Experimental perspectives for polarisation tagging

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Today menu with disclaimer!

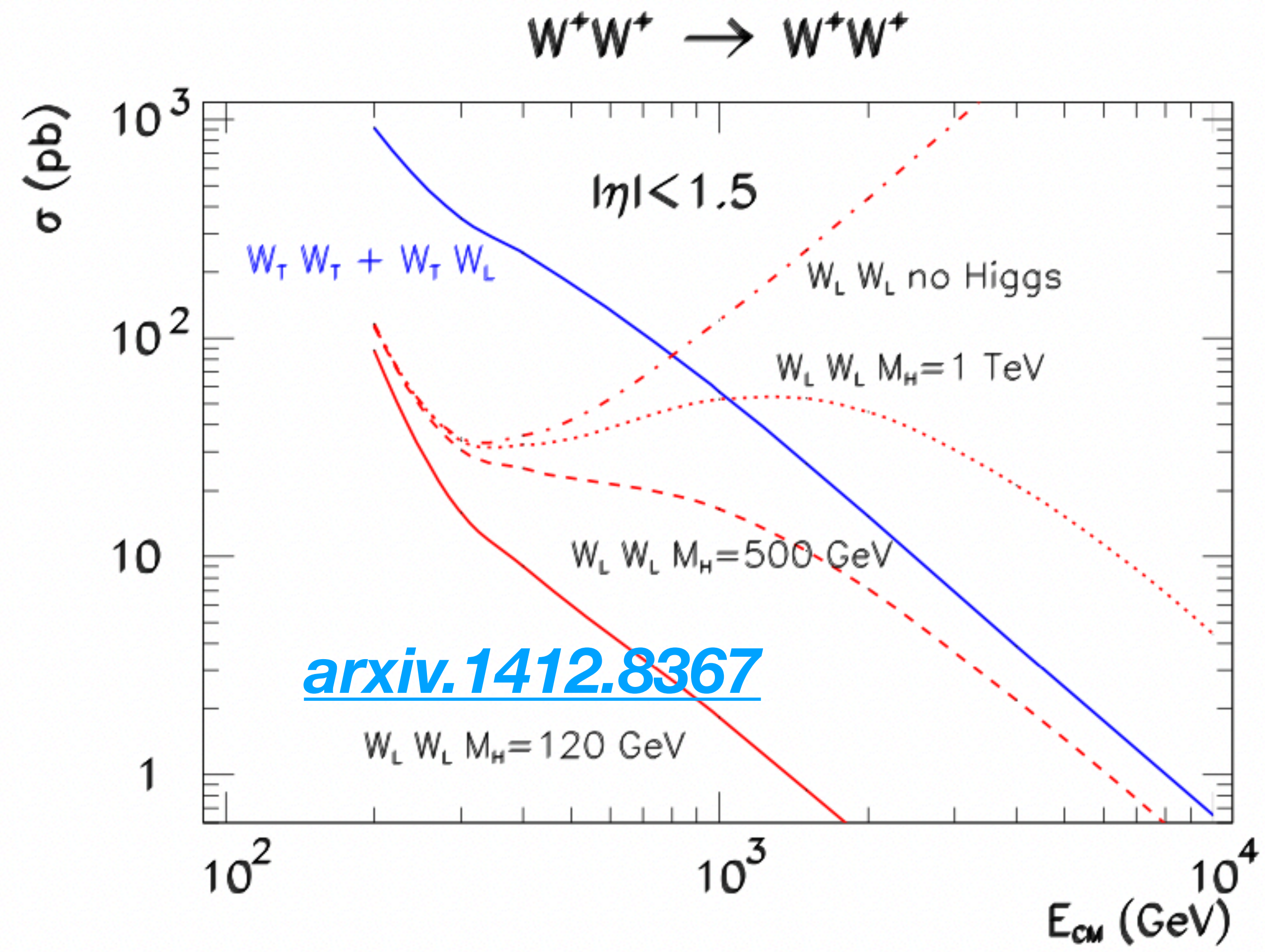
Experimental perspectives for polarisation tagging

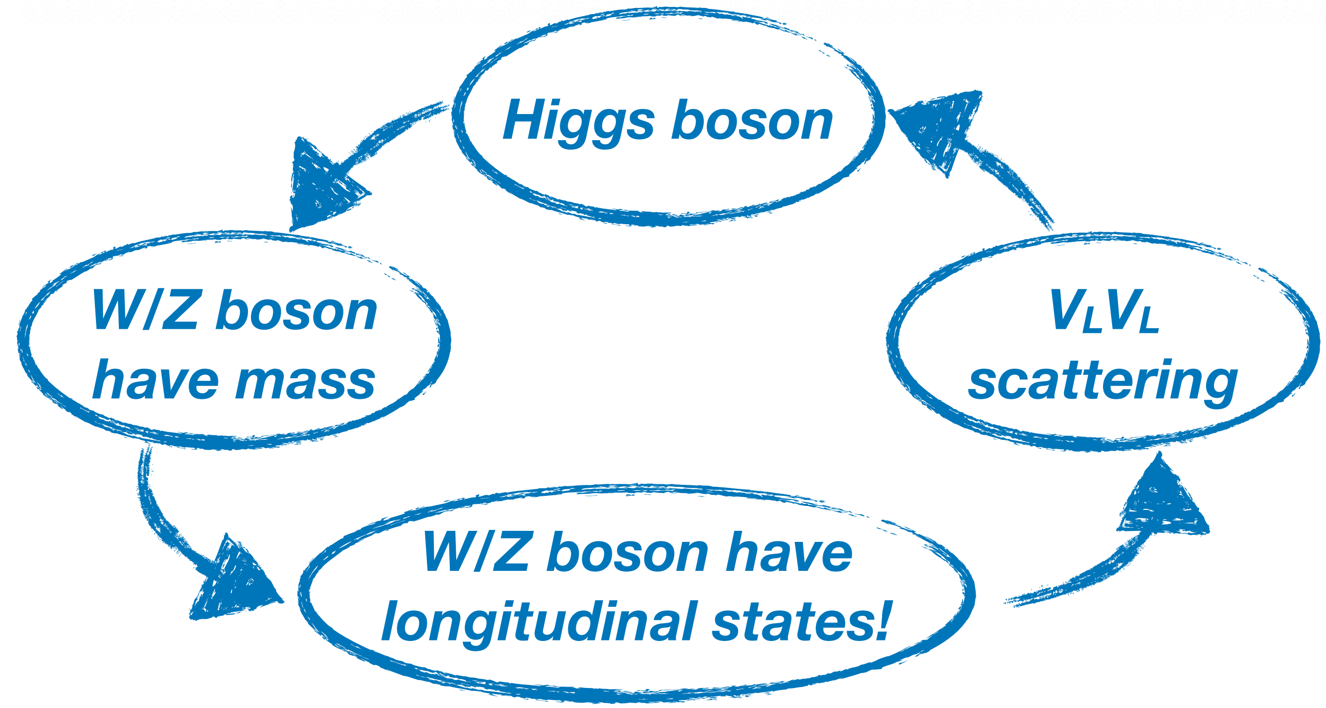
- **Introduction**
  - Why, how to and limitations in current measurements
- **Hadronic boson polarisation**
  - challenges w.r.t. leptonic boson
  - some solutions of the task
- **Looking towards to the future**
  - evolution of the task
  - applications in diboson measurements
- **Wrap-up**
  - Conclusions

Thanks a lot for the great chance to prepare this talk. The selection of material and its flow come from my person perspective of the topic!

Why boson polarisation (in multi-boson events)?

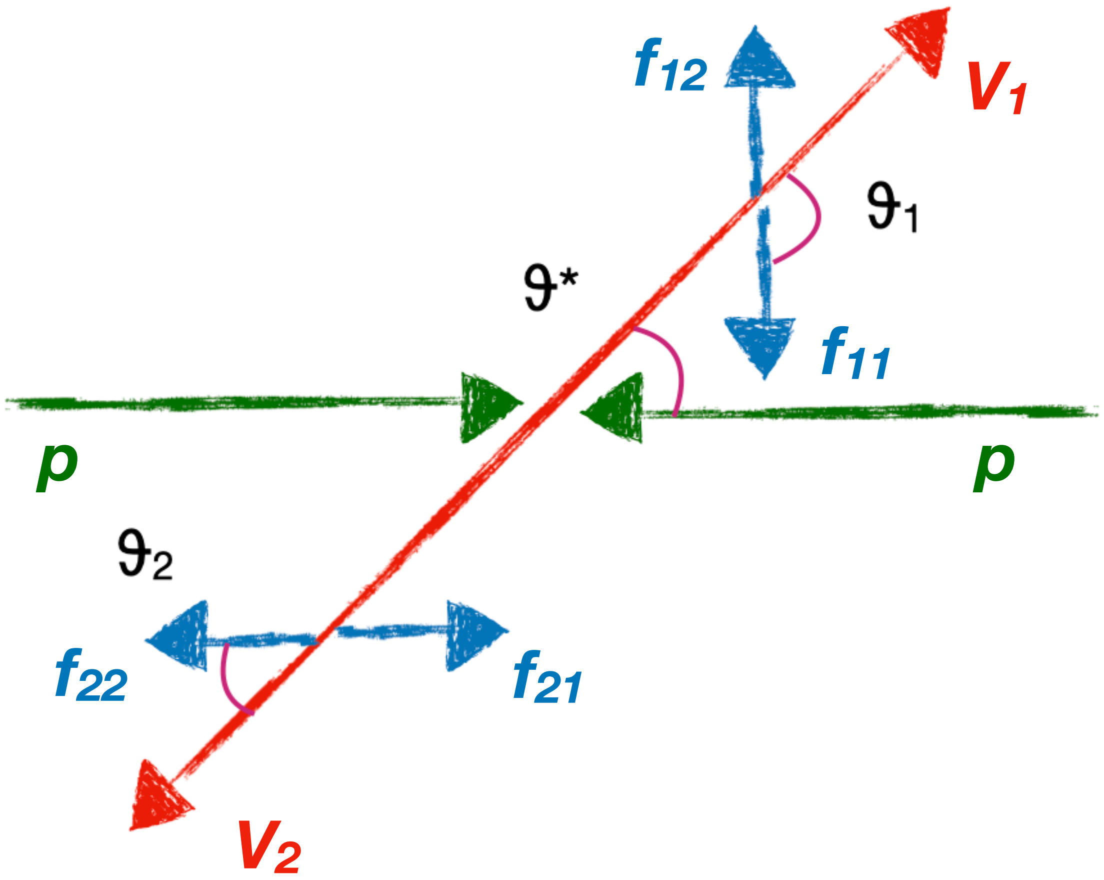
- Diboson interactions are a key process in the LHC program
  - according to the EWK sector the $W_L W_L$ scattering is violating the unitarity at the TeV scale
  - we expected something to happen with the LHC era
- After the Higgs discovery, we can say that the Higgs+EWK sector can mitigate this
  - however, this still needs to be directly confirmed at very high energy
- ***High-energy diboson interactions may still hide new physics!***





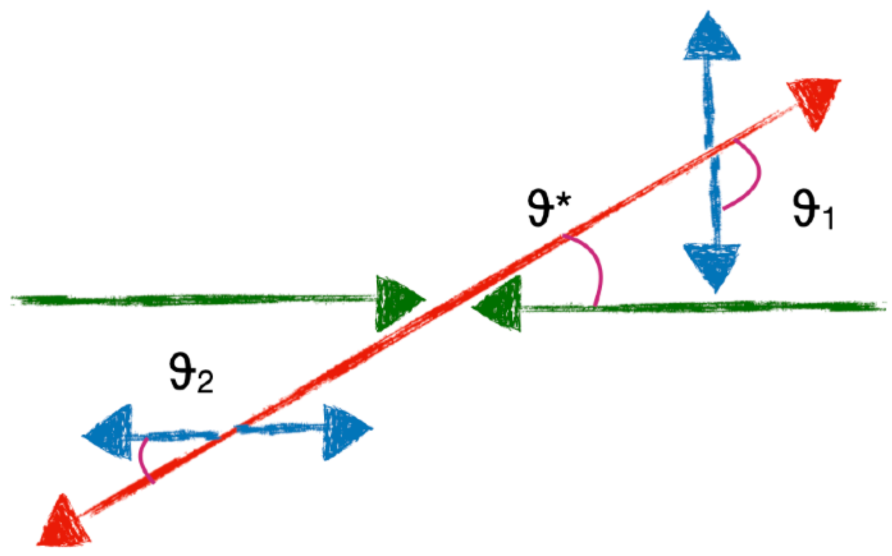
Boson polarisation definition

- Let's first set the stage about the meaning of boson polarisation
- ***Definition: scalar product of a particle spin with its momentum***
  - $h = \vec{S} \cdot \frac{\vec{p}}{|\vec{p}|}$
  - it describes the alignment of S with p
- What does it mean from the experimental side?
  - ***i.e. what can we measure?***
- The polarisation is ~correlation between the ***beam*** axis, ***parent*** (boson) axis and ***decay*** products axis
  - ϑ^*, ϑ_1, ϑ_2

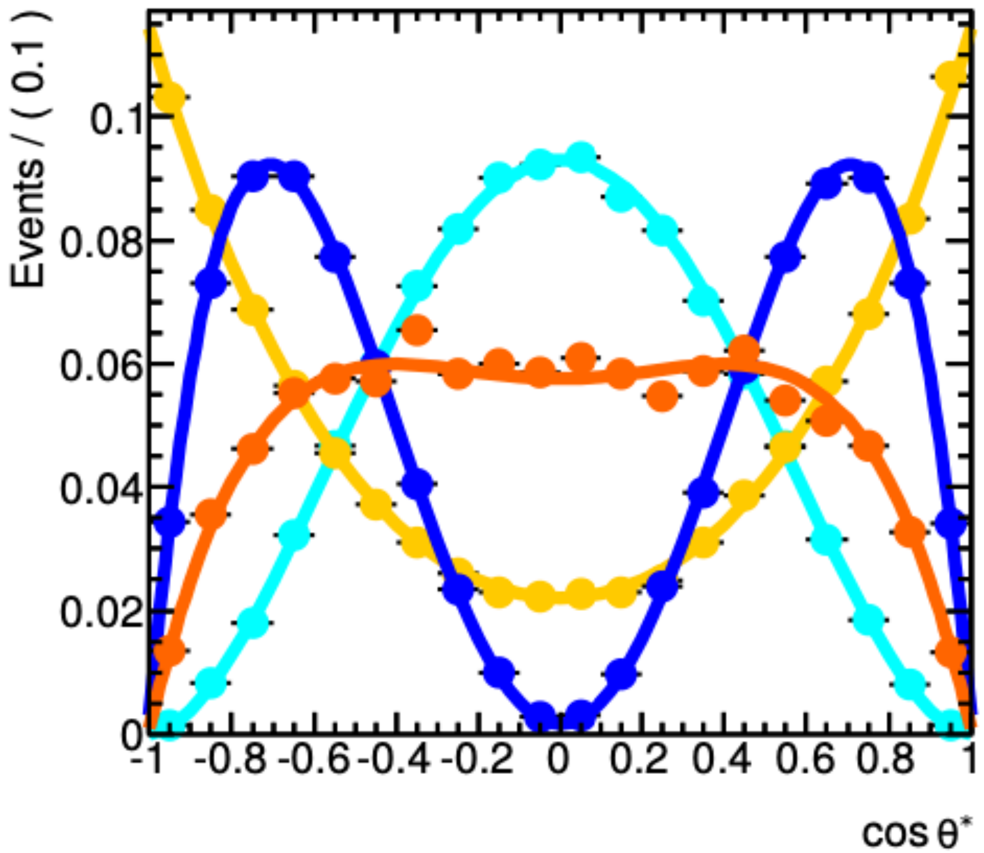


The production/decay angles

Y. Gao

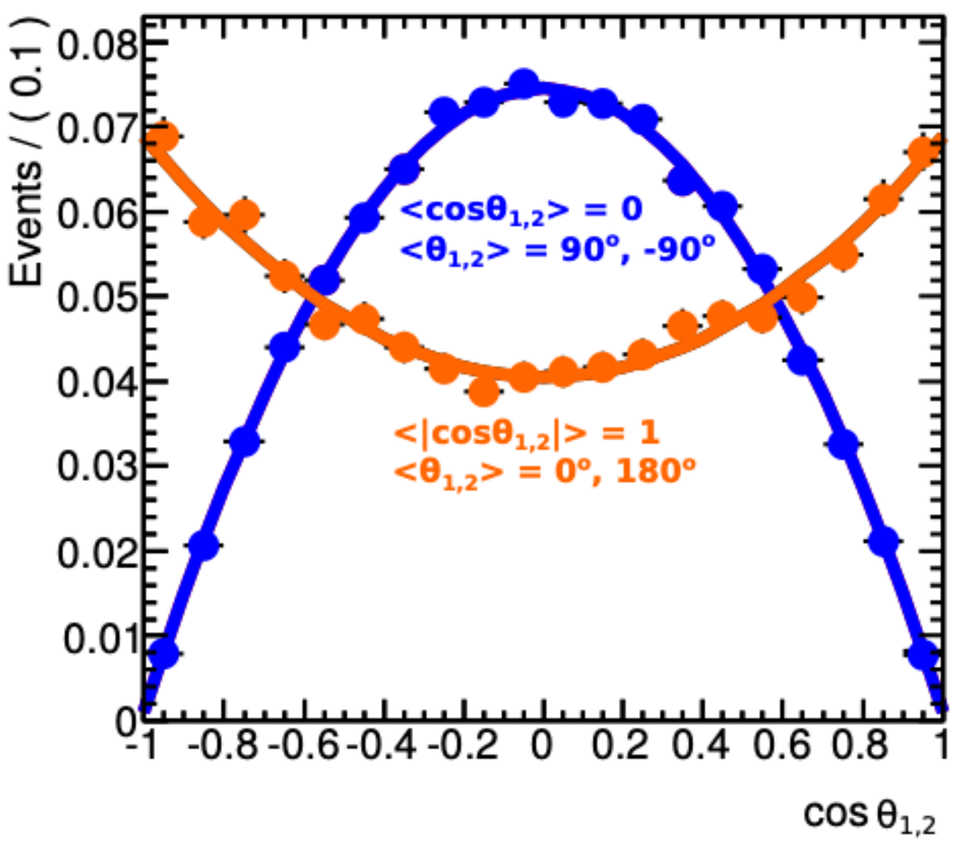


Production angle



— *qq —> ZZ, Z long*
— *qq —> ZZ, Z transv*
— *gg —> ZZ, Z long*
— *gg —> ZZ, Z transv*

Decay angle



— *Longitudinal*
— *Transverse*

Longitudinal: most probable perpendicular to parent axis
Transverse: most probable parallel to parent axis

How do we measure boson polarisation today?

