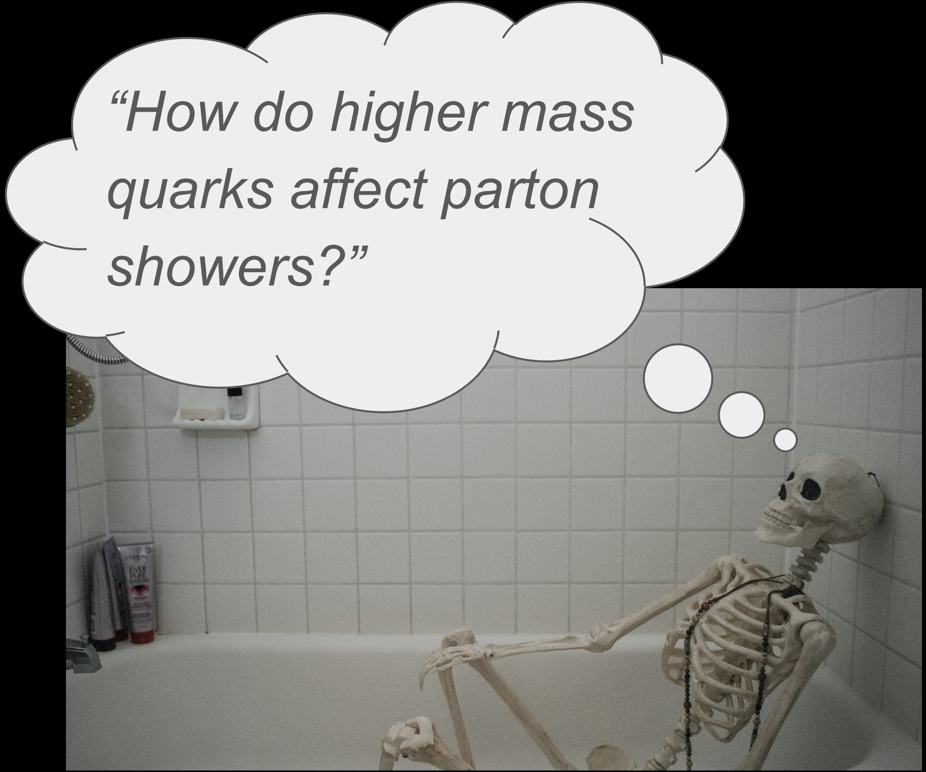
THE DEAD CONE EFFECT

By Emma Yeats

and a menagerie of knowledgeable ghosts and skeletons

What is the Dead Cone Effect?

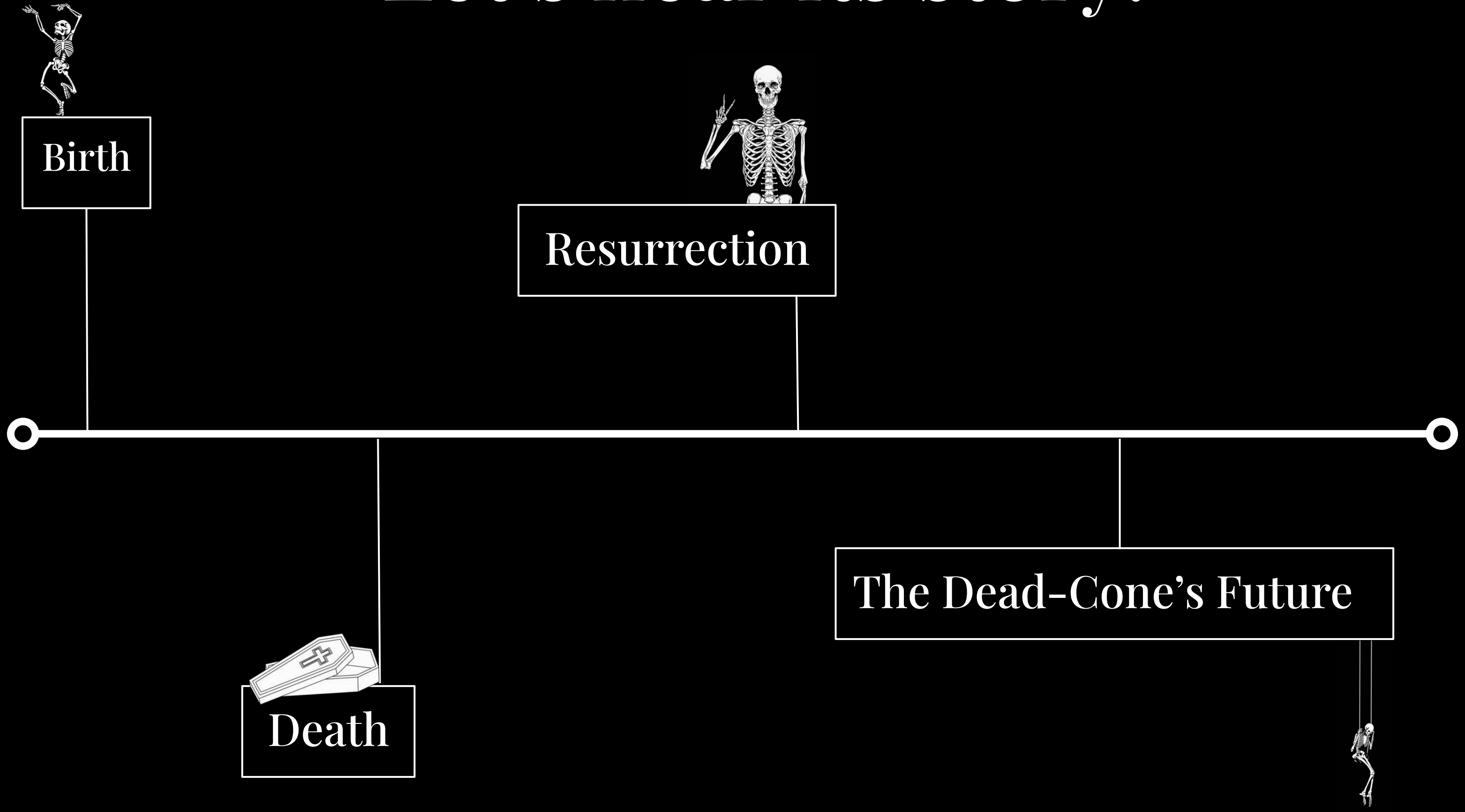
The Dead-Cone Effect is the answer to a simple question:



“How do higher mass quarks affect parton showers?”

We will move in chronological order through the life of the dead cone to understand and appreciate the recent measurement that came out May 2022!

Let’s hear its story!



Birth

Death

Resurrection

The Dead-Cone’s Future

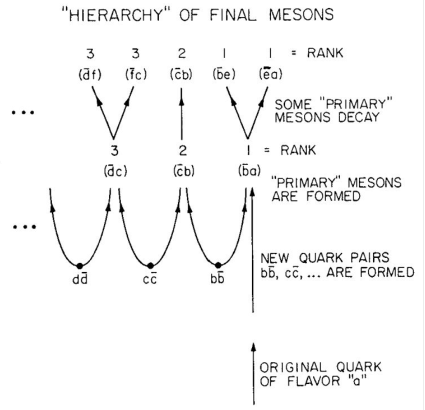
Birth

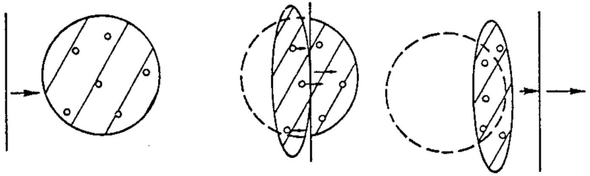
QCD and parton cascades

The story of the dead cone begins in the 1970's with the development of QCD and a frenzy of research on QCD processes like parton cascades that followed.

