ATLAS Jet Substructure Measurements

Deepak Kar
University of Witwatersrand

QMUL Virtual Seminar
November 19th, 2020

ATLAS Jet Substructure Measurements

and searches using unusual topologies

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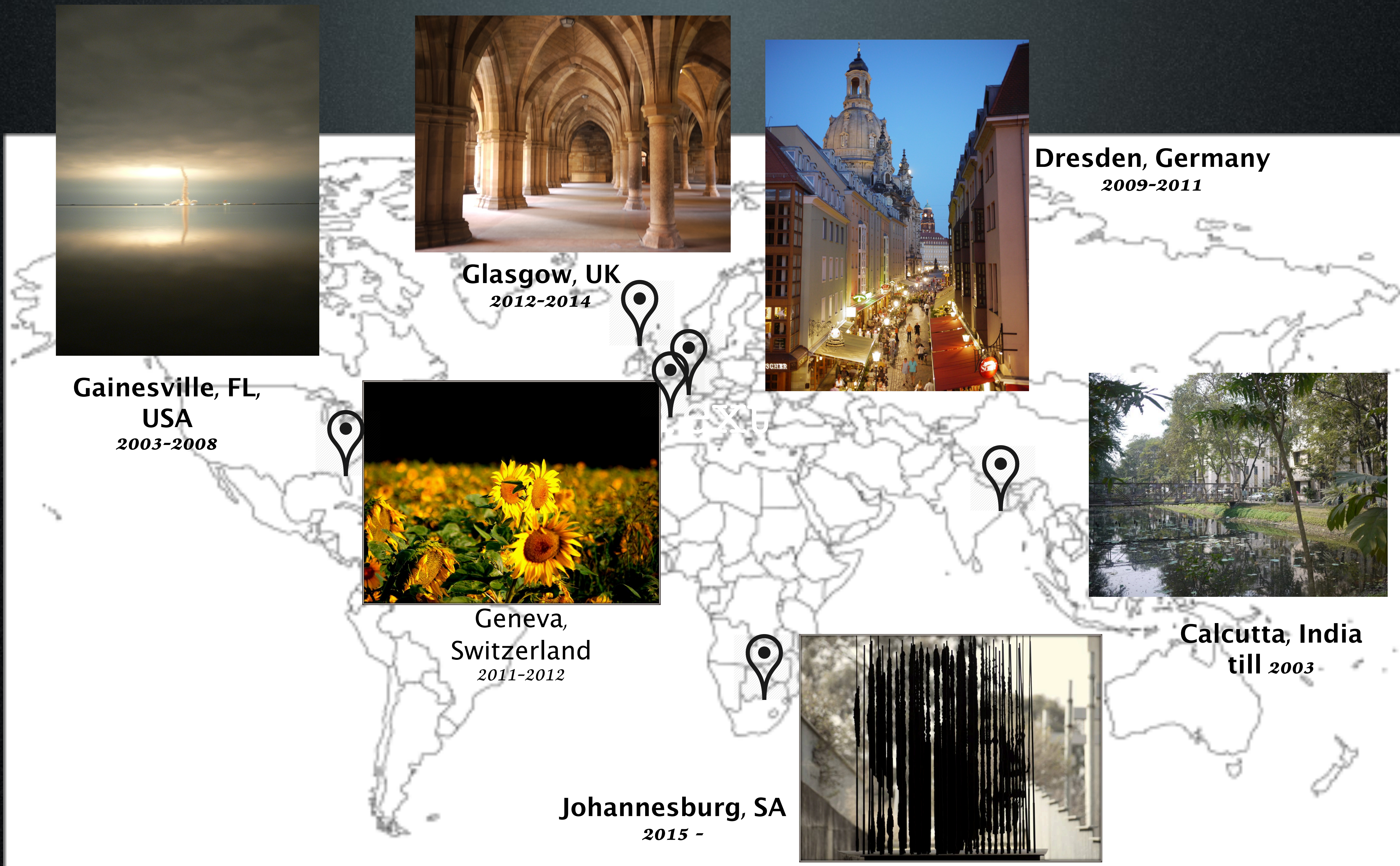
National Research Foundation

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

An amazing adventure…



Prologue

What do we do at the LHC?

1. Search for signatures of new physics

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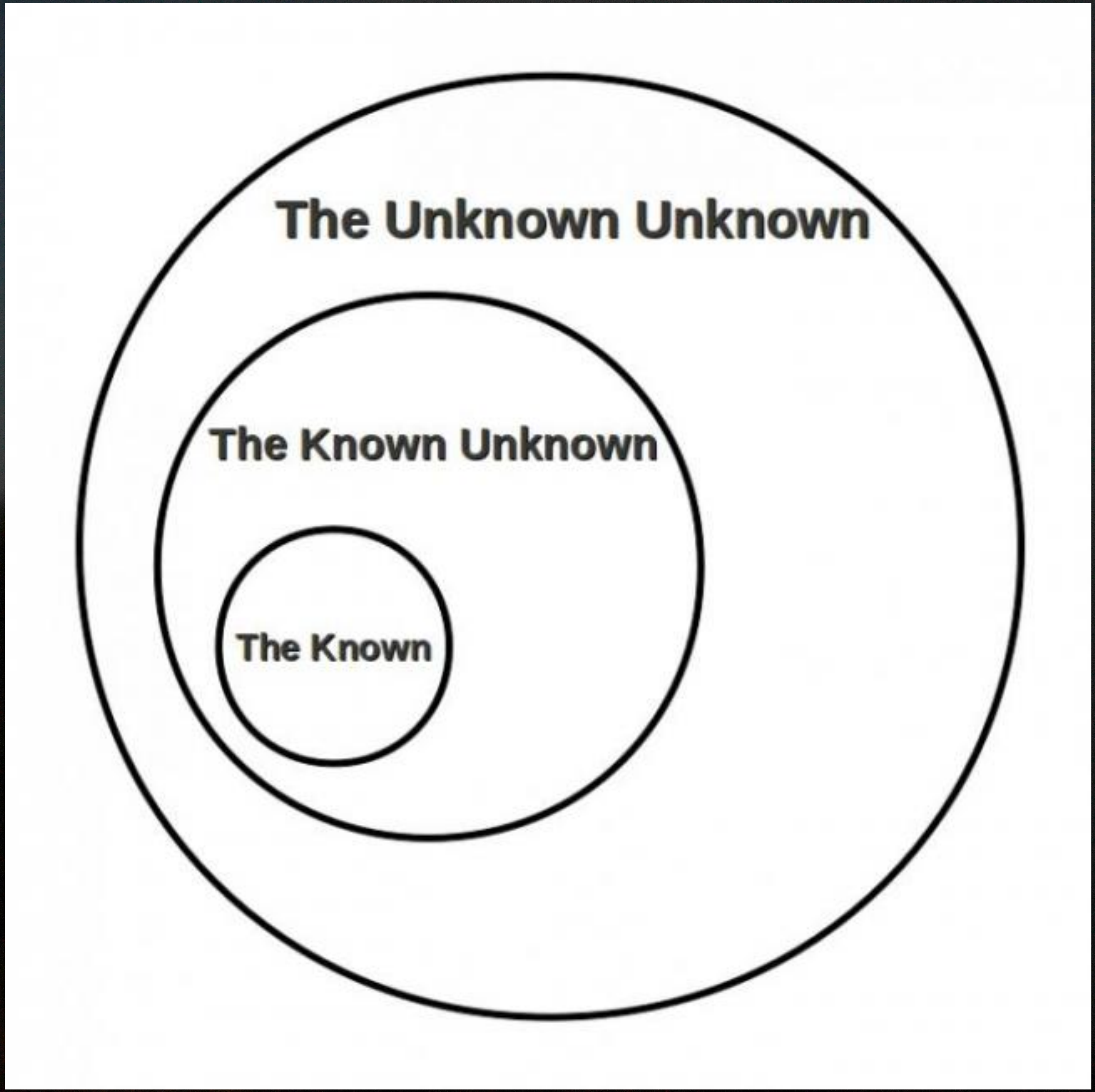
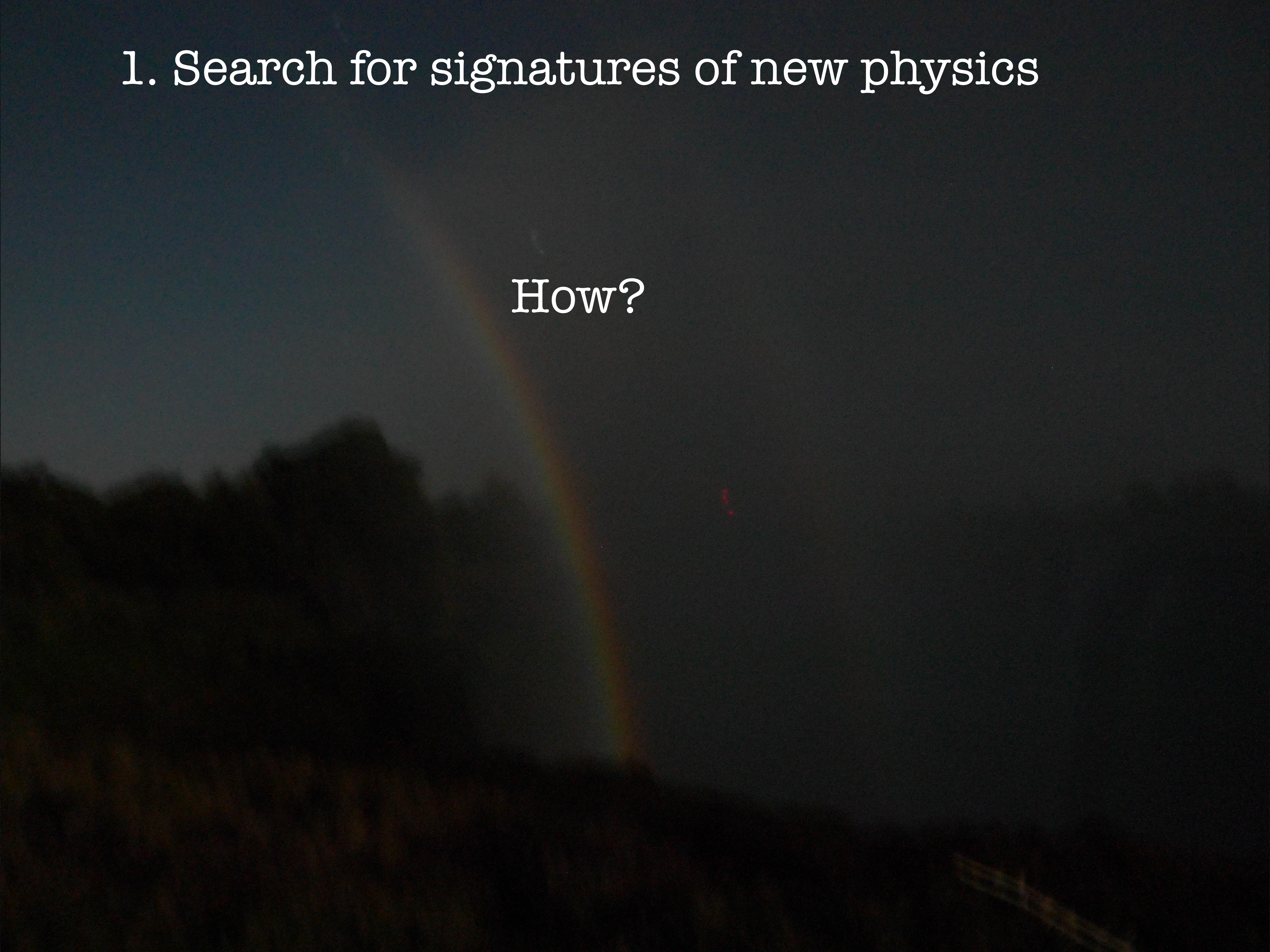


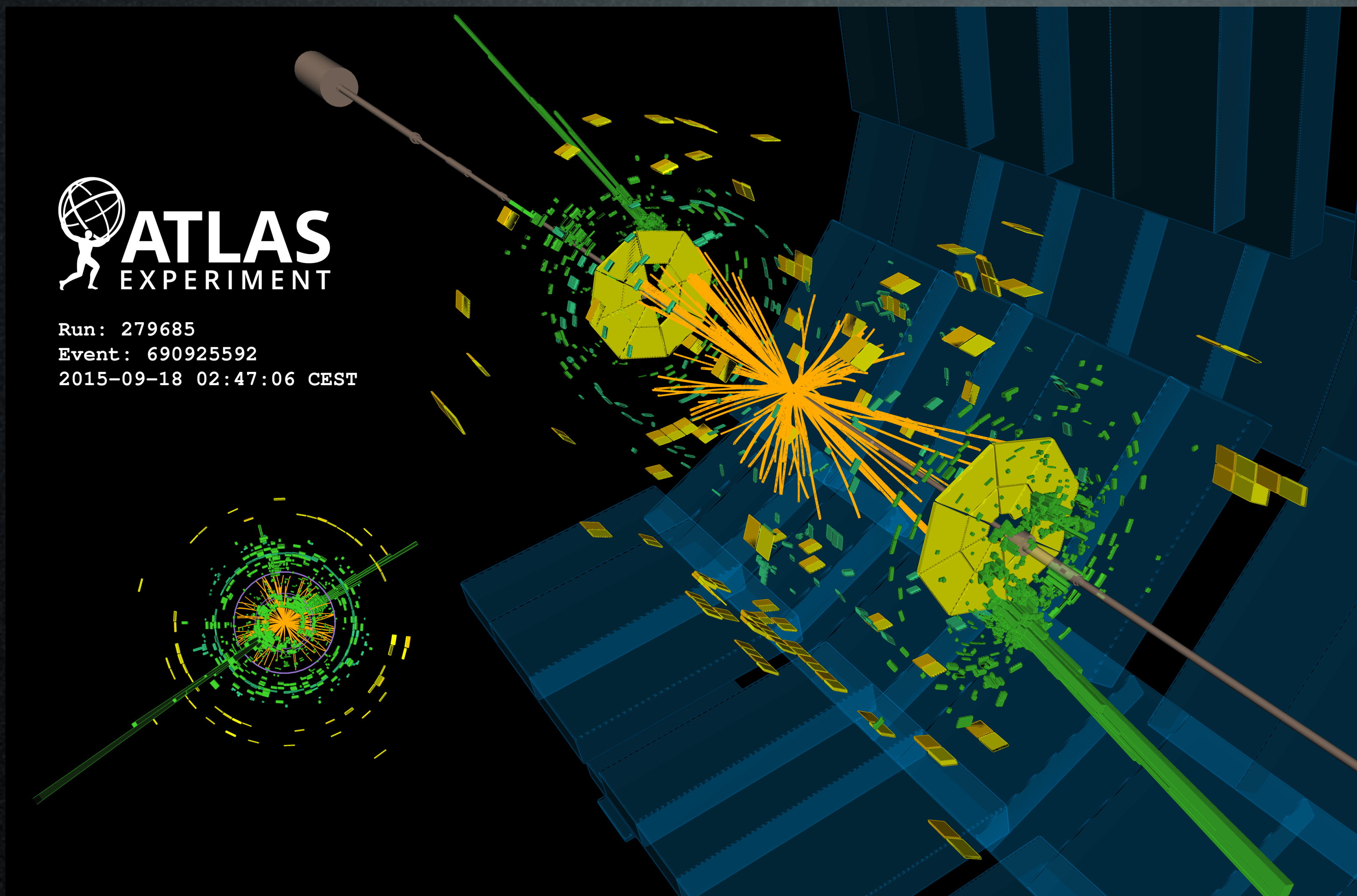

1. Search for signatures of new physics
How?

1. Search for signatures of new physics

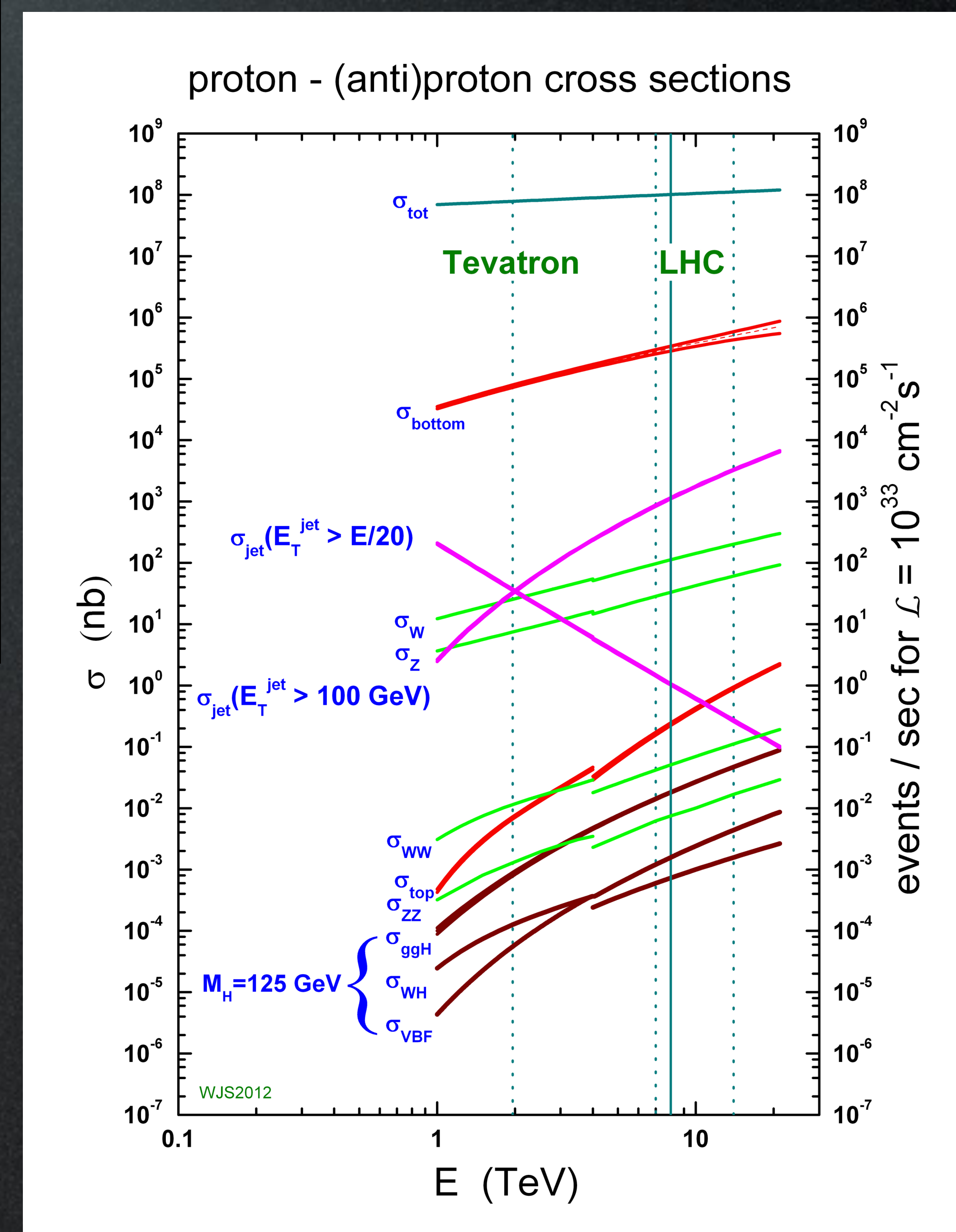
Bump hunting!

1. Search for signatures of new physics
2. Measure SM processes at a new energy regime

Jets



LHC is a jet factory!

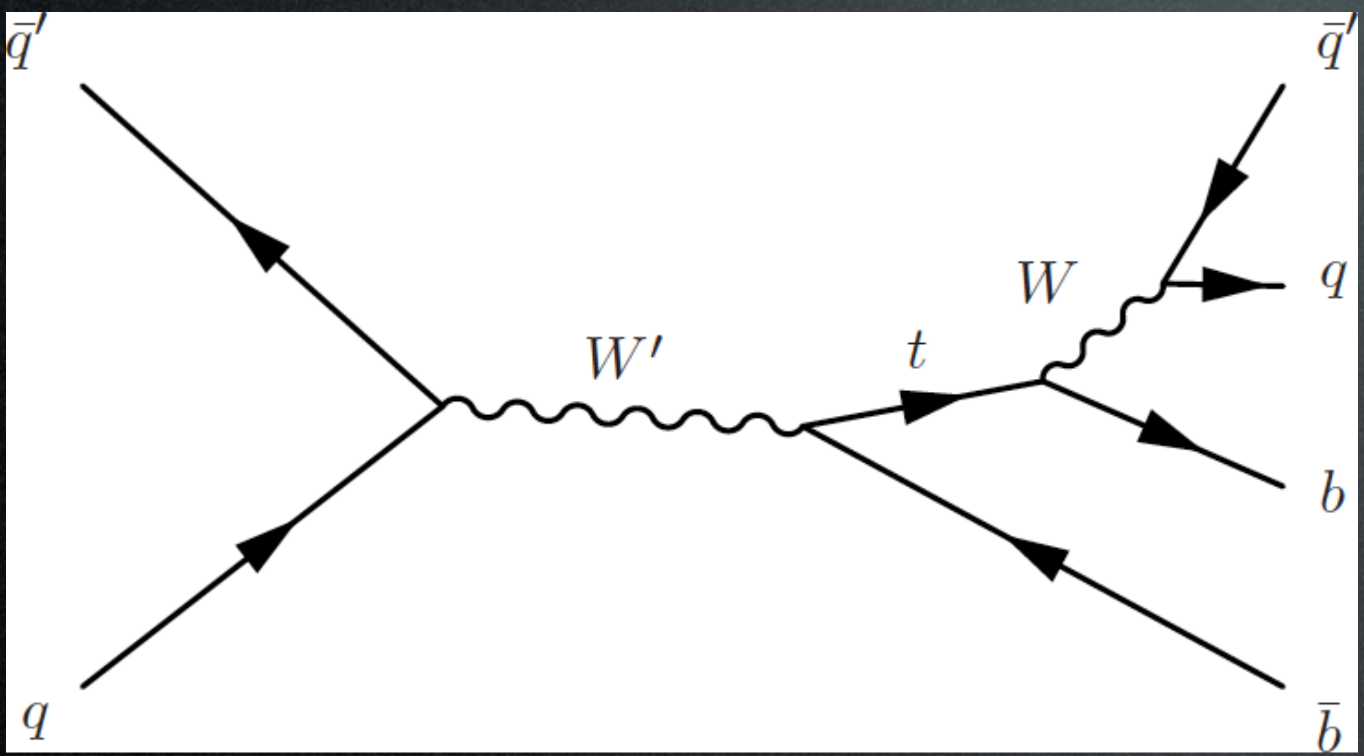


As a signal, test of QCD predictions

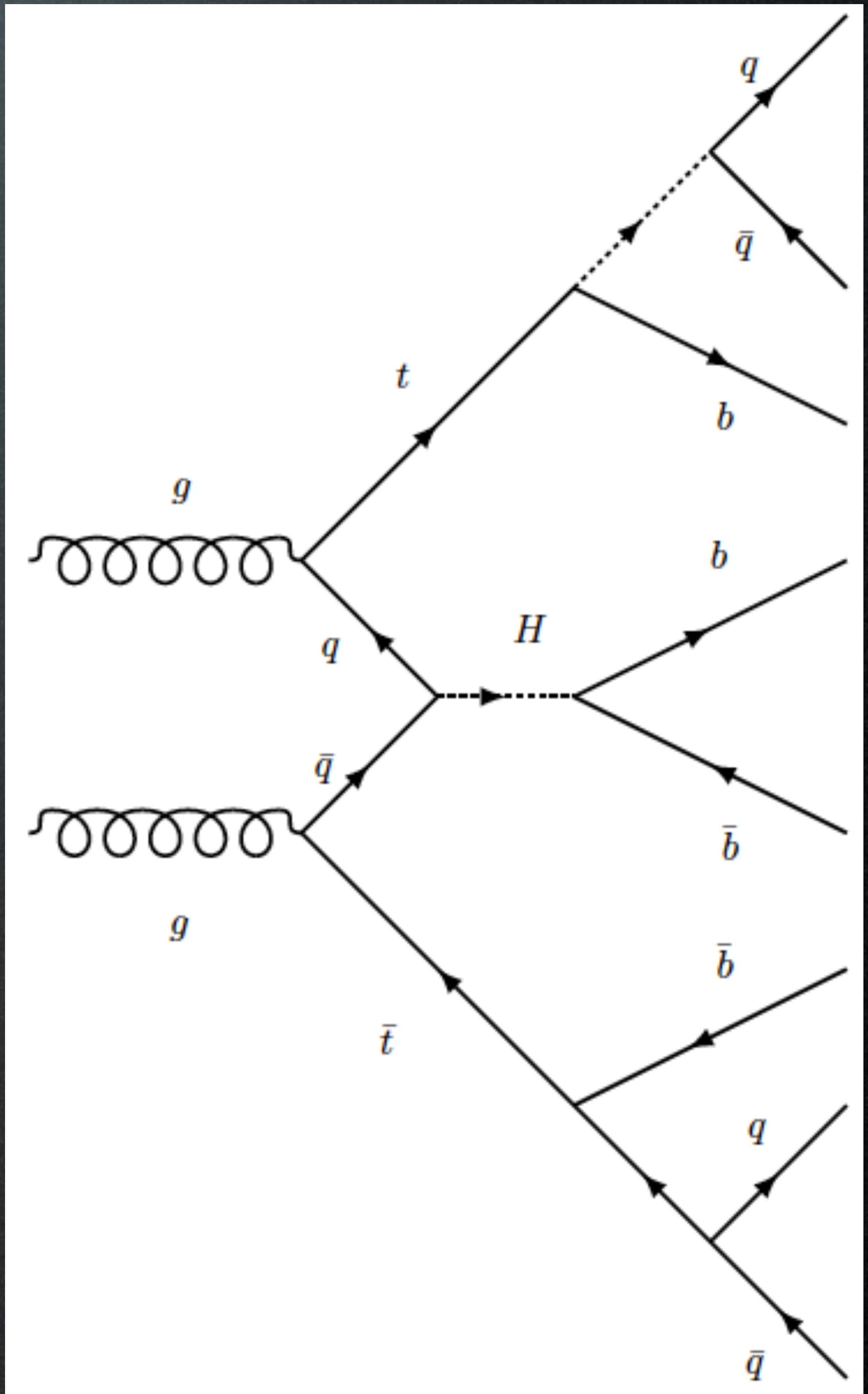
Background for most analyses

Searches with many jets

W prime (all hadronic)



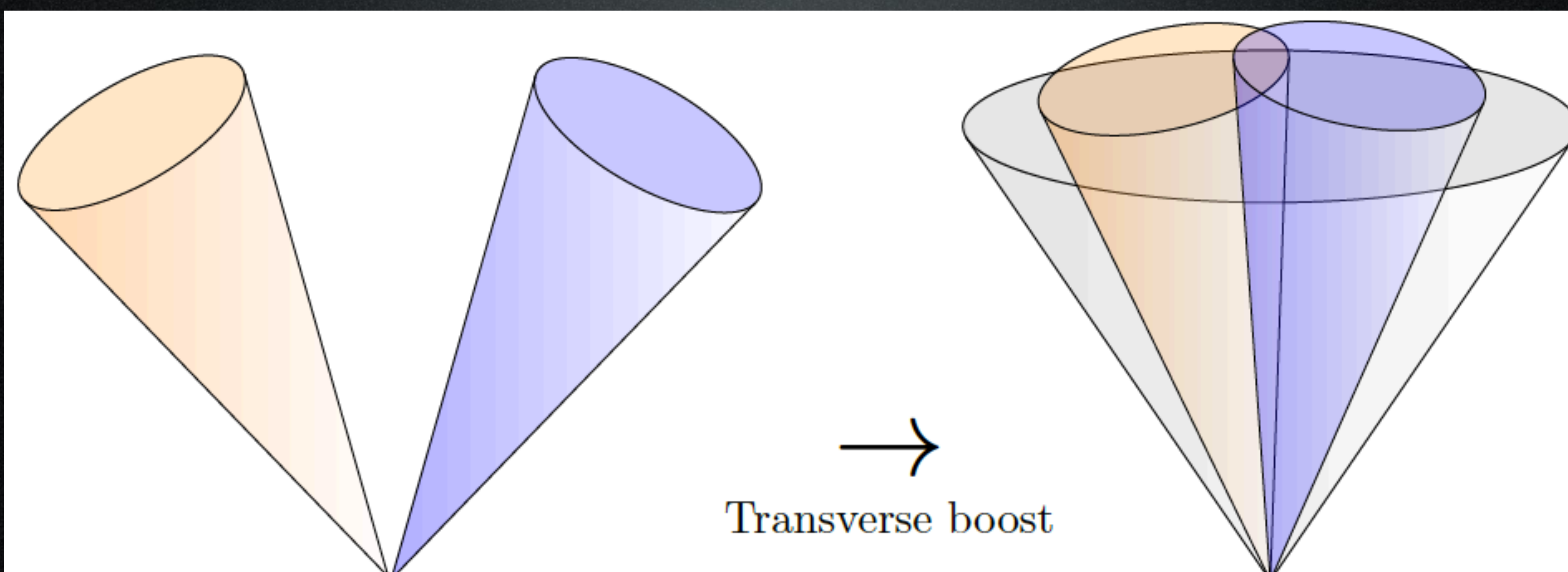
A combinatorial nightmare!



tth(bb)

Way out?

Use large-radius jets to encompass all decay products from a heavy hadronically decaying particle



Jets need to be groomed!

