Searching for the deadcone with iterative declustering of heavy-flavour jets

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Work in collaboration with Mateusz Ploskon, LBNL

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The dead cone

Probability for a heavy quark Q to radiate a soft gluon:

$$d\sigma_{Q\to Q+g} = \frac{\alpha_S}{\pi} C_F \frac{(2\sin\Theta/2)^2 d(2\sin\Theta/2)^2}{[(2\sin\Theta/2)^2+\Theta_0^2]^2} \frac{d\omega}{\omega} [1+O(\Theta_0,\omega)]$$ where $\Theta_0 = m_Q/E$

In the limit of small angles but still $\Theta \gg \Theta_0$.

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

light quark radiation probability, DLA limit

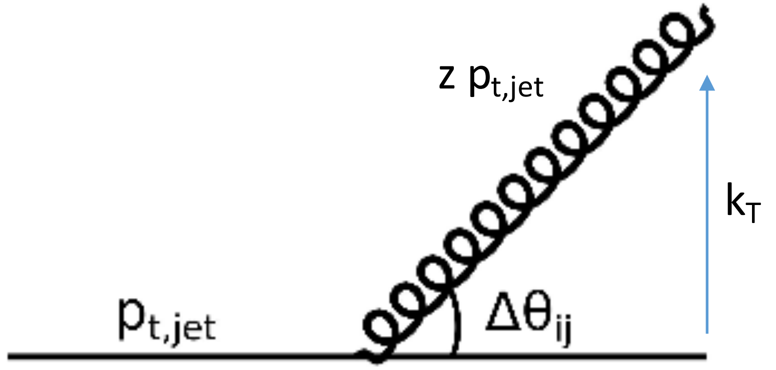
In the case where $\Theta < \Theta_0$

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

Radiation suppressed relative to the DLA limit

Y.Dokshitzer,V.A.Khoze and S.I.Troyan "On specific QCD properties of heavy quark fragmentation"

The dead cone



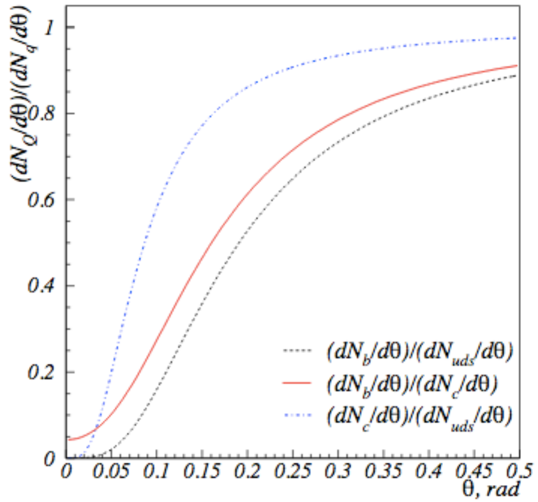
$\theta \sim k_T/zp_{t,jet}$

There are essentially 2 indirect consequences of the deadcone:

-Restriction of hard gluons with small k_T , which is the most probable component of the radiation ($P \sim \alpha_S(k_T^2)$) -> reduction of z, FF peaked at larger values of z

-Smaller intrajet multiplicities

Parametric ratios of angular yields



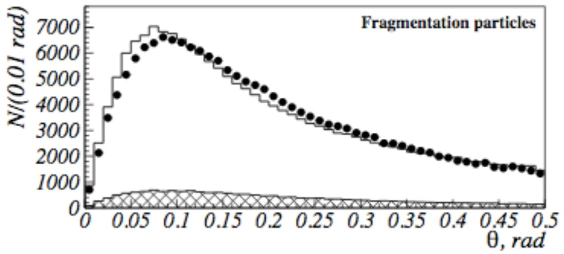
Battaglia, Orava,Salmi, DELPHI

We are interested in the direct visualization

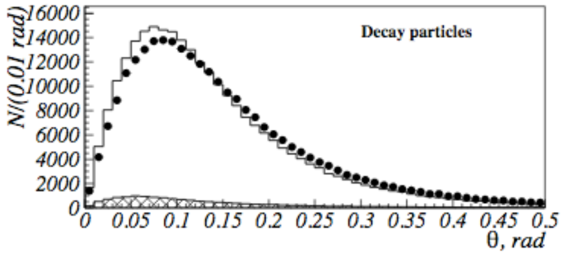
The experimental difficulties

-The decays of the heavy flavour particles happen at similar angular scales and fill the dead cone

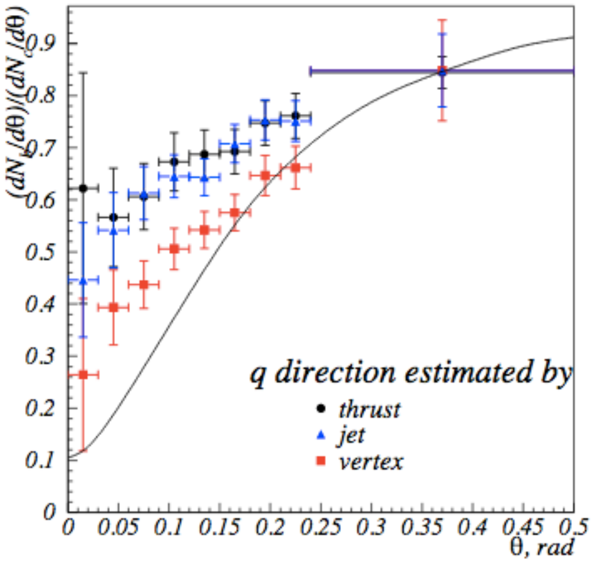
Battaglia,Orava,Sami "A study of depletion of fragmentation particles at small angles in b-jets with the DELPHI detector at LEP"
The first and only attempt of direct dead cone measurement



