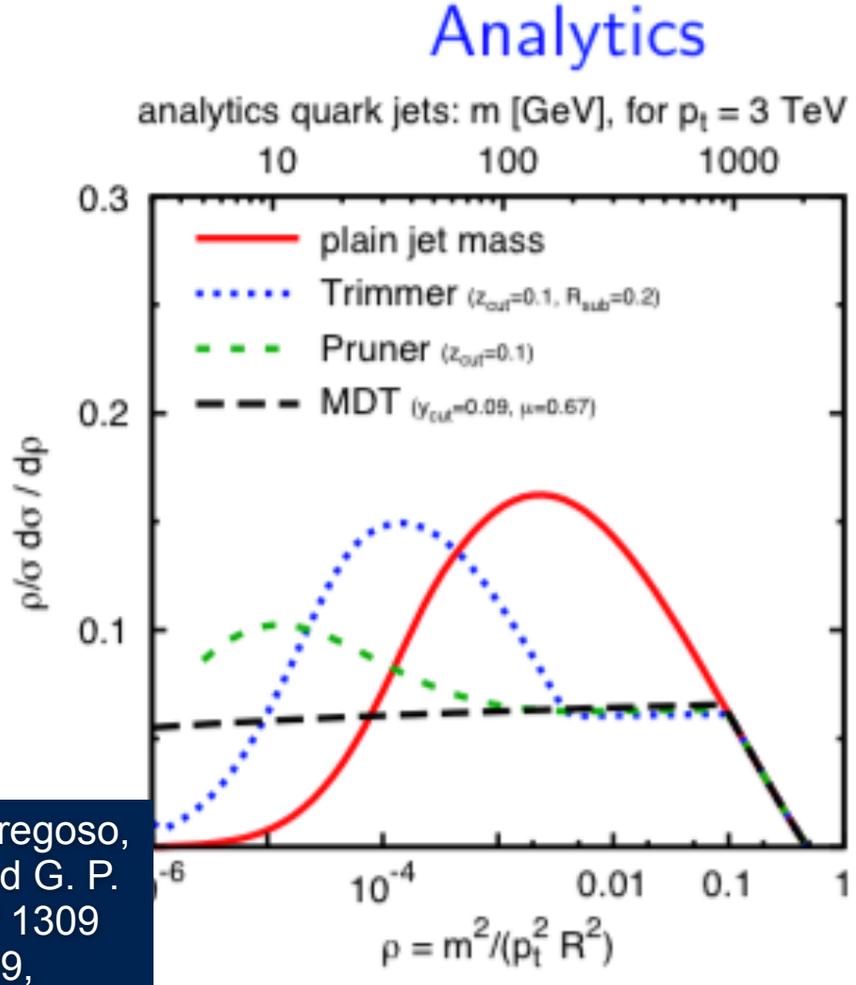
At "NLL" :

$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho} \simeq \frac{\alpha_s C_F}{\pi}\left(\ln\frac{1}{\rho}-\frac{3}{4}\right) e^{-\frac{\alpha_s C_F}{2\pi}\left(\ln^2\frac{1}{\rho}-\frac{3}{2}\ln\frac{1}{\rho}+\mathcal{O}(1)\right)}$$

$$\rho \equiv \frac{m^2}{p_t^2 R^2}$$

Slide from G. Soyez





Dasgupta, A. Fregoso, S. Marzani, and G. P. Salam, JHEP 1309 (2013) 029,

Jet Analytics

- First need to understand jet mass

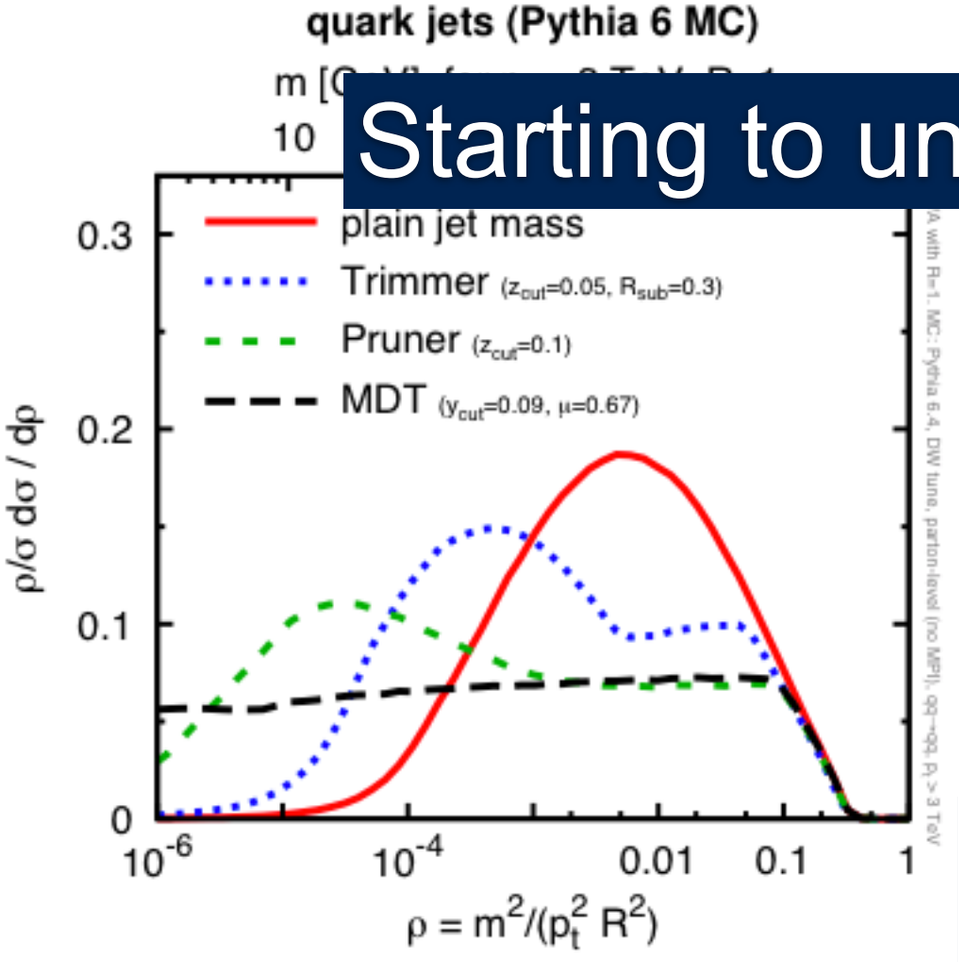
At "NLL" :

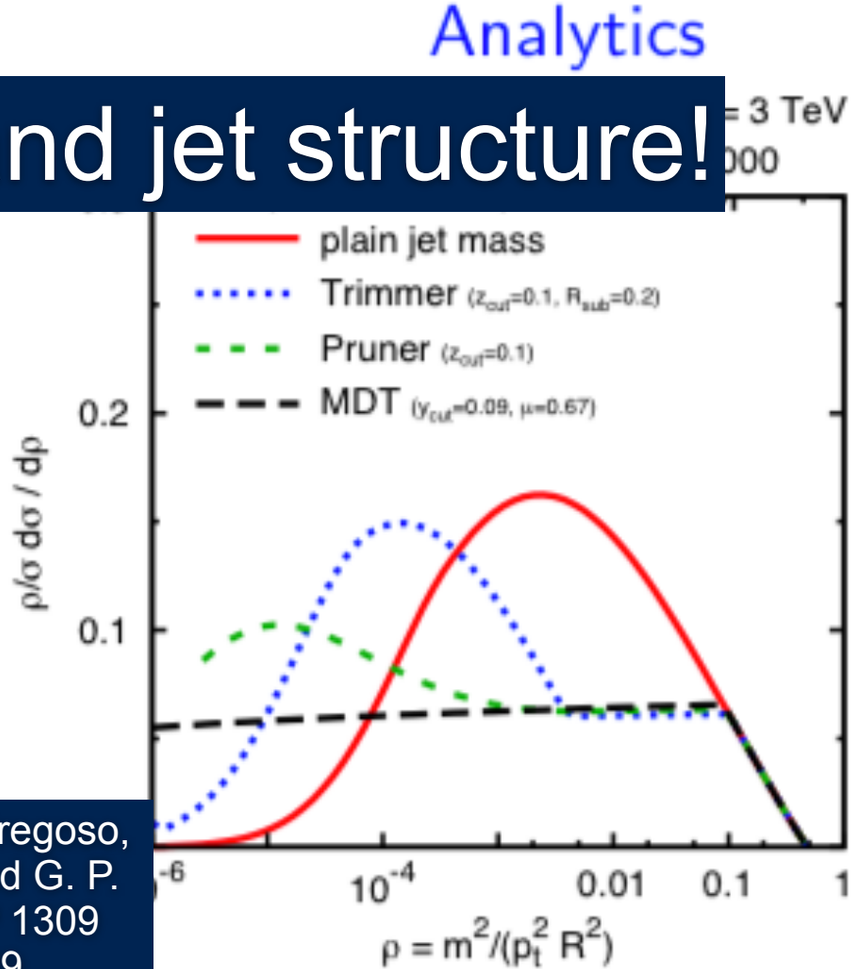
$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho} \simeq \frac{\alpha_s C_F}{\pi}\left(\ln\frac{1}{\rho}-\frac{3}{4}\right) e^{-\frac{\alpha_s C_F}{2\pi}\left(\ln^2\frac{1}{\rho}-\frac{3}{2}\ln\frac{1}{\rho}+\mathcal{O}(1)\right)}$$

$$\rho \equiv \frac{m^2}{p_t^2 R^2}$$

Slide from G. Soyez

Starting to understand jet structure!

