Hard Processes and Partons

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Hadronic jets in e^+e^- collisions

and

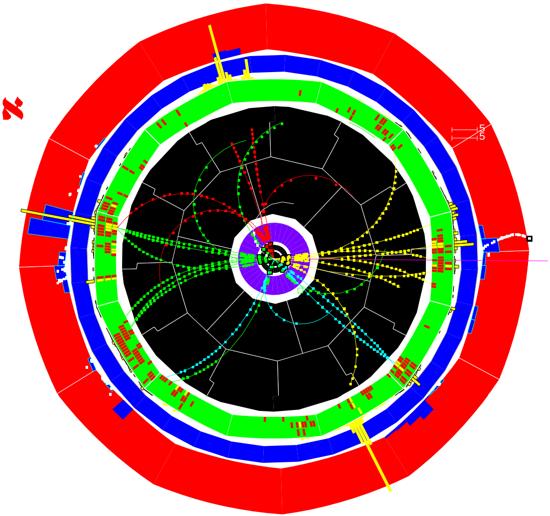
QCD radiophysics

Plan

- Quarks, Confinement and Hadrons
  - Kogut–Susskind picture of hadronization
  - Feynman plateau
  - $e^+e^- \longrightarrow$ two quark jets
- Gluon jets
  - Three-jet events
  - Ellis, Gaillard, Ross
  - Gluon hadronization: Lund string model
- Hadron production in-between jets
  - String effect
  - intERjet gluon radiation
- Internal structure of parton jets
  - Coherence in soft gluon emission. Chudakov effect.
  - intRAjet parton cascades
  - Hump-backed plateau
- LPHD puzzle

quark ⟶ hadrons

Existence of Jets was envisaged from "parton models" in the late 1960's.



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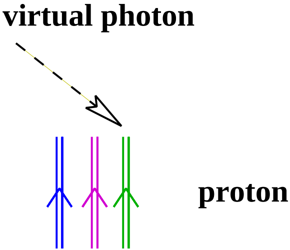

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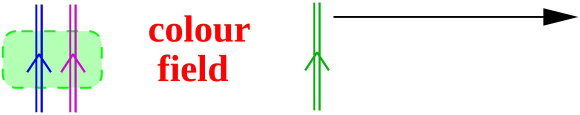

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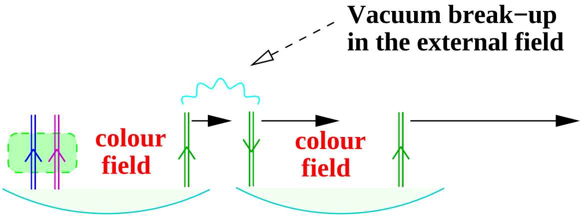

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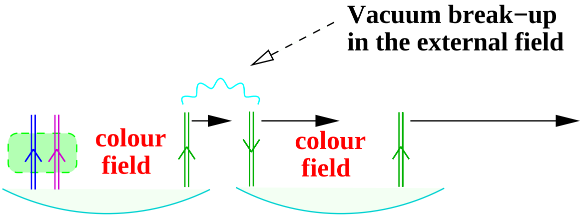
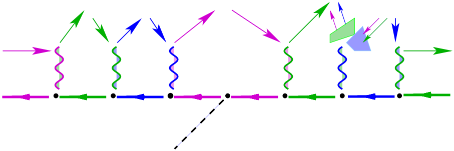


Repeating, one gets the "Feynman Plateau" :

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

Lund hadronization model

Phenomenological realization of the Kogut–Susskind scenario



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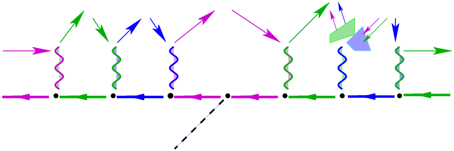

$\Longrightarrow$ a "String" of hadrons

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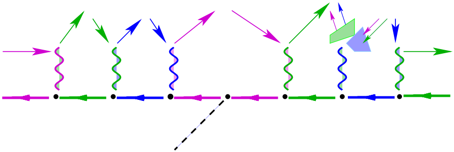

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The key features of the Lund hadronization model:

- Uniformity in *rapidity*: $dN_h = \text{const} \times \dfrac{d\omega_h}{\omega_h}$
- Limited $k_\perp$ of hadrons
- Quark combinatorics at work:
  - ☛ u, d vs. s
  - ☛ *mesons* vs. *baryons*

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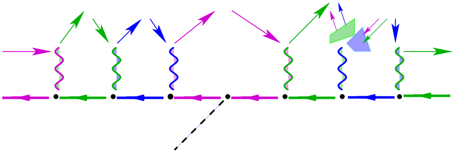

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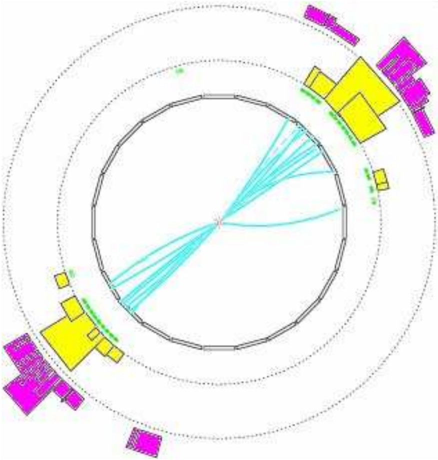
The crucial step: Stress on the *rôle of colour* in multiple hadroproduction

$q\bar{q} \longrightarrow$ hadrons



Near 'perfect' 2-jet event

2 well-collimated jets of particles.

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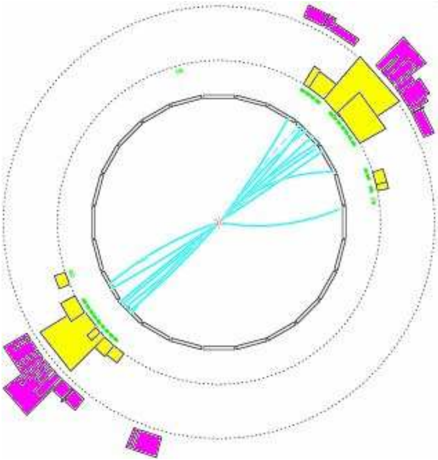

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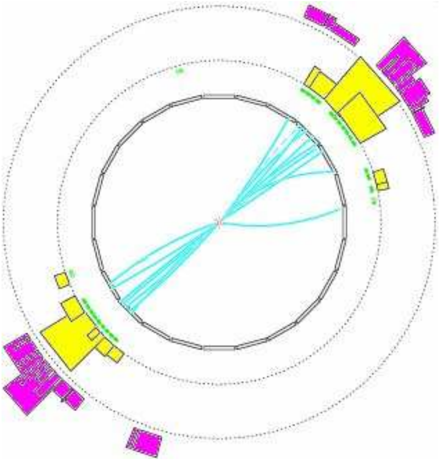

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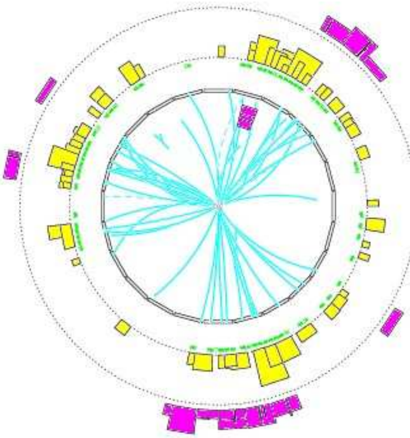
Moreover,

In 10% of e^+e^- annihilation events
— striking fluctuations !

Third jet



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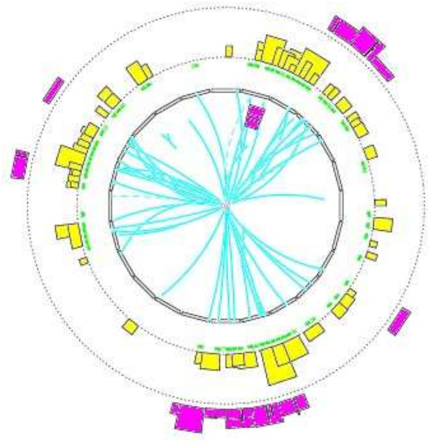