Particles not associated to the vertex

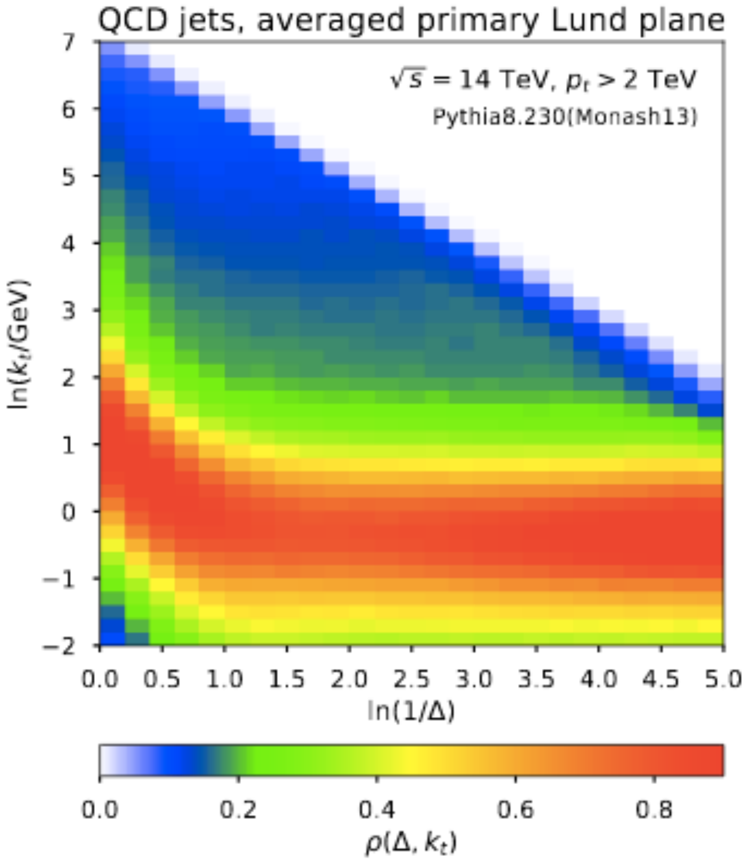


particles associated to the vertex



-Choice of a reference axis: jet axis, thrust, the direction of the vertex?

The iterative declustering and the Lund plane



Dreyer, Soyez,Salam JHEP 1812 (2018) 064

2D map of the jet tree filled via iterative declustering:

-Recluster the jet constituents with CA (a convenient metric for vacuum angular ordered showers)

-Uncluster it step by step, from the prongs that were merged last to the prongs that were merged first.

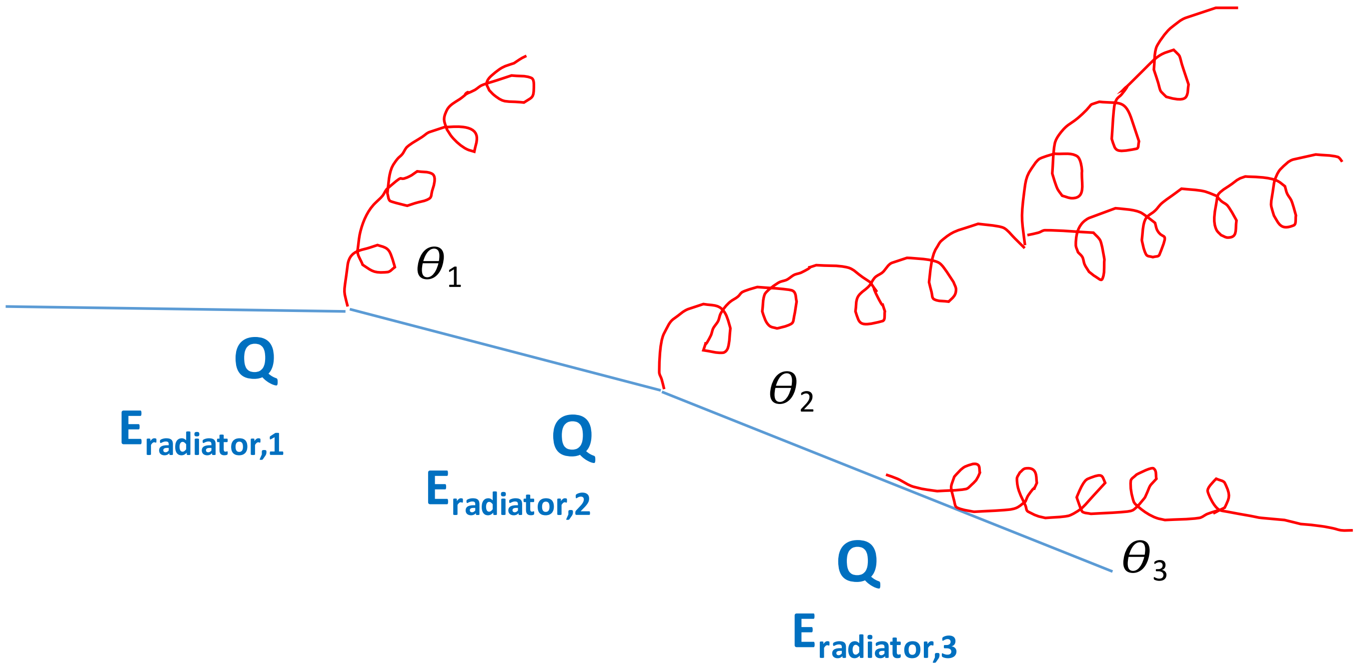
-Each time, register the scale k_T and the opening angle θ between the subleading and leading prong

