Theory introduction

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erc

BOOST Online 2021

What is this talk?

- **Personal** selection of theory developments relevant to BOOST
- Not technical, but emphasis on the ideas:
  What is it? How does it work? Why should you care?

Some of the topics:

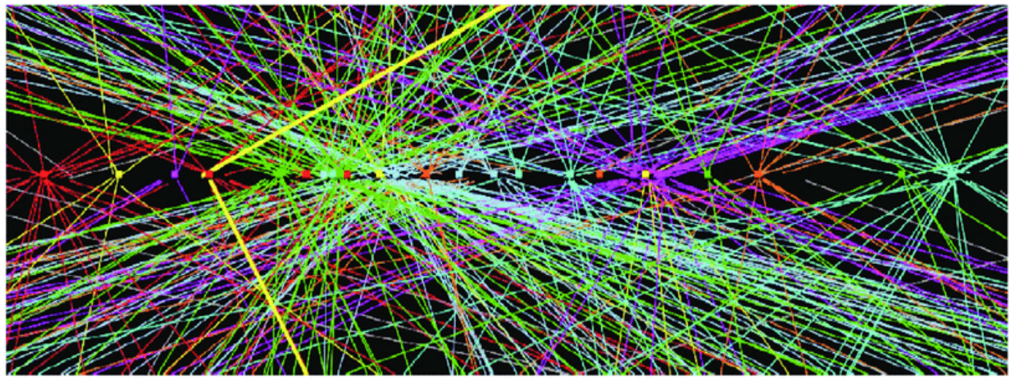
- Calculations for track-based measurements
- Anti-k_T jet function at NNLO
- Precise predictions for soft drop
- Nonperturbative effects
- Spin correlations

Experiment

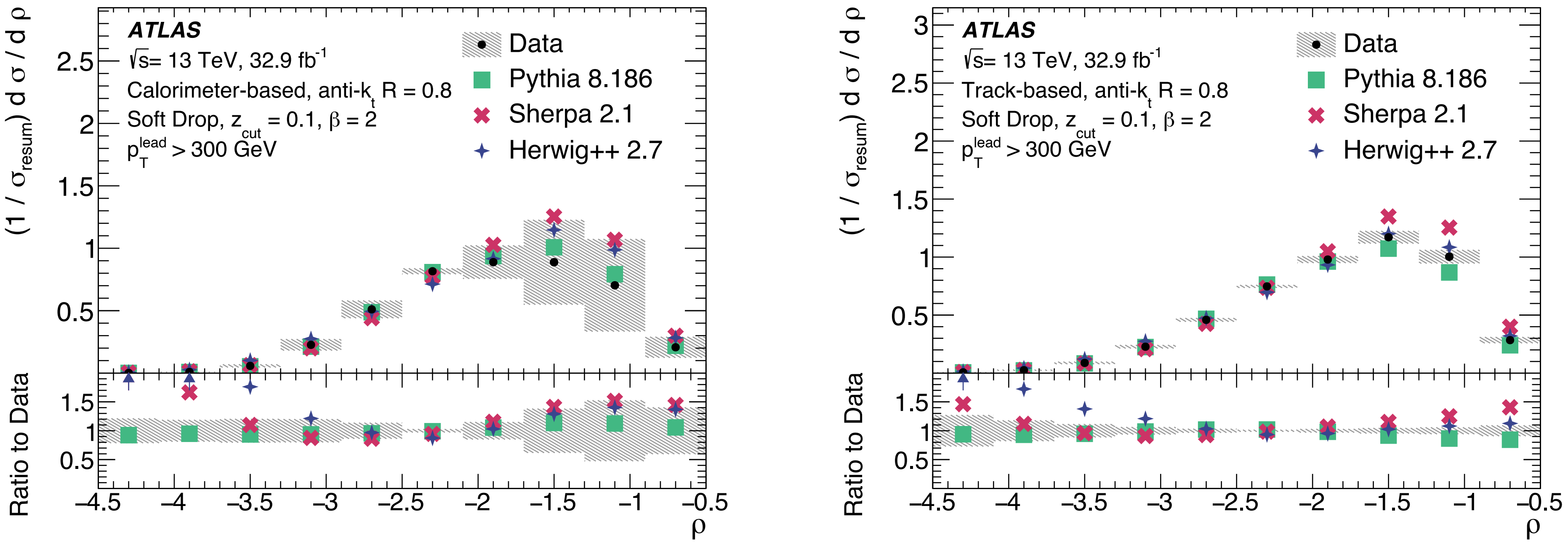
Theory

1. Calculations for track-based measurements

- **Motivation** for track-based measurements:
  - Superior angular resolution
  - Pile-up removal



- E.g. for groomed $\rho = \ln(m^2/p_T^2)$

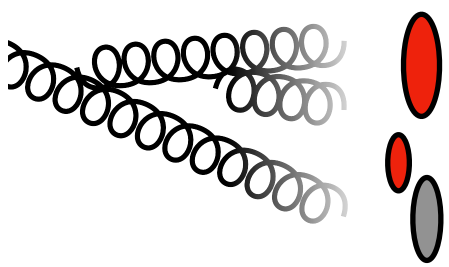


[ATLAS (2019)]

1. Calculations for track-based measurements

- **How it works:** IR divergences → absorbed in track functions
  [Chang, Thaler, Procura, WW (2013)]

- Track function describes momentum fraction *z* of initial parton that is converted to charged particles. E.g.:



$\pi^+(z_1)$
$\pi^+(z_2)$
$\pi^0(z_3)$

$$z_1 + z_2 + z_3 = 1$$

$$T_g(z) \propto \delta(z_1 + z_2 - z)$$

- Different from fragmentation function. For above configuration:

$$D_{g\to\pi^+}(z) \propto \delta(z_1 - z) + \delta(z_2 - z)$$

1. Calculations for track-based measurements

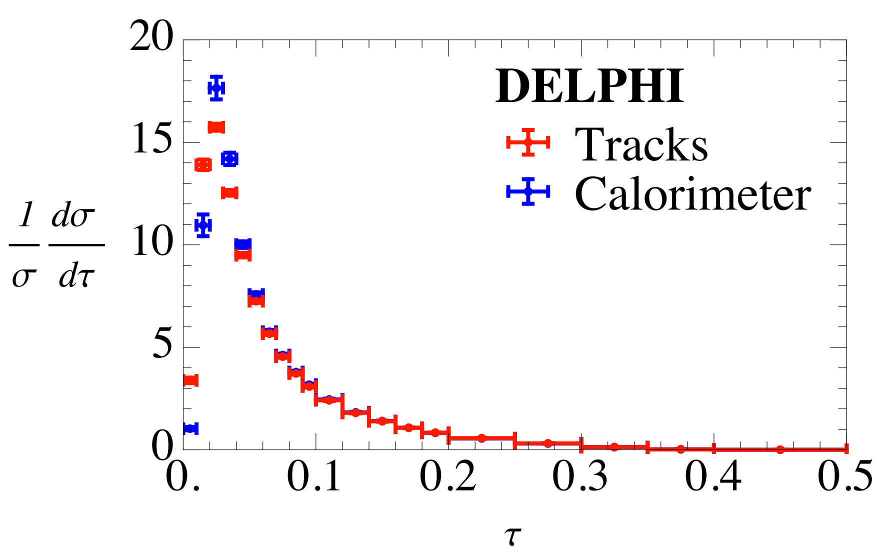
- **First experience:** difficult to implement with limited pay off.

