Jet Substructure

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Outline

- Jet algorithms
  - Definitions, features, hadronization & UE
- Jet substructure
  - Jet profiles, jet grooming
  - ATLAS diboson
  - Energy correlation functions
  - Quark-gluon jet discrimination
- Conclusions

Jet Algorithms

Jet observables should be:

- Computable from data in reasonable time
- Calculable in perturbative QCD
- Robust against non-perturbative effects
- Correctable for underlying event

Jet clustering algorithms

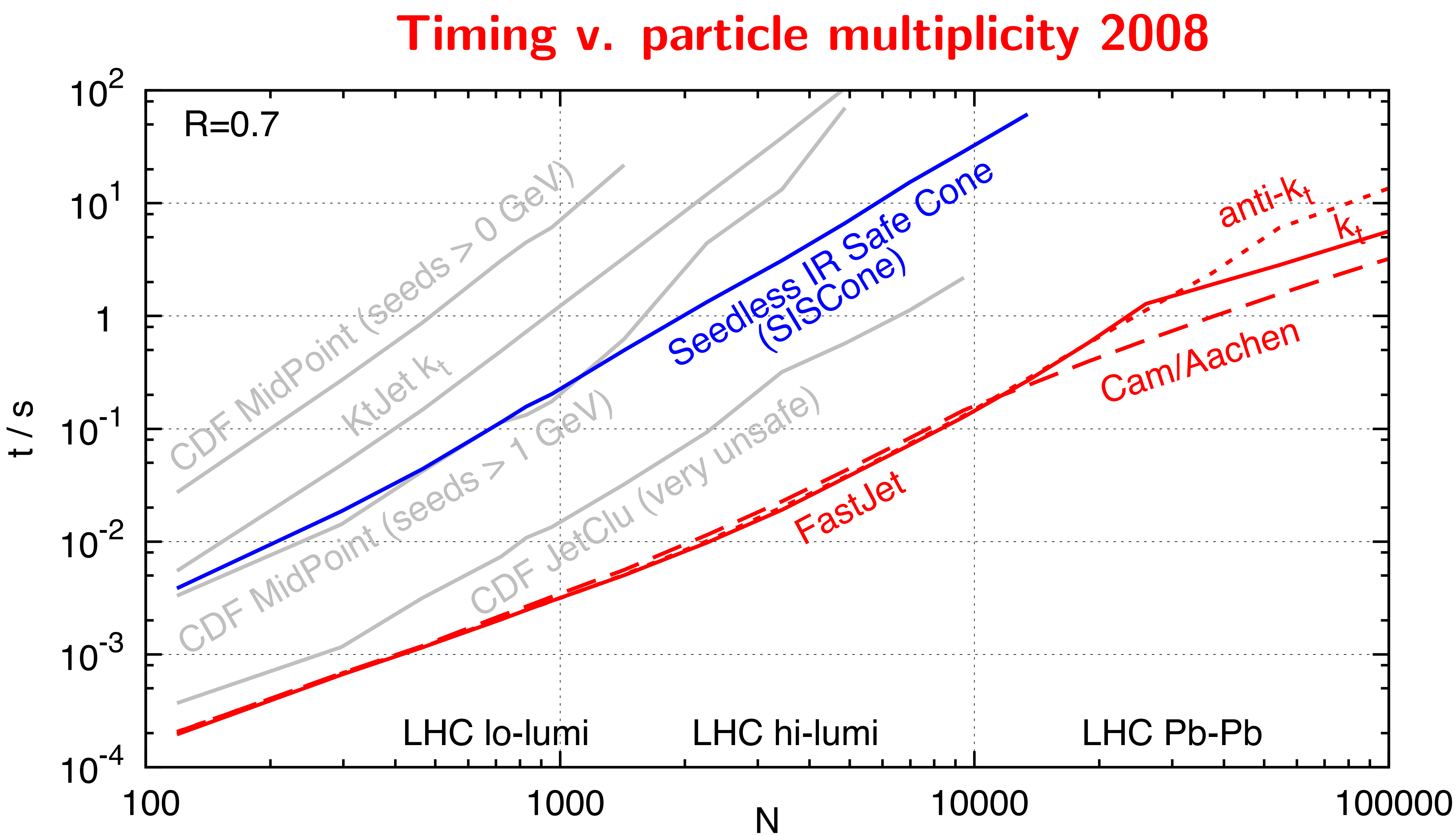
- Compute list of $\{d_{ij}, d_{iB}\}$

$$d_{ij} = \min\{p_{ti}^{2p}, p_{tj}^{2p}\}\frac{\Delta R_{ij}^2}{R^2}\ , \ d_{iB} = p_{ti}^{2p}\ , \ \ \Delta R_{ij}^2 \equiv (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

  - If d_{ij} is smallest, combine i & j
  - If d_{iB} is smallest, i is a jet: remove it from list
  - Repeat until list is empty
- $p = +1$: k_T algorithm (scale of running coupling)
- $p = 0$: Cambridge/Aachen algorithm (angular ordering)
- $p = -1$: anti-k_T algorithm (cone jets, not QCD dynamics)

[JADE algorithm: $d_{ij} \propto p_{ti}p_{tj}\Delta R_{ij}^2 \simeq m_{ij}^2$]

Jet algorithms: computation

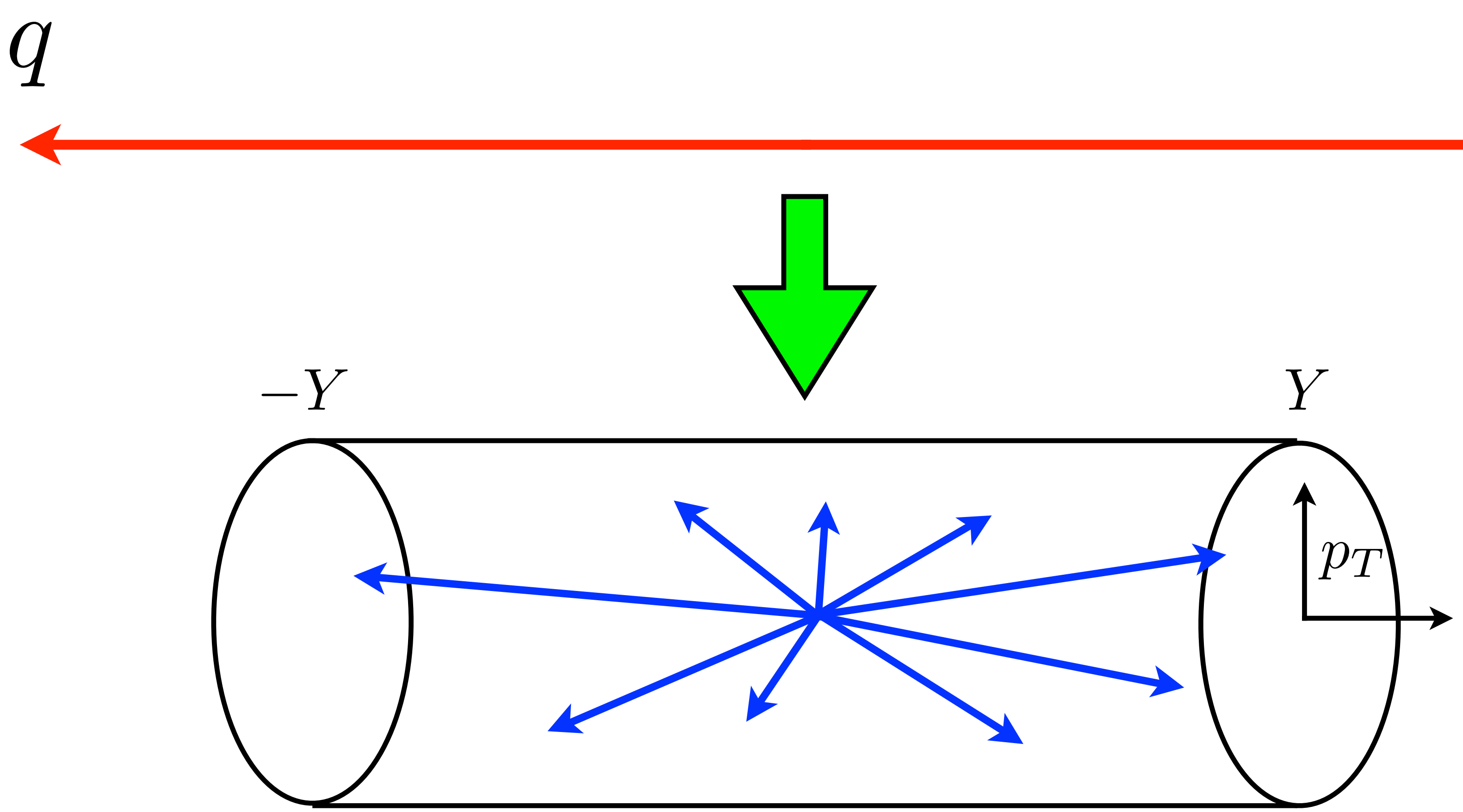


$$N^3 \to N \log N$$

FastJet: Cacciari & Salam, Phys Lett B 641(2006)57

Jet hadronization

- Simple “tube” model describes many features



$$\eta = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$

$$Q = E_{\rm cm} = \int d\eta\, d^2p_T\, \rho(p_T)p_T\cosh y = 2\lambda\sinh Y$$

$$\lambda = \int d^2p_T\, \rho(p_T)p_T = N_{\rm had}\langle p_T\rangle/2Y$$

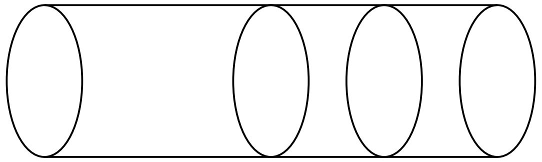
Jet hadronization

Dokshitzer, Leder, Moretti, BW, JHEP 08(1997)001

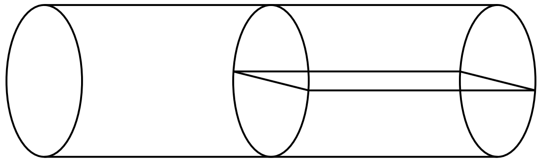
- Algorithm should classify tube as 2-jet
  - $\langle y_{3-\mathrm{jet}} \rangle$ smallest is best

$$y_{ij} = (k_t^2)_{ij}/Q^2$$

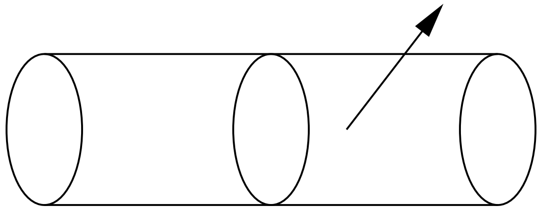
- JADE: $\langle y_{3-\mathrm{jet}} \rangle \sim \lambda/Q$



- LUCLUS, k_T: $\langle y_{3-\mathrm{jet}} \rangle \sim (\lambda \ln Q/Q)^2$

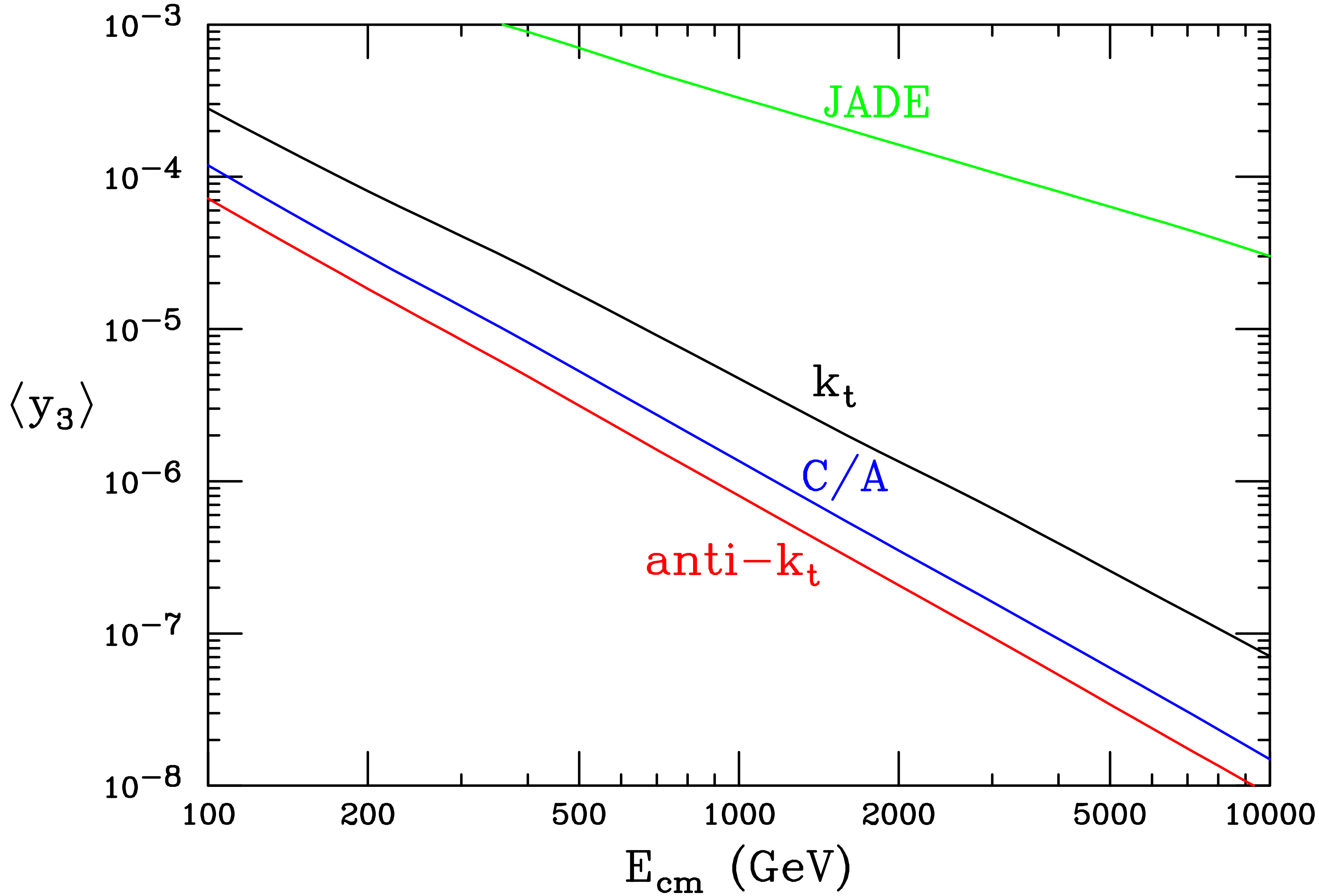


- Cambridge/Aachen: $\langle y_{3-\mathrm{jet}} \rangle \sim (\lambda \ln \ln Q/Q)^2$



