The Role of Event Generators
(in the exploration of QCD)

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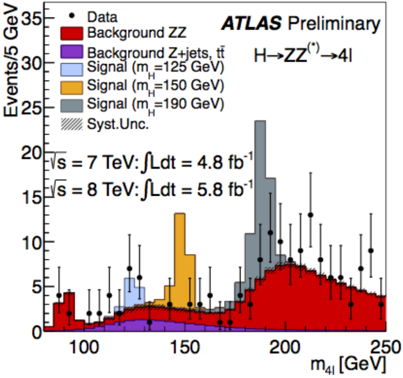
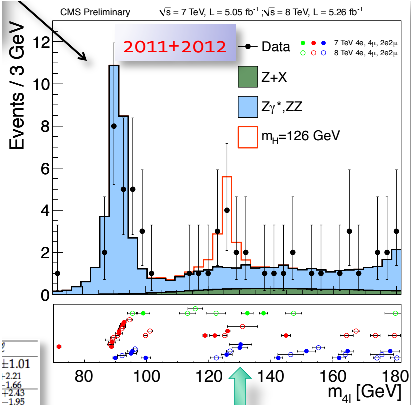
50 Years of Quantum Chromodynamics,
UCLA, 11 – 15 Sep 2023

Today event generators are taken for granted:

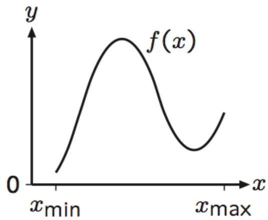


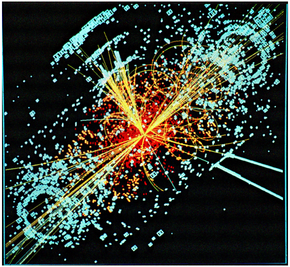


- Kinematics-dependent cross sections for signal + background.
- Smearing and acceptance from detector imperfections.
- Effects of underlying event and pileup.

How did we arrive here? What next?

Terminology





1997 CMS $\mathrm{H}^0 \to 2\ell 2j$

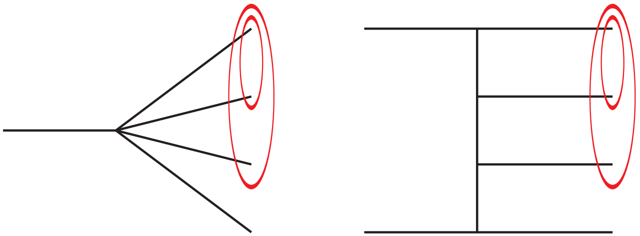
Monte Carlo: use random numbers to integrate or draw from a distribution. Converges faster than traditional integration for a multidimensional space. Standard example: flat probability in *n*-body phase space, or weighted by matrix element.

Event Generation: Monte Carlo simulation of a complete collision process.

Monte Carlo Event Generator (MCEG): longhand for event generator.

Detector simulation: geometry tracking and secondary collisions with detector materiel; GEANT recursively can use MCEGs.

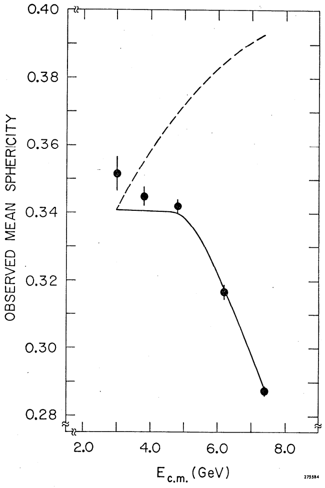
Monte Carlo pre-QCD



- 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.

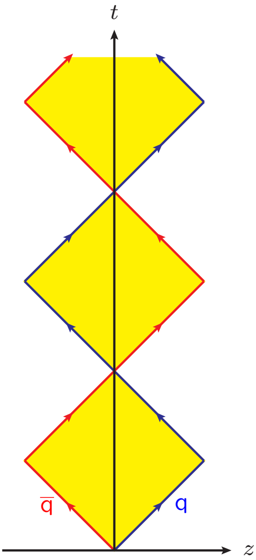
Corresponds to linear potential $V(r) \approx \kappa r$, where $\kappa \approx 1$ GeV/fm fixed from Regge trajectory slopes.

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

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

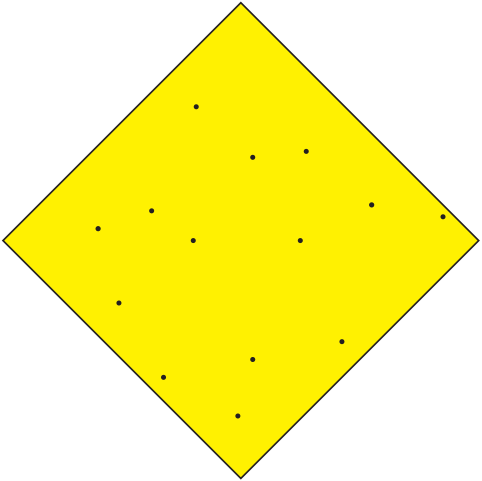
$(c = 1,\ m_{\mathrm{q}} \approx 0)$ for a $\mathrm{q}\overline{\mathrm{q}}$ pair flying apart along the $\pm z$ axis.

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.