-Always follow the hardest prong

The result is a flat 2D density map (except for the running of the coupling)

$$d\mathcal{P}_{\rm vac} = 2\frac{\alpha_s C_i}{\pi} d\log z\theta \, d\log\frac{1}{\theta}$$

The Lund plane for heavy flavours



We do the standard declustering process

We follow the prong containing the heavy flavor at each step

Negligible number of cases where the prong containing the heavy flavor is not the hardest, no ambiguity when comparing to light quarks

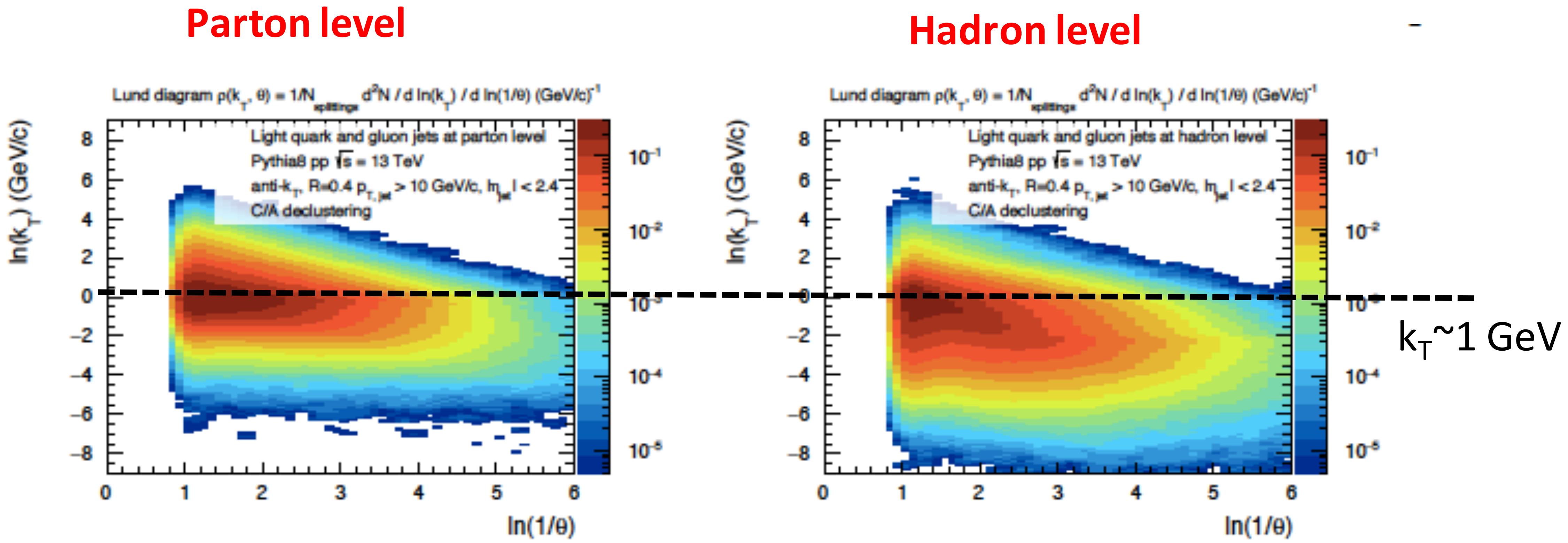
At each step of the jet tree we can access the angle of the splitting and the energy of the radiating parent subjet, $E_{radiator}$. For $\theta < m_Q/E_{radiator}$ we expect to see a suppression of splittings.

For low $E_{radiator}$, which means penetrating the jet to deep levels, the phase space for the dead cone observation grows.

The simulation exercise

- Pythia8 Tune 4C
- pp collisions at $\sqrt{s}$=13 TeV
- Select ccbar, bbar production channels
- At parton level the leading prong at each declustering step is the one containing the heavy parton
- At hadron level, we inhibit the decay of the B and D mesons and the leading prong at each declustering step the one containing the heavy meson.
- Antik$_T$ jets R=0.4, CA reclustering algo

