Jet physics in ATLAS
Lecture 3

Mathis Kolb

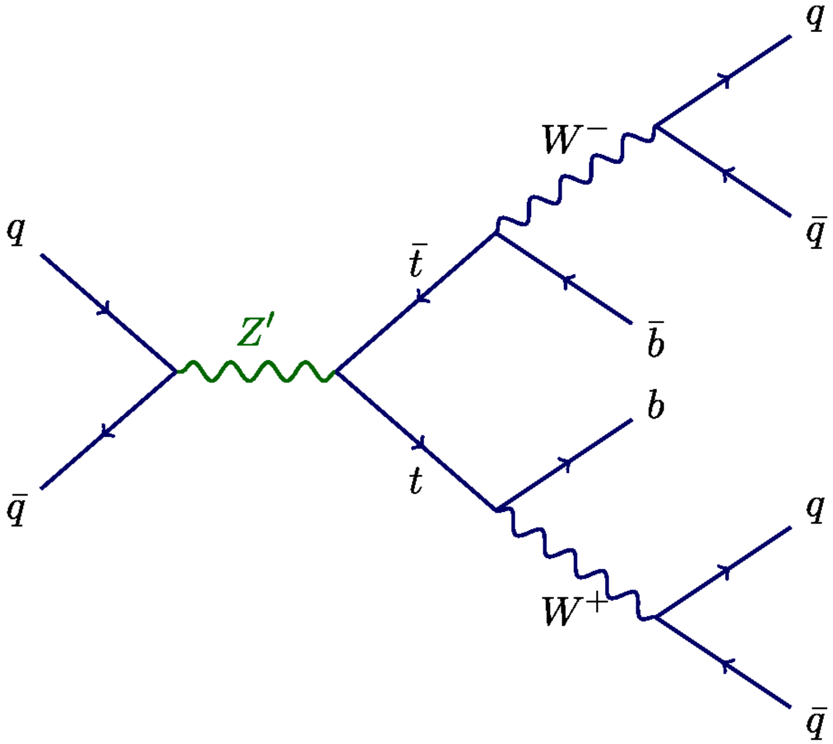
Student Lecture
RTG Particle Physics Beyond the Standard Model

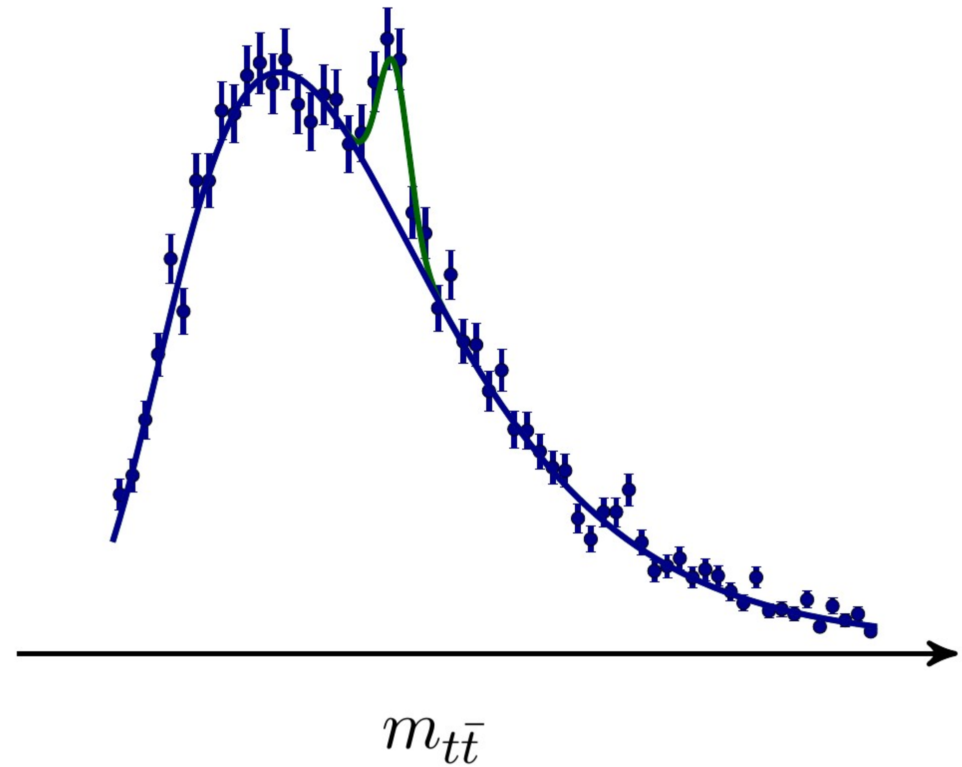
09.05.2018

Outline

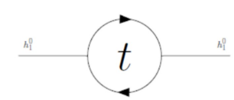
- Introduction
- Top quark pair production at the LHC
- Top and new physics
- Top quark tagging
  - Boosted case
    - Pile-up/Grooming
    - 2-variable tagger
  - Resolved case
    - Buckets of tops
- $t\bar{t}$ resonance search
- Summary

Top quark pairs

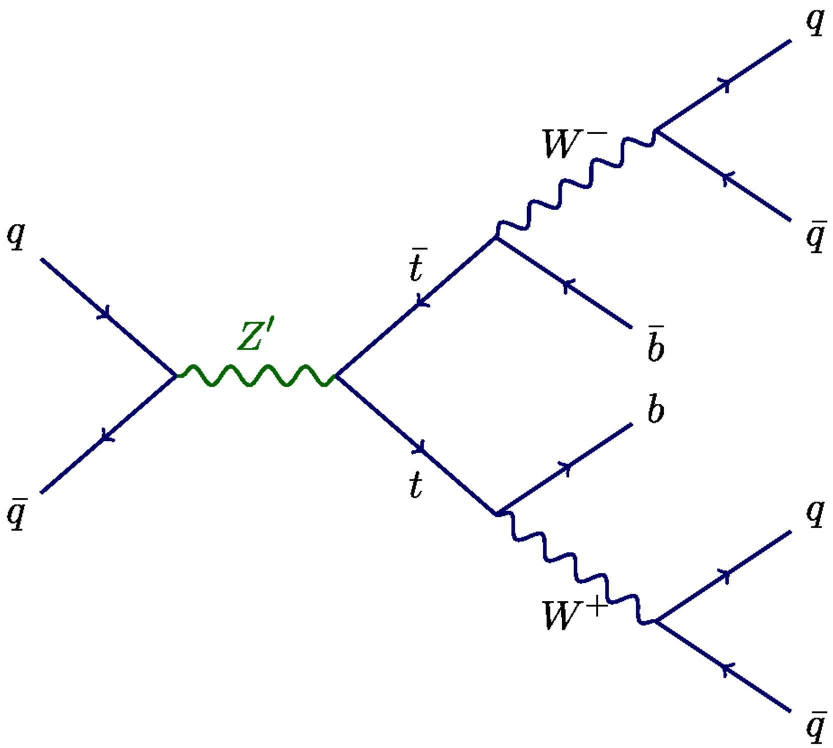


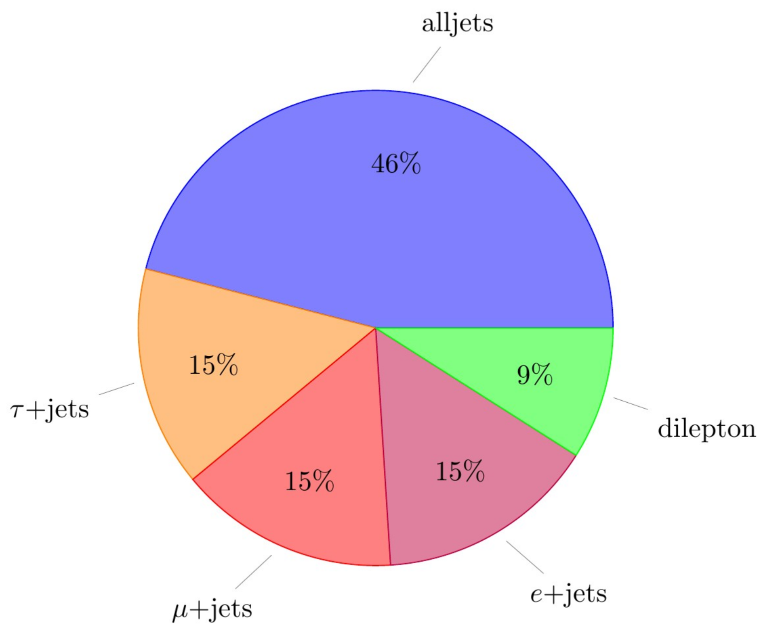


- Top has high mass 173 GeV
- Short lifetime Γ = 1.41 GeV $\longrightarrow$ Decays before hadronization
- $V_{tb} > 0.999$
- Largest Yukawa coupling
- General search for X $\longrightarrow$ $t\bar{t}$ resonances in all-hadronic final state
- Split $m_{t\bar{t}}$:
  - Low mass: resolved with small-R(=0.4) jets
  - High mass: boosted with large-R(=1.0) jets

$\delta m_h^2 \sim$  $-\frac{3}{4\pi} y_t^2 \Lambda_{SM}^2$

Search for X $\longrightarrow t\bar{t}$ resonances

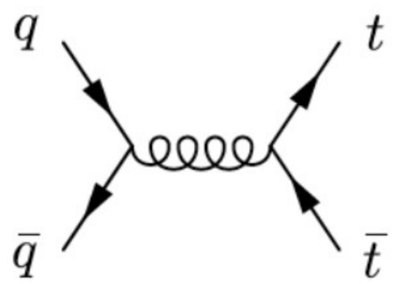




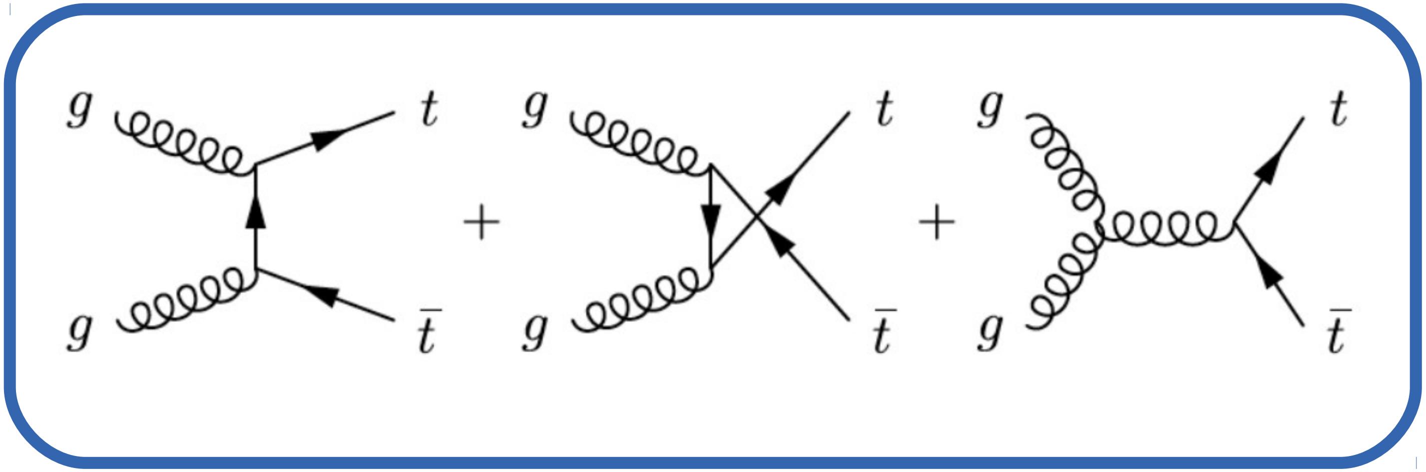
- All-hadronic has large branching fraction
- $t\bar{t}$ system can be fully reconstructed
- QCD multijets and SM $t\bar{t}$ are main backgrounds