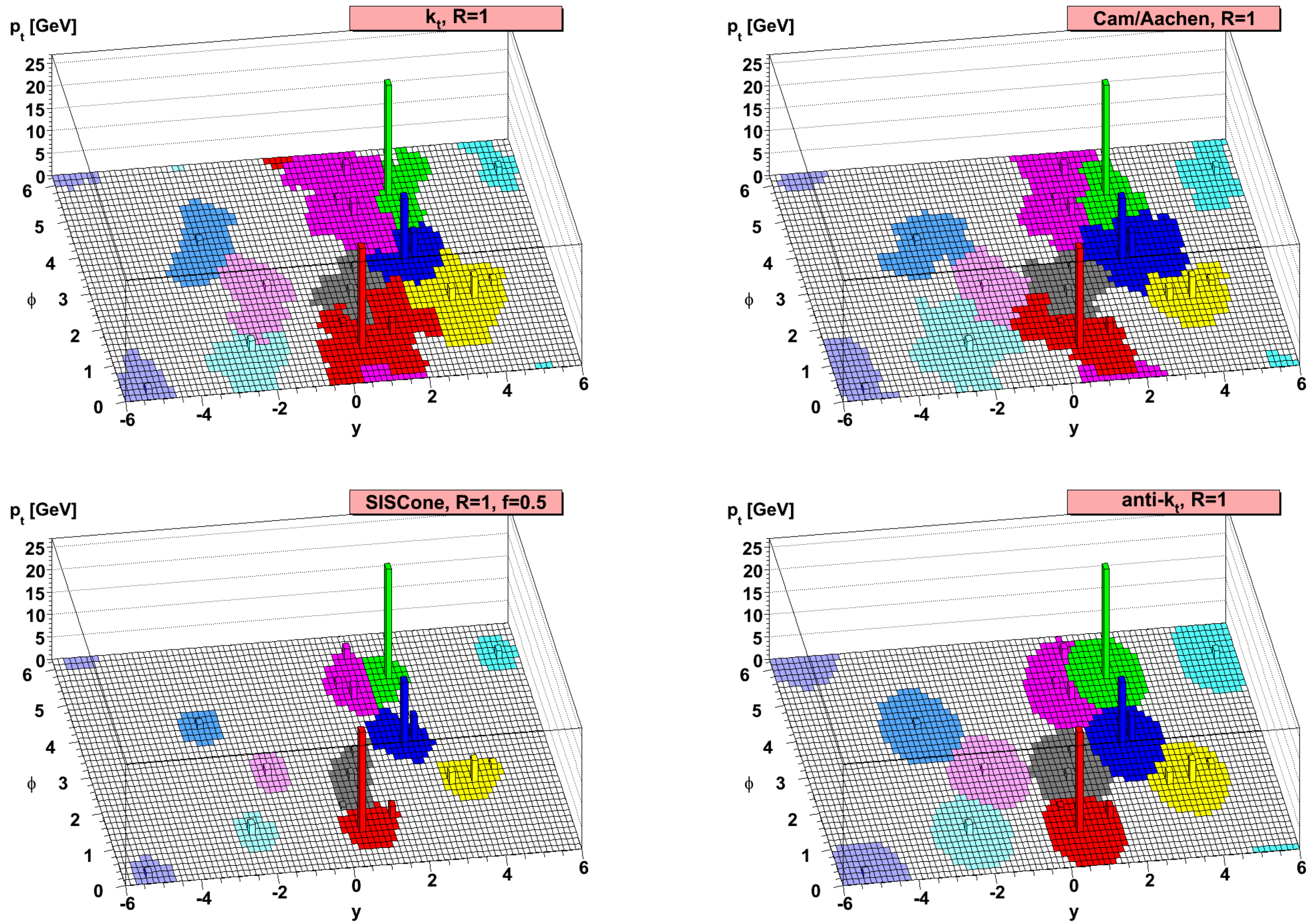
- Anti-k_T: $\langle y_{3-\mathrm{jet}} \rangle \sim (\lambda/Q)^2$

Jet algorithms: hadronization



- Anti-k_T is best for small hadronization effect

Jet algorithms: underlying event

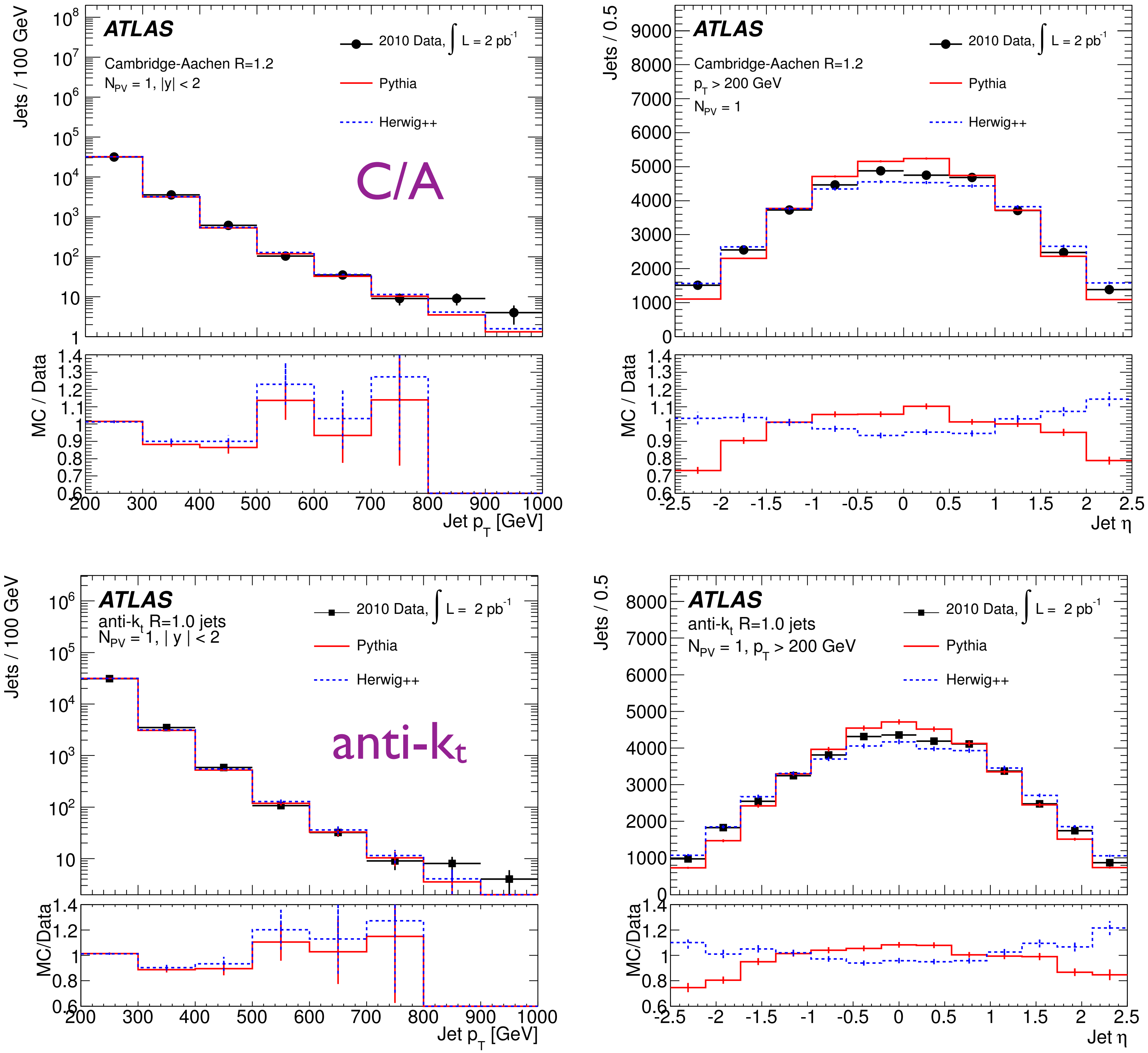


Cacciari, Salam, Soyez, JHEP04(2006)063

- Anti-k_T is best for controlled UE subtraction

Jet cross sections

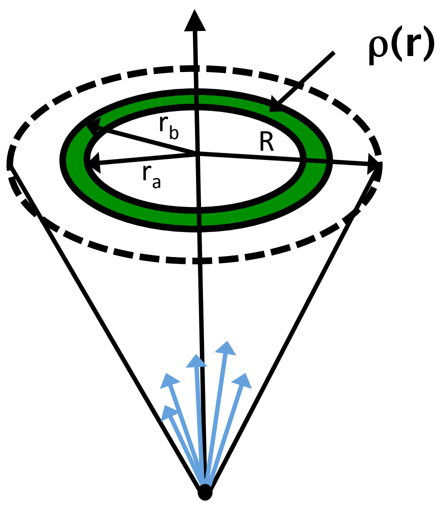
- Compared with stand-alone event generators (no matching or merging)
- Little difference between C/A and anti-k_T jet distributions



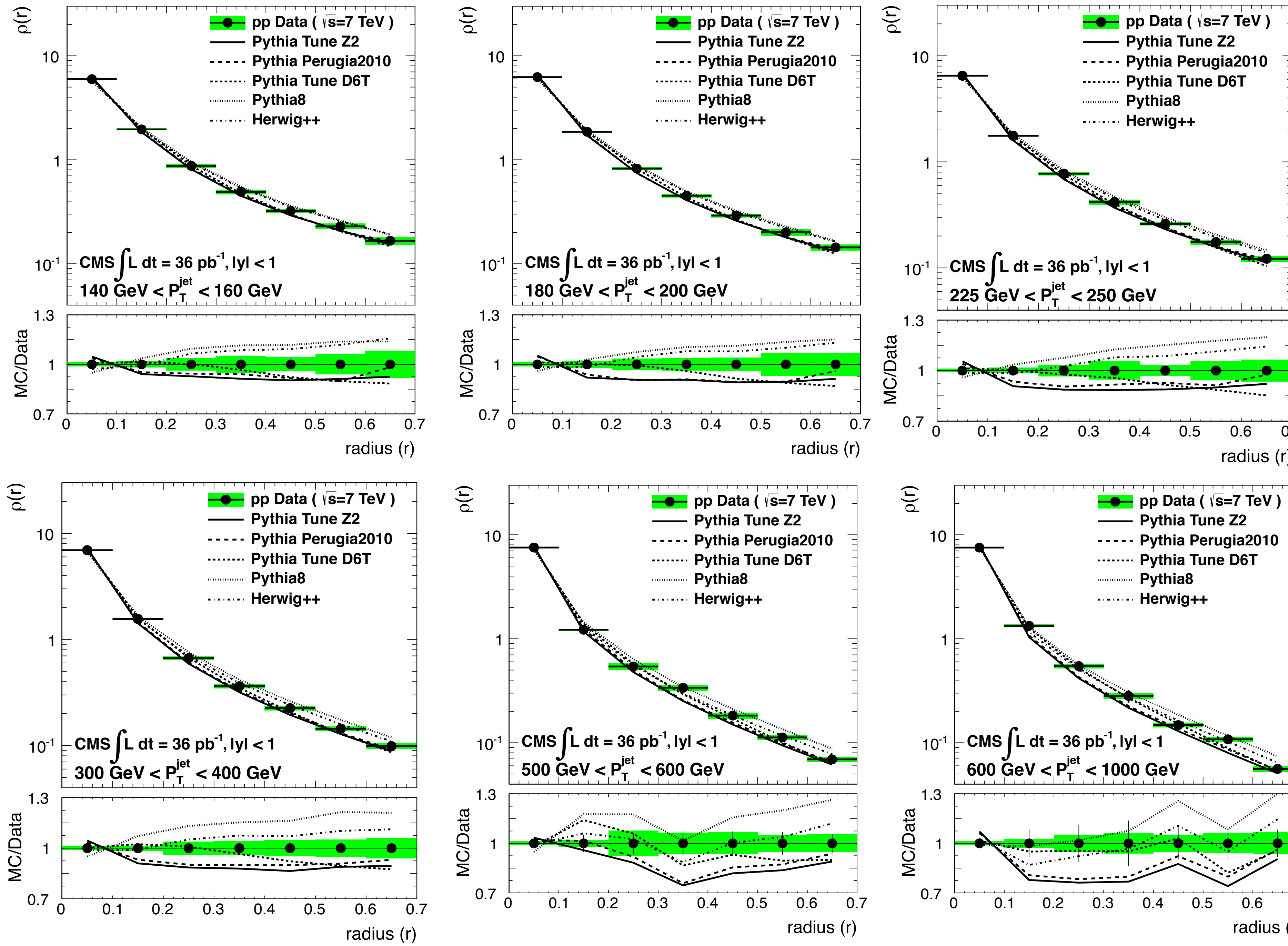
ATLAS, arXiv:1203.4606

Jet Substructure

Jet profiles



$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{r_a < r_i < r_b} p_{T,i}}{\sum_{r_i < R} p_{T,i}}$$



- Energy flow versus r < R
- Anti-k_T, R=0.7
- Different jet p_T bins

CMS, arXiv:1204.3170

- Stand-alone Herwig++ & Pythia describe fairly well (±20%)

Jet grooming

Butterworth, Davison, Rubin, Salam, arXiv:0802.2470
Dasgupta, Fregoso, Marzani, Salam, arXiv:1307.0007

- Aim is to "clean up" jets by reducing effects of soft QCD radiation, hadronization, underlying event, pileup, …
  - Especially to find boosted heavy object decays (V, H, t, …)
- E.g. (BDRS): sequentially de-cluster C/A jet, $J \to i + j$
  - throw away less massive* subjet if

$$y = \min\{p_{Ti}^2, p_{Tj}^2\}\Delta R_{ij}^2/m_J^2 \simeq \min\{p_{Ti}, p_{Tj}\}/\max\{p_{Ti}, p_{Tj}\} < y_{\rm cut}$$

  - Stop when $y > y_{\rm cut}$

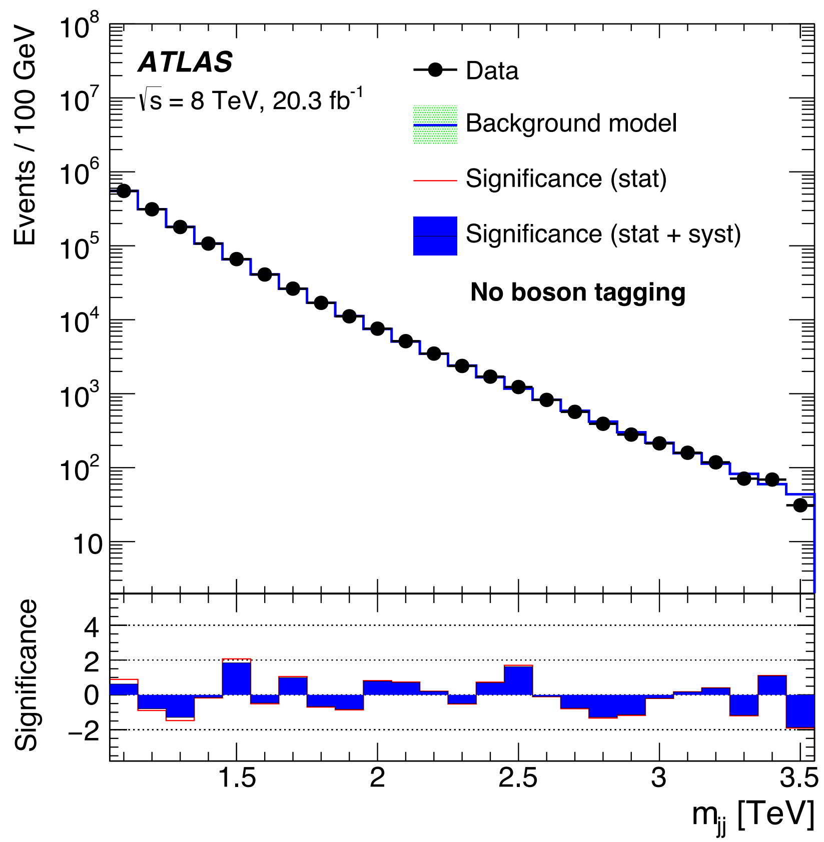
*Better (DFMS): throw away subjet with less $m_i^2 + p_{Ti}^2$

