# Truth Studies of Direct Stau-Pair Production with ATLAS

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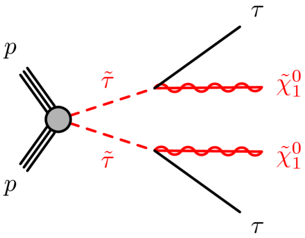
# Introduction

Motivation and goal

## Physical Motivation

- In many SUSY models the partner of the third generation is the lightest one.
- Co-annihilation between dark matter and a light stau leads to a dark matter relic density consistent with cosmological observations




Feynman diagram for direct stau pair production

## Model

- $\mathrm{m}(\tilde{\tau}) = 200$ GeV, $\mathrm{m}(\tilde{\chi}_1^0) = 1$ GeV
- Integrated luminosity: 80 fb$^{-1}$

## Goal

Finding good discriminating variables against background
mainly: Z+jets, W+jets, $t\bar{t}$

# Introduction

Event and object selection

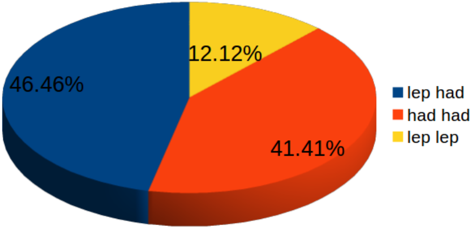
$$\tau^\pm \to \ell^\pm \bar{\nu}_\ell \nu_\tau \text{ or } \tau^\pm \to \text{hadrons} + \nu_\tau, \quad \ell = e, \mu$$

## Event selection

- $\tau_{\text{had}} - \tau_\ell$
- Opposite charge of $\tau_{\text{had}}$ and $\ell$
- $0$ b-Jets

## Object selection

- Jet: $p_T > 20$ GeV, $|\eta| < 2.8$
- $e$: $p_T > 25$ GeV, $|\eta| < 2.47$
- $\mu$: $p_T > 25$ GeV, $|\eta| < 2.5$
- $\tau$: $p_T > 20$ GeV, $|\eta| < 2.5$

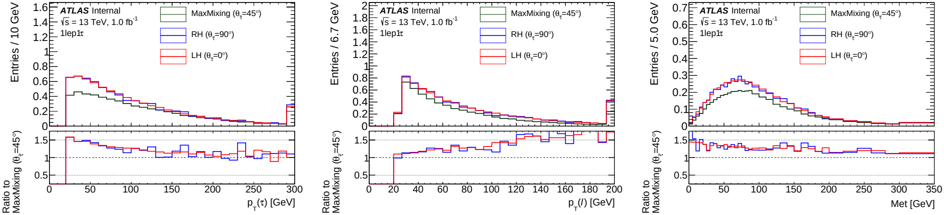



$\tau$-pair decay

# Introduction

## $\tilde{\tau}$-polarization

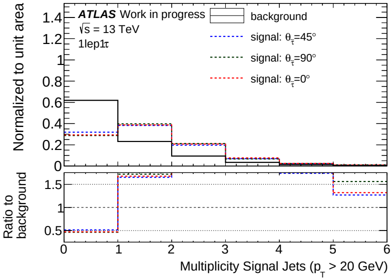
$\tilde{\tau}$ mass eigenstates: $$\begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{\tau}} & \sin\theta_{\tilde{\tau}} \\ -\sin\theta_{\tilde{\tau}} & \cos\theta_{\tilde{\tau}} \end{pmatrix} \begin{pmatrix} \tilde{\tau}_{\mathrm{LH}} \\ \tilde{\tau}_{\mathrm{RH}} \end{pmatrix} = R_{\tilde{\tau}} \begin{pmatrix} \tilde{\tau}_{\mathrm{LH}} \\ \tilde{\tau}_{\mathrm{RH}} \end{pmatrix}$$



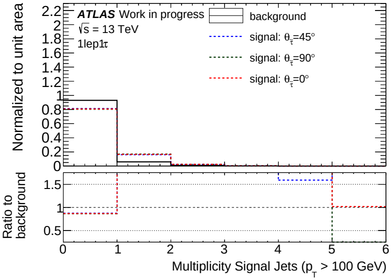

- Different mixing angle $\theta_{\tilde{\tau}}$ has an impact on different quantites
- Three different mixing angles $\theta_{\tilde{\tau}} = 0°, 45°, 90°$

# Multiplicity

## Jet multiplicity




Jet multiplicity for $p_T > 20$ GeV.