1970's:

- Invention of QCD, Parton cascade/shower models created for studying fragmentation
- 1977: development of Sterman-Weinberg cone-type algorithms for e+ e- collisions
- studies of hadron-hadron collisions and in e+ e- collisions
- Jet physics and quark-gluon plasma is born!
- Discovery of charm (1974) and bottom (1977) quarks





10.1016/0550-3213(78)90015-9 10.1103/PhysRevD.27.140 10.1103/PhysRevD.17.171

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HOT QUARK SOUP

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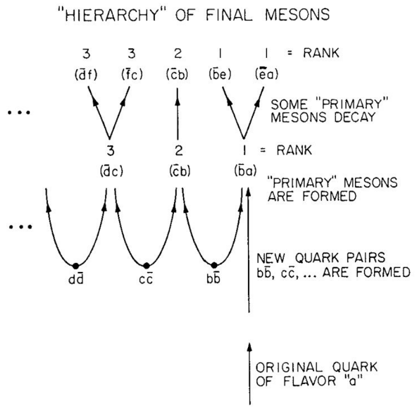

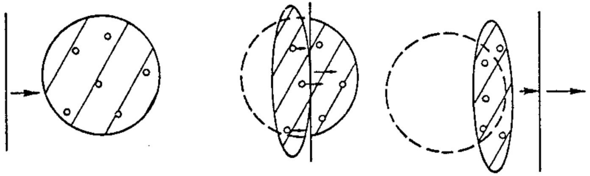

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- more jet and fragmentation physics
- Heavy quark decay dynamics (production and decay)

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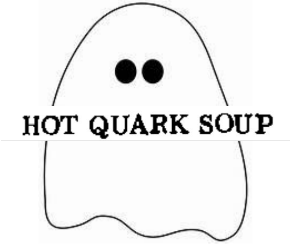

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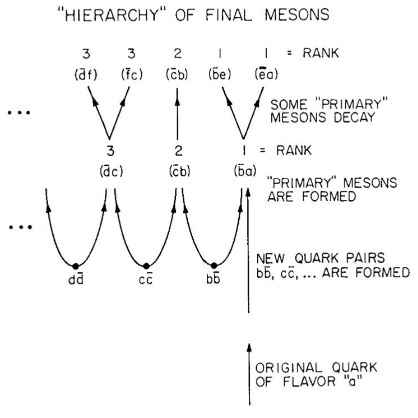

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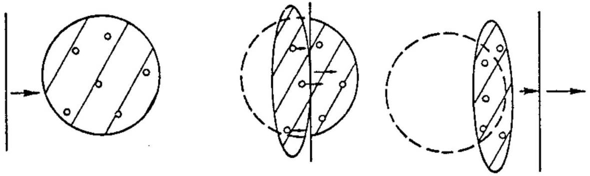

1990: Snowmass Accord

- Who is jet?

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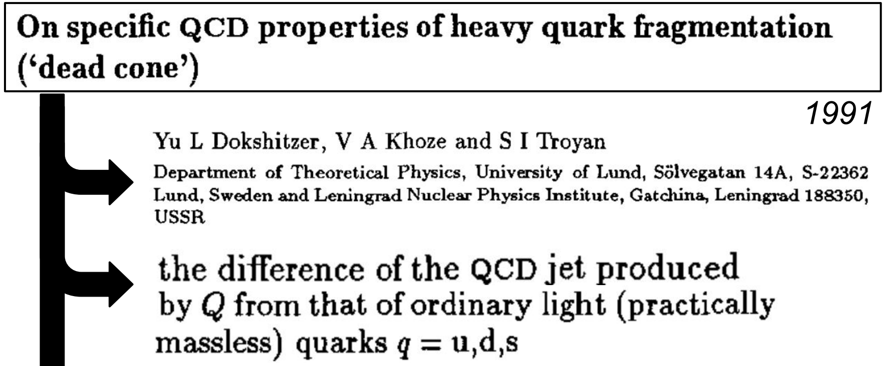
The dead cone in QCD

A natural next step was considering how these parton cascades/showers looked for heavy quark initiated jets.



On specific QCD properties of heavy quark fragmentation ('dead cone')

1991

Yu L Dokshitzer, V A Khoze and S I Troyan

Department of Theoretical Physics, University of Lund, Sölvegatan 14A, S-22362 Lund, Sweden and Leningrad Nuclear Physics Institute, Gatchina, Leningrad 188350, USSR

the difference of the QCD jet produced by Q from that of ordinary light (practically massless) quarks $q =$ u,d,s

Derives and points out that the differential cross section vanishes in the forward direction of the kinematic region. Coined this region the 'dead cone'

They also noted that the primary + secondary gluon radiation at large angles appears identical to that for light quark jets.

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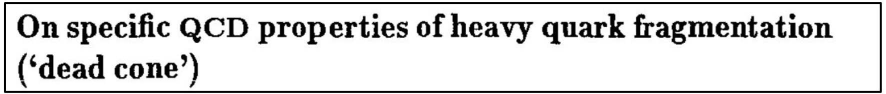

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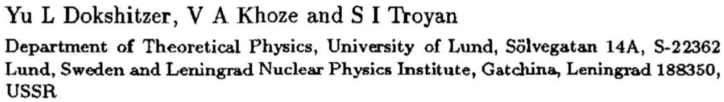

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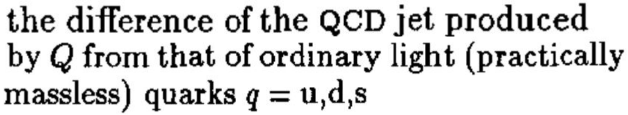

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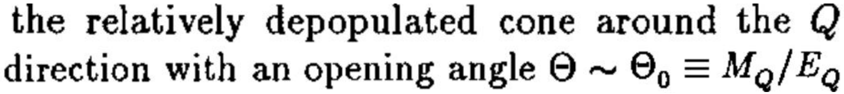
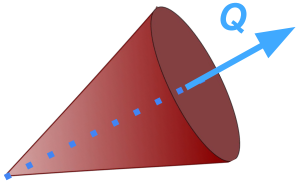
So, what *is* the '*dead cone*'?

- We are studying the limit of a relativistic, heavy quark emitting gluons, where:
    - ○ $E_Q \gg M_Q$
    - ○ $\Theta_0 \equiv M_Q/E_Q \ll 1$
- This paper found that the cross section vanishes in a cone around the heavy quark, with an opening angle $\Theta \sim \Theta_0$

So the dead cone is:



the relatively depopulated cone around the Q direction with an opening angle $\Theta \sim \Theta_0 \equiv M_Q/E_Q$



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Consequences of the dead cone

1.

Usually, gluon radiation is most intensive at small angles. But the dead cone effect suppresses it! So there will be fewer harder gluons

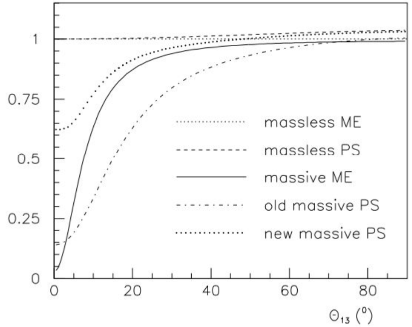
2.

This suppression leads to a significant difference in particle yields (compared to light flavor) which depends on the heavy quark mass.

- less statistics for heavy flavor initiated jets!

3.

Energy spectrum is considerably depopulated in the region of large momentum fractions



Gluon emission rate as a function of emission angle, calculated for 10 GeV gluon energy at √s=91 GeV

arXiv:hep-ph/0010012

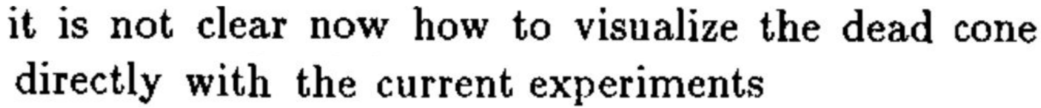
Requirements for measurement

Naturally, people wanted to verify this new theory with a measurement. But, a direct experimental measurement of the dead cone effect was… difficult to plan.

The authors give some advice:

- The Q initiated jet can be identified by some characteristic features of Q decays
- “A study of forward-particle production in Q-jets… free from ‘trivial’ perturbative bremsstrahlung, may help in the investigation”

But they also admitted:



it is not clear now how to visualize the dead cone directly with the current experiments

…which naturally led to…

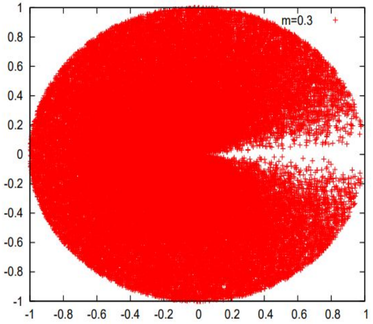
Death

Grasping for life

For the next ~30 years, measurement was essentially impossible.

Jet physics was still an infant field at the time (Snowmass Accord was held only a year prior to the dead cone's theoretical discovery)

They could measure energy losses (jet quenching), and consider theoretical dead cone effects on measurements



Monte Carlo simulation on the gluon emission angle, θ, off a heavy quark.

But, several things were needed still, like more data at high pT with improved statistics and, of course, better jet algorithms

https://arxiv.org/pdf/1203.5221.pdf

Advances in heavy-flavor physics

There were many important developments that paved the way for eventual measurement.