SM $t\bar{t}$ production

$$\sqrt{x_i x_j} \geq \frac{2m_t}{\sqrt{s}}$$

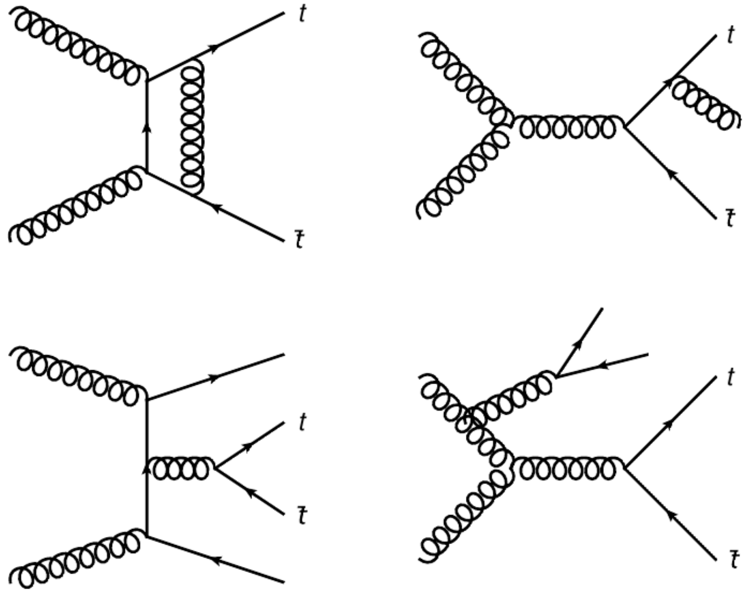


gg→ $t\bar{t}$ ~ 90% at LHC



- Mainly produced in pairs via gluon fusion
- Decays almost uniquely to b-quark and W-boson
- Extra jets in ~50% of inclusive tt events
- Inclusive $t\bar{t}$ cross-section uncertainty ~6%
- Produced singly too

SM $t\bar{t}$ production



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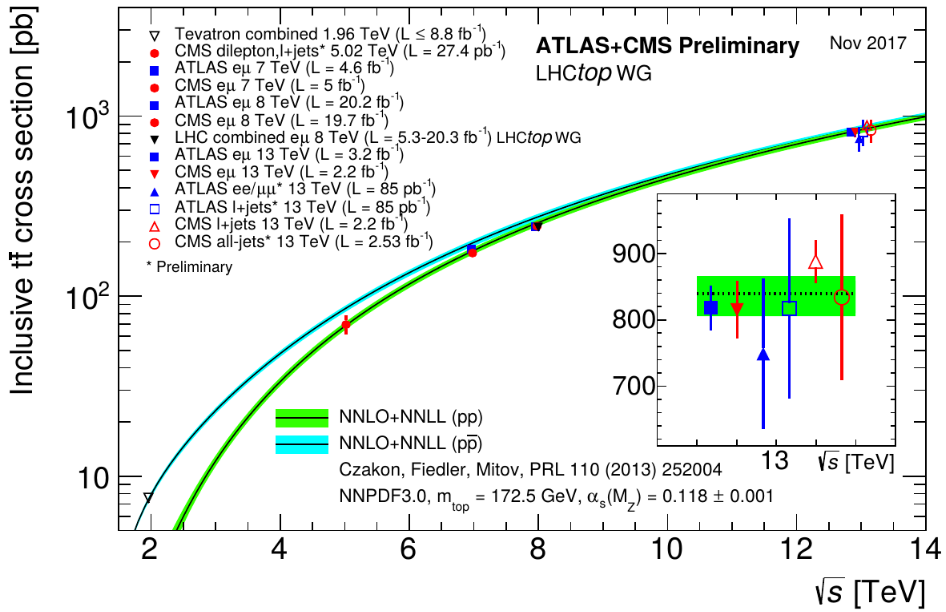

Source: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP

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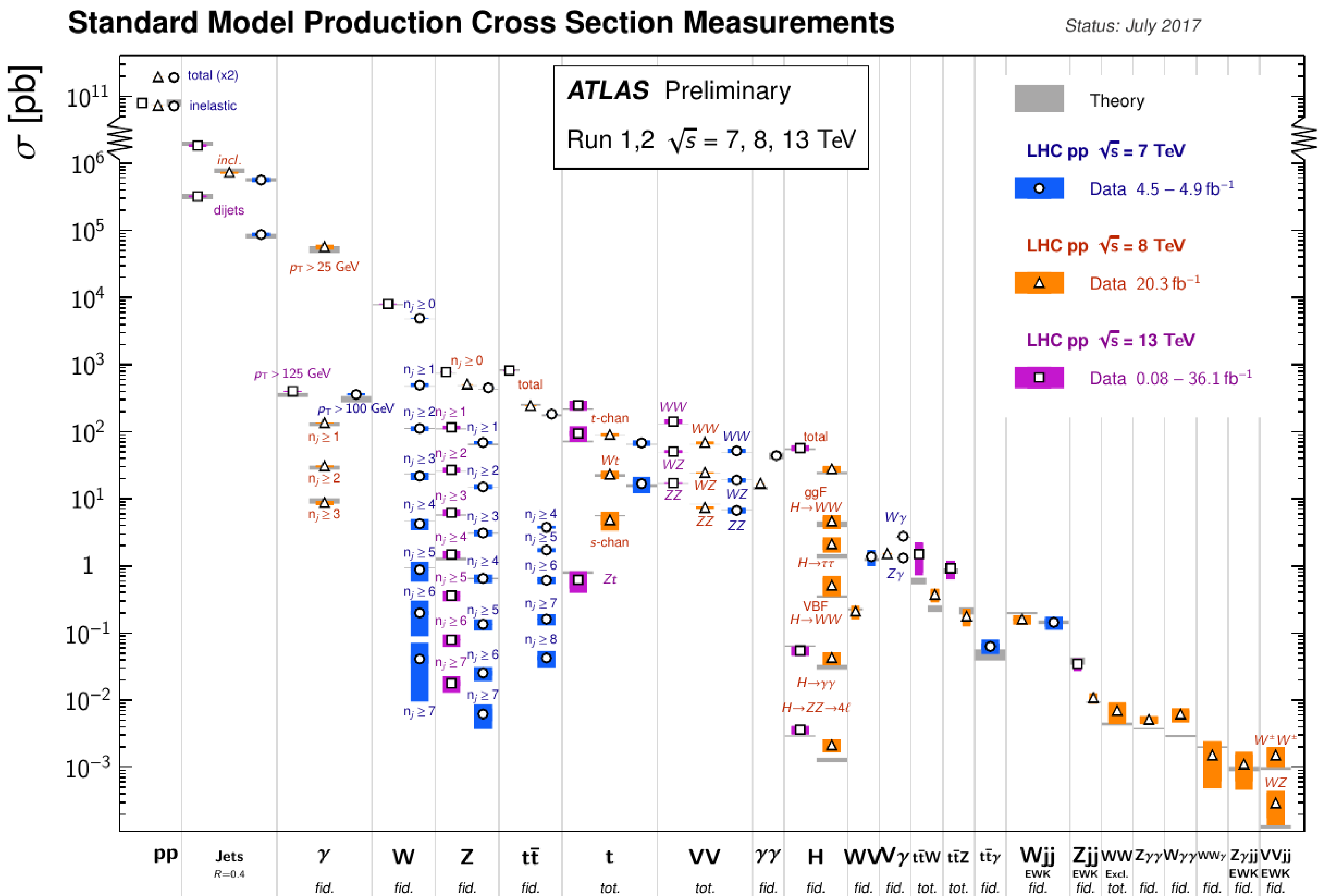
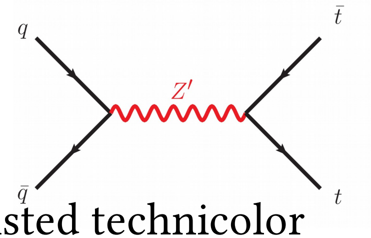


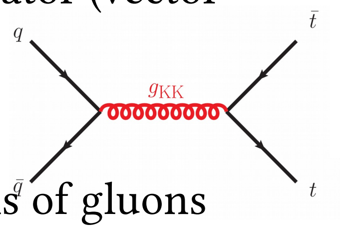
Source: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

Top and new physics

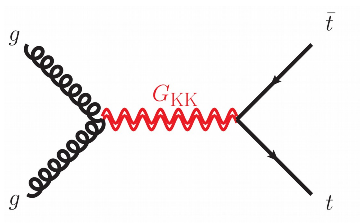
- Analysis strategy is general search
- Benchmark signals for interpretations:
  - Spin 1
    - Z'_{TC2} : Topcolor-assisted technicolor (TC2) Z' (narrow width: 1-3%)
    - Z'_{DM} : simplified model mediator (vector and axial-vector, width ~5%)



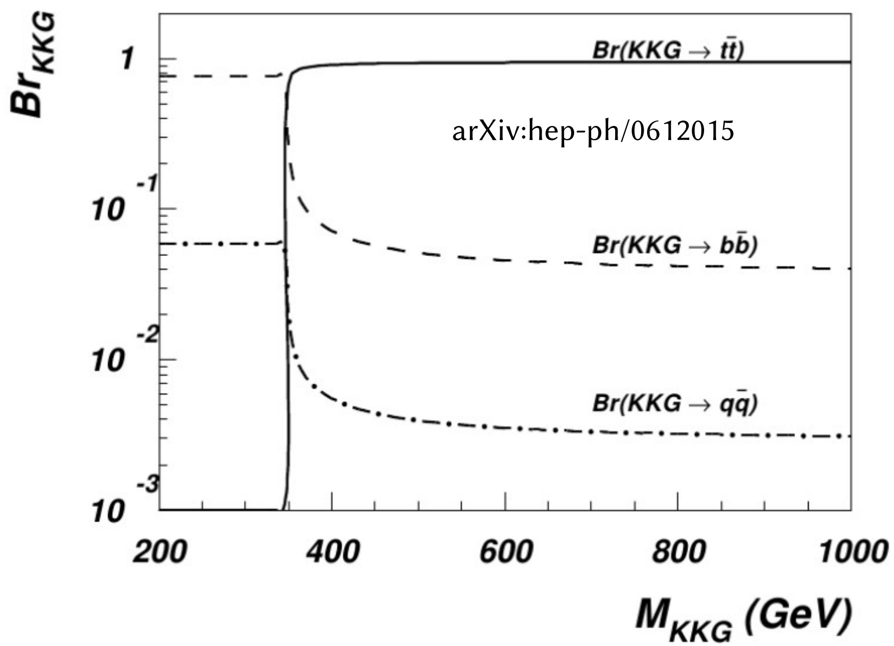
  - Spin 1
    - g_{KK} : Kaluza-Klein excitations of gluons (large width: 10% to 40%)



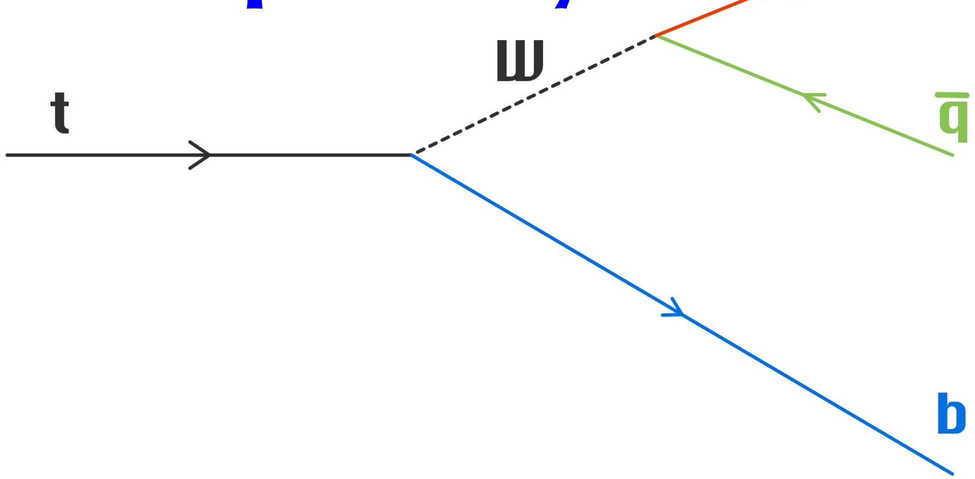
  - Spin 2
    - G_{KK} : Kaluza-Klein excitations of gravitons (narrow width: > 1%)



