Discussion on QCD White Paper(s) for CEPC

Peter Skands (Monash U)

Nonperturbative QFT remains among the most fundamental problems in physics

A day will come when someone (claims to) have a solution, or at least a systematically improvable approximation

(+ LHC ⟷ further refinements of phenomenological models of NP QCD)

Program of high-precision QCD measurements at CEPC/FCC-ee

Ultimate trial by fire for any future treatment of confinement in high-energy processes

+ α_s measurements

Basic requirements:

Measure effects of order Λ_{QCD} with high precision

Disentangle different "tracers": strangeness, baryons, mass, & spin → **PID**

Other aspects:

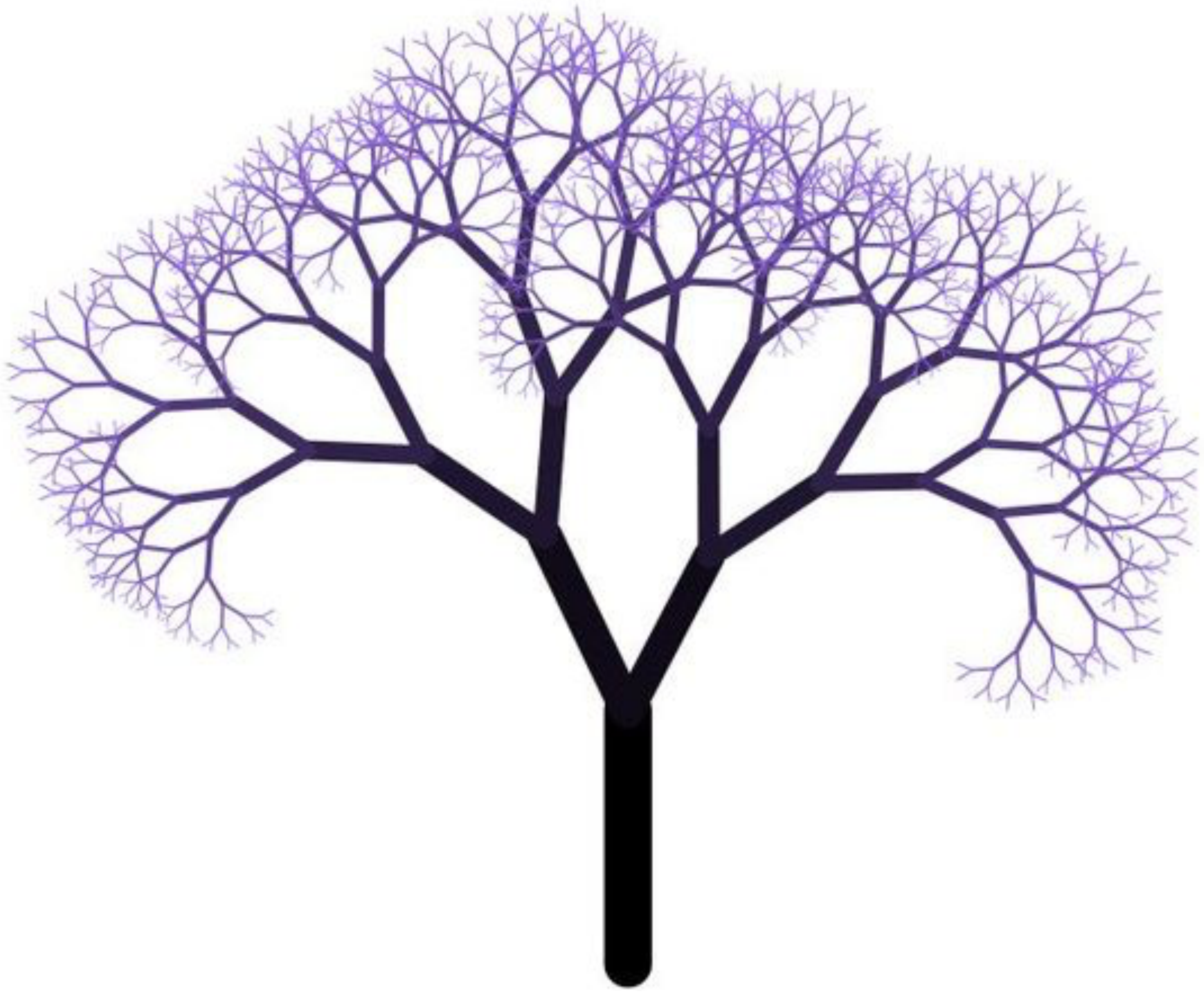
Fragmentation Functions, (Heavy) Flavour (Tagging), Quarkonia, (Rare) Hadron Decays, H→gg, Colour Reconnections (in Z, WW, ttbar), Power Corrections, interplay with EW and Higgs measurements, jet / particle flow calibrations, $\gamma\gamma$ collisions

CEPC Workshop

November 2018, IHEP, Beijing

QCD AT EE COLLIDERS

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



QCD AT EE COLLIDERS

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CEPC / FCC-ee have tremendous potential to make decisive & detailed measurements.

