# The Role of Event Generators in the exploration of QCD

Torbjörn Sjöstrand

Lund University, Lund, Sweden

DESY Physics Colloquium, 20 February 2024

# Recently QCD turned 50 . . .

**Current Algebra: Quarks and What Else?**

Harald Fritzsch[*†]

and

Murray Gell–Mann[**†]

CERN, Geneva, Switzerland

Proceedings of the XVI International Conference on High Energy Physics, Chicago, 1972. Volume 2, p. 135 (J. D. Jackson, A. Roberts, eds.)

**ADVANTAGES OF THE COLOR OCTET GLUON PICTURE**[☆]

H. FRITZSCH*, M. GELL-MANN and H. LEUTWYLER**
*California Institute of Technology, Pasadena, Calif. 91109, USA*

Received 1 October 1973

It is pointed out that there are several advantages in abstracting properties of hadrons and their currents from a Yang–Mills gauge model based on colored quarks and color octet gluons.

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

**Ultraviolet Behavior of Non-Abelian Gauge Theories***

David J. Gross† and Frank Wilczek
*Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540*
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field–theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

**Reliable Perturbative Results for Strong Interactions?***

H. David Politzer
*Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138*
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

# . . . and was celebrated


Eur. Phys. J. C (2023) 83:1125
https://doi.org/10.1140/epjc/s10052-023-11949-2

THE EUROPEAN PHYSICAL JOURNAL C

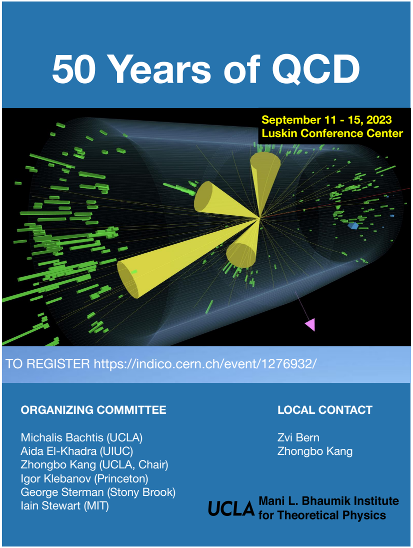
Review


## 50 Years of quantum chromodynamics

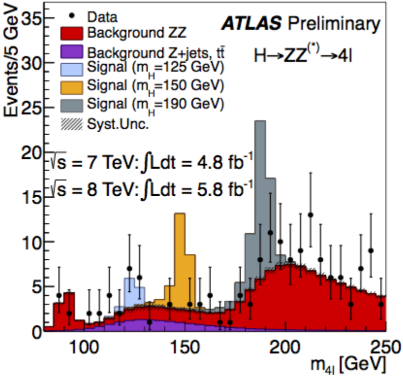
**Introduction and Review**

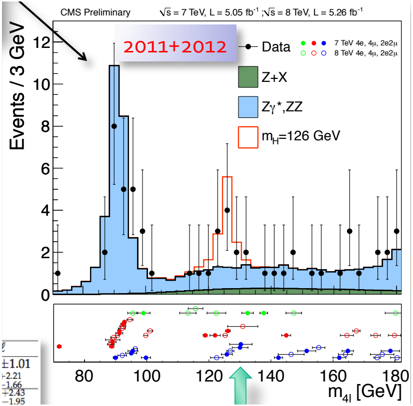

Franz Gross[1,2,a], Eberhard Klempt[3,b], Stanley J. Brodsky[4], Andrzej J. Buras[5], Volker D. Burkert[1], Gudrun Heinrich[6], Karl Jakobs[7], Curtis A. Meyer[8], Kostas Orginos[1,2], Michael Strickland[9], Johanna Stachel[10], Giulia Zanderighi[11,12], Nora Brambilla[5,12,13], Peter Braun-Munzinger[10,14], Daniel Britzger[11], Simon Capstick[15], Tom Cohen[16], Volker Crede[15], Martha Constantinou[17], Christine Davies[18], Luigi Del Debbio[19], Achim Denig[20], Carleton DeTar[21], Alexandre Deur[1], Yuri Dokshitzer[22,23], Hans Günter Dosch[10], Jozef Dudek[1,2], Monica Dunford[24], Evgeny Epelbaum[25], Miguel A. Escobedo[26], Harald Fritzsch[27], Kenji Fukushima[28], Paolo Gambino[11,29], Dag Gillberg[30,31], Steven Gottlieb[32], Per Grafstrom[33,34], Massimiliano Grazzini[35], Boris Grube[1], Alexey Guskov[36], Toru Iijima[37], Xiangdong Ji[16], Frithjof Karsch[38], Stefan Kluth[11], John B. Kogut[39,40], Frank Krauss[41], Shunzo Kumano[42,43], Derek Leinweber[44], Heinrich Leutwyler[45], Hai-Bo Li[46,47], Yang Li[48], Bogdan Malaescu[49], Chiara Mariotti[50], Pieter Maris[51], Simone Marzani[52], Wally Melnitchouk[1], Johan Messchendorp[53], Harvey Meyer[20], Ryan Edward Mitchell[54], Chandan Mondal[55], Frank Nerling[53,56,57], Sebastian Neubert[3], Marco Pappagallo[58], Saori Pastore[59], José R. Peláez[60], Andrew Puckett[61], Jianwei Qiu[1,2], Klaus Rabbertz[33,62], Alberto Ramos[63], Patrizia Rossi[1,64], Anar Rustamov[53,65], Andreas Schäfer[66], Stefan Scherer[67], Matthias Schindler[68], Steven Schramm[69], Mikhail Shifman[70], Edward Shuryak[71], Torbjörn Sjöstrand[72], George Sterman[73], Iain W. Stewart[74], Joachim Stroth[53,56,57], Eric Swanson[75], Guy F. de Téramond[76], Ulrike Thoma[3], Antonio Vairo[77], Danny van Dyk[41], James Vary[51], Javier Virto[78,79], Marcel Vos[80], Christian Weiss[1], Markus Wobisch[81], Sau Lan Wu[82], Christopher Young[83], Feng Yuan[84], Xingbo Zhao[55], Xiaorong Zhou[48]


636 pp!