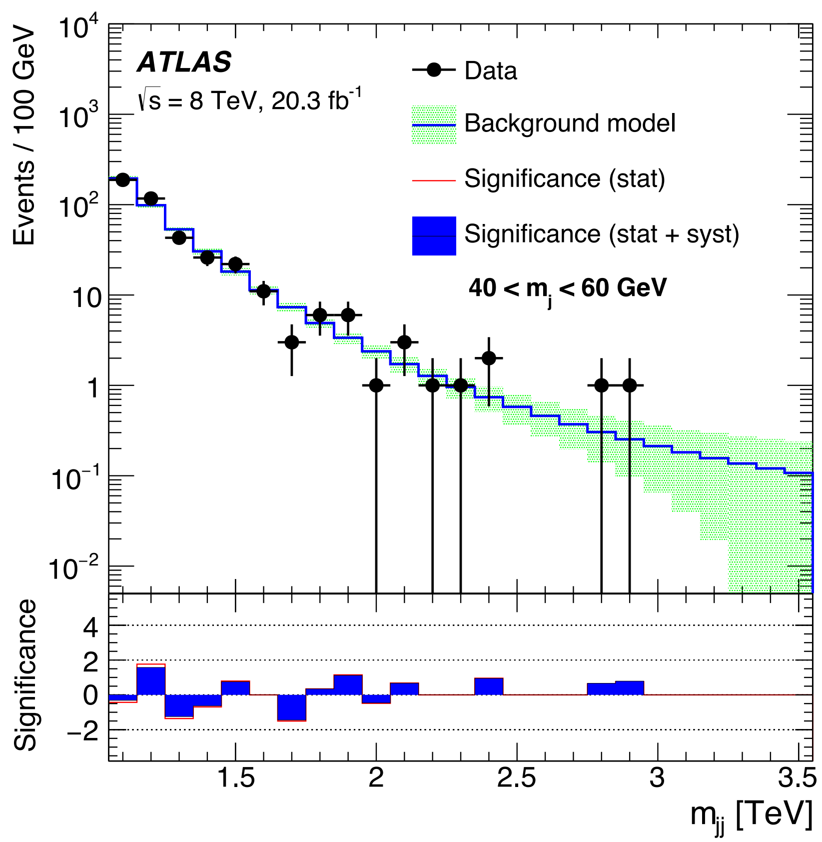
ATLAS Diboson

ATLAS grooming

ATLAS, arXiv:1506.00962

- C/A (R=1.2) dijets with m_{jj}>1.05 TeV, $|\eta_j|$<2, $|\Delta\eta_{jj}|$<1.2
- Each jet BDRS groomed with y_{cut}=0.04
- Resulting subjets reclustered (C/A) with R=0.3
- Keep 3 highest-p_T subjets of each jet [$V \to q\bar{q}(g)$]



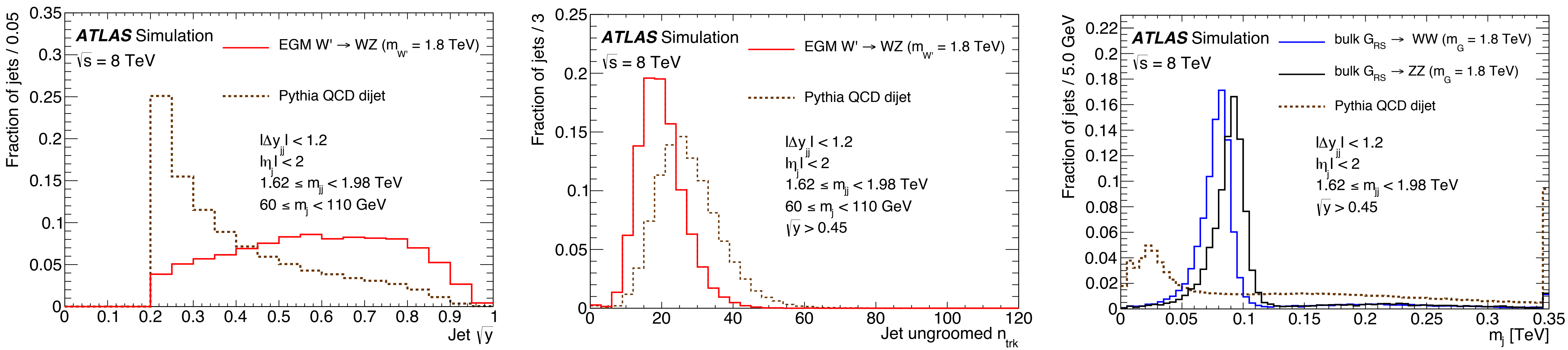


Diboson selection

- WZ, WW, ZZ selection:

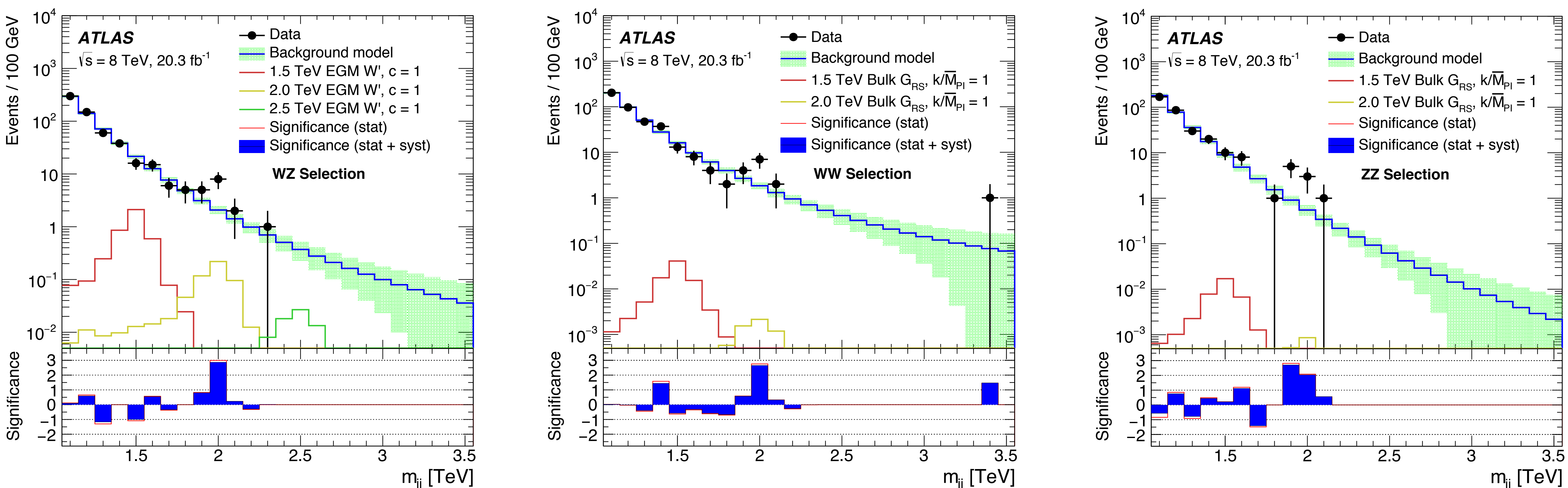
$$y > 0.2\,, \quad |m_J - m_V| < 13\,\mathrm{GeV}\,, \quad n_{\mathrm{tk}} < 30$$

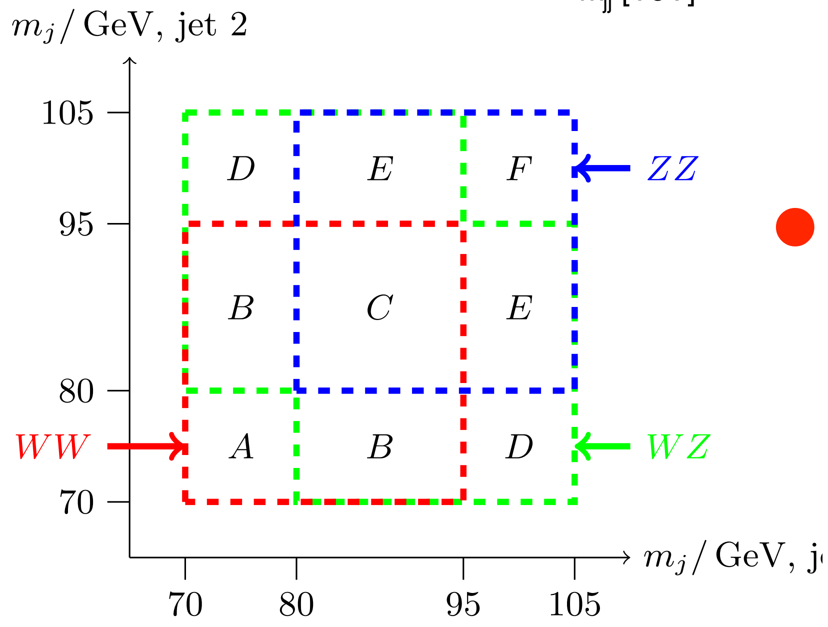
$$y = \min(p_{Tj_1}^2, p_{Tj_2}^2)\Delta R_{(j_1,j_2)}^2/m_J^2 \simeq \min(p_{Tj_1}, p_{Tj_2})/\max(p_{Tj_1}, p_{Tj_2})$$



Diboson signal

- After WZ, WW, ZZ selection

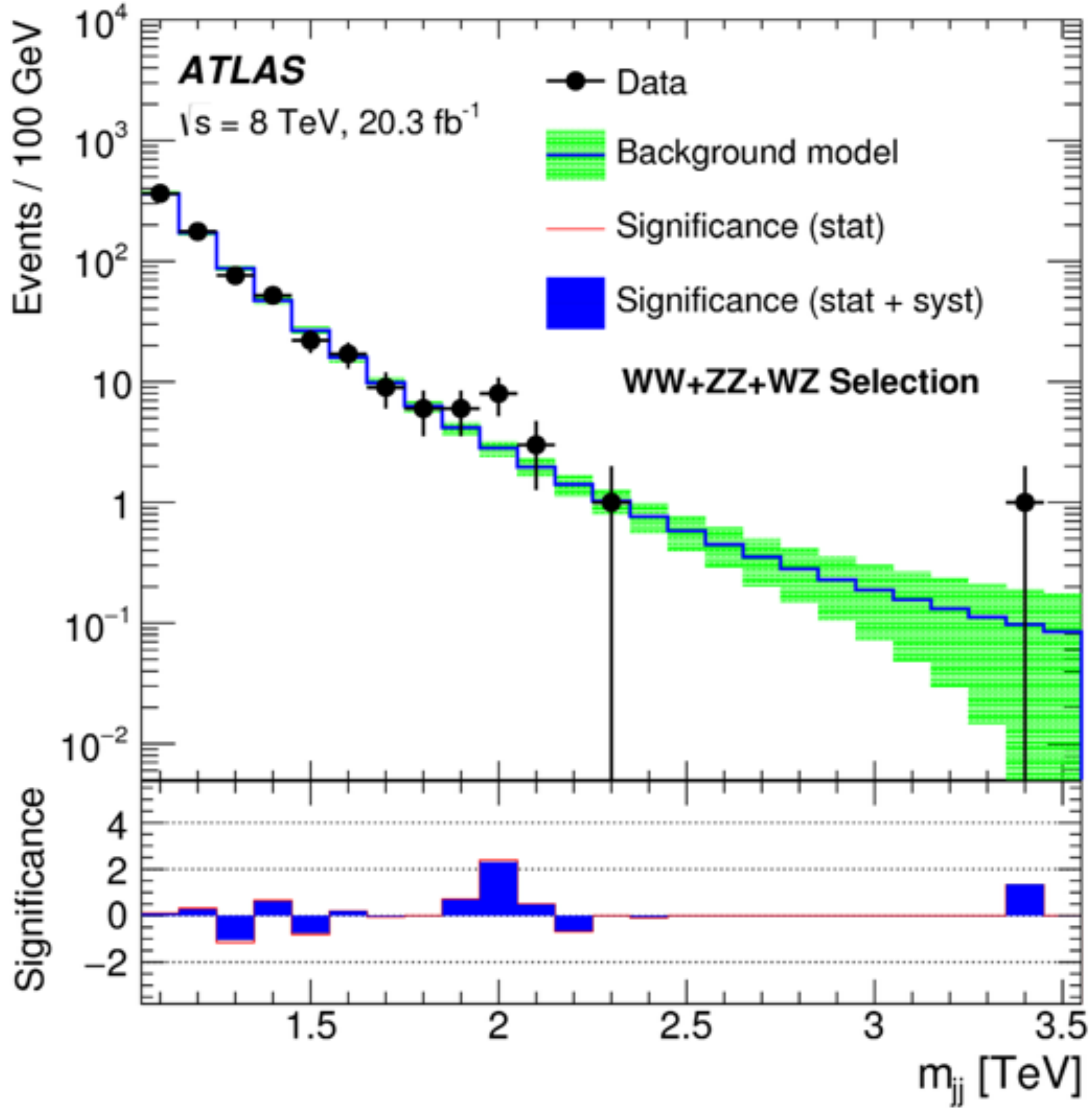




- Selections overlap: fits possible with WZ, WW or ZZ=0

Allanach, Gripaios, Sutherland, arXiv:1507.01638

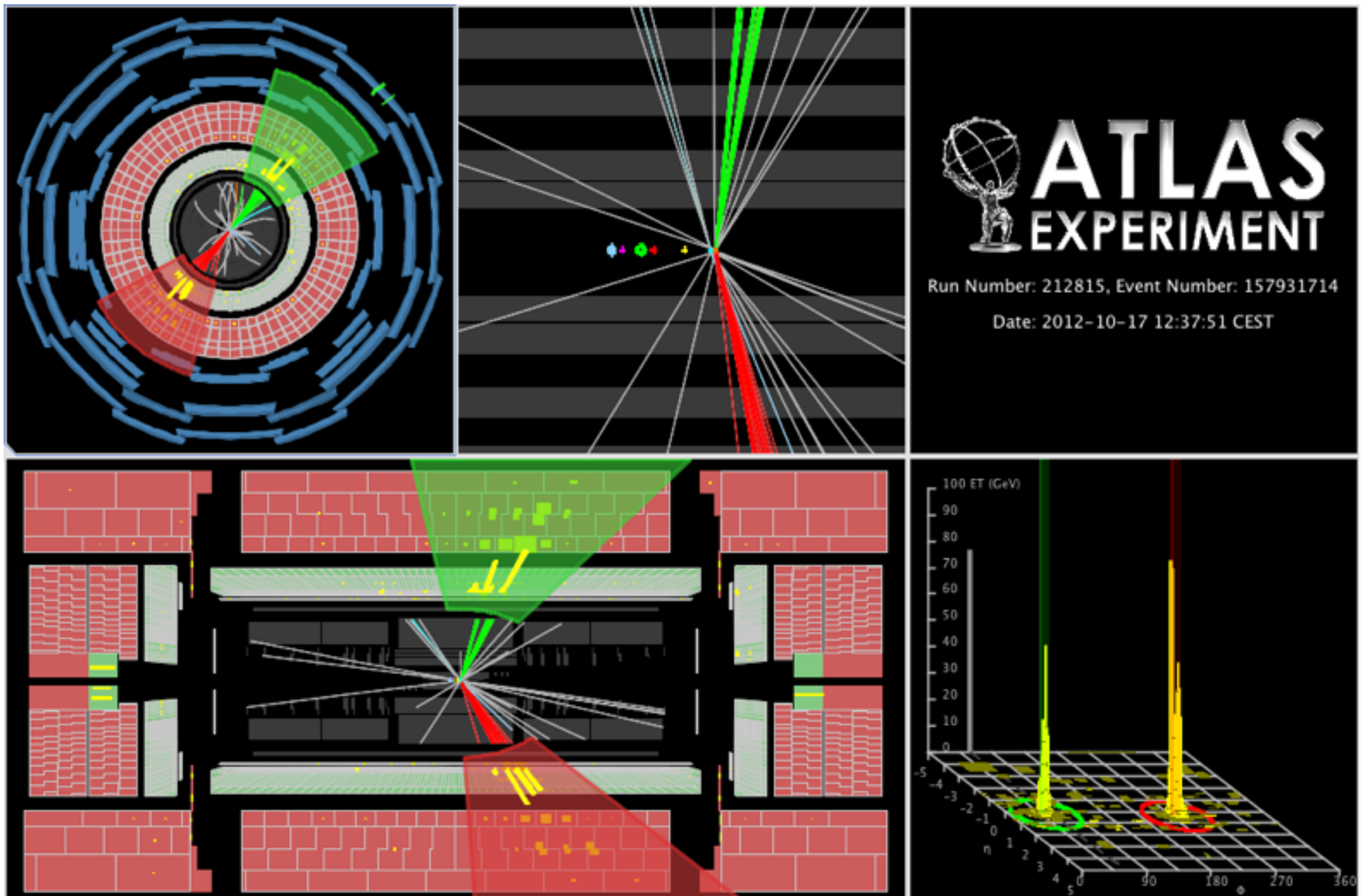
Diboson signal



- Combined sample is not so impressive

Diboson candidate

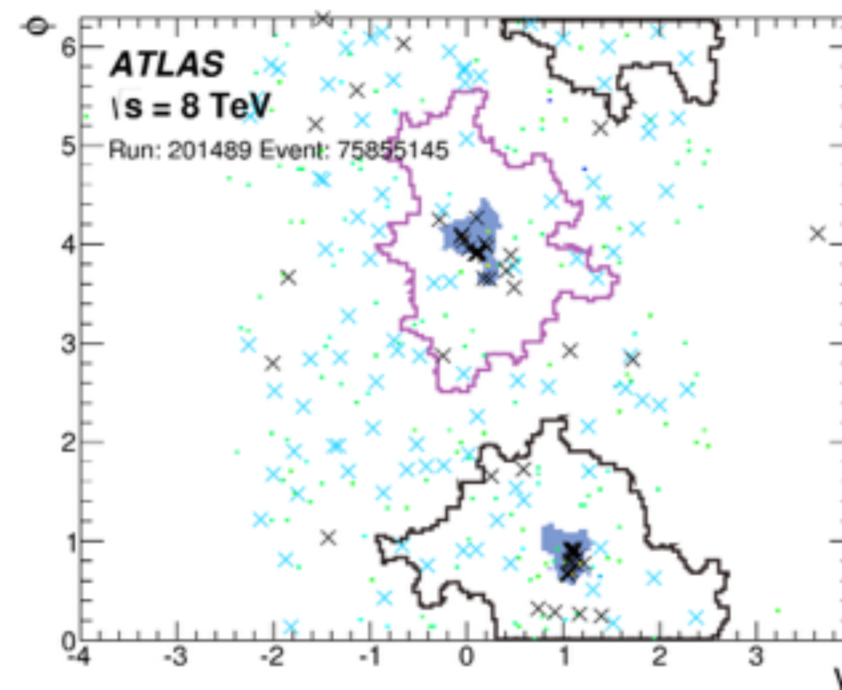
- An event satisfying VV selection:

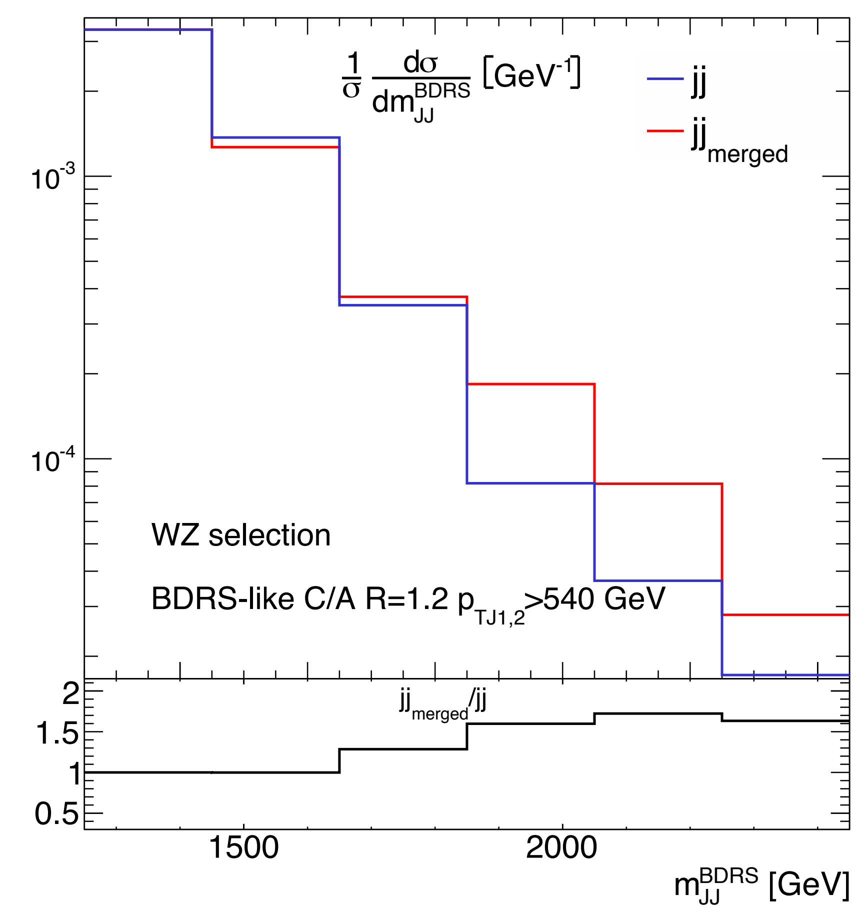


Diboson critique

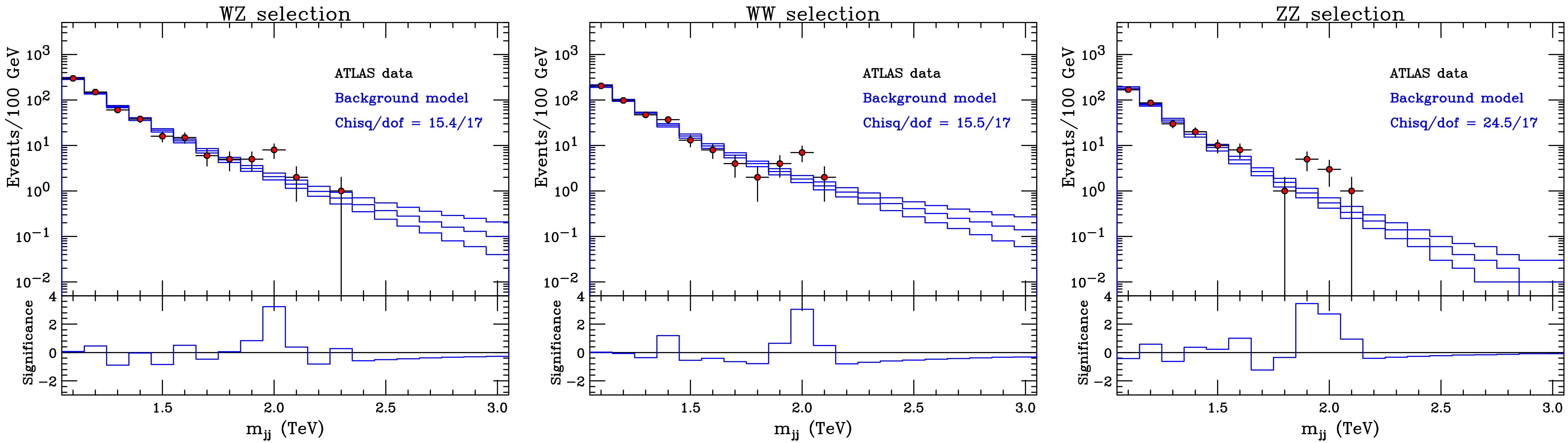
Gonçalves, Krauss, Spannowsky, arXiv:1508.04162

- Critique of ATLAS analysis:
  - R_{fat}=1.2 not appropriate for m_{VV}=2 TeV
  - $R_V \sim 2m_V/p_{TV} \sim 4m_V/m_{VV} \sim 0.2$
  - Data-driven background estimate is problematic: end of spectrum
  - PS MC validation is questionable
  - Suppose e.g. Background x (m_{jj}/TeV) …

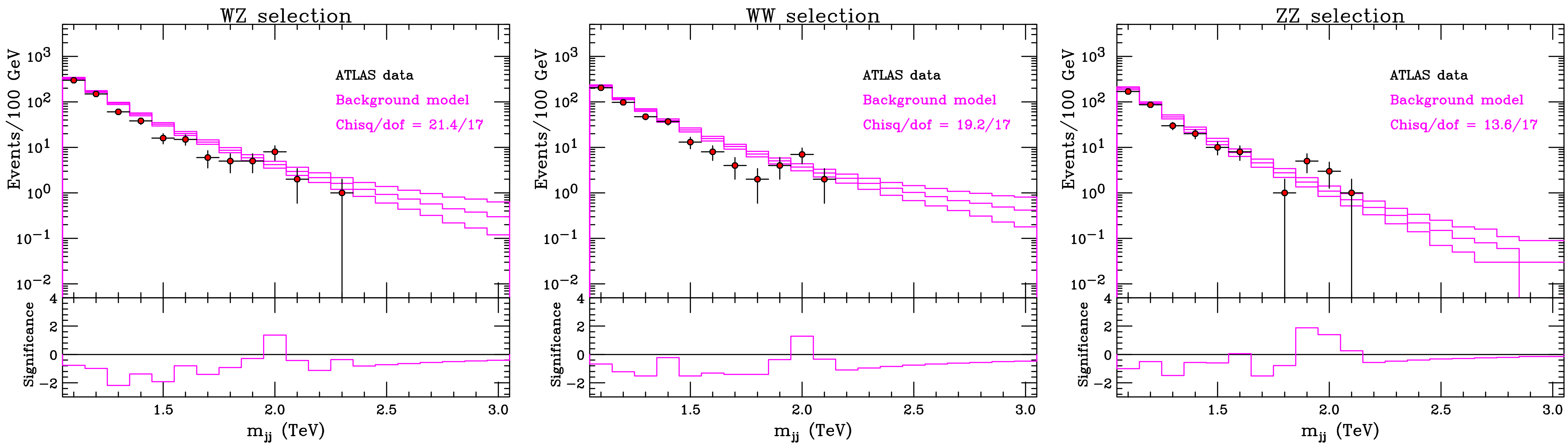




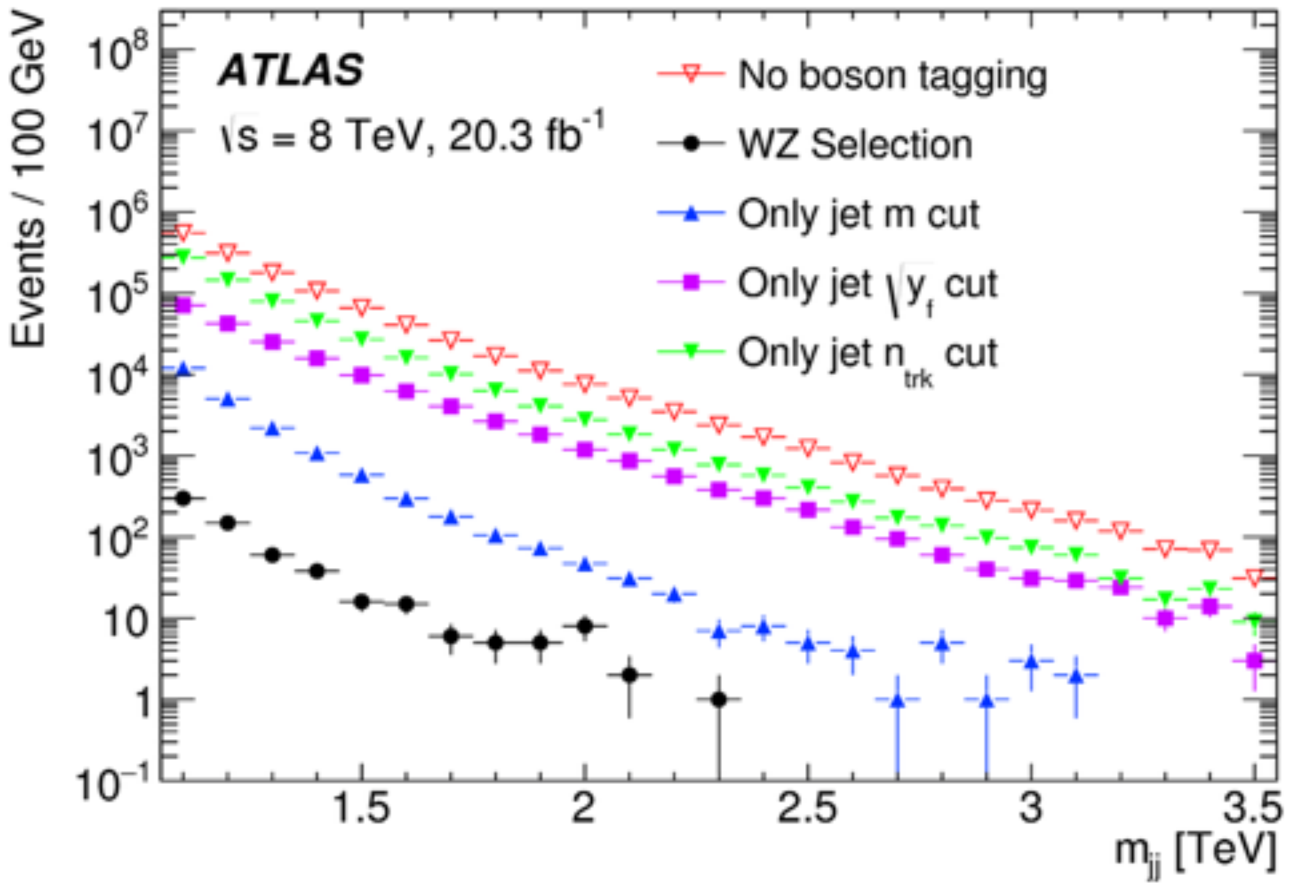
Background model

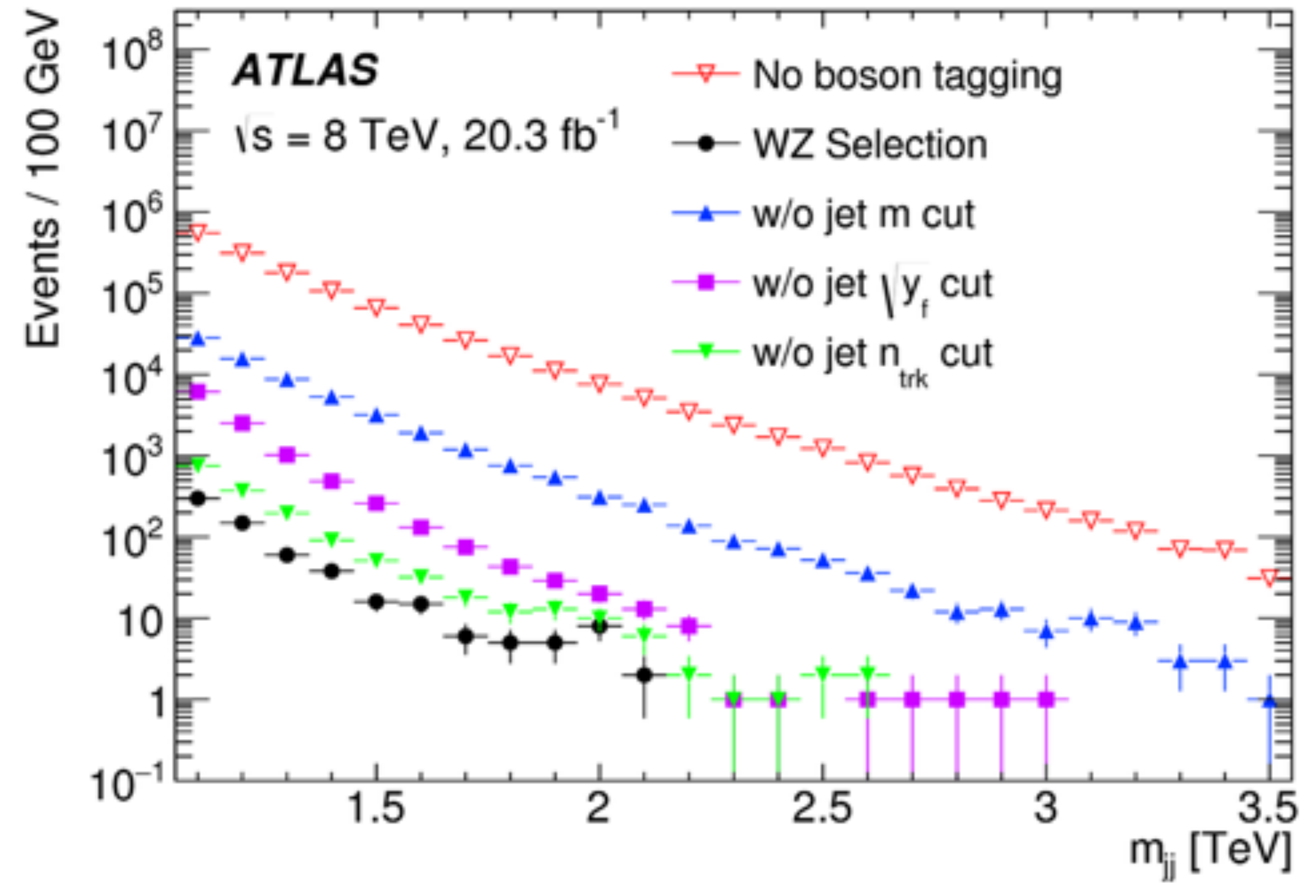


- Effect of Background x (m_{jj}/TeV):