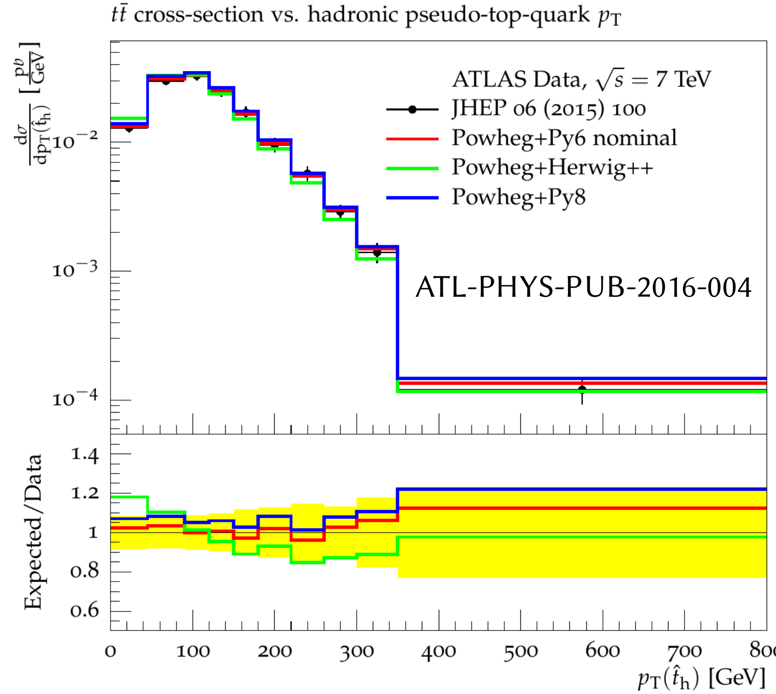
BR KK gluon ⟶ $t\bar{t}$ is 92.5%



Top decay

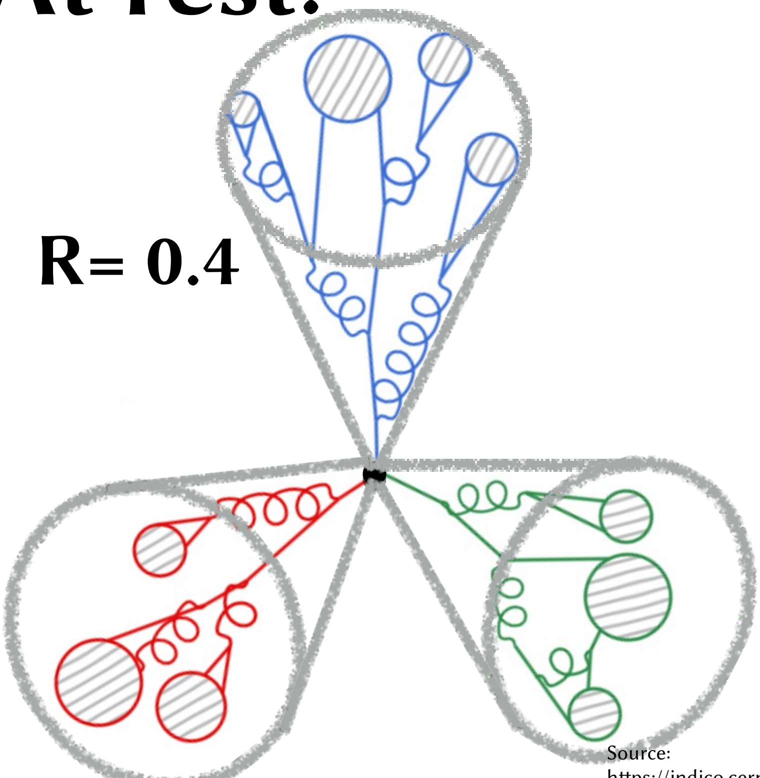


Peaks around p_T=100 GeV



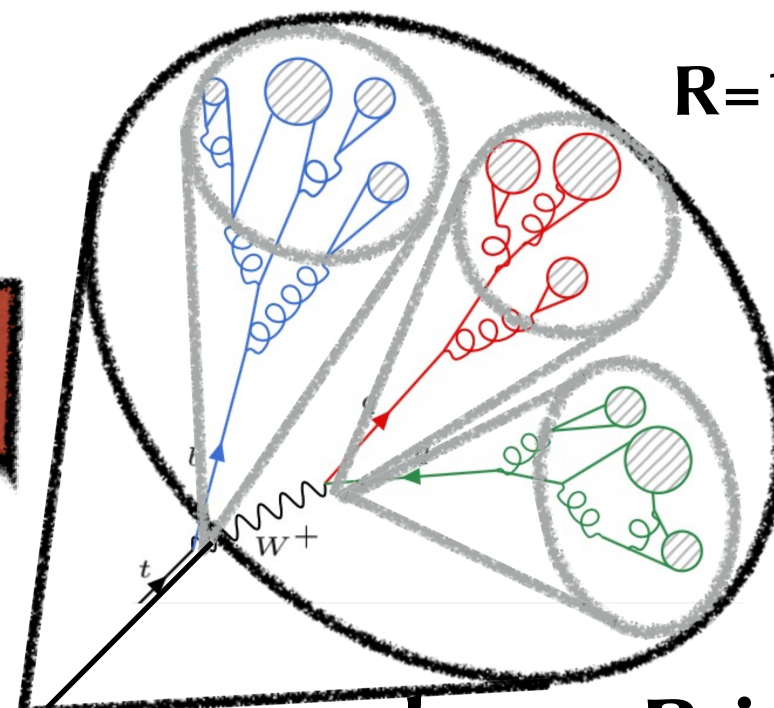
At rest:

R= 0.4



“Boost”

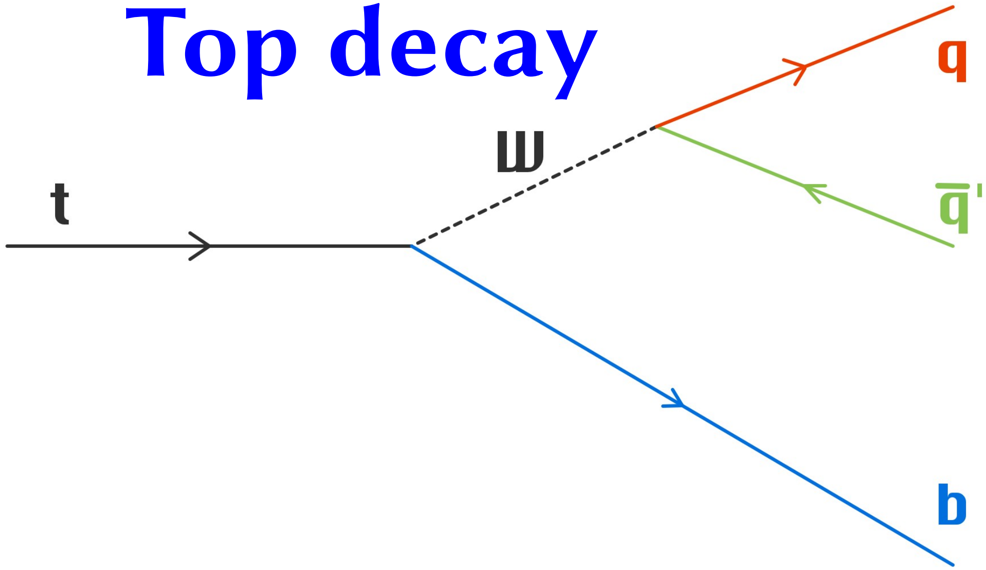
R=1

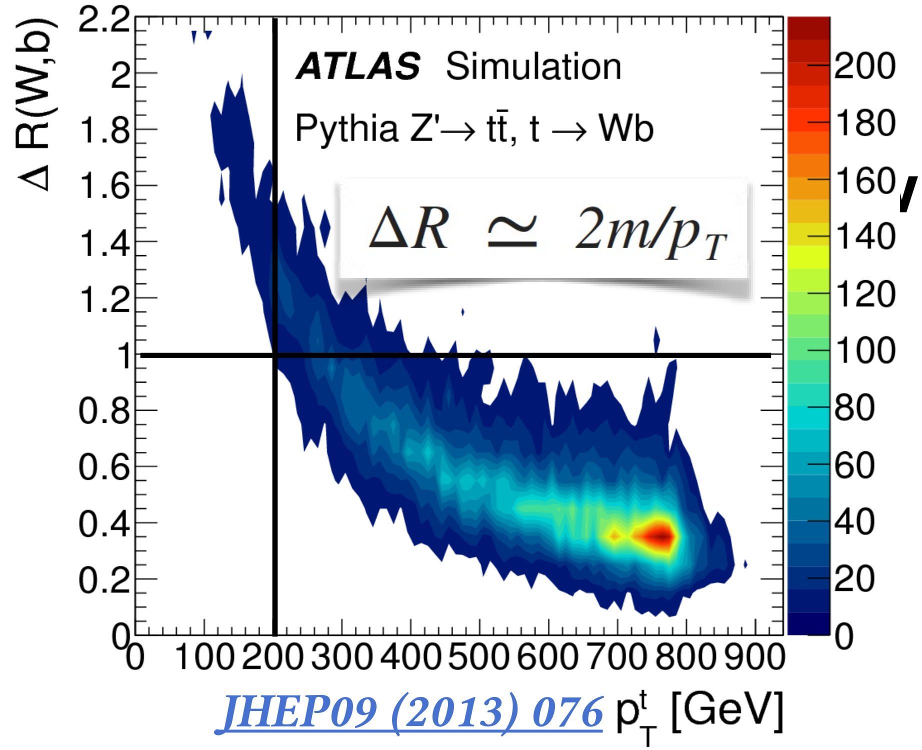


large R jet

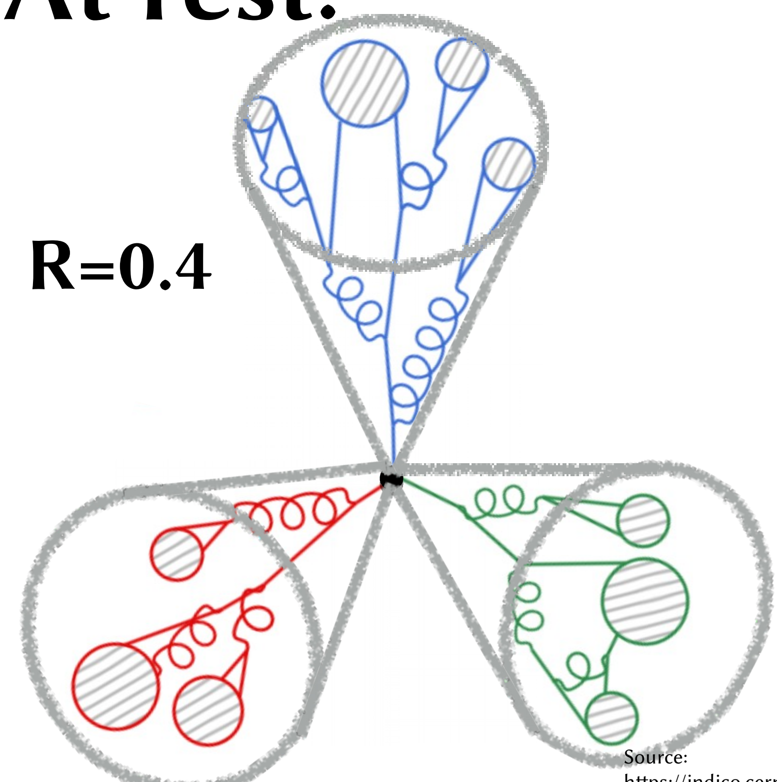
Source: https://indico.cern.ch/event/629638/contributions/2643115/attachments/1485662/2306756/Anders_Split17_.pdf