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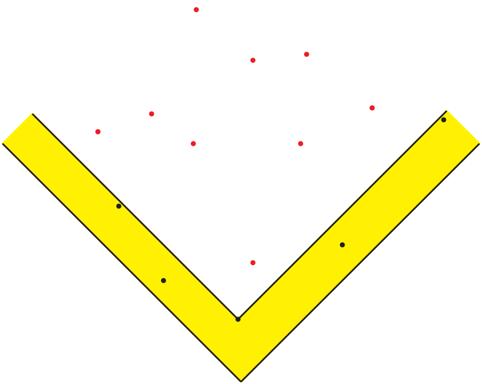

But a string cannot break
where it has already broken
$\Rightarrow$ remove vertices
in forward lightcone
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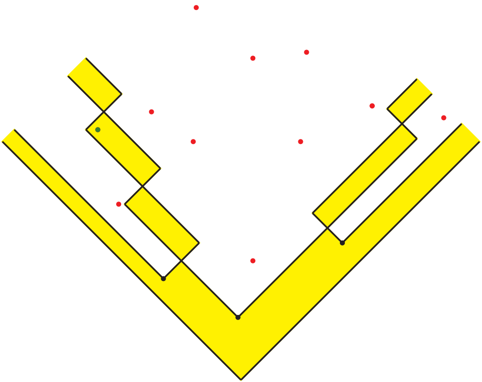

But a string cannot break
where it has already broken
$\Rightarrow$ remove vertices
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of another

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

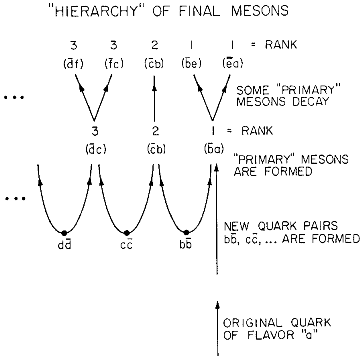
Drawback: continuous
hadron mass spectrum

The Field–Feynman Model (1978)

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

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

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

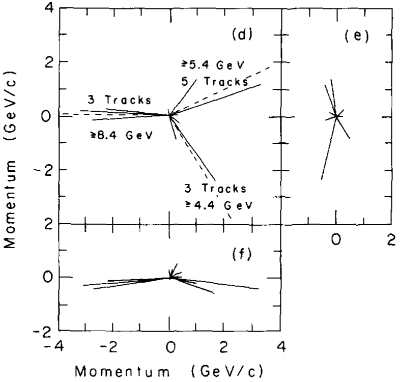


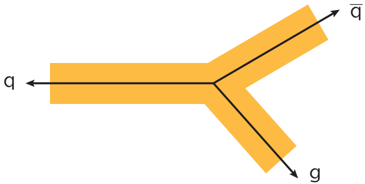
Conceptually less sophisticated than Artru-Mennessier,
but more useful and so immensely successful and influential.
Triggers development of more sophisticated event generators.

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, $\mathrm{g} = \mathrm{q}\overline{\mathrm{q}}$

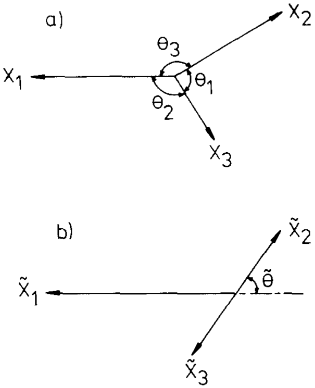


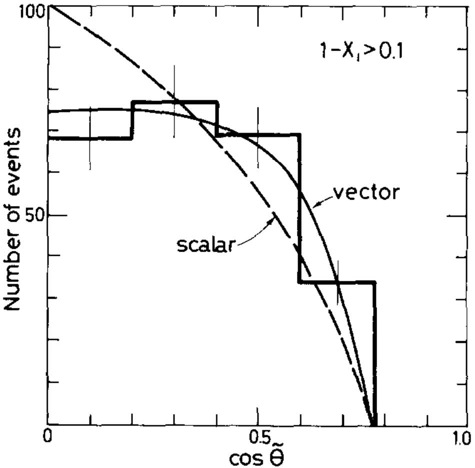


Key assumption:
particle production
aligned along jet axes,
with limited $p_\perp$ spread.

The Gluon Spin (1980)

Ellis–Karliner angle:



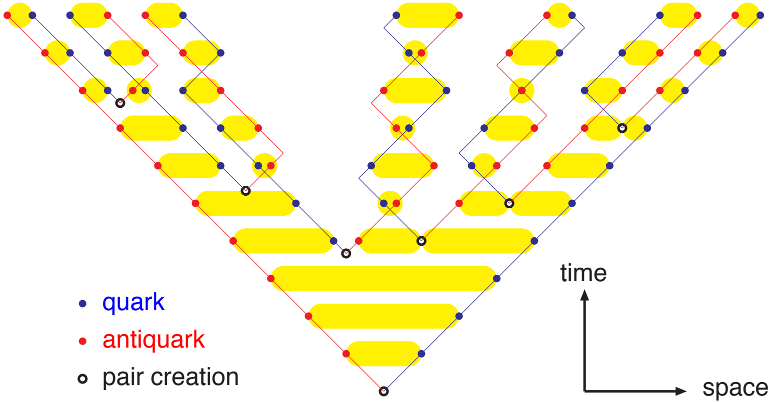


Based on comparisons with Hoyer simulation of both alternatives, taking into account 3-jet selection criteria etc.

