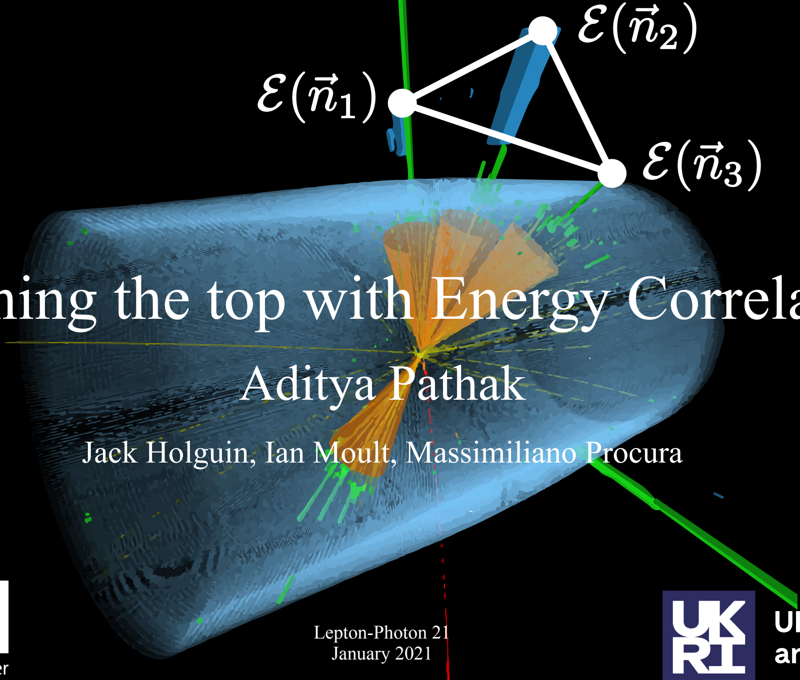


Weighing the top with Energy Correlators

Aditya Pathak

Jack Holguin, Ian Moult, Massimiliano Procura

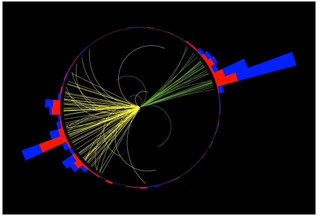
Lepton-Photon 21
January 2021

MANCHESTER 1824
The University of Manchester

UK Research and Innovation

The top quark mass and fate of the universe

Right now: An exciting era of precision collider physics!



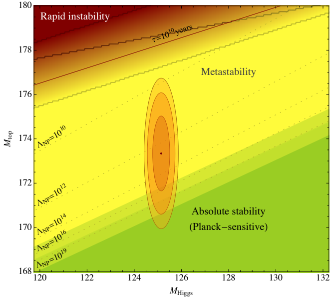
The top and the higgs masses determine the nature of the stability of the electroweak vacuum

[Buttazzo, et al., 2013][Andreassen, et al. 2014] [See Andrea Knue's talk]

→ Direct top mass the most precise:
$m_t^{\mathrm{MC}} = 173.34 \pm 0.76\,\mathrm{GeV}$ [World combination 1403.4427],
but ...

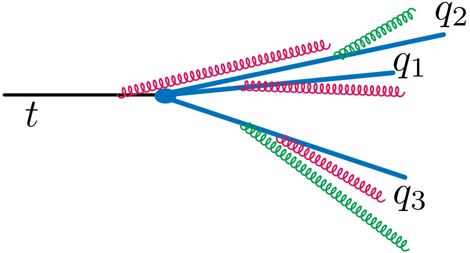
- *MC top mass parameter*: No field theoretic mass scheme, $\mathcal{O}(1)$ GeV theory uncertainty argued [Hoang 2004.12915]
- Sensitive to the parton shower, hadronization model [Hoang et al. 1807.06617]

→ Indirect cross section measurements not precise enough
$m_t^{\mathrm{pole}} = 172.9^{+2.5}_{-2.6}$ GeV [ATLAS, 1406.5375]
$m_t^{\mathrm{pole}} = 172.7^{+2.4}_{-2.7}$ GeV [CMS, 1701.06228]



Kinematic top mass measurements

Knowing kinematics of the top decay improves precision on m_t



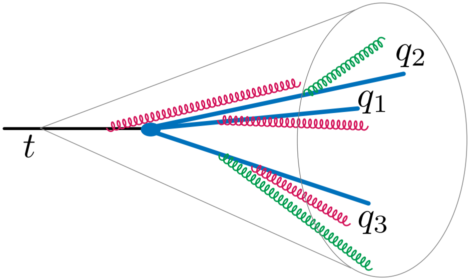
Kinematic top mass measurements

Consider the jet mass:

$$M_J^2 = \left(\sum_{i \in J} p_i^\mu \right)^2 \simeq m_t^2 + \Gamma_t m_t + \ldots$$

[Fleming et al. hep-ph/0703207, 0711.2079]

[Bachu, Hoang, AP, Mateu, Stewart 2012.12304]



Kinematic top mass measurements

Consider the jet mass:

$$M_J^2 = \left(\sum_{i \in J} p_i^\mu \right)^2 \simeq m_t^2 + \Gamma_t m_t + \dots$$