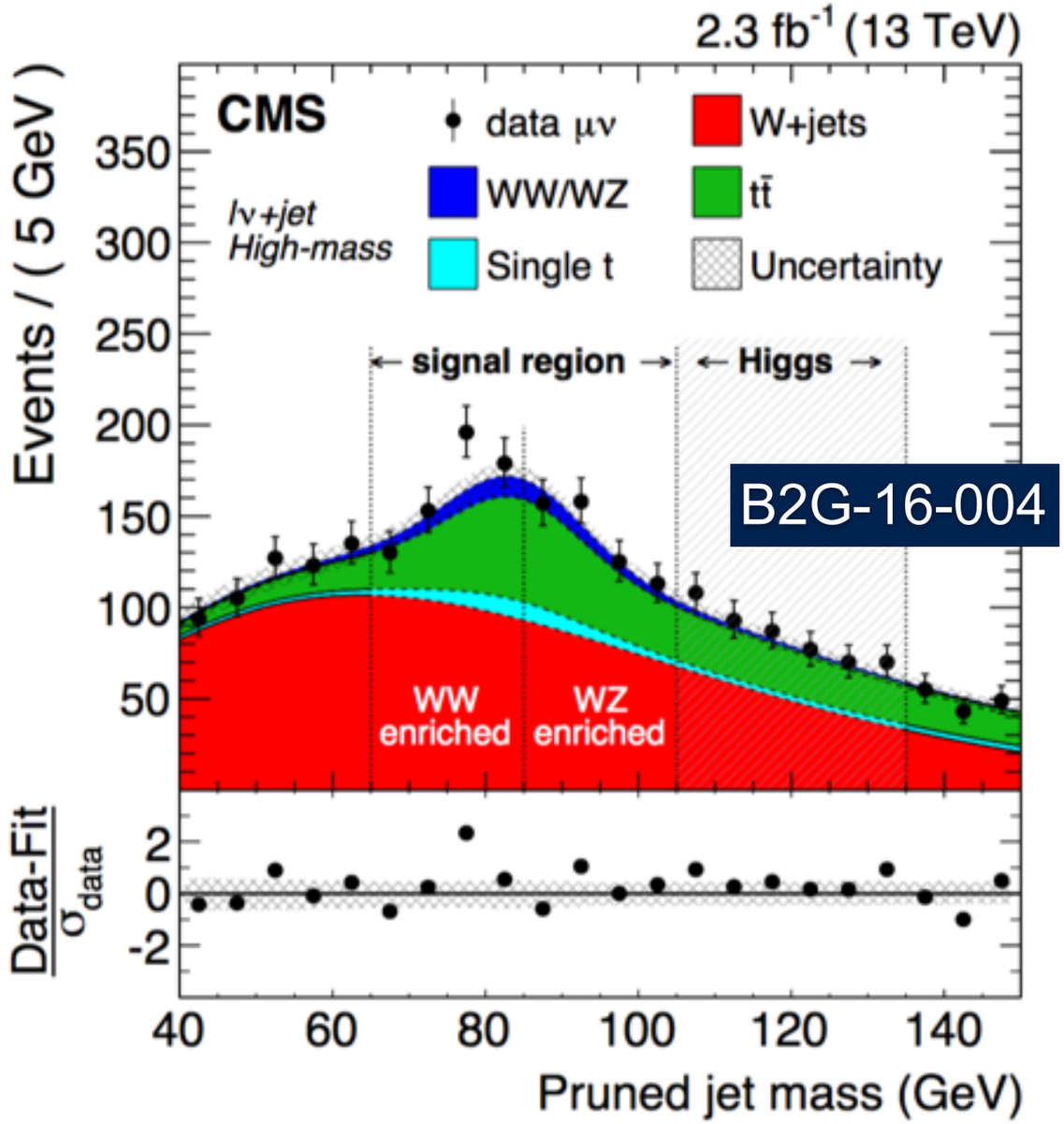




Dasgupta, A. Fregoso, S. Marzani, and G. P. Salam, JHEP 1309 (2013) 029,

Scaling : Why Does This Matter?

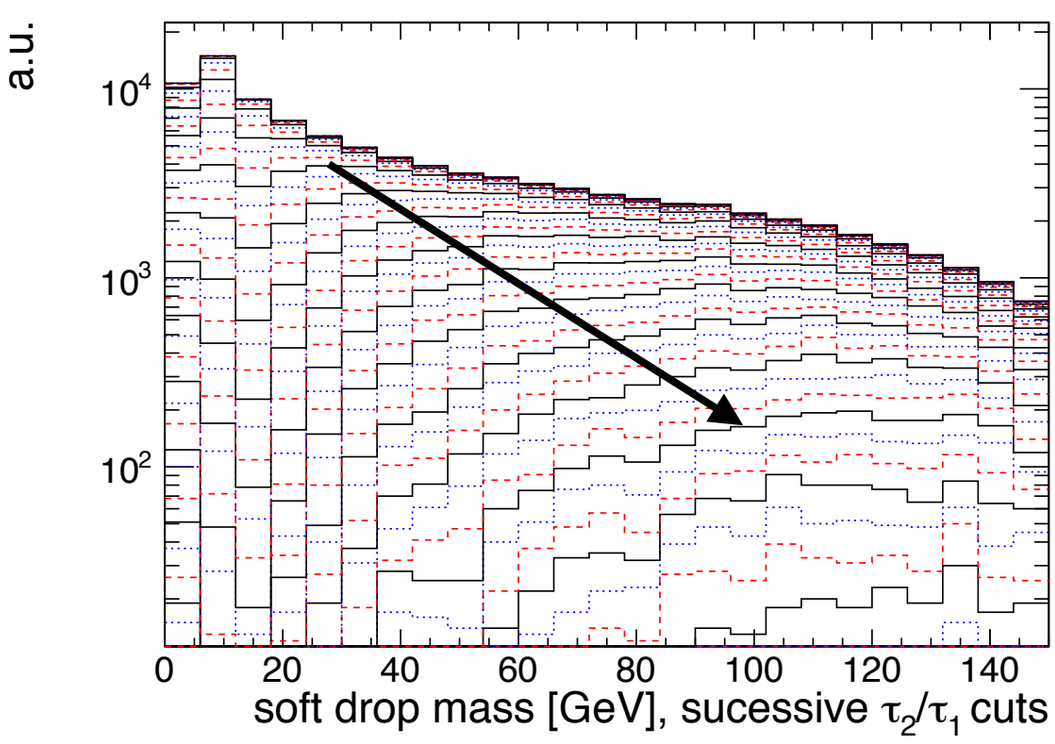
- To move forward, look at example analysis : WV resonances
  - QCD jet mass peaks roughly around the W mass
  - Want to smoothen the background to lower systematic uncertainties
- Soft drop helps, but does not completely solve the problem