TASSO (1980)

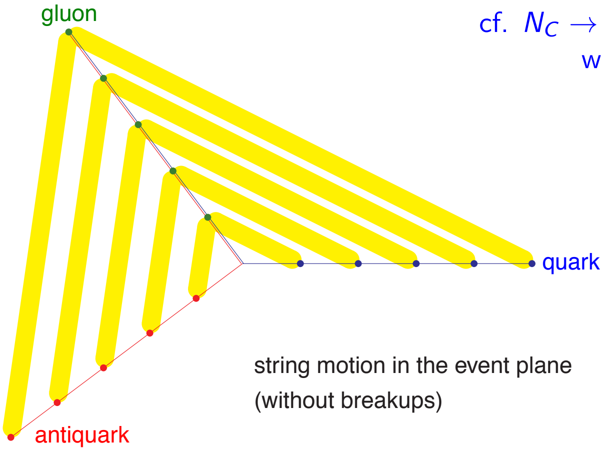
The Lund Model (1977 — 1982)

String breakup vertices have a spacelike separation
⇒ 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)

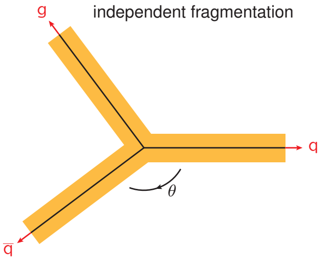
A gluon carries one colour and one anticolour. Thus it can be viewed as a kink on the string, carrying energy and momentum:

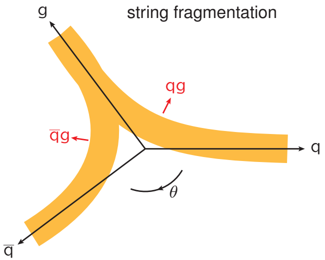


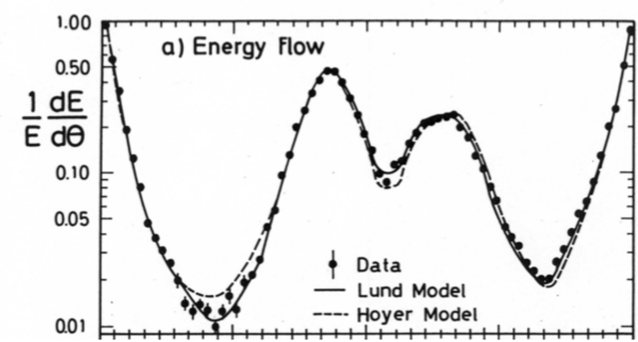
cf. $N_C \to \infty$ (planar QCD)
where $N_C / C_F = 2$.
('t Hooft, 1973)

The most characteristic feature of the Lund model.

The JADE Effect (1980)







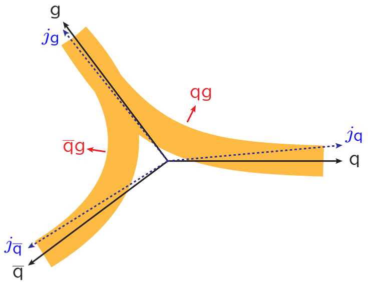
3 jets energy-ordered.

JADE (1980, 1983)

not confirmed by TASSO

The α_s Confusion ($\sim$ 1983)

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: $q\bar{q}$ jets more back-to-back;
gluon jet $\mathbf{p}$ 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 α_s).

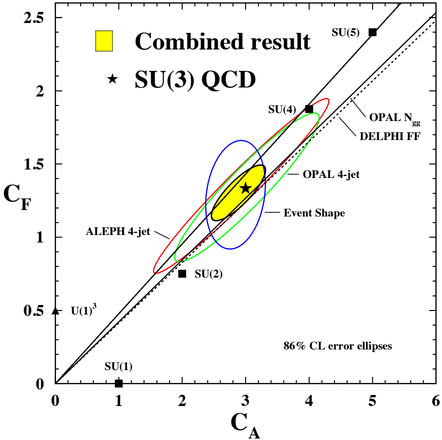
Ellis, Ross, Terrano (1980): NLO $q\bar{q}g$ rate (+ LO 4-parton):

- alternative calculations eventually falsified;
- required numerical integration by user as fn. of $(x_1, x_2; y)$;
- (possibility of negative 3-jet rate someplace).

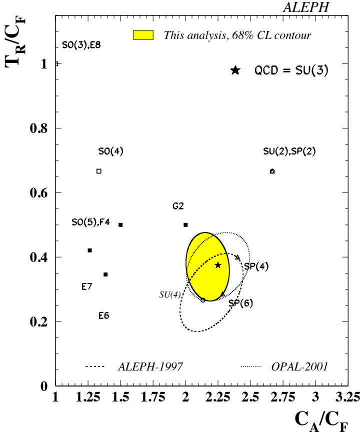
Settled down to ERT + strings from $\sim$ 1985

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)

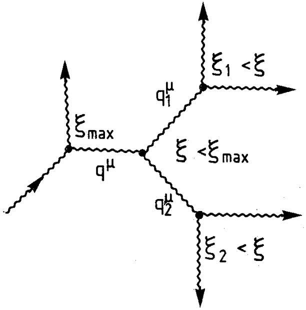
Ambiguous interpretation of evolution variable Q^2

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

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.

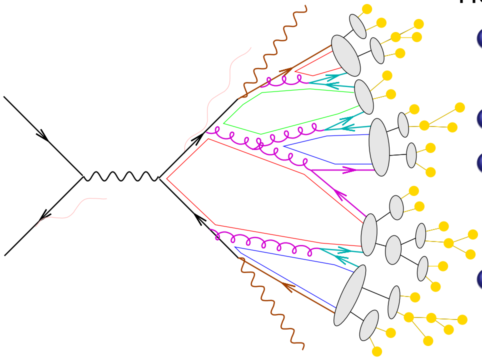
Note: softer partons tend to be emitted earlier and harder ones later.