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

Theory still evolving and new questions highlighted by LHC

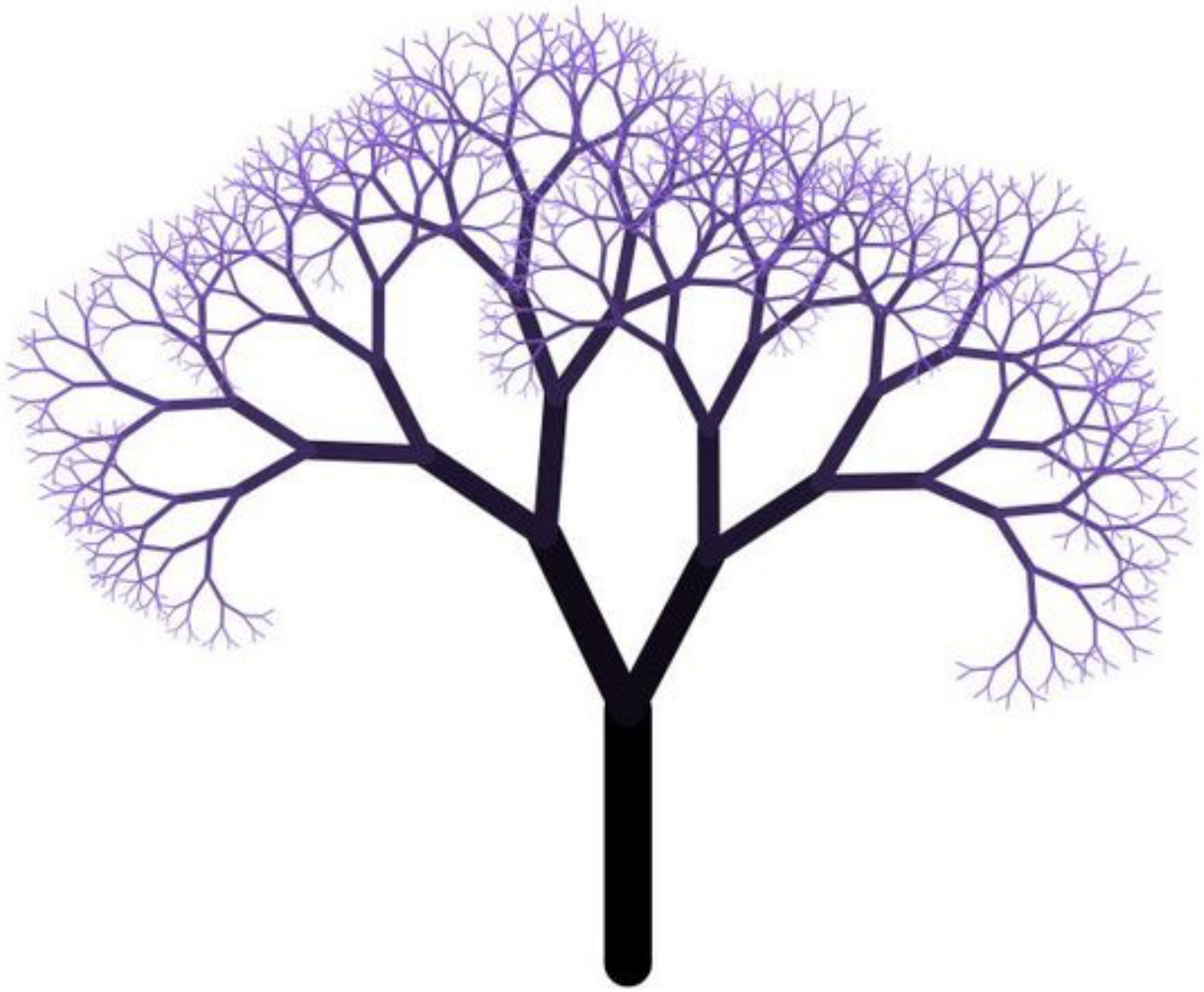
Confinement is still hard

LEP precision finally exhausted, almost 20 years after shutdown.

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

Within next decade: expect significant perturbative advances and next-generation hadronisation models.

+ QCD in γγ collisions, interplay with EW, H, BSM, Precision Legacy for future pp collider



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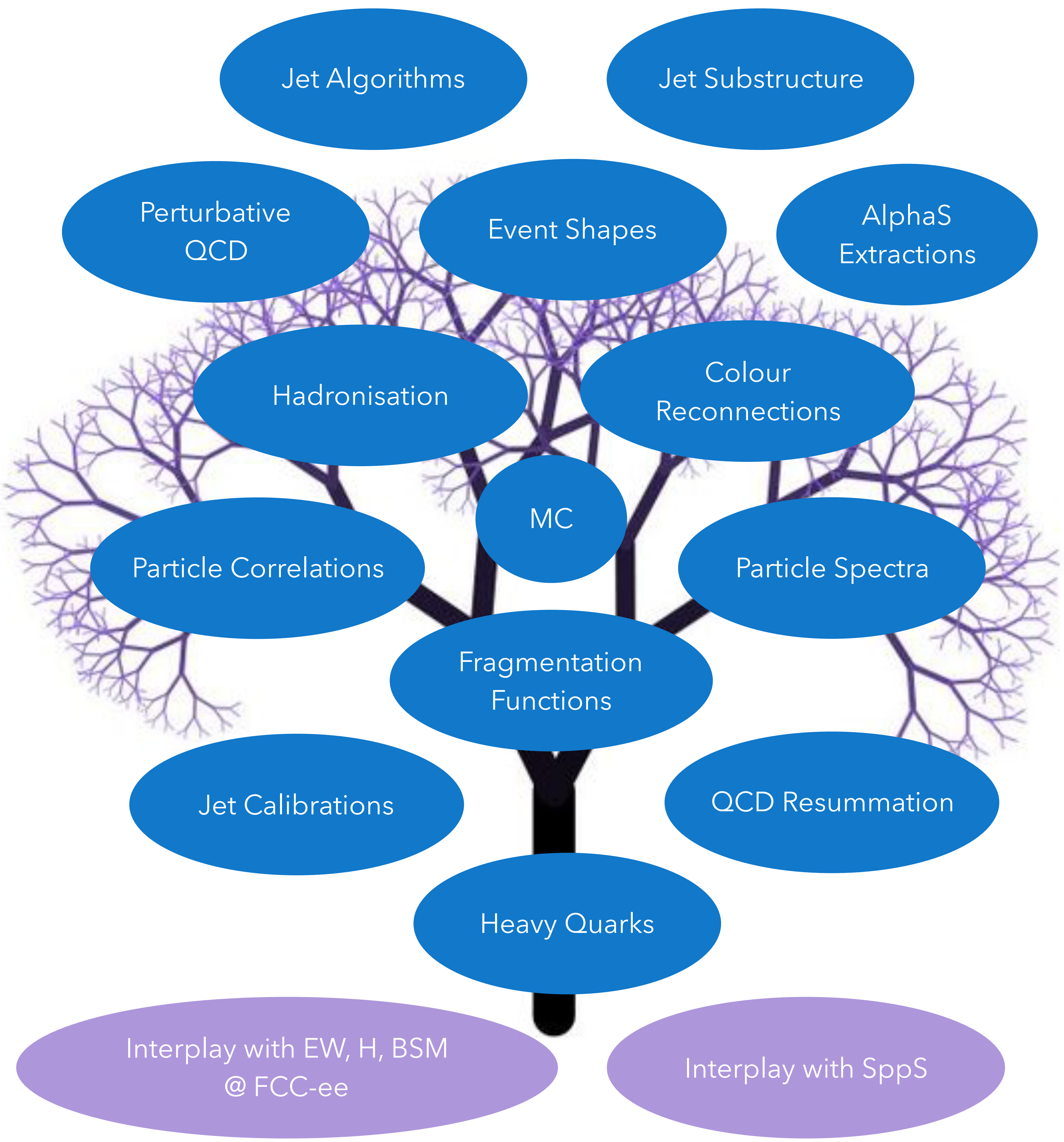


THEMES

Measure alphaS

High-Precision Z (and W) widths

High-Precision Event Shapes, Jet Rates, … (IR safe observables sensitive to alphaS)

Single-Inclusive Hadron Production and Decays

Fragmentation Functions; Hadron Spectra; (+ polarisation)

Exotic /rare hadrons, quarkonium, rare decays, …

+ Interplay with flavour studies (+ Interplay with DM annihilation)

Understanding Confinement (Multi-hadronic / Exclusive)

In high-energy processes → hadronisation

Hadron correlations, properties with respect to global ("string") axes

Dependence on (global and local) environment (distance to jets, hadronic density, flavours)

Power Corrections / Hadronisation Corrections

Interplay with high-p_T physics program

Low-Q region of event shapes, jet rates, jet substructure; jet flavour tagging, …

Crucial for alphaS measurements; also for jet calibration?

