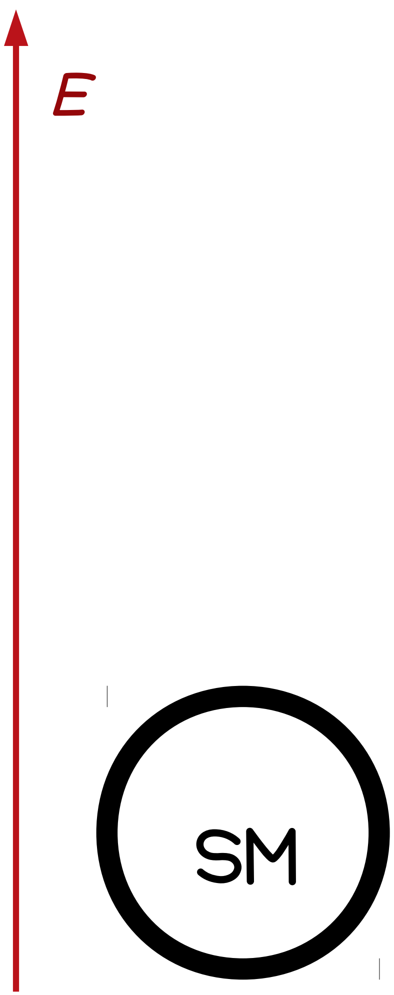
Identifying the many faces of EW jets with energy correlators

Marc Riembau
CERN

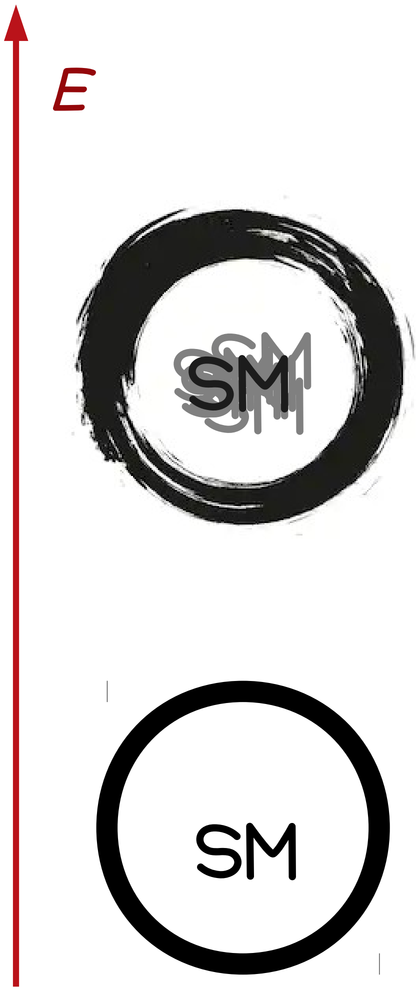
3rd October 2023

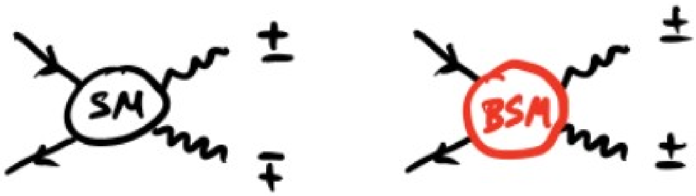
$$\mathcal{L}\,?$$



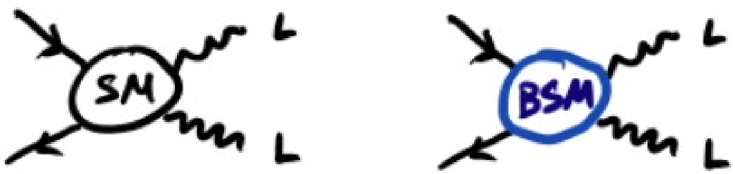
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}$$

$$\mathcal{L}\,?$$



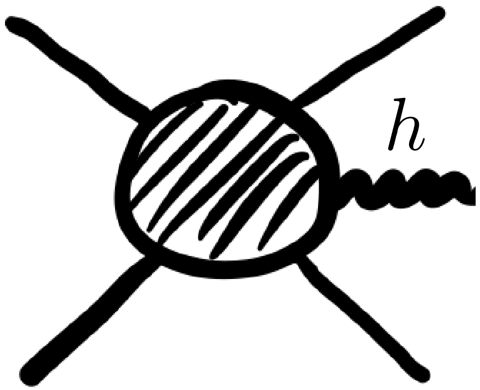


$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda}\mathcal{O}_i$$



$$\mathcal{L} = \mathcal{L}_{\text{SM}}$$

Decay density matrix

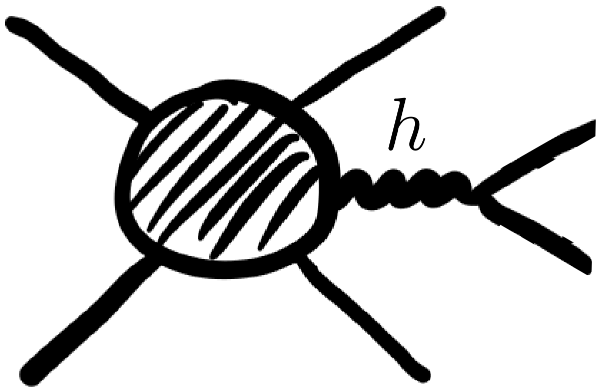


$$\mathcal{A}^{\text{prod}}_{V_h}$$

What does it mean to produce a Vector of helicity h?

Decay density matrix

$$\sum_h$$

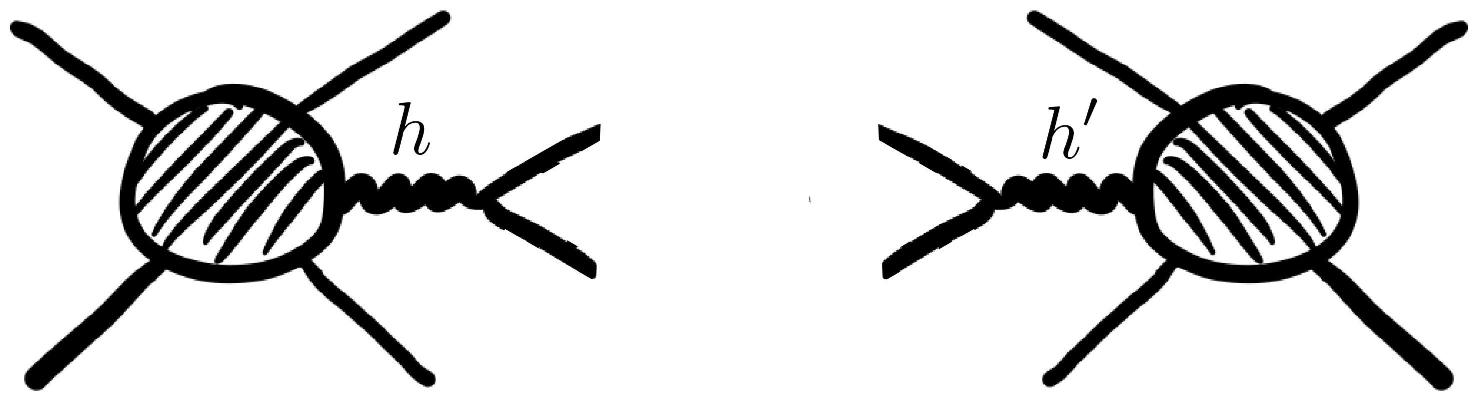


$$\mathcal{A}^{\text{prod}}_{V_h} \; \mathcal{A}^{\text{dec}}_{V_h \to X}$$

It decays, so not a single but a combination of helicities is produced

Decay density matrix

$$\sum_{h,h'}$$



$$d\sigma \propto \sum_{h,h'} \int d\Pi \, \mathcal{A}^{\text{prod}}_{V_h} \, \mathcal{A}^{\text{dec}}_{V_h \to X} \, (\mathcal{A}^{\text{prod}}_{V_{h'}})^* \, (\mathcal{A}^{\text{dec}}_{V_{h'} \to X})^*$$

