Improving the Standard Model predictions for V+jet decay coefficients

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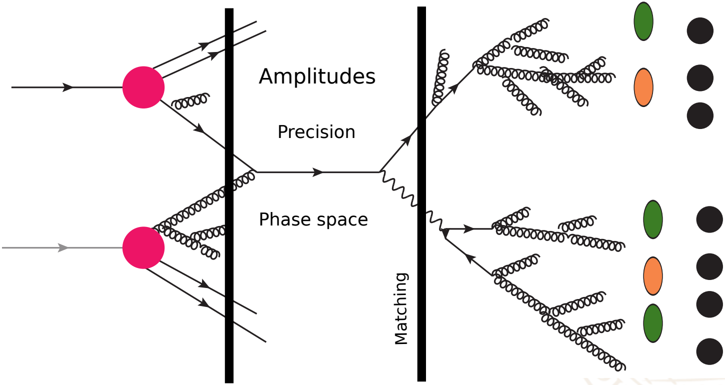
Lund PhD student day
December 7, 2022

[1] *and collaboration with:* M. Pellen, R. Poncelet, A. Popescu

LHC on the computer

- Proton-proton collision simulations
- My focus area during my PhD: *hard scattering*
- **High-precision phenomenology**



Today's talk

Electroweak corrections to the angular coefficients in finite-pT Z-boson production and dilepton decay

arXiv:2007.08867

Angular coefficients in W+j production at the LHC with high precision

arXiv:2204.12394

The colour matrix at next-to-leading-colour accuracy for tree-level multi-parton processes

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Precision (LHC) SM phenomenology

Decay coefficients for V+jet

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Decay coefficients for V+jet (Drell-Yan process)

- **Differential cross section** (5-dimensional) in V-boson kinematics expanded in **real spherical harmonics**

$$\frac{d\sigma}{dp_{T,V}dy_V dm_{ll}d\Omega} \propto \Big((1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big) \quad (1)$$

  with eight **angular/decay coefficients** $A_i(p_{T,V}, y_V, m_{ll})$
- Angles (θ, ϕ) are angles of $l^{\pm}$ in the **Collins-Soper frame**

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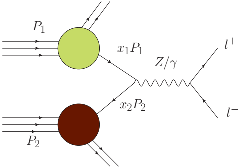
- This decomposition separates production mechanism and decay part



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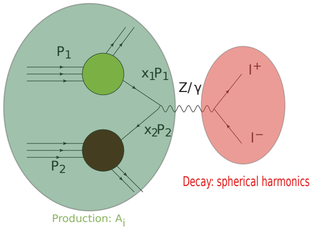
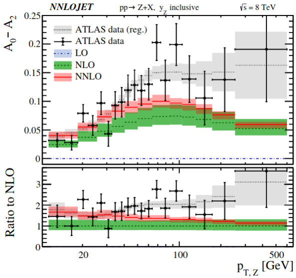


Decay coefficients for Z+jet: Lam-Tung relation

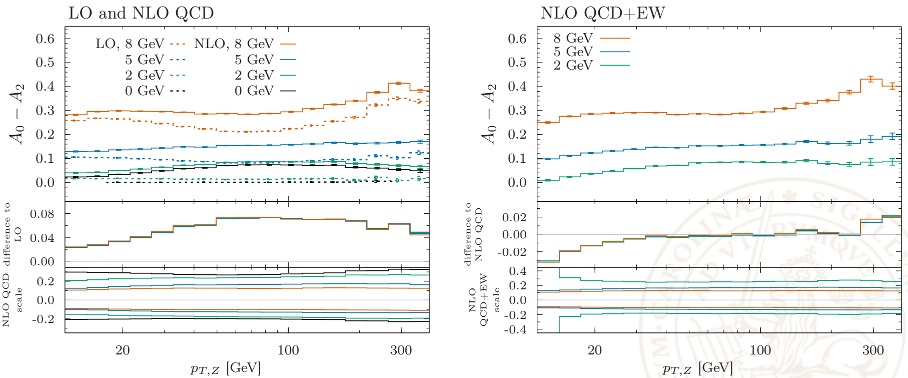
- Up to LO: **Lam-Tung relation** $A_0 - A_2 = 0$
- Predictions for Z+jet available at NNLO QCD[2]
- ATLAS and CMS (and runs at Tevatron) all measured **higher violation** of Lam-Tung than predicted by NNLO QCD at $p_{T,Z} > 20$ GeV