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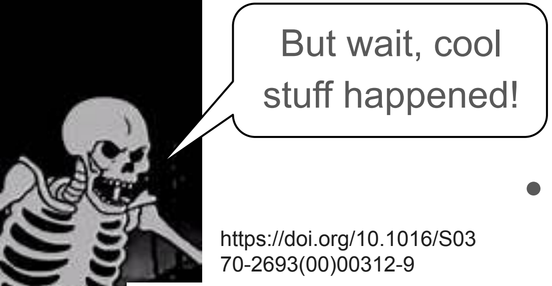

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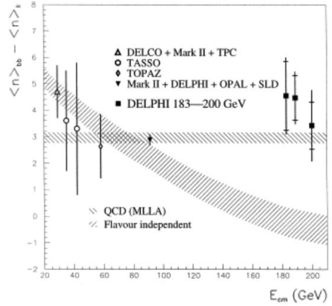

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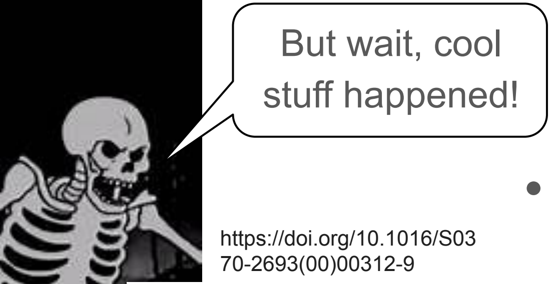

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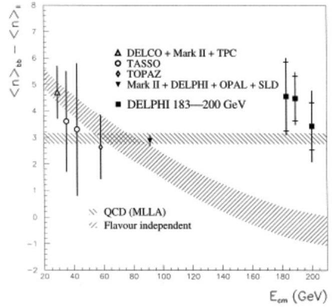

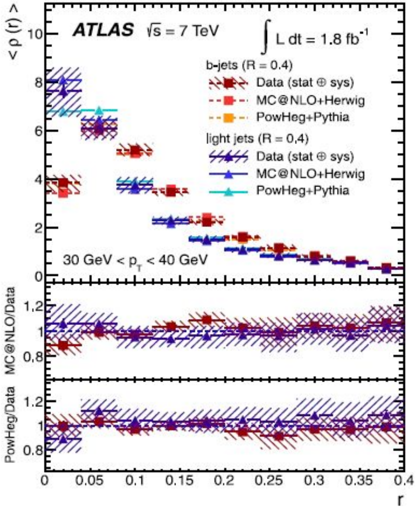

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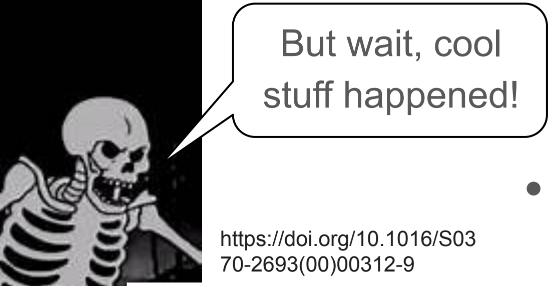

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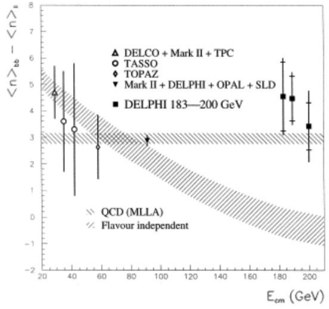

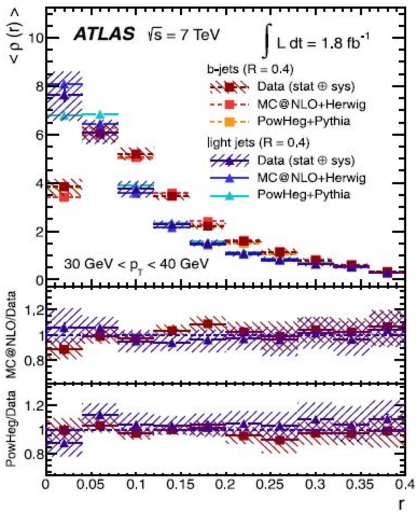

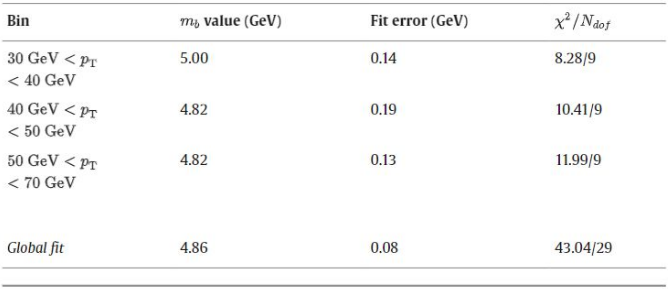

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30 GeV < p_T < 40 GeV	5.00	0.14	8.28/9
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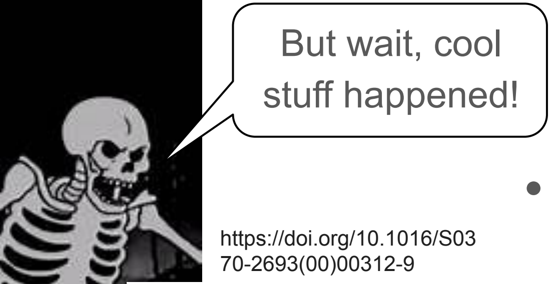

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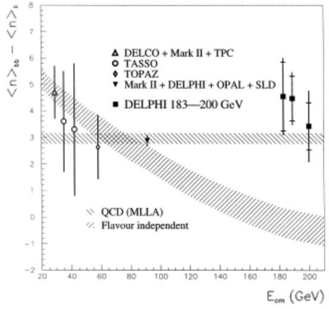

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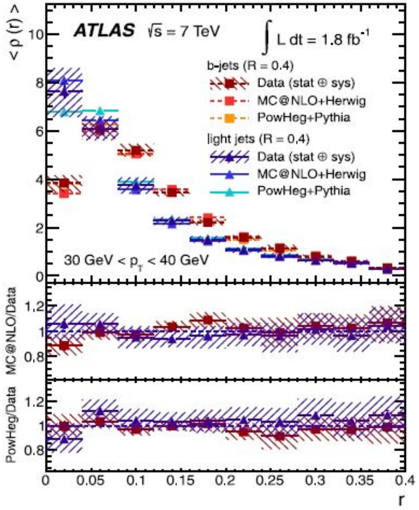

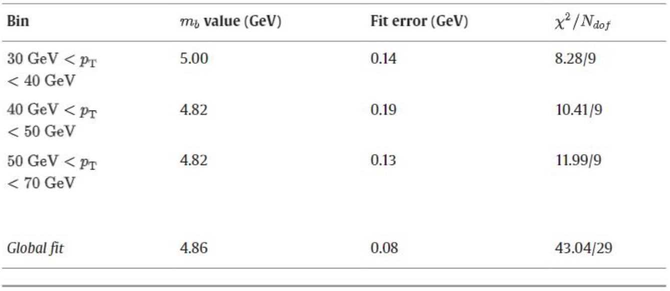

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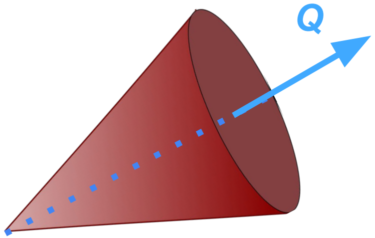
- *Leading particle effect:* As hard emissions are preferentially emitted at small angles, and are therefore suppressed for massive emitters, heavy quarks also retain a larger fraction of their original momentum compared to lighter quarks.
    - Established experimentally (ALEPH, OPAL, DELPHI, SLD)

https://doi.org/10.1016/j.nuclphysb.2014.10.021 https://doi.org/10.1140/epjc/s10052-013-2676-3

Challenges for measurement

Two challenges that prevented a measurement:

1. Dead cone region has contributions from hadronization or particles that don’t come from the gluon radiation of the initiating quark



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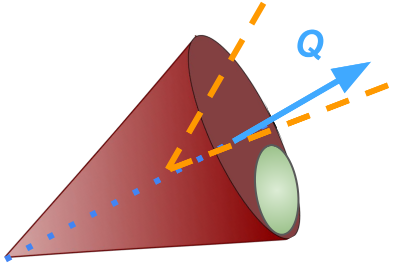