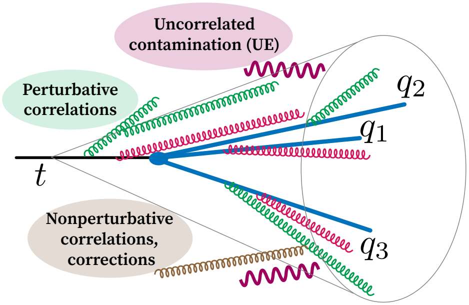
[Fleming et al. hep-ph/0703207, 0711.2079]

[Bachu, Hoang, AP, Mateu, Stewart 2012.12304]

Challenging to calculate:

→ Strongly correlated with the outside radiation

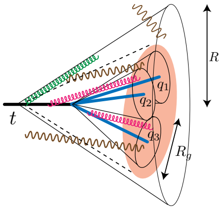
→ Precision spoiled by uncorrelated contamination (UE)



Kinematic top mass measurements

Consider **Soft drop jet mass**

$$M_{J,\mathrm{sd}}^2 = \Big(\sum_{i\in J^{\mathrm{groomed}}} p_i^\mu\Big)^2 \simeq m_t^2 + \Gamma_t m_t + \ldots$$

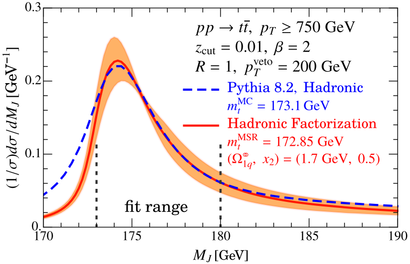


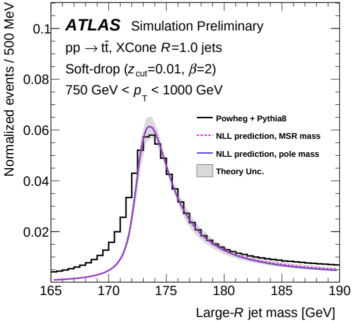
→ Removes wide-angle soft radiation

→ Improves robustness significantly for the LHC

[Hoang, Mantry, AP, Stewart 1708.02586] [Hoang, Mantry, Michel, AP, Stewart]

[ATL-PHYS-PUB-2021-034]





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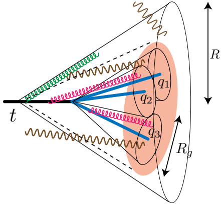


→ Removes wide-angle soft radiation

→ Improves robustness significantly for the LHC

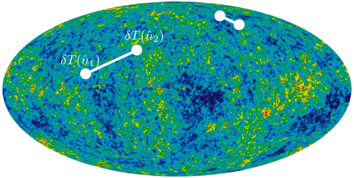
[Hoang, Mantry, AP, Stewart 1708.02586] [Hoang, Mantry, Michel, AP, Stewart]

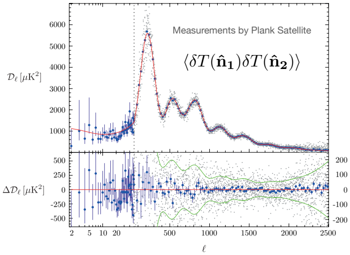
[ATL-PHYS-PUB-2021-034]

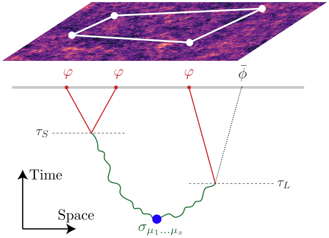
Still quite a challenging task to quantify the remaining corrections in '...'!

$$M_J^2 \simeq m_t^2 + \Gamma_t m_t +$$   

Correlation functions are extremely powerful!

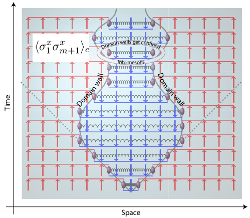




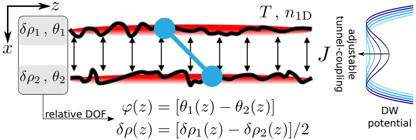


[Arkani-Hamed, Maldacena 1503.08043]

[Arkani-Hamed, Baumann, Lee, Pimentel;1811.00024]



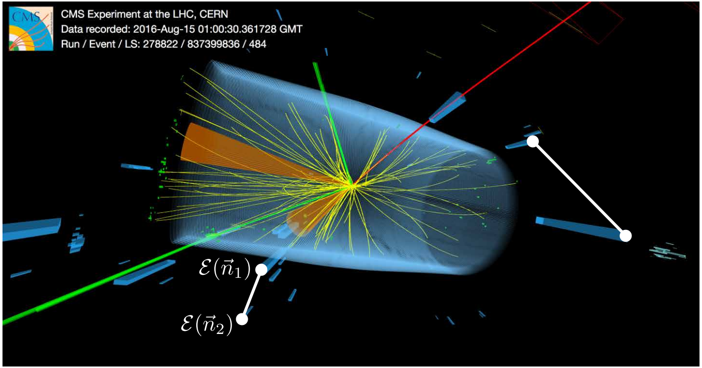
[Kormos et al. Nature Phys. 13, 2017]



$$G^N(\mathbf{z}, \mathbf{z}') = \langle [\varphi(z_1) - \varphi(z_1')] \dots [\varphi(z_N) - \varphi(z_N')] \rangle$$