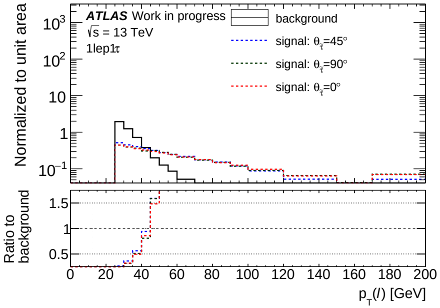


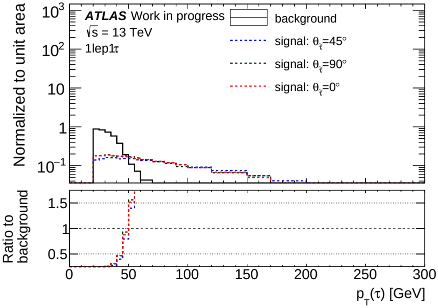

Jet multiplicity for $p_T > 100$ GeV.

High $p_T$ cut on jets with $p_T > 100$ GeV

# Kinematic distributions

Transverse momenta distribution for $\ell$ and $\tau$



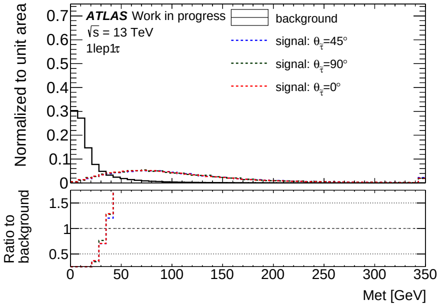



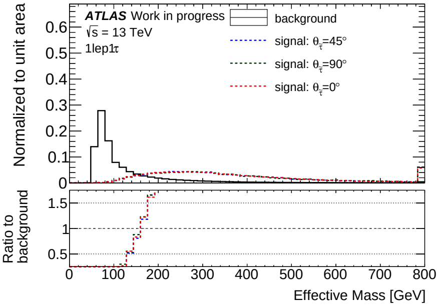

Transverse momenta $p_T(\ell)$'s

Transverse momenta of $p_T(\tau)$'s

# Kinematic distributions

## Missing transverse energy and effective mass



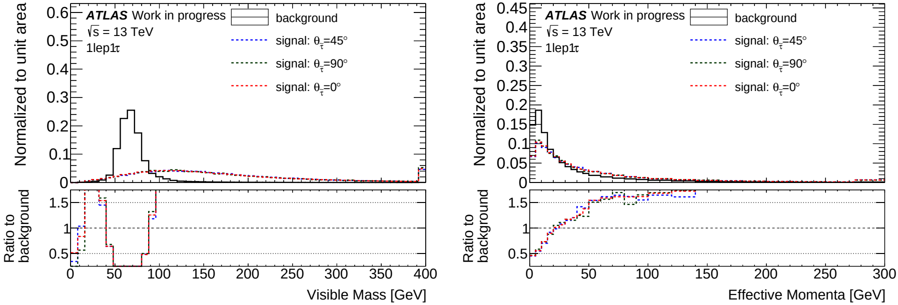




Missing transverse energy $E_T^{miss}$

$$m_{eff} = E_T^{miss} + \sum_{\ell,\tau,jet} |\mathbf{p}_T|$$

# Kinematic distributions

## Visible mass and effective momenta

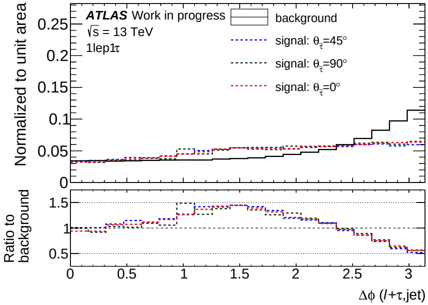



$$m_{\text{visible}} = \sqrt{(P_\ell + P_\tau)^2}$$

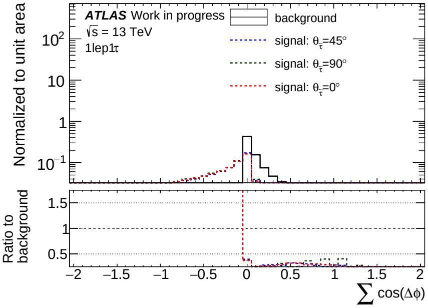
$$p_T(\mathbf{p}_\ell + \mathbf{p}_\tau + \mathbf{E}_T^{miss})$$