# Today event generators are taken for granted . . .

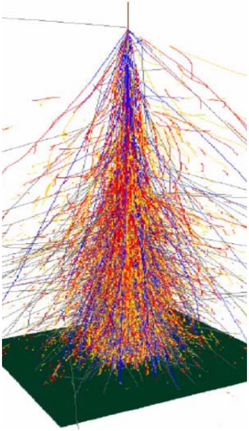


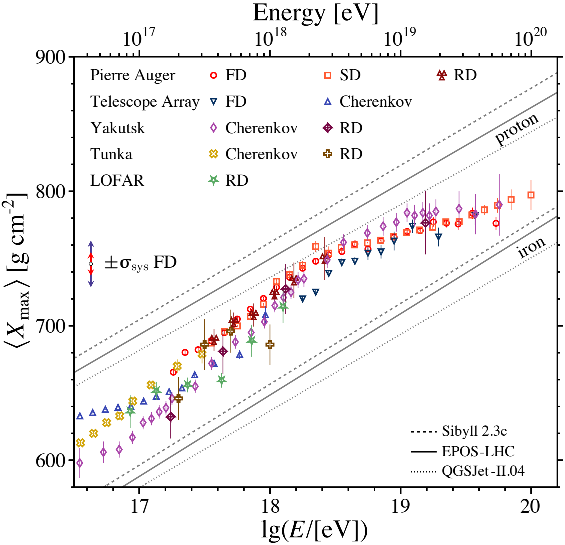




- Kinematics-dependent cross sections for signal + background.
- Smearing and acceptance from detector imperfections.
- Effects of underlying event and pileup.

QCD understanding is the crucial point!

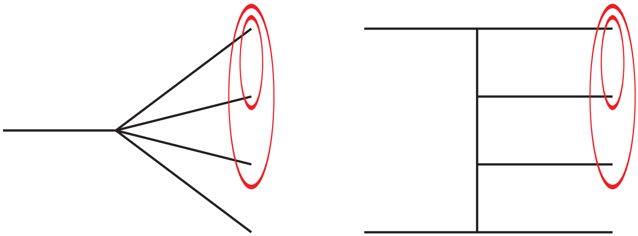
# . . . also in astroparticle physics






How did we arrive here? What next?

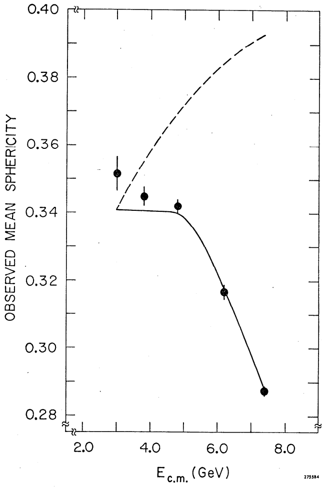
# Monte Carlo pre-QCD



- 1958: Kopylov addresses Fermi model of pions in nuclear collisions, by hand producing 200 random events.
- 1960: Kopylov; Raubold & Lynch : **M (mass) generator** for phase space, with OWL/FOWL implementation used for *s*-channel processes (mainly decays) through 70ies.
- 1968: James, "Monte Carlo Phase Space", CERN 68-15.
- 1969: Byckling & Kajantie, multiperipheral phase space for *t*-channel processes.

# Jet Production at SPEAR (1975)

- Determine jettiness and jet axis by sphericity measure (Bjorken & Brodsky).
- Compare isotropic phase space with "jet model" where one adds $|M|^2 = \exp(-\sum_i p_{\perp i}^2 / 2b^2)$.
- Jet model favoured at higher energies.
- With ansatz $\mathrm{d}\sigma/\mathrm{d}\Omega \propto 1 + \alpha \cos^2\theta$ $\alpha_{\mathrm{observed}} = 0.45 \pm 0.07 \Rightarrow$ $\alpha_{\mathrm{corrected}} = 0.78 \pm 0.12$.
- Quarks produced in $e^+e^-$ have spin 1/2 !




G. Hanson et al. (1975)

# The Simple String

String theory early approach to hadron structure. Here $1+1$-dimensional picture, i.e. no transverse oscillations.

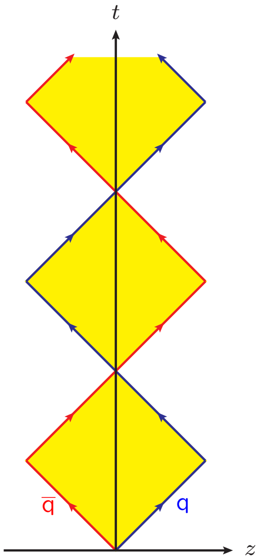
Corresponds to linear potential
$V(r) \approx \kappa r$, where $\kappa \approx 1$ GeV/fm
fixed from Regge trajectory slopes.

Yo-yo motion, where linearity between $(t, z)$ and $(E, p_z)$ gives

$$\left|\frac{\mathrm{d}E}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}t}\right| = \kappa$$

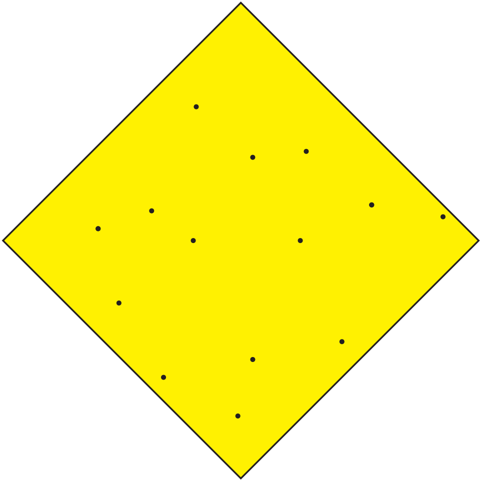
($c = 1$, $m_{\mathrm{q}} \approx 0$) for a $\mathrm{q}\overline{\mathrm{q}}$ pair flying apart along the $\pm z$ axis.

Later supported by lattice QCD.



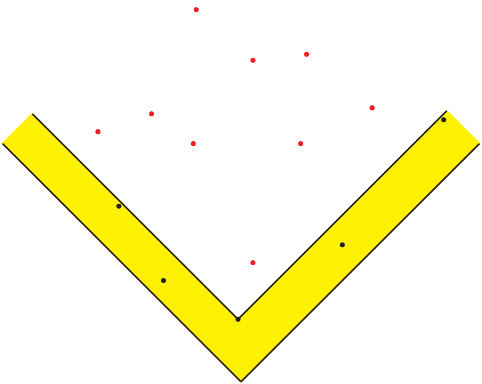
# The Artru-Mennessier Model (1974)

First (semi-)realistic hadronization model.
Assumes fragmentation local, and string homogeneous.
Thus constant probability per unit string area of breaking.