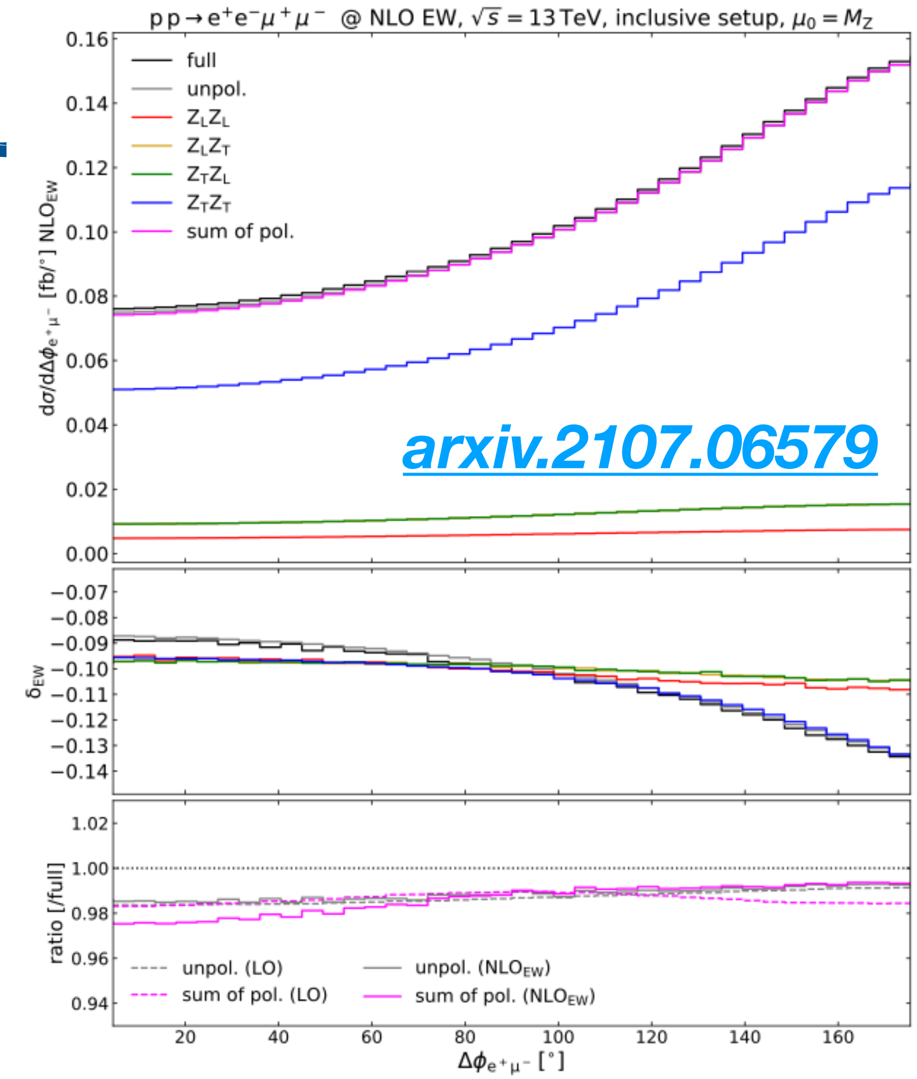
ATLAS link
CMS link

- Boson polarisation has been measured in single W or Z production:
  - W+jets: [*JHEP 72 (2012) 2001*], [*Phys. Lett. B 107 (2011) 021802*]
  - Z+ jets: [*JHEP 08 (2016) 159*], [*Phys. Lett. B 750 (2015) 154*]
- Also W polarisation in ttbar events
  - ATLAS: *Eur. Phys. J. C 79 (2019) 19*
  - CMS: *Phys. Lett. B 762 (2016) 512*
  - Combo: *JHEP 08 (2020) 051*
- Currently, the experimental interest is about measuring it in diboson events
  - both single and joint boson polarisation has been measured in several final states
  - all of them using leptonic final states

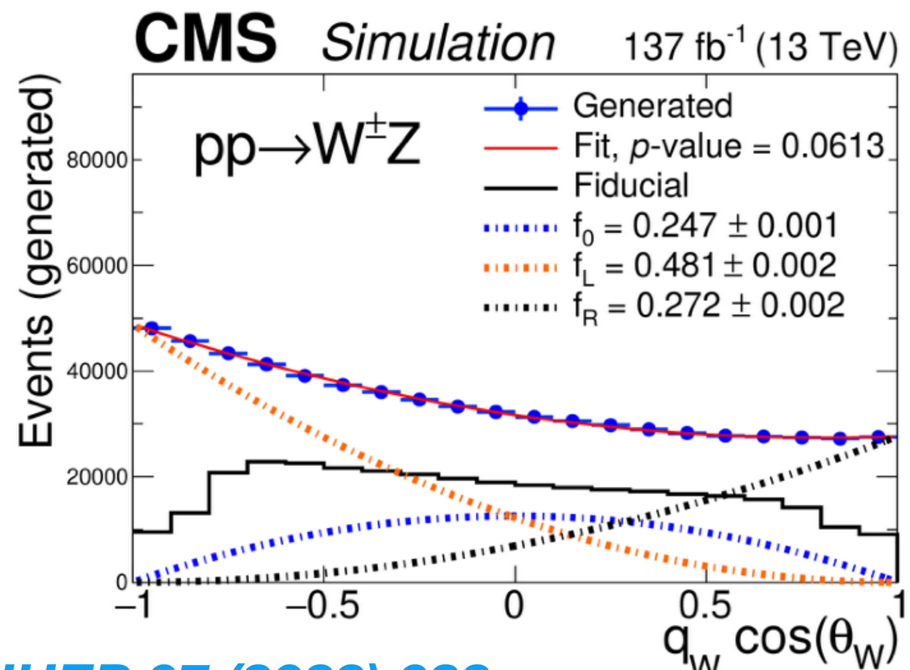
	inclusive	high-p_T	VBS
WW	-	-	-
	-	-	*Phys.Lett. B 812 2021*
WZ	*Phys. Lett. B 843 2023*	*Phys. Rev. Lett. 133*	-
	JHEP 07 (2022) 032	-	-
ZZ	*JHEP 12 (2023) 107*	-	-
	-	-	-

Polarisation with templates

- The angular information of the reconstructed final state are the key players
- Template approach
  - generate diboson polarisation aware samples
  - typically MadGraph used from experiments
- ***Pros: extract the polarisation fractions by fitting the separate components to the data in a template fit***
- ***Cons: account for corrections for fixed order calculations, usually, with ad-hoc re-weightings***
- Also other generators on the market
  - ***check the afternoon session for all the info!***



arxiv.2107.06579



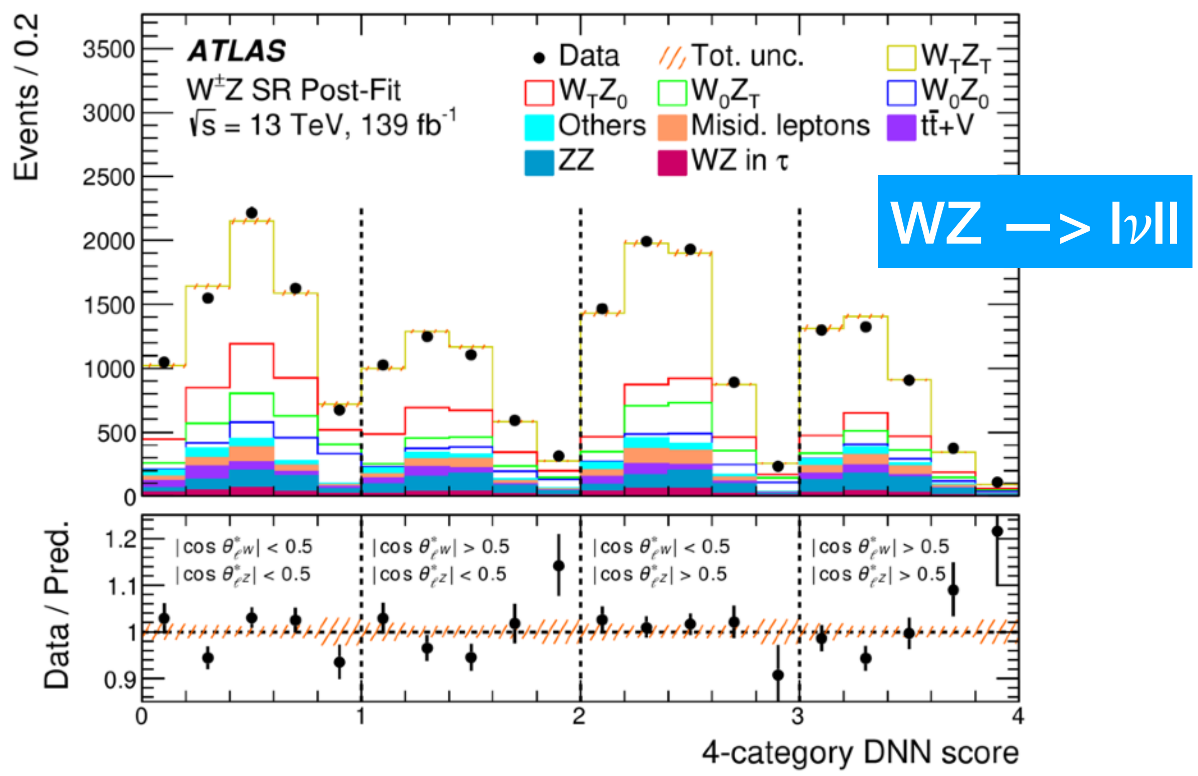
JHEP 07 (2022) 032

Boson polarisation: ML techniques

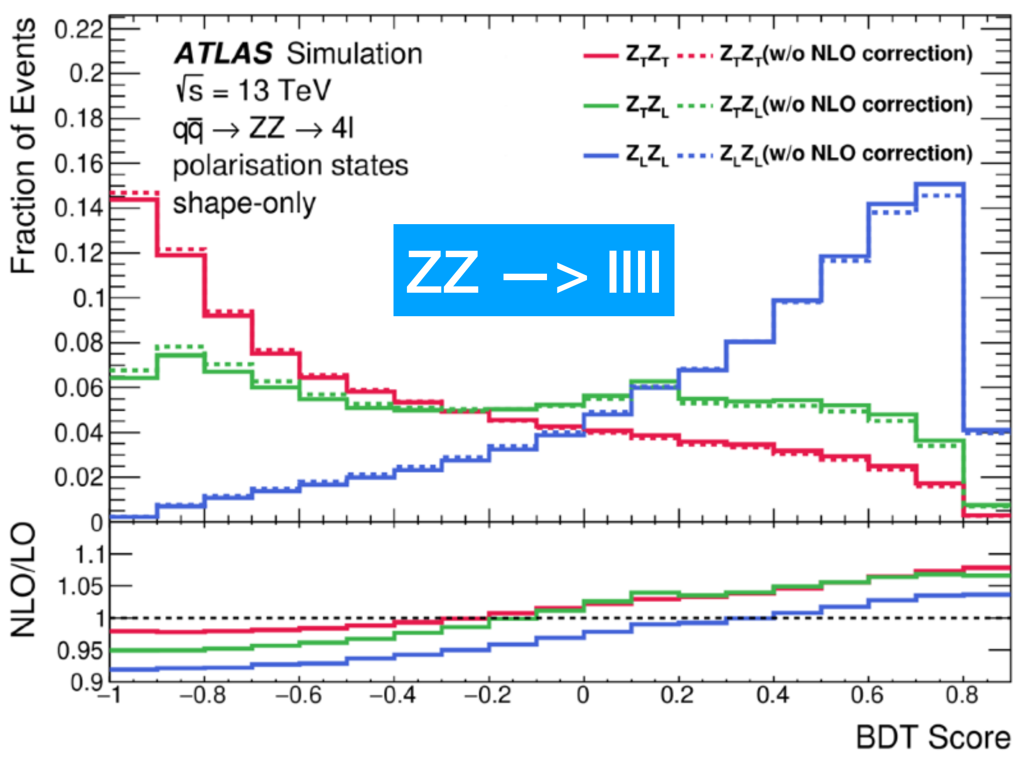
Full details in Max/Sergio talks

- ***Discrimination power from the angular information***
  - some can be limited from detector acceptance
  - more discrimination power in rest/helicity frame
- ***Machine Learning approaches can optimise the discrimination power in building a final discriminant***
  - typically, train the classifier to maximise the separation of one polarisation hypothesis vs all the others + background

[Phys. Lett. B 843 (2023) 137895]



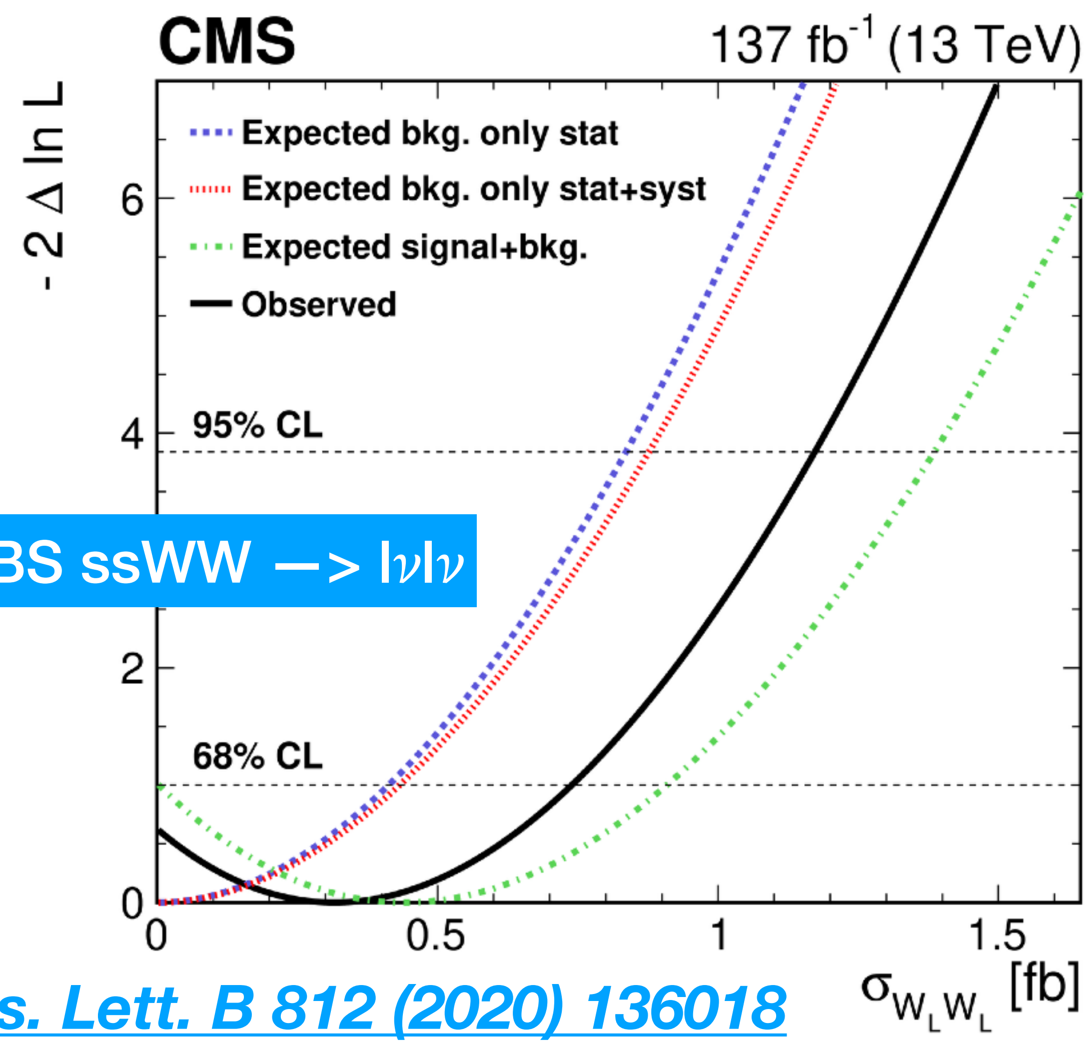
[JHEP 12 (2023) 107]



Boson polarisation: experimental limitations

- ***Statistical limitation***
  - fully leptonic final states are very cleaned but statistically limited when moving at higher p_T
- ***Modelling uncertainties***
  - among the systematics uncertainties, the ones related to the prediction of interference or fixed order corrections