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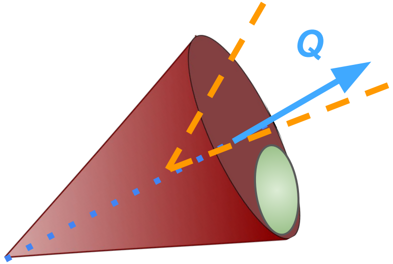

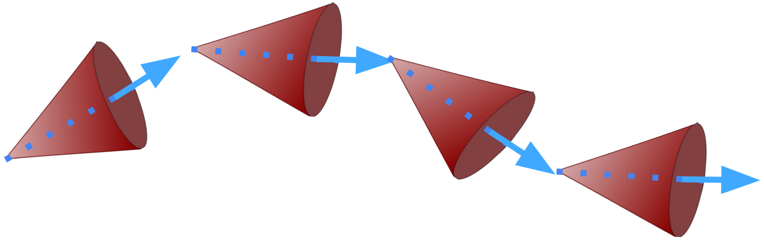

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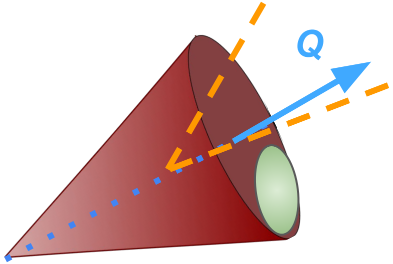

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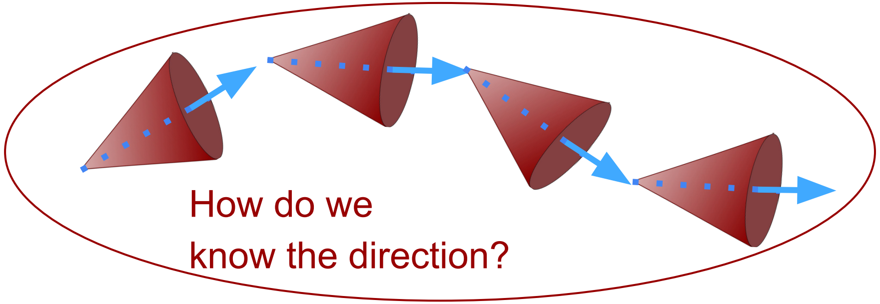


New declustering techniques, that trace through the shower and the kinematics of each emission, are required!

Advances in Jet Algorithms

Development of Sequential Recombination Algorithms

- Cambridge-Aachen (C/A) (1999) - clusters jet constituents solely based on the angular distance between them → angular ordering!
- anti-kT (2008)- standard choice for jet reconstruction because of high performance in reconstructing the original parton kinematics.
- Soft Drop Grooming (2014) - removes soft, wide angle radiation.

$$d_{ij} = \min(k_{T_i}^{2p}, k_{T_j}^{2p})\frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{T_i}^{2p}$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

p = an arbitrary parameter

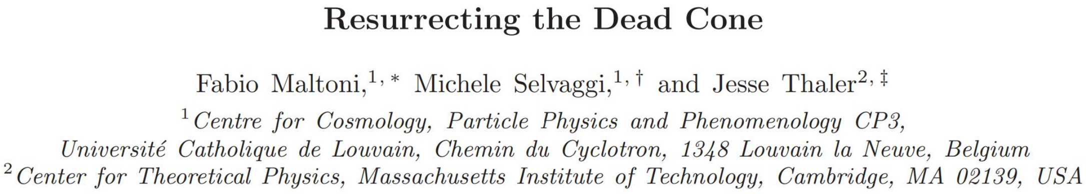
(inclusive) k_t: p = 1
CA: p = 0
anti-k_t: p = -1

(from Beatrice's Jet Algorithms presentation)

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

Resurrection

Resurrecting the Dead Cone Effect



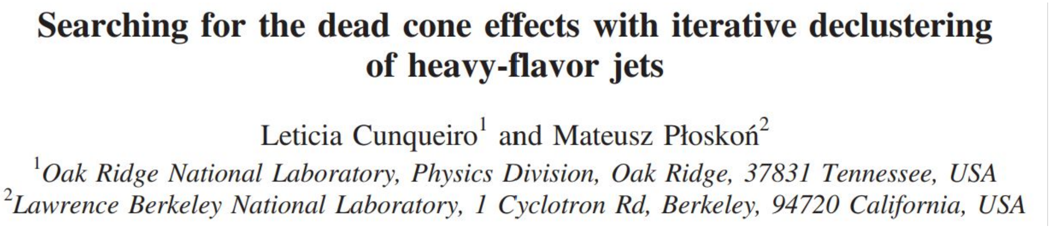
Resurrecting the Dead Cone

Fabio Maltoni,[1,*] Michele Selvaggi,[1,†] and Jesse Thaler[2,‡]

[1] *Centre for Cosmology, Particle Physics and Phenomenology CP3,*
Université Catholique de Louvain, Chemin du Cyclotron, 1348 Louvain la Neuve, Belgium
[2] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

Published in 2016

Refers only to boosted top quark events, but employed new declustering techniques: specifically suggested a large data sample and anti-kT (R=1) → C/A → softdrop



Searching for the dead cone effects with iterative declustering of heavy-flavor jets

Leticia Cunqueiro[1] and Mateusz Płoskoń[2]

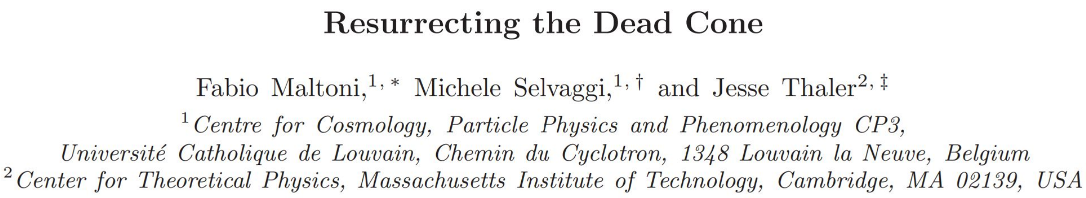
[1] *Oak Ridge National Laboratory, Physics Division, Oak Ridge, 37831 Tennessee, USA*
[2] *Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, 94720 California, USA*

Published in 2019

Prescribed using anti-kT (R=0.4) → C/A for charm and beauty quark jets

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.99.074027 https://arxiv.org/pdf/1606.03449.pdf

Resurrecting the Dead Cone Effect



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Fabio Maltoni,[1,*] Michele Selvaggi,[1,†] and Jesse Thaler[2,‡]

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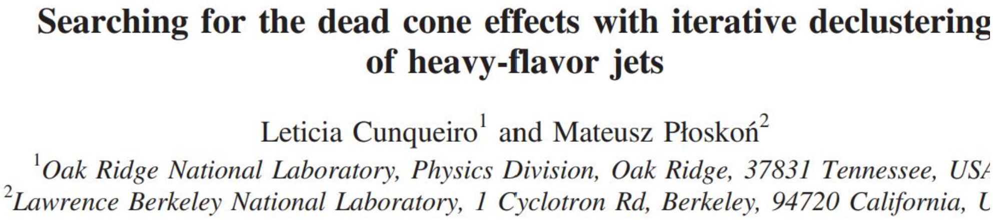
Published in 2016

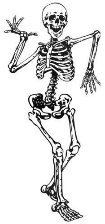
Refers only to boosted top quark events, but employed new declustering techniques: specifically suggested a large data sample and anti-kT (R=1) → C/A → softdrop



Searching for the dead cone effects with iterative declustering of heavy-flavor jets

Leticia Cunqueiro[1] and Mateusz Płoskoń[2]

[1] *Oak Ridge National Laboratory, Physics Division, Oak Ridge, 37831 Tennessee, USA*
[2] *Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, 94720 California, U*



Published in 2019

Prescribed using anti-kT (R=0.4) → C/A for charm and beauty quark jets

Used in measurement!

Alice Collaboration for D^0-tagged jets at 13 TeV

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.99.074027

https://arxiv.org/pdf/1606.03449.pdf

D^0-tagged jets

For this talk, we will look at heavy-flavor jet tagging with a D^0-meson.