# Angular distributions

## Correlations



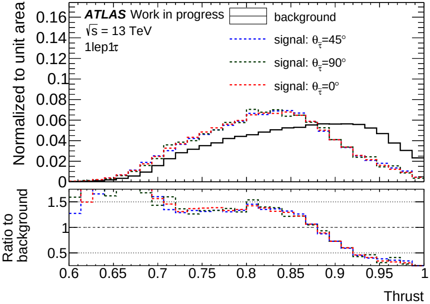

$\Delta\phi$ distribution between $\ell + \tau$ and leading jet

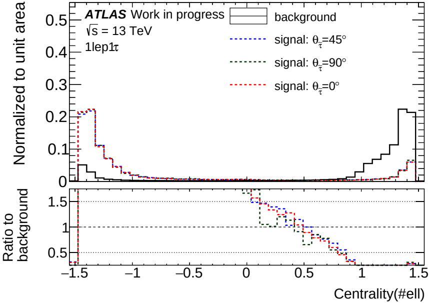



$\cos\Delta\phi(\ell,\, E_T^{miss}) + \cos\Delta\phi(\tau,\, E_T^{miss})$

# Event shape variables

## Thrust and centrality($\ell$)



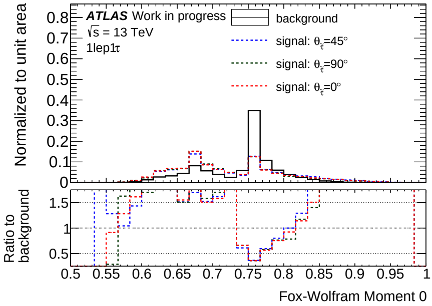



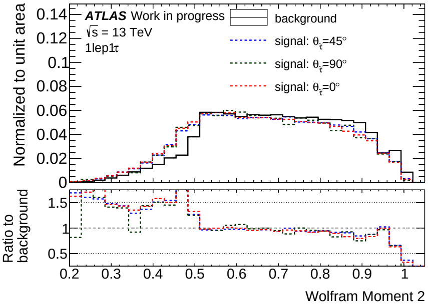

$$T = \max_{|\mathbf{n}|=1} \frac{\sum_i |\mathbf{n}\cdot\mathbf{p}_i|}{\sum_i |\mathbf{p}_i|}$$

Centrality for leptons

# Event shape variables

## Fox-Wolfram moments

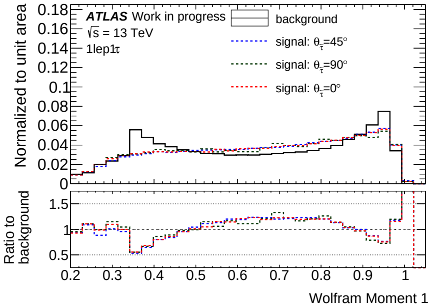


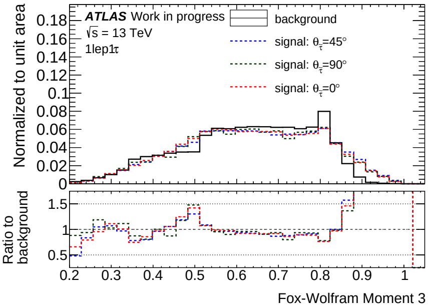




Fox-wolfram moments build from Legende polynomial
Fractions of the particles to the total energy

# Event shape variables

## Fox-Wolfram moments



# Summary

Cuts, significances and outlook

| Variable | Cut |
|---|---|
| $E_T^{miss}$ [GeV] | $> 40$ |
| $m_{vis}$ [GeV] | $> 80$ |
| $m_{eff}$ [GeV] | $> 150$ |
| $\Delta\phi(\ell + \tau, \text{jet})$ | $< 3.0$ |
| $\sum \cos \Delta\phi$ | $< 0.0$ |
| Thrust | $< 0.95$ |
| Centrality | $< 1.0$ |

## Outlook

- Study was perfomed at truth level
- Differences between signal and background
- Employ in multivariate analysis