PRECISION α_S MEASUREMENTS

(see FCC-ee QCD workshops & writeups)

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

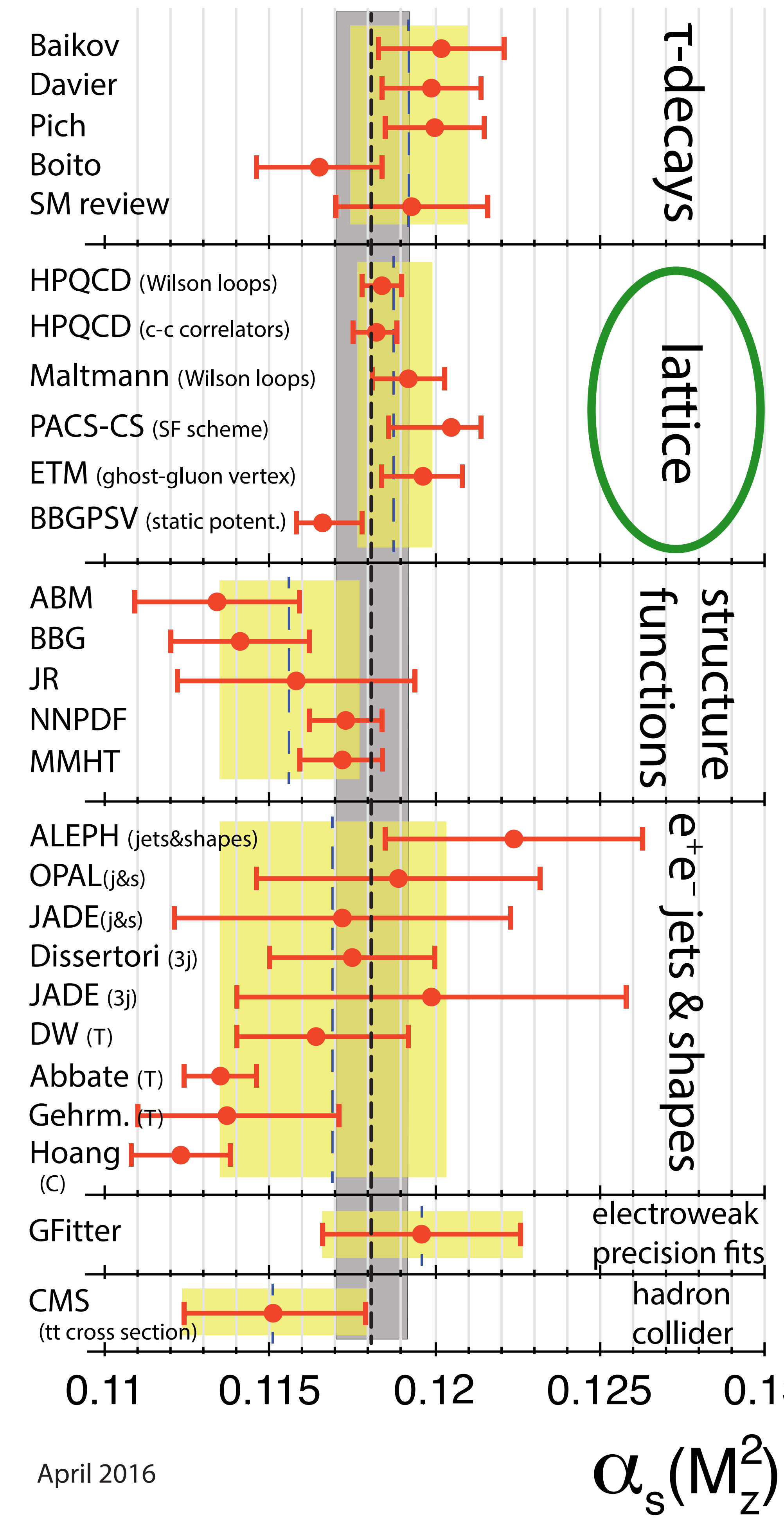
$N^3LL' + O(\alpha_s^3)$ + NPPC: $\alpha_s(m_Z) = 0.1123 \pm 0.0015$

[Hoang, Kolodubretz, Mateu, Stewart, PRD91(2015)094018]

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

PDG 2016

Subclass	$\alpha_s(M_Z^2)$
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 CEPC / FCC-EE

(see FCC-ee QCD workshops & writeups)

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

Main Observable:

$$R_\ell^0 = \frac{\Gamma_{\text{had}}}{\Gamma_\ell}$$

LO $\Gamma_f \propto (g_{V,f}^2 + g_{A,f}^2)$ $\quad g_{V,f} = g_{A,f}(1 - 4|q_f|\sin^2\theta_W)$

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

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

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

- 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, $\Delta R_l = 10^{-3}$
- → $\delta\alpha_s$ ~ 3 x 10^{-4} ($\delta\alpha_s$ ~ 1.6 x 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 (/CEPC?)
- 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?

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

Can do 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.

Bonus: high(er)-precision jet calibration (particle flow) ?

Accurate knowledge (+ modeling) of particle composition & spectra

➠ FRAGMENTATION FUNCTIONS

(see FCC-ee QCD workshops & writeups)