VBS ssWW —> $l\nu l\nu$



[Phys. Lett. B 812 (2020) 136018](https://doi.org/10.1016/j.physletb.2020.136018)

[Phys. Lett. B 843 (2023) 137895](https://doi.org/10.1016/j.physletb.2023.137895)

WZ —> $l\nu ll$

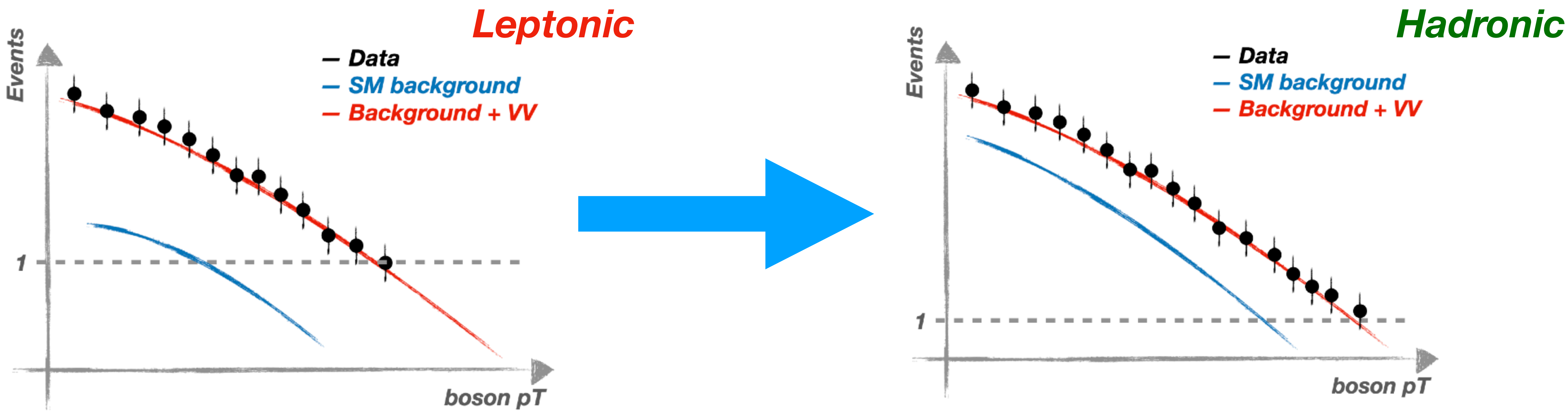
	Measurement		Prediction		
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV		$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.17 \pm^{0.02}_{0.02}$ (stat) $\pm^{0.01}_{0.02}$ (syst)	$0.16 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.02}_{0.03}$ (syst)	f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{XX}	$0.83 \pm^{0.02}_{0.02}$ (stat) $\pm^{0.02}_{0.01}$ (syst)	$0.84 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.03}_{0.02}$ (syst)	f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{00} obs (exp) sig.	7.7 (6.9) σ	3.2 (4.2) σ	f_{T0}	0.109 ± 0.001	0.058 ± 0.001
			f_{TT}	0.619 ± 0.007	0.646 ± 0.008

What can we do?

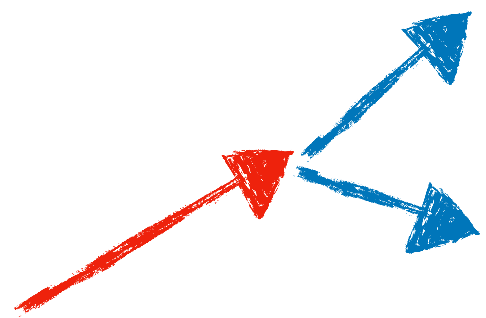
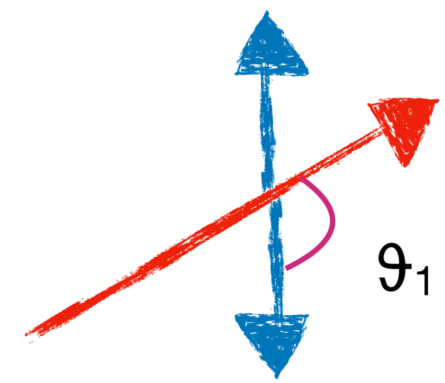
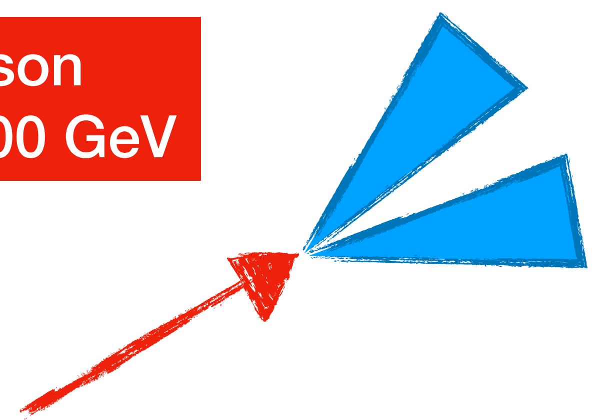
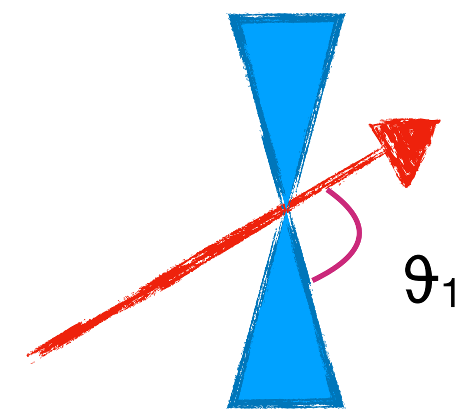
- Boson polarisation has been measured using leptonic decay channels and they can be improved once more data available
  - a matter of time!
- ***What is not covered yet***
  - we do not have measurements using final states with ***hadronic decay of bosons***
- ***Why?***
  - the answer involves at least a couple of aspects
- First, the hadronic reconstruction using jets significantly affects the ***experimental resolution*** to the decay products
  - polarisation aware jet tagging (***decay angle***)
- Then, further information can be exploited in diboson events (***production angle***) but QCD/EWK processes ***are still not observed*** (or close to be done) in these final states
  - waiting for higher luminosity but we are not too far!

What can we do? (II)

- Boson polarisation has been measured using leptonic decay channels and they can be improved once more data available
  - a matter of time!
- ***What is not covered yet***
  - we do not have measurements using final states with ***hadronic decay of bosons***
- ***Is it important/interesting to cover?***
  - final states with hadronic decays allows to reach and probe higher energies w/o waiting for new data taking



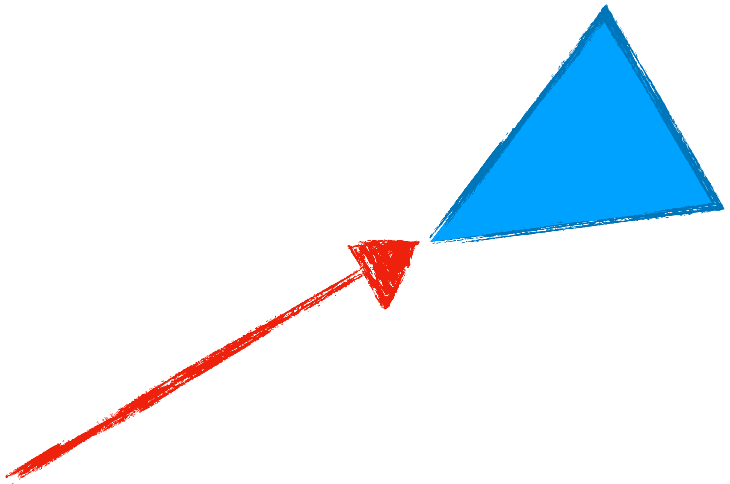
Boson level tagging with jets

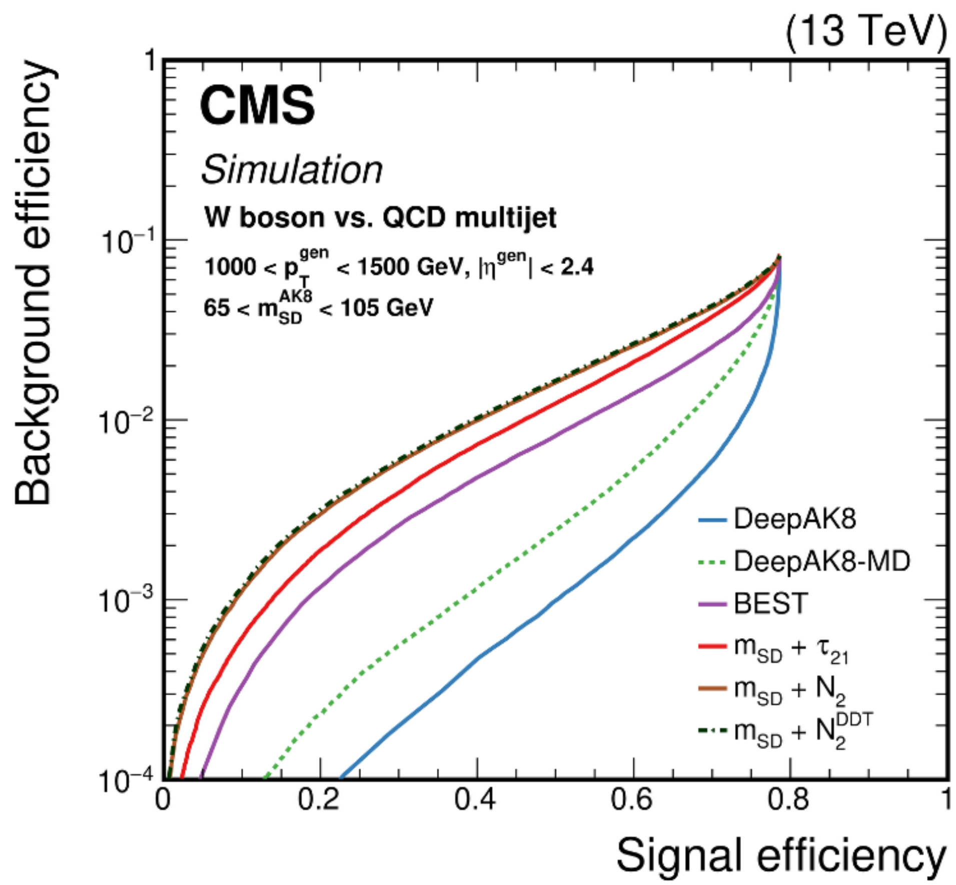
	Laboratory frame	Rest frame
Particle level (qq)		
Jet level (resolved jj) — boson $p_T < 200$ GeV		
Jet level (merged J) — boson $p_T > 200$ GeV		??? polarisation angle, no more

j = small-R 0.4 PFlow/Puppi
J = Large-R 1.0 or 0.8 UFO/Puppi

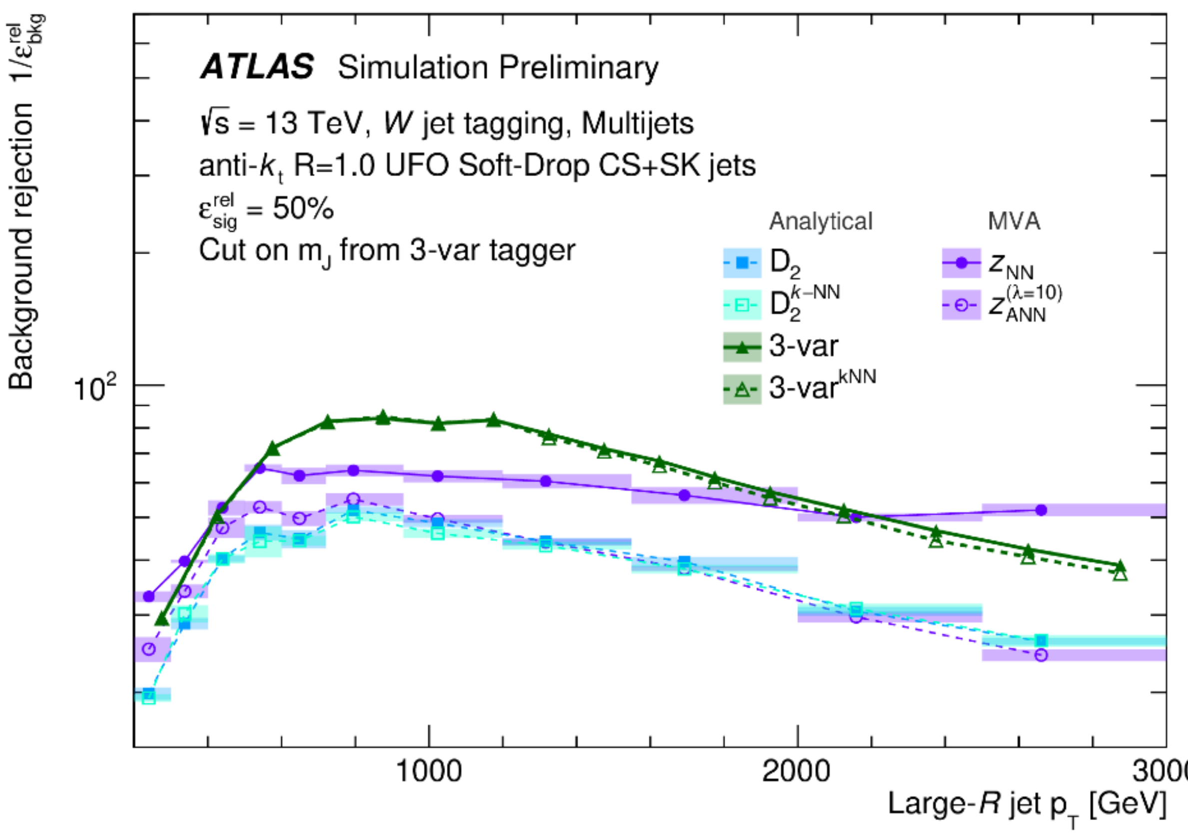
How to at high p_T boson regime?

- For high-p_T bosons, > 200 GeV, the 2 bodies decay can not be resolved at the detector level
    - it seems we can not use the discriminating information of ϑ_1
- ***What can we do?***
    - look at the jet sub-structure
- ***How?***
    - well known solution in the general boson tagging problem, i.e. W/Z vs q/g initiated jets





JINST 15 (2020) P06005

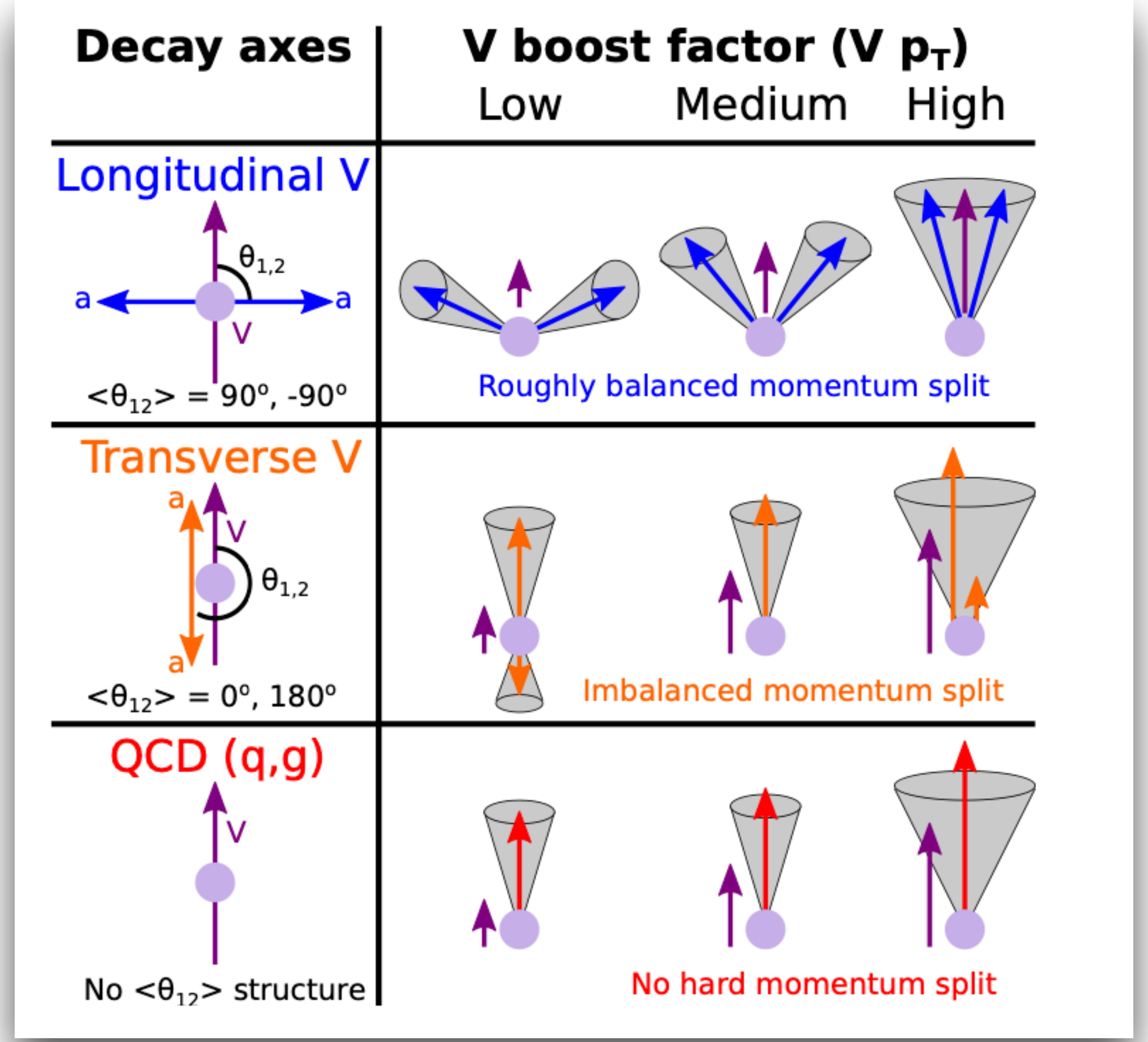


ATL-PHYS-PUB-2021-029

Jet polarisation as a classification task

- The most natural approach seems to extend the well know solution of the boson jet tagging to the boson polarisation
  - ***binary classification task: transverse vs longitudinal***
- ***What inputs?***
  - discrimination power in the jet sub-structure (JSS) related to the ***momentum imbalance*** of the two prongs
- ***What techniques?***
  - individual variables or ML using JSS variables or jets constituents