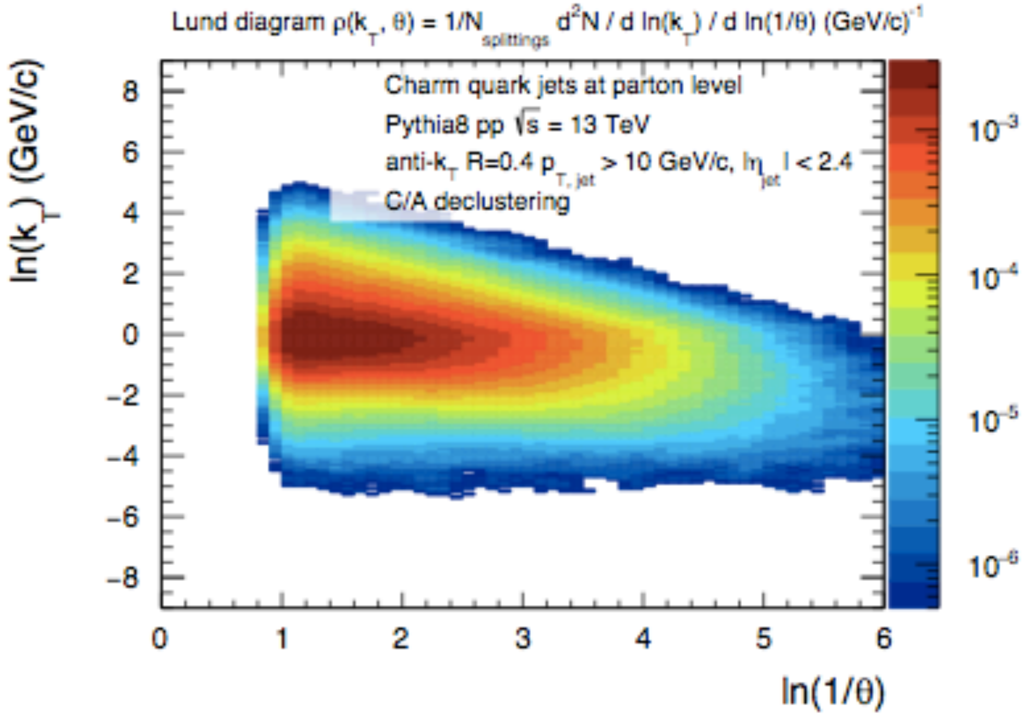
The inclusive Lund map



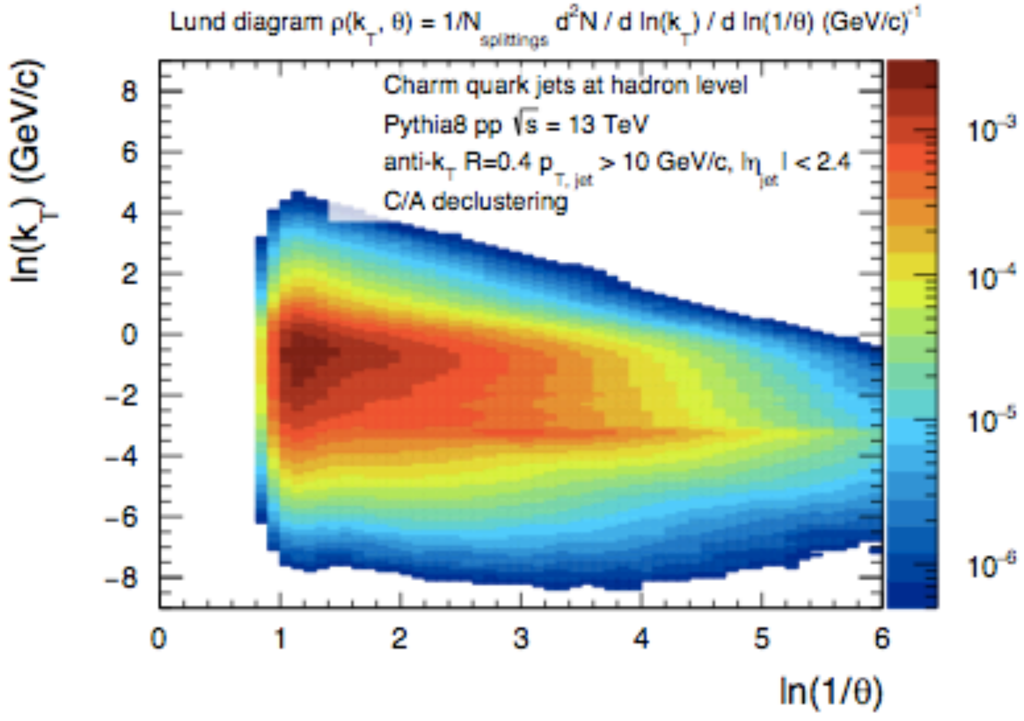
Non-perturbative effects can be removed/isolated by cutting the region $\ln(k_T)<0$