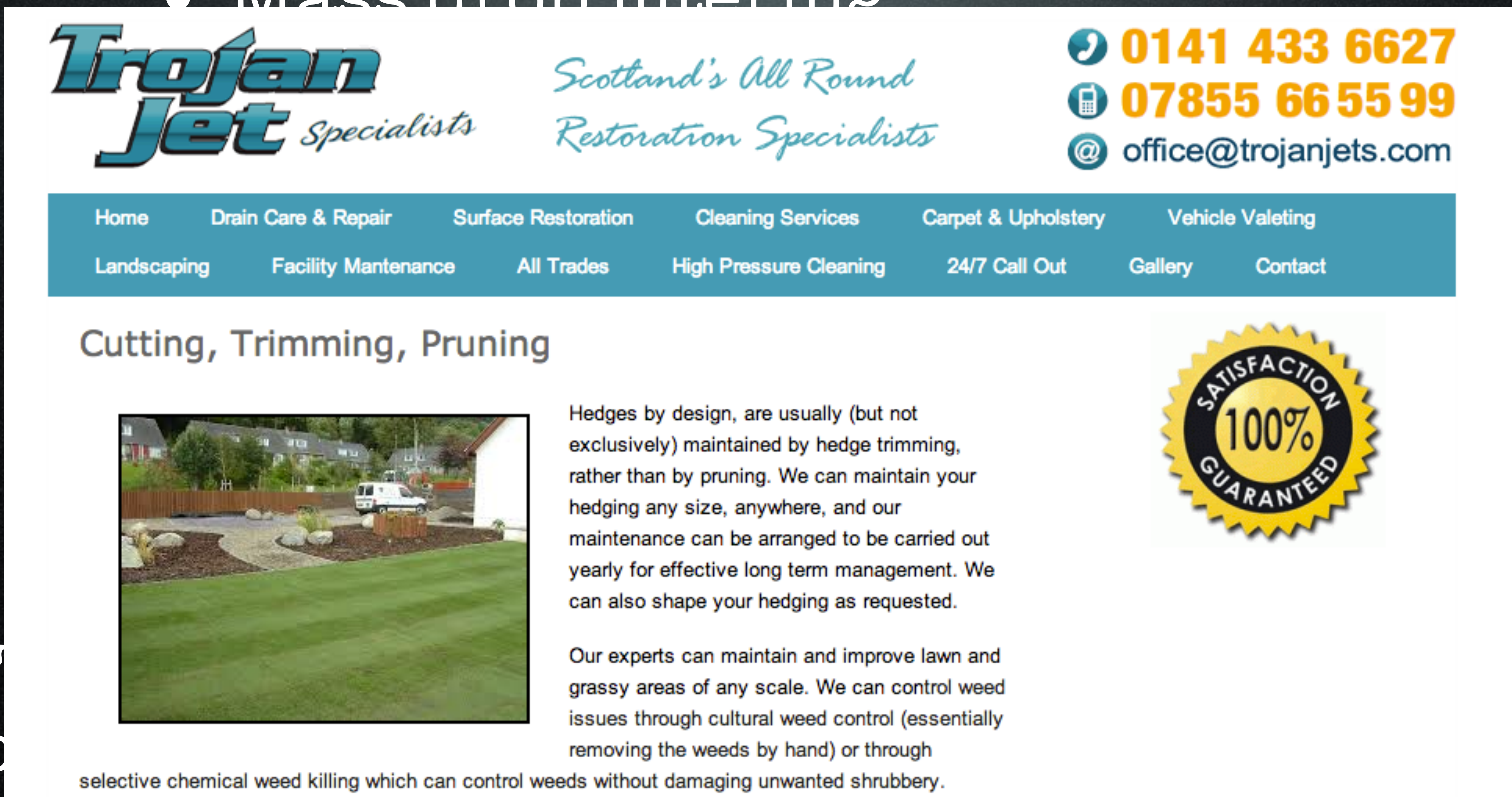
- Mass drop filtering
- Pruning
- Trimming
- Soft Drop

Why?

The large-radius jets not only include particles coming from the interesting decays, but also from pileup, underlying event ....

Jets need to be groomed!

- Mass drop filtering



co ... m

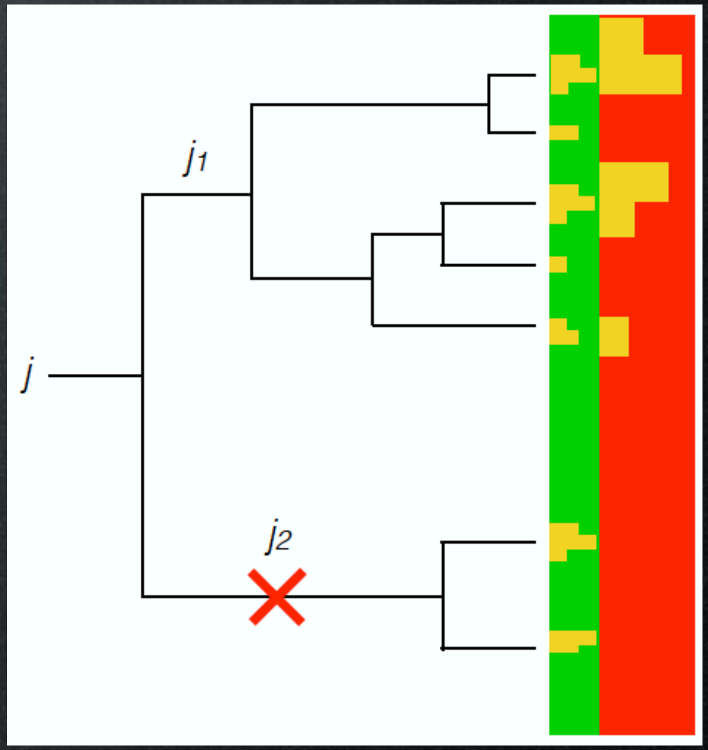
pileup, underlying event ....

Soft Drop

Start with a jet $\boxed{j}$ and it is split into last two subjets

If:

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



Then $\boxed{j}$ is the final soft drop jet.

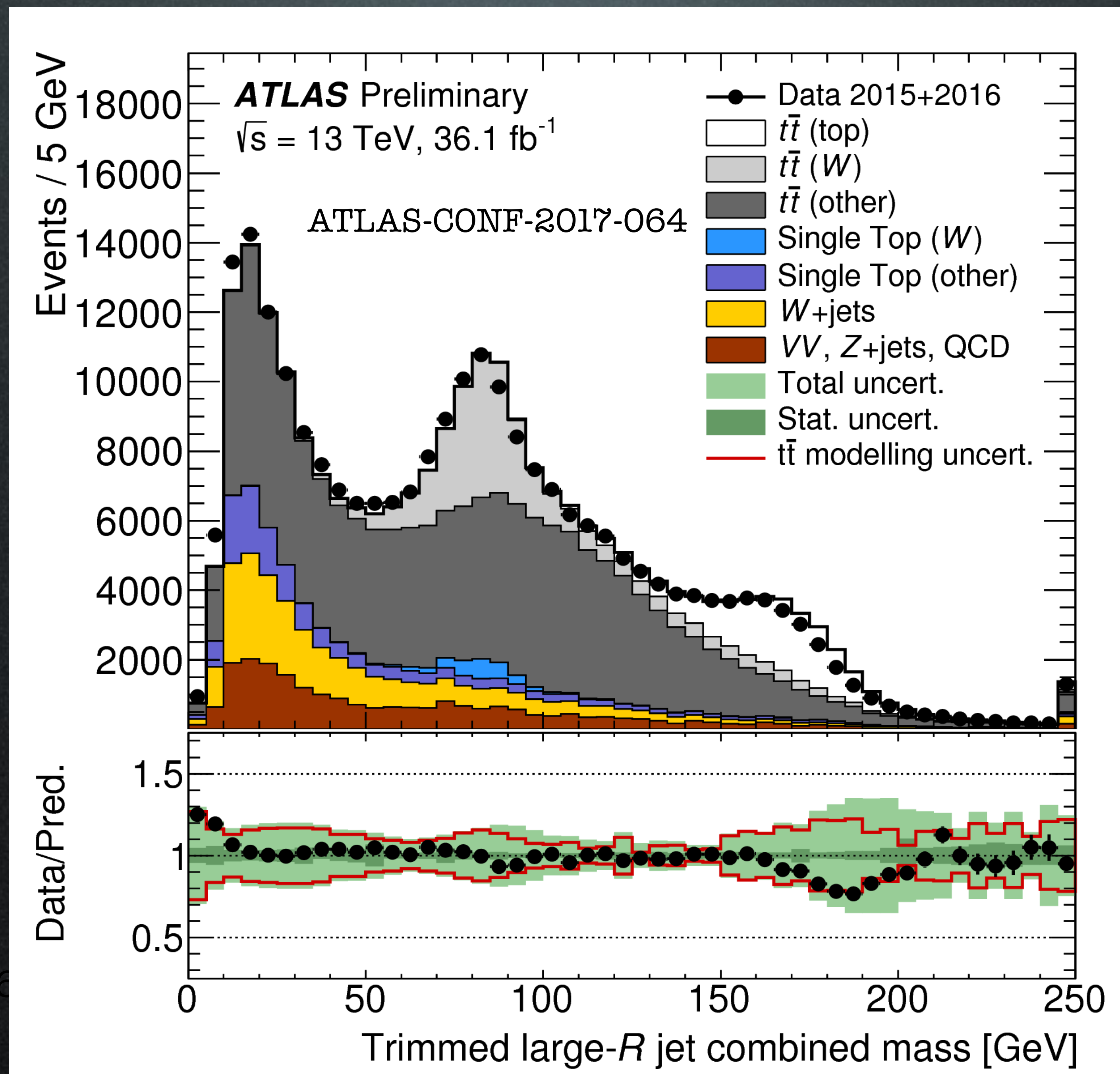
Otherwise the higher p_T subjet is taken as $\boxed{j}$ and iterated ...

Advantage: can be compared directly to analytic calculations

Effect of Gardening?

Effect of Gardening?

W and Top Mass

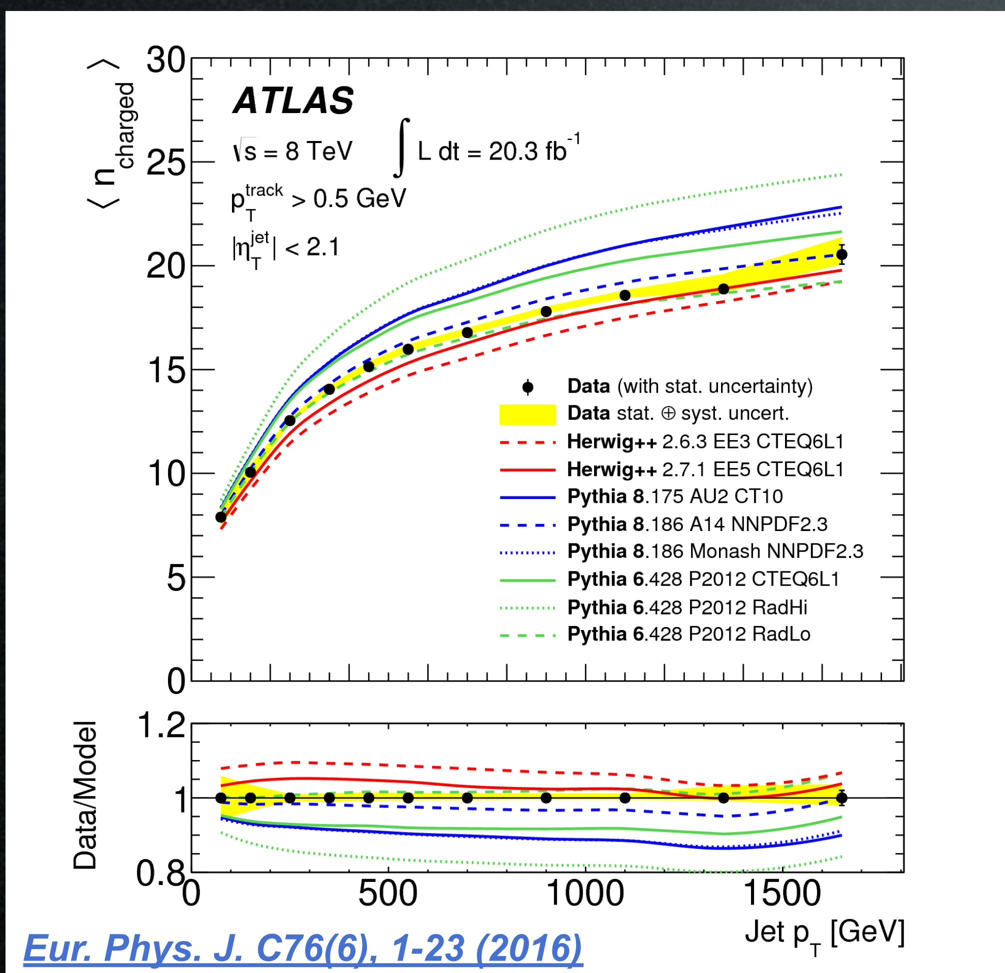


Eur. Phys. J. C 76(3) (2016

Mass peaks clearly visible over background!

A detour: measurements

Why Measurement?



Eur. Phys. J. C76(6), 1-23 (2016)

Jet (sub)structure is mostly dependent on Parton Shower models

Non negligible differences from data are observed in MC predictions

(Unfortunately) Grooming to get rid of uncorrelated radiation also throws away the soft part we wish to tune to!

"Your garbage is my treasure"

Attributed to Stefan Prestel

Why Measurement?

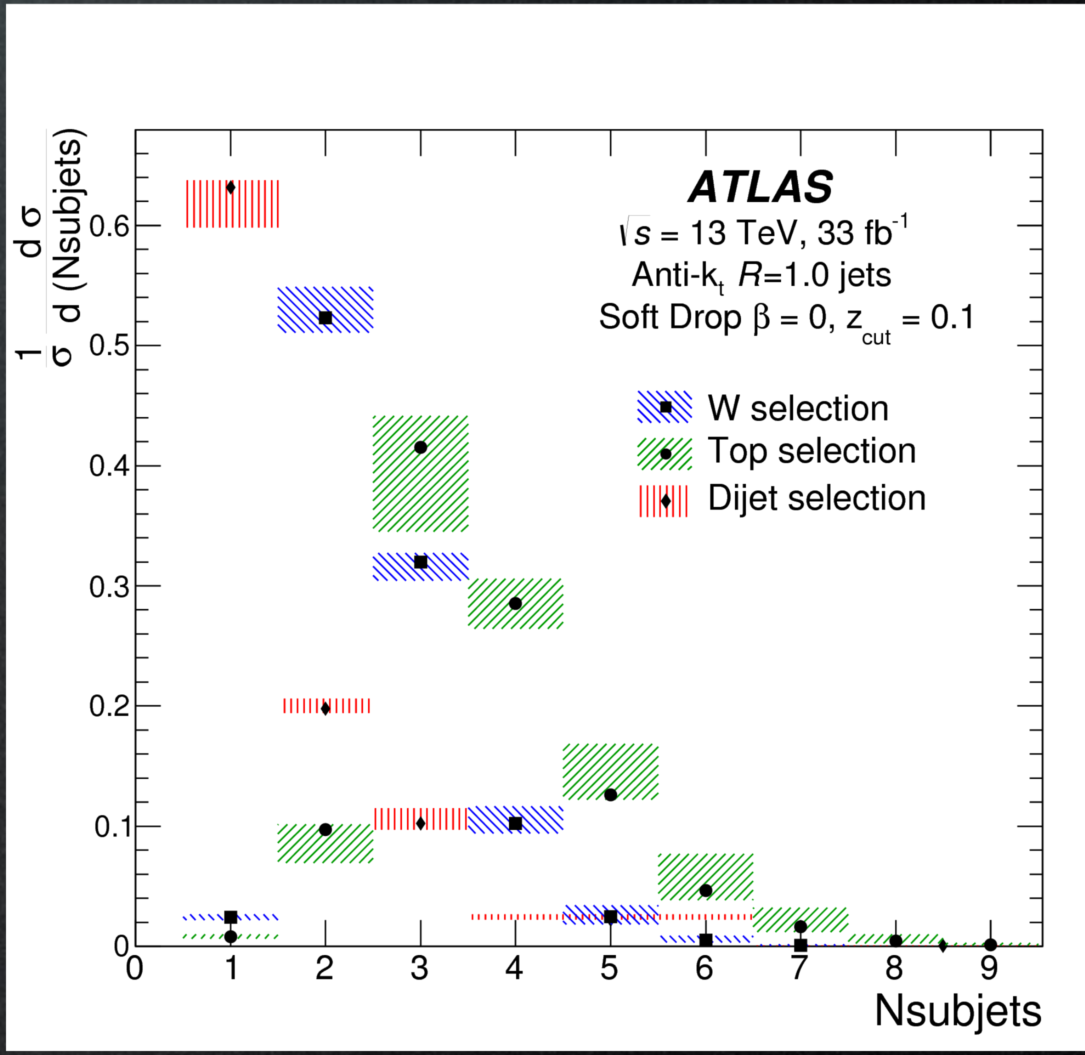
Sensitive to both perturbative and non-perturbative QCD (“precision substructure”)

Input to tune/improvement models and analytic calculations

Helps in tagging algorithm development.

Most comprehensive jet substructure measurement at the LHC

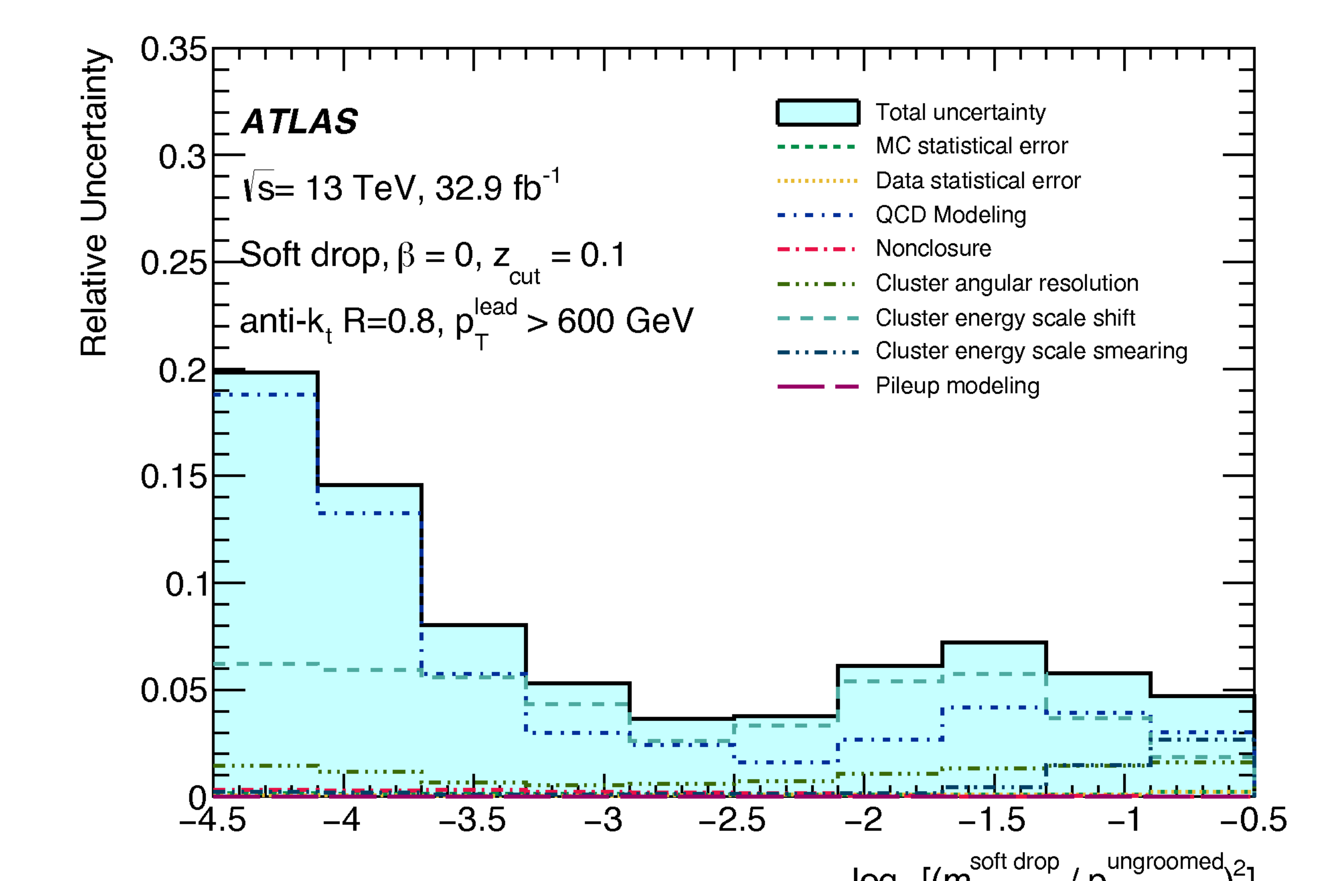
Trimmed Softdrop ($\beta = 0$)	$\times$	W top dijet	$\times$	ECF(2, 3) $D_2^{(\beta=1)}$ $C_2^{(\beta=1)}$ $\tau_{1,2,3}^{WTA}$ + ratios LH angularity N subjets



Comparison between topologies + Test of MC modelling

	Detector level	Particle level
Dijet selection:		
Two trimmed anti-k_t $R = 1.0$ jets	$p_{\mathrm{T}} > 200$ GeV $\lvert\eta\rvert < 2.5$	$p_{\mathrm{T}} > 200$ GeV $\lvert\eta\rvert < 2.5$
Leading-p_{T}trimmed anti-k_t $R = 1.0$ jet	$p_{\mathrm{T}} > 450$ GeV	
Top and W selections:		
Exactly one muon	$p_{\mathrm{T}} > 30$ GeV $\lvert\eta\rvert < 2.5$ $\lvert z_0 \sin(\theta)\rvert < 0.5$ mm and $\lvert d_0/\sigma(d_0)\rvert < 3$	$p_{\mathrm{T}} > 30$ GeV $\lvert\eta\rvert < 2.5$
Anti-k_t $R = 0.4$ jets	$p_{\mathrm{T}} > 25$ GeV $\lvert\eta\rvert < 4.4$ JVT output > 0.5 (if $p_{\mathrm{T}} < 60$ GeV)	$p_{\mathrm{T}} > 25$ GeV $\lvert\eta\rvert < 4.4$
Muon isolation criteria	If $\Delta R(\mu, \mathrm{jet}) < 0.04 + 10$ GeV $/p_{\mathrm{T},\mu}$: muon is removed, so the event is discarded	None
$E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\mathrm{T}}^{\mathrm{W}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV , $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{\mathrm{W}} > 60$ GeV	
Leptonic top	At least one small-radius jet with $0.4 < \Delta R(\mu, \mathrm{jet}) < 1.5$	
Top selection:		
Leading-p_{T}trimmed anti-k_t $R = 1.0$ jet	$\lvert\eta\rvert < 1.5$, $p_{\mathrm{T}} > 350$ GeV , mass > 140 GeV $\Delta R(\mathrm{large{-}radius\ jet}, b\text{-tagged jet}) < 1$ $\Delta\phi(\mu, \mathrm{large{-}radius\ jet}) > 2.3$	
W selection:		
Leading-p_{T}trimmed anti-k_t $R = 1.0$ jet	$\lvert\eta\rvert < 1.5$, $p_{\mathrm{T}} > 200$ GeV , mass > 60 GeV and mass < 100 GeV $1 < \Delta R(\mathrm{large{-}radius\ jet}, b\text{-tagged jet}) < 1.8$ $\Delta\phi(\mu, \mathrm{large{-}radius\ jet}) > 2.3$	

Uncertainty for JSS measurements



arXiv:1711.08341

Leading experimental uncertainty from calorimeter cell-cluster energy, resolution, efficiency etc.

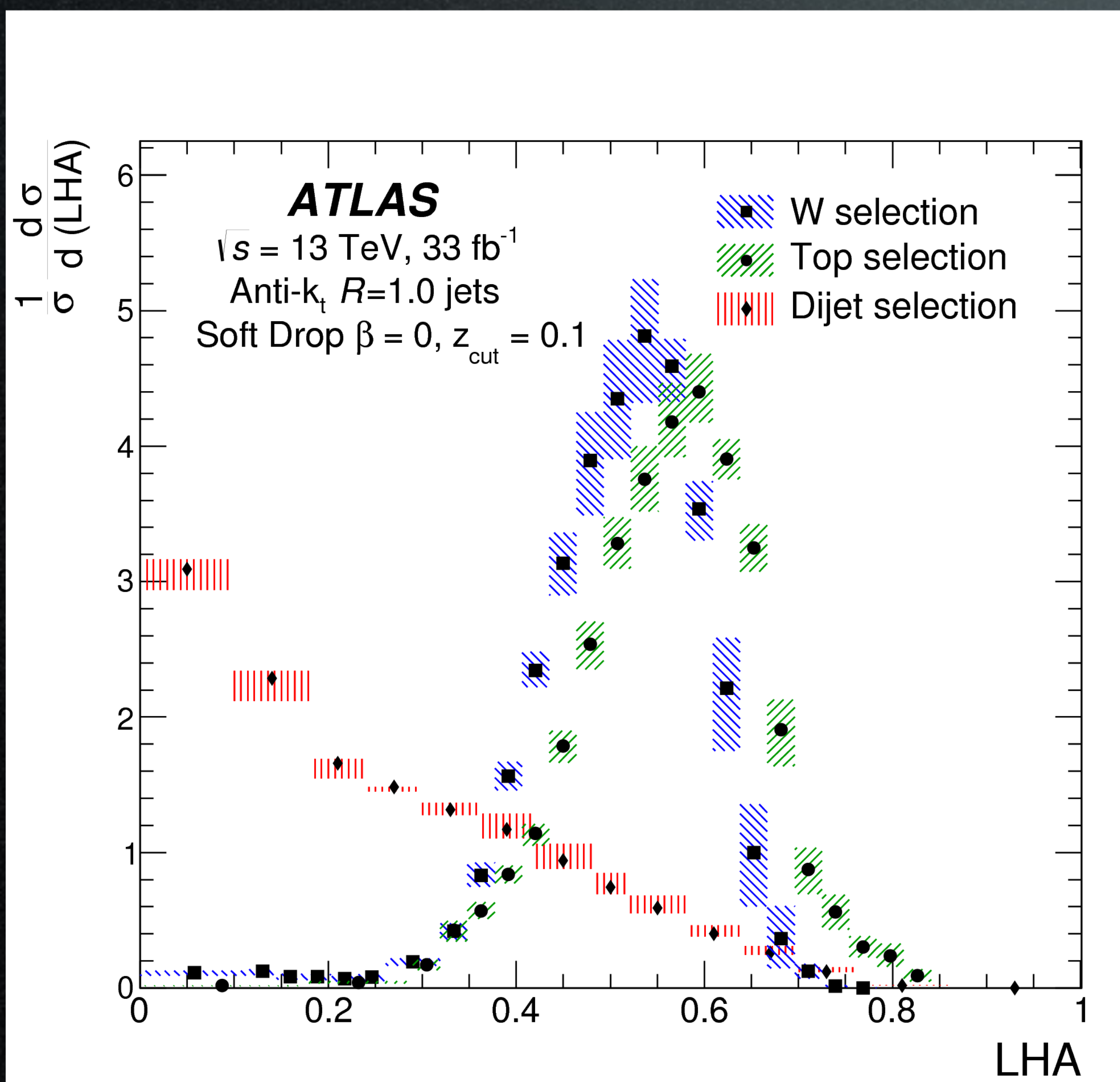
Cluster energy scale and resolution uncertainties estimated by track to cluster E/p ratio, angular resolution uncertainty by relative position shift

Reconstruction efficiency from unmatched tracks to clusters

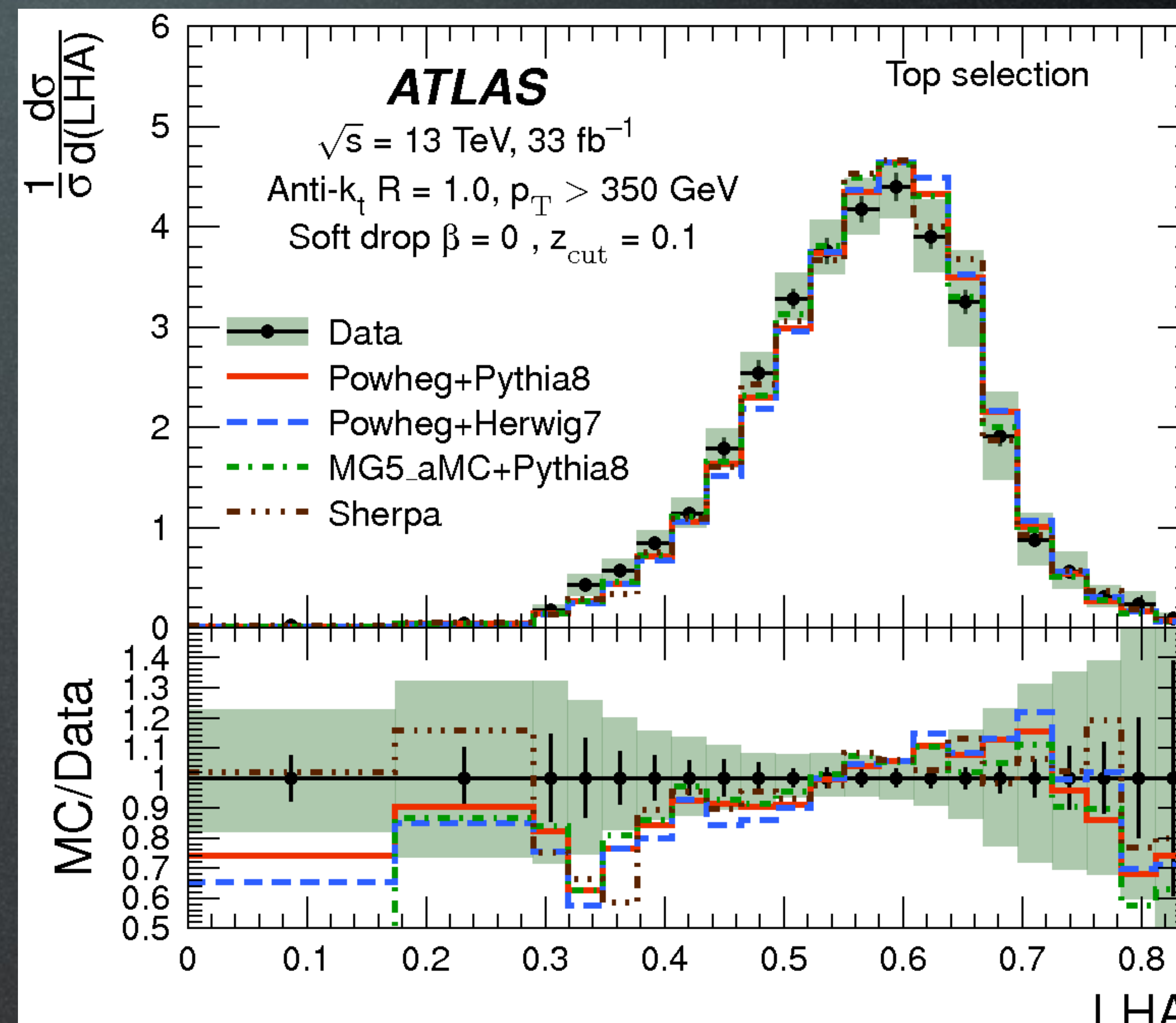
Les Houches Angularity

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta,$$

κ=1, β=1/2



Softer/central additional radiation in dijet



Shifted peak in MCs

N-Subjettiness

Quantify the degree to which jet radiation is aligned along specific subjet axes.