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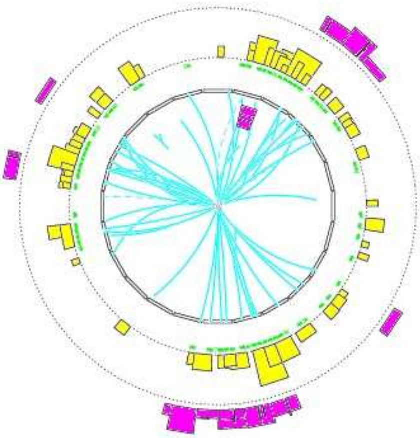

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The first QCD analysis was done by J.Ellis, M.Gaillard & G.Ross (1976)

- Planar events with large $k_\perp$;
- How to measure gluon spin ;
- Gluon jet – softer, more populated.

How does gluon hadronize?

QCD possesses $N_c^2 - 1$ gauge fields — vector gluons g.

At large distances, they are supposed to "glue" quarks together.

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B.Andersson, G.Gustafson & C.Peterson, Lund Univ., Sweden (1977)

Gluon $\simeq$ quark-antiquark pair:
$3 \otimes \bar{3} = N_c^2 = 9 \quad \simeq \quad 8 = N_c^2 - 1$.
Relative mismatch : $\mathcal{O}(1/N_c^2) \ll 1$ (the large-N_c limit)

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Lund model interpretation of a *gluon* —

Gluon – a "*kink*" on the "string" (colour tube)
that connects the quark with the antiquark

Colour "drag"

Look at hadrons produced in a $q\bar{q}$+photon e^+e^- annihilation event.

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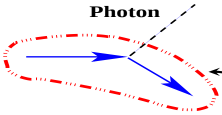

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The hot-dog of hadrons that was "*cylindric*" in the cms, is now *lopsided* [boosted string]

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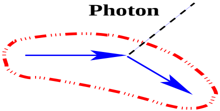

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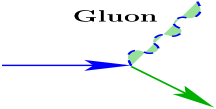

Now substitute a gluon for the photon in the same kinematics.

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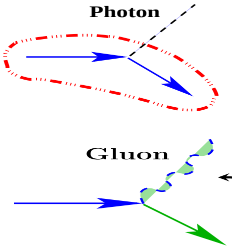

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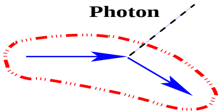

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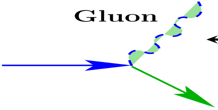

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Lund: hadrons = the sum of two independent (properly boosted) colorless substrings, made of

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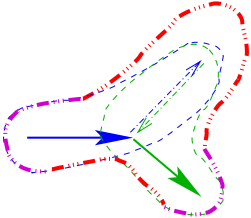

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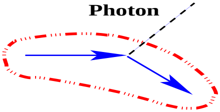

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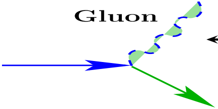

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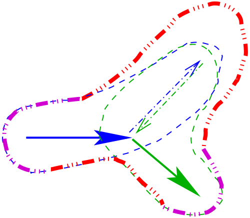

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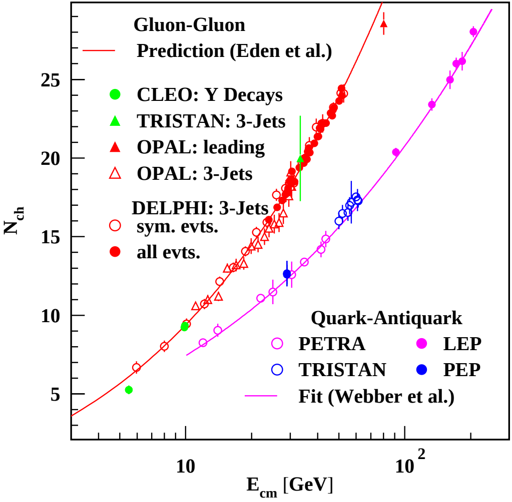
The first immediate consequence :

