NNV Annual meeting

November 1st, 2019

Jet Substructure

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Wouter Waalewijn

arXiv:1901.06389

arXiv:1911.xxxxx

UNIVERSITY OF AMSTERDAM

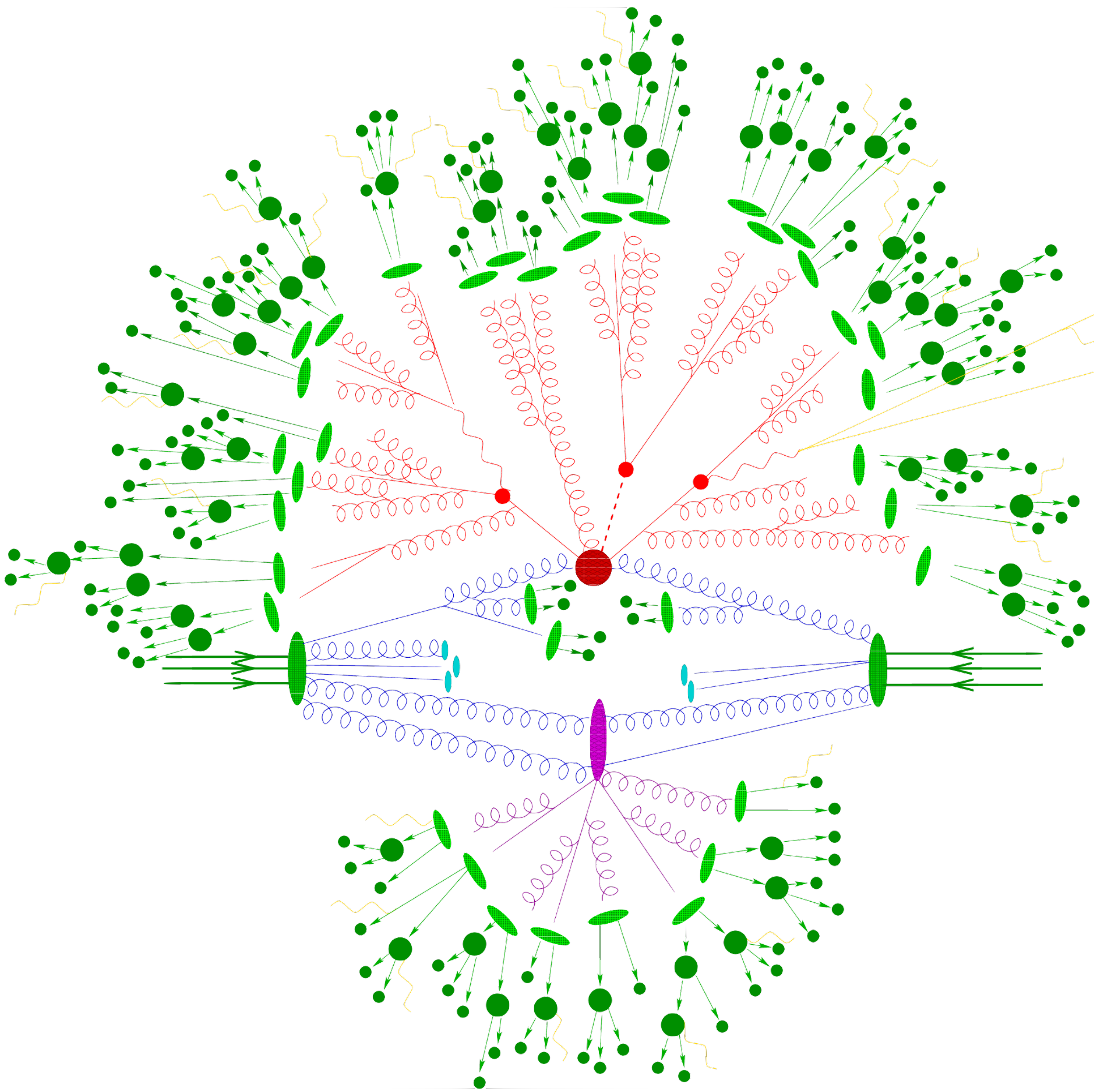
Nikhef

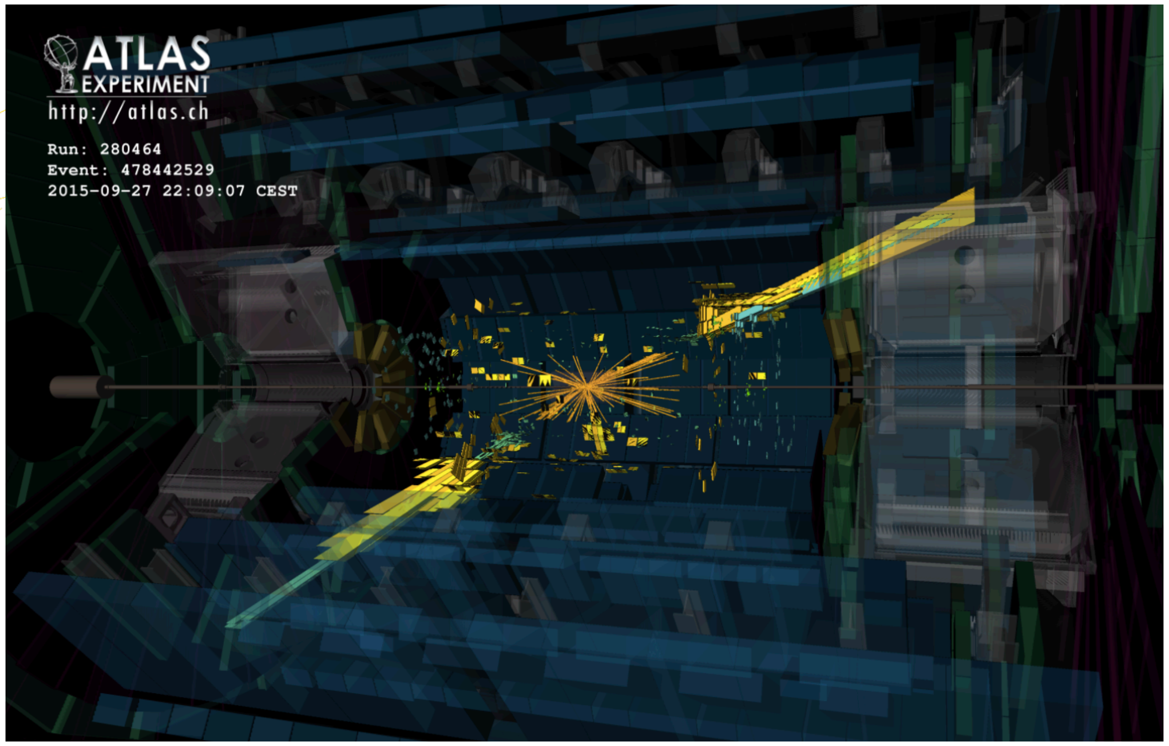
Outline

- What are jets and why do they form?
- What is jet substructure?
- Jet contamination and grooming
- Jet shape and jet axes
- Conclusions

What are jets?

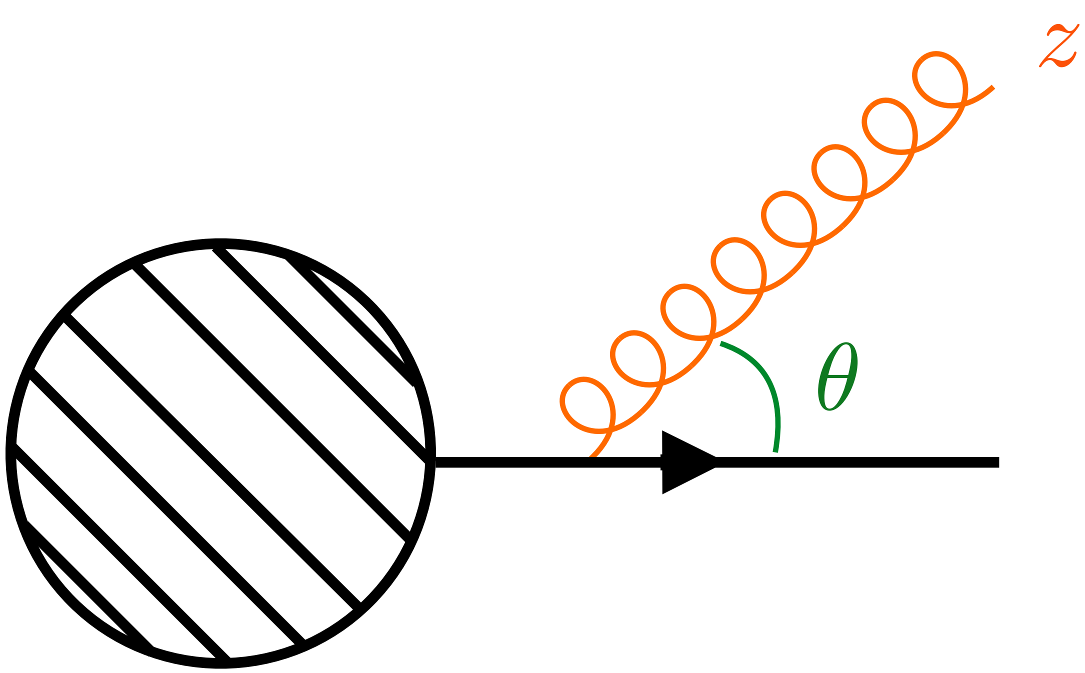
- Jets are sprays of collimated particles arising from energetic quarks or gluons





Why do jets form?

- Emergent phenomena arising from QCD Lagrangian



$$\propto \int \frac{\mathrm{d}z}{z} \frac{\mathrm{d}\theta}{\theta}$$

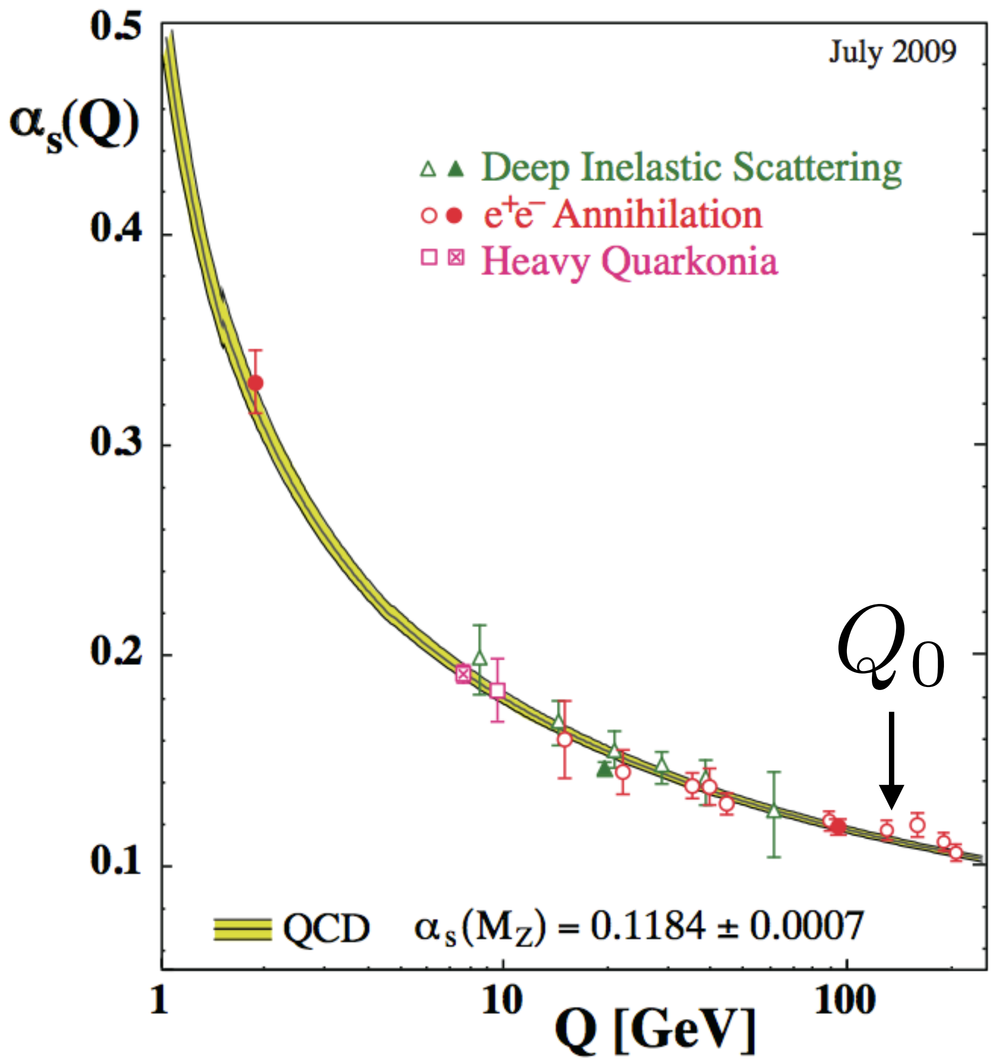
soft singularity

collinear singularity

- High probability of multiple soft and collinear emissions

Why do jets form?

- Asymptotic freedom and running of the coupling



$\alpha_s(Q_0)$

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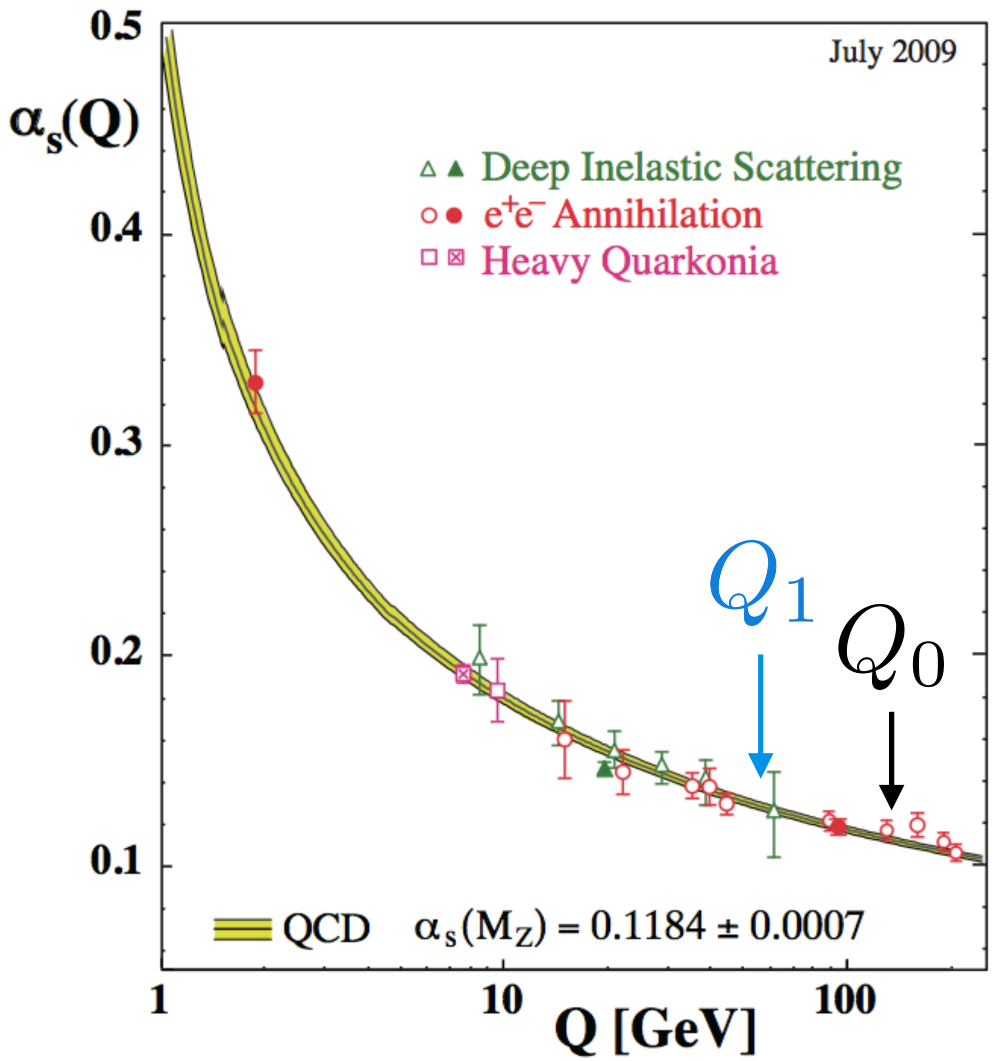

