Strong interaction physics at future high-energy e^+e^- colliders

Michael Winn
Irfu/CEA, university Paris-Saclay

Ecole de Gif, Strasbourg, 19th of November

Lecture on strong interaction physics

- experimental and theoretical physics of the strong interaction
  $\rightarrow$ diverse set of concepts, methods and research directions

- frequent criticism
  $\rightarrow$ motivation from outside not as clear as for other disciplines

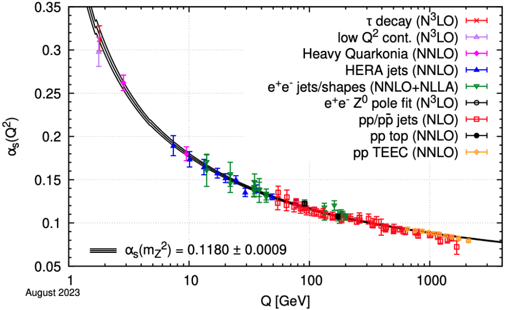
- Any overview for future collider for particle physics

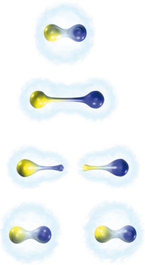
  $\rightarrow$ torn between completeness & identification of driving questions & needs for electroweak physics
  $\rightarrow$ limited by the lecturers horizon and knowledge

  $\rightarrow$ Goal today: give you a taste why QCD research is not only needed, but fascinating at a future collider

  favor overview vs. details: a choice with disadvantages
  focus on FCCee (most material available): some comparisons where deemed needed

Quantum chromodynamics: the theory of strong interaction





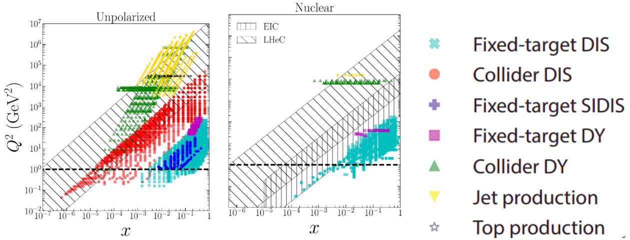
Left: QCD review PDG, right: picture from GSI.

- QCD established theory of the strong interaction since the 70ies
- Outstanding properties:
  $\rightarrow$ Asymptotic freedom & confinement
- Why QCD at a lepton collider? $\rightarrow$ part of the answer already in this slide!

Why lepton colliders and not hadron machines

- ESPPU 2020:
  '**An electron-positron Higgs factory is the highest-priority next collider.** '
  $\rightarrow$ this consensus of the highest priority has not changed.
- FCC-hh directly attractive for many 'QCD-people':
  $\rightarrow$ fear of missing diversity at lepton collider
  $\rightarrow$ fear of missing enthousiasm for lepton collider
- still hard to judge for me (and most of 'us') today being socialised in heavy-ion physics at the LHC
  $\rightarrow$ impressed by motivation & determination when embedded in LHCb group in Orsay for precision tests
- FCC-hh in any case unrealistic:
  technology not ready (magnets, detectors) for leap w.r.t. LHC in lumi/energy
  cost prohibitive for small time gap after LHC
- brief discussion of lepton-hadron machines
  LHeC relevant since discussed as a possible intermediate step

LHeC: genuine QCD motivation



ARNP Vol. 70, 2020 , for nuclear case without low-x by LHC charm/beauty production data.

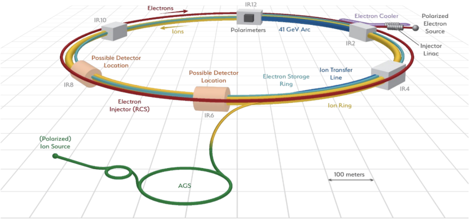
- ep: electron beam > 50 GeV: $\sqrt{s} = 0.2 - 1.3$TeV ($\times$ 4 HERA), $L_{inst} = 10^{34}$ cm^{-2}s^{-1} ($\times$ 10^2-10^3 HERA) $\approx$ 100 fb^{-1}, $\approx$ 1 ab^{-1} total
- ePb: $\sqrt{s_{eN}} = 0.74$ TeV ($\times$ 10 EIC): $L_{inst,eN} = 0.7 \cdot 10^{33}$ cm^{-2}s^{-1} ($\approx$ EIC)
- LHeC: ultimate machine for saturation physics

  kinematic reach $\approx$ LHC but DIS + nuclear targets, French theory active on physic case
- precision collinear PDFs for hadronic collisions, α_s determination
- important to lever LHC (+FCC-hh) QCD+BSM, but limited number of experimentalists as first priority
- convert one interaction point from hh to eh focus at LHC

numbers for top energies: P. Newman at DIS 2024 link, The LHeC at the HL-LHC, JPGNPP 48 (2021), EIC CDR

Electron-Ion Collider: the very next collider

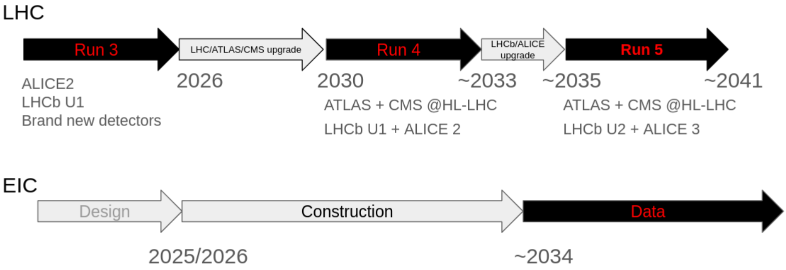
- Polarized beams: e, p, d/3He
- e beam 5-10 (18) GeV
- Luminosity $L_{ep} \sim 10^{33\text{-}34}$ $cm^{-2}sec^{-1}$ (100-1000 times HERA)
- 20-100 (140) GeV Variable CoM
- Nuclei from p to Uranium
- Two interaction regions
- One detector from day-0, strong wish for a second detector



EIC in a nutshell from F. Bossu at French GT4 workshop

- Electron-Ion Collider: a lepton-hadron machine replacing a hadron-hadron machine (Relativistic heavy-ion collider)
- only one lepton-hadron collider before: HERA (DESY)
  → nuclear targets not at HERA, no hadron beam polarisation at HERA, lepton beam unpolarised at injection

