MCs & Precision QCD at Future e^+e^- Machines

Peter Skands (Monash U)

Perturbative QCD: High Accuracy

Expect a new generation of precision showers merged through (N)NLO

Nonperturbative QCD: High Resolution

Next generation of e^+e^- machines ➡ **trial by fire** not just for any post-LHC advanced hadronisation models, but also for ***any future solution*** *(or systematically improvable approximation)* ***to the problem of confinement***.

➡ Need **Good PID & Good Momentum Resolution** $\ll O(\Lambda_{\mathrm{QCD}}) \sim 100\,\mathrm{MeV}$

+ Synergies with EW & Higgs Physics Goals (MC uncertainties)

CEPC Workshop
October 2020, Shanghai

MC Generators — Perturbative Processes

Slide borrowed from A. Hoang (yesterday's EW session)

- Fast machinery from LHC, just change initial state
- Less modeling for color neutralization processes needed
- NLO-matched MC generators standard.

Validation of NLO QCD for e^+e^- Collisions

	MG5_AMC			WHIZARD		
Process	σ^{LO}[fb]	σ^{NLO}[fb]	K	σ^{LO}[fb]	σ^{NLO}[fb]	K
$e^+e^- \to jj$	622.3(5)	639.3(1)	1.02733	622.73(4)	639.41(9)	1.02678
$e^+e^- \to jjj$	340.1(2)	317.3(8)	0.93297	342.4(5)	318.6(7)	0.9305
$e^+e^- \to jjjj$	104.7(1)	103.7(3)	0.99045	105.1(4)	103.0(6)	0.98003
$e^+e^- \to jjjjj$	22.11(6)	24.65(4)	1.11488	22.80(2)	24.35(15)	1.06798
$e^+e^- \to jjjjjj$	N/A	N/A	N/A	3.62(2)	0.0(0)	0.0
$e^+e^- \to b\bar{b}$	92.37(6)	94.89(1)	1.02728	92.32(1)	94.78(7)	1.02664
$e^+e^- \to b\bar{b}b\bar{b}$	$1.644(3) \cdot 10^{-1}$	$3.60(1) \cdot 10^{-1}$	2.1897	$1.64(2) \cdot 10^{-1}$	$3.67(4) \cdot 10^{-1}$	2.2378
$e^+e^- \to t\bar{t}$	166.2(2)	174.5(3)	1.04994	166.4(1)	174.53(6)	1.04886
$e^+e^- \to t\bar{t}j$	48.13(5)	53.36(1)	1.10867	48.3(2)	53.25(6)	1.10248
$e^+e^- \to t\bar{t}jj$	8.614(9)	10.49(3)	1.21777	8.612(8)	10.46(6)	1.21458
$e^+e^- \to t\bar{t}jjj$	1.044(2)	1.420(4)	1.3601	1.040(1)	1.414(10)	1.3595
$e^+e^- \to t\bar{t}t\bar{t}$	$6.45(1) \cdot 10^{-4}$	$11.94(2) \cdot 10^{-4}$	1.85117	$6.463(2) \cdot 10^{-4}$	$11.91(2) \cdot 10^{-4}$	1.8428
$e^+e^- \to t\bar{t}t\bar{t}j$	$2.719(5) \cdot 10^{-5}$	$5.264(8) \cdot 10^{-5}$	1.93602	$2.722(1) \cdot 10^{-5}$	$5.250(14) \cdot 10^{-5}$	1.92873
$e^+e^- \to t\bar{t}b\bar{b}$	0.1819(3)	0.292(1)	1.60533	0.186(1)	0.293(2)	1.57527
$e^+e^- \to t\bar{t}H$	2.018(3)	1.909(3)	0.94601	2.022(3)	1.912(3)	0.9456
$e^+e^- \to t\bar{t}Hj$	$0.2533(3) \cdot 10^{-0}$	$0.2665(6) \cdot 10^{-0}$	1.05212	0.2540(9)	0.2664(5)	1.04889
$e^+e^- \to t\bar{t}Hjj$	$2.663(4) \cdot 10^{-2}$	$3.141(9) \cdot 10^{-2}$	1.1795	$2.666(4) \cdot 10^{-2}$	$3.144(9) \cdot 10^{-2}$	1.17928
$e^+e^- \to t\bar{t}\gamma$	12.7(2)	13.3(4)	1.04726	12.71(4)	13.78(4)	1.08418
$e^+e^- \to t\bar{t}Z$	4.642(6)	4.95(1)	1.06636	4.64(1)	4.94(1)	1.06467
$e^+e^- \to t\bar{t}Zj$	0.6059(6)	0.6917(24)	1.14168	0.610(4)	0.6927(14)	1.13565
$e^+e^- \to t\bar{t}Zjj$	$6.251(28) \cdot 10^{-2}$	$8.181(21) \cdot 10^{-2}$	1.30875	$6.233(8) \cdot 10^{-2}$	$8.201(14) \cdot 10^{-2}$	1.31573
$e^+e^- \to t\bar{t}W^\pm jj$	$2.400(4) \cdot 10^{-4}$	$3.714(8) \cdot 10^{-4}$	1.54747	$2.41(1) \cdot 10^{-4}$	$3.695(9) \cdot 10^{-4}$	1.5332
$e^+e^- \to t\bar{t}\gamma\gamma$	0.383(5)	0.416(2)	1.08618	0.382(3)	0.420(3)	1.09952
$e^+e^- \to t\bar{t}\gamma Z$	0.2212(3)	0.2364(6)	1.06873	0.220(1)	0.240(2)	1.09094
$e^+e^- \to t\bar{t}\gamma H$	$9.75(1) \cdot 10^{-2}$	$9.42(3) \cdot 10^{-2}$	0.96614	$9.748(6) \cdot 10^{-2}$	$9.58(7) \cdot 10^{-2}$	0.98277
$e^+e^- \to t\bar{t}ZZ$	$3.788(4) \cdot 10^{-2}$	$4.00(1) \cdot 10^{-2}$	1.05597	$3.756(4) \cdot 10^{-2}$	$4.005(2) \cdot 10^{-2}$	1.0663
$e^+e^- \to t\bar{t}W^+W^-$	0.1372(3)	0.1540(6)	1.1225	0.1370(4)	0.1538(4)	1.12257
$e^+e^- \to t\bar{t}HH$	$1.358(1) \cdot 10^{-2}$	$1.206(3) \cdot 10^{-2}$	0.888	$1.367(1) \cdot 10^{-2}$	$1.218(1) \cdot 10^{-2}$	0.8909
$e^+e^- \to t\bar{t}HZ$	$3.600(6) \cdot 10^{-2}$	$3.58(1) \cdot 10^{-2}$	0.99445	$3.596(1) \cdot 10^{-2}$	$3.581(2) \cdot 10^{-2}$	0.9958

Just pick what you need!

Not so fast..

MC Generators — How precise are they?

Slide borrowed from A. Hoang (yesterday's EW session)

- Multipurpose MC generators (Pythia, Herwig, Whizard, Sherpa) can simulate all aspects of particle production and decay at the observable level

How precise are they?

My additions

- The theoretical precision is tied to the precision of the parton showers, for a few very simple observable NLL, mostly LL or less. (Though showers do include some further all-orders aspects, such as exact conservation of energy and momentum, not accounted for in this counting.)
- Tuned hadronization models compensate (partly) for the deficiency but scale differently with $\sqrt{s} \Longrightarrow$ **scaling studies**
- In general we have $\boxed{\text{observable precision}} > \boxed{\text{theoretical precision}}$

  CEPC ➤ high statistics from 10 – 250 GeV (via ISR from Z pole)

- MCs are currently not very precise tools to extract QCD parameters or provide estimate of hadronization corrections to high-order perturbative analytical calculations
- NLO-matching does only improve the first hard gluon radiation. Does not improve observables governed by parton shower dynamics.

MC Generators ➤ Next Generation

Slide borrowed from A. Hoang (yesterday's EW session)

- NLL precise parton showers with full coherence and improved models are an important step that needs to be taken (many different aspects, work already ongoing).

e.g. second order kernel — Li, Skands '16

double emssion — Höche Prestel' 14, '15

amplitude evolution (full coherence, non-global logs, color reconnection) — Forshaw, Holguin, Plätzer '19; Gieseke, Kirchgaesser, Plätzer,' Siodmok '19; Martinez, Forshaw, De Angelis, Plätzer, Seymour '18

New generation of MCs needed!

→ Definitely possible, community should support it more enthusiastically.

First shower models (Leading Log, Leading Colour) ~ 1980.

40 years later, now at the threshold of the next **major** breakthrough!

Second-Order Shower Kernels?

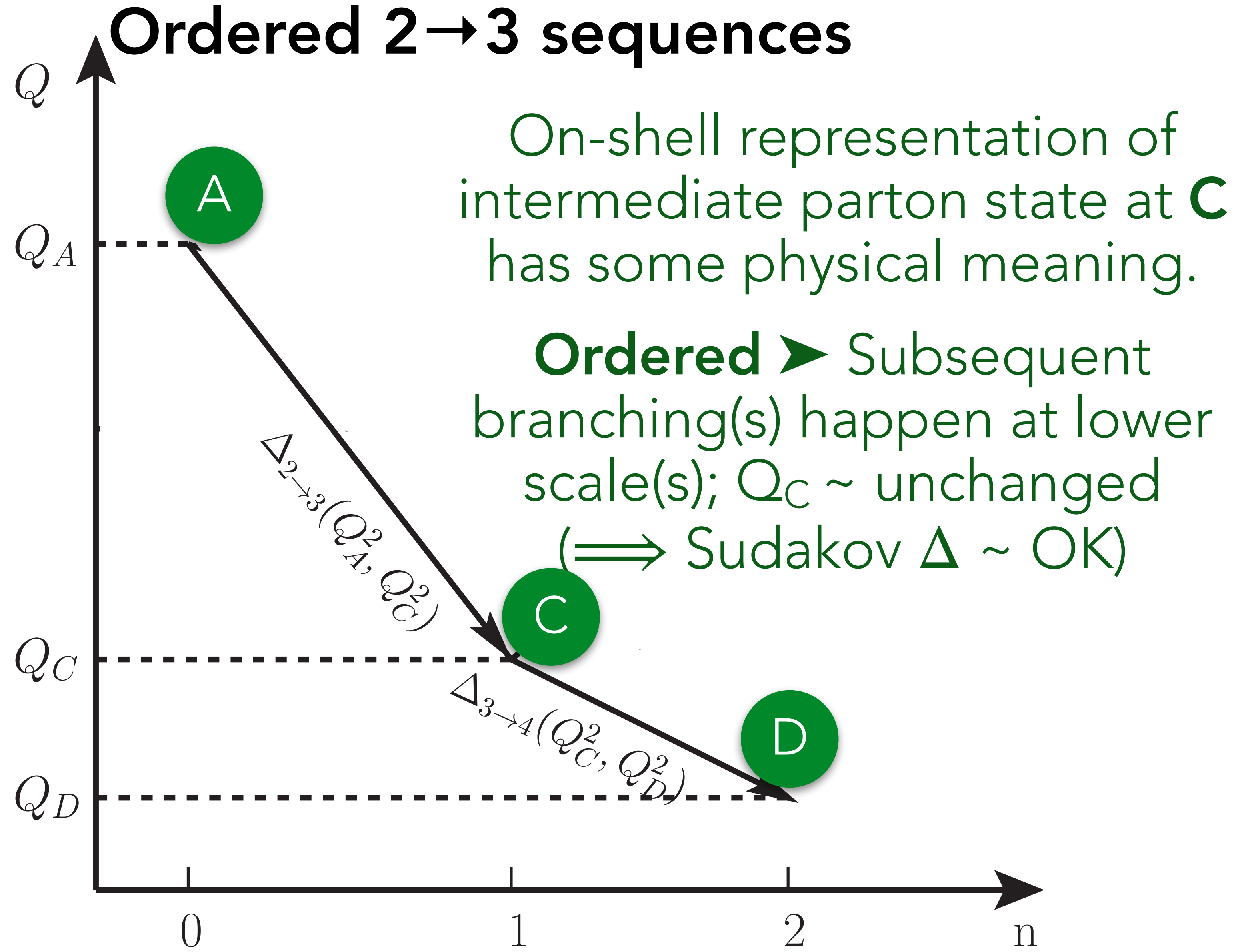
Li & PS, ***PLB* 771 (2017) 59** (arXiv:1611.00013) + ongoing work