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

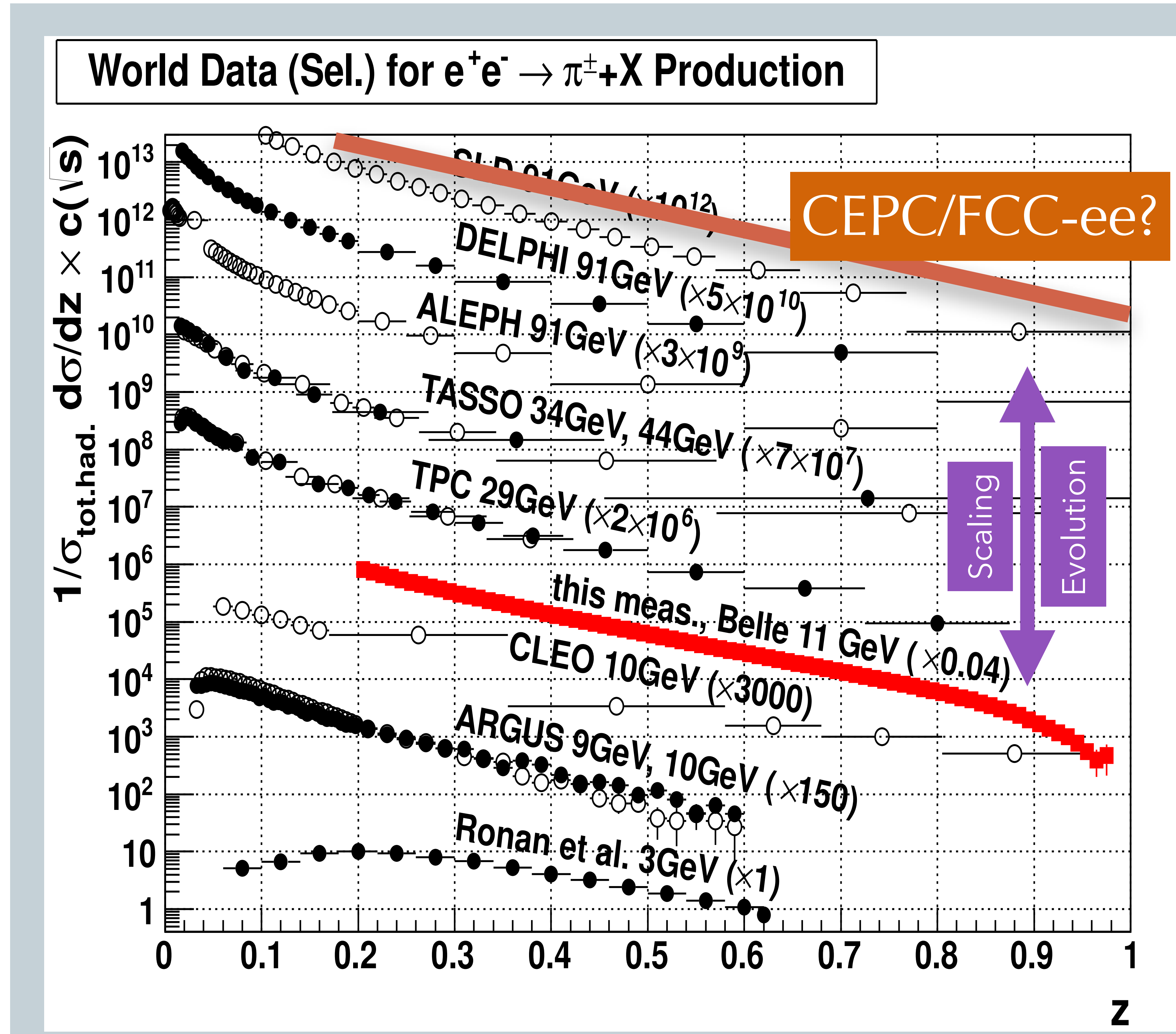
FFs from Belle to FCC-ee *[A. Vossen]*

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% |p| resolution (expected)



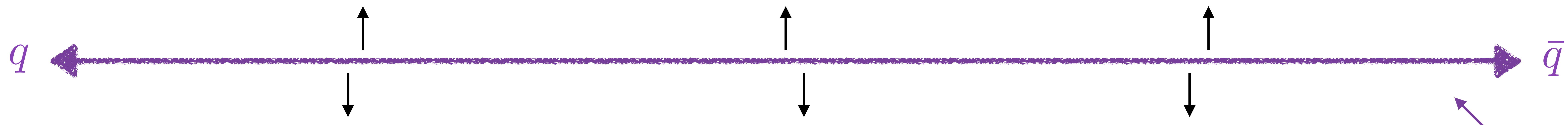
Flavour structure for FFs of hyperons and other hadrons that are difficult to reconstruct in pp and SIDIS.

- Will depend on Particle Identification capabilities.

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

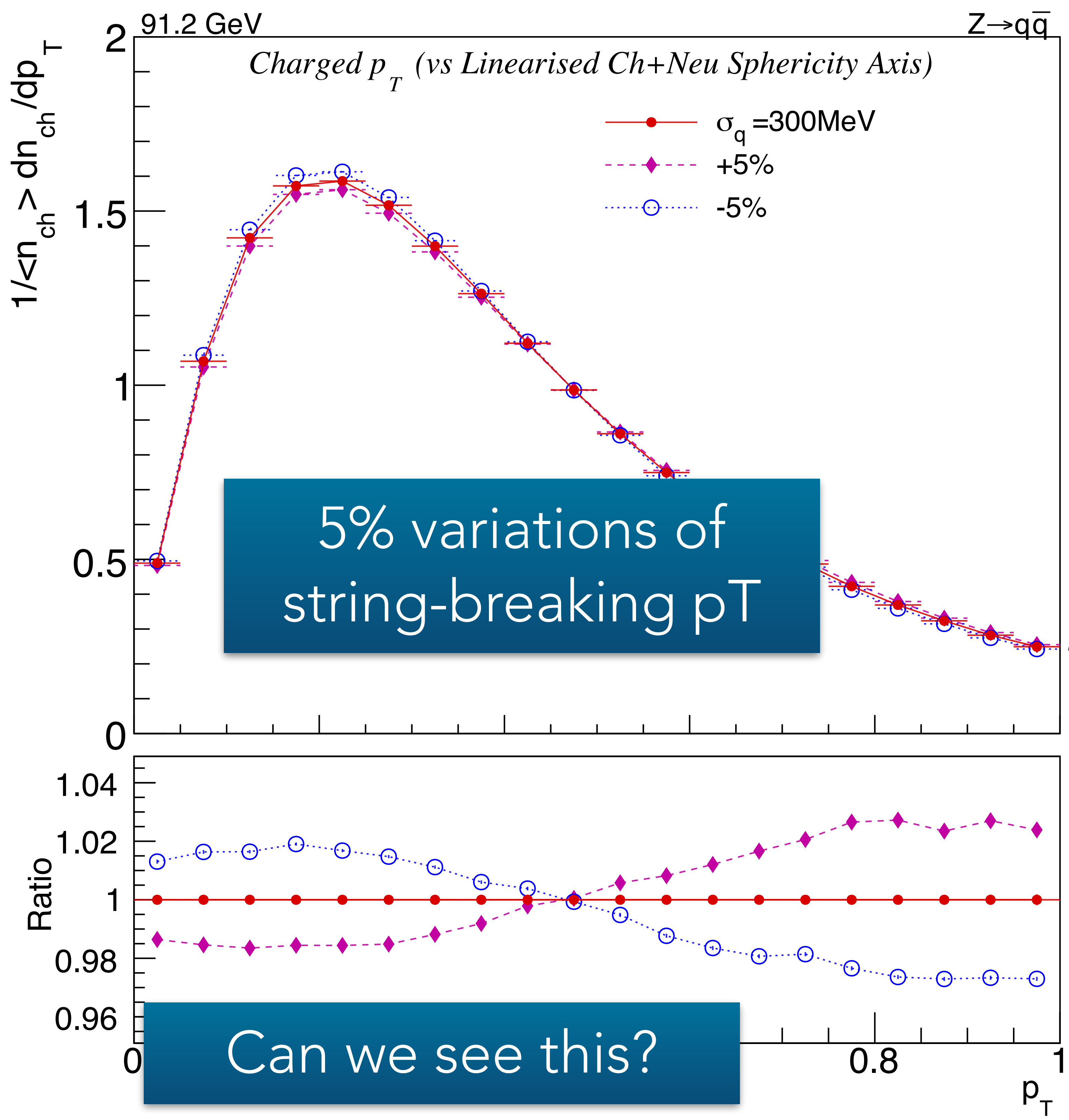
- 3 tracker hits down to 30-40 MeV allows to reach $z = 10^{-3}$ ($\ln(z) = -7$)
- Kluth: if needed, could get O(LEP) sample in ~ 1 minute running with lower B-field

