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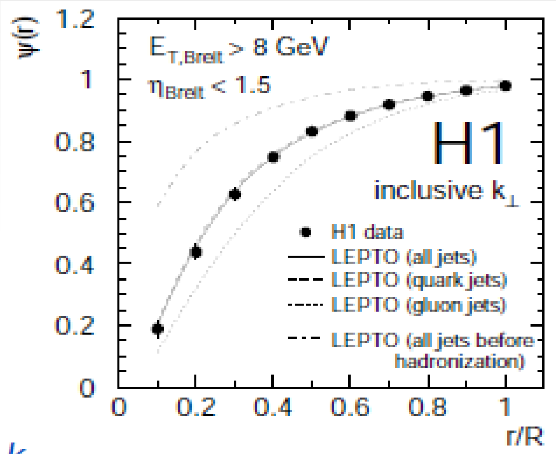
Jet substructure and boosted objects at the LHC

1) General concepts and think-around
2) Precision era for boosted physics
3) Identification of heavy objects
4) Application to the searches

On behalf of the CMS and Atlas collaborations

1.1) A bit of history

- Jet shapes existed already in the previous generation of colliders (LEP, HERA, Tevatron) times.
  - Study QCD parameters and soft gluon effects.
  - Improve jets calibration for non-compensated calorimeters.
  - Distinguish jets flavours:
    - quark, gluon – all sorts of energy flows;
    - c-jet, b-jet – “charge” flow like vertices or displaced tracks.
    - Up/down – jet charge (see later...).



DESY-98-208

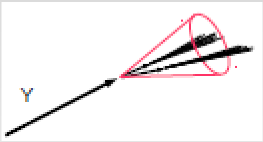
- But the QCD matrix element: $d\sigma \sim \alpha_S \, d\theta / \theta \; dk_T / k_T$
  - No intrinsic mass above b-quark mass (4-5 GeV depending on the definition). Just QCD radiation.

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

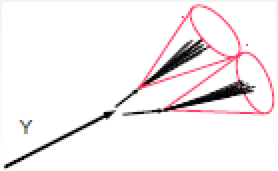
  - No intrinsic angular scale = no instrinsic multipolar structure.

1.2) The boosted regime and substructure

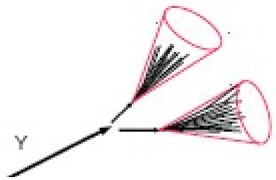
1) Substructure : $\Delta R < R_j$

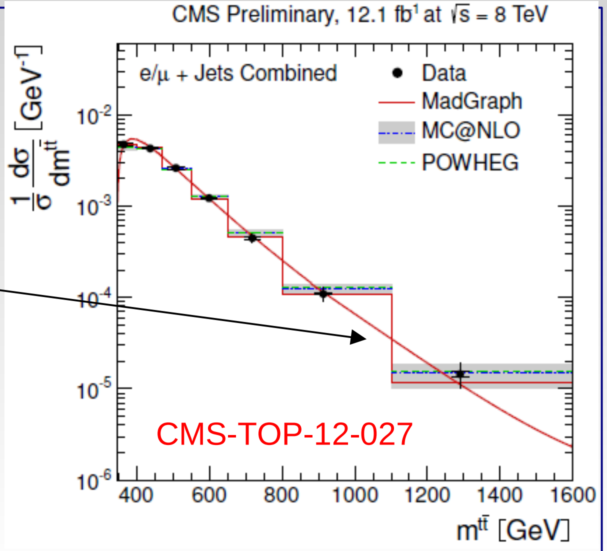


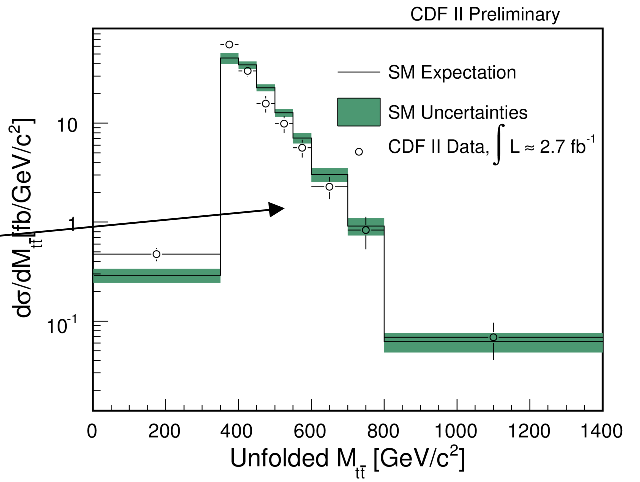
2) Transition region : $\Delta R \sim R_j$



3) Separated jets : $\Delta R > R_j$

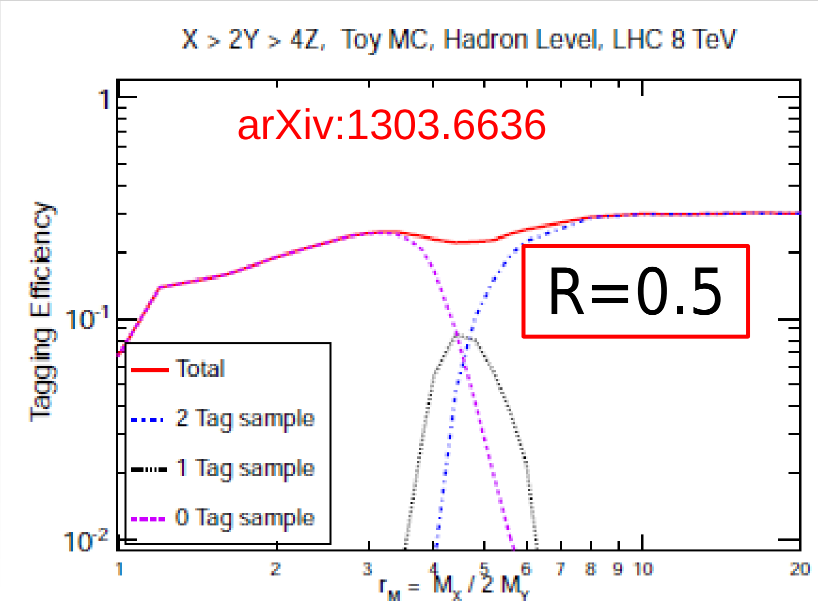


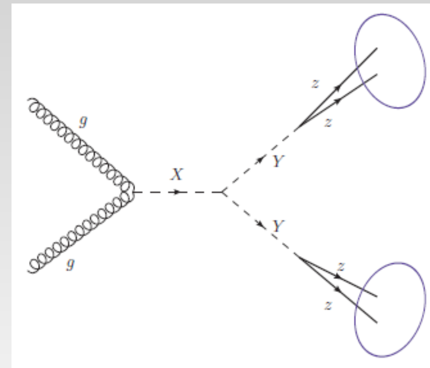




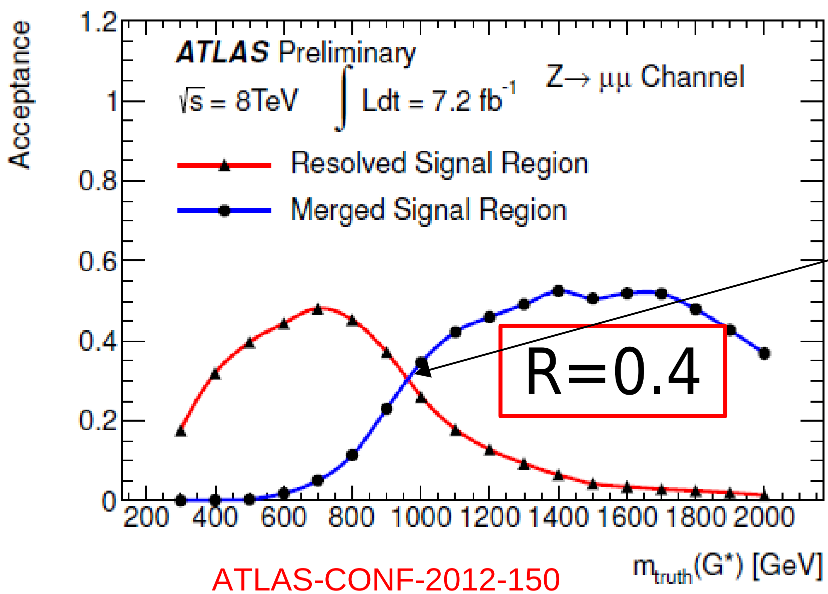
Typically pair production: $\Delta R = \frac{4M_Y}{M_X} \approx \frac{2M_Y}{p_T} \approx \gamma_Y$ $\Delta R = \frac{4M_t}{M_{tt}}$

1.3) The boosted regime and substructure





		P_{min} or $P_{T,min}$ (GeV)	
M (GeV)		R = 0.4	R = 0.7
b	5	25	15
W	80	400	230
Z	91	460	260
H	125	625	360
Top	171	880	500
New ???		???	???



$$p_Y = \frac{2M_Y}{\Delta R_{\min}}$$

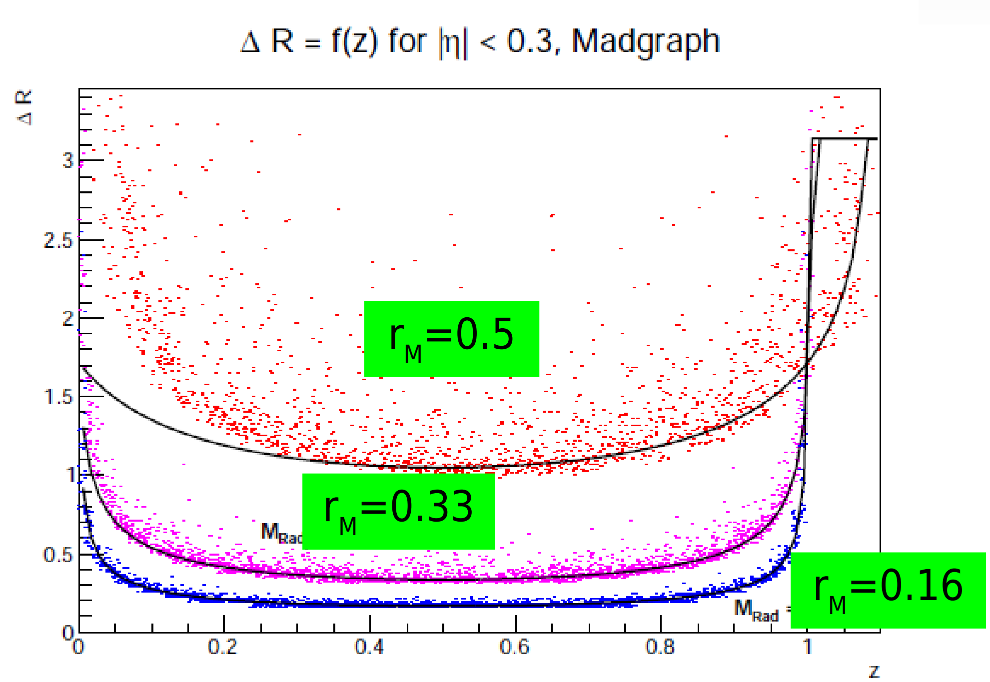
1.4) The boosted regime and substructure

- All V taggers might be described in the plane:

$$z = \frac{p_{T,1}}{p_T}$$

$$\Delta R = \sqrt{(\phi_2 - \phi_1)^2 + (\eta_2 - \eta_1)^2}$$

- In Y rest frame: 1 degrees of freedom θ^* .
- Boost: 1 degree of freedom r_M. Then $\Delta R = f(\theta)$!



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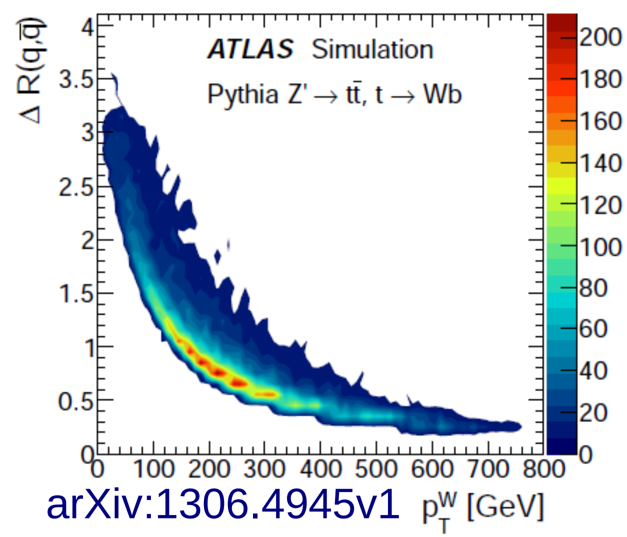
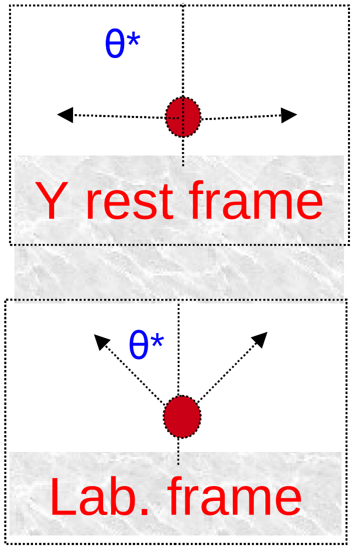
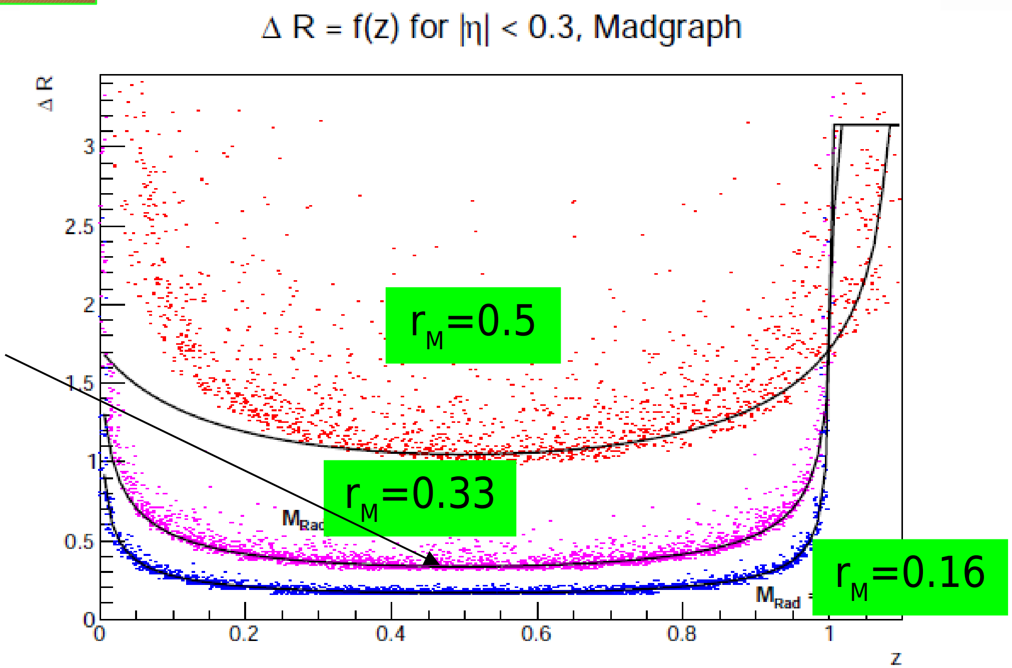


arXiv:1306.4945v1

Symmetric - low ΔR



$$\Delta R = \frac{4M_Y}{M_X}$$



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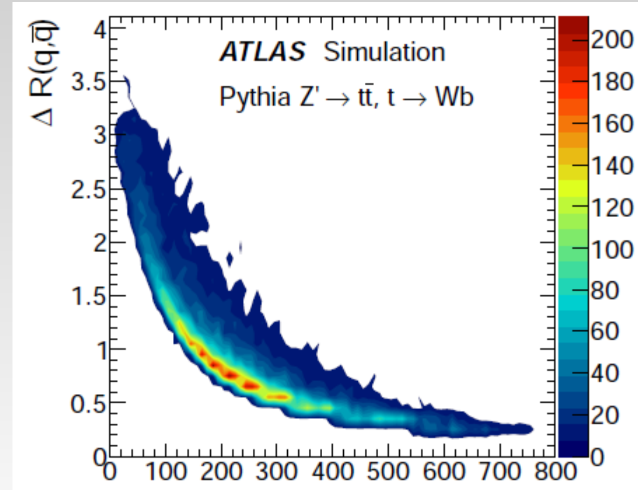

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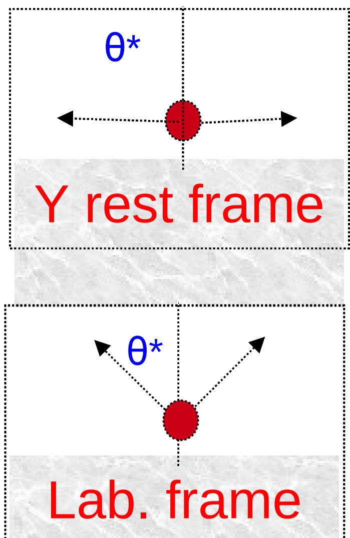

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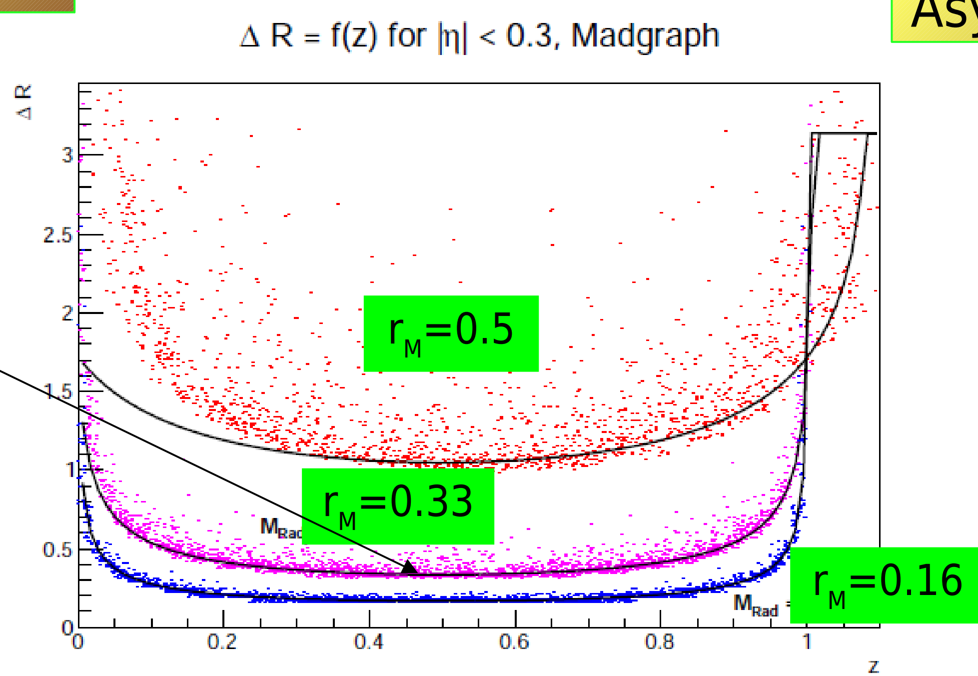
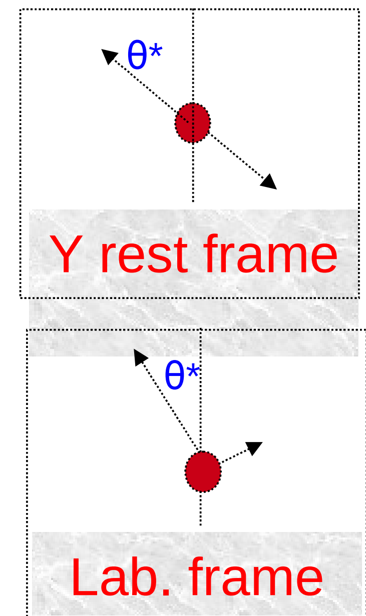


Asymmetric - high ΔR



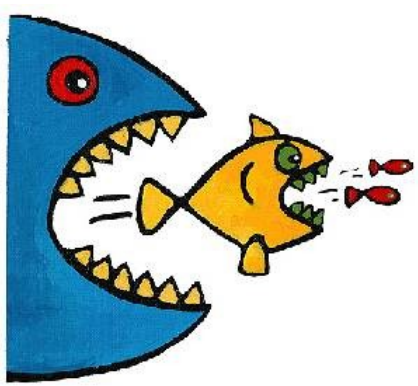
1.5) Jet clustering and substructure: role of the clustering order