$$\equiv \; d\rho^{\text{prod},V}_{h,h'} \; d\rho^{\text{dec},V}_{h,h'}$$

Full process is determined by the production and decay density matrices

Decay density matrix

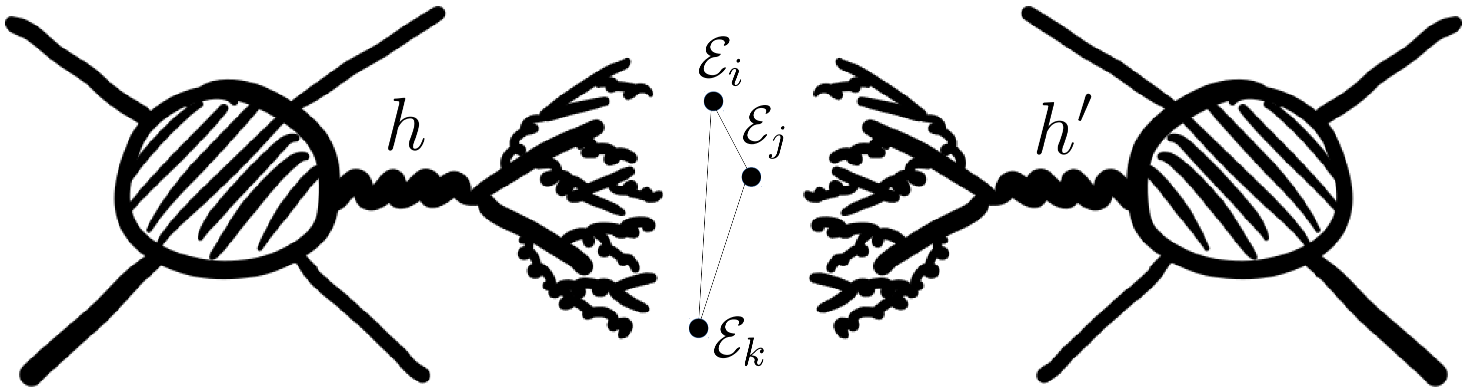
$$\sum_{h,h'}$$

Option A) Define some appropiate observable using jet substructure
Potentially use several observables and ML

Problems: Theoretically opaque
Not clear control of systematics

Decay density matrix

$$\sum_{h,h'}$$



Option A) Define some appropiate observable using jet substructure
Potentially use several observables and ML

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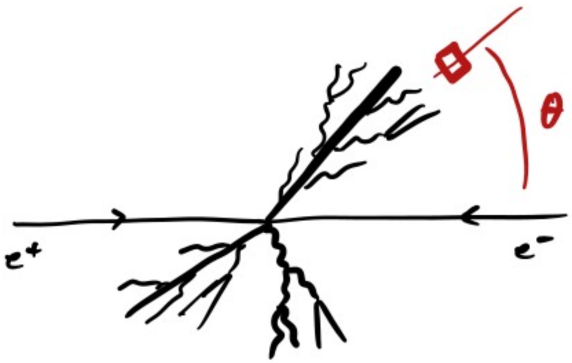
Option B) Energy Correlators

Energy Correlators

Energy Correlators



Basham, Brown, Ellis, Love '78

An experimental measure is presented for a precise test of quantum chromodynamics. This measure involves the asymmetry in the energy-weighted opening angles of the jets of hadrons produced in the process $e^+e^- \to$ hadrons at energy W. It is special for several reasons: It is reliably calculable in asymptotically free perturbation theory; it has rapidly vanishing (order $1/W^2$) corrections due to nonperturbative confinement effects; and it is straightforward to determine experimentally.

$$\frac{d\langle E\rangle}{d\chi} = \sum_i \int d\Omega |\mathcal{A}|^2 E_i \delta(\cos\theta_i - \chi)$$

Sveshnikov, Tkachov '95

$$\mathcal{O}_{\hat{n}_i}|\alpha\rangle = \sum_i E_i \delta(\hat{p}_i - \hat{n}_i)|\alpha\rangle$$

Energy weights have an operatorial deifnition

$$\frac{d\langle E\rangle}{d\chi} = L_{\mu\nu} \int d^4x \langle 0|j^\mu(x)\mathcal{O}_{\hat{n}} j^\nu(0)|0\rangle$$

Energy Correlators

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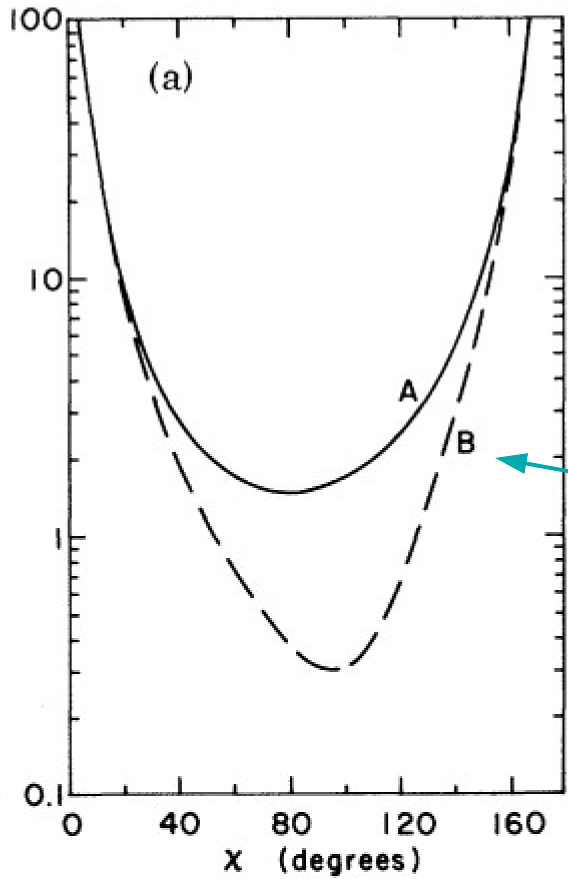
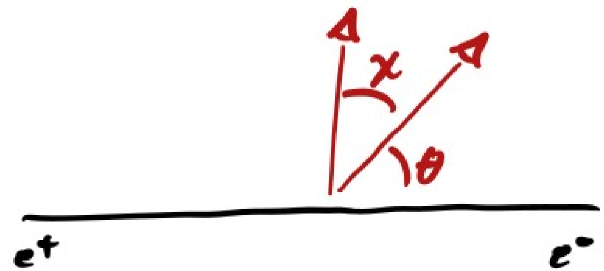


$\frac{d\langle E\rangle}{d\chi} =$ ... $i - \chi)$



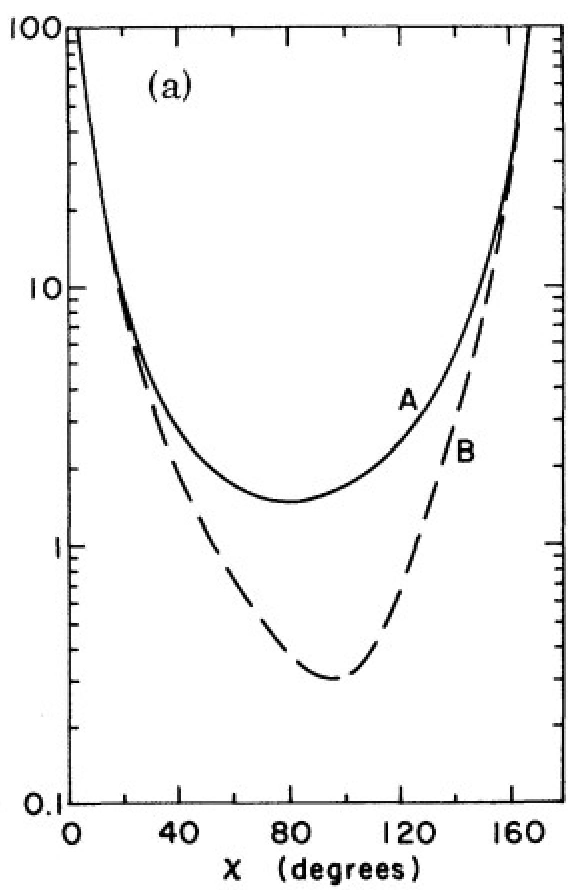
S

$\mathcal{O}$ $|\alpha\rangle$

$$\langle EE\rangle(\chi) \sim A(\chi) + B(\chi)\cos\theta$$ finition

$$\int d^4x \langle 0|j^\mu(x)\mathcal{O}_{\hat{n}} j^\nu(0)|0\rangle$$

Energy Correlators



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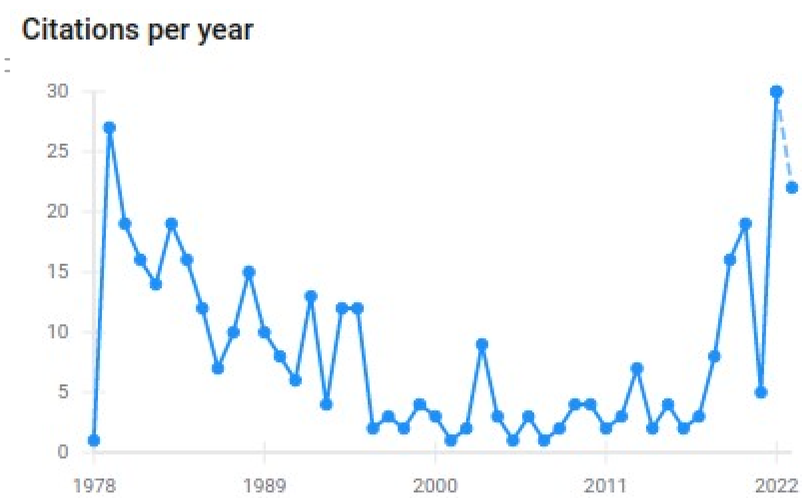
Energy Correlations in electron - Positron Annihilation: Testing QCD

