Specific features of Heavy Quarks

Dead Cone and around

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Plan :

1. Open flavour mesons. Parton model: "leading particle effect"

2. Remark: Heavy Quark and QCD coupling

3. Radiation off massive quark

4. Heavy Quark initiated jets:
   Energy Loss, light hadron multiplicity and Dead Cone

5. Gluon radiation and hadrons. LPHD

6. Gluon formation and hadronisation
   Non-perturbative effects and Dead Cone (good news)

7. Beauty. ALICE vs DELPHI

Heavy Quark's operational definition : $M_Q \gg \Lambda_{\rm QCD}$

Finite mass is the only source of HQ specificity (*but the* ***top*** *one*)

Consequences : Hadron structure

A heavy quark and its light partner antiquark, inside an ***open flavour*** meson have the **same velocity**. Therefore, they share meson energy as

$$E_Q/E_q \simeq M_Q R$$

with $R \sim 1/\mu, \quad \mu = \mathcal{O}(\Lambda_{\rm QCD})$

- effective light quark "mass"

An old parton model prediction.

Hidden flavour mesons - quasi-Coulomb structure

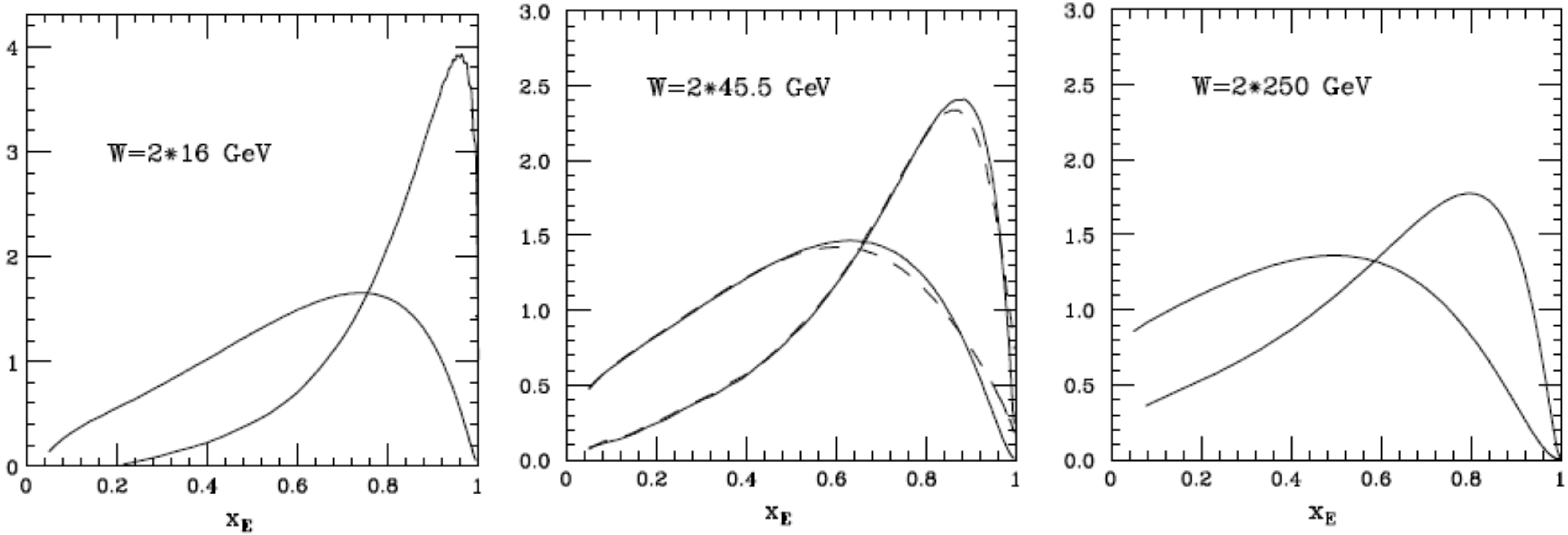
C-family - marginally; B-family - way better.

I'

Heavy quark fragmentation

The ***leading particle effect*** is clearly seen experimentally in the HQ fragmentation functions.

pQCD calculable Q-> Q(x_E) spectra (D & Khoze & Troyan, PRD 1995)



Evolution of inclusive c, b from W = 32 GeV to W = 500 GeV c.m.s. energy

Mark : In spite of the fact that the "**soft gluon corner**" $1 - x_E \sim \Lambda/M_Q$ is, formally speaking, **a non-PT domain,** the spectrum stays under PT control

QCD interaction strength

From the very start of the now almost 50-year-old HQ history,
they were considered to be (p)QCD friendly beasts:

large *mass* = ***large*** *momentum scale* = ***short*** *distances* = ***small*** *coupling* = ...

And, indeed, this is true. ***SOMETIMES***

QCD (QED) interaction strength - running coupling -
does not depend on the nature of the (colour) charge bearer

In particular, on the quark mass !

Ward identity ; Conservation of (colour) current

What actually matters for quantifying the scale of the coupling argument
is *characteristic gluon virtuality* which may - or may not - be driven by M_Q .

Depends on the **observable** one is looking at

Gluon radiation

$$dw_V = \frac{C_F\alpha_s}{\pi}\frac{dz}{z}\frac{\beta}{v}\int_{-1}^{1} d\cos\Theta_c \left\{ 2(1-z)\,\frac{\beta^2\sin^2\Theta_c}{(1-\beta^2\cos^2\Theta_c)^2} + z^2\left[\frac{1}{1-\beta^2\cos^2\Theta_c} - \frac{1}{2}\right]\zeta_V^{-1}\right\}$$

"Classical part" of gluon radiation

independent of the production process and of the nature of the emitters !

z gluon energy fraction

β quark velocity

Θ_c gluon emission angle

} in the cms of $Q\bar{Q}$

$$\tilde{\gamma}_{q\to q(x)+g} = \frac{C_F\alpha_s}{\pi}\left[\frac{x}{1-x} + (1-x)\cdot\frac{1}{2}\right]$$

$$\tilde{\gamma}_{g\to g(x)+g} = \frac{C_A\alpha_s}{\pi}\left[\frac{x}{1-x} + (1-x)\cdot(x+x^{-1})\right]$$

Gluon radiation off heavy Q

Multiple hadron production in hard processes is derived from the QCD parton cascade processes that are dominated by gluon bremsstrahlung.

An essential difference in the structure of **heavy-** and light-quark jets (q = u, d, s) results from dynamical restriction on the phase space for primary gluon radiation : radiation off an energetic quark Q with mass M and energy E_Q >> M is ***suppressed*** inside the forward cone with an opening half-angle M/E_Q,- the "***dead cone***" **.**

This is in full analogy with QED where photon radiation is suppressed at ***small angles*** with respect to the direction of the radiating massive charged particle.

Suppression of the ***energetic*** gluon emission with low transverse momenta $\mathbf{k_t}$ results, in turn, in the decrease of the heavy quark ***energy losses***.

This provides pQCD explanation of the ***leading particle effect***

and reduces medium induced ***radiative*** energy losses (LMP effect).

HQ jet multiplicity

Dead cone depleting light hadron multiplicity.