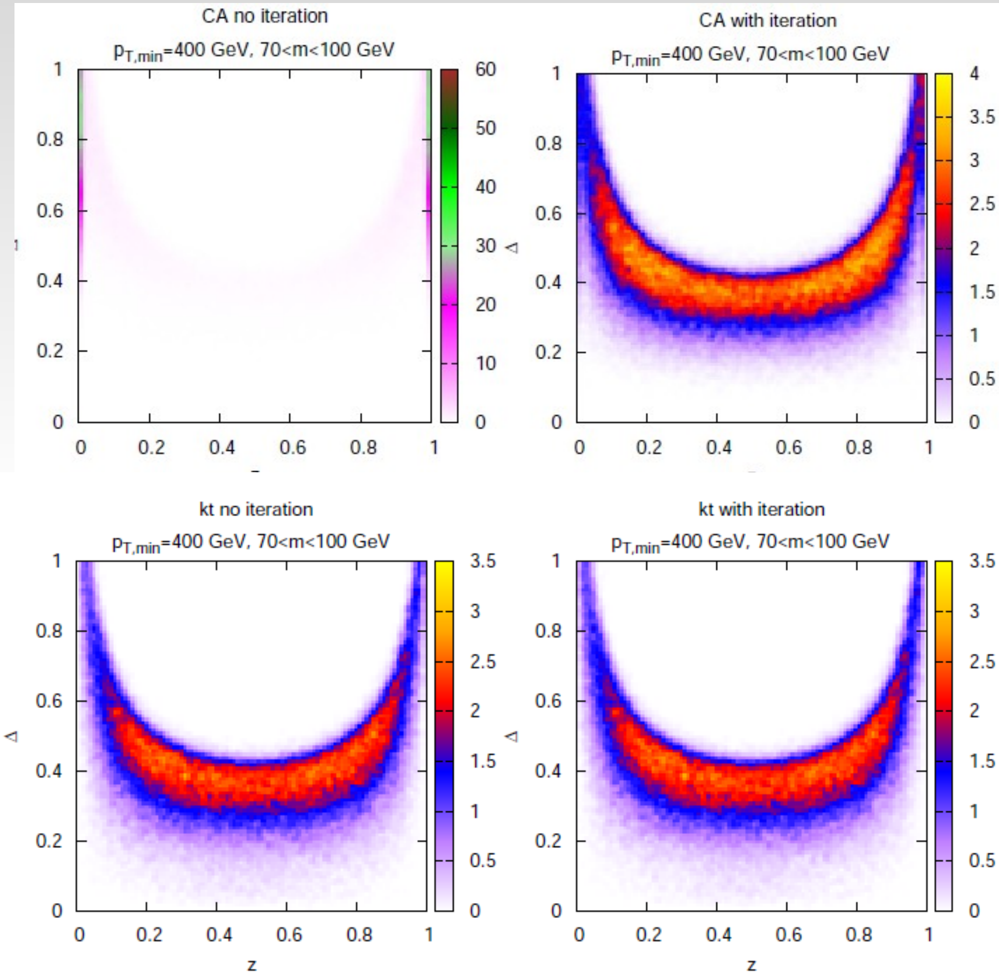
$$d_{ij} = min(k_{ti}^n, k_{tj}^n)\Delta R_{ij}^2 / R^2$$

N = 1: k_T – “Small fish eat first”

N = 0: CA - “Closest fish eat first“

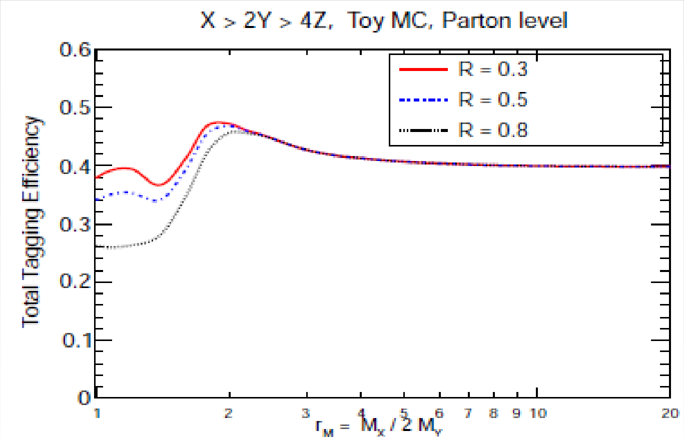
N = -1: anti-k_T “Big fish eat first”



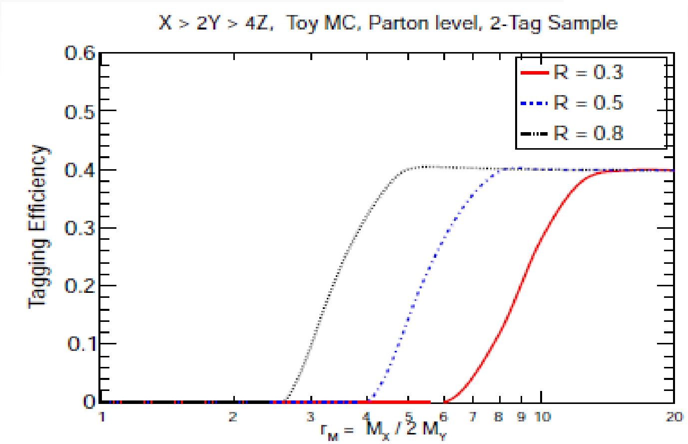


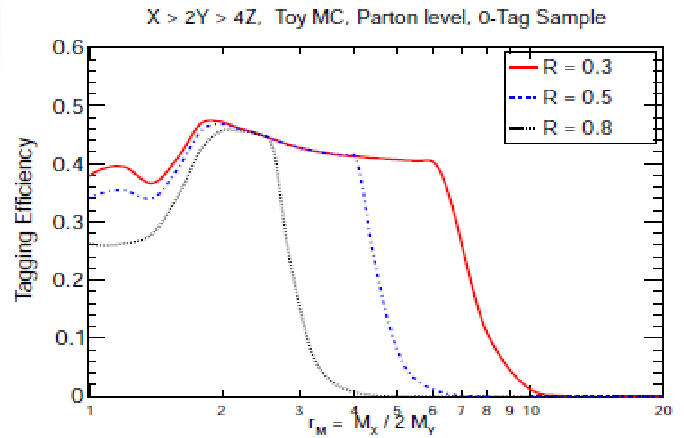
arXiv:1209.2858

1.5) Jet clustering and substructure: role of R



arXiv:1306.6219





- Pairing of jets (superstructure) or looking for subjets (substructure) is an equivalent activity! Fronter defined by R and M(V).
- You need jets to make sense in QCD and calibration.
- One can tune super/sub-structure cuts to have a smooth transition.

1.6) V-tagging in a nutshell

- Remove soft large angle radiation
- Remove PU and UE

GROOMING :
prunning, trimming, filtering

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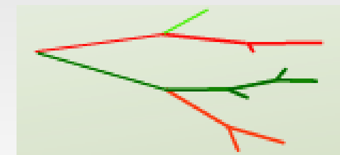
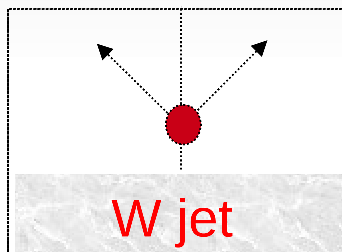
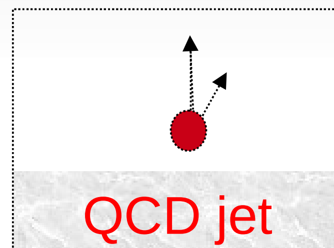


TAGGING:
N-subj.,
Splitting
scales...

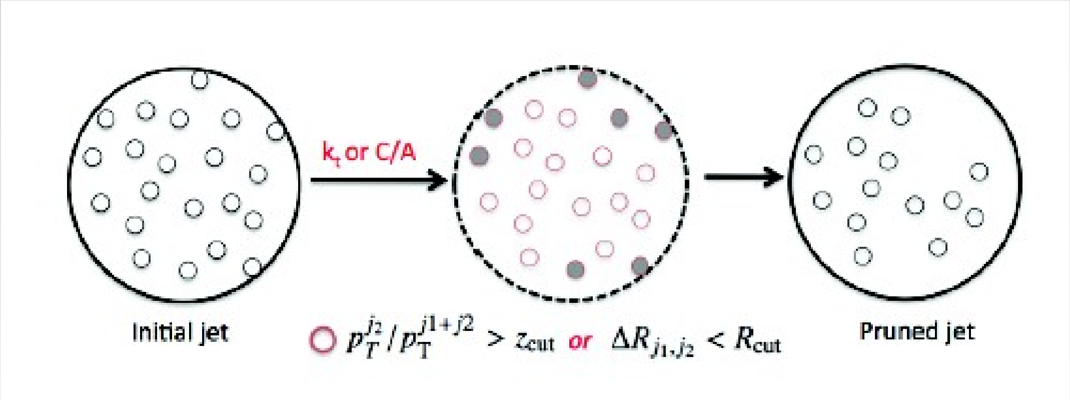




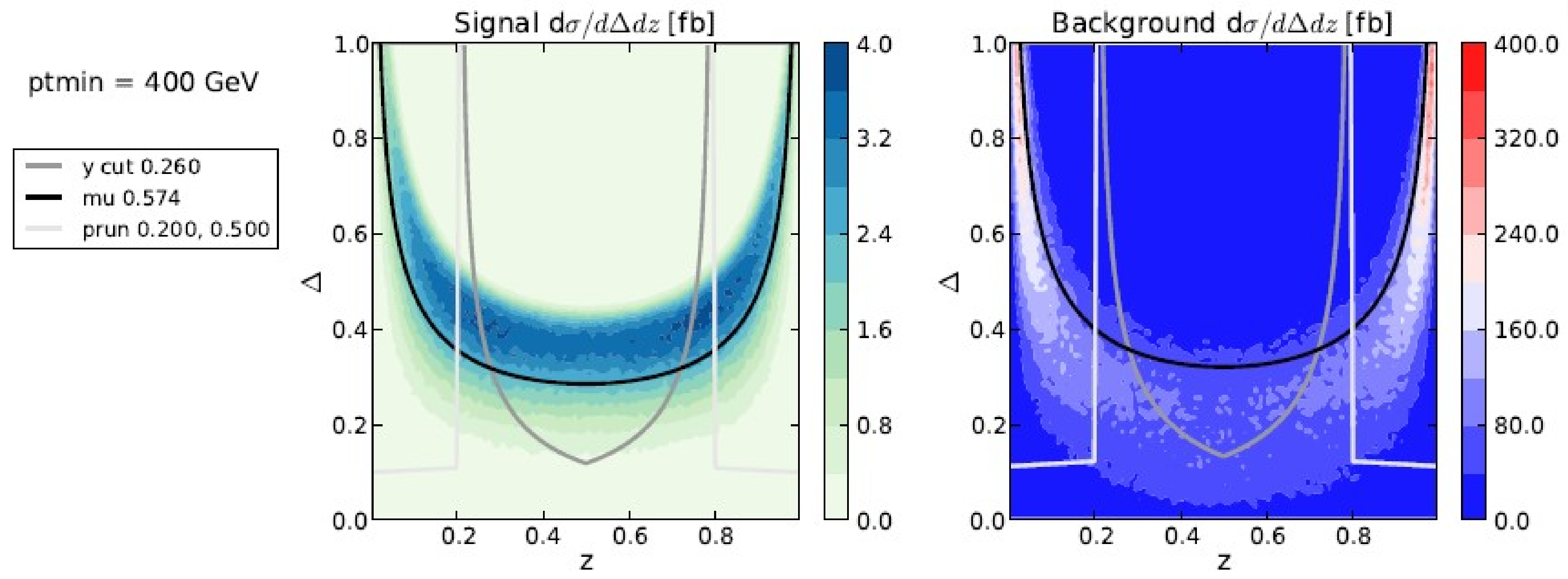
TAGGING :
Jet mass,
Mass drop...

- Use taggers to decide if the jet looks like a “rather symmetric massive dipole” or “hard parton with a soft/collinear radiation”.
- Could be done after or before grooming.
- Need to account for possible FSR in V production.
- For example: Jet mass works well only after grooming;
Pruning can degradate N-subjettiness by removing asymmetric W;

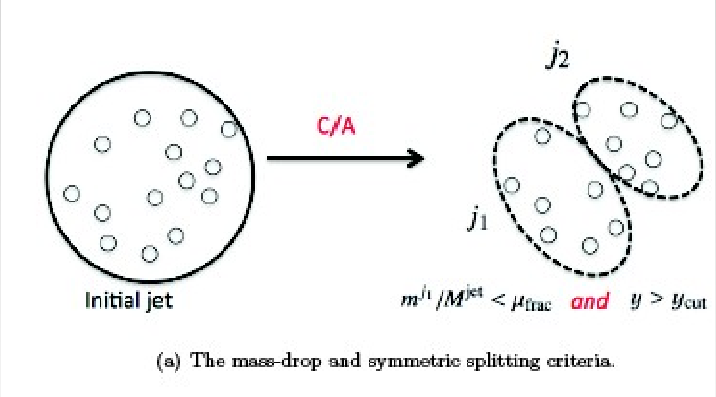
1.7) Algos: Prunning algorithm



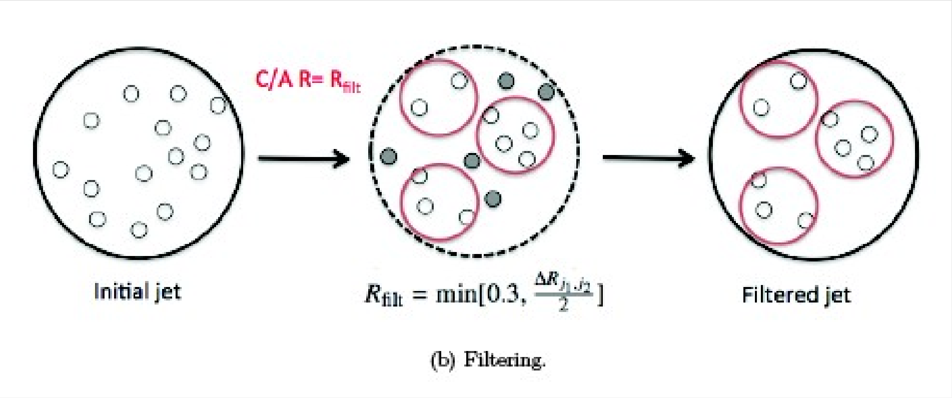
arXiv:1209.2858



1.8) Algos: Mass drop + Filtering

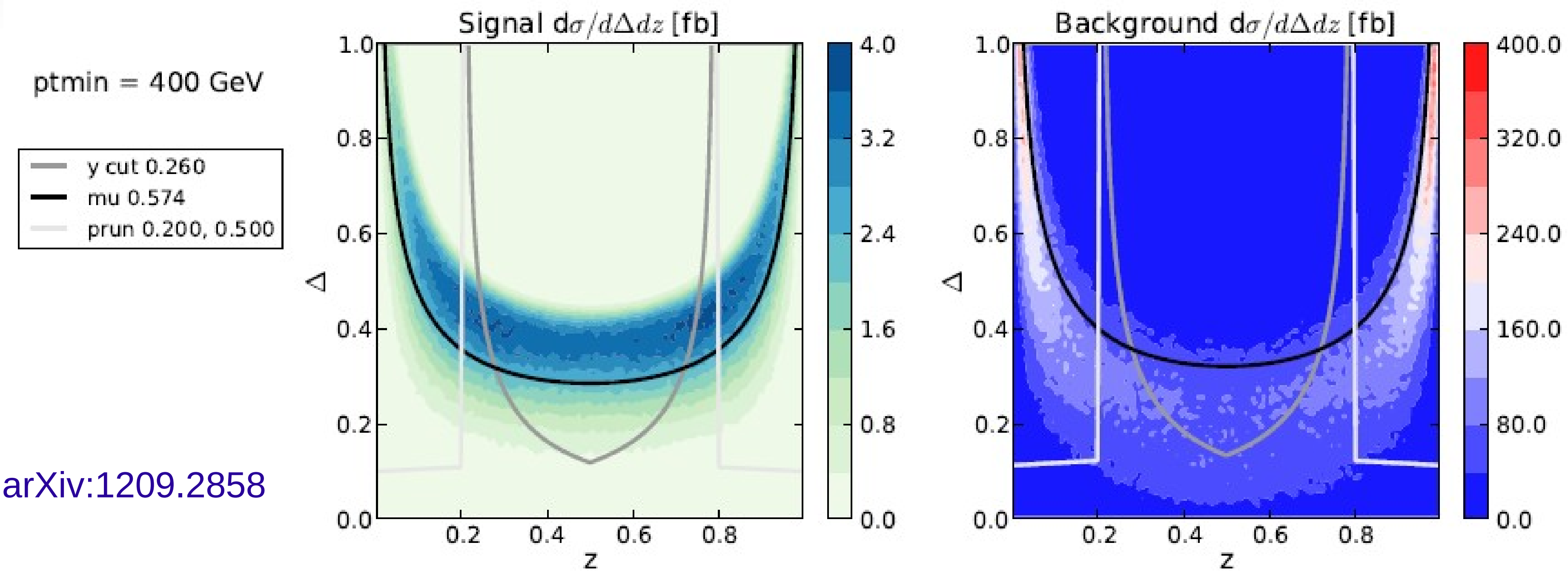


(a) The mass-drop and symmetric splitting criteria.



(b) Filtering.

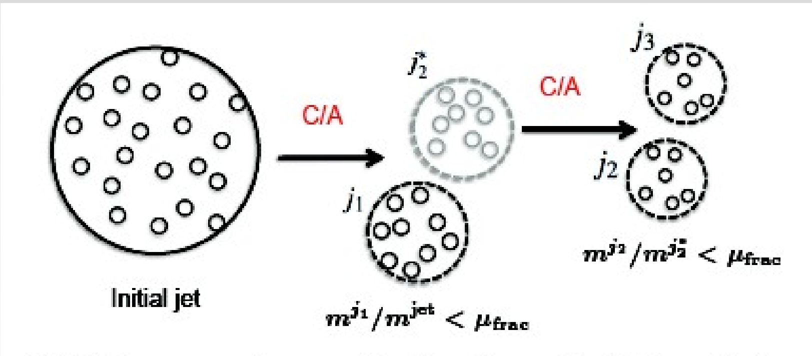
Allow up to 3 subjets to account for FSR.



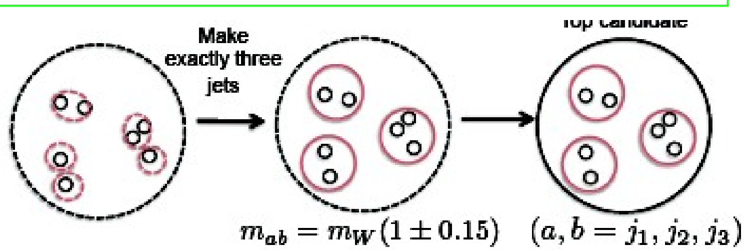
arXiv:1209.2858

1.9) Top tagging: generalisation

Filtering + mass drop generalisation



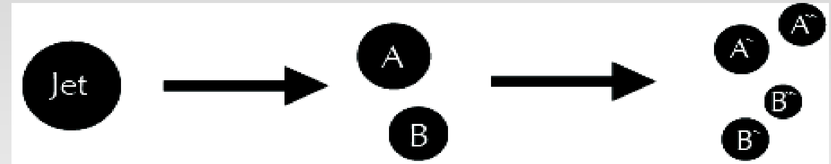
Iteratively produce N subjets without no « substructure »



Recluster into few bricks (5) to allow some QCD radiation.
Then combine into 3 groups using W and top mass constraints.

Atlas : HEP TOP TAGGER
arXiv:1306.4945v1

Prunning generalisation



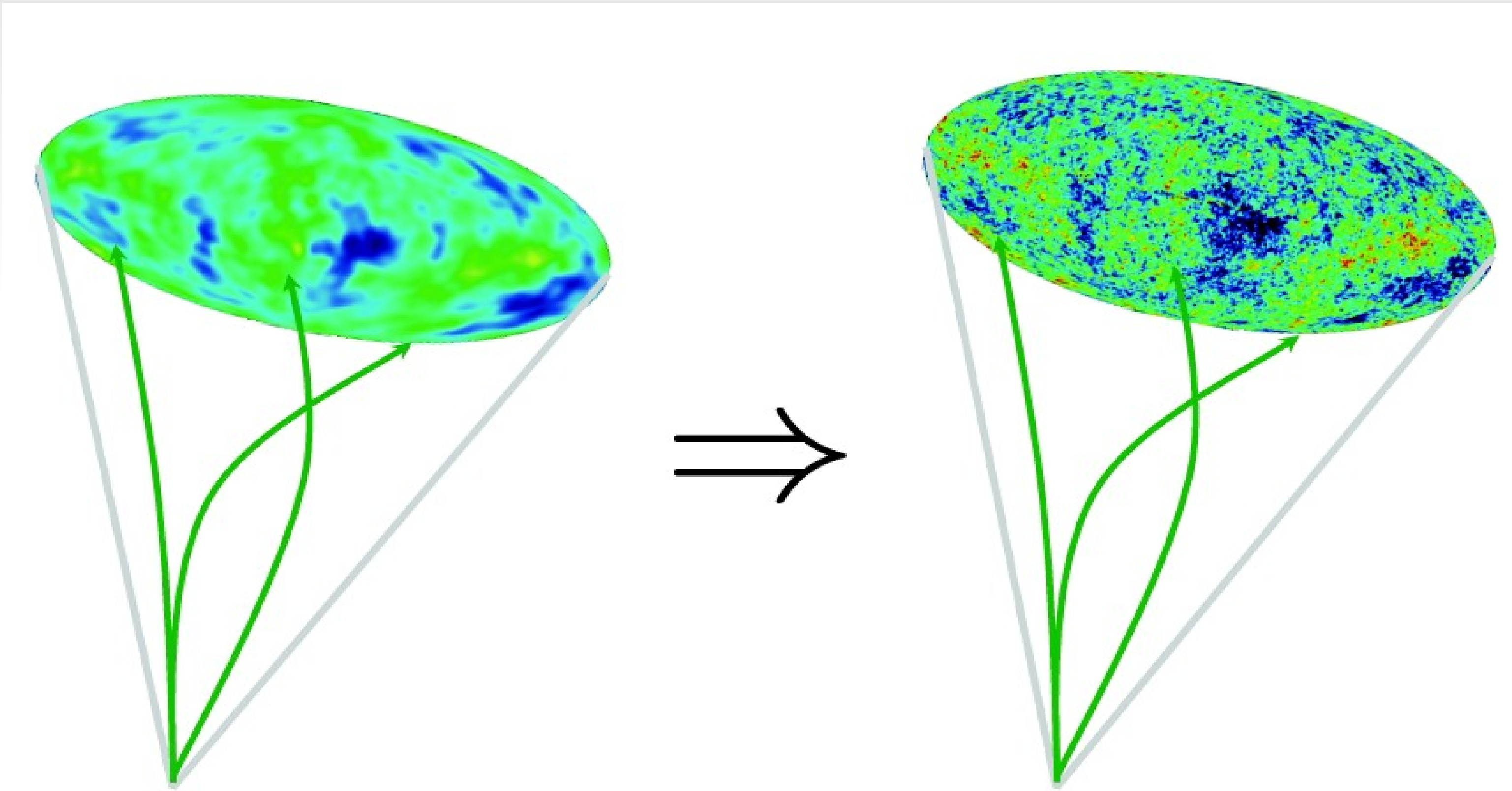
Iteratively uncluster up to 4 subjets: symmetric splittings and not too far away.