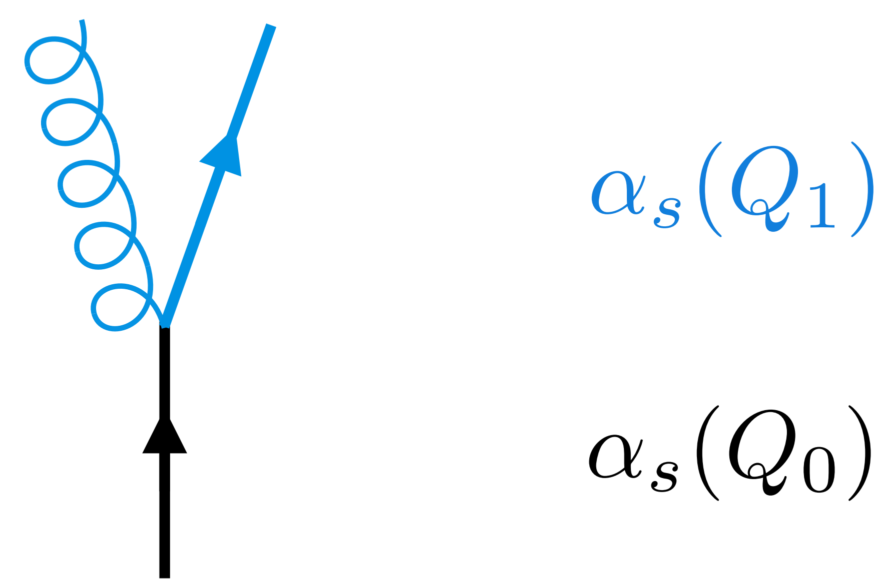

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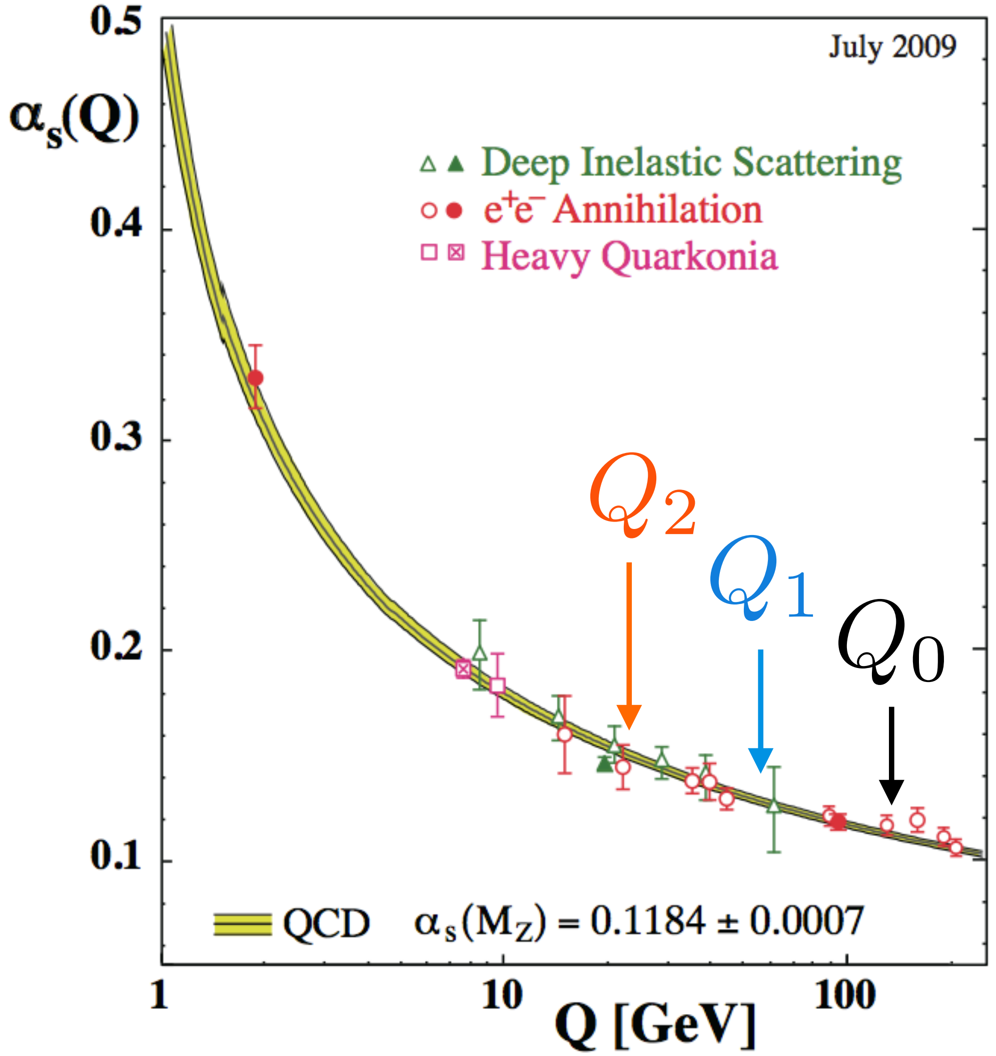

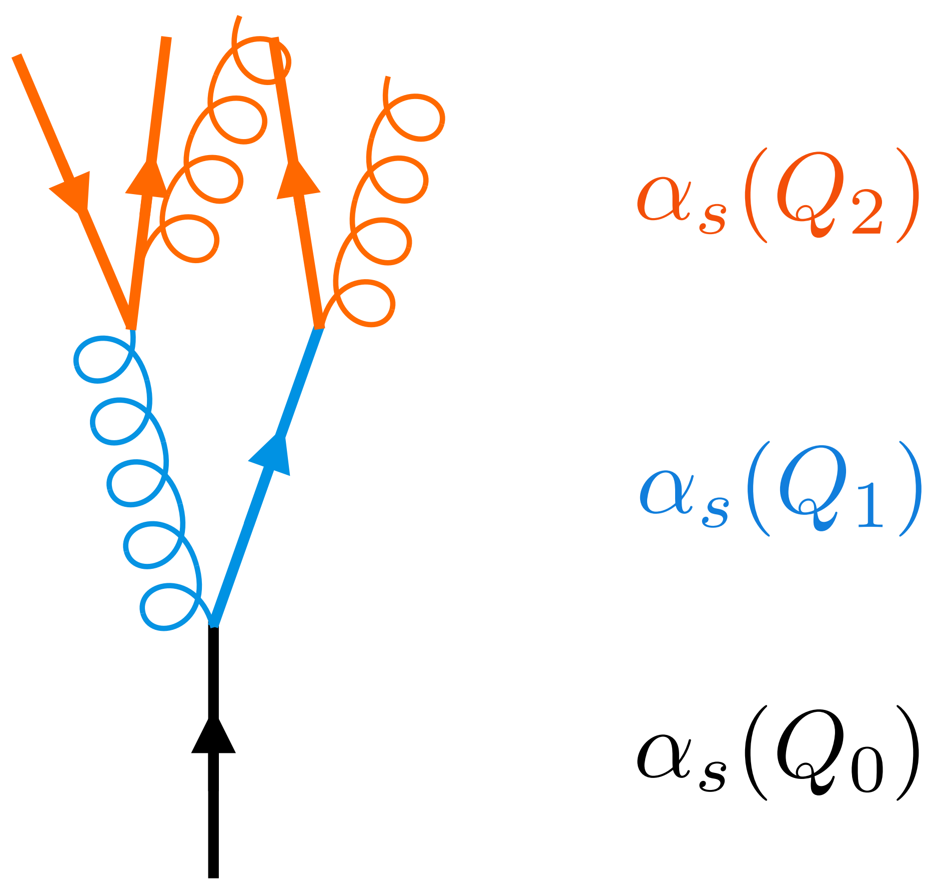

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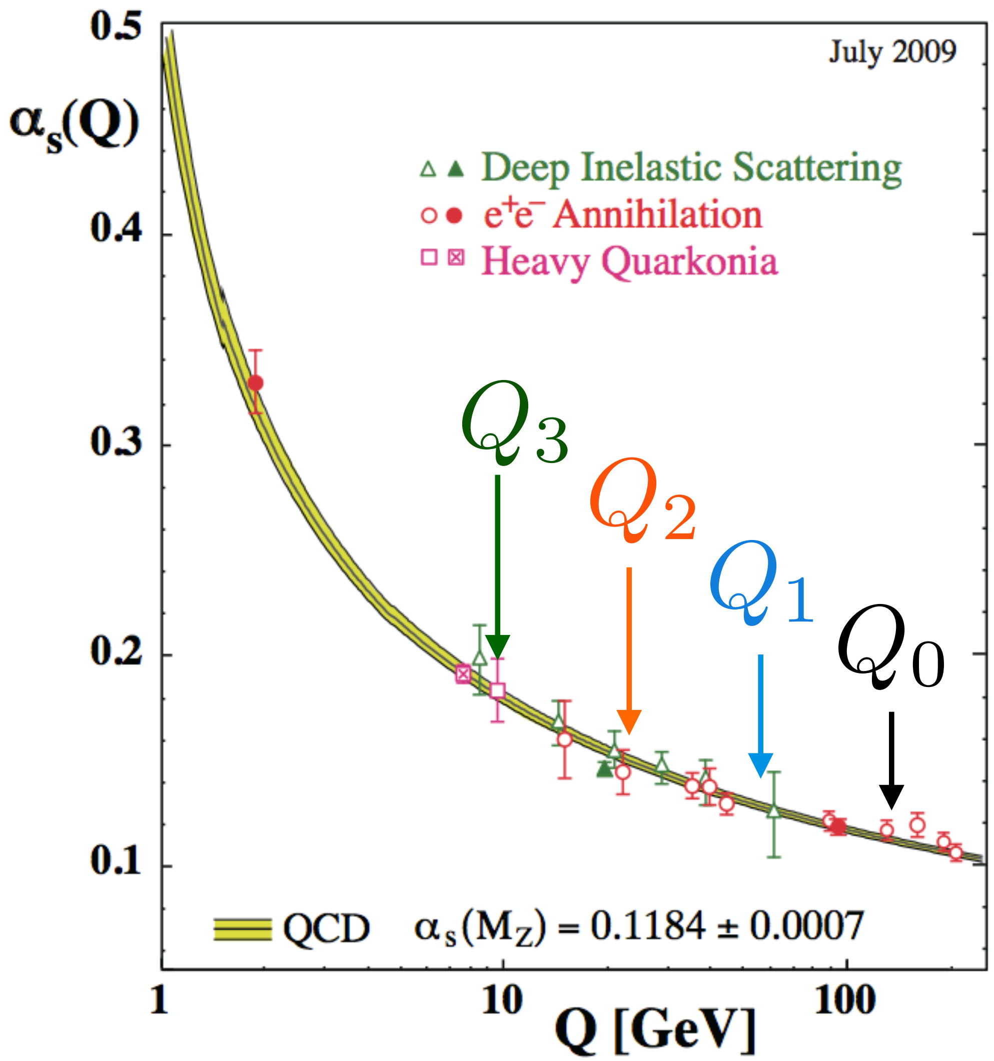