4) HL-LHC + Electron-Ion Collider timeline



LHC and EIC will be running in parallel for 5-10 years

- Strongly beneficial for physics output during this period
  → hadron structure beyond collinear factorisation + saturation
- synergy & dependence of EIC instrumentation from ongoing LHC

  prominent technology example: CMOS pixel detectors for tracking

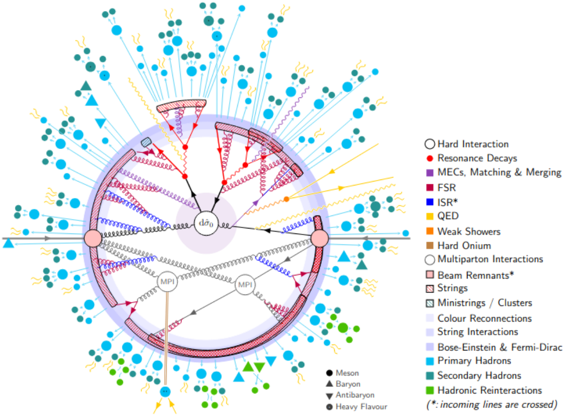
Further reading

- QCD and collider physics: the pink book, Ellis, Stirling, Webber link
- the black book of QCD, Campbell, Huston, Krauss link
- Electron-Positron Physics at the Z, Green, Lloyd, Ratoff and Ward

Outline

- Status of QCD before the next lepton collider
- Motivation for QCD at future lepton collider
- QCD precision measurements
- QCD goes non-perturbative at e^+e^-
- Conclusions

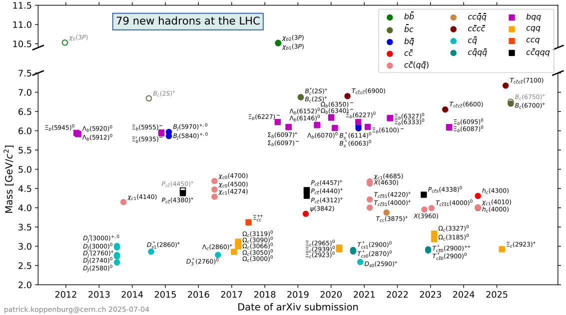
QCD at colliders today



Taken from Pythia 8 arXiv:2203.11601

- active research area with major advancements in last 25 years since last high-energy lepton collider LEP2
  $\rightarrow$ a panorama

QCD at colliders: spectroscopy



Compilation by P. Koppenburg for states found at the LHC link

- Spectroscopy renaissance with heavy-quark exotica: c/b-factories, LHC(b)
- many states that don't fit in standard quark model
- strong theory activity
- LHCb Upgrade 1 & Belle-2 and HL-LHC with LHCb U2
  $\rightarrow$ continuation of progress with increasing luminosities

QCD at colliders: spectroscopy frontier

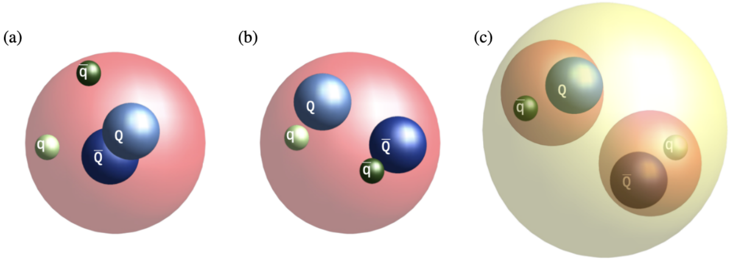
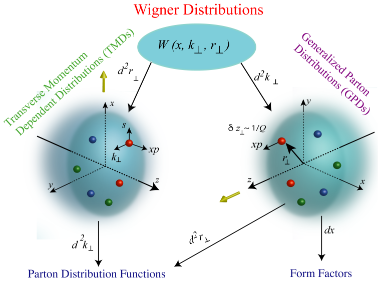
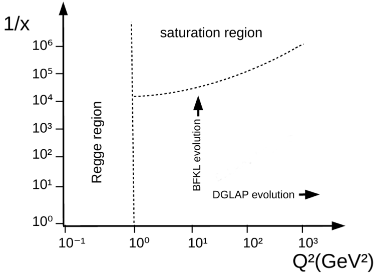


illustration taken from C. Hanhart arXiv:2504.06043

- nature of the discovered states to be clarified case by case
- example for different inner structures proposed for Tetraquarks discovered in LHCb (e.g. $Tcc^{+} D^{0} D^{0} \pi^{+}$), states can also mix

QCD at colliders: hadron structure frontier





right: adapted from pink book.

beyond collinear factorisation

- transverse momentum dependent distributions
  $\rightarrow$ input for precision Electroweak physics
- generalised parton distribution functions
  $\rightarrow$ spin/mass decomposition of hadrons in terms of partons
- non-linear regime of QCD: hadrons at high energy no longer dilute, but system with high-gluon occupation
  inconclusive in γ/proton + proton/nucleus so far

QCD at colliders: strongly interacting matter hadronisation

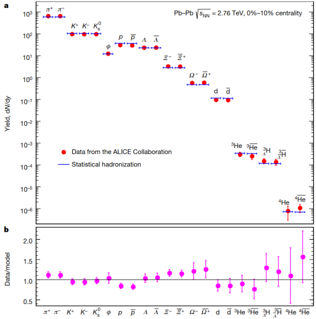


Fig. 1 | Hadron abundances and predictions of the statistical hadronization model. a, d*N*/d*y* values for different hadrons and nuclei, measured at mid-rapidity (red circles), including the hypertriton $^{3}_{\Lambda}H$, are compared with the statistical hadronization analysis (blue bars). The data are from the ALICE Collaboration for central Pb–Pb collisions at the LHC[53–59]. **b**, The ratio of the data to statistical hadronization predictions (model), with errors bars determined only from the data as the quadratic sum of statistical and systematic uncertainties.

$$\ln Z_{gc} = \sum_i \pm g_i \frac{V}{2\cdot\pi^2}\int_0^\infty dp p^2 \ln(1 \pm e^{-\beta\cdot(E_i(p)-\mu_i)})$$

$$n_i = \frac{g_i}{2\cdot\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}$$

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I3} I_{3,i}$$

$$E_i = \sqrt{p^2 + m_i^2}, g_i \text{ : degeneracy,i:species}$$

taken from Andronic et al. Nature 561 (2018)