[Schweigler et al. 1505.03126]

Correlators for collider physics



For a precise theoretical formulation:

→ Consider correlation functions of energy flow operators: $\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\ldots\mathcal{E}(\vec{n}_N)\rangle$ [Hofman, Maldacena; 0803.1467]

→ Cannot work with local operators: need light ray operators

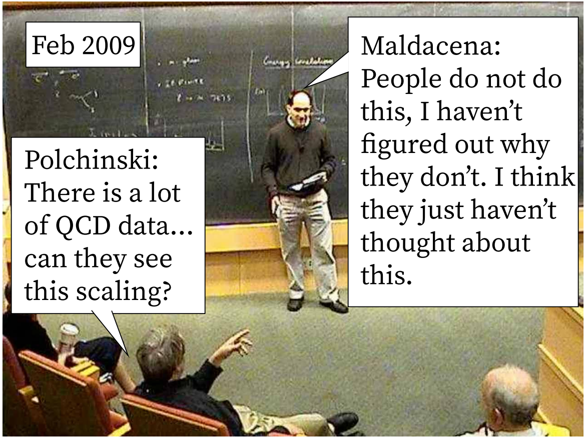
[Hofman, Maldacena; 0803.1467][Sveshnikov, Tkachov hep-ph/9512370][Kravchuk, Simmons-Duffin 1805.00098]

→ Borrow a wealth of insights from CFT and string theory

[Hofman, Maldacena; 0803.1467][Belitsky et al. 1311.6800][Korchemsky, Sokatchev 1504.07904][Kologlu et al. 1904.05905, 1905.01311]

Why have ***we*** not already been using correlators?

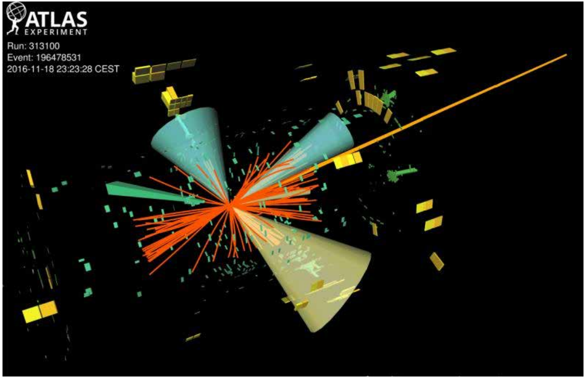
Cosmic variance is not an excuse for collider physics!



[KITP Seminar, Feb 2009; 47 min into the talk]

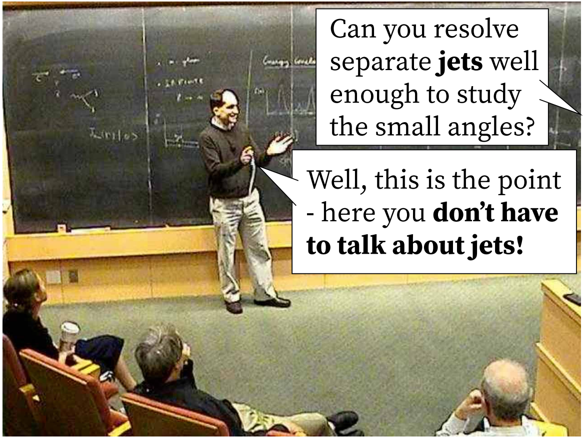
Why have ***we*** not already been using correlators?

Since the beginning of the LHC we have exclusively focused on jet-based observables (m_J, τ_a, $e_n^{(\alpha)}$, ...)



Why have ***we*** not already been using correlators?

Energy-correlators only require angles to be measured precisely!

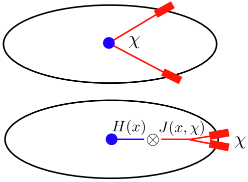


[KITP Seminar, Feb 2009; 49 min into the talk]

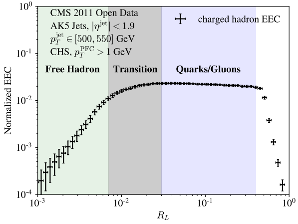
→ Can be computed on tracks! [Chang, Procura, Thaler, Waalewijn, 1303.6637][Moult, van Velzen, Waalewijn, Zhu 2108.01674]

Progress in recent years

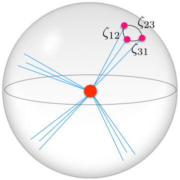
- → Resummation in the small angle limit in SCET
- → EEC: mapping transition from perturbative to free hadron phase
- → EEEC: Interference in the squeezed limit



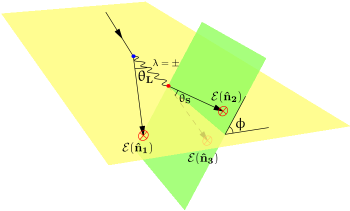
[Dixon, Moult, Zhu, 1904.01310]