The goal of jet tagging is to select jets initiated by a specific heavy quark (in this case, a charm quark)

First, search for the presence of a D0 meson ($c\underline{u}$)

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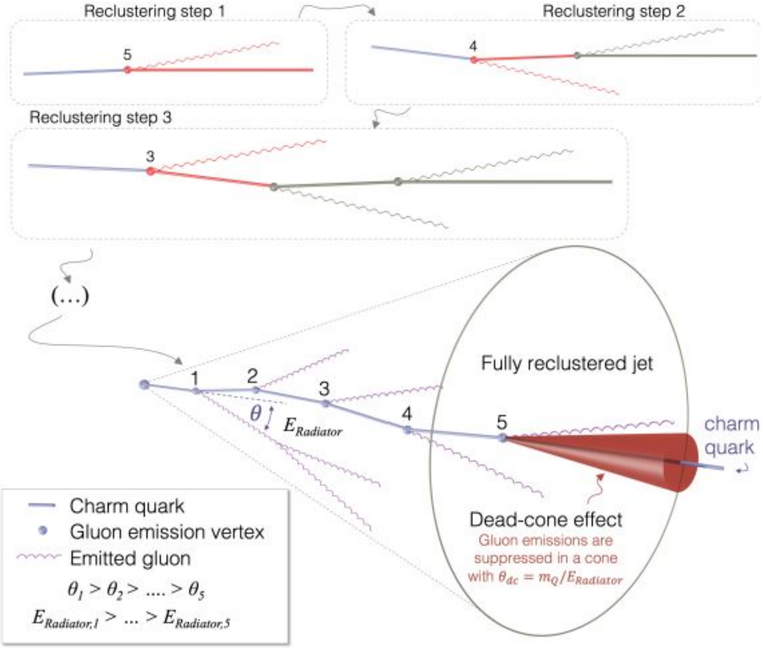
Thus the jet 4-vector is a proxy for the charm quark 4-vector initiating the shower!

So at this point in the measurement, we have anti-kT constructed jets, all containing a D0 meson!

Reconstructing the jet shower

Once those anti-kT jets containing a D0 meson are selected, we can reconstruct the parton cascade by reclustering with Cambridge-Aachen (C/A) algorithm.



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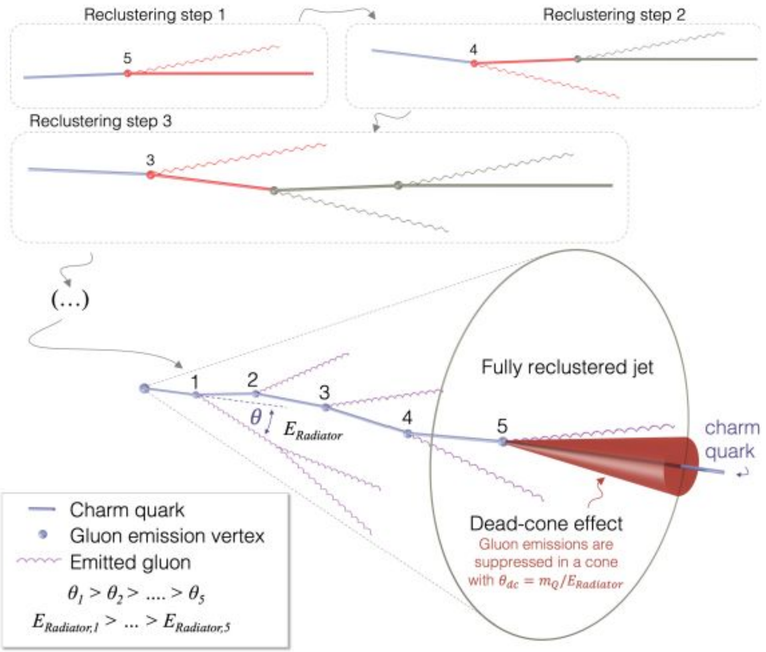

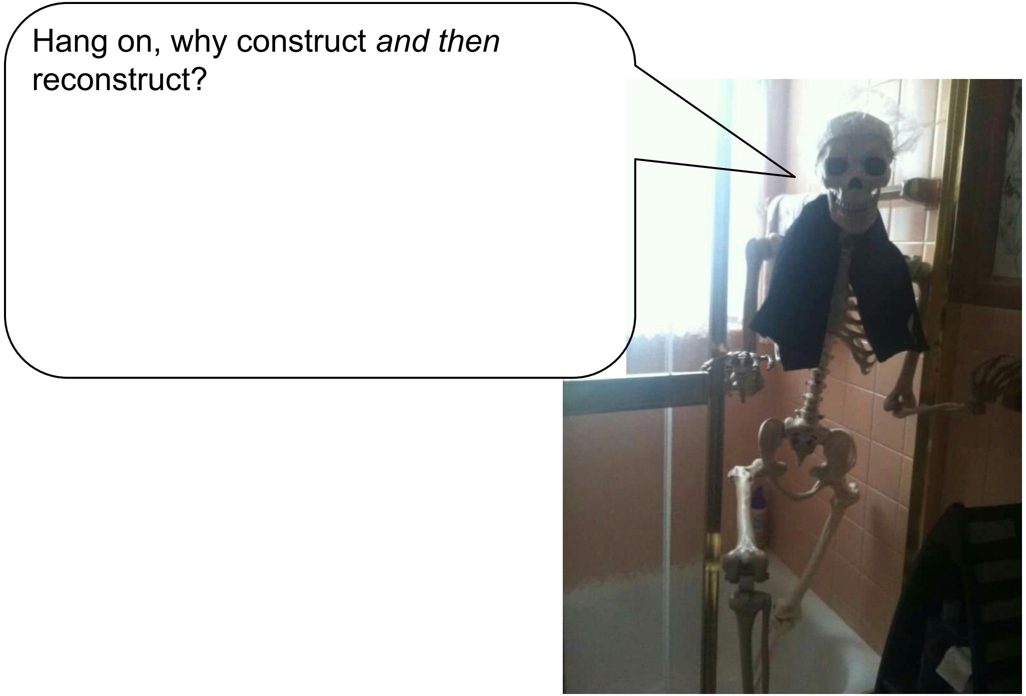

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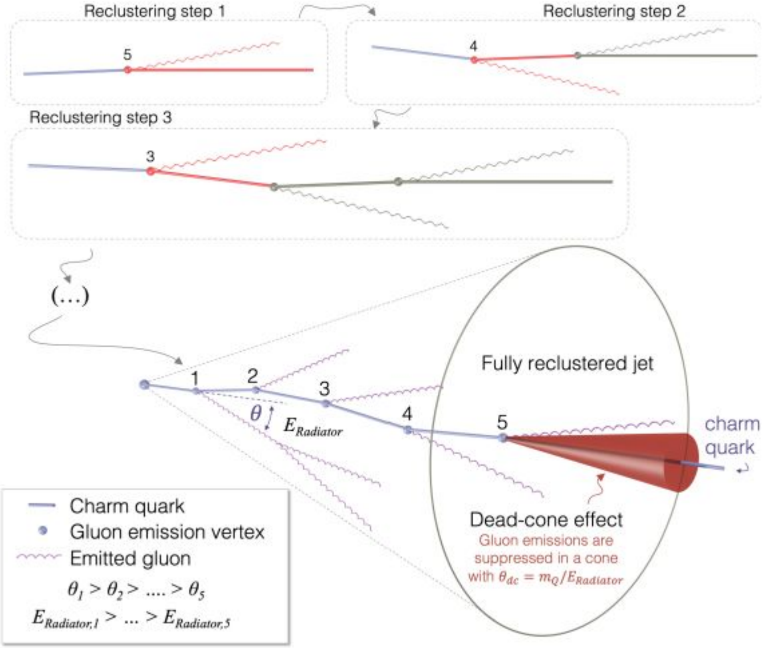

Hang on, why construct *and then* reconstruct?

- anti-kT is good for reconstructing original parton kinematics (charm quark)
- C/A is good for angular-ordering the shower

We want both to preserve both of these properties for this measurement!

Think of it as, anti-kT is reconstructing a jet that stands as a proxy for the charm quark, and then C/A is doing angular ordering on that jet.