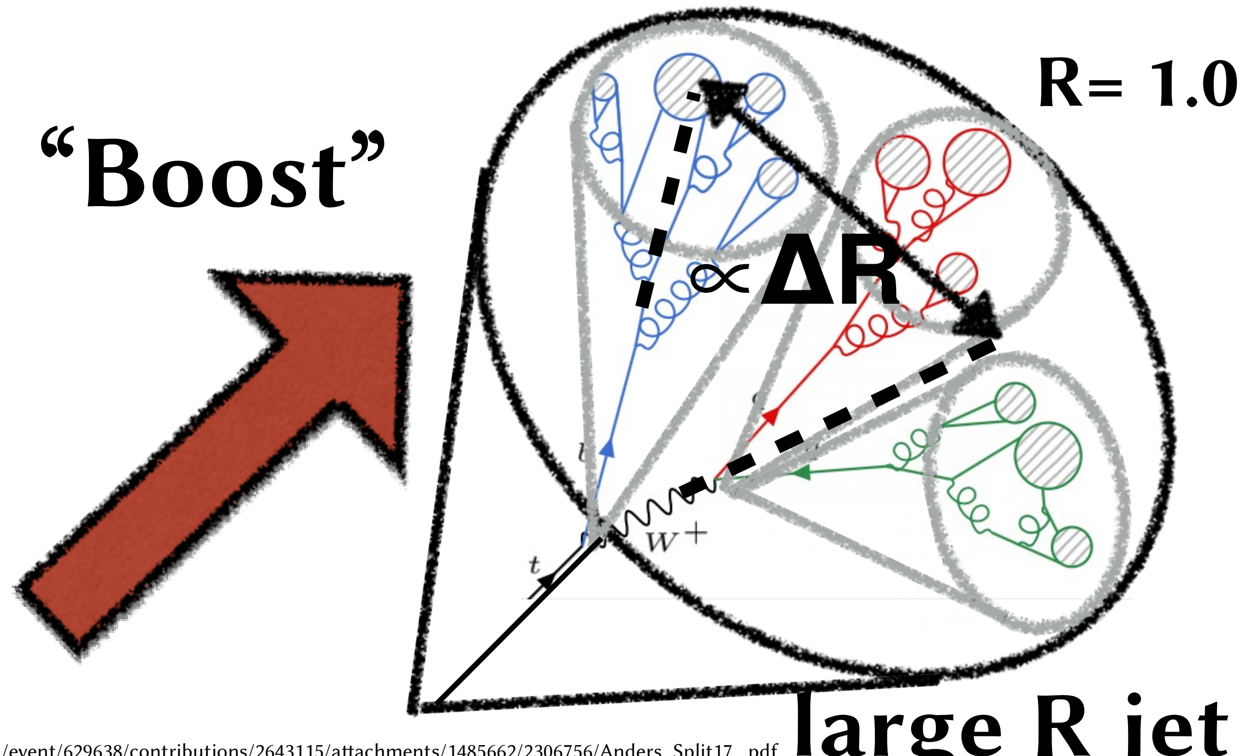
Top decay





At rest:





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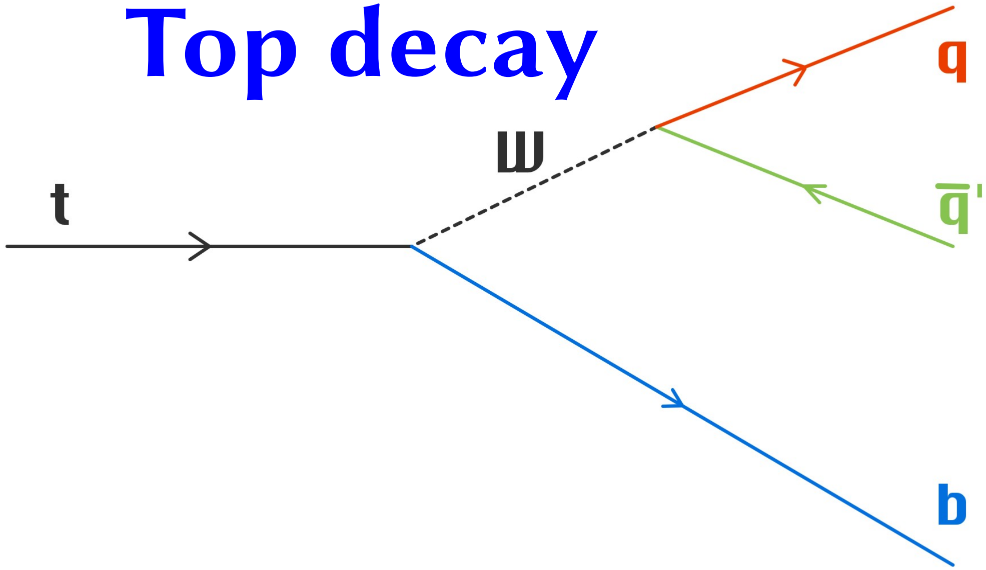
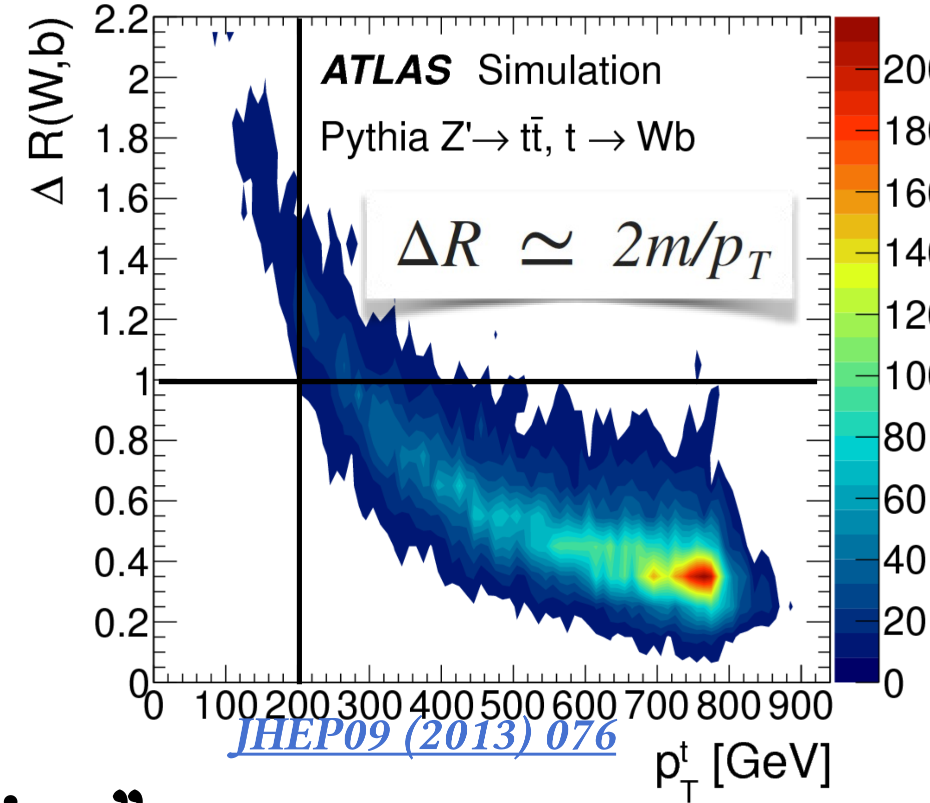
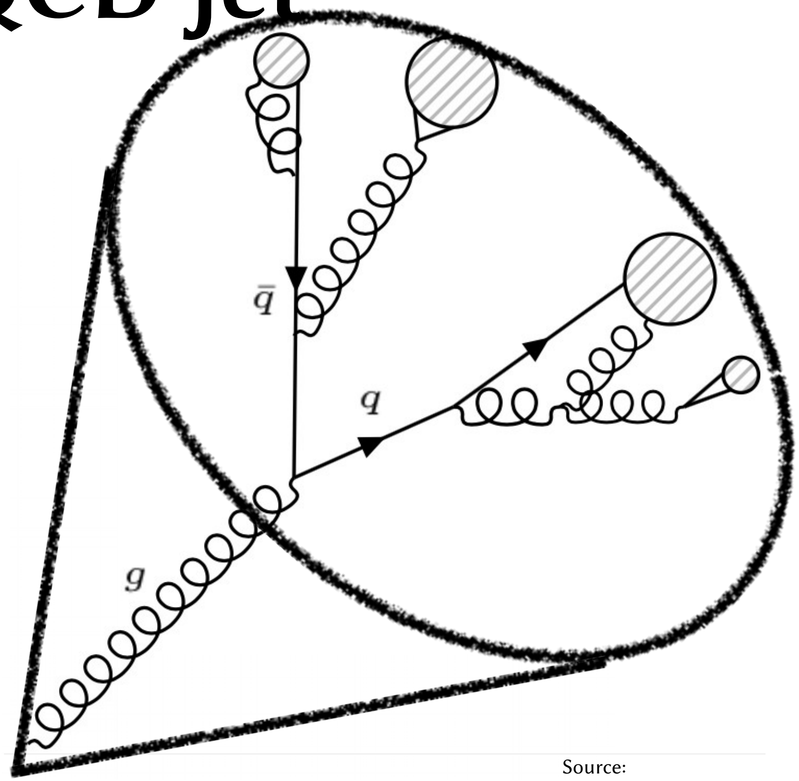
Top decay





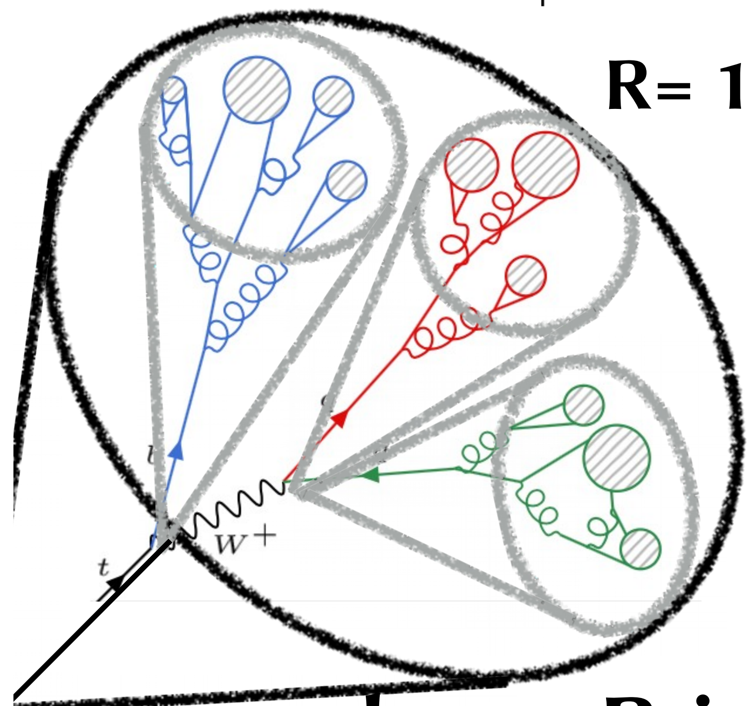
[JHEP09 (2013) 076]

"QCD jet"



"Top jet"