Elements

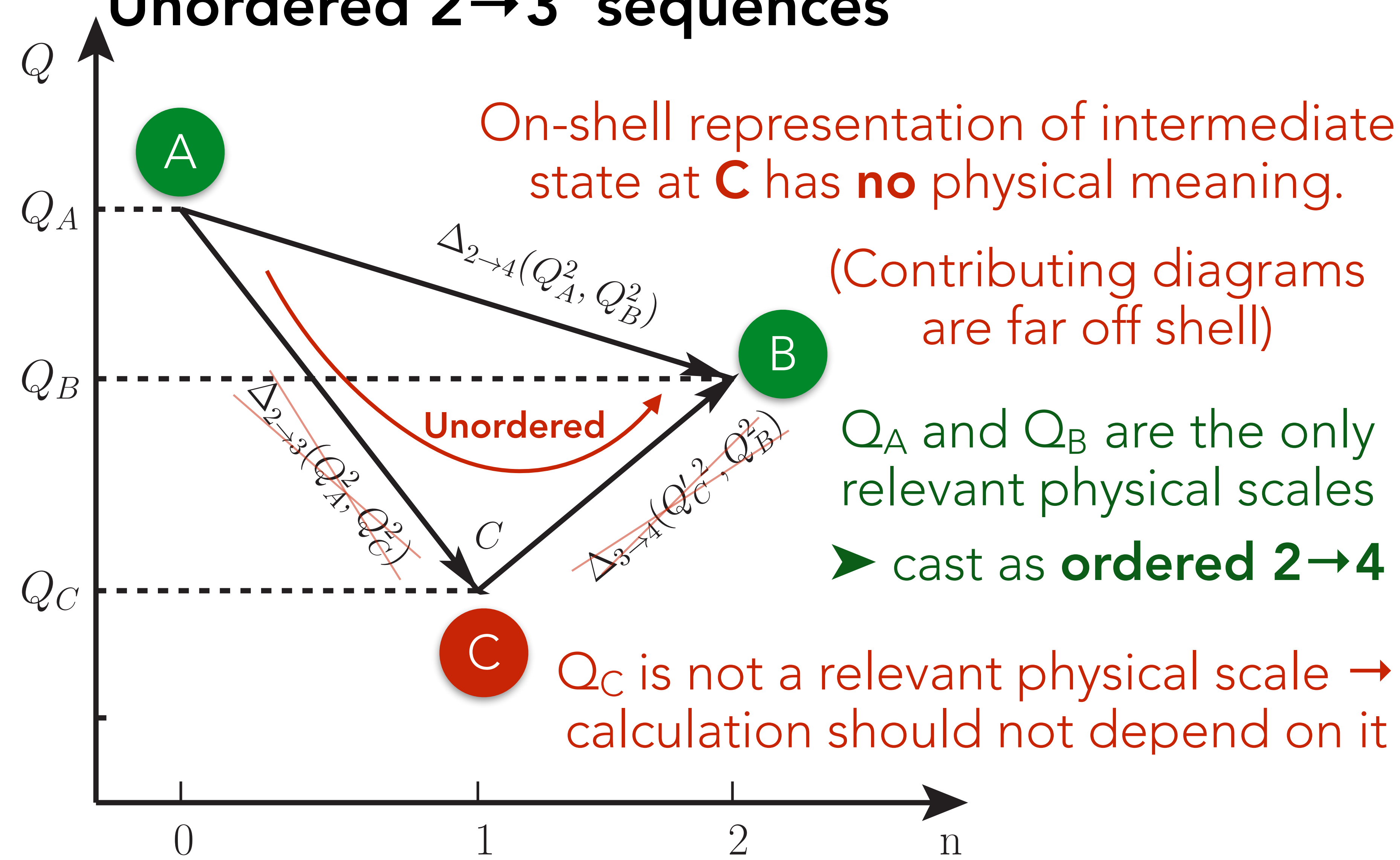
Iterated dipole-style $2 \to 3$ and new "direct $2 \to 4$" branchings populate complementary phase-space regions.

- Ordered clustering sequences ➡ iterated $2 \to 3$ (+ virtual corrections ~ differential K-factors)
- Unordered clustering sequences ➡ direct $2 \to 4$ (+ in principle higher $2 \to n$, ignored for now)

Ordered 2→3 sequences



Unordered 2→3 sequences



Our approach: continue to exploit iterated on-shell $2 \to 3$ factorisations …

… but in unordered region let $\mathbf{Q_B}$ define evolution scale for double-branching (integrate over Q_C)

Second-Order Shower Evolution Equation

Li & PS, ***PLB* 771 (2017) 59** (arXiv:1611.00013) + ongoing work

Putting 2→3 and 2→4 together ⇨ evolution equation for dipole-antenna with $\mathcal{O}(\alpha_s^2)$ kernels:

~ POWHEG inside exponent
(Hoeche, Krauss, Prestel ~ MC@NLO inside exponent)

Iterated 2→3
with (finite) one-loop correction

Direct 2→4
(as sum over "a" and "b" subpaths)

$$\frac{d\Delta(Q_0^2,Q^2)}{dQ^2} = \int d\Phi_{\text{ant}} \Big[\delta(Q^2 - Q^2(\Phi_3))\, a_3^0 \times \Big(1 + \frac{a_3^1}{a_3^0} + \sum_{s\in a,b}\int_{\text{ord}} d\Phi_{\text{ant}}^s\, R_{2\to4}\, s_3'\Big)\Delta(Q_0^2,Q^2) + \sum_{s\in a,b}\int_{\text{unord}} d\Phi_{\text{ant}}^s \delta(Q^2 - Q^2(\Phi_4)) R_{2\to4}\, s_3\, s_3' \Delta(Q_0^2,Q^2)\Big]$$

(2→)3→4 antenna function

(2→)3→4 MEC

2→4 as explicit product x MEC

Only generates double-unresolved singularities, not single-unresolved

Note: the equation is formally identical to:

$$\frac{d}{dQ^2}\Delta(Q_0^2,Q^2) = \int \frac{d\Phi_3}{d\Phi_2}\,\delta(Q^2 - Q^2(\Phi_3))\left(a_3^0 + a_3^1\right)\Delta(Q_0^2,Q^2) + \int \frac{d\Phi_4}{d\Phi_2}\,\delta(Q^2 - Q^2(\Phi_4))\, a_4^0\,\Delta(Q_0^2,Q^2)\,, \quad (3)$$

poles

poles

But on this form, the pole cancellation happens *between* the two integrals

Limited manpower but expect this in PYTHIA within the next ~ 2 years.

Opportunities & Requirements

Expect current developments (if sustained) to produce new generation of highly precise perturbative MC models by 2030.

Standalone fixed-order calculations probably very limited applicability, e.g. for accuracy beyond NNLO.

For all other cases, expect (N)NLO matched and merged with next-generation showers or inclusive resummations (not covered here).

Tests and Validations

Require observables sensitive to subtle sub-LL differences.

E.g., sensitive to "direct" $n \to n+2$ branchings, multi-parton correlations (e.g., triple-energy correlations, cf Komiske's talk) and multi-parton coherence, subleading N_C, …

Scaling studies with $\sqrt{s}$ ➤ can disentangle power corrections, beta function, …

CEPC/FCC-ee ➤ statistics to focus on small but "clean" corners of phase space

Important to develop a battery of such tests; relevant also for LHC

Requirements (?)

Excellent **resolution** of **jet substructure**, and excellent **jet flavour tagging** (+ Z $\to 4b, 4c, 2b2c$)

Forward coverage, to access **low** $\sqrt{s}$ **~ 10-20 GeV** via ISR from Z pole?

$e^+e^- \to WW$: Resonance Decays

Current MC Treatment ~ Double-Pole Approximation

~ First term in double-pole expansion (cf. Schwinn's talk in yesterday's EW session)

+ Some corrections, e.g., in PYTHIA:

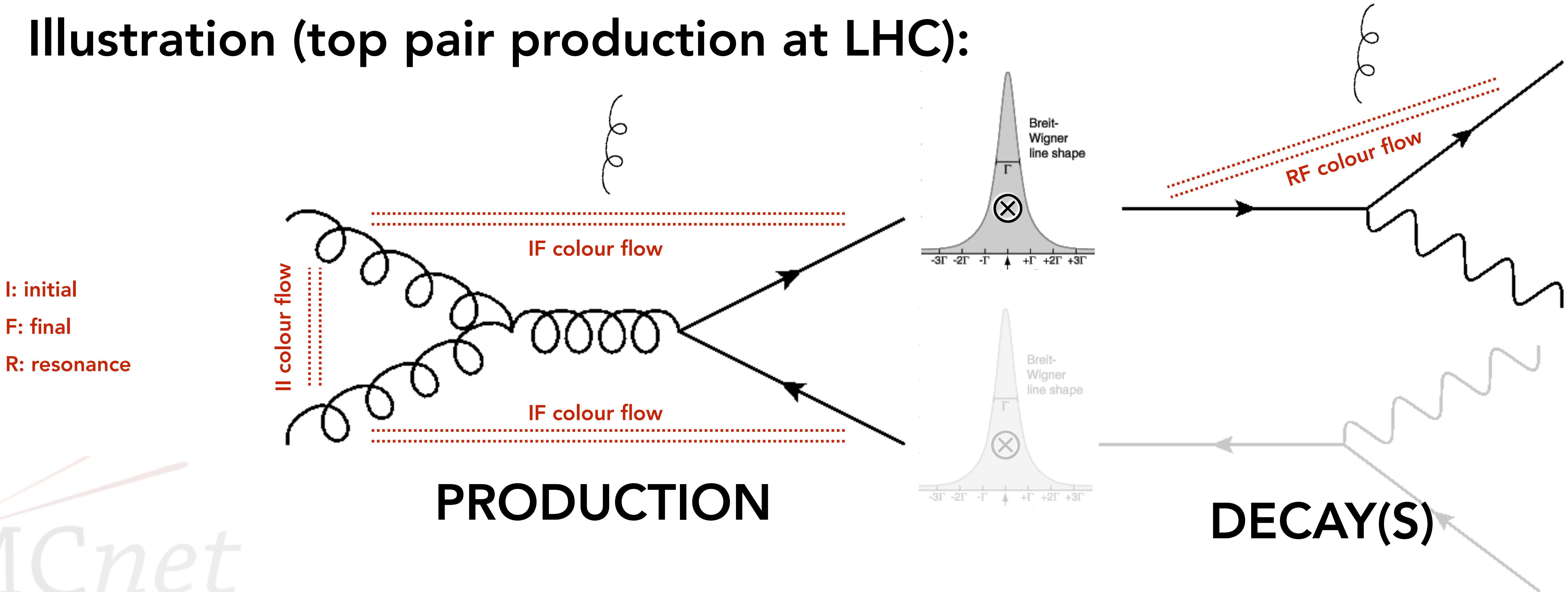
Independent Breit-Wigners for each of the W bosons, with running widths.