# The Artru-Mennessier Model (1974)

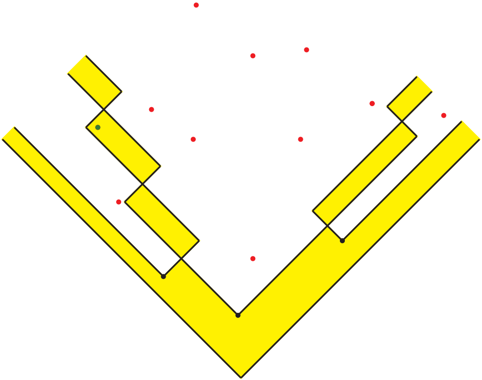
First (semi-)realistic hadronization model.
Assumes fragmentation local, and string homogeneous.
Thus constant probability per unit string area of breaking.



But a string cannot break
where it has already broken
⇒ remove vertices
in forward lightcone
of another

# The Artru-Mennessier Model (1974)

First (semi-)realistic hadronization model.
Assumes fragmentation local, and string homogeneous.
Thus constant probability per unit string area of breaking.



But a string cannot break where it has already broken
$\Rightarrow$ remove vertices in forward lightcone of another

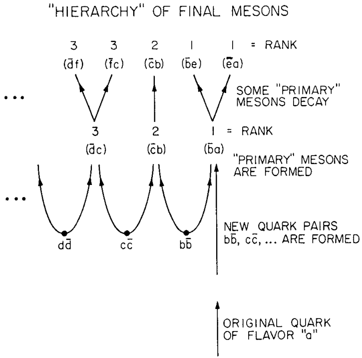
$\Rightarrow$ dampening factor $\exp(-\mathcal{P}\tilde{A})$, where $\tilde{A}$ is string area in the backwards lightcone

Drawback: continuous hadron mass spectrum

# The Field–Feynman Model (1978)

Describes single quark jet as recursive split-off of one hadron at a time w.r.t.

- new flavour $u\bar{u}, d\bar{d}$ or $s\bar{s}$,
- produced hadron (V or PS meson),
- Gaussian transverse momentum,
- fraction of remaining $E + p_z$.



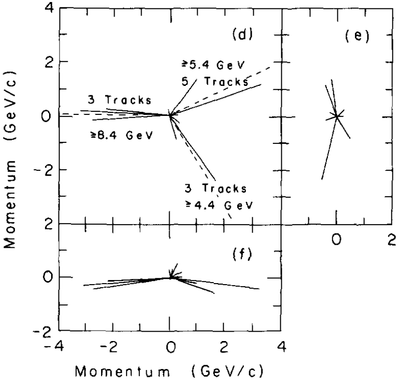

But single jet, so no $E$, $\mathrm{p}$, flavour, colour conservation.
And no understanding of space–time picture, notably time ordering.

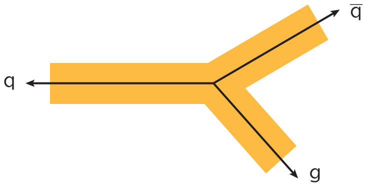
Conceptually less sophisticated than Artru-Mennessier,
but more useful and so immensely successful and influential.
Triggers development of more sophisticated event generators.

# Independent Fragmentation (1979)

FF-based generators for PETRA physics:

- TASSO (internal, 1979), 2 + 3 jet MEs
- Hoyer et al. (1979), 2 + 3 jet MEs, $\mathrm{g} = \mathrm{q}$
- Ali et al. (1980), 2 + 3 + 4 jet MEs, $\mathrm{g} = \mathrm{q}\overline{\mathrm{q}}$

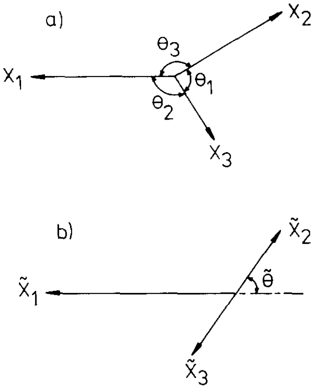


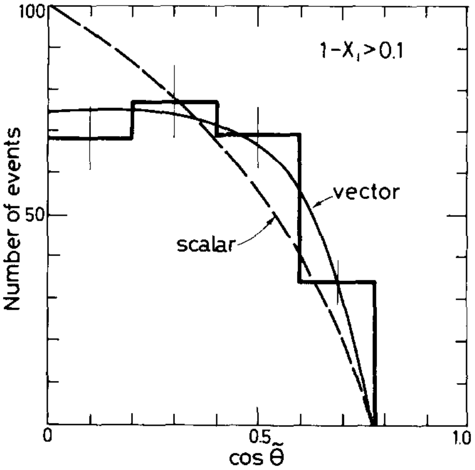




Key assumption:
particle production
aligned along jet axes,
with limited $p_{\perp}$ spread.

# The Gluon Spin (1980)

Ellis–Karliner angle:



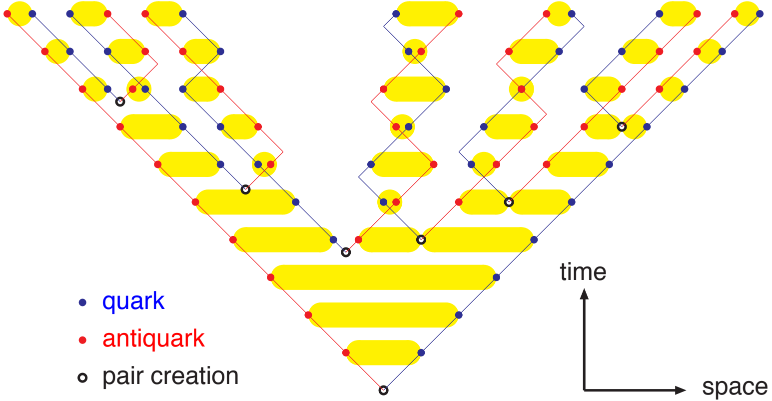




Based on comparisons with Hoyer simulation of both alternatives, taking into account 3-jet selection criteria etc.

TASSO (1980)

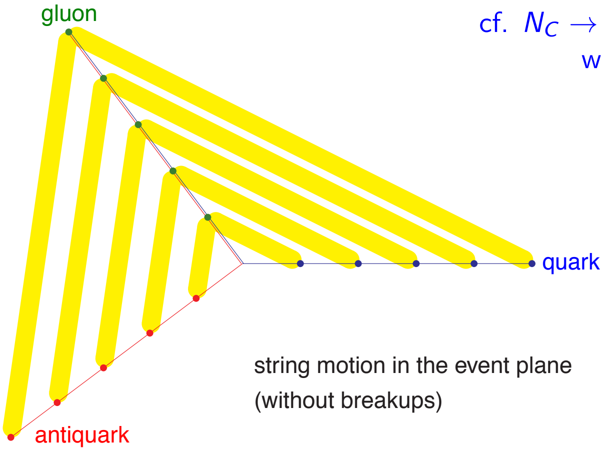
# The Lund Model (1977 — 1982)

String breakup vertices have a spacelike separation
$\Rightarrow$ can use recursive fragmentation from ends inwards
with onshell hadrons, like FF,
but give overall space–time picture similar to Artru-Mennessier.