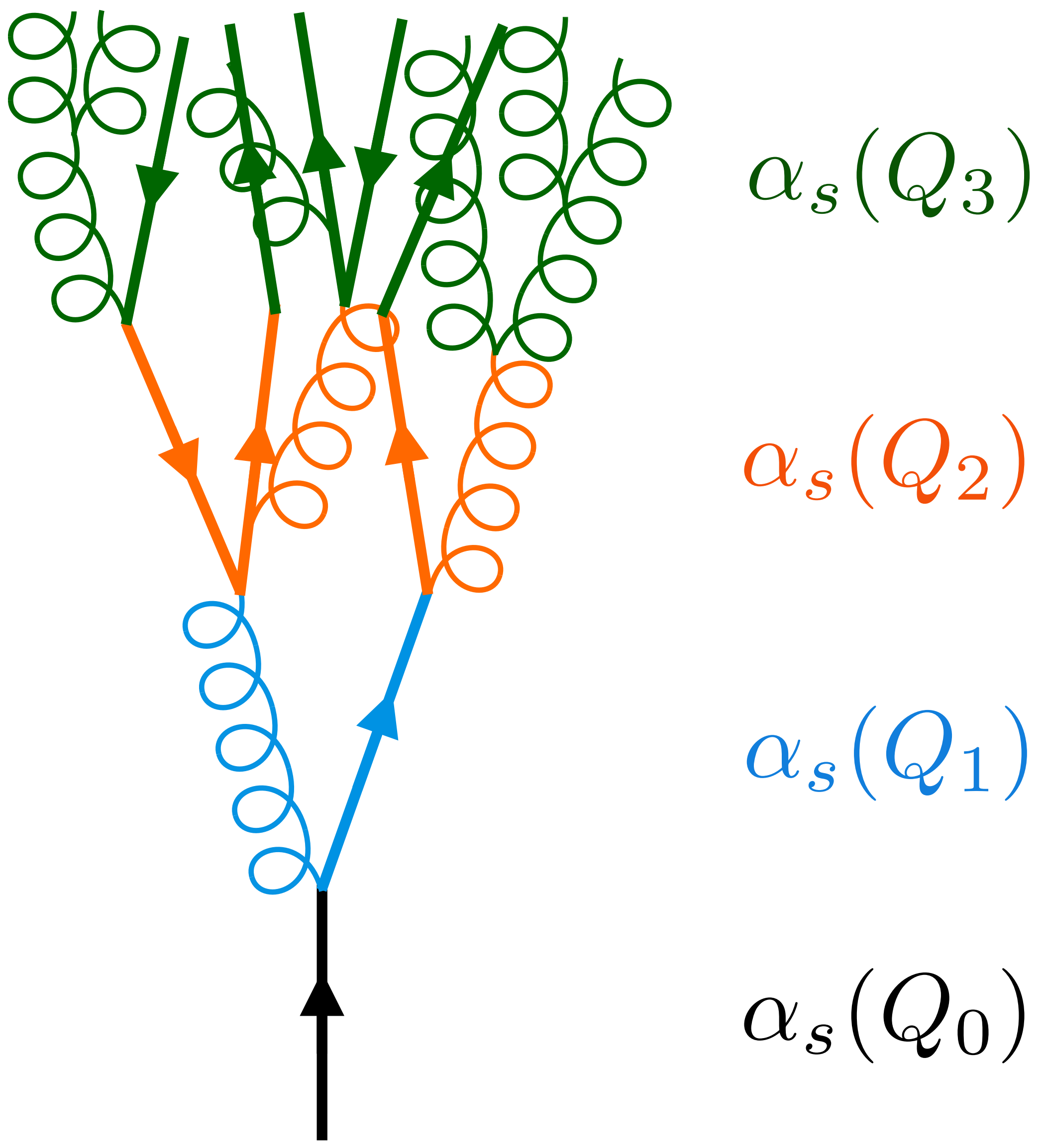

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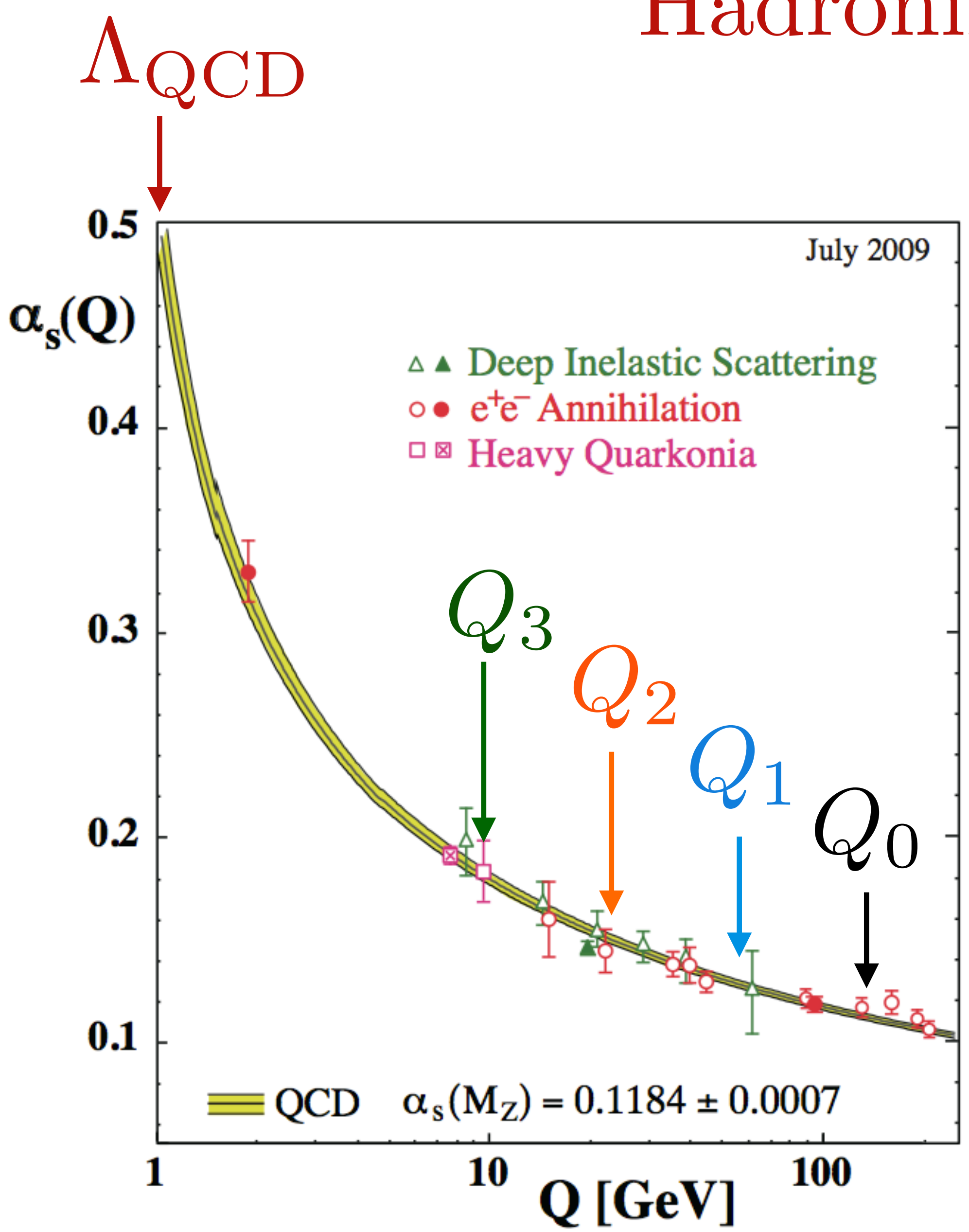
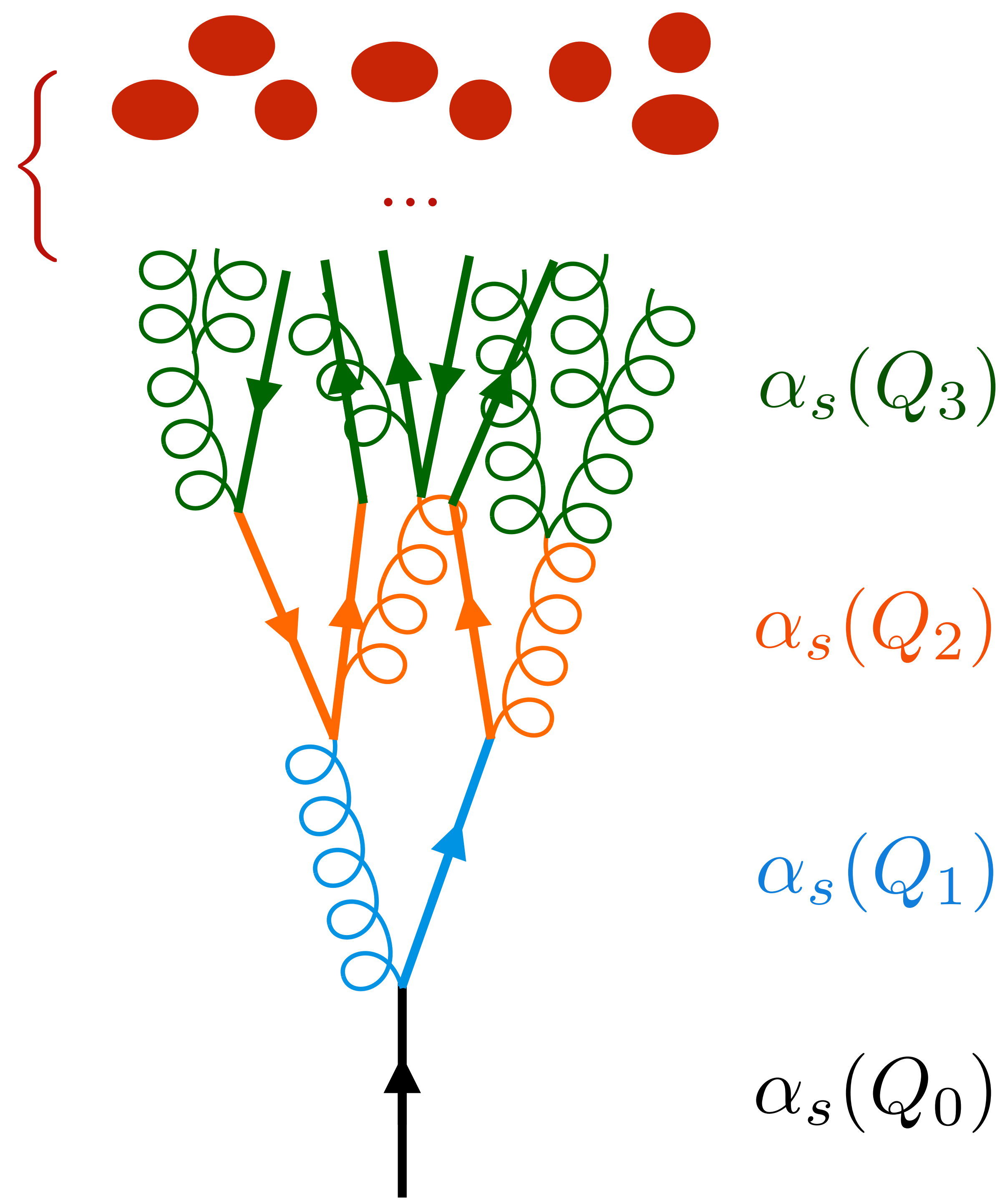




How to define a jet?

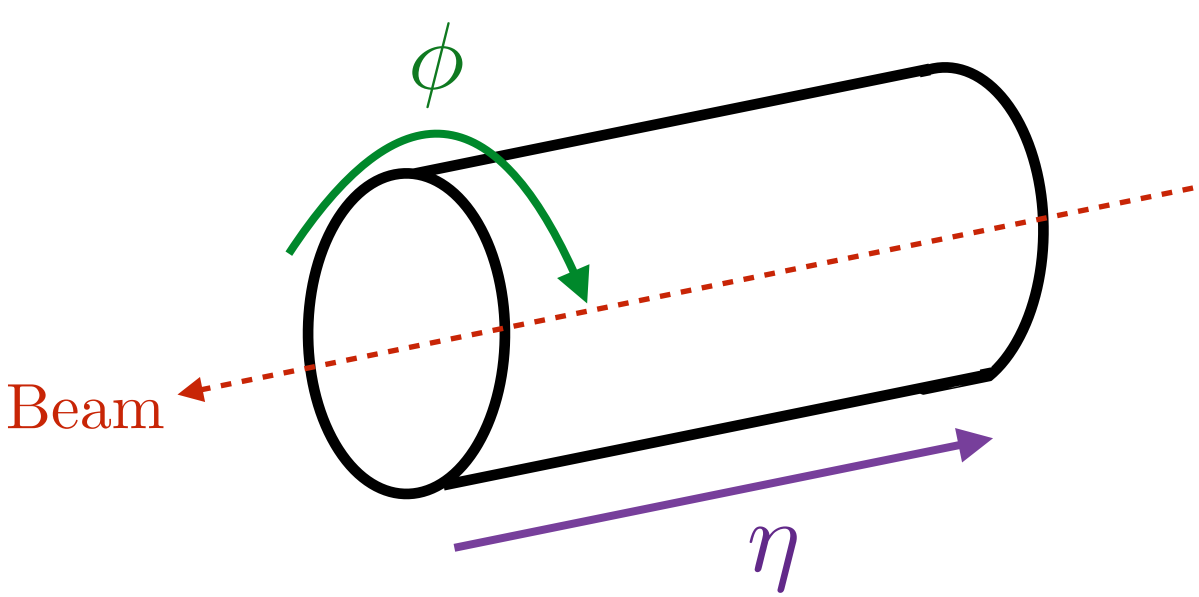
- We use jet algorithms to define a jet
- Default at the LHC: anti-k_t algorithm

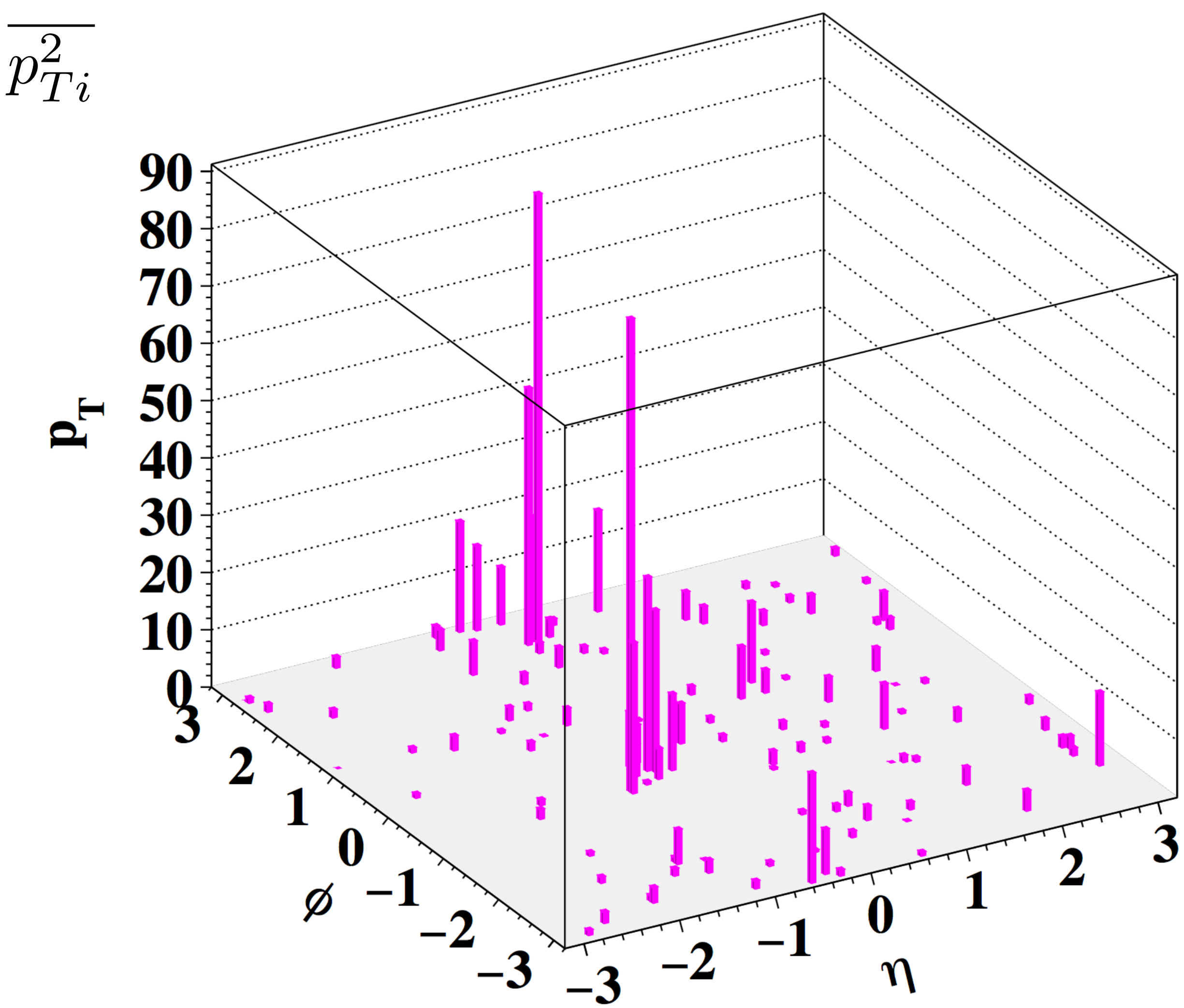
Cacciari, Salam, Soyez '08

- Recursively cluster particles with the smallest distance

$$d_{ij} = \min\left(\frac{1}{p_{Ti}^2}, \frac{1}{p_{Tj}^2}\right) \frac{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}{R^2}$$