4-fermion ME used to generate correlated kinematics for the W decays.

Each W decay treated at NLO + shower accuracy.

No interference / coherence between ISR, and each of the W decay showers

Illustration (top pair production at LHC):

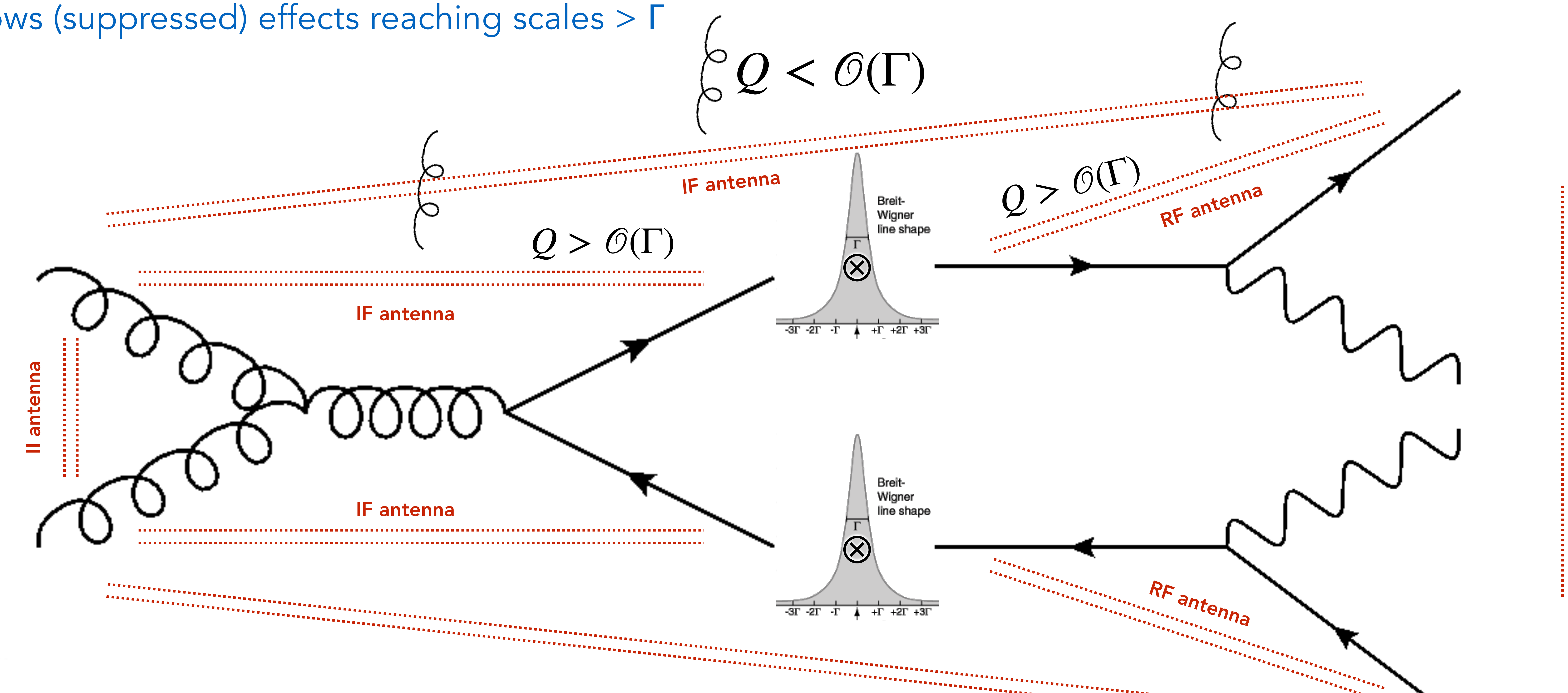


Decays of unstable resonances introduced in shower evolution at an average scale Q ~ Γ

Cannot act as emitters or recoilers below that scale; only their decay products can do that.

The more off-shell a resonance is, the higher the scale at which it disappears.

- Roughly corresponds to strong ordering (as measured by propagator virtualities) in rest of shower.
- Allows (suppressed) effects reaching scales > Γ



Automatically provides a natural treatment of finite-Γ effects.

Expect in next Pythia release (8.304)

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

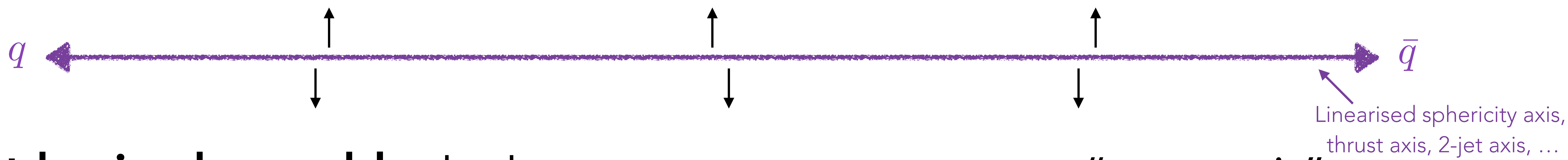
Handles: mass, strangeness, and spin. Need at least one of each meson & baryon isospin multiplet. Flavour separation crucial. (LEP $|p_K|$ > 250 MeV)

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

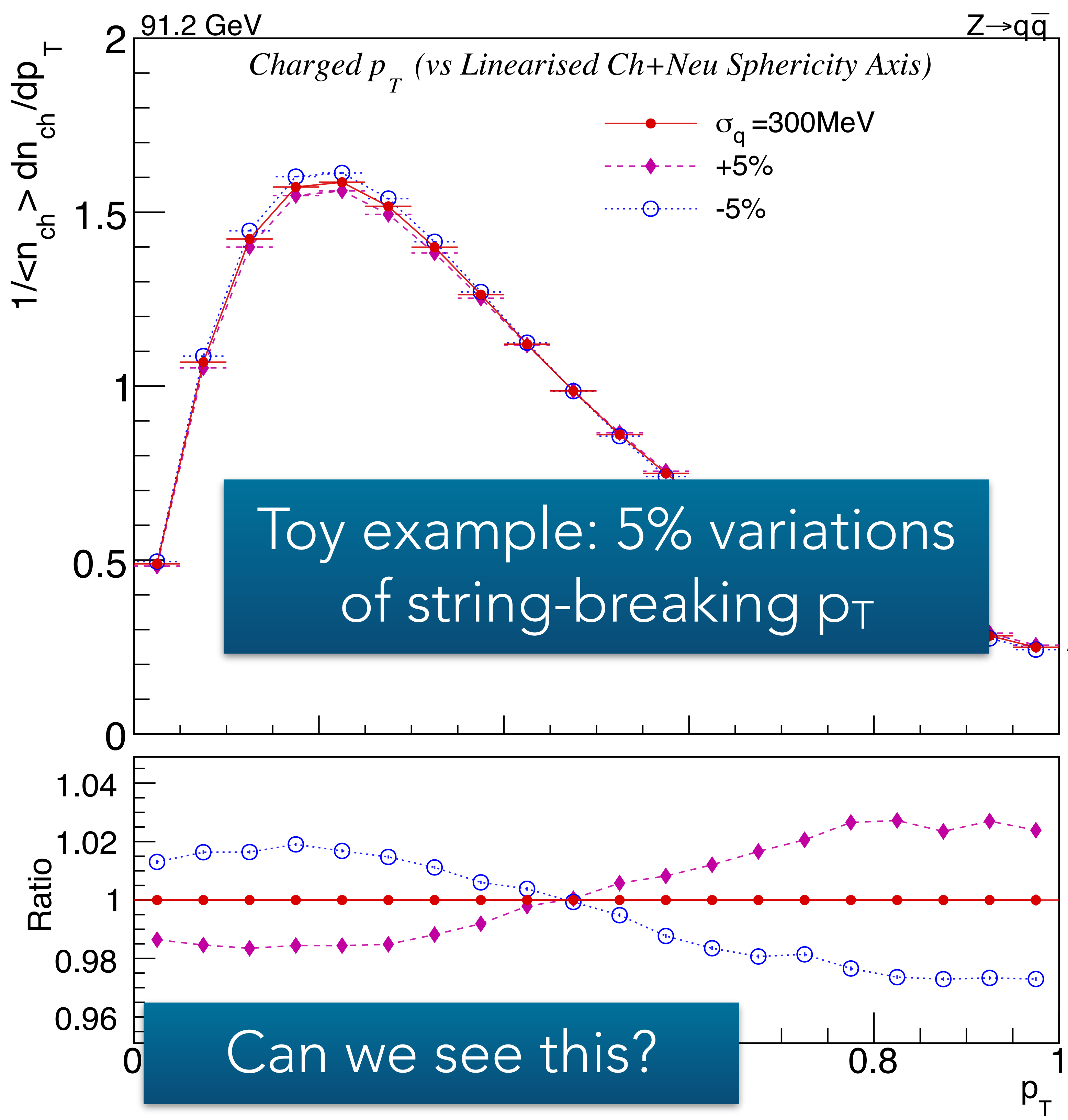
Bonus: high(er)-precision jet calibration (particle flow) ?