# The Lund Gluon Picture (1980)

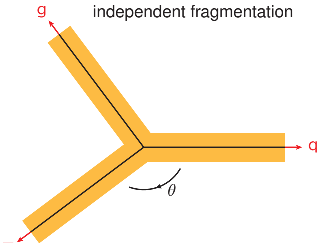
A gluon carries one colour and one anticolour. Thus it can be viewed as a kink on the string, carrying energy and momentum:

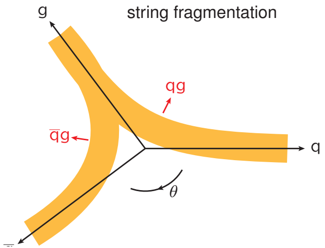


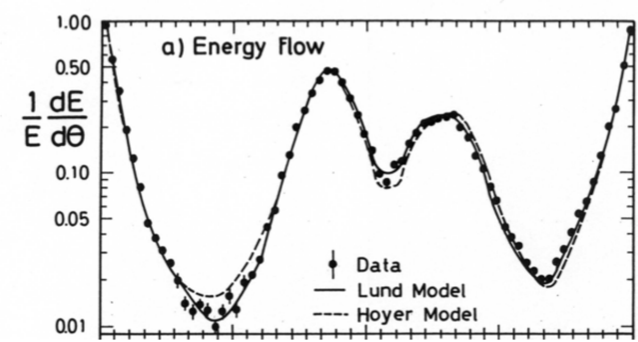

cf. $N_C \to \infty$ (planar QCD)
where $N_C/C_F = 2$.
('t Hooft, 1973)

*The* most characteristic feature of the Lund model.

# The JADE Effect (1980)



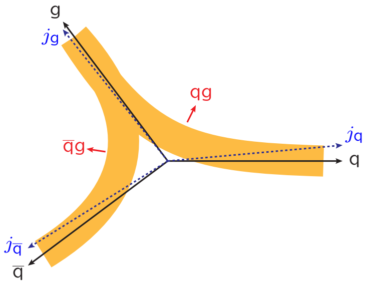




3 jets energy-ordered.
JADE (1980, 1983)

not confirmed by TASSO

# The $\alpha_s$ Confusion ($\sim$ 1982)

CELLO (1982): $\alpha_{s,\mathrm{Lund}}/\alpha_{s,\mathrm{Hoyer}} \approx 1.5$ from 3-jet rate at LO!
$(E, \mathbf{p})$ not preserved when massless partons become massive jets!




Lund: $q\overline{q}$ jets more back-to-back;
gluon jet **p** most reduced.

Hoyer: jet directions preserved;
$\mathbf{p_i}$ rescaled for $\sum \mathbf{p_i} = \mathbf{0}$
$\Rightarrow$ gluon energy increased.

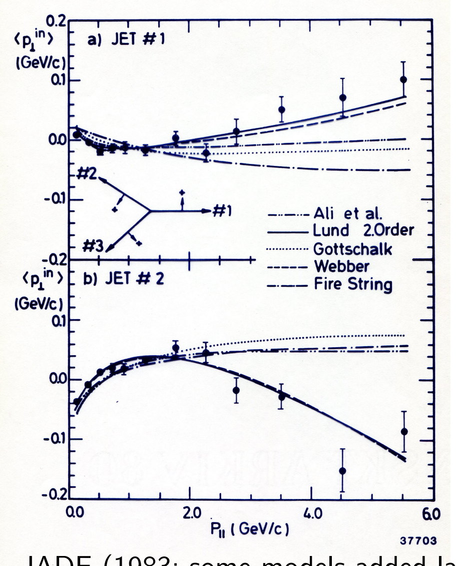
Ali: allow overall boost
$\Rightarrow$ closer to Lund (for $\alpha_s$).

---

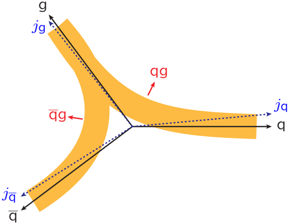
Ellis, Ross, Terrano (1980): NLO $q\overline{q}g$ rate (+ LO 4-parton):

- calculations by a Hamburg/Wuppertal group disagreed
- required numerical integration by user as fn. of $(x_1, x_2; y)$;
- (possibility of negative 3-jet rate someplace).

# The $\alpha_s$ Confusion ($\sim$ 1983)




JADE (1983; some models added later)

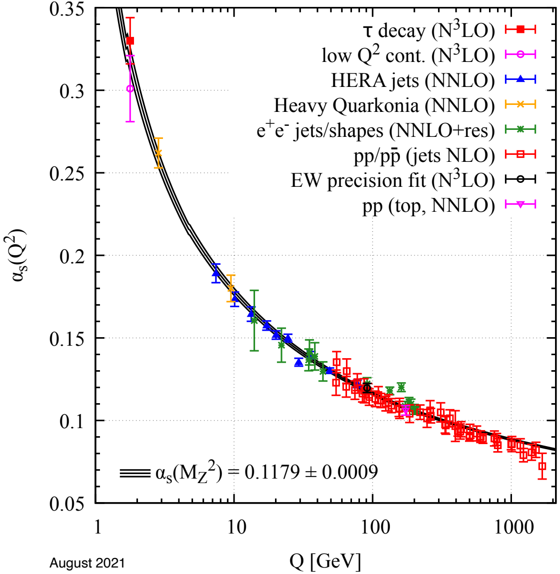



Progress:

- Jets are crooked!
- TASSO found bug
- ERT confirmed

Settled down to
ERT + strings
from $\sim$ 1985

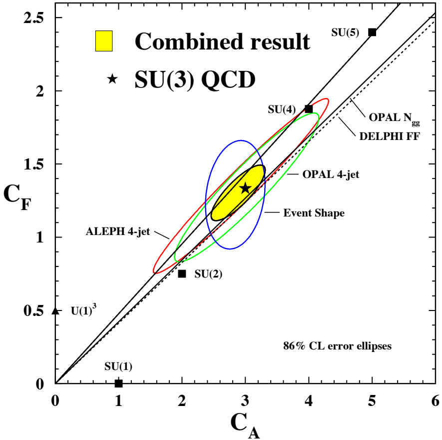
# The running of $\alpha_s$ (2021)



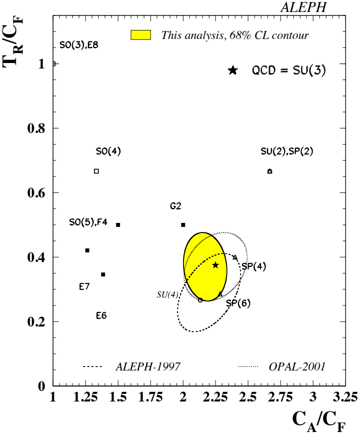

PETRA:
early "precision" measurements,
but limited statistics
makes hints of
running inconclusive.