C.Louis Basham (Washington U., Seattle), Lowell S. Brown (Washington U., Seattle), Stephen D. Ellis (Washington U., Seattle), Sherwin T. Love (Washington U., Seattle)

Aug, 1978

$\frac{d\langle E\rangle}{d\chi}$



$\mathcal{O}$

$|\alpha\rangle$

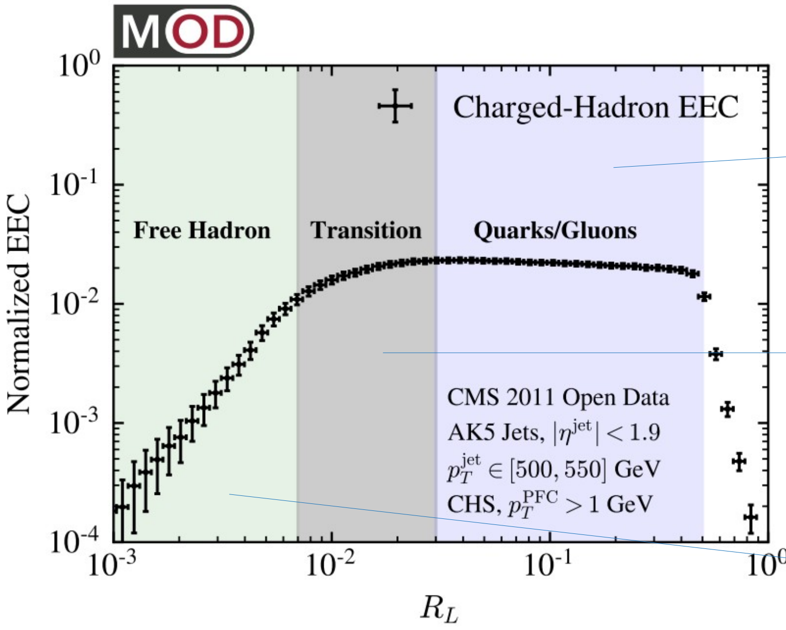
$$\int d^4x \langle 0|j^\mu(x)\mathcal{O}_{\hat{n}} j^\nu(0)|0\rangle$$

Hofman, Maldacena '08

$$\langle 0|j^\mu(x)\mathcal{O}_{\hat{n}}\mathcal{O}_{\hat{n}'}j^\nu(0)|0\rangle \sim \frac{1}{\theta^\gamma}\langle 0|j^\mu(x)\widetilde{\mathcal{O}}_{\hat{n}}j^\nu(0)|0\rangle + \dots\,, \qquad \cos\theta = \hat{n}\cdot\hat{n}'$$

Nearby detectors obey an OPE. This prediction can be tested in QCD:

Komiske, Moult, Thaler, X. Zhu '22



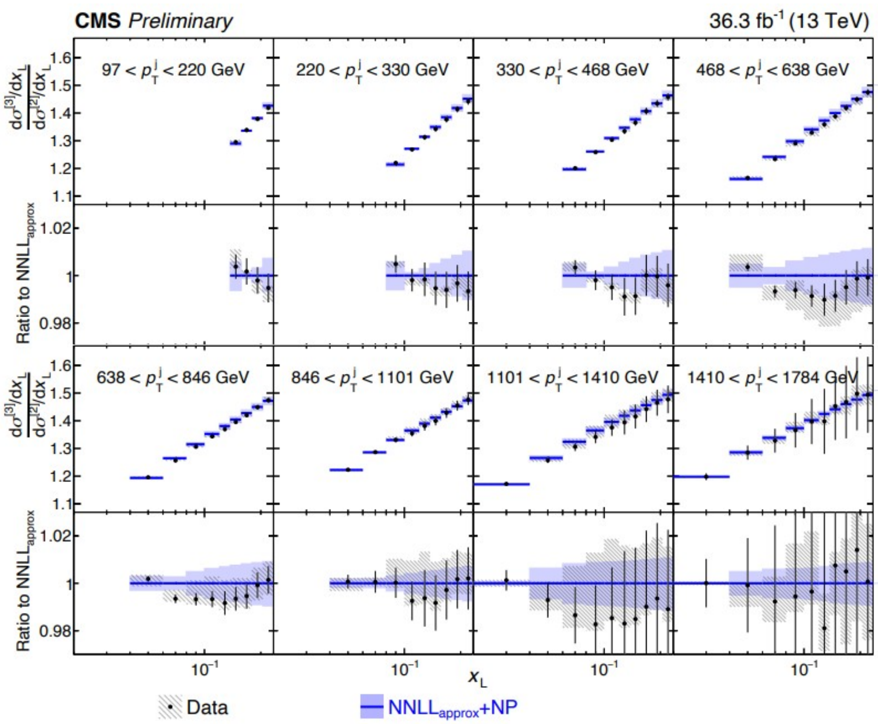
$$1 \gg \theta \gg \Lambda_{QCD}/E_{jet}$$

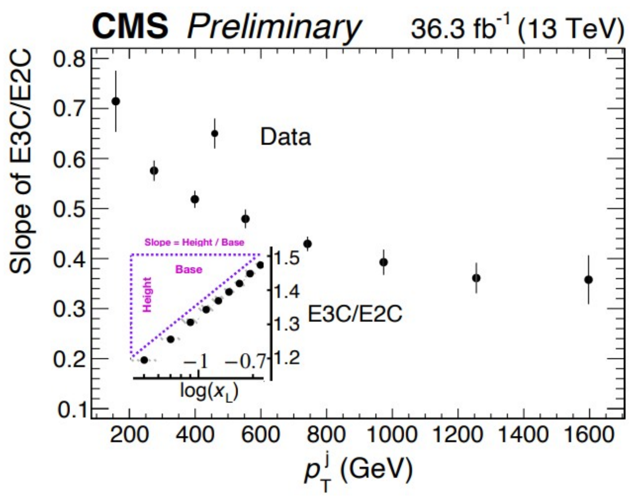
$$\theta \sim \Lambda_{QCD}/E_{jet}$$

$$\Lambda_{QCD}/E_{jet} \gg \theta$$

It can in fact be used to measure alpha_s inside jets

Chen, Gao, Li, Xu, Zhang, X. Zhu '23
CMS-PAS-SMP-22-015 '23





$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

~4% precision
Most important sources are QCD scale in th calc and energy scale of jet
Most precise determination of alpha_s using jet substructure, previous is ~10% in CMS-TOP-17-013

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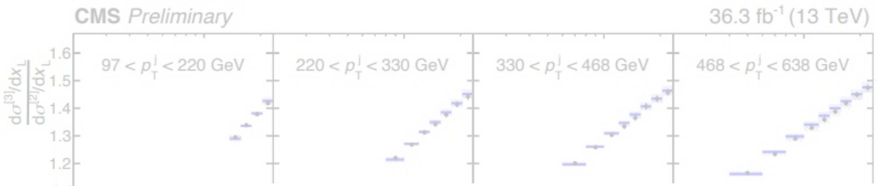
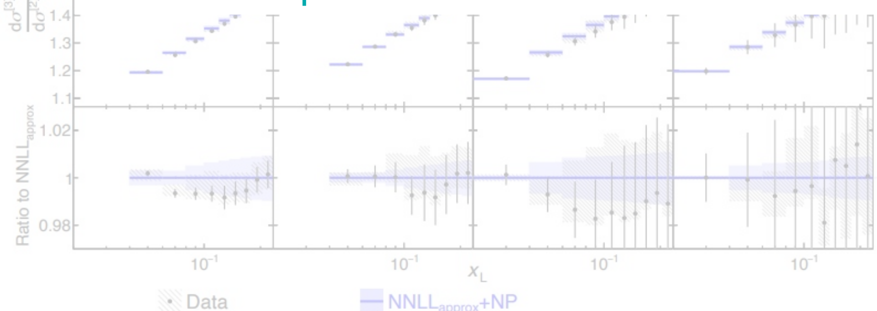
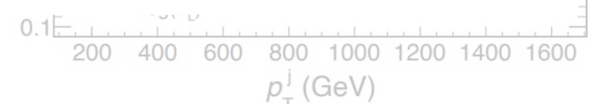