Lund map for D jets

Parton level

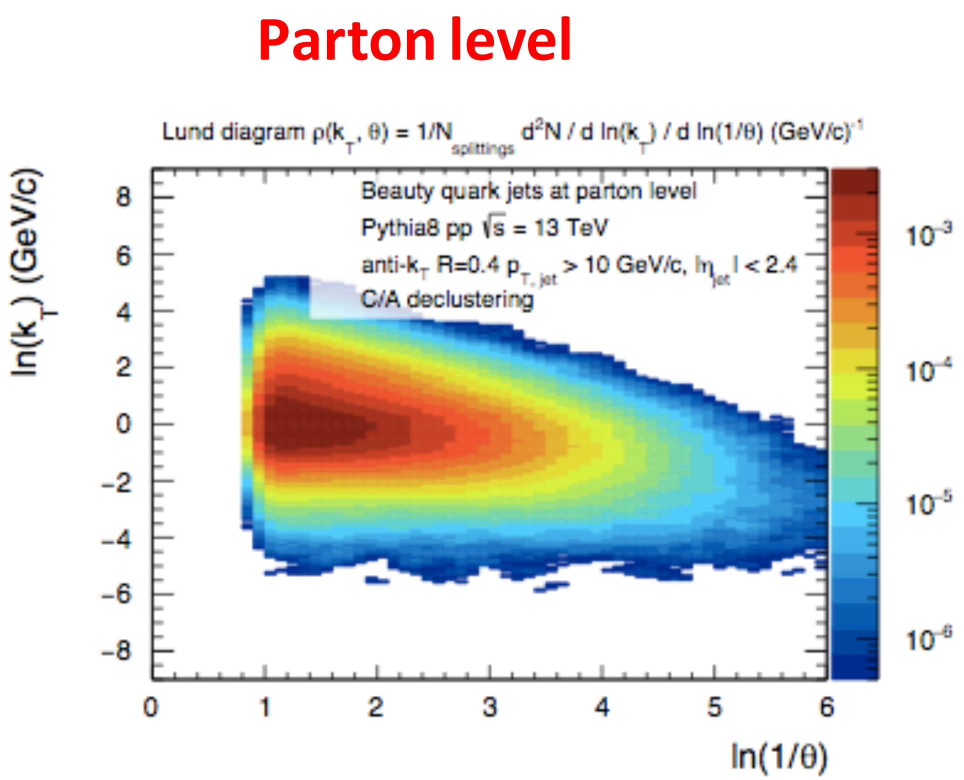


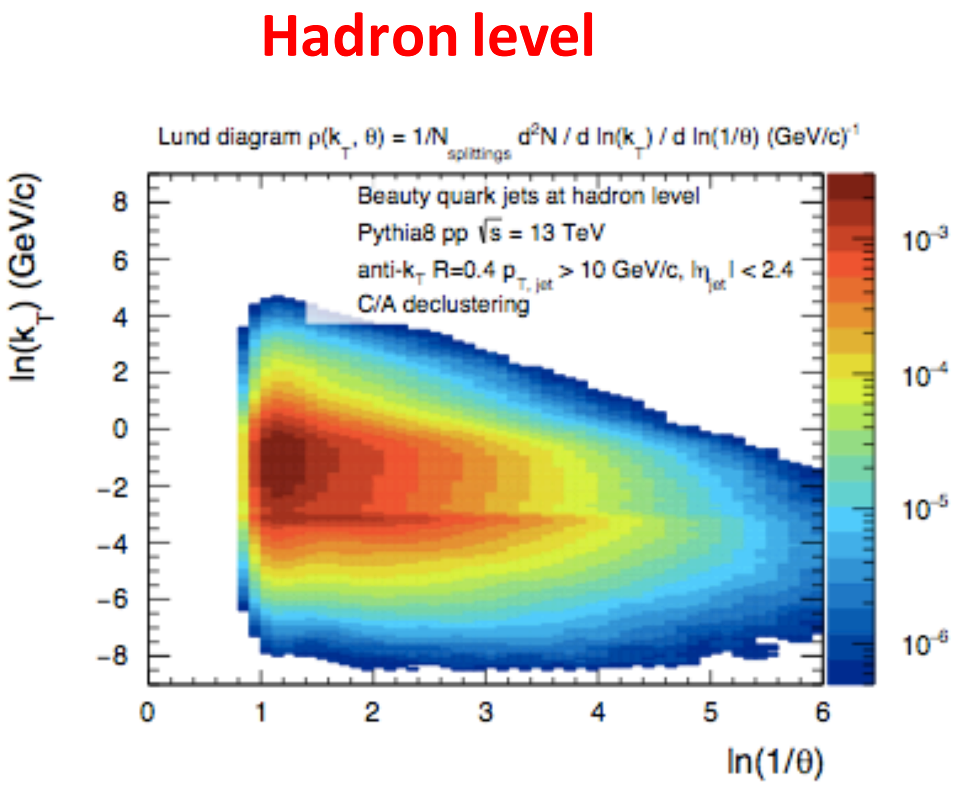
Hadron level



Pythia hadronization of the heavy flavour jets creates structure bands in the very soft region k_T~0.02 GeV