- Momentum fraction criterion: $p_T^{subjet} > 0.05 \times p_T^{jet}$
- Adjacency criterion: $\Delta R(C_1, C_2) > 0.4 - 0.0004 \times pT(C)$

Select events where subjets and jet satisfy W and top mass constraints.

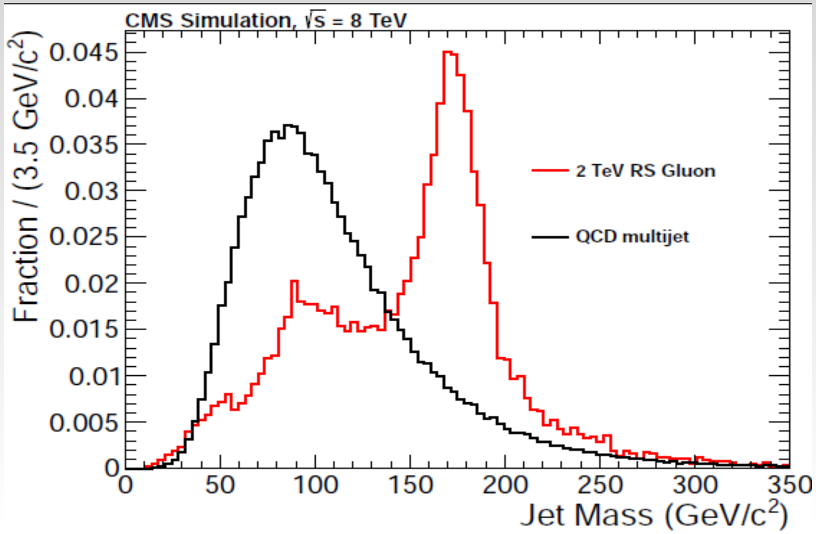
CMS/JHU tagger :
arXiv:1204.2488

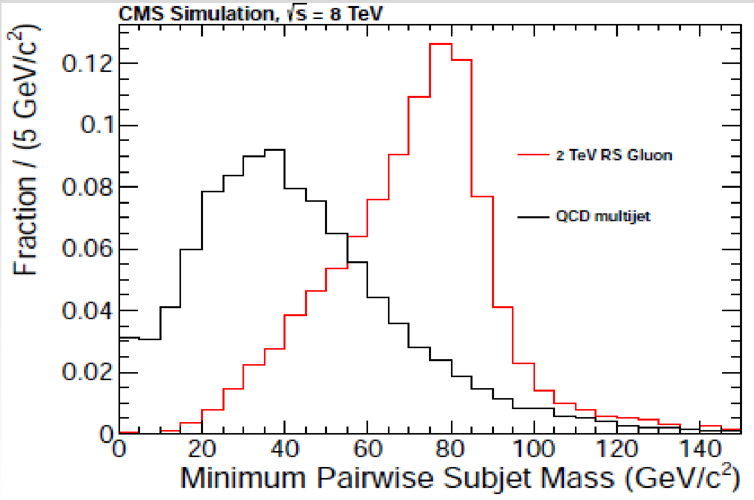
Precision era for boosted physics:
Example of the jet mass



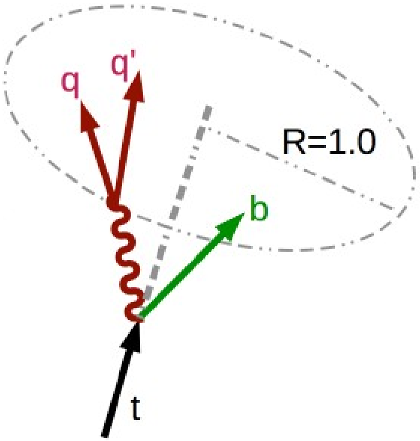
2.0) A small discussion based on the ttbar

CMS-JME-13-006

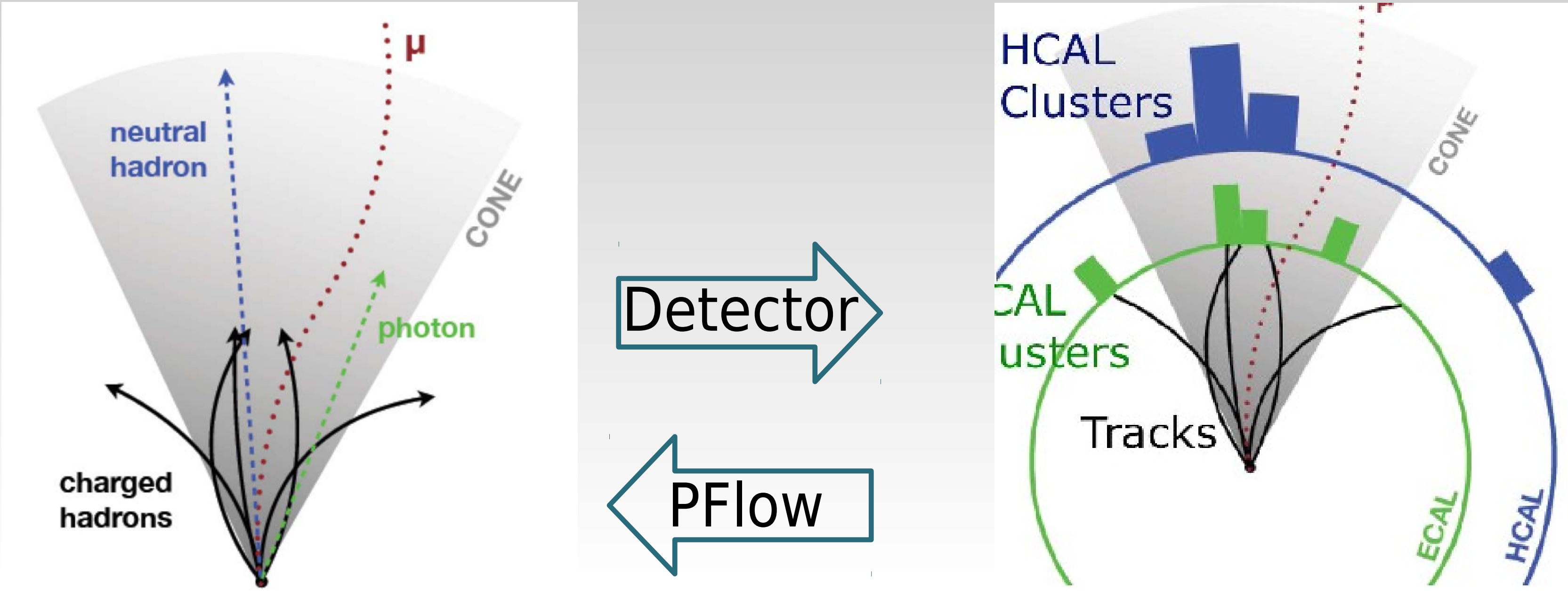




- Boosted top jets with 3 subjets:
  - Top jet mass shows a peak at top (fully boosted) and W (partially boosted) mass with 1 FSR subjet.
  - Minimum pair-wise mass: peak around W for top jet



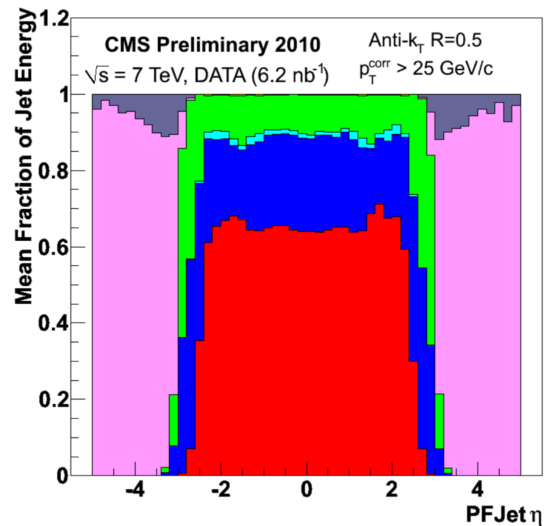
2.1) Jet reconstruction at CMS



Particles

Clusters and tracks

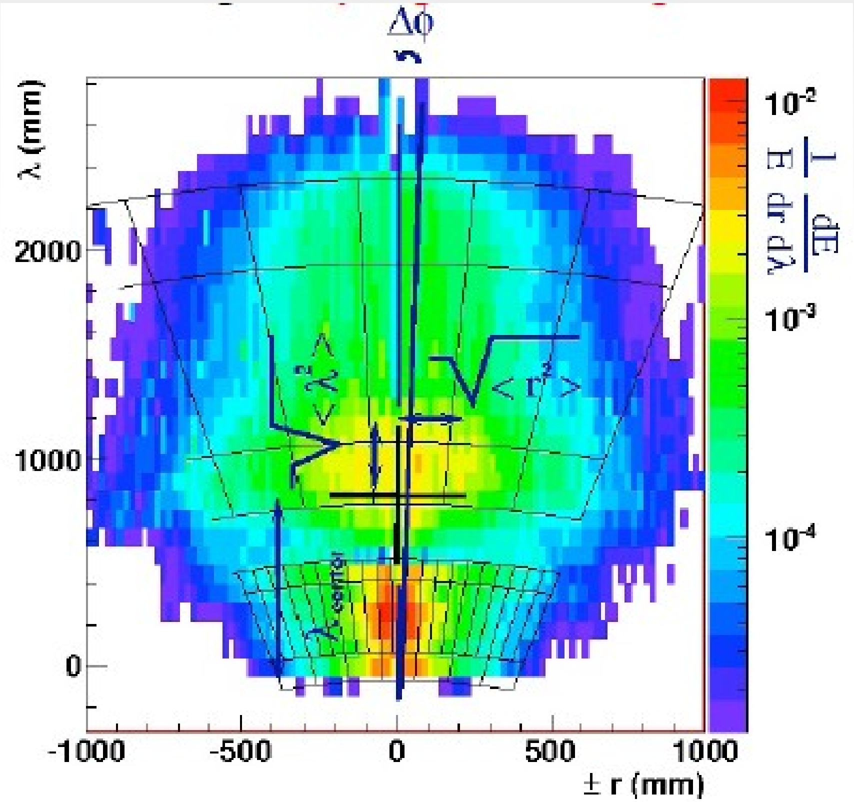
- O(5-10%) difference between rec jets and gen jets before calibration.
- Tracking provides a sensitivity to the details of the jet shapes and jet mass.
- 4-momenta are massive: m(π), m(K^0)...



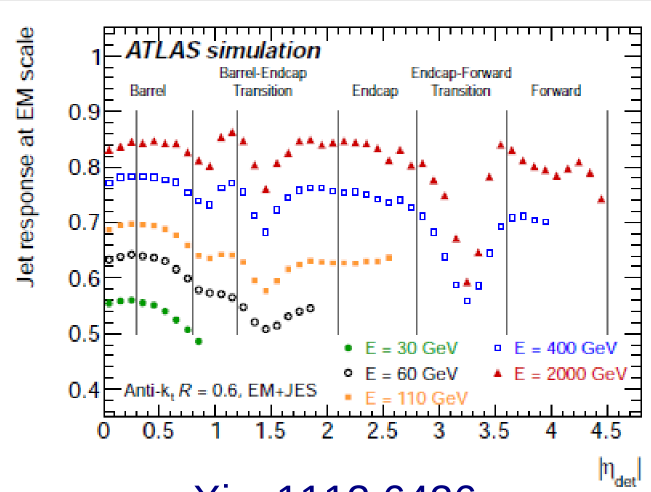
2.1) Jet reconstruction at Atlas

- Calo jets: calibrated topo clusters (heritage of non compensating LAr calorimeters H1/CDF).
- Track jets: tracks coming from the primary vertex.

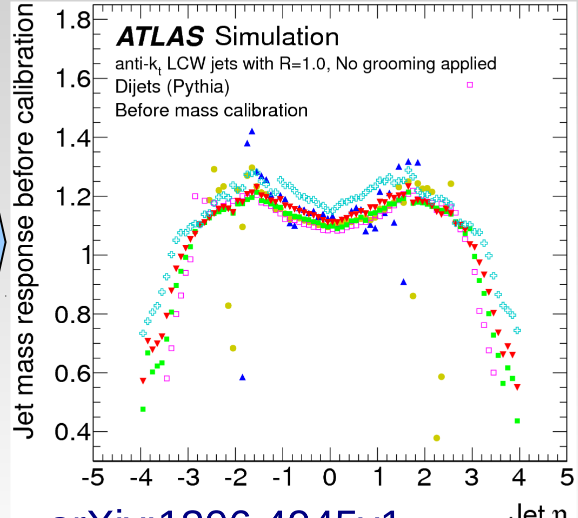
- Find seed cells above noise threshold.
- Proceed with a 3D clustering around it.
- Consider topo-clusters calibration by reweighting the different layers to bring the response to the EM scale.
- 4-momentum build under assumptions:
  - Massless particles
  - Coming from primary vertex



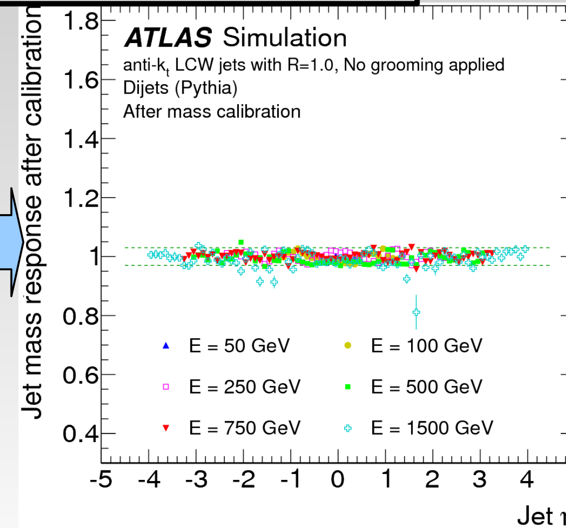
2.2) Jet mass calibration for substructure studies



arXiv :1112.6426

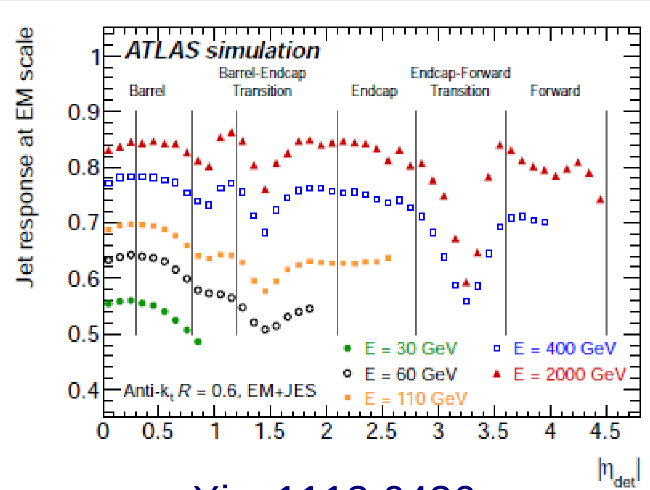


arXiv:1306.4945v1



- ATLAS: p_T calib.; O(20%) remain eff.; additional mass calib., no PU calib.

2.2) Jet mass calibration for substructure studies



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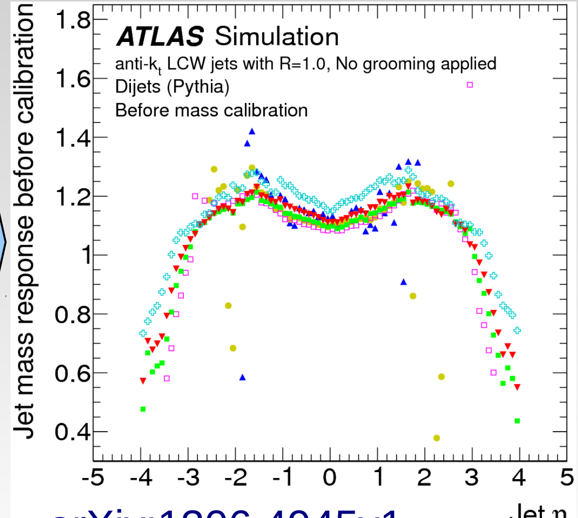

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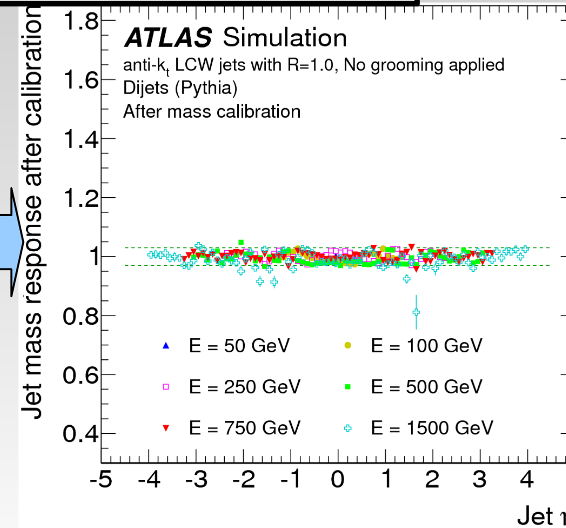

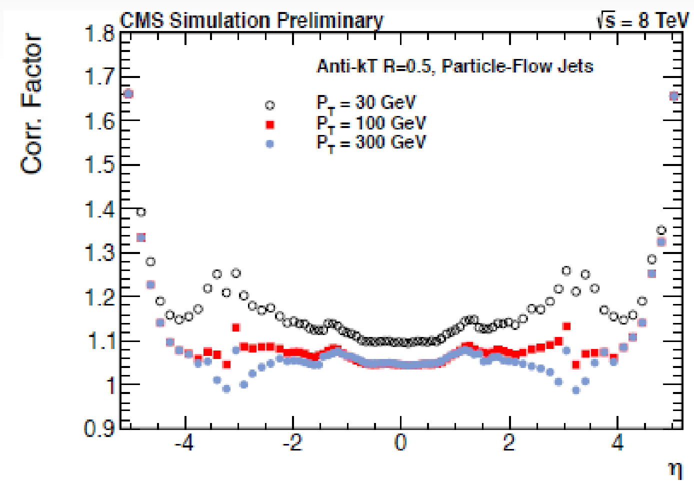

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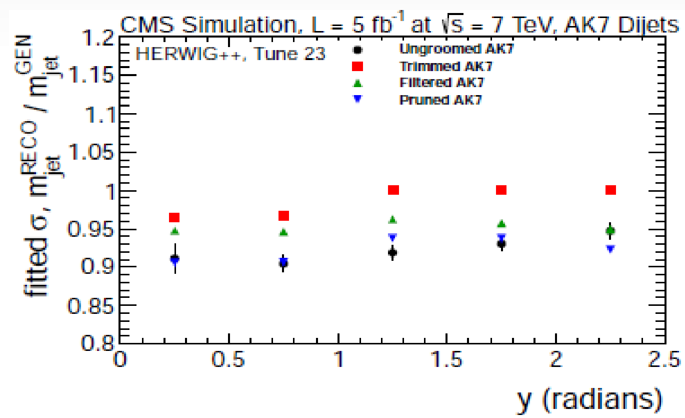
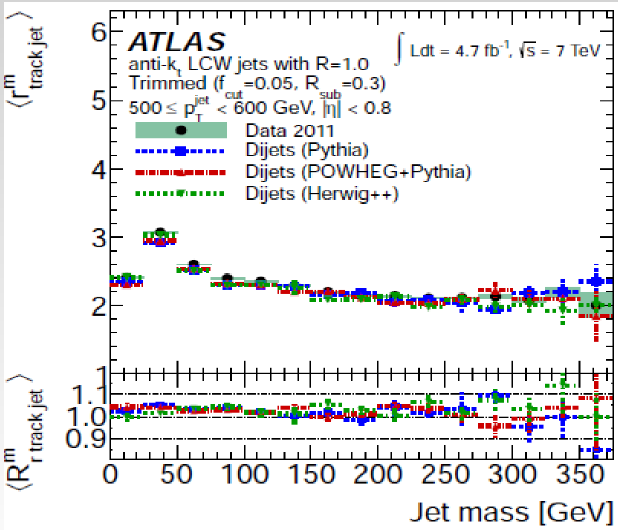
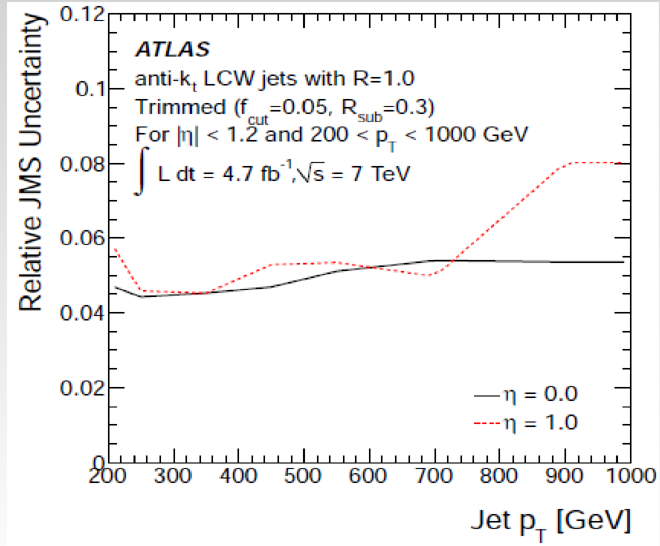


arXiv:1303.4811

- ATLAS: p_T calib.; O(20%) offset in mass; extra mass calib., no PU calib.
- CMS: p_T calib. with PU corr. (track + jet Area); O(5%) offset in Mass;