This is an instance of a recent use.
For more examples, see **Kyle Lee's theory overview talk at Boost 2023**

The bottom line is that energy correlators are theoretically clean and experimentally accessible probes of QCD





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Decay density matrix

Ricci, Riembau, '22

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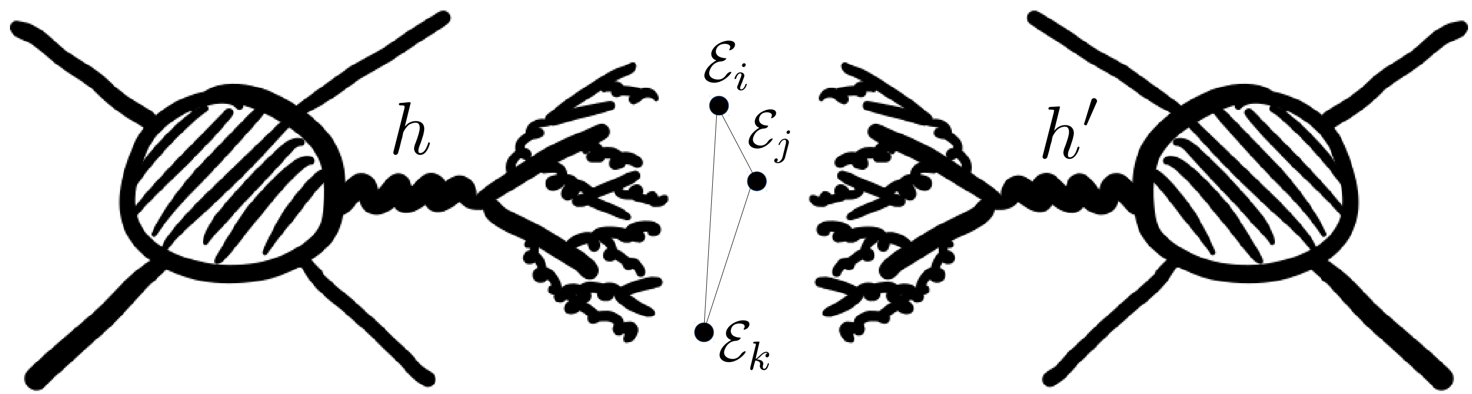
$$\sum_{h,h'}$$



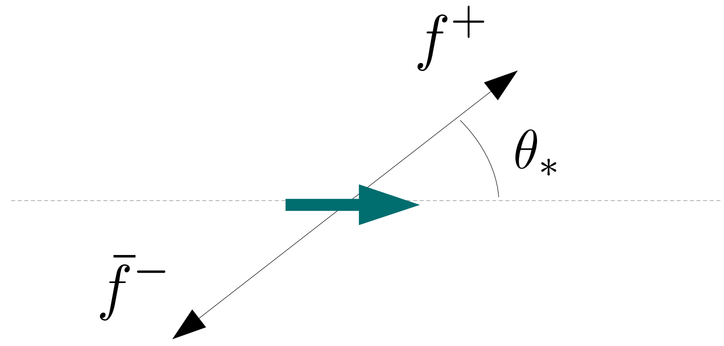
$$d\sigma \;\propto\; \sum_{h,h'} \int d\Pi\; \mathcal{A}^{\text{prod}}_{V_h}\; \mathcal{A}^{\text{dec}}_{V_h \to X}\; \mathcal{E}_1 \cdots \mathcal{E}_N\; (\mathcal{A}^{\text{prod}}_{V_{h'}})^*\; (\mathcal{A}^{\text{dec}}_{V_{h'} \to X})^*$$

$$\equiv\; d\rho^{\text{prod},V}_{h,h'}\;\; d\rho^{\text{dec},V}_{h,h'}[\{\mathcal{E}_1, \ldots, \mathcal{E}_N\}]$$

For hadronic decays, we study the density matrix of energy correlators

Ricci, Riembau, '22

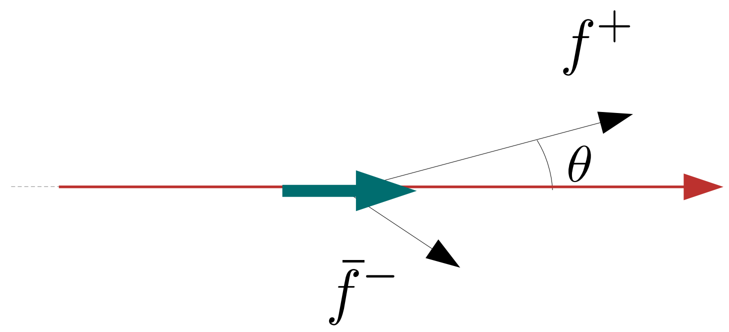
W rest frame



$$\mathcal{A}_+ \propto e^{i\phi}\frac{1+\cos\theta_*}{2} \qquad \mathcal{A}_0 \propto \sin\theta_* \qquad \mathcal{A}_- \propto e^{-i\phi}\frac{1-\cos\theta_*}{2}$$

Ricci, Riembau, '22

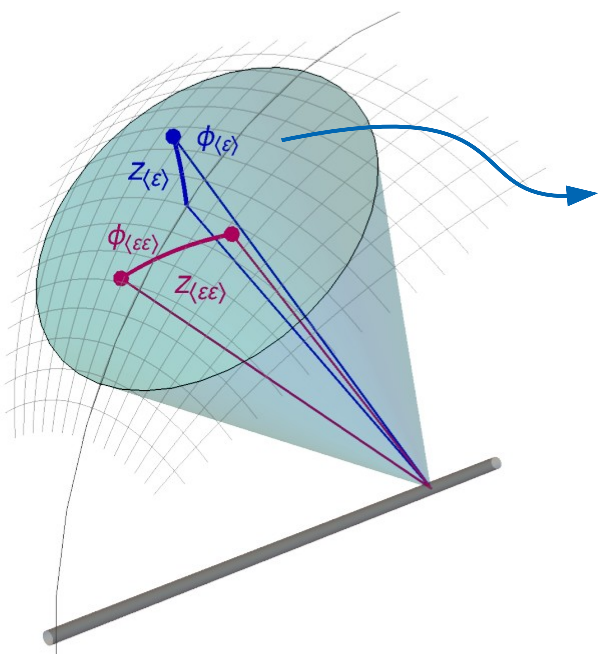
W LAB frame



$$z_\star \equiv \frac{m_W^2}{E_W^2}$$

$$\mathcal{A}_+ \propto e^{i\phi} x \qquad \mathcal{A}_0 \propto \sqrt{x(1-x)} \qquad \mathcal{A}_- \propto e^{-i\phi}(1-x)$$