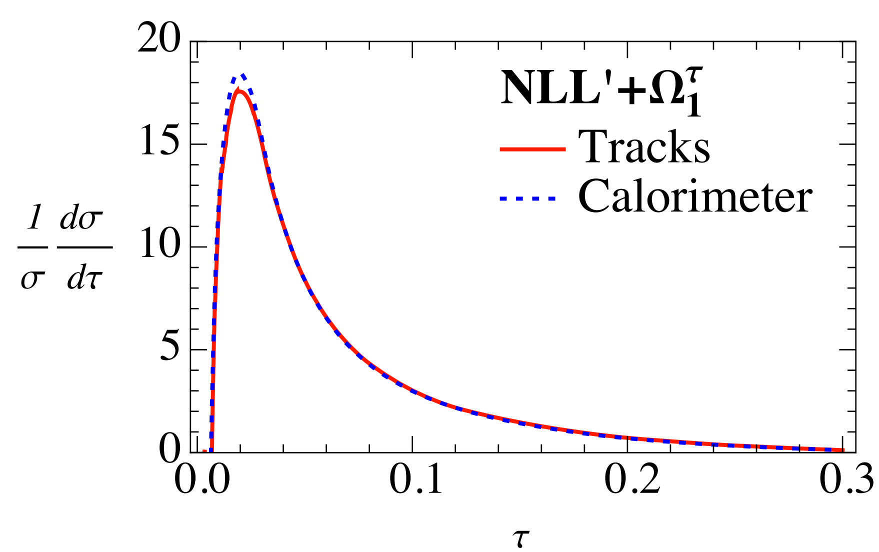
Track-based thrust (similar to jet mass) [Chang, Thaler, Procura, WW (2013)]

- Calculation of jet function is complicated:

$$
\begin{aligned}
\bar{J}(\bar{s}, x, \mu) = {} & \left(\delta(\bar{s}) + \frac{\alpha_s C_F}{2\pi}\left[\frac{2}{\mu^2}\mathcal{L}_1\left(\frac{\bar{s}}{\mu^2}\right) - \frac{2g_1^L}{\mu^2}\mathcal{L}_0\left(\frac{\bar{s}}{\mu^2}\right) + \delta(\bar{s})\left(g_2^L - \frac{\pi^2}{6}\right)\right]\right) T_q(x) + \frac{\alpha_s C_F}{2\pi}\int_0^1 \mathrm{d}x_2 \int_0^1 \frac{\mathrm{d}z}{z} \\
& \times \left\{\frac{1}{\mu^2}\mathcal{L}_0\left(\frac{\bar{s}}{\mu^2}\right)(1+z^2)\mathcal{L}_0(1-z) + \delta(\bar{s})\left[(1+z^2)\mathcal{L}_1(1-z) + \ln\left(\frac{xz^2}{[x-(1-z)x_2]x_2}\right)(1+z^2)\mathcal{L}_0(1-z) + 1-z\right]\right\} \\
& \times T_q\left(\frac{x-(1-z)x_2}{z}\right) T_g(x_2)\,.
\end{aligned}
$$

- Effect of track-based measurement is small:



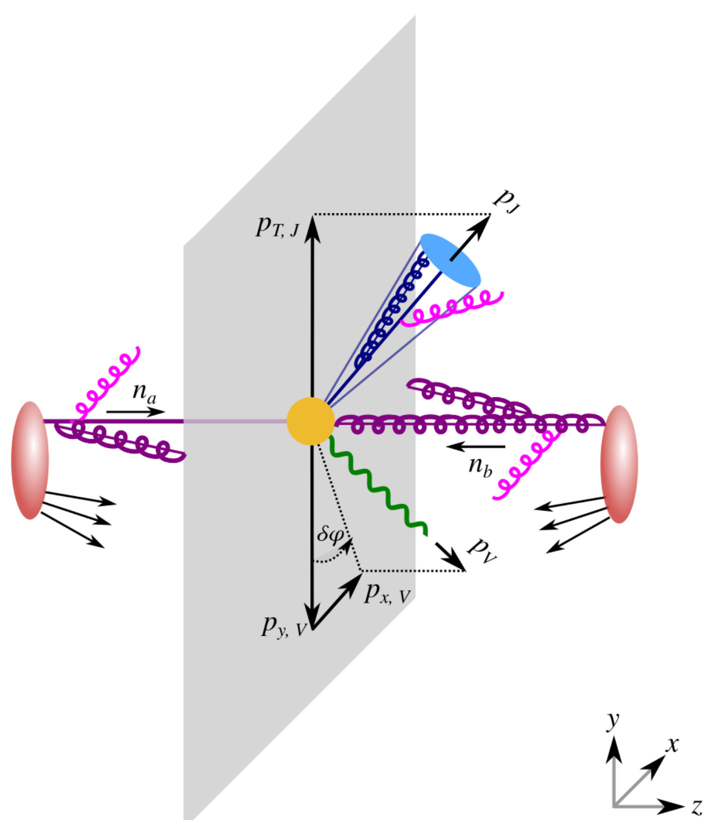


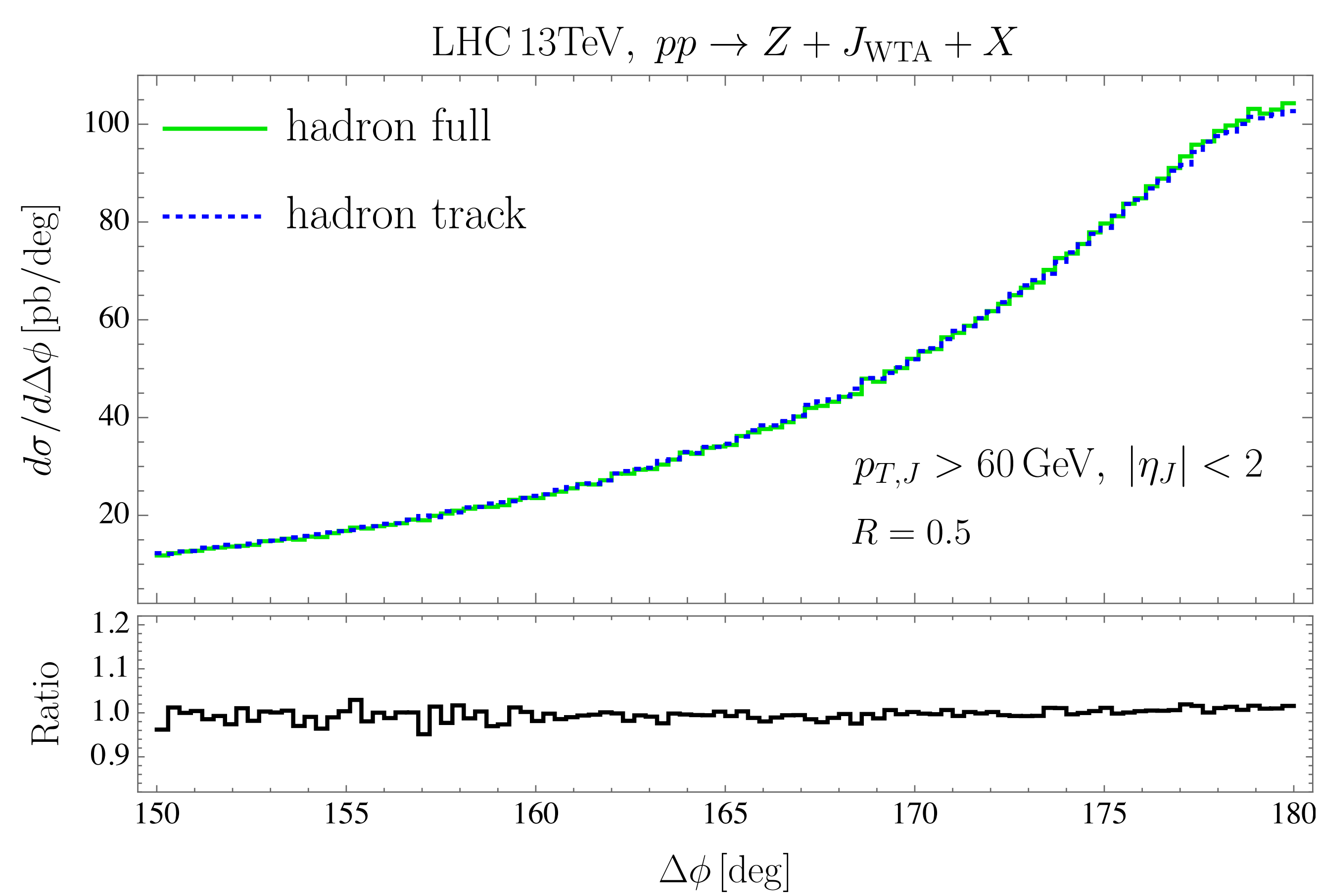
1. Calculations for track-based measurements

- **New observables:** small effect from switching to tracks.

Azimuthal angle in Z+jet, using winner-take-all (WTA) axis:

- Effect of tracks only starts at NNLL accuracy, because WTA doesn't depend on the detailed pattern of soft radiation
  [Chien, Rahn, Schrijnder van Velzen, Shao, WW, Wu (2020)]



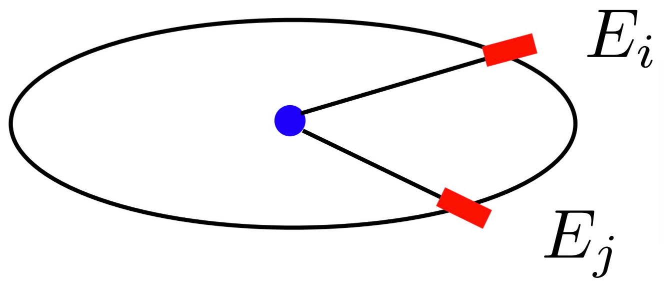


1. Calculations for track-based measurements

- **New observables:** easy to implement.