2.3) Jet mass scale uncertainty

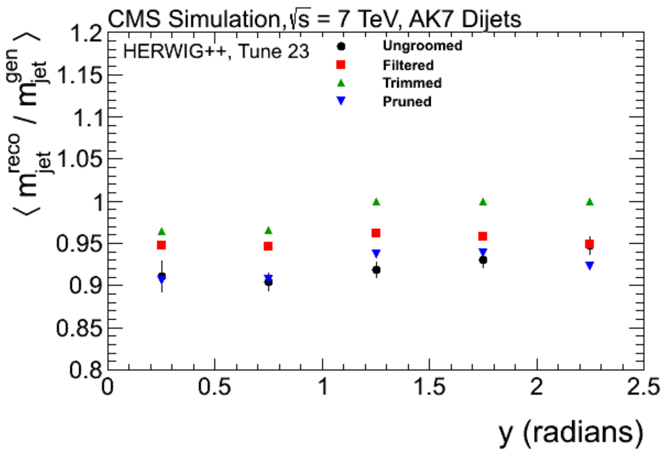




$$r^{p_T}_{\text{track jet}} = \frac{p_T^{\text{jet}}}{p_T^{\text{track jet}}}, \qquad r^{m}_{\text{track jet}} = \frac{m^{\text{jet}}}{m^{\text{track jet}}},$$

$$R^{p_T}_{r\ \text{track jet}} = \frac{r^{p_T,\text{data}}_{\text{track jet}}}{r^{p_T,\text{MC}}_{\text{track jet}}}, \qquad R^{m}_{r\ \text{track jet}} = \frac{r^{m,\text{data}}_{\text{track jet}}}{r^{m,\text{MC}}_{\text{track jet}}}.$$

arXiv:1306.4945v1

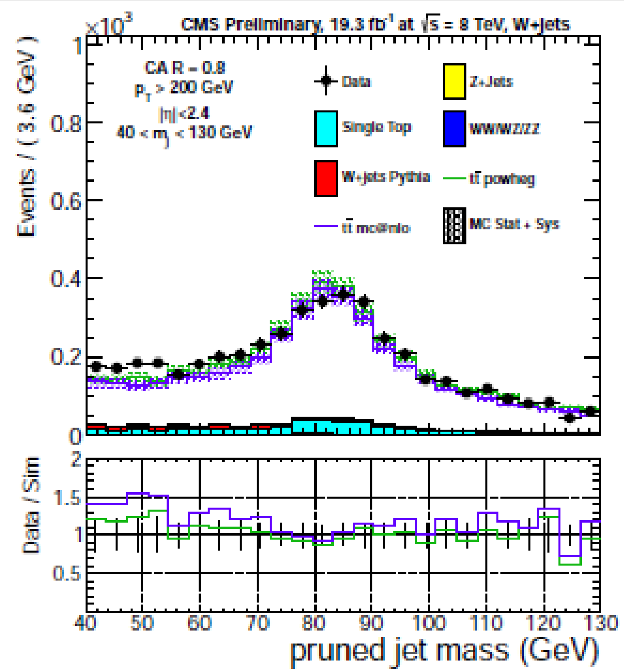


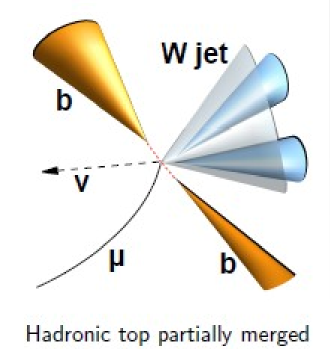
arXiv:1303.4811

- ATLAS scheme: calo jets mass scale cross check with track jets using double ratio.
  - O(4%) uncertainty considered. Small dependence on the grooming.
- CMS scheme (to be updated): grooming change the energy response by 3%
  - 3% uncertainty considered.
  - 1% for W mass scale (see later).

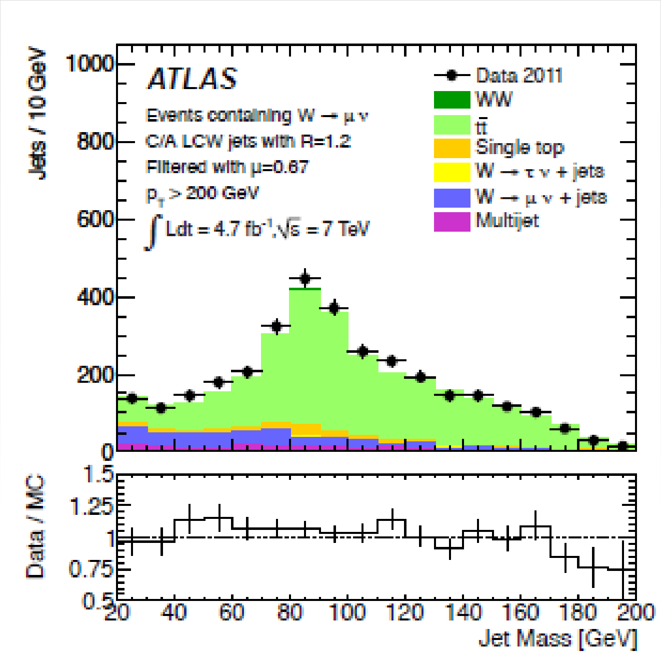
2.4) Mass scale measurement with W jets in ttbar

CMS-JME-13-006





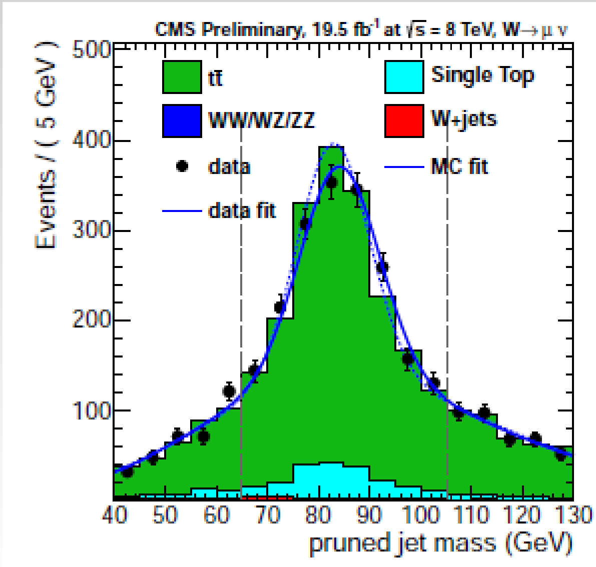
arXiv:1306.4945v1



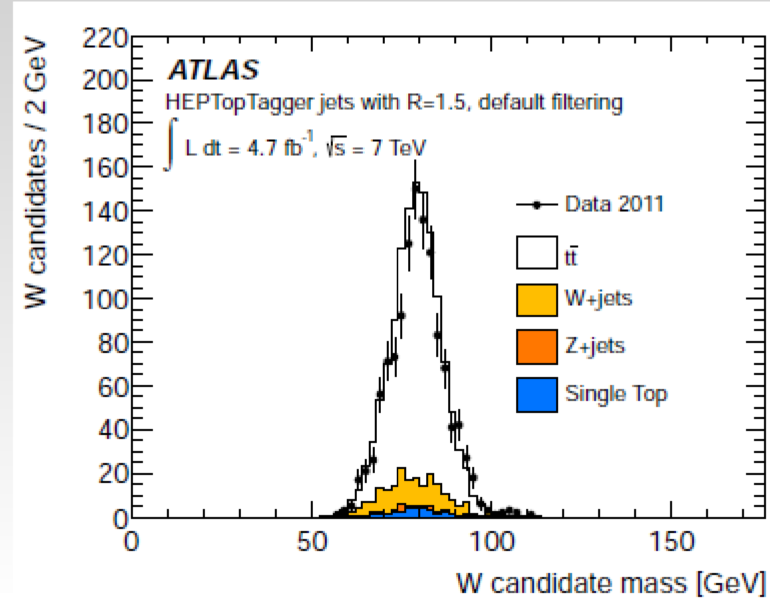
- Prunned mass distribution for C/A fat jets with R = 0.8 with p_T > 200 GeV (W→μν candidate + b-tagged AKT5 jet)

- Filtered mass distribution for C/A fat jets with R = 1.2 with p_T > 200 GeV. (W→μν candidate + b-tagged AKT4 jet)

2.4) Mass scale measurement with W jets in ttbar

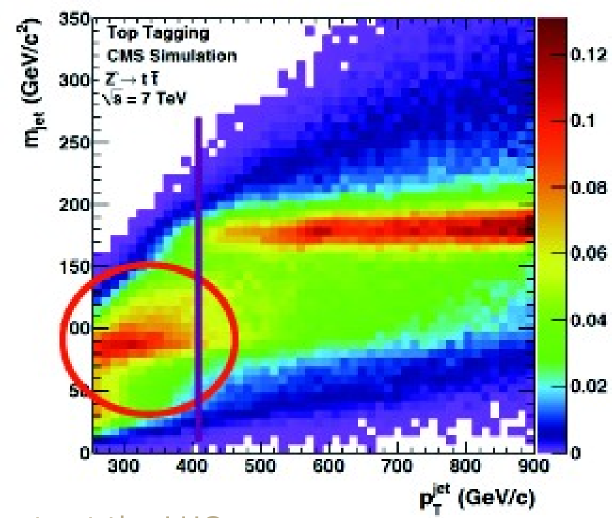


$$\langle m \rangle_{\rm sim} = 83.4 \pm 0.4\ {\rm GeV}\,,$$
$$\langle m \rangle_{\rm data} = 84.5 \pm 0.4\ {\rm GeV}\,,$$



$$\mu_{\rm data} = 86.9 \pm 0.8\ {\rm GeV}$$
$$\mu_{\rm MC} = 87.4 \pm 0.2\ {\rm GeV}$$

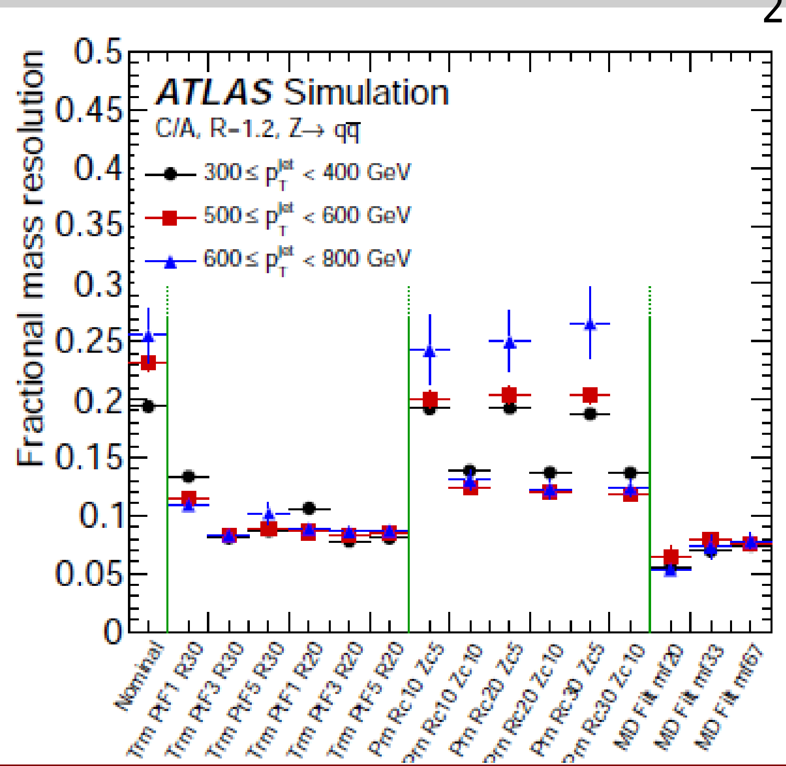
- Allow to monitor the jet mass calibration for groomed jets with real substructure.
- O(1%) uncertainty observed in both experiments.
- But tool limited to $p_{T,j} \in [\frac{2M_W}{R_j}, \frac{2M_t}{R_j}] \approx [200\ {\rm GeV}, 450\ {\rm GeV}]$ to go further subjet mass have to be considered.



2.5) Mass resolution study with W jets in ttbar

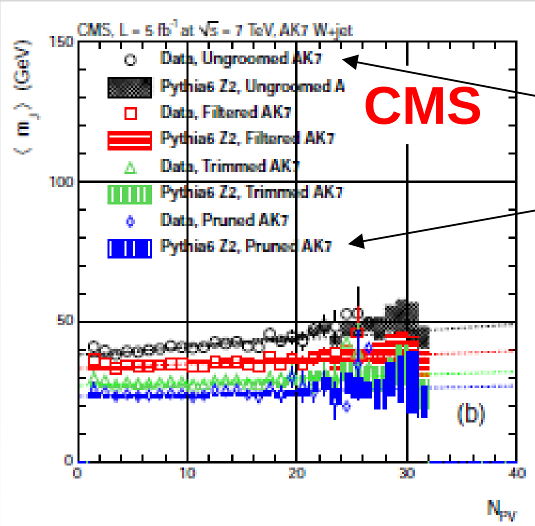
CMS

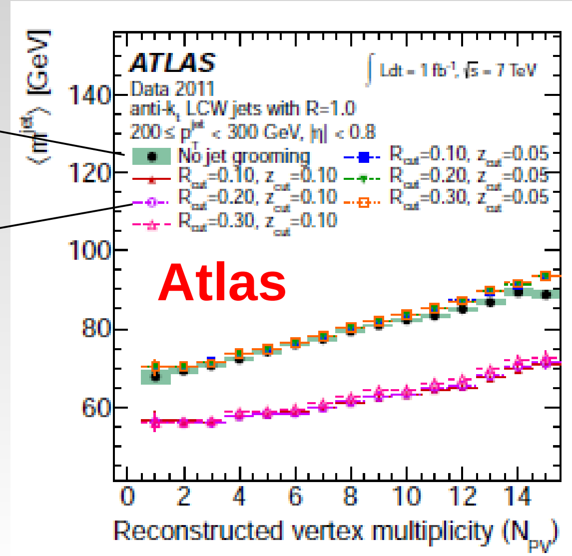
$$\langle m \rangle_{\rm sim} = 83.4 \pm 0.4\ {\rm GeV}\ ,\ \sigma_{\rm sim} = 7.5 \pm 0.4\ {\rm GeV}$$
$$\langle m \rangle_{\rm data} = 84.5 \pm 0.4\ {\rm GeV}\ ,\ \sigma_{\rm data} = 8.7 \pm 0.6\ {\rm GeV}$$

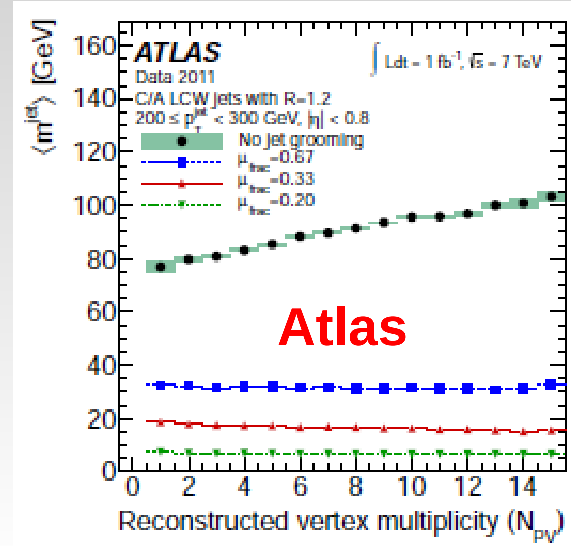


- CMS:
  - Pruned CA8 with z_{cut} = 0.1 and R_{cut} = 0.25: Resolution ~ 8%.
  - W mass resol. underestimated by MC by 16% (10% for jet p_T resol.).
- ATLAS:
  - Resolution measured in W mass but not provided in arXiv:1306.4945v1.
  - Resolution with CMS parameters 12%, but 8% reached with trimming.

2.6) Pile-up dependance



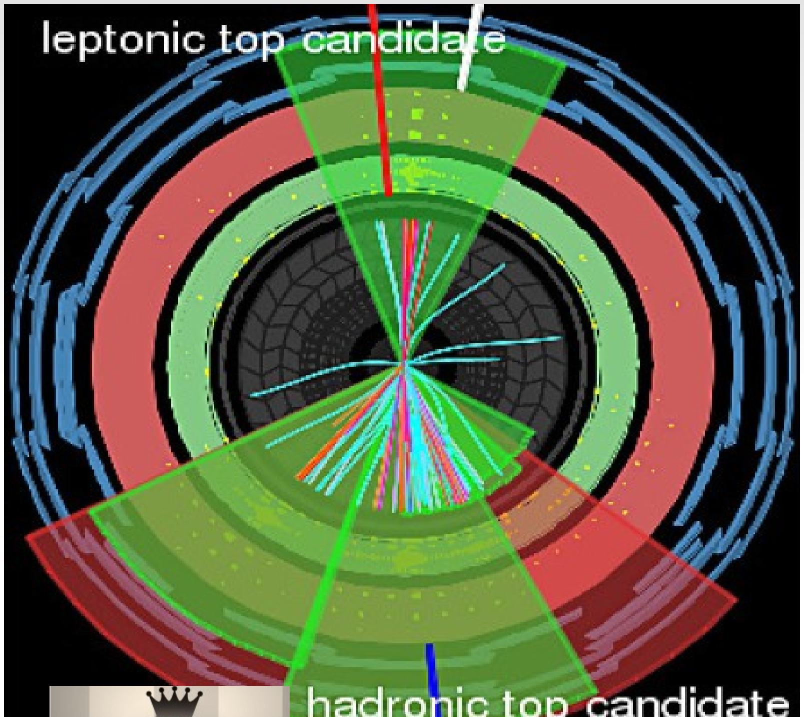


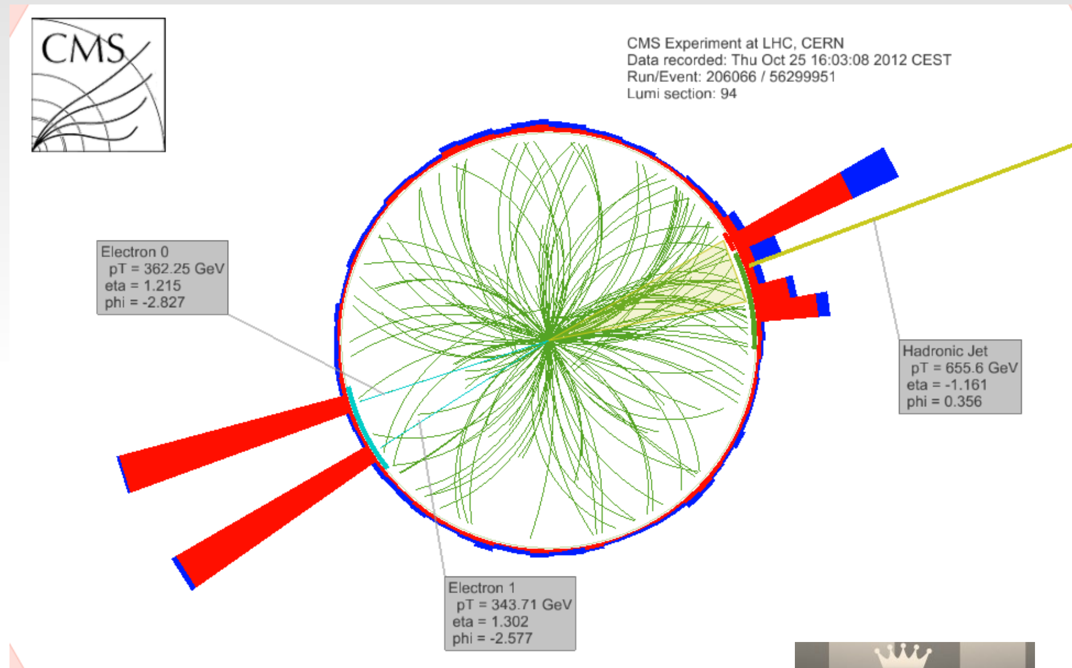


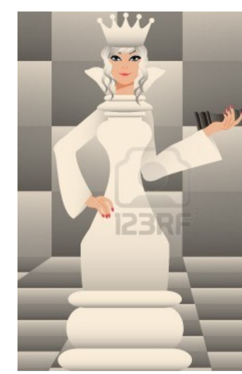
arXiv:1303.4811 arXiv:1306.4945v1

- CMS: Jet 4-momentum corrected for PU (charged particles + jet area).
  - Jet p_T PU dependence very small, but a residual mass dependence exist.
  - Grooming remove PU dependence Prunning the most efficient.
- ATLAS: Jet 4-momentum not explicitly corrected for those studies for PU. But signal reconstruction in LAr have by construction a reduced PU dependence
  - Significant mass dependence on PU.
  - Reduced by grooming: Prunning not efficient, but trimming very efficient.
- In general grooming reduce the effective jet area and therefore PU dependence.