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

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).

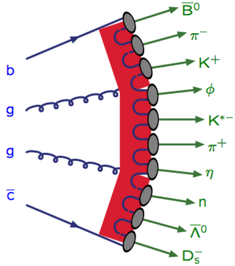


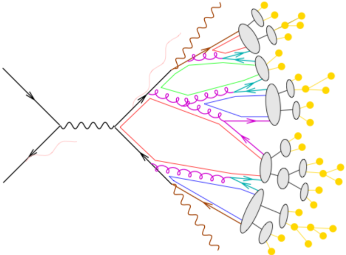
Herwig scheme:

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 g_2
around a (hard) $\mathrm{q\overline{q}g_1}$ topology is approximately

$$W(\mathbf{n}_2) \sim N_c \left(\widehat{\mathrm{qg_1}} + \widehat{\mathrm{\overline{q}g_1}} \right) - \frac{1}{N_C} \widehat{\mathrm{q\overline{q}}}$$

where a dipole factor

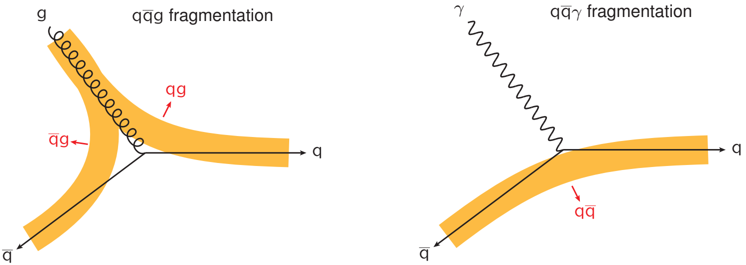
$$\widehat{ab} \sim \frac{(p_a p_b)}{(p_a p_{\mathrm{g}_2})(p_b p_{\mathrm{g}_2})} \propto \frac{(1 - \mathbf{n}_a \mathbf{n}_b)}{(1 - \mathbf{n}_a \mathbf{n}_2)(1 - \mathbf{n}_b \mathbf{n}_2)}$$

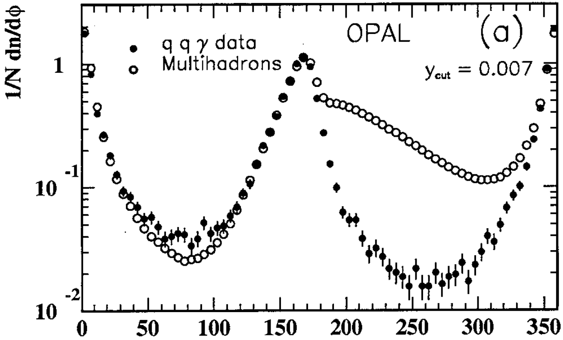
for massless partons with $p_i = E_i(1; \mathbf{n}_i)$

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)



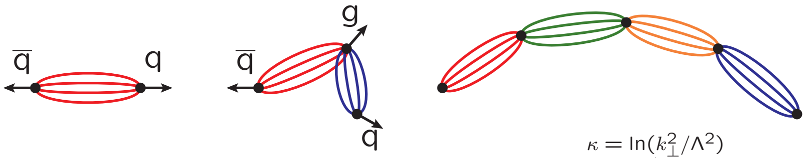


particle flow in the event plane; 3-jet selection, but third jet location not fixed

OPAL (1995)

The Dipole Shower (1986)

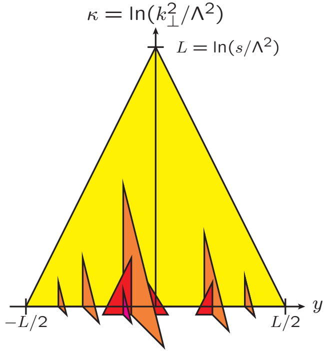
G. Gustafson (1986): dual description of partonic state:
partons connected by dipoles ⇔ dipoles stretched between partons
parton branching ⇔ dipole splitting



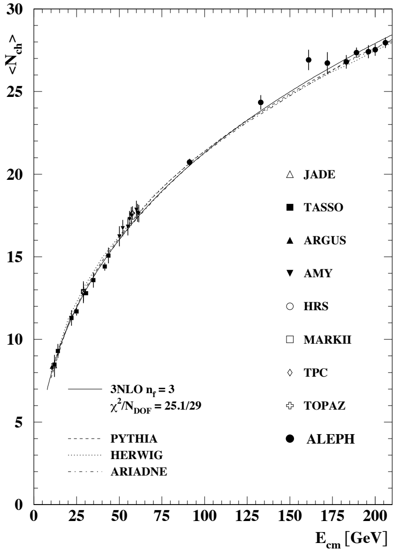
$p_\perp$-ordered dipole emissions ⇒
coherence (cf. angular ordering).

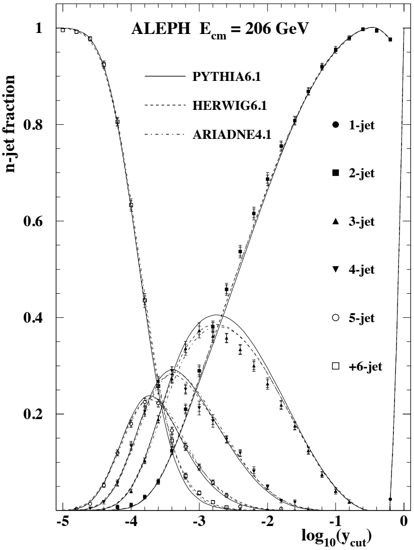
2 → 3 on-shell parton branchings
with local $(E, \mathbf{p})$ conservation.
ARIADNE shower + many more.