Energy-energy correlator (EEC):

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\chi} = \sum_{i,j} \int \mathrm{d}\sigma \, \frac{E_i E_j}{Q^2} \, \delta(\chi - \theta_{ij})$$



- This is a weighted cross section
- Conversion to tracks is simple: $E_i \to \int \mathrm{d}x_i \, T_i(x_i) \, x_i E_i$
  [Chen, Moult, Zhang, Zhu (2020)]
- Tracks are essential to measure EEC at small angles.

1. Calculations for track-based measurements

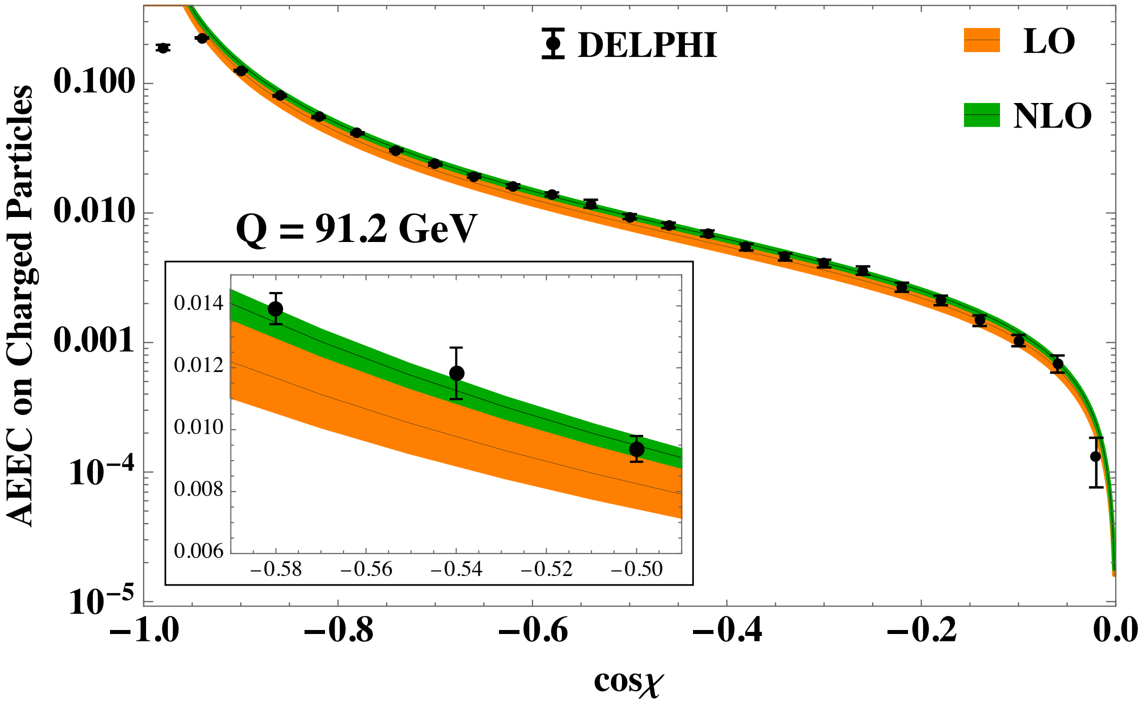
- **New calculations:** track function and track-based EEC at $\mathcal{O}(\alpha_s^2)$ [Li, Moult, Schrijnder van Velzen, WW, Zhu (to appear soon)]

- Evolution of track function moments:

$$\frac{d}{d\ln\mu^2}T_g(3,\mu) = -\gamma_{gg}(4,\mu)T_g(3,\mu) + \left(\frac{\alpha_s}{4\pi}\right)^2\left(C_A^2\left(24\zeta_3 - \frac{278}{15}\pi^2 + \frac{767263}{4500}\right) - \frac{2}{3}C_A n_f T_F\right)T_g(2,\mu)T_g(1,\mu)$$
$$+\left(\frac{\alpha_s}{4\pi}\right)^2\left(C_A T_f\left(\frac{23051}{1125} - \frac{28}{15}\pi^2\right) - C_F T_f \frac{28}{15}\right)T_g(1,\mu)\sum_i T_{q_i}(1,\mu)T_{\bar{q}_i}(1,\mu) + \ldots.$$

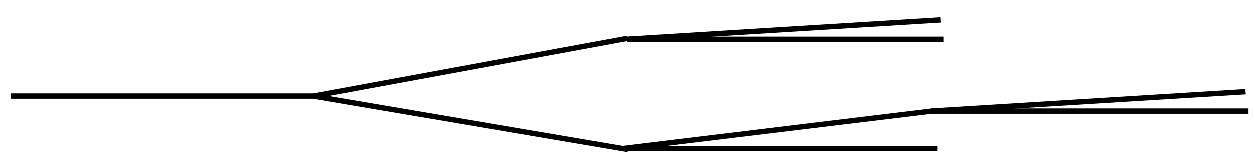
- Track-based EEC asymmetry:

→ For more see Yibei Li's talk



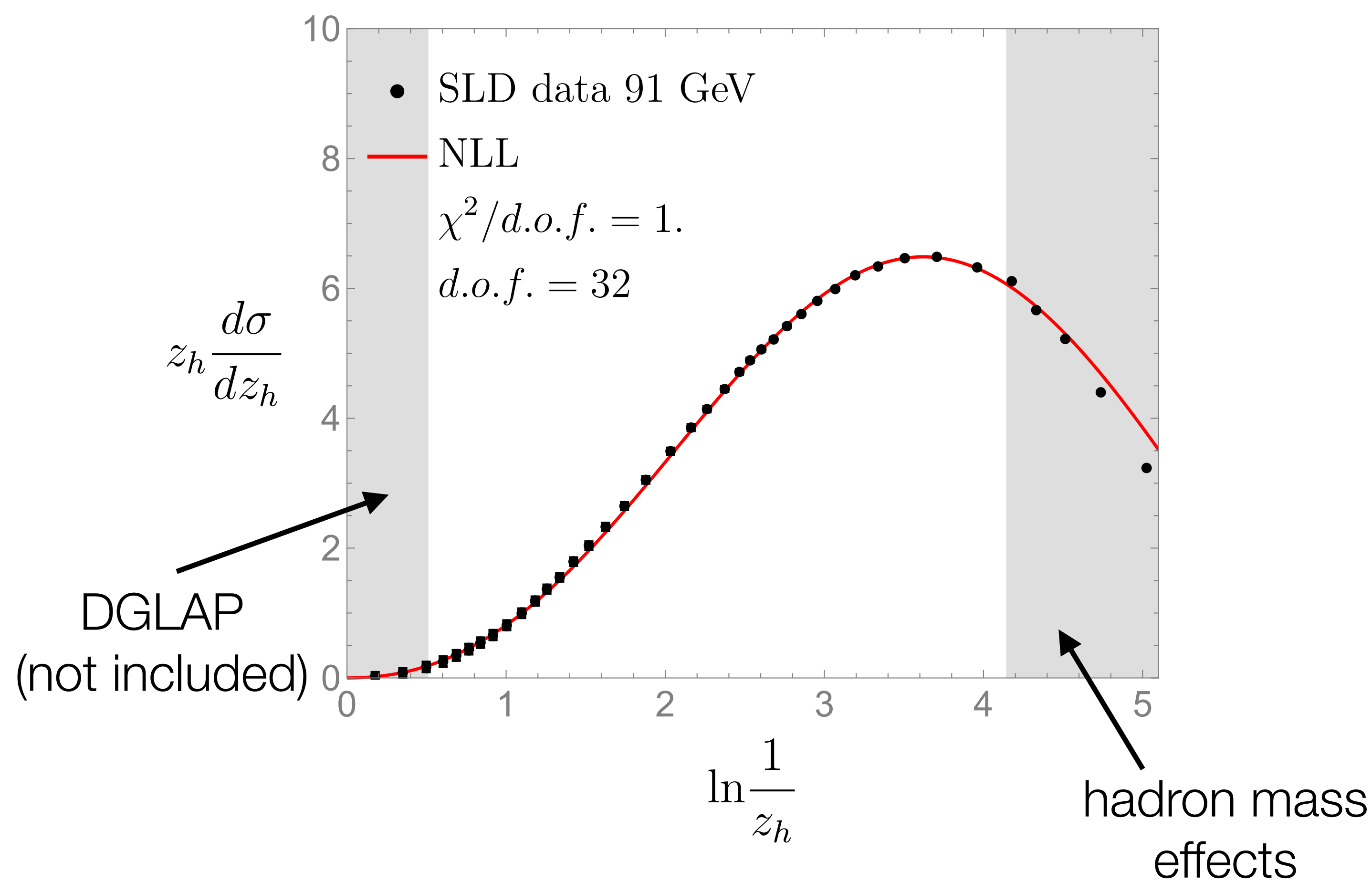
2. Charged hadron fragmentation

- **Related development:** predicting the fragmentation spectrum of charged hadrons from small z_h resummation [Neill (2020)]



- Only 3 parameters: cut off Λ of evolution, frozen coupling α_s, normalization factor

- Promising results!
  → track functions?