Identification of boosted V bosons and top quarks



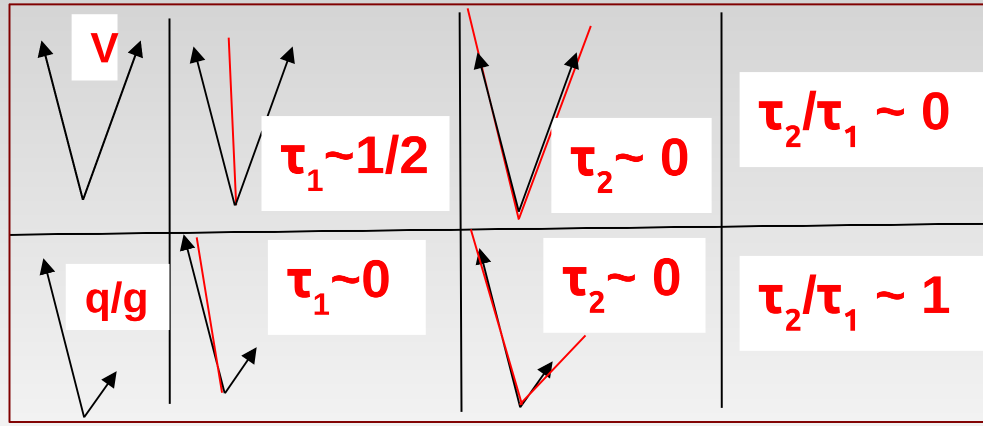


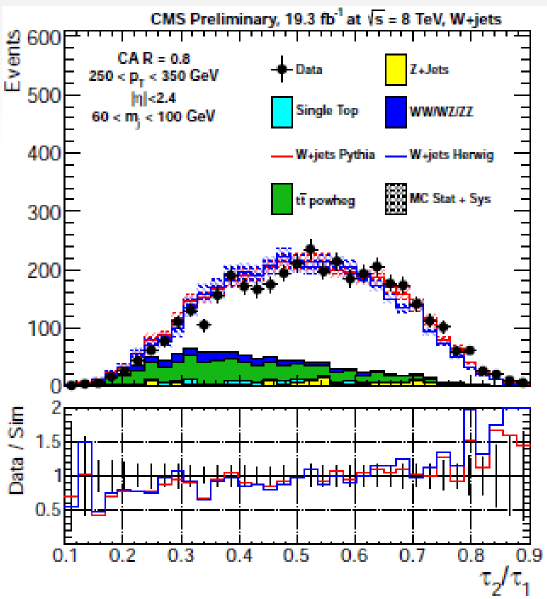


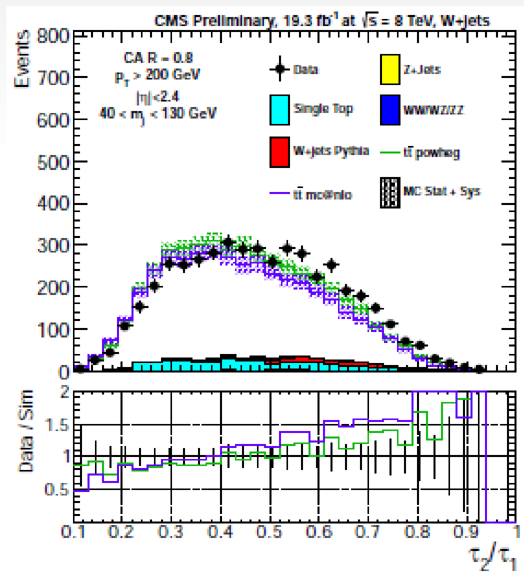
3.1) N-subjettiness

$$\tau_N = \frac{1}{d_0}\sum_k p_{Tk} \times \min(\delta R_{1k}, \delta R_{2k}, ..., \delta R_{Nk})$$

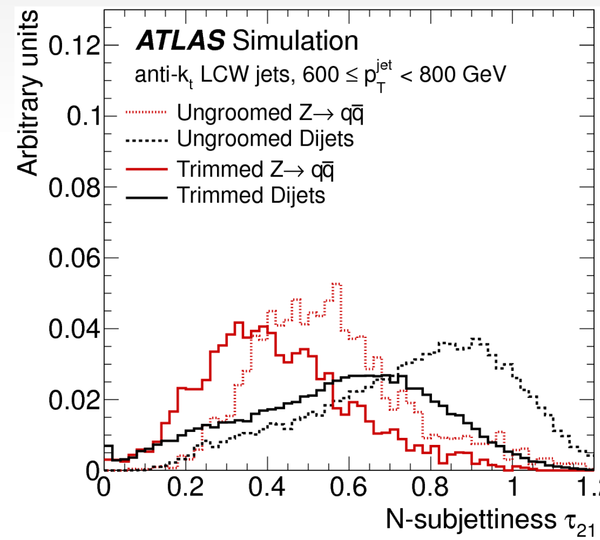
$$d_0 \equiv \sum_k p_{Tk} \times R$$







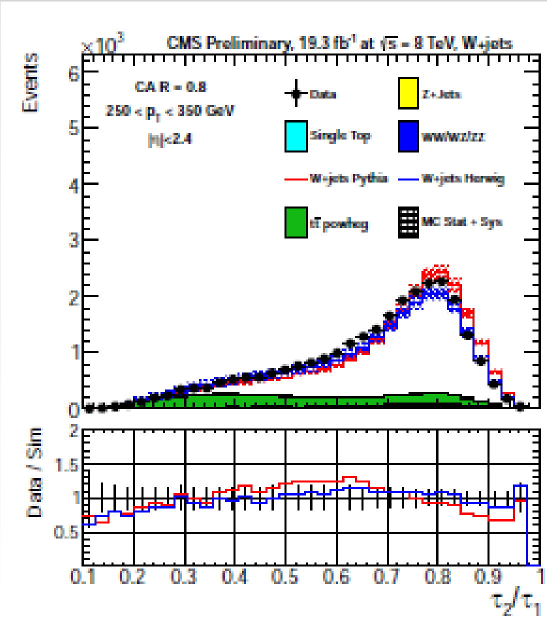
CMS-JME-13-006



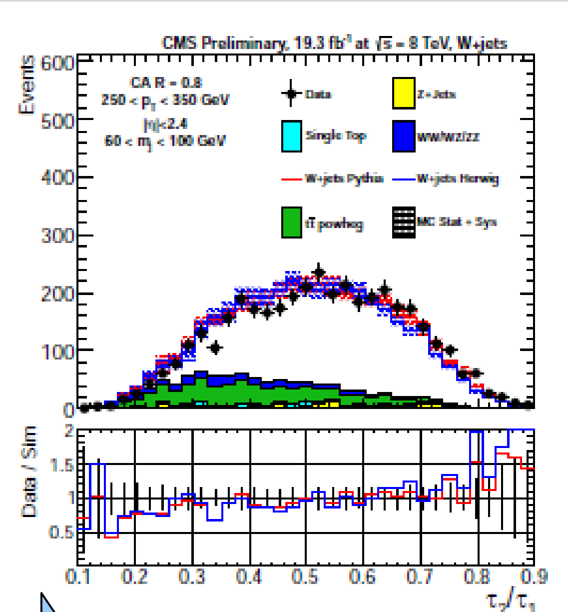
arXiv:1306.4945v1

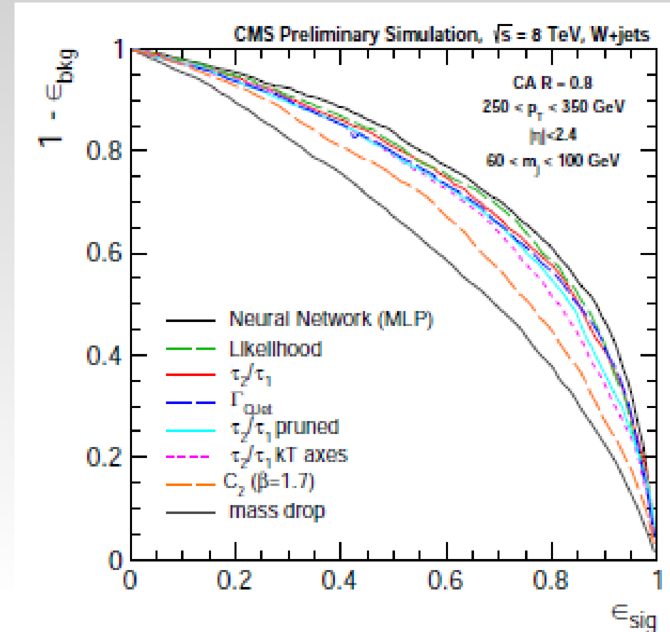
- N-subjettiness indicate the polarity of the jet (monopole, dipole etc...)

3.2) W tagger optimisation



Mass cut

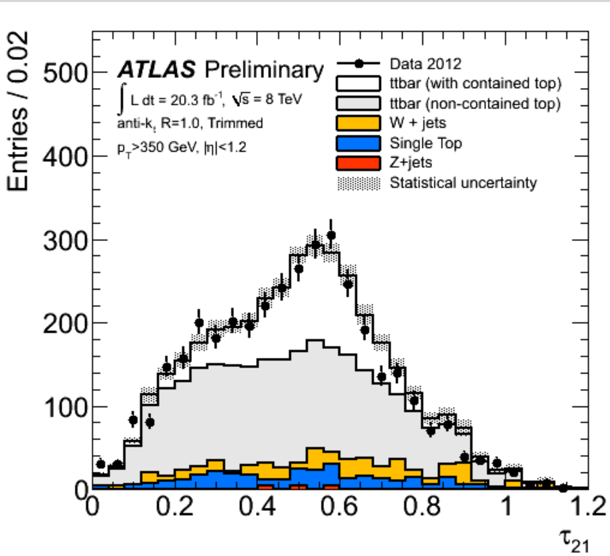


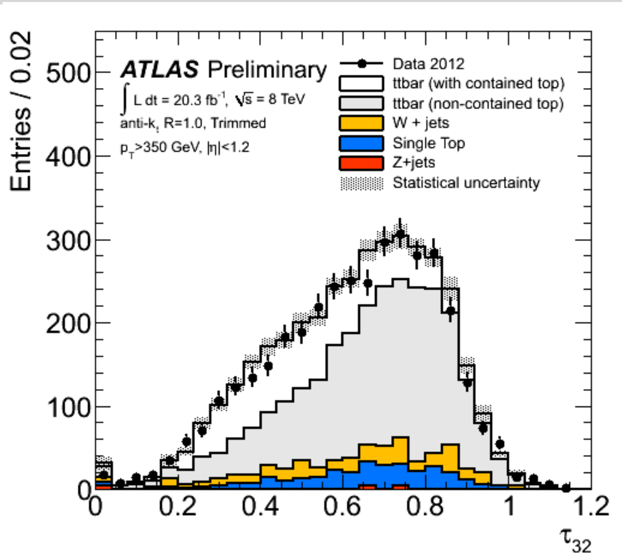


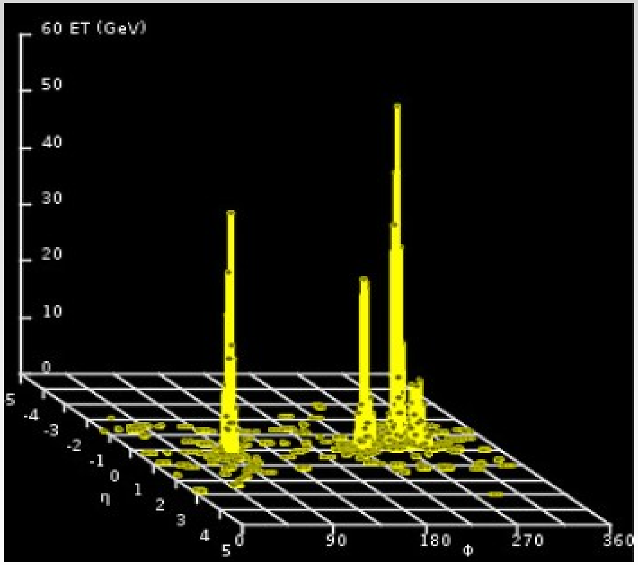
CMS-JME-13-006

- N-subjettiness correlated to the prunned W mass: normal need a “dipole” structure for a large mass.
- On top of mass cut - A combination of many taggers (N-subjettiness, mass drop, C_2 etc...) improve slightly the S-B separation wrt to N-subjettiness.
- More taggers considered by ATLAS: splitting scales etc...
- Additional taggers brings 80% bkg rejection for 60% signal efficiency wrt to the jet mass.

3.3) Top tagging: generalisation







ATLAS-CONF-2013-052

- In top tagging we face a recursive splitting effect:
  - τ_{21} shows the top → Wb splitting
  - τ_{23} shows the top → Wb → qqb splitting.
- Other taggers:
  - splitting scales √d12, √d23 (ATLAS-CONF-2013-084).
  - Template method arXiv:1211.2202 (1211.2202)

3.4) W charge

- Jet charge does it make sense? Sum track charges would never work = non-infrared quantity 

3.3) W charge

- Jet charge does it make sense? Sum track charges would never work = non-infrared quantity.
- Idea! Weight the track charge by it's momentum power something (to be tuned).

$$Q_j = \frac{1}{(p_{T\,j})^{\kappa}} \sum_{i \in \mathrm{Tr}} q_i \times (p_T^i)^{\kappa}$$

- Does it work?

arXiv:1209.3019

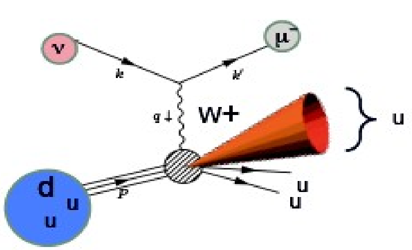
3.3) W charge

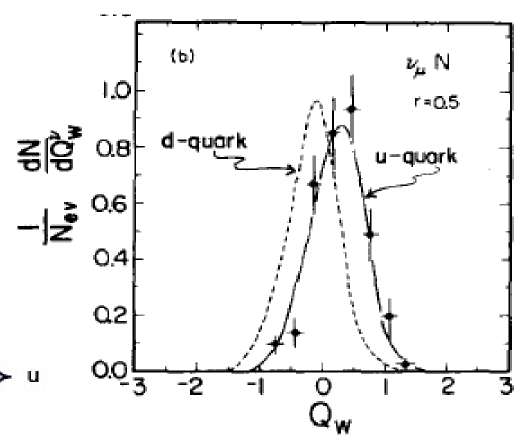
- Jet charge does it make sense? Sum track charges would never work = non-infrared quantity :(
- Idea! Weight the track charge by it's momentum power something (to be tuned).

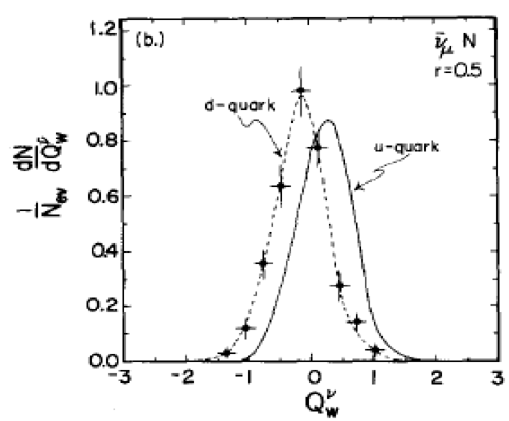
$$Q_j = \frac{1}{(p_{T\,j})^{\kappa}} \sum_{i \in \mathrm{Tr}} q_i \times (p_T^i)^{\kappa}$$

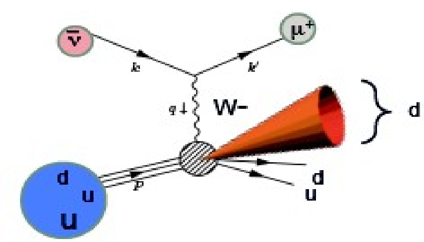
- Yes it does!

Fermilab Data (1980)







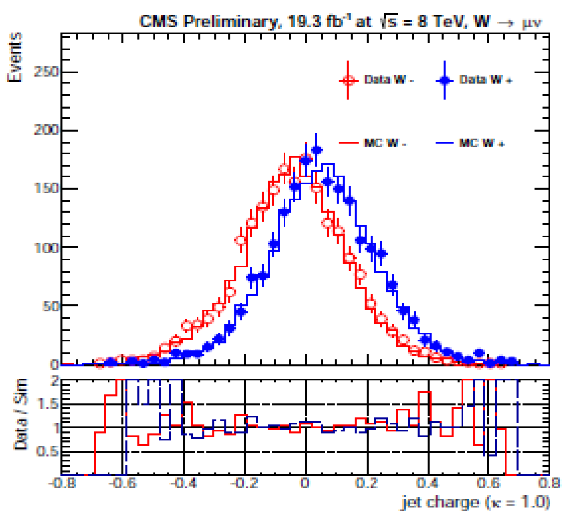


3.3) W/Z charge

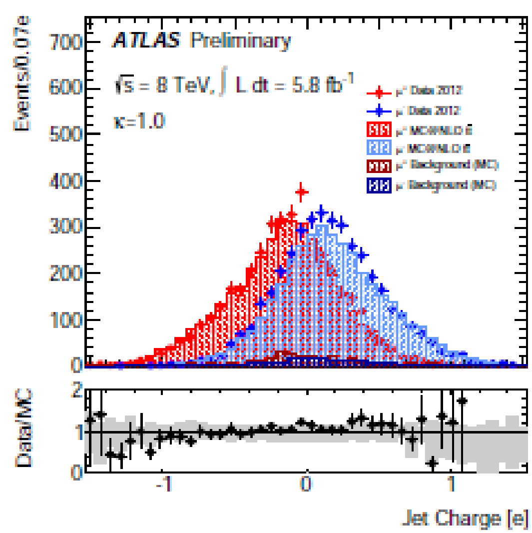
- Idea! Weight the track charge by it's momentum power something (to be tuned).

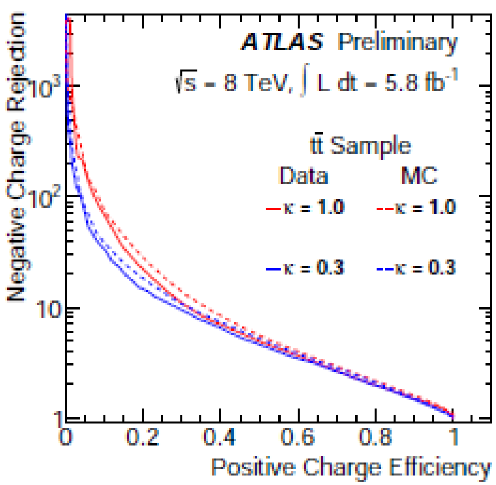
$$Q_j = \frac{1}{(p_{T\,j})^{\kappa}} \sum_{i \in \mathrm{Tr}} q_i \times (p_T^i)^{\kappa}$$

- Does it still exist with 40 PU and 100 GeV jets?
  - Why not suggested out theorists fiends (2012 - arXiv:1209.3019v3).
  - It works answered CMS/Atlas in 2013.
- k = 0.3: tracks democracy is preferred to k = 1.0 leading track oligarchy.



CMS-JME-13-006



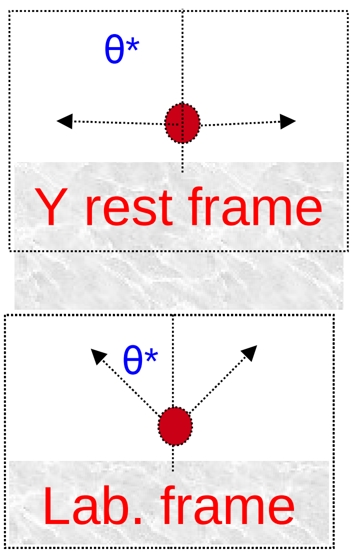


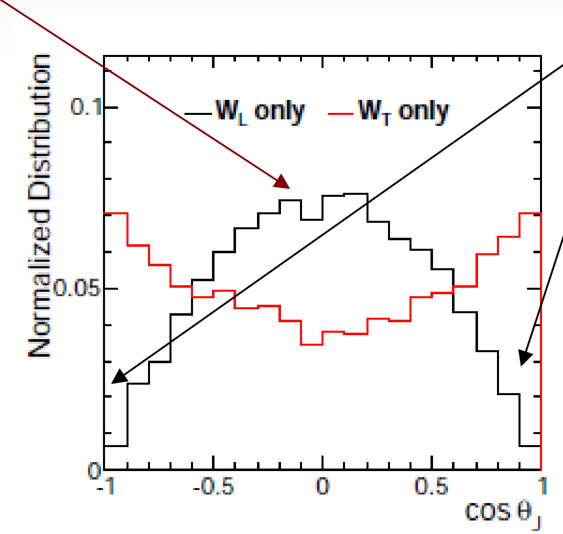
ATLAS-CONF-2013-086

3.4) W/Z polarization

- Jets substructure → Subjets → Could we measure the polarization?
- Measure polarization = Measure subjet angles + boost into V rest frame. No JES involved.
- But there is a trick with the acceptance...
    - No sensitivity to the parity (no quark – anti-quark tagging yet)
    - Better acceptance for WL than WT

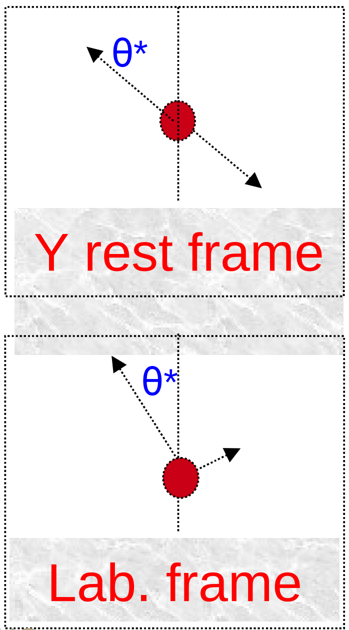
Symmetric
low ΔR
$\cos\theta^* \sim 0$





CMS-JME-13-006

Asymmetric
high ΔR
$\cos\theta^* \sim \pm 1$

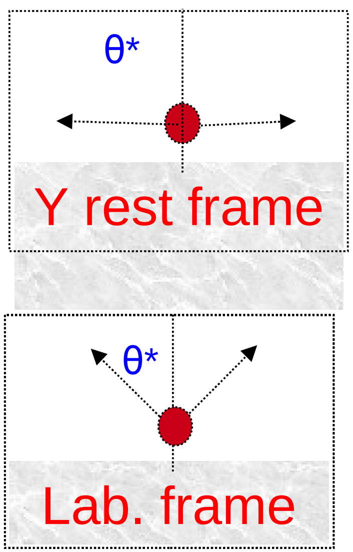


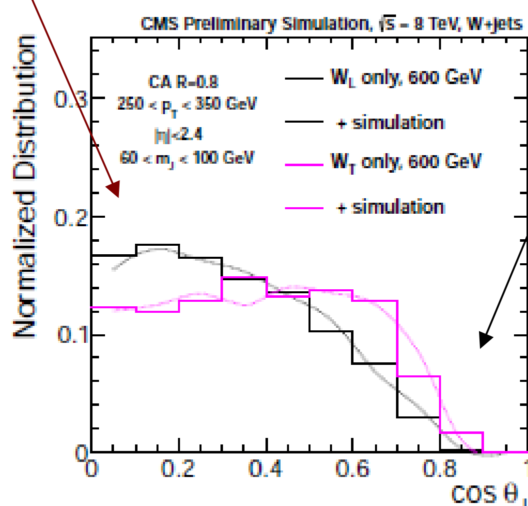
3.4) W/Z polarization

- Jets substructure → Subjets → Could we measure the polarization?
- Measure polarization = Measure subjet angles + boost into V rest frame. No JES involved.
- But there is a trick with the acceptance...
  - No sensitivity to the parity (no quark – anti-quark tagging yet)
  - Better acceptance for WL than WT