# Colour Factors ($\sim$ 1991)

Angular correlations in LEP four-jet events
help disentangle colour factors $C_A = N_C$, $C_F$ and $T_R$.
**Final confirmation of QCD!**




compiled by S. Kluth (2003)




ALEPH (2003)

# Parton Showers Intro

- Equivalent Photon Approximation (Bohr; Fermi; Weiszäcker, Williams, 1934)
- **DGLAP**: Gribov, Lipatov (1971), Altarelli, Parisi (1977), Dokshitzer (1977)
- Jet calculus: Konishi, Ukawa, Veneziano (1979)
- First shower (?): Wolfram (+ Fox, Field) (1979)
- More: Odorico (1980), Kajantie, Pietarinen (1980), ...

DGLAP:

$$\begin{aligned} \mathrm{d}\mathcal{P}_{a\to bc} &= \frac{\alpha_{\mathrm{s}}}{2\pi}\,\frac{\mathrm{d}Q^2}{Q^2}\,P_{a\to bc}(z)\,\mathrm{d}z \\ P_{\mathrm{q}\to\mathrm{qg}} &= \frac{4}{3}\,\frac{1+z^2}{1-z} \\ P_{\mathrm{g}\to\mathrm{gg}} &= 3\,\frac{(1-z(1-z))^2}{z(1-z)} \\ P_{\mathrm{g}\to\mathrm{q\overline{q}}} &= \frac{n_f}{2}\,(z^2+(1-z)^2) \end{aligned}$$

**Sudakov form factor**:

$$\Delta(Q_1^2, Q_2^2) = \exp\left( - \int_{Q_2^2}^{Q_1^2} \int_0^1 \mathrm{d}\mathcal{P}_{a\to bc} \right)$$

Event generation with the **veto algorithm**.

# Angular Ordering (1983)

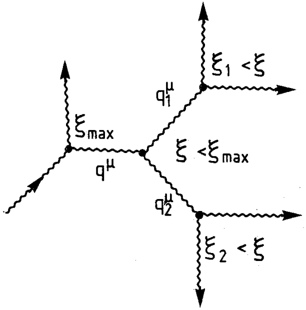
Ambiguous interpretation of evolution variable $Q^2$

$$\frac{\mathrm{d}M^2}{M^2}\mathrm{d}z = \frac{\mathrm{d}p_\perp^2}{p_\perp^2}\mathrm{d}z = \frac{\mathrm{d}\theta^2}{\theta^2}\mathrm{d}z$$

since $p_\perp^2 \approx z(1-z)M^2$ and $\theta^2 \approx M^2/(z(1-z))$.

Marchesini, Webber (1983):
effects of soft-gluon destructive interference can be emulated in an angularly-ordered cascade.

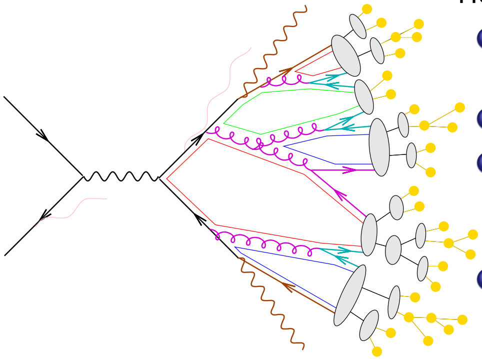
Note: softer partons tend to be emitted earlier and harder ones later.




$$\xi \approx 1 - \cos\theta \approx \theta^2/2$$

# The Cluster Model (1980)

Wolfram (1980), Webber (1983), . . . :
"preconfinement" ≈ adjacent partons in a shower form low-mass systems (when evolved to a low cut-off scale $Q_0$).

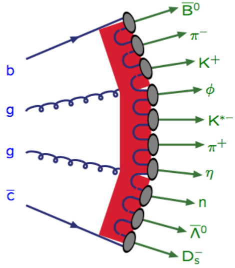


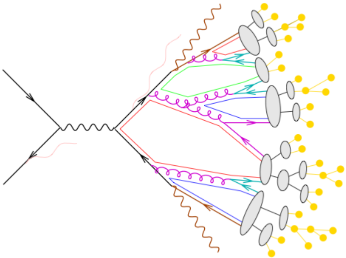
Herwig scheme:

1. Force $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ branchings ($m_{\mathrm{g}} > 2m_{\mathrm{u/d}}$ on lattice).
2. Form colour singlet clusters.
3. Decay high-mass clusters to smaller clusters along "string" direction.
4. Decay clusters to 2 hadrons according to phase space times spin weight.

Many further refinements added over the years.

# String vs. Cluster



| | | |
|---|---|---|
| program | PYTHIA | Herwig, SHERPA |
| model | string | cluster |
| energy–momentum picture | powerful | simple |
| | predictive | unpredictive |
| parameters | few | many |
| flavour composition | messy | simple |
| | unpredictive | in-between |
| parameters | many | few |

Free parameters abound in each nonperturbative description.

# The Dipole Approach (1985)

Azimov, Dokshitzer, Khoze, Troyan (1985):
the radiation pattern of a secondary soft gluon $\mathrm{g}_2$ around a (hard) $\mathrm{q}\overline{\mathrm{q}}\mathrm{g}_1$ topology is approximately

$$W(\mathbf{n}_2) \sim N_c \left( \widehat{\mathrm{qg}_1} + \widehat{\overline{\mathrm{q}}\mathrm{g}_1} \right) - \frac{1}{N_C} \widehat{\mathrm{q}\overline{\mathrm{q}}}$$

where a dipole factor

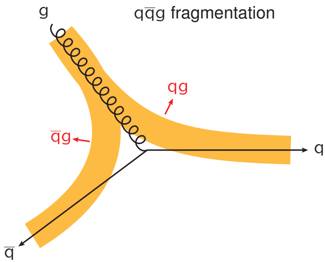
$$\widehat{ab} \sim \frac{(p_a p_b)}{(p_a p_{\mathrm{g}_2})(p_b p_{\mathrm{g}_2})} \propto \frac{(1 - \mathbf{n}_a \mathbf{n}_b)}{(1 - \mathbf{n}_a \mathbf{n}_2)(1 - \mathbf{n}_b \mathbf{n}_2)}$$