Median discovery significance $= \frac{s}{\sqrt{b}}$

| | $\theta_{\tilde{\tau}} = 0°$ | $\theta_{\tilde{\tau}} = 45°$ | $\theta_{\tilde{\tau}} = 90°$ |
|---|---|---|---|
| no cuts | $0.031 \pm 0$ | $0.026 \pm 0$ | $0.031 \pm 0$ |
| with cuts | $1.504 \pm 0.014$ | $1.280 \pm 0.013$ | $1.500 \pm 0.026$ |
| with cuts+1jet | $0.663 \pm 0.012$ | $0.487 \pm 0.012$ | $0.695 \pm 0.032$ |
| with cuts+0jet | $1.363 \pm 0.014$ | $1.080 \pm 0.013$ | $1.344 \pm 0.025$ |

**End**

With special thanks to:

Johannes Josef Junggeburth
&
Zinonas Zinonos

# Backup

## Centrality

Computation of centrality for leptons:

$$\text{centrality}(\ell) = \frac{A + B}{\sqrt{A^2 + B^2}}$$

with

$$A = \frac{\sin \Delta\phi(E_T^{miss}, \ell)}{sin\Delta\phi(\ell, \tau)}$$

$$B = \frac{\sin \Delta\phi(E_T^{miss}, \tau)}{sin\Delta\phi(\ell, \tau)}$$

The sphericity tensor is defined as

$$S^{\alpha\beta} = \frac{\sum_i p_i^{\alpha} p_i^{\beta}}{\sum_i |\vec{p}_i|^2}$$

By standard diagonalization of $S^{\alpha\beta}$ one may find three eigenvalues $\lambda_1$, $\lambda_2$ and $\lambda_3$ (with $\lambda_1 + \lambda_2 + \lambda_3 = 1$). The sphericity of the event is then defined as:

$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

Sphericity is essentially a measure of the summed $p_{\perp}^2$ with respect to the event axis A 2-jet event corresponds to $S \approx 0$ and an isotropic event to $S \approx 1$

# Backup

## Thrust

The quantity thrust $T$ is defined by

$$T = \max_{|\mathbf{n}|=1} \frac{\sum_i |\mathbf{n} \cdot \mathbf{p}_i|}{\sum_i |\mathbf{p}_i|}$$

and the thrust axis $\mathbf{v}_1$ is given by the $\mathbf{n}$ vector for which maximum is attained. The allowed range is $1/2 \leq T \leq 1$, with a 2-jet event corresponding to $T \approx 1$ and an isotropic event to $T \approx 1/2$.

# Backup

## Fox-wolfram moments

The Fox-Wolfram moments $H_l$, $l = 0, 1, 2, \ldots$, are defined by

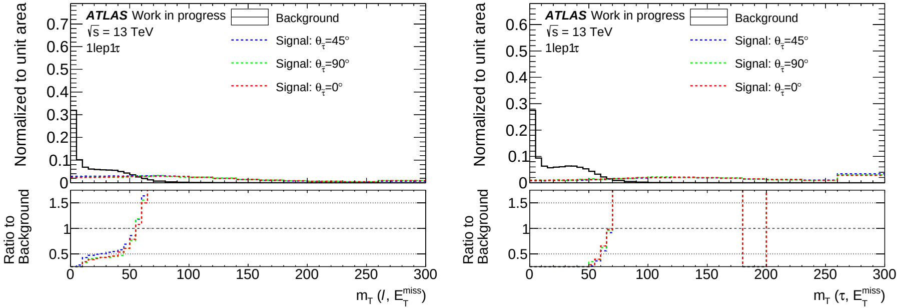
$$H_l = \sum_{i,j} \frac{|\mathbf{p}_i||\mathbf{p}_j|}{E_{vis}^2} P_l(\cos\theta_{ij})$$

where $\theta_{ij}$ is the opening angle between hadrons $i$ and $j$ and $E_{\text{vis}}$ the total visible energy of the event. Note that also autocorrelations, $i = j$, are included. The $P_l(x)$ are the Legendre polynomials. If

momentum is balanced then $H_1 \equiv 0$. 2-jet events tend to give $H_l \approx 1$ for $l$ even and $\approx 0$ for $l$.