Double Multiplicity of hadrons in fragmentation of the *gluon*

Comparing hadron multiplicities



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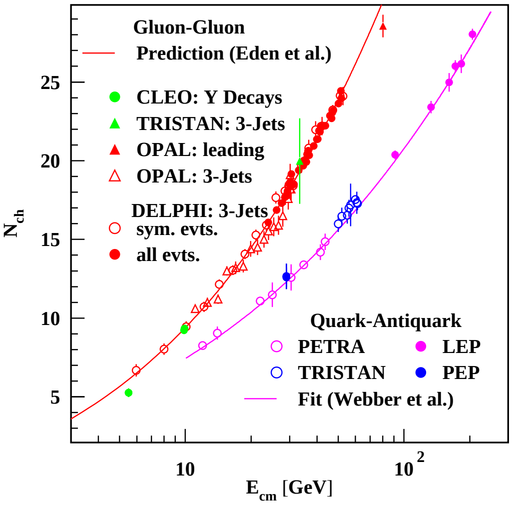

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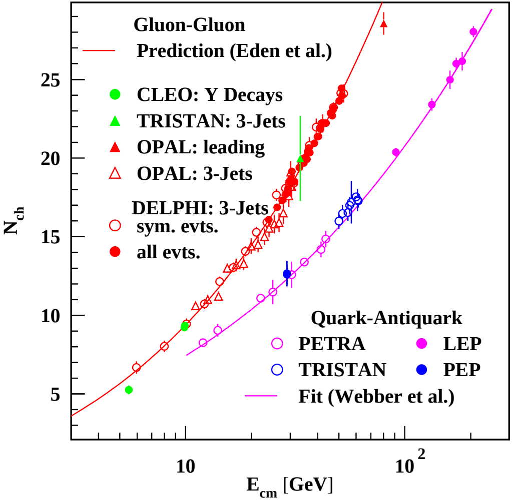

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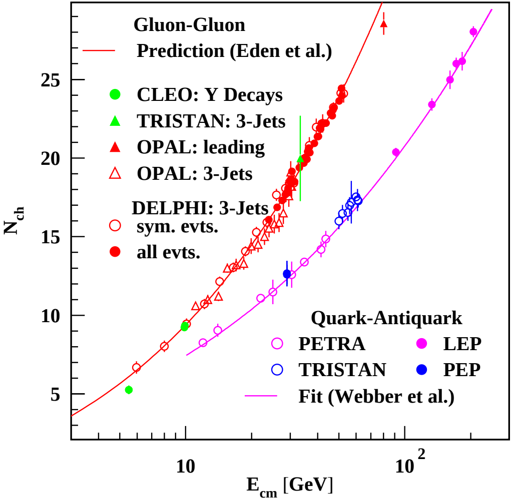

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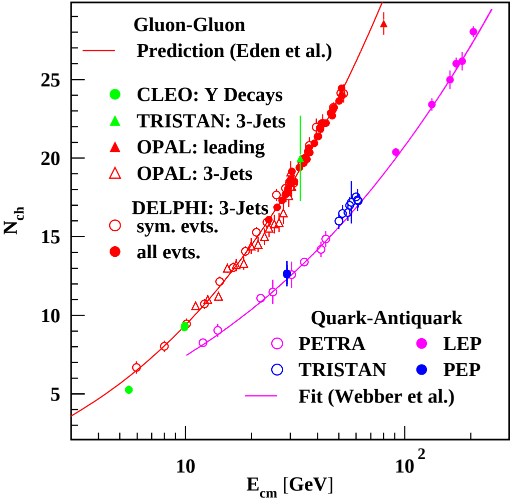

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Now let's look at a more subtle consequence of Lund wisdom

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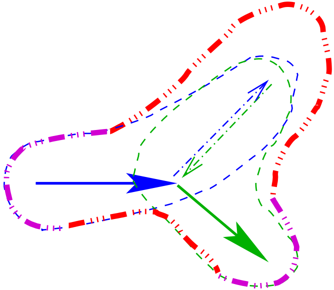

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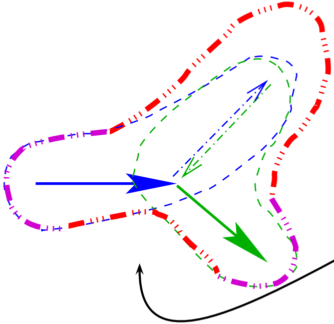

