QCD @ FCC-ee

1st FCC Physics Workshop, 16-20 Jan 2017, CERN

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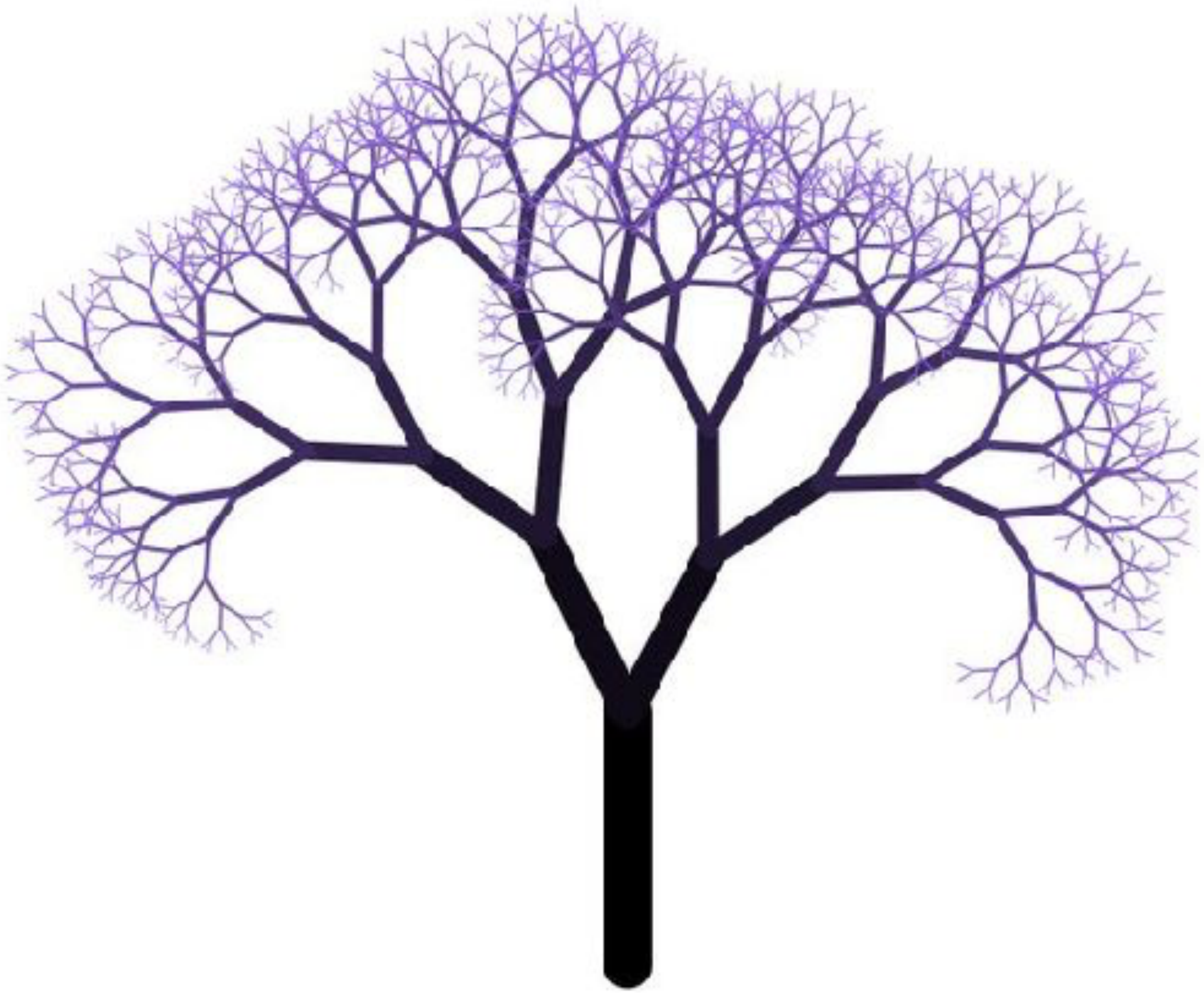
On behalf of the FCC-ee working group "QCD & gamma-gamma physics"

(Condensed from the contributions to the 2015 and 2016 QCD@FCC-ee workshops, with thanks to all participants)

QCD: (the only) **unbroken Yang-Mills theory that can be compared directly with experiment. Rich structure.**



QCD AT EE COLLIDERS

QCD: (the only) **unbroken Yang-Mills theory that can be compared directly with experiment. Rich structure.**