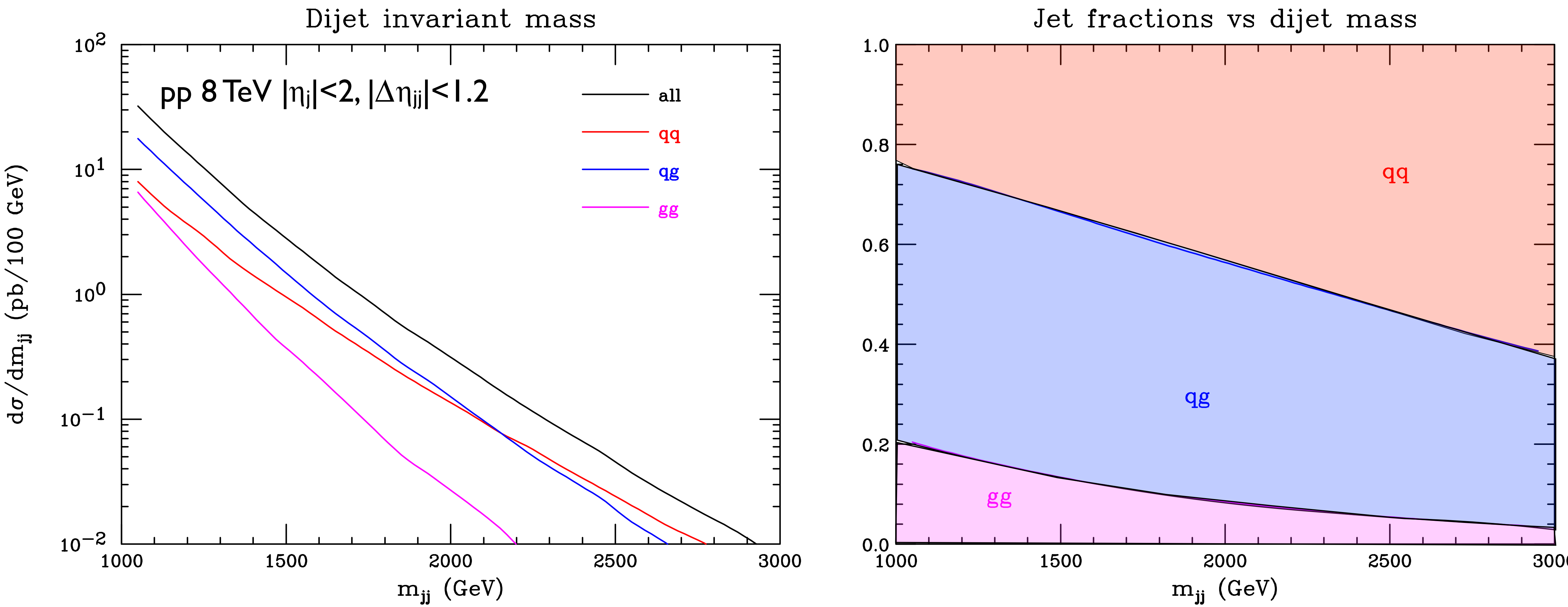
Effects of selection cuts





- Need to:
  - compare background model with all these data
  - understand effects of VV selection on q and g jets

Dijet background



- At 2 TeV, ~1/3 gluon jets, ~2/3 quark jets

Energy Correlation Functions

Energy Correlation Functions

Larkoski, Salam, Thaler, arXiv:1305.0007

$$e_2^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{1 \le i < j \le n_J} p_{Ti} p_{Tj} R_{ij}^{\beta} \,, \qquad R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$

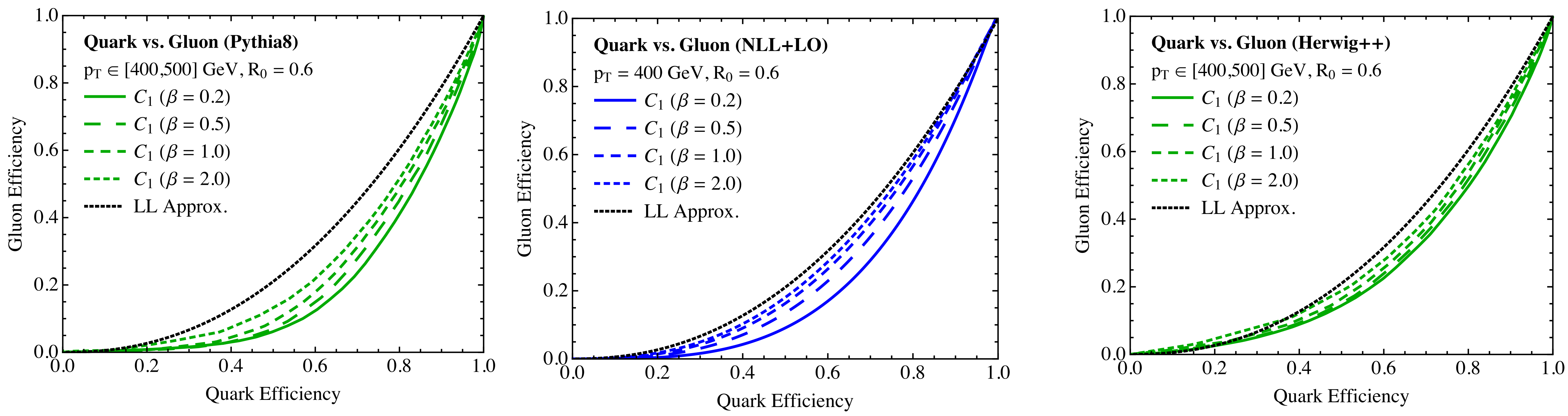
$$e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{1 \le i < j < k \le n_J} p_{Ti} p_{Tj} p_{Tk} R_{ij}^{\beta} R_{ik}^{\beta} R_{jk}^{\beta}$$

$$C_N(\beta) = e_{N+1}^{(\beta)} e_{N-1}^{(\beta)} / [e_N^{(\beta)}]^2$$

- Small C_N favours N subjets:
  - C_1 for q/g discrimination (new physics S/B)
  - C_2 for vector or Higgs boson tagging
  - C_3 for top tagging

C_1 for q/g discrimination

$$C_1(\beta) = e_2^{(\beta)} \simeq \sum_{i<j\in J} z_i z_j \theta_{ij}^{\beta} \qquad C_1(2) \simeq m_J^2/p_{TJ}^2$$

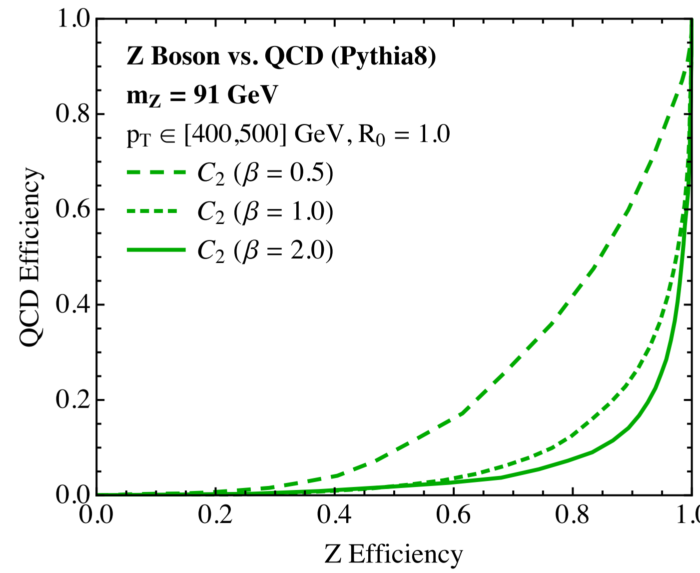


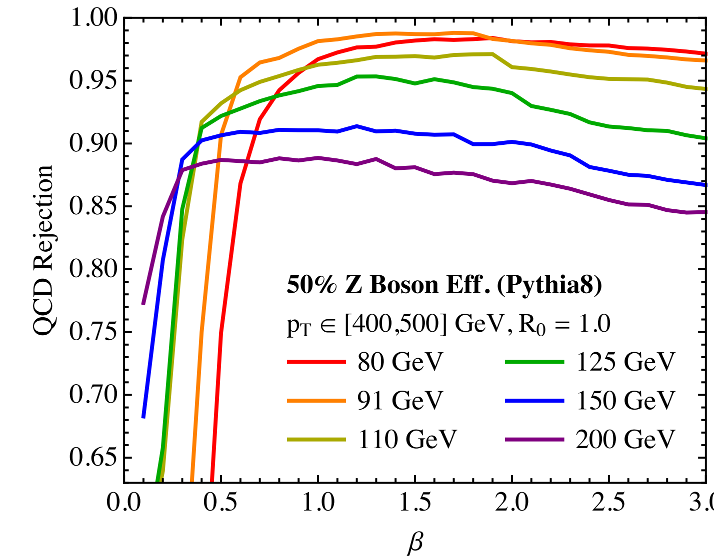
- Leading-log (LL) $\epsilon_g = \epsilon_q^{9/4}$ independent of β
- At NLL small β gives more q/g discrimination
  - Pythia8, Herwig++ show same trend, but
  - Pythia more, Herwig less than NLL

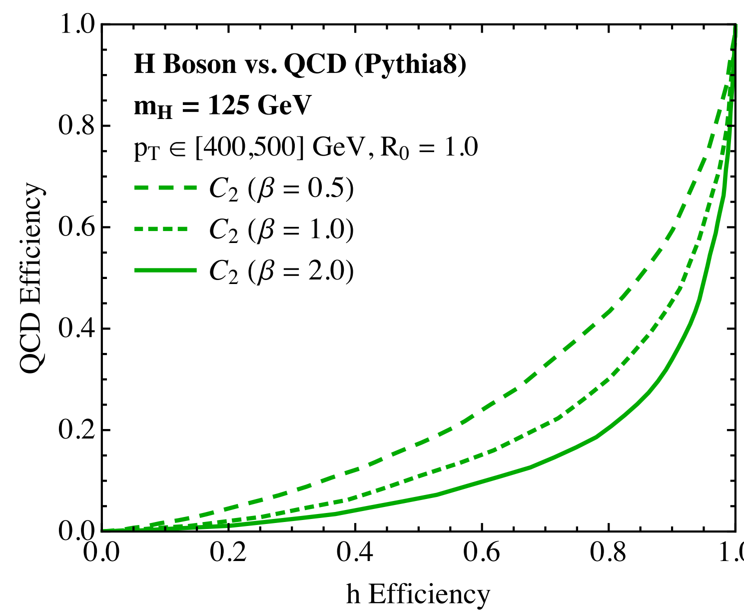
C_2 for V or H tagging

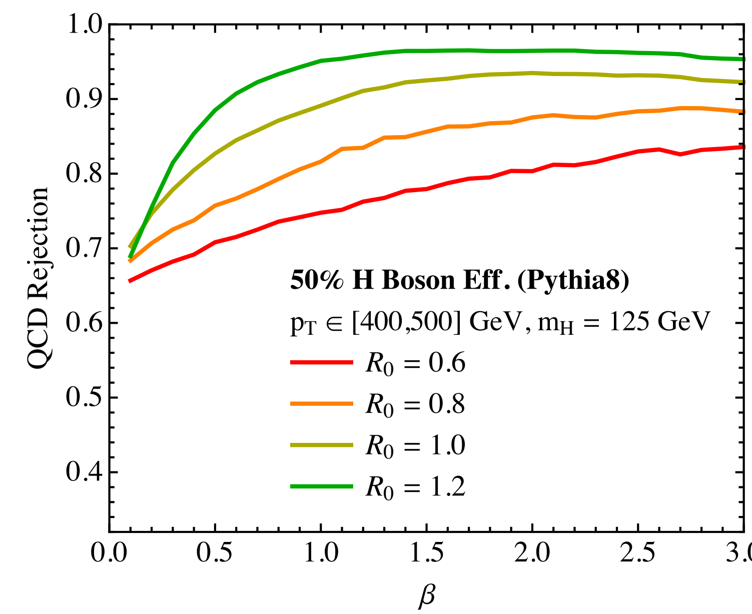
$$\boxed{C_2(\beta) = e_3^{(\beta)}/[e_2^{(\beta)}]^2}$$

- No analytical results yet
- MC suggests optimal β depends on jet mass
  - NB: $e_2^{(2)} \simeq m_J^2/p_{TJ}^2$
- For H demand 2 b tags