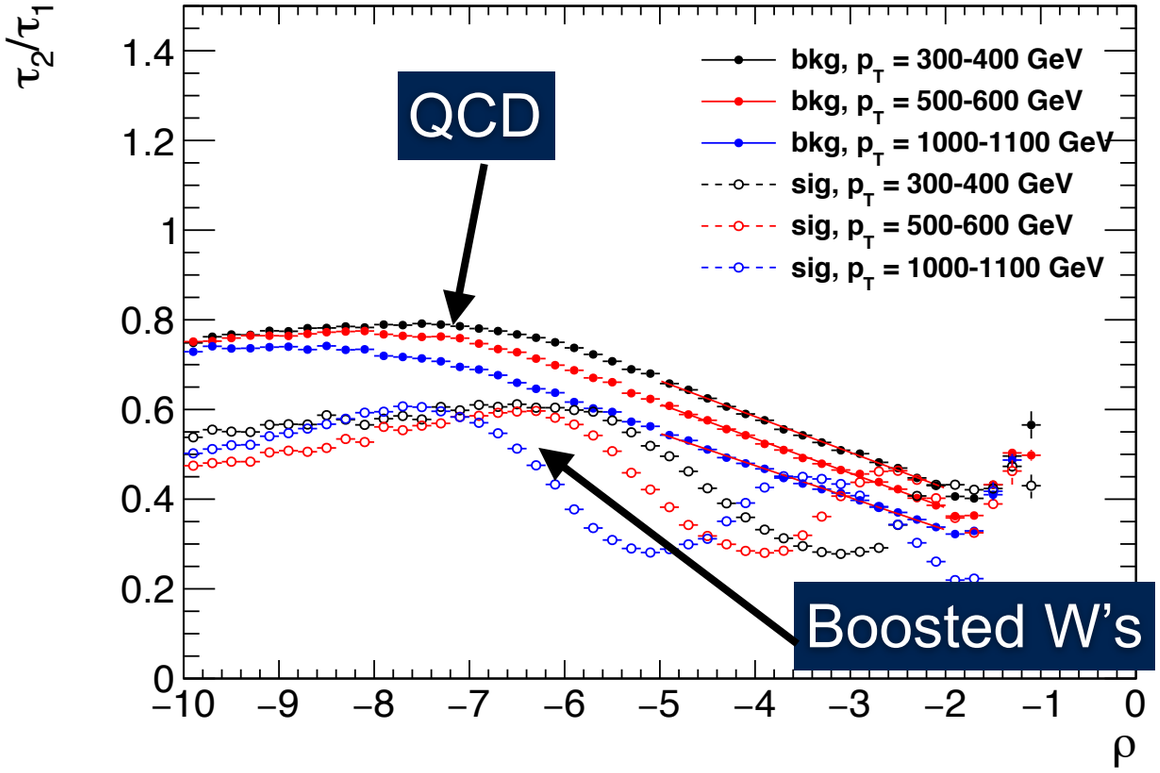


Scaling : Designing Decorrelated Taggers

Nontrivial m, pt scaling back again:
Peak creeps into W mass window

look at the correlation of τ_{21} with mass and pT





Want to remove the residual pT + mass dependences!

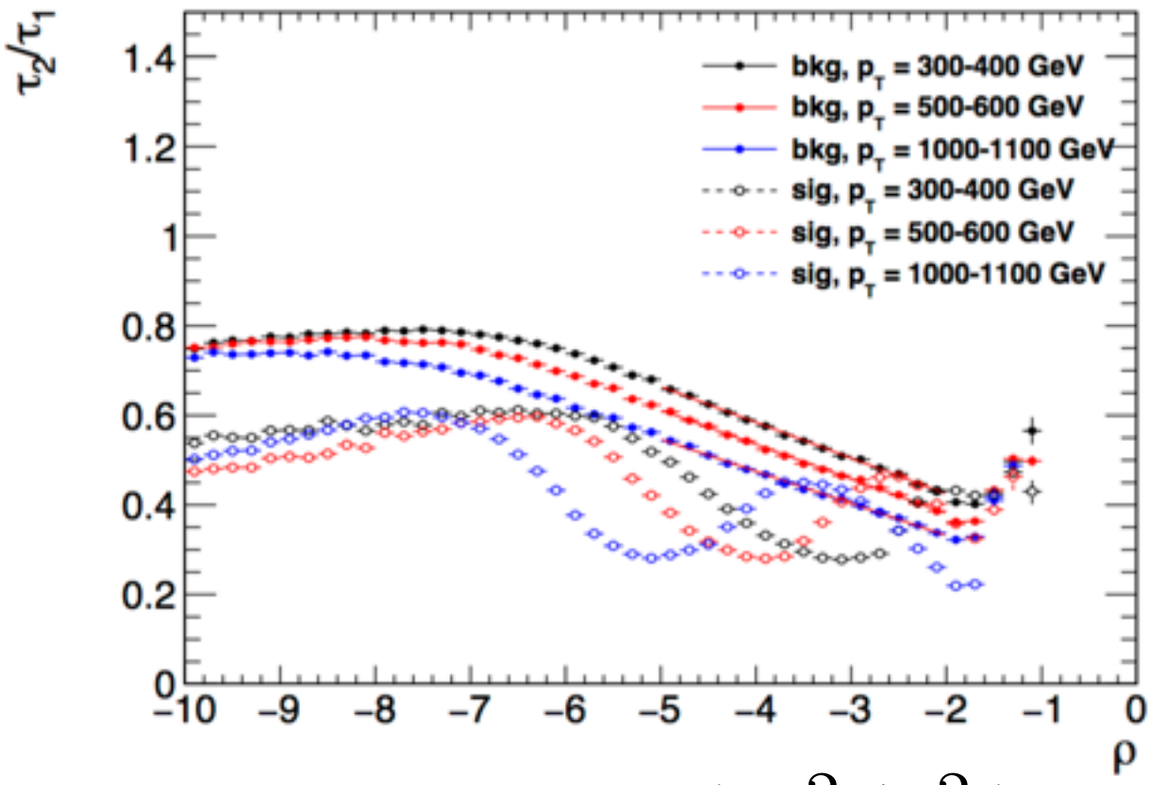
Scaling : Designing Decorrelated Taggers

- Rescale variable to remove pt dependence:

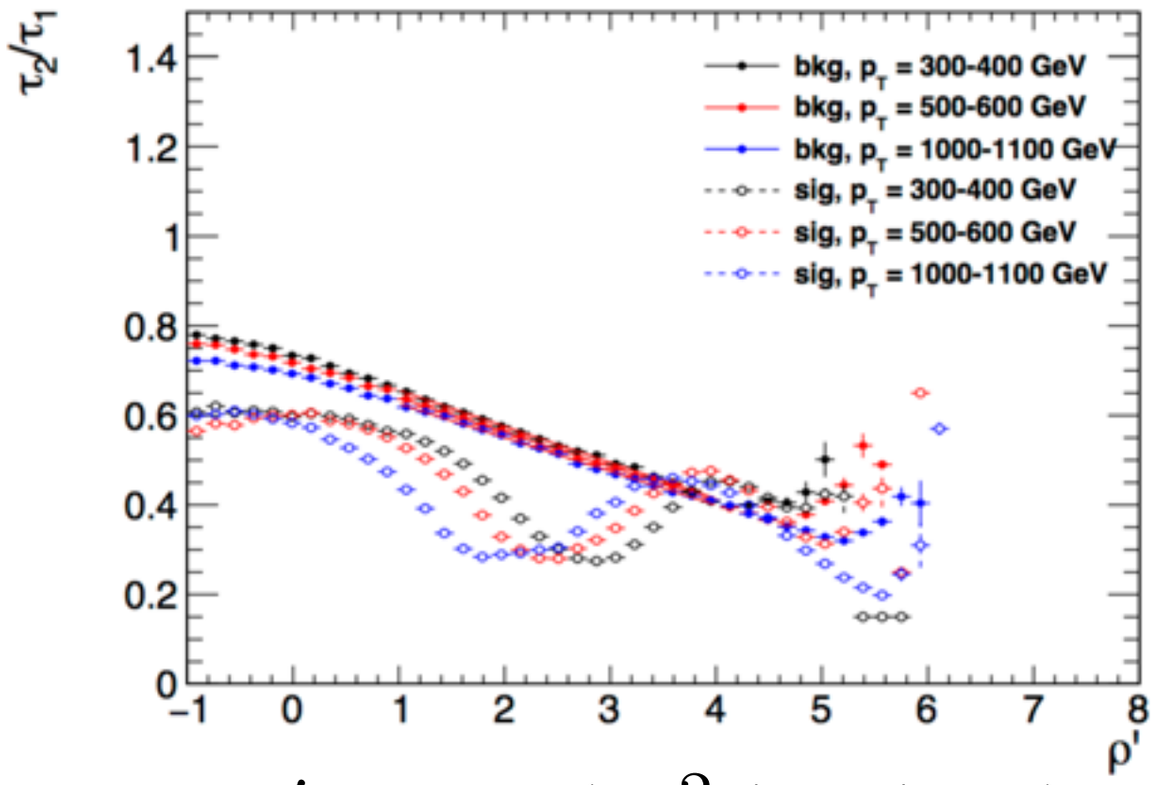
Define:

$\rho' = \rho^{DDT} = \log(m^2/pT/\mu)$

μ is to make it dimensionless, set to 1 GeV



$$\rho = \log\left(m^2/p_T^2\right)$$



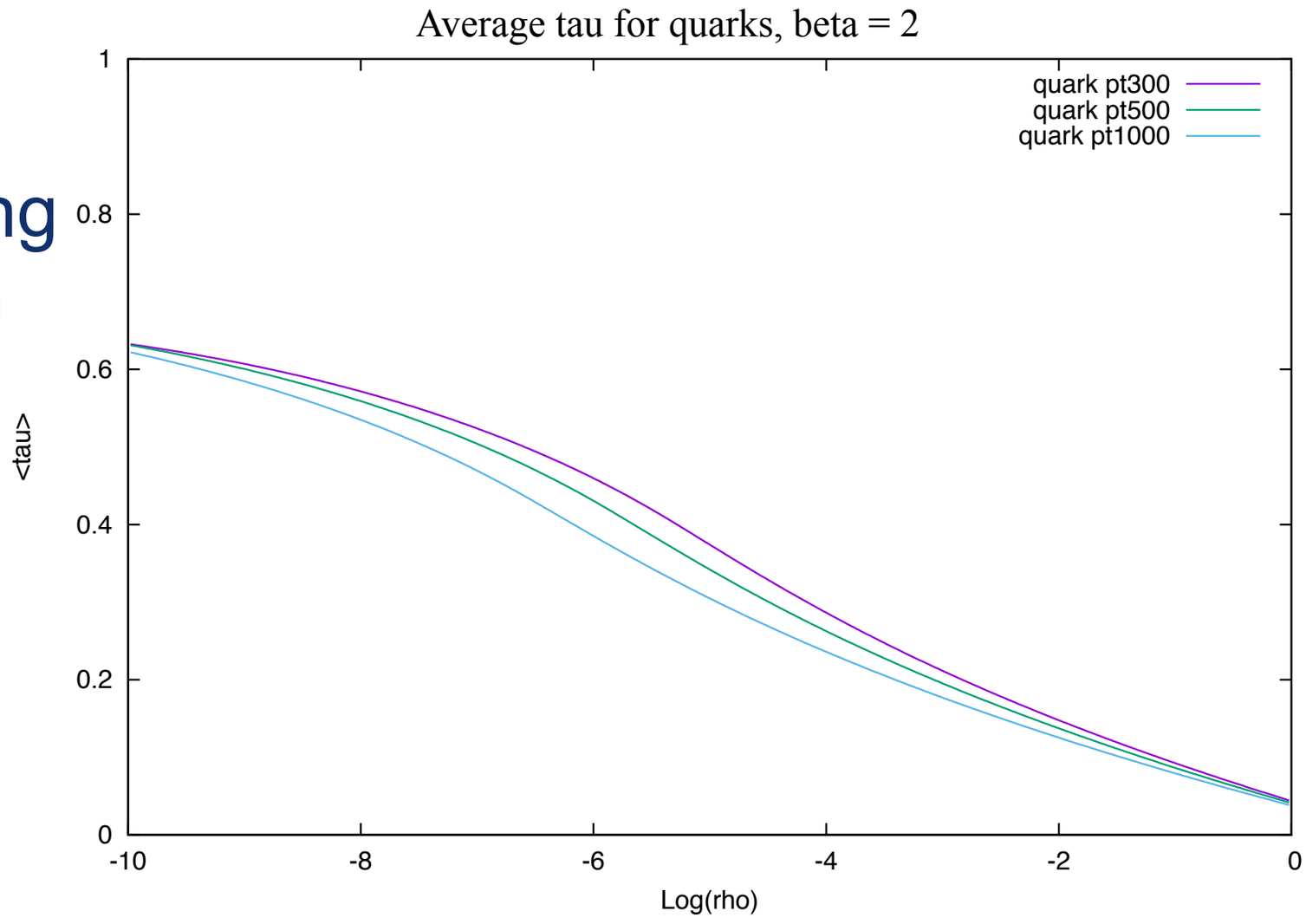
$$\rho' = \log\left(m^2/p_T/mu\right)$$

Scaling : Designing Decorrelated Taggers

- Dependence of tau on rho has a log(pt) scaling

$$\rho' = \log\left(m^2/p_T/\mu\right)$$

- What is the mu?
  - Currently calculating this, manifestation of alpha_s scaling



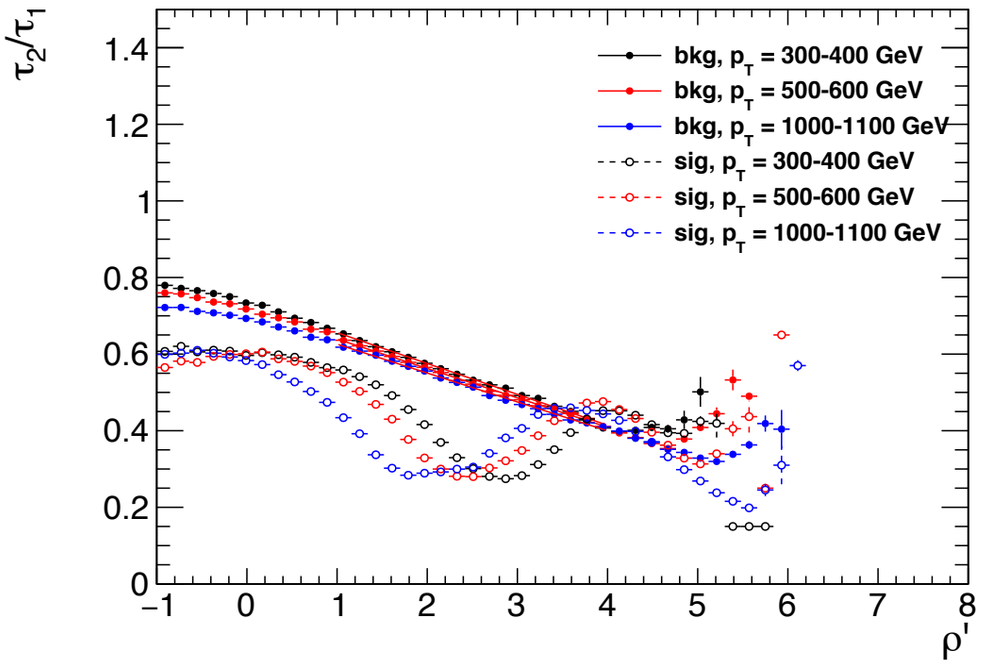
Work in progress :
from J. Baron, S. Marzani, L. Schunk, G. Soyez

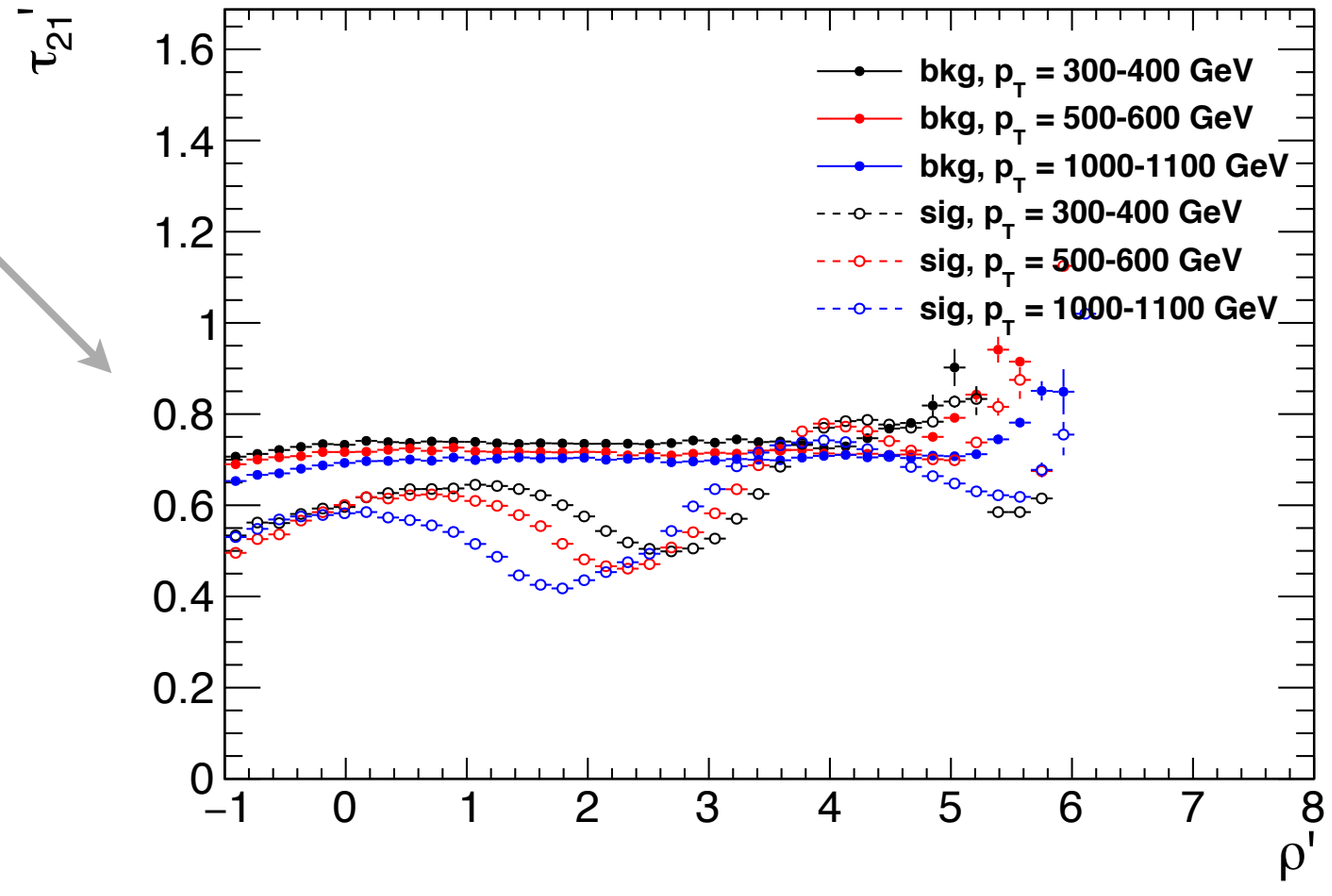
Scaling : Designing Decorrelated Taggers