[2] R. Gauld, A. Gehrmann-De Ridder, T. Gehrmann, *et al.* High Energ. Phys. 2017, 3 (2017)

Angular coefficients for Z+jet: results

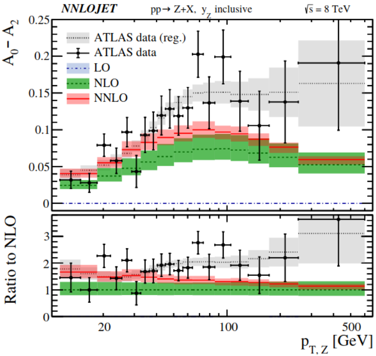
- Lam-Tung violation $A_0 - A_2$ (differentially in the Z-boson p_T) at LO and NLO QCD (left) and NLO QCD+EW (right) [3]

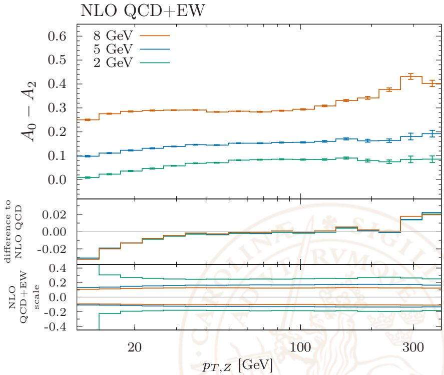


[3] R. Frederix, T. Vitos, arXiv:2007.08867

Angular coefficients for Z+jet: results

- Lam-Tung violation $A_0 - A_2$ at NNLO QCD with ATLAS data (left) [4] and NLO QCD+EW (right)

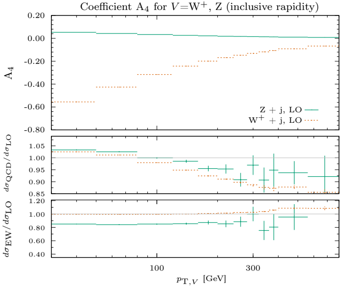




- Electroweak effects move violation **towards the data** for the **low-p_T region**
- In **high-p_T region**, electroweak effects are negligible

[4] R. Gauld, A. Gehrmann-De Ridder, T. Gehrmann, *et al*, High Energ. Phys. 2017, 3 (2017)

Angular coefficients for W+jet: motivation

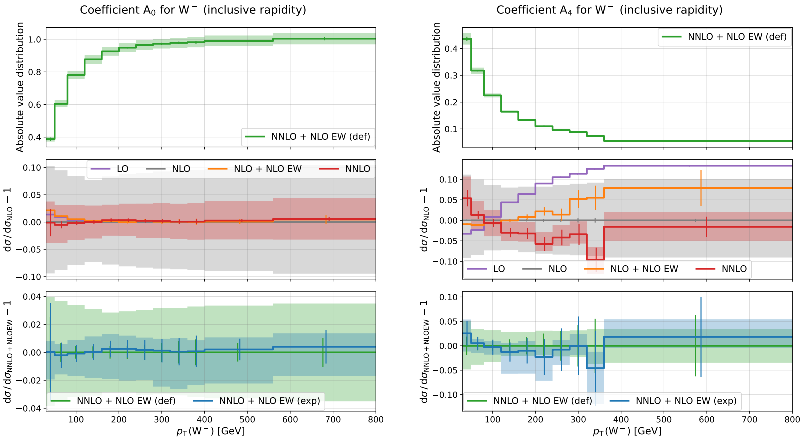


- $W^{\pm}$+jet more difficult to measure due to the neutrino
- (partly) Direct decay coefficient measurements by CDF (1.8 TeV)[5]
- ATLAS: template fits of distributions to measure W-boson mass
- Improve fluctuations by an unfolding to Z+jet [6]