Multiplicity of accompanying gluon radiation (NLL) :

$$N_{q\bar{q}}(W) \; - \; N_{Q\overline{Q}}(W) \; = \; N_{q\bar{q}}(\sqrt{e}M) \cdot [1 + \mathcal{O}(\alpha_s(M))]$$

$$N^h_{q\bar{q}}(W) - N^h_{Q\overline{Q}}(W) \; = \; \mathrm{const}(W).$$

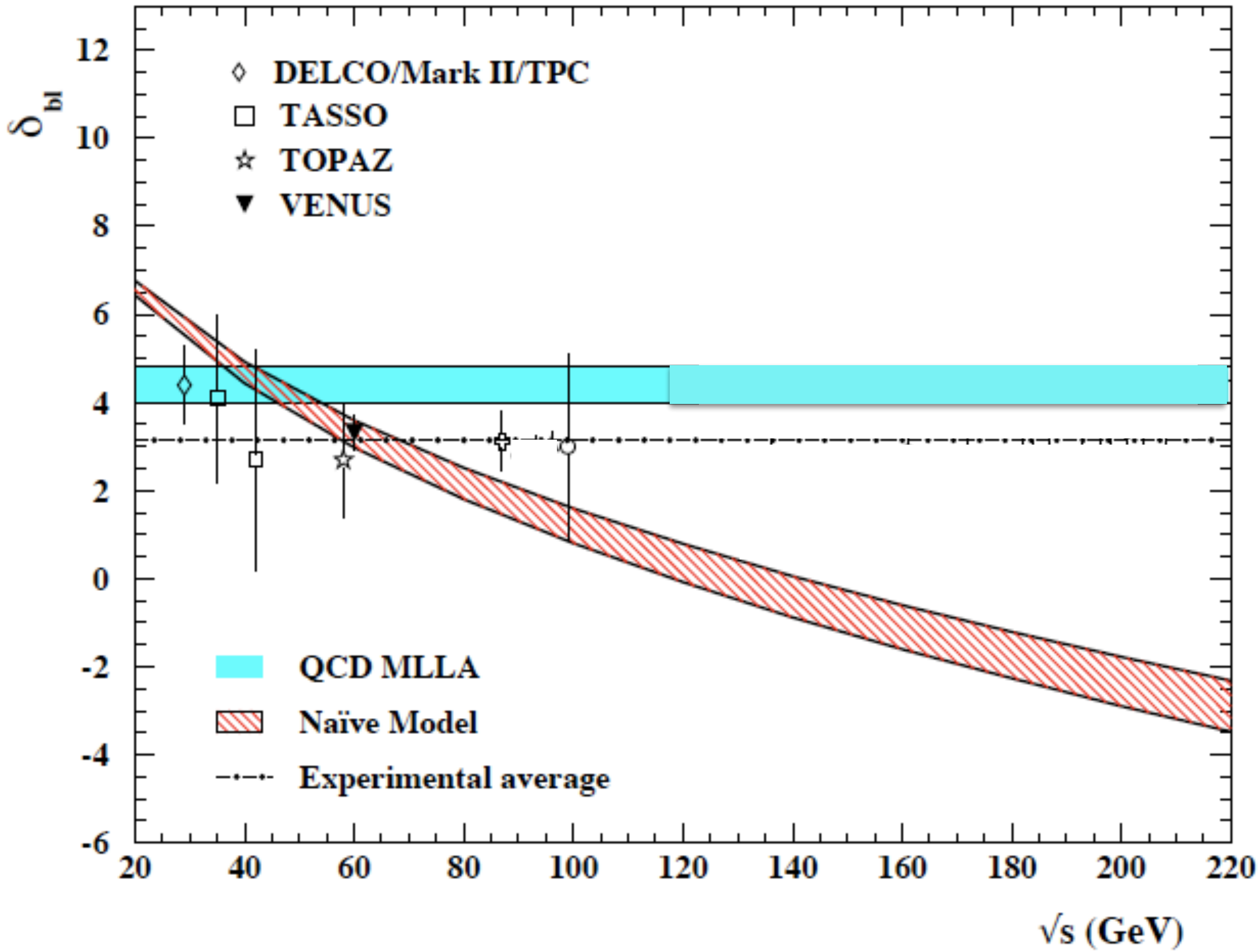
This QCD prediction is in marked contrast with the expectation of the so-called ***naive model***, which related the multiplicities in light and heavy quark events based on the idea of the ***reduction of the energy scale*** :

$$N^h_{Q\overline{Q}}(W) = N^h_{q\bar{q}}((1 - \langle x_Q \rangle)W) \qquad \langle x_Q \rangle = \frac{2\langle E_Q \rangle}{W}, \;\; 1 - \langle x_Q \rangle = \mathcal{O}(\alpha_s(W))$$

$$N^h_{q\bar{q}}(W) - N^h_{Q\overline{Q}}(W) \; \propto \; \sqrt{\alpha_s} \ln \frac{1}{\alpha_s} \cdot N^h_{q\bar{q}}(W)$$

wrong

4"