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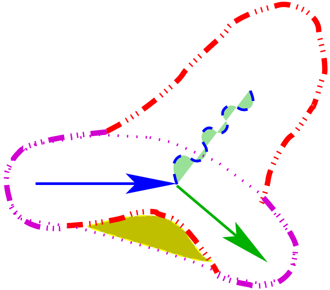

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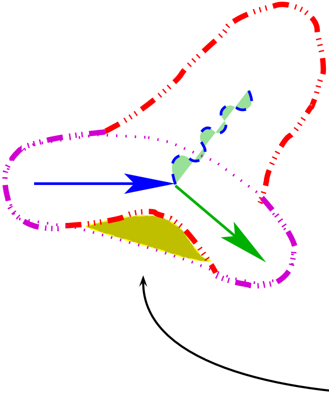

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from the QCD point of view

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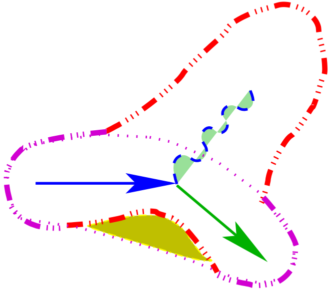

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QCD prediction :

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

(experiment: 2.3 ± 0.2)

Ratios of hadron flows between jets in various multi-jet processes — example of non-trivial CIS (collinear-and-infrared-safe) QCD observable [recall G.V.'s lecture]

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born *later* (time ordering) does *not* mean being born *independently*	$\Longrightarrow$	*Coherence* in radiation of soft gluons (photons) with $x \ll 1$ — the ones that determine the bulk of secondary parton multiplicity!

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Rediscovery of the *quantum-mechanical nature* of gluon radiation played the major rôle in understanding the *internal structure* of jets as well.

Why "*rediscovery*"?
Because, under the spell of the probabilistic parton cascade picture (that we discussed last week), theorists managed to make serious mistakes in the late 70's when they indiscriminately applied it to parton multiplication in jets.

Subtlety: When gauge fields (conserved currents) are concerned,

born *later* (time ordering) does *not* mean being born *independently*	$\Longrightarrow$	*Coherence* in radiation of soft gluons (photons) with $x \ll 1$ — the ones that determine the bulk of secondary parton multiplicity!

Recall an amazing historical example: Cosmic ray physics (mid 50's); conversion of high energy photons into e^+e^- pairs in the emulsion

Chudakov effect

Charged particle leaves a track of ionized atoms in photo-emulsion.

electron track

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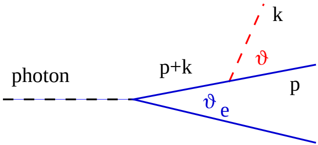
Transverse distance between two charges
(size of the e^+e^- dipole) is

$\rho_\perp \simeq c\, t \cdot \vartheta_e$



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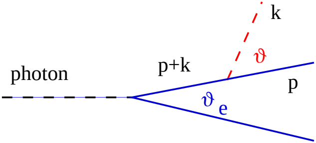

The photon is emitted after the time (lifetime of the virtual $p+k$ state)

$$t \simeq \frac{(p+k)_0}{(p+k)^2} \simeq \frac{p_0}{2p_0k_0(1-\cos\vartheta)} \simeq \frac{1}{k_0\vartheta^2} \simeq \frac{1}{k_\perp}\cdot\frac{1}{\vartheta} = \lambda_\perp \cdot \frac{1}{\vartheta}$$

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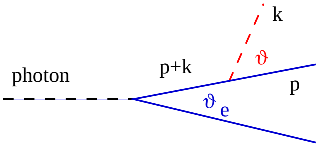
$\vartheta < \vartheta_e$ – independent radiation off e^- & e^+



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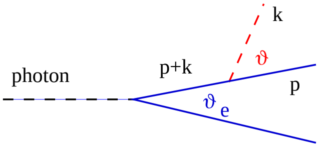

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$\vartheta > \vartheta_e$ – no emission ! $(\rho_\perp < \lambda_\perp)$

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intRAjet coherence

Angular Ordering is *more restrictive* than the fluctuation time ordering:
$\vartheta \le \vartheta_e$ versus $\vartheta \le \vartheta_e \cdot \sqrt{\frac{p_0}{k_0}}$ that follows from