This LO calculation gives a good prediction for the one-point correlator

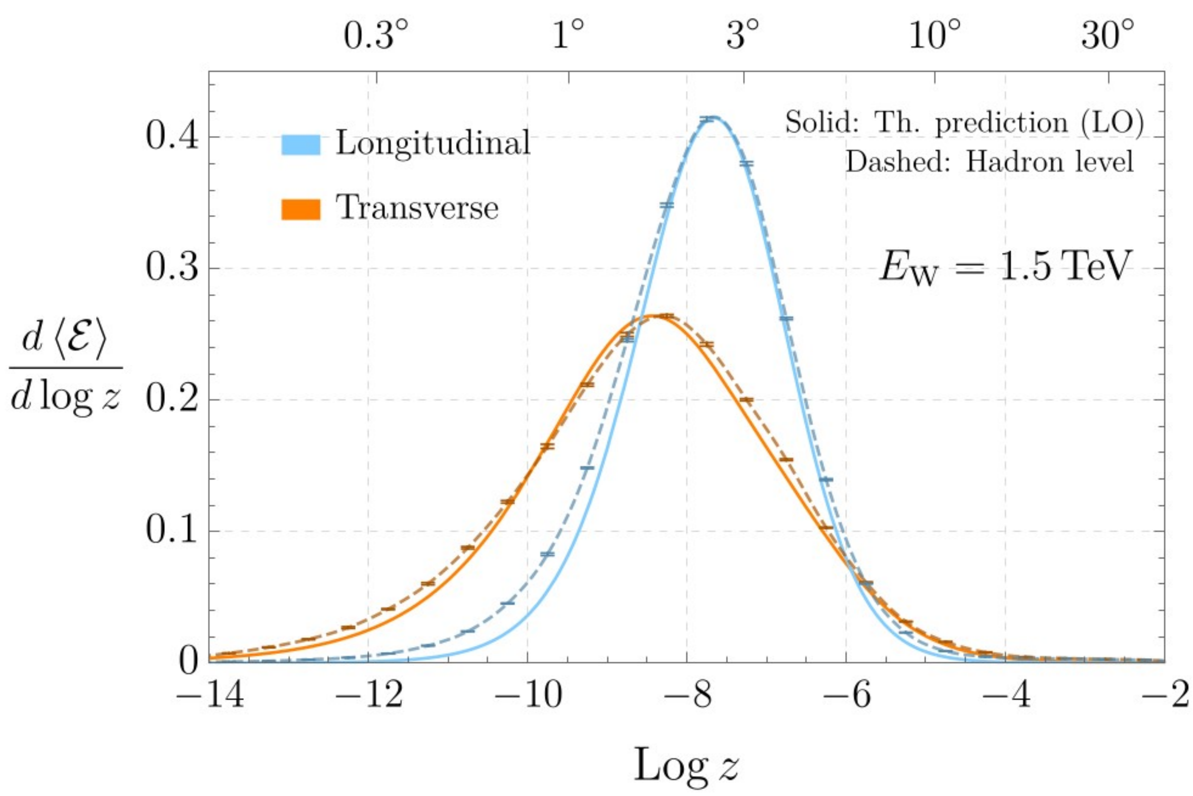


$$x(z) = \frac{1}{1 + 4z/z_\star}$$

$$z \ll z_\star \quad \Rightarrow \quad \mathcal{A}_+ \sim 1, \quad \mathcal{A}_0 \sim \sqrt{z/z_\star}, \quad \mathcal{A}_- \sim z/z_\star$$

One-point Energy Correlator

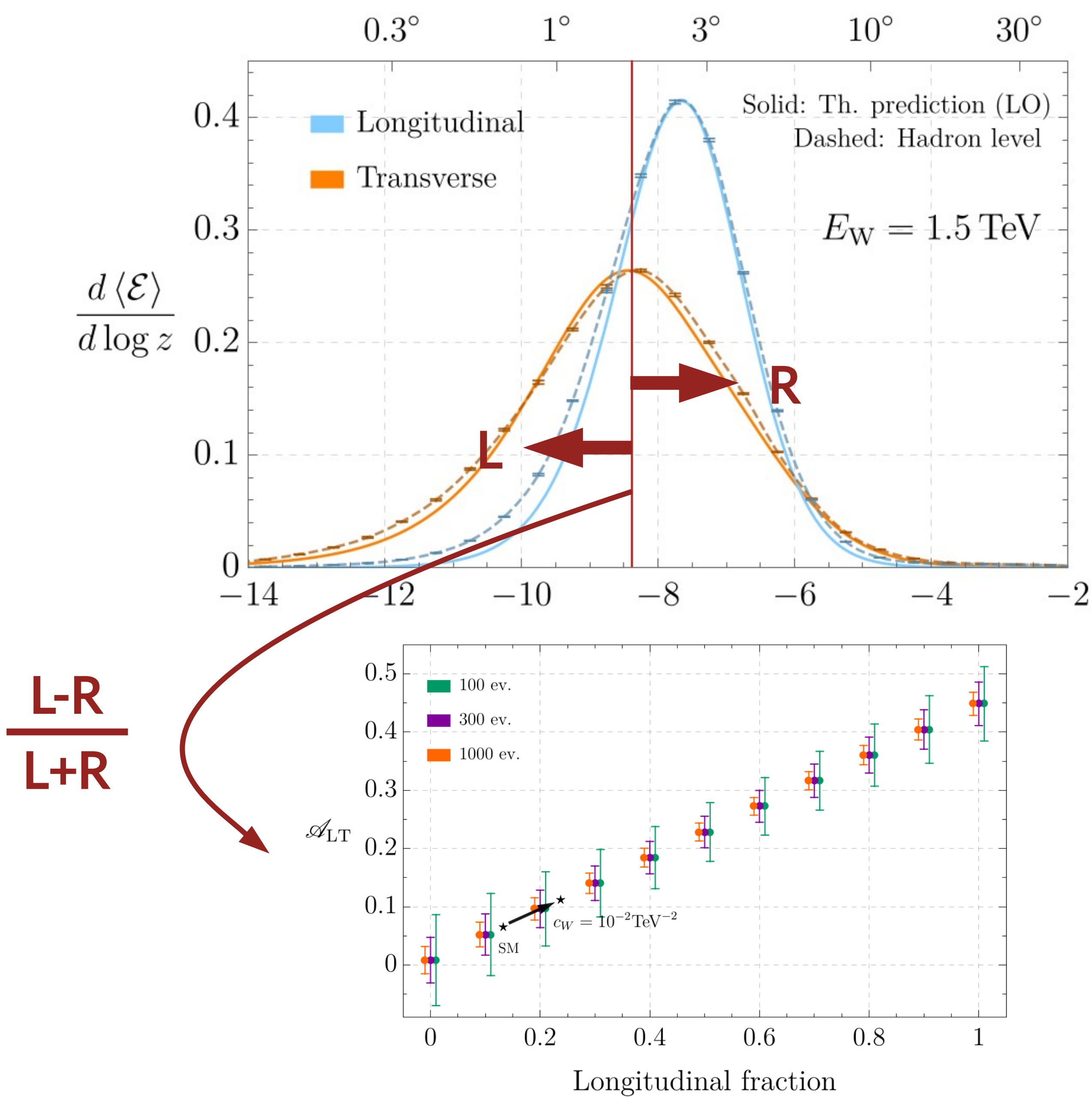
Ricci, Riembau, '22



- Basic kinematics explains Transverse and Longitudinal distributions' shape
- Transverse jets tend to deposit more energy in the central region (small z)
- Recall: this is from ensamble of events. Individual events very different.