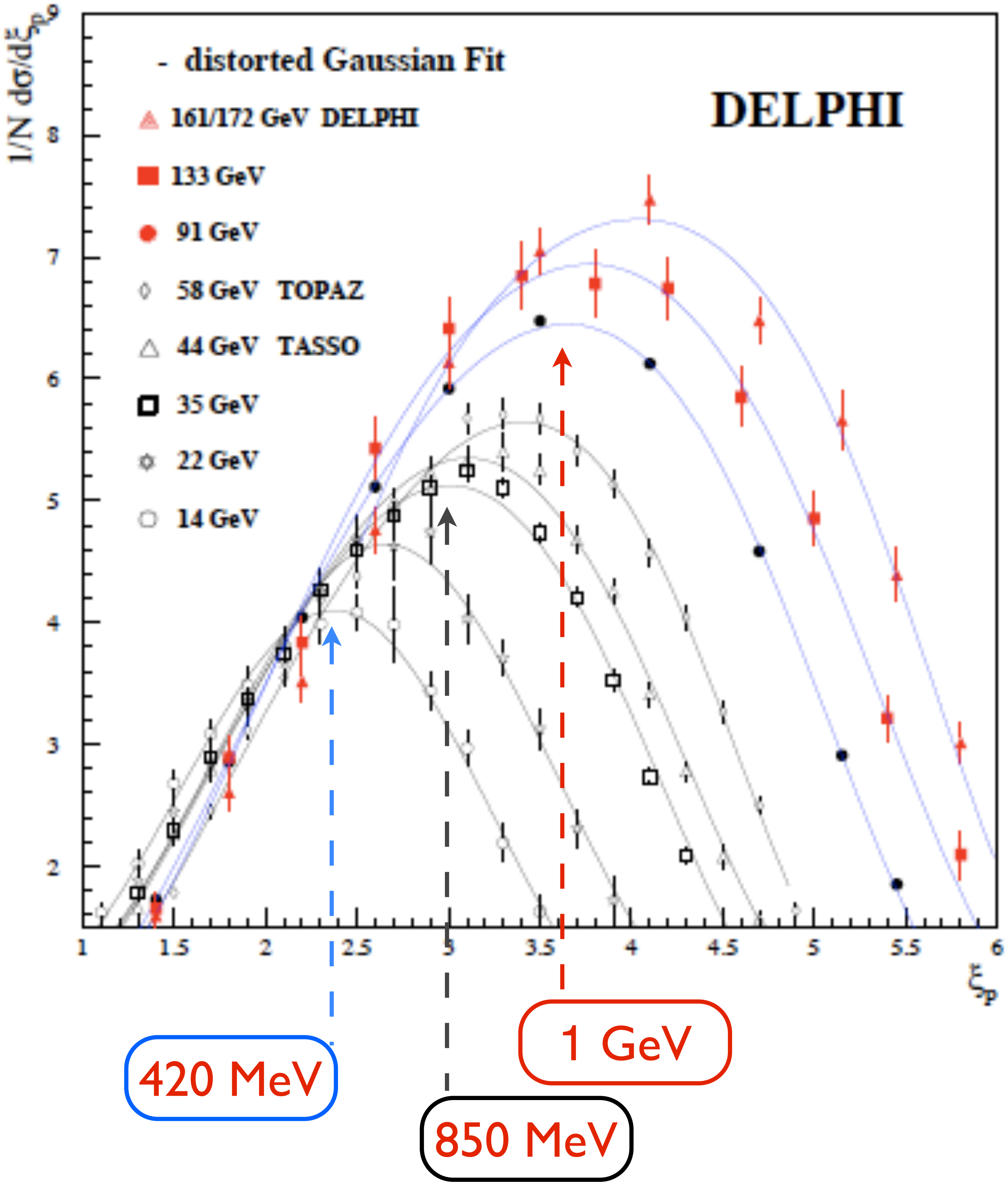


Energy dependence of the multiplicity difference btw bottom and light-q jets

LPHD. Energy spectrum

pQCD predicts distribution of radiated gluons. How about hadrons?

From (pre)LEP, HERA, Tevatron, LHC experiments we learn that ***energy spectra*** of hadrons in jets are mathematically similar to that of gluons.



Observation of parton-hadron similarity was initially met with serious scepticism:

disturbingly small hadron momenta!

By looking at hadron content of a jet with ***restricted opening angle*** one studies smaller hardness scales but in a ***cleaner environment*** :

due to ***Lorentz boost***, hadrons forming characteristic coherent "QCD **hump**" become ***relativistic***

Local Parton-Hadron Duality (LPHD) hypothesis verified

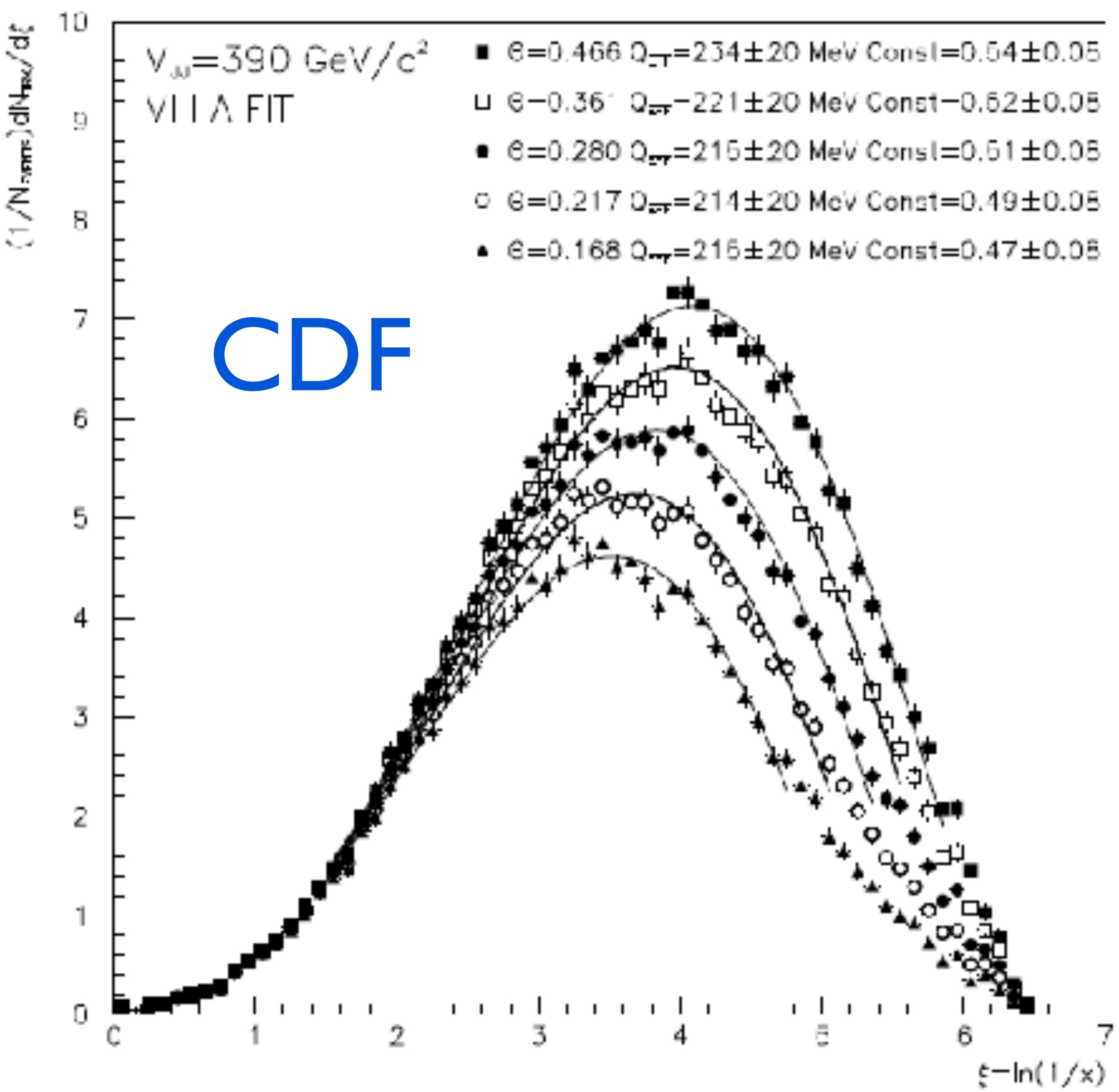
Selecting hadrons inside a cone **0.14** around a quark jet with $\mathbf{E_{jet}=100}$ **GeV** one would see that very *dubious* **Q=14 GeV** curve but now with the maximum ***boosted*** from **0.45 GeV** to **6 GeV !**