$$\tau_N \equiv \frac{1}{d_0} \sum_{k=1}^{M} \Big(p_{\mathrm{T},k} \times \underbrace{\Delta R_{\mathrm{min},k}}_{\text{distance to nearest subjet}} \Big)$$

$d_0 = R \times$ sum of p_T of all constituents

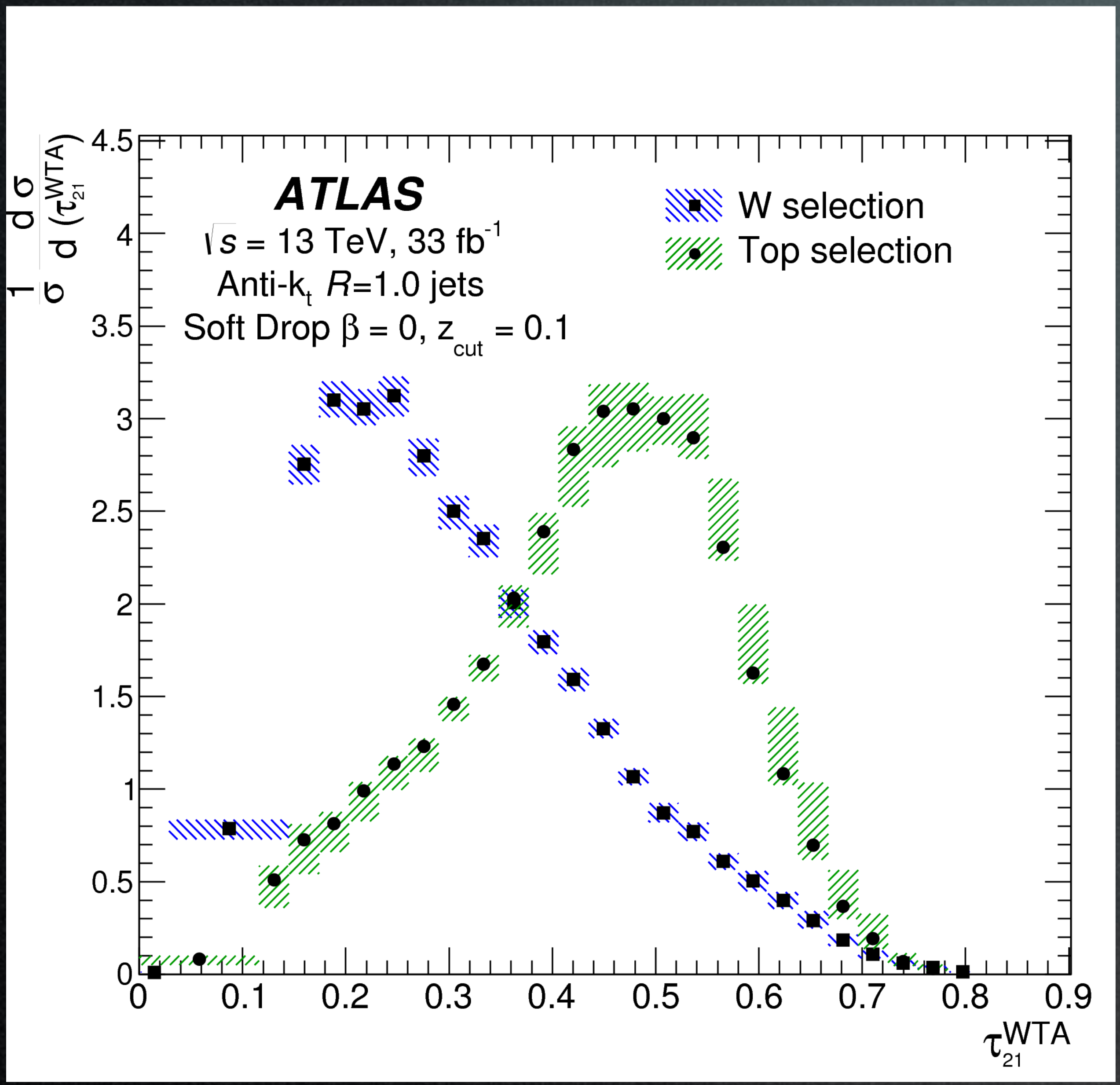
Smaller values: N or less energy deposits

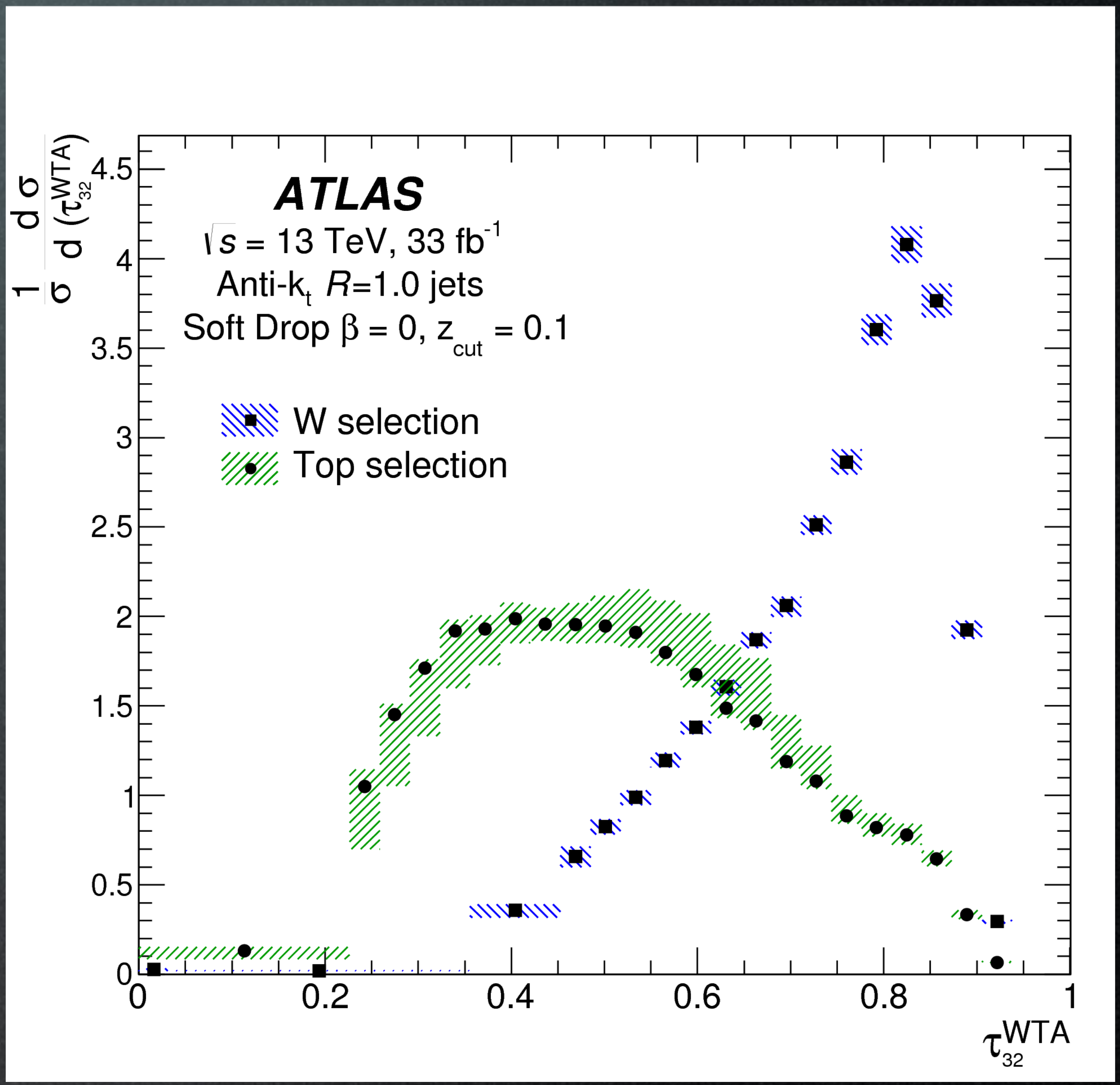
Larger values: more than N energy deposits

$\tau_{N-1} > \tau_N$ for N prong substructure

Calculated by k_t clustering the constituents, and requiring exactly N subjets

NSubjettiness ratios





Visible difference in two and three-prong substructures

ECF

Over all constituents (beta: angular exponent):

$$\mathrm{ECF}(1,\beta) = \sum_i p_{Ti}$$

$$\mathrm{ECF}(2,\beta) = \sum_{i<j} p_{Ti}\, p_{Tj}\, (R_{ij})^\beta \leftarrow$$ [see Banfi, Salam, Zanderighi; Jankowiak, Larkoski]

$$\mathrm{ECF}(3,\beta) = \sum_{i<j<k} p_{Ti}\, p_{Tj}\, p_{Tk}\, (R_{ij}R_{jk}R_{ki})^\beta$$

$$\mathrm{ECF}(N,\beta) = \sum_{\text{sets of } N} (N \text{ energies}) \times \left(\binom{N}{2} \text{ angles}\right)^\beta$$

ECF(N+1) << ECF(N) for N subjets

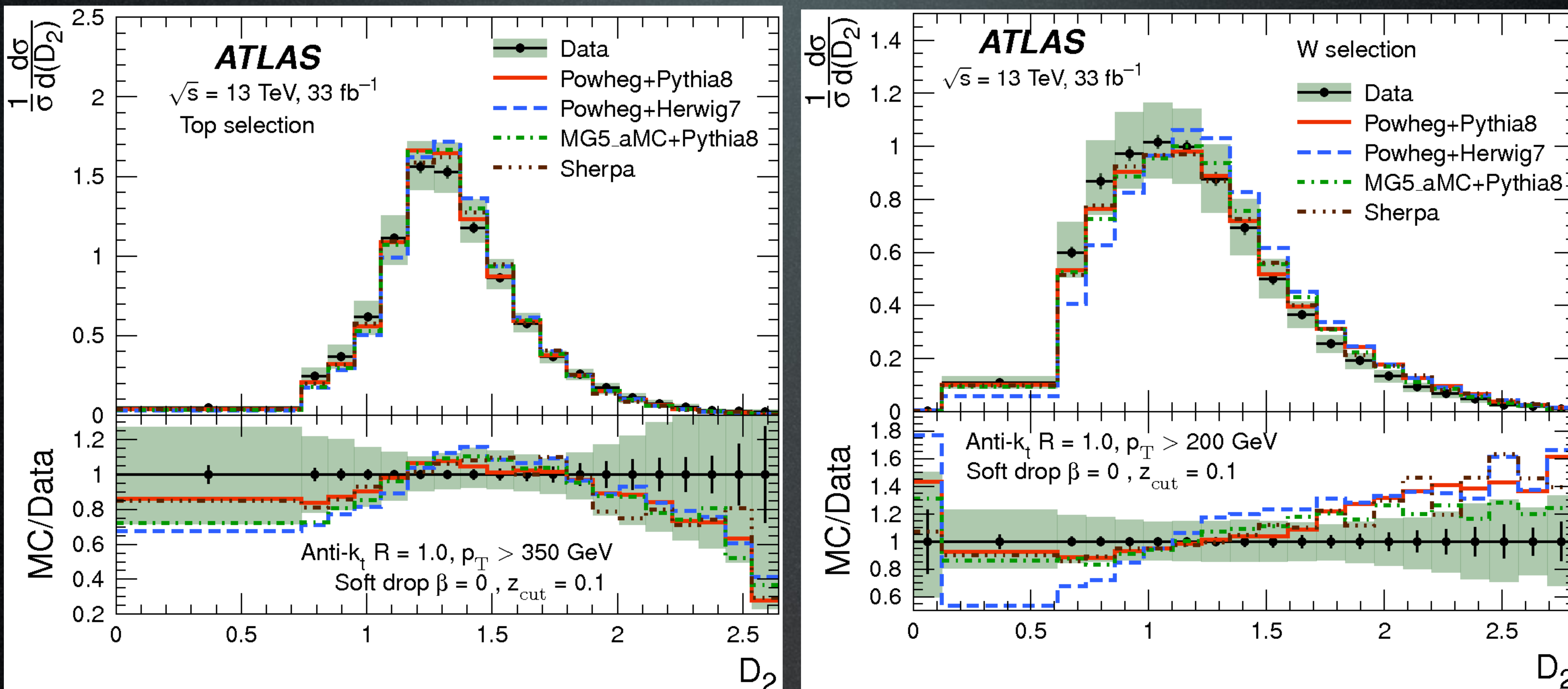
Define (double) ratio = [ECF(N+1)/ECF(N)]/[ECF(N)/ECF(N-1)]

$$C_N^{(\beta)} = \frac{\mathrm{ECF}(N+1,\beta)\,\mathrm{ECF}(N-1,\beta)}{\mathrm{ECF}(N,\beta)^2}$$

Analogous to Nsubjettiness ratio

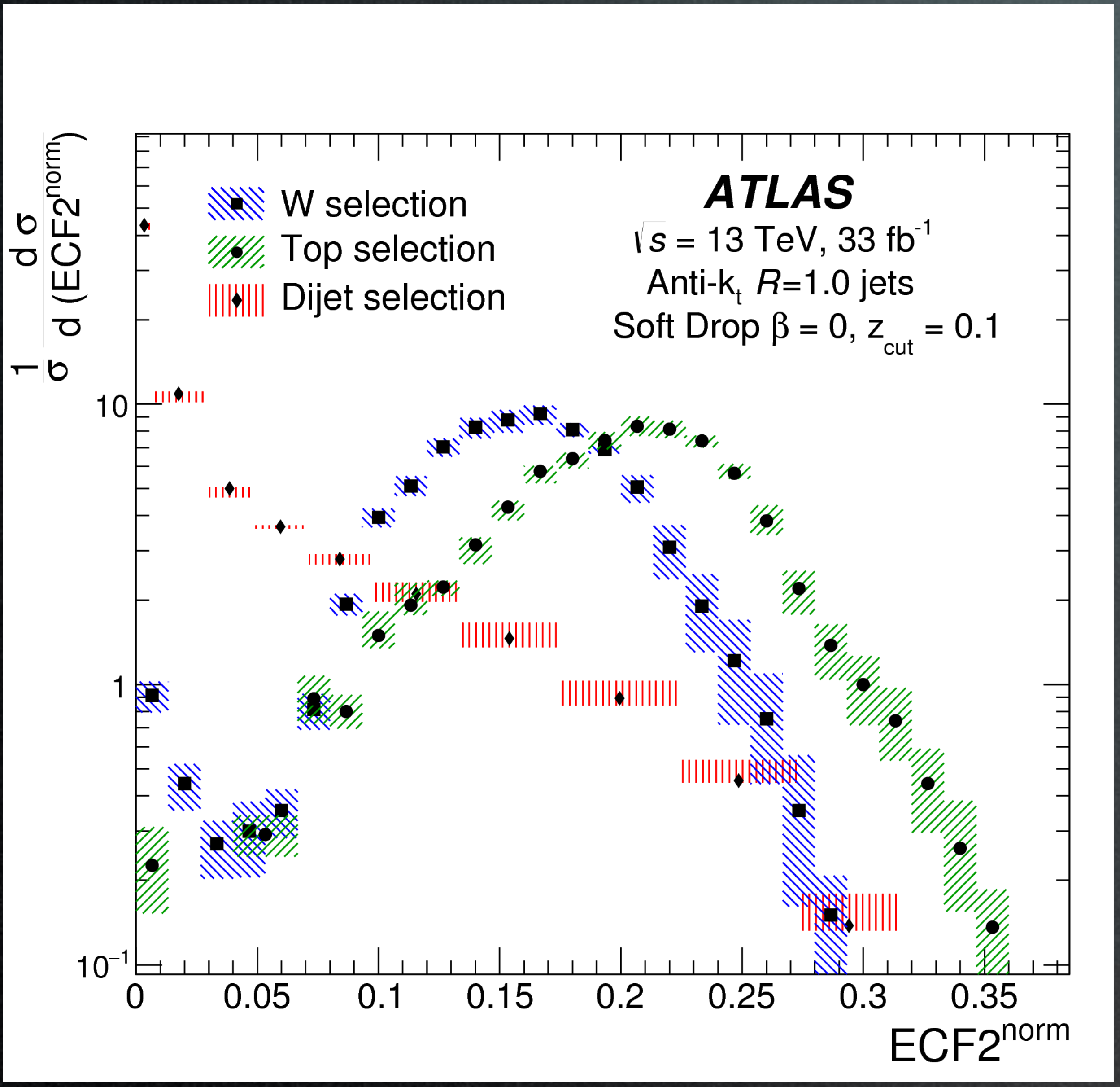
Large C_N: more than N subjets, extra radiation is not correlated with leading order N subjets.
For small C_N: the additional radiation is soft/collinear