End of era of testing $SU(3)_C$ → Precision determinations of α_s

Understanding jet (sub)structure

Testing models of confinement and (non-perturbative) QCD effects

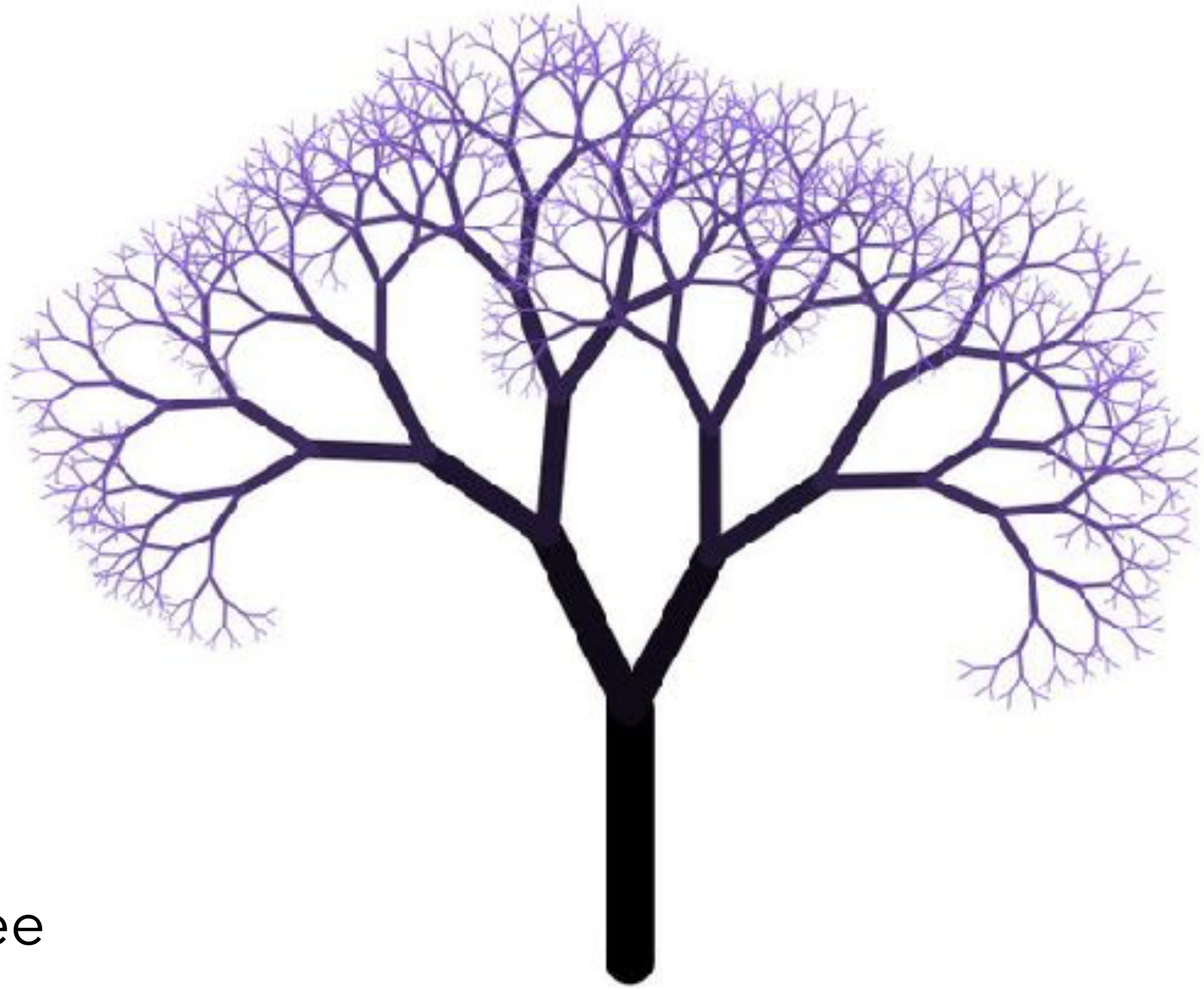
Monte Carlo tuning & constraints

Fragmentation Functions

QCD in $\gamma\gamma$ collisions

Interplay with EW, H, BSM @ FCC-ee

Precision Legacy for FCC-hh



QCD WG ACTIVITIES (+ RESOURCES)

High-precision α_s measurements from LHC to FCC-ee

Oct 2015: Slides on indico.cern.ch/event/392530

Proceedings at arXiv:1512.05194

Parton Radiation and Fragmentation from LHC to FCC-ee

Nov 2016: Slides on indico.cern.ch/event/557400

Proceedings to appear on arXiv soon

FCC-ee γγ session at Photon 2017 (CERN)

May 22-26 2017: https://indico.cern.ch/event/604619/

Join the WG to receive notifications

Join QCD WG at http://CERN.ch/FCC-ee (join us, subscribe)