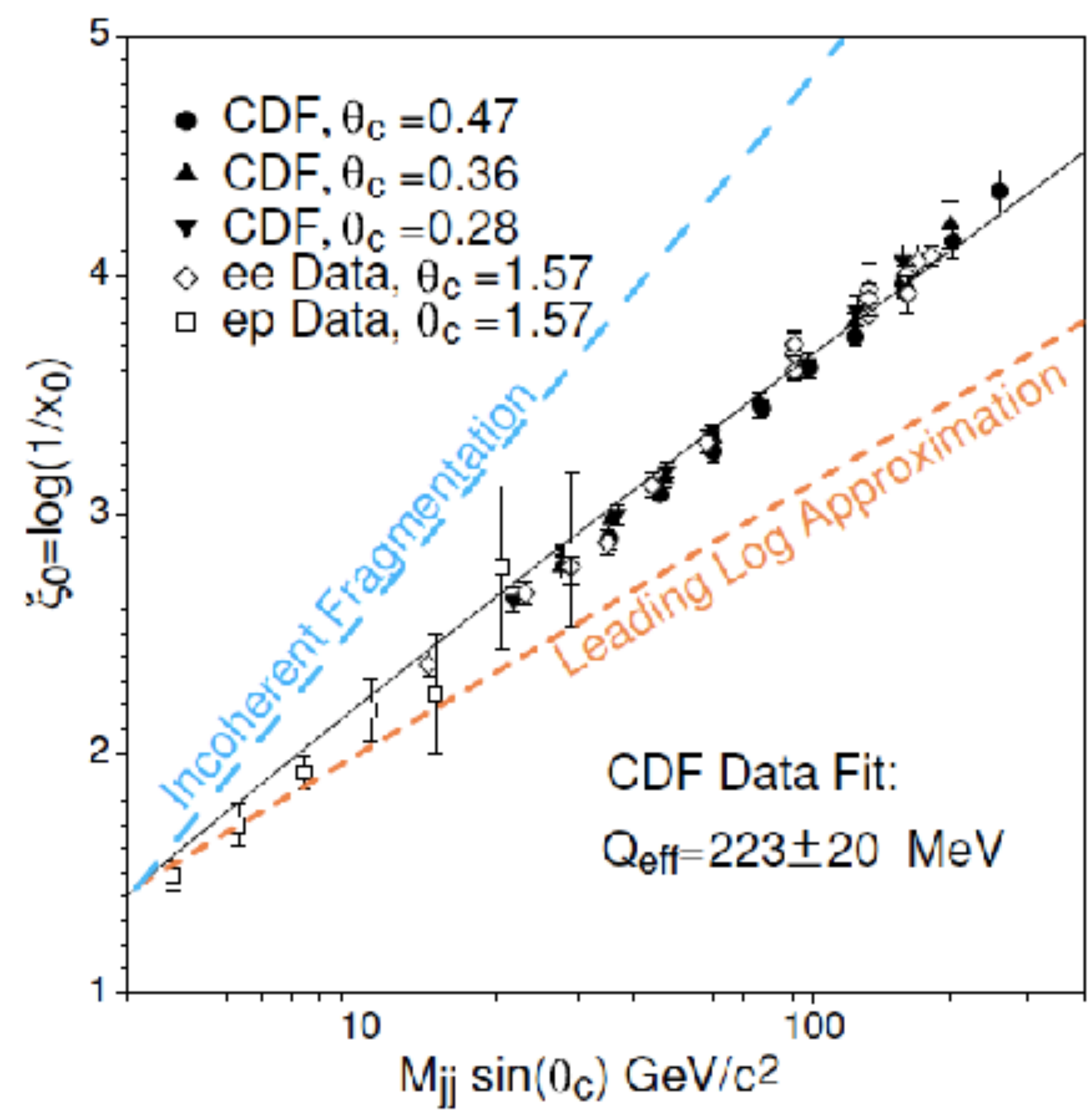
jets with restricted "opening angle"

Position of the Hump as a function of the ***hardness*** of the jet $Q = M_{jj} \sin \Theta_c$

is a ***parameter-free*** *pQCD prediction*

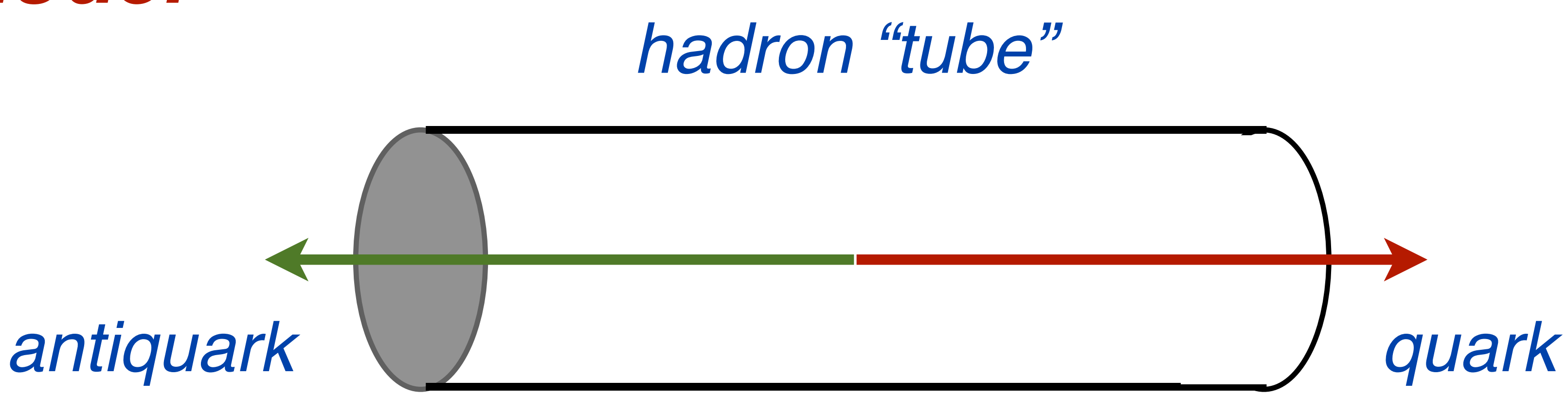
The plot combines ***e⁺e⁻***, ***DIS*** and ***hh*** data **!**