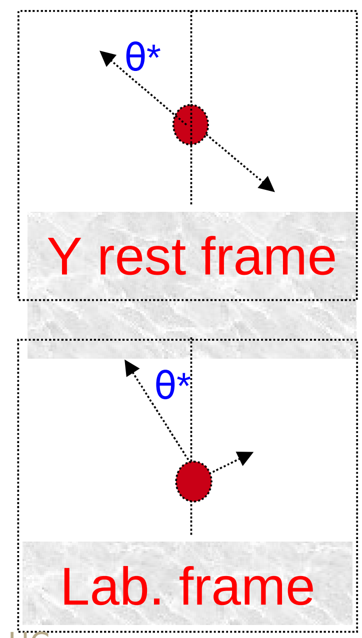
Symmetric
low ΔR
$\cos\theta^* \sim 0$

Asymmetric
high ΔR
$\cos\theta^* \sim \pm 1$





CMS-JME-13-006

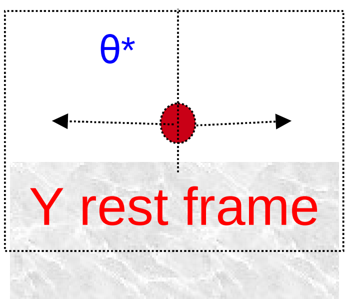


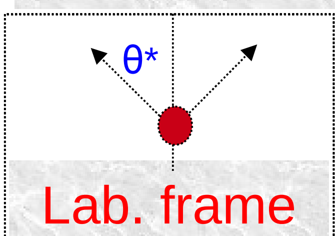
3.4) W/Z polarization

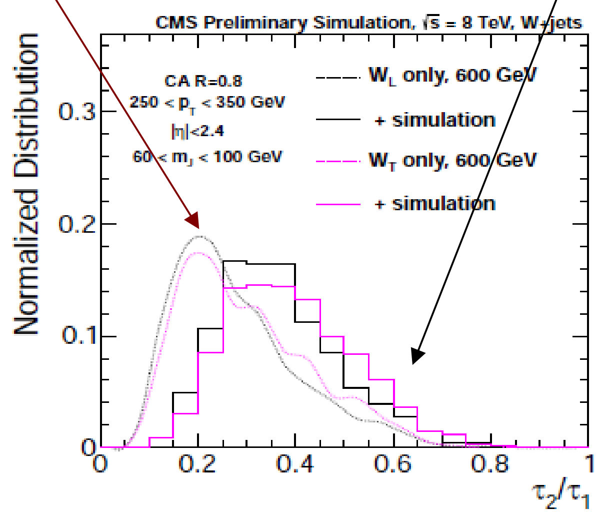
- Jets substructure → Subjets → Could we measure the polarization?
- Measure polarization = Measure subjet angles + boost into V rest frame. No JES involved.
- But there is a trick with the acceptance...
  - W_L are in average more dipolar than W_T

Symmetric
low ΔR
cos θ* ~ 0

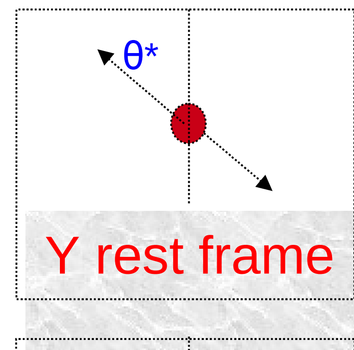
Asymmetric
high ΔR
cos θ* ~ ± 1

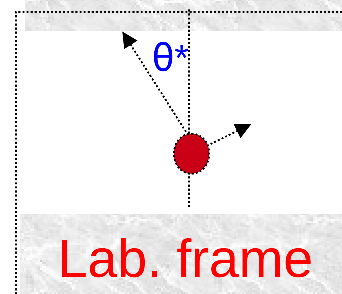






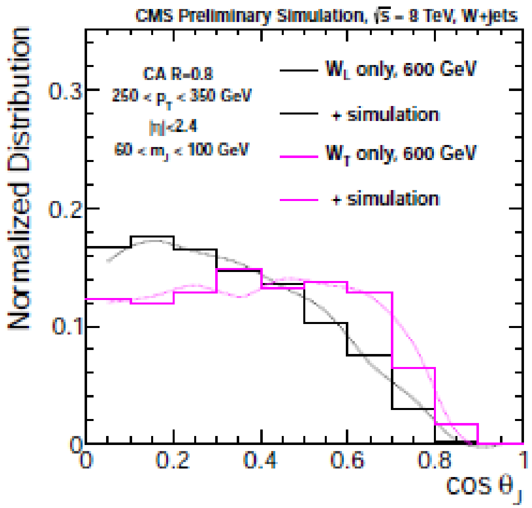
CMS-JME-13-006





3.4) W/Z polarization

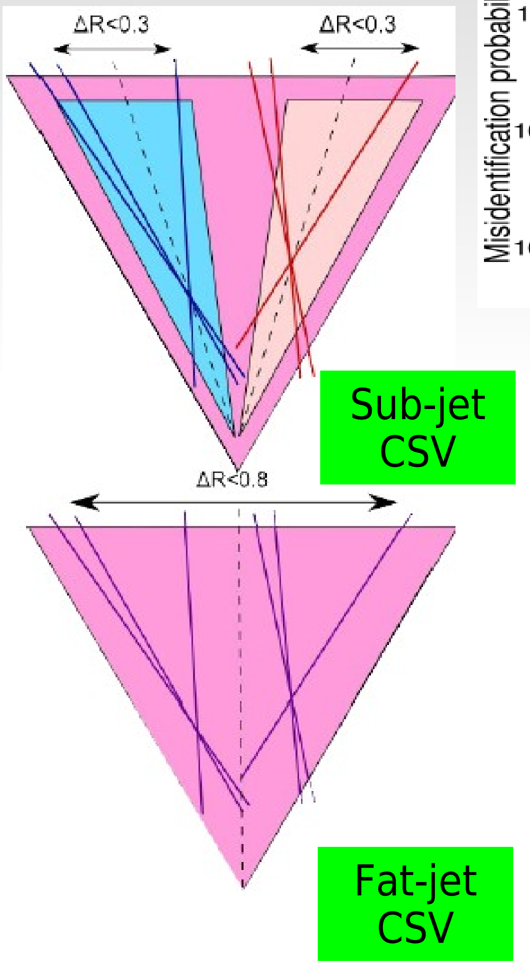
- Jets substructure → Subjets → Could we measure the polarization?
- Measure polarization = Measure subjet angles + boost into V rest frame. No JES involved.
- But there is a trick with the acceptance...
  - No sensitivity to the parity (no quark – anti-quark tagging yet)
  - Better acceptance for W_L than W_T
- CMS measured the resolution:
  - $\sigma(\Delta R)$ ~ 10 mrad : $\sigma(\Delta R)/\Delta R$ ~ 3% for p(W) = 500 GeV!!!
  - Do not impact W_L/W_T separation

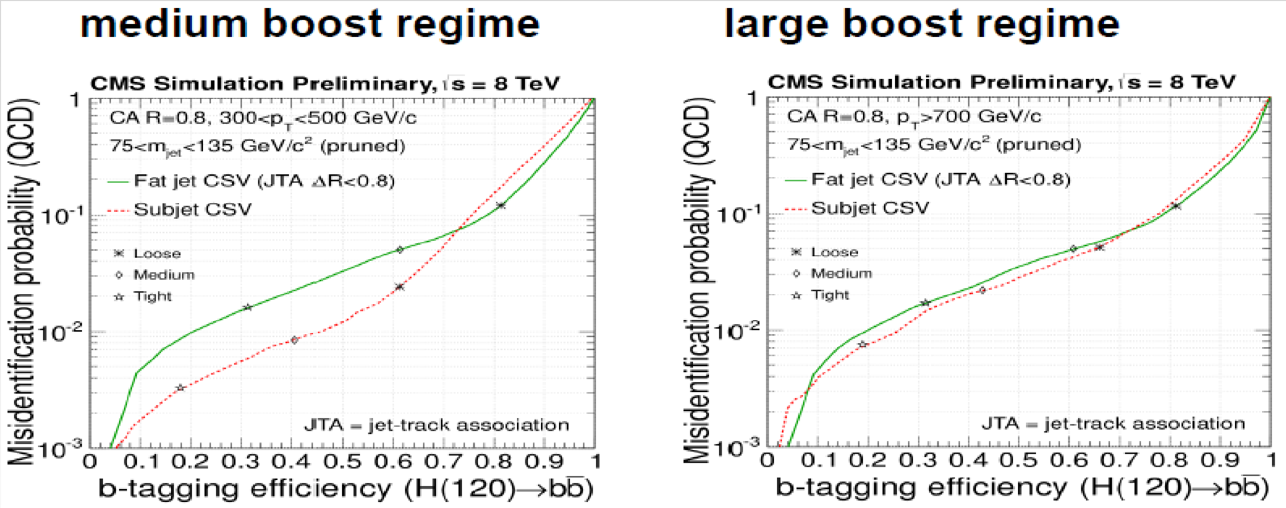


CMS-JME-13-006

3.5) Subjet b-tagging

CMS-BTV-13-001





- We need to prepare the boosted H→ bb program (first interesting source of bb jets).

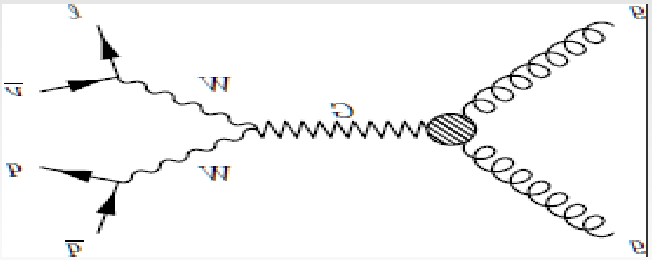
B-tagging for highly boosted tops shall be improved.

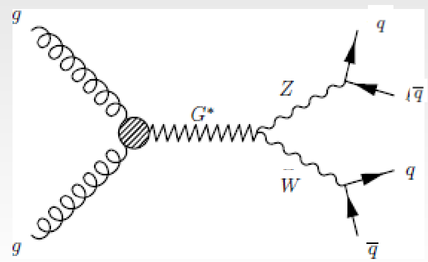
- CSV tagger: combine vertex and track counting info.
- Fat-jet CSV tagger: apply CSV to Fat jets.
- Subjet tagger: CSV tagger within R < 0.3.

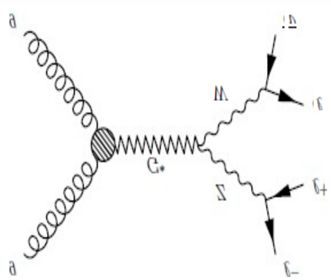
  2 tags for b and 1 for top.

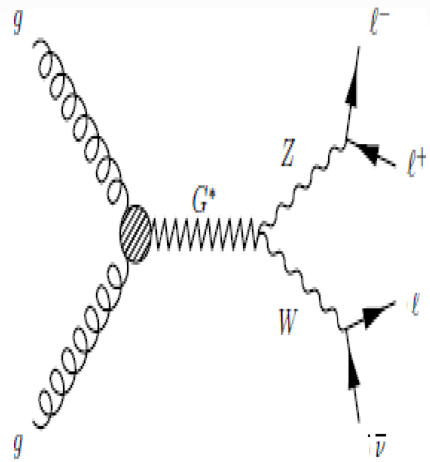
- Subjet b-tagging doing a great job till the subjets start to merge. Tested in data with ttbar events.

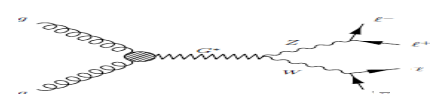
Application to the searches

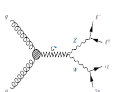


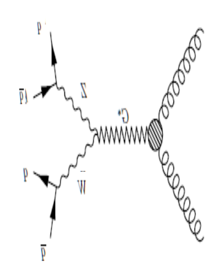




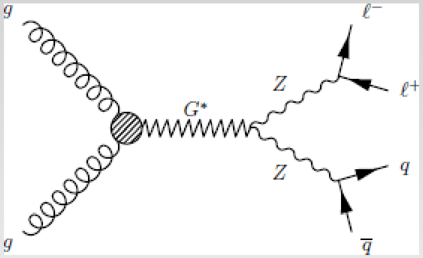


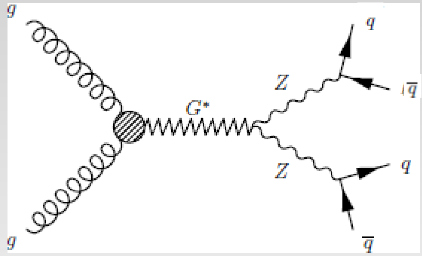


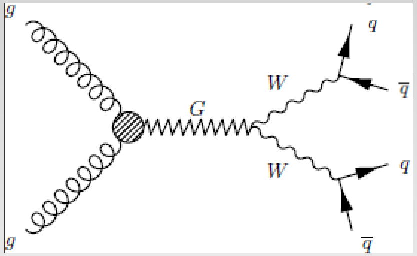


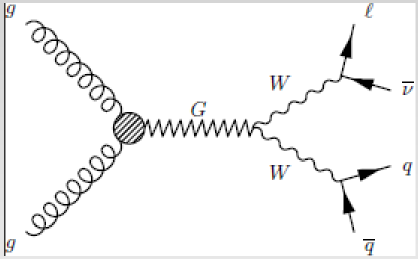


4.1) VV searches









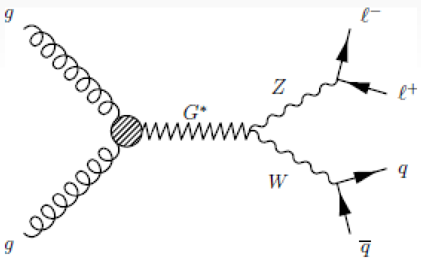
8 TeV : CMS-EXO-12-022
7 TeV : CMS arXiv:1211.5779

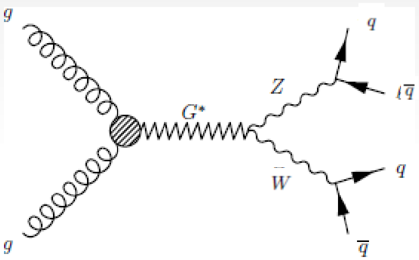
8 TeV : ATLAS-CONF-2012-150

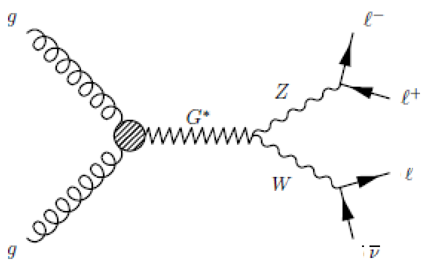
8 TeV : CMS-EXO-12-024
7 TeV : CMS arXiv:1212.1910

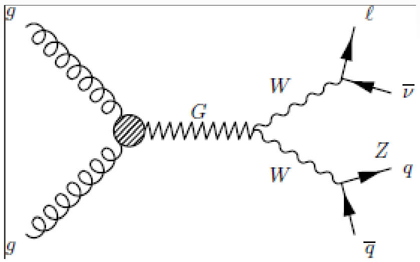
8 TeV : CMS-EXO-12-021

7 TeV : ATLAS
arXiv:1305.0125









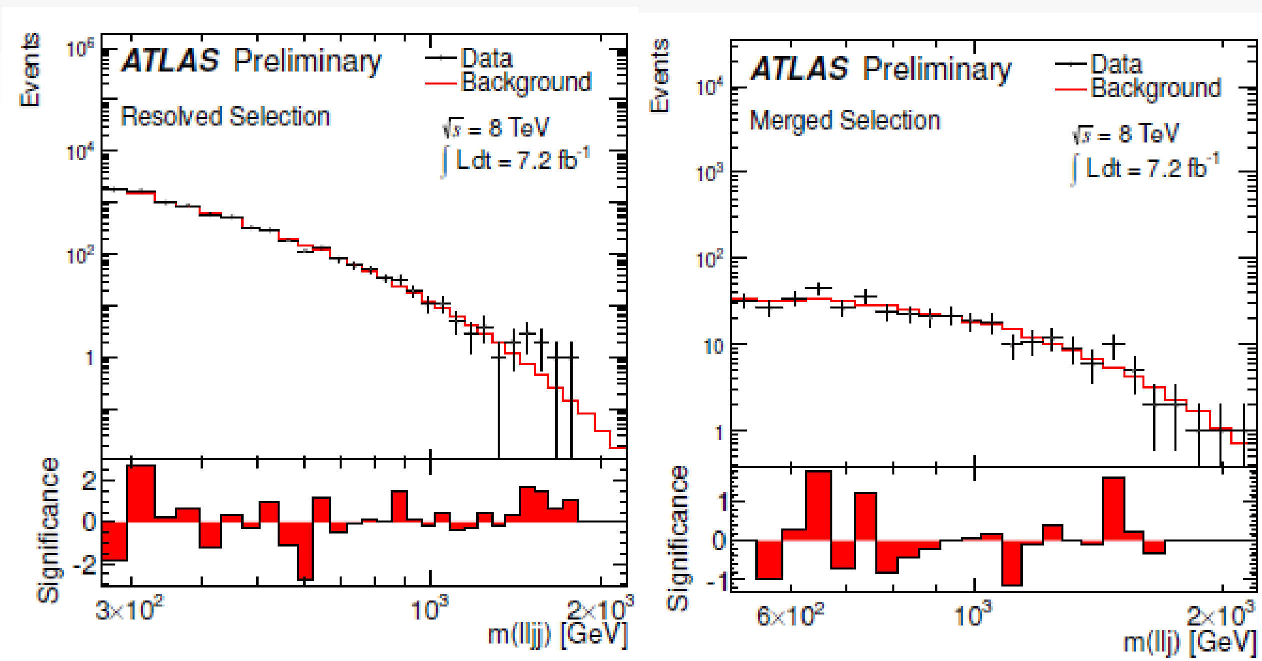
* Interesting Boosted ttbar and tb searches not presented here :
B2G-13-005, B2G-13-006
arXiv:1211.2202
See : A. Spieza talk

8 TeV : CMS-EXO-12-025
7 TeV : CMS arxiv:1206.0433

8 TeV : ATLAS-CONF-2013-015
7 TeV : arXiv:1204.1648

4.2) Background fitting technique

- Smooth background is fitted using either CTEQ inspired power low, either (leveled) exponential. Blind to background nature.
- Ideal for bump search.
- Works well if abundant background and no turn on or inflection points.
- Limitations: function arbitrary, signal may bias background function, « flat » constraints on the background parameters.



$$f(m; p_{0,1,2,3}) = p_0 \cdot \frac{(1-x)^{p_1}}{x^{p_2+p_3\cdot\ln(x)}},$$

$$x = m_{\ell\ell jj}/\sqrt{s} \text{ or } m_{\ell\ell j}/\sqrt{s}$$

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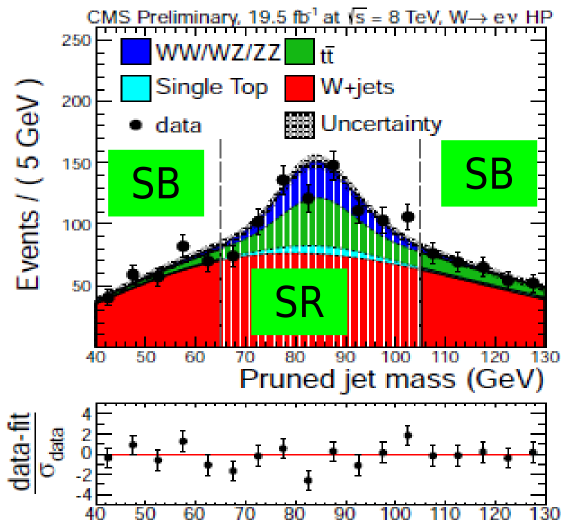
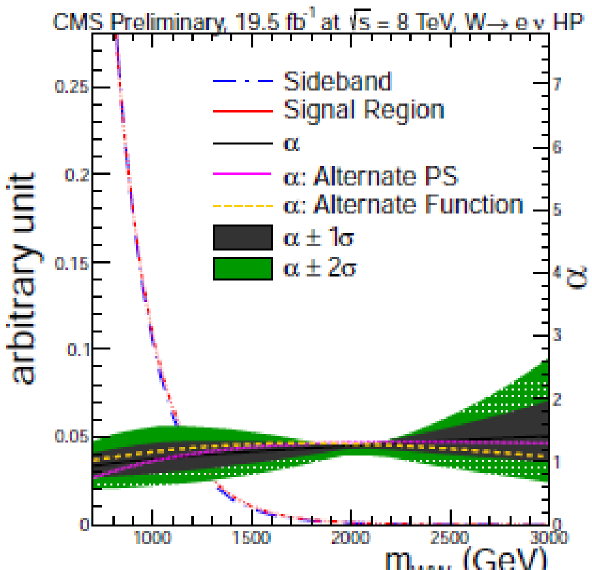
4.3) Side band technique