[5] CDF Collaboration arXiv:hep-ex/0504020
[6] ATLAS Collaboration arXiv:1701.07240

Angular coefficients for W+jet: results, inclusive rapidity

- The coefficients A_0 (left) and A_4 (right) for W^- signature, inclusive in rapidity [7]



[7] M. Pellen, R. Poncelet, A. Popescu, T. Vitos. arXiv:2204.12394

Angular coefficients for W+jet: EW non-closure effect[8]

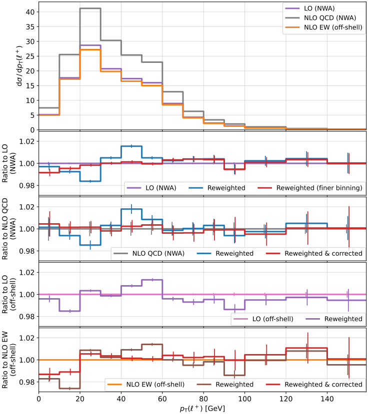
- The expansion to spherical harmonics is no longer valid when EW splittings are allowed ($1 \to 3$ kinematics)

[8] M. A. Ebert, *et al.*. arXiv:2006.11382

Angular coefficients for W+jet: EW non-closure effect[8]

- The expansion to spherical harmonics is no longer valid when EW splittings are allowed ($1 \to 3$ kinematics)

- NLO EW (off-shell) versus reweighted with A_i show good agreement (except first few beins)



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Further projects

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- Spin correlation for top-anti-top pair production

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Combining the EW Sudakov approximation with NLO QCD + parton shower via reweighting

- Combine the implemented EW Sudakov in MG5_aMC@NLO with NLO QCD+parton shower

Conclusions and outlook

V+jet decay coefficients

- Negligible electroweak effects for high-p_T region of the Z-boson Lam-Tung relation
- Presented for the first time high-precision predictions for W+jet decay coefficients

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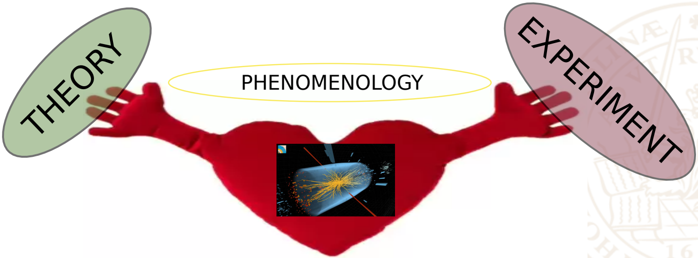
Outlook:

- Open platform for questions: meetings? slack?

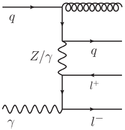


Thank you for listening!

- **This project**: Calculate electroweak corrections to the dominant angular coefficients and Lam-Tung relation
- **Fixed-order**: $pp \to \{e^+e^-, \mu^+\mu^-\} + j$ at 8 TeV with MadGraph5_aMC@NLO at

$$\text{NLO QCD+EW} := \text{LO}_1 + \text{LO}_2 + \text{NLO}_1 + \text{NLO}_2$$

- Introduce **single lepton p_T cut** to avoid double IR (2-loop) singularity $\to$ vary cut to extrapolate to the full phase space of the dilepton pair



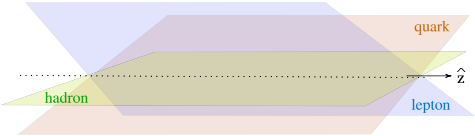
- Use moments method for each coefficient in $A_i f(\theta, \Phi)$

$$A_i \propto \frac{\int \mathrm{d}\Omega \mathrm{d}\sigma f(\theta,\Phi)}{\int \mathrm{d}\Omega \mathrm{d}\sigma} \tag{3}$$

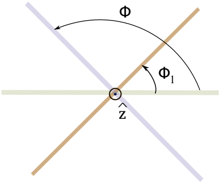
- **Note!** Due to the ratio-nature of the ocefficients, EW Sudakovs are not necessarily expected to show up!