+ Let us know about any studies you have done that pertain to QCD @ FCC-ee

FRAGMENTATION FUNCTIONS

S. Moch (& others): field now moving towards NNLO accuracy: **1% errors** (or better)

FFs from Belle to FCC-ee *[A. Vossen]*

Precision of TH and EXP big advantage

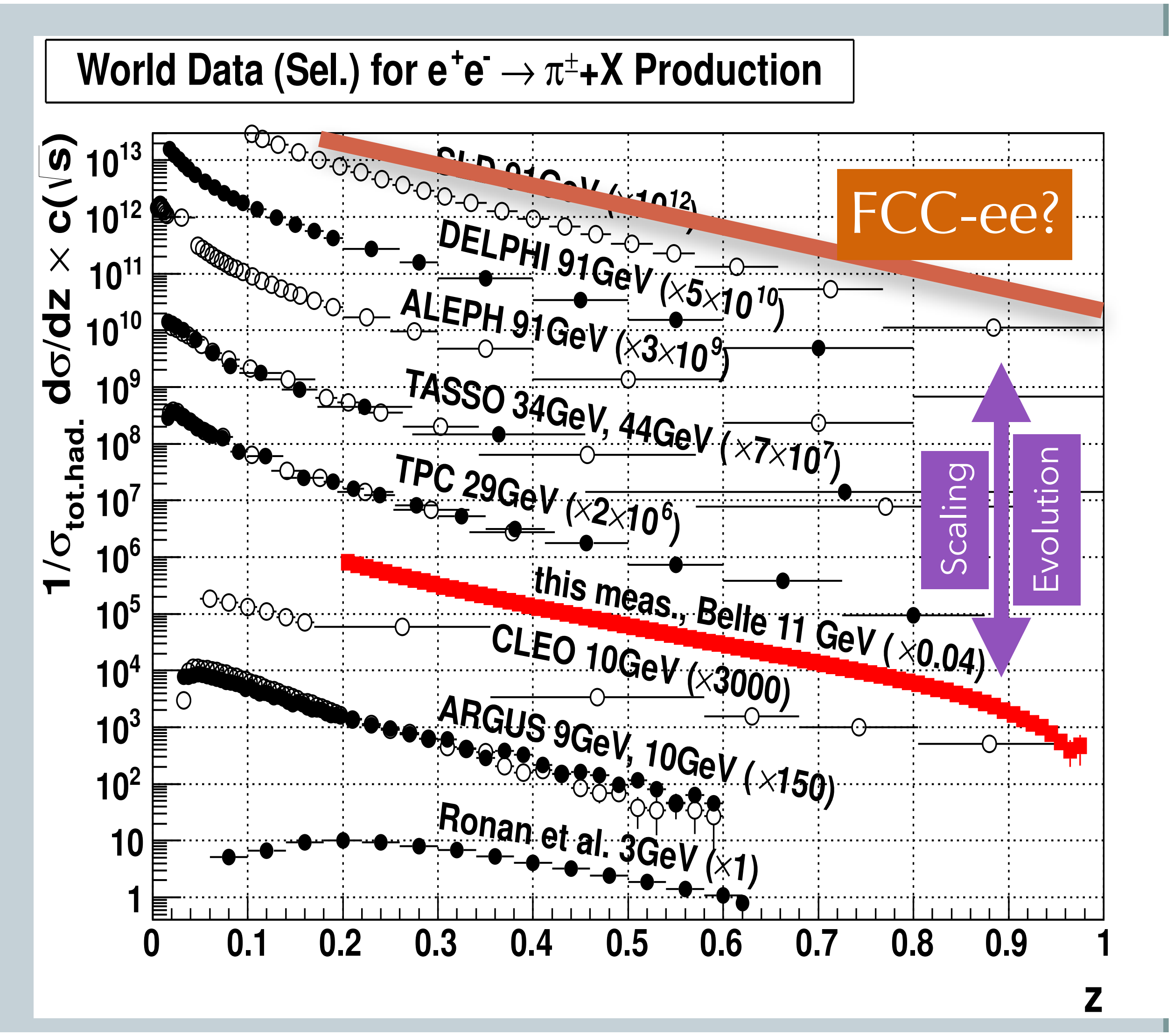
- Complementary to pp and SIDIS

Evolution:

- Belle has FCC-ee like stats at 10 GeV.
- FCC-ee: very fine binning all the way to z=1 with 1% lpl resolution (expected)

Flavour structure for FFs of hyperons and other hadrons that are difficult to reconstruct in pp and SIDIS.

- Will depend on Particle Identification capabilities.



Low Z: Higher ee energy (than Belle) → smaller mass effects at low z.