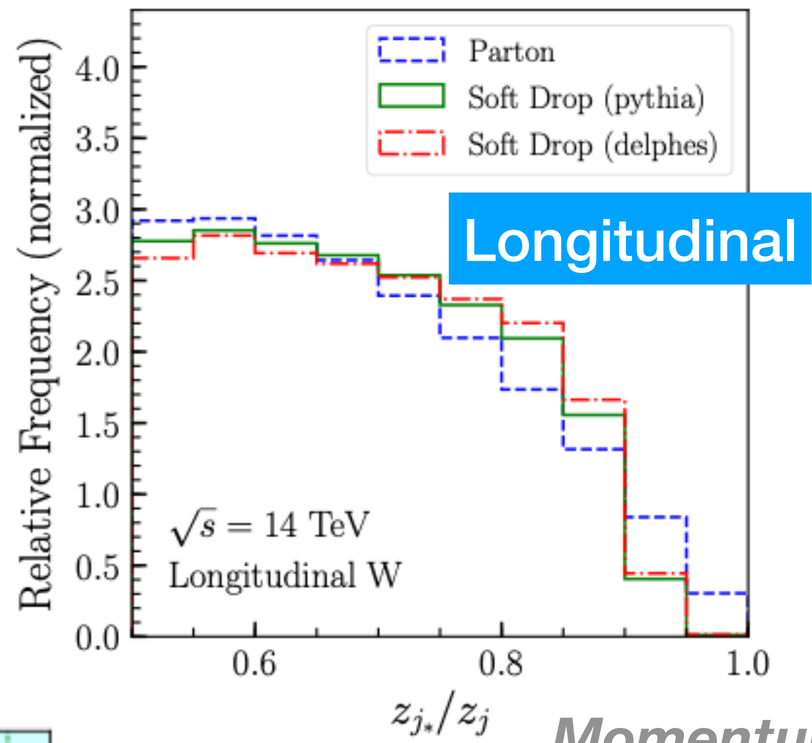
Image from Steven Schramm

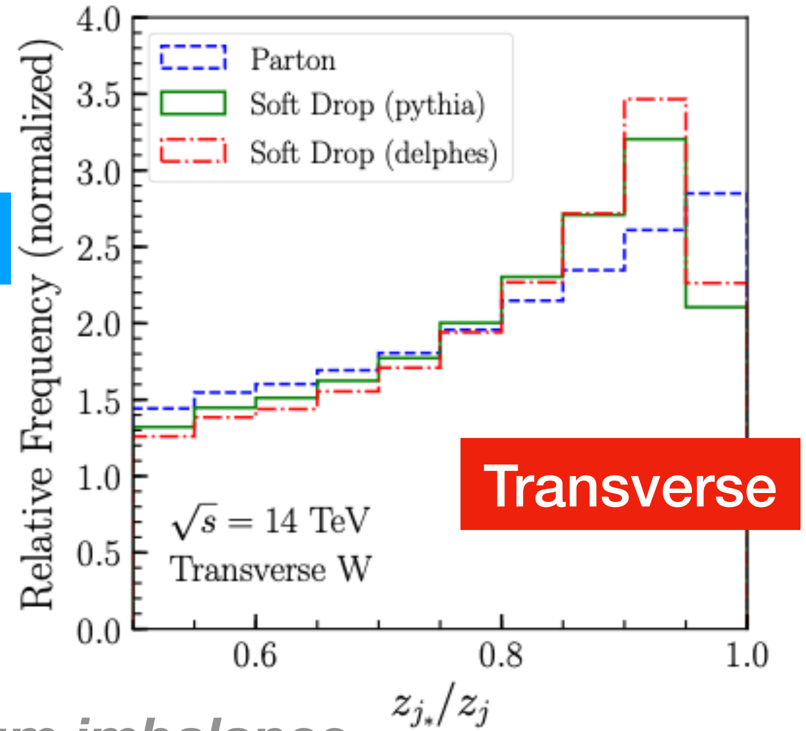


Performances of JSS

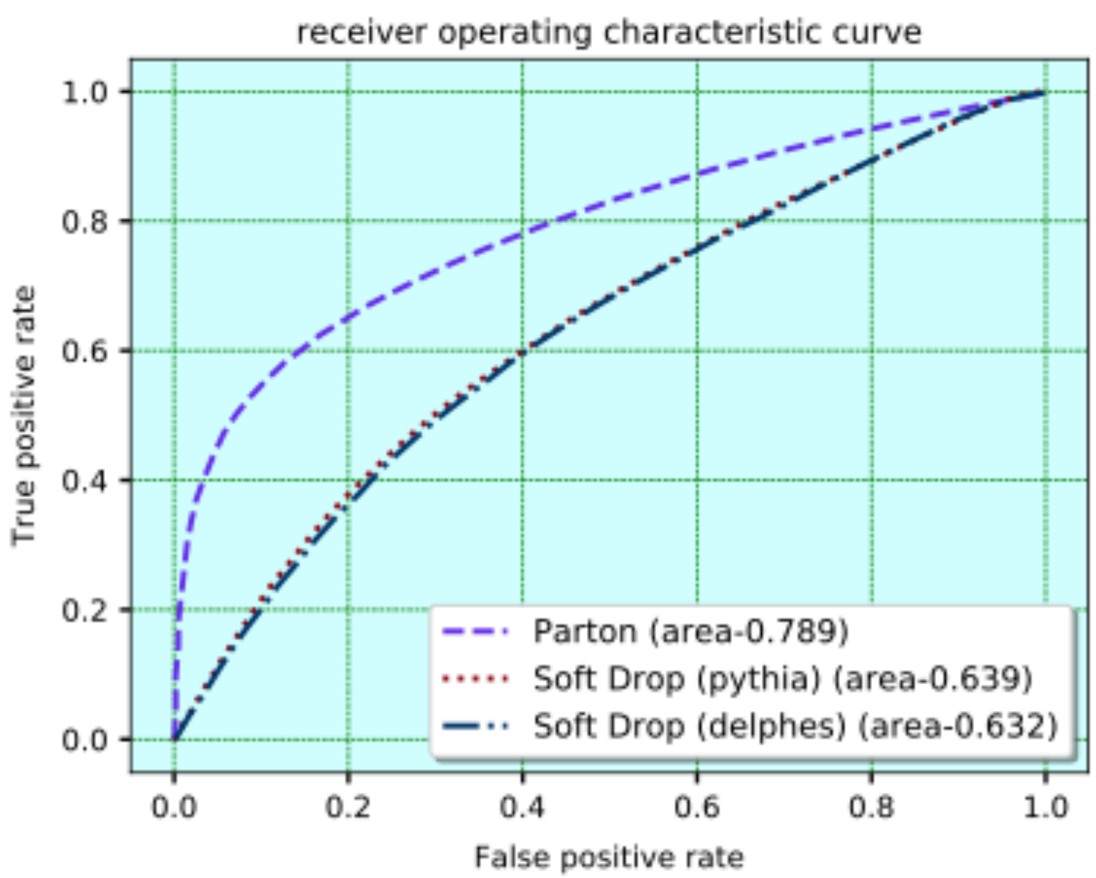
arxiv.2110.02773

- Variables as the momentum imbalance show discrimination power
  - ***combine few variables into a BDT approach to maximise the separation***





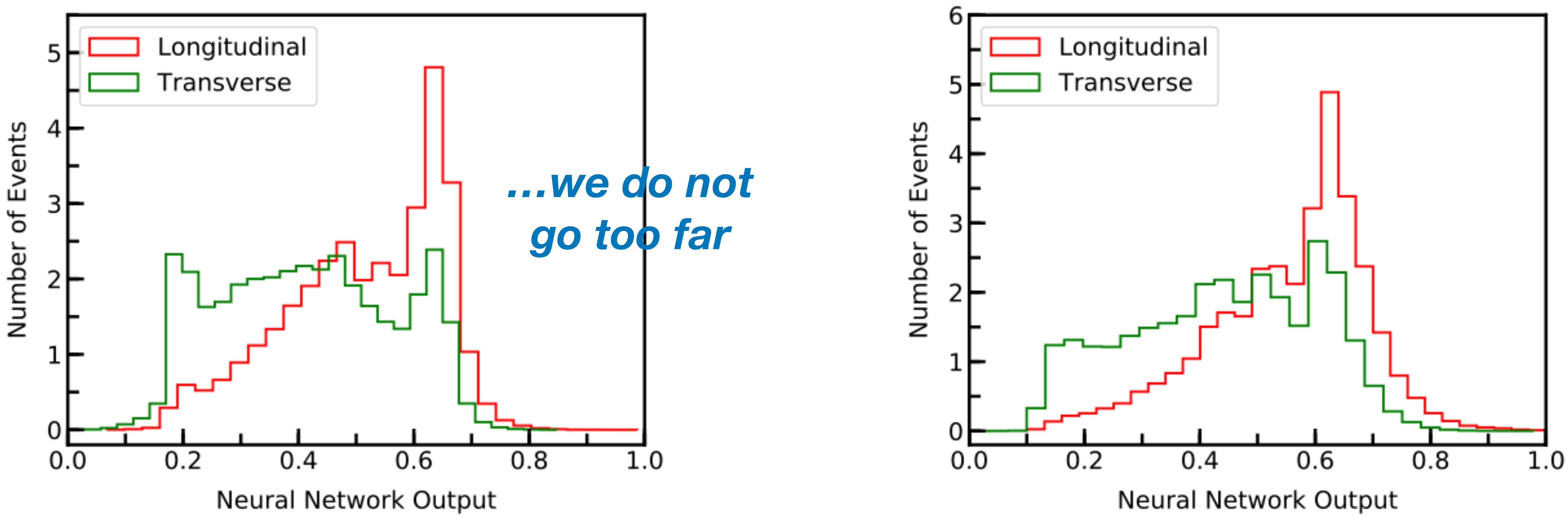
Momentum imbalance in the large-R jet



- Performances:
  - unfortunately, strongly affected from the detector resolution
  - ***@50% efficiency —> ~33% contamination!***

Let's try a deeper ML approach

- Likely, the JSS are not powerful enough? Affected too much from the detector resolution?
    - JSS are not used for W/Z/top tagging problems from long time
    - ***instead, we moved to use more advanced Deep Learning to explore the low level jets constituents!***
- Let's try with ***jet images***, i.e. jets constituents processed using a DL approach

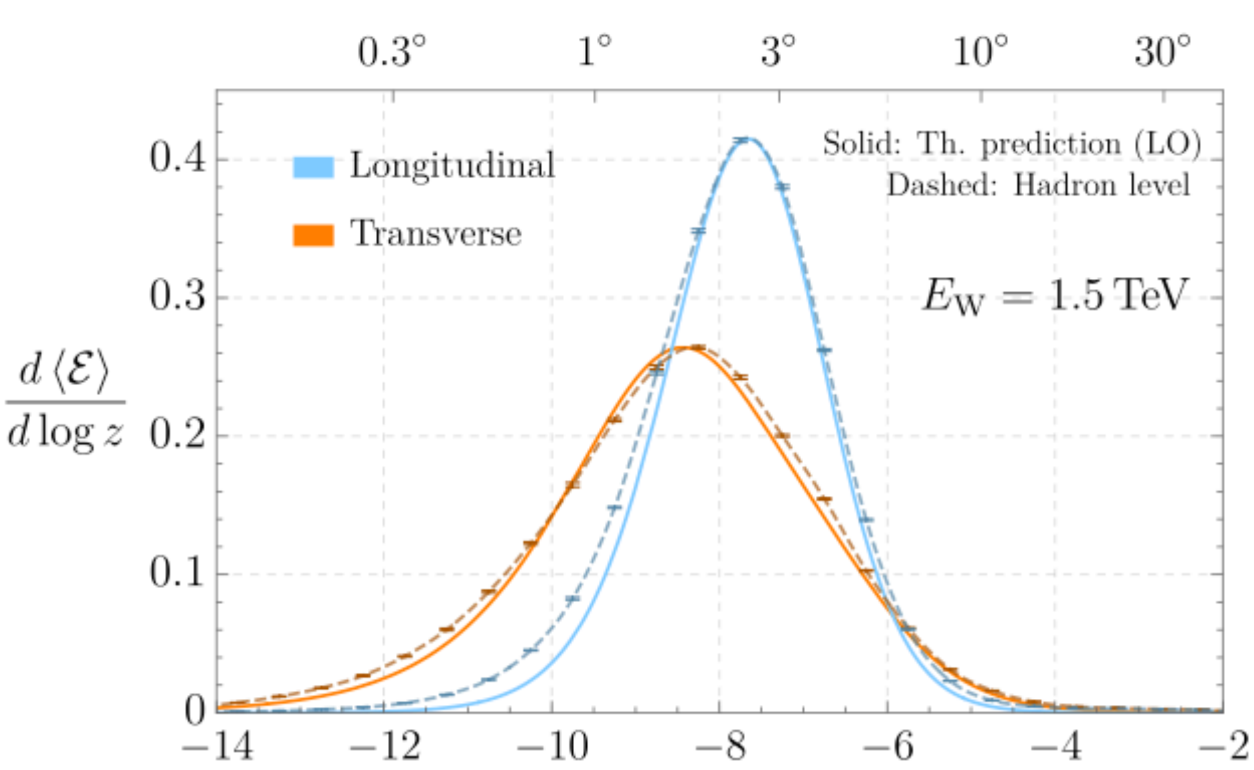


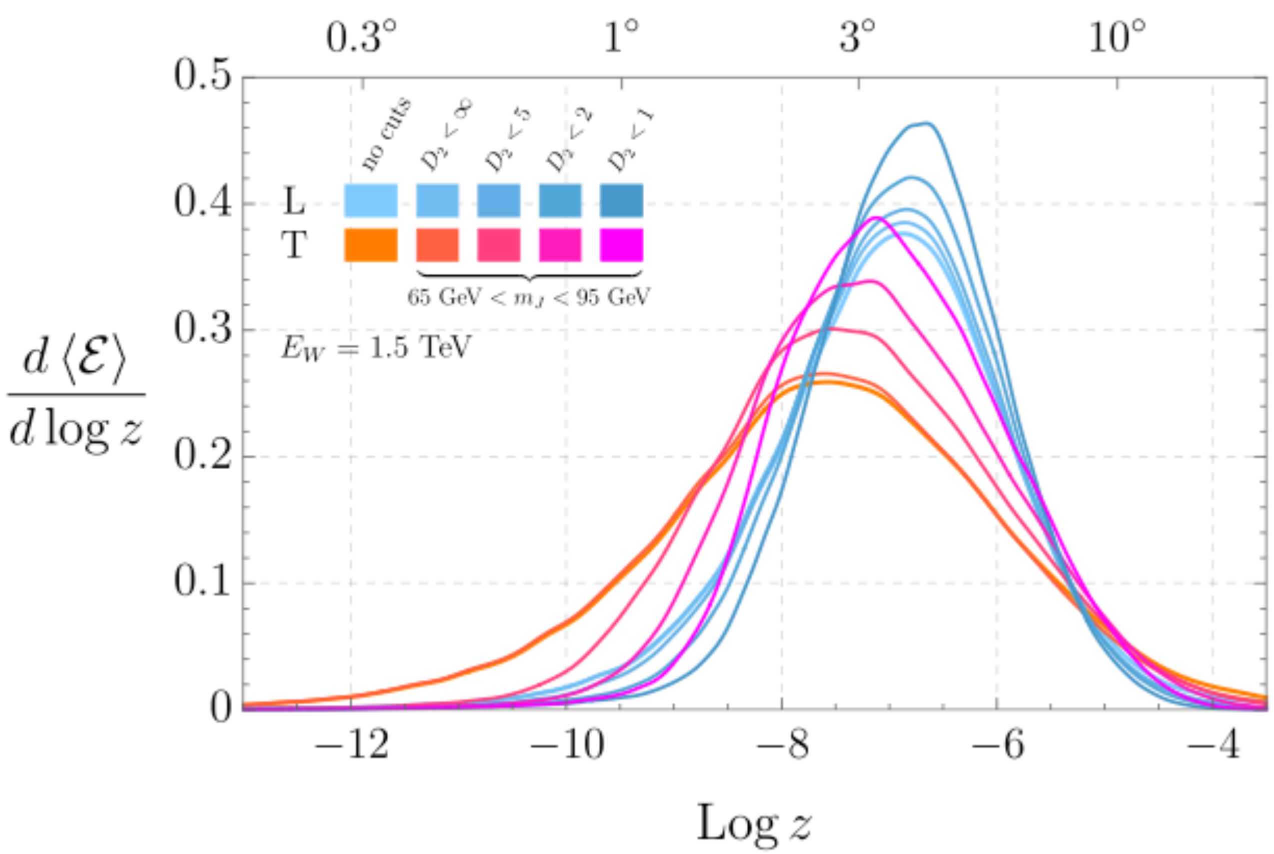
(a) $200 \leq p_T \leq 300$ (b) $400 \leq p_T \leq 500$