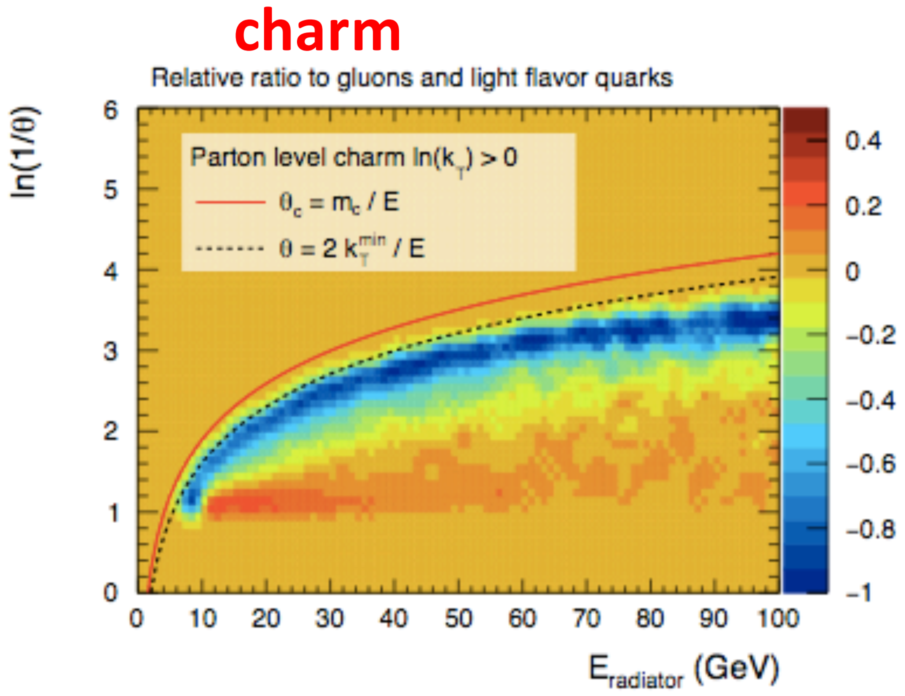
Lund maps for B jets

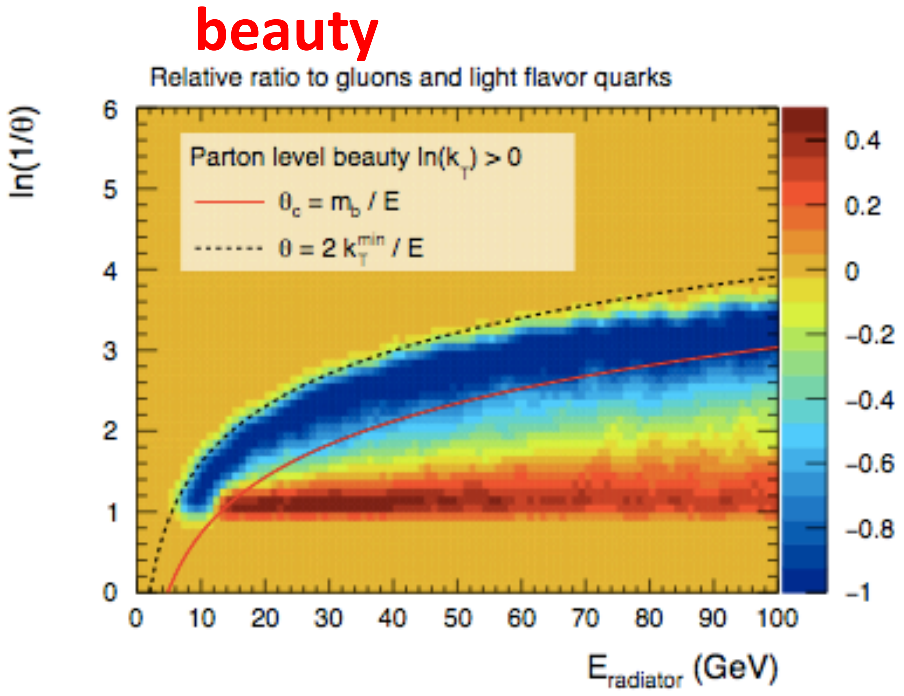




Already by eye, without further analysis, one can see that the angle distributions are different for heavy and light partons, the low angle reach is more limited for the heavy flavors

Exposing the dead cone at parton level



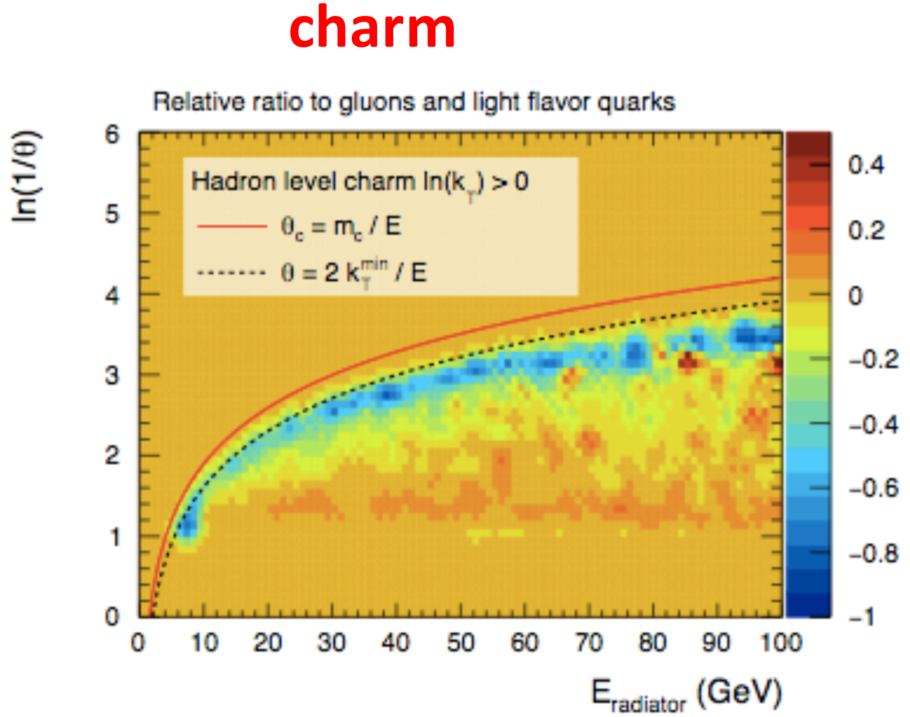


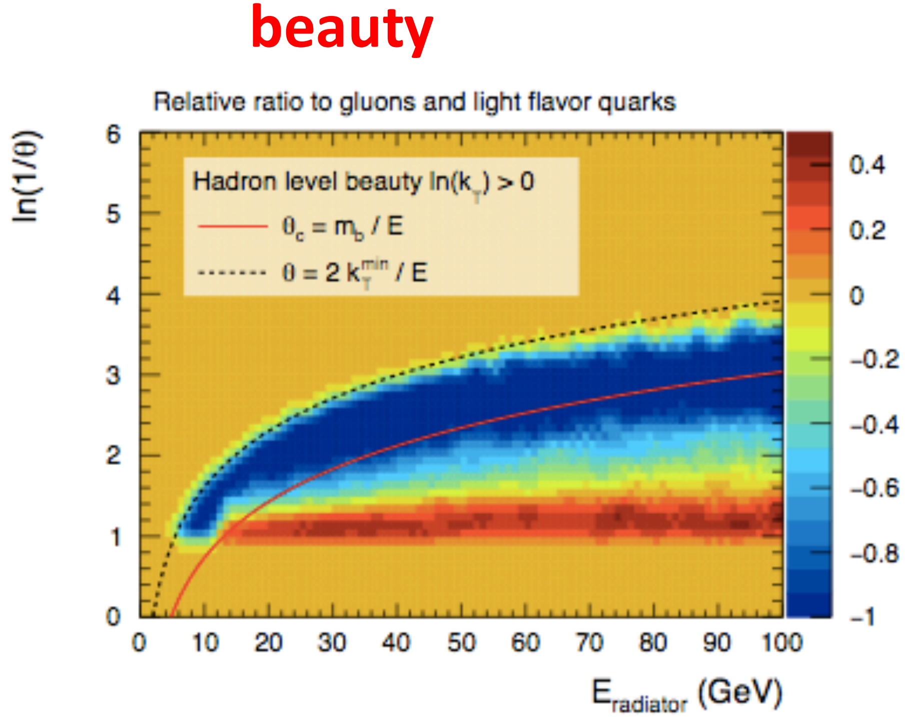
$$Q = \frac{P^{Q}(log(1/\theta), E_{radiator}) - P^{inc}(log(1/\theta), E_{radiator})}{P^{inc}(log(1/\theta), E_{radiator})}$$