$$d_i = \frac{1}{p_{Ti}^2}$$





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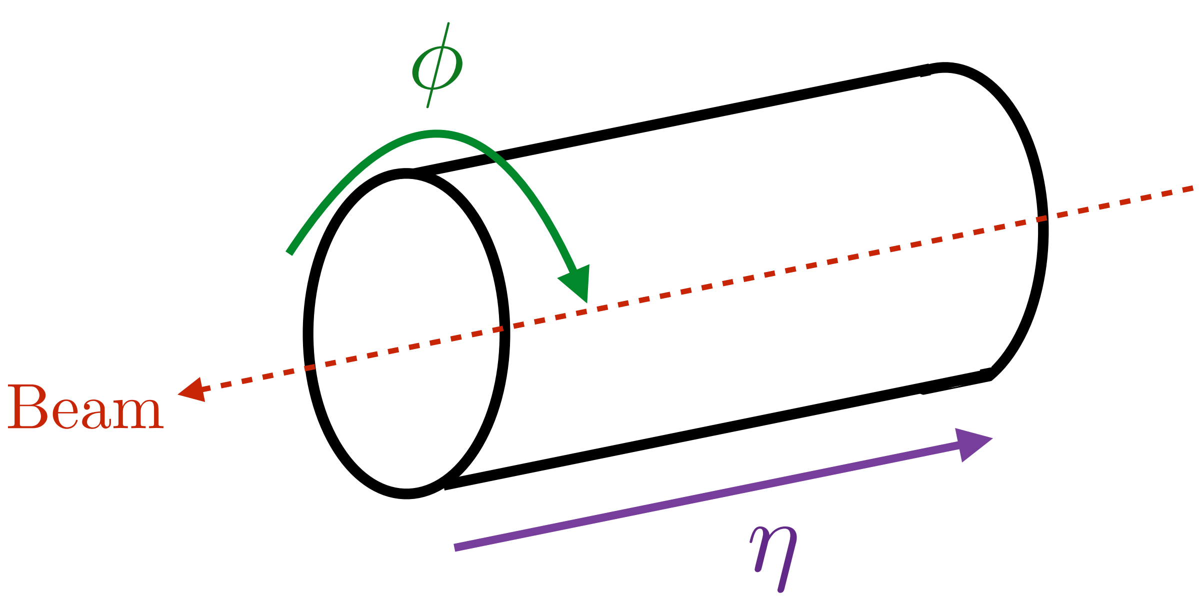
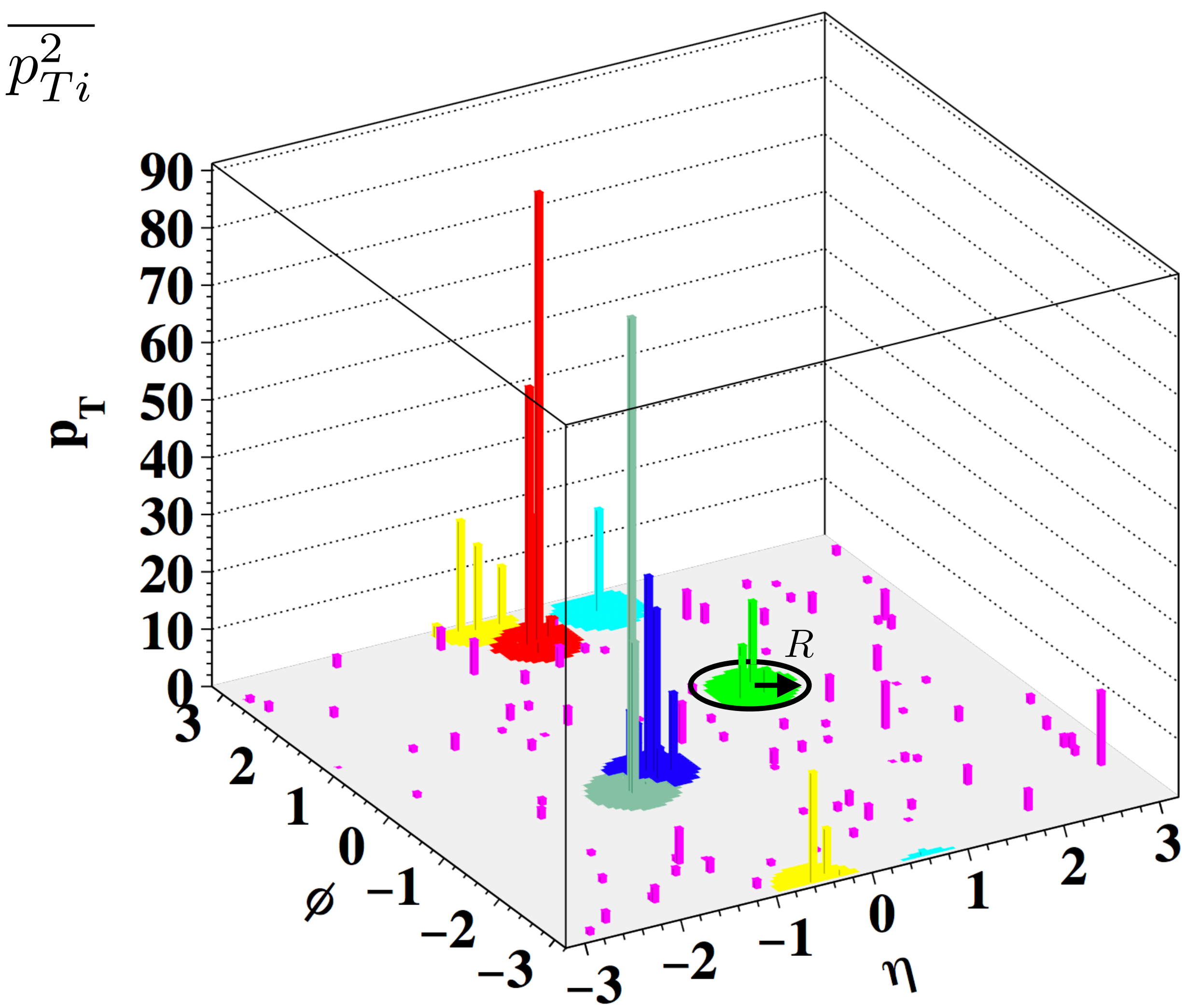
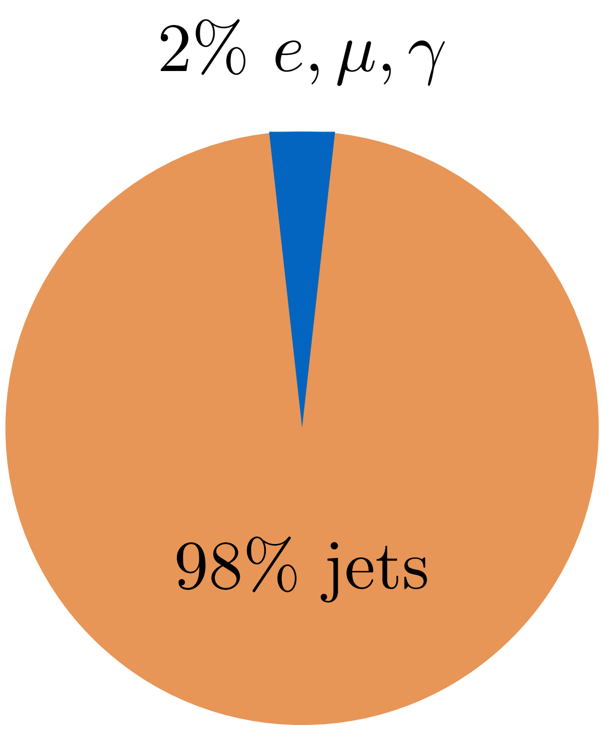




Jets

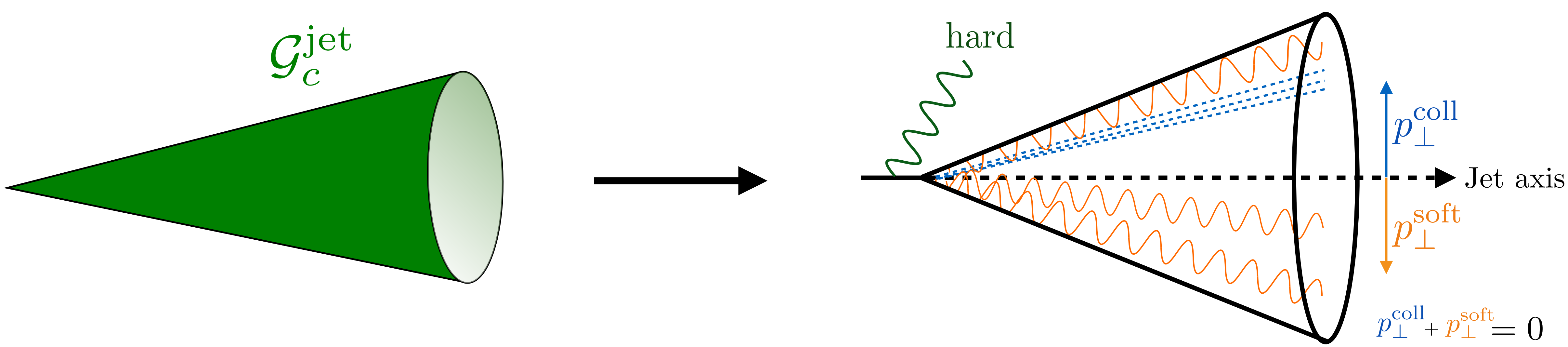
- Jets are ubiquitous at the LHC
- Emergent phenomena acting as a proxy for the underlying hard parton and can teach us about QFT
- Provide precision tests of the SM
- Important for BSM searches



Higgs decay channels

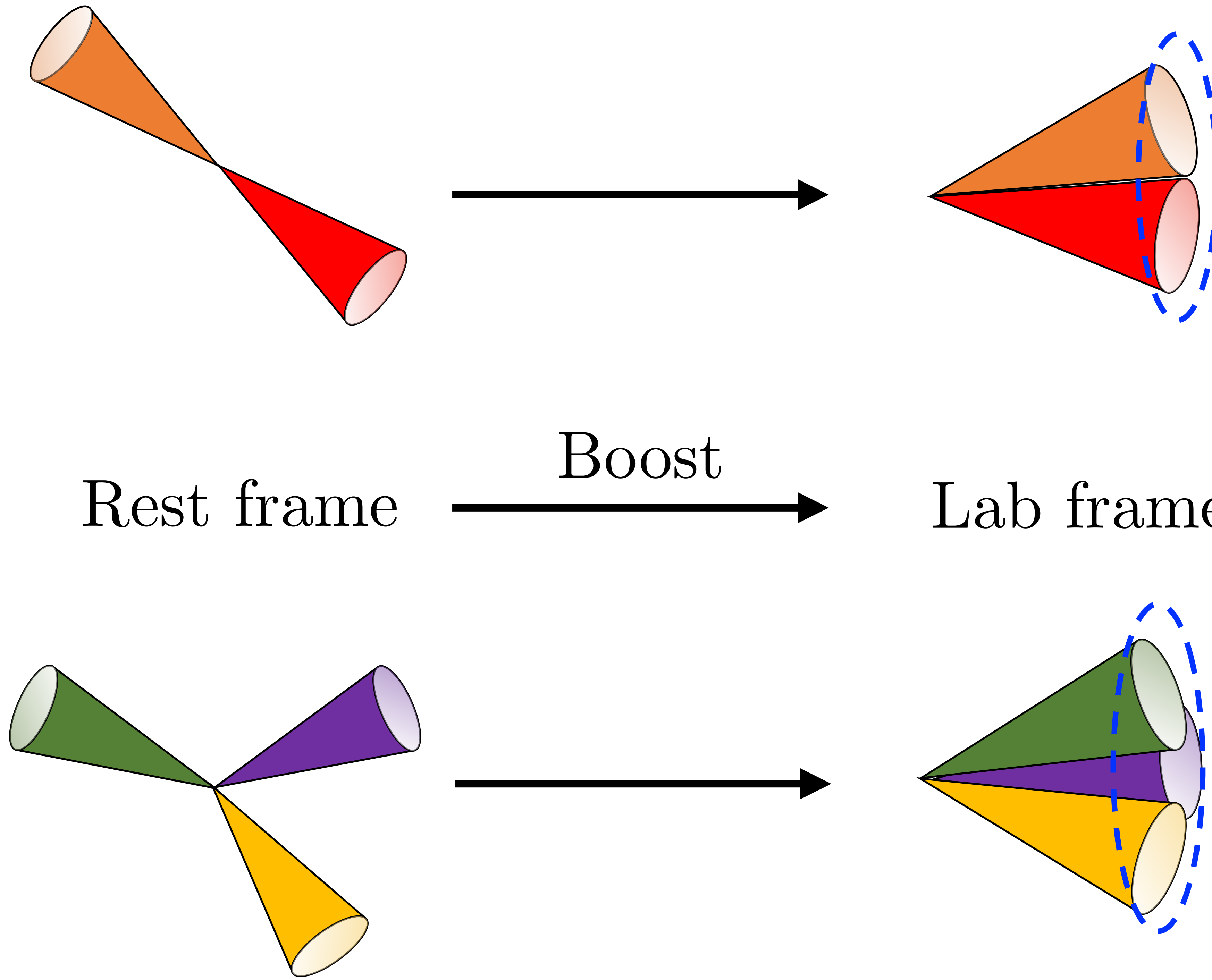
Jet substructure

- Jet substructure are the tools exploiting the information encoded in the radiation pattern inside jets
- Fine granularity of ATLAS and CMS detectors allow us to see inside the jet
- Quark/Gluon jet discrimination
- Precision tests of the SM and new physics searches

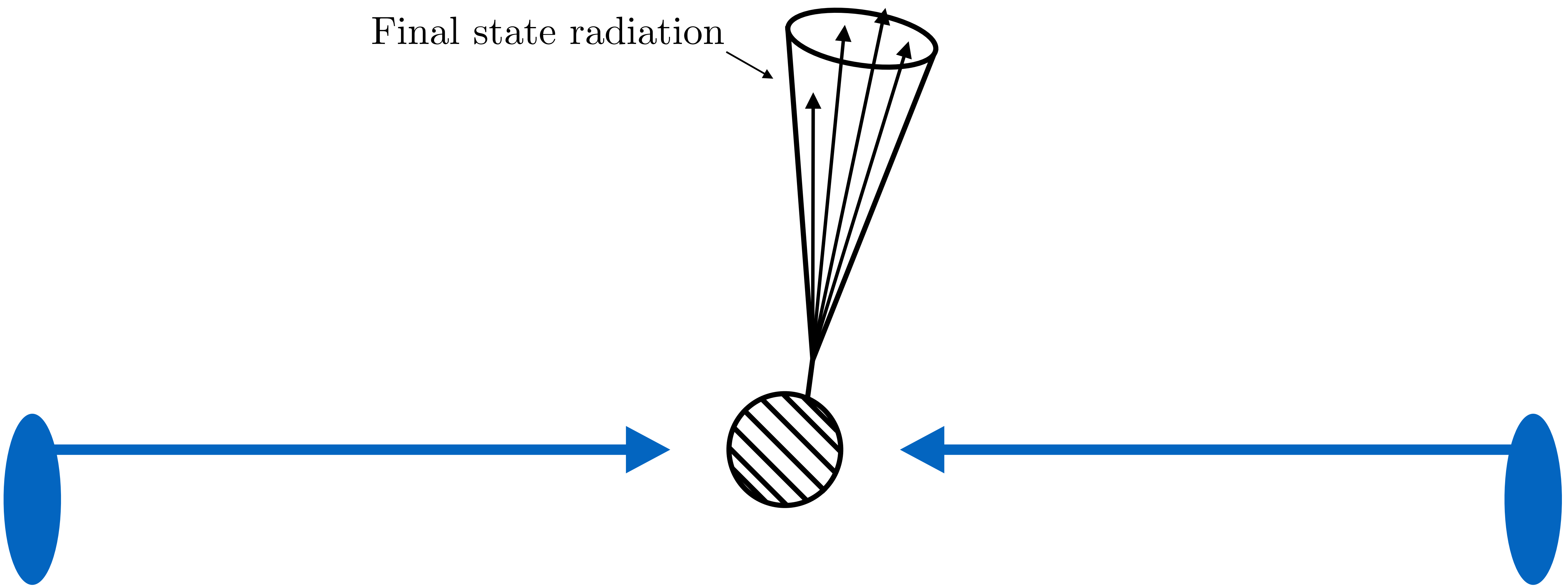


Jet substructure

- Used to distinguish boosted heavy particles from QCD jets
- 2 prong jets:
  - H/W/Z
- 3 prong jets:
  - Top quark