3. Anti-k_T jet function at NNLO

- **Goal:** calculate collinear radiation in jet to higher orders.
- For example, for the exclusive Higgs + 1 jet production:

$$
\begin{aligned}
\mathrm{d}\sigma_{\mathrm{NLL}'} \;=\; & \mathrm{d}\Phi_H \mathrm{d}\Phi_J\, \mathcal{F}(\Phi_H, \Phi_J) \sum_{a,b} \int \mathrm{d}x_a \mathrm{d}x_b \frac{1}{2\hat{s}} (2\pi)^4 \delta^4 (q_a + q_b - q_J - q_H) \\
& \times \overline{\sum_{\text{spin}}} \overline{\sum_{\text{color}}} \mathrm{Tr}(H \cdot S)\, \mathcal{I}_{a,i_a j_a} \otimes f_{j_a}(x_a)\, \mathcal{I}_{b,i_b j_b} \otimes f_{j_b}(x_b) J_J(R) .
\end{aligned}
$$

[Liu, Petriello (2013)]

- **Complicated measurement:** veto on additional jets requires all collinear partons to be clustered into one jet. For 3 partons:

$$\rho_{ij} < \min(\rho_{ik}, \rho_{jk}, \rho_i, \rho_j, \rho_k) \qquad\qquad \Delta R^2_{\tilde{ij},k} \leq R^2$$

partons *i* and *j* cluster first — all partons are inside jet

3. Anti-k$_T$ jet function at NNLO

- Can't simply numerically integrate due to poles
- **Recent calculation:** goes over different clustering histories, uses sector decomposition and soft subtractions
  [Liu, Liu, Moch (2021)]

$$J = 1 + \frac{\alpha_s}{2\pi} C_F \left(\frac{13}{2} - \frac{3\pi^2}{4} \right) + \frac{\alpha_s^2}{4\pi^2} \big(1.55(1) C_F^2 - 95.08(1) C_A C_F + 13.530(5) C_F N_F T_F \big) \, ,$$

for $\mu = p_T R$

- This holds a lot of promise for jet substructure calculations.

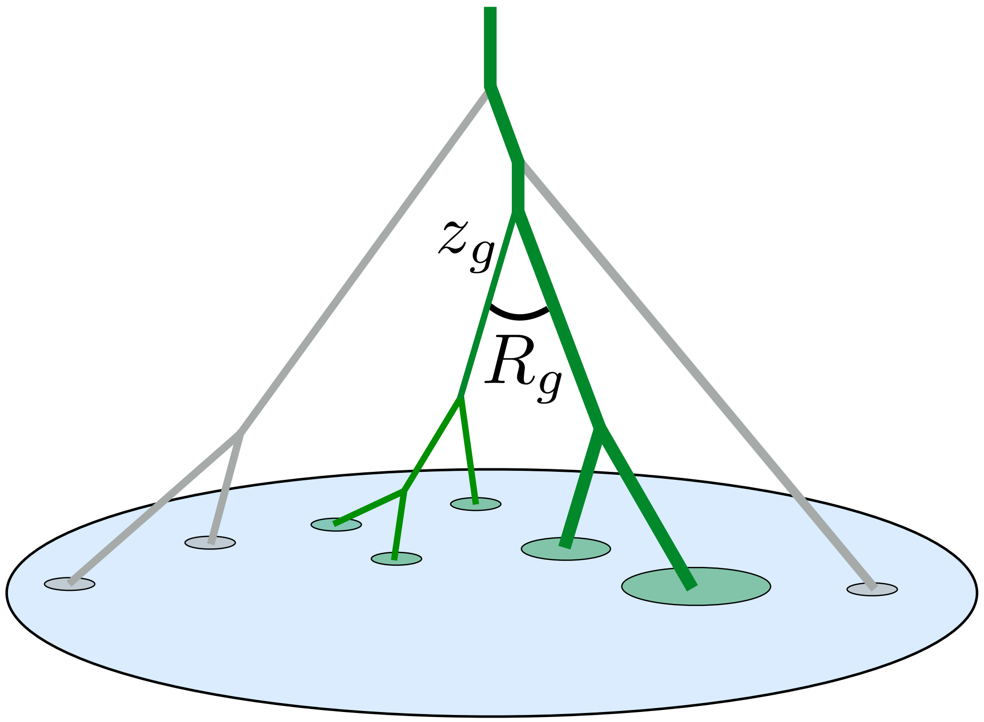
4. Precise predictions for soft drop

- **Motivation**: soft drop momentum sharing z_g probes QCD splitting function, and many measurements available
- **Goal**: obtain results beyond leading logarithmic accuracy, and estimate of theory uncertainty

Soft drop:

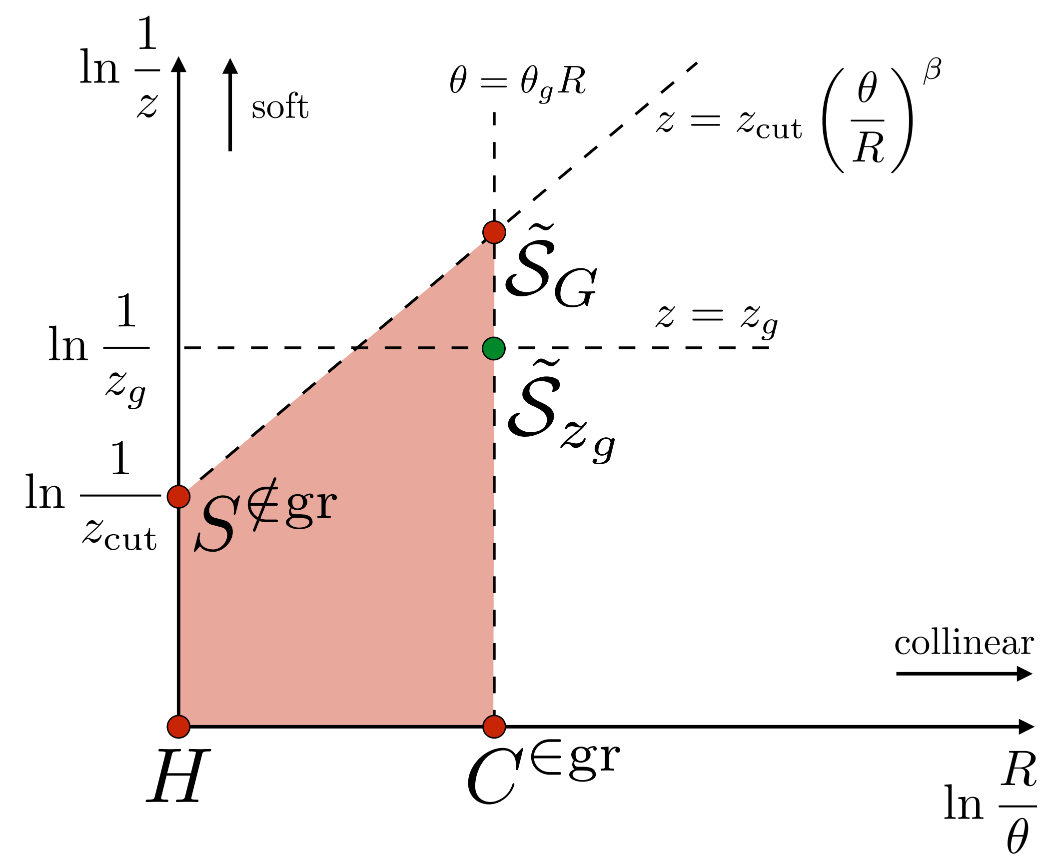
- Recluster the jet using Cambridge/Aachen.
- Decluster, throwing away softer branch, until its p_T fraction z satisfies