Accurate knowledge (+ modeling) of particle composition & spectra

Transverse Fragmentation ⇔ Momentum Resolution

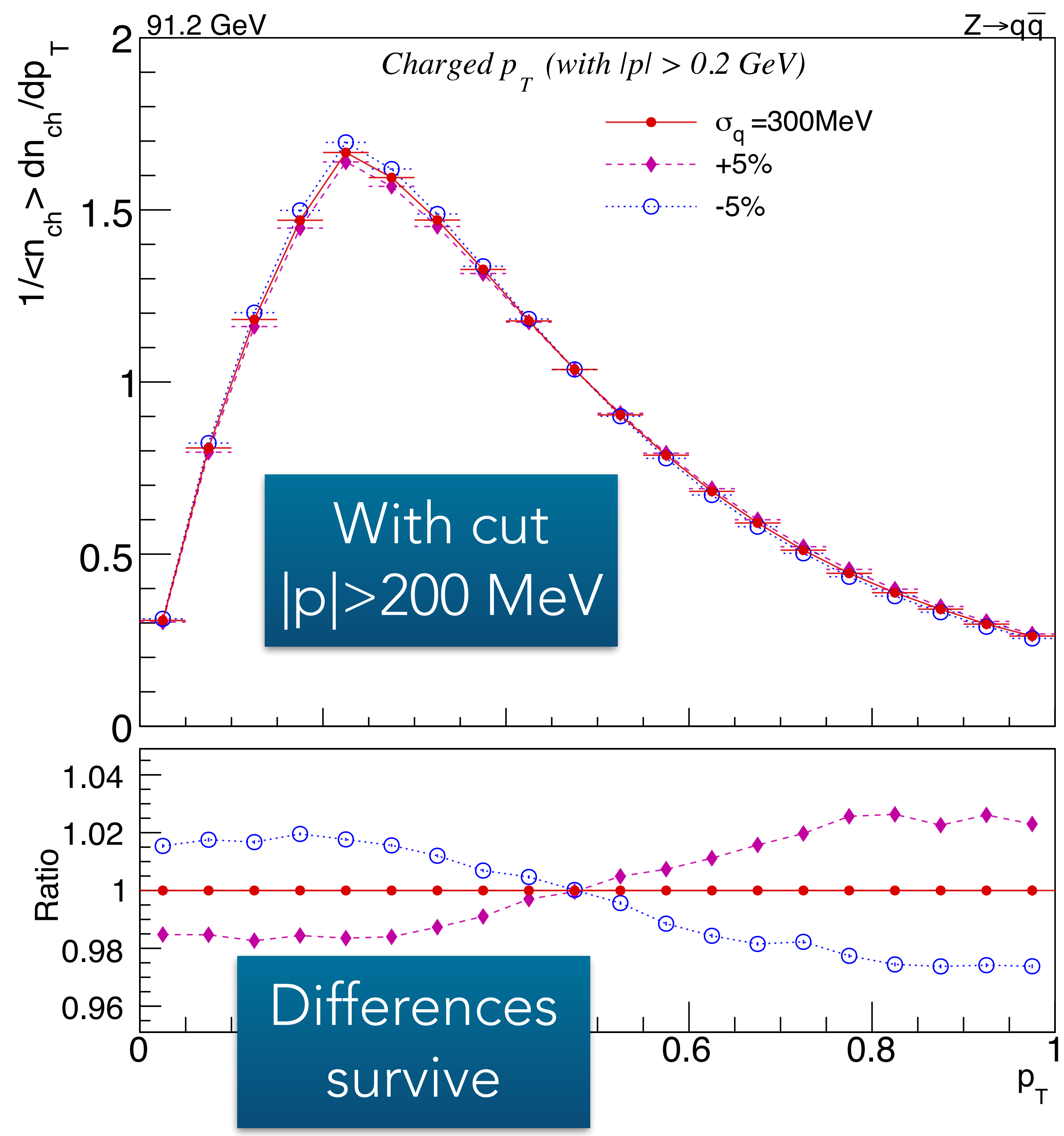


Most basic observable: hadron p_T spectra, transverse to "event axis"



Toy Example

Perturbatively dominated power-law tail



Effects of order Λ_{QCD} ~ 100 MeV ⇔ Coverage for |p| < Λ_{QCD}?

p_T kicks from hadronisation

Pythia ~ Gaussian ~ 300 MeV (+ ρ decays)

Acts as a sort of lower bound on hadron p_T. Difficult for any hadron to have |p| < 300 MeV.

To check this, look for pions with |p| < 300 MeV

➤ Probe of confinement mechanism for non-relativistic pions

Data from both LEP and LHC indicate more soft pions; why?

Thermal vs Gaussian spectra?

Unresolved perturbative effects vs genuine string-breaking effects?

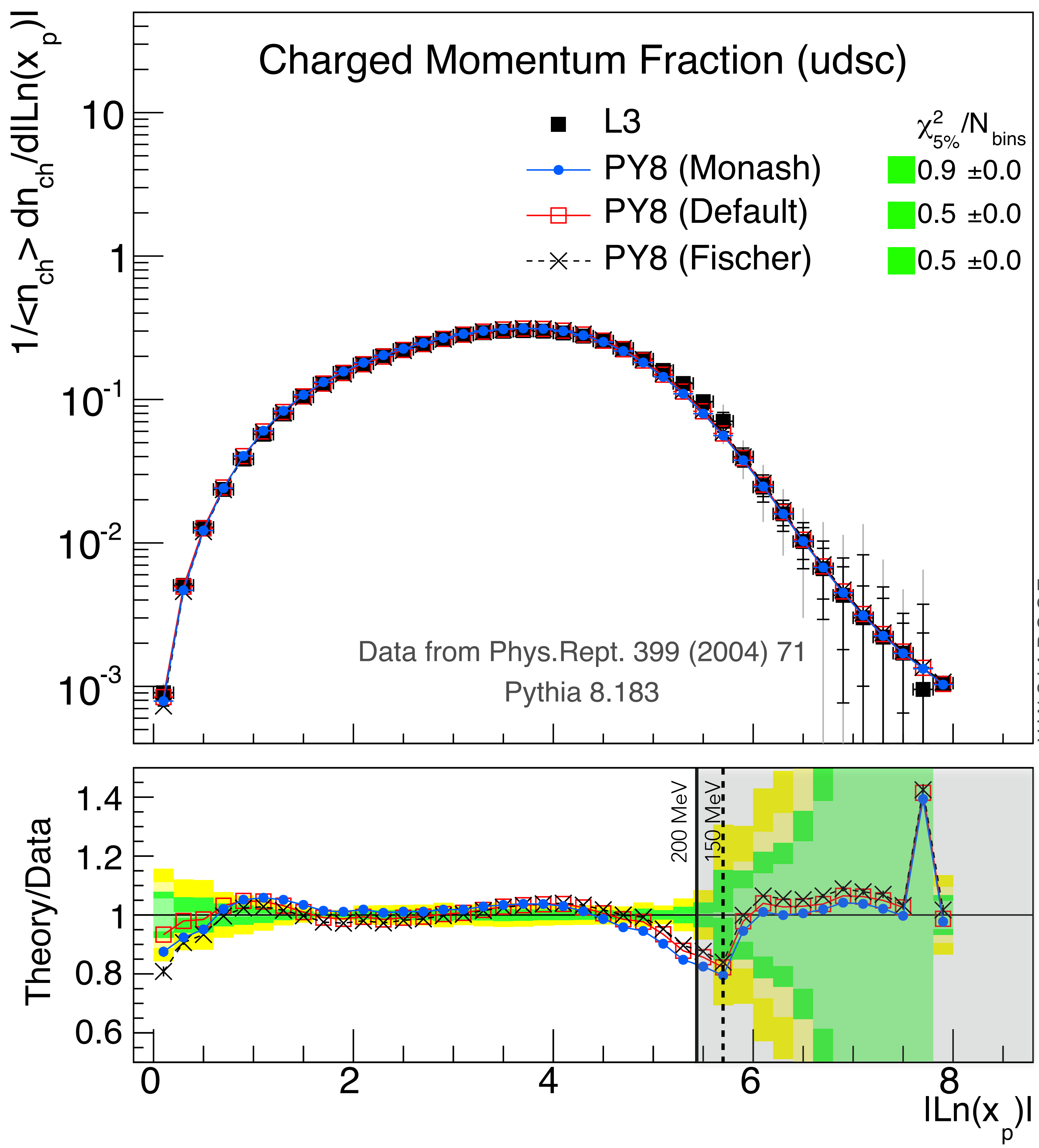
Mismodelled resonance decays?

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

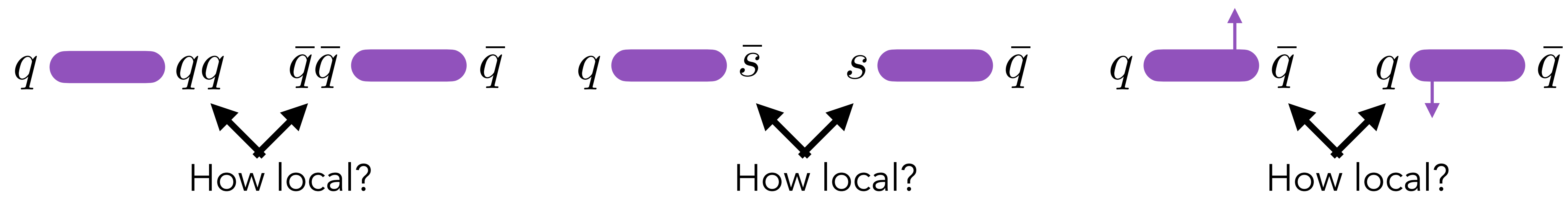
3 hits down to ~ 50 MeV ?

Special runs / setups with lower thresholds?

Example from LEP



The point of MC generators: address more than one hadron at a time!



Further precision non-perturbative aspects: How local is hadronisation?

Baryon-Antibaryon correlations — both OPAL measurements were statistics-limited (Kluth); would reach OPAL systematics at 10^8 Z decays ($\rightarrow 10^9$ with improved systematics?)