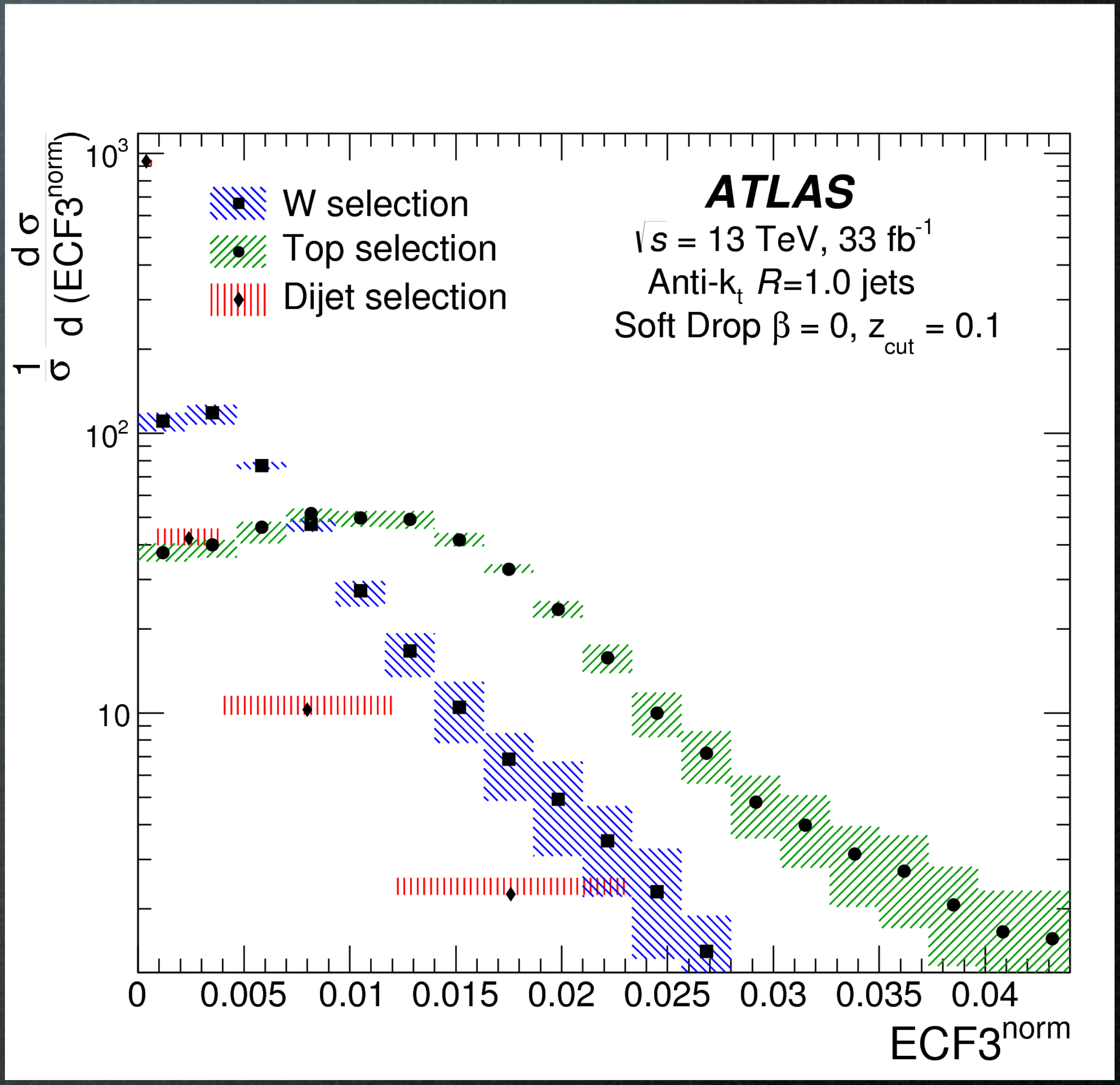
D2



Again shifted peak in W, models overestimating gluon radiation

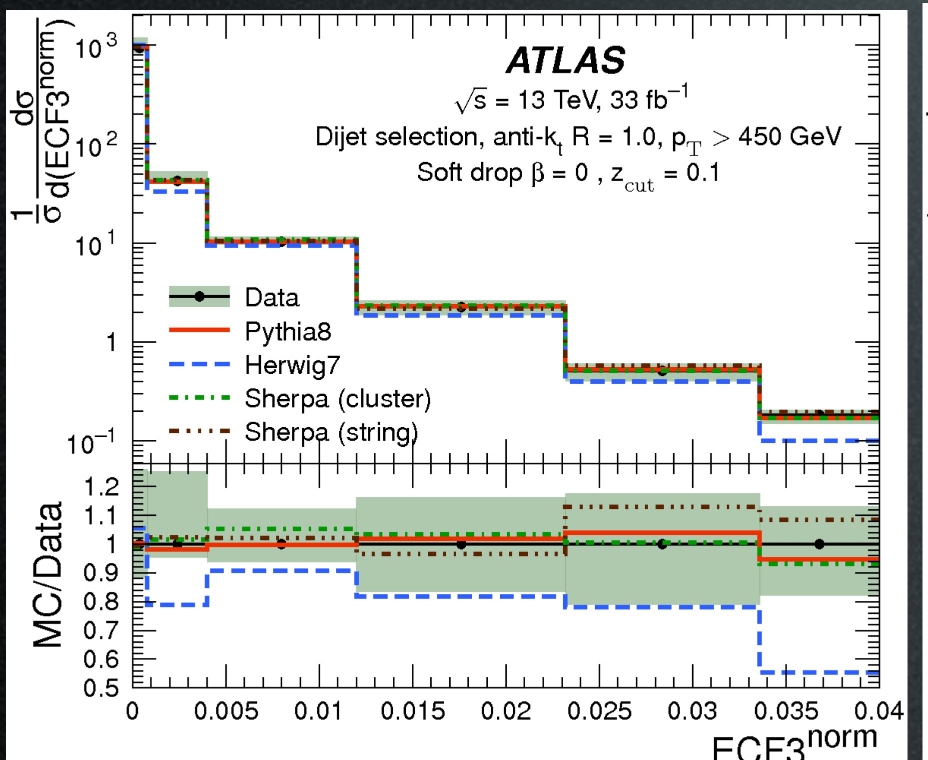
ECF

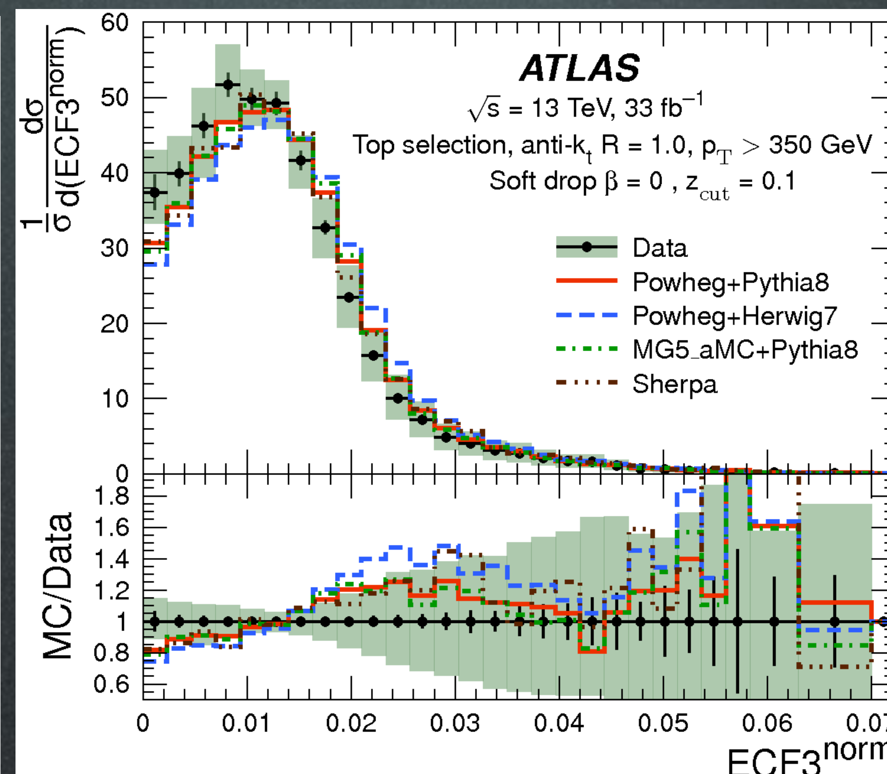


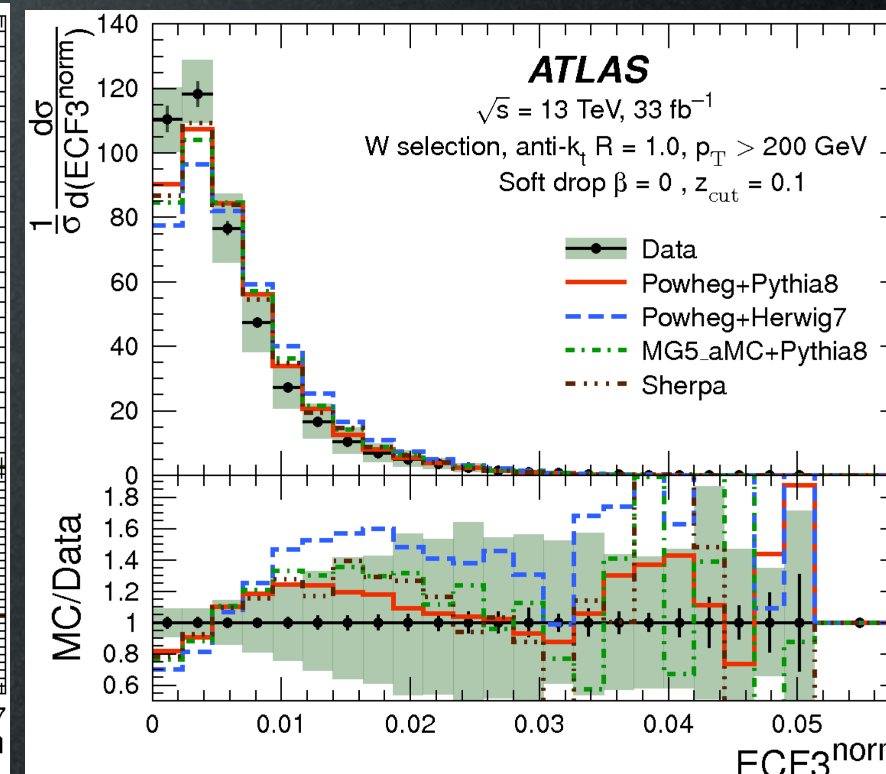


Visible difference in one, two and three-prong substructures

ECF3 Modelling



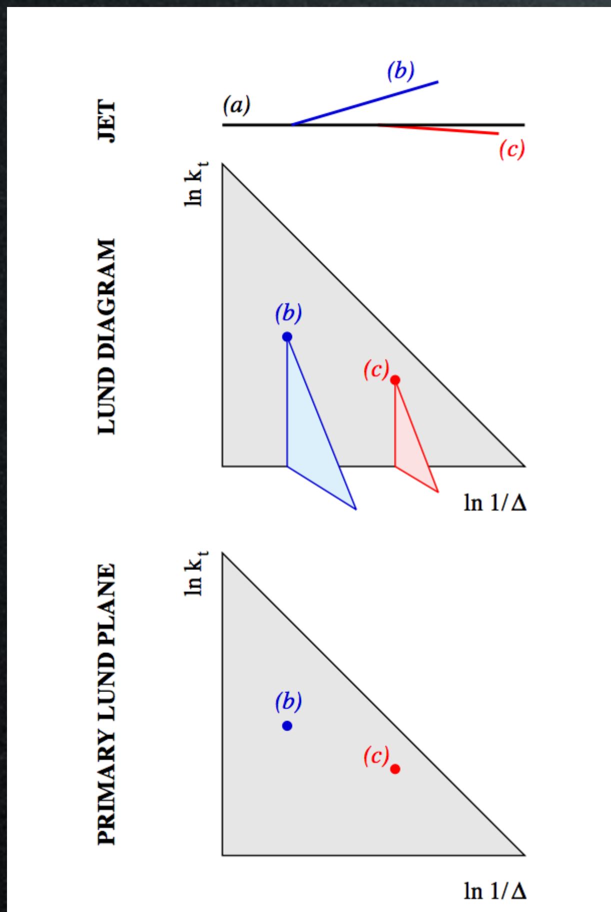




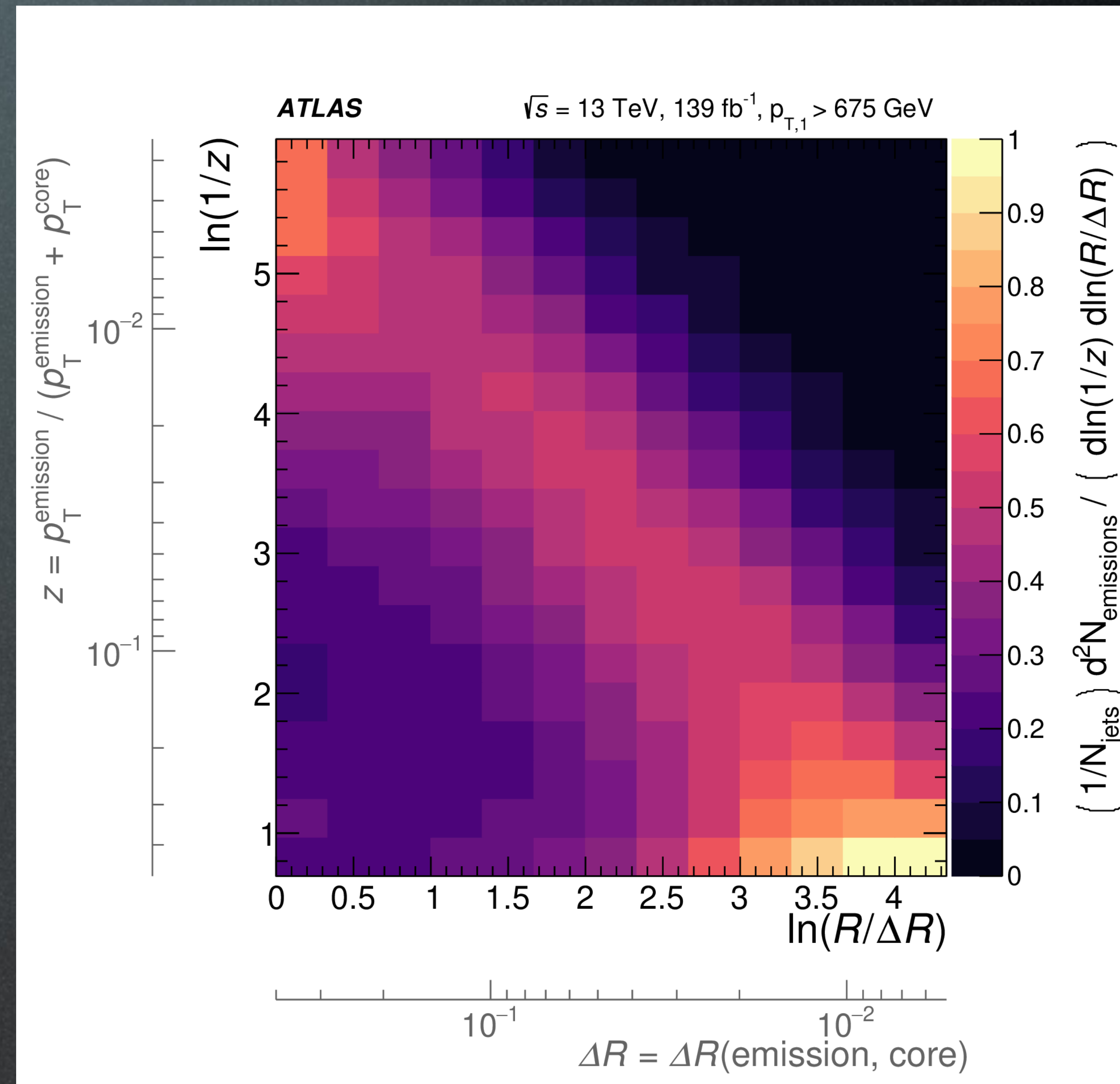
Models do better for dijets than top/W

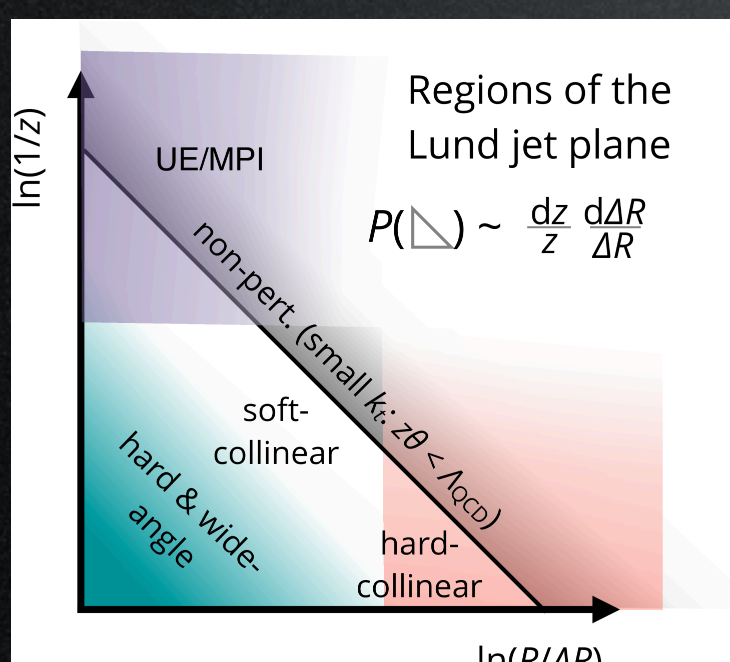
Phys. Rev. Lett. 124, 222002 (2020)

Lund Plane



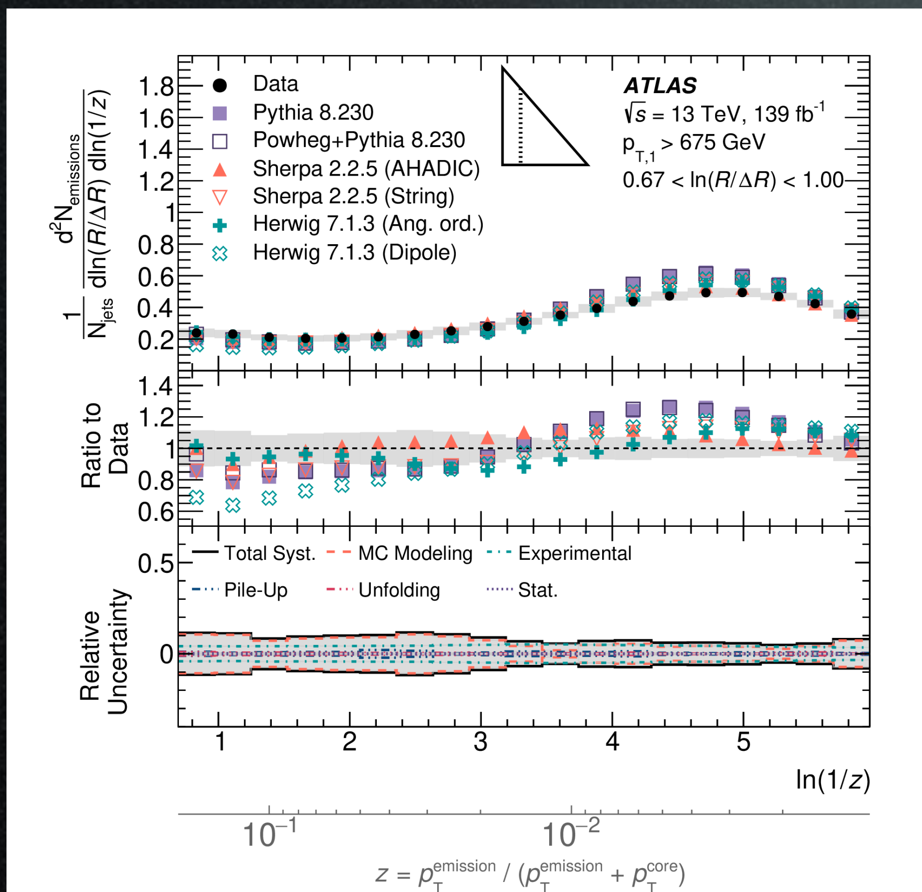
Probing emmission inside a jet



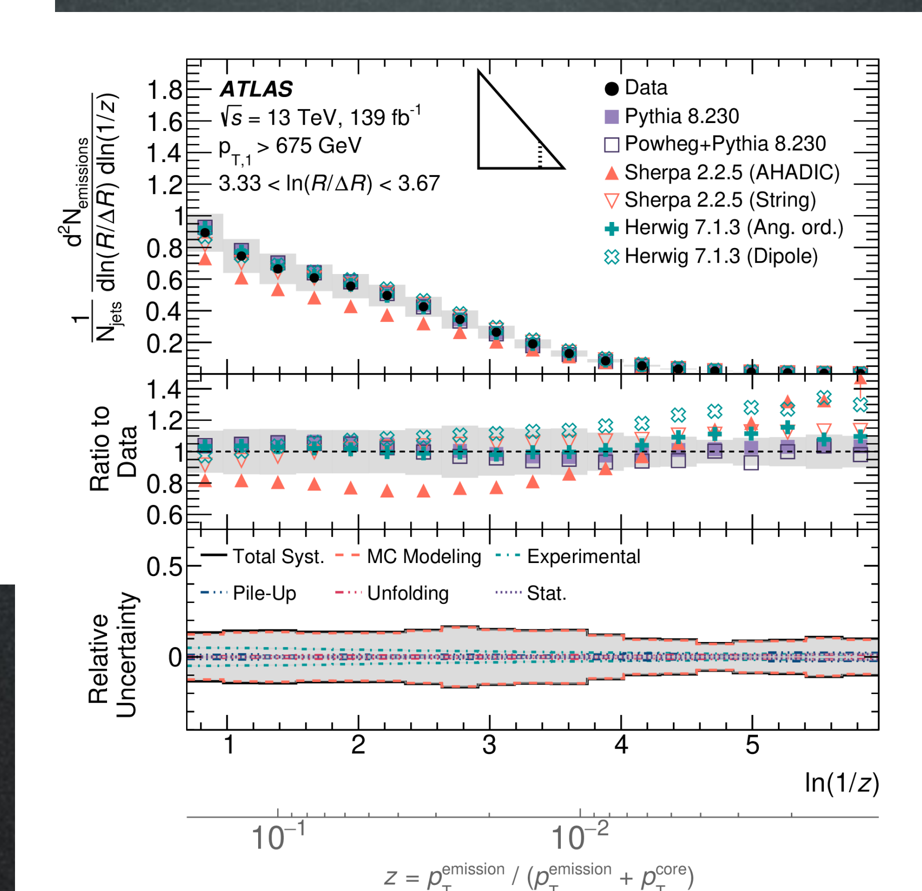


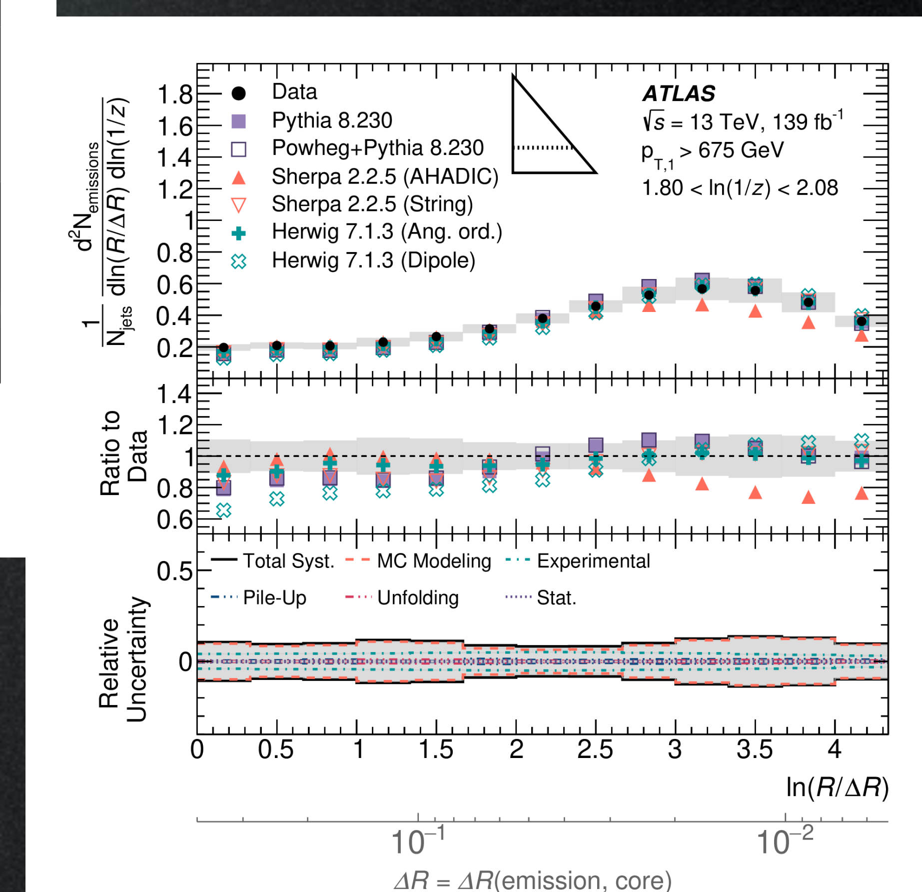
Measured for the first time: highlight of Boost2019

Data-MC comparions



Non-negligible difference!



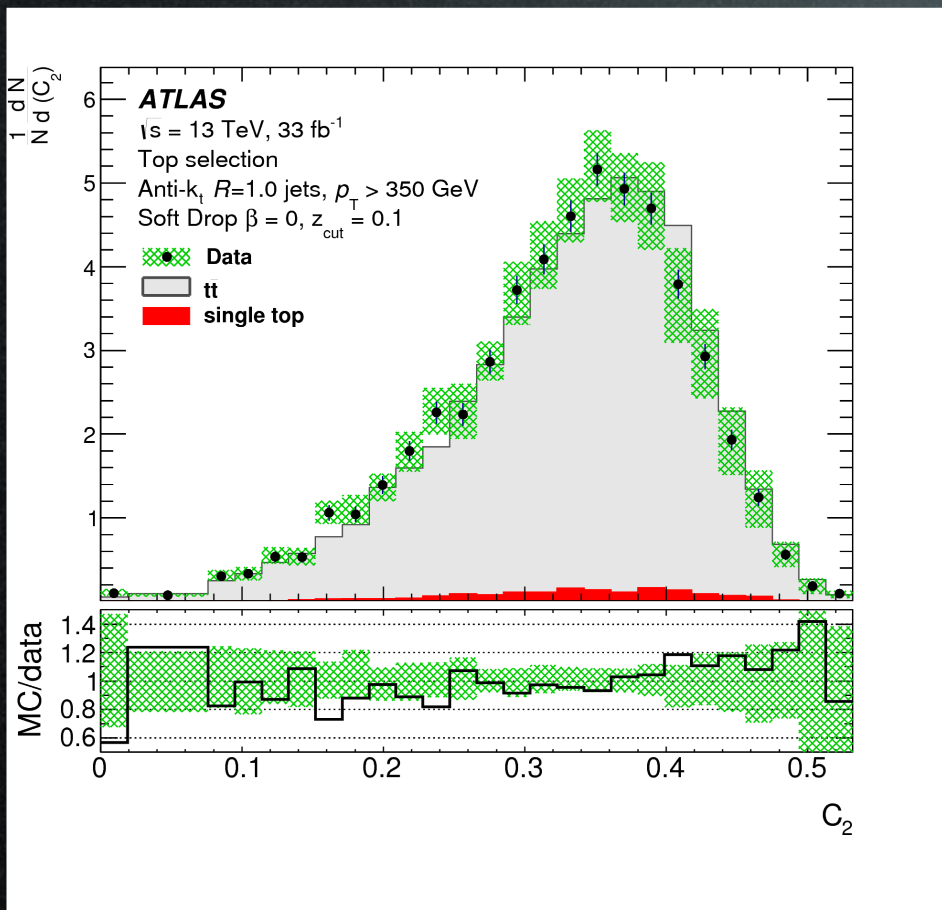


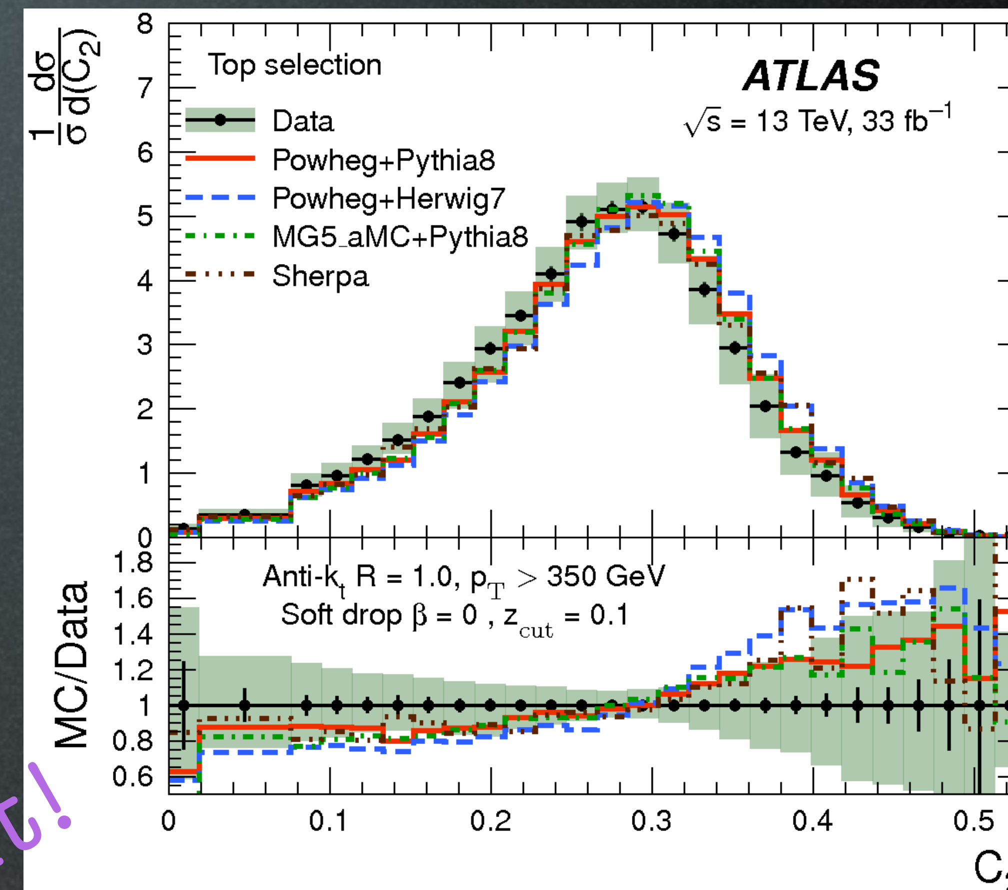
Can LJP help in improving generator/ finding new physics?

Smearing

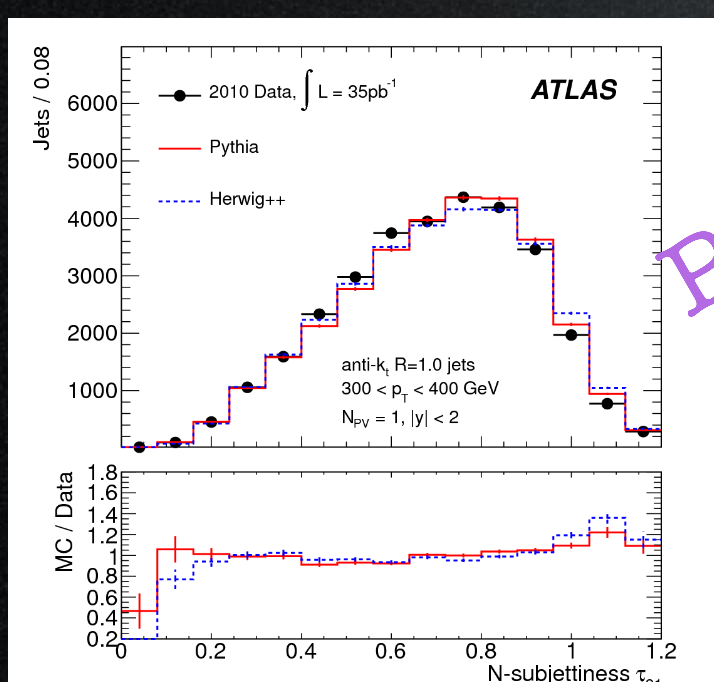
- Delphes only smears JES, so a larger-R jet p_T and and mass smearing(s) are realistic, but not any substructure variables, which show no difference.
- Whereas just as an example, if we construct JSS observables only with charged particles, and apply the typical charged particle p_T and angular smearing, we see significant effect, which is more inline with experimental results.

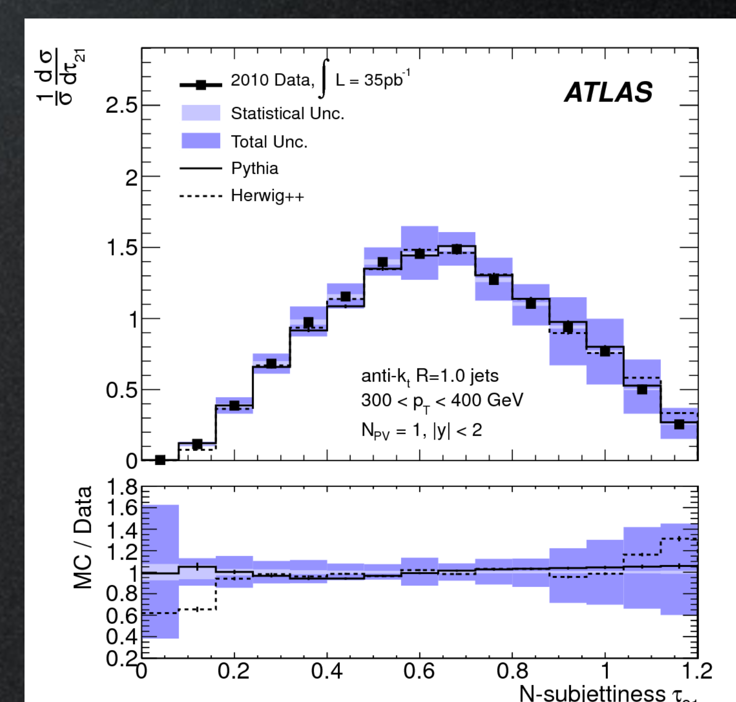
Smearing





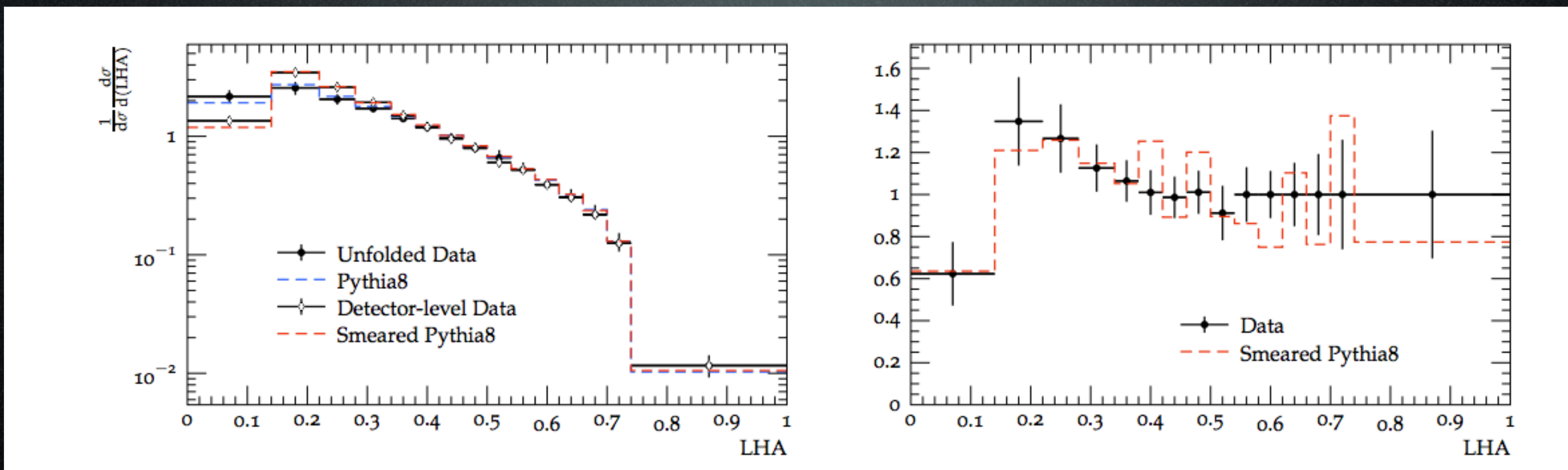
Pronounced shift!





arXiv:1910.01637 [hep-ph]

JSS Smearing in Rivet
(with Andy Buckley and Karl Nordstrom)



- Smeared p_T and η of the clusters, constructed by adding individual constituents.
- Tuned the smearing to the ATLAS reco/gen ratios as shown.

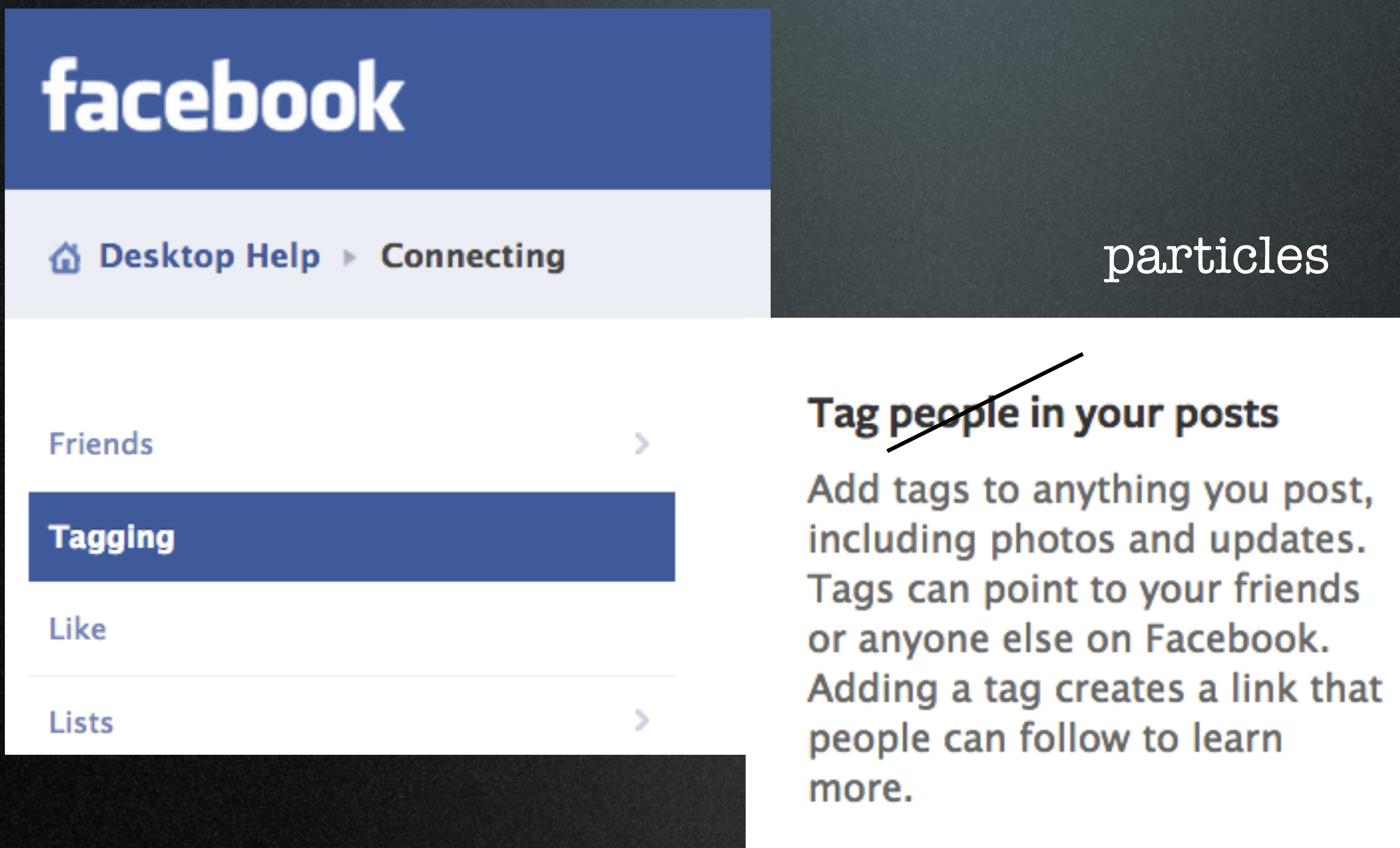
James Monk Why are you smearing Rivet? It's great, I won't have a word said against it! 🙂

5

Haha · Reply · 10w

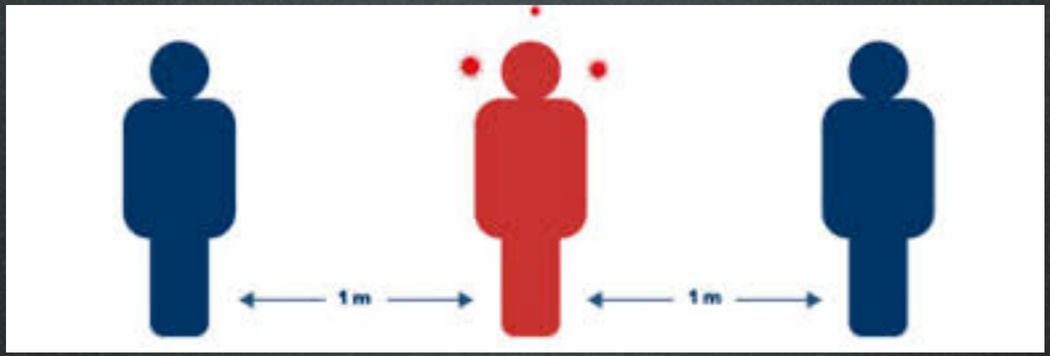
Tagging Boosted Objects: observables and taggers

particles



Target is to identify jets resulting from the decay of top quark or Higgs against jets coming from light quark/gluons.