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



Example of e^+e^- Event Properties



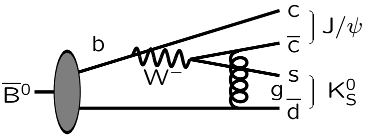


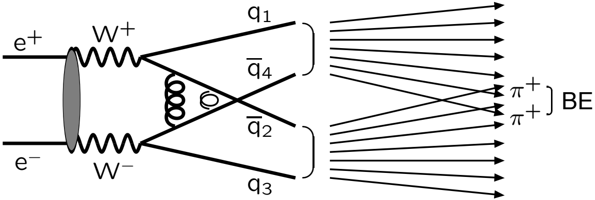
Need both showers and hadronization!

ALEPH (2003)

Interconnection

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

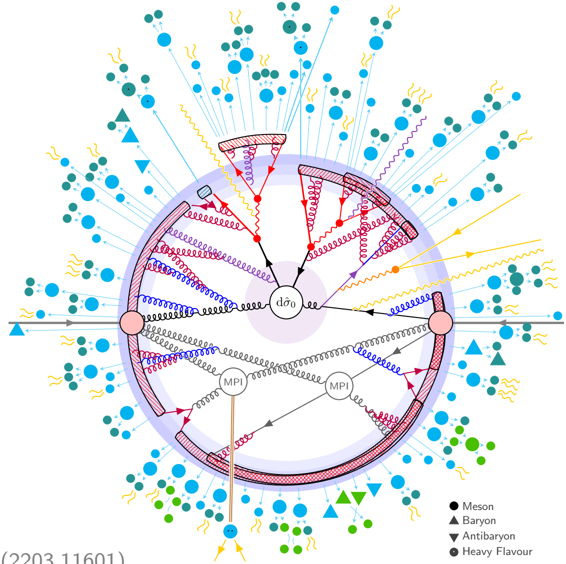




At LEP 2 search for effects in $e^+e^- \to W^+W^- \to q_1\overline{q}_2\, q_3\overline{q}_4$:

- 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 2.8σ.
- Bose-Einstein $\langle \delta M_W \rangle \lesssim 100$ MeV : full effect ruled out (while models with ~ 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

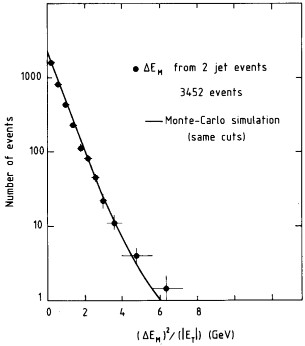
- Early days mostly simple longitudinal phase space. Evolved over time, e.g. UA5 Monte Carlo tuned to multiplicity distribution, y and $p_{\perp}$ spectra, particle composition, etc., but no jets and weak on correlations.
- 1980 ISAJET begun by F. Paige and S. Protopopescu for ISABELLE studies.
  Main 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), ...

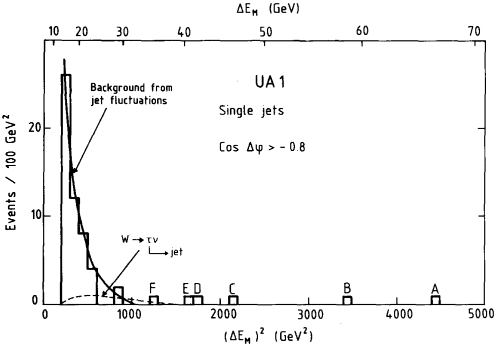
Early Days: SUSY Speculations (1984)

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 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.

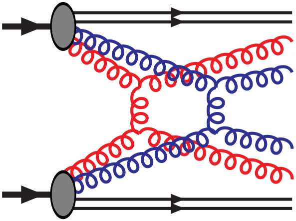
Herwig (successor to EARWIG, begun in 1984):
originated in coherent showers (angular ordering);
cluster hadronization as simple complement.

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):

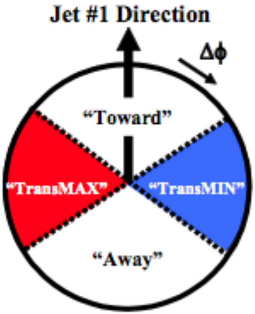
$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \quad \to \quad \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4}\,\theta\left(p_\perp - p_{\perp\mathrm{min}}\right) \qquad \text{(simpler)}$$

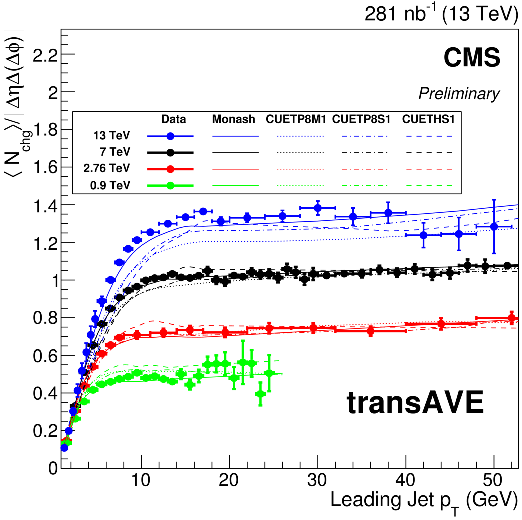
$$\text{or} \quad \to \quad \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2} \qquad \text{(more physical)}$$

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)

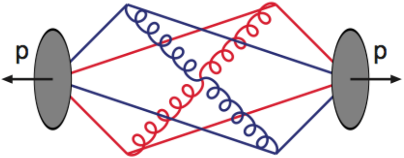




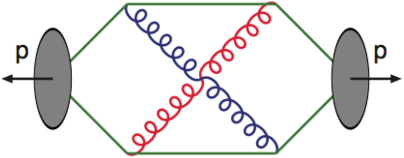
Protons are extended ⇒ impact-parameter. "Trigger bias" for hard interactions to occur in central collisions.