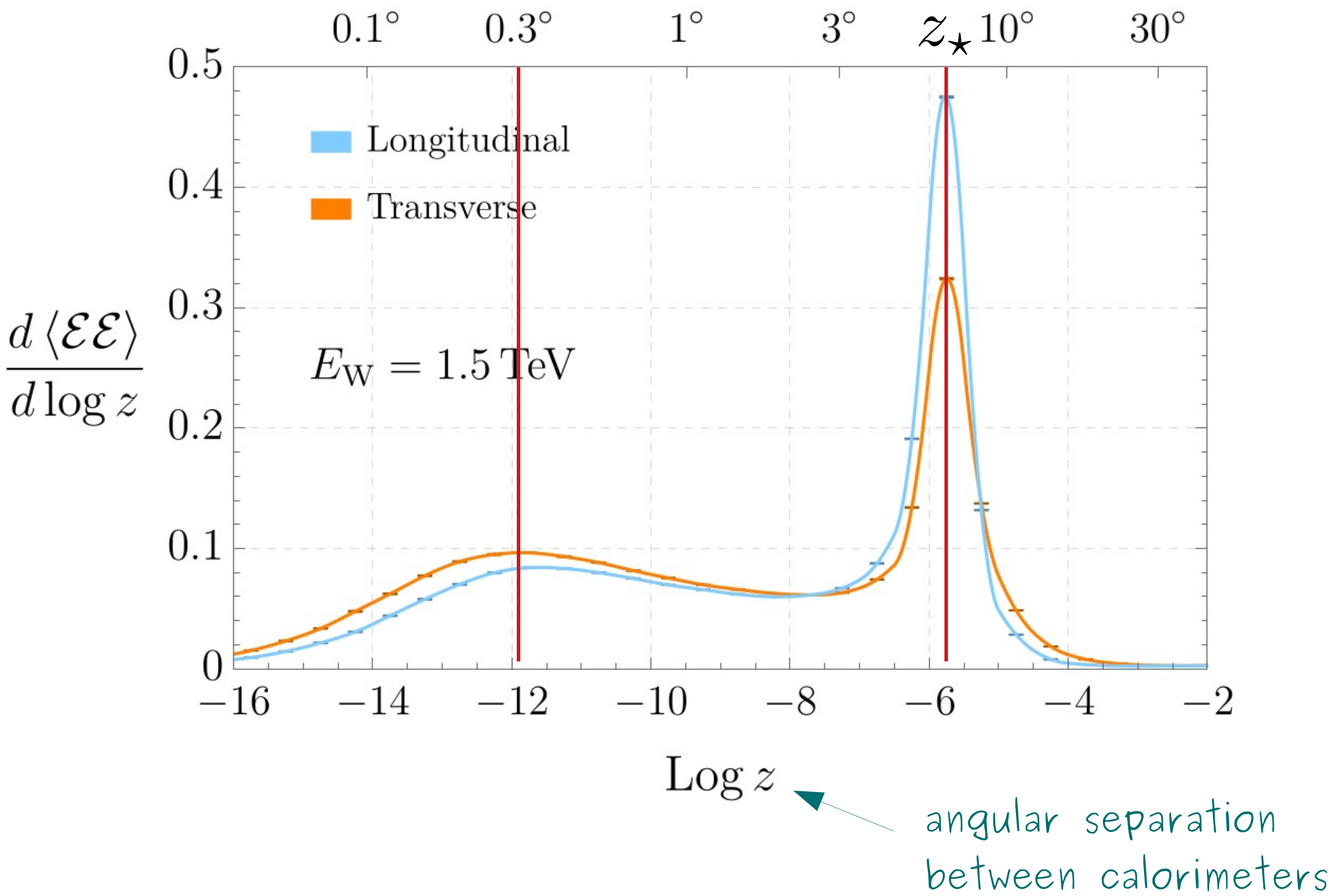
One-point Energy Correlator

Ricci, Riembau, '22



Two-point Energy Correlator

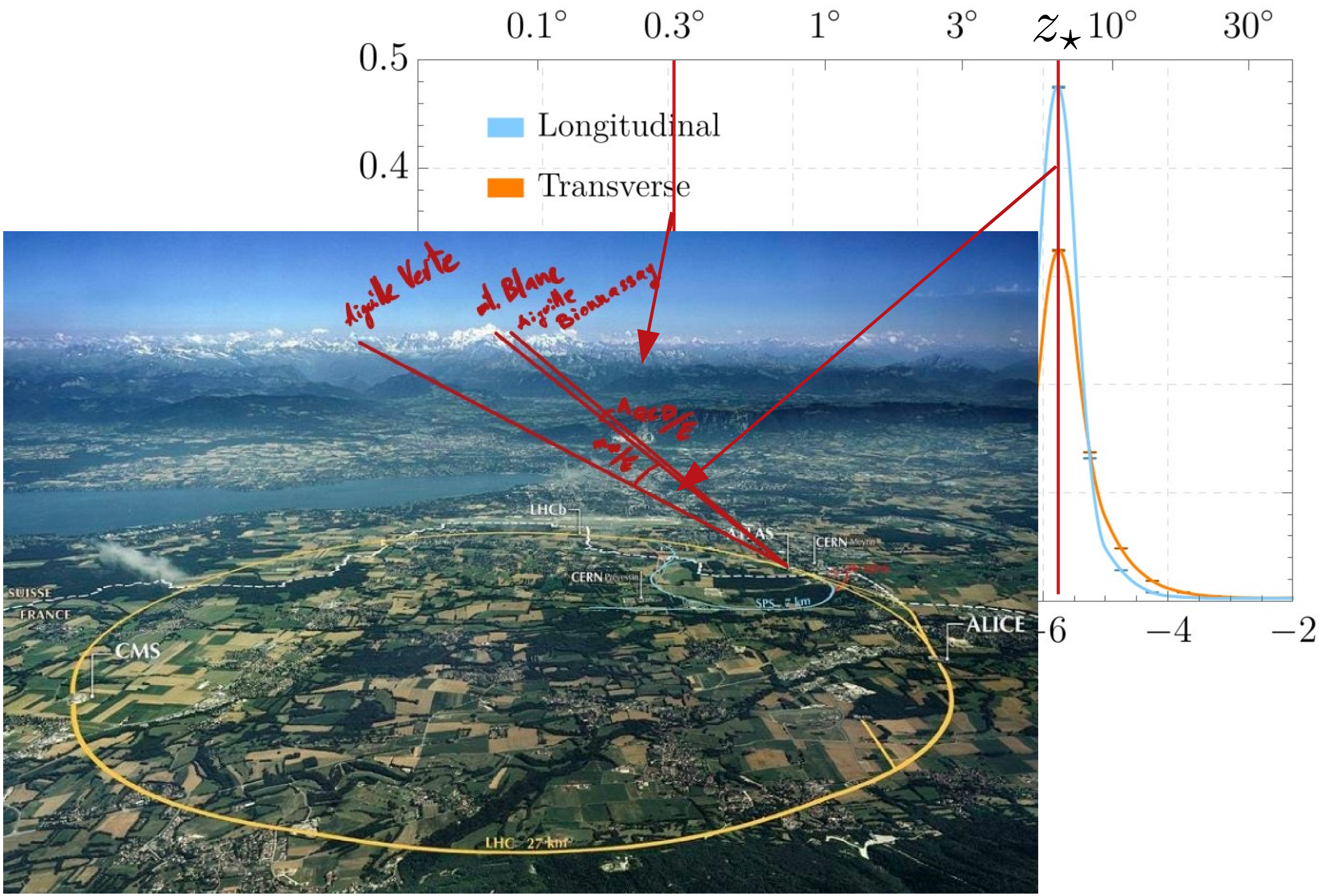
Ricci, Riembau, '22



The z dependence of the two-point correlator cannot be used to separate L and T

Two-point Energy Correlator

Ricci, Riembau, '22



Off-diagonal entries: Interference

Ricci, Riembau, '22

$$d\rho^{V}_{hh'} \sim e^{i\Delta h \phi}\,, \quad \Delta h \equiv h - h'$$

– Inclusive quantities not sensitive to interference

– Ignorance on "which quark" the calorimeters are placed: $\begin{matrix} \phi \to \pi + \phi \\ x \to 1 - x \end{matrix}$ redundancy

– Two types of interference:

$$|\Delta h| = 2$$

Transverse – Transverse interference

Redundancy acts trivially, easy

$$|\Delta h| = 1$$

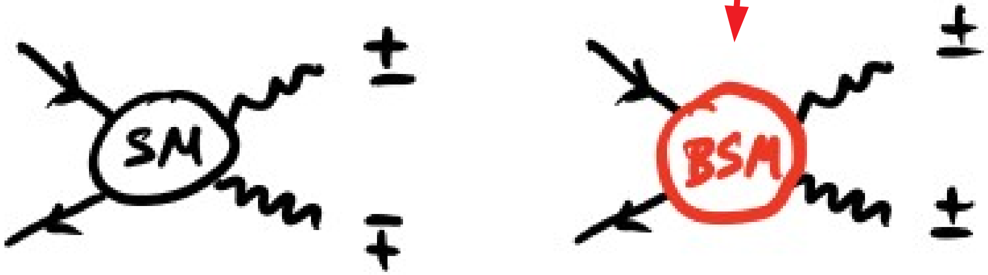
Transverse – Longitudinal interference

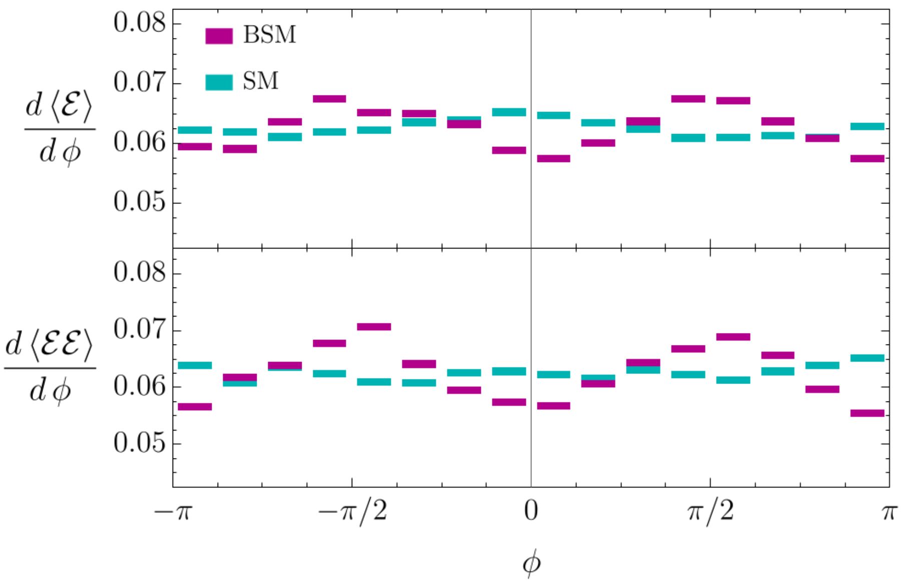
Redundancy acts nontrivially,
each process needs dedicated study