- 3 tracker hits down to 30-40 MeV allows to reach $z = 10^{-3}$ ($\ln(z) = -7$)
- Kluth: if needed, could get O(LEP) sample in ~ 1 minute running with lower B-field

gluon FFs, heavy-quark FFs, p_T dependence in hadron + jet, polarisation,…

HADRONISATION (AND LOW Z)

Confinement wasn't solved last century

Models **inspired by QCD** (hadronisation models) explore the non-perturbative quagmire (until it is solved and **uninspired** models can move in)

FFs and IR safety (power corrs) observe from a safe distance

Expect Track reconstruction (3 hits) **down to 30-40 MeV << Λ_{QCD}**

Below Λ_{QCD} → can study genuine non-perturbative dynamics

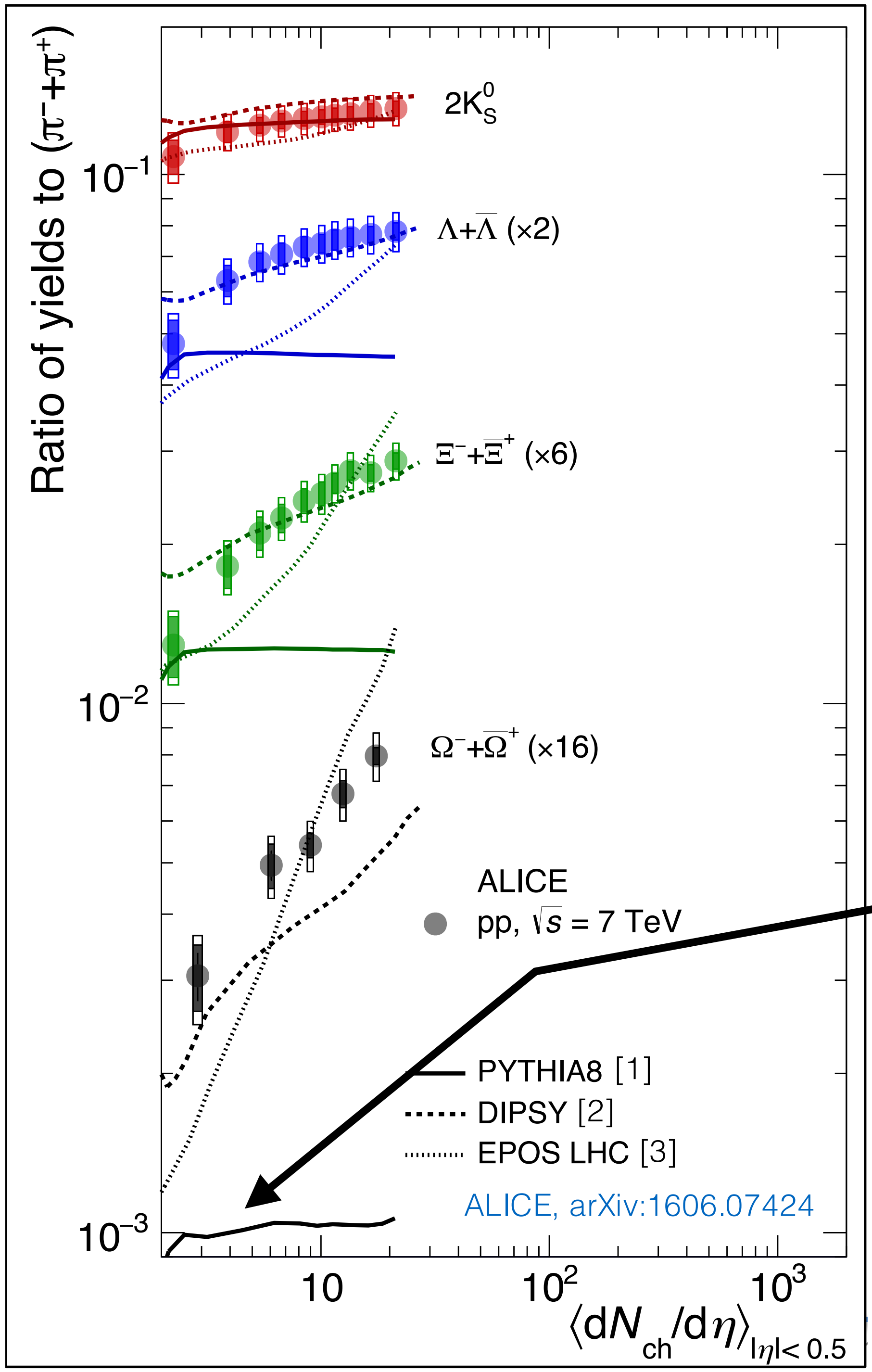
Handles: mass, strangeness, and spin. Need at least one of each meson & baryon isospin multiplet. Flavour separation crucial. (LEP $|p_K| > 250$ MeV)

QUESTIONS: detailed mechanisms of hadron production. Is strangeness fraction constant or dynamic? Thermal vs Gaussian spectra. Debates rekindled by LHC observations of strangeness enhancement. *[Next slide]*

Bonus: high-precision jet calibration (particle flow)

Accurate knowledge (+ modeling) of particle composition & spectra

STRANGENESS ENHANCEMENTS (IN PP)



D.D. Chinellato – 38th International Conference on High Energy Physics

ALICE: clear enhancement of strangeness with (pp) **event multiplicity**

Especially for multi-strange baryons

No corresponding enhancement for protons (not shown here but is in ALICE paper)

→ must really be a strangeness effect

Measurements of phi now underway

Jet universality: jets at LHC modelled the same as jets at LEP

→ Flat line ! (cf PYTHIA)

Some models anticipated the effect!