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

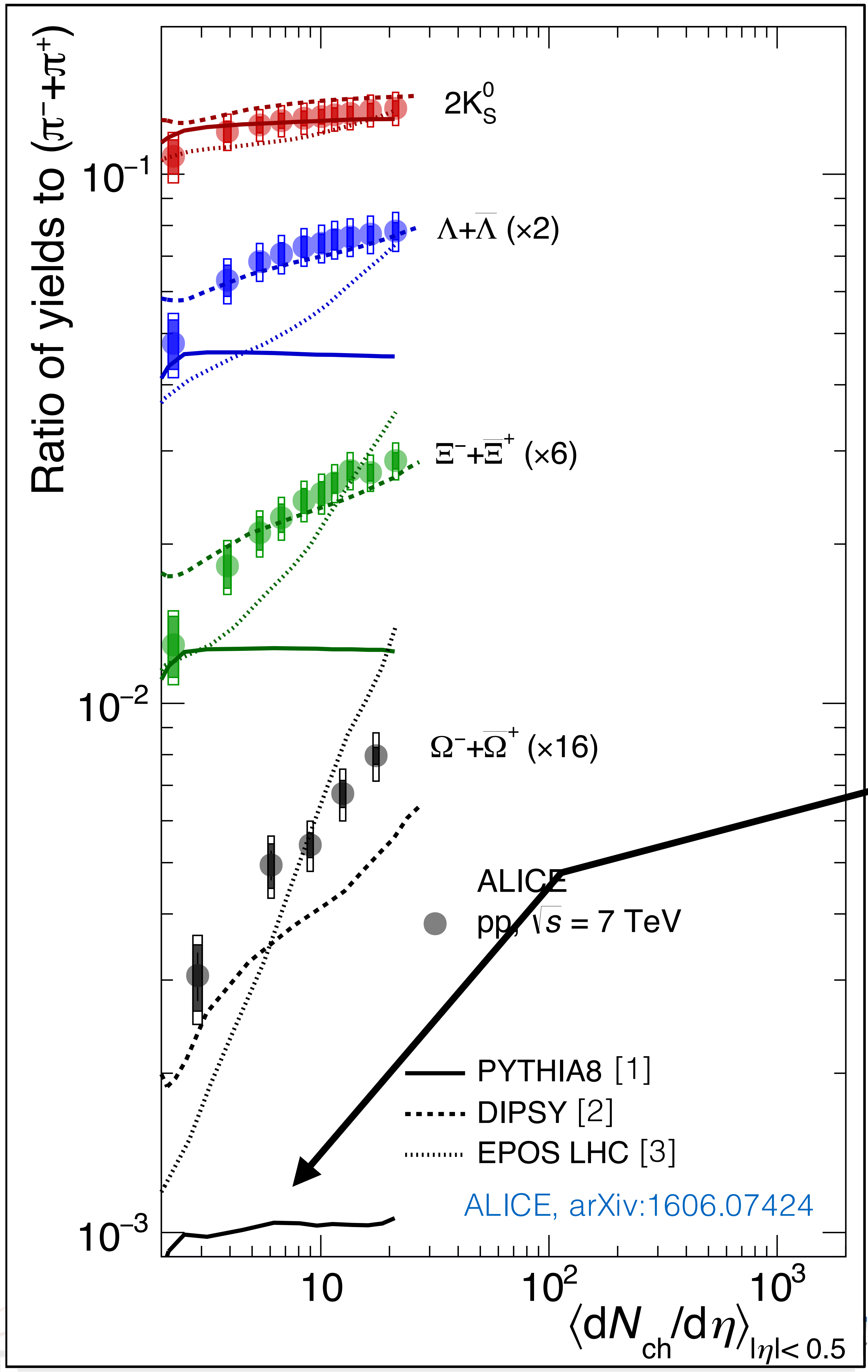
\+ Bose-Einstein Correlations & Fermi-Dirac Correlations

Identical baryons (pp, ΛΛ) **highly** non-local in string picture — puzzle from LEP; correlations across multiple exps & for both pp and ΛΛ → Fermi-Dirac radius ~ 0.1 fm ≪ r_p (Metzger)

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

Leading baryons in g jets?
(discriminates between string/cluster models)
High-x baryons

Strangeness (in PP)



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

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

No corresponding enhancement for protons (not shown here but is in ALICE paper) → must really be a strangeness effect

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

Requires **good PID** + high statistics

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

Colour Reconnections

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**

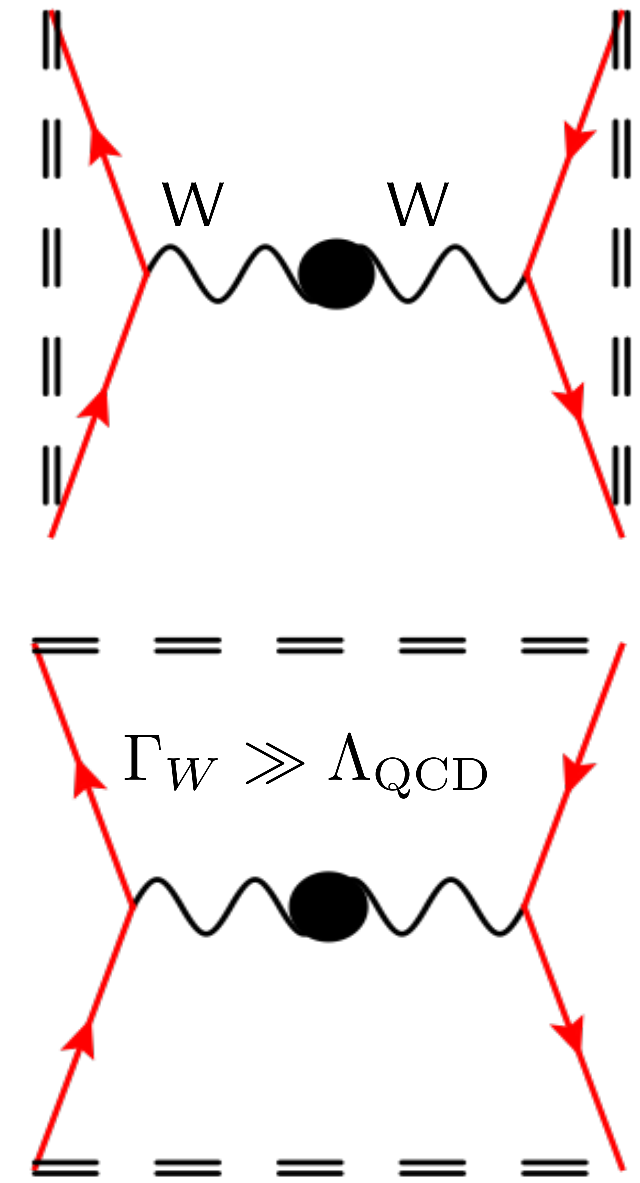
LC

$\mathcal{O}(1)$

CR

$\sim\mathcal{O}\left(\frac{1}{N_C^2}\right)$

$\otimes$ kinematics



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?

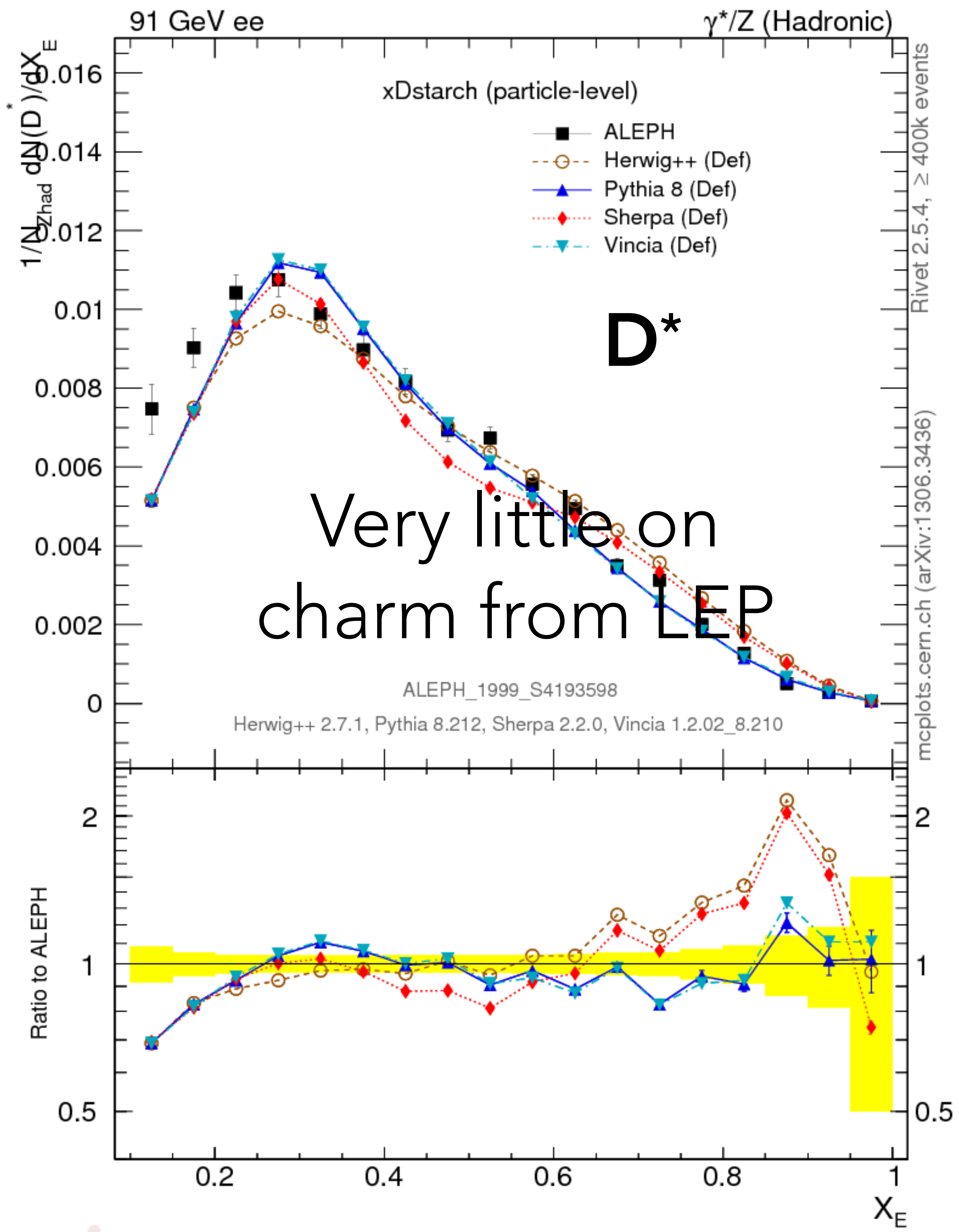
Little done for CEPC/FCC-ee so far … (to my knowledge)
Plenty of room to play with models, observables, …