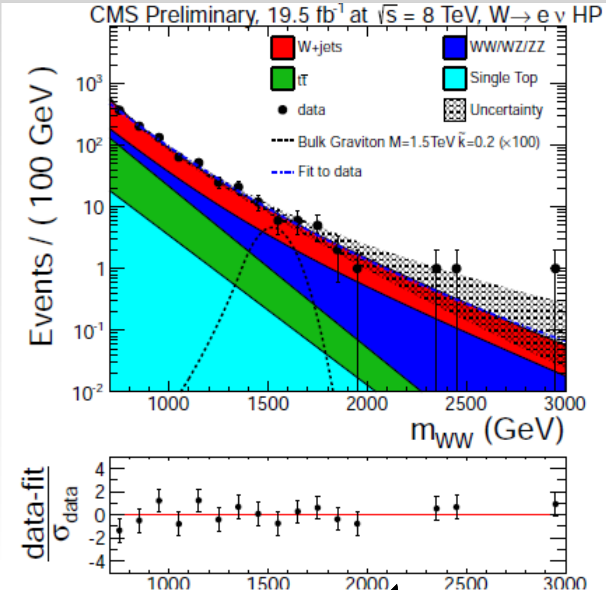
- Alternative approach for major background:
  - Take shape from data in jet mass side band
  - Use MC as transition function SB->SR $\alpha = N_{\text{MC, SR}} / N_{\text{MC, SB}}$ and input to extract $f_{\text{Bkg, SB}}$
- For minor backgrounds: use MC
- Limitations:
  - How do I believe MC to do the transition function. Need tests: SB $\rightarrow$ SB.
- Ideal : show that both methods converge

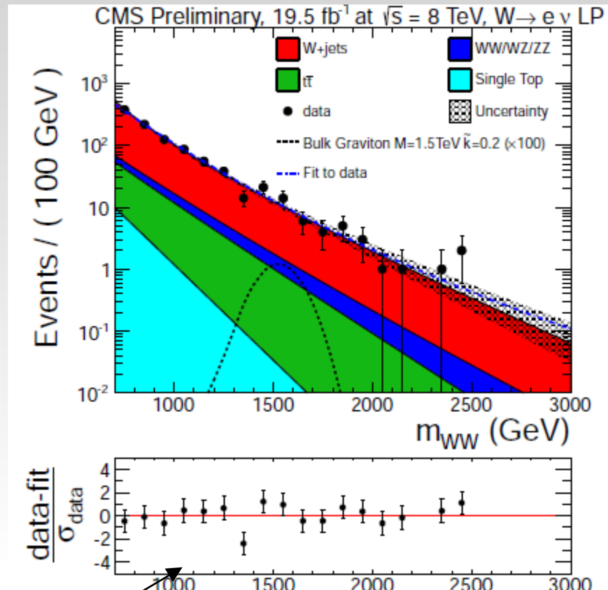
$$N_{\text{data, SR}} = N_{\text{data, SB}} \times f_{\text{Bkg, SB}} \times \alpha$$

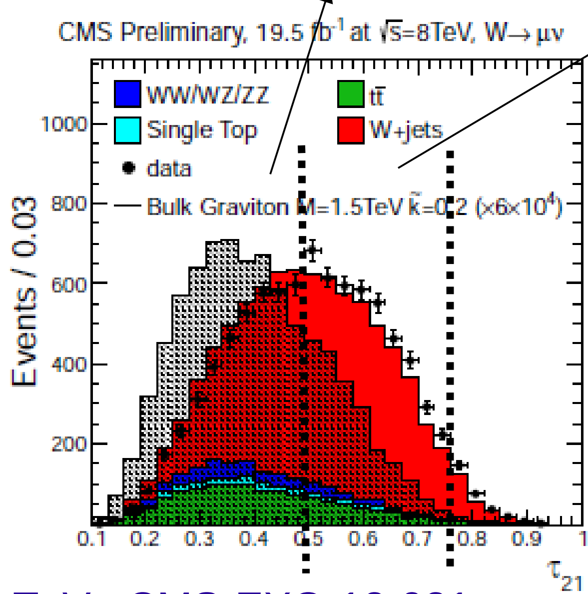




4.3) Side band technique: WW example



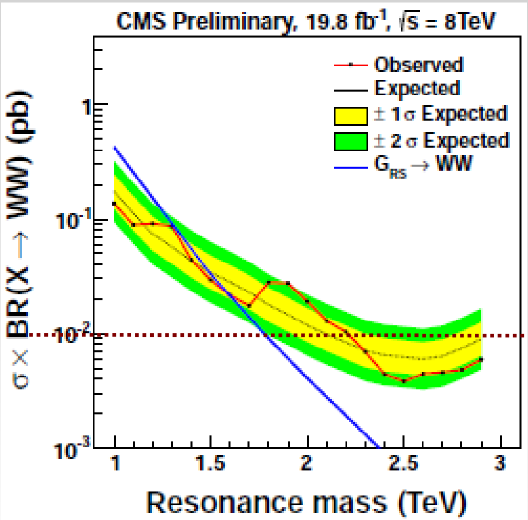


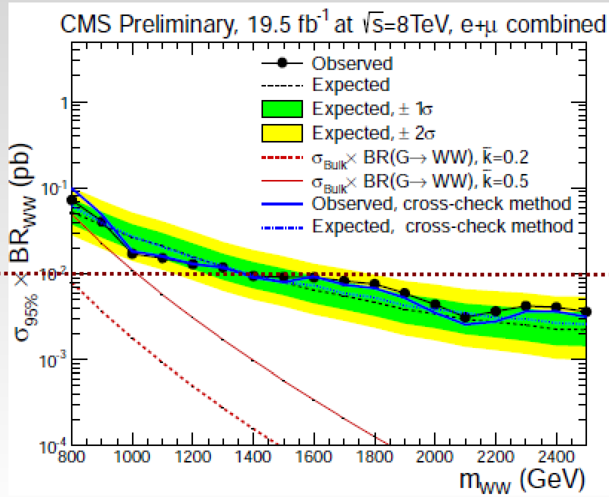


- Analysis done with high purity and low purity (important at high mass) categories.
- Electron and muon channels.
- Electron benefit from better resolution at high mass.

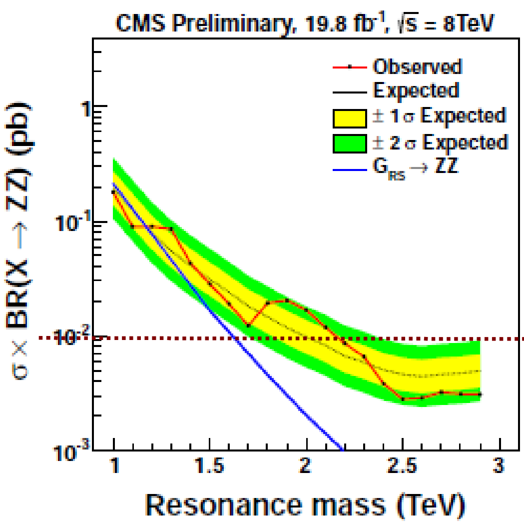
8 TeV : CMS-EXO-12-021

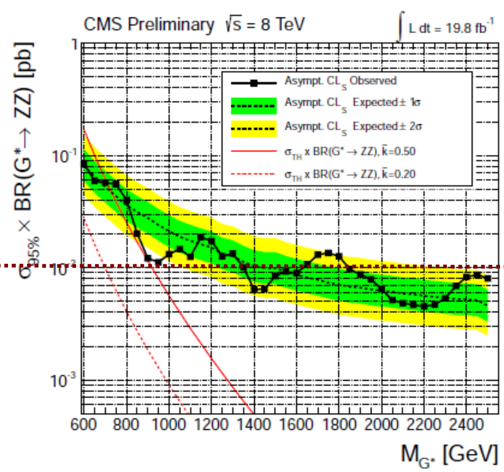
4.4) VV searches results

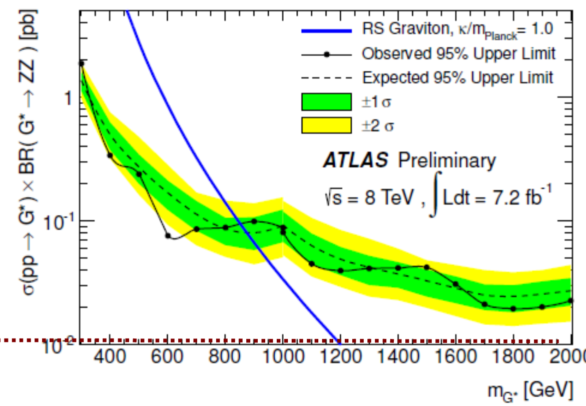




WW hypothesis



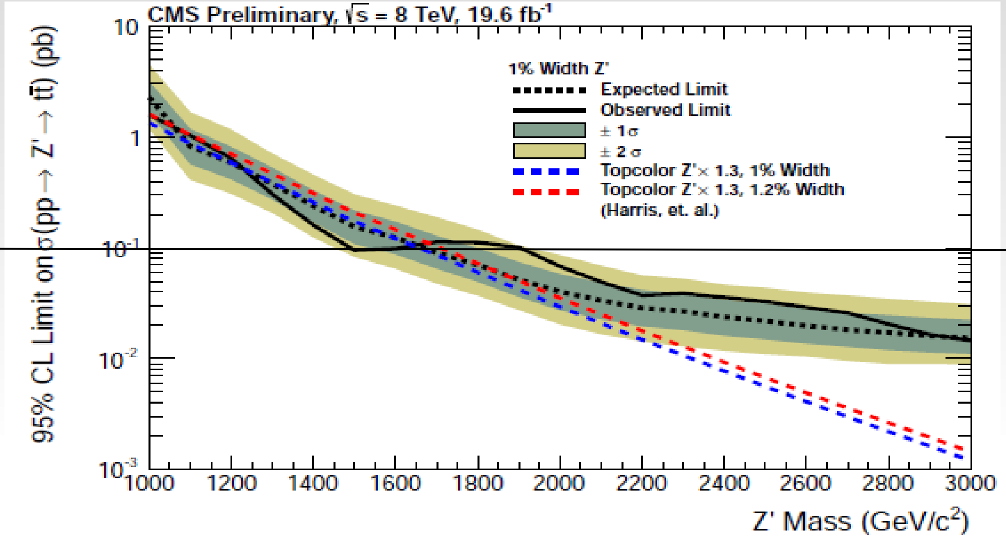


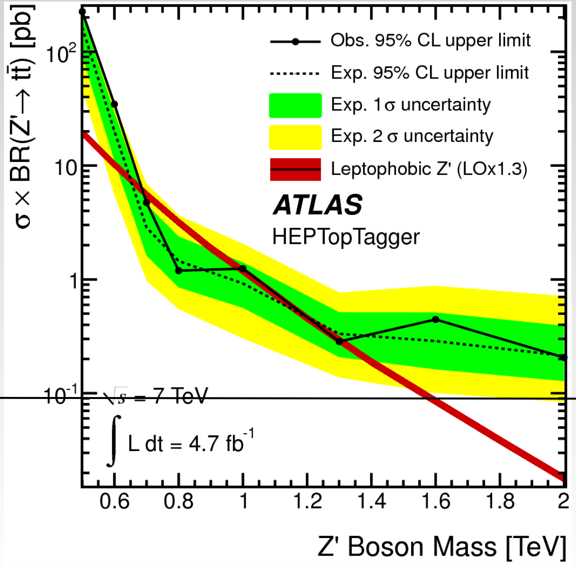


ZZ hypothesis

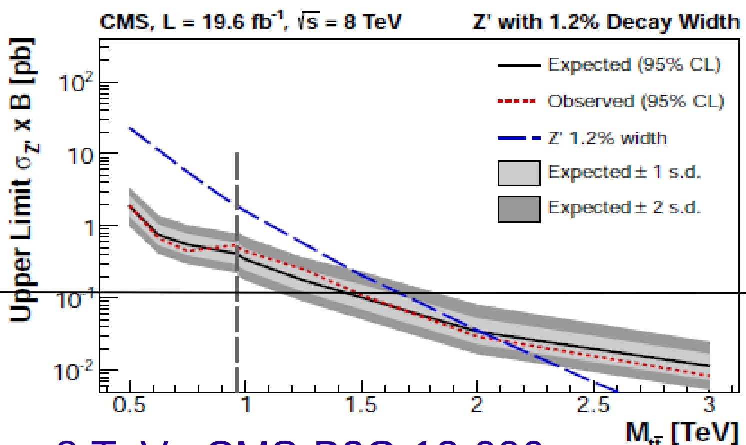
4.5) ttbar searches results

8 TeV : CMS-B2G-12-005

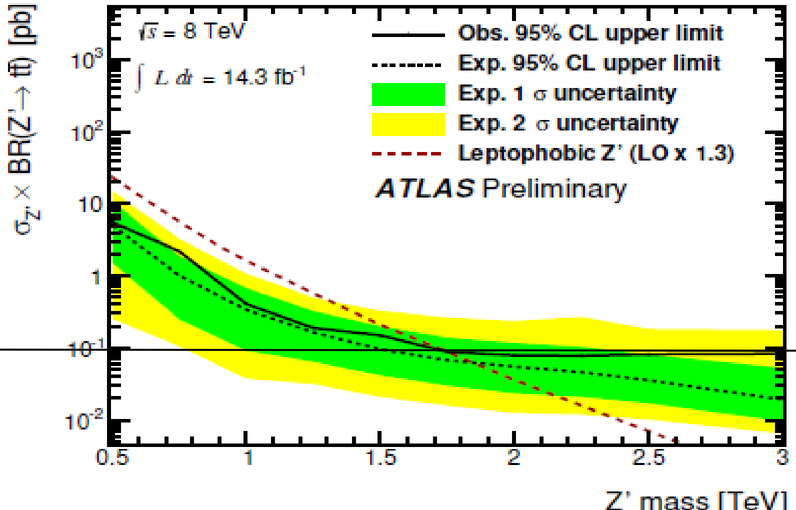




arXiv:1211.2202



8 TeV : CMS-B2G-12-006

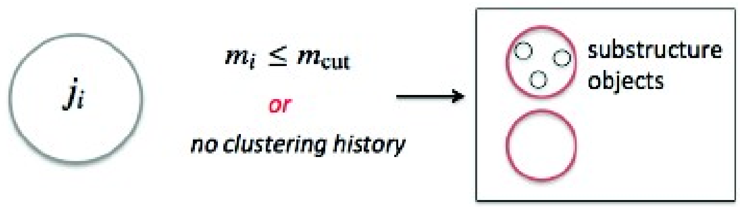


ATLAS-CONF-2013-052

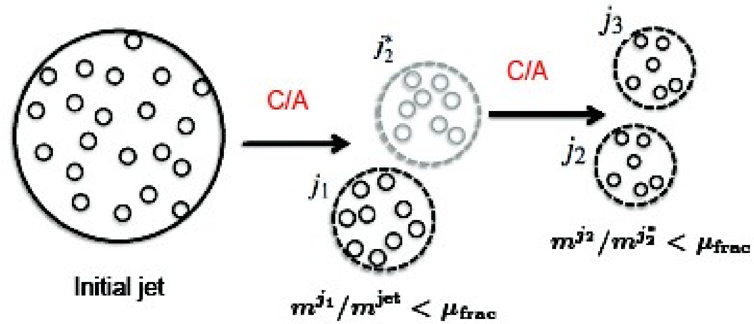
SUMMARY

- Jets substructure: bring quark final states back into the EW physics.
- The community is shaping out O(100 people) and regular workshops. The most important BOOST (last 2 weeks ago).
- Theory:
  - One of the most active domains in pQCD today.
  - Suggest new taggers: did we explored all the information we have?
  - Think about very boosted jets where grooming/taggers start to fail.
  - Check MC tuning.
  - Provide resummations and adapt taggers (see A.Kulesza plenary).
- Experiment:
  - study the taggers behavior on the real data and interplay with the detector and PU. First papers in 2012. Push taggers to their limits (high PU, high p_T).
  - Searching for new physics above TeV in VV/ttbar final states.
  - Preparation of VV scattering in SM for EWSB/Unitarization study.
- See A. Spiezia (CMS) and F. Merritt (ATLAS) parallel talks this afternoon.

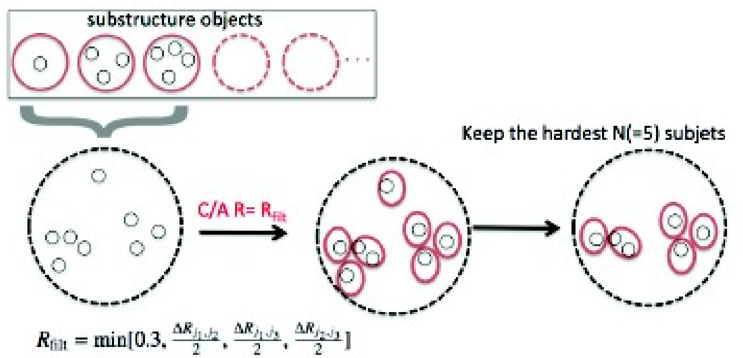
BACKUP



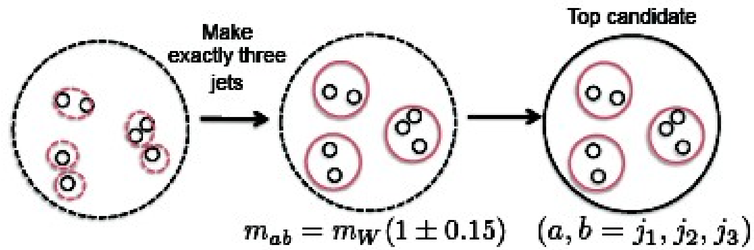
(a) Every object encountered in the declustering process is considered a 'substructure object' if it is of sufficiently low mass or has no clustering history.



(b) The mass-drop criterion is applied iteratively, following the highest subjet-mass line through the clustering history, resulting in N_i substructure objects.



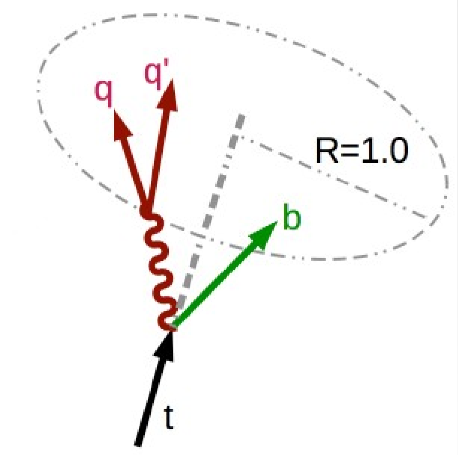
(c) For every triplet-wise combination of the substructure objects found in (b), recluster the constituents into subjets and select the $N_{\rm subjet}$ leading-$p_{\rm T}$ subjets, with $3 \leq N_{\rm subjet} \leq N_i$ (here, $N_{\rm subjet} = 5$).



(d) Recluster the constituents of the $N_{\rm subjet}$ subjets into exactly three subjets to make the top candidate for this triplet-wise combination of substructure objects.

1.3) Check of the calibration in CMS data

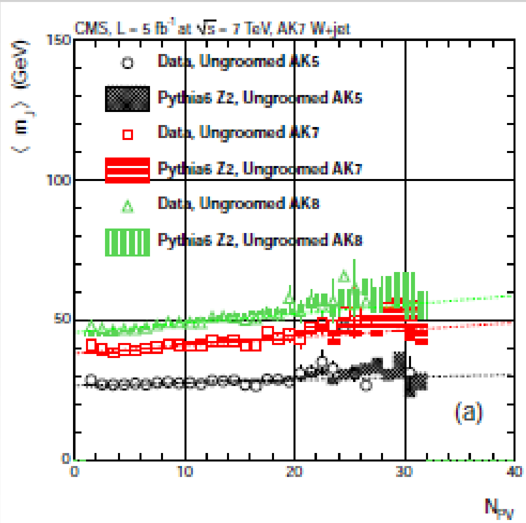
- Q: Does MC model substructure variables well in an interesting use case--top jets?
  - μ+jets decay channel with a b-tagged jet to obtain a top-enriched sample

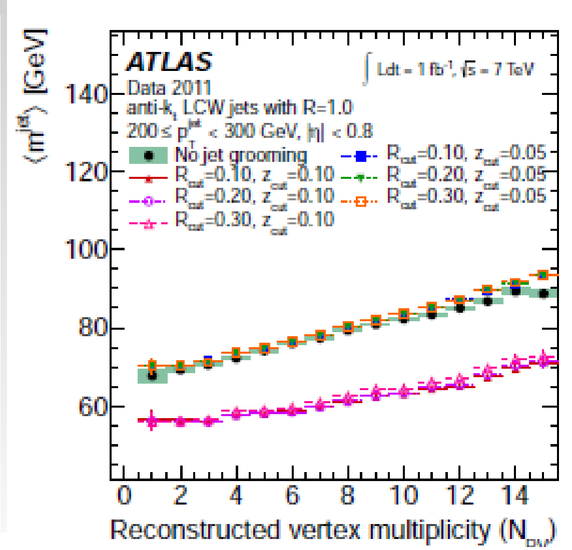


- Q: How do substructure variables perform if not all decay pr
contained? Does MC moc
well?
  - Split MC events into tv
categories: with fully-c
and non-contained top
  - Study substructure as a function of number of k_t subjets

Event with a fully-contained top jet:
- All three daughters within $\Delta R < 1.0$ of truth top, before radiation
- Plots for highest p_T jet, not necessarily the top jet