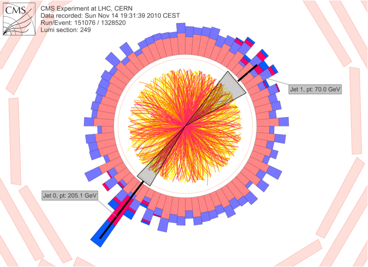
- particle averages from hadronisation
  $\rightarrow$ very 'simple' in nucleus-nucleus collisions
  $\rightarrow$'Hadron resonance gas'
- extract temperature and chemical potentials
  $\rightarrow$ experimental phase diagram
- more predictive than hadronisation in electron-positron, electron-proton, proton-proton

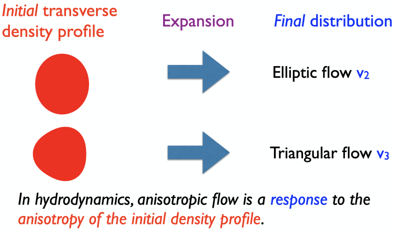
  thermal model also even in ee:

  however more microcanonical, precise

  physics interpretation unclear

QCD at colliders: strongly interacting matter signatures

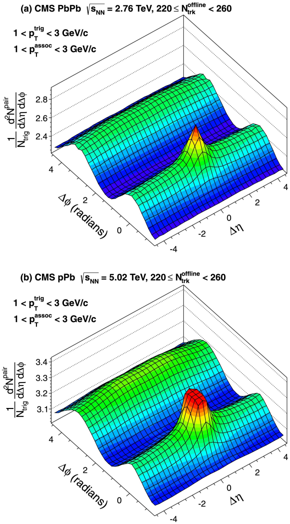




right: taken from J.-Y. Ollitrault

- finite temperature QCD at colliders with heavy-ion collisions: a whole field of its own
- key signatures found at RHIC and confirmed at LHC: energy loss and hydrodynamic flow + signatures of deconfinement and chiral restoration with quarkonia and dileptons
- strong experimental signatures for hydro in energy loss
  $\rightarrow$ precision studies of strongly interacting matter
  $\rightarrow$ last 3 years: constraints on nuclear structure

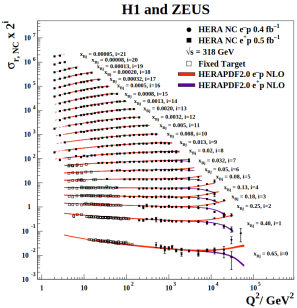
QCD at colliders: strongly interacting matter everywhere?

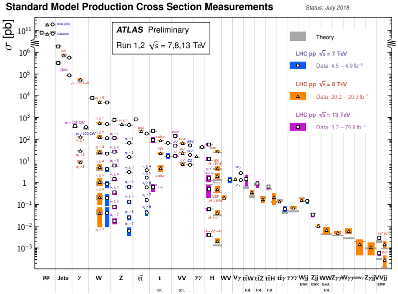


PLB, Volume 724, Issues 4–5, 23 July 2013, Pages 213-240

- proton-proton collisions and mainly proton-lead collisions as starting point of a broad investigation of nucleus-nucleus signatures in smaller collision systems
  → 2013 and onwards result explosion
- among others: long range correlations in angular space
  → 'Collectivity' found in small collision systems
- today: features of proton-lead correlation data described by hydrodynamic models
- limits of hydrodynamic concepts: still main driver of field
- energy loss discovered in 2025 in Oxygen-Oxygen collisions!

QCD at colliders: success of perturbative QCD at large Q^2



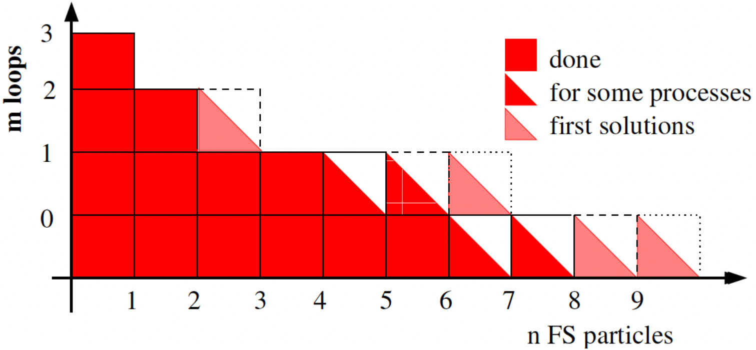


$$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{\mathrm{d}^2\sigma^{e^{\pm}p}_{\mathrm{NC}}}{\mathrm{d}x_{\mathrm{Bj}}\mathrm{d}Q^2} \cdot \frac{Q^4 x_{\mathrm{Bj}}}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_{\mathrm{L}} ,$$

Left: Eur.Phys.J.C 75 (2015) 12, 580, Right: taken from link

- Legacy of HERA deep-inelastic scattering:
  precision test of perturbative QCD over several orders of magnitudes
  $\rightarrow$ back-bone of proton structure knowledge
- beautiful consistency between experiment and theory based on PDFs and higher order perturbative QCD for production processes at LHC

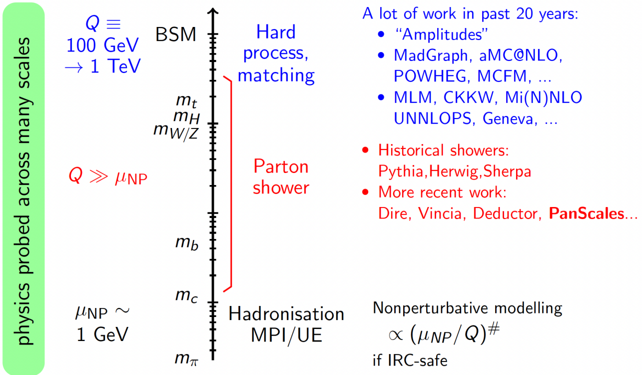
QCD at colliders: theory at large Q^2 higher order



taken from Frank Krauss (2018 Orsay lecture), tree and NLO fully automated.