DIPSY (high-tension overlapping strings)

EPOS (thermal hydrodynamic "core")

Is it thermal? Or stringy? (or both?)

Basic check in ee→WW: two strings

(LEP: total Ω rate only known to ± 20%)

COLOUR RECONNECTIONS

T. Sjöstrand, W. Metzger, S. Kluth, C. Bierlich

At LEP 2: hot topic (by QCD standards): 'string drag' effect on W mass

Non-zero effect convincingly demonstrated at LEP-2

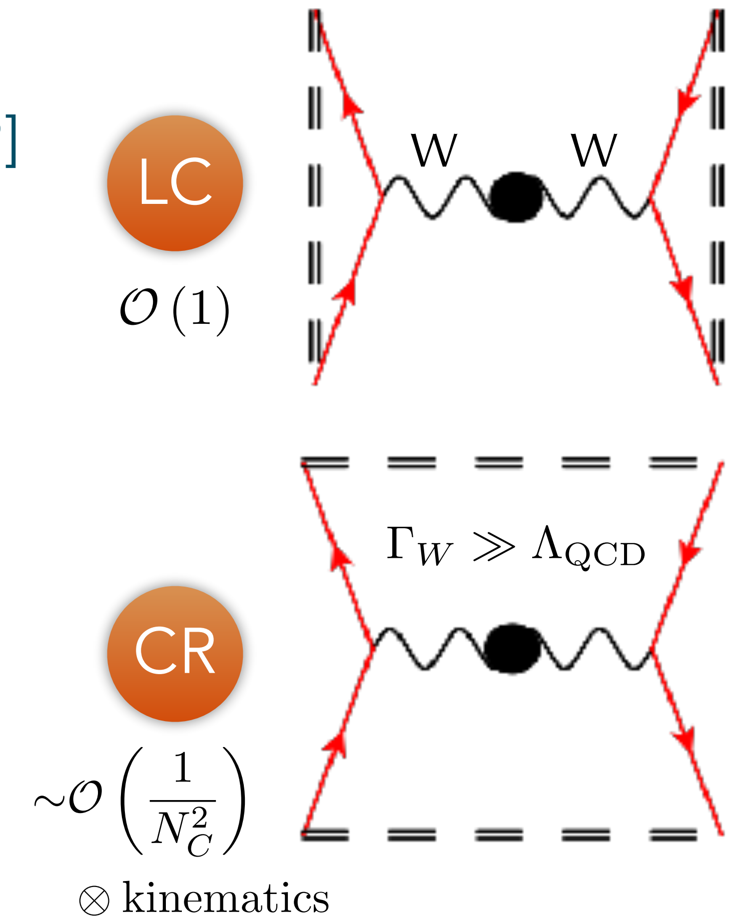
No-CR excluded at 99.5% CL [Phys.Rept. 532 (2013) 119]

But not much detailed (differential) information

Thousand times more WW at FCC-ee

Sjöstrand: turn the W mass problem around; use huge sample of semi-leptonic events to measure m_W

→ use as constraint to measure CR in hadronic WW



Has become even hotter topic at LHC

It appears jet universality is under heavy attack.
Fundamental to understanding & modeling hadronisation

Follow-up studies now underway at LHC.

High-stats ee → other side of story

Also relevant in (hadronic) ee→tt, and Z→4 jets

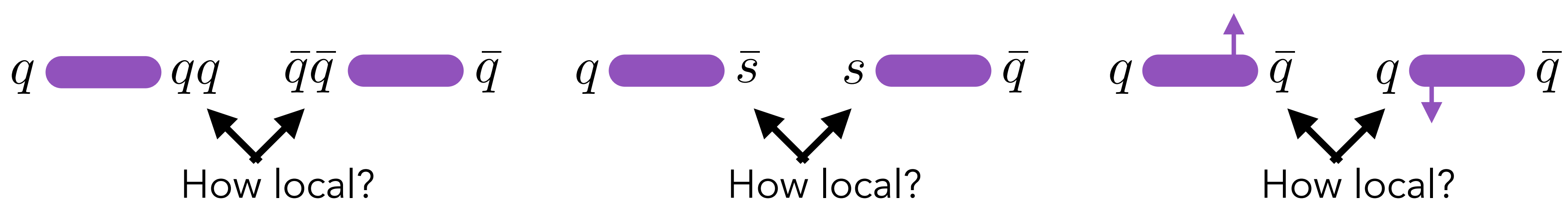
+ Overlaps → interactions?
increased tensions (strangeness)?
breakdown of string picture?