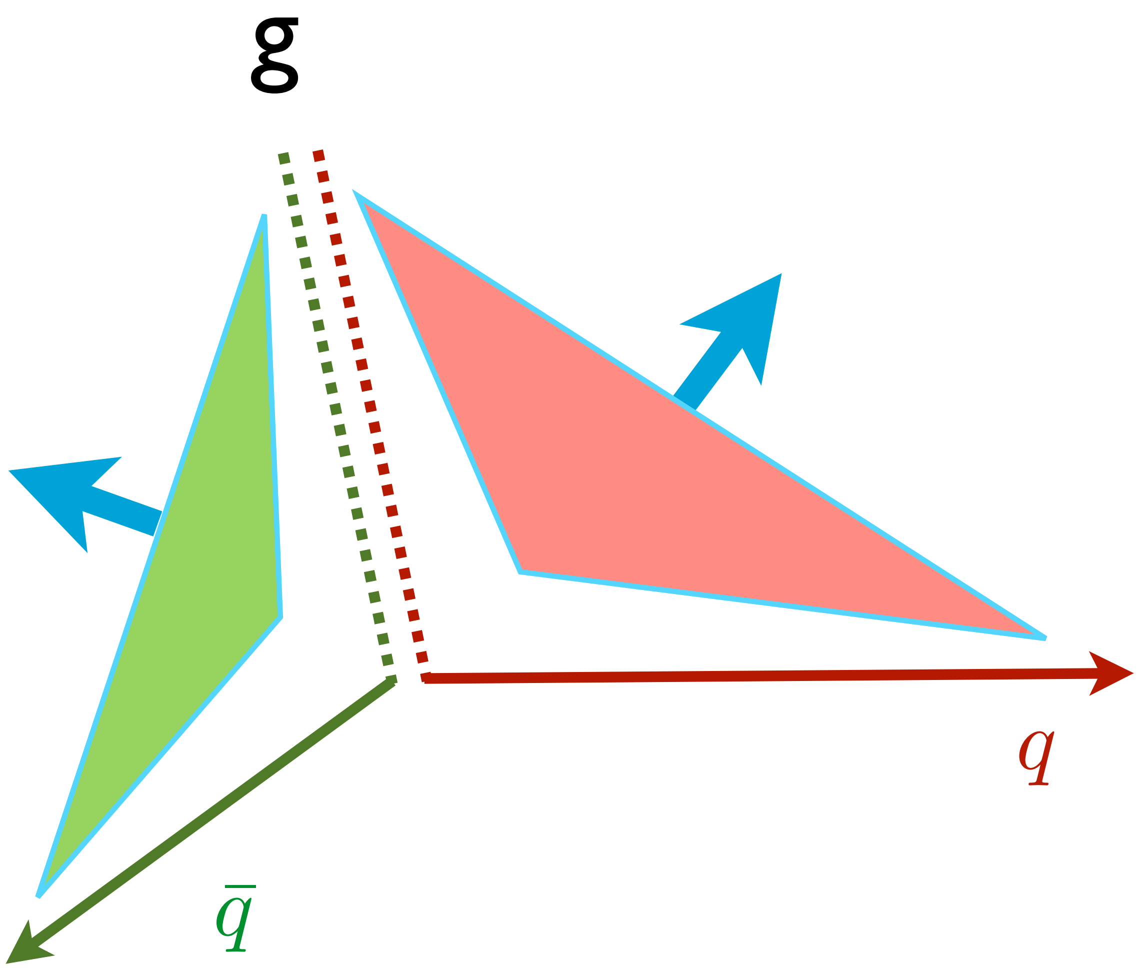




Angular wonders

Lund model





Lund "String effect"

kinematical effect of a boosted hotdog

8 = 3*3

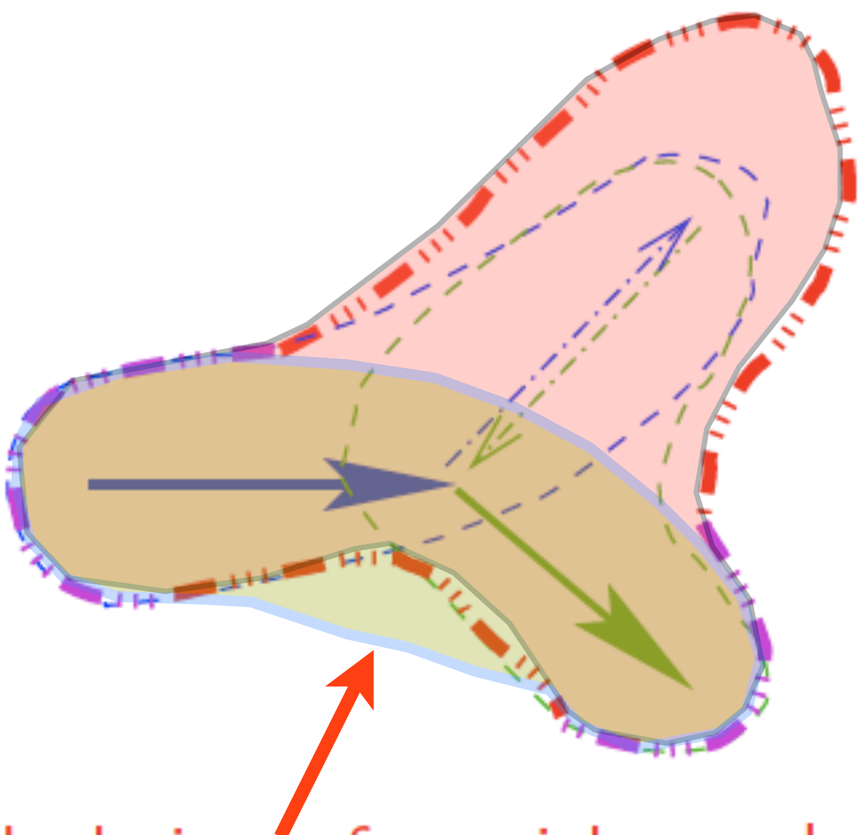
Lund's stress on ***topology*** of the dominant ***colour flow*** found support from **p**QCD

5'

LPHD. Angular distribution

The story of inter-jet hadron flows that manifest subtle dynamics of ***coherent soft gluon radiation*** off multi-parton antennae are even more spectacular than that of inclusive energy spectra.

String Effect is just one (but the most famous) example of "**QCD Radiophysics**"



depletion of particle production in the $q\bar{q}$ valley

Comparison of hadron flows between 3-jet $q\bar{q} + g$ and $q\bar{q} + \gamma$ in the same kinematics

QCD prediction :
$$\frac{dN_{q\bar{q}}^{(q\bar{q}\gamma)}}{dN_{q\bar{q}}^{(q\bar{q}g)}} \simeq \frac{2(N_c^2-1)}{N_c^2-2} = \frac{16}{7}$$

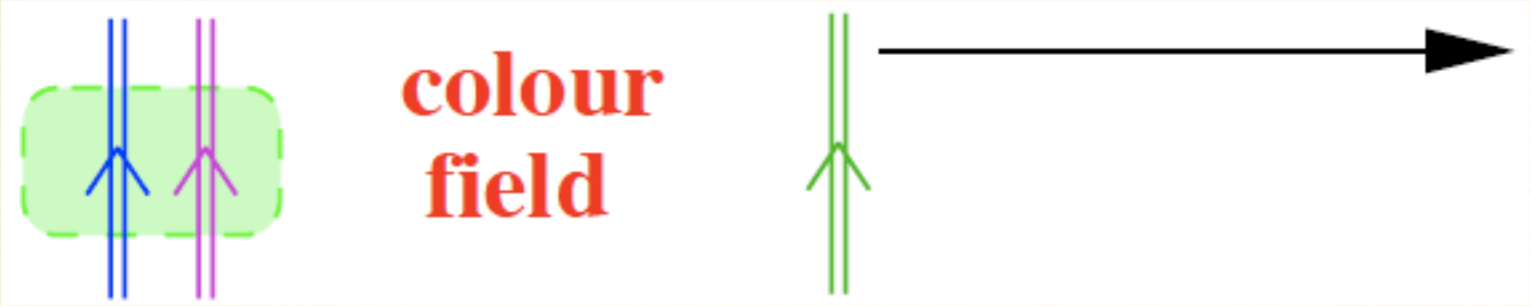
(experiment: 2.3 ± 0.2)

Importantly, information about angular distribution of glue is imprinted upon miserable 100-300 MeV momentum pions!