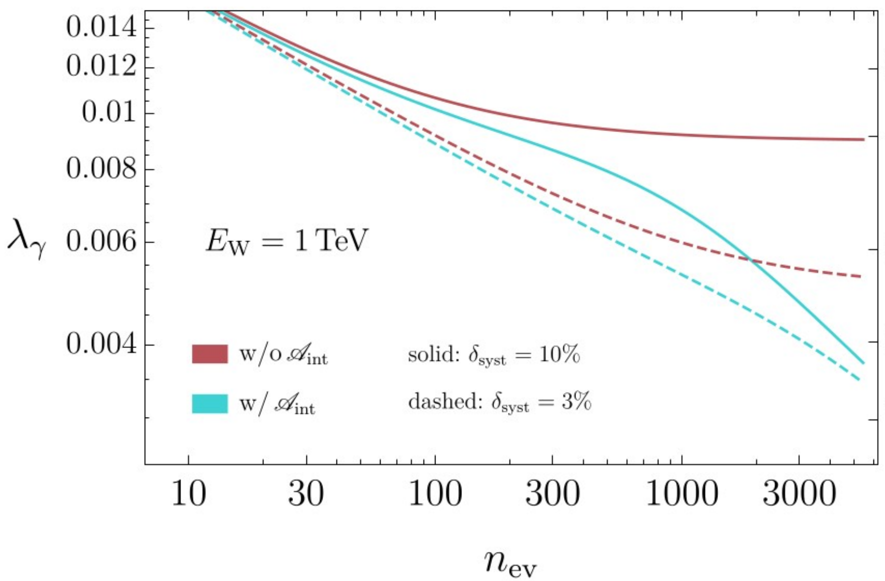
Off-diagonal entries: Interference

$$\mathcal{O}_{3W} = \epsilon^{ABC} W^A_{\mu\nu} W^B_{\nu\rho} W^C_{\rho\mu}$$

$$|\Delta h| = 2$$



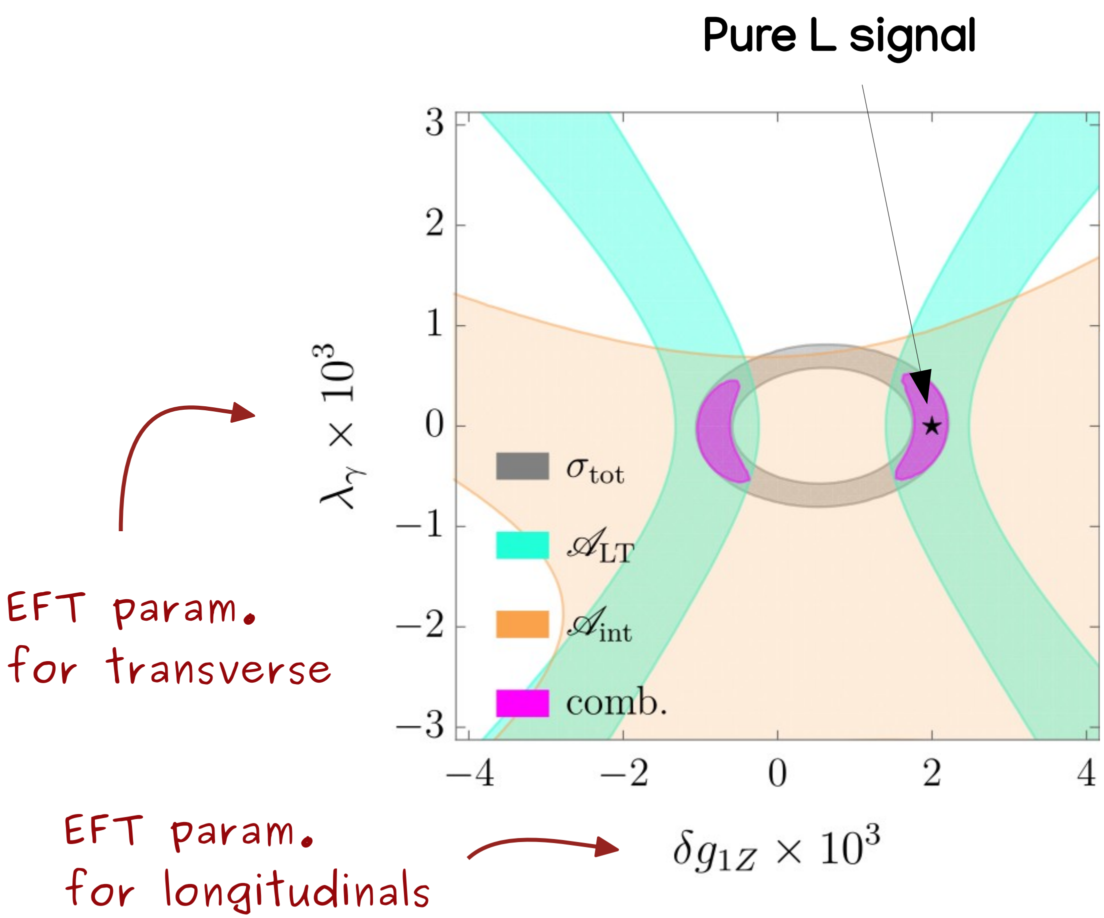




– Interference pattern shows up in the azimuthal dependence of the Ecs

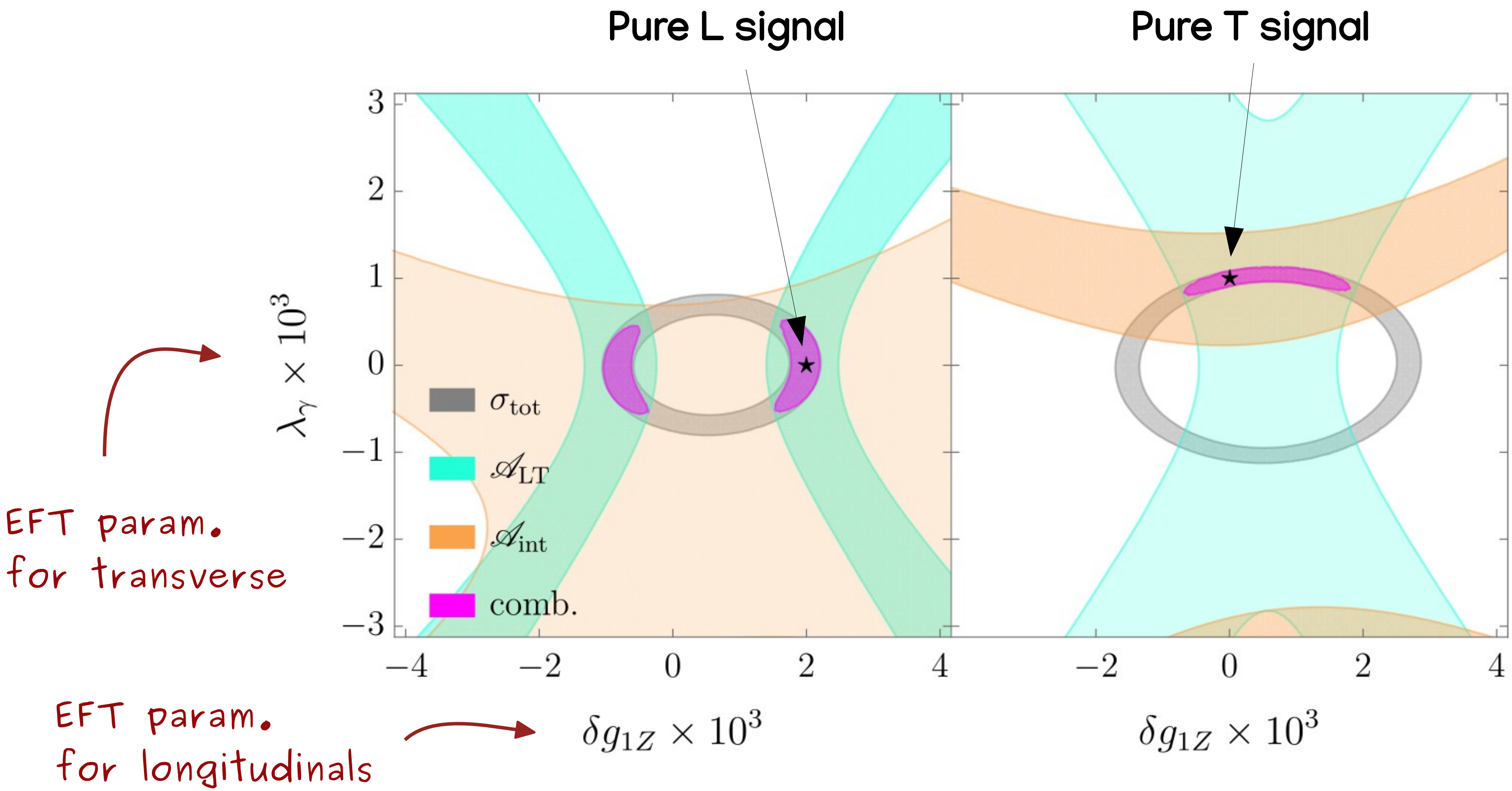
– Measuring the interference leads to linear sensitivity to BSM effects

Impact on BSM scenarios



The one-point correlator identifies the excess coming from an anomalous production of longitudinal modes

Impact on BSM scenarios



The one-point correlator identifies the excess coming from an anomalous production of longitudinal modes

The azimuthal dependence of the correlators identifies the interference term

Towards the LHC

Problem: LHC is not a monoenergetic beam of W bosons.