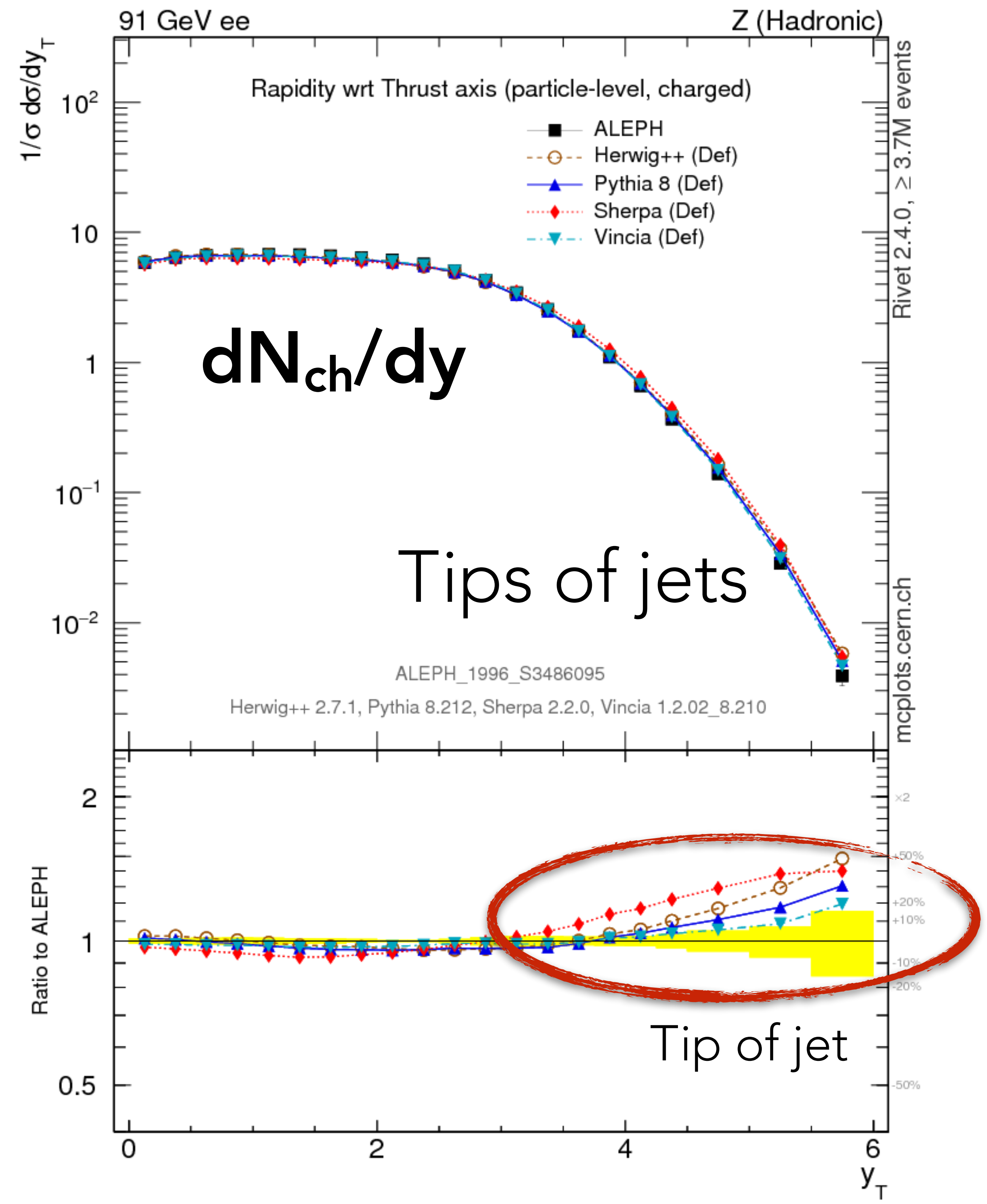
Overviews of recent models:
arXiv:1507.02091 , arXiv:1603.05298

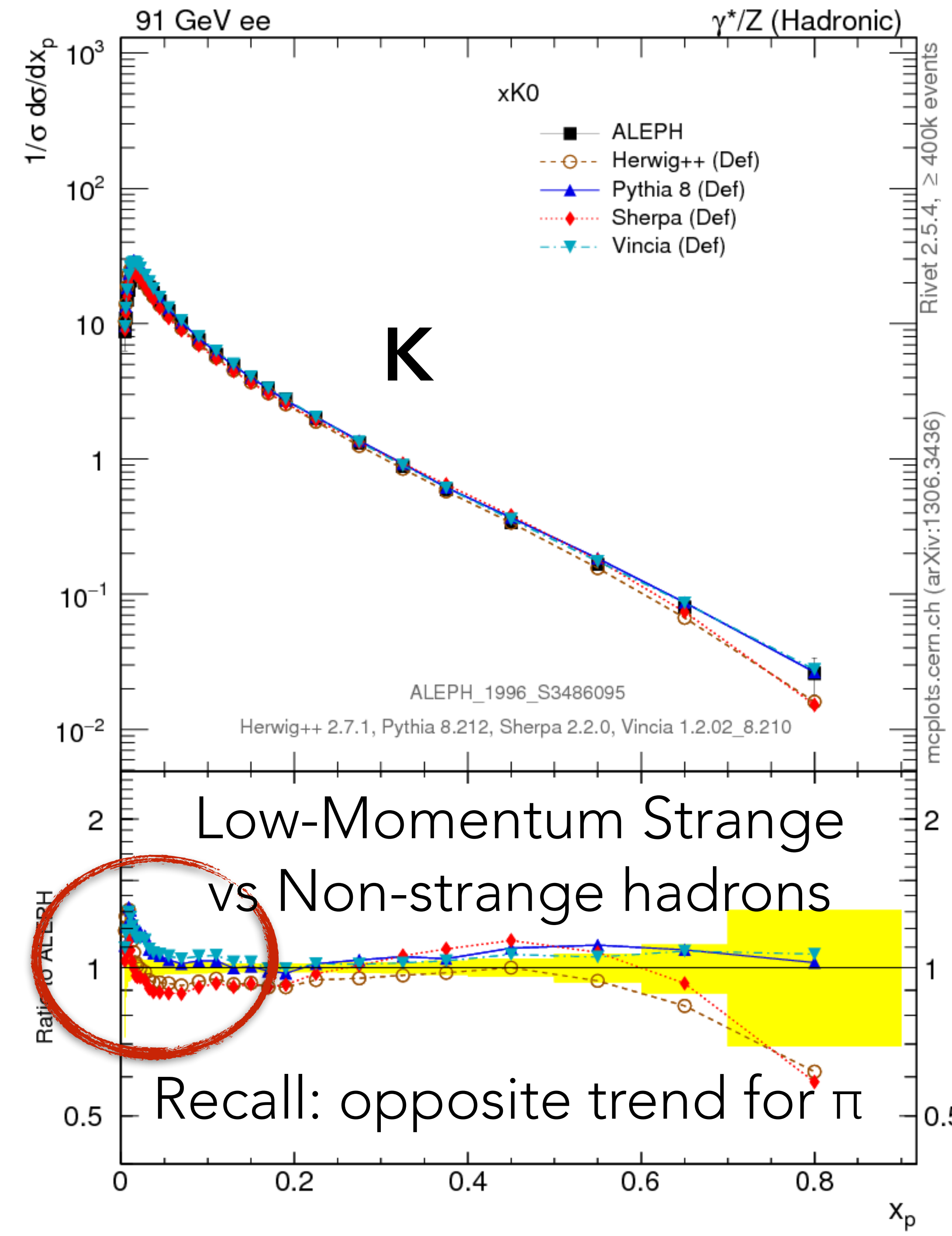
Plenty of other interesting detailed features

(plots from mcplots.cern.ch)

Just a few examples







Capabilities for hadrons from decays (π⁰, η, η′, ρ, ω, K*, φ, **Δ**, Λ, Σ, Σ*, Ξ, Ξ*, Ω, …)

\+ **heavy-flavour** hadrons

Very challenging; conflicting measurements from LEP

Cornell potential

Potential V(r) between **static** (lattice) and/or **steady-state** (hadron spectroscopy) colour-anticolour charges:

$$V(r) = -\frac{a}{r} + \kappa r$$

Coulomb part

String part
Dominates for $r \gtrsim 0.2\,\mathrm{fm}$

Lund string model built on the asymptotic large-*r* linear behaviour

But intrinsically only a statement about the late-time / long-distance / steady-state situation. Deviations at early times?

Coulomb effects in the grey area between shower and hadronization?
Low-*r* slope > κ favours "early" production of quark-antiquark pairs?

+ Pre-steady-state thermal effects from a (rapidly) **expanding string?**

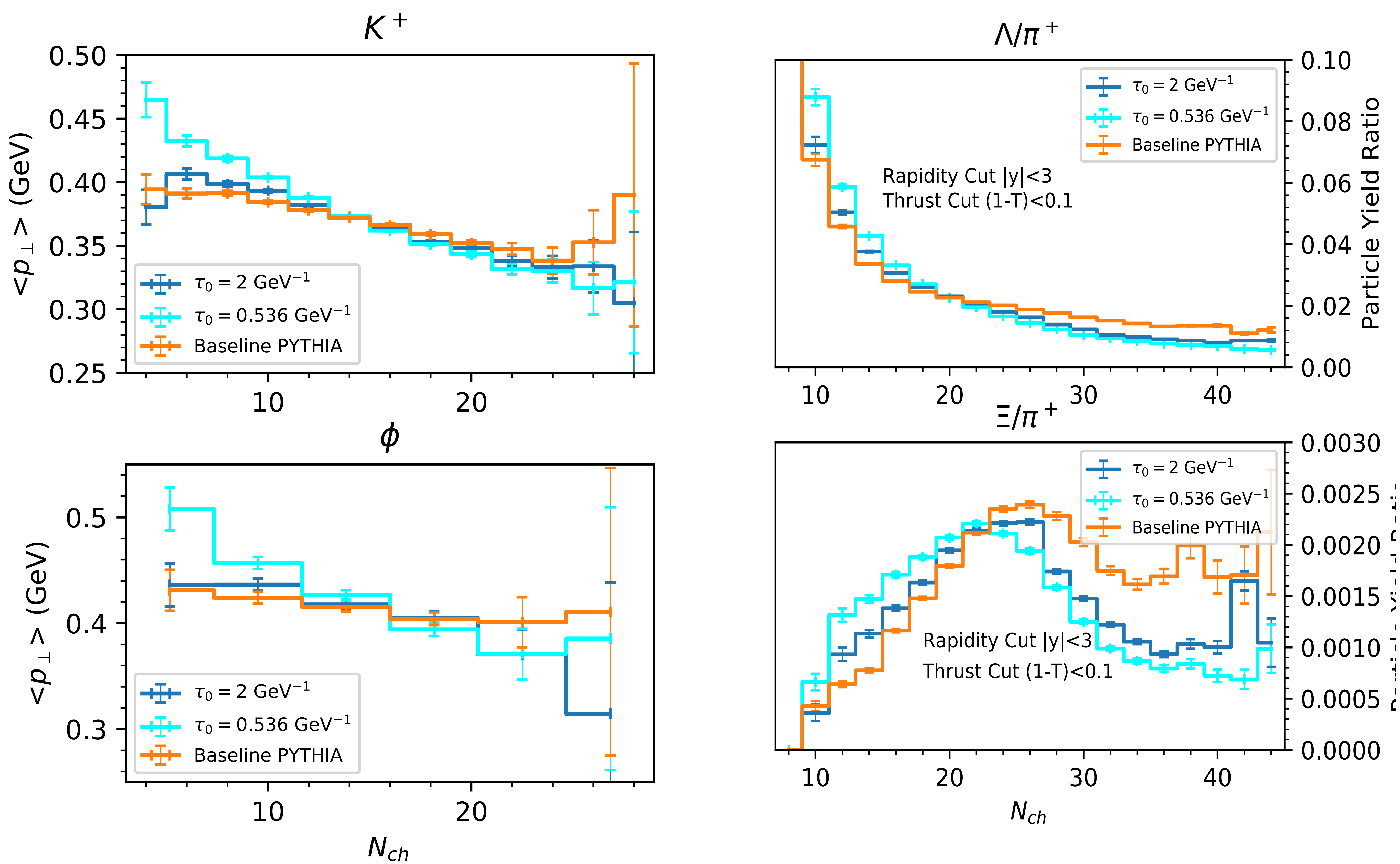
Berges, Floerchinger, and Venugopalan JHEP 04(2018)145)

N. Hunt-Smith & PS arxiv:2005.06219

Model constrained to have same average tension as Pythia's default "Monash Tune"

➤ same average N_{ch} etc ➤ main LEP constraints basically unchanged.