$$z > z_{\text{cut}} \left(\Delta R_{12}/R\right)^{\beta}$$



4. Precise predictions for soft drop

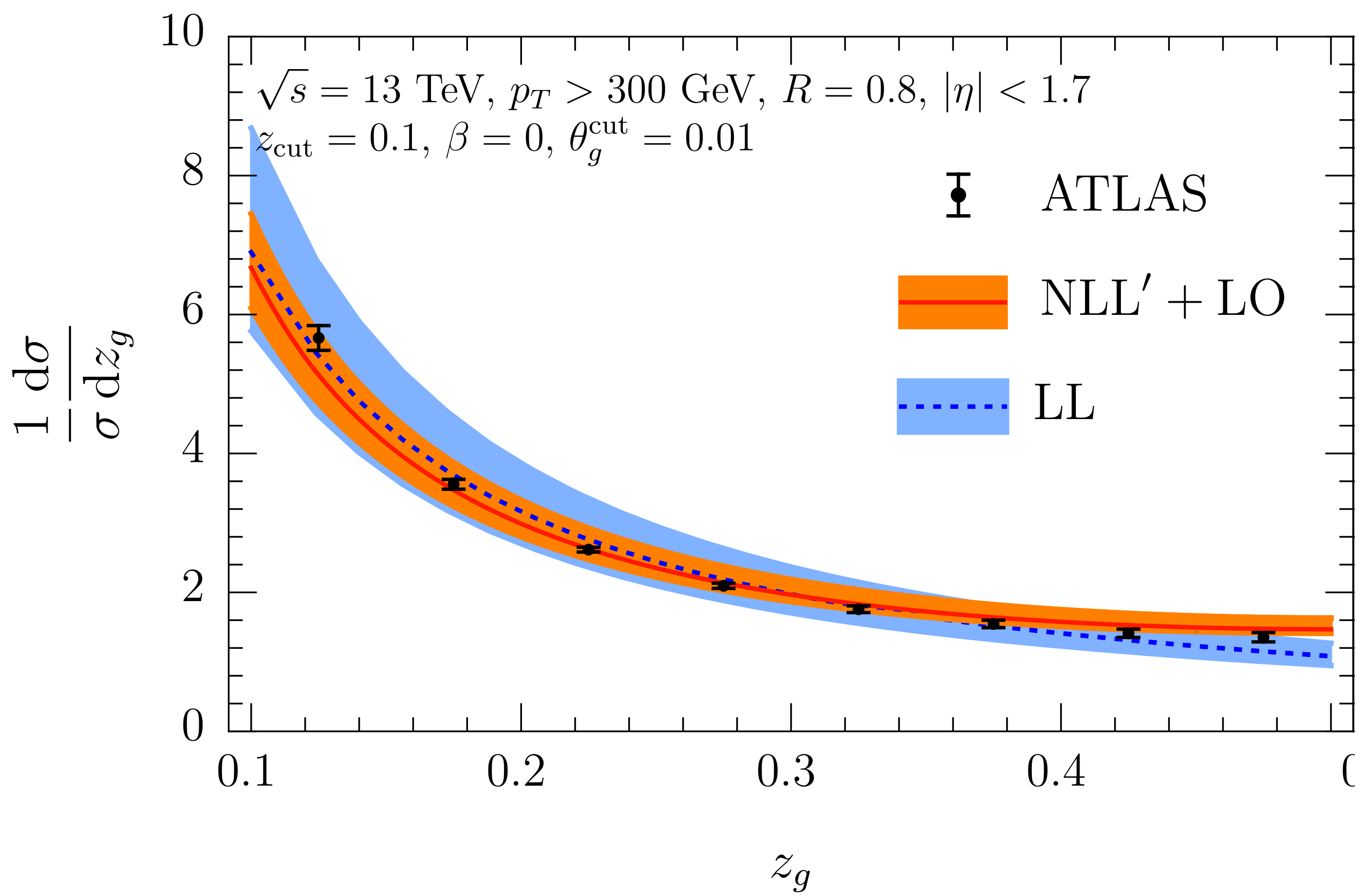
- **Approach**: factorization in Soft-Collinear Effective Theory
- Differential also in groomed jet radius $R_g = \theta_g R$ because for $\beta > 0$ the measurement is only Sudakov safe
- Modes in SCET correspond to corners of Lund plane
- Emission that sets z_g requires special treatment
- Non-global logarithms arise for modes at same angular scale



[Cal, Lee, Ringer, WW (2021)]

4. Precise predictions for soft drop

- **Results** show good agreement with data



→ For more see Pedro Cal's talk

5. Nonperturbative effects for soft drop

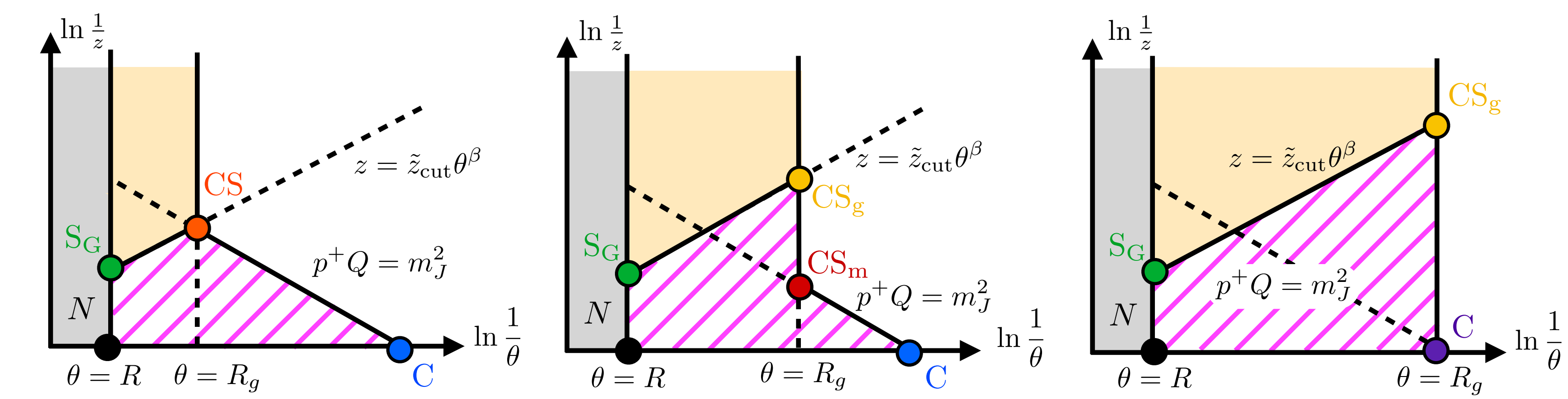
- **Starting point:** analytic understanding of nonperturbative effects for soft drop [Hoang, Mantry, Pathak, Stewart (2019)]

$$\frac{d\sigma_\kappa^{\rm had}}{dm_J^2 d\Phi_J} = \frac{d\hat\sigma^\kappa}{dm_J^2 d\Phi_J} - Q\,\Omega_{1\kappa}^{\varpi} \frac{d}{dm_J^2}\left(C_1^\kappa(m_J^2, Q, z_{\rm cut}, \beta, R)\, \frac{d\hat\sigma^\kappa}{dm_J^2 d\Phi_J}\right)$$
$$+ \frac{Q\left(\Upsilon_{1,0}^\kappa + \beta\,\Upsilon_{1,1}^\kappa\right)}{m_J^2}\, C_2^\kappa(m_J^2, Q,\, z_{\rm cut}, \beta, R)\, \frac{d\hat\sigma^\kappa}{dm_J^2 d\Phi_J} + \ldots$$

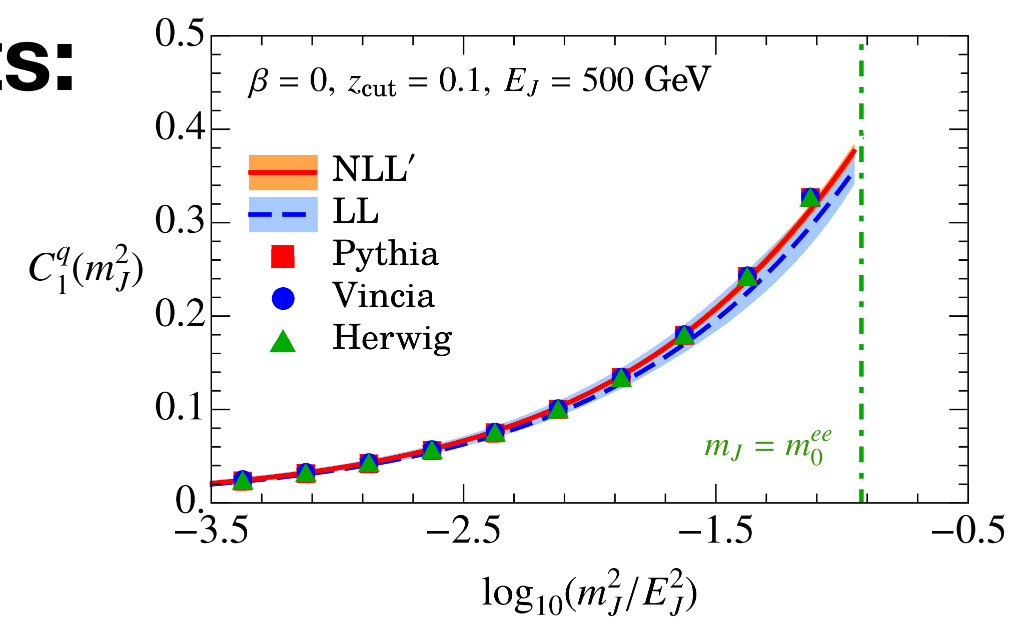
- Leading effect described by few nonperturbative parameters
- First term describes effect of nonperturbative momentum <u>in</u> groomed jet, second its effect on the grooming condition
- Perturbative coefficients $C_{1,2}$ follow from cross section differential in m_J^2 and θ_g, and previously extracted at LL. E.g. $C_1 \propto \langle \theta_g \rangle$