Reconstructing the jet shower

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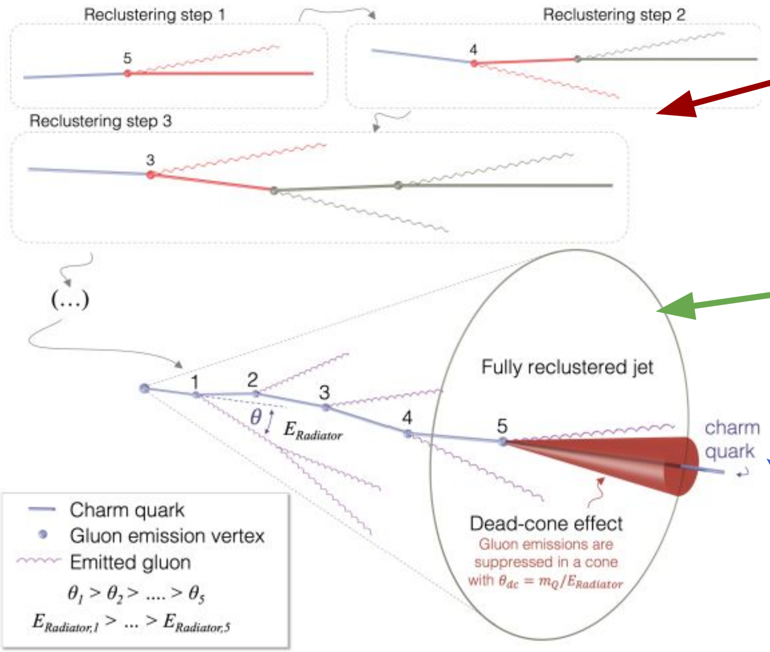


C/A reclustering: particles separated by smallest angles are brought together first (top panels)

Once *re*clustered, then *de*clustered to access the whole history

- Here each splitting is numbered by declustering steps
- $E_{radiator}$ and θ decrease with each splitting

The heavy quark remains in the shower to the end

- Dead cone effect is where the gluon emissions are suppressed in the region $\theta_{dead\text{-}cone} = m_Q / E_{radiator}$ (increases in size through the shower)

The Observable R(θ)

For the measurement itself, they studied this variable R(θ) in bins of k_T and $E_{radiator}$, which is the ratio of the normalized splitting angle (θ) distributions.

$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \bigg/ \frac{1}{N^{\mathrm{inclusive\ jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\ jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}},\, E_{\mathrm{Radiator}}}$$

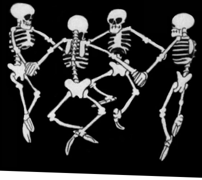
- θ = splitting angle
- $E_{radiator}$ = dropping energy of quark which is radiating gluons
- Probability for parton to split is proportional to ln(1/θ)*ln(k_T) at LO in QCD

In the absence of mass effects, the charm quark is expected to have the same radiating properties as a light quark. In this limit, we would expect the following:

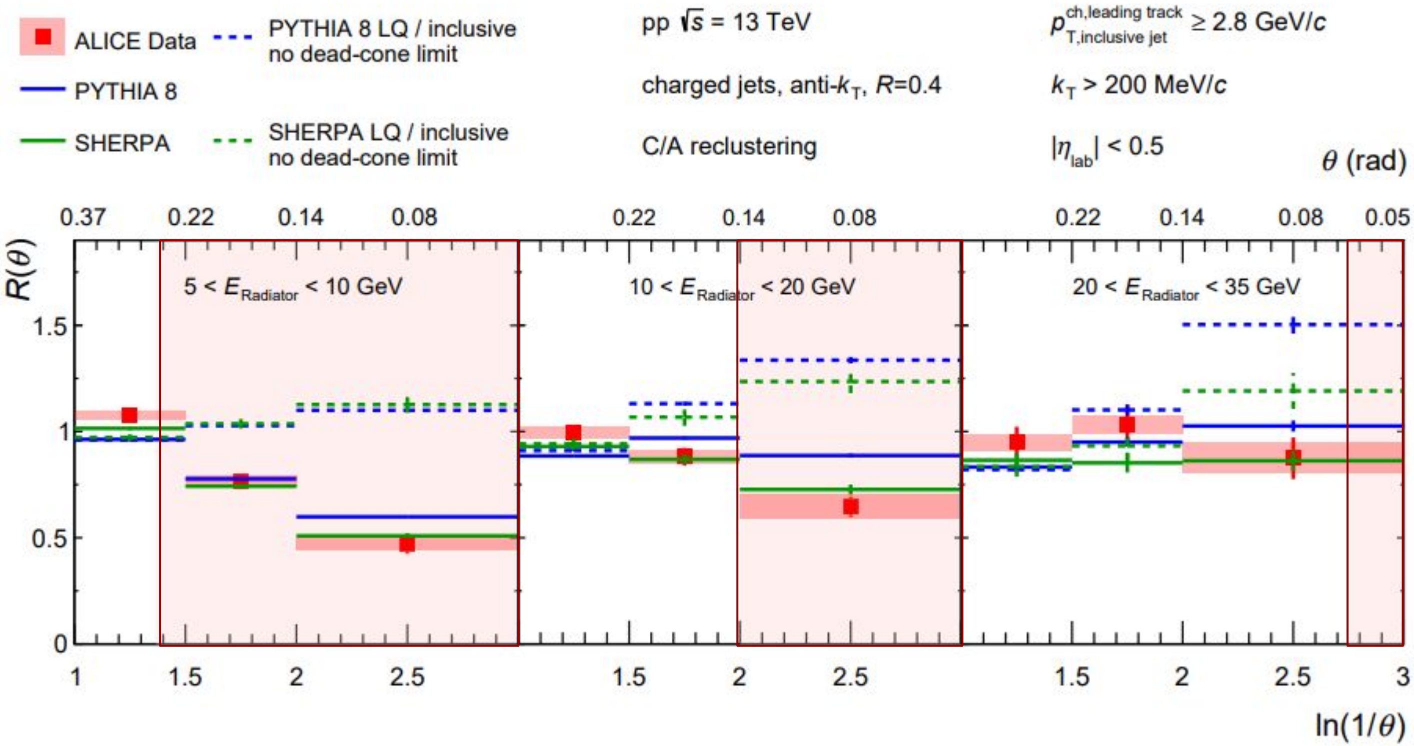
$$R(\theta)_{\mathrm{no\,dead-cone\,limit}} = \frac{1}{N^{\mathrm{LQ\,jets}}} \frac{\mathrm{d}n^{\mathrm{LQ\,jets}}}{\mathrm{d}\ln(1/\theta)} \bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}},\, E_{\mathrm{Radiator}}}$$

Important note for later: when inclusive sample is all light quarks, this is ==1.
But when it is has gluons, this can go greater than 1!

Measurement



The first direct measurement is below, done by ALICE at √s=13 TeV!



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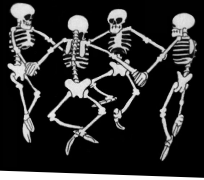

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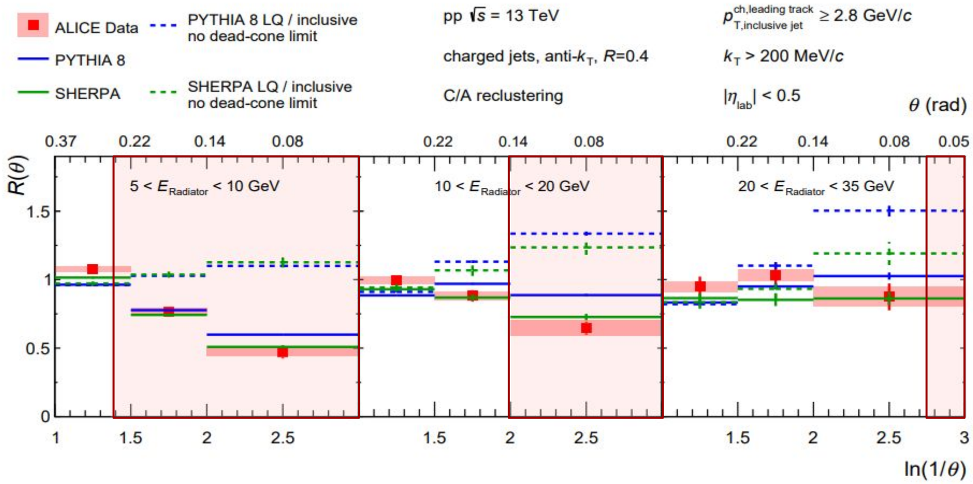


- These three boxes are three different energy intervals for E_{radiator}
- $R(\theta) \geq 1$ is the “no dead cone” limit
- Data in small red boxes; large red boxes are region where we expect to see a suppression
- PYTHIA/SHERPA result for mentioned $R(\theta)$ are blue and green solid lines
- Dashed lines are ratio of Light Quark jets to inclusive jets

If there is no dead cone (limit from previous slide) then $R(\theta)$ should be greater than/equal to 1.

ALICE data very closely matches the simulation results! Go dead-cone!