But expect different fluctuations / correlations, e.g. with multiplicity N_{ch}.



- ➤ Want to study (suppressed) tails with very low and very high N_{ch}.
- ➤ These plots are for LEP-like statistics.
- ➤ Would be crystal clear at CEPC/ FCC-ee

MCs & Precision QCD at Future e^+e^- Machines

Perturbative QCD: High Precision

Measurements of α_s with unprecedented accuracy (not covered here)

Good jet substructure & flavour tagging crucial to vet **N^{n}LO QCD** + **Next Generation** of Showers

➥ Accurate starting point for non-perturbative modelling of Hadronisation

Interplays with EW & Higgs Physics Goals

Impact of (in)accurate MC predictions? ⇔ Identify & Communicate crucial areas for improvements?

Nonperturbative QCD: High Resolution

Confinement / Non-perturbative QFT remains fundamentally unsolved

Next generation of e^+e^- machines ➡ **trial by fire** not just for any post-LHC advanced models, but also for any future *solution* or systematically improvable approximation.

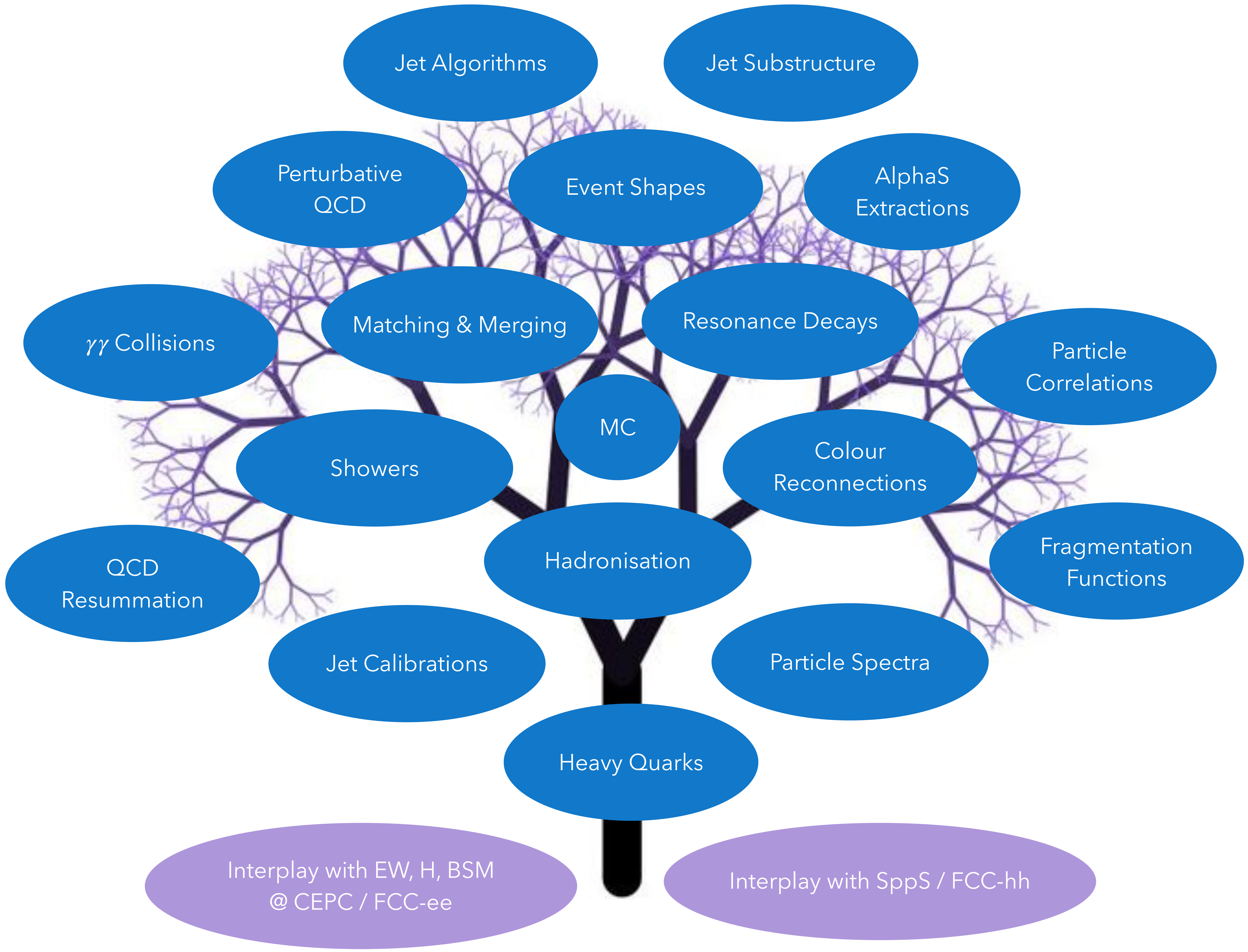
➥ Good PID crucial to reveal **details of final states** ⇔ **disentangle** strangeness, baryons, mass, spin

➥ Good Momentum Resolution crucial to measure $\mathcal{O}(\Lambda_{\mathrm{QCD}}) \sim 100$ MeV effects with **high precision**

Theory keeps evolving long after beams are switched off ➤ Aim high!

MCnet

Summary — QCD at EE Colliders



Extra Slides

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]

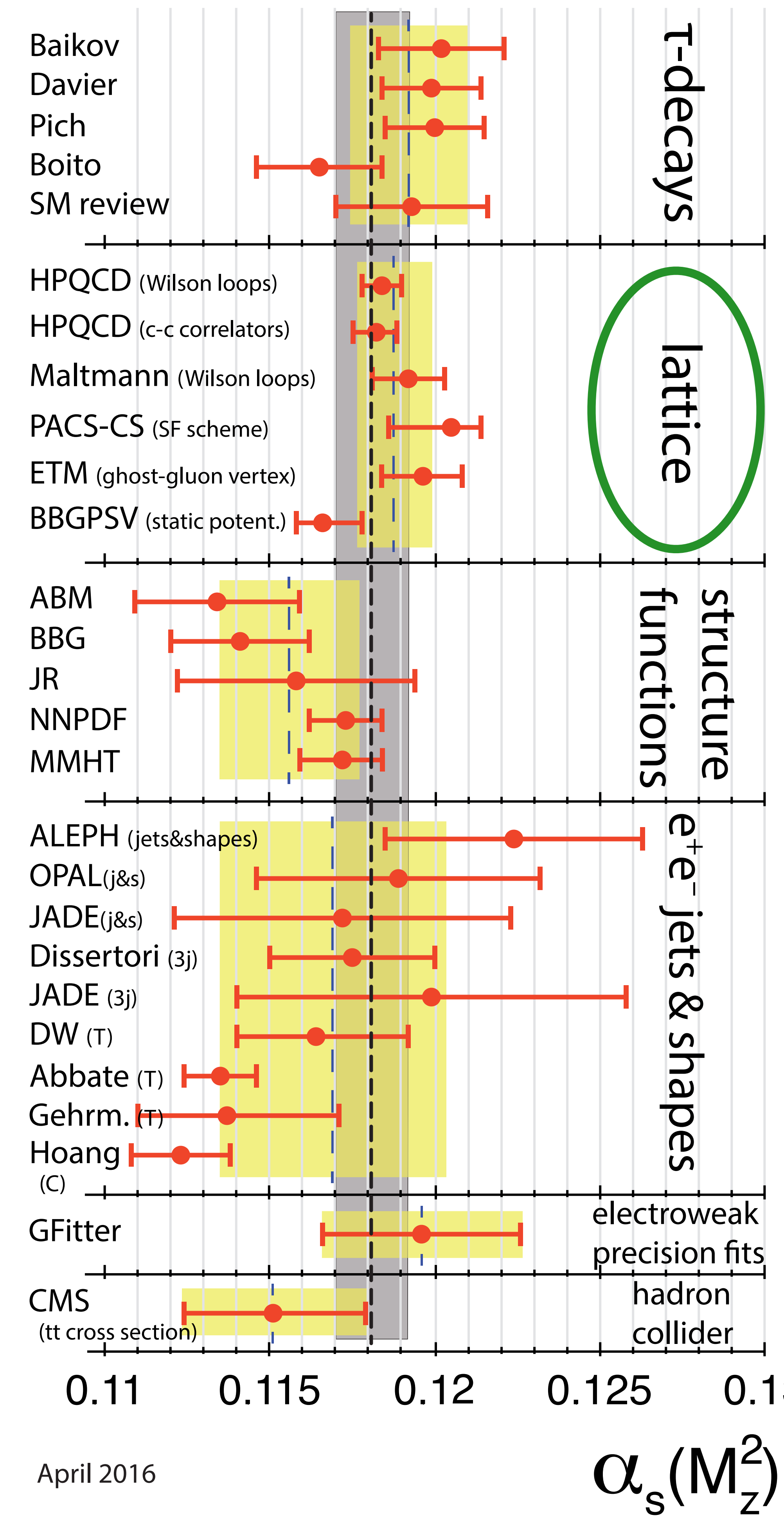
+ New resummations → new $\alpha_s(m_Z)$ extractions

E.g., 2015 SCET-based C-parameter reanalysis
N^{3}LL′ + O(α_s^3) + NPPC: $\alpha_s(m_Z)$ = 0.1123 ± 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:

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

QCD corrections to $\Gamma_{\rm had}$ 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 CEPC / FCC-ee

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

- Can be calculated (after Higgs discovery) or use measured $\sin^2\theta_{\rm eff}$
- 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($W_{\rm had}$) 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?