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



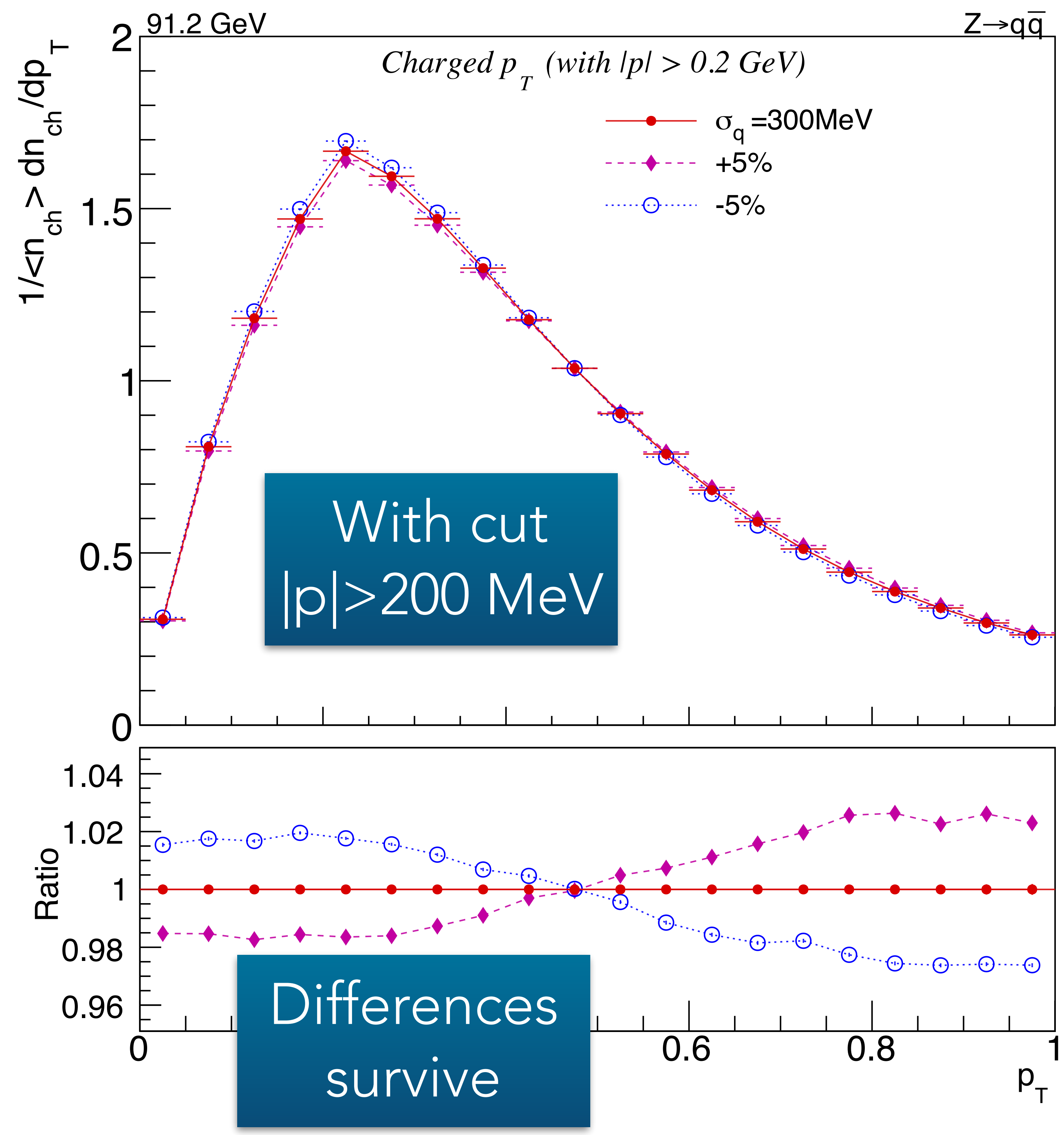
Linearised sphericity axis,
thrust axis,
2-jet axis,
...

Hadron pT spectra, transverse to dominant event axis



Toy Example

Perturbatively dominated power-law tail



EFFECTS OF ORDER Λ_{QCD}

p_T kicks from hadronisation: Gaussian pT distribution with width ~ 300 MeV (+ ρ decays)

Difficult for any hadron to have |p| < 300 MeV.

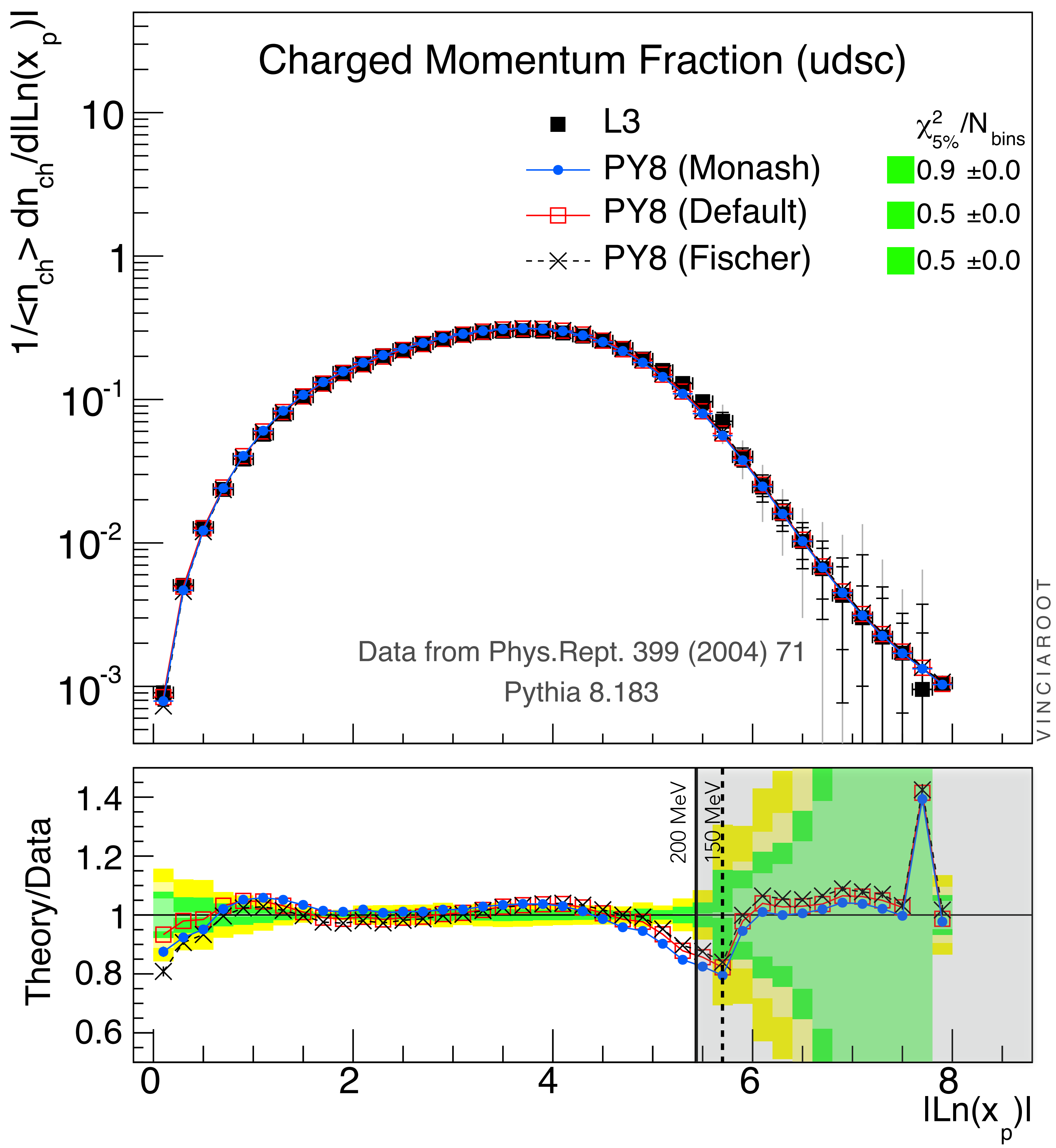
To check this, measure pions with |p| < 300 MeV. (OK.)