Overviews of recent models: arXiv:1507.02091 , arXiv:1603.05298

OTHER PARTICLE CORRELATIONS

Octet neutralisation? (zero-charge gluon jet with rapidity gaps) → **neutrals**
Colour reconnections, glueballs, …

Leading baryons in g jets?
(discriminates between string/cluster models)
high-E baryons



Further precision non-perturbative aspects

Baryon-Antibaryon correlations: how local is hadronisation?

Kluth: both OPAL measurements were statistics-limited; would reach OPAL systematics at 10^8 Z decays (→ 10^9 with improved systematics?)

+ Strangeness correlations, p_T, spin/helicity correlations ("screwiness"?)

Bose-Einstein Correlations & Fermi-Dirac Correlations

Identical baryons! (pp, ΛΛ) ; highly non-local in string picture

W. Metzger emphasised remaining Fermi-Dirac radius puzzle: correlations at LEP across multiple experiments & for both pp and ΛΛ → 0.1 fm << r_p (MC dependent? Were pΛ cross checks ever done? see EPJC 52 (2007) 113)

JET (SUB)STRUCTURE : WHAT IS QUARK?

LEP: 45-GeV quark jet fragmentation → What is gluon?

Inclusive: gluon FF only appears at NLO (similar to gluon PDF at HERA)

3-jet events. Game of low sensitivity (3rd jet) vs low statistics (Z→bbg)

(Initially only "symmetric" events; compare q vs g jets directly in data)

Expect naive C_A/C_F ratios between quarks and gluons [next slide]

Many subtleties. Coherent radiation → no 'independent fragmentation', especially at large angles. Parton-level "gluon" only meaningful at LO.

… and is it healthy?

Note: highly relevant interplay with Q/G sep @ LHC & FCC-hh: S/B

Language evolved: Just like "a jet" is inherently ambiguous,"quark-like" or "gluon-like" jets are ambiguous concepts See Les Houches arXiv:1605.04692

Define taggers (adjective: "q/g-LIKE") using only final-state observables

Optimise tagger(s) using clean (theory) references, like X->qq vs X->gg

QUARKS AND GLUONS

G. SOYEZ, K. HAMACHER, G. RAUCO, S. TOKAR, Y. SAKAKI

Handles to split degeneracies

$H \to gg$ vs $Z \to qq$

Can we get a sample of $H \to gg$ pure enough for QCD studies?

Requires good **$H \to gg$ vs $H \to bb$**;

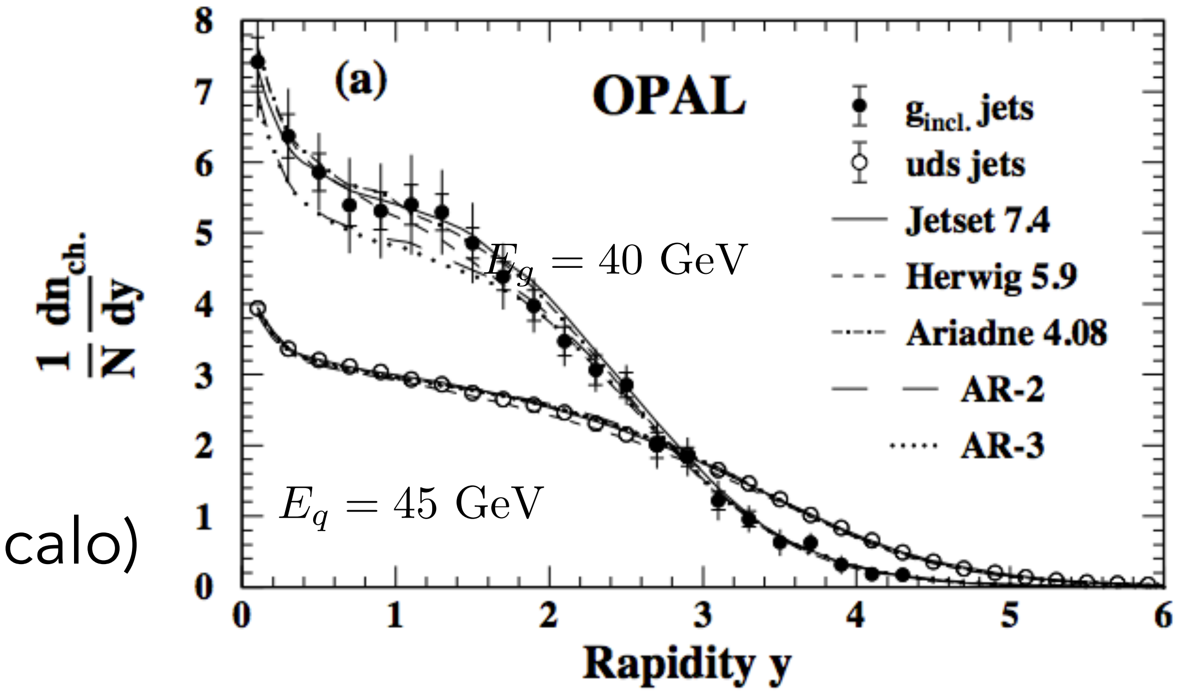
Driven by Higgs studies requirements?