Principle of (social) distancing in object reconstruction!

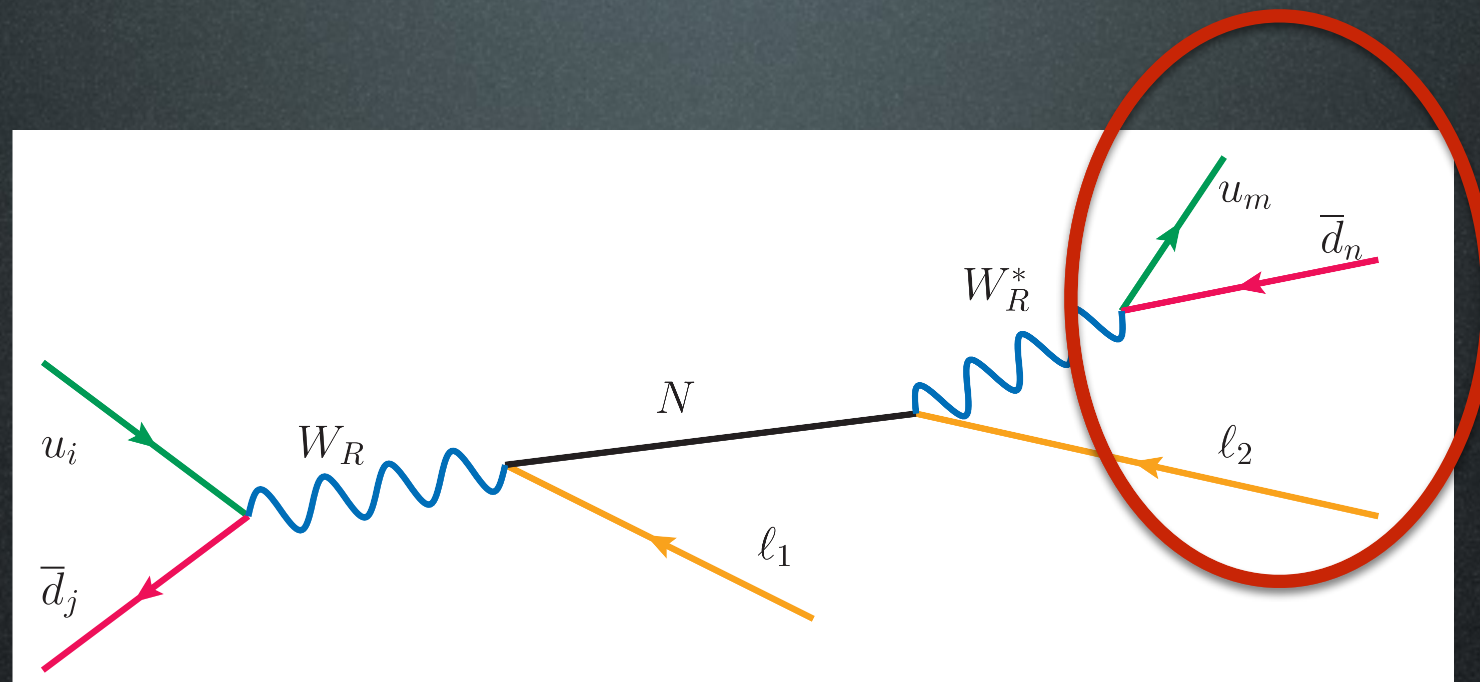


we followed it before it was cool …

Principle of (social) distancing in object reconstruction!

- Object reconstruction algorithms run independent of one another
- Same detector signature can result in multiple objects being reconstructed, results in fakes!
- Electrons as jets, and vice versa (jets contain neutral pions!)
- Overlap removal to address the double counting

But who ordered that?

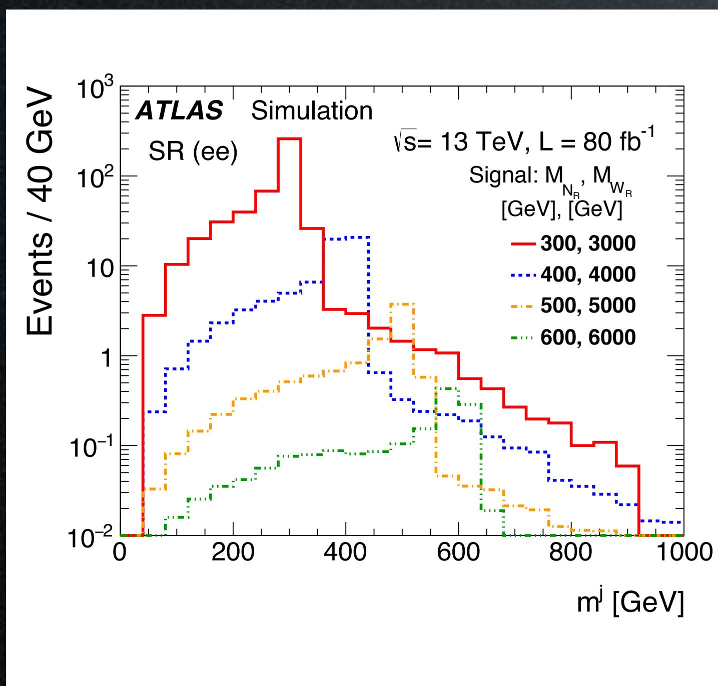


Boosted heavy neutrino search:
electron in a large-radius jet

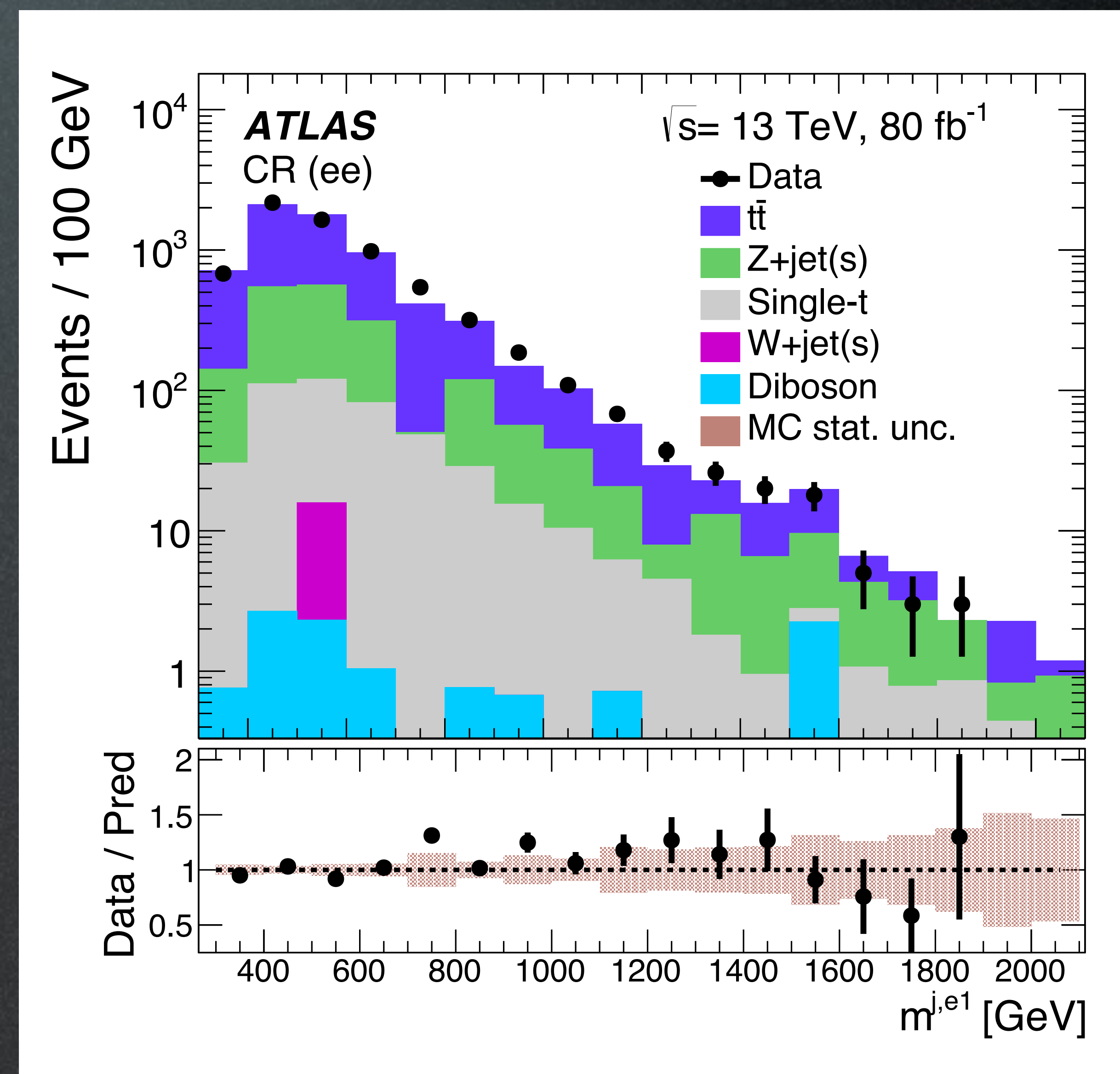
In ATLAS electron reconstruction assumed no nearby real jet, and applies implicit isolation requirement. That reduces signal efficiency, and the presence of such a jet affects the electron performance numbers

Boosted Heavy Neutrino Search

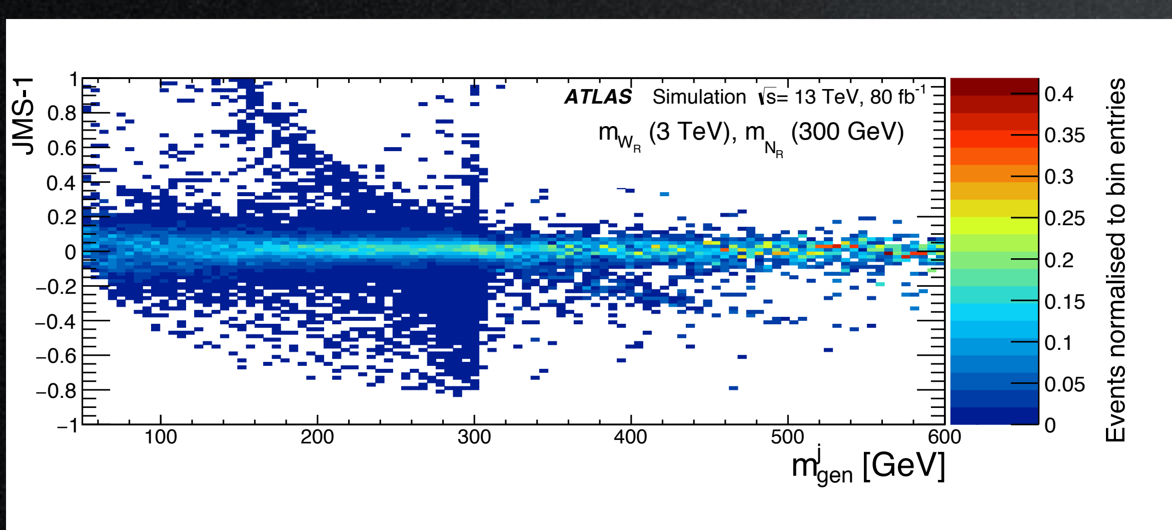
Debarati Roy: former postdoc



Good neutrino mass reconstruction



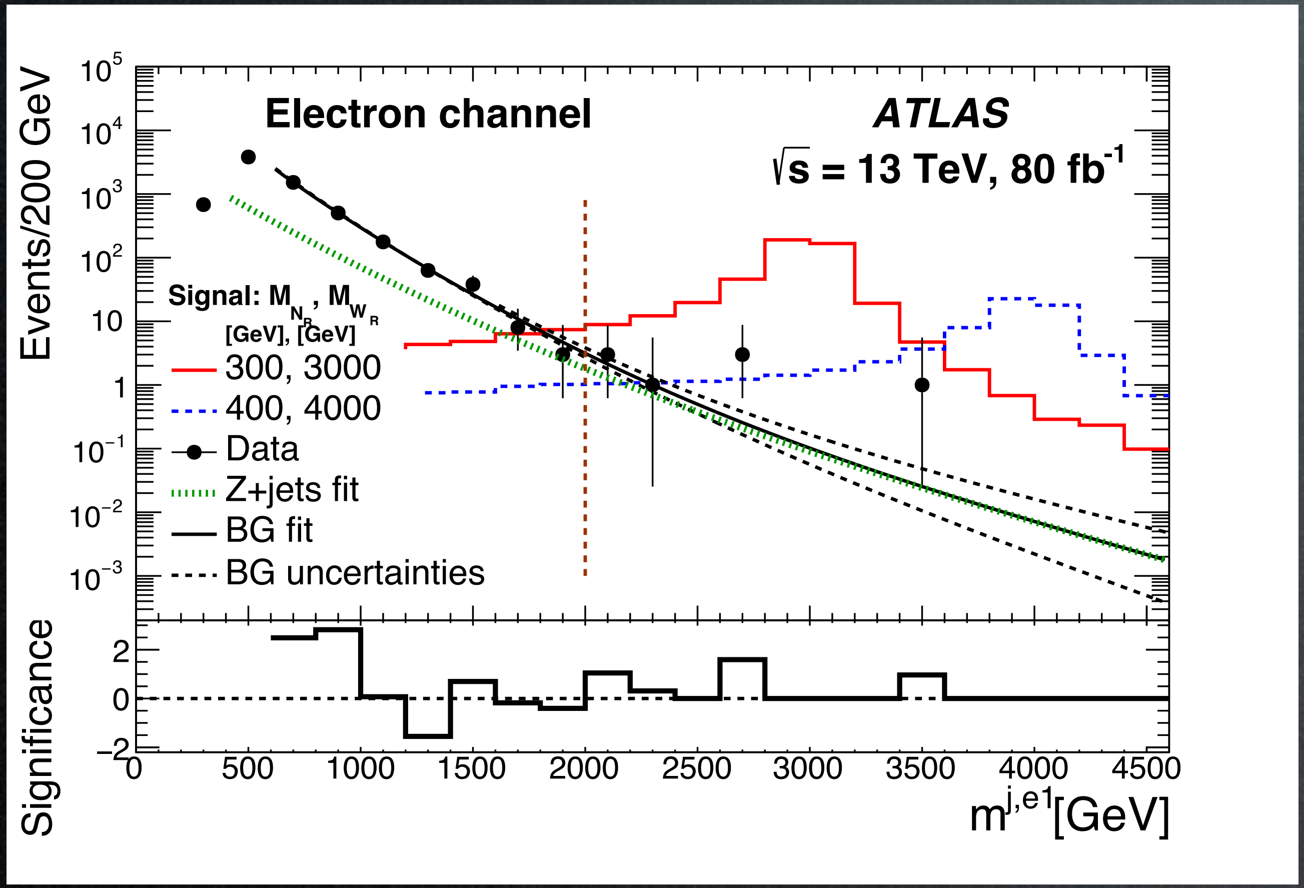
JMS well modelled



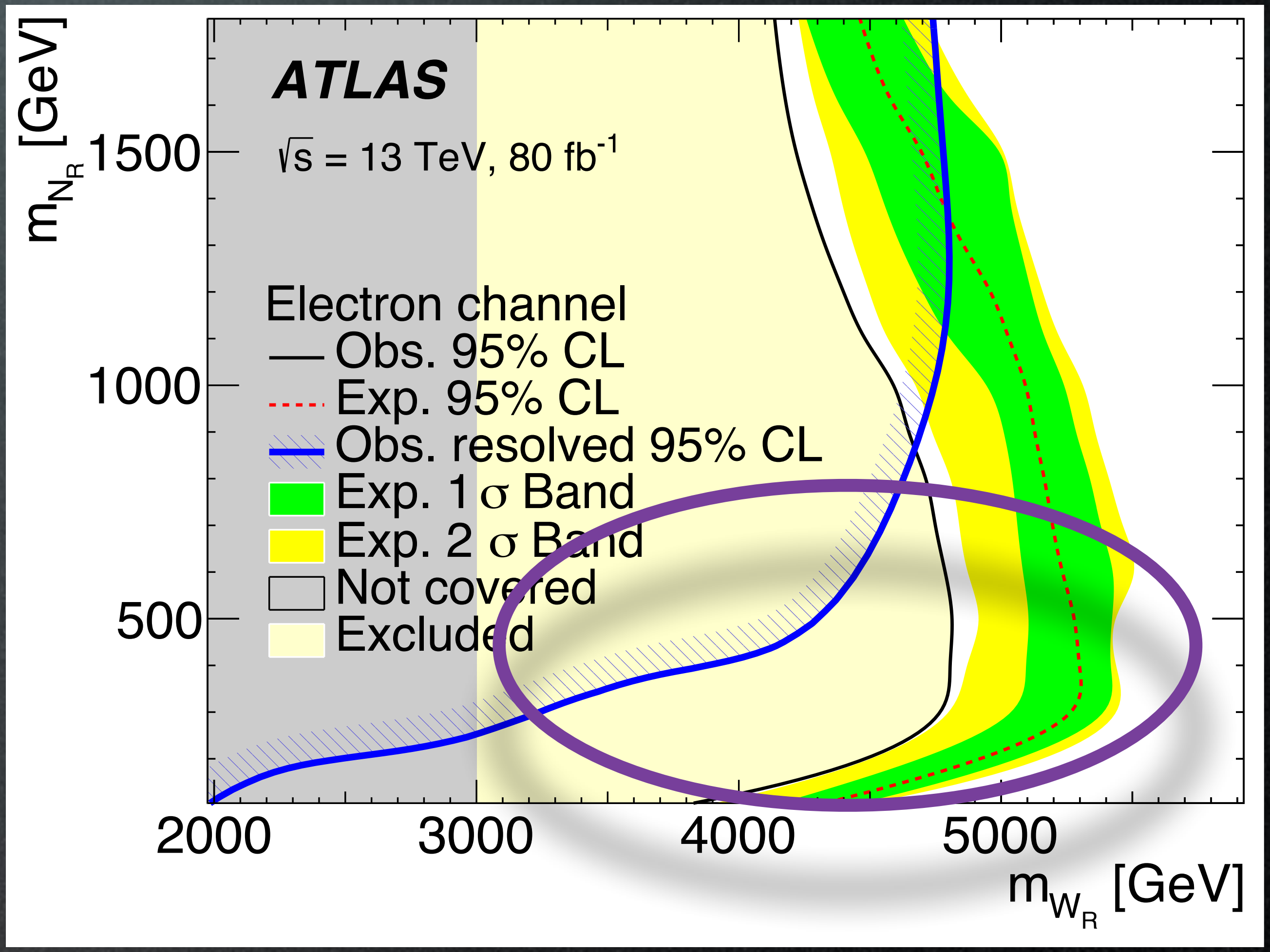
CR well modelled

Phys. Lett. B 798 (2019) 134942

Boosted Heavy Neutrino Search

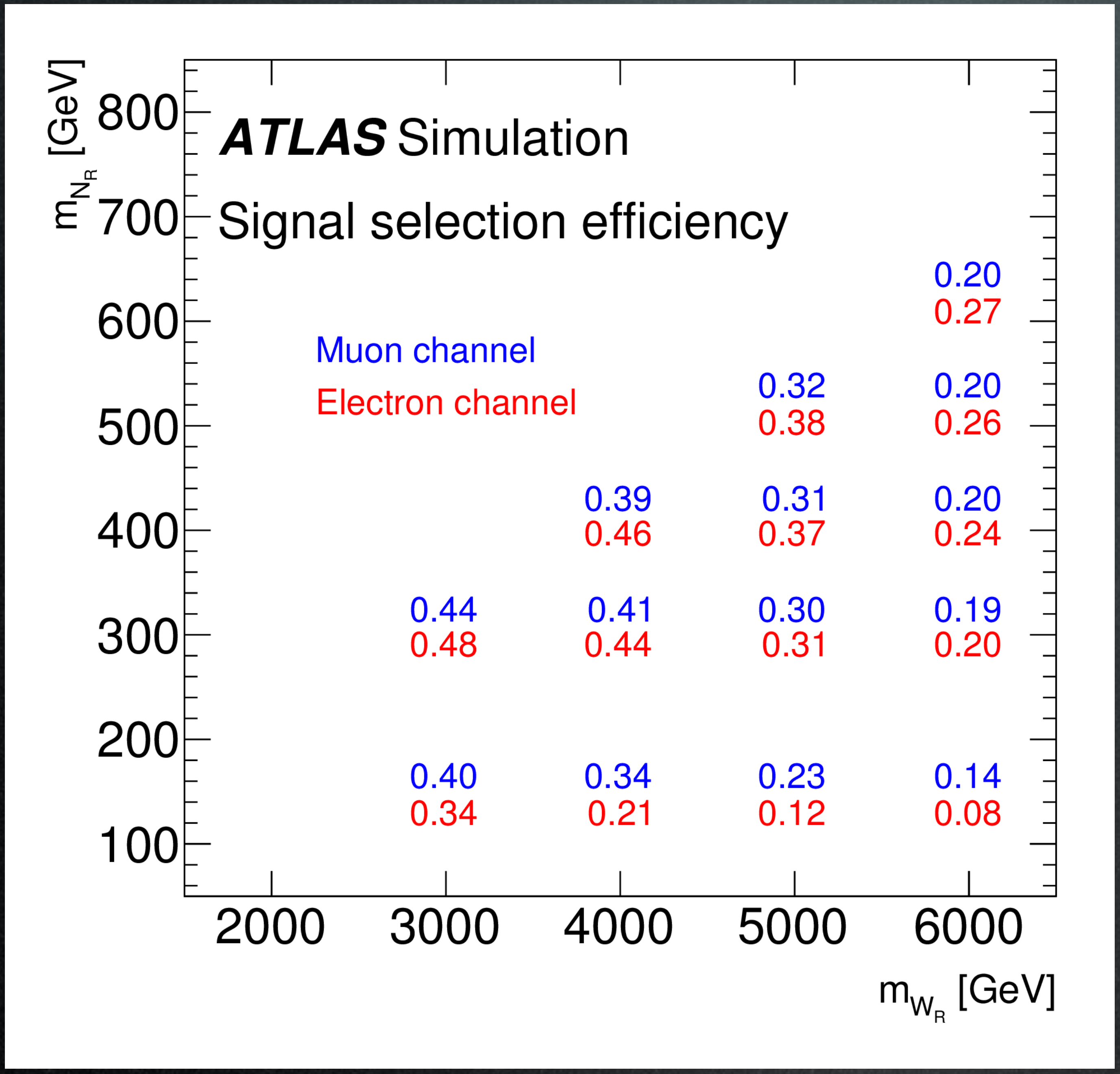


Very small background due to the extreme topology



Complementary strength from resolved analysis

Ongoing: extending it to full Run 2 data



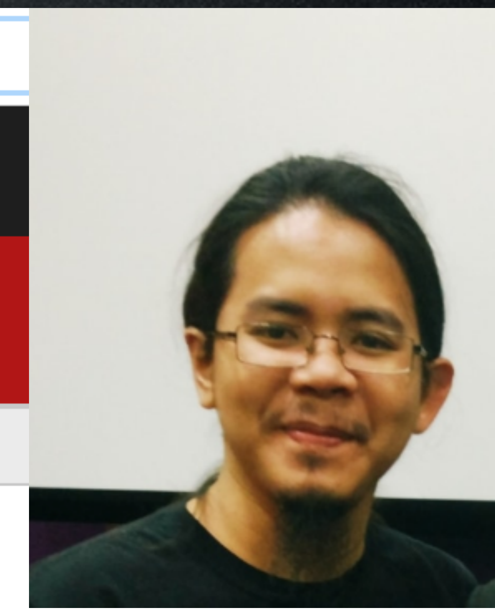
Can we improve electron reconstruction in dense hadronic environment?

Lawrence Davou:
current PhD student

Why stop at electrons?

Why stop at electrons?

Marvin Flores
current postdoc



https://arxiv.org/abs/1905.08026

Cornell University

arXiv.org > hep-ph > arXiv:1905.08026

High Energy Physics – Phenomenology

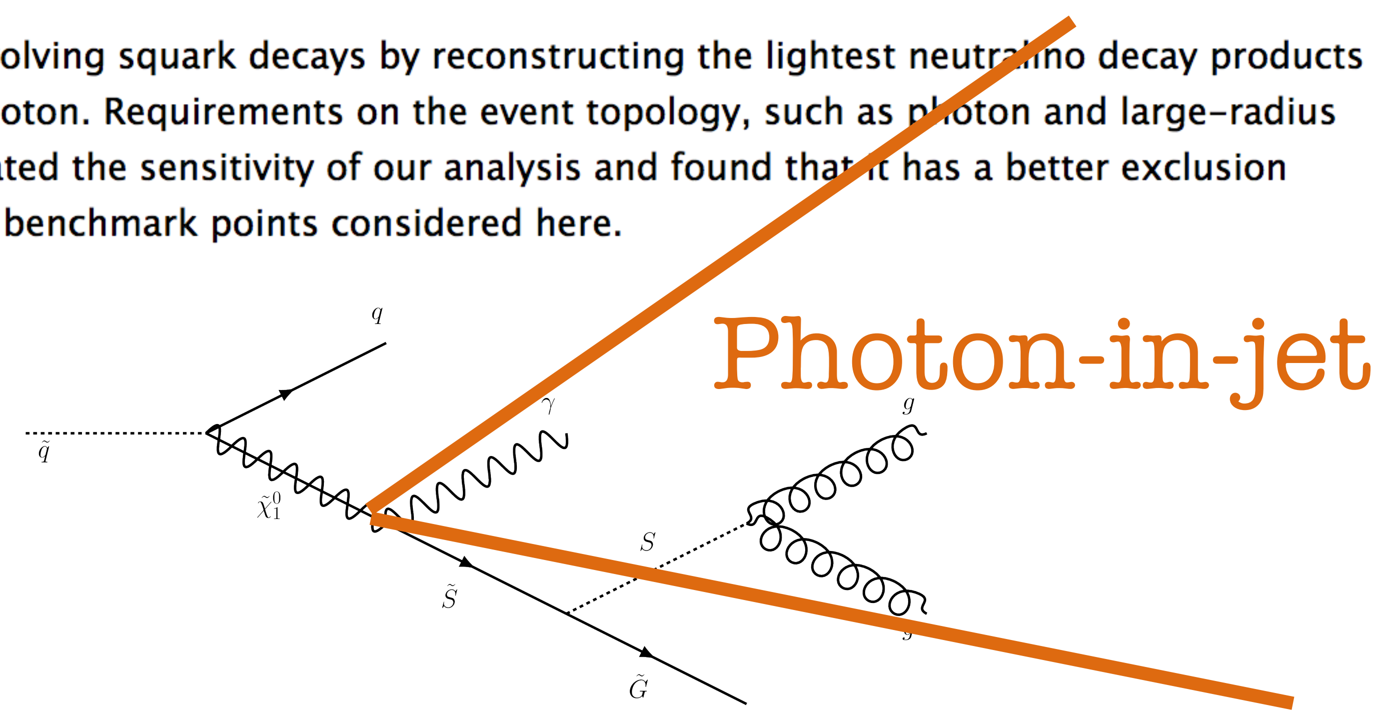
Constraining Stealth SUSY with illuminated fat jets at the LHC

Marvin Flores, Deepak Kar, Jong Soo Kim

(Submitted on 20 May 2019)

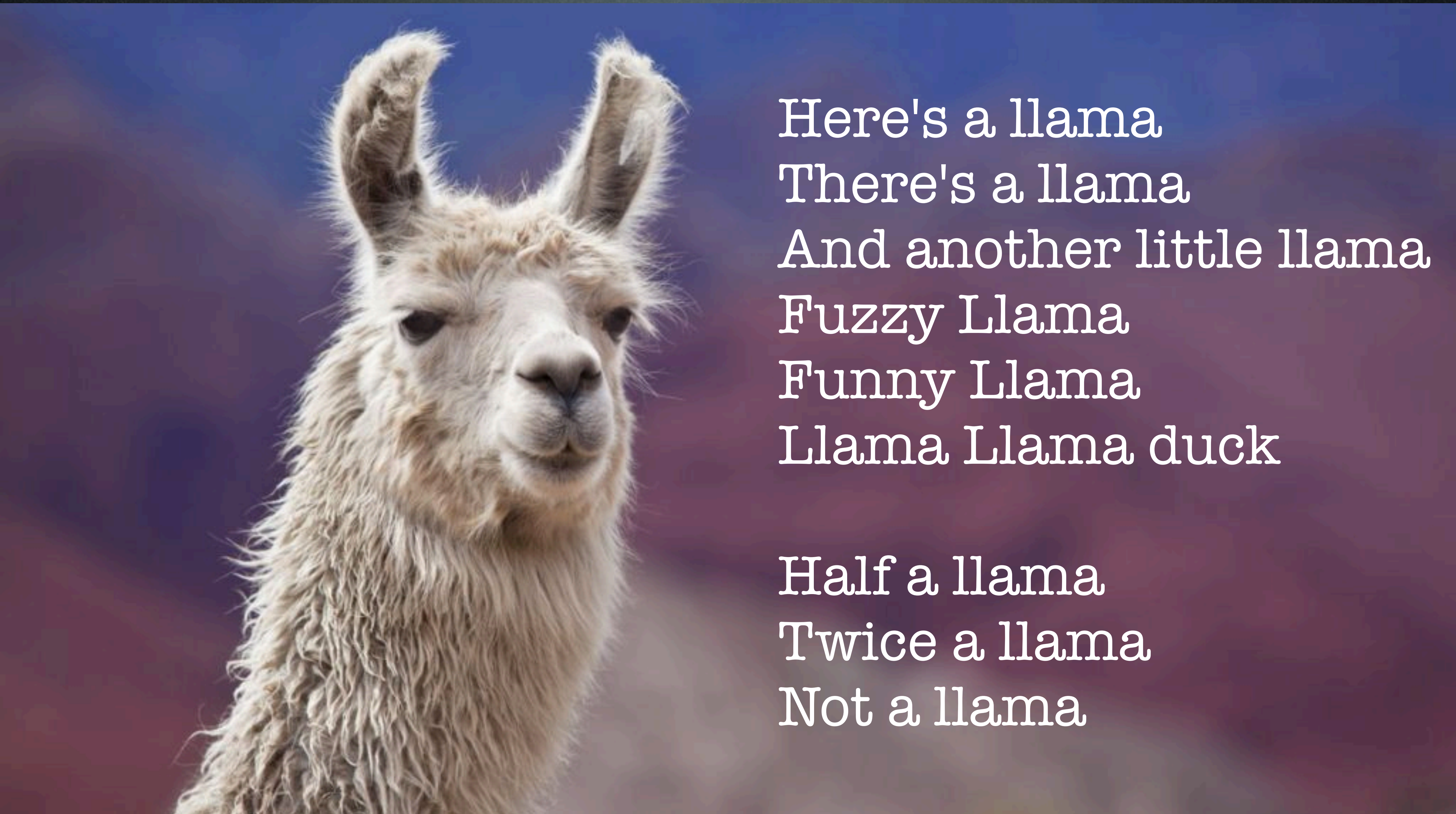
We investigate the discovery potential of a Stealth SUSY scenario involving squark decays by reconstructing the lightest neutralino decay products using a large-radius jet containing a high transverse momentum photon. Requirements on the event topology, such as photon and large-radius jet multiplicity result in less background than signal. We also estimated the sensitivity of our analysis and found that it has a better exclusion potential compared to the strongest existing search for the specific benchmark points considered here.