Now linear correlation constant in bins of pT!

trivial transformation

$$\tau_{21}^{DDT} = \tau^{21} - M \times \rho^{DDT}$$



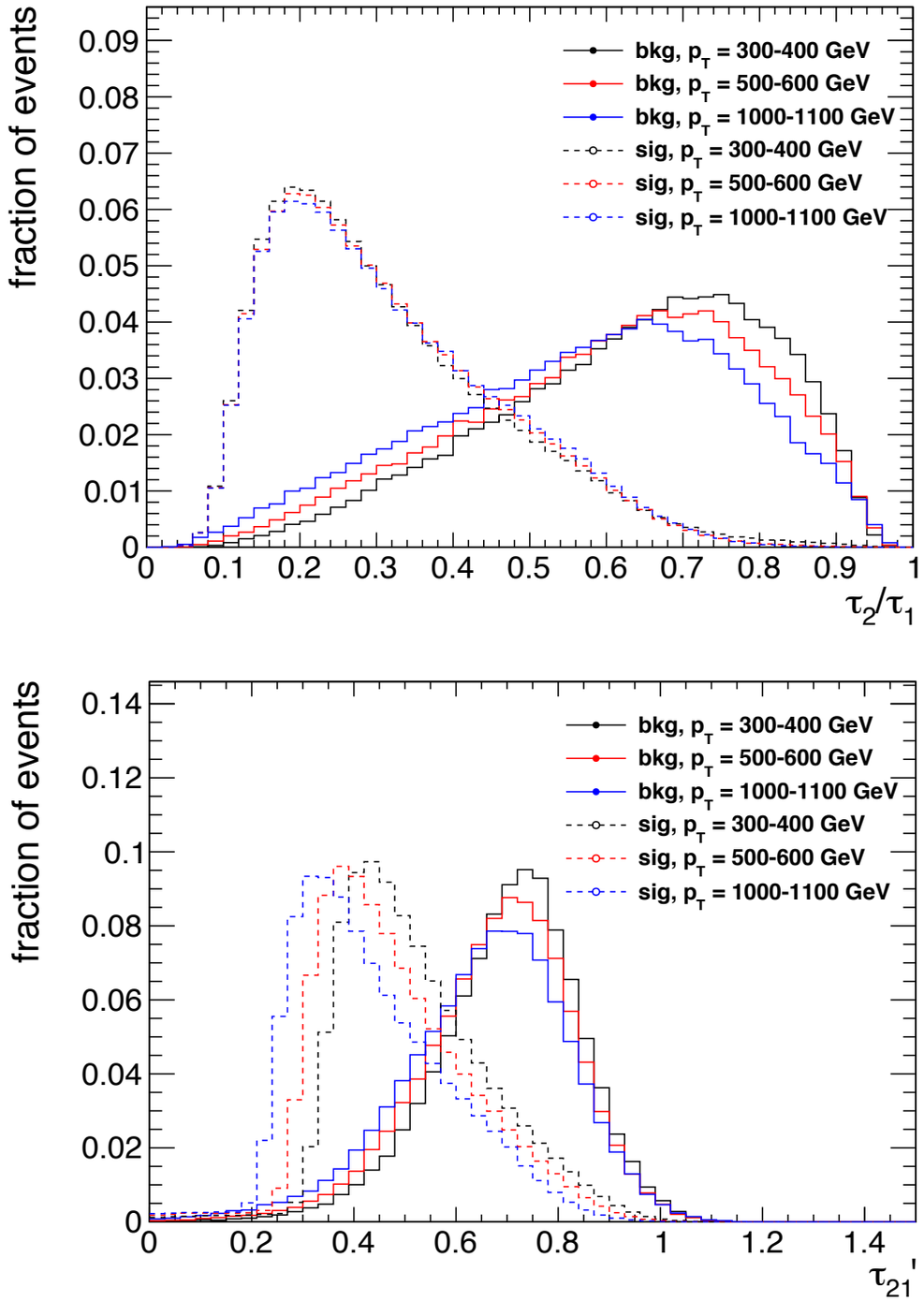


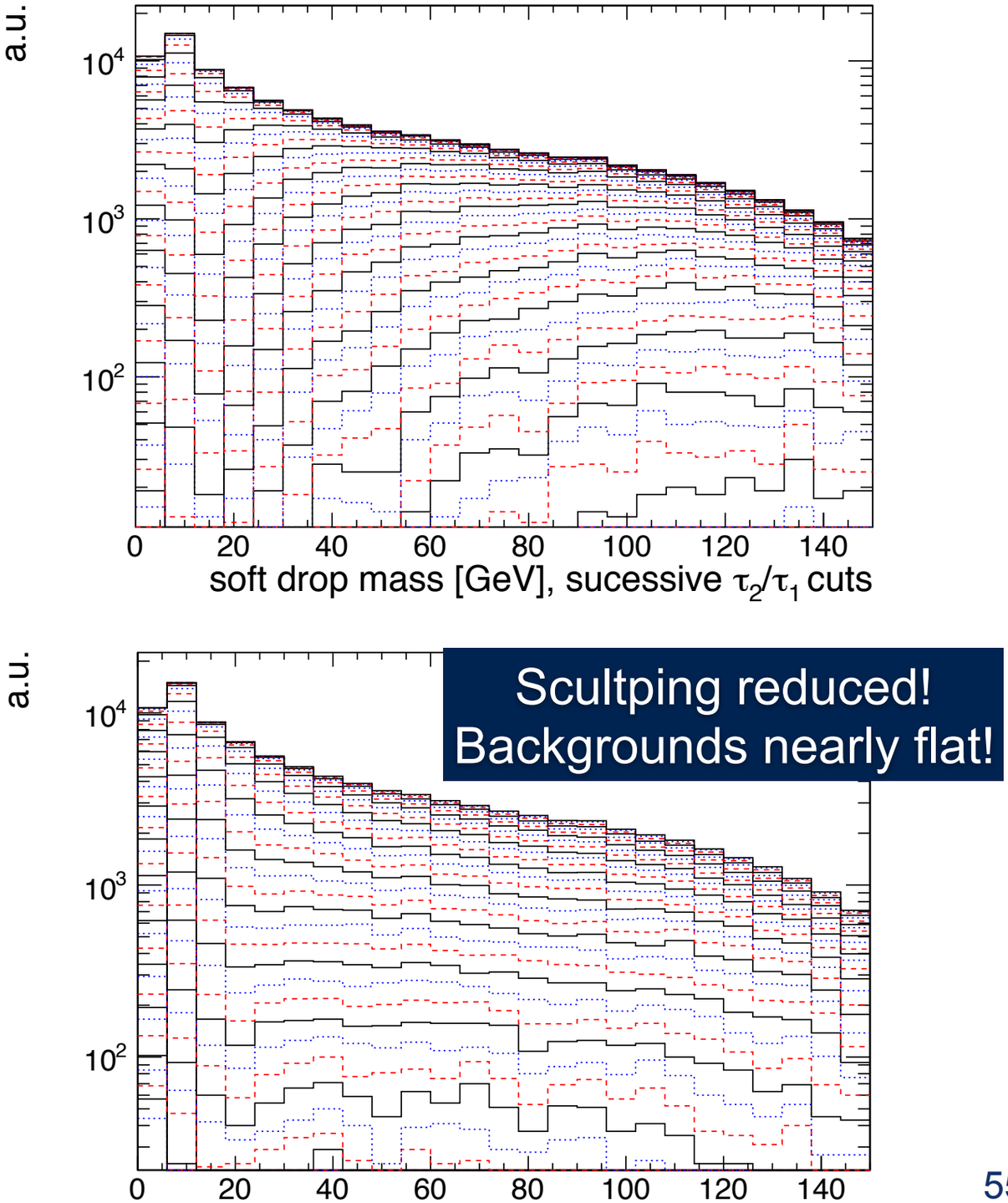
now τ_{21}^{DDT} is uncorrelated with ρ^{DDT}!
makes background estimation easier!