Data from both LEP and LHC indicate softer pion spectrum

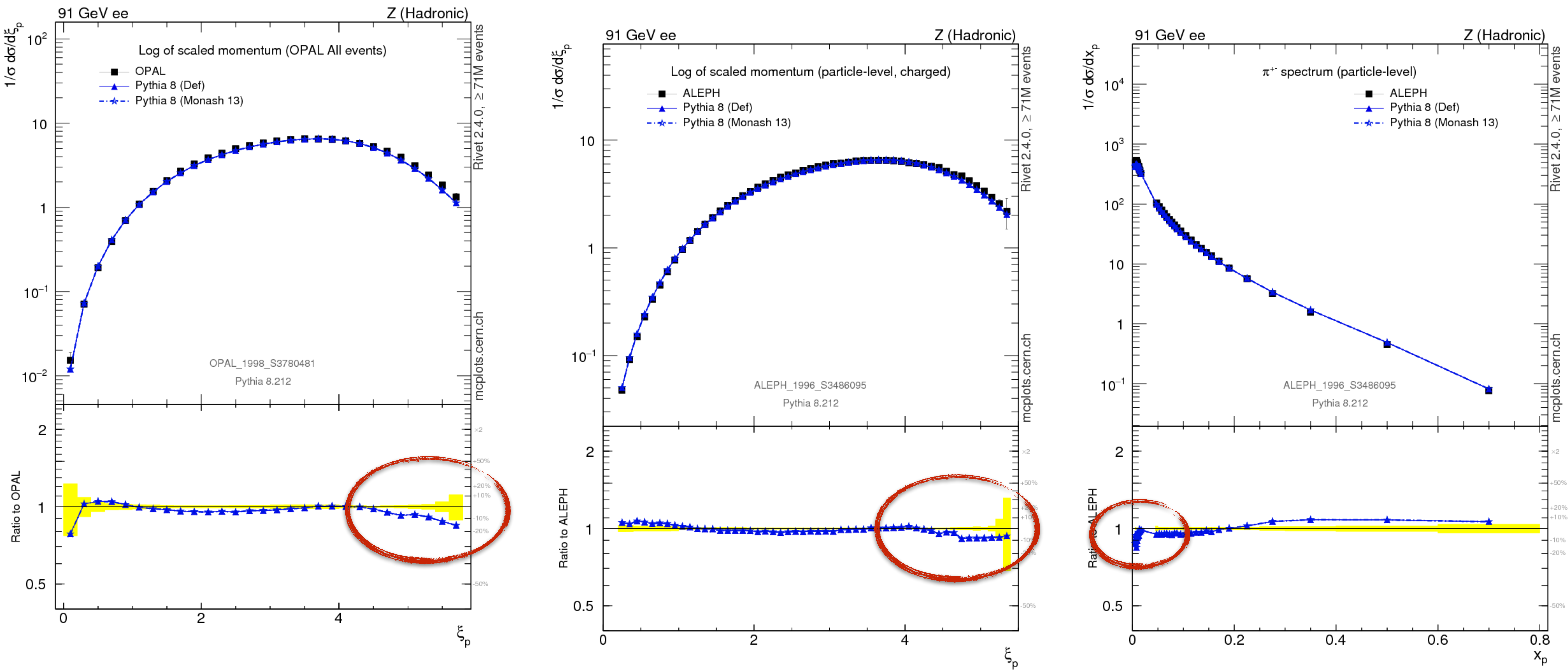
Cut at |p| = 200 MeV makes this tough to examine clearly

- 3 hits down to ~ 50 MeV ?
- Special runs / setups with lower thresholds?

Example from LEP



(plots from mcplots.cern.ch)



Point of view A: small effects, and didn't you say toy model anyway?

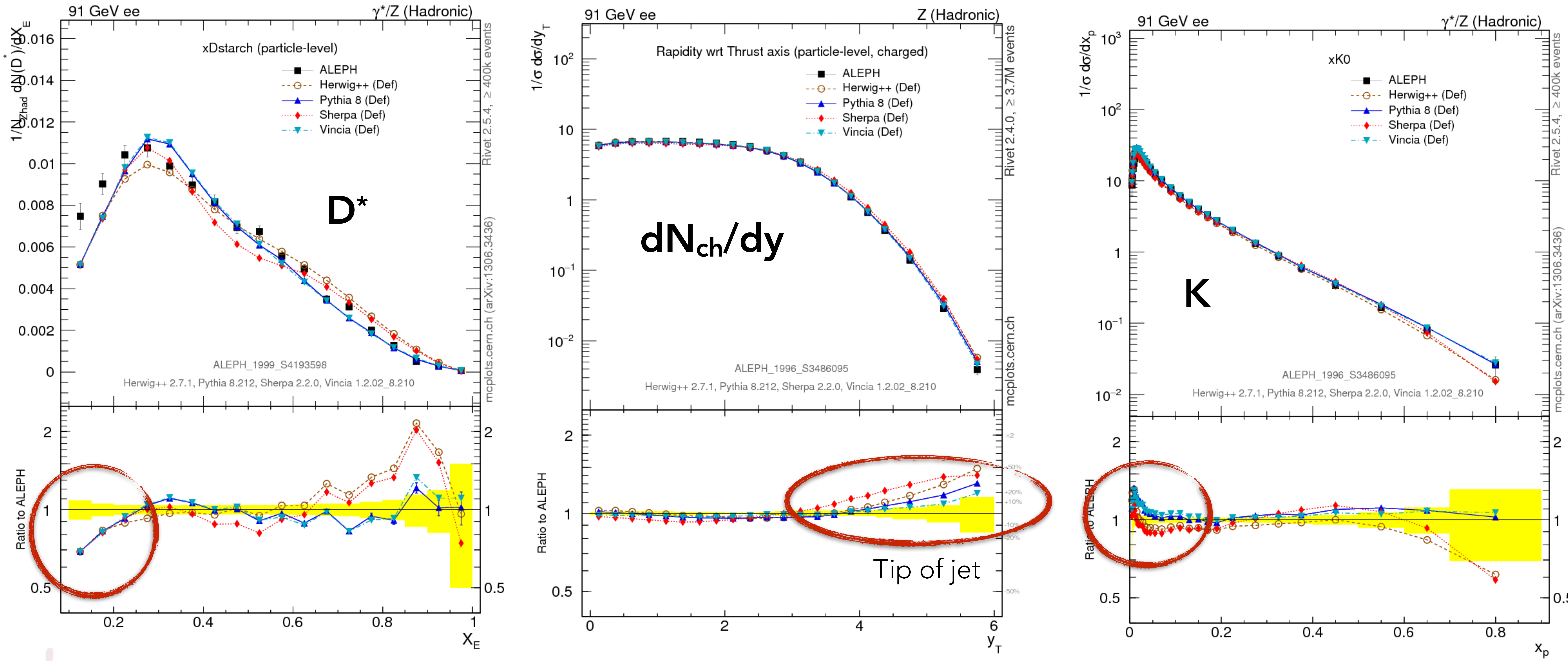
Point of view B: this illustrates the kinds of things we can examine, with precise measurements

Flavour (in)dependence? (Controlling for feed-down?) Gauss vs Thermal?