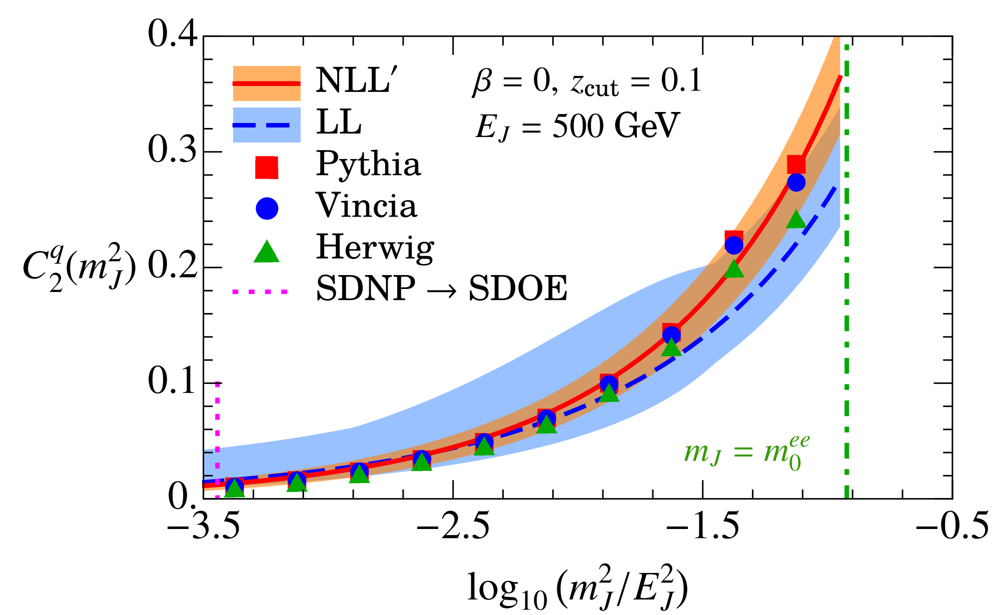
5. Nonperturbative effects for soft drop

- Approach: factorization in Soft-Collinear Effective Theory
- Under the hood: three different regimes that need to be calculated and matched



- **Results:**





→ For more see Adi Pathak's talk

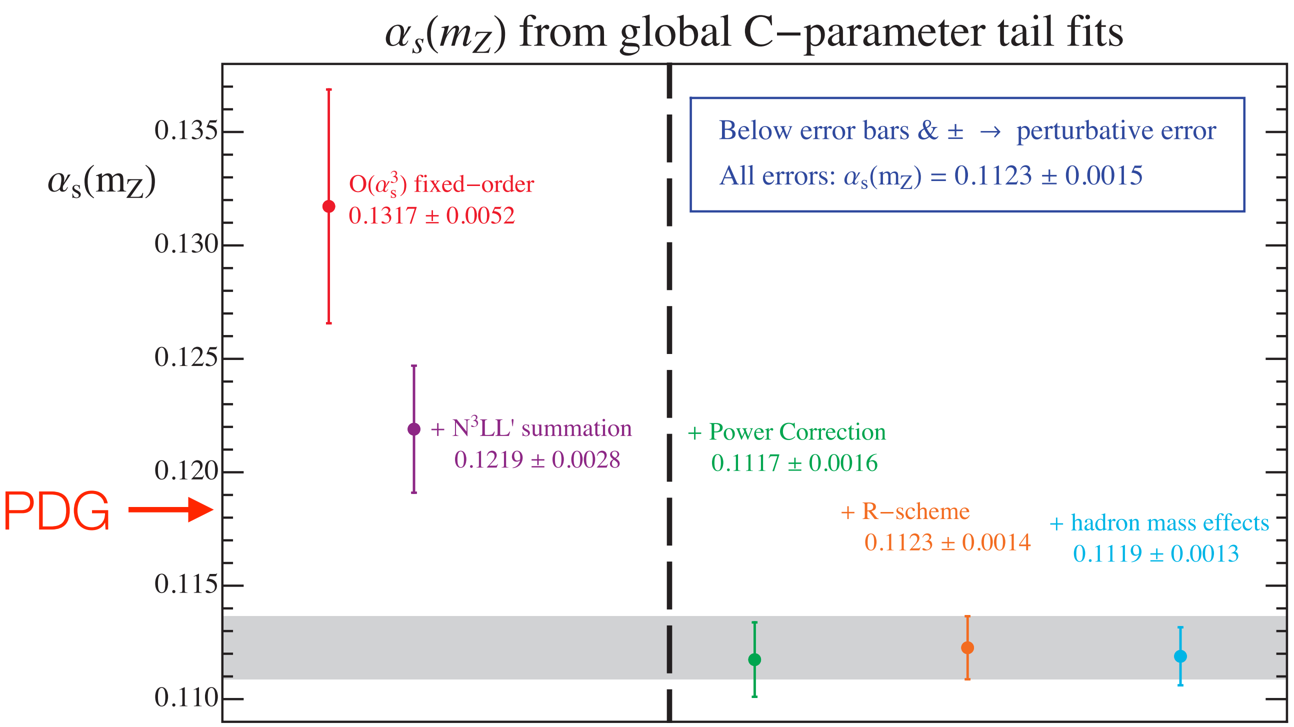
[Pathak, Stewart, Vaidya, Zoppi (2020)]

6. Nonperturbative effects for *C*-parameter

- **Background**: most precise extractions of α_s from e+e- event shapes give small values, due to nonperturbative effects.
- E.g. for *C*-parameter

$$C = \frac{3}{2}\frac{\sum_{i,j}|\vec{p}_i||\vec{p}_j|\sin^2\theta_{ij}}{\left(\sum_i|\vec{p}_i|\right)^2}$$

PDG



[Hoang, Kolodrubetz, Mateu, Stewart (2015)]

- **Potential problem**: leading nonperturbative correction only valid in 2-jet region.

6. Nonperturbative effects for C-parameter

- **Explorative study**: compare nonperturbative effects at C=0 (Sudakov peak) and C=3/4 (Sudakov shoulder)
  [Luisoni, Monni, Salam (2020)]

- Single nonperturbative emission shifts C with proportionality constant ζ

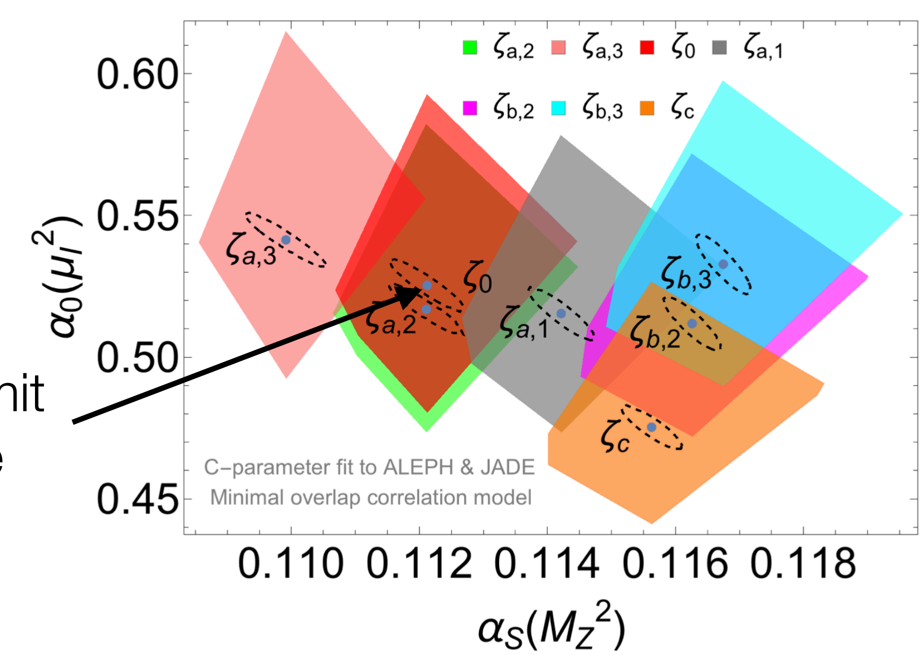
C=0: $$\Delta C = \frac{k_T}{Q}\frac{3}{\cosh\eta} + \mathcal{O}\left(\frac{k_T^2}{Q^2}\right) \qquad \zeta(0) = \int_{-\infty}^{\infty} \mathrm{d}\eta\, \frac{3}{\cosh\eta} = 9.42$$