Scaling : Designing Decorrelated Taggers

- Keeping the same ROC performance, can **reduce sculpting** of backgrounds

transformation τ_{21} to τ_{21}^{DDT}

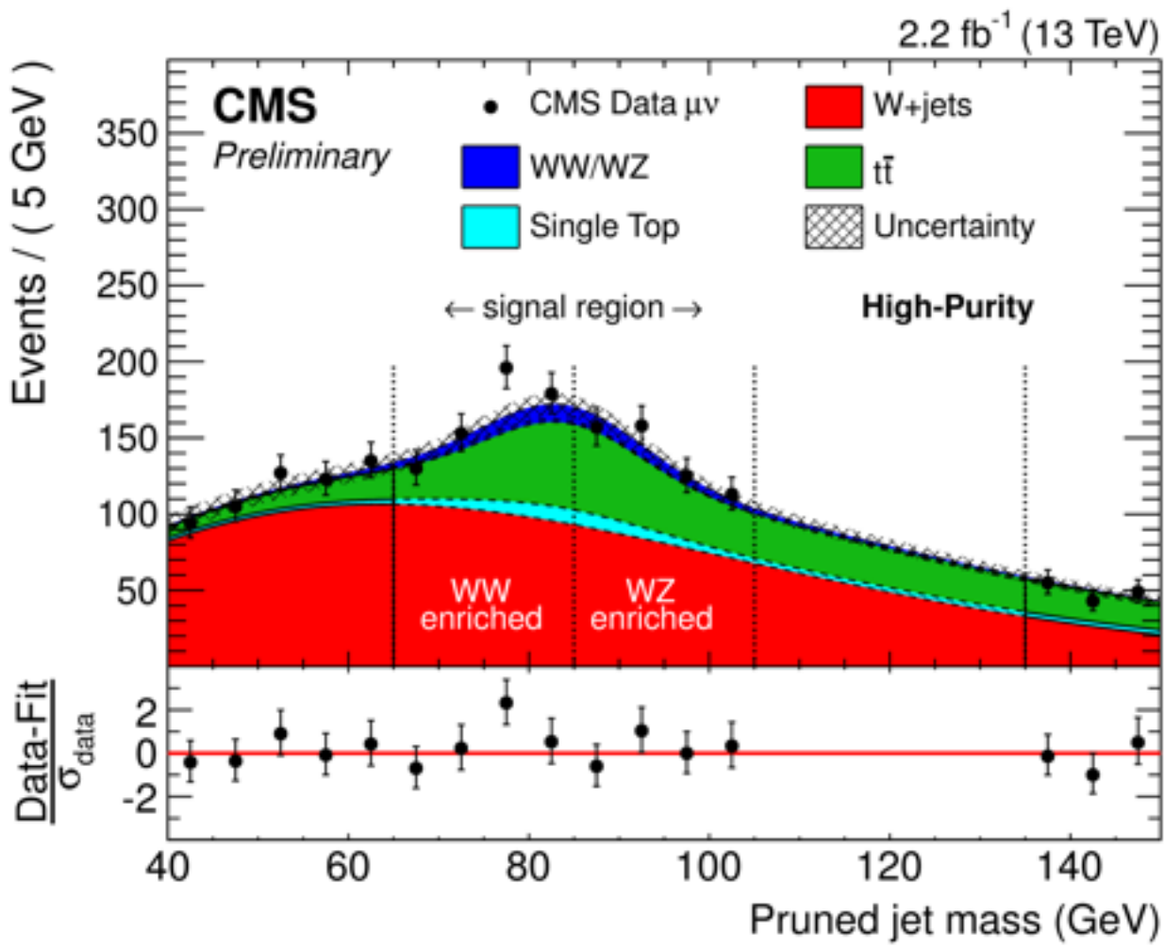




Scultping reduced!
Backgrounds nearly flat!

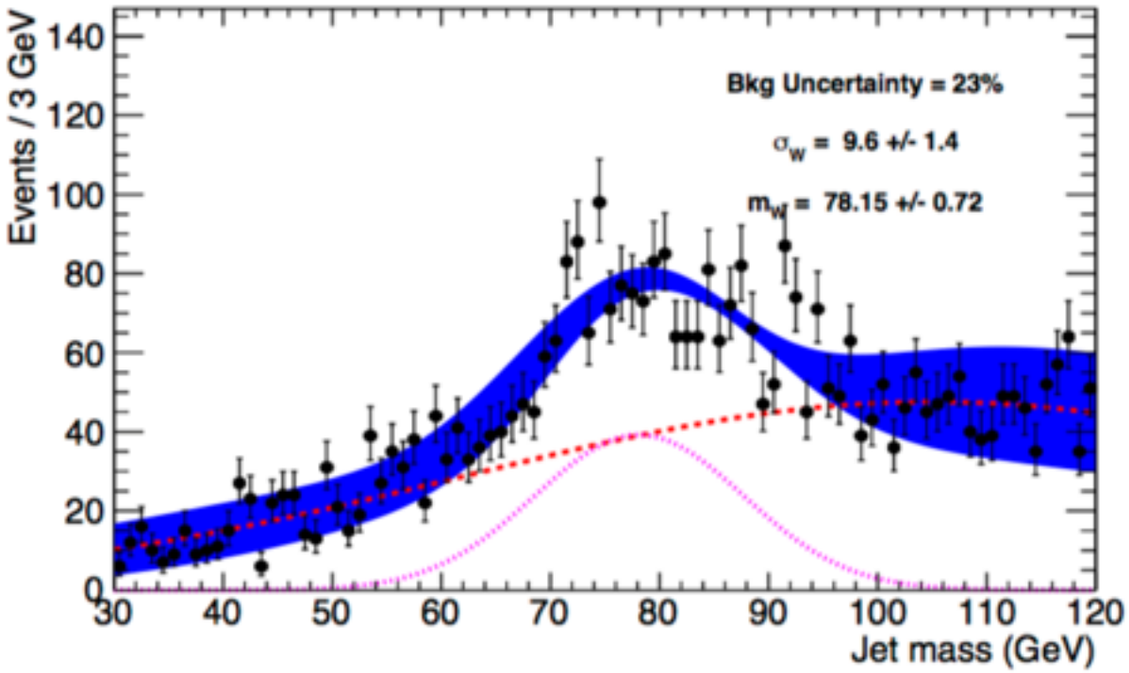
Scaling : Designing Decorrelated Taggers

- Example : Semileptonic diboson search
  - Signal: WW resonances
  - Background: QCD
- CMS search employs shape-based fit in “pass” and “fail” categories
- ATLAS also uses “pass” and “fail” categories

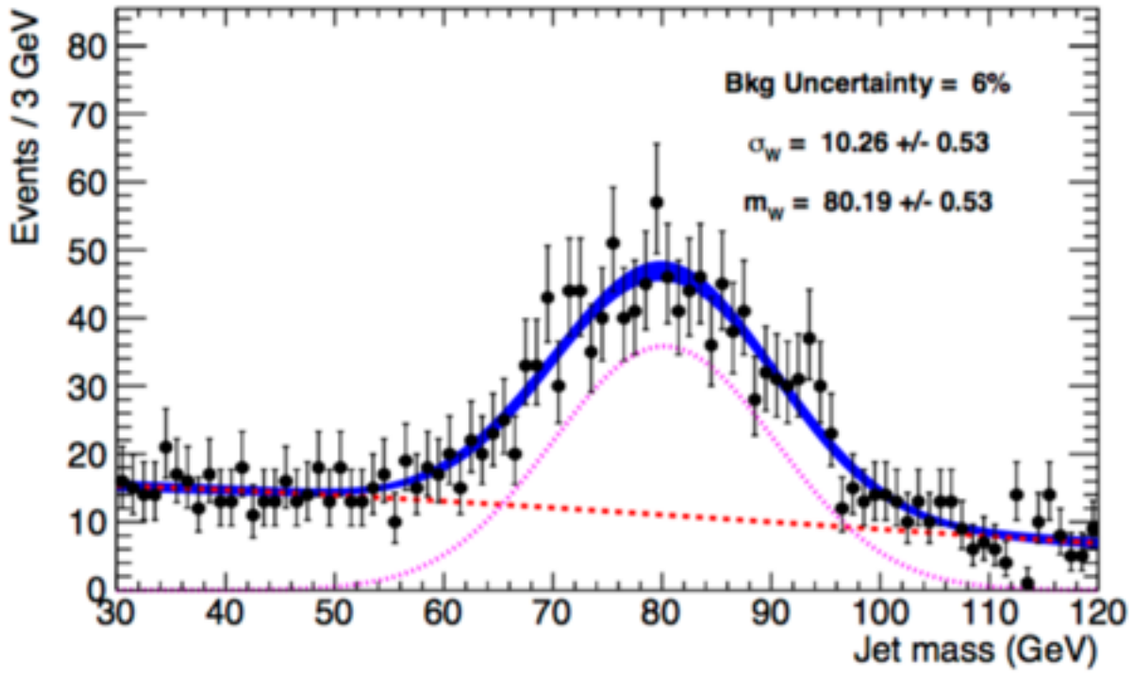


Scaling : Designing Decorrelated Taggers

- Now apply DDT:
  - Backgrounds are better behaved! Reduced systematics!
  - Example: m = 2 TeV