PLENTY OF INTERESTING FEATURES

(plots from mcplots.cern.ch)

Just a few examples



Capabilities for hadrons from decays (π^0, η, η′, ρ, ω, K*, φ, **Δ**, Λ, Σ, Σ*, Ξ, Ξ*, Ω, …)
+ heavy-flavour hadrons

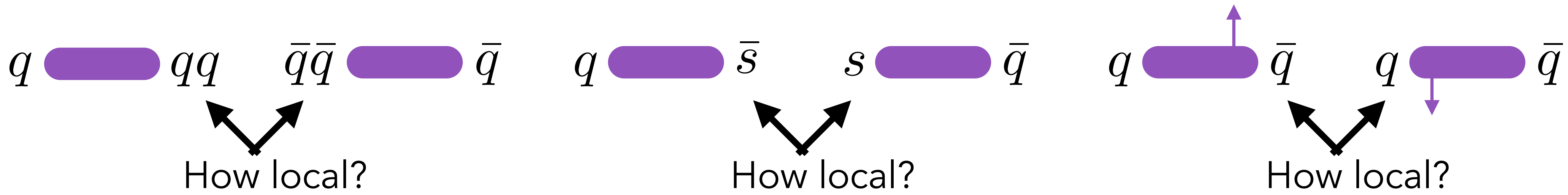
Very challenging; conflicting measurements from LEP

HADRON CORRELATIONS

(see FCC-ee QCD workshops & writeups)

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?)

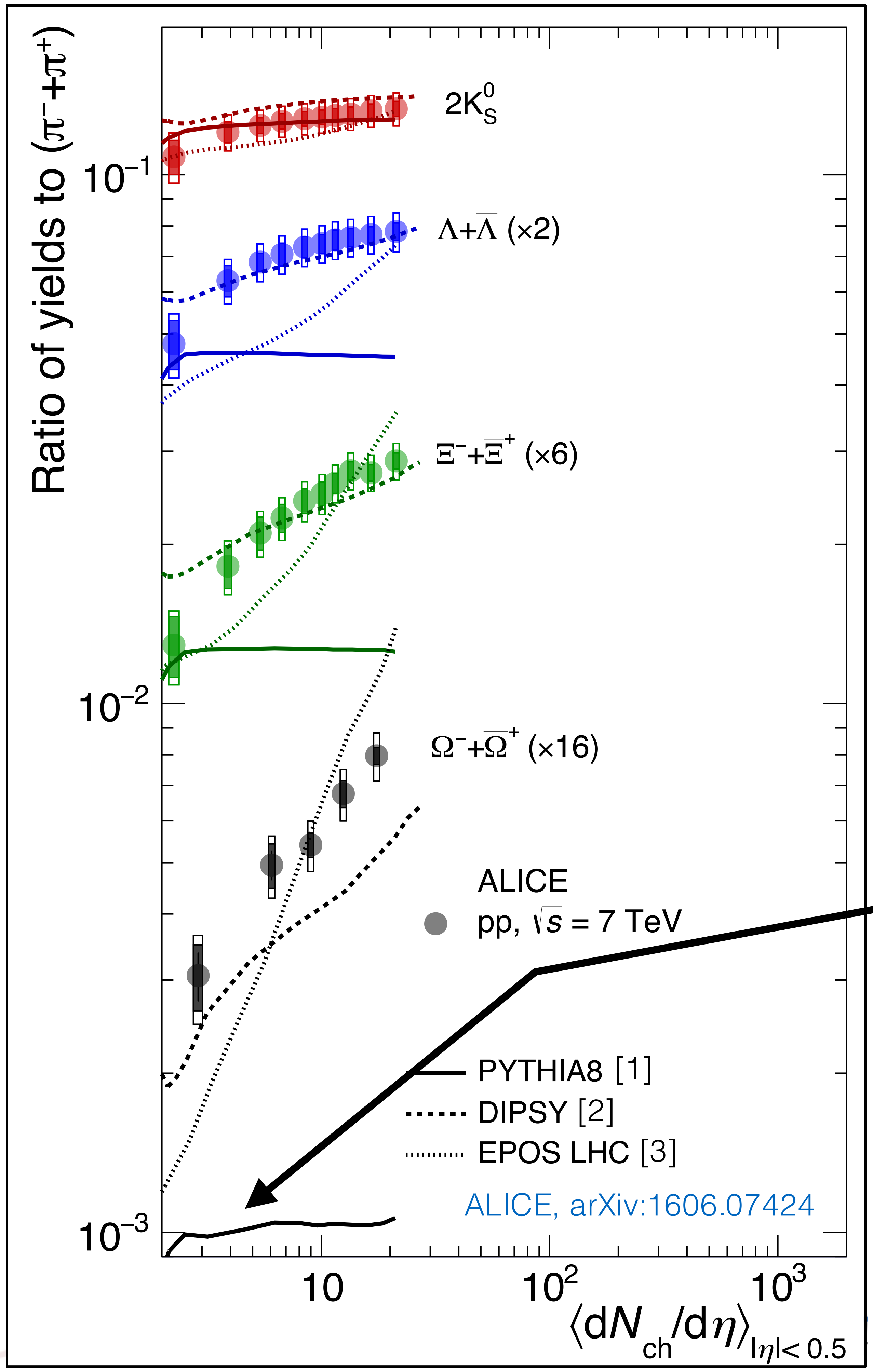
+ Strangeness correlations, p_T, spin/helicity correlations ("screwiness"?)

Bose-Einstein Correlations & Fermi-Dirac Correlations

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

W. Metzger: 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)

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

(see FCC-ee QCD workshops & writeups)