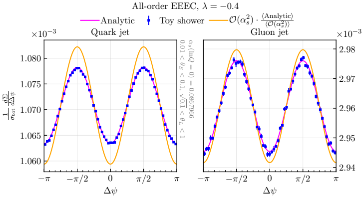
[Komiske, Moult, Thaler, Zhu]



[Chen, Luo, Moult, Yang, Zhang, Zhu 1912.11050]

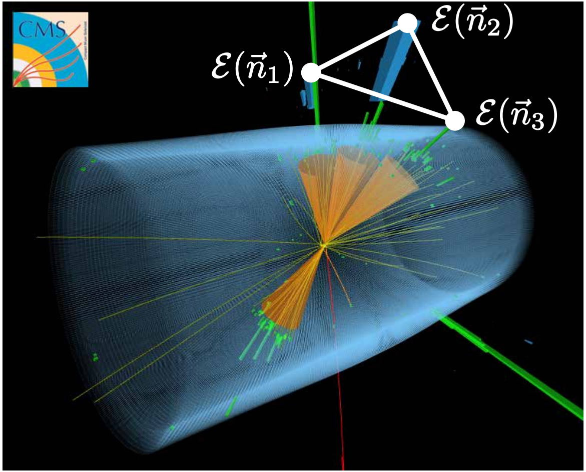


[Chen, Moult, Zhu 2104.00009]



[Karlberg, Salam, Scyboz, Verheyen 2103.16526]

Probing the top with the three-point correlator

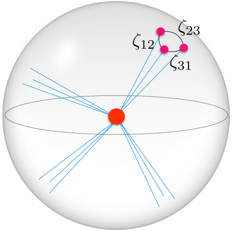


$$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\mathcal{E}(\vec{n}_3)\rangle_t \equiv \frac{\langle \psi_t|\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\mathcal{E}(\vec{n}_3)|\psi_t\rangle}{\langle \psi_t|\psi_t\rangle}$$

Three-point correlator:

$$G^{(n)}(\zeta_{12},\zeta_{23},\zeta_{31}) = \int \mathrm{d}\sigma\, \widehat{\mathcal{M}}^{(n)}(\zeta_{12},\zeta_{23},\zeta_{31})$$

$$\widehat{\mathcal{M}}^{(n)}(\zeta_{12},\zeta_{23},\zeta_{31}) = \sum_{i,j,k} \frac{E_i^n E_j^n E_k^n}{Q^{3n}} \delta\left(\zeta_{12} - \hat{\zeta}_{ij}\right) \delta\left(\zeta_{23} - \hat{\zeta}_{ik}\right) \delta\left(\zeta_{31} - \hat{\zeta}_{jk}\right)$$



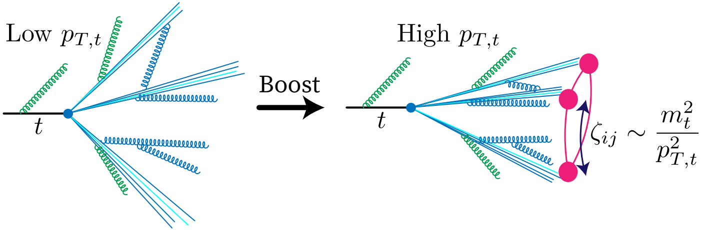
In the CFT limit EEEC exhibits a featureless power law

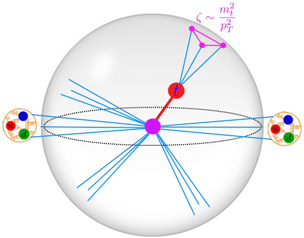
[Dixon, Moult, Zhu, 1904.01310][Korchemsky 1905.01444][Kologlu et al. 1905.01311]

$$G^{(1)}(\zeta_{12},\zeta_{23},\zeta_{31}) \xrightarrow{\text{CFT}} \zeta_{31}^{-1+\gamma(4)} G(z,\bar{z})\,,$$

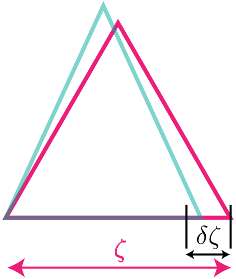
$$z\bar{z} = \zeta_{12}/\zeta_{31}\,, \qquad (1-z)(1-\bar{z}) = \zeta_{23}/\zeta_{31}$$

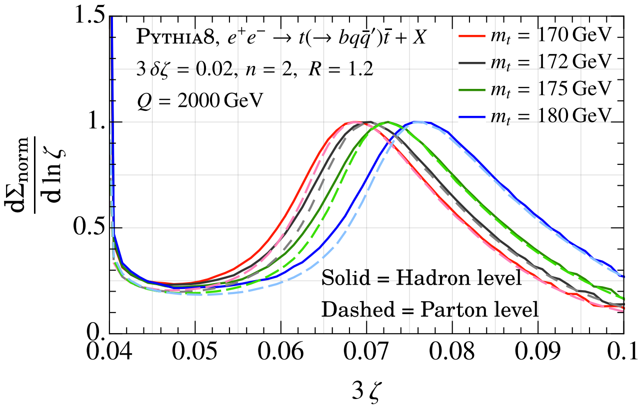
The top quark decay imprints m_t as a characteristic scale in the 3-point correlator:





Study the simplest configuration of an equilateral triangle $\hat{\zeta}_{ij} = \zeta$:





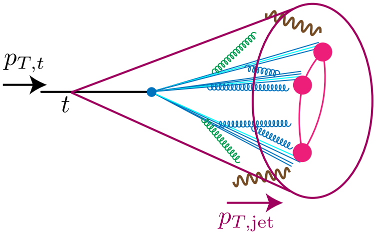
→ Hadronization effects: small effect on the peak $\Delta m_t^{\text{Had.}} \sim 230$ MeV.