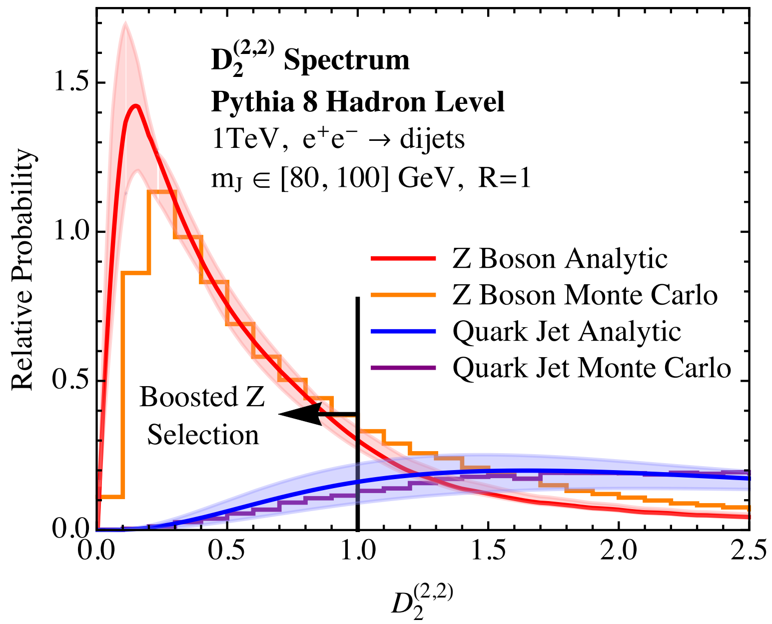


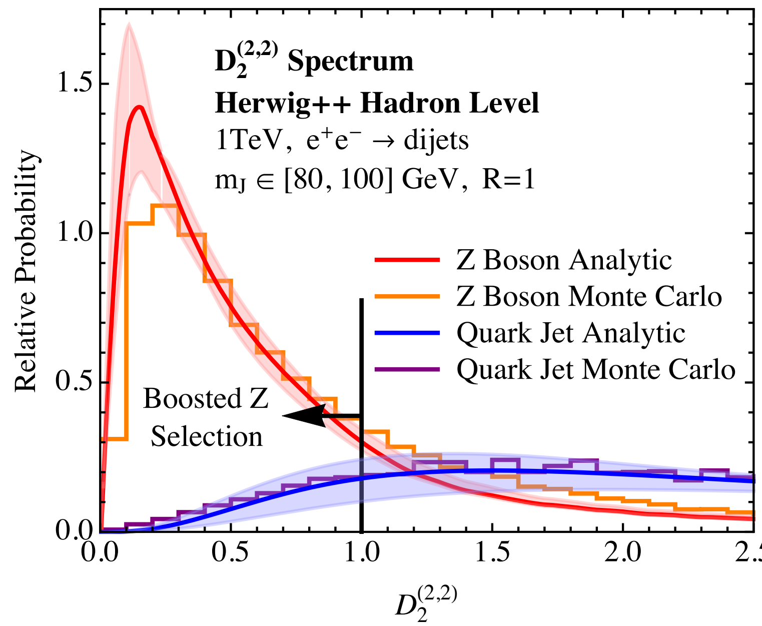


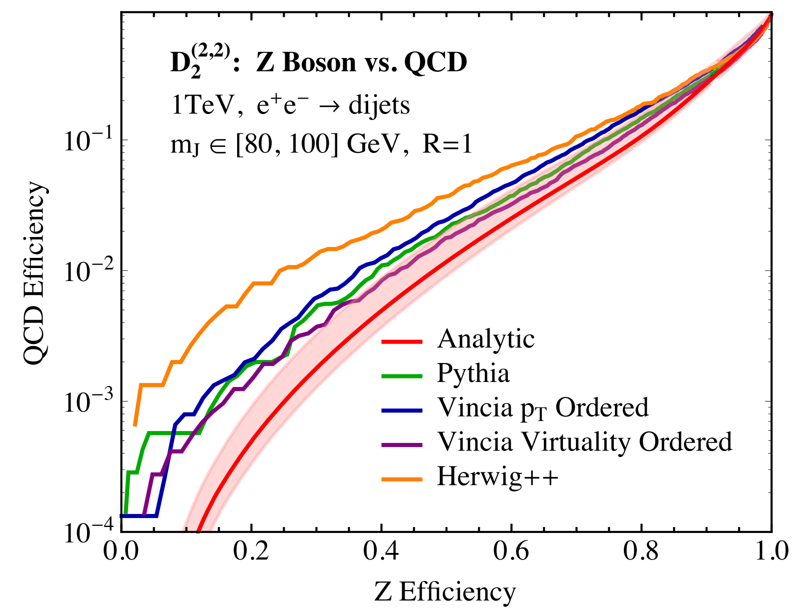
D_2 for V or H tagging

$$\boxed{D_2(\beta) = e_3^{(\beta)}/[e_2^{(\beta)}]^3}$$

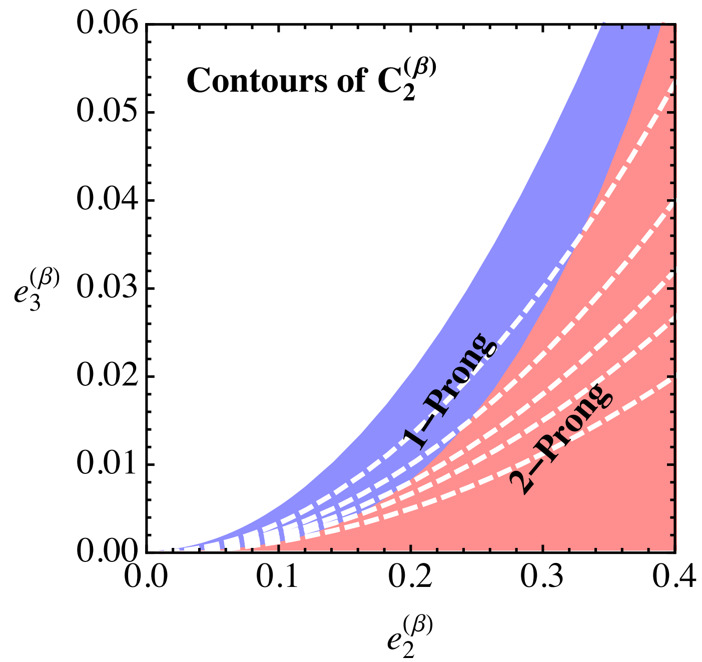
Larkoski, Moult, Neill, arXiv: 1409.6298, 1507.03018

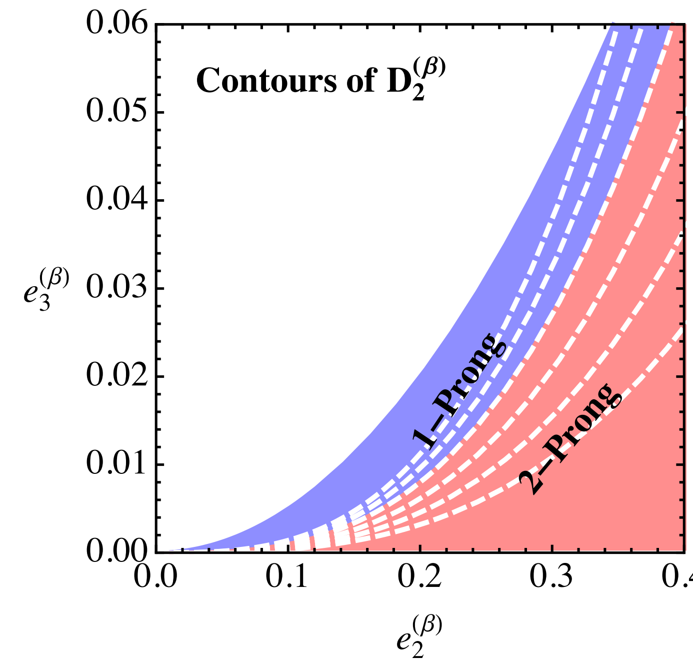






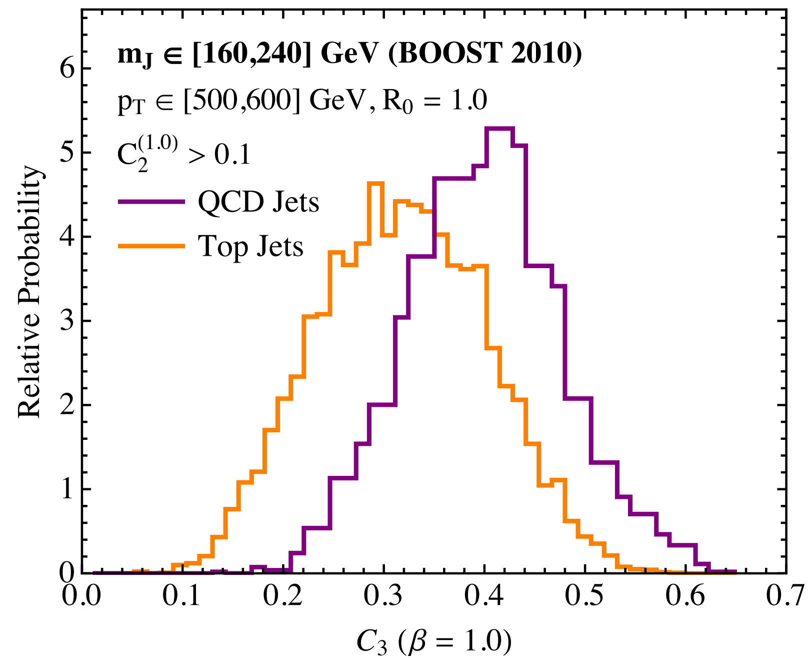
- Small D_2 favours 2 subjets
  - Cleaner than C_2 for V or H boson tagging?
  - Cut on jet mass implies $0.026 < e_2^{(2)} < 0.040$

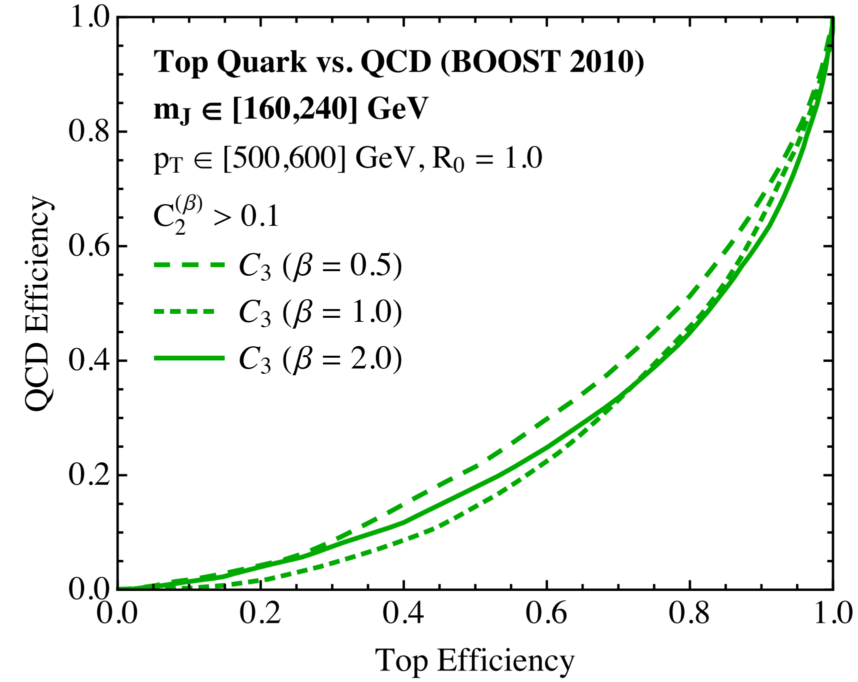




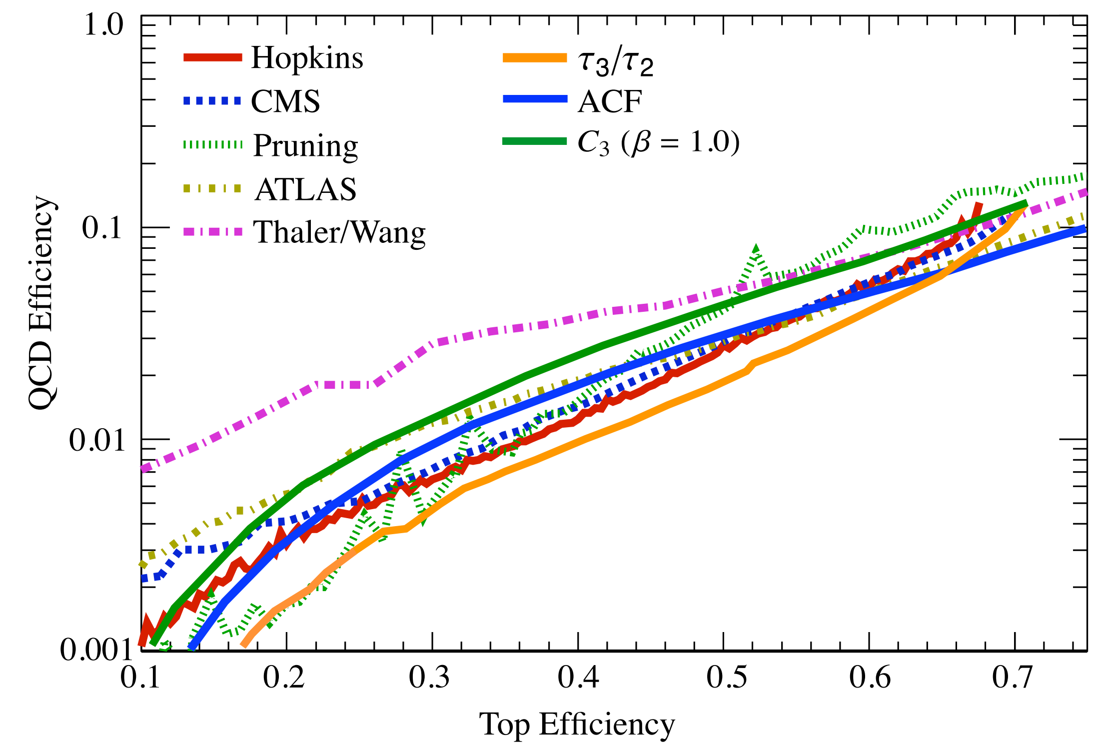
C_3 for top tagging

$$\boxed{C_3(\beta) = e_4^{(\beta)} e_2^{(\beta)} / [e_3^{(\beta)}]^2}$$





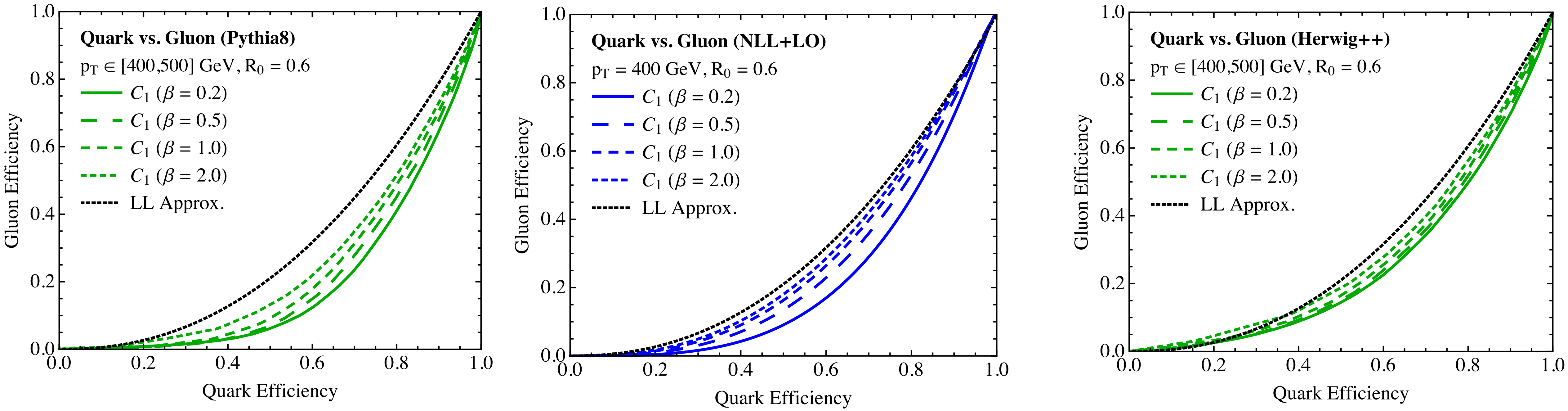
- No analytical results yet
- MC suggests β=1 optimal
- Performance comparable with other top taggers



Quark-Gluon Jet Discrimination

C_1 for q/g discrimination

$$C_1(\beta) = e_2^{(\beta)} \simeq \sum_{i<j\in J} z_i z_j \theta_{ij}^{\beta} \qquad C_1(2) \simeq m_J^2/p_{TJ}^2$$



- Leading-log (LL) $\epsilon_g = \epsilon_q^{9/4}$ independent of β
- At NLL small β gives more q/g discrimination
  - Pythia8, Herwig++ show same trend, but
  - Pythia more, Herwig less than NLL

Track Multiplicity

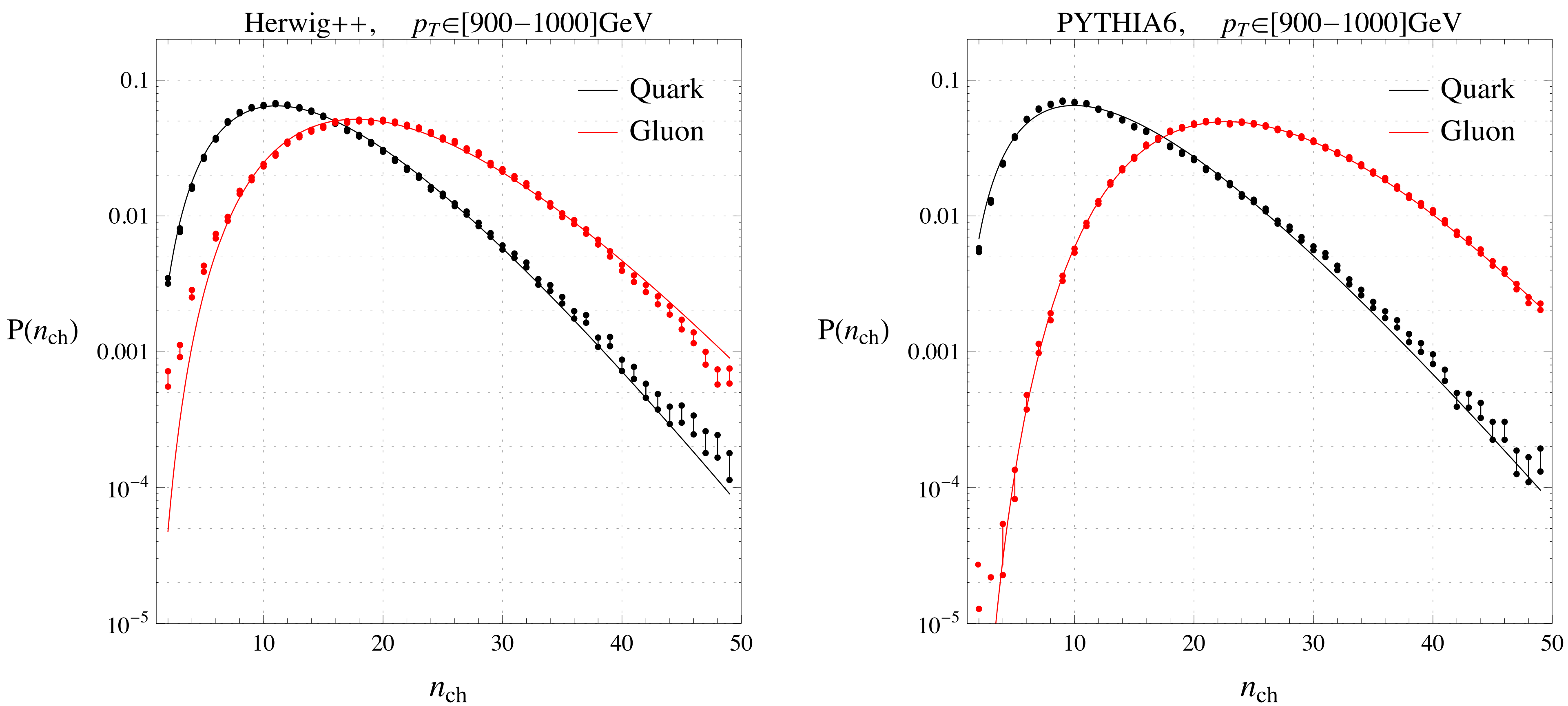
Y.Sakaki, priv.comm.