Part I of the solution:

$$\frac{E_i}{E_J} = \frac{p_{T,i}}{p_{T,J}} + \mathcal{O}(z_\star^{1/2})$$

$$\frac{z}{z_\star} = \frac{\Delta R^2}{R_\star^2} + \mathcal{O}(z_\star^{1/2})$$

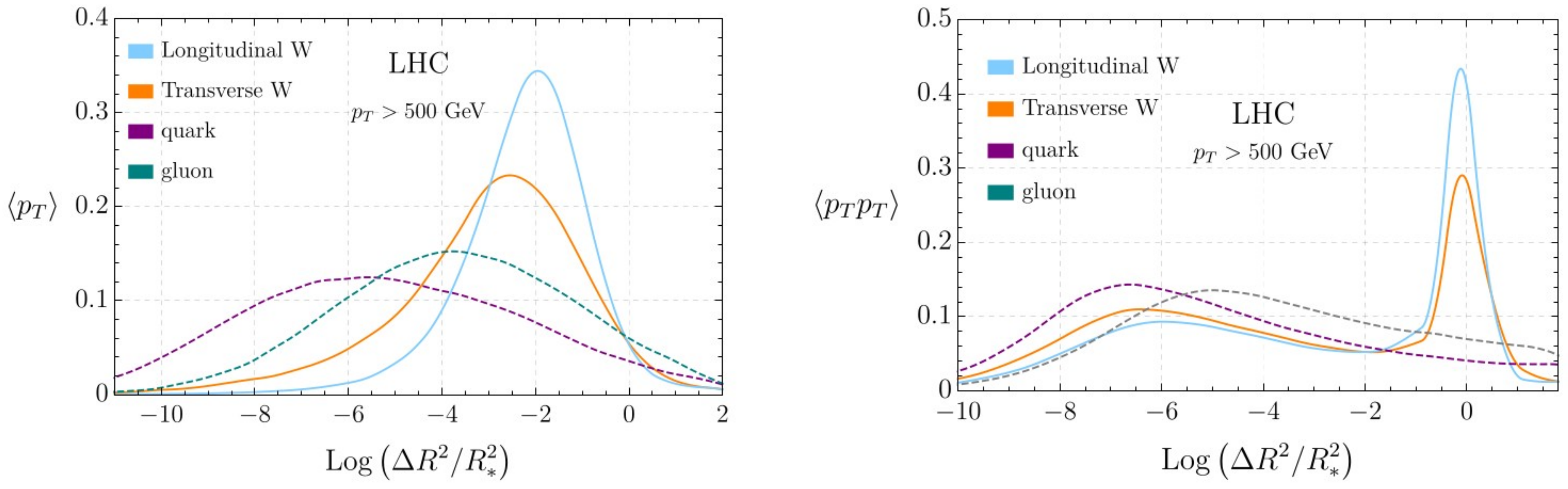
$$R_\star^2 = 4m_V^2/p_{T,J}^2$$

Up to $\mathcal{O}(z_\star^{1/2})$, energy and angular ratios are equivalent to boost invariant objects.

Part II of the solution:

Up to $\mathcal{O}(z_\star)$, amplitudes only depend on the ratio $\frac{z}{z_\star}$, not on z alone

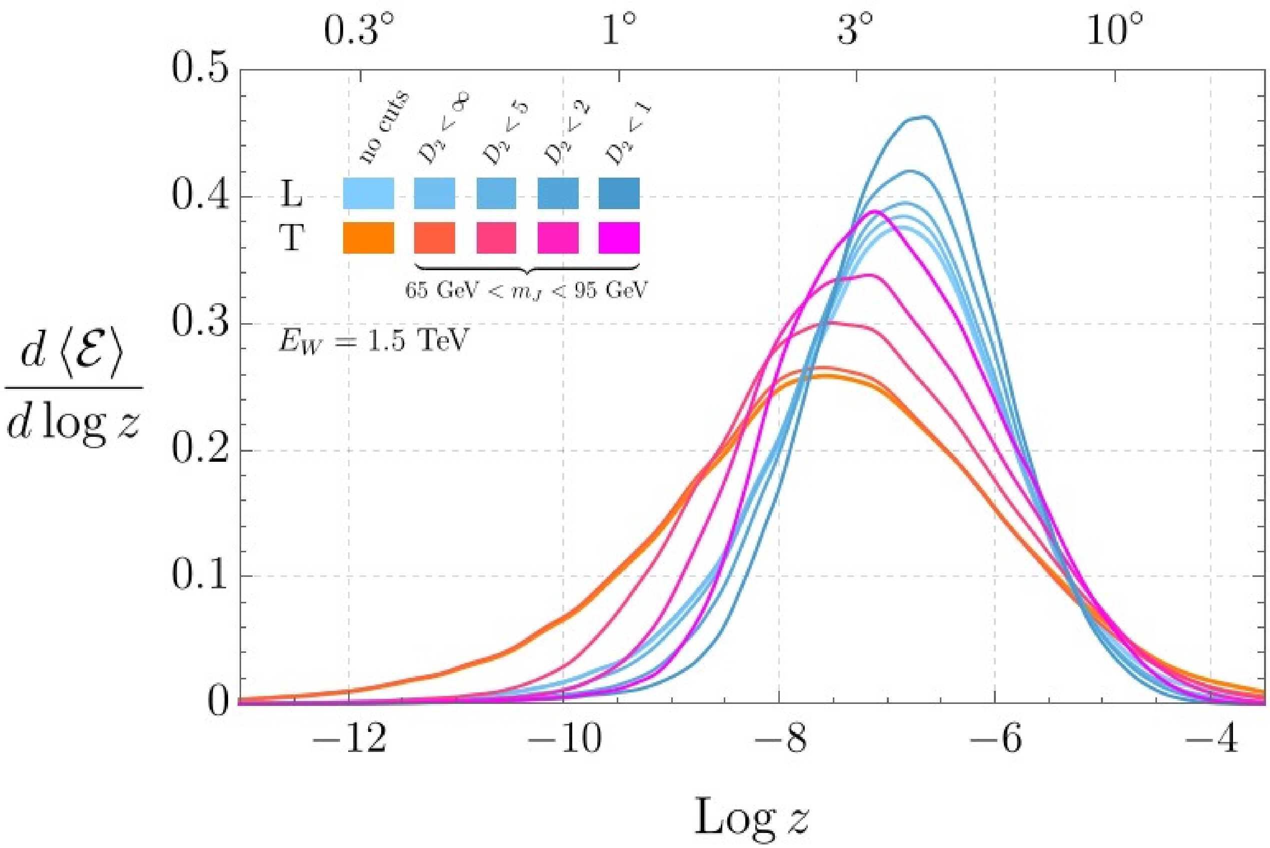
Towards the LHC



By rescaling the angular separations and using boost invariant variables, pT correlators of W jets at the LHC are identical to Energy Correlators of a monoenergetic W boson beam.

Towards the LHC

Impact of selection cuts to the one-point correlator:



- Jet mass and n_track have irrelevant impact.
- D_2, however, has a strong bias towards cutting off more Transv. than Long.
- The reason is kinematical: low z is in one-to-one with having all energy deposited in a single q, which leads to larger D_2 values.
- Polarization studies require revisiting QCD vs EW discrimination.

Conclusions

Angular separation z of one-pont EC discriminates L and T vector bosons

Azimuthal dependence of one- and two-point EC shows $|\Delta\Phi|=2$ interference

EC are useful to characterize BSM physics

Impact of QCD jets and selection criteria needs to be explored further

Thank you!