→ Peaked at $\zeta_{\text{peak}} \approx 3m_t^2/Q^2$: peak dominated by hard decay of the top.

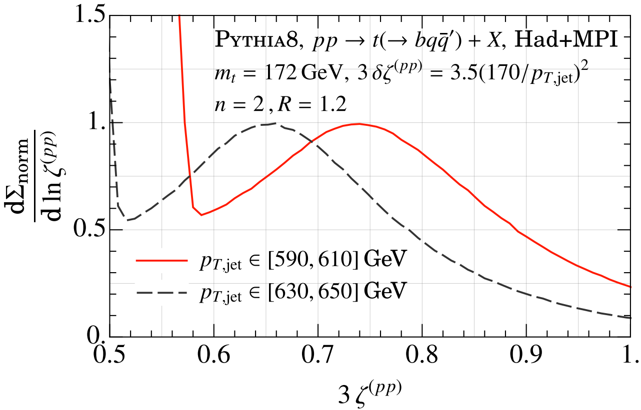
→ Resilient to collinear radiation $\alpha_s \ln\zeta_{\text{peak}} < 1$: fixed order perturbation theory sufficient.

EEEC on top: measurement at the LHC

At the LHC we can measure EEEC on jets containing top decay products:



Unlike EEEC, $p_{T,\text{jet}}$ is susceptible to hadronization and underlying event:
→ Consider multiple $p_{T,\text{jet}}$ bins



Assuming that $p_{T,\text{jet}}$ can be unfolded to 1 GeV accuracy, then

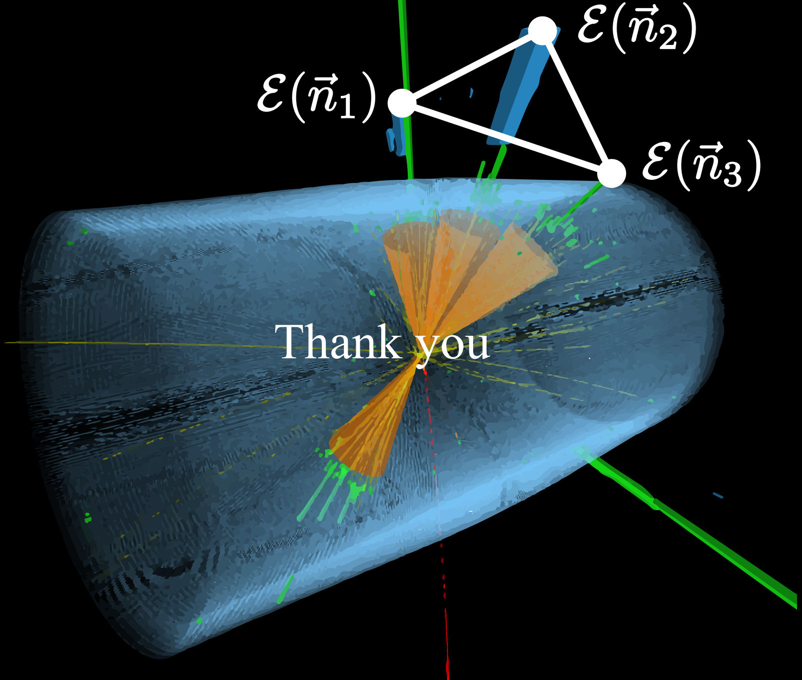
→ Differences between parton, hadron and with MPI: well less than 1 GeV (likely less than 500 MeV)

→ Impact of the UE: less than 300 MeV (in the Pythia MPI model)

The EEEC observable is fully robust against the UE: Obtain corrections to $p_{T,\text{jet}}$ *independently*

Conclusions

1. Correlation functions are powerful tools for precision collider physics.
2. The 3-point correlation function is very sensitive to the top mass.
3. Very small hadronization corrections to the normalized 3-point correlator.
4. The only sizable corrections from hadronization and the UE enter solely into $p_{T\text{jet}}$.
5. Corrections to the jet p_T are observable-independent and can be independently studied and quantified.