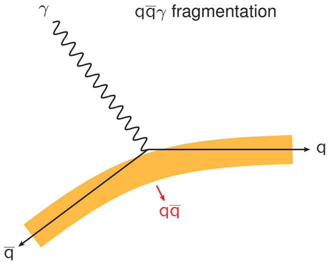
for massless partons with $p_i = E_i(1; \mathbf{n}_i)$

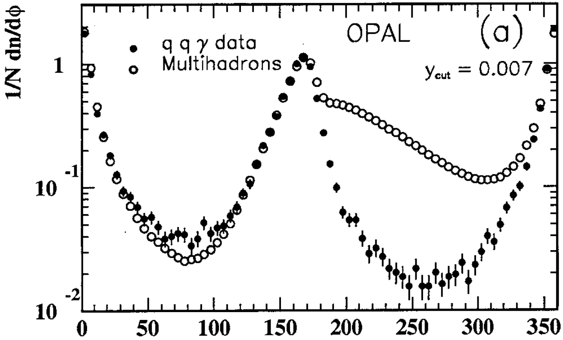
Perturbative soft-gluon emissions give the same radiation pattern as the nonperturbative string picture in the $N_C \to \infty$ limit.

Both effects contribute, but in absolute terms the perturbative contribution increases with energy and overtakes the constant string one at around $E_{\mathrm{CM}} = 100$ GeV ($=$ LEP 1).

# Photon vs. Gluon Emission (1985)



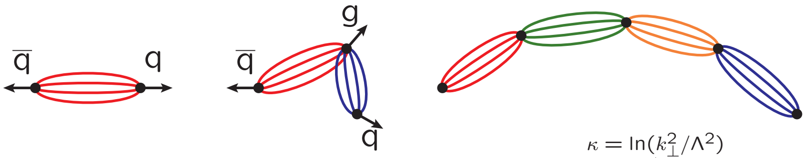




particle flow in the event plane; 3-jet selection, but third jet location not fixed

OPAL (1995)

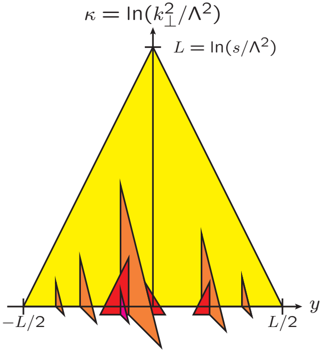
G. Gustafson (1986): dual description of partonic state:
partons connected by dipoles ⇔ dipoles stretched between partons
**parton branching ⇔ dipole splitting**



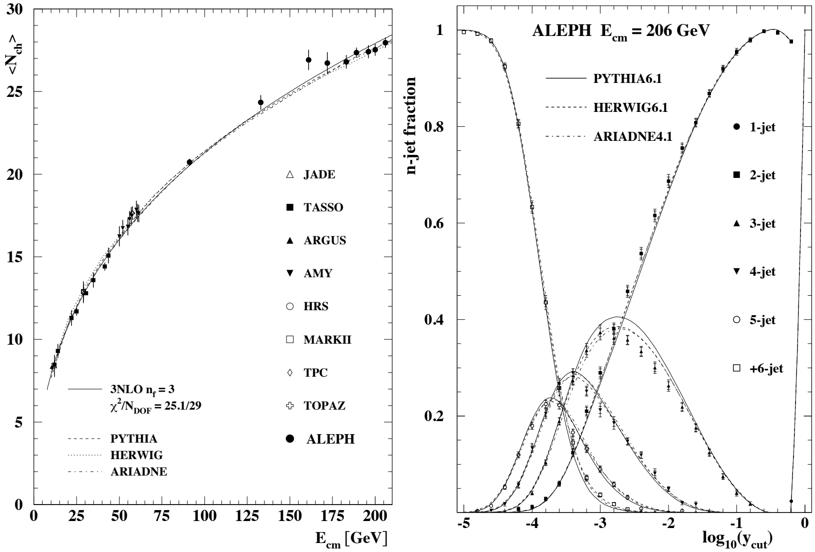

$p_\perp$-ordered dipole emissions ⇒
**coherence** (cf. angular ordering).

$2 \to 3$ on-shell parton branchings
with local $(E, \mathbf{p})$ conservation.
ARIADNE shower + many more.

B. Andersson, G. Gustafson (1990):
neat representation in **Lund plane**
(hot topic today).



# Example of $e^+e^-$ Event Properties

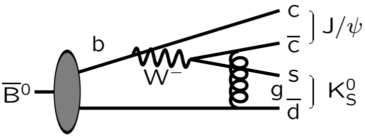


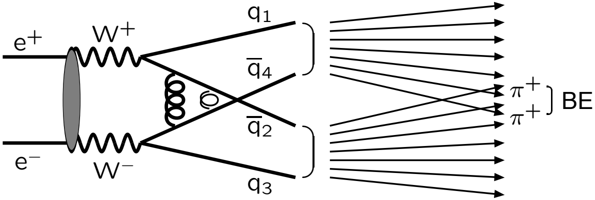

Need both showers and hadronization!

ALEPH (2003)

# Interconnection

Colour rearrangement well established e.g. in B decay.

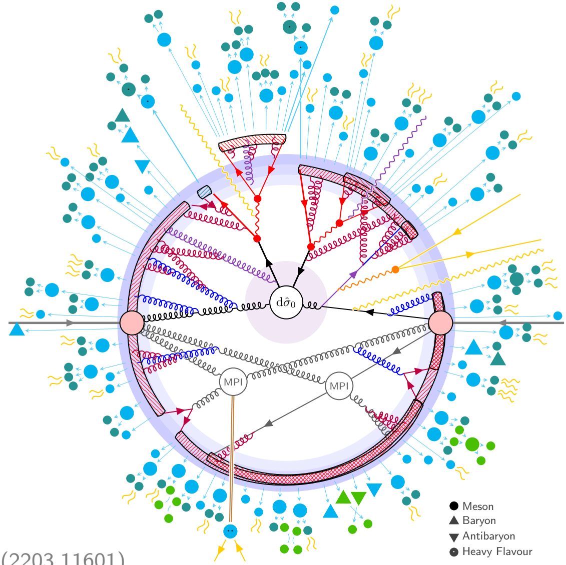



At LEP 2 search for effects in $e^+e^- \to W^+W^- \to q_1\overline{q}_2\, q_3\overline{q}_4$:

- perturbative $\langle \delta M_W \rangle \lesssim$ 5 MeV : negligible!
- nonperturbative $\langle \delta M_W \rangle \sim$ 40 MeV : **favoured**; no-effect option ruled out at $2.8\sigma$.
- Bose-Einstein $\langle \delta M_W \rangle \lesssim$ 100 MeV : full effect ruled out (while models with $\sim$ 20 MeV barely acceptable).