- collinear pQCD: NLO revolution → automation of loop calculations of fully differential cross sections
- advancements on NNLO and N^{3}LO, see PDG review for references link

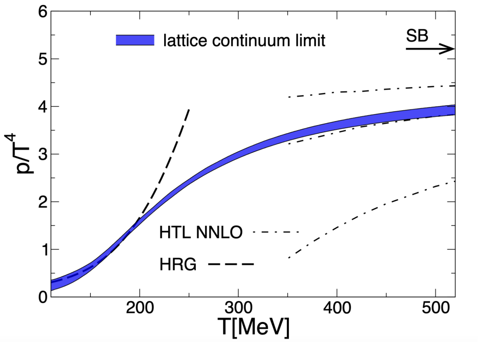
QCD@colliders: partons final state→ jets→ parton shower



taken from Gregory Soyez

- large theory effort to push precision
  developments of parton showers at next-to-leading logarithm accuracy
  → hadronisation modelling hard wall for precision at some point

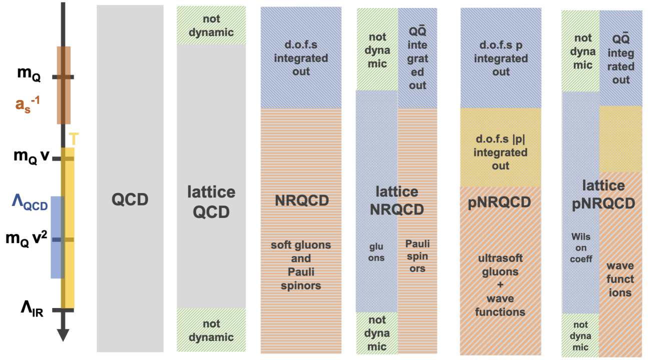
QCD at colliders: theory progress from the lattice



PLB 370 (2014) 99 (BW), see also Hot-QCD: PRD 90 (2014) 094503 (Hot-QCD)

- lattice QCD calculations at physical parameters
- relevant for vacuum and for finite temperature
- example equation of state of strongly interacting matter as function of temperature at vanishing chemical potentials for conserved quantum numbers

QCD at colliders: theory progress effective field theory



A. Rothkopf Phys.Rept. 858 (2020) 1

- various type of effective field theories to address different regimes of QCD
  $\rightarrow$ example for heavy quarkonium physics ($c\bar{c}$ & $b\bar{b}$ bound states)
- another prominent example: high-energy limit, color glass condensate

QCD-research-intrinsic open quests today

Significant advances on many fronts, but no quantitative/conceptual understanding of:

- **emergence of mass and spin** of hadrons from partons, in particular role of gluons
- **hadronisation**
- conditions for & characteristics of **thermalisation** of strongly interacting matter
- **inner structure**, i.e. degrees of freedom, phase transitions and transport properties of strongly interacting matter
- high-energy limit of QCD: **saturation**

Future facilities for QCD research starting in next 10 years
HL-LHC: ATLAS/CMS + ALICE3 & LHCb U2: all quests, heavy-ions for thermalisation and inner structure

EIC: 2 precision for emergence + saturation

Facility for Antiproton and ion research (FAIR, Germany): high-luminosity fixed-target nucleus-nucleus collisions, hadronisation, thermalisation, inner structure

Why studying QCD at a future lepton collider?

Twofold motivation

- precision QCD
  $\rightarrow$ required for standard model precision test
- study emergent phenomena of QCD
  intrinsic motivation to progress on hadronisation, thermalisation, saturation

Theory must match experiment precision

a challenge at a completely different scale than the NLO revolution prior to LHC since 'interference' with non-perturbative physics aka hadronisation, see Banfi, CERN 2022

Precision QCD

At LHC: QCD $\rightarrow$ backgrounds for direct searches

'QCD: The theory of evil'

Quote from Tilman Plehn LHC physics lecture in Heidelberg.

Lepton collider:
$\rightarrow$ possibly a background, but also most of the signal
$\rightarrow$ cannot afford to see it as the theory of evil

Hadronic final states at electron-positron colliders

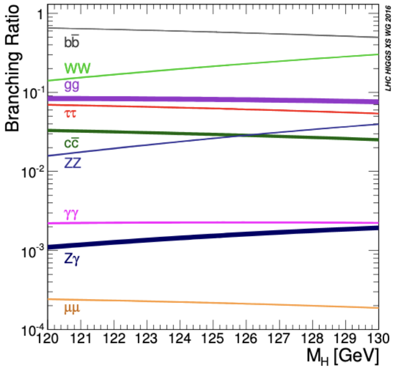
W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\ell^+\nu$	[a]	$(10.86\pm\ 0.09)$ %	
Γ_2	$e^+\nu$		$(10.71\pm\ 0.16)$ %	
Γ_3	$\mu^+\nu$		$(10.63\pm\ 0.15)$ %	
Γ_4	$\tau^+\nu$		$(11.38\pm\ 0.21)$ %	
Γ_5	hadrons		$(67.41\pm\ 0.27)$ %	

Z DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	e^+e^-		$(\ 3.3632\pm0.0042)$ %	
Γ_2	$\mu^+\mu^-$		$(\ 3.3662\pm0.0066)$ %	
Γ_3	$\tau^+\tau^-$		$(\ 3.3696\pm0.0083)$ %	
Γ_4	$\ell^+\ell^-$	[a]	$(\ 3.3658\pm0.0023)$ %	
Γ_5	$\mu^+\mu^-\mu^+\mu^-$			
Γ_6	$\ell^+\ell^-\ell^+\ell^-$	[b]	$(\ 4.55\ \ \pm0.17\ \ )\times10^{-6}$	
Γ_7	invisible		$(20.000\ \pm0.055\ )$ %	
Γ_8	hadrons		$(69.911\ \pm0.056\ )$ %	
Γ_9	$(u\overline{u}+c\overline{c})/2$		$(11.6\ \ \pm0.6\ \ )$ %	
Γ_{10}	$(d\overline{d}+s\overline{s}+b\overline{b})/3$		$(15.6\ \ \pm0.4\ \ )$ %	
Γ_{11}	$c\overline{c}$		$(12.03\ \pm0.21\ )$ %	
Γ_{12}	$b\overline{b}$		$(15.12\ \pm0.05\ )$ %	