$\mathcal{E}(\vec{n}_2)$
$\mathcal{E}(\vec{n}_1)$
$\mathcal{E}(\vec{n}_3)$
Thank you

Supplementary slides

More on correlation functions of energy flow operators

Energy flow operators are natural objects in QFT:

$$\mathcal{E}(\vec{n}) = \int_0^\infty dt \lim_{r\to\infty} r^2 n^i T_{0i}(t, r\vec{n})$$

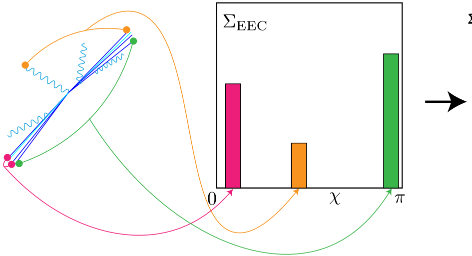
that can be used to define energy weighted cross sections:

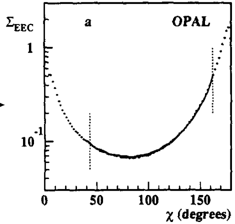
$$\sigma_w = \int d^4x e^{iq\cdot x} \langle 0|\mathcal{O}(x)\, \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\ldots\mathcal{E}(\vec{n}_N)\, \mathcal{O}^\dagger(0)|0\rangle$$

such as the 2-point correlator (EEC):

$$\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\chi} = \sum_{ij}\int \frac{E_i E_j}{Q^2}\delta(\vec{n}_i\cdot\vec{n}_j - \cos\chi)\mathrm{d}\sigma$$

Each event contributes to multiple bins, with the final distribution being an ensemble average over all events:



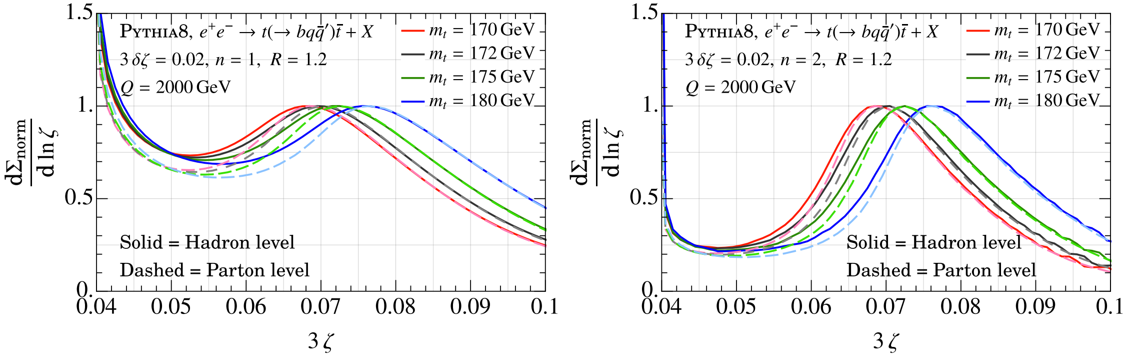


[Opal collboration, Z. Phys. C59 (1993) 21]

EEEC on tops: Compare different energy weights

Study the simplest configuration of an equilateral triangle $\hat{\zeta}_{ij} = \zeta$:

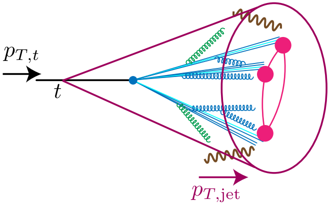
$$\frac{\mathrm{d}\Sigma(\delta\zeta)}{\mathrm{d}Q\mathrm{d}\zeta} = \int \mathrm{d}\zeta_{12}\mathrm{d}\zeta_{23}\mathrm{d}\zeta_{31} \int \mathrm{d}\sigma \widehat{\mathcal{M}}_{\Delta}^{(n)}(\zeta_{12},\zeta_{23},\zeta_{31},\zeta,\delta\zeta)$$

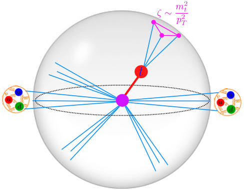


→ $n = 2$ is not IRC safe, but can be computed using the track-functions formalism

EEC on tops: *nitty-gritty* of measurements in hadron collisions

At the LHC we can measure EEEC on jets containing top decay products:





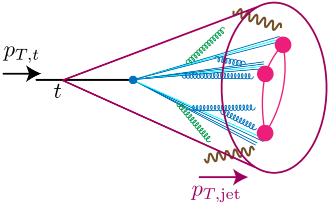
Measurement operator for pp collisions:

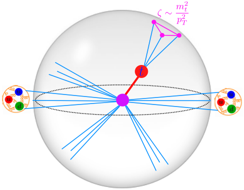
$$\widehat{\mathcal{M}}^{(n)}_{(pp)}(\zeta_{12},\zeta_{23},\zeta_{31}) = \sum_{i,j,k\,\in\,\mathrm{jet}} \frac{(p_{T,i})^n (p_{T,j})^n (p_{T,k})^n}{(p_{T,\mathrm{jet}})^{3n}}\,\delta\left(\zeta_{12}-\hat{\zeta}^{(pp)}_{ij}\right)\delta\left(\zeta_{23}-\hat{\zeta}^{(pp)}_{ik}\right)\delta\left(\zeta_{31}-\hat{\zeta}^{(pp)}_{jk}\right)$$

$$\hat{\zeta}^{(pp)}_{ij} = \Delta R_{ij} = \sqrt{\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2}$$

EEEC on tops: *nitty-gritty* of measurements in hadron collisions

At the LHC we can measure EEEC on jets containing top decay products:





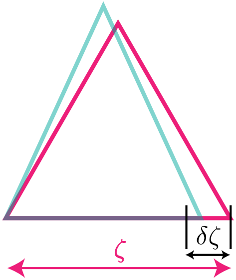
The peak the distribution is determined by $p_{T,t}$ and *not* $p_{T,\mathrm{jet}}$. But the parton level top $p_{T,t}$ is not directly accessible, so consider

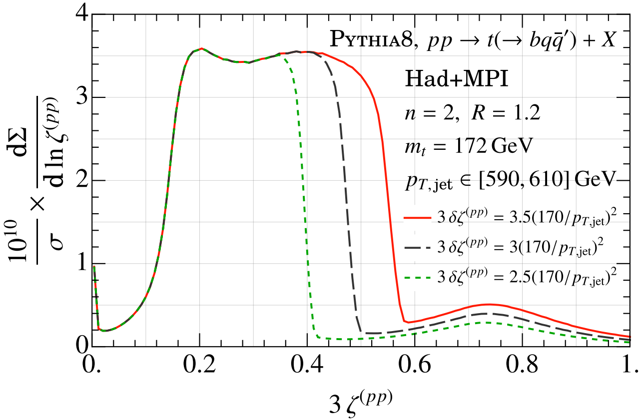
$$\frac{\mathrm{d}\Sigma(\delta\zeta)}{\mathrm{d}p_{T,\mathrm{jet}}\mathrm{d}\zeta} = \frac{\mathrm{d}\Sigma(\delta\zeta)}{\mathrm{d}p_{T,t}\mathrm{d}\zeta}\,\frac{\mathrm{d}p_{T,t}}{\mathrm{d}p_{T,\mathrm{jet}}}$$

Because of energy weighting and small angle limit, the basic properties of $\mathrm{d}\Sigma(\delta\zeta)/\mathrm{d}p_{T,t}\mathrm{d}\zeta$ are completely insensitive to the underlying event.

Impact of asymmetry cut $\delta\zeta$

Asymmetry cut $\delta\zeta$ only constrains triangles with $\zeta > 2\delta\zeta$





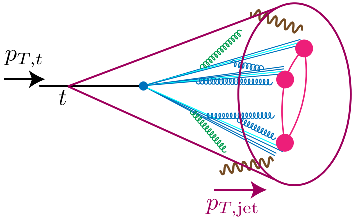
$$\frac{d\Sigma}{d\zeta} \approx 4(\delta\zeta)^2\, G^{(n)}(\zeta,\zeta,\zeta;m_t)\,, \qquad \delta\zeta \ll \zeta$$

Effects of hadronization and underlying event in pp collisions

Hadronization and MPI will impact the jet p_T:

$$p_{T,\text{jet}}^{\text{Had.}} = p_{T,\text{jet}}^{\text{part.}} + \delta p_T^{\text{Had.}}\,, \qquad p_{T,\text{jet}}^{\text{UE}} = p_{T,\text{jet}}^{\text{Had.}} + \delta p_T^{\text{UE}}$$

[Dasgupta, Magnea, Salam; 0712.3014]



$p_{T,\text{jet}}$ appears in two places:

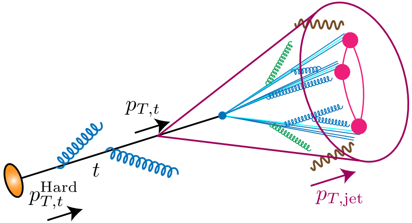
1. $p_{T,\text{jet}}$ appears in the measurement operator

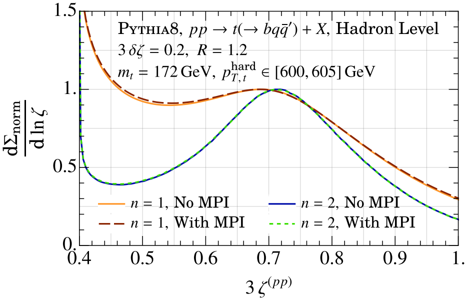
$$\widehat{\mathcal{M}}^{(n)}_{(pp)}(\zeta_{12},\zeta_{23},\zeta_{31}) = \sum_{i,j,k\,\in\,\text{jet}} \frac{(p_{T,i})^n (p_{T,j})^n (p_{T,k})^n}{(p_{T,\text{jet}})^{3n}}\,\delta\left(\zeta_{12} - \hat{\zeta}^{(pp)}_{ij}\right)\delta\left(\zeta_{23} - \hat{\zeta}^{(pp)}_{ik}\right)\delta\left(\zeta_{31} - \hat{\zeta}^{(pp)}_{jk}\right)$$

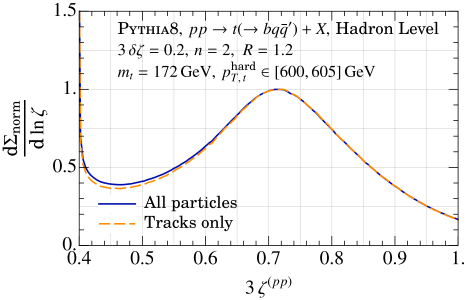
2. The state $|\psi_t\rangle$ in hadron colliders in $\langle\psi_t|\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\mathcal{E}(\vec{n}_3)|\psi_t\rangle$ cannot be described by a local operator and needs to be constrained via $p_{T,\text{jet}}$.