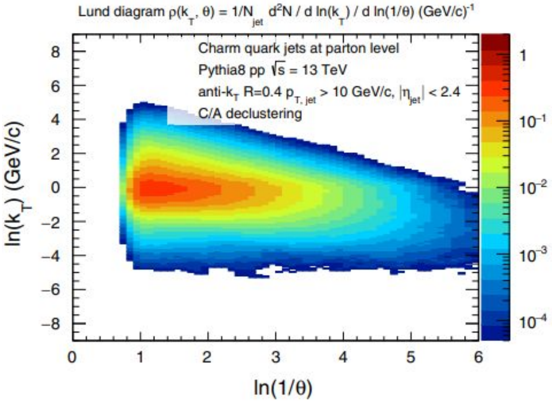
Achieved definitive observation ($>5\sigma$) for the $5 < E_{\text{radiator}} < 10$ GeV range!

Why does the LQ/inclusive ratio increase with ln(1/θ)?

The inclusive sample is dominated by massless gluons and nearly massless light quark-initiated jets. When inclusive sample is gluon dominated, $R(\theta)$ (LQ/Inclusive) becomes >1 at smaller angles, as quarks fragment at a lower rate and more collinearly than gluons.

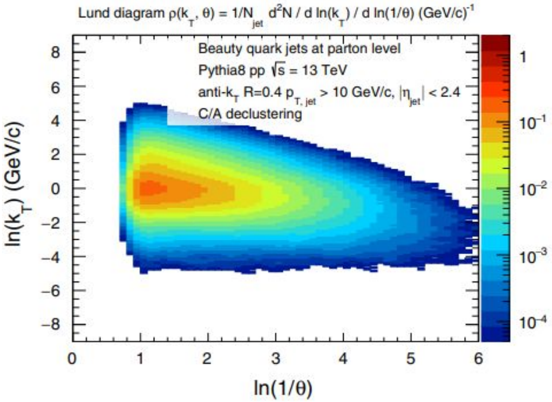
The Dead-Cone’s Future

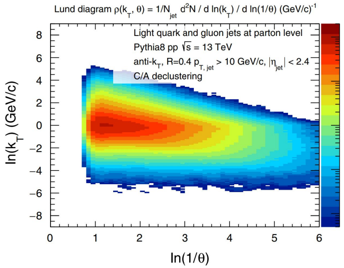
From charm to beauty and top



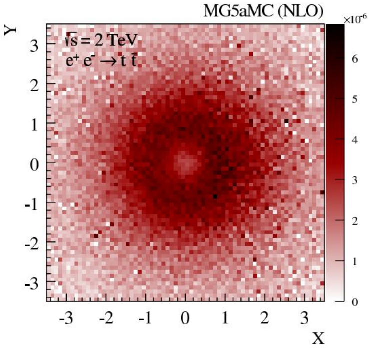
A study of the mass dependence of the dead cone effect is an ideal future project

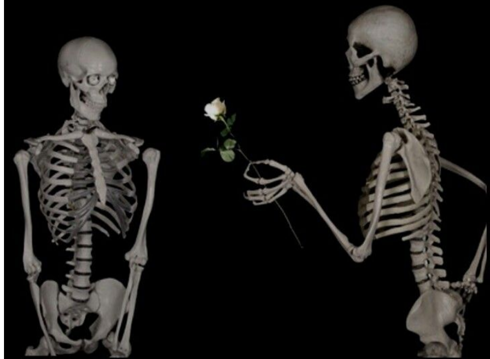
- Measuring the dead cone of jets containing a reconstructed beauty hadron should employ the same steps as the recent measurement.
- A method to measure top-boosted jets was proposed as well in e e → t $\underline{t}$ (less obscured by decay daughters and non-perturbative physics)





(Light quark baseline)

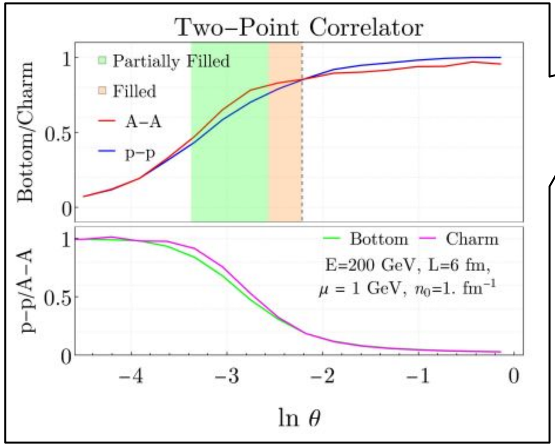


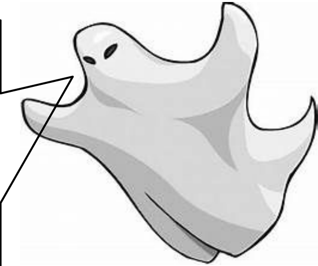


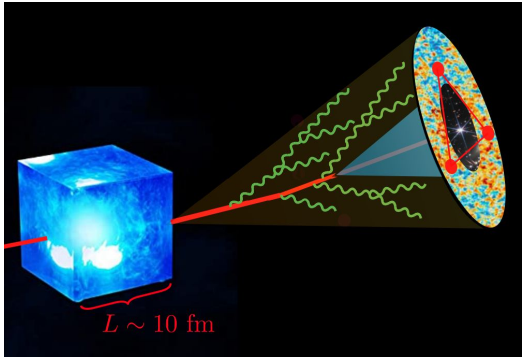
The dead-cone and heavy ions

Future study of the dead cone in heavy-ion collisions:

- Interesting regime to study because there is suppression from dead cone but enhancement from in-medium interactions
    - partons interact strongly with the hot QGP that is formed and undergo energy loss through medium-induced radiation
- If a dead cone is observed for these medium-induced emissions, it would confirm the theoretical understanding of the in-medium QCD radiation (primary tool used to characterize the high-temperature phase of QCD matter)
    - energy-energy correlators (EECs) could be uniquely suited to sort out this suppression/enhancement! (perturbative vs nonperturbative)



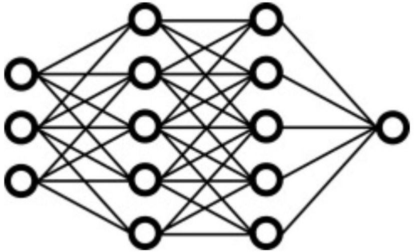




https://arxiv.org/pdf/2211.11789.pdf

https://arxiv.org/pdf/2307.15110.pdf

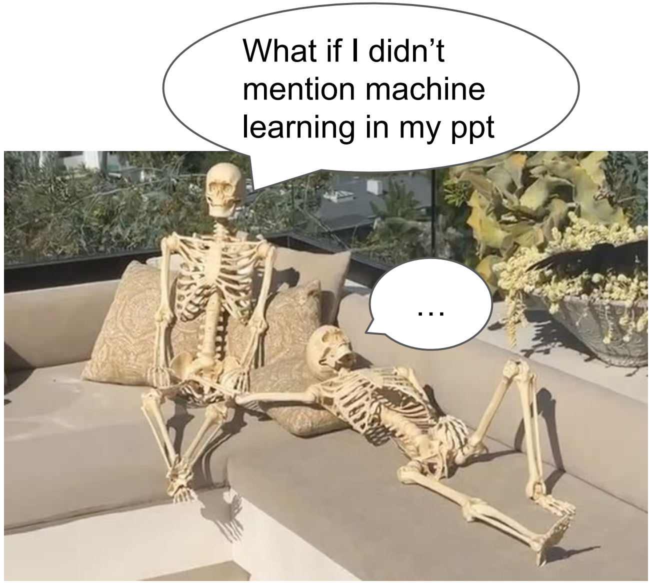
Machine learning applications

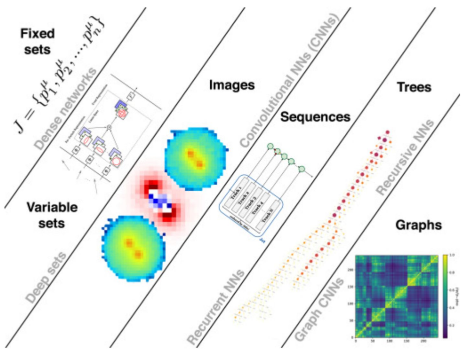


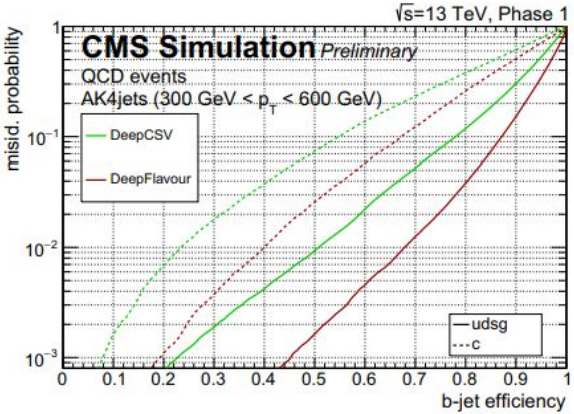
Future high-precision measurements using these techniques on charm and beauty-tagged jets could experimentally constrain the magnitude of the quark masses.