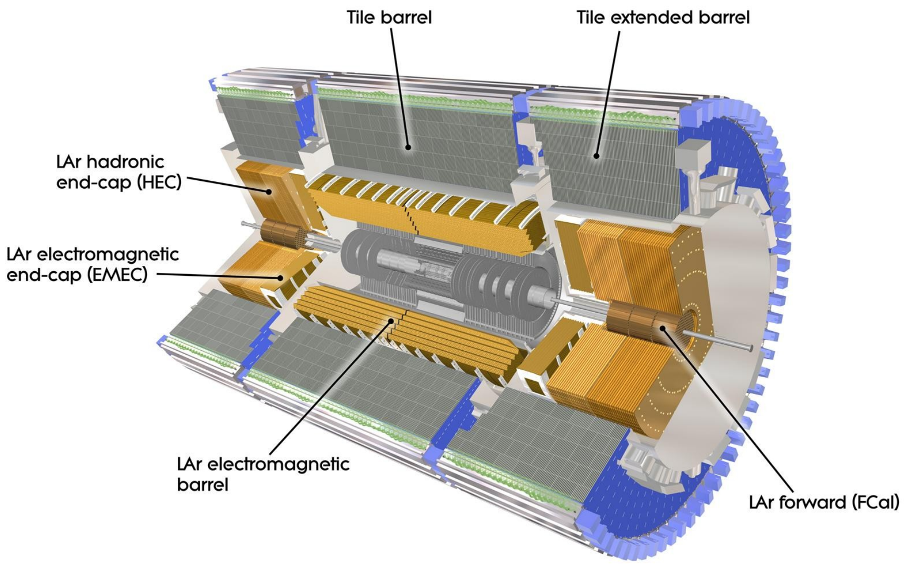
R= 1.0



large R jet

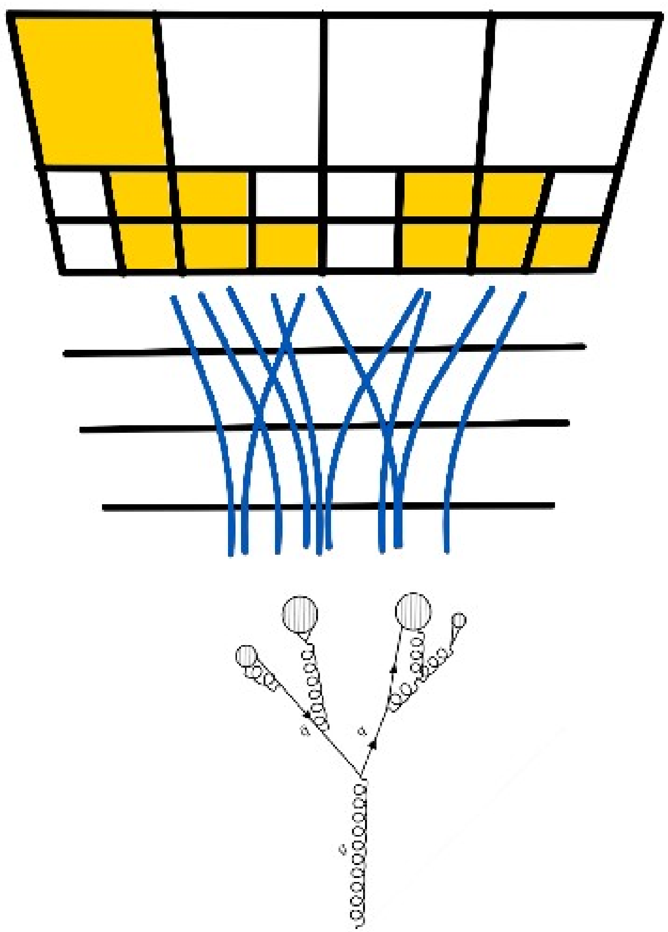
Source:
https://indico.cern.ch/event/629638/contributions/2643115/attachments/1485662/2306756/Anders_Split17_.pdf

ATLAS



Tracking	
p_T range (GeV)	> 0.1
$1/p_T$ resolution (%)	$5 \times 10^{-4} \oplus 0.015$
d_0 resolution (μm)	$140 - 20$
ECAL	
E resolution (%)	$0.1/\sqrt{E} \oplus 0.007$
granularity	0.025×0.025
HCAL	
E resolution (%)	$0.5/\sqrt{E} \oplus 0.03$
granularity $\eta \times \phi$	0.1×0.1

arXiv:1803.06991



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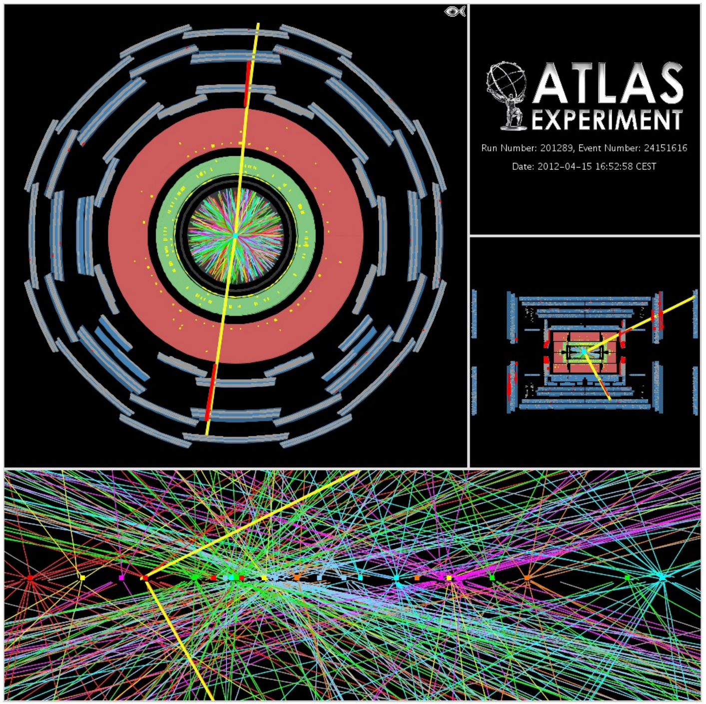
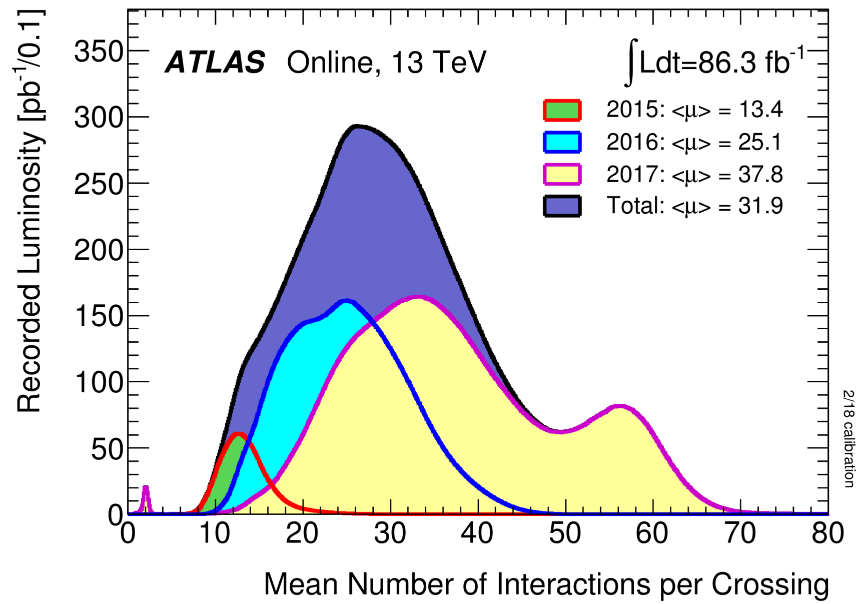
Pileup





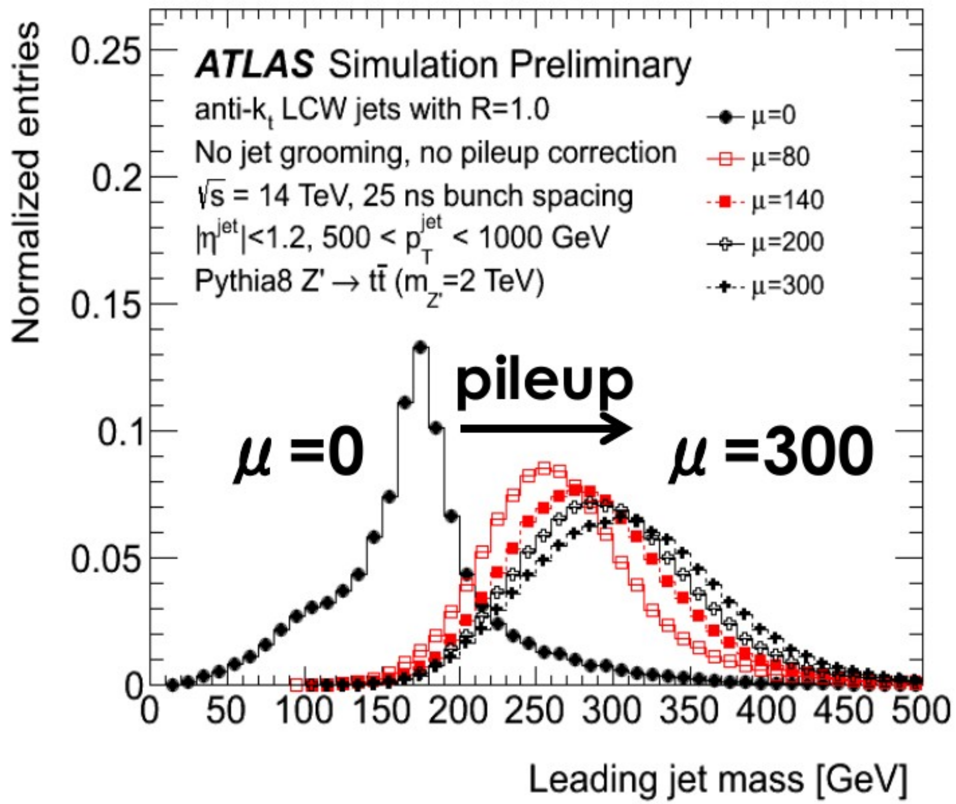
- <μ>: mean number of interactions per crossing
- n_{PV}: number of reconstructed primary vertices
- Contribution of up to 10 bunch pairs to signal

⟶ In-time pileup and out-of-time pileup

Effect of pile-up

- Additional energy creates offset
- Fluctuations can generate fake pileup jets
- Pile-up mitigation is important for better precision in search and measurements

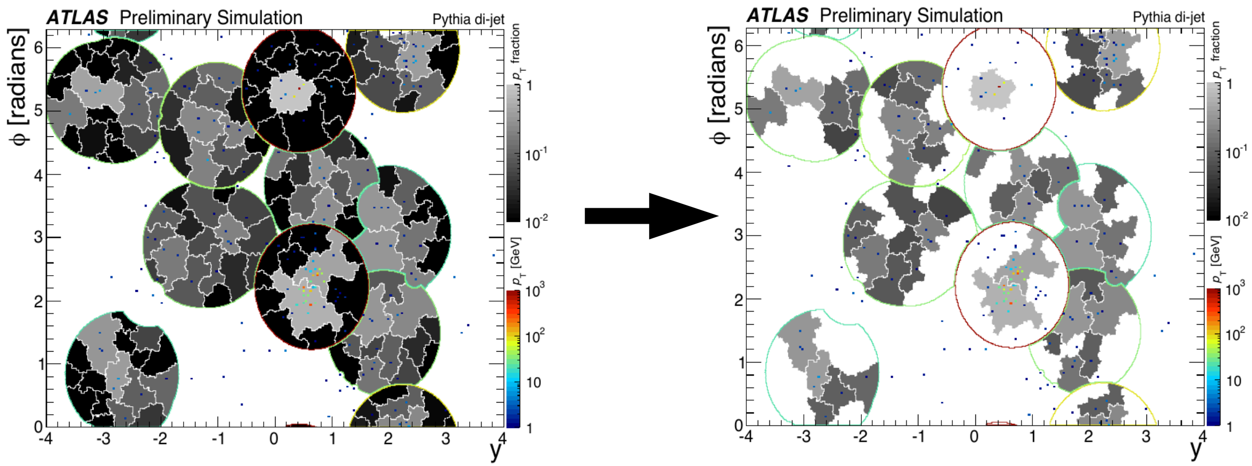
Top jet mass



Source: https://indico.cern.ch/event/384410/attachments/767308/1052475/SLACSeminar_Ariel_V21.pdf