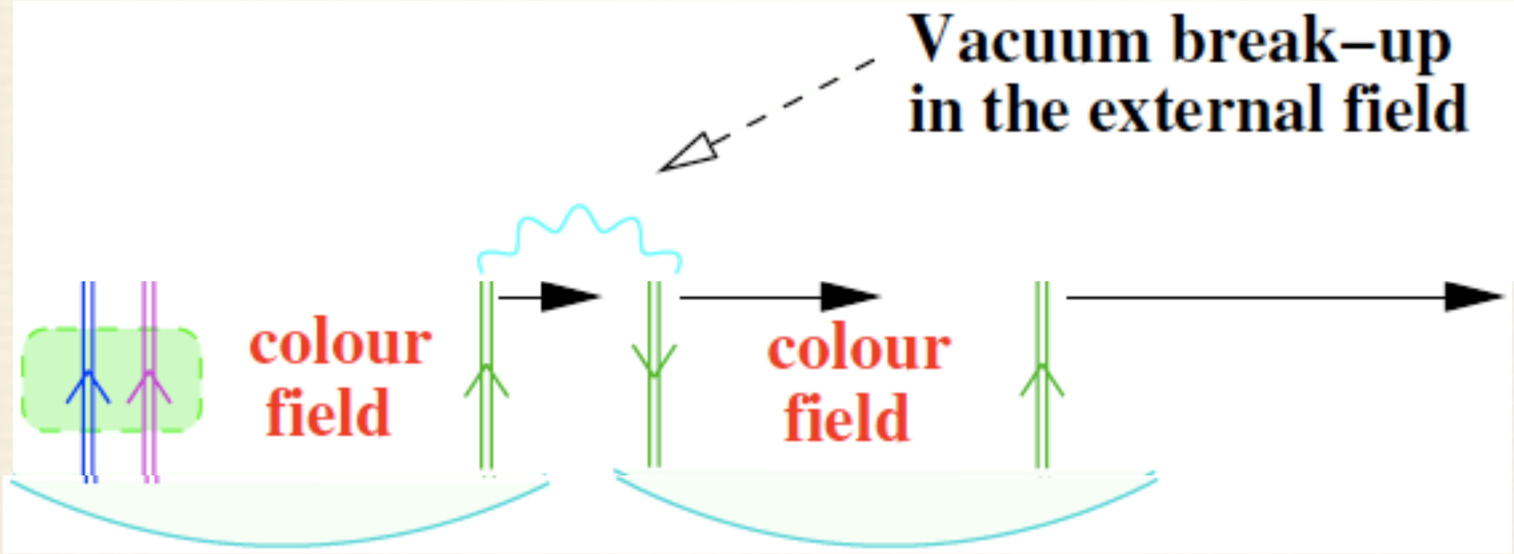
Message: confinement – *transformation of QCD partons into hadrons* – has ***non-violent*** nature: no visible energy–momentum reshuffling at the hadronisation stage!

Kogut–Susskind picture

- In a DIS a *green* quark in the proton is hit by a virtual photon
- The quark leaves the stage and the colour field starts to build up



- A *green–anti-green* quark pair pops up from the vacuum, splitting the system into two globally blanched sub-systems.



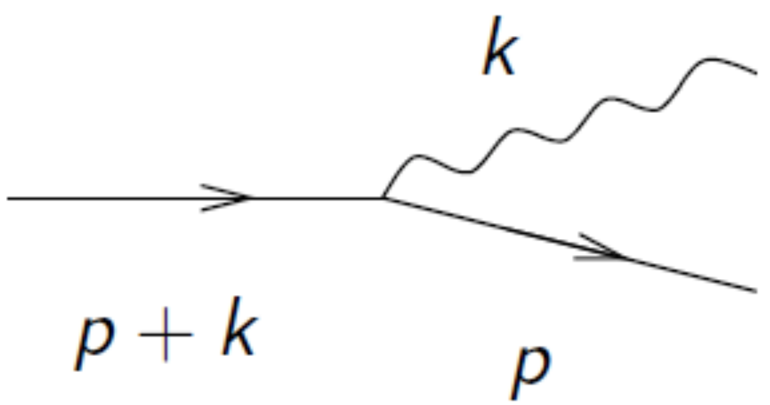
"One" hadron per $\frac{\Delta\omega}{\omega}$; Hadron multiplicity $\propto \ln Q$.

Gluon's life and death

What is the condition for a **gluon** to behave as an ***independent coloured object*** and thus as an ***additional source of new particles?***

It takes certain time to emit a gluon.

The formation time can be simply estimated as a ***lifetime*** of the virtual **(p + k)** quark state



Making use of the Heisenberg uncertainty principle, with account of the Lorentz contraction,

$$t_g^{\text{form}} \sim \frac{1}{M_{virt}} \cdot \frac{E}{M_{virt}} = \frac{E}{(p+k)^2} \approx \frac{E}{kE\Theta^2} \approx \frac{k}{k_\perp^2}$$

Comparing with the hadronization time, $t_g^{\text{hadr}} \approx kR^2$,

$$t_g^{\text{form}} \sim \frac{k}{k_\perp^2} \quad < \quad t_g^{hadr} \sim kR^2$$

the gluon's being is guaranteed *iff* its transverse momentum is large:

$$k_\perp > R^{-1} = \text{a few hundred MeV.}$$

The "***get-born-before-dying***" condition agrees with the ***coupling*** behaviour : $\alpha_s(k_\perp^2)$

Gluons : 3+1

- $R^{-1} \ll k_\perp \ll k \sim \sqrt{Q^2}$

  - the domain of ***quasi-collinear*** hard parton splittings leading to the scaling violation effects in DIS structure functions and jet fragmentation (inclusive particle distributions)

- $R^{-1} \ll k_\perp \sim k \ll \sqrt{Q^2}$

  - ***large angle soft*** gluon emission responsible for drag effects in interjet multiplicity flows

- $R^{-1} \ll k_\perp \ll k \ll \sqrt{Q^2}$

  - ***double-logarithmic*** (soft & collinear) gluon bremsstrahlung off quarks and gluons causing jet multiplicity grow with energy and determining QCD parton Form Factors

All these are legitimate, PT-controllable, QCD sub-processes.

Parton pairs with small relative transverse momenta lie beyond PT control.

Look at gluon radiation at the ***lower edge*** of the PT phase space : $k_\perp \sim R^{-1}$.