# Backup

## Transverse mass for lepton und tau



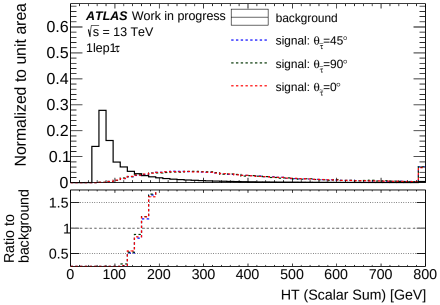

The quantity

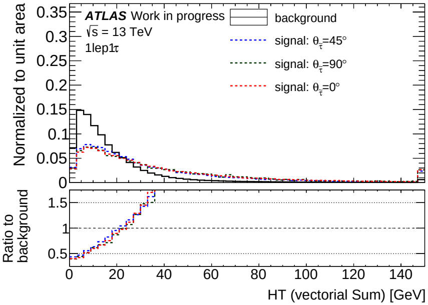
$$M_T^2 = 2|\mathbf{p}_T^{(1)}||\mathbf{p}_T^{(2)}|(1 - \cos\phi_{12})$$

is called transverse mass, where $\mathbf{p}_T^{(1)} = \mathbf{E}_T^{\text{miss}}$ and $\phi_{ij}$ is defined as the angle between particles $i$ and $j$ in the transverse plane.

# Kinematics

## HT(scalar sum) and HT(vectorial sum)



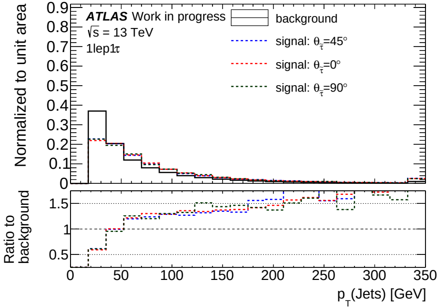



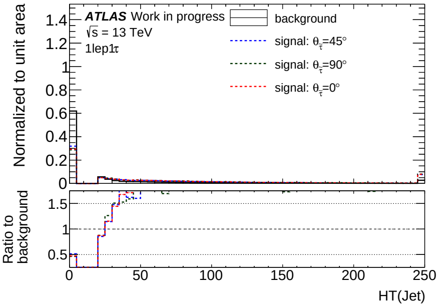

$$\mathrm{HT}_{\mathrm{scal}} = |\mathbf{p}_1^{\ell}| + |\mathbf{p}_1^{\tau}| + E_T^{\mathrm{miss}} + \sum_{jets} |\mathbf{p}_T|$$

$$\mathrm{HT}_{\mathrm{vec}} = p_T(\mathbf{p}_1^{\ell} + \mathbf{p}_1^{\tau} + \mathbf{E}_T^{\mathrm{miss}} + \sum_{jets} \mathbf{p}_T)$$

# Kinematic distributions

## For jets



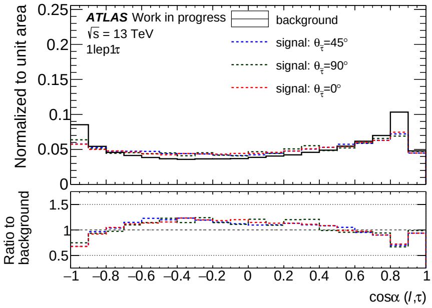



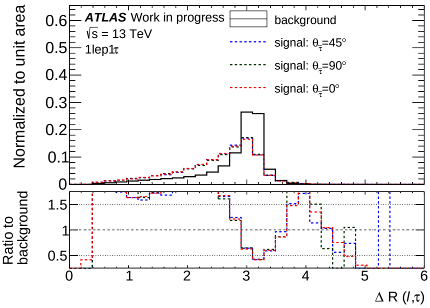

$p_T$ distribution of the leading jet

$$HT(Jet) = \sum_{jets} |\mathbf{p_T}|$$

# Angular distributions

## Lepton - tau correlations



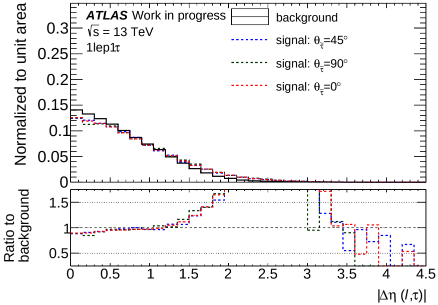



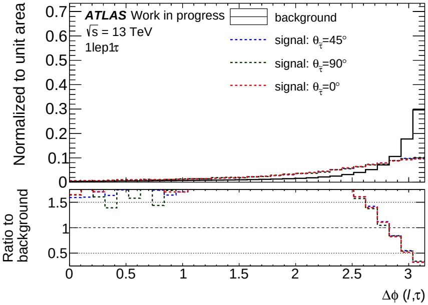

$$\cos\alpha = \cos\left(\sphericalangle(\ell,\tau)\right)$$

$$\Delta R(\ell,\tau) = \sqrt{(\Delta\phi_{\ell,\tau})^2 + (\Delta\eta_{\ell,\tau})^2}$$