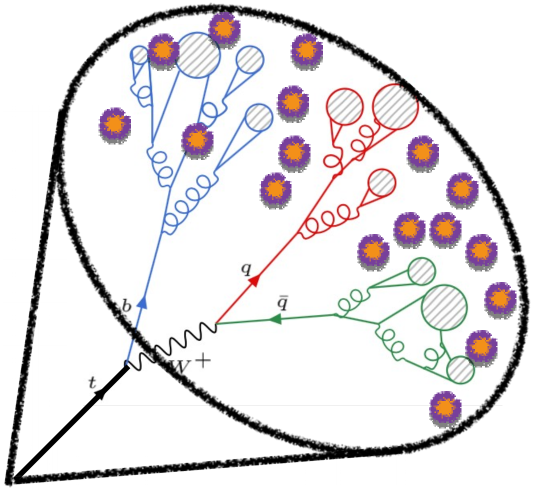
Pile-up mitigation

- Four classes of techniques
  1) Constituent level suppression
  2) Area-median subtraction
  3) Jet-vertex tagging
  4) Grooming effectively reduces the jet area
- Choice depends on R
- Grooming:
  - Trimming
  - Pruning
  - Filtering

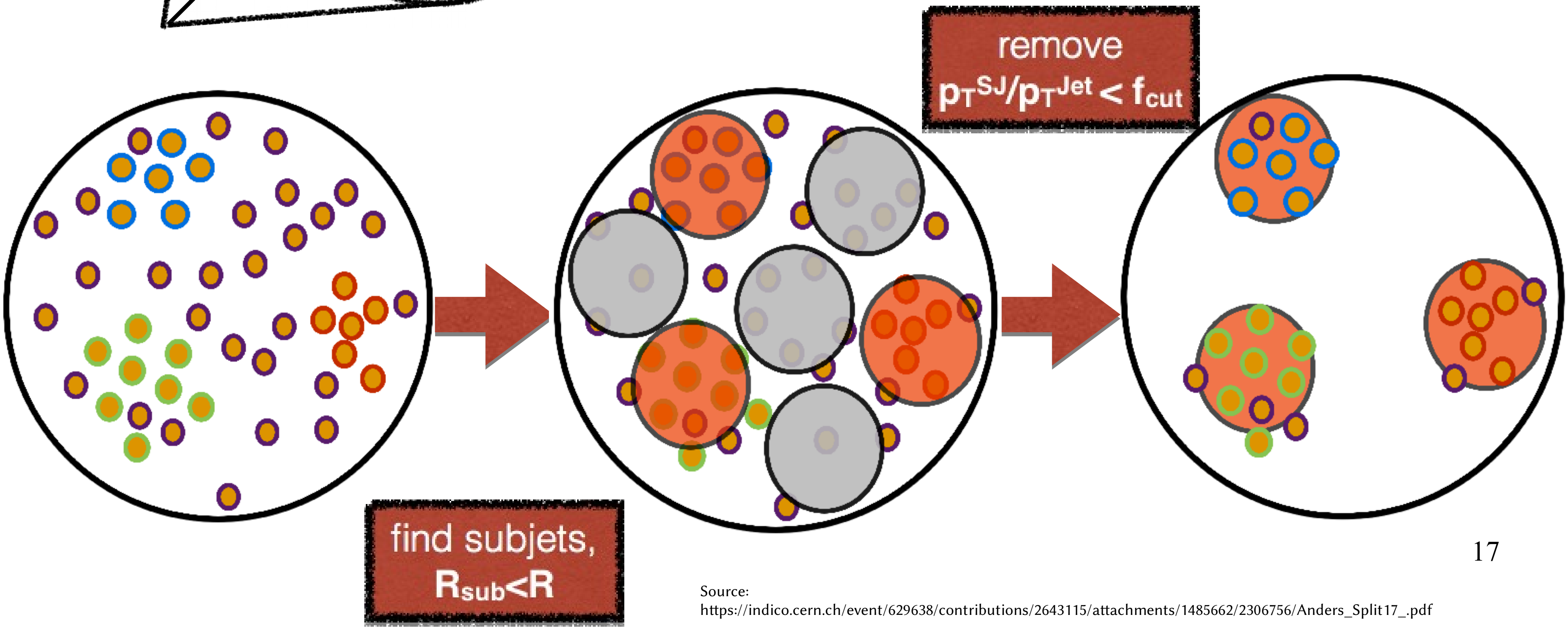


Source: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApprovedBOOST2014EventDisplays#Trimming_QCD_Jets

Trimming



- Pile-up adds "junk" for large-R jet
- Grooming "cleans" the jet
- ATLAS: R_{sub}=0.2, f_{cut} = 0.05

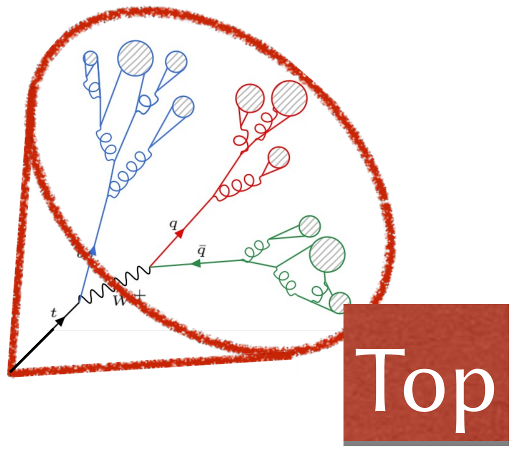


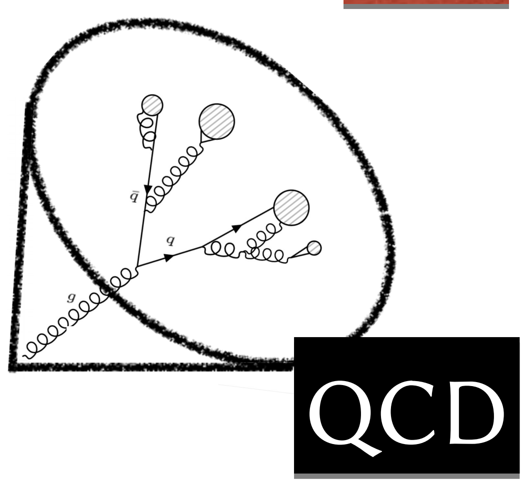
Source:
https://indico.cern.ch/event/629638/contributions/2643115/attachments/1485662/2306756/Anders_Split17_.pdf

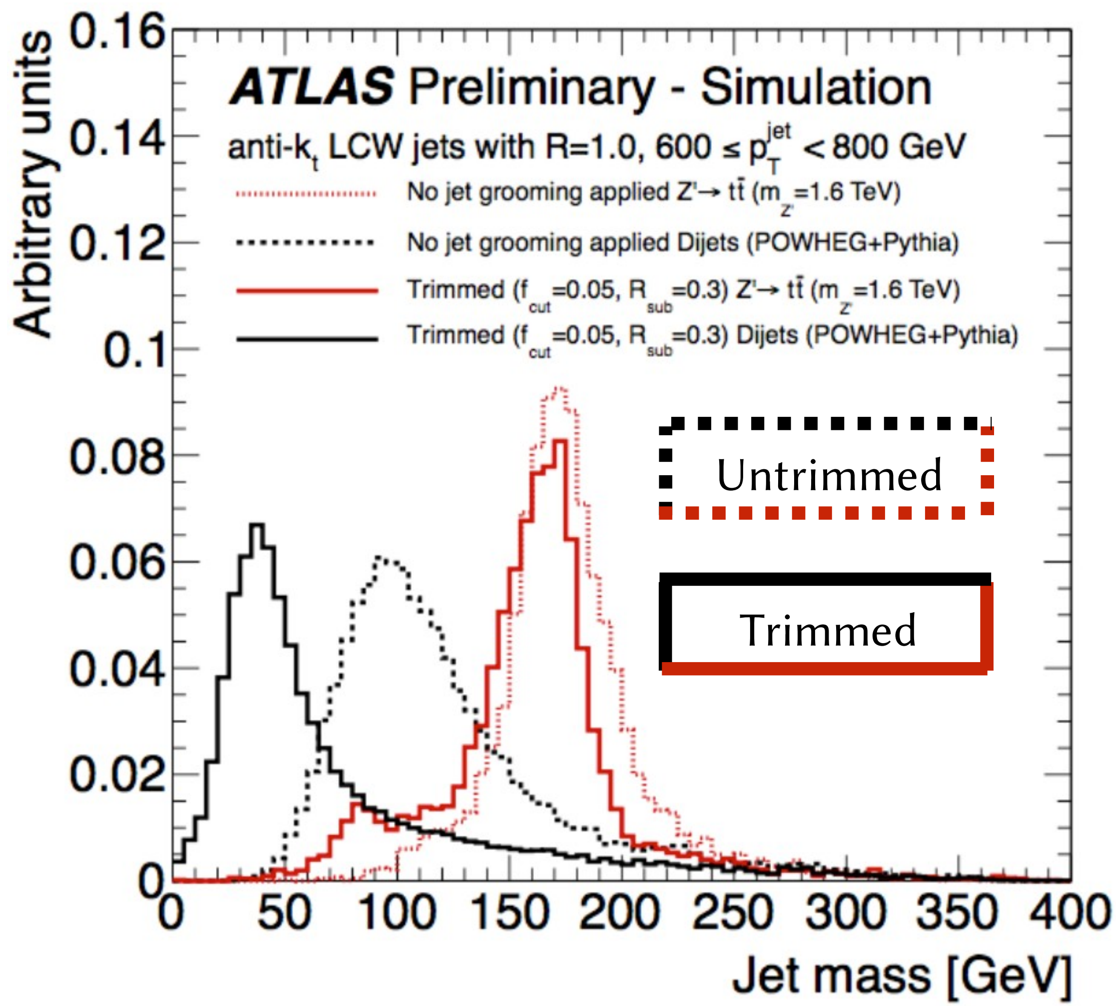
Trimming performance

- Jet mass: sum over all cluster

$$m_{jet}^2 = \left(\sum_i E_i\right)^2 - \left(\sum_i p_i\right)^2$$







Source:
https://indico.cern.ch/event/629638/contributions/2643115/attachments/1485662/2306756/Anders_Split17_.pdf

Pruning

- Remove soft protojets at large angle
- At every merging step i+j⟶p calculate

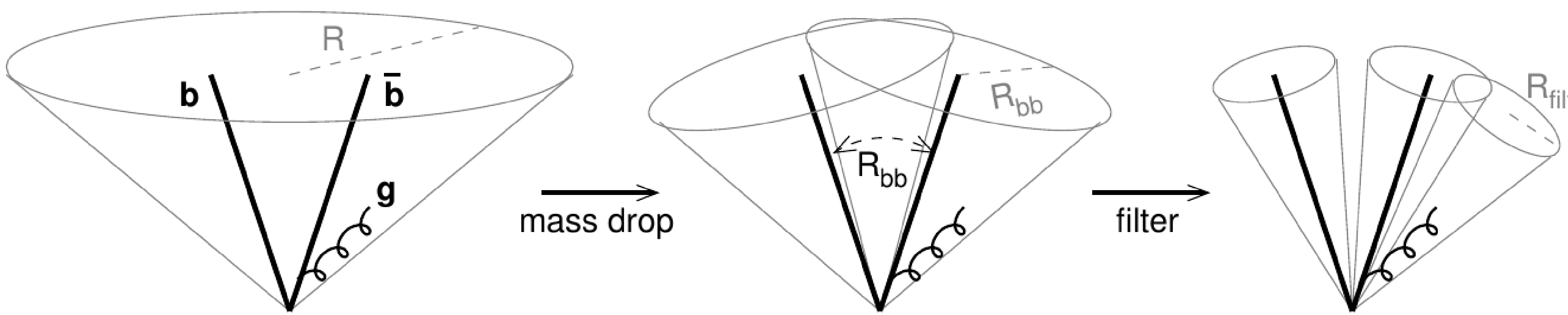
$$z \equiv \min(p_{T,i}, p_{T,j})/p_{T,p}$$