- Compare Z+q, Z+g (R=0.4, min p_{Ttk}=1GeV)

$$P_{q/g}(n) = \left(\frac{k_{q/g}\, n}{\langle n\rangle_{q/g}}\right)^{k_{q/g}} \frac{\exp\left(-k_{q/g}\, n/\langle n\rangle_{q/g}\right)}{n\,\Gamma(k_{q/g})},$$

$$\langle n\rangle_i = N_i\left(1 + d_i\, a + d_i'\, a^2\right) a^p \exp(c/a), \qquad a = \sqrt{\alpha_S\left(p_T^2\right)/6\pi}$$

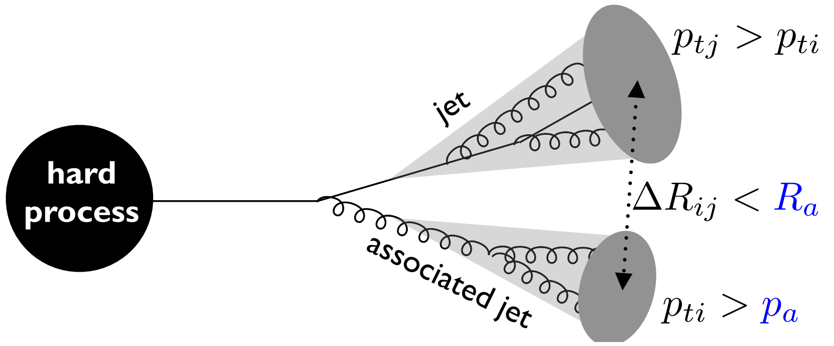
- Again Pythia discriminates more than Herwig

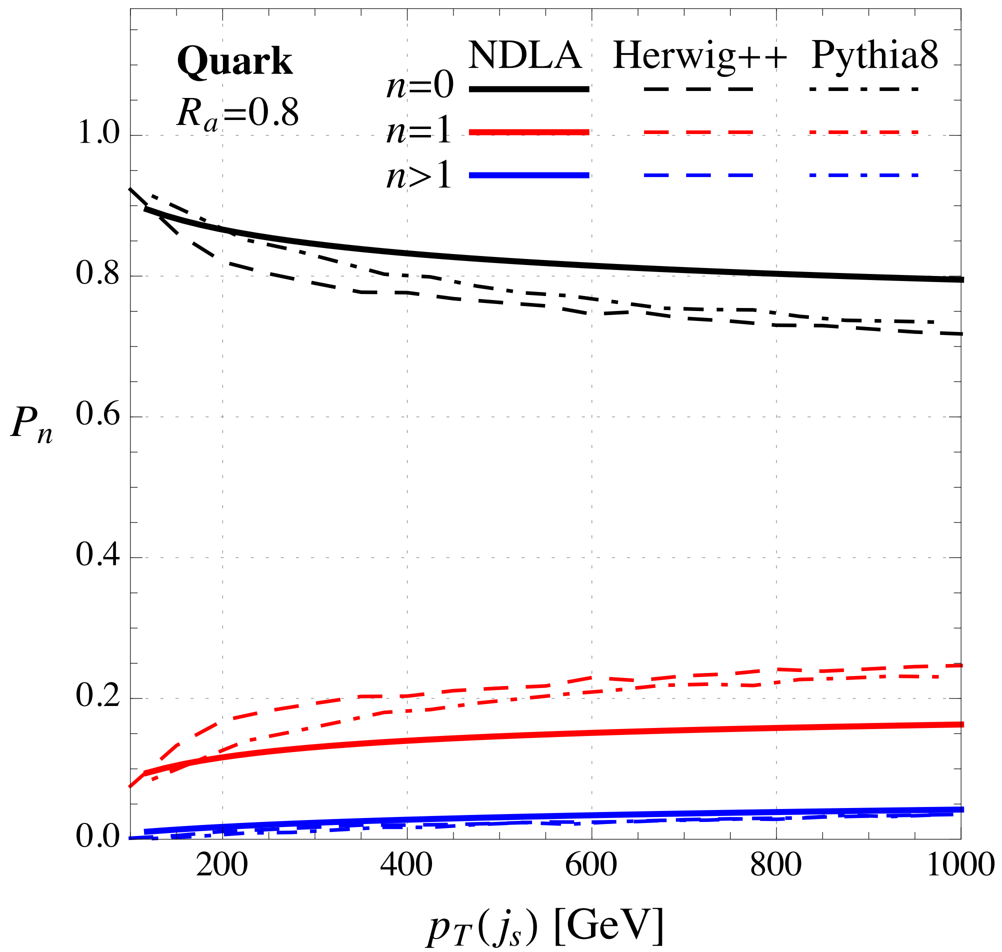


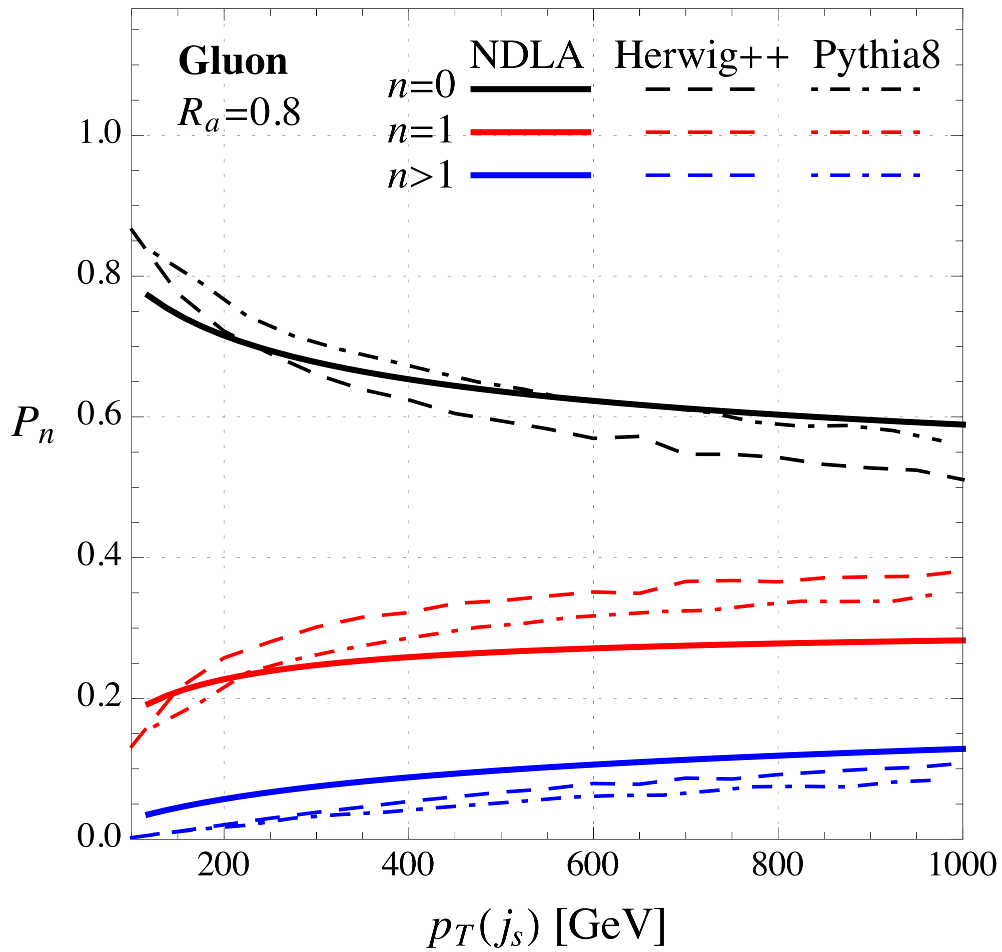
Associated Jets

Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, BW, arXiv:1501.04794

- Z+q vs Z+g (R=0.4)
- Gluons have more 'nearby' jets: $\Delta R < R_a = 0.8$, $p_T > p_a = 20$ GeV



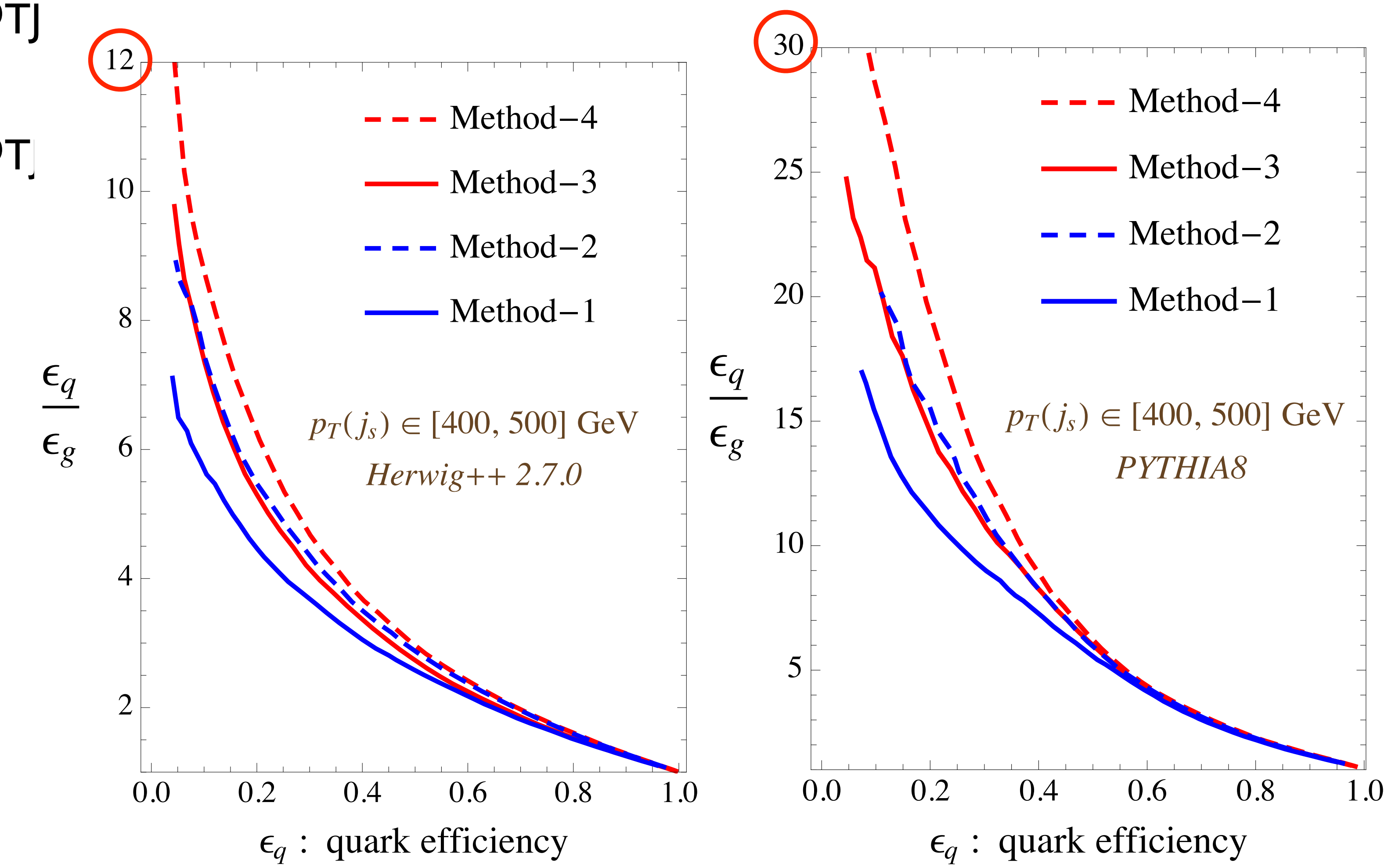




Multivariate Analysis

Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, BW, arXiv:1501.04794

- Boosted Decision Tree analysis
  - Method 1: n_{trk}, $C_1(\beta=0.2)$
  - Method 2: n_{trk}, $C_1(\beta=0.2)$, assoc
  - Method 3: n_{trk}, $C_1(\beta=0.2)$, m_J/p_{TJ}
  - Method 4: n_{trk}, $C_1(\beta=0.2)$, m_J/p_{TJ} assoc
- Again Herwig < Pythia
  - Note change of scale!