arxiv.2102.05124

One more: energy correlators

- A different approach to probe the jet substructure coming from longitudinal or transverse polarised bosons
  - approach to describe the energy correlation among the constituents of the jet
  - discriminant power but still limited
- Additional information for the today discussion:
  - ***the discrimination power is affected from the solution of the general boson tagger problem, i.e. V-vs-q/g, as shown when the 2-prong correlation function D_2 is used***
  - ***correlators sensitive to the interference effect between SM and BSM***





arxiv.2207.03511

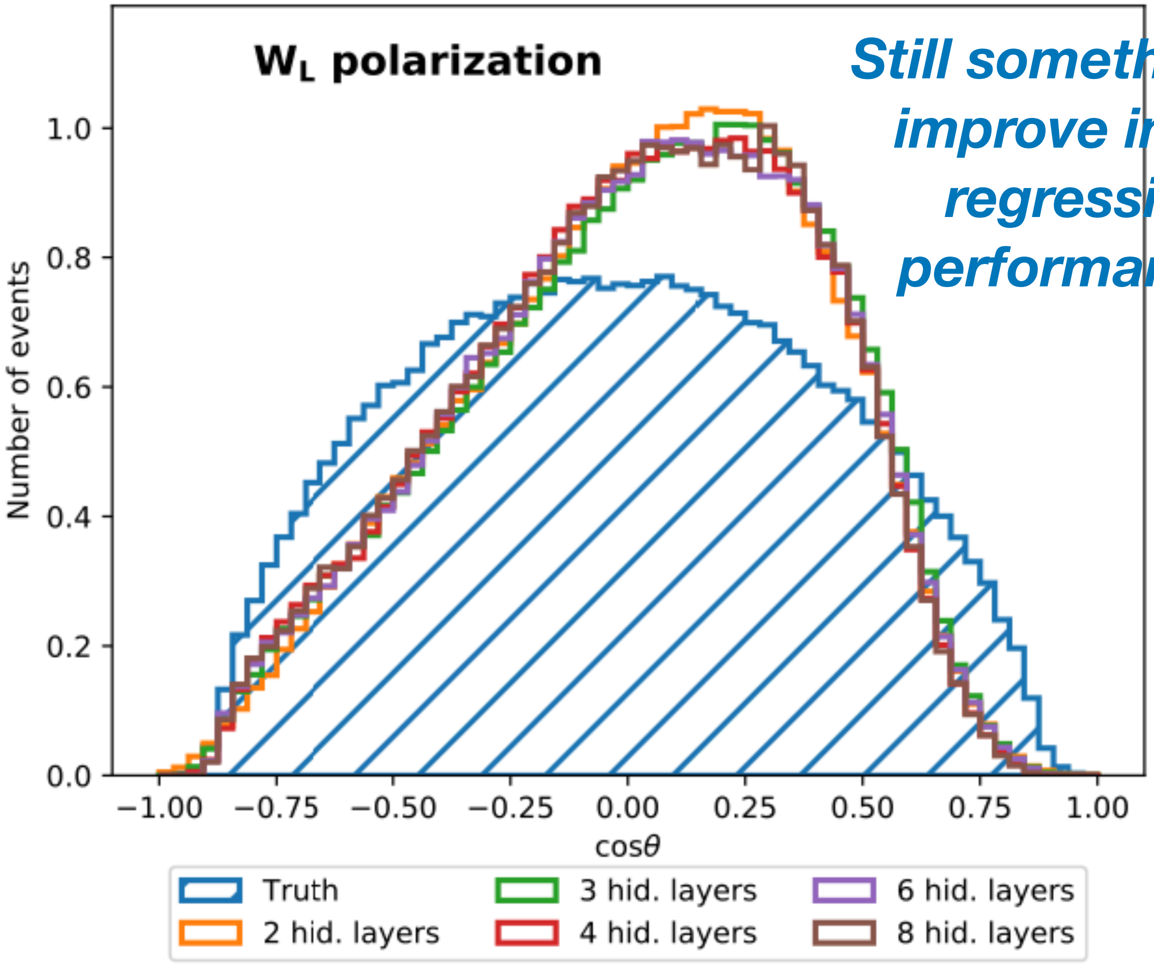
Beyond classification task?

- ***The binary classification task is clearly challenging***
  - several studies show that, roughly, for 1/2 boson classified properly 1/3 is misclassified
- ***Why is it so challenging?***
  - transverse and longitudinal bosons differs for the angular separation between the two quarks (jet sub-structure)
  - but the angular separation is dictated also by the boson (jet) p_T
- ***Warning:***
  - different polarisation end up in different part of the detector
  - the same p_T cut is more stringent for one state than the other (i.e. same p_T bin comparisons might not be fair…)
- ***Let's stop for a second and think about it, what is our real goal?***
  - do we really need to classify T-vs-L at the jet level?
  - we, likely, want ultimately to measure the polarisation ratio

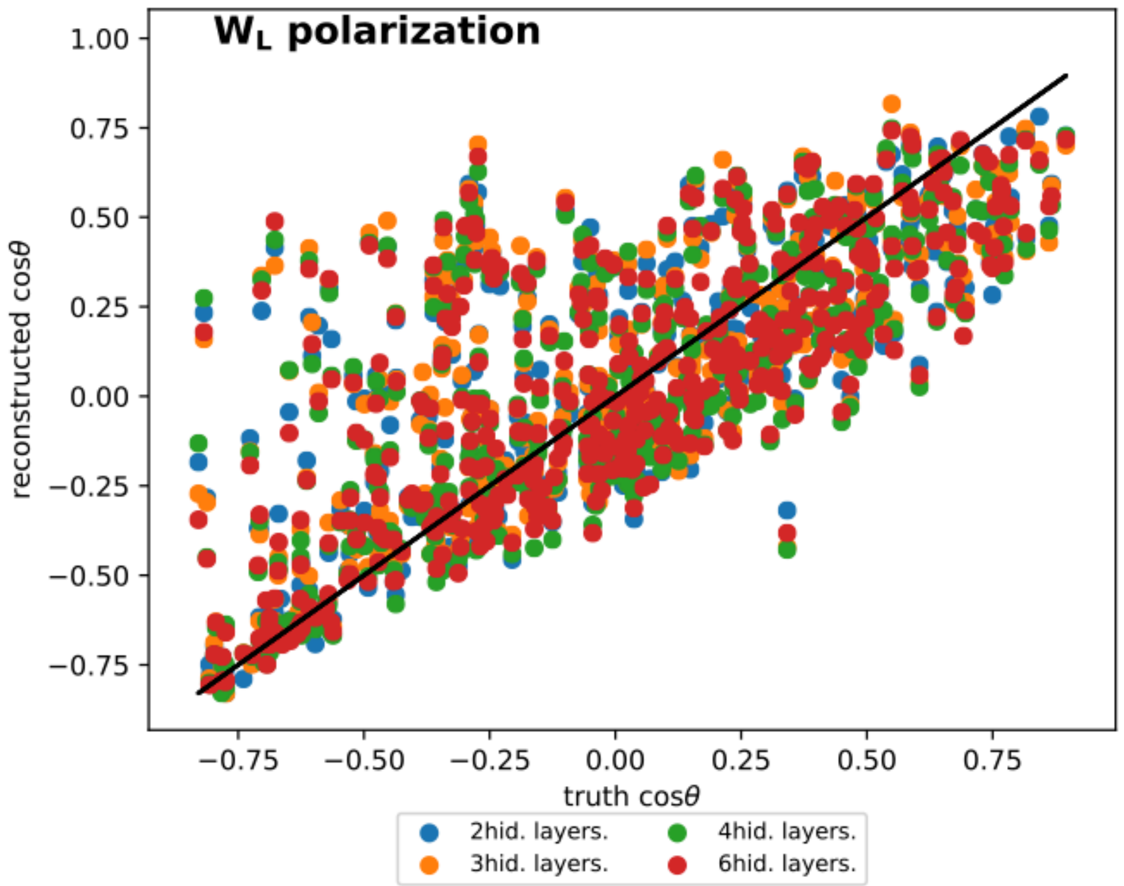
Regression in VBS VV events

arxiv.2008.05316

- Redefining the task could be useful:
  - *input: jet sub-structure or constituents*
  - *output: regressed $\cos\vartheta_1$*
- If we can build a variable that is a proxy of the $\cos\vartheta_1$ we can use it to extract the polarisation fractions
  - approach in the VBS VV semi-leptonic but using the ***W decaying leptonically***



Still something to improve in the regression performances



(Potential) Applications

- ***The jet level polarisation tagger is a definitely a challenging approach***
  - having this in mind, anyway, we want to have a ***clear physics target*** in mind
  - the core task is interesting but it should be a tool to make some physics
- ***What can we measure (and not only)?***
  - polarisation fractions predicted from the SM in diboson events
  - BSM model predict different polarisation states from SM
- ***Why semi-leptonic/fully-hadronic channels?***
  - in principle, more signal events due to BR
  - allow to probe higher p_T phase space

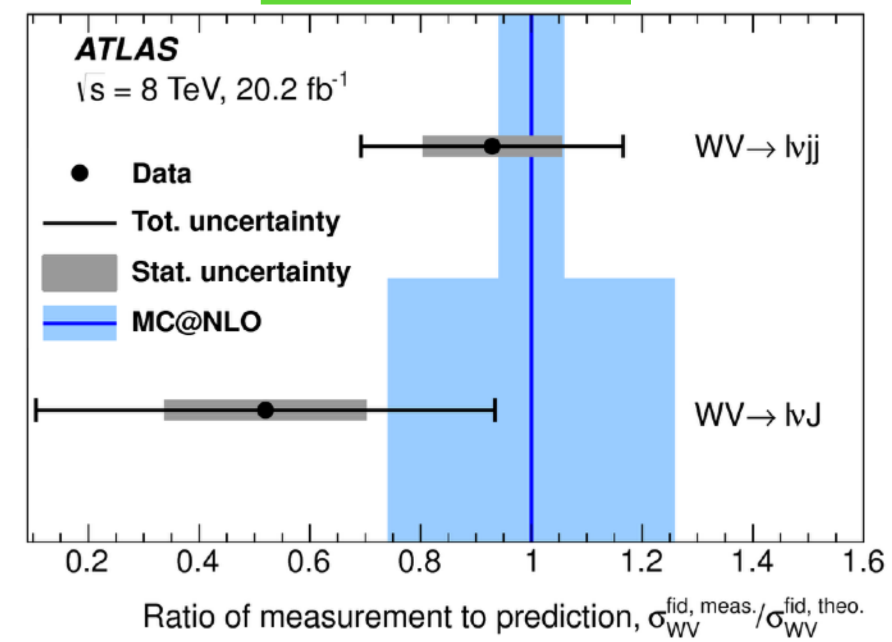
		semi-leptonic	fully-hadronic
Inclusive	WW	$l\nu qq$	qqqq
or	WZ	$l\nu qq/\nu\nu qq/llqq$	qqqq
VBS	ZZ	$\nu\nu qq/llqq$	qqqq

BR(VV—>1234)		W $l\nu$ 21,6	Z $\nu\nu$ 20,5	Z ll 6,8	W qq 67,6	Z qq 69,2
W $l\nu$	21,6	*4,7*	*4,4*	*1,5*	*14,6*	*14,9*
Z $\nu\nu$	20,5	-	*4,2*	*1,4*	*13,9*	*14,2*
Z ll	6,8	-	-	*0,5*	*4,6*	*4,7*
W qq	67,6	-	-	-	*45,7*	*46,8*
Z qq	69,2	-	-	-	-	*47,9*

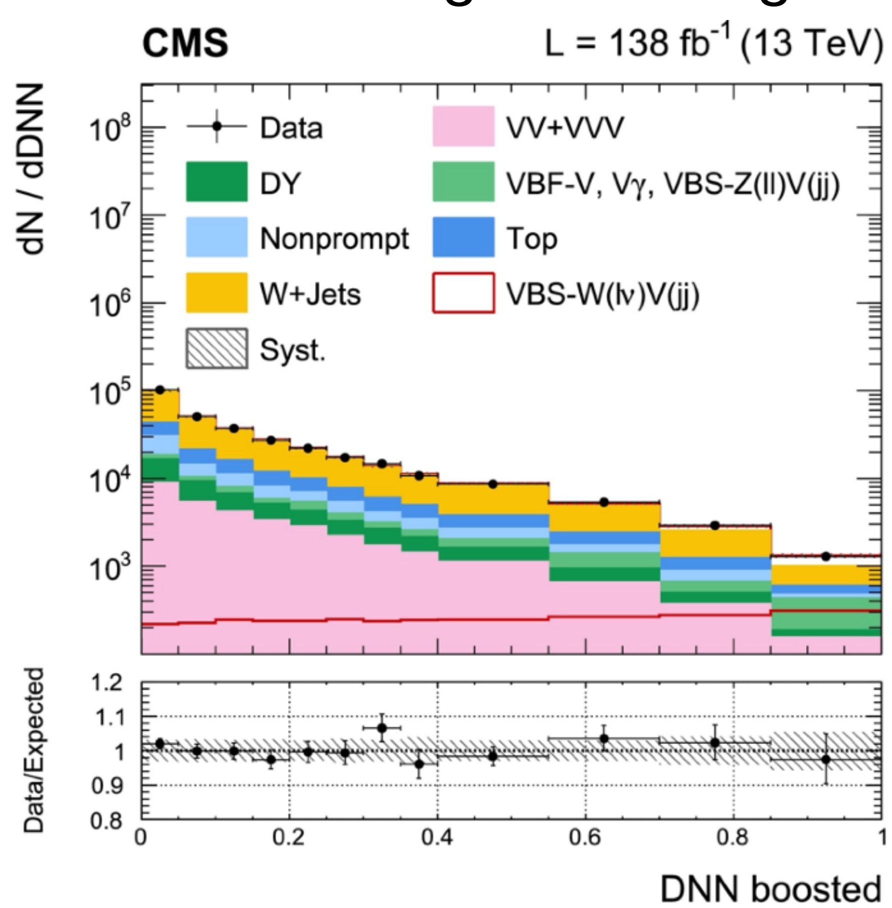
Status of the VV sensitivity in these channels

- ***What do we need to make this happen?***
- First, we need access to the diboson events
  - > (>) 5σ desirable
- ***VV semi-leptonic***
  - inclusive: 4.5σ @Run-1!!! no result @Run-2
  - VBS: ATLAS 2.7σ @36/fb (*Phys. Rev. D 100 (2019) 032007*) CMS 4.4 @138/fb
- ***VV fully-hadronic***
  - even lower given the higher QCD multi-jets background

VV semi-lep



Eur. Phys. J. C 77 (2017) 563

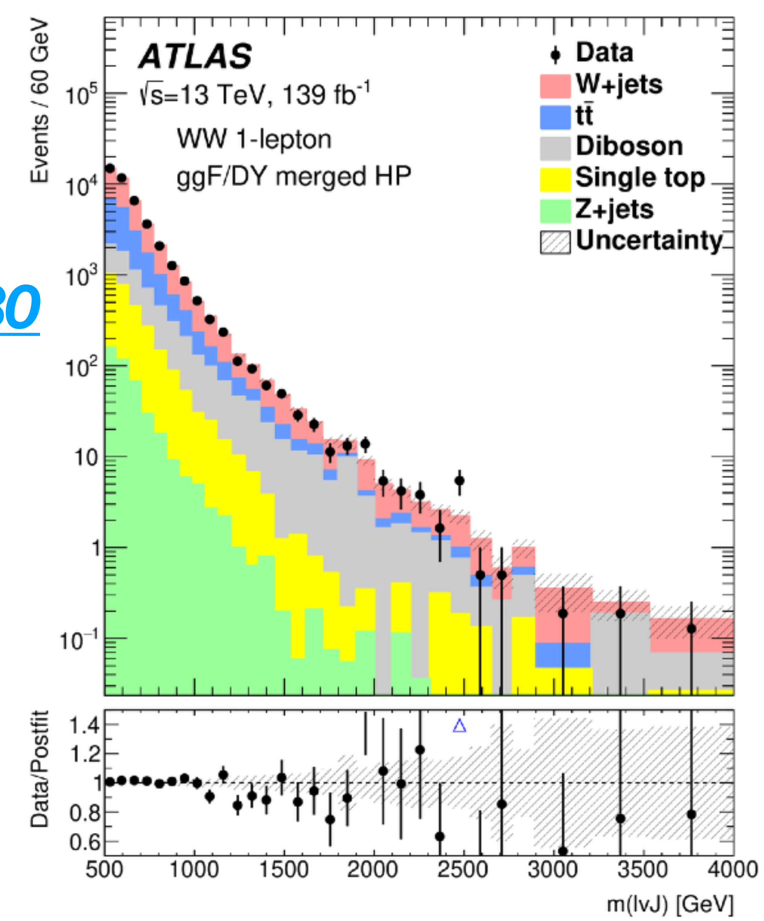


VBS WV semi-lep

Phys. Lett. B 834 (2022) 137438

VV semi-lep (search)