- Discard softer protojet if

$$z < z_{\text{cut}} \text{ and } \Delta R_{ij} > D_{\text{cut}}$$

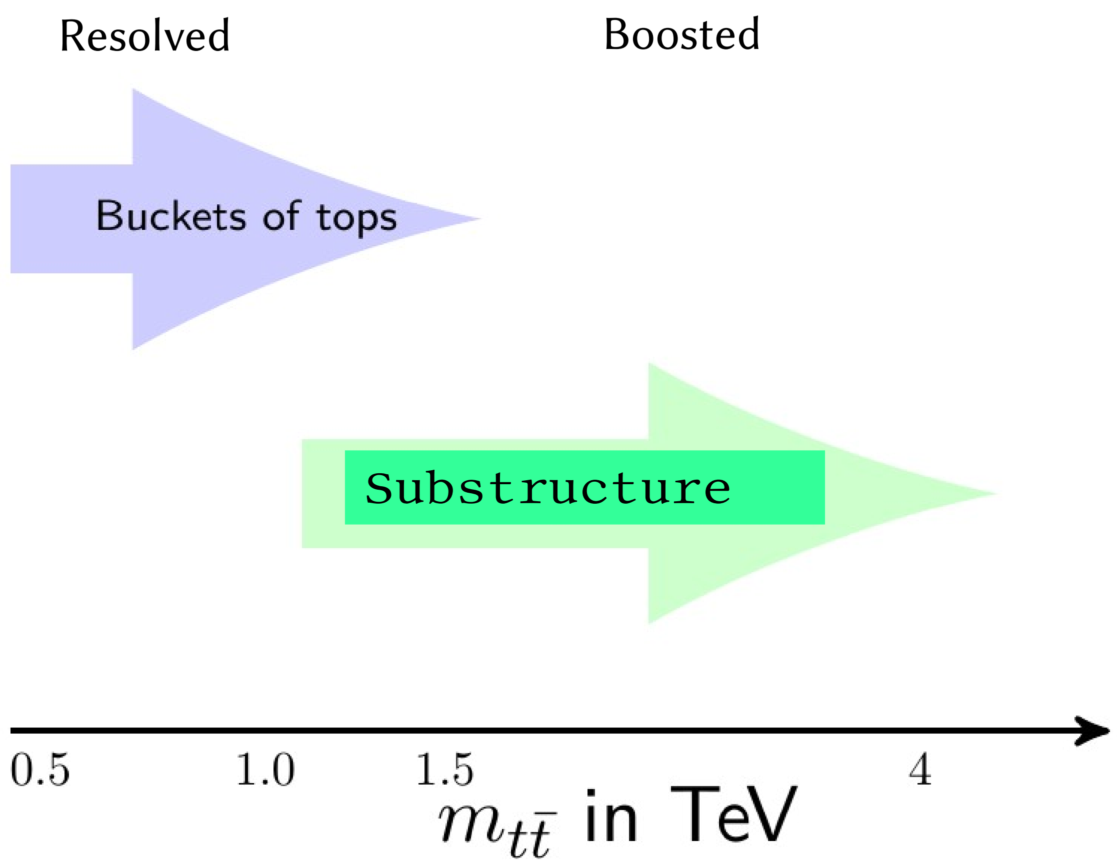
Filtering

- Hybrid of tagging and grooming
- Constituents of a fat jet are inclusively clustered with filter radius << jet radius
- Only N subjets with largest p_T are kept
- Mass drop filtering in $H \longrightarrow bb$:



Source: arXiv:0802.2470

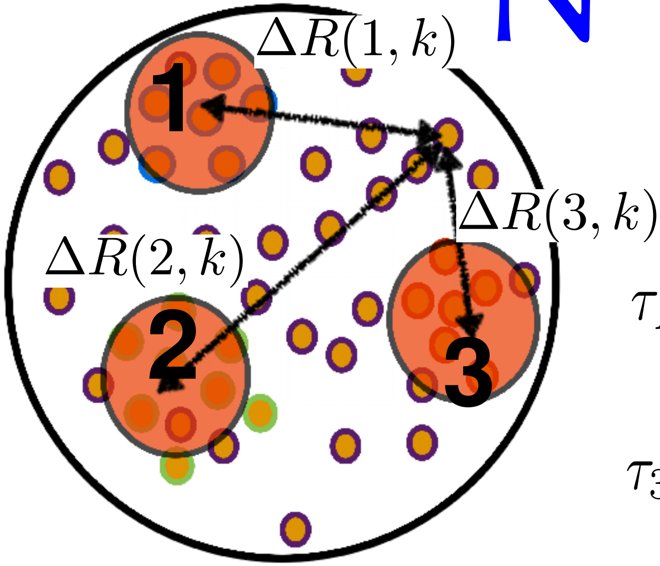
Top tagging



Resolved
Boosted
Buckets of tops
Substructure
0.5
1.0
1.5
4
$m_{t\bar{t}}$ in TeV

JHEP 03 (2011) 015

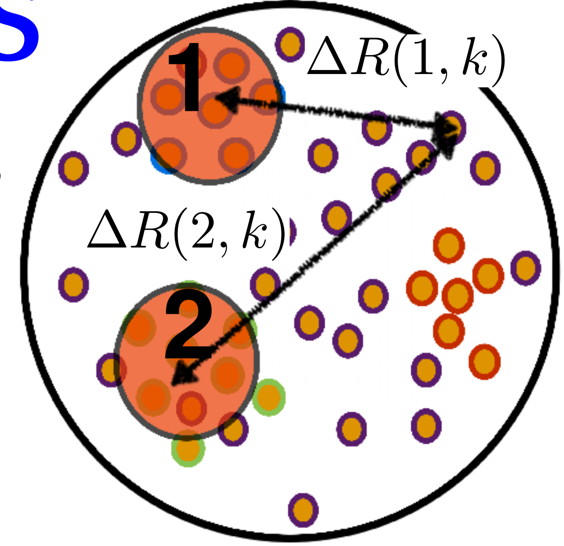
N-subjettiness

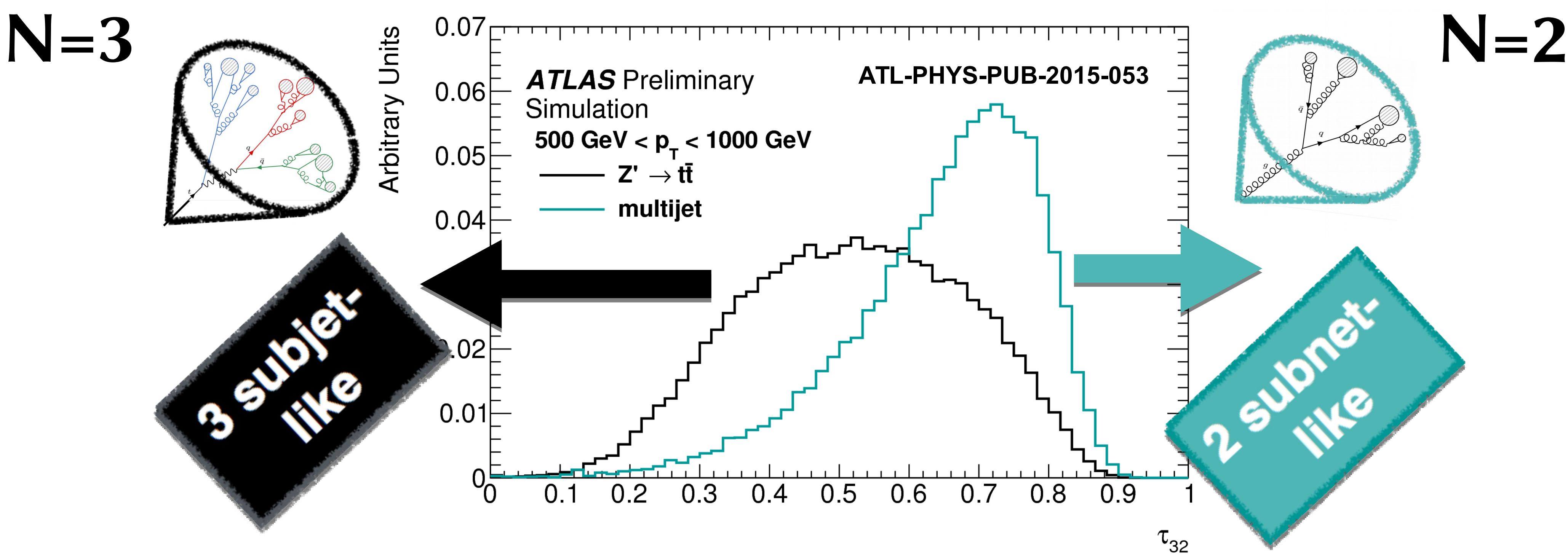


Exclusice reclustering to N subjets

$$\tau_N \equiv \frac{\sum_{k=1}^{M} \left(p_{T,k} \times \min(\Delta R_{jk})\right)}{\sum_{k=1}^{M} p_{T,k}}$$

$$\tau_{32} \equiv \frac{\tau_3}{\tau_2} \text{ separates 3 and 2 subjets}$$





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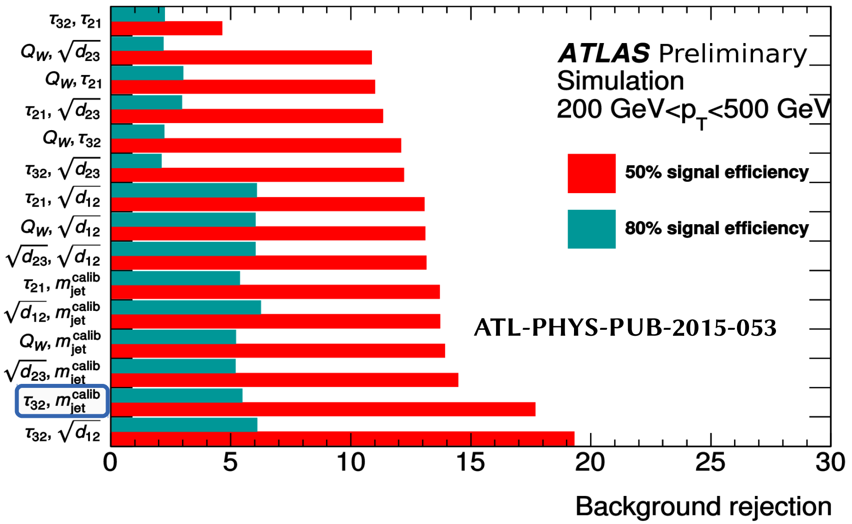
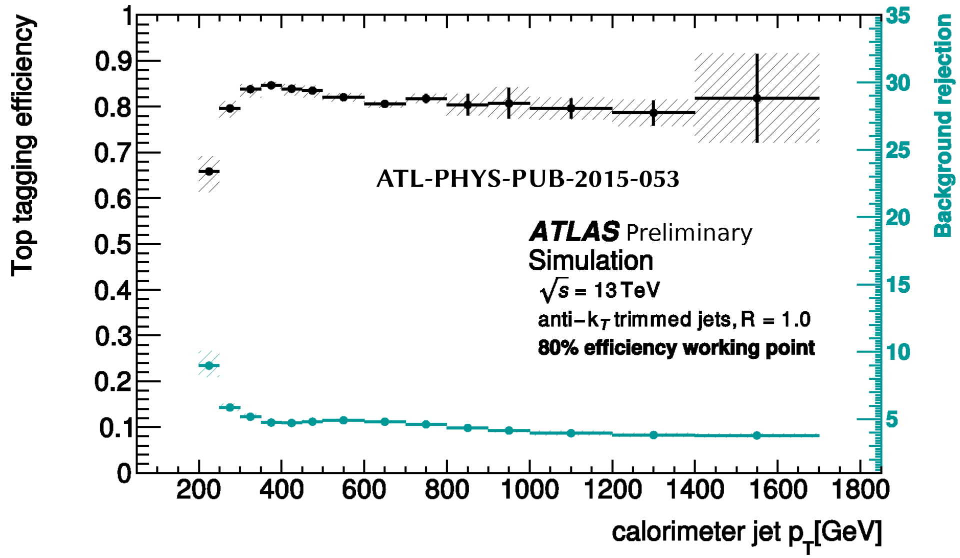
2-variable ATLAS top tagger