Comments: 6 pages, 5 figures
Subjects: High Energy Physics – Phenomenology (hep-ph)
Cite as: arXiv:1905.08026 [hep-ph]
(or arXiv:1905.08026v1 [hep-ph] for this version)

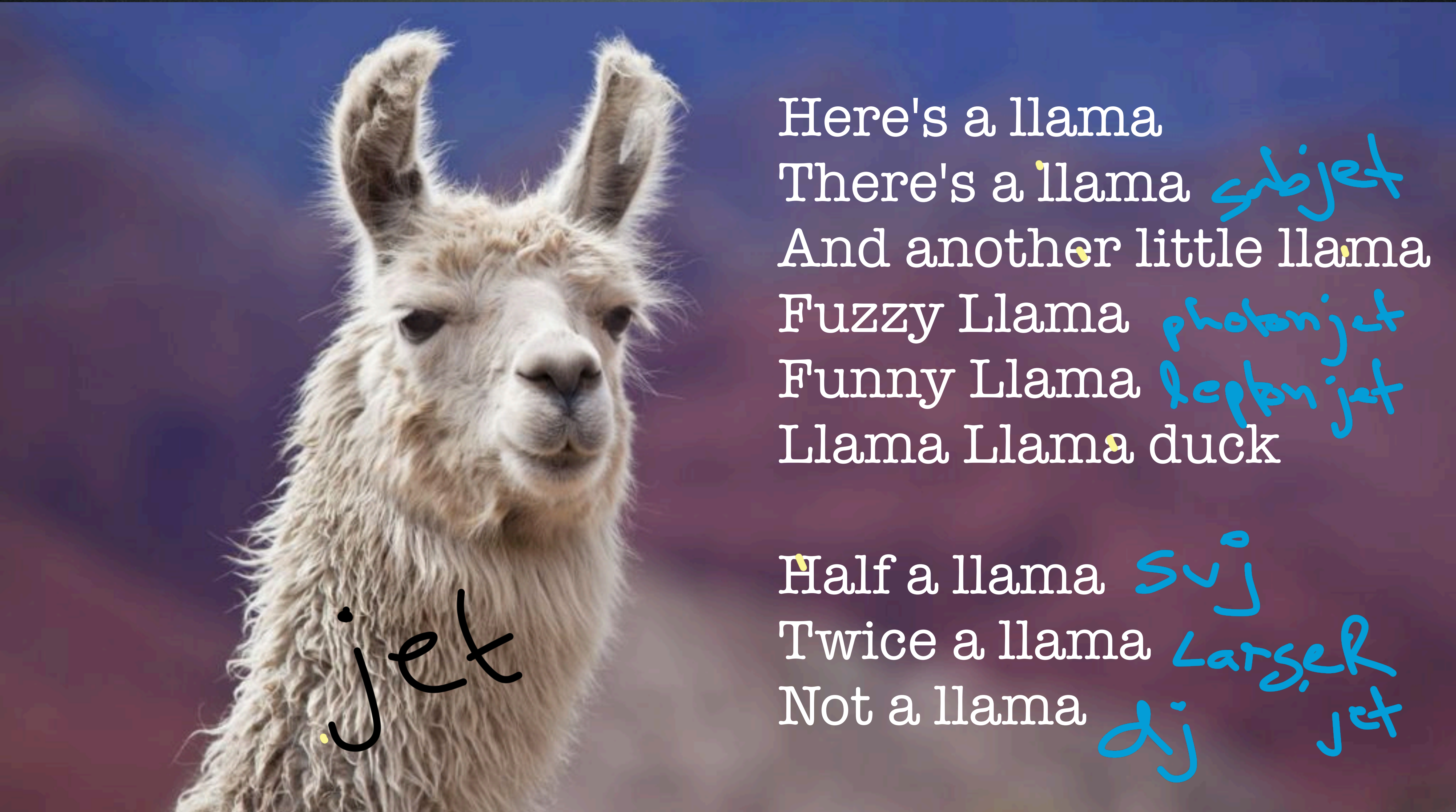


Submission history

From: Marvin Flores [view email]
[v1] Mon, 20 May 2019 12:19:37 UTC (251 KB)

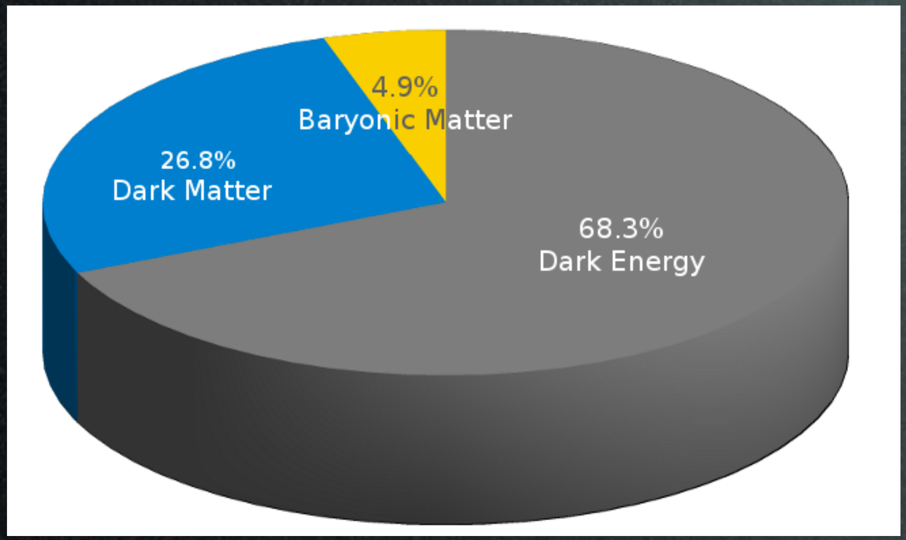

Here's a llama
There's a llama
And another little llama
Fuzzy Llama
Funny Llama
Llama Llama duck

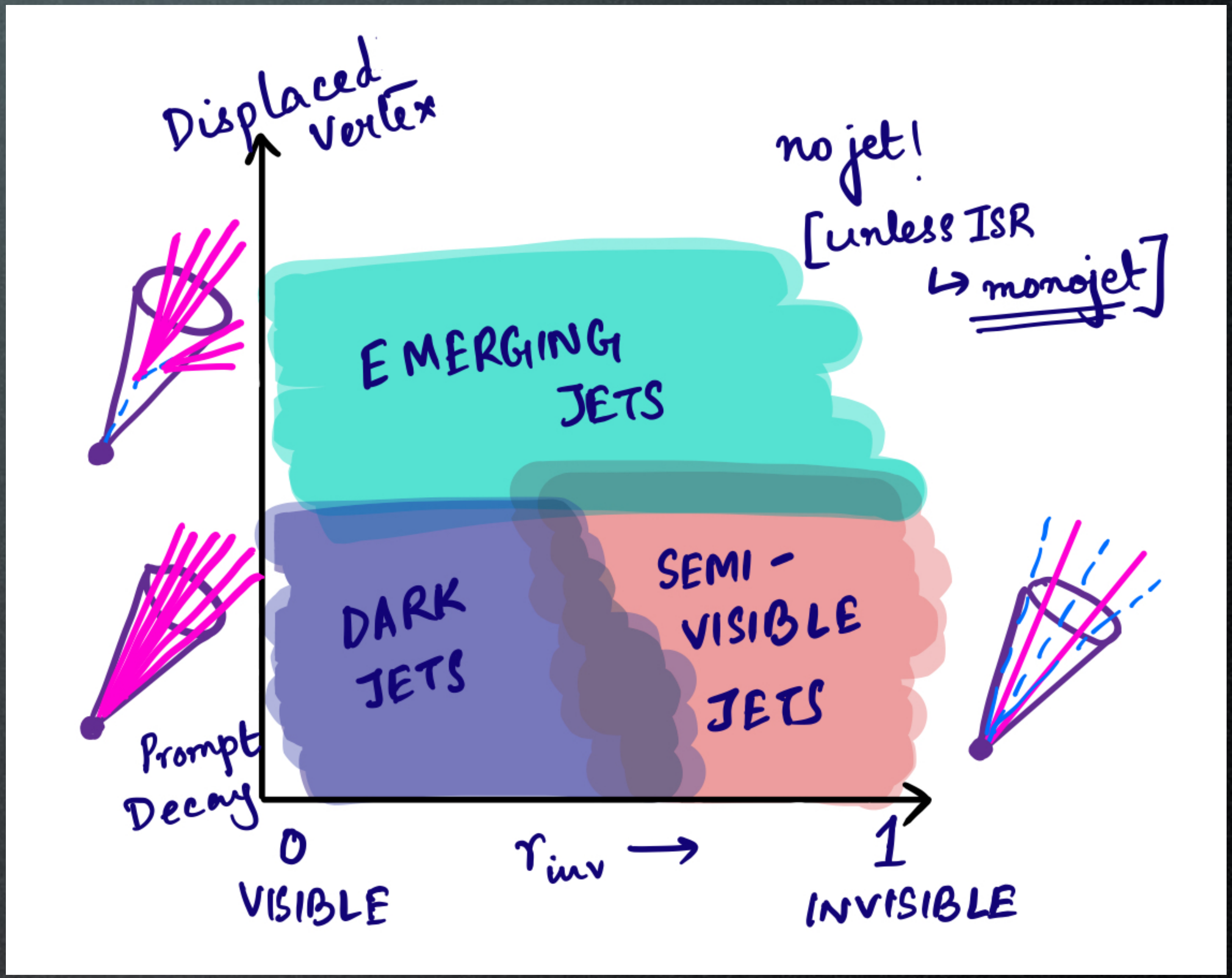
Half a llama
Twice a llama
Not a llama


Here's a llama
There's a llama subjet
And another little llama
Fuzzy Llama photonjet
Funny Llama leptonjet
Llama Llama duck

Half a llama suj
Twice a llama Larger jet
Not a llama dj
jet

Dark and semi-visible jets



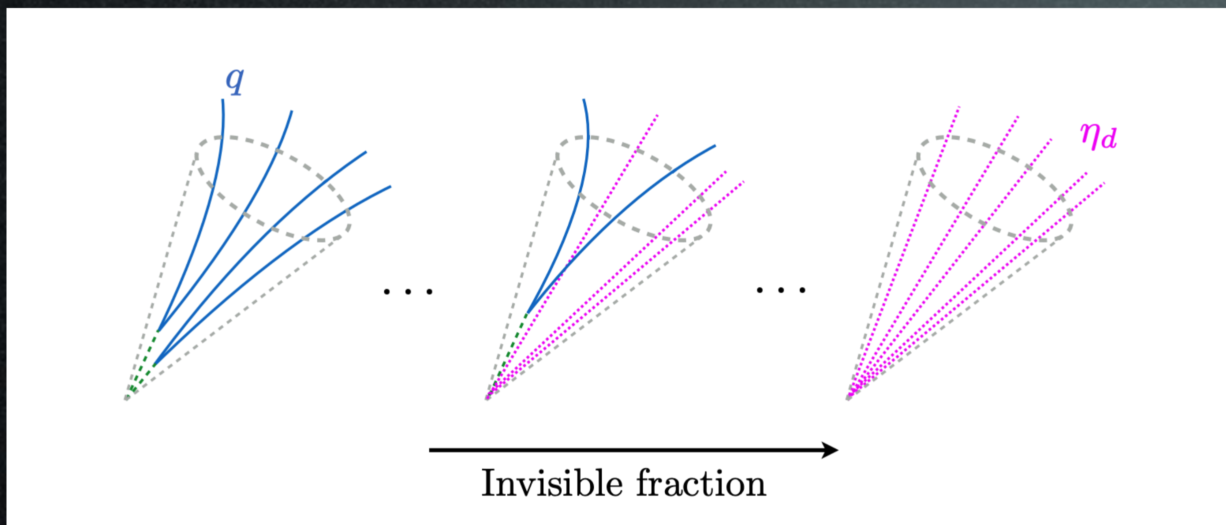


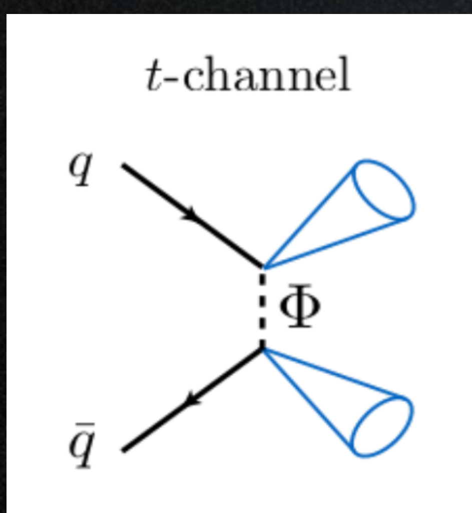
Tasnuva Chowdhury
current postdoc

Dark hadrons decaying in a QCD-like fashion, fully (dark jets) or partially back to visible sector (semi-visible jets, based on Cohen et al)

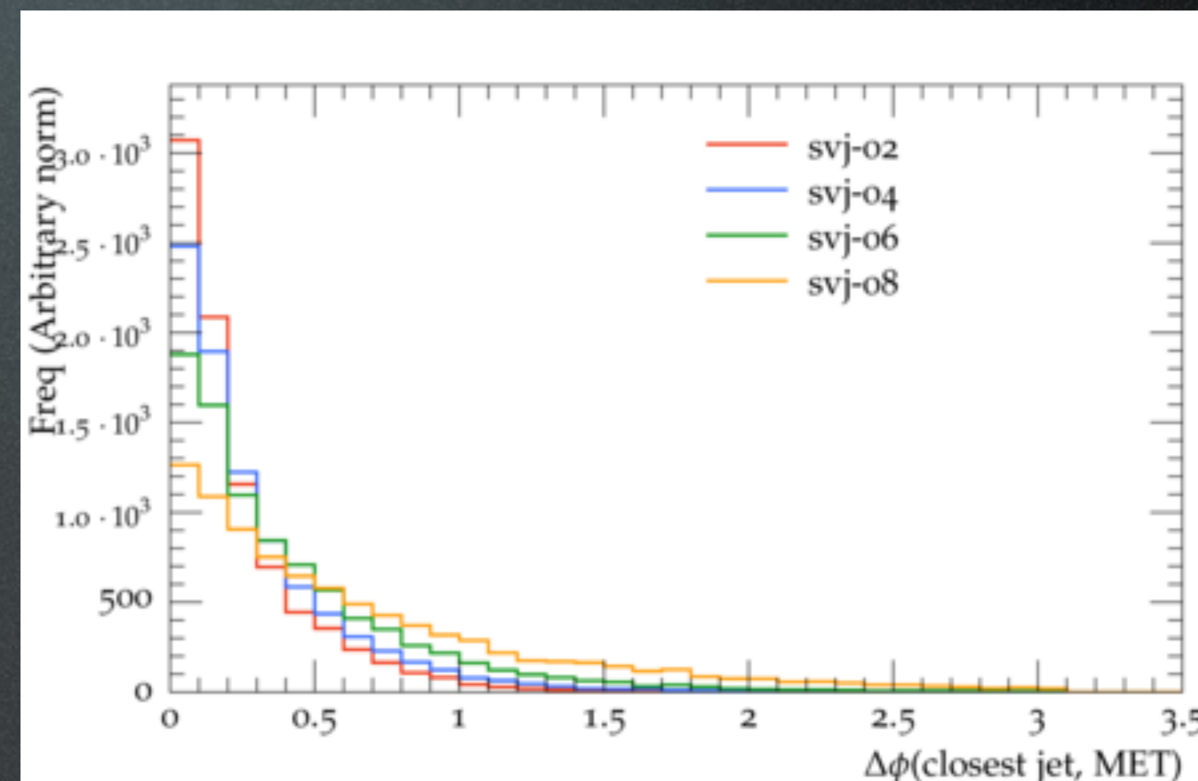
Sukanya Sinha:
current PhD student

Semi-visible Jets





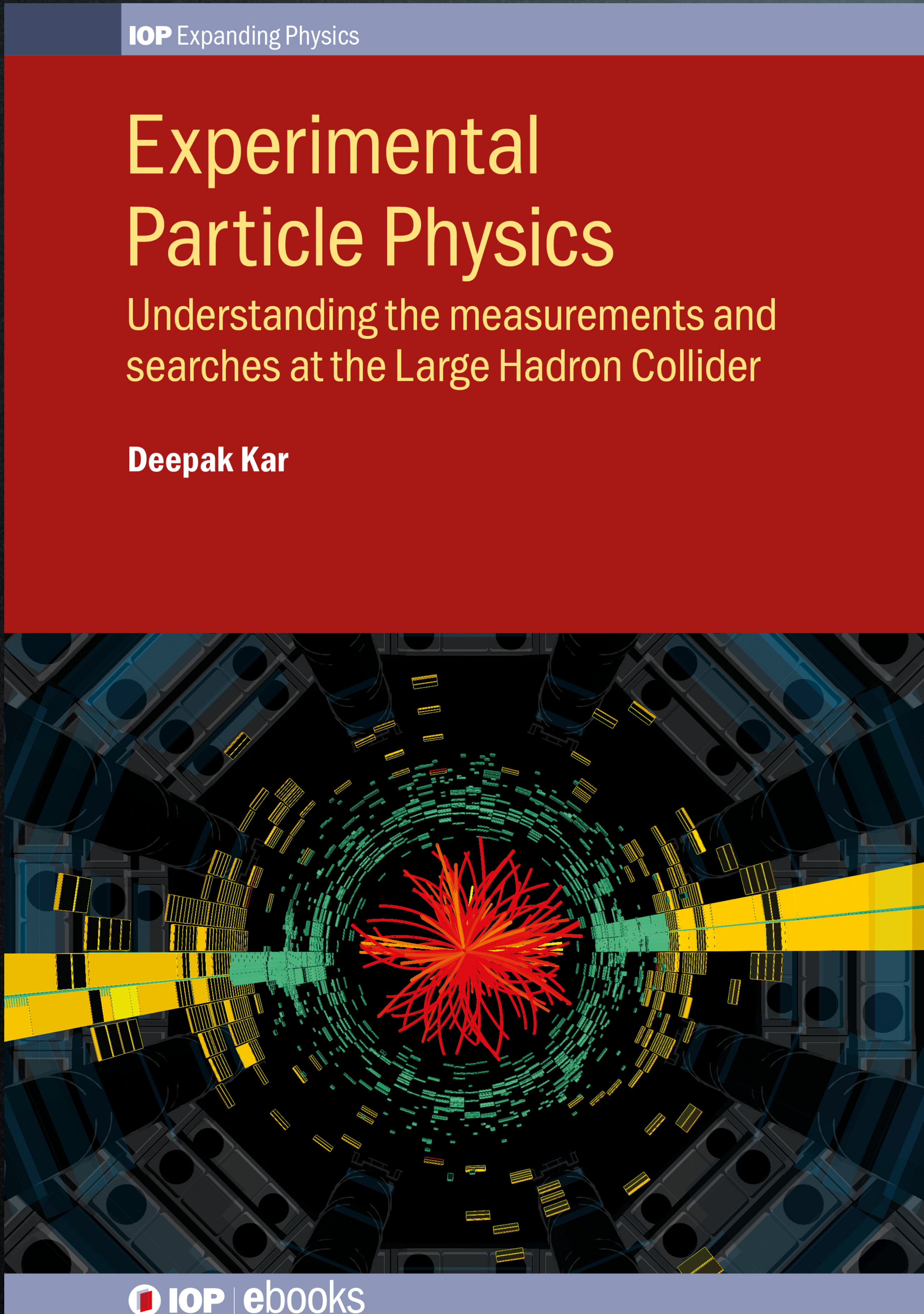
R_{inv} = Ratio of stable dark hadrons over number of hadrons



MET aligned with a jet, a topology we have not yet looked at in ATLAS!

Mvelo Dlamini
current masters student

Potential use of substructure to identify these jets!
See: https://arxiv.org/abs/2007.11597

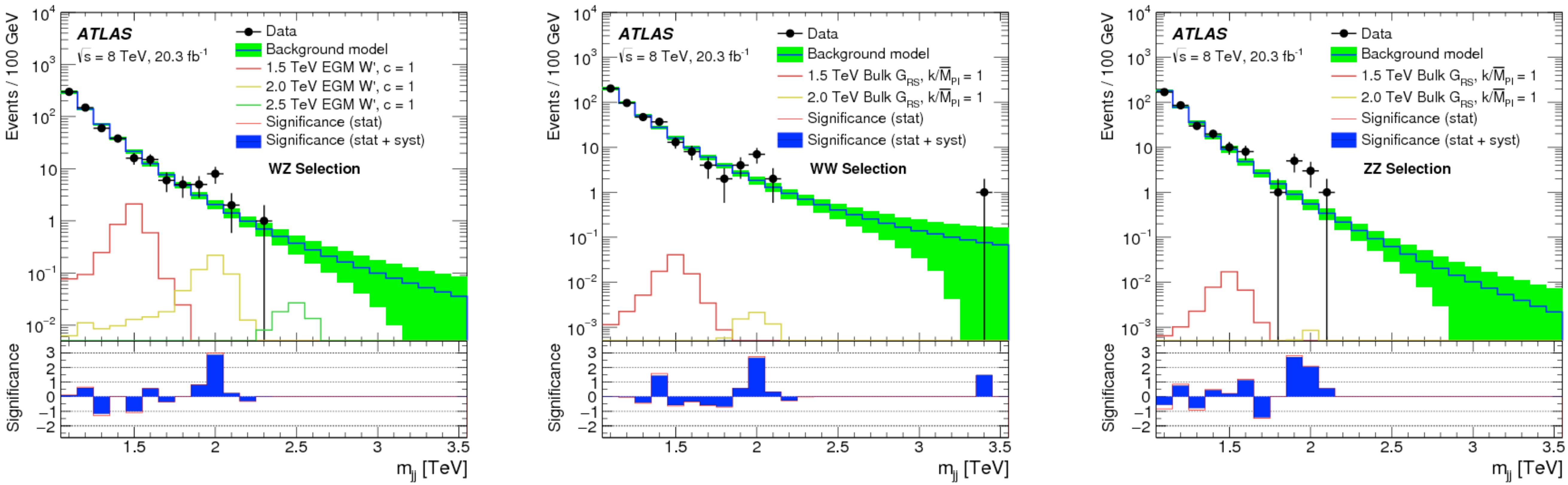


After almost a year's effort (and drawing figures over last Christmas holidays!)