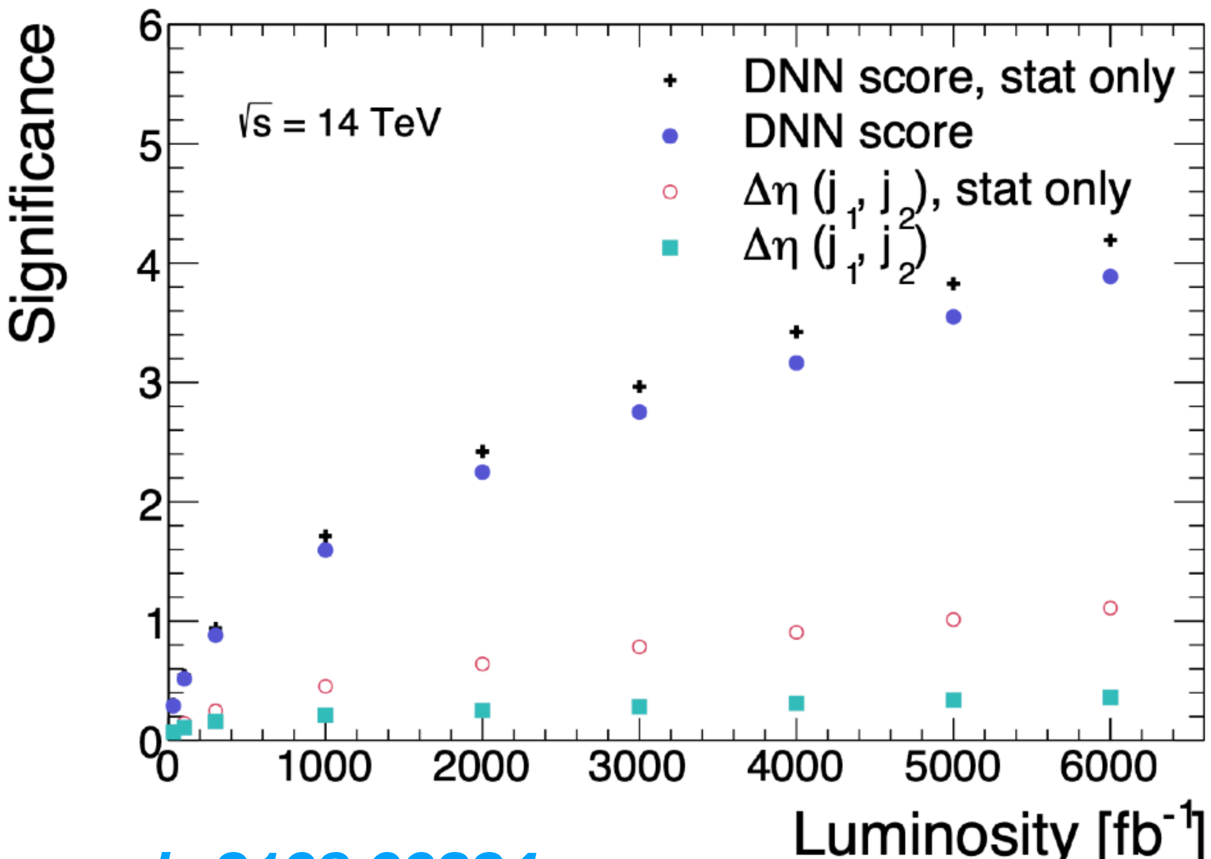
Eur. Phys. J. C 80 (2020) 1165



Looking into the future

- Measurements of boson polarisation in ***VBS*** signature
  - ***VV semi-leptonic prospect***
- Not only measurements: boson polarisation is different in SM or BSM productions
  - ***dim-6 EFT searches***

VBS $W_L V_L$ semi-leptonic



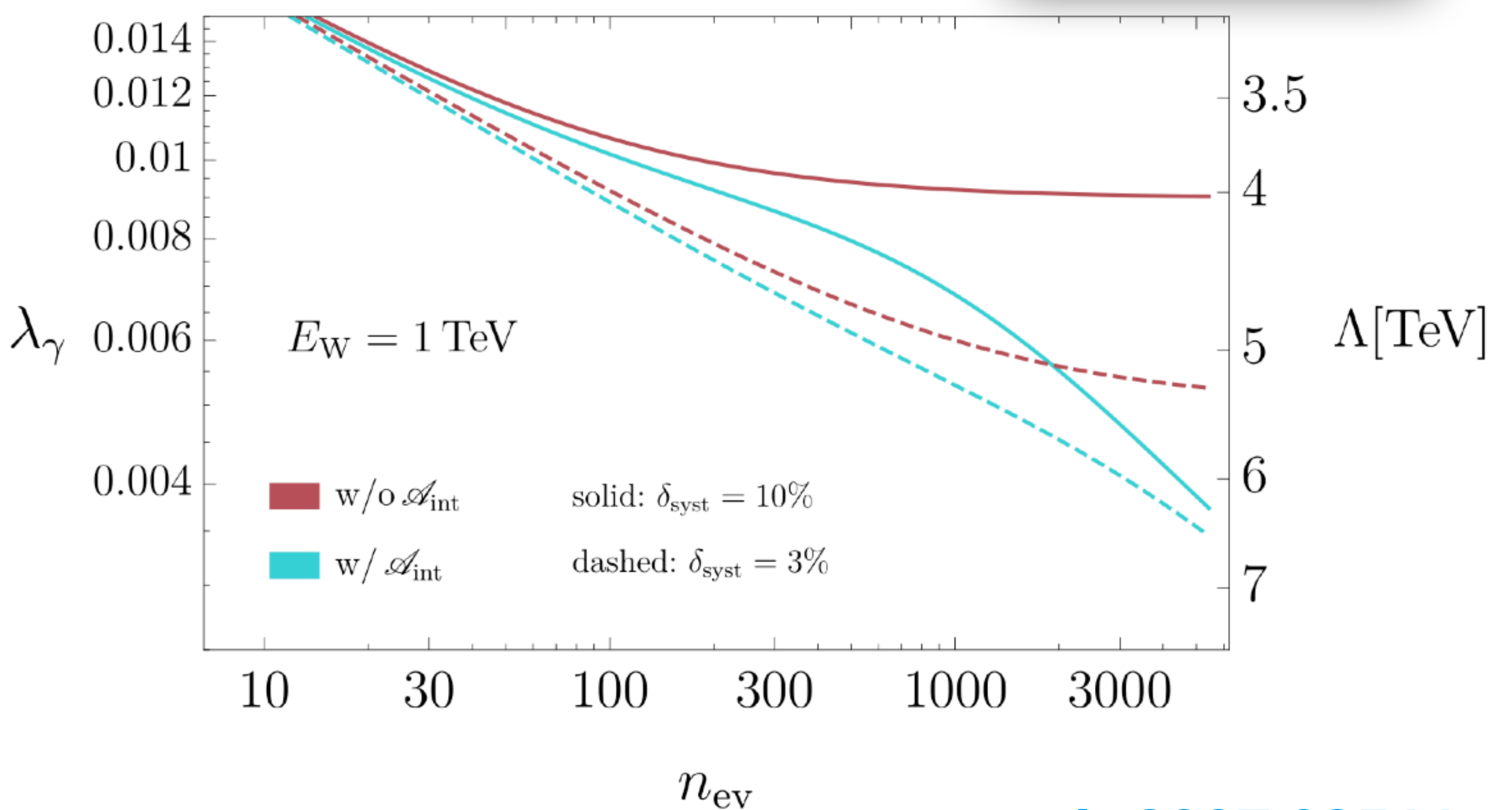
arxiv.2108.00324

More EFT framework details in MBI talks for sure!

$$c_{WWW}\frac{v^2}{\Lambda^2}\frac{g^3}{m_W^2}\epsilon^{ABC}W^A_{\mu\nu}W^B_{\nu\rho}W^C_{\rho\mu},$$

$$\lambda_\gamma = -6g^2 c_{WWW}\frac{v^2}{\Lambda^2},$$

VV fully-hadronic dim-6 EFT c_W constraint

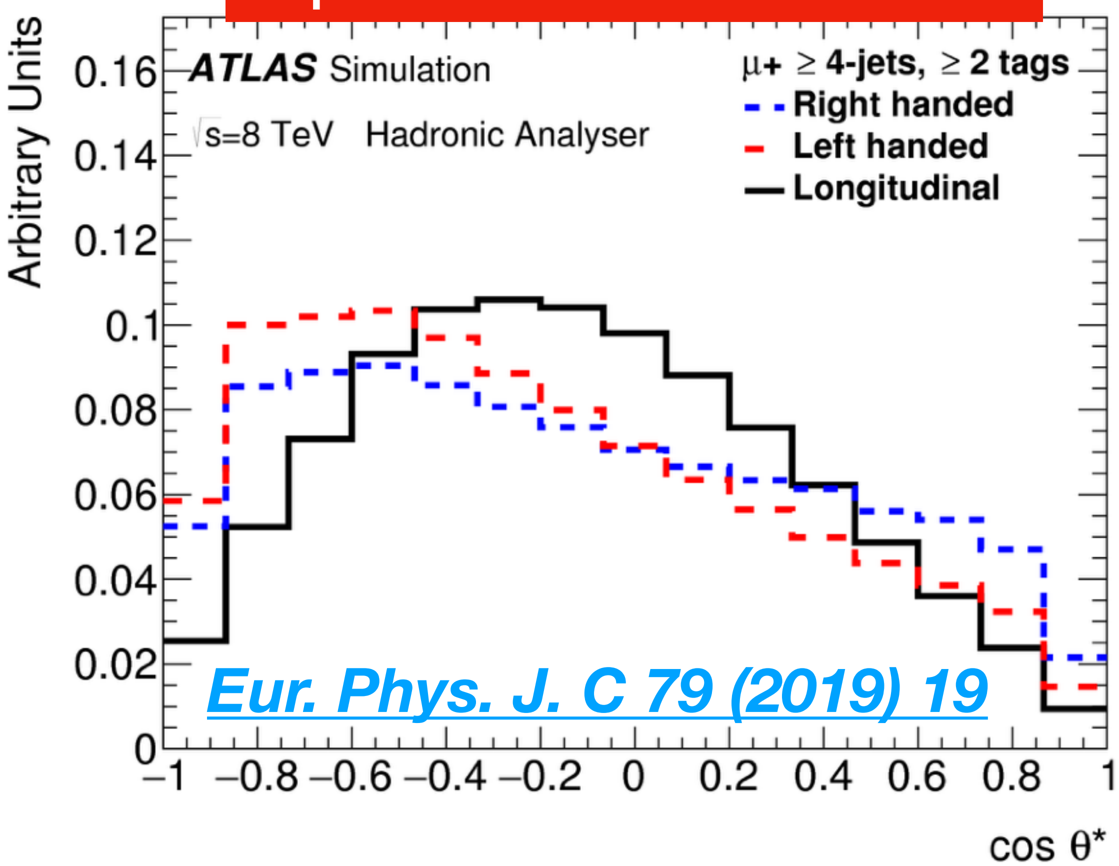


arxiv.2207.03511

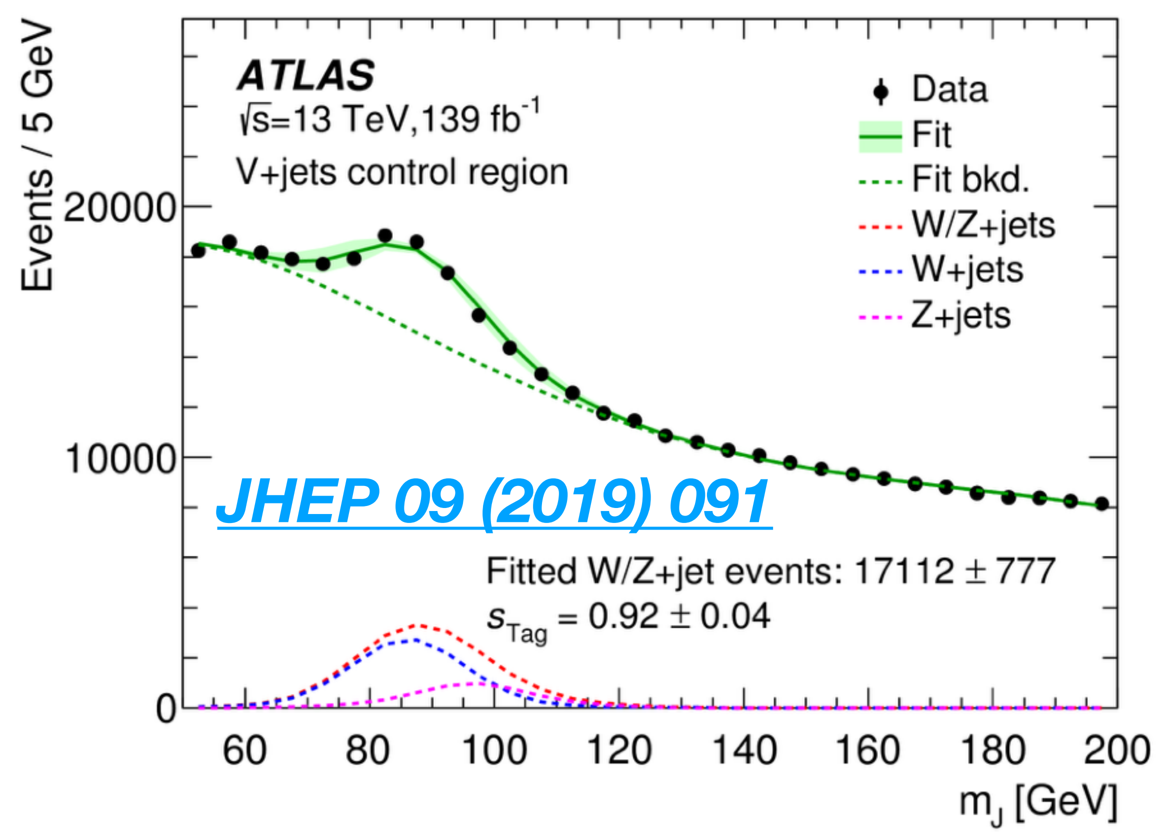
Last but not least…

- As shown, several pheno studies testing jet-substructure to solve the polarisation jet task
  - usage of the jet sub-structure or constituents
- From the experimental point of view, a tagger is made from the algorithm and from the calibration of it (as the inputs used are NOT calibrated)
  - ***Calibration matters!!!***
- How to do that: challenge for us experimentalist
  - ***ttbar events: W is 3/4 longitudinal; V+jets events: W is 3/4 transverse***

W polarisation in ttbar events



V tagger calibration in V(qq)+jets events



Conclusions

Experimental perspectives for polarisation tagging

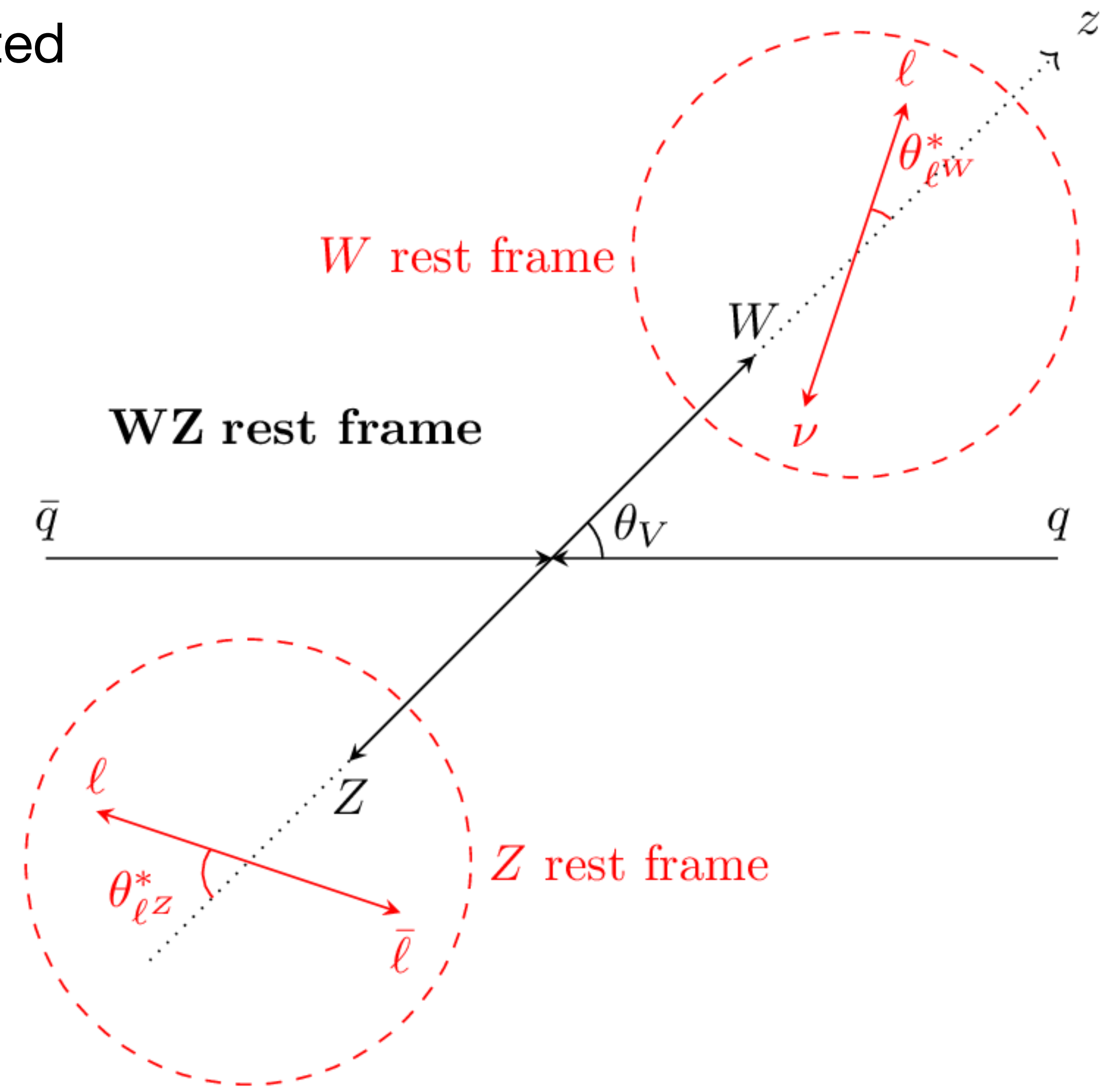
- ***Boson (single and joint) successfully measured in VV events, what is next?***
  - looking at hadronic boson decay
- ***Jet boson polarisation tagging***
  - very challenge task (definition and not only)
- ***A tool for VV Physics***
  - potentiality in measuring higher p_T phase space
  - and constraint BSM physics
- ***Wrap-up***
  - looking forward to new LHC and VV (not leptonic) results!