Effects of hadronization and underlying event in pp collisions

If the state $|\psi_t\rangle$ is fully specified (through *unphysical* $p_{T,t}^{\text{hard}}$) one achieves complete insensitivity to the UE (despite $p_{T,\text{jet}}$ in $\mathcal{M}^{(n)}_{(pp)}$)



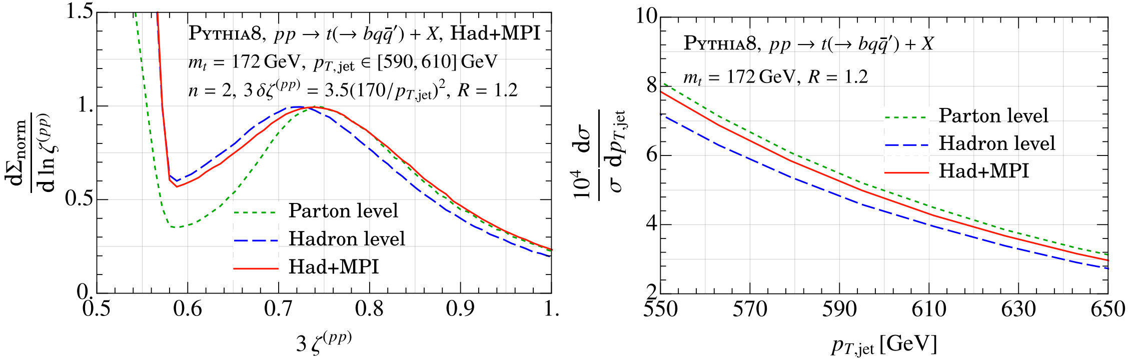




Dependence on $p_{T,\text{jet}}$ in $\mathcal{M}^{(n)}_{(pp)}$ drops out when normalized

Hadronization and UE effects directly related to the $p_{T,\text{jet}}$

The state $|\psi_t\rangle$ must be specified through $p_{T,\text{jet}}$, but the corrections to the $p_{T,\text{jet}}$ can be *independently* specified (something like PDFs)



Obtaining the top mass from multiple $p_{T,\text{jet}}$ bins

1. Parameterize the all orders peak position:

$$\zeta^{(pp)}_{\text{peak}} = 3(1+\mathcal{O}(\alpha_s))\frac{m_t^2}{f(p_{T,\text{jet}}, m_t, \Lambda_{\text{QCD}})^2} \equiv 3(1+\mathcal{O}(\alpha_s))\frac{m_t^2}{(p_{T,\text{jet}} + \Delta(p_{T,\text{jet}}, m_t, \alpha_s, \Lambda_{\text{QCD}}))^2}$$

2. Work with

$$y(\zeta^{(pp)\text{v}}_{\text{peak}}, p^{\text{v}}_{T,\text{jet}}) = \left(\zeta^{(pp)\text{ref}}_{\text{peak}} - \zeta^{(pp)\text{v}}_{\text{peak}}\right)\left(\frac{3(1+\mathcal{O}(\alpha_s))}{p^{\text{v}}_{T,\text{jet}}} - \frac{3(1+\mathcal{O}(\alpha_s))}{p^{\text{ref}}_{T,\text{jet}}}\right)^{-1},$$

3. Define

$$\Delta(p^{\text{ref}}_{T,\text{jet}}, m_t, \alpha_s, \Lambda_{\text{QCD}}) = \Delta^{\text{ref}}, \qquad \Delta(p^{\text{v}}_{T,\text{jet}}, m_t, \Lambda_{\text{QCD}}) = \Delta^{\text{ref}} + \Delta^{\text{v}}(p^{\text{v}}_{T,\text{jet}} - p^{\text{ref}}_{T,\text{jet}}, m_t, \alpha_s, \Lambda_{\text{QCD}})$$

4. Solve for y:

$$y(p^{\text{v}}_{T,\text{jet}}, \Delta^{\text{ref}}, \Delta^{\text{v}}) = \frac{m_t}{p^{\text{ref}}_{T,\text{jet}}}\frac{p^{\text{ref}}_{T,\text{jet}}}{p^{\text{ref}}_{T,\text{jet}} + \Delta^{\text{ref}}}\left(1 - \frac{2p^{\text{ref}}_{T,\text{jet}}\Delta^{\text{ref}} + (\Delta^{\text{ref}})^2}{2(p^{\text{v}}_{T,\text{jet}})^2} + \frac{\left(p^{\text{ref}}_{T,\text{jet}} + \Delta^{\text{ref}}\right)^2\left(\Delta^{\text{ref}} + \Delta^{\text{v}}\right)}{8(p^{\text{v}}_{T,\text{jet}})^3} + \mathcal{O}\left(\frac{1}{(p^{\text{v}}_{T,\text{jet}})^4}\right)\right)$$

5. The asymptotic value for $p^{\text{v}}_{T,\text{jet}}$ depends only on m_t and Δ^{ref}.

Obtaining the top mass from multiple $p_{T,\mathrm{jet}}$ bins