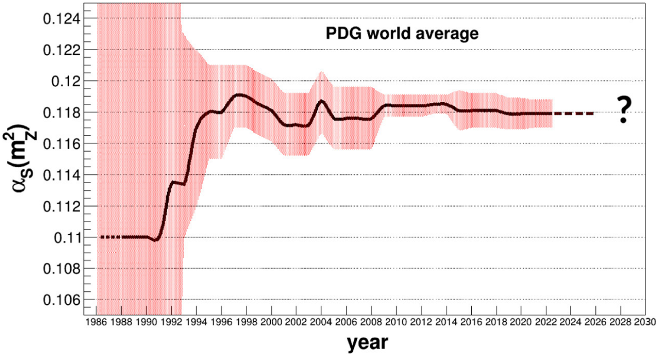


PDG experiment

PDG theory for Higgs

- hadronic final states from gauge bosons and from Higgs boson
  $\rightarrow$ dominate total rates
  $\rightarrow$ simplest environment for QCD: color-less initial state, no underlying event
  $\rightarrow$ dominated by 2-jet events $q\bar{q}$ and gg (new!)
- let's use them to understand more about QCD

Precision strong coupling constant measurement



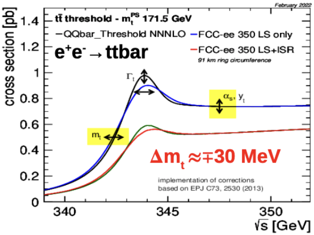
taken from α_S-review link

- precision 2024 $\alpha_S(m_Z^2) = 0.1180 + 0.0009$ (0.8% uncertainty)
- least precisely known coupling
  $\delta\alpha \approx 10^{-10} << \delta G_F \approx 10^{-7} << \delta G \approx 10^{-5} << \delta\alpha_S \approx 10^{-2}$

Precision QCD: coupling constant → why it matters

Process	σ (pb)	$\delta\alpha_s(\%)$	PDF $+\alpha_s(\%)$	Scale(%)
ggH	49.87	± 3.7	-6.2 +7.4	-2.61 +0.32
ttH	0.611	± 3.0	$\pm$ 8.9	-9.3 +5.9

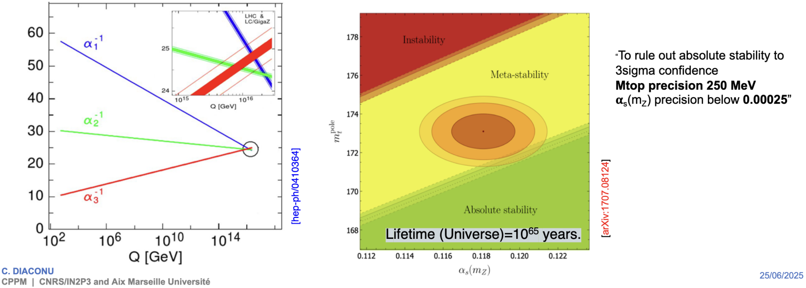
Partial width	intr. QCD	para. m_q	para. α_s
$H \to b\bar{b}$	$\sim 0.2\%$	1.4%	0.4%
$H \to c\bar{c}$	$\sim 0.2\%$	4.0%	0.4%
$H \to gg$	$\sim 3\%$	$< 0.2\%$	3.7%



taken from David d'Enterria

- precision on strong coupling limits precision on theory standard model prediction for a number of channels
- future e^+e^- colliders can improve significantly over LEP
  → potential of Lattice QCD to be clarified: systematic uncertainties will play a role as well when going to 0.1% precision

Precision QCD: coupling constant → why it matters



taken from Cristinel

- in the grand scheme of things: decisive parameter of the Standard model

Precision QCD: coupling constant from Z/W hadronic width FCCee

- Q extracted from N³LO fit of combined Γ_W, R_W W boson pseudo-observ.:

- The W and Z hadronic widths :

$$\Gamma^{\rm had}_{\rm W,Z}(Q) = \Gamma^{\rm Born}_{\rm W,Z}\left(1+\sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm EW} + \delta_{\rm mix} + \delta_{\rm np}\right)$$

- The ratio of W, Z hadronic-to-leptonic widths :

$$\mathrm{R}_{\rm W,Z}(Q) = \frac{\Gamma^{\rm had}_{\rm W,Z}(Q)}{\Gamma^{\rm lep}_{\rm W,Z}(Q)} = \mathrm{R}^{\rm EW}_{\rm W,Z}\left(1+\sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm mix} + \delta_{\rm np}\right.$$

- FCC-ee:

– Huge W pole stats. ($\times 10^4$ LEP-2).

– Exquisite syst./parametric precision:

$$\Gamma^{\rm tot}_{\rm W} = 2088.0 \pm 1.2\ \mathrm{MeV}$$

$$\mathrm{R_W} = 2.08000 \pm 0.00008$$

$$m_{\rm W} = 80.3800 \pm 0.0005\ \mathrm{GeV}$$

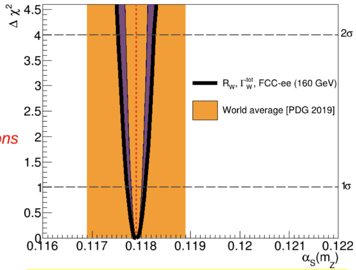
$$|V_{cs}| = 0.97359 \pm 0.00010$$ ← $O(10^{12})$ D mesons

– TH uncertainty to be reduced by $\times 10$ by computing missing α_s^5, α^2, α^3, $\alpha\alpha_s^2$, $\alpha\alpha_s^2$, $\alpha^2\alpha_s$ terms

- 150! times better precision than today:

$\alpha_s(m_z) = 0.101 \pm 0.027$ (±27%) ➡ **$\alpha_s(m_z) = 0.11790 \pm 0.00023$ (±0.2%)**

DdE, Jacobsen: arXiv:2005.04545 [hep-ph]



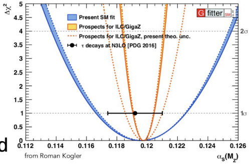
see details in: arXiv:2005.04545

Precision QCD: coupling constant from Z/W hadronic width LC

- α_s measurements at LC (ILC/Giga-Z):

  ±0.6% from Z pseudoobservables
  <1% from τ hadronic decays, evt. shapes, jet rates

  However, current claim is that α_s will be taken instead from lattice-QCD (see M. Peskin, May 14th): Expected uncertainties under discussion with latt. experts



arXiv:1512.05194 [hep-ph]

- α_s measurements at LEP3:

  Same physics goals as FCC-ee modulo worse stat. (~4 times less Z) & worse syst. (e.g. beam energy calibration/spread) uncertainties.