backup

Boson polarisation: final states

- The measurements performed so far are all using final states with leptons
  - smaller SM background, i.e. phase spaces dominated from QCD/EWK VV productions
  - final state semi-/fully-reconstructed
    - WZ —> lvll
    - ZZ —> llll
- aaa
  - aaa
- ***aaa***

likely, to backup



ZZ polarisation limitation

Contribution	Relative uncertainty [%]
Total	24
Data statistical uncertainty	23
Total systematic uncertainty	8.8
MC statistical uncertainty	1.7
Theoretical systematic uncertainties	
$q\bar{q} \to ZZ$ interference modelling	6.9
NLO reweighting observable choice for $q\bar{q} \to ZZ$	3.7
PDF, α_s and parton shower for $q\bar{q} \to ZZ$	2.2
NLO reweighting non-closure	1.0
QCD scale for $q\bar{q} \to ZZ$	0.2
NLO EW corrections for $q\bar{q} \to ZZ$	0.2
$gg \to ZZ$ modelling	1.4
Experimental systematic uncertainties	
Luminosity	0.8
Muons	0.6
Electrons	0.4
Non-prompt background	0.3
Pile-up reweighting	0.3
Triboson and $t\bar{t}Z$ normalisations	0.1

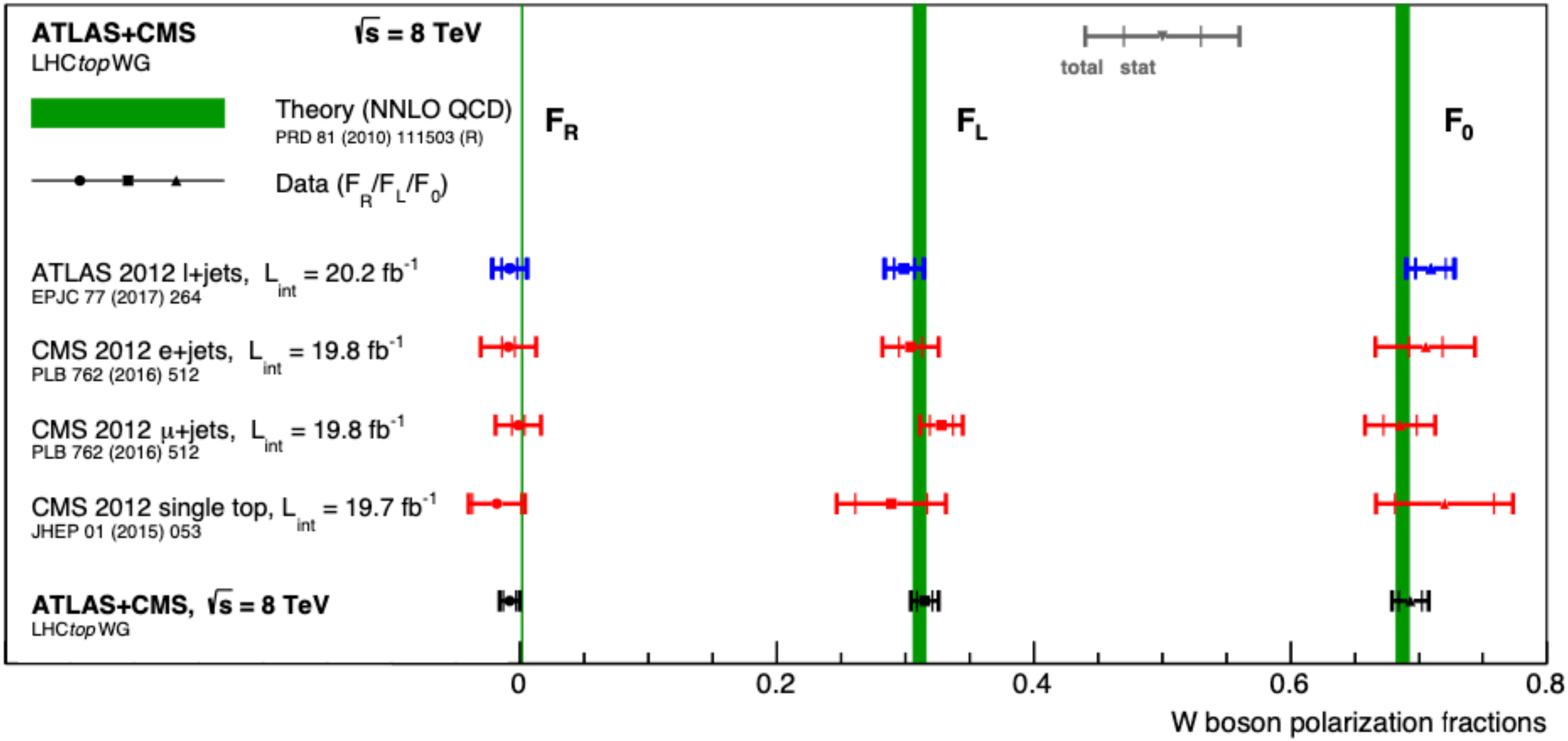
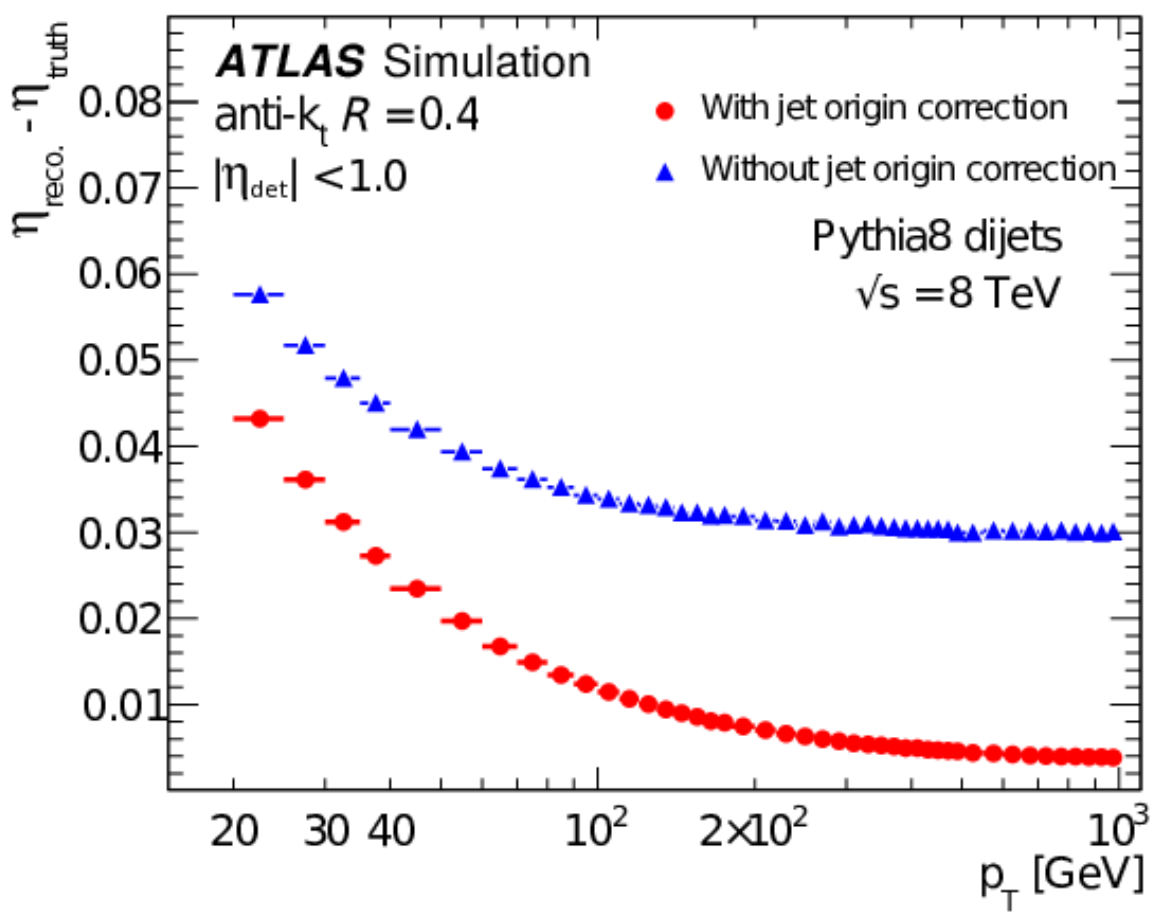
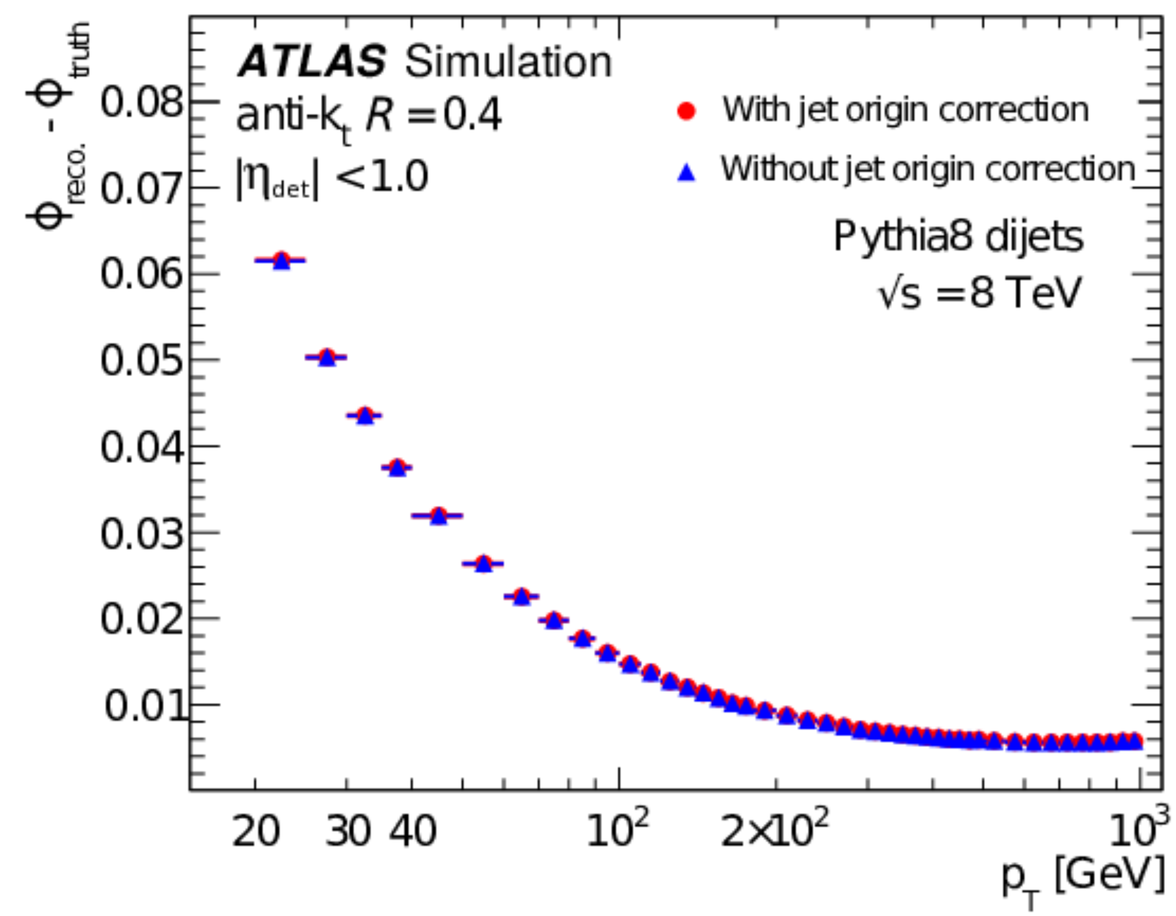


Figure 2: Overview of the four measurements, as well as the results of the combination. The inner and outer error bars correspond to the statistical and the total uncertainties, respectively. The inner bars for the combination include also the background determination uncertainties. The vertical solid line indicates the predictions of NNLO QCD calculations [1].

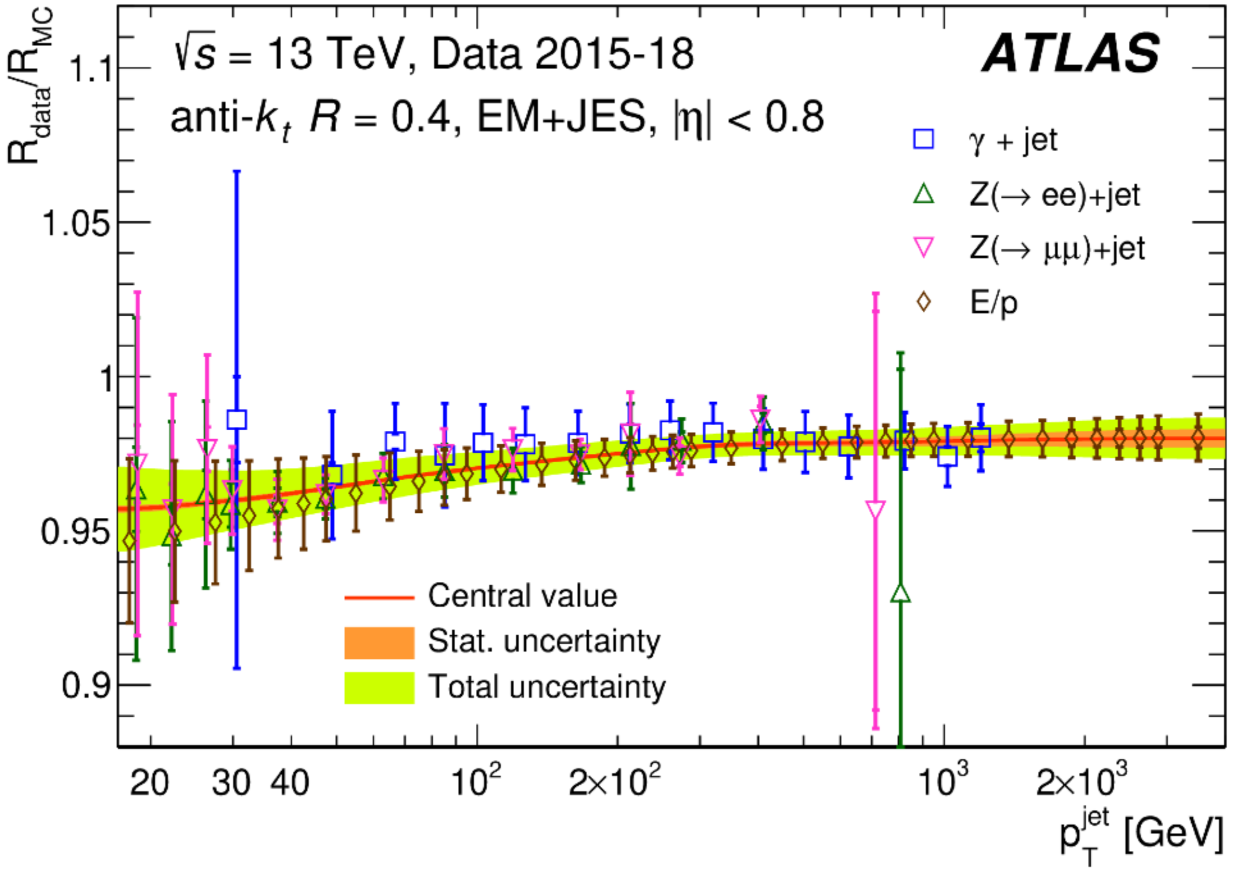
Jet axis resolution

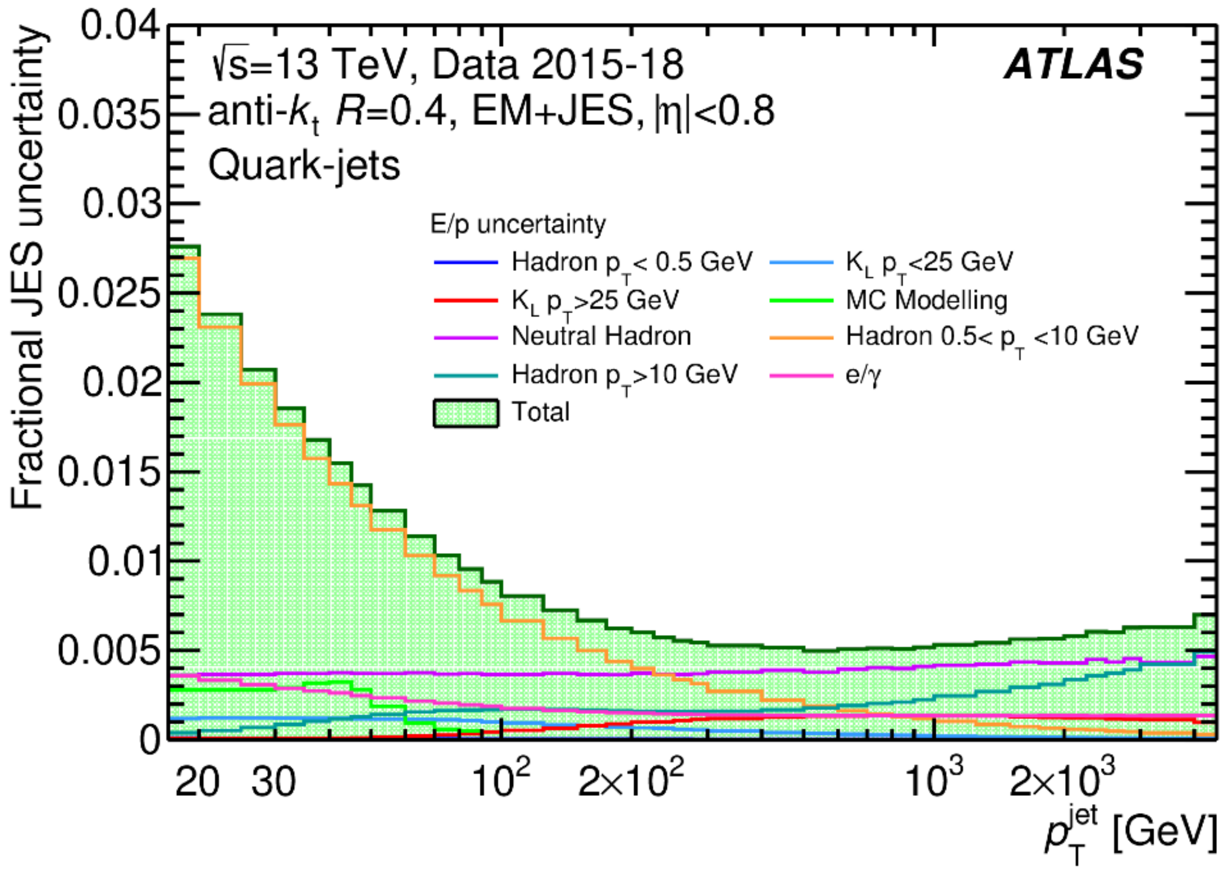
https://cds.cern.ch/record/2693121/plots