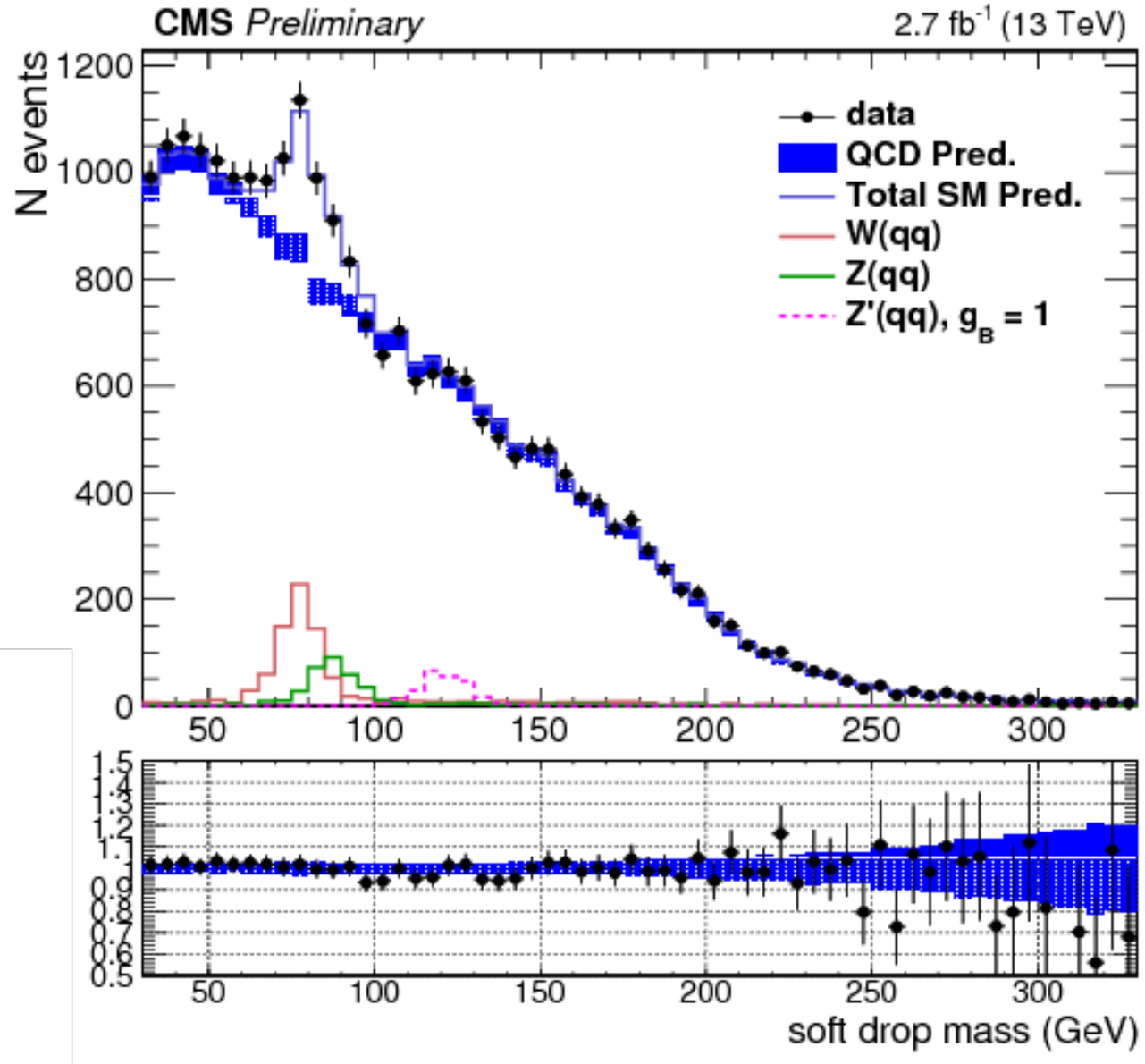
Bkg normalization unc: 23%

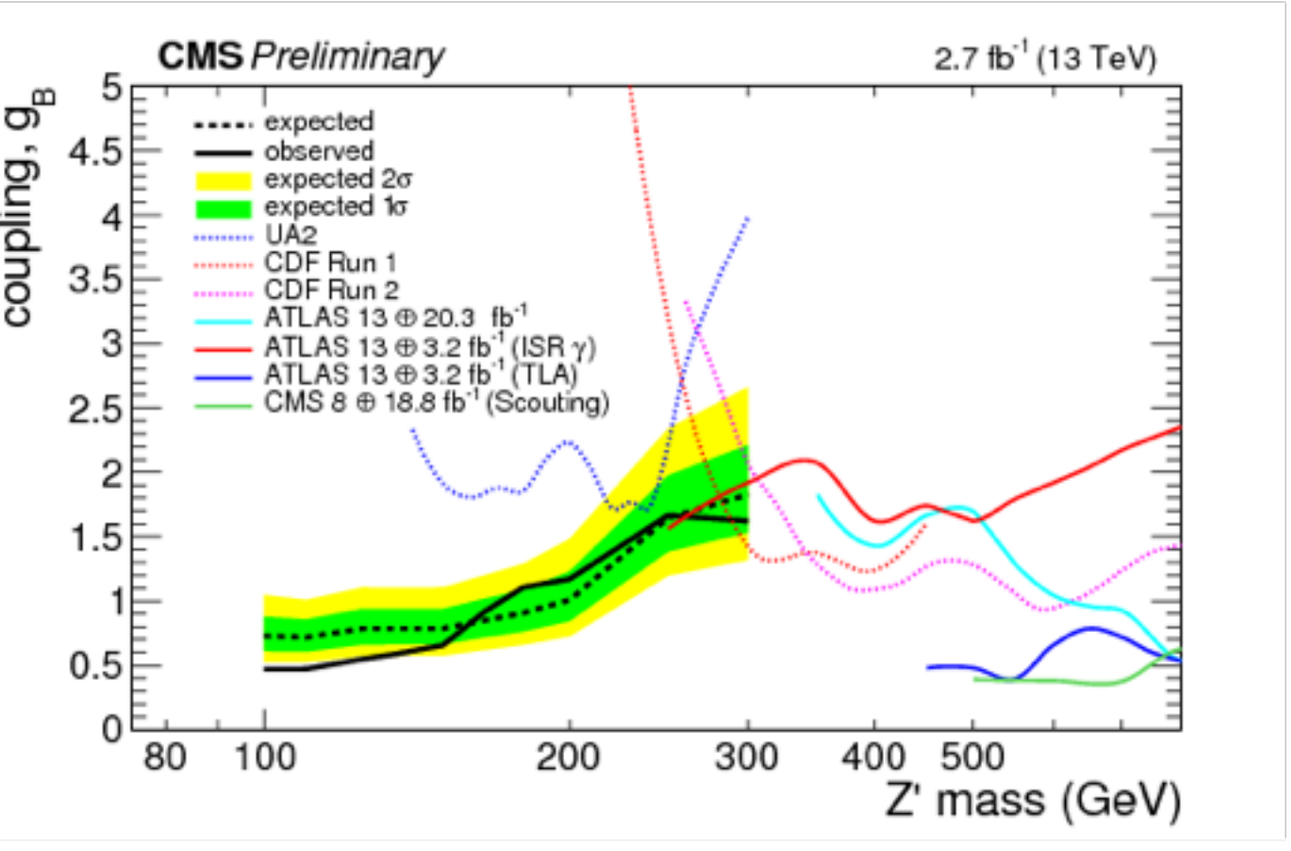


Bkg normalization unc: 6%

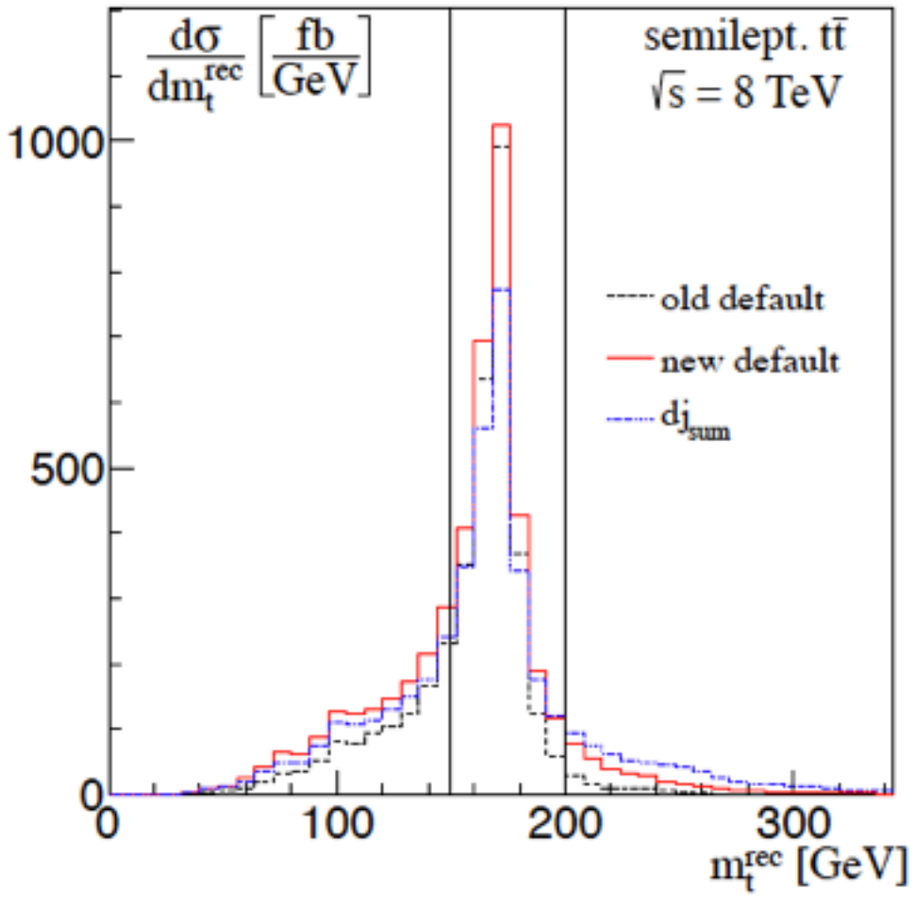
Scaling : Designing Decorrelated Taggers

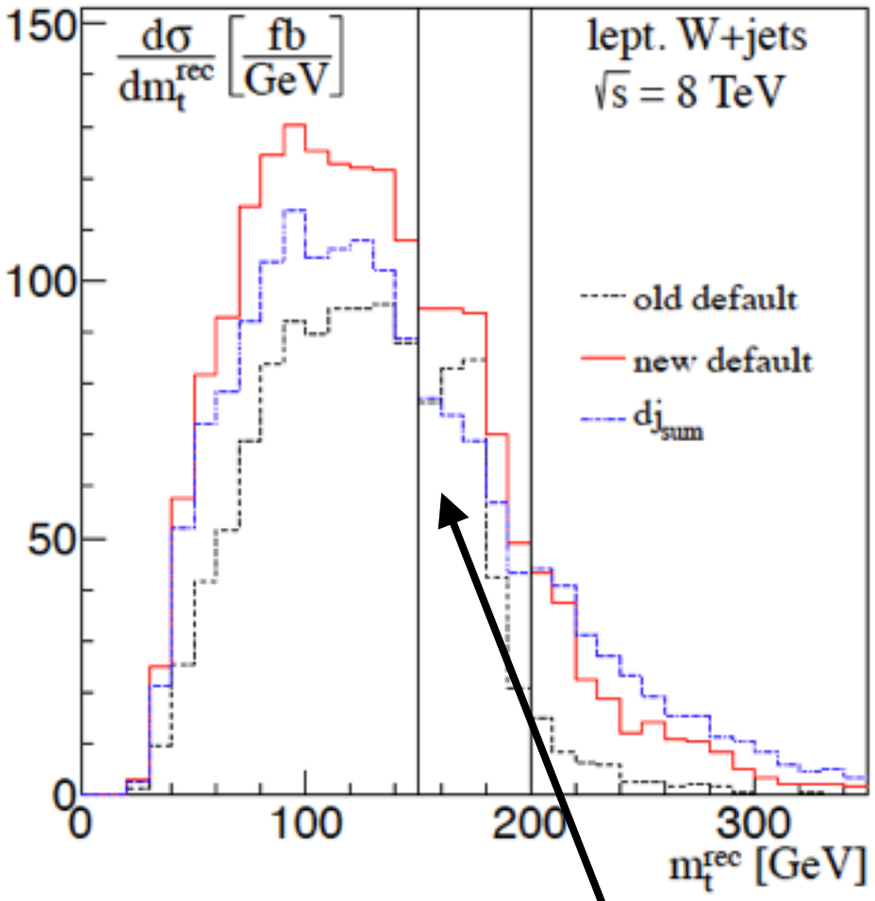
- Example :
  - Low-mass Z->dijets
  - Needs smooth turn-on at low jet mass to see the Z peak
  - Limits have not been improved here since UA2!





Improving scaling/sculpting : HEPTTV2





Yay! Blip in bkg is gone!

Benchmarking an Even Better HEPTopTagger

Anders, Bernaciak, Kasieczka, Plehn, Schell

arXiv:1312.1504

Better angularities : D2

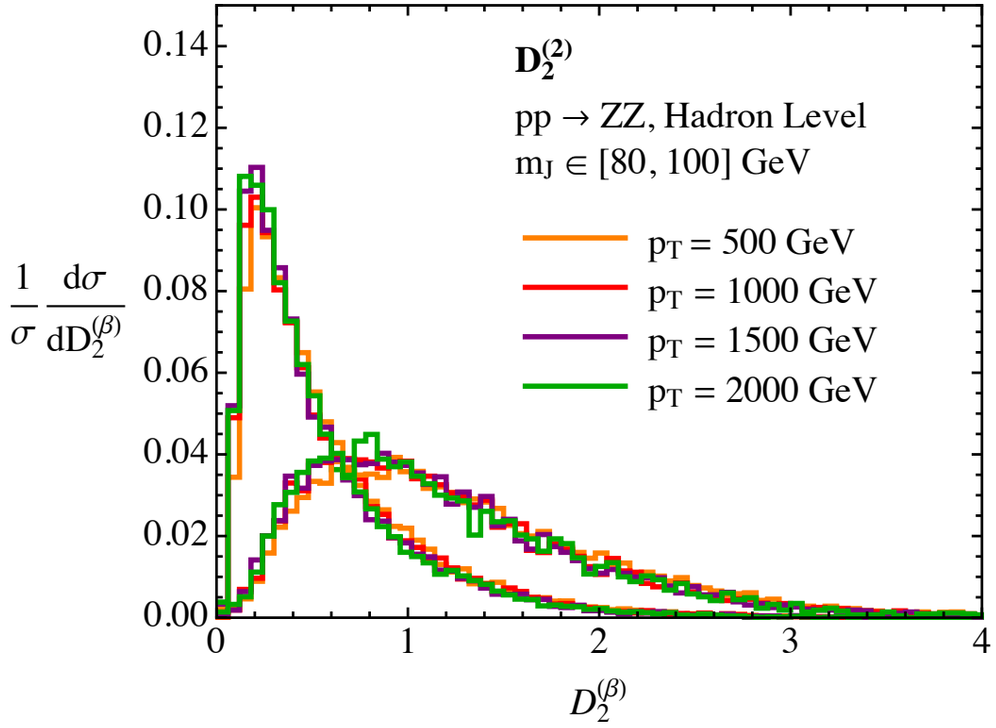
Stability

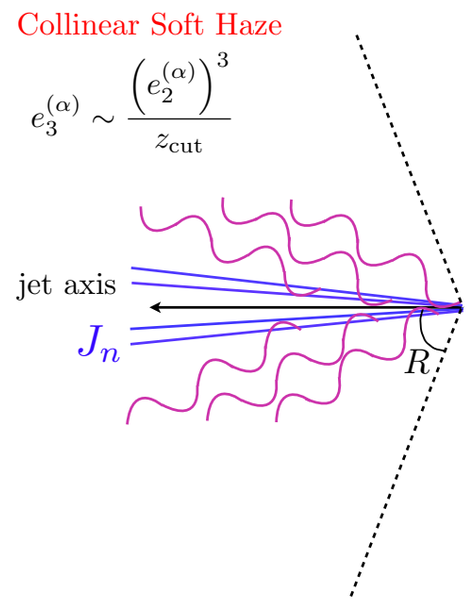
JHEP 1612 (2016) 153

- Soft dropped D_2 distribution largely independent of
  - jet mass
  - jet p_T

Slide from Ian Moult

$$D_2^{\text{max,softdrop}} \sim \frac{1}{2 z_{\text{cut}}}$$





- Extremely stable discriminant!
- Expansion about small values insufficient to describe endpoint.

Outlook

- Lots of analyses ongoing on CMS for Moriond
- Algorithms are becoming very robust and well understood
- Moving away from MC-level ROC curves, looking at systematic behavior to improve to the next generation
  - Utilizing theory community input in the coming turns
- Stay tuned this year for many exciting results!
  - One in addition : jet mass measurement with mMDT/soft drop beta=0, compared to analytic calculation beyond NLL for the first time!

Backups