  ±0.2% (stat) from Z pseudoobservables
  ±0.9% (stat) from W hadronic decays

- α_s measurements at MuColl:

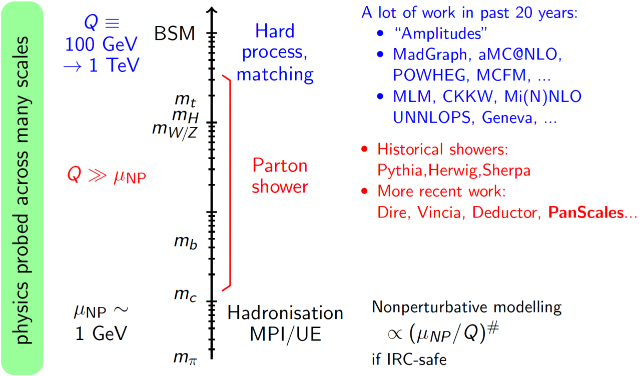
- Determination of $\alpha_s(Q)$ running over Q = 1–10TeV e.g. via evt. shapes, EECs
- High-precision $\alpha_s(m_Z)$ from measurements of neutrino SFs at a far-forward detector.

Taken from D. d'Enterria.

Precision QCD: comments on coupling constant

- in principle 2-jet rate, shape variables and others more sensitive to α_S
  $\rightarrow$ stronger sensitivity to non-perturbative physics: goes with $1/Q$ decreases with centre-of-mass energy
  $\rightarrow$ ultimate systematic uncertainty will depend on progress on hadronisation, see e.g. discussion by Peskin link: favouring LQCD

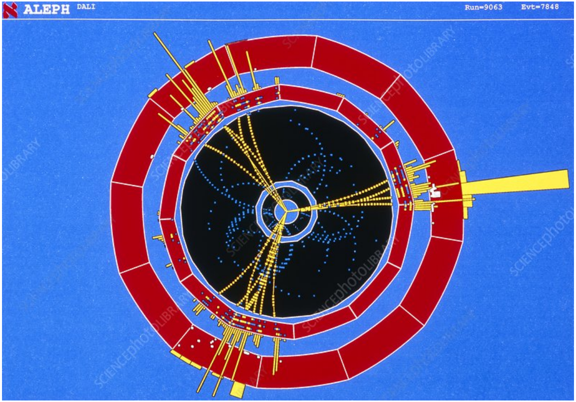
Precision QCD: Jet physics



Taken from G. Soyez.

- Hadronic final state at high energy: jets
- parton shower and hadronisation central objects of study
- focus on one example where future lepton collider can bring new inputs

Precision QCD with a gluon factory

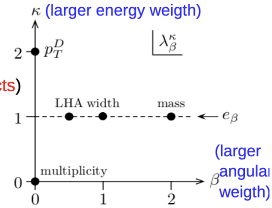


Aleph LEP mercedes star event like in the gluon discovery at DESY.

- previous lepton colliders
  $\rightarrow$ hadronic final state at born level $q\bar{q}$ $\rightarrow$ gluons only as 'third' jet
- hadron collider: despite dominance of gluons over wide region of phase space $\rightarrow$ difficult to isolate
- Higgs factory $\rightarrow$ gluon factory

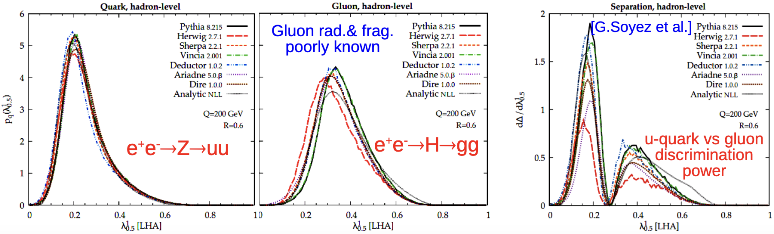
Precision QCD with a gluon factory

- State-of-the-art jet substr. studies based on Lund Plane & angularities: $$\lambda^{\kappa}_{\beta} = \sum_{i\in\text{jet}} z_i^{\kappa}\theta_i^{\beta},$$ (normalized $E^n \times \theta^n$ products)
- "Sudakov"-safe variables of jet constituents: multiplicity, LHA, width/broadening, mass/thrust, C-parameter,...



[Larkoski,Salam,Thaler,13]
[Larkoski,Thaler,Waalewijn,14]

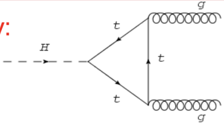
- k=1: IRC-safe computable (N^nLO+N^nLL) via SCET (but uncertainties from non-pQCD effects)
- MC parton showers differ on gluon (less so quark) radiation patterns:



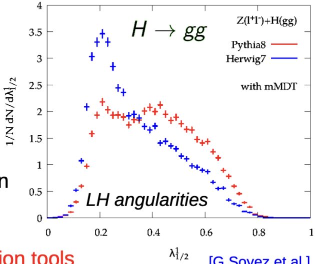
FCC Week 2022, Paris, May'22 16/23 David d'Enterria (CERN)

Precision QCD with a gluon factory

- Exploit FCC-ee H(gg) as a "pure gluon" factory: H→gg (BR~8% accurately known) provides 100.000 extra-clean digluon events.



- Multiple handles to study gluon radiation & g-jet properties:
  - Gluon vs. quark via H→gg vs. Z→qq (Profit from excellent g,b separation)
  - Gluon vs. quark via Z→bbg vs. Z→qq(g) (g in one hemisphere recoiling against 2-b-jets in the other).
  - Vary E_{jet} range via ISR: $e^+e^- \to Z^*,\gamma^* \to jj(\gamma)$
  - Vary jet radius: small-R down to calo resolution



[G.Soyez et al.]

- Multiple high-precision analyses at hand:
  – Higgs/BSM/flavour: Improve q/g/Q discrimination tools
  – pQCD: Check N^{n}LO antenna functions. High-precision QCD coupling.
  – non-pQCD: Gluon fragmentation: Octet neutralization? (zero-charge gluon jet with rap gaps). Colour reconnection? Glueballs ? Leading η's,baryons?