C=3/4: $$\Delta C = \frac{3\sqrt{3}}{2}\frac{\sin^2\phi}{2\cosh\eta - \cos\phi}\frac{k_T}{Q} + \mathcal{O}\left(\frac{k_T^2}{Q^2}\right) \qquad \zeta(3/4) = 4.49$$

- Effect of different interpolations on extraction of α_s:

- **Relevant** for α_s from jetsubstructure

using 2-jet limit everywhere

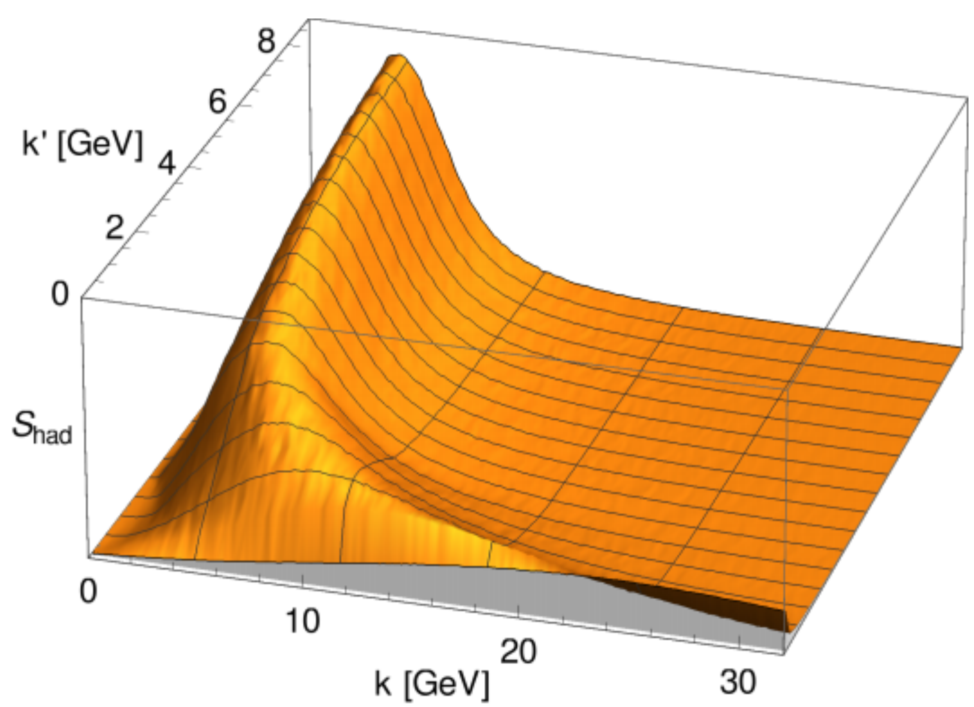


7. Nonperturbative effects in the parton shower

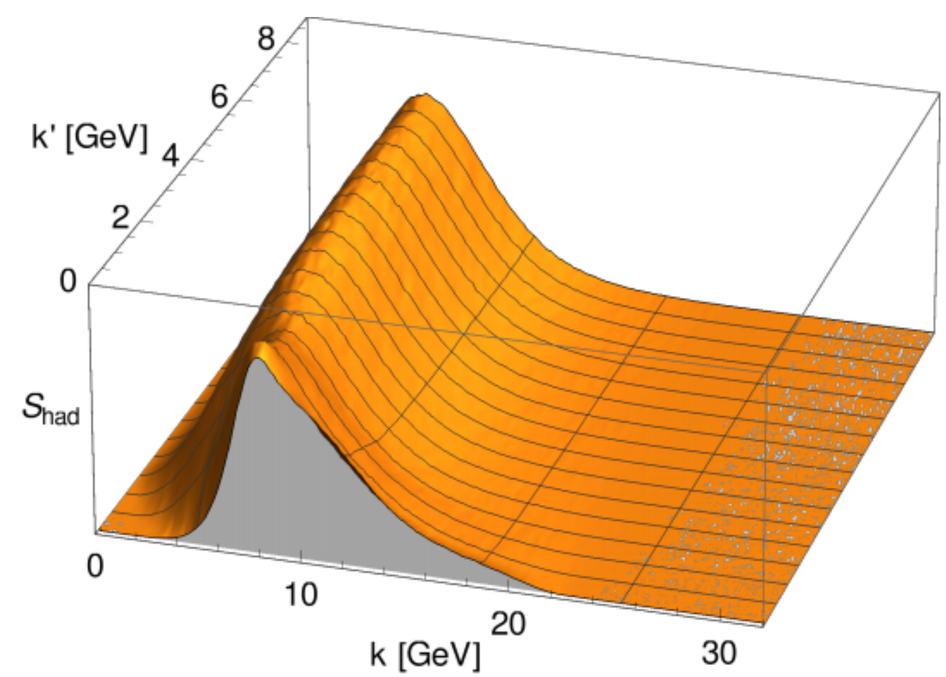
- **Opposite perspective**: revise hadronization model to make it consistent with factorization [Hoang, Platzer, Samitz (to appear)]

- **Motivation:** enable direct comparisons between parton shower and analytic resummation (for e.g. m_t extraction)

Before:



After:

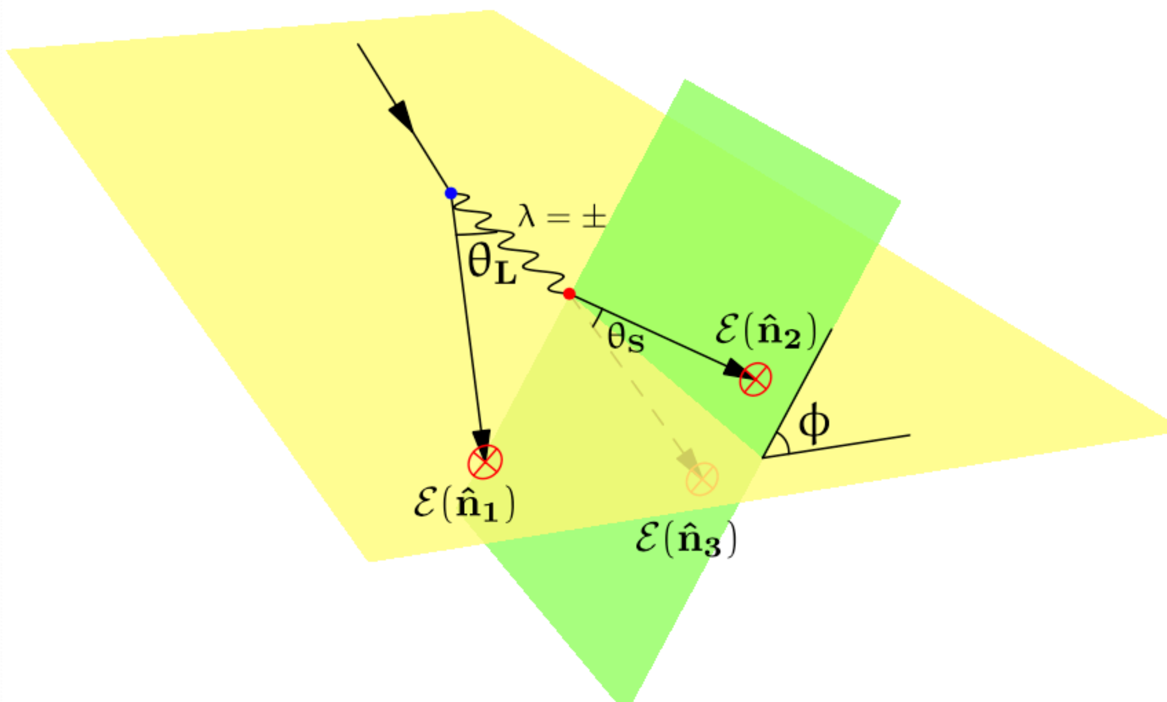


[Presented at SCET 2021 by Samitz]