Supporting Material

The Run 1 Bump at 2 TeV

arXiv:1506.00962

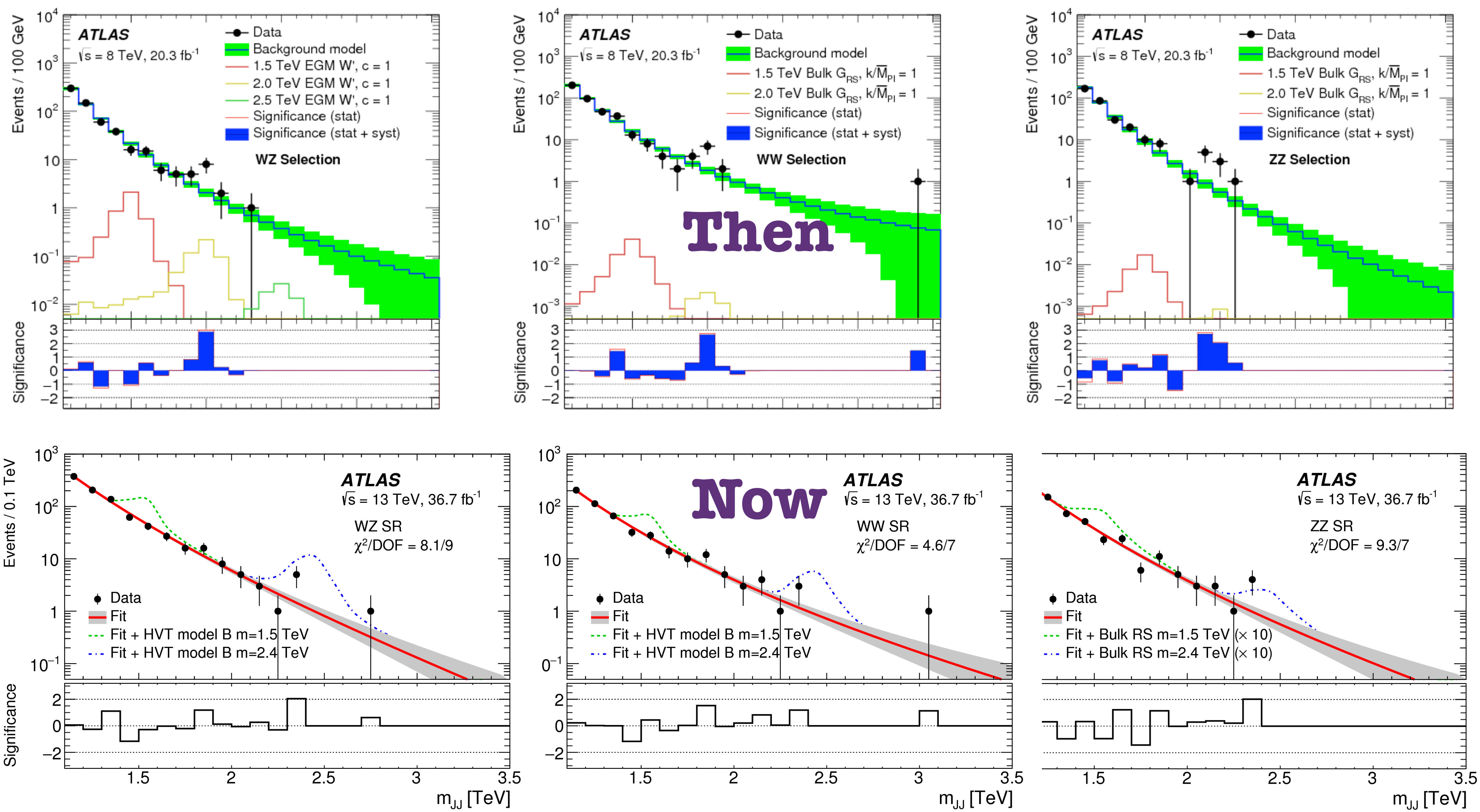


Invariant mass of two boson-tagged large radius jets

The Run 1 Bump at 2 TeV

arXiv:1506.00962

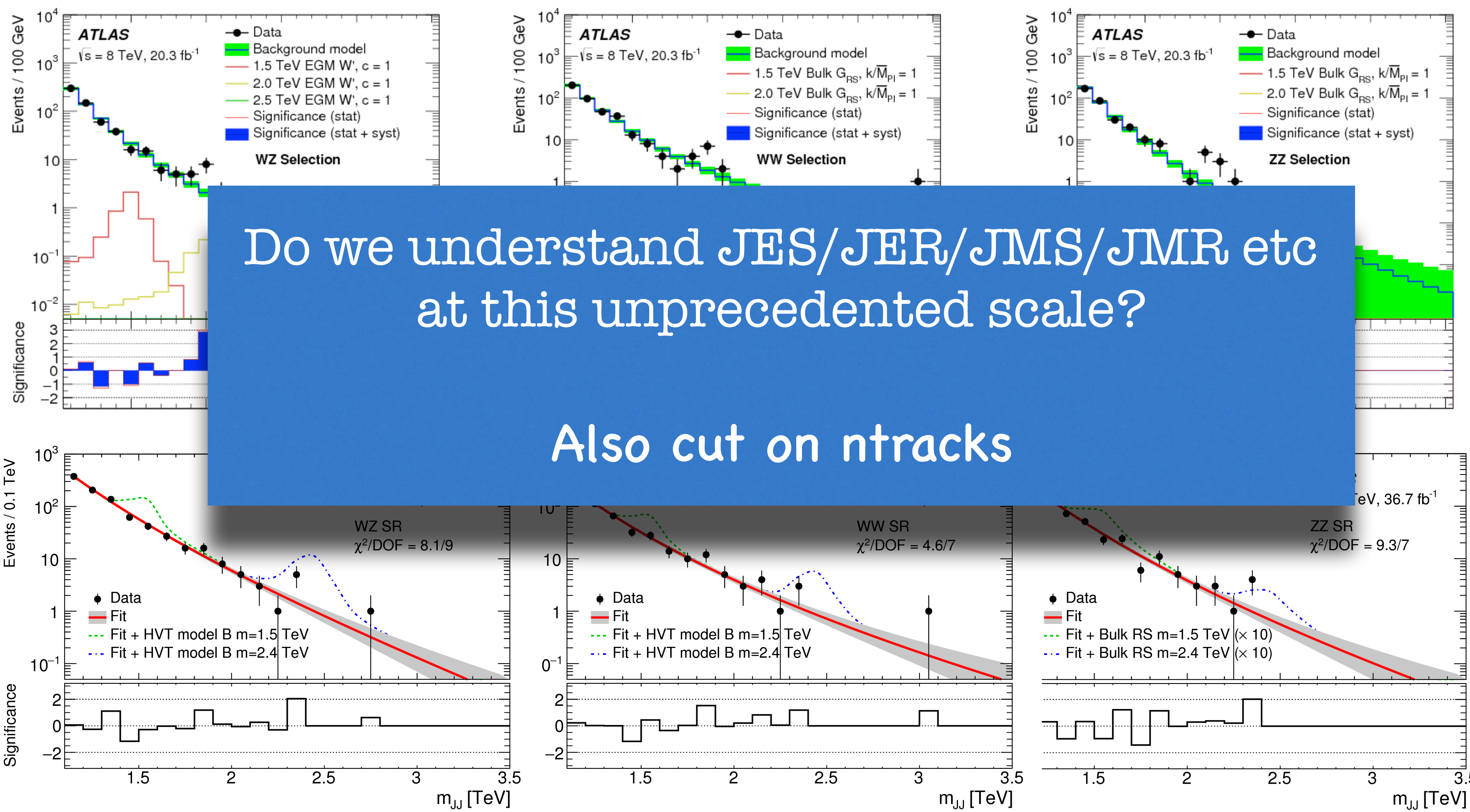
arXiv:1708.04445



The Run 1 Bump at 2 TeV

arXiv:1506.00962

arXiv:1708.04445

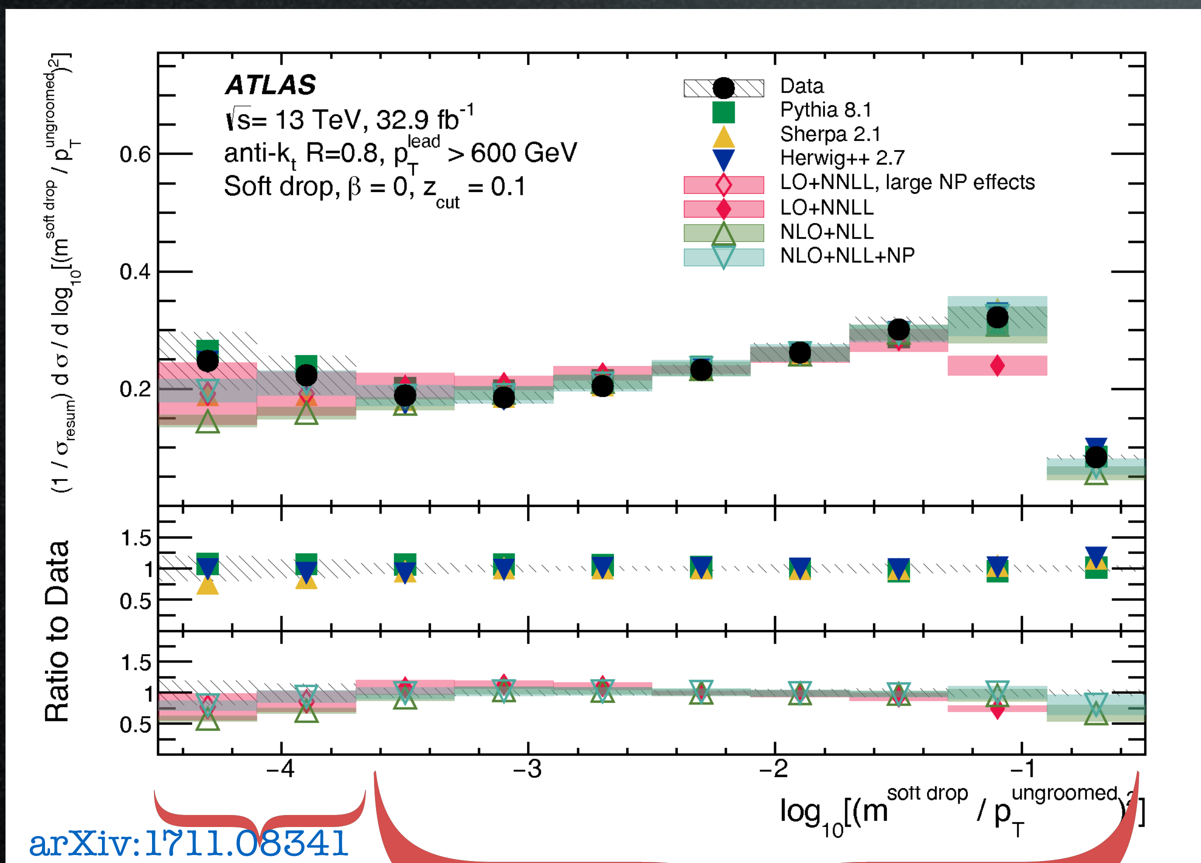


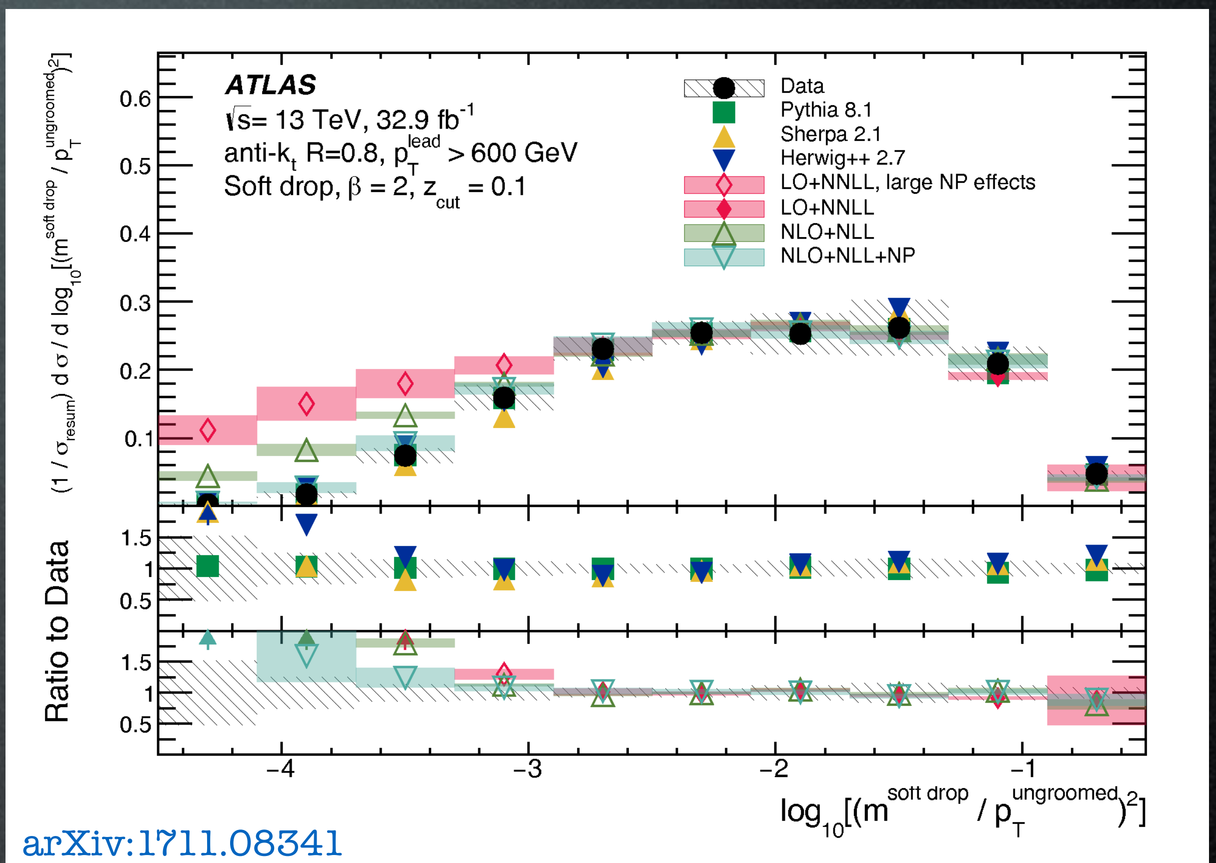
Do we understand JES/JER/JMS/JMR etc at this unprecedented scale?

Also cut on ntracks

Soft-dropped Jet Mass

Ratio of the soft-drop mass to the ungroomed jet transverse momentum





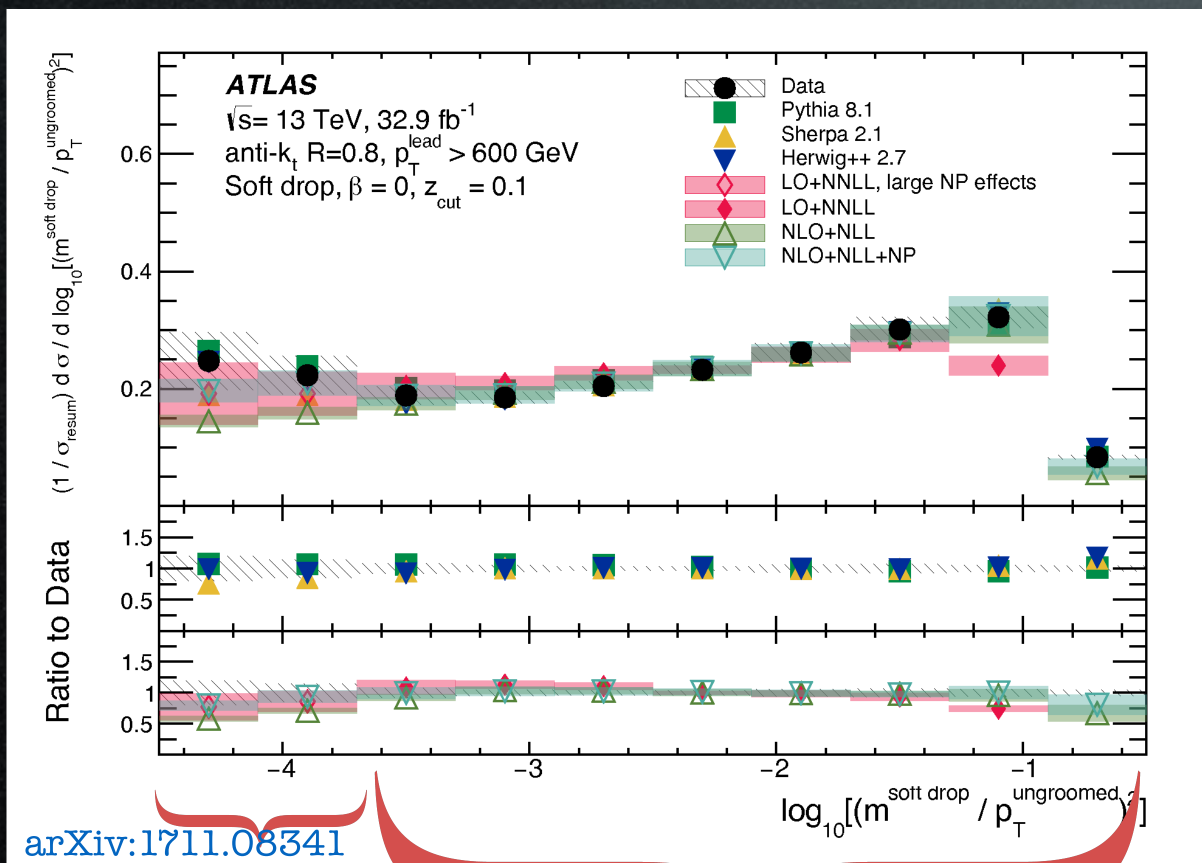
Collinear emission region

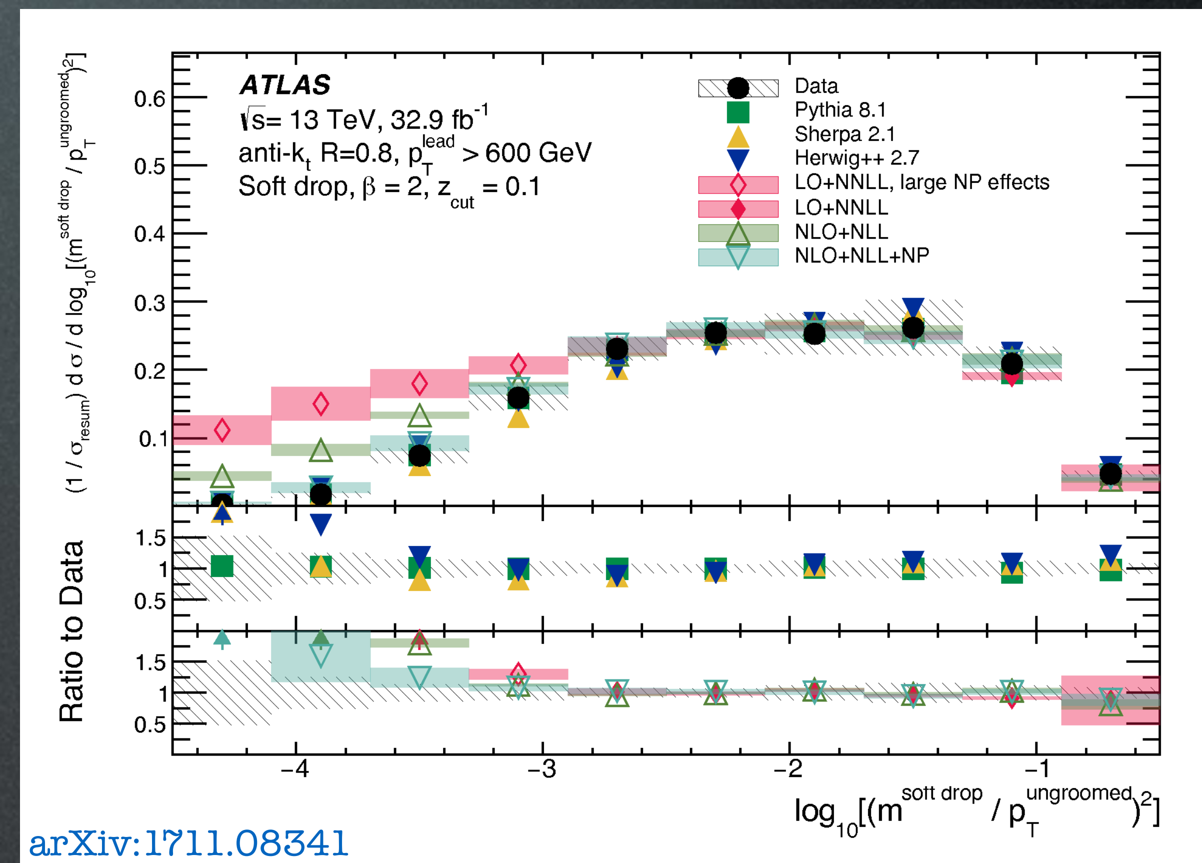
Resummation region

Higher beta
(smaller fraction of soft energy removed)

Soft-dropped Jet Mass

Ratio of the soft-drop mass to the ungroomed jet transverse momentum



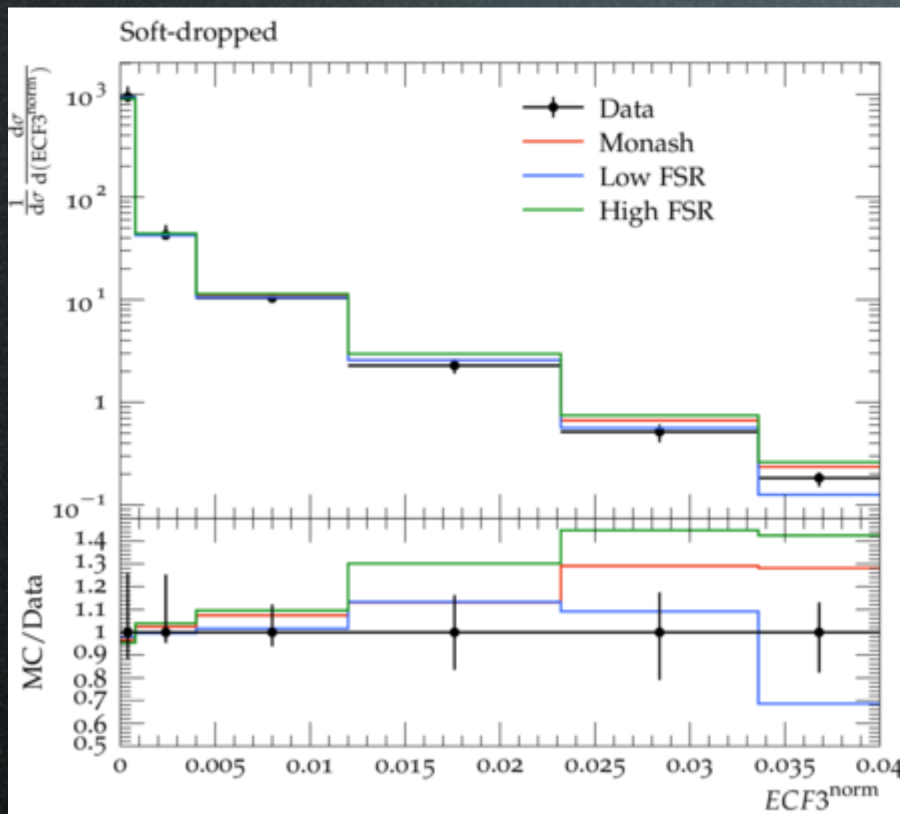


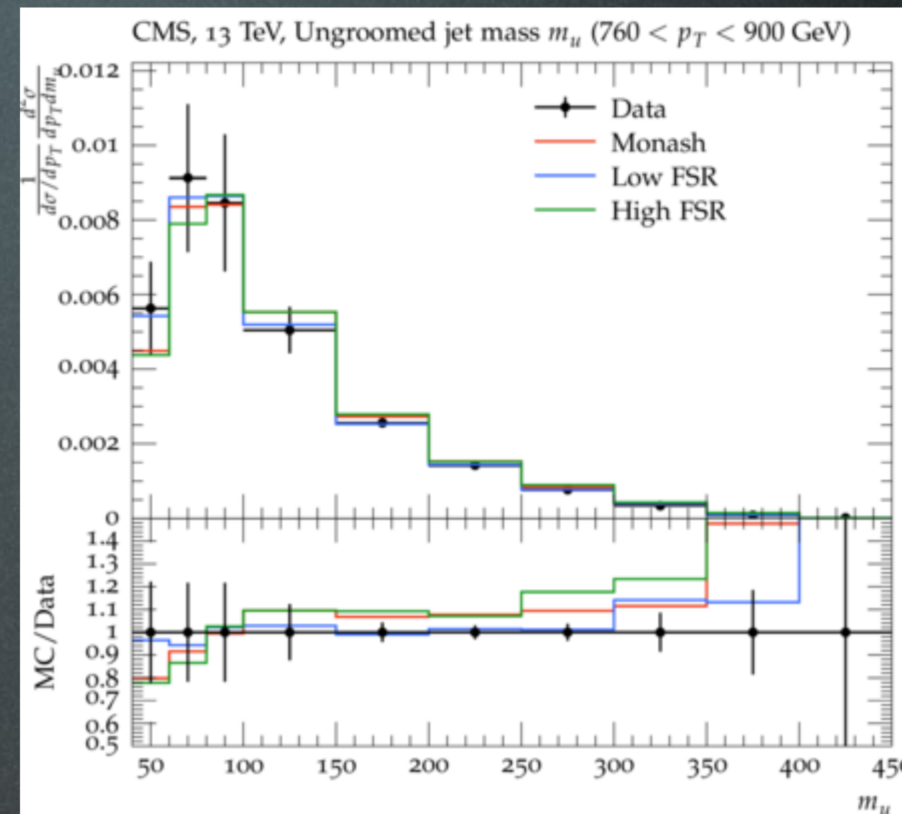
Largest difference between MC and analytic calculation in NP region

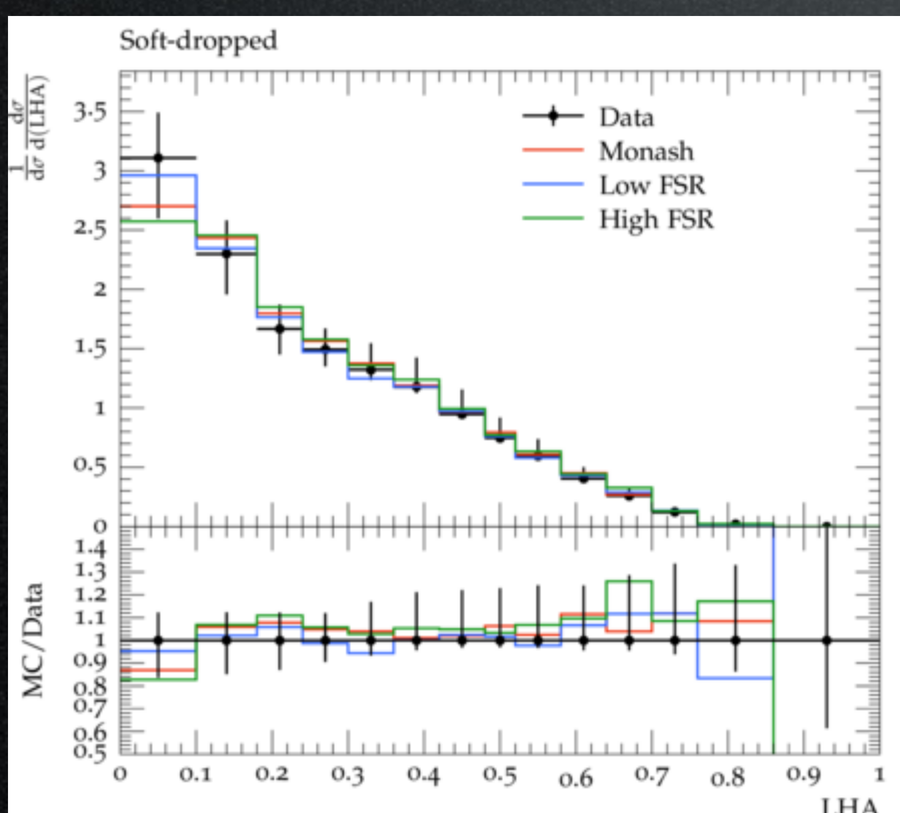
NLO+NLL+NP better at low logρ

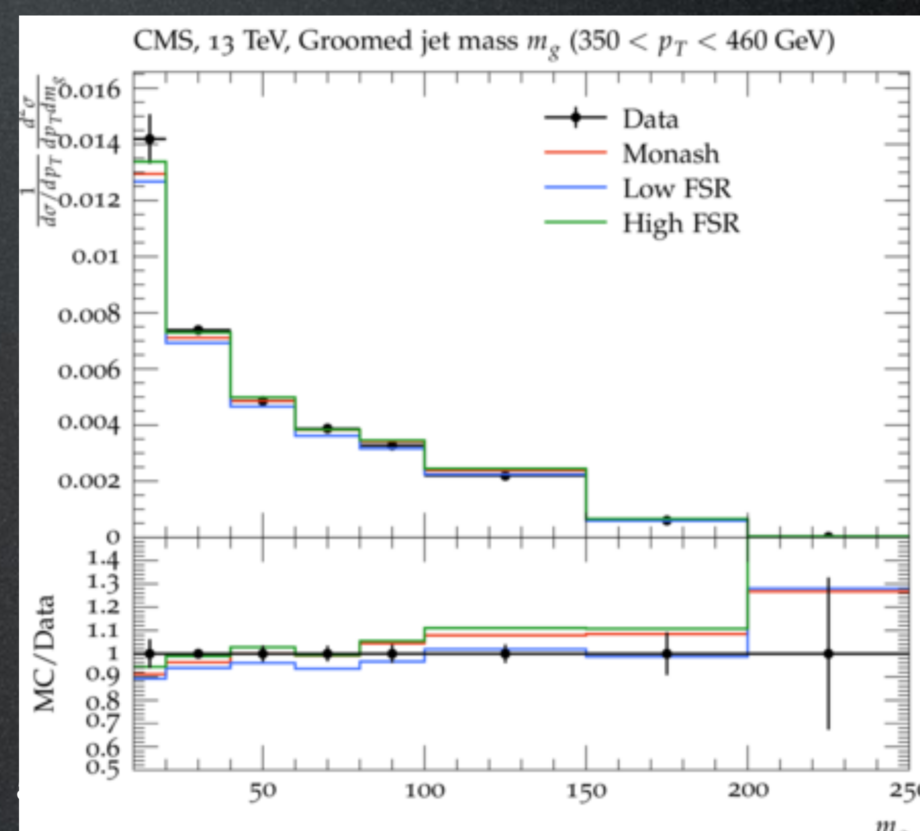
Good agreement at resummation region for both MC and calculations