Precision QCD: theory requirements

	Observable	Missing higher-order & power-suppressed corrections
$\alpha_s(m_Z)$ in e^+e^-	Hadronic Z width	$\mathcal{O}(\alpha_s^5)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_s\alpha^3)$, $\mathcal{O}(\alpha_s^2\alpha^2)$
	Hadronic W width	$\mathcal{O}(\alpha_s^5)$, $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_s\alpha^2)$, $\mathcal{O}(\alpha_s\alpha^3)$, $\mathcal{O}(\alpha_s^2\alpha^2)$
	Hadronic τ width	$\mathcal{O}(\alpha_s^5)$
	Hadronic event shapes (Z, W, H decays)	N^3LO differential, $N^{3,4}LL$ resummation, power corrections
	Inclusive jet rates	3-jet cross sections at N^3LO, 4-jets at N^2LO, 5-jets at NLO
$\alpha_s(m_Z)$ in latt.	Lattice QCD results	$\mathcal{O}(\alpha_s^6)$ β-function; $\mathcal{O}(\alpha_s^5)$ heavy quark decoupling; $\mathcal{O}(\alpha_s^4)$ static potential
	(α_s extractions; quark masses m_c, m_b)	$\mathcal{O}(\alpha_s^3)$ lattice perturbation theory matching (lattice coupling to $\alpha_s^{\overline{MS}}$ etc.)
m_W, m_{top} in e^+e^-	$\sigma(e^+e^- \to W^+W^-)$ vs. $\sqrt{s}$	EW N^2LO: $\mathcal{O}(\alpha^2)$, Mixed EW-QCD: $\mathcal{O}(\alpha_s\alpha^2)$, $\mathcal{O}(\alpha_s^2\alpha)$
	$\sigma(e^+e^- \to t\bar{t})$ vs. $\sqrt{s}$	NRQCD: $\mathcal{O}(\alpha_s^5)$, Non-resonant: $\mathcal{O}(\alpha_s^5)$,
		$O(\alpha_s^3)$ differential; QED: $\mathcal{O}(\alpha^3)$ at NNLL
QCD in Higgs	$H \to b\bar{b}$ width	N^4LO (massive b-quark); N^4LO differential (massless b-quark)
	$H \to gg$ width	N^5LO (heavy-top limit), N^4LO (massive top)
		N^4LO differential, N^3LO differential (massive top)
e^+e^-,e-p, p-p PS	MC simulations for $e^+e^- \to X$ processes	$N^{2,3}LO$ matched to $N^{2,3}LL$ PS.
		Permille control of non-perturbative QCD effects (hadronization, CR,...)
$\alpha_s(m_Z)$ in DIS	ep $\to$ hadrons (PDF and α_s determination)	$N^{3,4}LO$ evolution equations and inclusive cross sections
	ep $\to$ jets (α_s determination)	N^3LO cross sections

Taken from David d'Enterria

Emergent phenomena

At hadron collider:
QCD $\rightarrow$ Strict reductionism fails to understand strong interaction phenomena in the non-perturbative regime

'More is different'

(Andersen)

This motivation is independent of the presence of beyond the standard model physics.
Electron-positron collisions allow to progress on some of these quests: $\rightarrow$ only a selection, e.g. don't discuss spectroscopy opportunities

QCD with $\gamma\gamma$ collisions

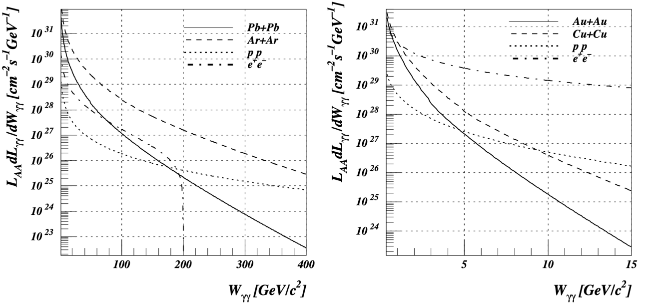


Figure 3. Effective $\gamma\gamma$ luminosity at LHC (left) and RHIC (right) for different ion species and protons as well as at LEP II. In pp and e^+e^- collisions, L_{AA} corresponds to the pp or e^+e^- luminosity. Reprinted from Ref. [3] with permission from Elsevier.

review of UPC at LHC

- analogue to ultra-peripheral collisions (UPC) at the LHC in PbPb
  $\rightarrow$ LHC: first observation of $\gamma\gamma to \gamma\gamma$, first hadron collider g-2 of τ
  $\rightarrow$ much more to come in Run 3 and at HL-LHC
- major background source at e^+e^- collider
  $\rightarrow$ unique QCD physics

QCD with $\gamma\gamma$ collisions

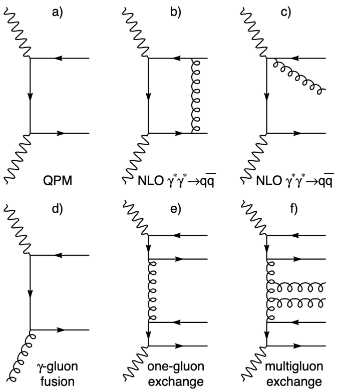
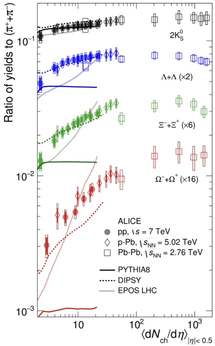


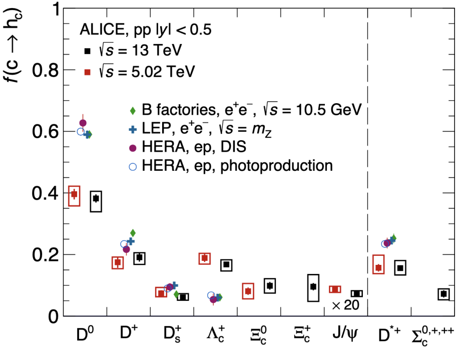
Figure 1: Examples of diagrams contributing to the process $\gamma^*\gamma^* \to hadrons$: a) QPM, b) and c) $\mathcal{O}(\alpha_s)$ QCD corrections to the QPM diagram, d) photon-gluon fusion, e) one-gluon exchange and f) multigluon ladder exchange.

diagrams for $\gamma^*\gamma^* \to$ *hadrons*, from L3 publication link

- discriminate between detection of lepton or not in reaction $ee \to \gamma\gamma ee$: no tag, single tag, double tag
  $\to$ hadronic final state: from soft to test of photon structure function F_2 analogue to proton structure to perturbative QCD
- spectroscopy: $\gamma\gamma \to H$ complementary quantum numbers w.r.t. e^+e^-, e.g. heavy speudoscalars $\eta_{c,b}$
- tests of non-linear QCD in $\gamma^*\gamma^* \to$ *hadrons*: saturation
  $\to$ LEP inconclusive on effects of BFKL evolution
- physics program to be developed