Jet contamination and NP effects



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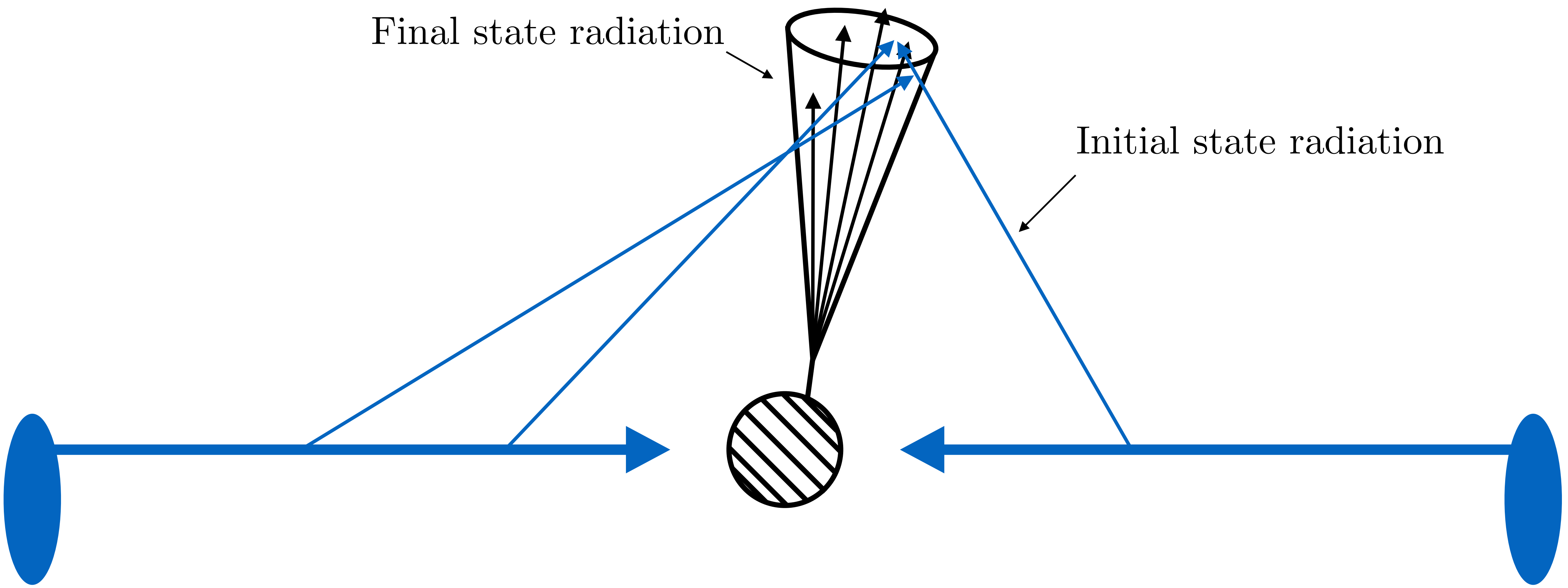

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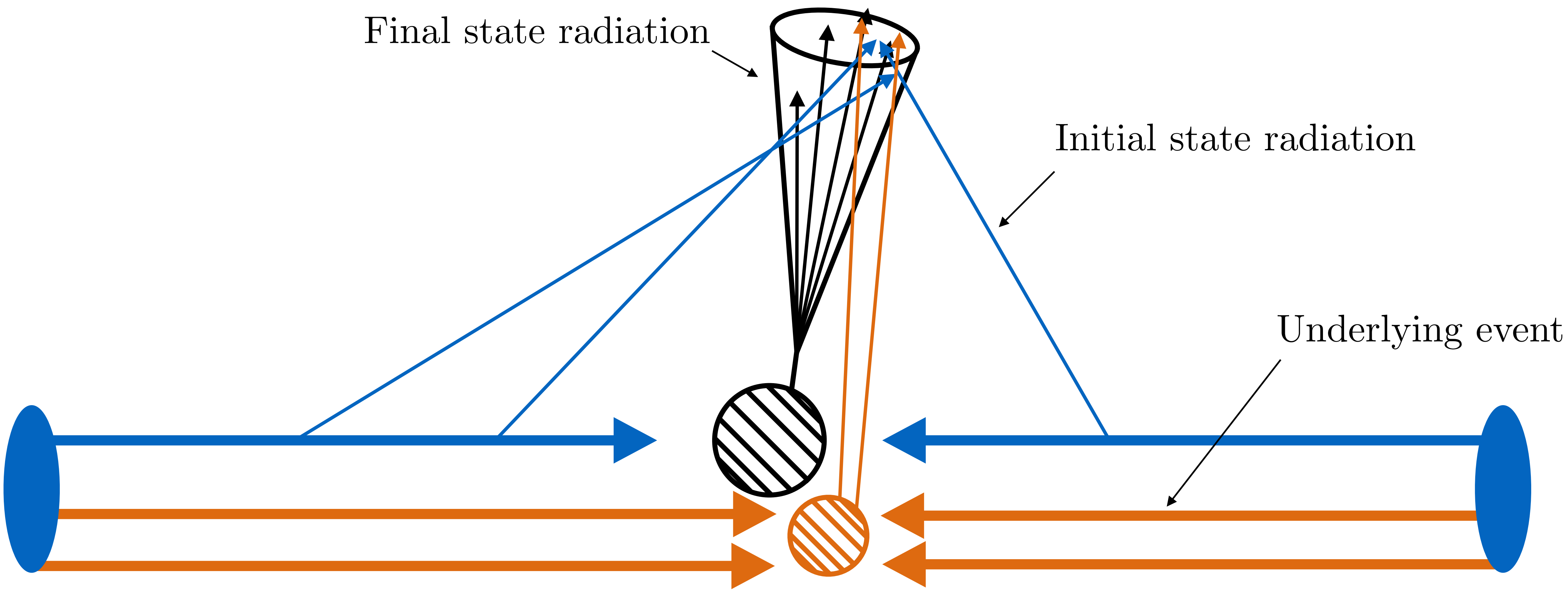

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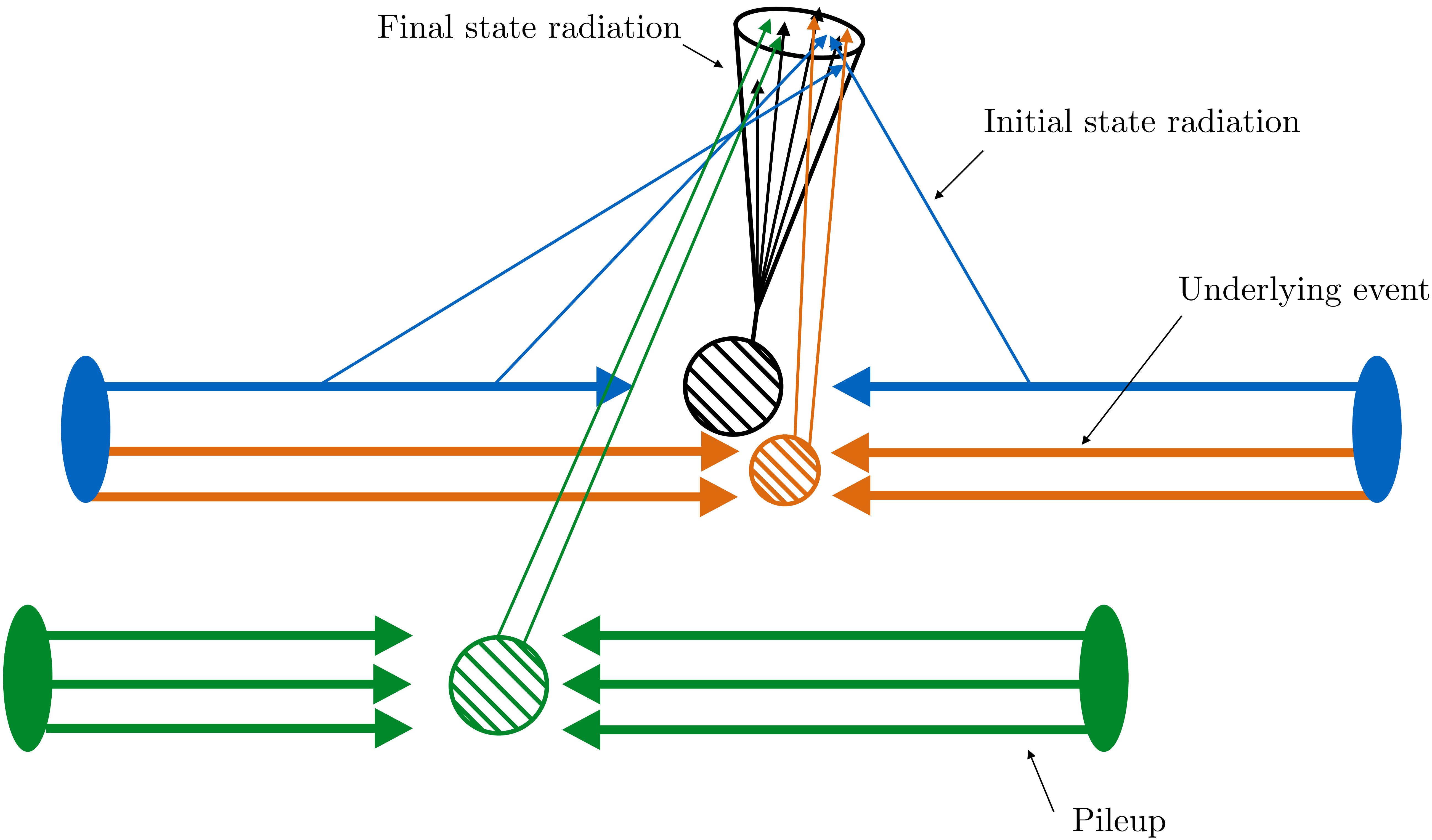

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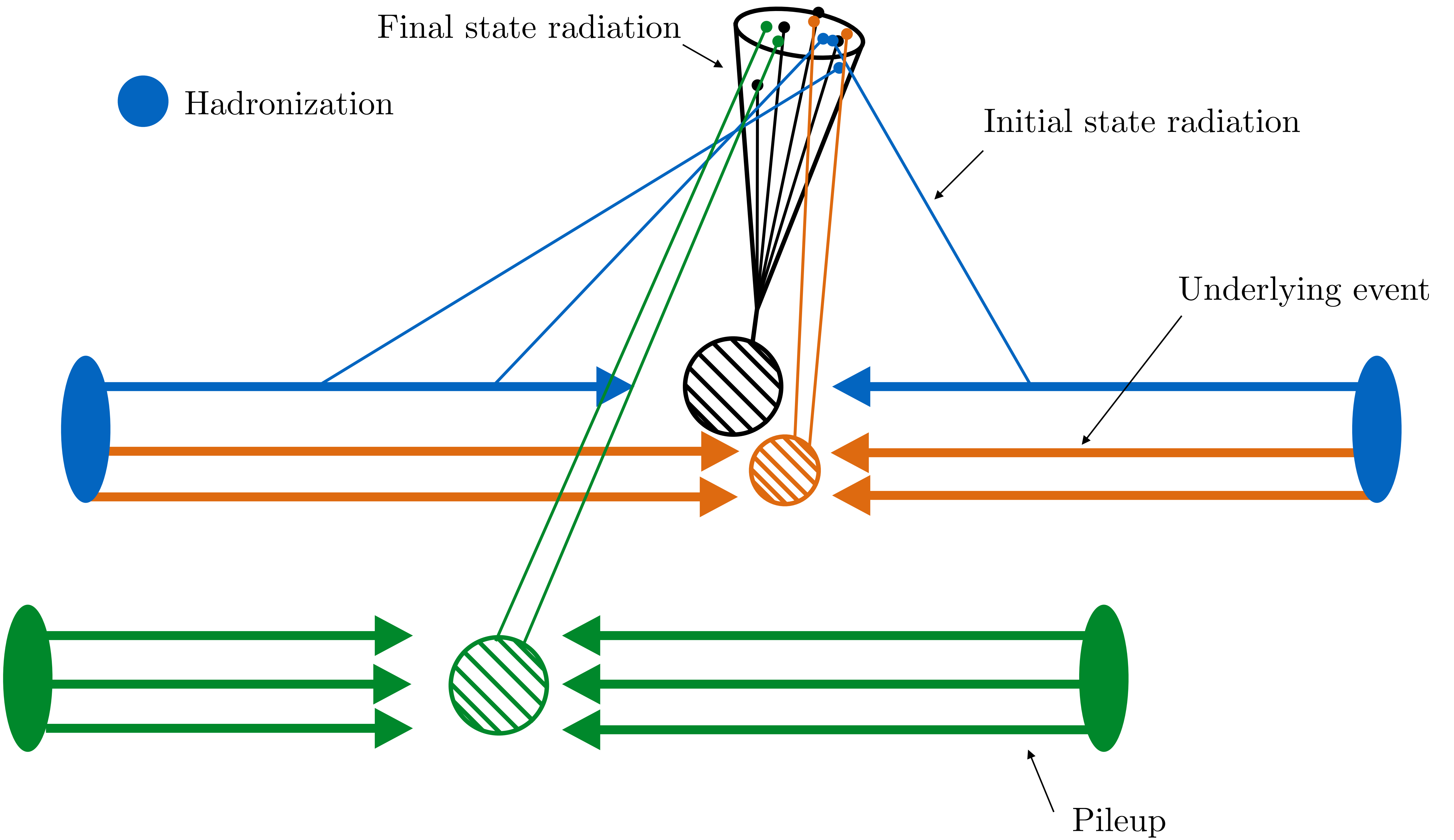
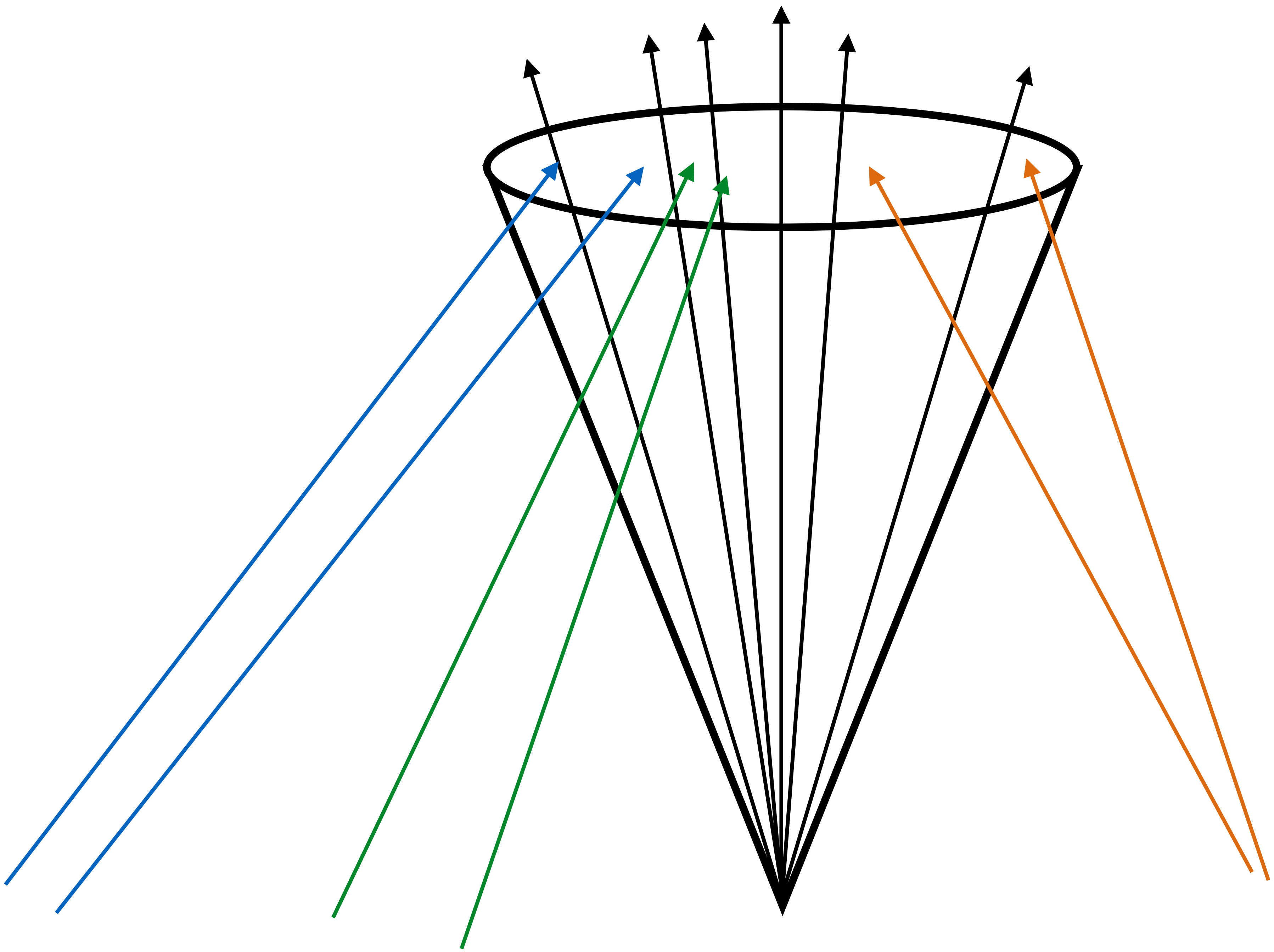