Colour Reconnection (1985)

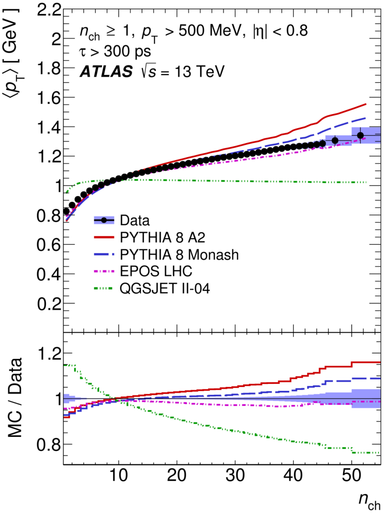
$\langle p_\perp \rangle(n_{ch})$ is very sensitive to colour flow



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

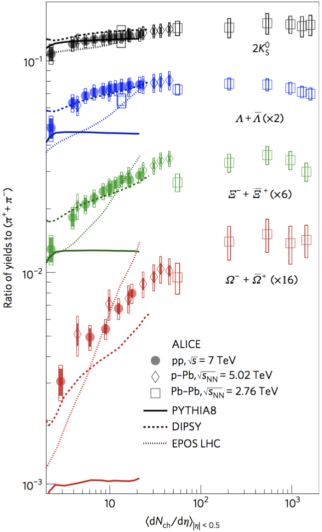
Overall generators are successful for perturbative physics.
What about nonperturbative physics at the LHC?

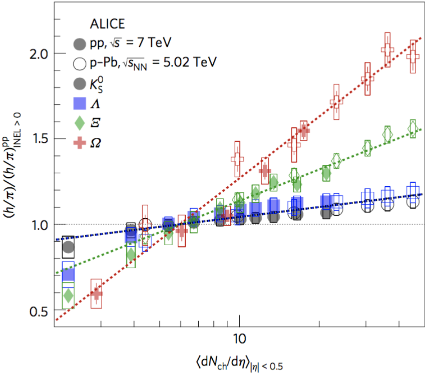
Jet universality old concept; current interpretation:
A hadronization model, once tuned to LEP data,
should be directly applicable to other collisions, notably LHC pp.
(AA Quark–Gluon Plasma physics excepted.)

Proven wrong at the LHC, in particular by

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

Strangeness enhancement (2016)



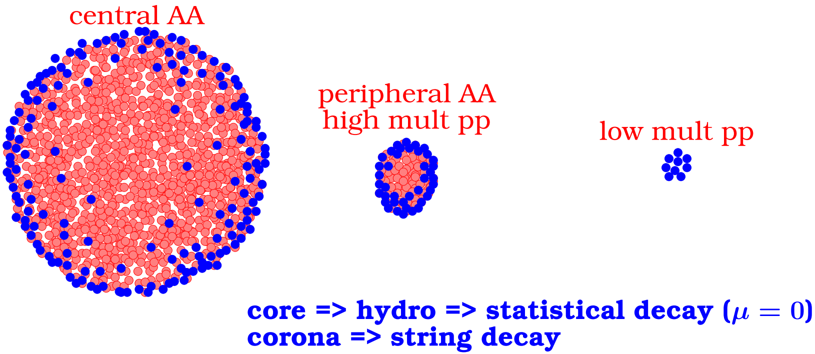


(Also observed in $\mathrm{B_s}/\mathrm{B}^0$ by LHCb.)

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

The Core–Corona Solution (2007)

Currently most realistic “complete” approach:
mix discrete strings with continuous quark–gluon plasma.



Allows smooth transition. Implemented in **EPOS** MC
K. Werner, PRL 98 (2007) 152301

Qualitatively agrees with ALICE, but too steep rise.

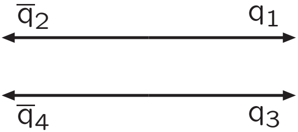
The Rope Solution (2015)

Dense environment $\Rightarrow$ several intertwined strings $\Rightarrow$ **rope**.

Sextet example:

$3 \otimes 3 = 6 \oplus \overline{3}$

$C_2^{(6)} = \frac{5}{2} C_2^{(3)}$



At first string break $\kappa_{\mathrm{eff}} \propto C_2^{(6)} - C_2^{(3)} \Rightarrow \kappa_{\mathrm{eff}} = \frac{3}{2}\kappa$.

At second string break $\kappa_{\mathrm{eff}} \propto C_2^{(3)} \Rightarrow \kappa_{\mathrm{eff}} = \kappa$.

Multiple ~parallel strings $\Rightarrow$ random walk in colour space.