- After modification the shift is independent of C parameter

8. Spin effects in jet substructure

- **Insight:** three-point energy correlator is sensitive to spin effects [Chen, Moult, Zhu (2020)]
- In the limit $\theta_S \ll \theta_L$ the intermediate gluon is almost on-shell, and interference between both helicities leads to ϕ dependence



- At $\mathcal{O}(\alpha_s^2)$:

$$\frac{d\sigma_q}{d\theta_L\, d\theta_S\, d\phi} \propto 10.54 + 0.1156 n_f + (0.1778 - 0.0593 n_f)\cos(2\phi)$$

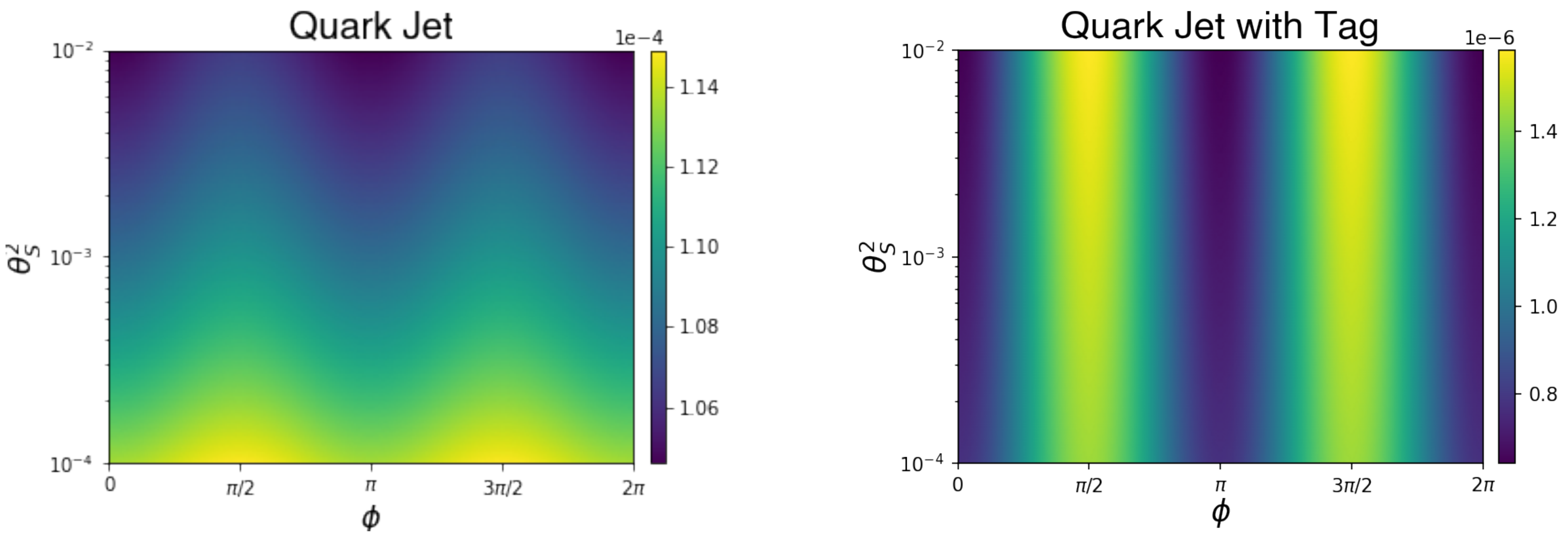
$$\frac{d\sigma_g}{d\theta_L\, d\theta_S\, d\phi} \propto (35.28 + 1.24 n_f) + (0.4 - 0.133 n_f)\cos(2\phi)$$

- Unfortunately $n_f = 5$ makes this effect small

8. Spin effects in jet substructure

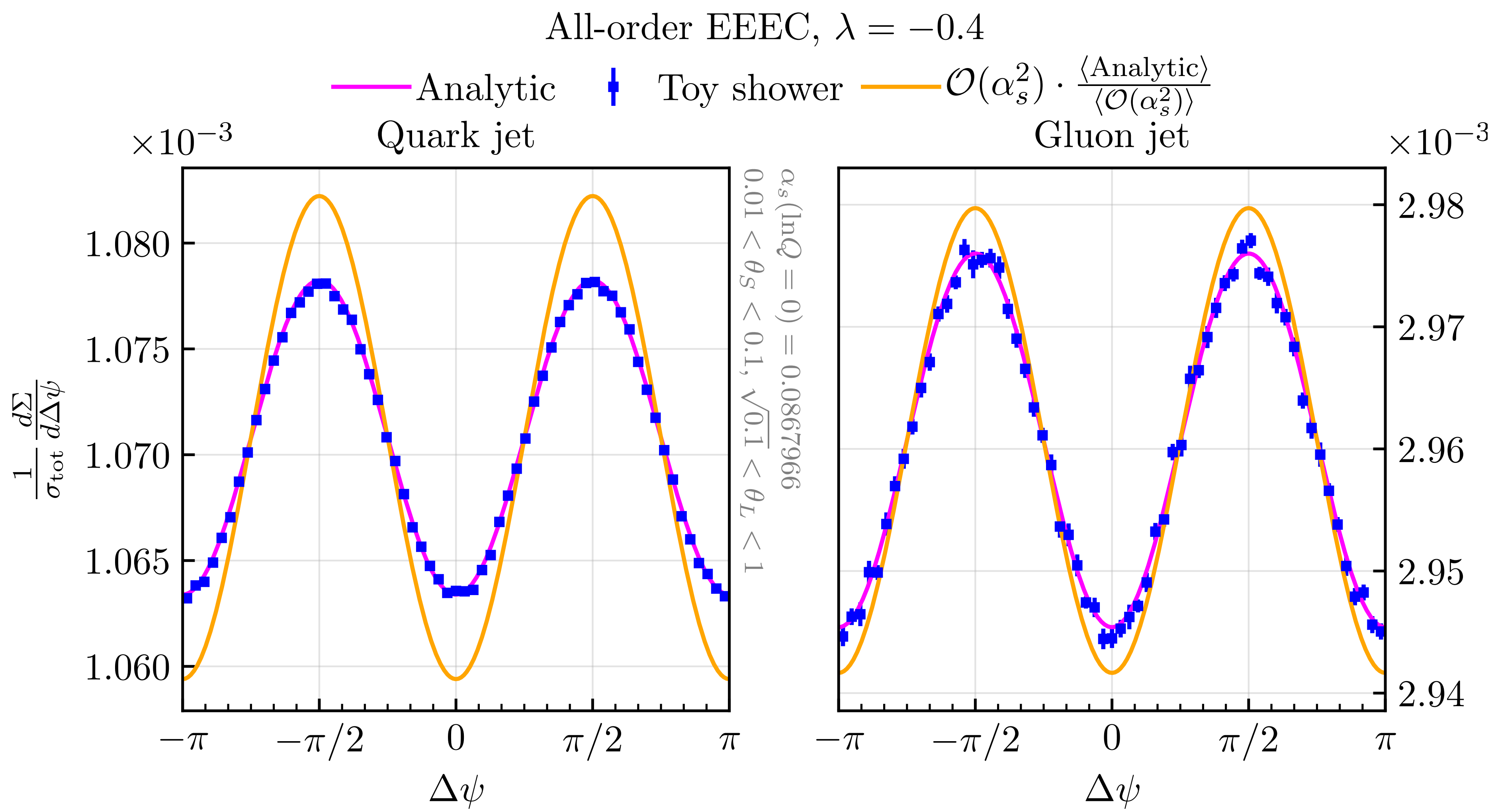
→ see Ian Moult's talk for light-ray OPE and resummation

- Resulting spin interference is more visible when b-tagging:



9. Spin effects in parton showers

- Spin correlations **implemented** in PanScales shower
  [Karlberg, Salam, Scyboz, Verheyen (2021)]
- Excellent agreement for azimuthal asymmetry in EEEC



→ For more see Alexander Karlberg's talk

Summary

- Calculations for **track-based** measurements are possible, also at $\mathcal{O}(\alpha_s^2)$ [1]. We can get the charged hadron spectrum from z_h resummation [2]. How about the track function?
- **Precise predictions** enable precise comparisons to data [4] and better descriptions of nonperturbative effects [5]. Extreme precision with real jet algorithms within reach [3].
- The parton shower **hadronization** model can be made to conform to factorization [7], but what is the correct description? [6]
- **Spin correlations** can be probed by jet substructure [8] and encoded in parton showers [9].

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Thank you!