Jet Grooming

- Grooming: Procedure to remove contamination from jet
- Before grooming:



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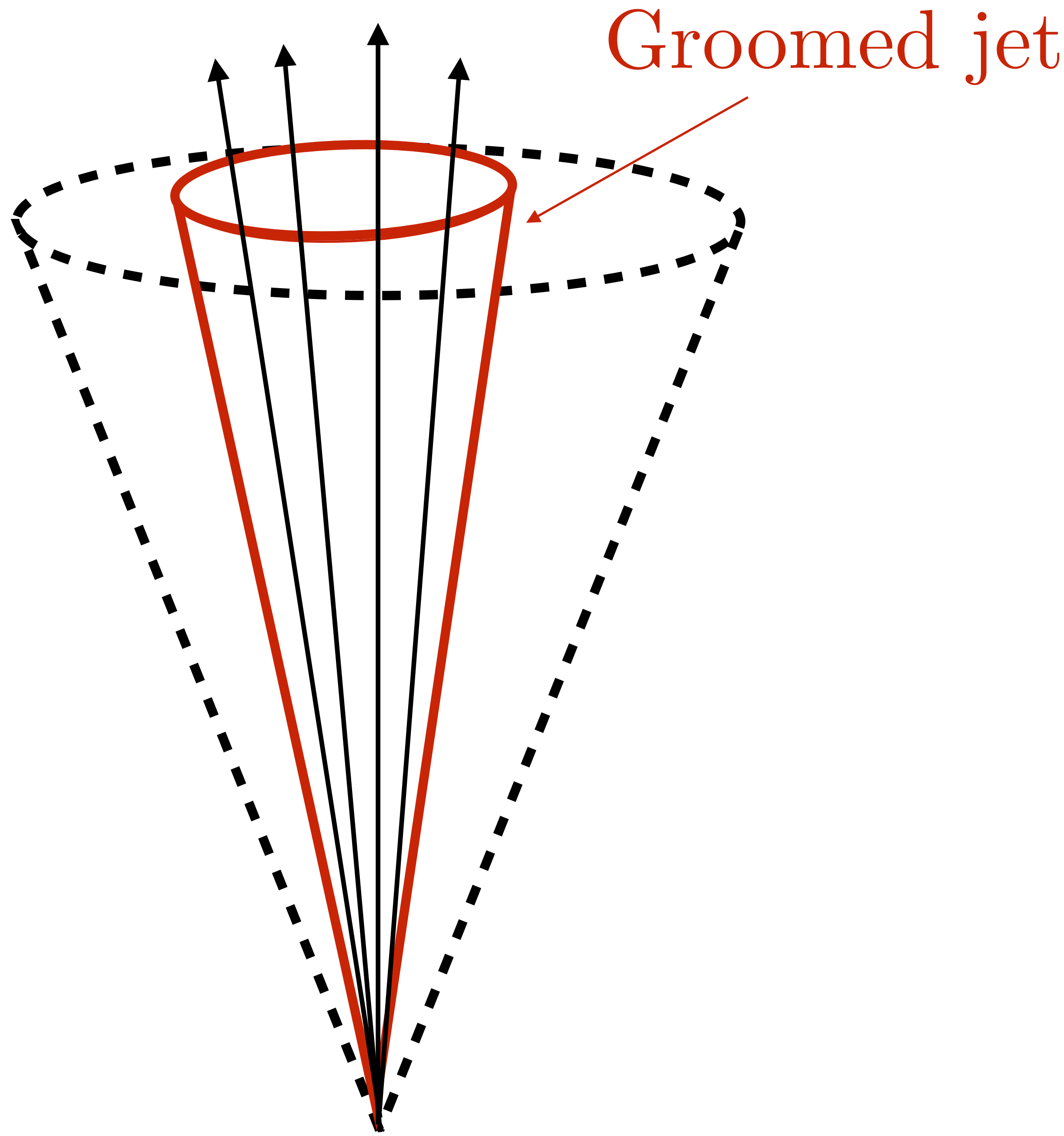
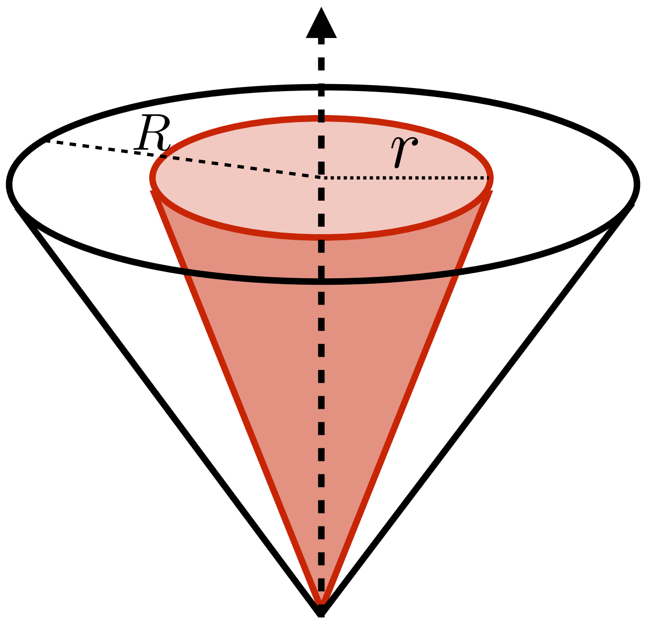
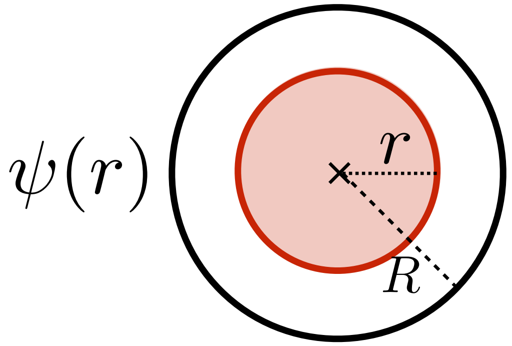


Substructure example: Jet shape





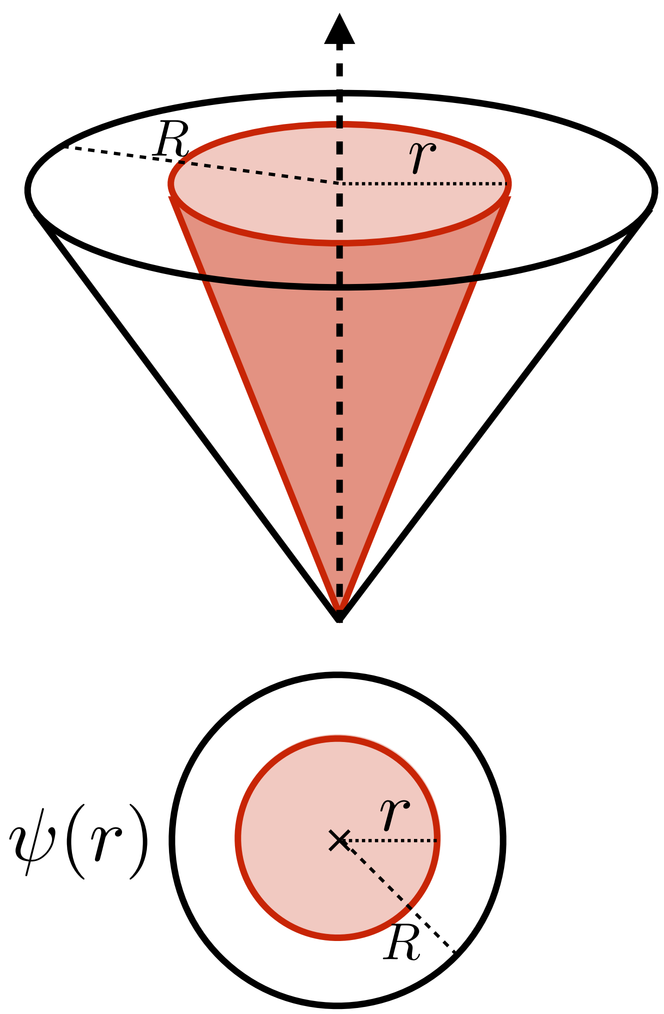
$R =$ Jet radius

$r =$ Subjet radius

$$z_r = \frac{p_T^{\text{subjet}}}{p_T^{\text{jet}}}$$

$$\psi(r) = \frac{\sum_{r_i < r} p_{Ti}}{\sum_{r_i < R} p_{Ti}}$$

Substructure example: Jet shape



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$$z_r = \frac{p_T^{\text{subjet}}}{p_T^{\text{jet}}}$$

$$\psi(r) = \frac{\sum_{r_i<r} p_{Ti}}{\sum_{r_i<R} p_{Ti}}$$

Theory:

$$\psi(r) = \int_0^1 \mathrm{d}z_r \, z_r \frac{\mathrm{d}\sigma}{\mathrm{d}p_T \mathrm{d}\eta \mathrm{d}z_r}$$

Jet shape

- Why the jet shape?

Ellis, Kunzt, Soper '92
Seymour '98
Li, Li, Yuan '11
Chien, Vitev '14

- Classic jet substructure observable
- Existing data sets include pp, $p\bar{p}$, ep, e^+e^- and heavy-ion
- Constrain parton shower event generators (had. models, underlying event contributions)
- Quark/Gluon jet discrimination
- BSM searches, top physics

Sketch of the calculation

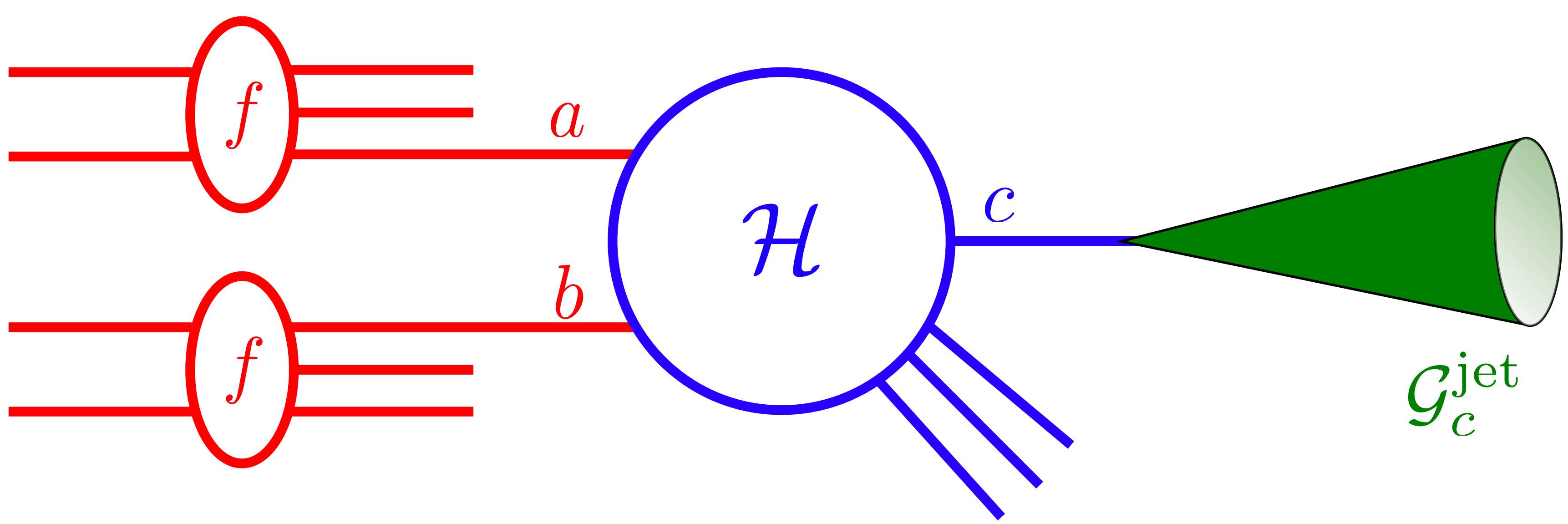
- $R \ll 1$ ⟶ Factorize jet from remaining cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T \mathrm{d}\eta \mathrm{d}z_r} = f_a \otimes f_b \otimes \mathcal{H}_{ab}^c \otimes \mathcal{G}_c^{\mathrm{jet}} \left[1 + \mathcal{O}(R^2)\right]$$

Kaufmann, Mukherjee, Vogelsang '15

Kang, Ringer, Vitev '16

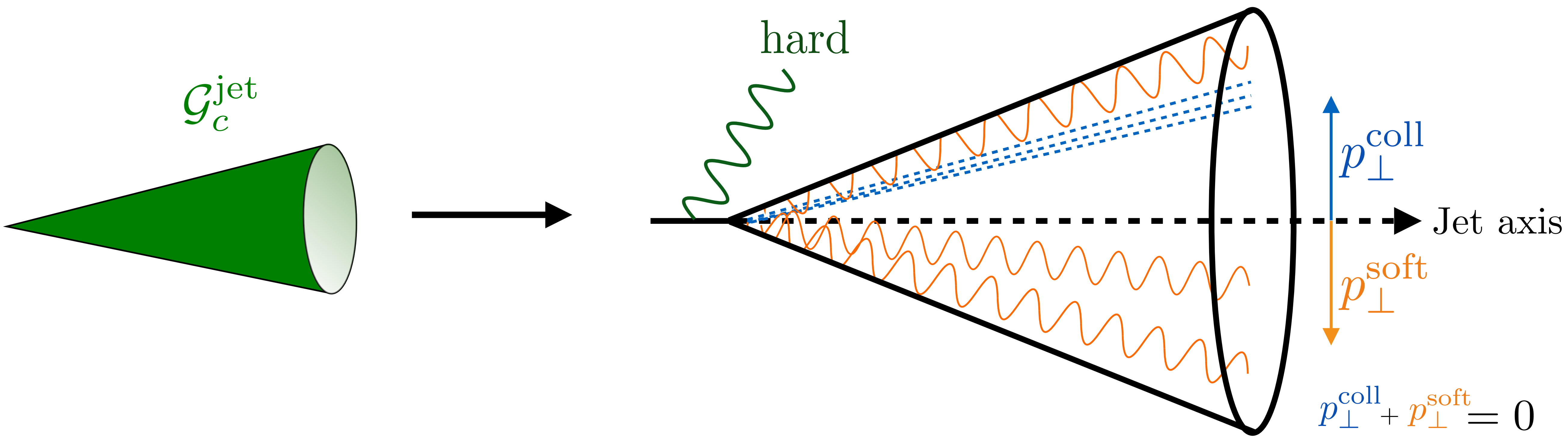
Dai, Kim, Leibovich '16



Sketch of the calculation

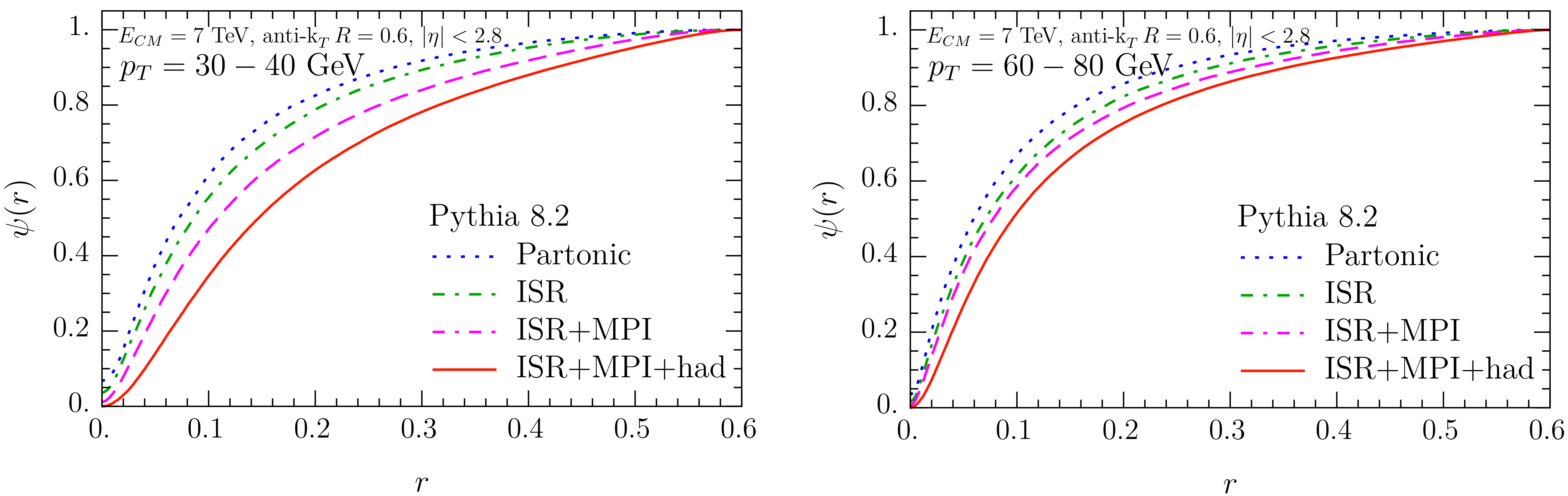
- Perform factorization for $r \ll R$

$$\mathcal{G}_c^{\rm jet}(z, z_r, p_T R, r/R, \mu) = \sum_d H_{cd}\left[C_d \otimes S_d\right]\left[1 + \mathcal{O}\left(\frac{r}{R}\right)\right]$$