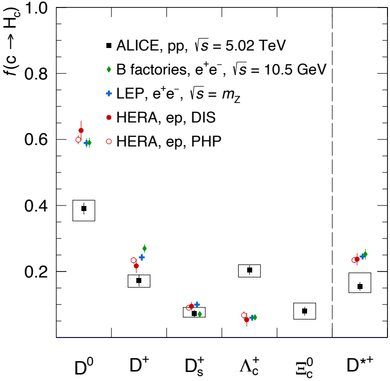
Larger $\kappa_{\mathrm{eff}} \Rightarrow$ less tunneling suppression $\exp\left(-\frac{\pi m_{\mathrm{q}}^2}{\kappa_{\mathrm{eff}}}\right)$

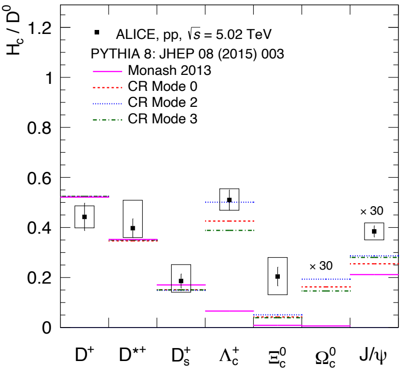
- more strangeness
- more baryons
- mainly agrees with ALICE, but p/π overestimated

Bierlich, Gustafson, Lönnblad, Tarasov, JHEP 1503, 148;
from Biro, Nielsen, Knoll (1984), Białas, Czyz (1985), ...

The charm baryon enhancement (2017)

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





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

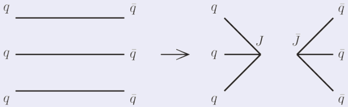
Ordinary string reconnection

(q$\bar{q}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection

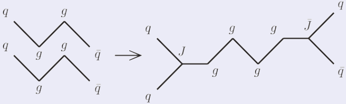
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection

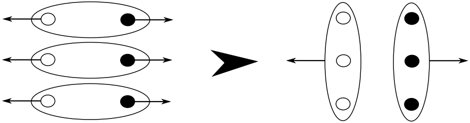


(q$\bar{q}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection

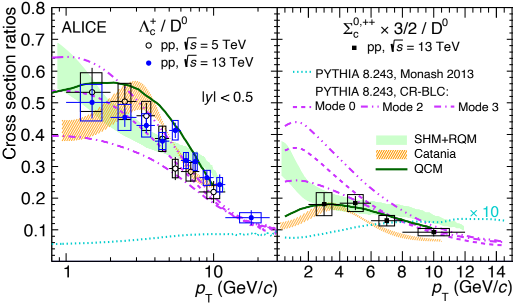


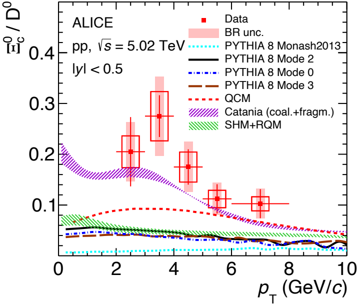
(Depends on number of gluons)

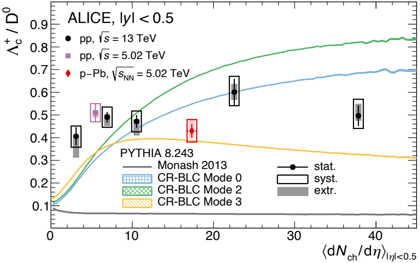


Triple-junction also in HERWIG cluster model (2017).

Charm baryon differential distributions (2021)



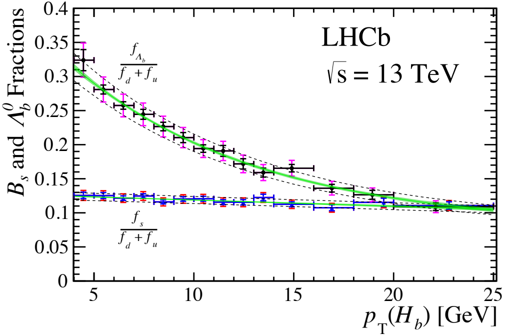




"Vacuum behaviour" recovered at larger $p_{\perp}$.

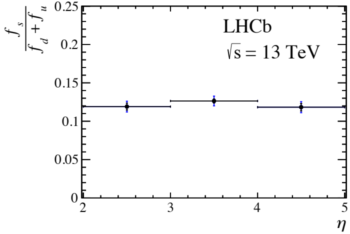
QCDCR does well for some distributions, but less so for others, so improvements needed.

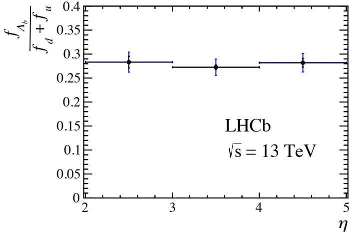
The beauty baryon enhancement (2019)



LHCb has found enhancement of Λ_b^0 production at small $p_\perp$, but flat in η.

No model comparisons available, but consistent.