# Angular distributions

## Lepton - tau correlations



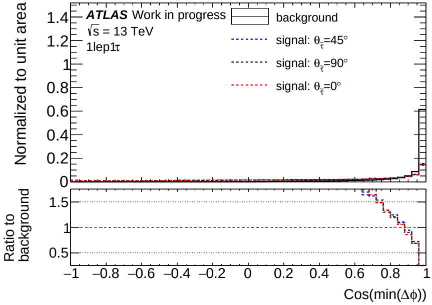



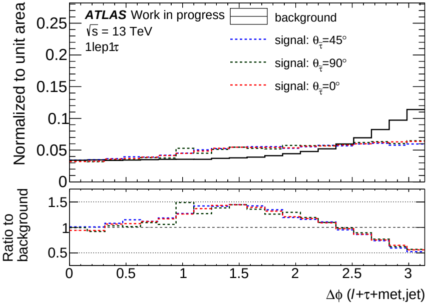

$\Delta\eta$ distribution between leptons and taus

$\Delta\phi$ distribution between leptons and taus

# Angular distributions

## Delta phi



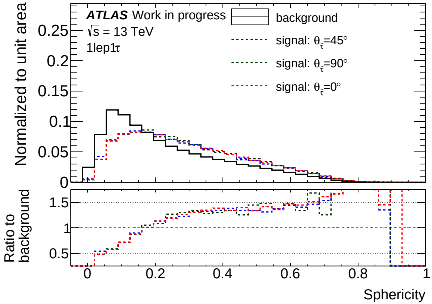



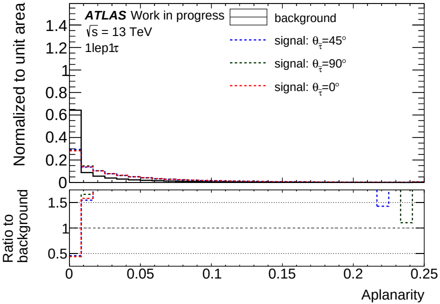

Cosine of the minimum distribution of $\Delta\phi(\ell, E_T^{miss})$ and $\Delta\phi(\tau, E_T^{miss})$

$\Delta\phi$ distribution between leptons + taus + $E_T^{miss}$ and the leading jet

# Event shape variables

## sphericity and spherocity




$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p}_i|^2}$$

$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

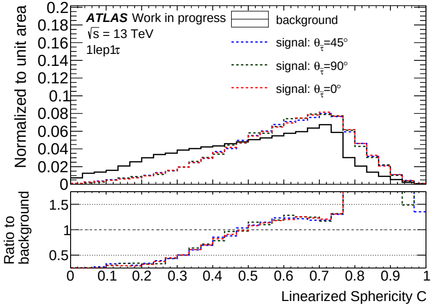
A 2-jet event corresponds to $S \approx 0$ and an isotropic event to $S \approx 1$

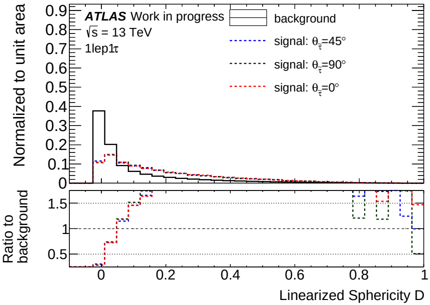
$$A = \frac{3}{2}\lambda_1$$

It measures the transverse momentum component out of the event plane: a planar event has $A \approx 0$ and an isotropic one $A \approx \frac{1}{2}$

# Event shape variables

## Linearized sphericity C and linearized sphericity D




$$C = 3(\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3)$$

$$D = 3(\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3)$$

$C$ is used to measure the 3-jet structure and vanishing for a perfect 2-jet event

$D$ is used to measure the 4-jet structure and is vanishing for a planar event