$Z \to bbg$ vs $Z \to qq(g)$ →

g in one hemisphere recoils against b-jets in other hemisphere: **b tagging**

Study differential shape(s): N_{ch} (+low-R calo)

(R ~ 0.1 also useful for jet substructure)



Scaling: radiative events → Forward Boosted

(Also useful for FFs & general scaling studies)

Scaling is **slow**, logarithmic → prefer large lever arm

$E_{CM} > E_{Belle}$ ~ 10 GeV **[~ 10 events / GeV at LEP];**

Useful benchmarks could be E_{CM} ~ 10 (cross checks with Belle), 20, **30** (geom. mean between Belle and m_Z), 45 GeV ($=m_Z/2$) and 80 GeV = m_W

Multi-jet events

At LEP: kicked off the subfield of matrix-element matching & merging

Transformed QCD collider phenomenology from being one of fixed-order vs Monte Carlo calculations to being fixed-order **+** Monte Carlo.

Blazed the trail for LHC state of the art: **Multi-jet NLO merging**

P Richardson
(parton showers since LEP)

- For the first time in many years more work on the accuracy of the parton-shower algorithms.
- Needed as we go to higher accuracy for the matrix elements.
- $1/N_c$ (Plätzer, Sjödahl JHEP 1207 (2012) 042), (Nagy, Soper, JHEP 1507 (2015) 119)
- Subleading logs (Li, Skands, arXiv:1611.00013)
- This is the area where there is probably the greatest potential for improvement.
- If we can consistently improve the logarithmic accuracy.

Expect 2nd-order showers within the next decade, screaming for "2nd-order" validations.

PRECISION α_s MEASUREMENTS

CURRENT STATE OF THE ART: O(1%)

LEP: Theory keeps evolving long after the beams are switched off

Recently, NNLO programs for 3-jet calculations

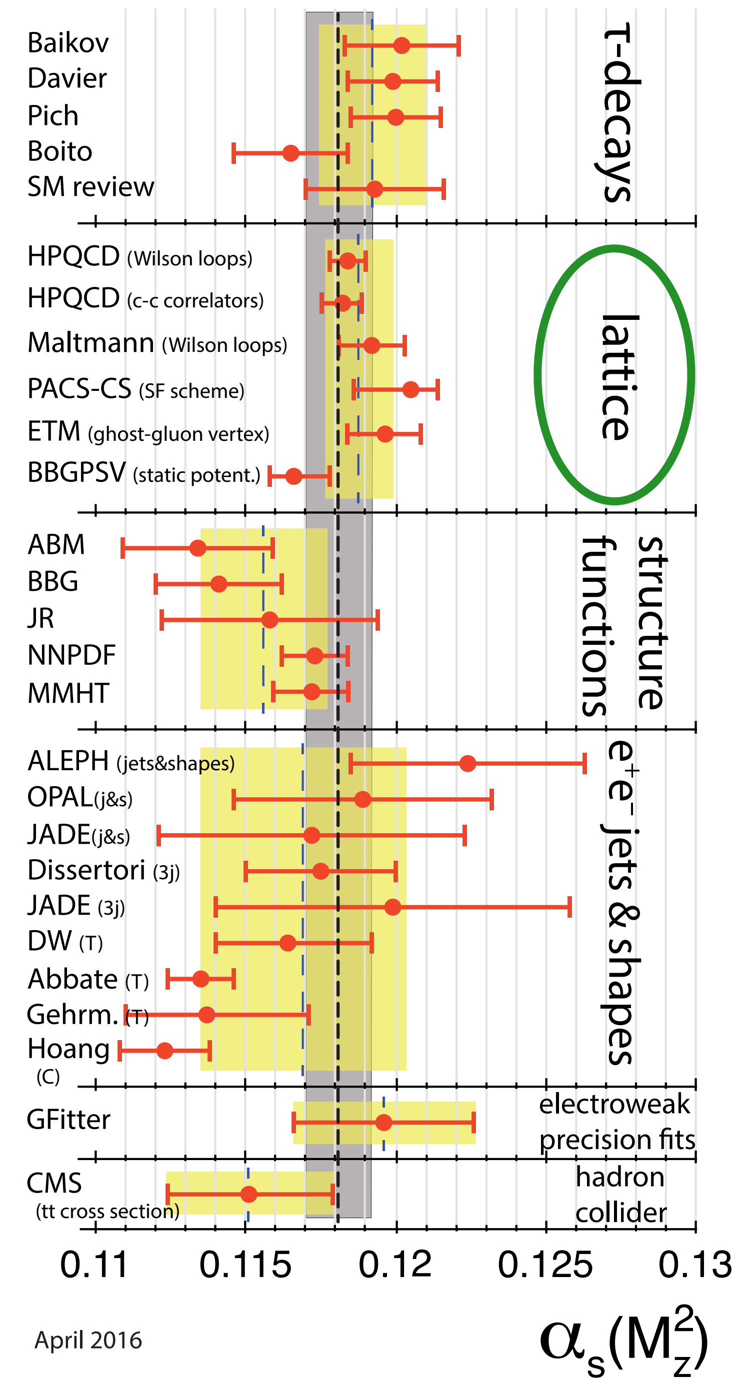
[Weinzierl, PRL 101, 162001 (2008)]; EERAD [Gehrmann-de-Ridder, Gehrmann, Glover, Heinrich, CPC185(2014)3331]