Non perturbative effects

- Study nonperturbative (ISR, MPI and hadronization) effects on the jet shape using Pythia



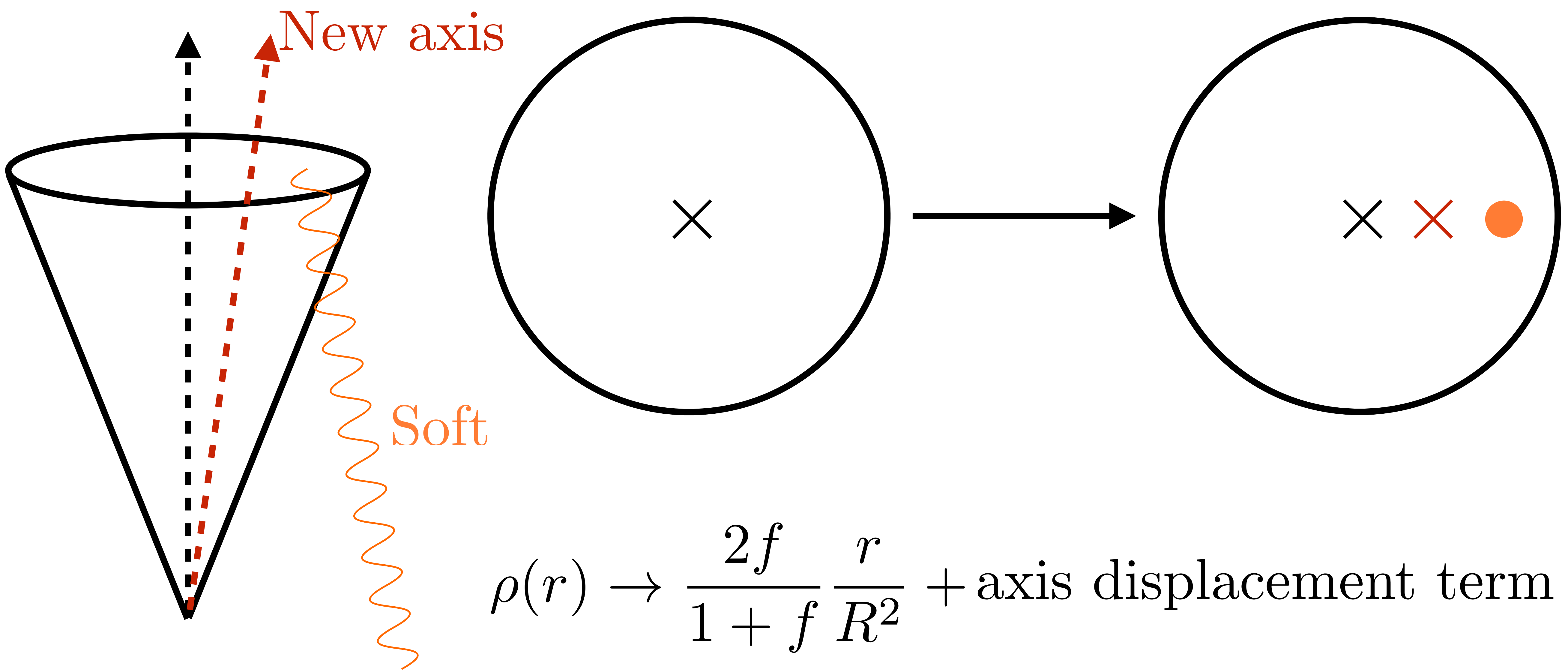
Significant nonperturbative effects!

- Need model to describe nonperturbative effects

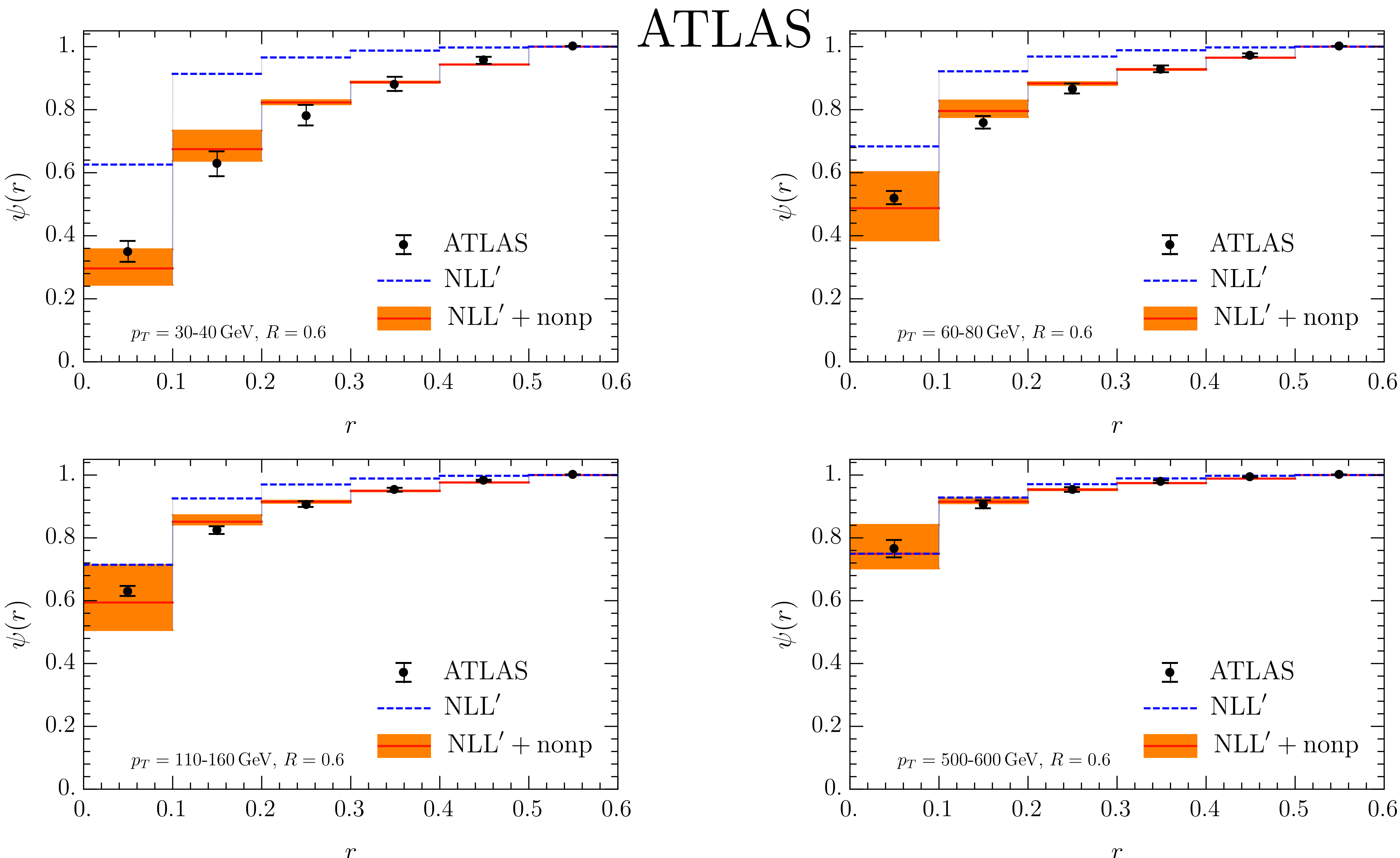
Non perturbative effects

Non perturbative model:

1 particle contamination



$$\rho(r) \to \frac{2f}{1+f}\frac{r}{R^2} + \text{axis displacement term}$$

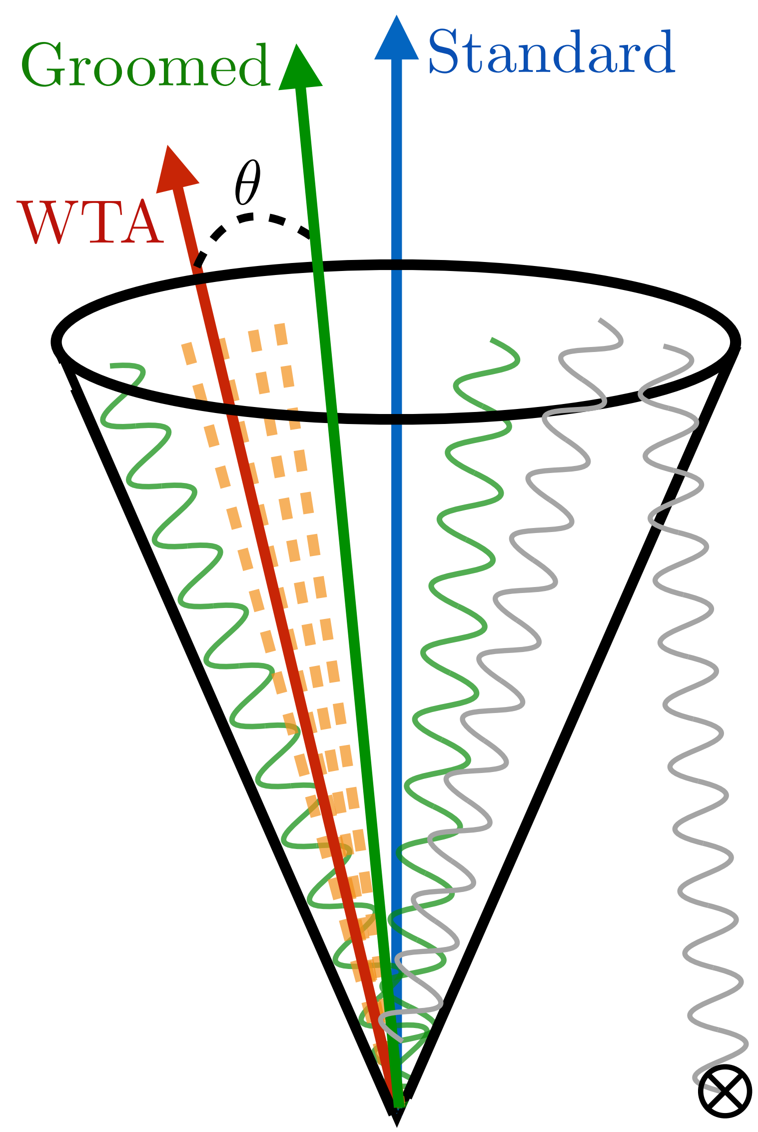


- Fit parameter f for central curves: $f \propto \dfrac{1}{p_T}$

Angle between jet axes

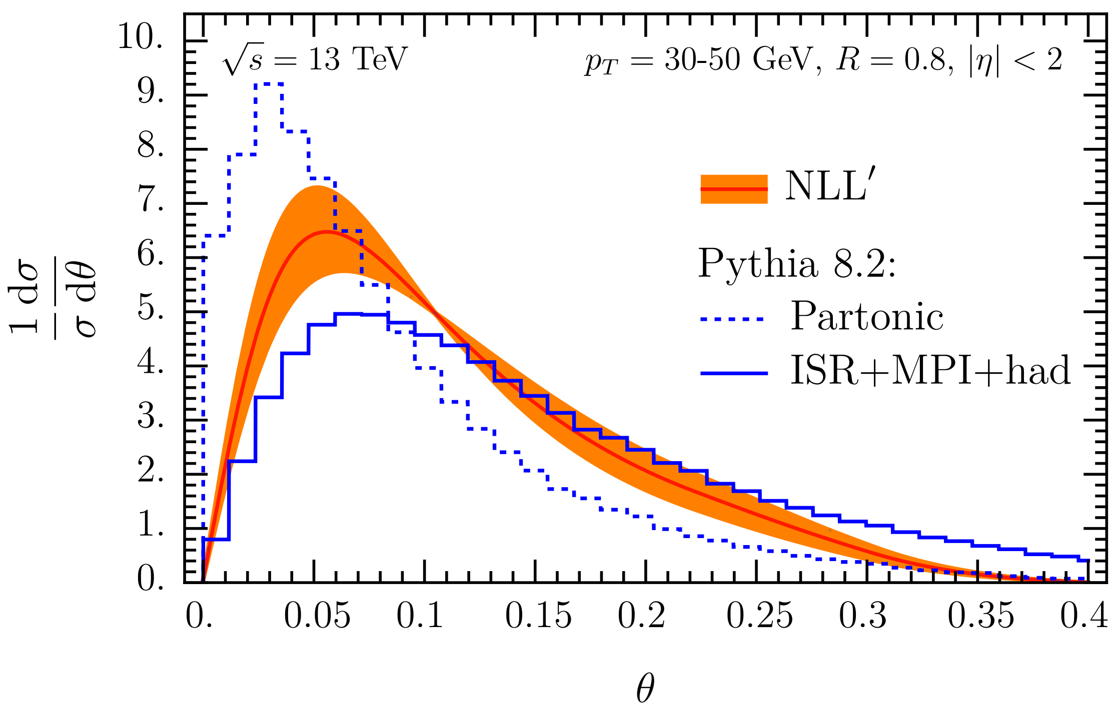
- Axis direction can have significant effect on observable