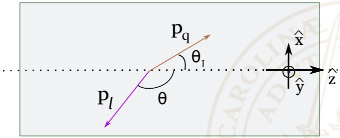
Decay coefficients: Collins-Soper frame

- $pp \to Z/\gamma + X \to l^+ l^- + X$ [7]: in Collins-Soper frame



- Introduce polar and azmuthal angles θ_1, Φ_1 of quark compared to the hadron plane



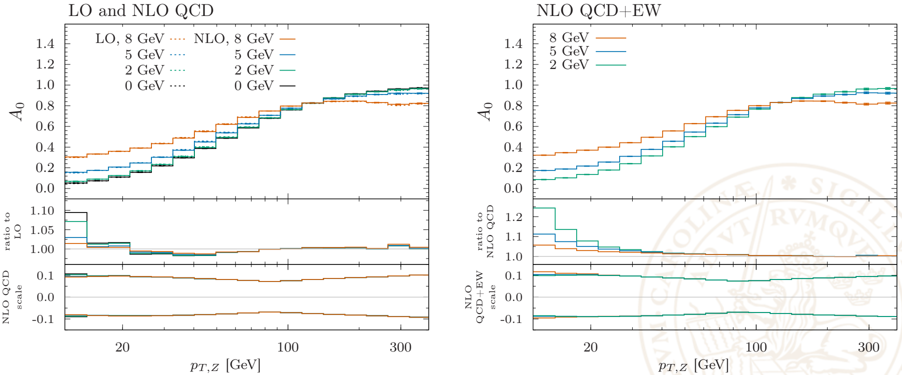


- Angles θ, Φ are the angles of the (negatively charged) lepton l^-

[7] J.-C. Peng *et al.*, arXiv:1511.08932

Decay coefficient for Z+jet: results

- Distributions for A_0
- Negligible electroweak corrections



Decay coefficient for Z+jet: results

- Distributions for A_1
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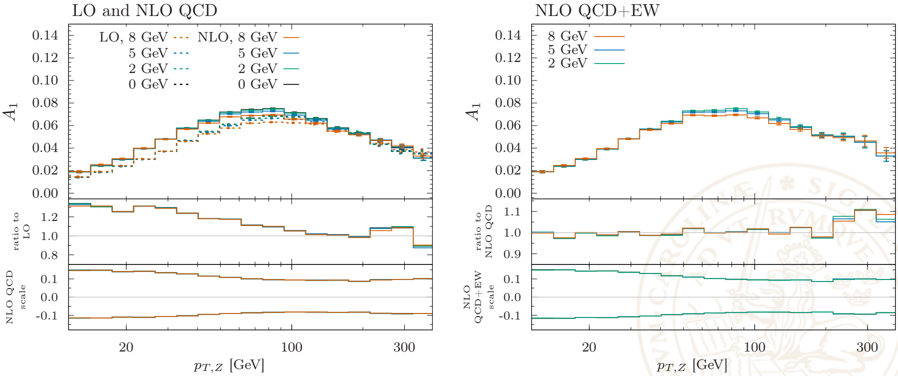
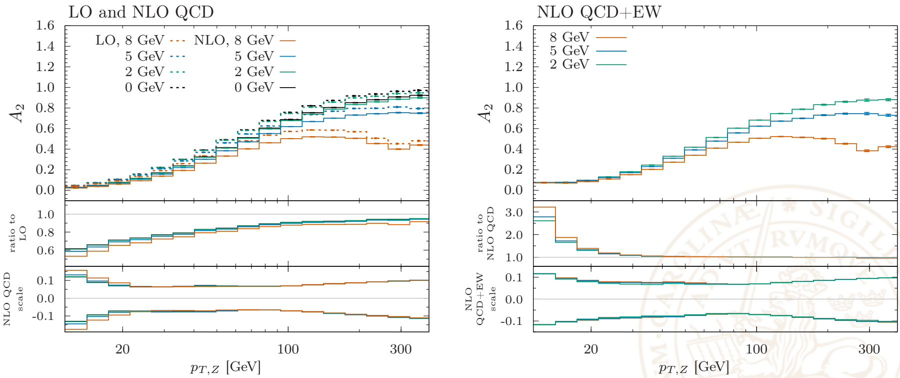