The cut $\log(k_T)>k_T^{min}$ translates into $E_{radiator} > k_T^{min}/z\theta$. The black dashed line corresponds to the kinamtic limit of z=0.5, above which there are no more entries in the inclusive reference

We can identify regions of phase space where P^Q =-1, meaning no radiation off the heavy quark radiator. **The suppression of large angles couples to the suppression of large z**

Exposing the dead cone at hadron level





$$Q = \frac{P^{Q}(log(1/\theta), E_{radiator}) - P^{inc}(log(1/\theta), E_{radiator})}{P^{inc}(log(1/\theta), E_{radiator})}$$

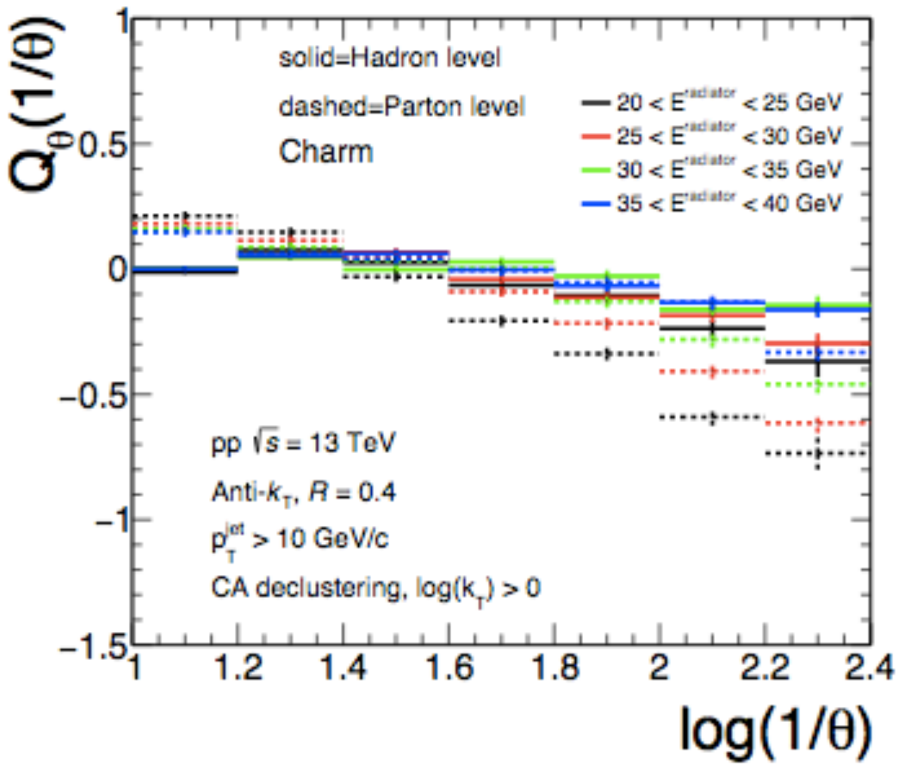
At hadron level the effects are smeared but not washed out

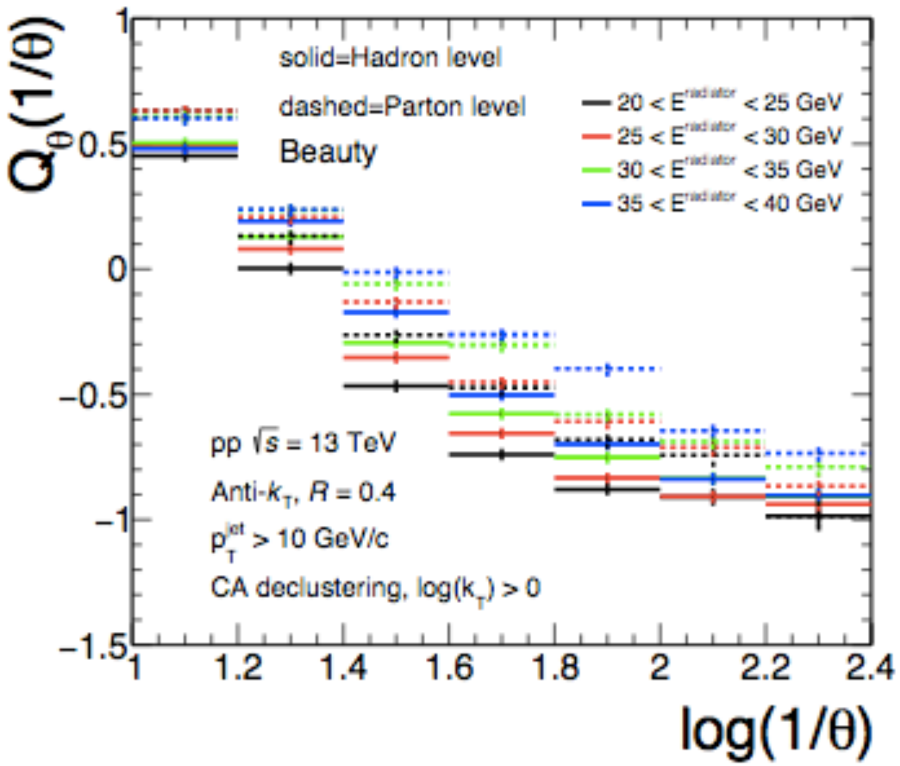
As expected: the higher $E_{radiator}$ is, the dead cone effects appear at smaller angles.