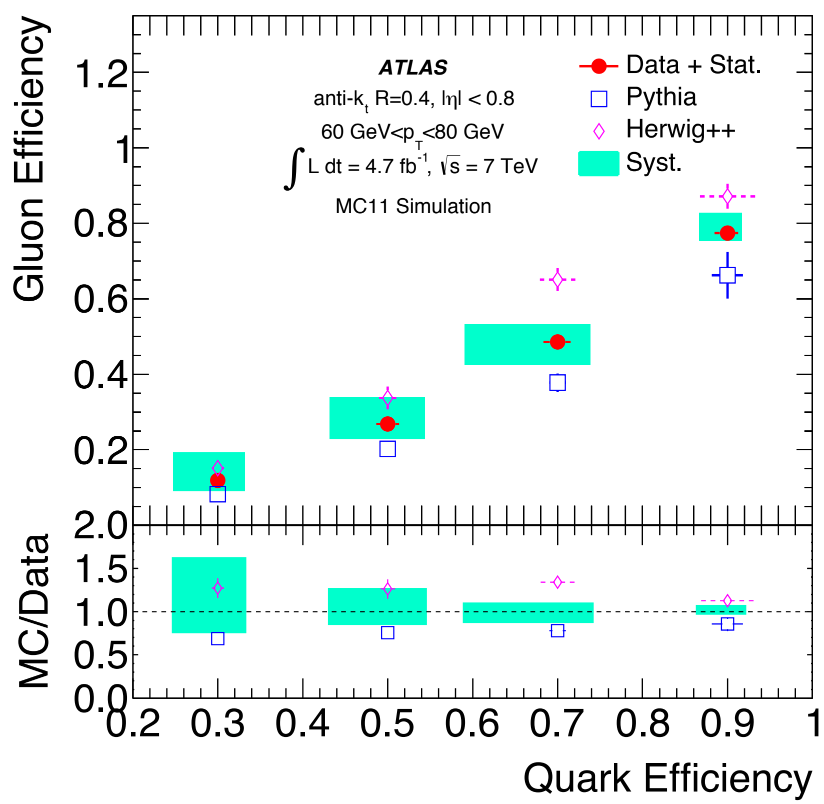
ATLAS q/g analysis

ATLAS, arXiv:1405.6583

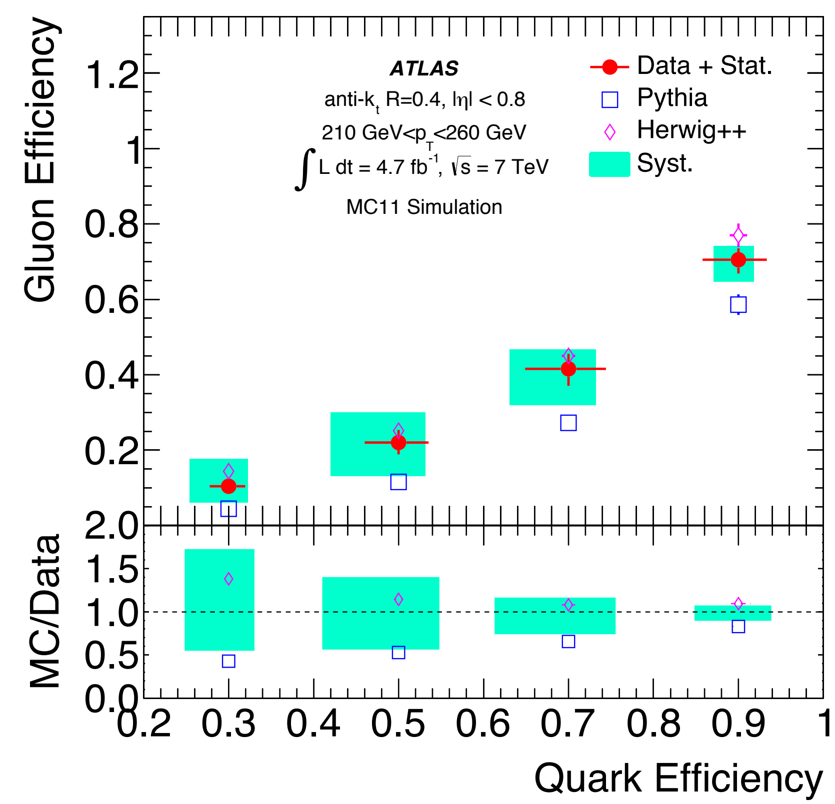
- Likelihood based on n_{trk} and track jet width

$$w = \frac{\sum_i p_{\mathrm{T},i} \times \Delta R(i, \mathrm{jet})}{\sum_i p_{\mathrm{T},i}}$$

60<p_{TJ}<80 GeV



210<p_{TJ}<260 GeV



- Data closer to Herwig++ (less discrimination than Pythia)

Subjets in jets

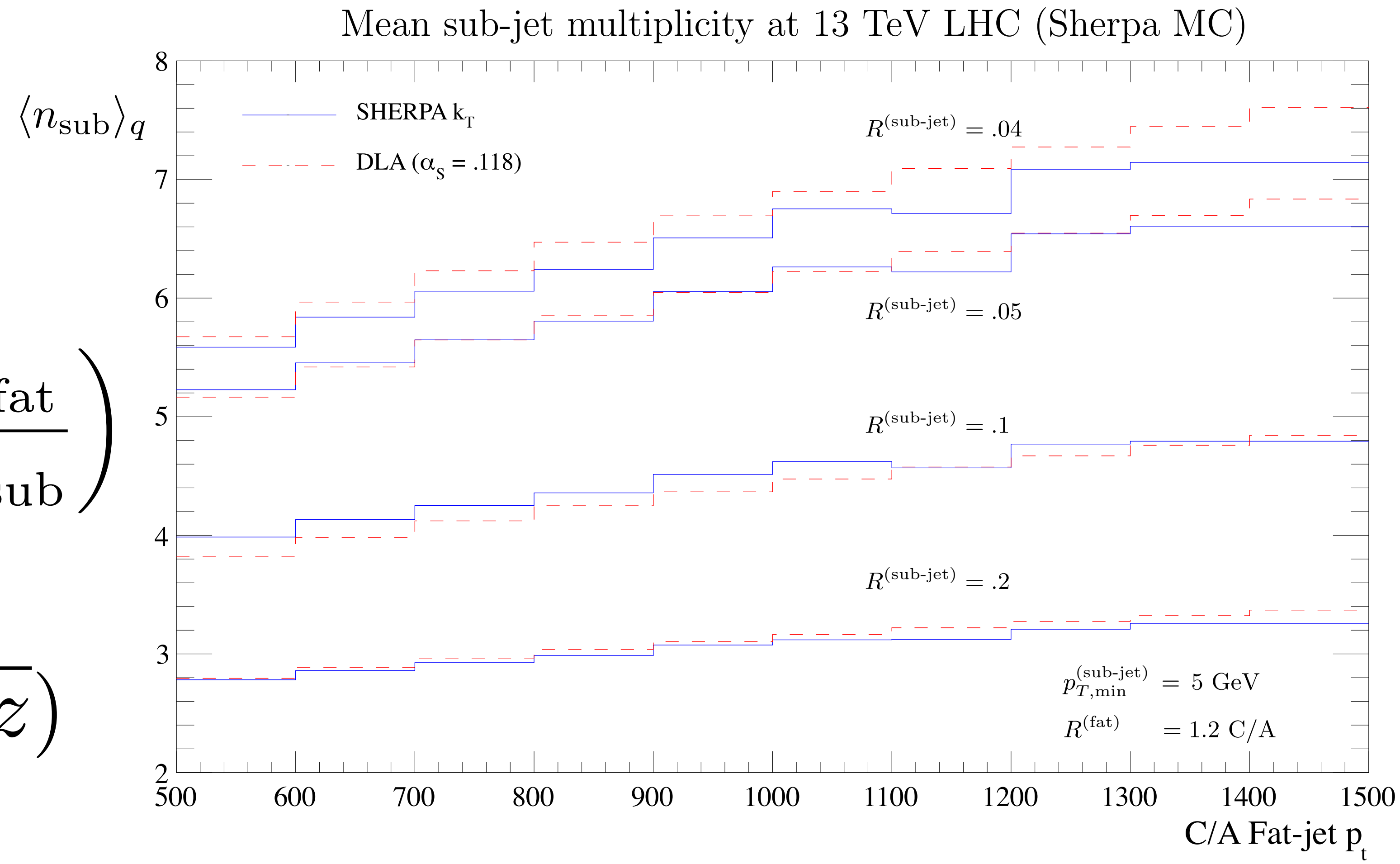
Gerwick, Gripaios, Schumann, BW, arXiv:1212.5235

- Summing leading double logs:

$$\langle n_{\rm sub}\rangle_g \sim I_0(\sqrt{z})$$

$$z = 24\frac{\alpha_{\rm S}}{\pi}\ln\left(\frac{p_{T\rm fat}}{p_{T\rm sub}}\right)\ln\left(\frac{R_{\rm fat}}{R_{\rm sub}}\right)$$

$$\langle n_{\rm sub}\rangle_q \sim \frac{5}{9}+\frac{4}{9}I_0(\sqrt{z})$$



- Agrees quite well with quark jets from Sherpa MC

Subjets in jets

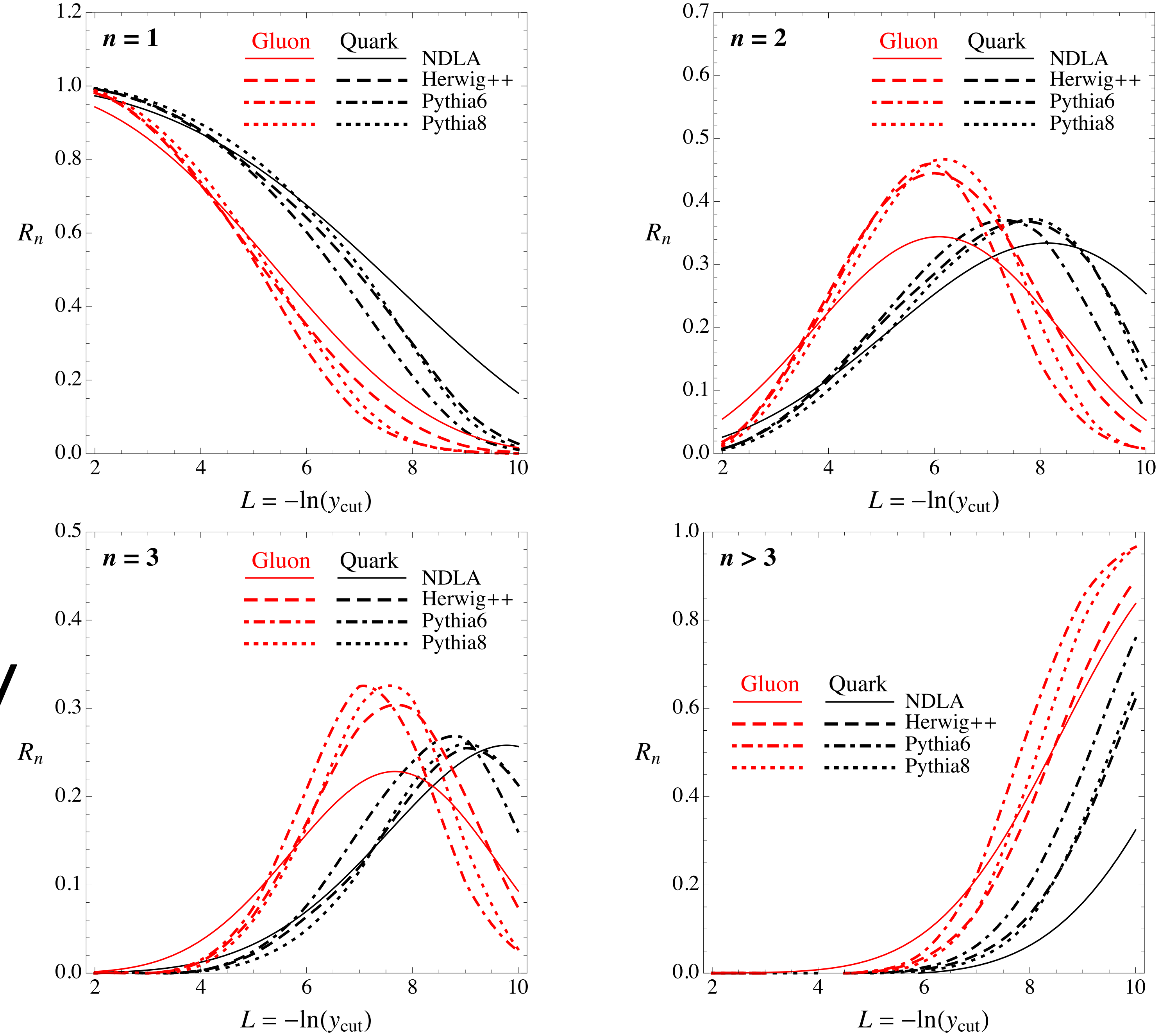
Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, BW, arXiv:1501.04794

- Subjets at k_t-resolution y_{cut}

$$y_{ik} = \min\{p_{ti}^2, p_{tk}^2\}\frac{\Delta R_{ik}^2}{R^2 p_j^2} > y_{\rm cut}$$

- Perturbatively calculable and less MC dependent than n_{trk} (for $L=-\ln(y_{cut})<6$)
- $L\sim6$: $\min\{p_{Ti},p_{Tk}\}\ \Delta R_{ik}\sim10$ GeV
- Not yet used for q/g tagging

$500<p_{TJ}<600$ GeV, R=0.4



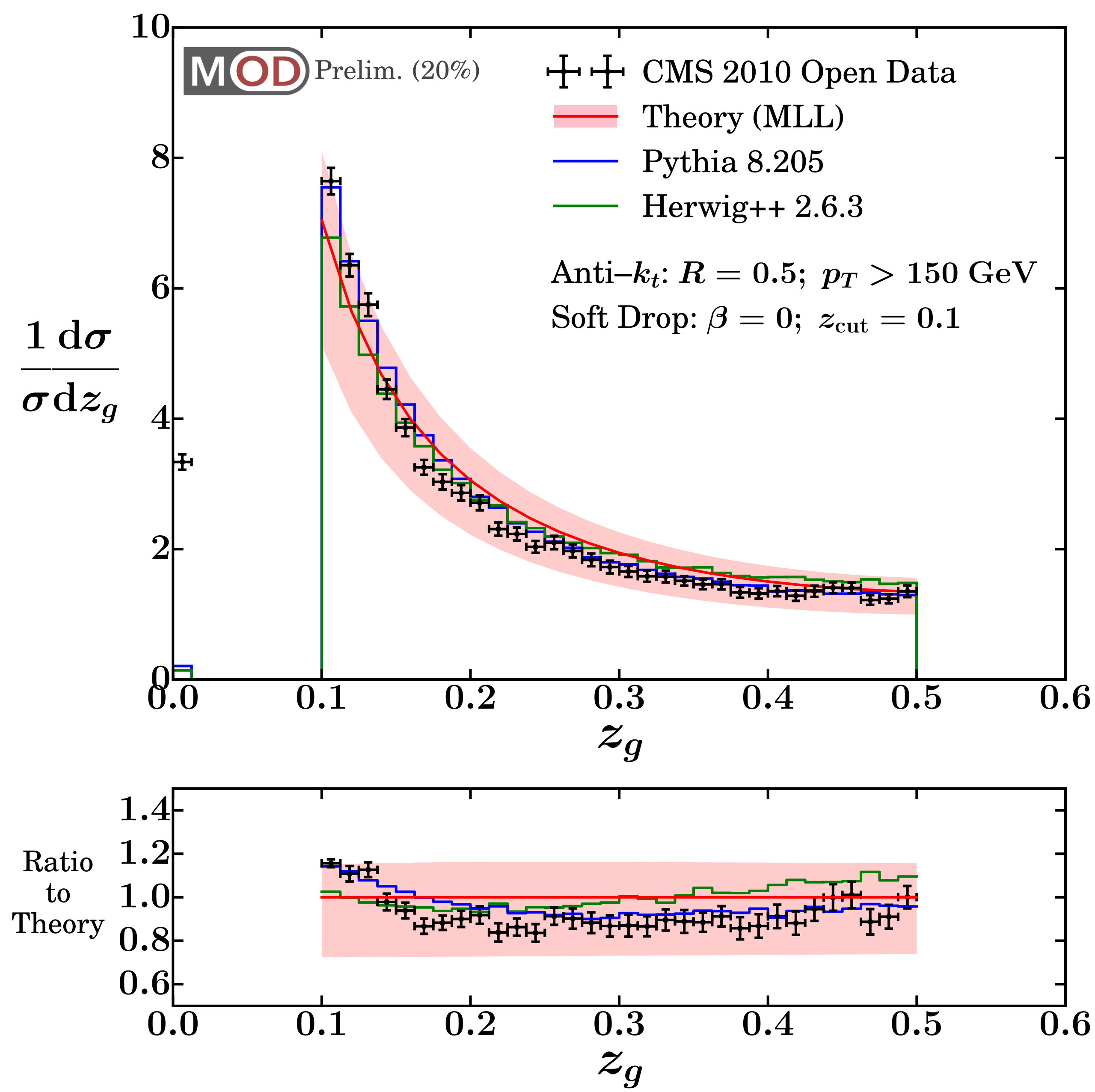
Conclusions

- Need more analytical studies of jet grooming and tagging (signals and backgrounds)
  - Also comparisons with state-of-the-art MCs (matched & merged)
- ATLAS diboson: great interest for Run II
  - Need more background studies (see above)
- Quark-gluon discrimination: great interest for new physics searches
  - Hard work to get beyond factor of 2 or 3

Backup

Measuring Splitting Function

Larkoski, Marzani, Thaler, arXiv:1502.01719 Thaler, BOOST2015



- Decluster (C/A) jet until

$$z_g = \frac{\min\{p_{Ti}, p_{Tj}\}}{p_{Ti} + p_{Tj}} > z_{\text{cut}} = 0.1$$

- then (LO)

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} = \frac{\overline{P}_j(z_g)}{\int_{z_{\text{cut}}}^{1/2} \overline{P}_j(z)\,\mathrm{d}z}$$

- where (indistinguishably for j=q,g)

$$\overline{P}_j(z) = P_j(z) + P_j(1-z)$$