# The structure of an LHC pp collision




(2203.11601)

- Hard Interaction
- Resonance Decays
- MECs, Matching & Merging
- FSR
- ISR*
- QED
- Weak Showers
- Hard Onium

---

- Multiparton Interactions

---

- Beam Remnants*
- Strings
- Ministrings / Clusters
- Colour Reconnections
- String Interactions
- Bose-Einstein & Fermi-Dirac
- Primary Hadrons
- Secondary Hadrons
- Hadronic Reinteractions

*(*: incoming lines are crossed)*

# Hadron Collision Generators

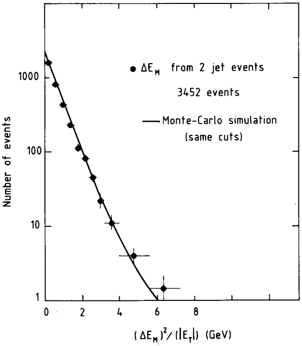
- Early days mostly simple longitudinal phase space.
  Evolved over time, e.g. UA5 Monte Carlo tuned to multiplicity distribution, $y$ and $p_\perp$ spectra, particle composition, etc., but no jets and weak on correlations.
- 1980 ISAJET begun by F. Paige and S. Protopopescu for ISABELLE studies.
  Main generator for most $\mathrm{pp}/\mathrm{p\overline{p}}$ physics in the 1980'ies.
- 1982: (Wolfram), Fox, Field, Kelly $\Rightarrow$ FieldAJet
  used to present SSC predictions, but never public (and slow)
- Other generators developed but with limited impact:
  COJETS/WIZJET (R. Odorico, 1984),
  EUROJET (B. Van Eijk, 1985), . . .

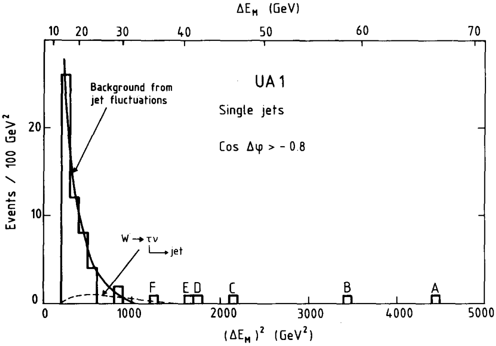
# Early Days: SUSY Speculations (1984)

Volume 139B, number 1,2 PHYSICS LETTERS 3 May 1984

**EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON (S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV**

UA1 Collaboration, CERN, Geneva, Switzerland




S. Ellis, R. Kleiss, J Stirling: cocktail of small SM contributions!

Also UA1 1984 "40 GeV top signal" eventually went away.

# Current Workhorses

Herwig, PYTHIA and Sherpa offer convenient frameworks for LHC $\mathrm{pp}$ physics studies, covering all aspects above, but with slightly different history/emphasis:

PYTHIA (successor to JETSET, begun in 1978):
originated in hadronization studies;
still special interest in soft physics.

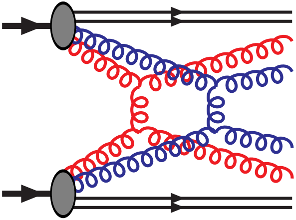
Herwig (successor to EARWIG, begun in 1984):
originated in coherent showers (angular ordering);
cluster hadronization as simple complement.

Sherpa (APACIC++/AMEGIC++, begun in 2000):
has own matrix-element calculator/generator;
originated with matching & merging issues.

# MultiParton Interactions (1985)

1. Multiple cut pomerons and dual topological unitarization, and
2. double (hard) parton scattering

combined to picture with multiple (semi)perturbative interactions:



Colour screening from finite proton size (confinement):

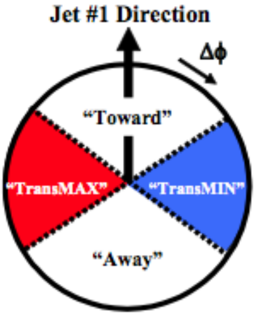
$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \quad \to \quad \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4}\,\theta\left(p_\perp - p_{\perp\mathrm{min}}\right) \qquad \text{(simpler)}$$

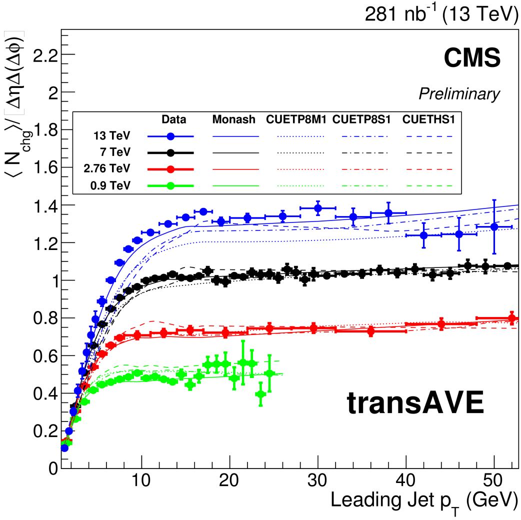
$$\text{or} \quad \to \quad \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2} \qquad \text{(more physical)}$$

**At LHC** $p_{\perp 0} \approx 3$ **GeV and** $\langle n_{\mathrm{MPI}} \rangle \approx 3 - 4$**.**
Absolutely essential for minimum-bias and underlying event: average activity level and fluctuations. DPS also observed at LHC.

# The Pedestal Effect (1983)

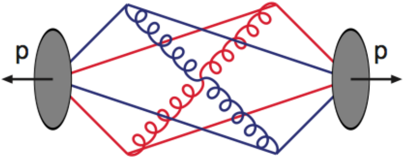
Events with hard scale (jet, W/Z) have more underlying activity! (UA1, 1983)



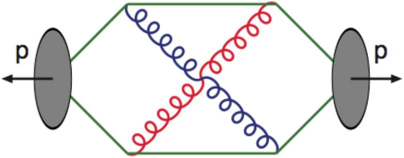




Protons are extended ⇒ impact-parameter. "Trigger bias" for hard interactions to occur in central collisions.