An appearance of a "**gluer**" is a signal of switching on of the ***real strong interaction*** : $\left(t^{\text{form}} \sim t^{\text{hadr}}\right)_{\text{gluer}}$

Inclusive spectrum of **gluers** reproduces the ***Feynman hadron plateau*** !

$$dN = \left[\int_{k_\perp \sim R^{-1}} \frac{dk_\perp^2}{k_\perp^2} \, 4C_F \frac{\alpha_s(k_\perp^2)}{4\pi} \right] \frac{dk}{k} = \text{const} \cdot \frac{dk}{k}$$

Gluers, hadronisation and Dead Cone

Hadronisation time: **in the rest frame,** $t_{\rm hadr} \sim R$

With account of the Lorentz boost,

$$t_{\rm hadr} = ER^2 \longrightarrow t_{\rm Q} = ER^2 \cdot \frac{1}{M_Q R} = \frac{R}{\Theta_{\rm Q}}$$

Light quark/gluon — **Heavy quark**

Switching on the NP strong interaction (= hadronisation) can be triggered by looking at formation time of a "***gluer***" - gluon on the edge of PT: $k_{\perp({\rm gluer})} \sim R^{-1}, \quad \alpha_s(k^2_{\perp({\rm gluer})}) = \mathcal{O}(1)\,.$

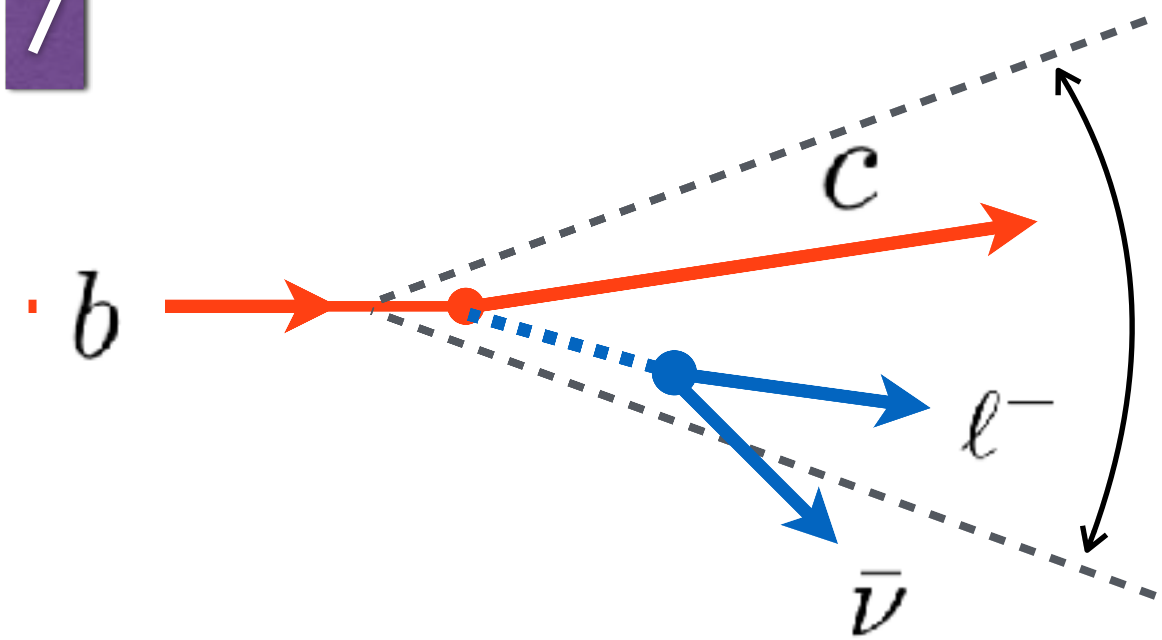
Angles of gluers (= produced hadrons)

$$\Theta_{\rm gluer} = \frac{(k_\perp)_{\rm gluer}}{\omega} = \frac{1}{\omega R} = \frac{R}{\omega R^2} = \frac{R}{t_{\rm hadr}} \gtrsim \frac{R}{t_{\rm Q}} = \Theta_{\rm Q}$$

The very last gluer responsible for $c \longrightarrow D\,.$

All the rest have ***larger*** angles. No NP filling-in!

Good news !



$$\Theta_b = \frac{M_b}{E_b}$$

IF C- and B- quark masses were indeed ("parametrically") large...

Look at light hadron multiplicity in a quark jet:

$$N_{\text{hadr}}(E) = N_q(E) - N_q(M_b) + \left[N_q(M_b) - N_q(M_c)\right] + N_q(M_c)$$

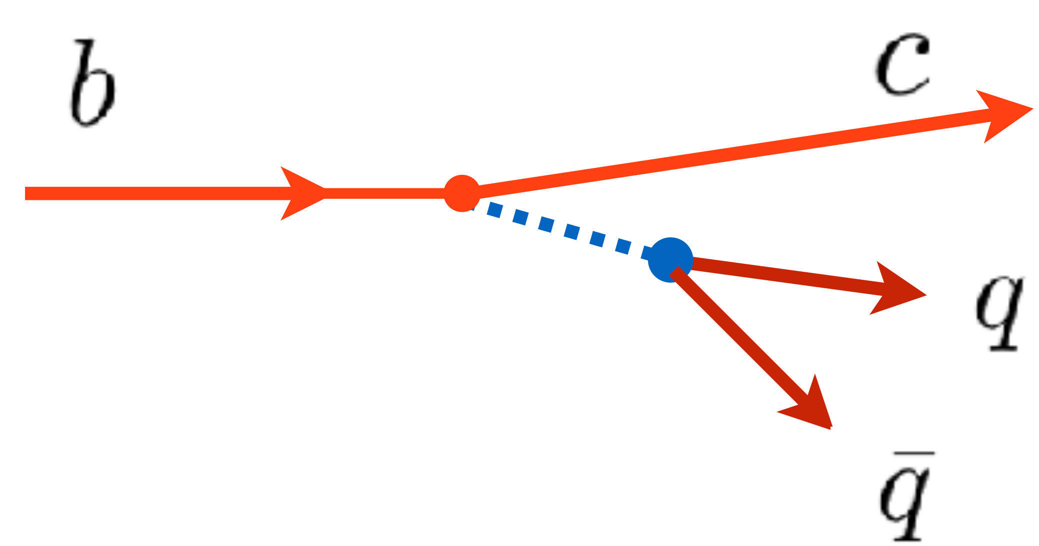
B

C

Subtlety:

hadron multiplicities in **semi-leptonic** and "**3-jet**" B-decays differ by an "extra E+E-"

Certain statistical contamination of the C-cone possible.