- Could employ machine learning techniques to separate quark and gluon emissions

Using deep learning, for instance, could make the dead cone easier to see just by making jet algorithms more efficient.







10.1016/j.physrep.2019.11.001

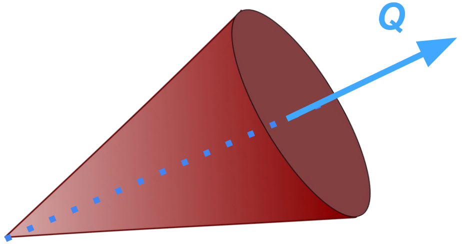
10.1088/1742-6596/1085/4/042029

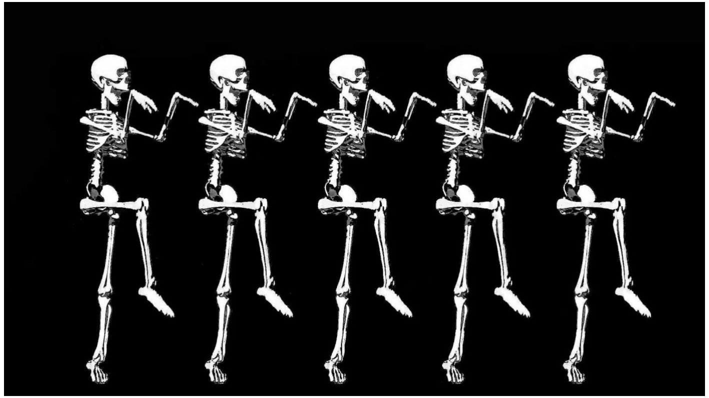
Conclusions

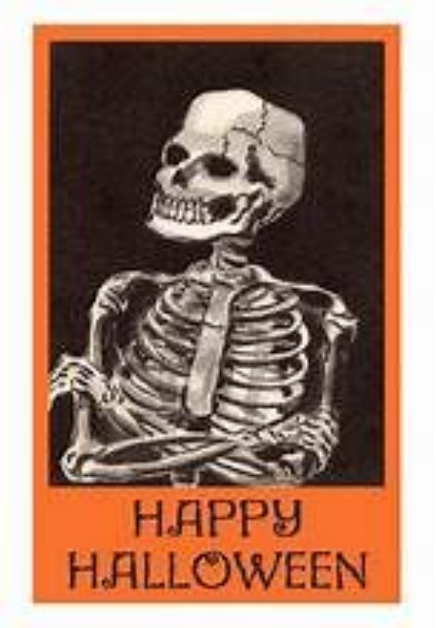
In conclusion, we have:

- Learned about the dead cone's story
- Discussed in detail the recent direct measurement by ALICE
- Looked into what's in store for studies of this interesting phenomenon

Thanks for listening!







Fin

Deserving ghosts + skellys

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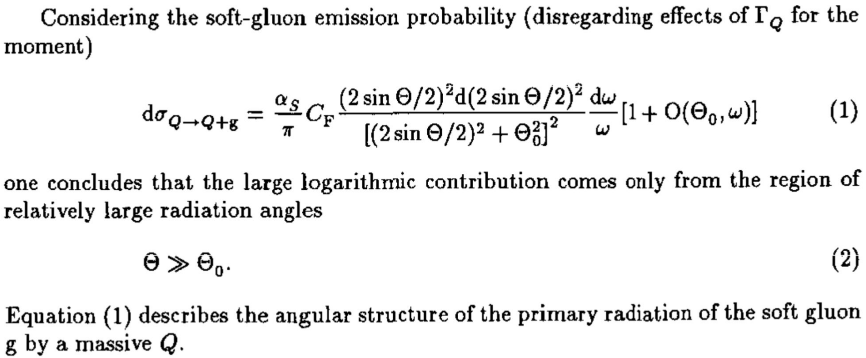
https://arxiv.org/pdf/1709.04464.pdf

A discussion on quark masses

“The quark masses are fundamental constants of the standard model of particle physics and needed for all numerical calculations within its framework. Because of confinement, their values are commonly inferred through their influence on hadronic observables. An exception is the top quark, which decays before it can hadronize, as its mass can be constrained experimentally from the direct reconstruction of the decay final states [39] (see Ref. [40] for a review of top mass measurements at the Fermilab Tevatron and CERN LHC). By accessing the kinematics of the showering charm quark, before hadronization, and directly uncovering the QCD dead-cone effect, our measurement provides direct sensitivity to the mass of quasi-free charm quarks, before they bind into hadrons”

Derivation



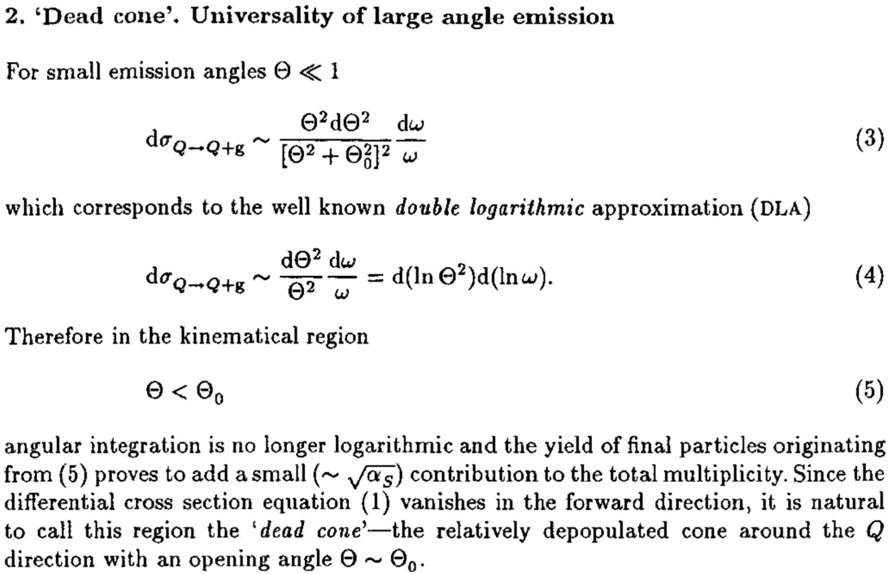
Considering the soft-gluon emission probability (disregarding effects of Γ_Q for the moment)

$$\mathrm{d}\sigma_{Q\to Q+\mathrm{g}} = \frac{\alpha_S}{\pi} C_\mathrm{F} \frac{(2\sin\Theta/2)^2 \mathrm{d}(2\sin\Theta/2)^2}{[(2\sin\Theta/2)^2+\Theta_0^2]^2}\frac{\mathrm{d}\omega}{\omega}[1+\mathrm{O}(\Theta_0,\omega)] \tag{1}$$

one concludes that the large logarithmic contribution comes only from the region of relatively large radiation angles

$$\Theta \gg \Theta_0. \tag{2}$$

Equation (1) describes the angular structure of the primary radiation of the soft gluon g by a massive Q.



2. 'Dead cone'. Universality of large angle emission

For small emission angles $\Theta \ll 1$

$$\mathrm{d}\sigma_{Q\to Q+\mathrm{g}} \sim \frac{\Theta^2 \mathrm{d}\Theta^2}{[\Theta^2+\Theta_0^2]^2}\frac{\mathrm{d}\omega}{\omega} \tag{3}$$

which corresponds to the well known *double logarithmic* approximation (DLA)

$$\mathrm{d}\sigma_{Q\to Q+\mathrm{g}} \sim \frac{\mathrm{d}\Theta^2}{\Theta^2}\frac{\mathrm{d}\omega}{\omega} = \mathrm{d}(\ln\Theta^2)\mathrm{d}(\ln\omega). \tag{4}$$

Therefore in the kinematical region

$$\Theta < \Theta_0 \tag{5}$$

angular integration is no longer logarithmic and the yield of final particles originating from (5) proves to add a small ($\sim\sqrt{\alpha_S}$) contribution to the total multiplicity. Since the differential cross section equation (1) vanishes in the forward direction, it is natural to call this region the '*dead cone*'—the relatively depopulated cone around the Q direction with an opening angle $\Theta \sim \Theta_0$.

Sequential Recombination Powers