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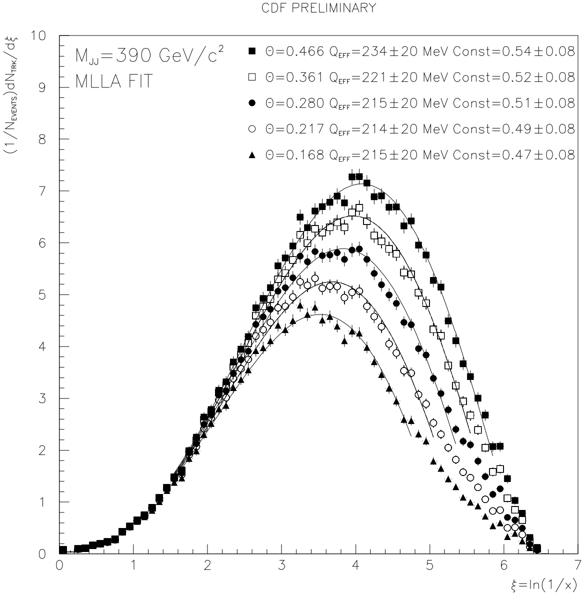
while the softest particles (that seem to be the easiest to produce) should not multiply at all !

Hump-backed plateau



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$pp \to 2$ jets

Charged hadron yield as a function of $\ln(1/x)$ for different values of jet hardness, versus (MLLA) QCD prediction.

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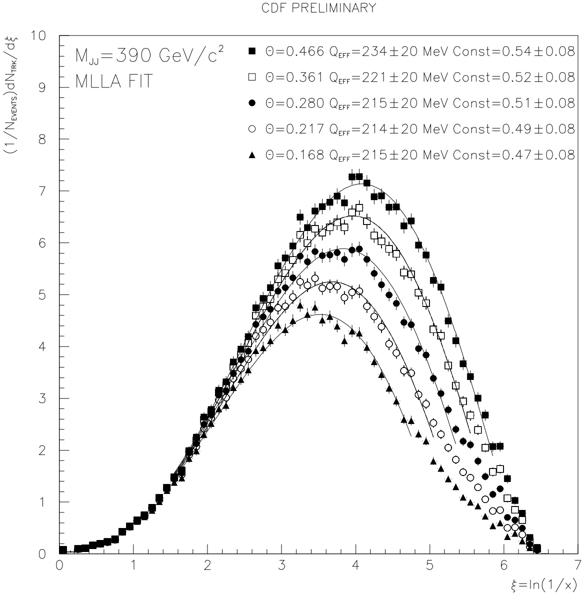

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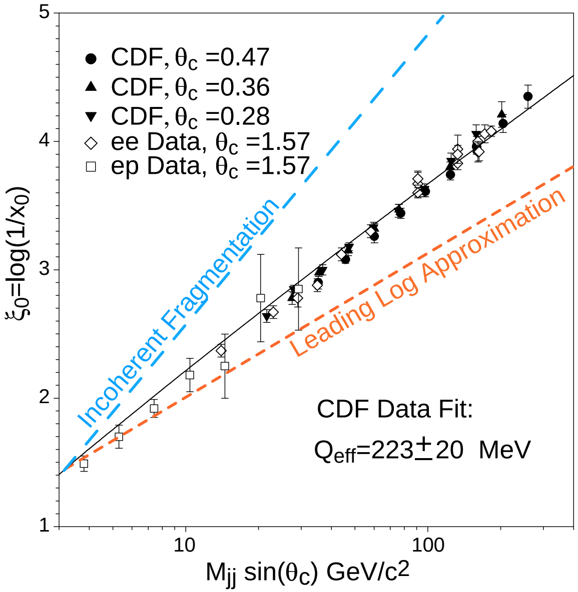
One free parameter – overall normalization (the number of final π's per extra gluon)

Hump (continued)