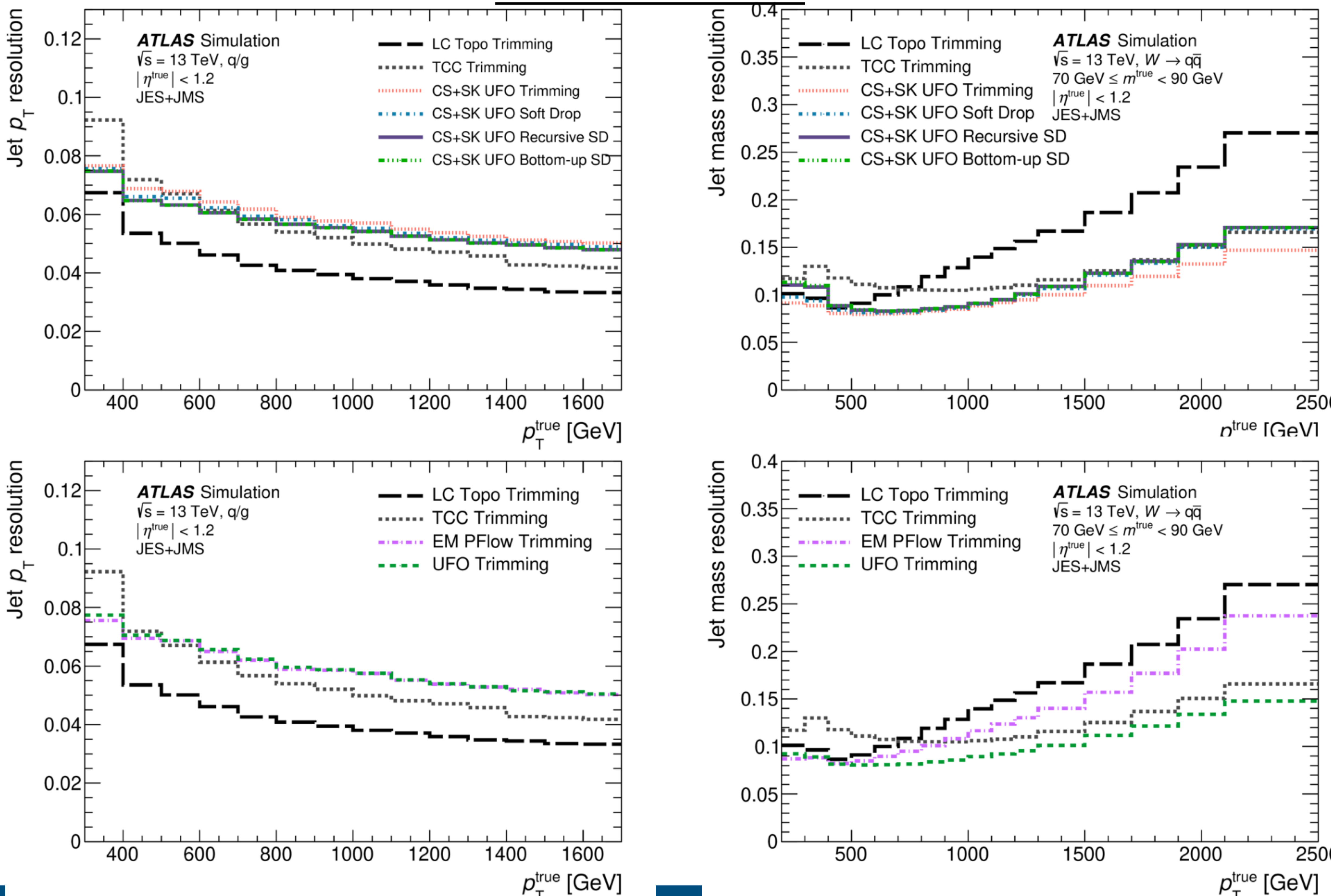
Small-R jets calibration



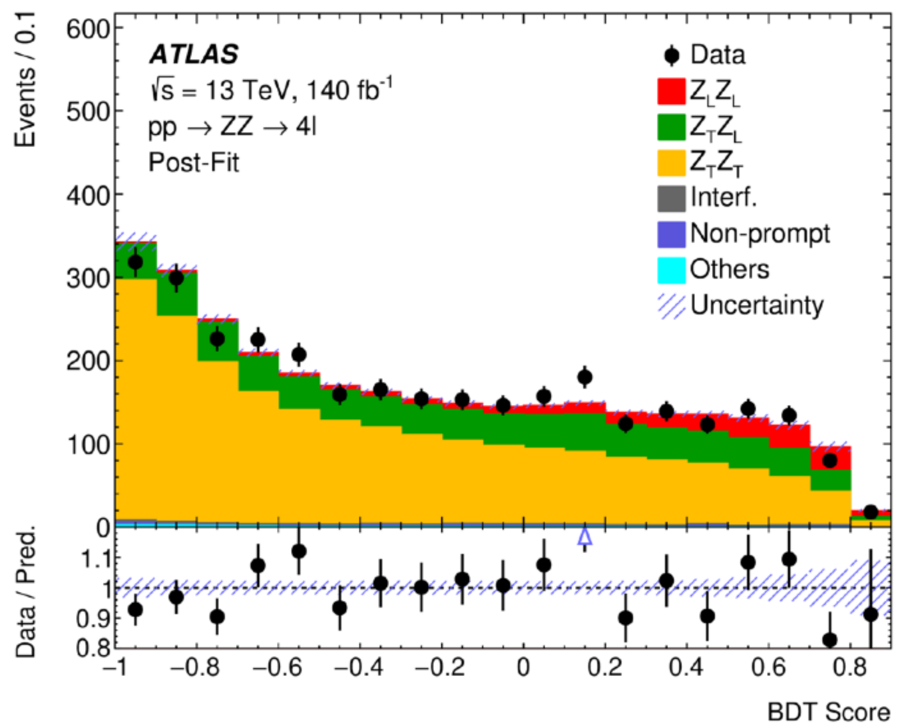


Large-R jets performances

JETM-2018-06



ZZ: some polarisation variables



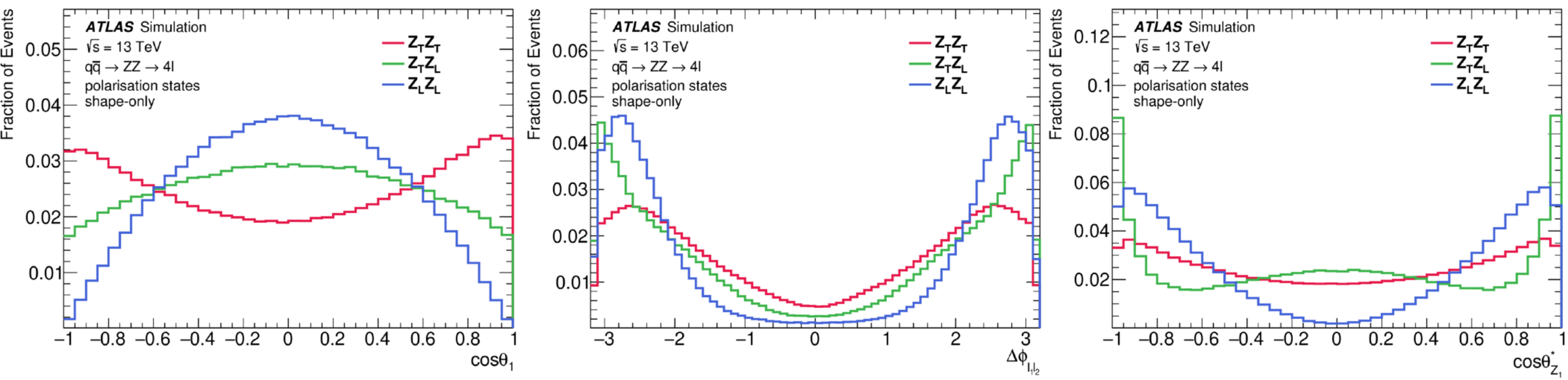
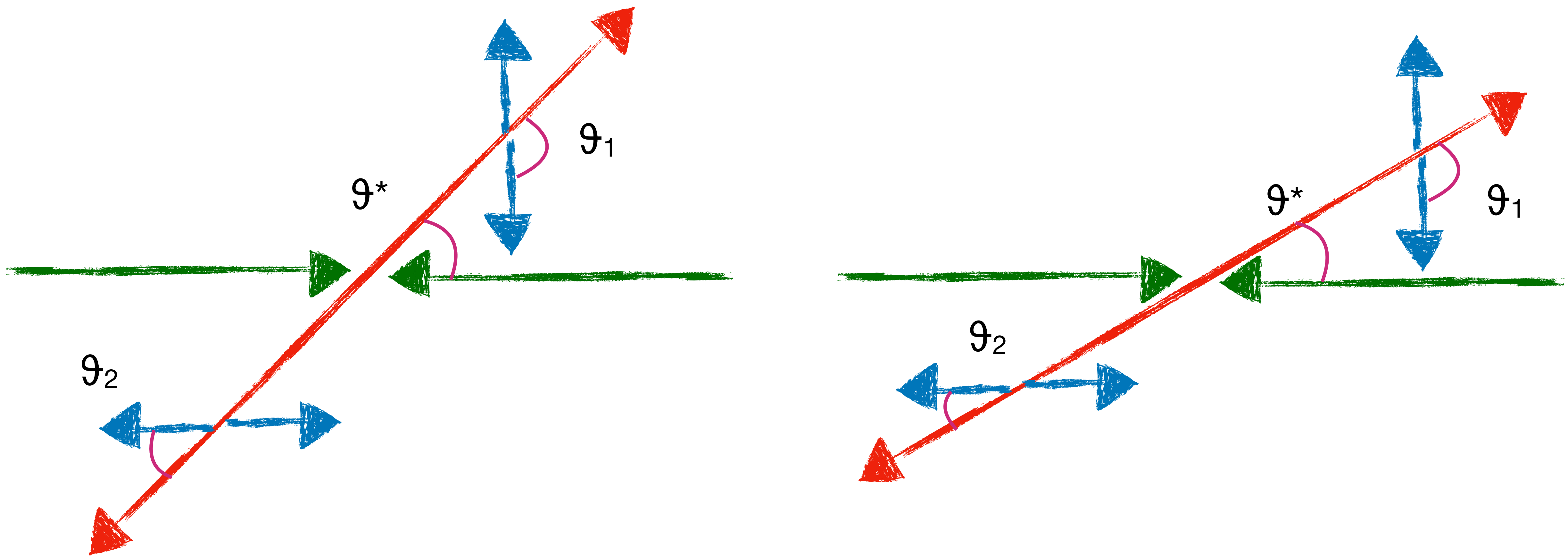


Figure 6: For ResNet Structure, we stack several ResNet blocks with the network shown above. Output of the first block yields the same dimension as the original image and second block deduces the dimension. After the deduction, the convoluted images is followed by flattening and dense network to produce a single output.

are normalized to 1. We observe that the cut on m_J has only mild effects on the spectrum. However, a selection on D_2 can have a large impact. The D_2 observable is defined as

$$D_2 = \frac{\frac{1}{E_J^3} \sum_{i<j<k} E_i E_j E_k \, z_{ij} z_{jk} z_{ki}}{\left(\frac{1}{E_J^2} \sum_{i<j} E_i E_j \, z_{ij} \right)^3}, \qquad (9)$$

where the sums run over the jet constituents. Low values of D_2 correspond to jets that look like two-prong while larger values correspond to one-prong jets, in this way cut selections can be designed to reject gluonic jets. In Fig. 8 we see, however, that



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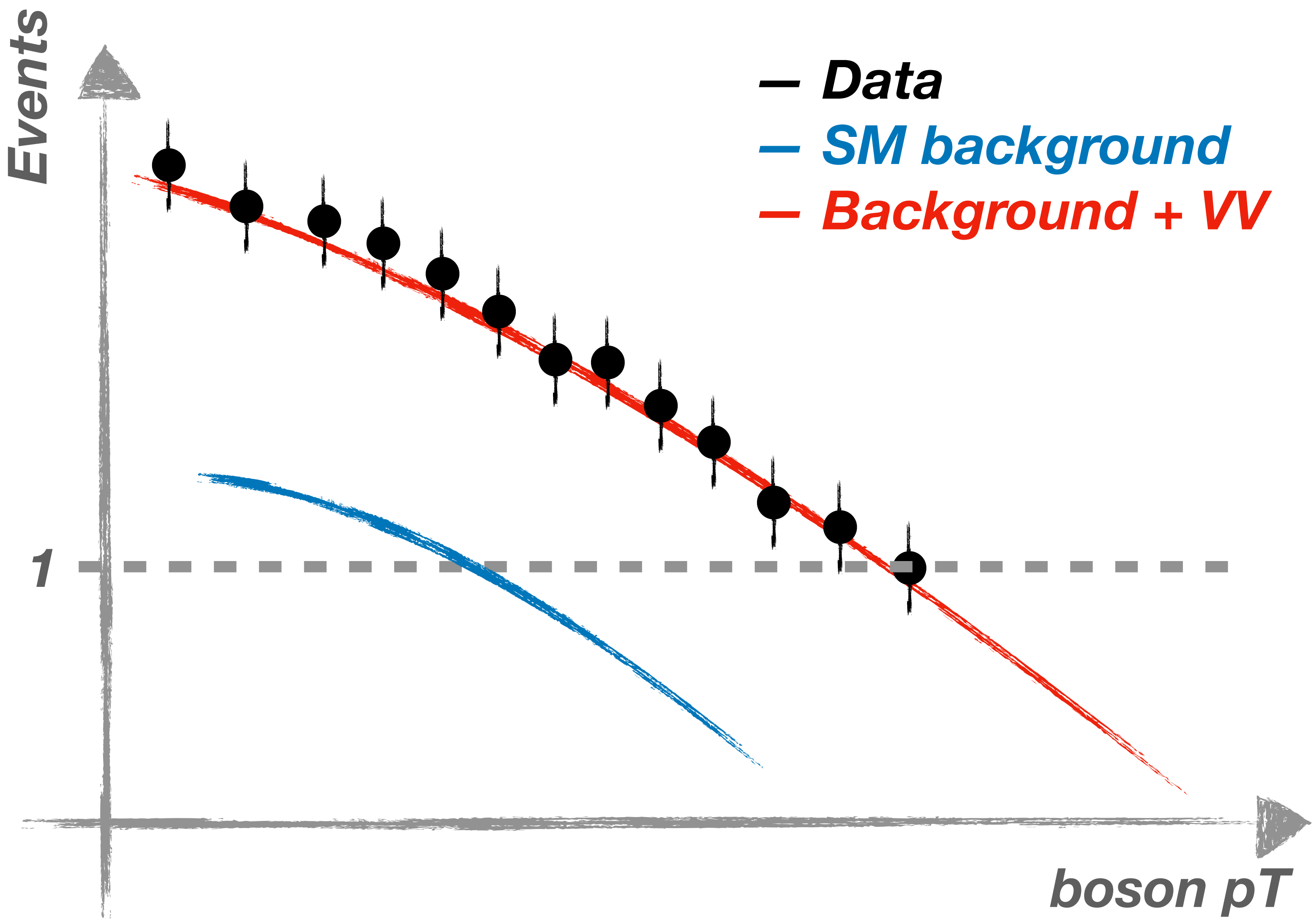

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