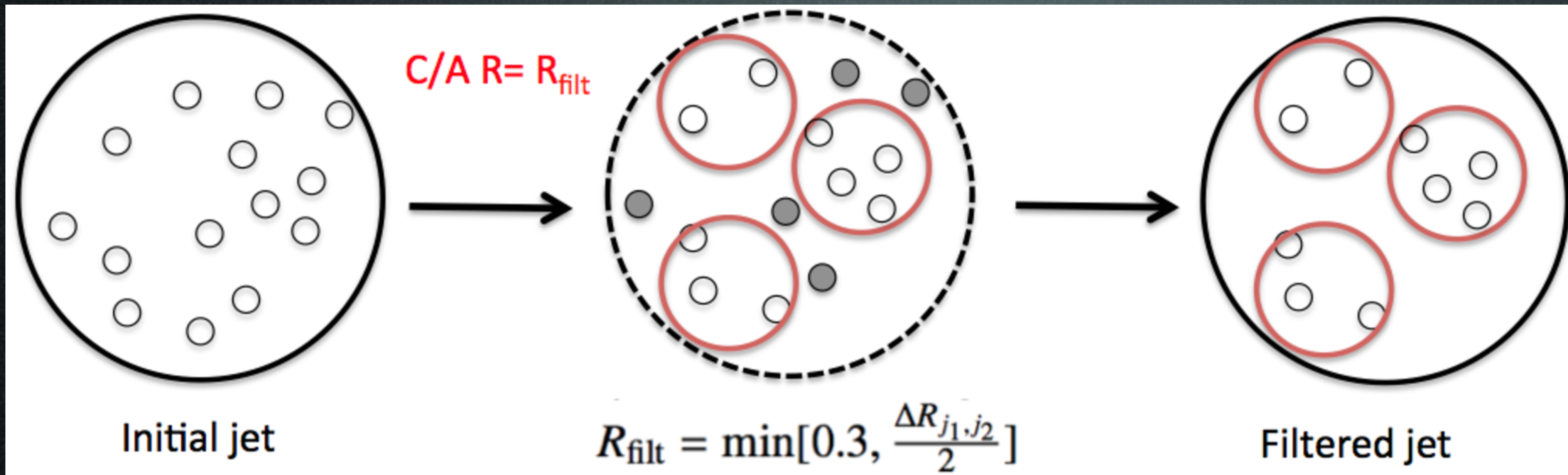
More on Modelling



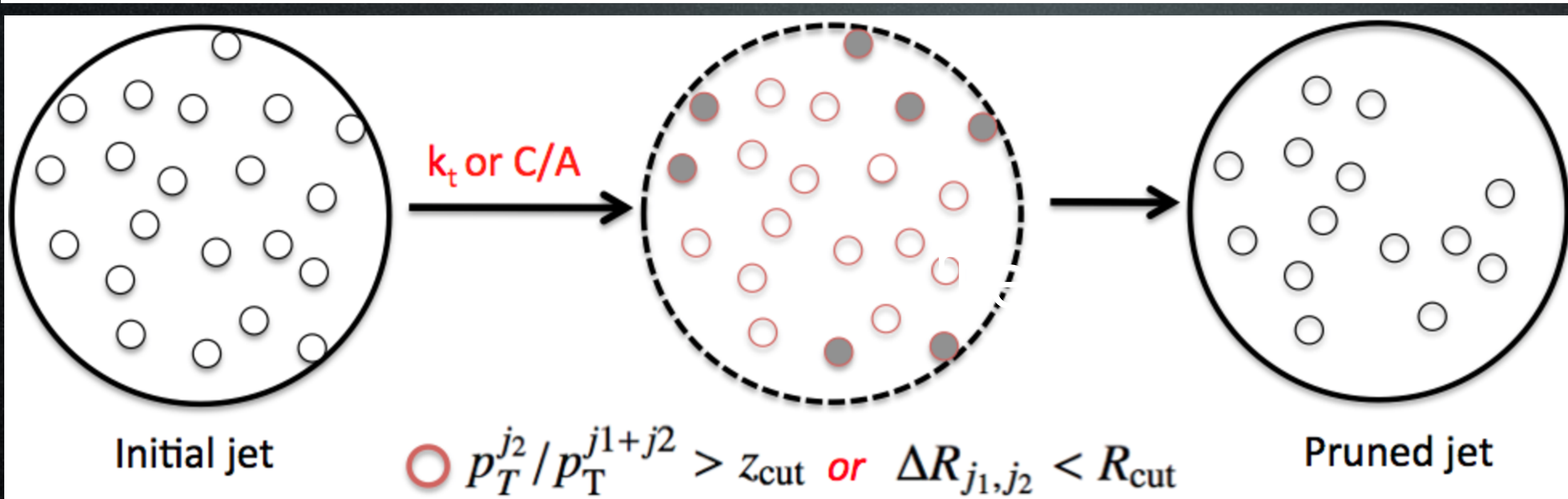




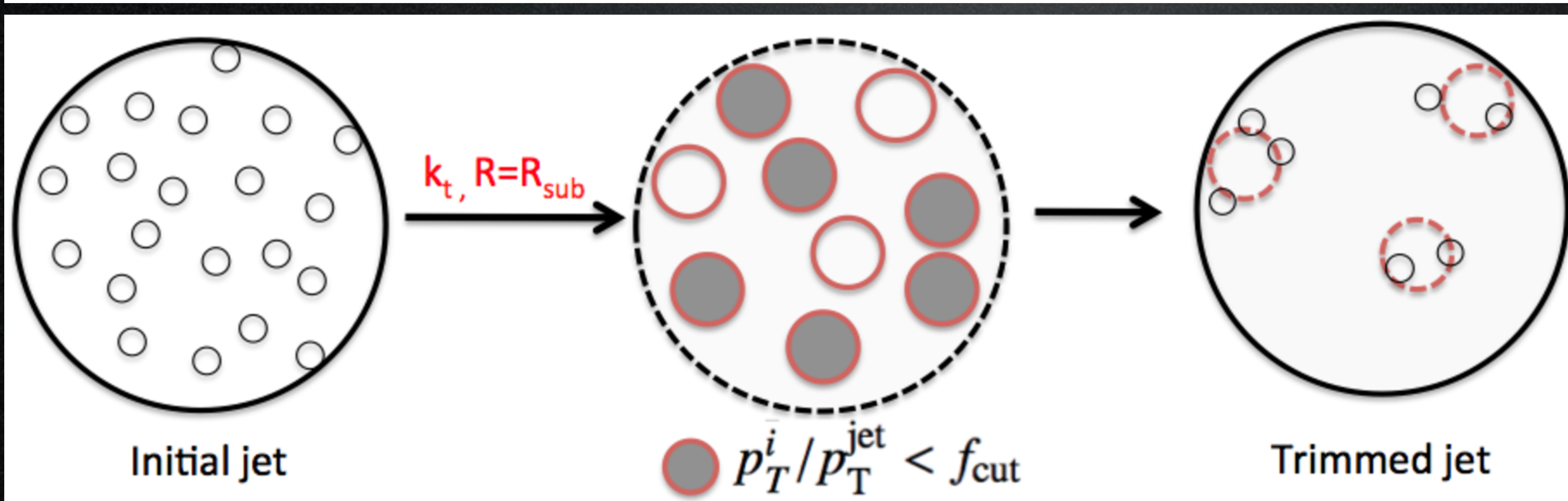




Filtering

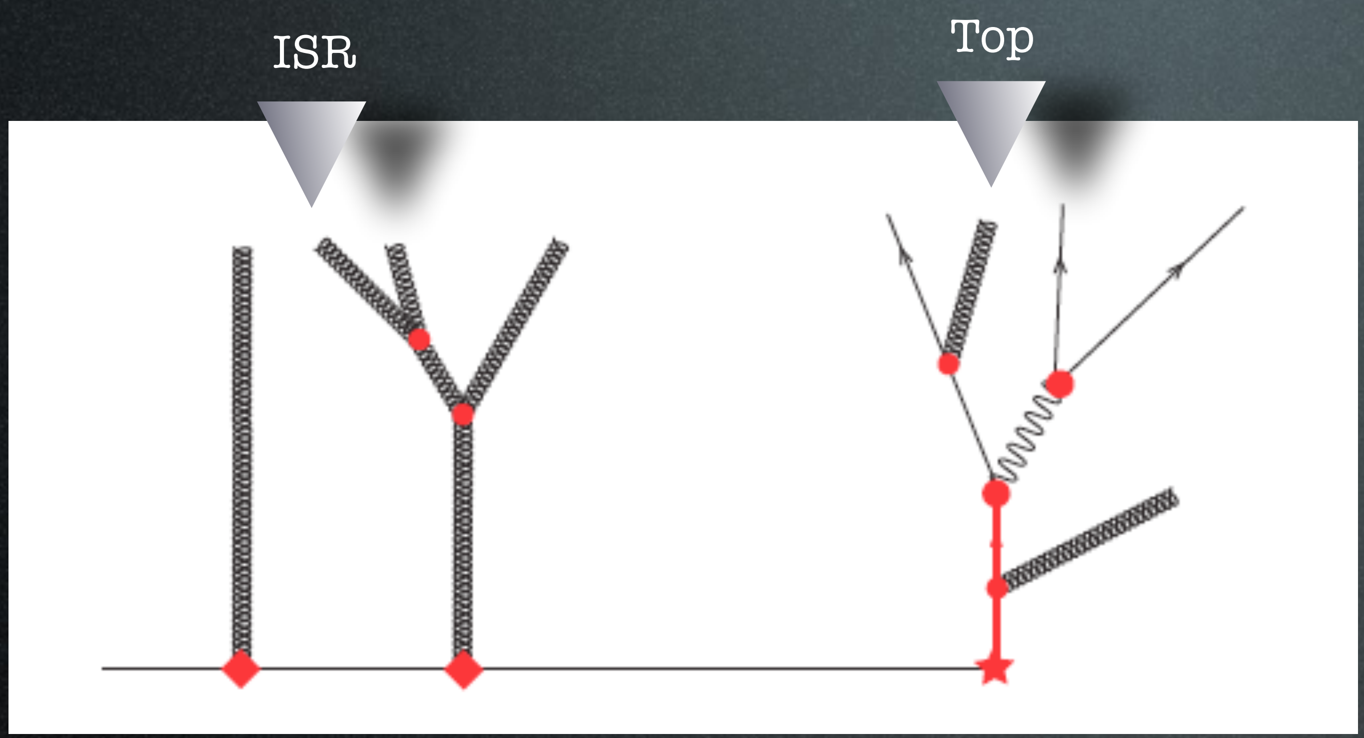


Prunning



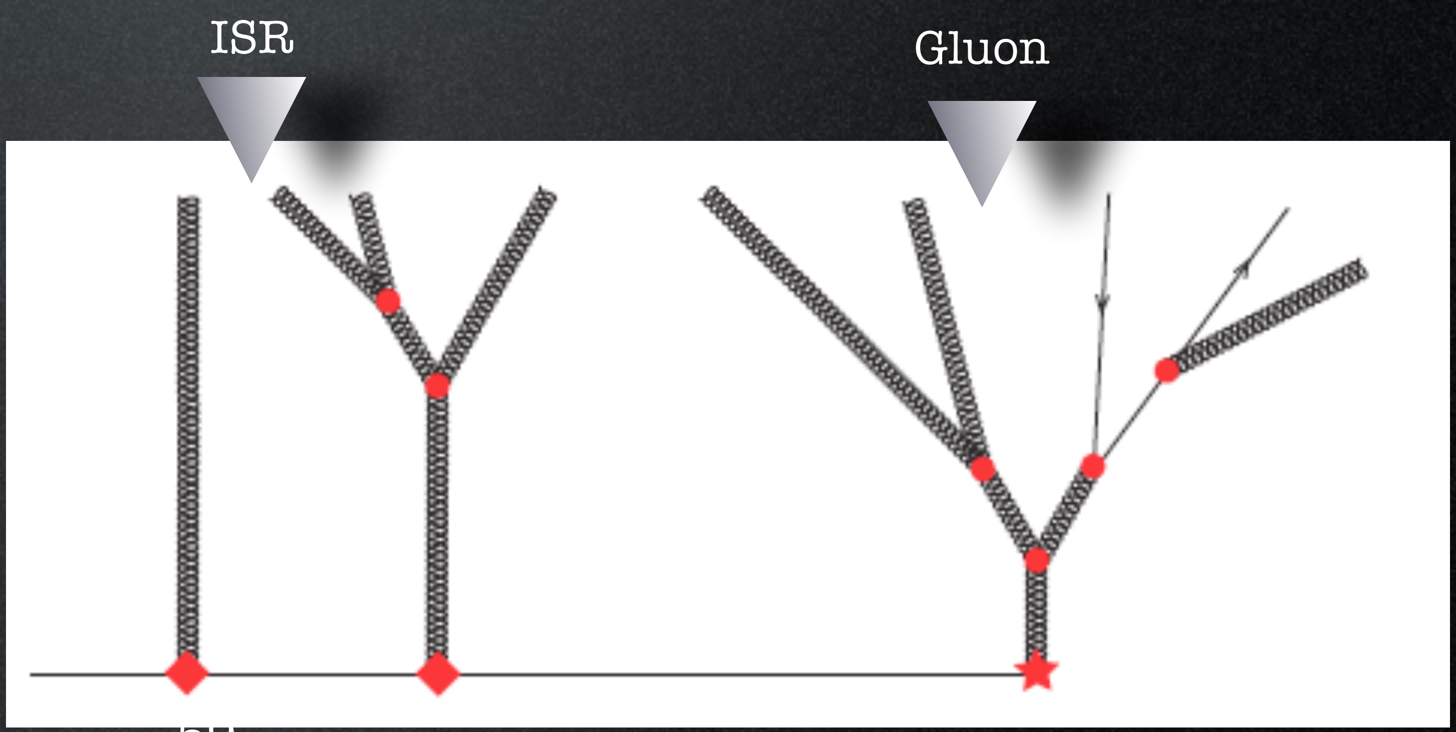
Trimming

Shower Deconstruction



Top quark jet shower history

vs.

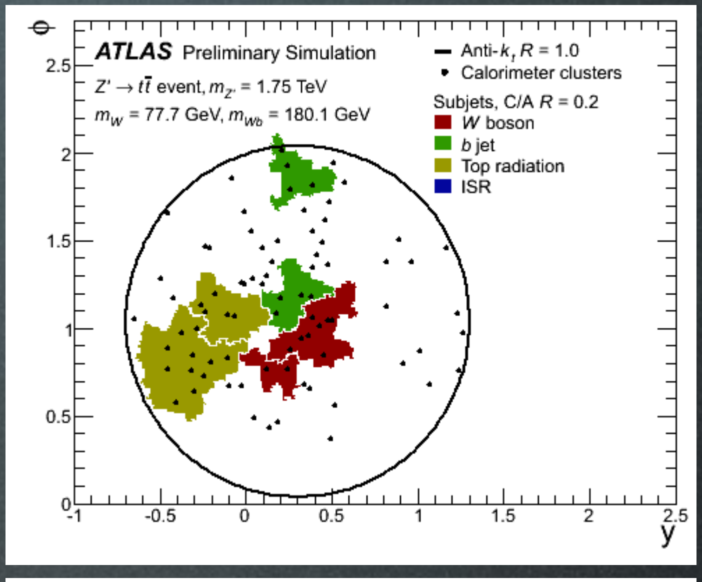


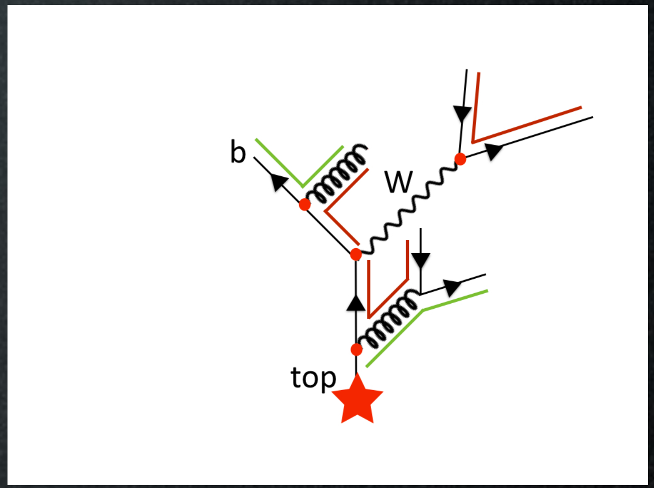
Light quark jet shower history

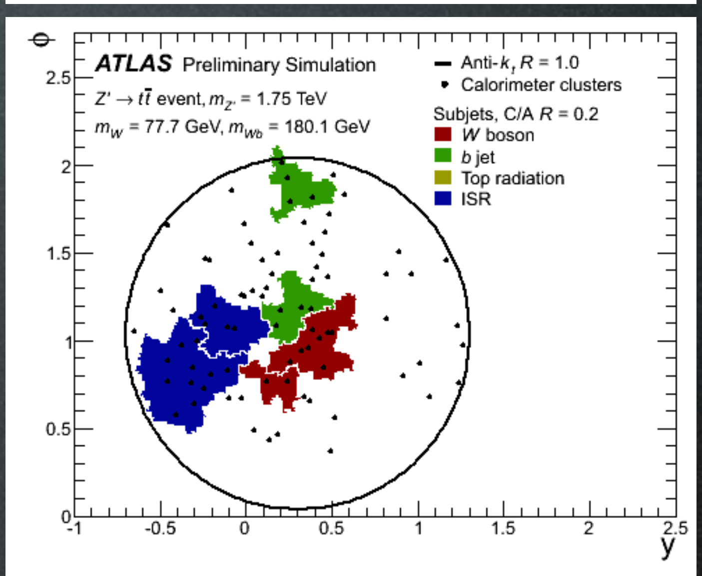
Shower Deconstruction

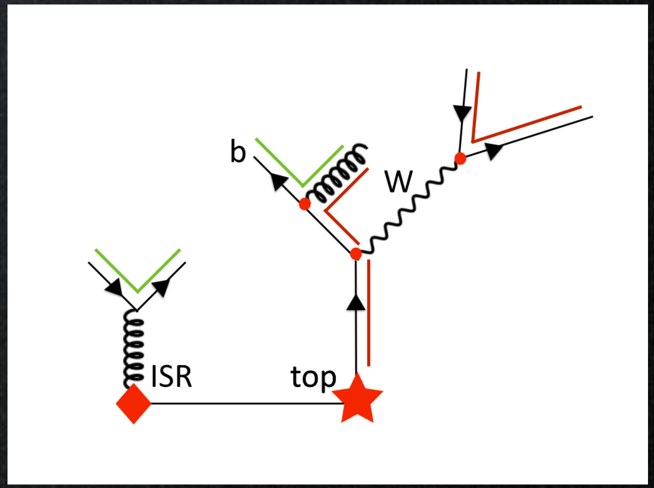
- Decompose the large-radius jet into small radius **subjets.**
- Build all possible shower histories with the subjets.
- Assign probability whether signal-like or background-like.
- A single analytic function:

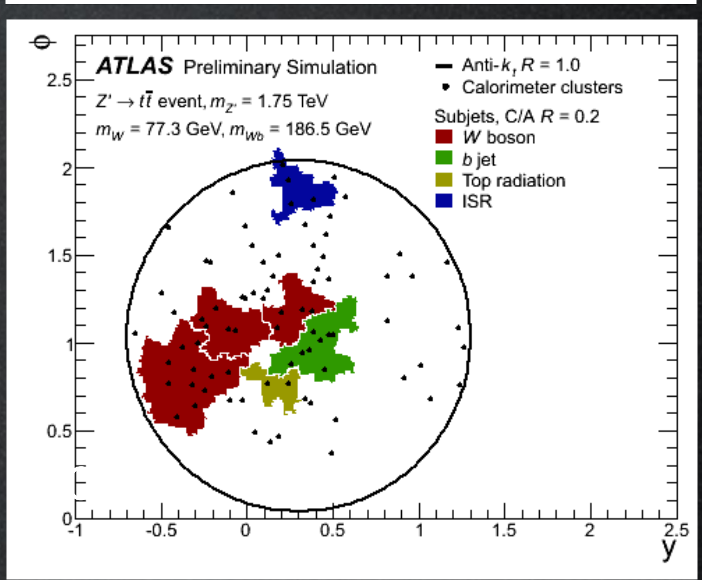
$$\chi(\{p\}_N) = \frac{P(\{p\}_N|\mathrm{S})}{P(\{p\}_N|\mathrm{B})}$$

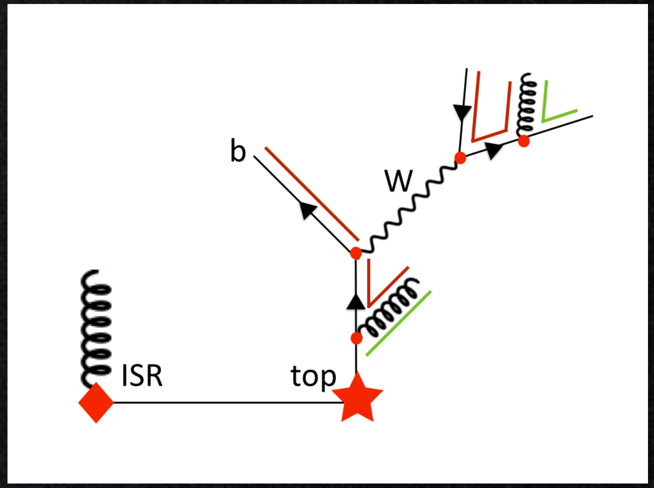












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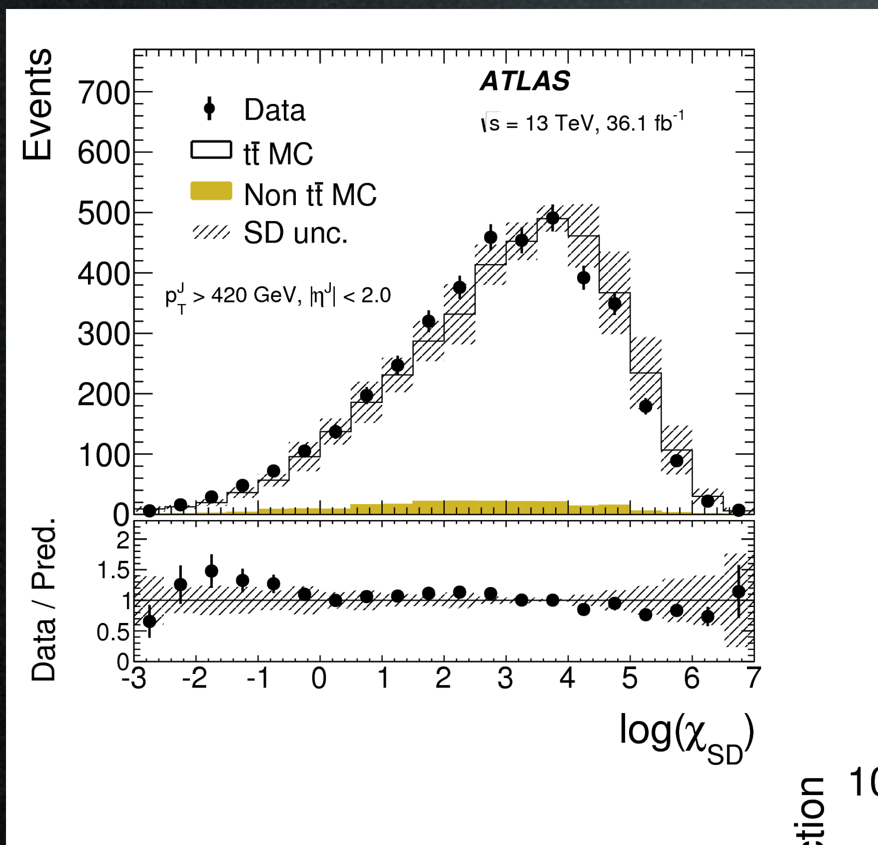
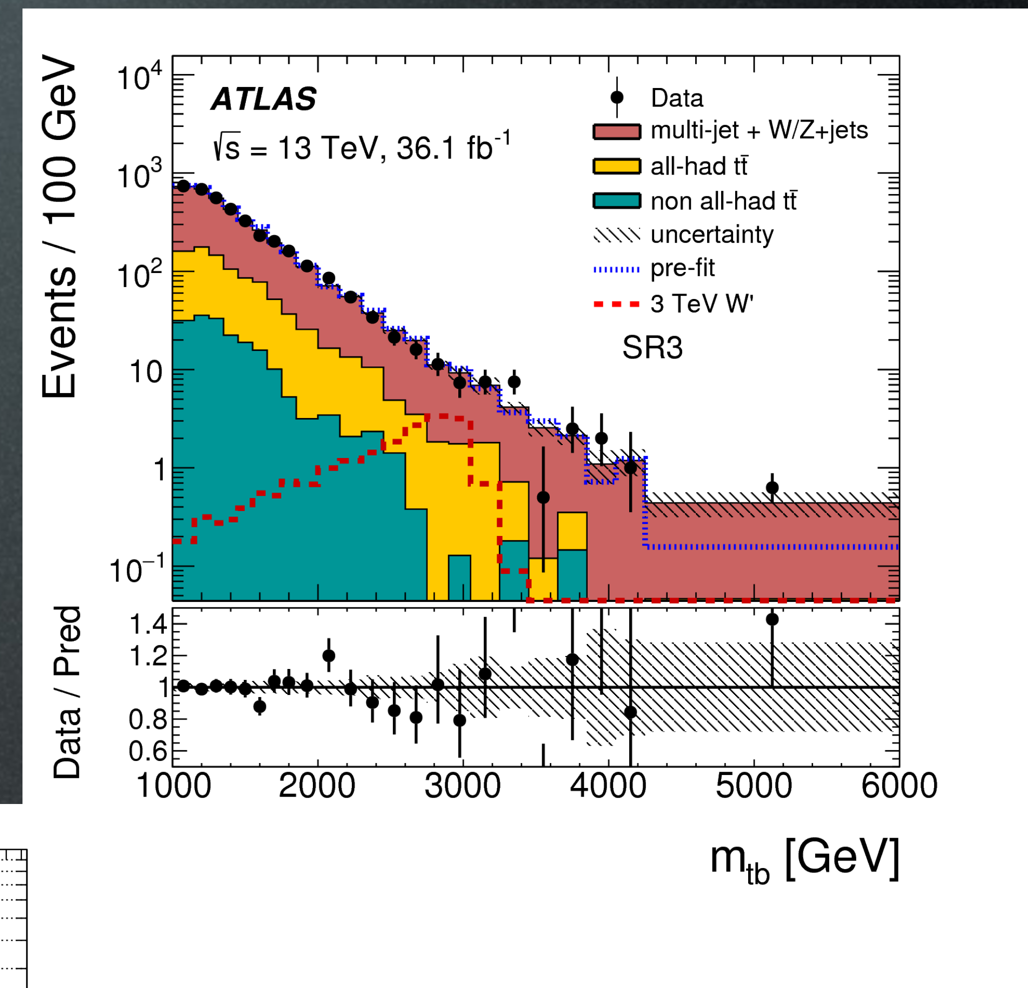
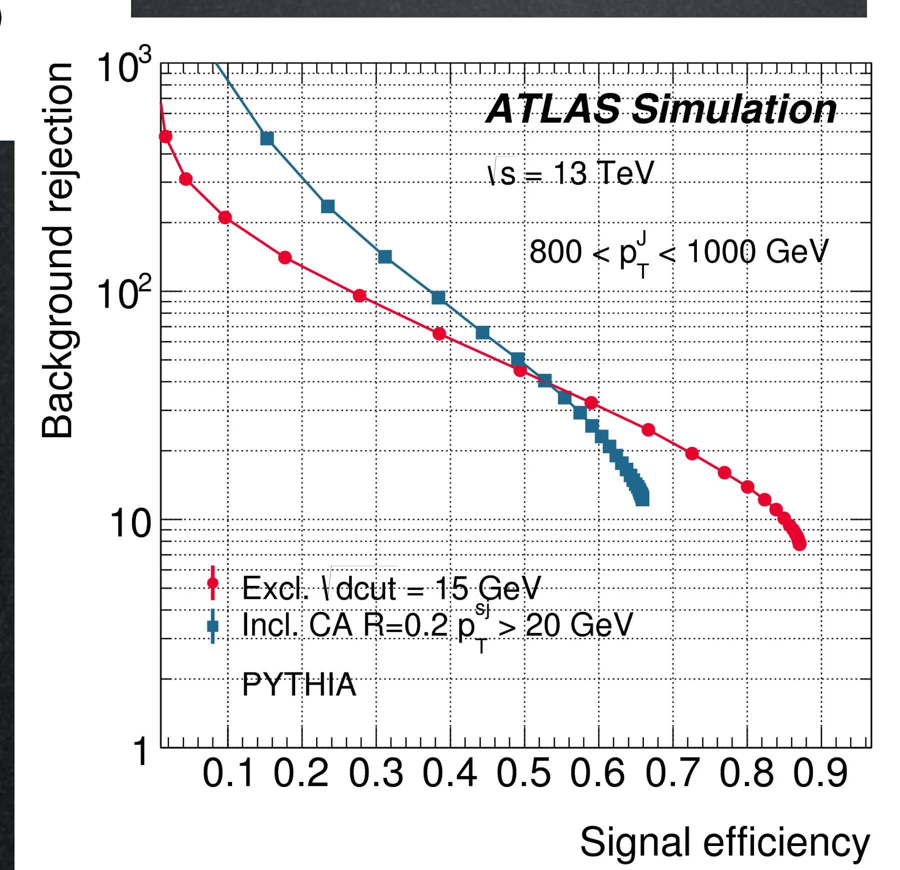
All hadronic W' search



First result using SD





Large improvement in SD performance

No excess seen :-(

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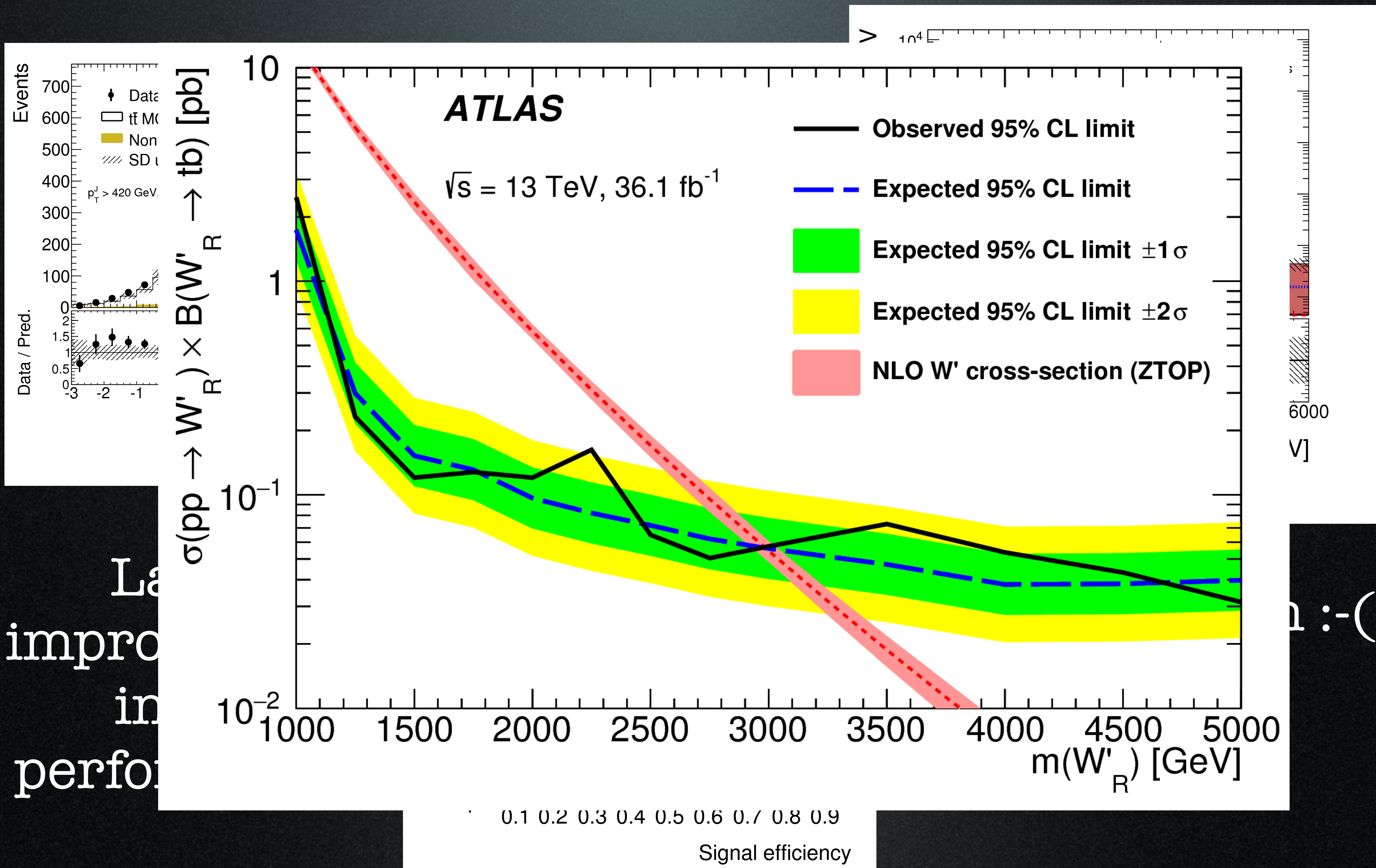
All hadronic W' search



La

impro n :-(

in

perfor