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

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

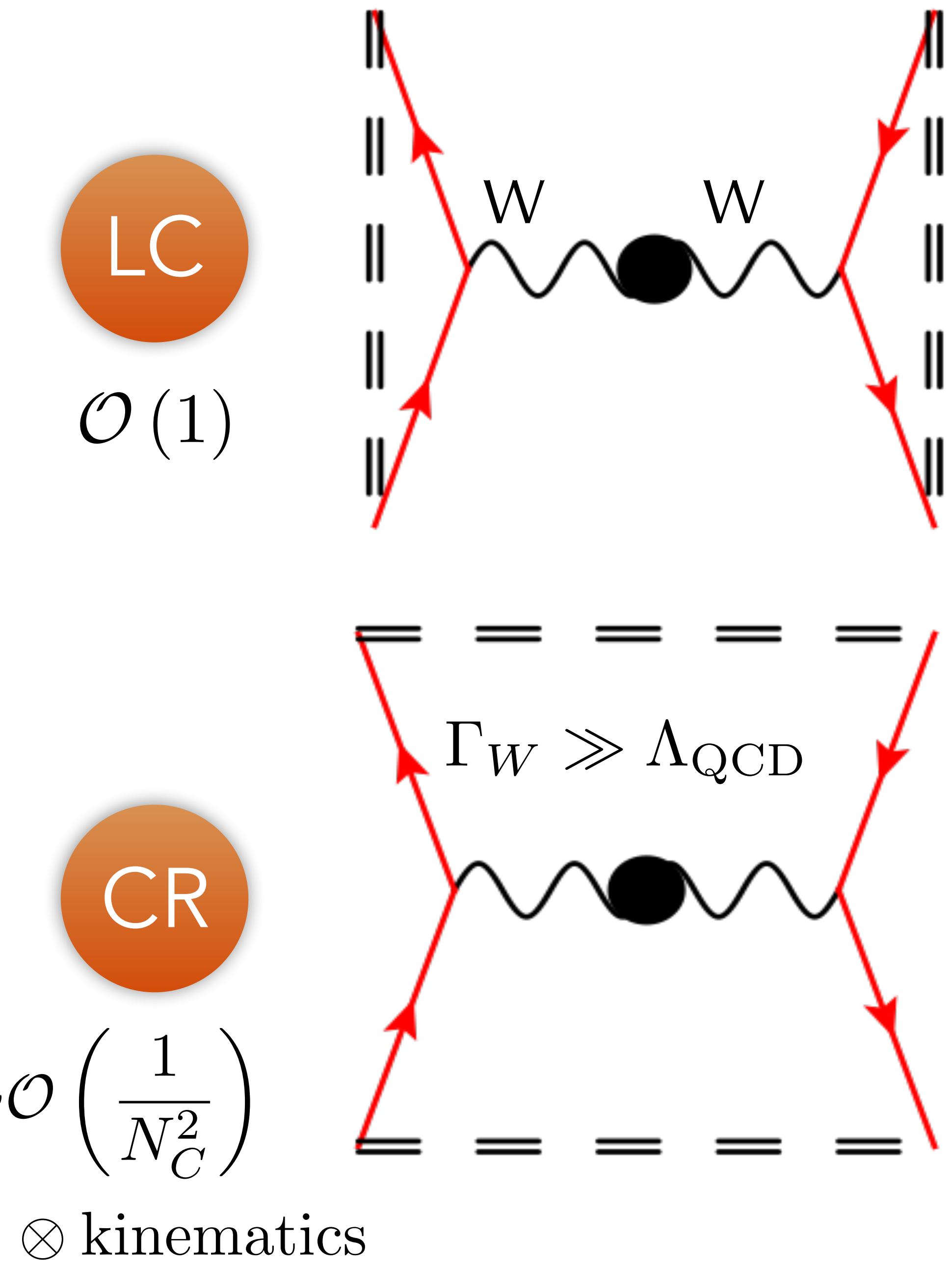
Non-zero effect convincingly demonstrated at LEP-2

- No-CR excluded at 99.5% CL [Phys.Rept. 532 (2013) 119]
- **But not much detailed (differential) information**

Thousand times more WW at CEPC / FCC-ee

Turn the W mass problem around; use threshold scan + huge sample of semi-leptonic events to measure m_W

→ input 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?

Little done for CEPC/FCC-ee so far …
Plenty of room to play with models, observables, …

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

JET (SUB)STRUCTURE

LEP: mainly 45-GeV quark jet fragmentation

Inclusive: gluon FF only appears at NLO

3-jet events. Game of low sensitivity (3rd jet) vs low statistics ($Z\rightarrow b\bar{b}g$)

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

Naive C_A/C_F ratios between quarks and gluons verified

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

➠ **Quark/gluon separation/tagging**

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

(see FCC-ee QCD workshops & writeups)

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

Handles to split degeneracies

H→gg vs Z→qq

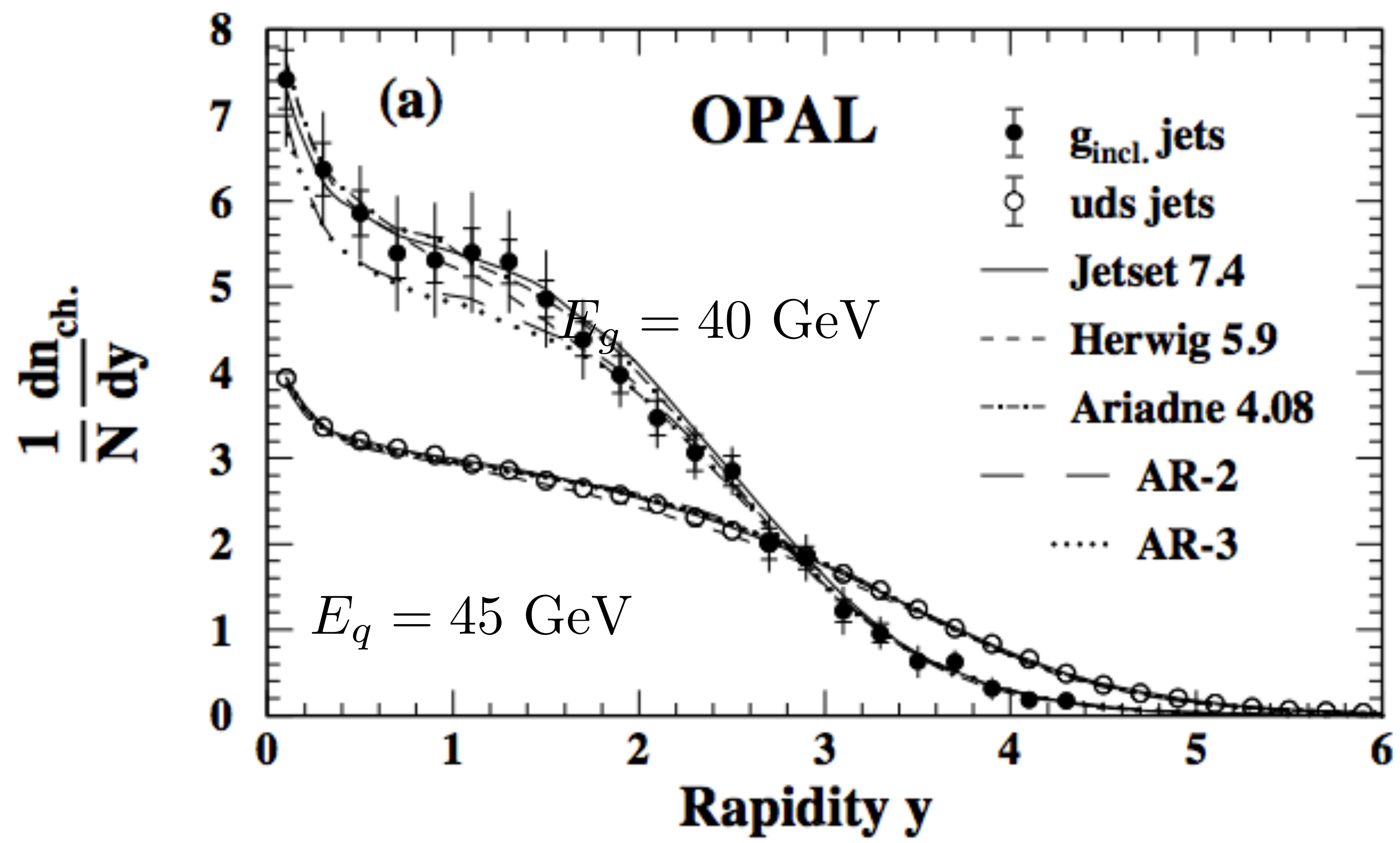
- Can we get a sample of H→gg pure enough for QCD studies?
- Requires good **H→gg vs H→bb**;
- Driven by Higgs studies requirements?

Z→bbg vs Z→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

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

←(Also useful for FFs & general scaling studies)

- $E_{CM} > E_{Belle}$ ~ 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