+ New resummations → new $\alpha_s(m_Z)$ extractions

E.g., 2015 SCET-based C-parameter reanalysis
$N^3LL' + O(\alpha_s^3)$ + NPPC: $\alpha_s(m_Z) = 0.1123 \pm 0.0015$
[Hoang, Kolodubretz, Mateu, Stewart, PRD91(2015)094018]

ee currently the least precise subclass (due to large spread between individual extractions) →

Subclass	PDG 2016	$\alpha_s(M_Z^2)$
τ-decays		0.1192 ± 0.0023
lattice QCD		0.1188 ± 0.0011
structure functions		0.1156 ± 0.0021
e^+e^- jets & shapes		0.1169 ± 0.0034
hadron collider		0.1151 ± 0.0028
ewk precision fits		0.1196 ± 0.0030



See also PDG QCD review and references therein

+ 2016 Moriond α_s review [d'Enterria]: arXiv:1606.04772
+ 2015 FCC-ee α_s workshop proceedings: arXiv:1512.05194

Maximum a factor 3 further reduction possible (without FCC-ee). [Some participants believed less.]

PRECISION α_S AT FCC-EE

STATISTICS ALLOW TO AIM FOR $\delta\alpha_s/\alpha_s$ < 0.1%

Main Observable:

$$R_\ell^0 = \frac{\Gamma_{\text{had}}}{\Gamma_\ell} \qquad \text{LO} \quad \Gamma_f \propto (g_{V,f}^2 + g_{A,f}^2) \qquad g_{V,f} = g_{A,f}(1 - 4|q_f|\sin^2\theta_W)$$

QCD corrections to Γ_{had} known to 4th order

- Kuhn: Conservative QCD scale variations → O(100 keV) → $\delta\alpha_s \sim 3 \times 10^{-4}$
- Comparable with the target for FCC-ee

Electroweak beyond LO $\quad g_{A,f} \to \sqrt{1+\Delta\rho_f}\, g_{A,f} \qquad \sin^2\theta_W \to \sqrt{1+\Delta\kappa_f}\,\sin^2\theta_W = \sin^2\theta_{\text{eff}}^f,$

- Can be calculated (after Higgs discovery) or use measured $\sin^2\theta_{\text{eff}}$
- Mönig (Gfitter) assuming Δm_Z = 0.1 MeV, $\Delta\Gamma_Z$ = 0.05 MeV, $\Delta R_l = 10^{-3}$
- → $\delta\alpha_s \sim 3 \times 10^{-4}$ ($\delta\alpha_s \sim 1.6 \times 10^{-4}$ without theory uncertainties)

Better-than-LEP statistics also for W → high-precision R_W ratio !

- Srebre & d'Enterria: huge improvement in BR(W_{had}) at FCC-ee
- Combine with expected $\Delta\Gamma_W$ = 12 MeV from LHC (high-m_T W) & factor-3 improvement in $|V_{cs}|$ → similar α_s precision to extraction from Z decays.

SUMMARY

FCC-ee will not be built to study QCD

But it has tremendous potential to make decisive & detailed measurements.

LEP precision finally exhausted, almost 20 years after shutdown.

Theory is still evolving and new questions are highlighted by LHC

Confinement is still hard

Current generation of theory models show few (albeit some) discrepancies with LEP

Soon: second-order-everything and next-generation hadronisation models.
FCC-ee can't come soon enough!