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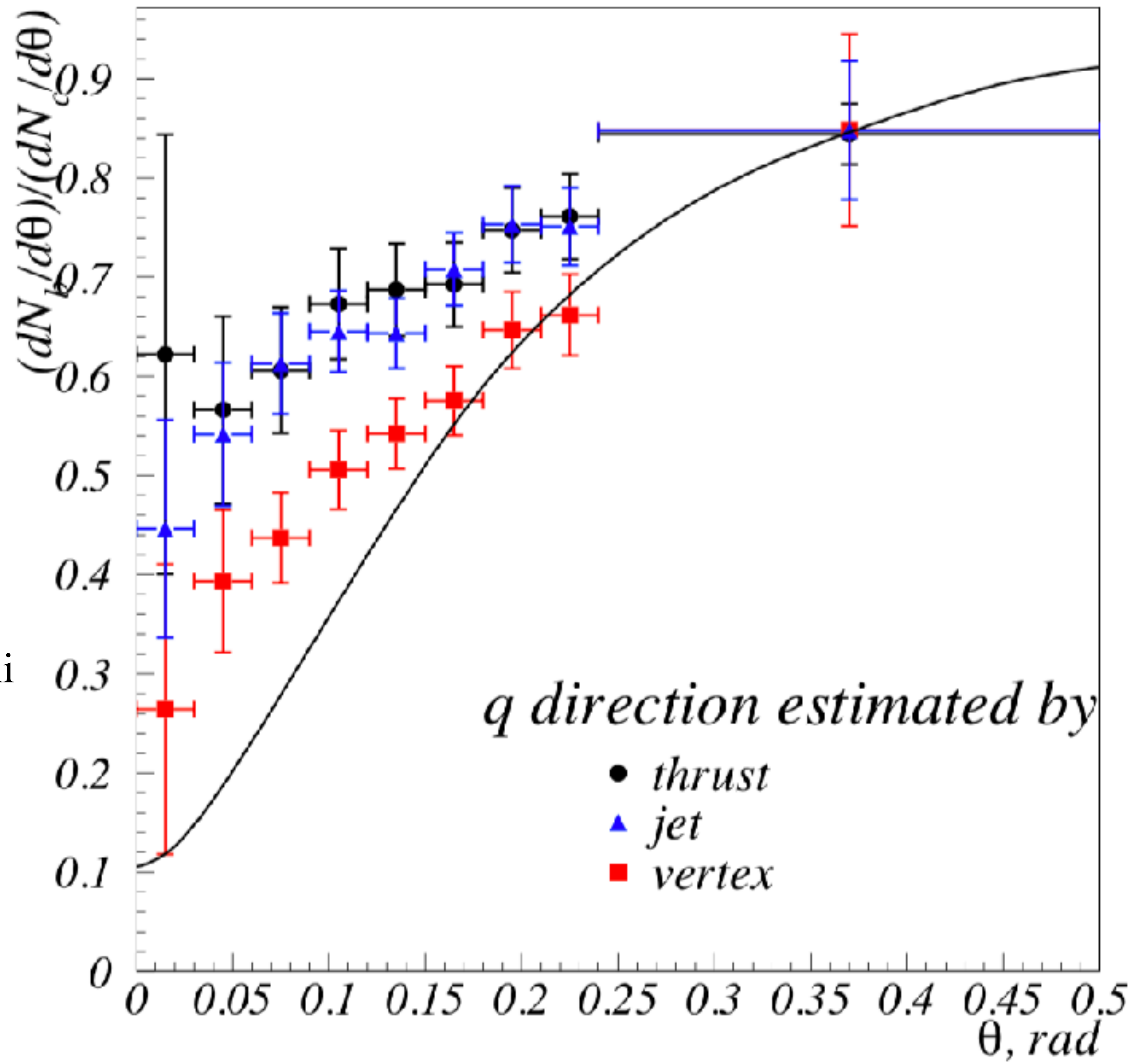
DELPHI B/C ratio (2004). Which direction to use?..



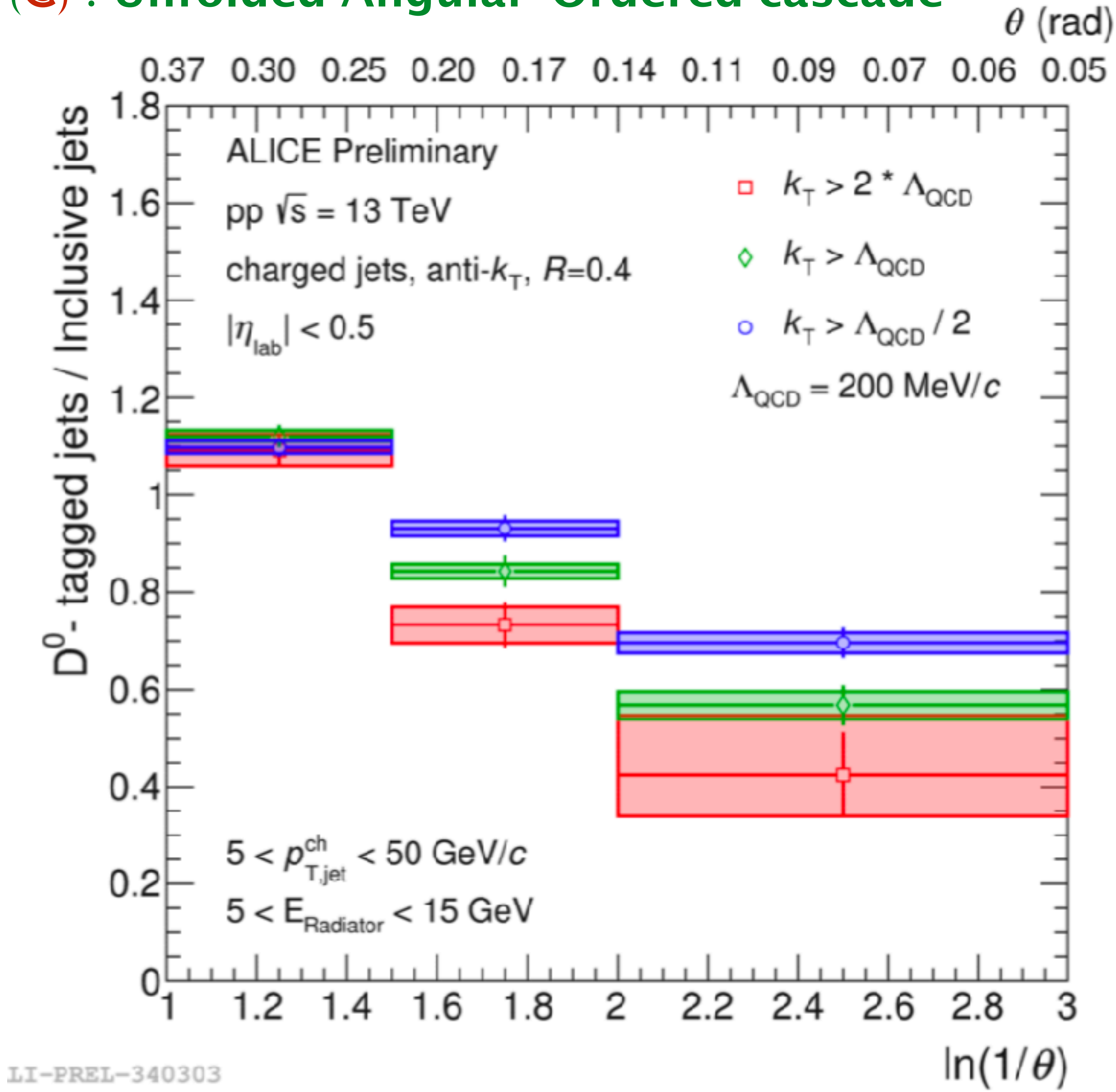
analysis by

Battaglia, Orava, Salmi
Helsinki

initiated by

V.A. Khoze

ALICE (©) . Unfolded Angular-Ordered cascade



punchline

Studies of inter-jet particle flows (QCD radiophysics)
intra-jet parton multiplication (inclusive spectra)

at LEP and elsewhere
have taught us about the key features of hadroproduction :

The ***colour field*** that an ensemble of hard **partons** develops, determines, on the "one-to-one" basis, the structure of final flows of **hadrons**.

When viewed globally, confinement is about "renaming"
a flying-away quark into a flying-away pion
rather than "pulling" opposite colours back together.

Applied to Heavy Quarks, "gentle confinement"
manifests itself in the Dead Cone phenomenon

Bravo ALICE !

and B-bis !