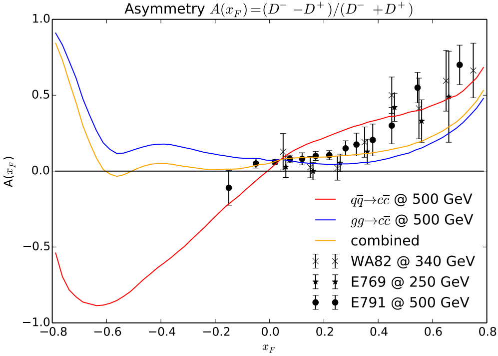


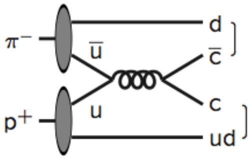


Beam drag effects (2000)

Colour flow connects hard scattering to beam remnants. Can have consequences, e.g. in $\pi^- \mathrm{p}$:

$$A(x_\mathrm{F}) = \frac{\sigma(\mathrm{D}^-) - \sigma(\mathrm{D}^+)}{\sigma(\mathrm{D}^-) + \sigma(\mathrm{D}^+)}$$



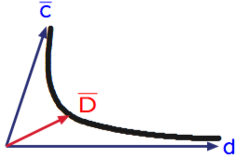


If low-mass string e.g.:

$\bar{\mathrm{c}}\mathrm{d} : \mathrm{D}^-, \mathrm{D}^{*-}$

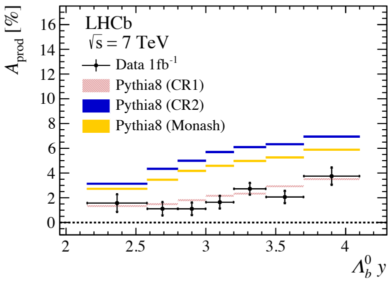
$\mathrm{cud} : \Lambda_\mathrm{c}^+, \Sigma_\mathrm{c}^+, \Sigma_\mathrm{c}^{*+}$

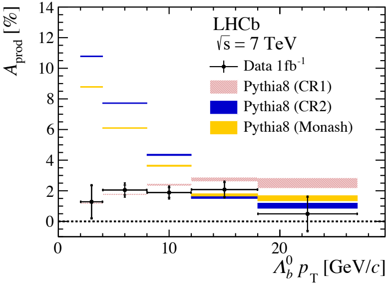
$\Rightarrow$ flavour asymmetries



Can give D "drag" to larger x_F than c quark.

Bottom asymmetries (2021)





$$A(y), A(p_\perp) = \frac{\sigma(\Lambda_\mathrm{b}^0) - \sigma(\overline{\Lambda}_\mathrm{b}^0)}{\sigma(\Lambda_\mathrm{b}^0) + \sigma(\overline{\Lambda}_\mathrm{b}^0)}$$

CR1 = QCDCR, with no enhancement at low $p_\perp$.

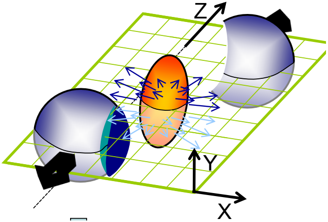
Enhanced Λ_b production at low $p_\perp$, like for Λ_c, dilutes asymmetry?

Asymmetries observed also for other charm and bottom hadrons.

Warning: fragmentation function formalisms unreliable at low $p_\perp$.

May lead to incorrect conclusions about intrinsic charm.

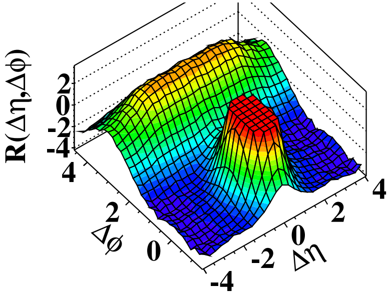
The Ridge Effect (2010)



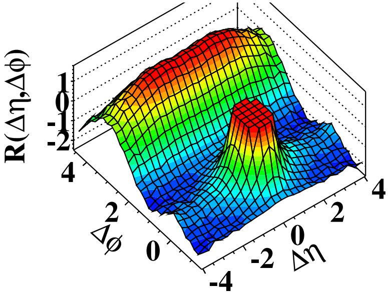
Elliptic flow in AA predicted from geometry + pressure.

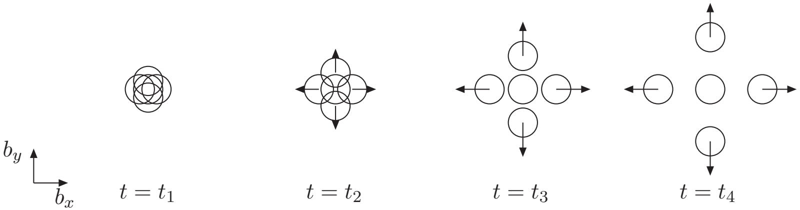
Not so for pp, and yet ridge is observed at high multiplicities:

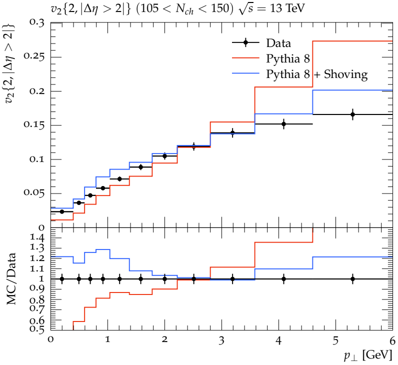
(c) CMS N ≥ 110, p_T>0.1GeV/c



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







Overlapping string at early times can give repulsive push, so strings get transverse motion, imparted to hadrons produced from them.

Can give ridge and flow, in azimuth and $p_\perp$.

Hadronic rescattering can also contribute.

Apologies

Stefan Höche will bring the story up-to-date with respect to

- perturbative higher-order calculations,
- next-to-leading-log parton showers, and
- the matching and merging of matrix elements and showers.

Even so, many aspects not covered, e.g.

- Quark–Gluon Plasma modelling of heavy ion collisions,
- HERA ep physics: rapidity gaps, photoproduction, . . . ,
- LEP $\gamma\gamma$ physics,
- σ_{tot}, ρ, diffraction,
- cosmic ray physics (cascades in the atmosphere),
- heavy flavour production, 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;
- α_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.

(Except hybrid models like EPOS?)