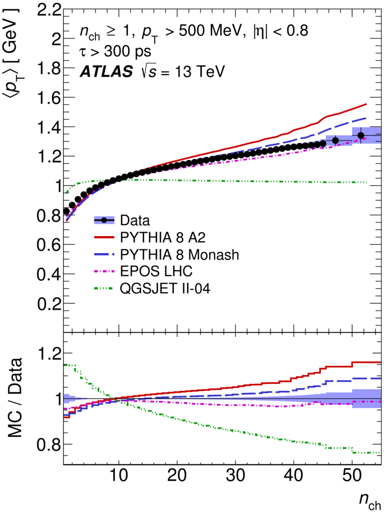
$\langle p_\perp \rangle(n_{ch})$ is very sensitive to colour flow




long strings to remnants $\Rightarrow$ much $n_{ch}$/interaction $\Rightarrow \langle p_\perp \rangle(n_{ch}) \sim$ flat




short strings (more central) $\Rightarrow$ less $n_{ch}$/interaction $\Rightarrow \langle p_\perp \rangle(n_{ch})$ rising



# The Breakdown of Jet Universality

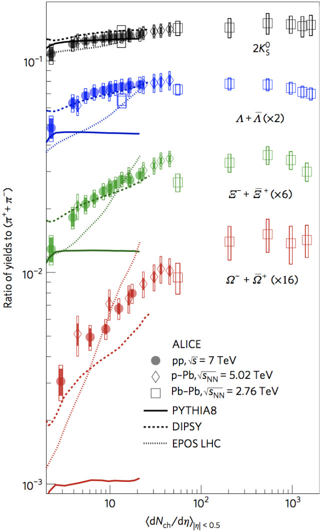
Overall generators are successful for perturbative physics.
What about nonperturbative physics at the LHC?

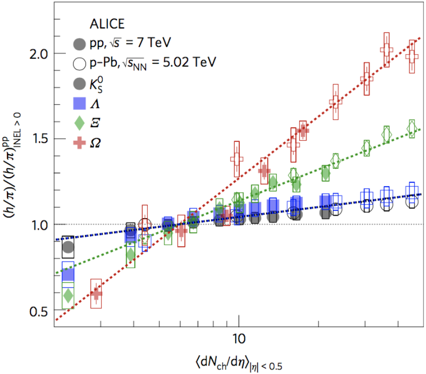
Jet universality old concept; current interpretation:
A hadronization model, once tuned to LEP data,
should be directly applicable to other collisions, notably LHC $\mathrm{pp}$.
(AA Quark–Gluon Plasma physics excepted.)

**Proven wrong at the LHC**, in particular by

- strange baryon enhancement,
- charm/bottom hadron composition, and
- the ridge and collective flow.

# Strangeness enhancement (2016)



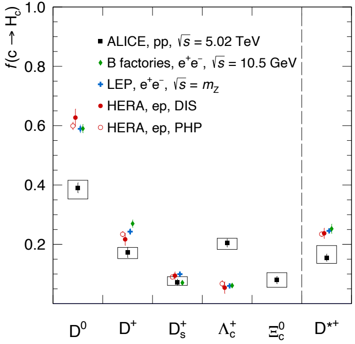

(Also observed in $\mathrm{B_s}/\mathrm{B}^0$ by LHCb.)

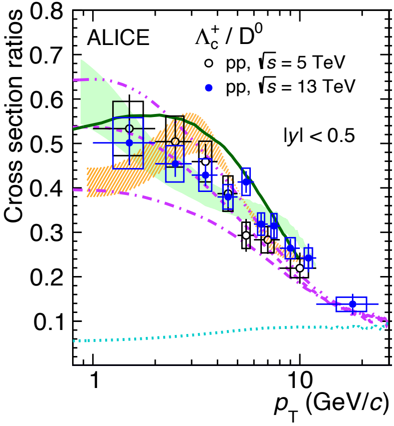
**Signs of QGP in high-multiplicity pp collisions? If not, what else?**

Core–corona? Ropes?

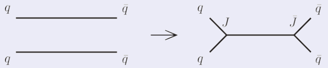
# The charm baryon enhancement (2017)

In 2017/21 ALICE found/confirmed strong enhancement of charm baryon production, relative to LEP, HERA and default PYTHIA.



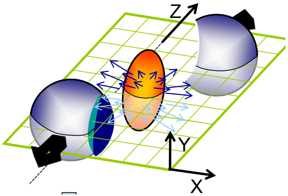

**Double junction reconnection**




(qq: 1/3, gg: 10/64, model: 2/9)

Christiansen, Skands (2015): QCD-inspired CR (QCDCR)

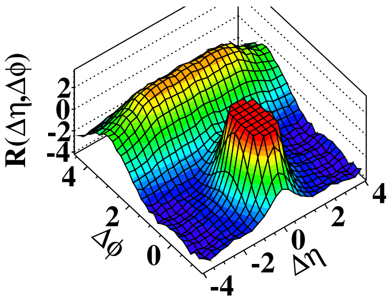
# The Ridge Effect (2010)



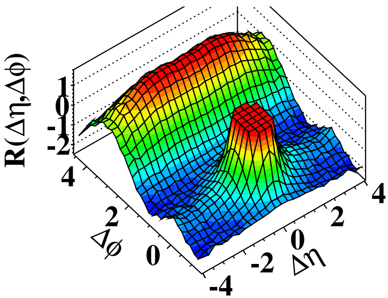

Elliptic flow in AA predicted from geometry + pressure.

Not so for pp, and yet ridge is observed at high multiplicities:

(c) CMS N ≥ 110, $p_T$>0.1GeV/c




(d) CMS N ≥ 110, 1.0GeV/c<$p_T$<3.0GeV/c




QGP? Shove/repulsion? Hadronic rescattering?

# Apologies

Many high-energy physics aspects not covered, e.g.

- perturbative higher-order calculations,
- next-to-leading-log parton showers, and
- the matching and merging of matrix elements and showers.
- Parton Distribution Functions,
- HERA $\mathrm{ep}$ physics: PDFs, rapidity gaps, photoproduction, . . . ,
- LEP $\gamma\gamma$ physics,
- $\sigma_{\mathrm{tot}}$, $\rho$, diffraction,
- heavy flavour production,
- Quark–Gluon Plasma modelling of heavy ion collisions,
- cosmic ray physics (cascades in the atmosphere), and
- QCD aspects of BSM physics,
  e.g. hidden sectors with showers and hadronization.

# Summary

With the help of event generators we have established that

- quarks have spin $1/2$;
- gluons have spin 1;
- colour factors $C_A = 3$, $C_F = 4/3$, $T_R = 1/2$ as expected;
- $\alpha_\mathrm{s}$ runs in agreement with QCD and $\alpha_\mathrm{s}(M_\mathrm{Z}) \approx 0.12$;
- perturbative evolution is strongly influenced by coherence;
- confinement leads to hadronization along colour lines (strings or cluster chains);
- multiparton interactions and colour reconnection are needed;
- jet universality is broken at low $p_\perp$ and high multiplicity.

**Nonperturbative pp LHC physics not yet fully understood.**
**Several ideas floating around, but no complete picture.**