Position of the Hump as a function of

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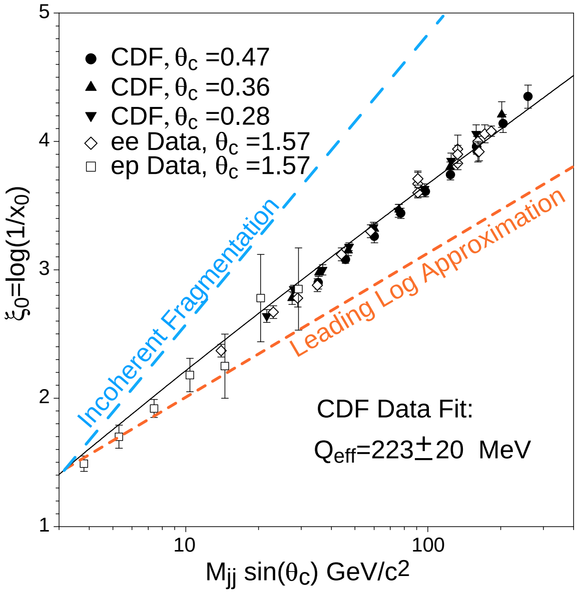

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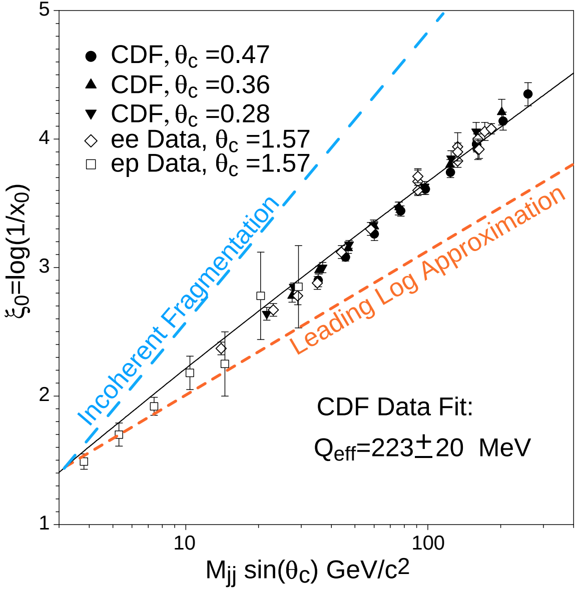

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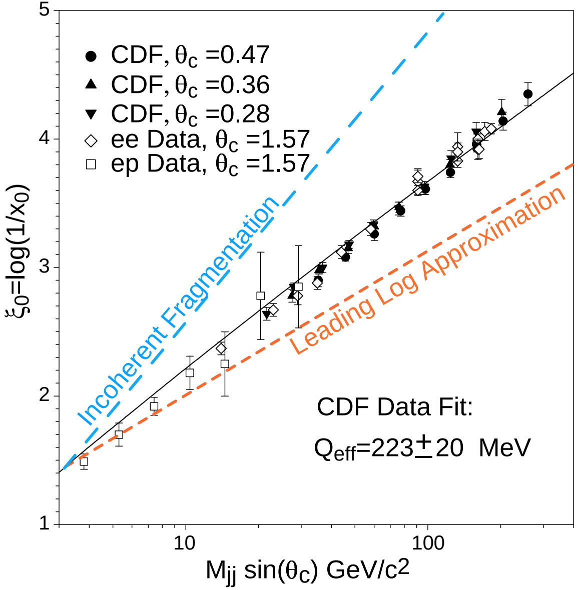

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Mark Universality:
same behaviour seen in e^+e^-, DIS (ep), hadron–hadron coll.

Soft Confinement

So, the *ratios* of particle flows between jets (intERjet radiophysics), as well as the *shape* of the inclusive energy spectra of secondary particles (intRAjet cascades) turn out to be formally calculable (CIS) quantities. Moreover, these perturbative QCD predictions actually work.

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We should rather feel *puzzled* than satisfied.

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Résumé.

Thanks to AF and to IR-CO-safety we can compute σ_T in terms of the simplest lowest order diagram with just $q\bar{q}$ in the final state. However this is by no means the correct description of the final state . . . (G.V.)

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Calculation of σ_T from 1st principles – the robust example of *IR-CO-safety*. However, we can derive a thing or two about the structure of the *final state* — ensemble of jets stemming from primary q's and g's — as well.

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But this is another story . . .