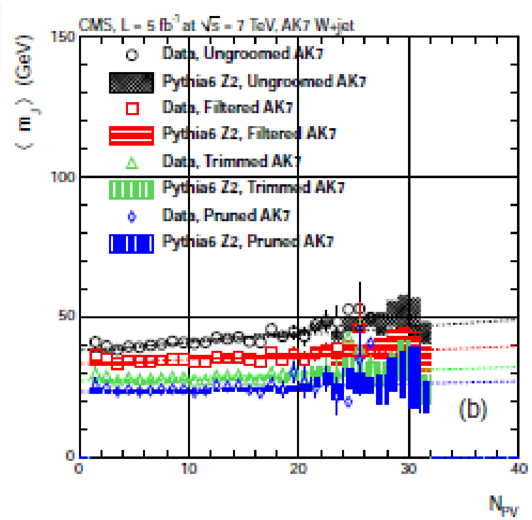
1.3) Pile-up effect

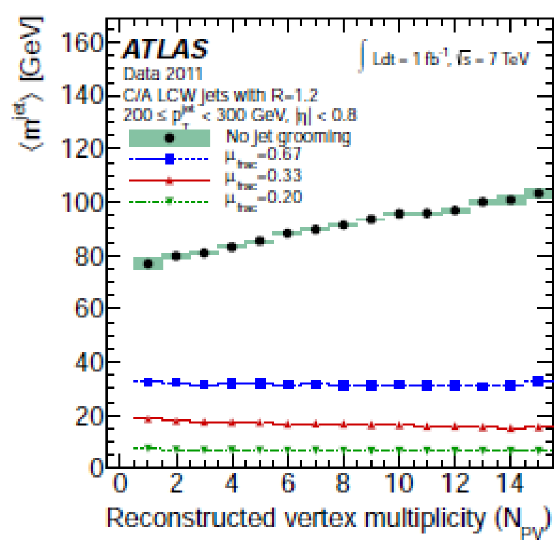




$$\Delta R_{j_1,j_2} < R_{\mathrm{cut}} \times (2m^{\mathrm{jet}}/p_{\mathrm{T}}^{\mathrm{jet}})$$

$$p_{\mathrm{T}}^{j_2}/p_{\mathrm{T}}^{j1+j2} > z_{\mathrm{cut}}$$



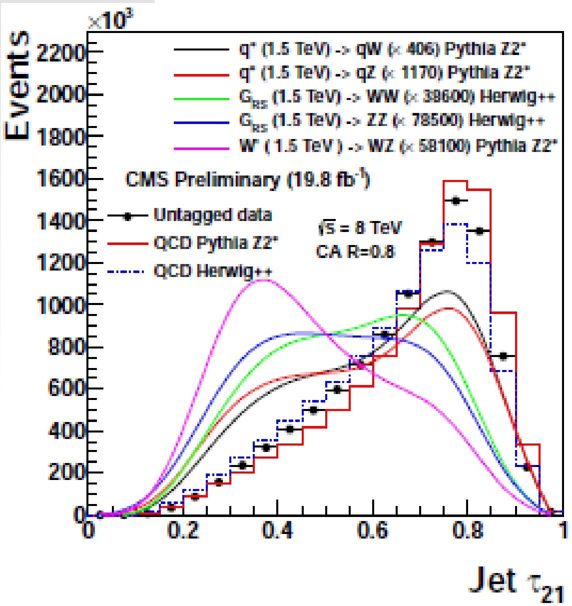


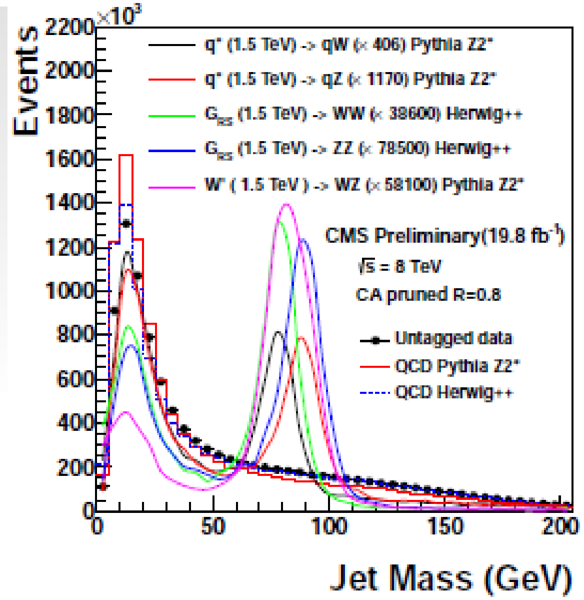
$$z_{ij} = \frac{\min(p_{\mathrm{T}i}, p_{\mathrm{T}j})}{p_{\mathrm{T}i} + p_{\mathrm{T}j}} < z_{\mathrm{cut}}$$

$$\Delta R_{ij} > D_{\mathrm{cut}} \equiv \alpha \cdot \frac{m_J}{p_{\mathrm{T}}},$$

1.3) Pile-up effect

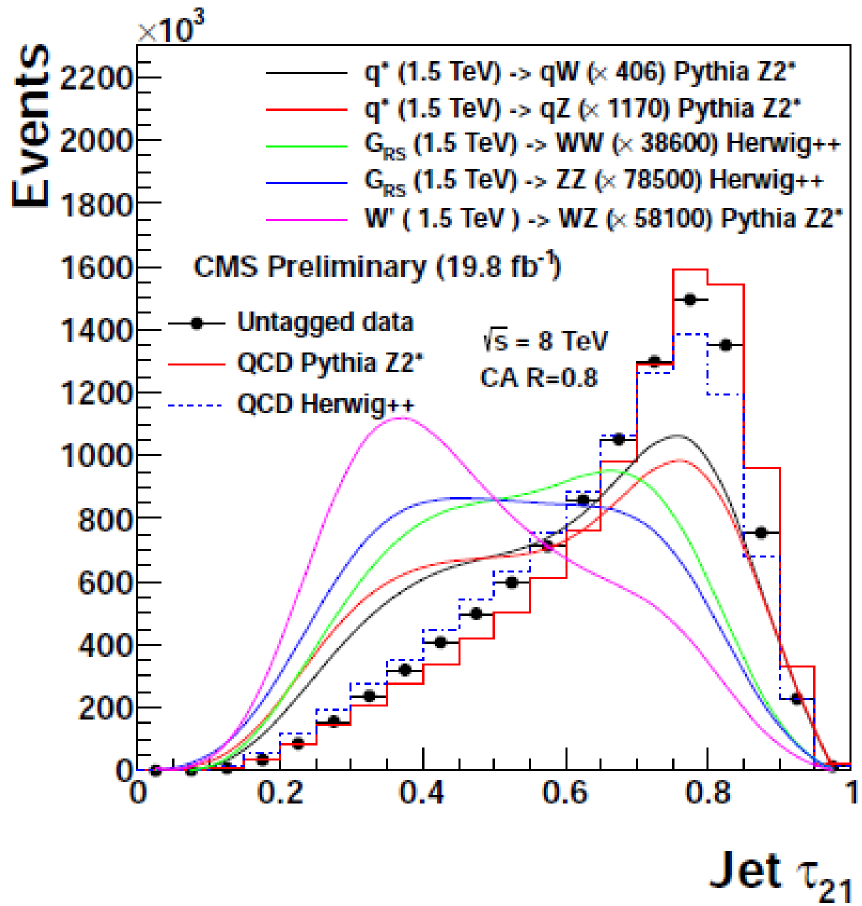
- Background: smooth fit (S+B) to data (no need for BG MC)
- Simultaneous fit to high-purity ($\tau_2/\tau_1 < 0.5$) and low-purity ($0.5 < \tau_2/\tau_1 < 0.75$) data

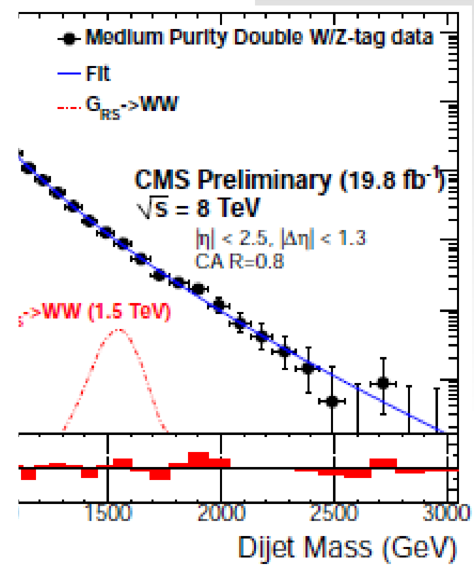




1.3) Pile-up effect

- Background: smooth fit (S+B) to data (no need for BG MC)
- Simultaneous fit to high-purity ($\tau_2/\tau_1 < 0.5$) and low-purity





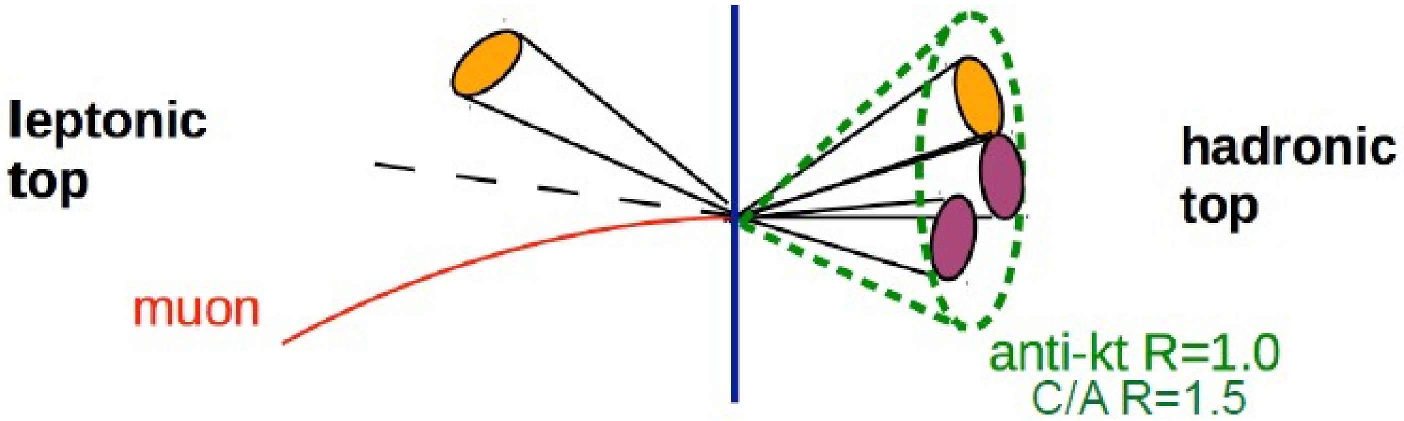
1.3) Check of the calibration in CMS data

- One triggered muon with $p_T > 25$ GeV, $|\eta| < 2.5$, and relative miniisolation < 0.05
- $E_T^{miss} + m^W_T > 60$ GeV
- One b-tagged anti-k_t R = 0.4 jet within $\Delta R < 1.5$ of the selected muon

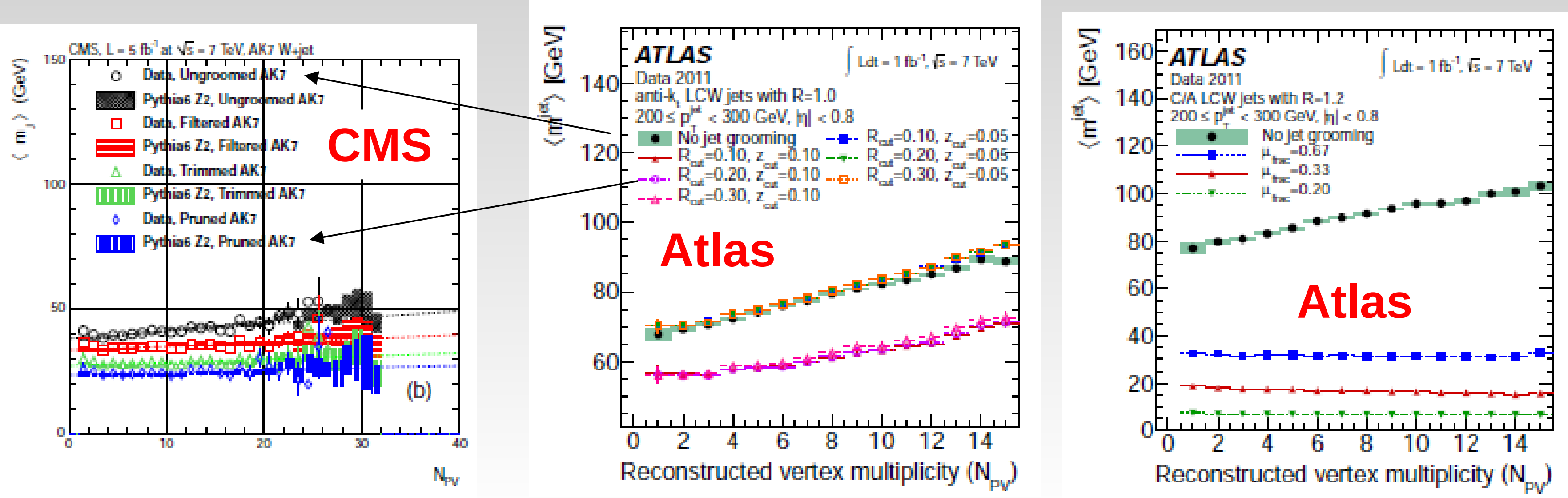
- At least one trimmed anti-k_t R=1.0 jet

- OR -

- At least one C/A R=1.5 jet which passes HEPTopTagger selection
- Both cases: $p_T > 200$ GeV and $|\eta| < 1.2$



2.6) Pile-up dependance



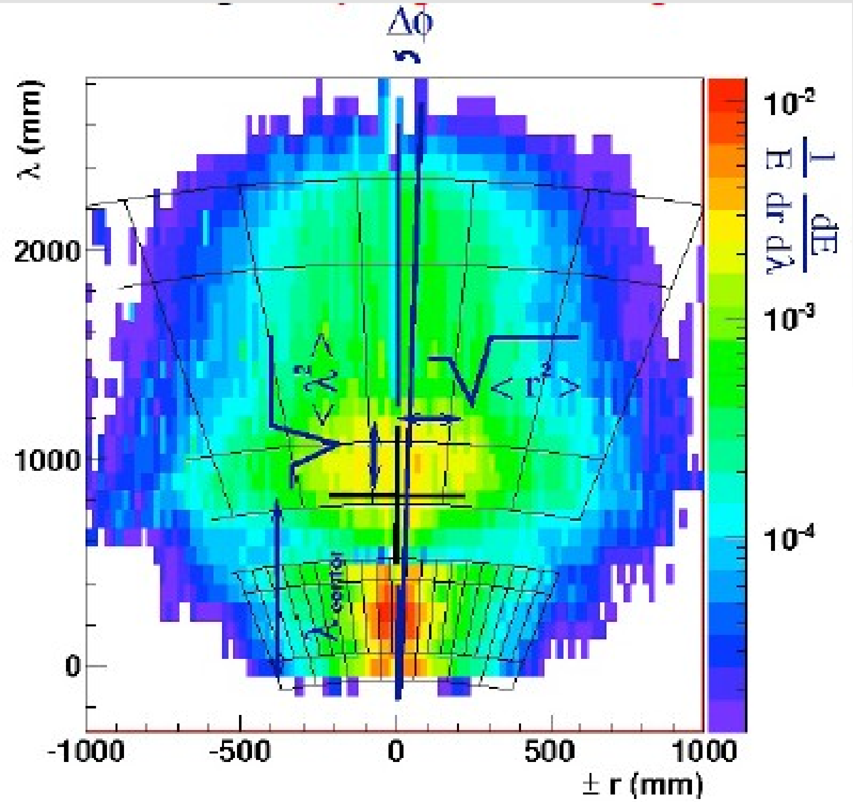
2.1) Jet reconstruction at Atlas

Input to jet reconstruction: topological clusters

Since the Tevatron and H1, new techniques for combining calorimeter cells have been explored such as 3-dimensional clustering, or topological clustering

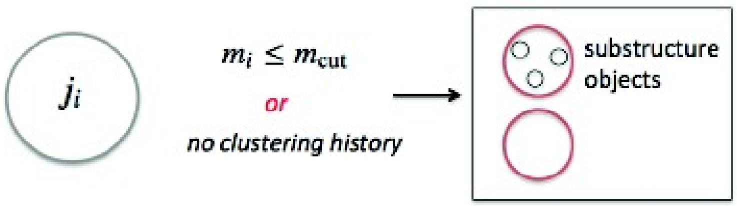
1. Find seed cells above some noise threshold ($E_{cell}/\sigma_{cell}^{noise} \geq N_{threshold}$)
2. Then cluster cells around that in 3-dimensions, successively allowing in more cells
   - For example: 4σ seed, several layers of 2σ cells, last layer of all cells

These clusters can then be used as the basic object of calibration instead of entire jets! Will focus here on early data approaches



algorithm that includes noise suppression [73]. The resulting topo-clusters are considered as massless four-momenta, such that $E = |\vec{p}|$. They are classified as either electromagnetic

1.9) HEP TOP TAGGER: generalisation



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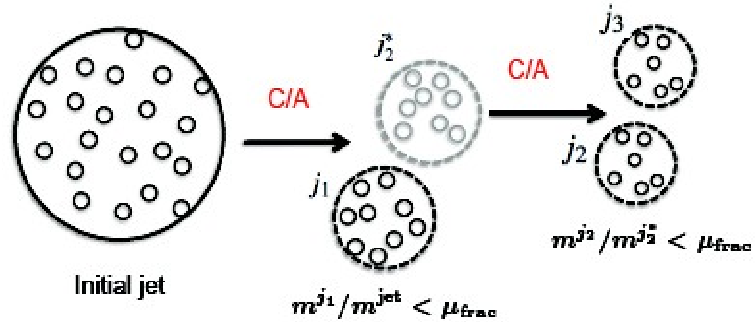

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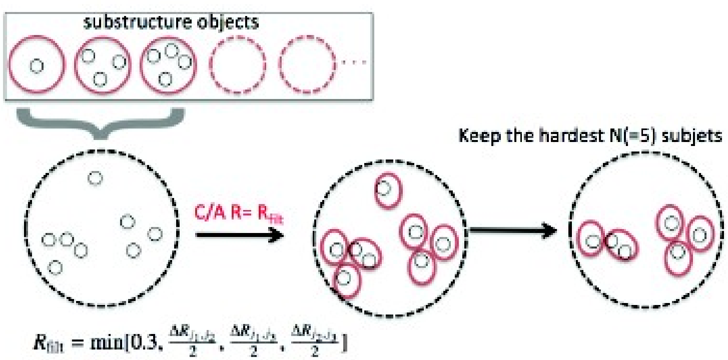

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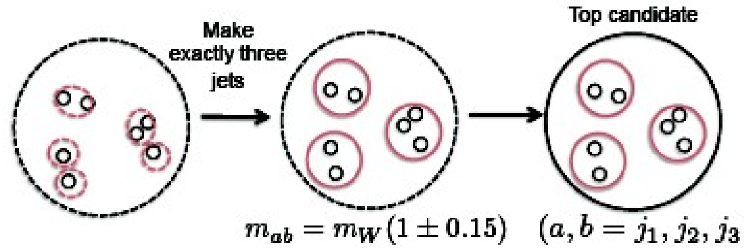
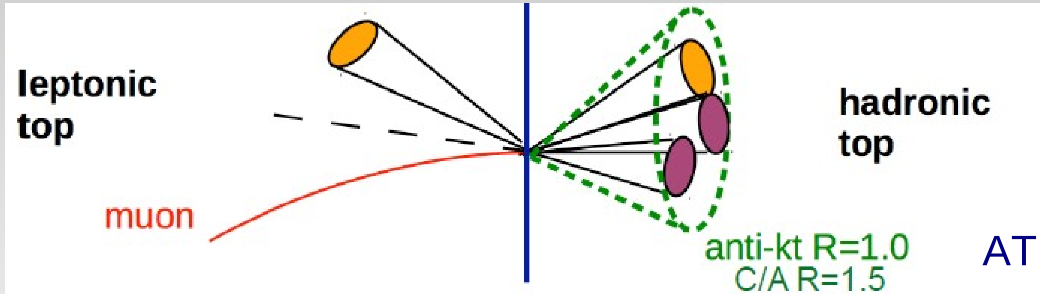
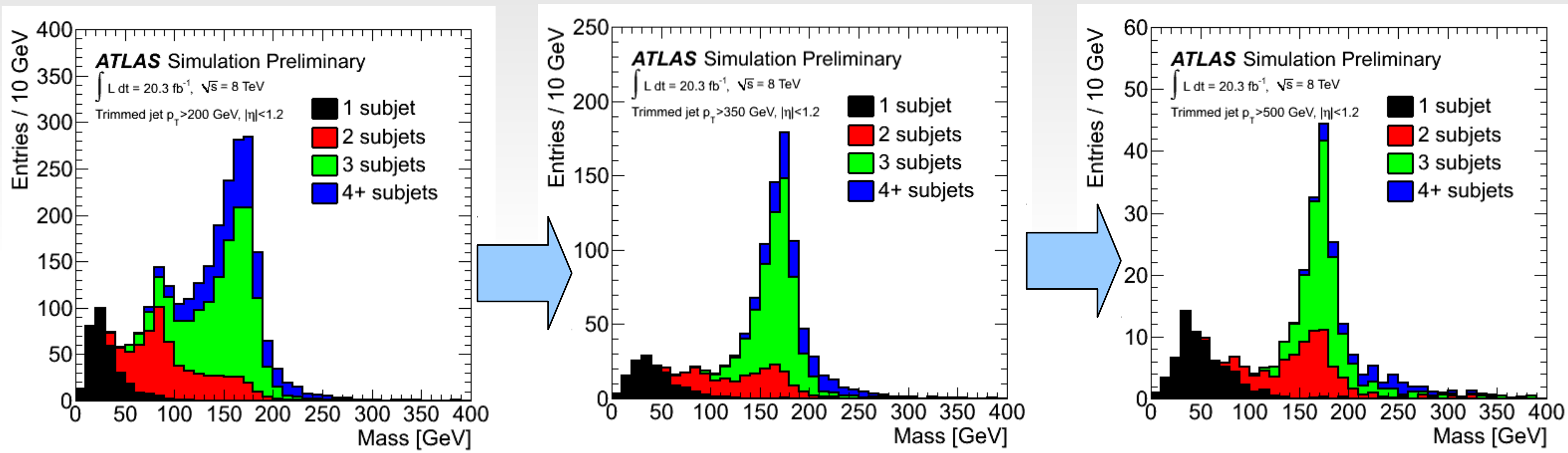


(d) Recluster the constituents of the $N_{\rm subjet}$ subjets into exactly three subjets to make the top candidate for this triplet-wise combination of substructure objects.

arXiv:1306.4945v1



ATLAS-CONF-2012-150



- 2-subjets sample peak at W mass and 3-subjets at the top mass.
- At high p_T 2-subjets sample start to peak at top mass. Subjets are not resolved anymore by trimming parameters.
- 3 subjets at low p_T peaks also at W mass: QCD radiation.

4 subjets: QCD radiation.