Emergent phenomena: hadronisation

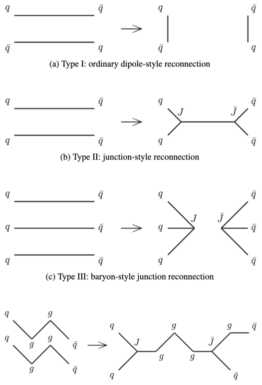




- event generators tuned on LEP data
  $\rightarrow$ badly fail at the LHC
- scaling as function of final state particle density
- non-universality of charm hadronisation fractions
  baryons severly underestimated

$\rightarrow$ let's go back to e^+e^-

Emergent phenomena: hadronisation - natural extensions



(a) Type I: ordinary dipole-style reconnection

(b) Type II: junction-style reconnection

(c) Type III: baryon-style junction reconnection

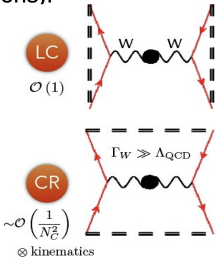
(d) Type IV: zipper-style junction reconnection

taken from arXiv:1505.01681

- event generators simplifying
  $\rightarrow$ confining potential usually only between two partons
  $\rightarrow$ QCD allows for more
  see e.g. in Christiansen, Skands arXiv:1505.01681 for implementation in String model: 'next-to-leading colour'
- strong effect in hadronic environment
  $\rightarrow$ subtle effect in e^+e^-:
  but there, we can be precise with fixed initial state!

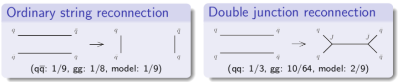
Emergent phenomena: hadronisation - WW as clean test

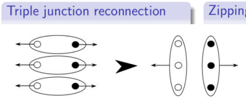
- Colour reconnection among partons is source of uncertainty in m_W in multijet final states (also m_{top} inv. mass, aGC extractions):
- CR "string drag" impacts $e^+e^- \to WW(4j)$ final state (also $e^+e^- \to$ ttbar, $e^+e^- \to ZZ(4j)$, $H \to 4j$,...):
  - Shifted masses & angular correlations (CP studies).
  - Combined LEP $e^+e^- \to WW(4j)$ data best described with 49% CR, 2.2σ away from no-CR.



- Exploit 10^8 W stats at FCC-ee to measure m_W leptonically & hadronically and constrain CR:

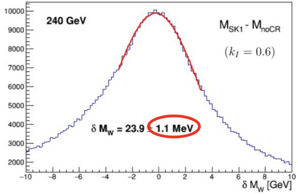
"Recent" PYTHIA option: QCD-inspired CR (QCDCR) (1505.01681):





Zipping reconnection

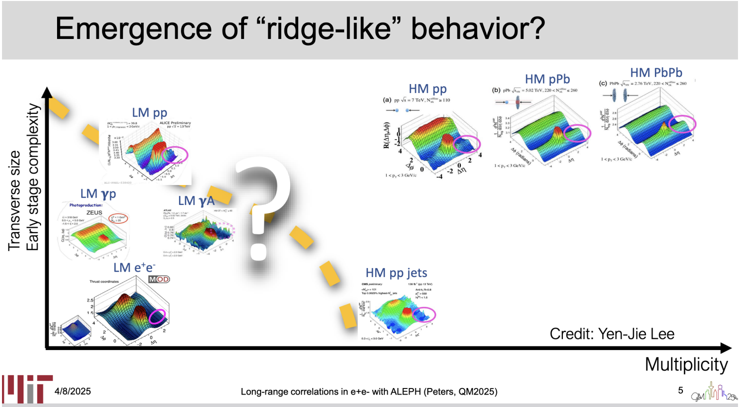
Triple-junction also in HERWIG cluster model. (1710.10906)



M_W shift due to CR effect, modelled using the SKI scenario

taken from David d'Enterria

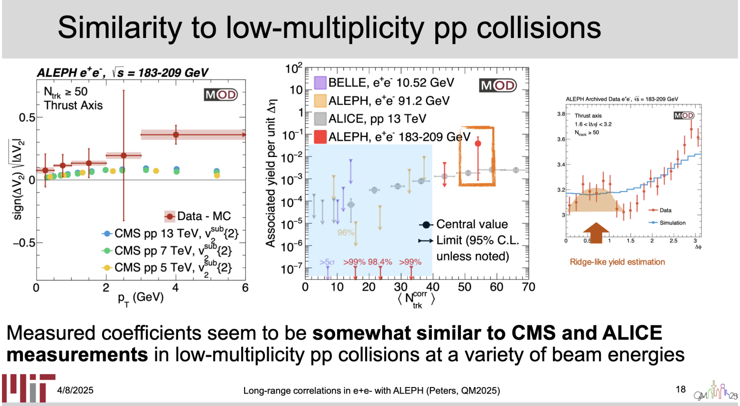
Emergent phenomena: long-range correlations at e^+e^-



taken from QM talk 2025 LEP2 reanalysis

- LEP goes heavy-ion
  $\rightarrow$ important input for understanding of long-range correlations whether signal seen in electron-positron collisions
- future lepton collider will provide far larger statistics and higher collision energy for larger number of final state particles

Emergent phenomena: long-range correlations at e^+e^-



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Conclusion

- QCD: a very diverse field

- lepton collider
  unique precision measurements in the perturbative and non-perturbative regime of QCD
  → required to reduce uncertainties on standard-model properties
  → intrinsic motivation to understand emergent phenomena: hadronisation, collectivity & high-energy limit

- hadronisation
  unsolved problem of particle physics
  → ultimate limitation of any measurement involving jets even at lepton collider
  → a breakthrough can't be promised, but a lepton collider with high luminosity is the best chance since it is the cleanest environment at hand

- if saturation not pinned down at the LHC or the EIC:
  $\gamma^*\gamma^*$ a very clean environment to search for it

A last remark

- QCD: the theory of evil? $\rightarrow$ No!
- half best friend $+$ half stranger
  $\rightarrow$ we still don't know its most interesting sides.