For D jets, the effects appear at measurable angles of ~0.1 rad for radiator energies of 10-30 GeV

For B jets, one can go higher in radiator energy and still have effects at angles of the order of 0.1 rad

1D projections: the measurable observable





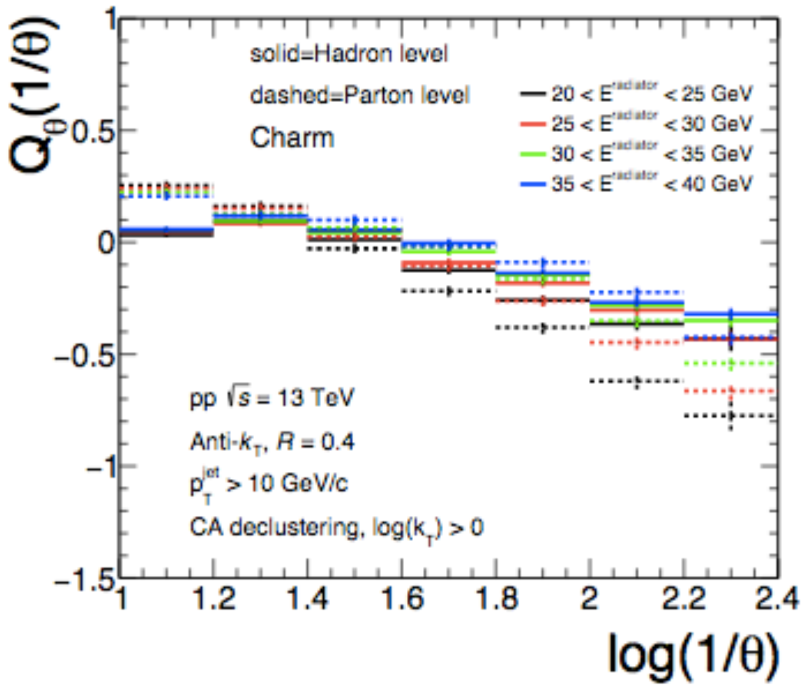
$$Q_\theta = \frac{P^Q(1/\theta) - P^{inc}(1/\theta)}{P^{inc}(1/\theta)}, E_{radiator} \in (E_{min}, E_{max})$$

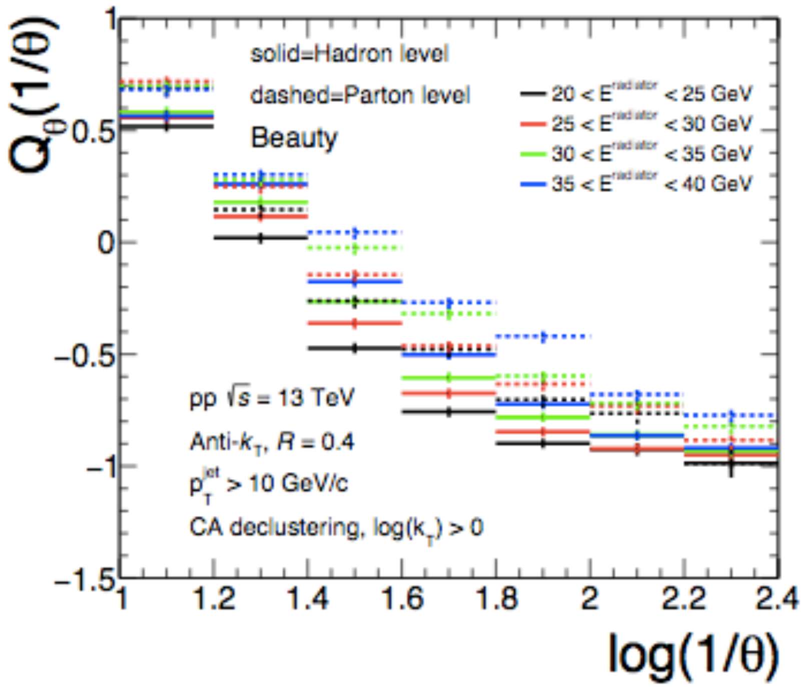
For $E_{radiator}$=20 GeV,

D-jets are suppressed by 30% relative to inclusive at $\boldsymbol{\theta}$ ~0.1 rad

B-jets are suppressed by nearly by 100% relative to inclusive at $\boldsymbol{\theta}$ ~0.1 rad

1D projections: the measurable observable





Inclusive jets are not an optimal reference, due to strong contribution of gluon jets. When only light quarks are used as a reference, the dead cone effects are enhanced.

In the experiment there are techniques to enrich the quark fraction:

-consider substructure of jets recoiling from a boson

-statistically, use shapes sensitive to q/g differences such as pTD or angularity

-ML…

Notes and Plans

-We have shown that iterative declustering is a tool that allows to access the deepest branches of C/A jet trees which correspond to the smaller splitting angles and that can uncover dead cone related effects.

-Great opportunity to measure for the first time a fundamental property of QCD at colliders

-Our exercise was done using Pythia, other generators need to be explored

-We have tested the impact of switching on/off the flavour creation kernel, no impact in the considered kinamtic range. This is of course an important point that has to be studied in detail: if we follow thru the declustering procedure a heavy quark that comes from a gluon splittings, the dead cone observation will be darkened.

-The ideal measurement will require fully reconstructed heavy flavours, access to low energy subjets of about 10-20 GeV and a detector that allows to resolve subjets at angular distances of 0.1 radians.

Thaler dead cone

The impact of non-perturbative effects