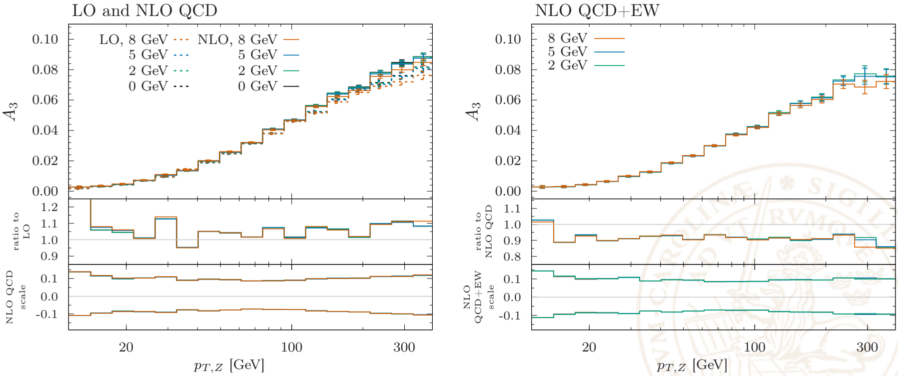
Decay coefficients for Z+jet: results

- Distributions for A_2



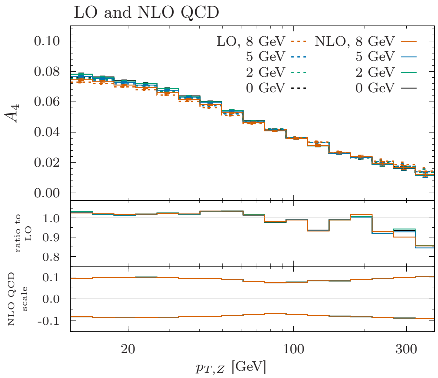
Decay coefficients for Z+jet: results

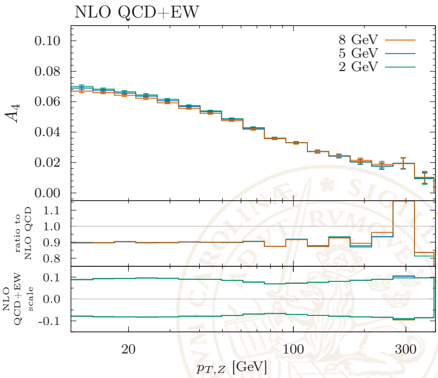
- Distributions for $\boldsymbol{A_3}$
- Same -10% electroweak corrections



Decay coefficients for Z+jet: results

- Distributions for A_4
- Same -10% electroweak corrections





Angular coefficients for W+jet: setup

- **This project**: Calculate and combine NNLO QCD and NLO EW corrections to the angular coefficients
- **Fixed-order**: $pp \to \{e^+ \nu_e\} + j$ at 13 TeV at:

$$\text{NLO EW} := \text{LO}_1 + \text{LO}_2 + \text{NLO}_2$$
$$\text{NNLO QCD} := \text{LO}_1 + \text{NLO}_1 + \text{NNLO}_1$$

- MadGraph5_aMC@NLO (for NLO EW) and STRIPPER (for NNLO QCD) [8]
- Combining NLO EW and NNLO QCD, default way (unexpanded):

$$\mathrm{A}_i^{\text{default}} = \frac{N}{D}, \tag{4}$$

- Expansion in α_s:

$$\mathrm{A}_i^{\text{exp}} = A + \alpha_s B + \alpha_s^2 C, \tag{5}$$

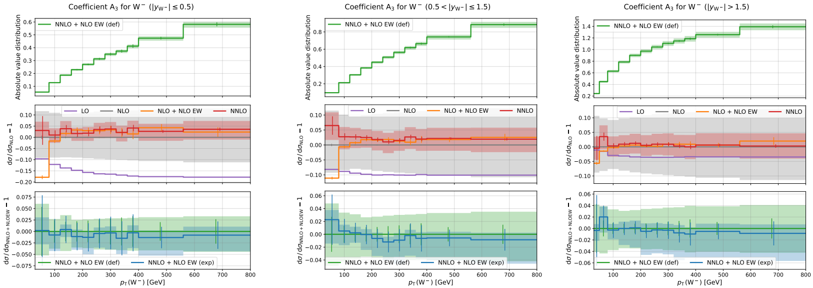
- Inclusion of NLO EW through an overall K-factor (avoids $p_T(l)$ cut dependence)

$$\mathrm{A}_{i,\text{QCD+EW}} = K_{\text{NLO EW}} \times \mathrm{A}_i, \tag{6}$$

[8] M. Czakon arXiv:1005.0274

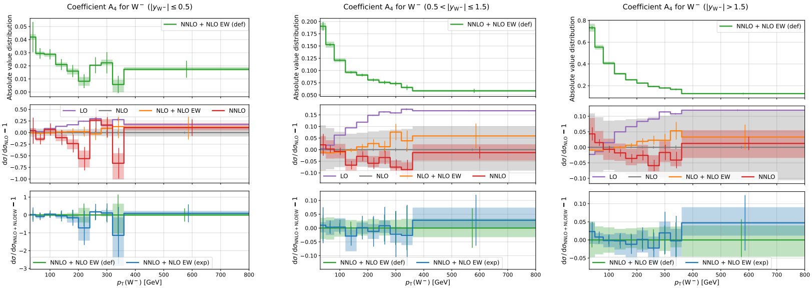
Decay coefficients for W+jet: results

- The coefficients A_3 in various rapidity bins



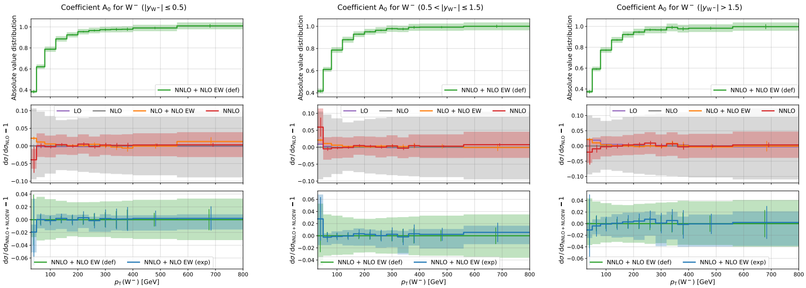
Decay coefficients for W+jet: results

- The coefficients A_4 in various rapidity bins



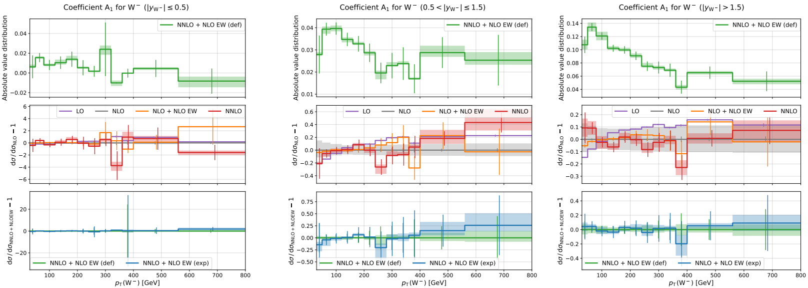
Decay coefficients for W+jet: results

- The coefficients A_0 in various rapidity bins
- No rapidity dependence (same for A_2)
- Mid: $|y| \leq 0.5$, mid-central: $0.5 \leq |y| \leq 1.5$, forward: $|y| \geq 1.5$



Decay coefficients for W+jet: results

- The coefficients A_1 in various rapidity bins
- Note: different y-scales!
- Heavily rapidity-dependent (same for A_3 and A_4)
- Mid: $|y| \leq 0.5$, mid-central: $0.5 \leq |y| \leq 1.5$, forward: $|y| \geq 1.5$



Decay coefficients for W+jet: results

- The coefficients A_2 in various rapidity bins