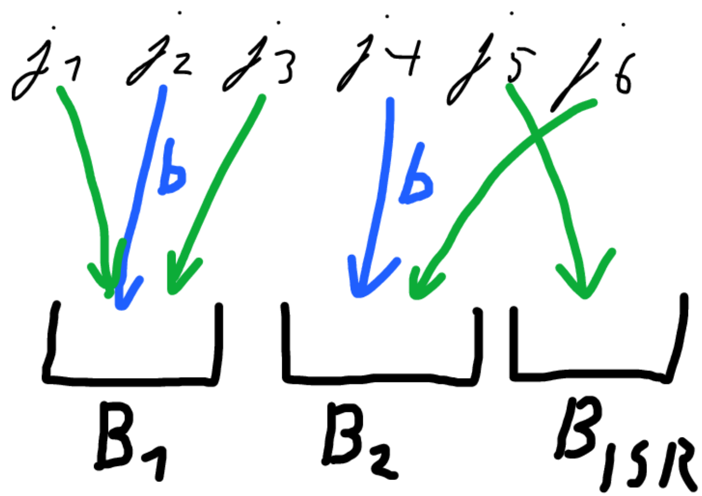


- ATLAS large-R baseline: anti-kt R=1.0 trimmed (R_{sub}=0.2, f_{cut}=0.05)
- Check 2-variable combinations
- Studied background rejection at 50% and 80% signal efficiency
- Best combination m_{jet} and τ_{32}

Buckets of tops

JHEP 1308 (2013) 086

- Targetting mass range mtt < 1.3 TeV
- Using well understood and calibrated anti-k_T (R=0.4) jets
- Reconstruct moderate p_T = 100 - 400 GeV top quark pairs ⟶ Aim at low masses < 1.3 TeV
- Jets grouped into 3 Buckets (B_{top1}, B_{top2}, B_{ISR})
- Minimize metric Δ for all jet combinations
- By construction B1 closer to true top mass



$$\Delta^2 = \omega\Delta^2_{B_1} + \Delta^2_{B_2}$$

$$\Delta_{B_i} = |m_{B_i} - m_t|, \quad m^2_{B_i} = \left(\sum_{j\in B_i} p_j\right)^2$$

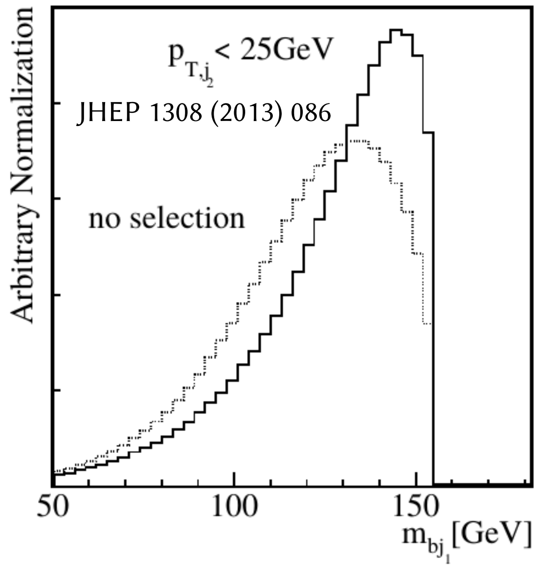
$$\omega = 100 \longrightarrow \Delta_{B_1} < \Delta_{B_2}$$

W reconstruction inside of buckets

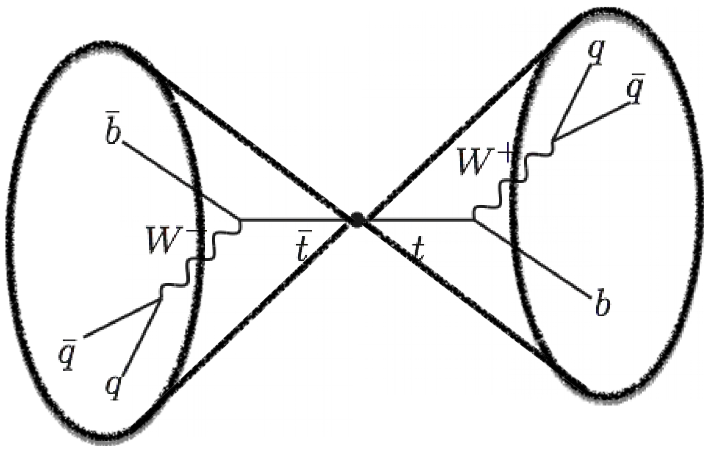
- 3jet-buckets with W candidate (t_W)
- New metric for 2-jet buckets with no W candidate (t_-) $\longrightarrow$ reduced mass
- Endpoint $\sqrt{m_t^2 - m_W^2} \simeq 155$ GeV
- New metric for t_- buckets:

$$\Delta_B^{bj} = \begin{cases} |m_B - 145\,| & \text{if } m_B \leq 155 \\ \infty & \text{else} \end{cases}$$

t_- buckets, parton level, JHEP **1308** (2013) 086



Event selection



- Resolved:
  - Small-R jets (pT>25 GeV) > 5
  - Small-R jets (pT>75 GeV) > 4
  - At least 2 b-tagged jets
- Boosted:
  - 2 large-R jets

Analysis strategy

- Top reconstruction efficiency
- Background estimation
- Systematics
- Validation
- Limits

Top reconstruction efficiency

$$\epsilon(\text{Doubletag}) = \frac{\text{Top reconstruction selection}}{\text{Pre-selection}}$$

$$\epsilon(\text{Matching}) = \frac{\text{Geometrical matching}}{\text{Top reconstruction selection AND Pre-selection}}$$

- Geometrical matching $\min(\Delta R(t_i^{\text{reco}}, t_j^{\text{truth}})) < 0.3$
- Top selection on mass windows and $p_T > 200$ GeV

Background estimation

- ABCD method

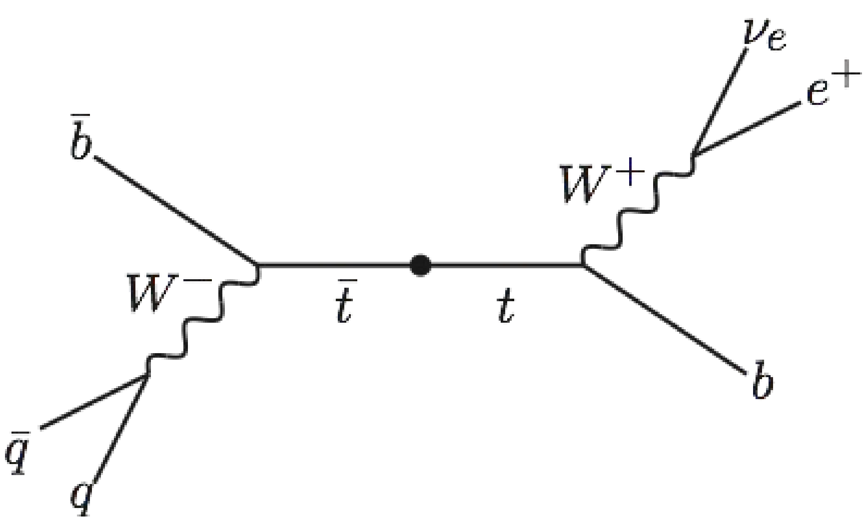
$$\frac{dn_D^{\mathrm{QCD}}}{dm_{t\bar{t}}} = \frac{n_C^{\mathrm{QCD}}}{n_A^{\mathrm{QCD}}} \times \frac{dn_B^{\mathrm{QCD}}}{dm_{t\bar{t}}}$$

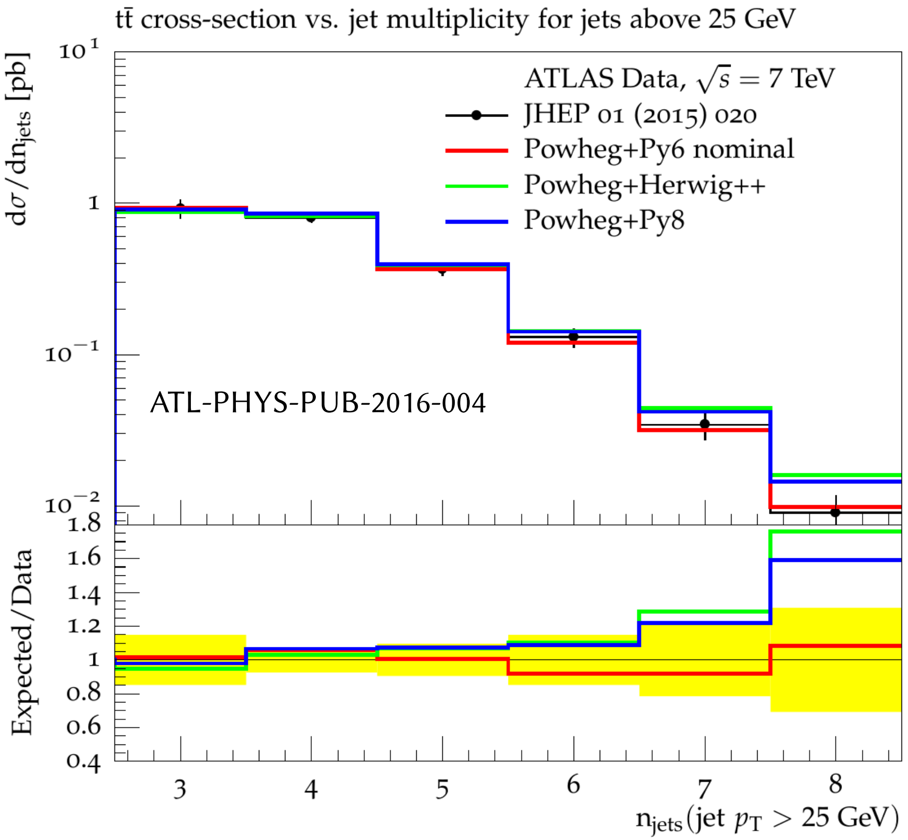
$$L(n_A, n_B, n_C, n_D | \nu, \Theta_\nu) = \prod_{i=A,B,C,D} \frac{e^{-\nu_i} \nu_i^{n_i}}{n_i!}$$

Systematics

- Large uncertainties from $t\bar{t}$ modelling and
- Jet uncertainties
  - Jet energy scale and resolution

$t\bar{t}$ modelling





Profile Likelihood fit

- Frequentist approach using CL_s method is used to set limits on upper production cross-section
- Parameter of interest μ and nuisance parameter Θ
- Likelihood

$$L(\mu, \Theta) = \prod_{i=0}^{\text{channels,bins}} \frac{e^{-\mu a_{Z',i}\sigma_{Z'} + b_i} (\mu a_{Z',i}\sigma_{Z'} + b_i)^{D_i}}{\Gamma(D_i + 1)} C(\Theta)$$

- Profile likelihood ratio test statistic Λ

$$\Lambda(\mu) = \frac{L(\mu, \hat{\hat{\Theta}}(\mu))}{L(\hat{\mu}, \hat{\Theta})}$$

- Test statistic -2ln(Λ(μ)) is distributed according to a χ^2-distribution with one degree of freedom

Summary

- Specific Top and boson taggers
- Jet substructure techniques are established and successfully applied in searches and measurements
- Top tagging crucial for $t\bar{t}$ resonance searches
- More pile-up and boost in the future