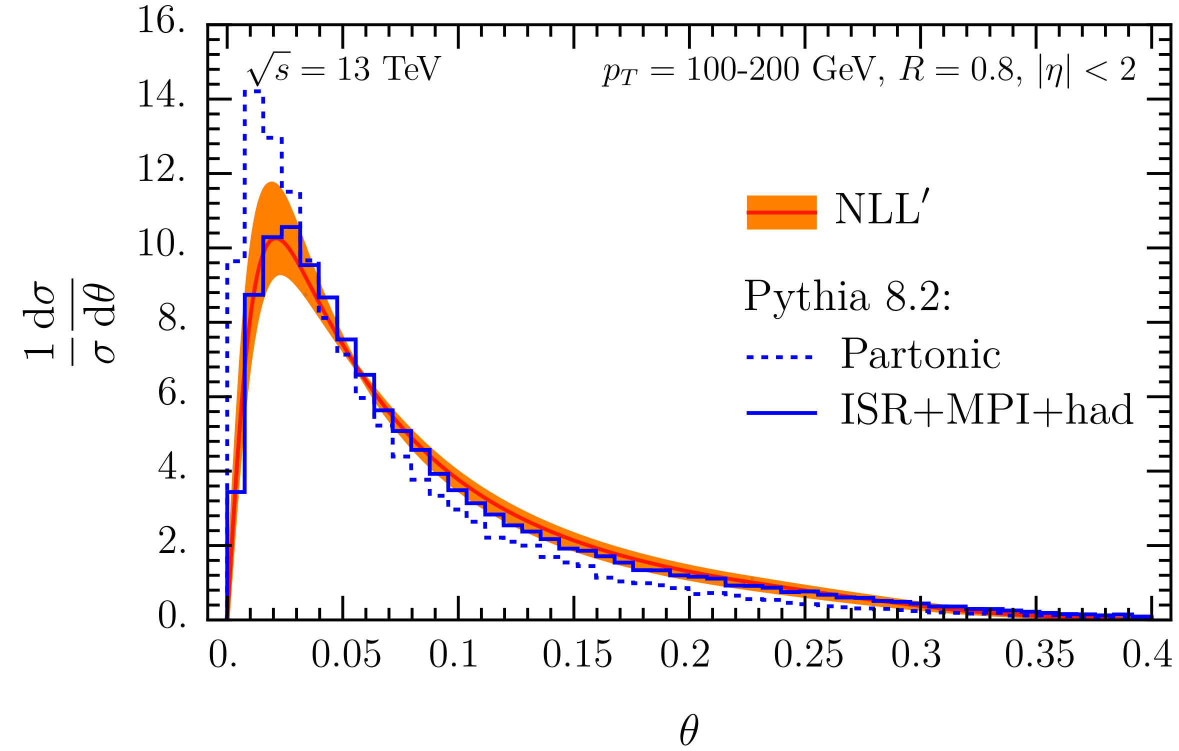
- Begs the question: can we predict the angle between the different jet axes?

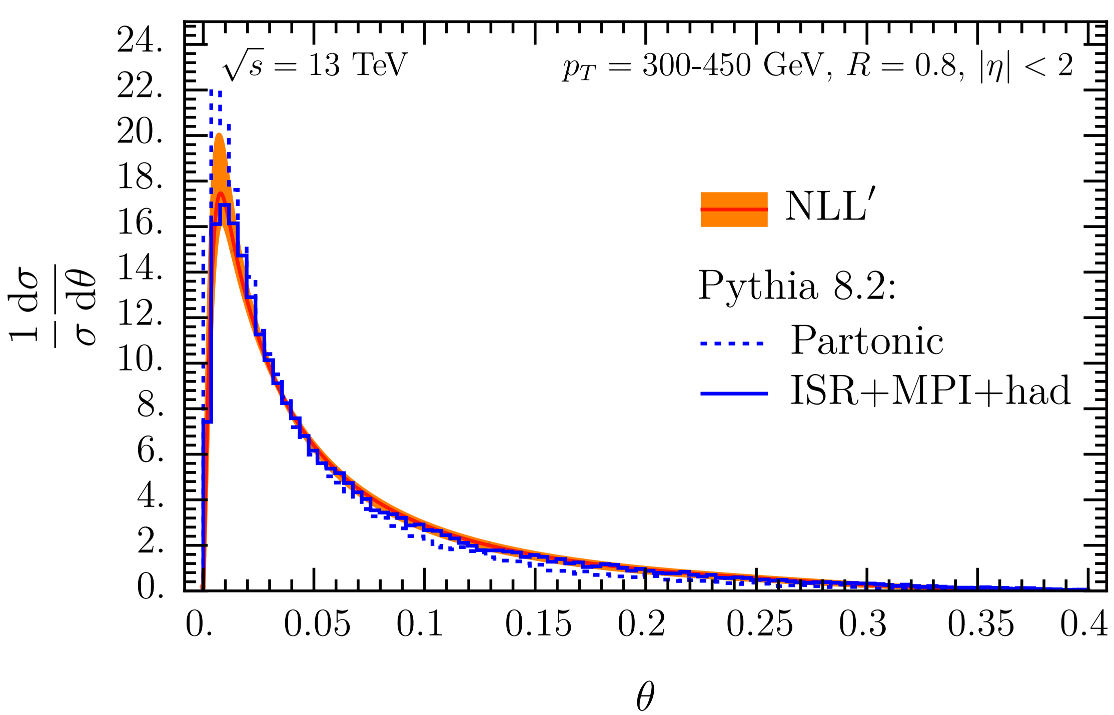


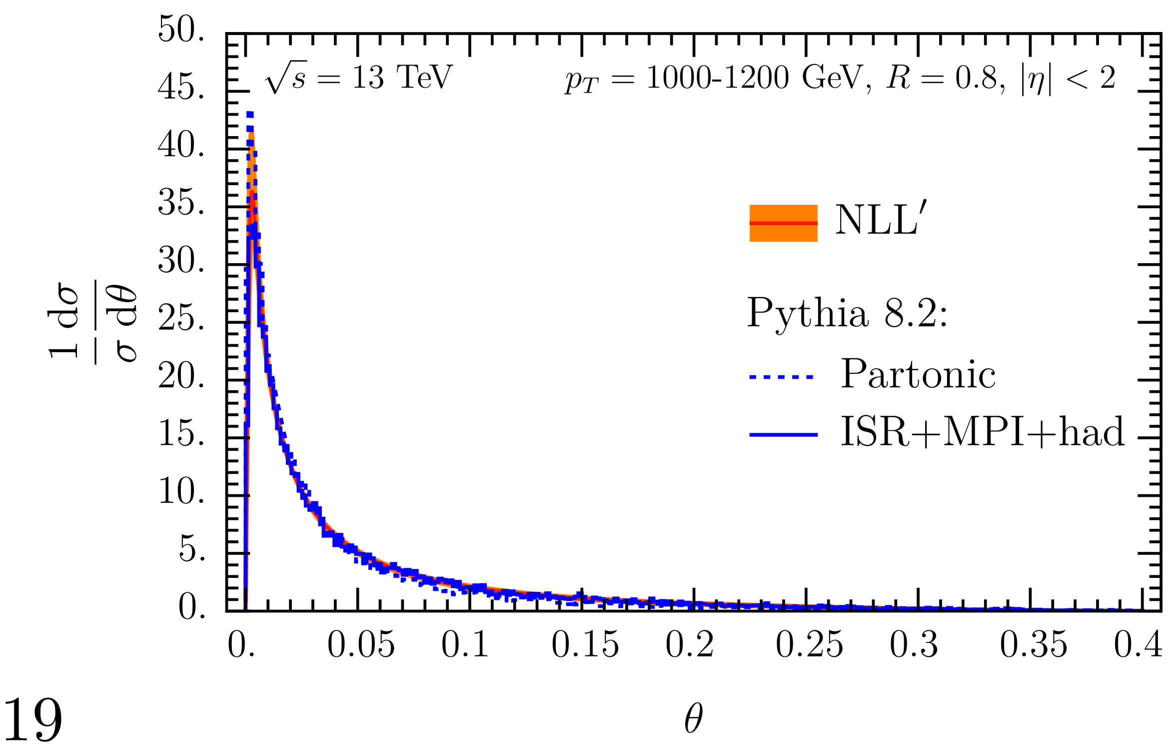
Angle between jet axes

- Indeed we can, coming soon to arXiv







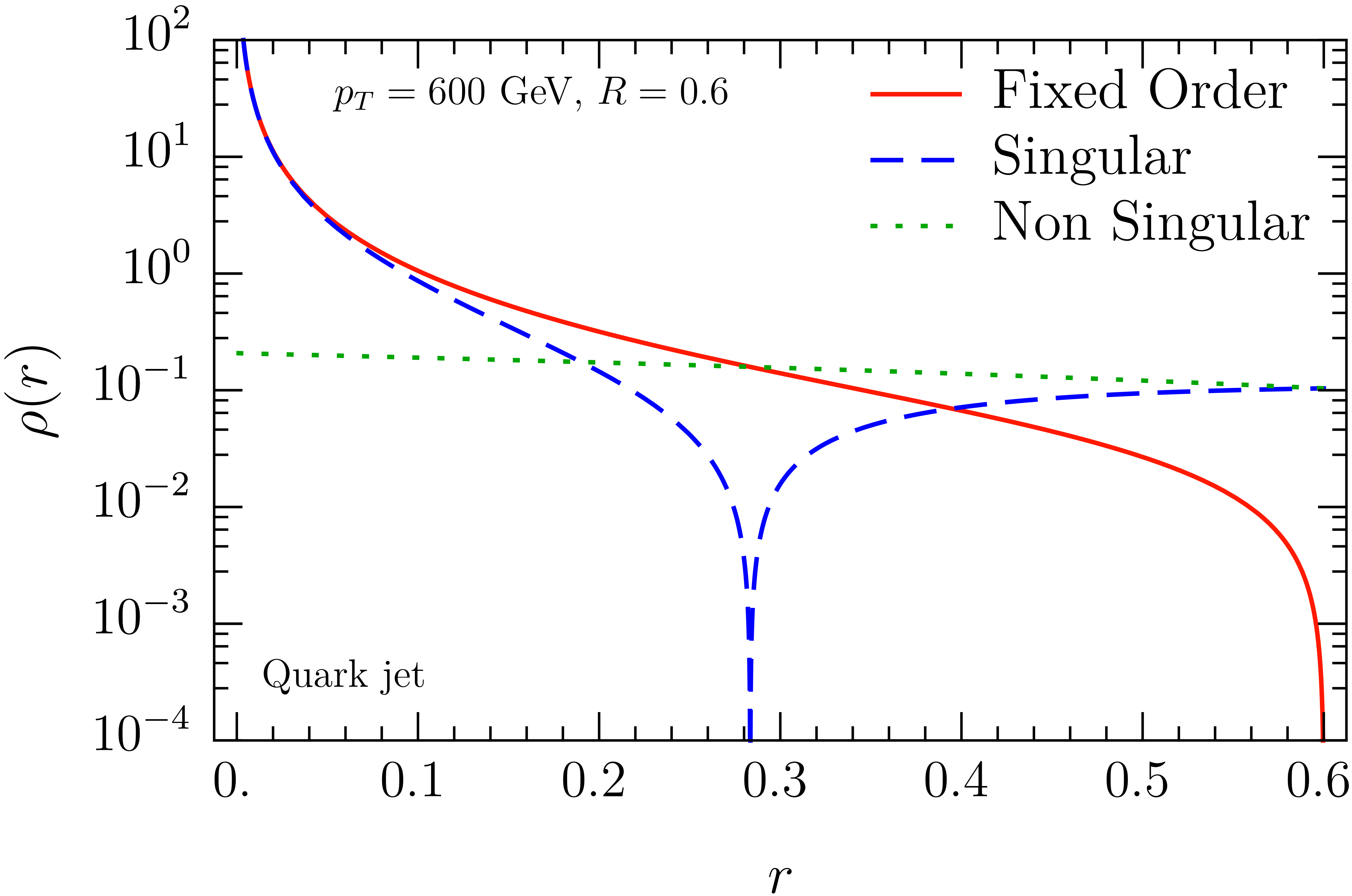


Conclusions

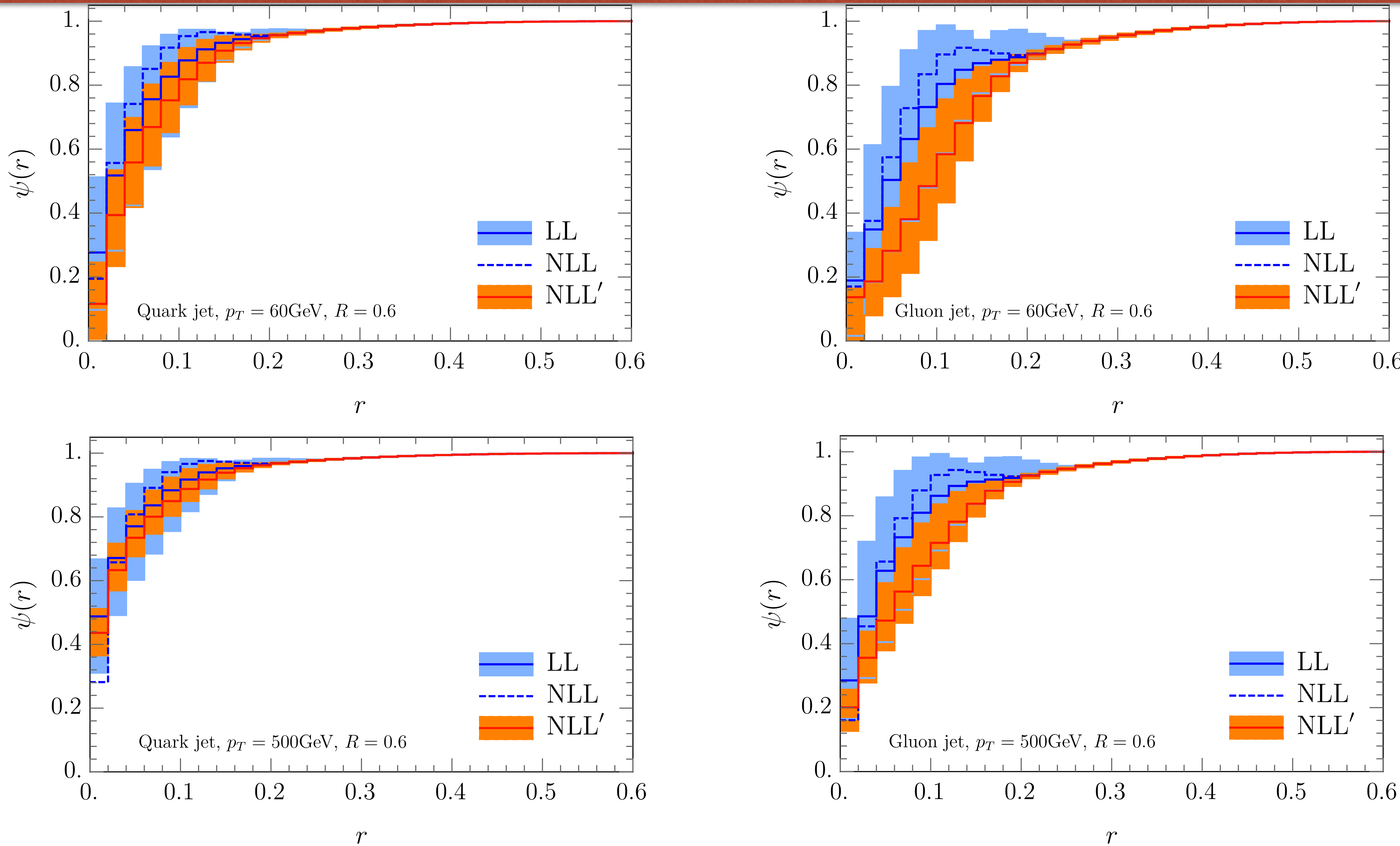
- Jet substructure is a rich and exciting field
- Provides innovative ways to do BSM searches and probe the SM in extreme regions of phase-space
- Requires new theoretical insights

④ Resummation and Matching

◆ Checking refactorization and choosing transition points



⑤ Implementation



- Good convergence
- All matched to NLO