Fragmentation Functions

(see FCC-ee QCD workshops & writeups)

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

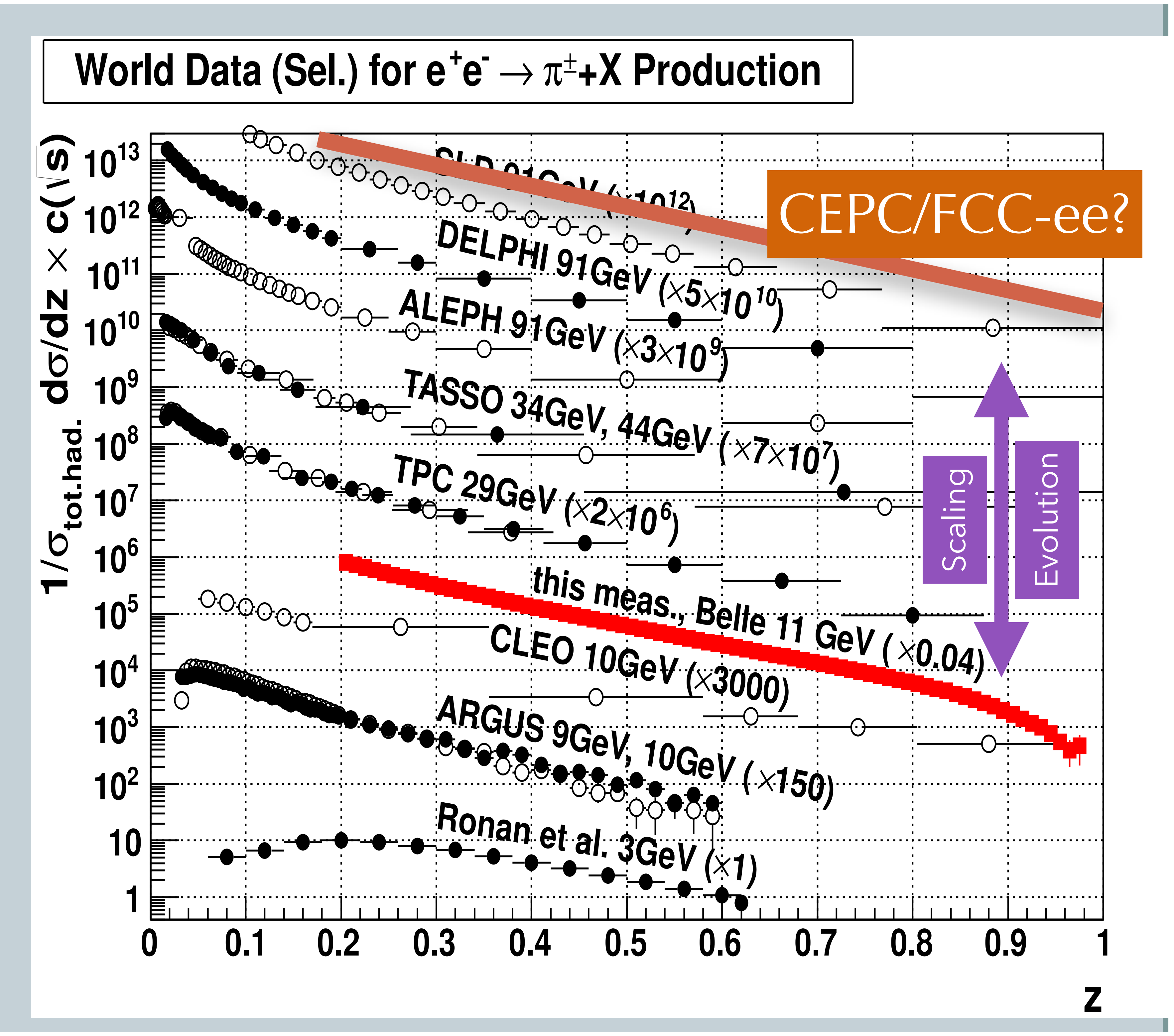
FFs from Belle to FCC-ee *[A. Vossen]*

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.

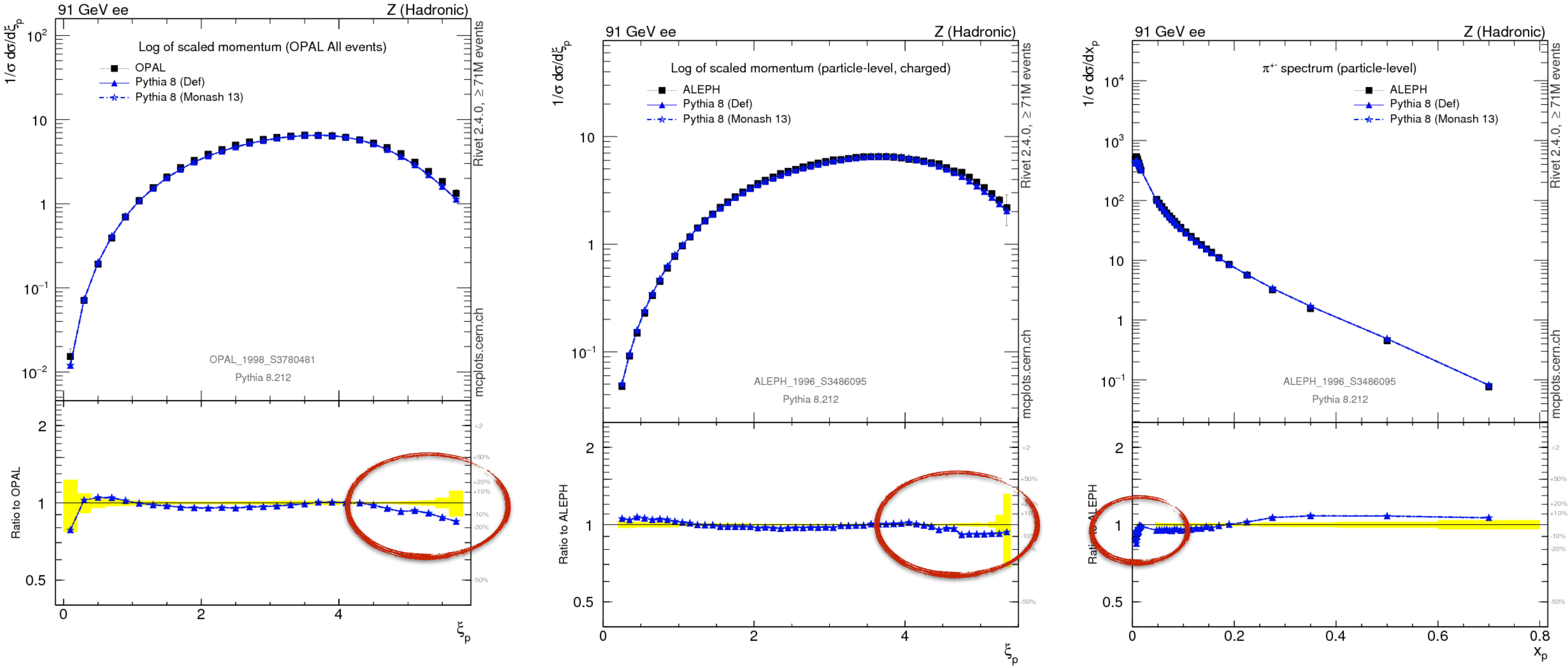
- Will depend on Particle Identification capabilities.

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,…

L3 are you crazy?



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?

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 ($Z \to b\bar{b}g$)

(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

Quarks and Gluons

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

Handles to split degeneracies

H→gg vs Z→qq

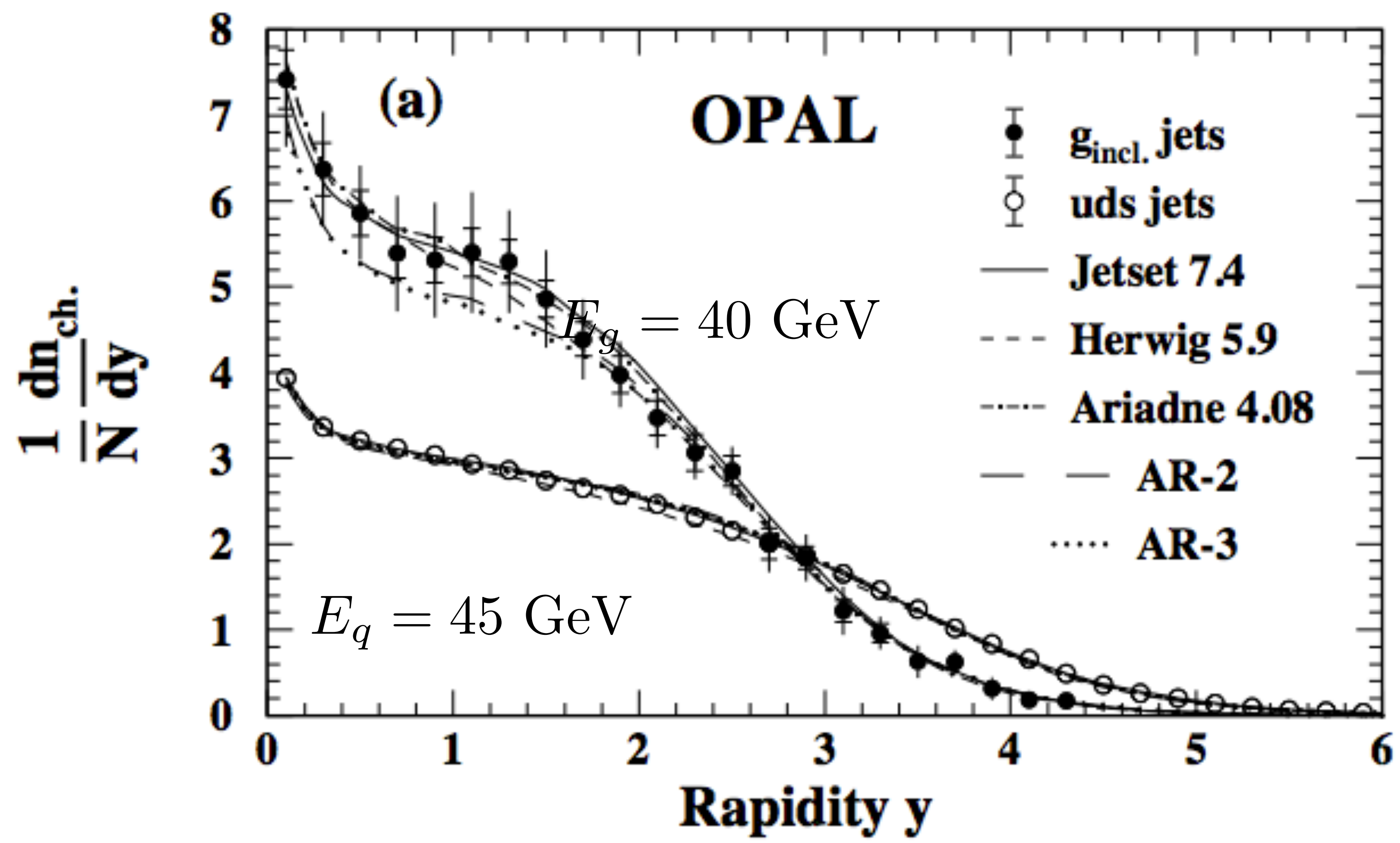
- Can we get a sample of H→gg pure enough for QCD studies?
- Requires good **H→gg vs H→bb**;
- Driven by Higgs studies requirements?

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

Unordered Clusterings of 4-Jet Events (ee k_T, E scheme)

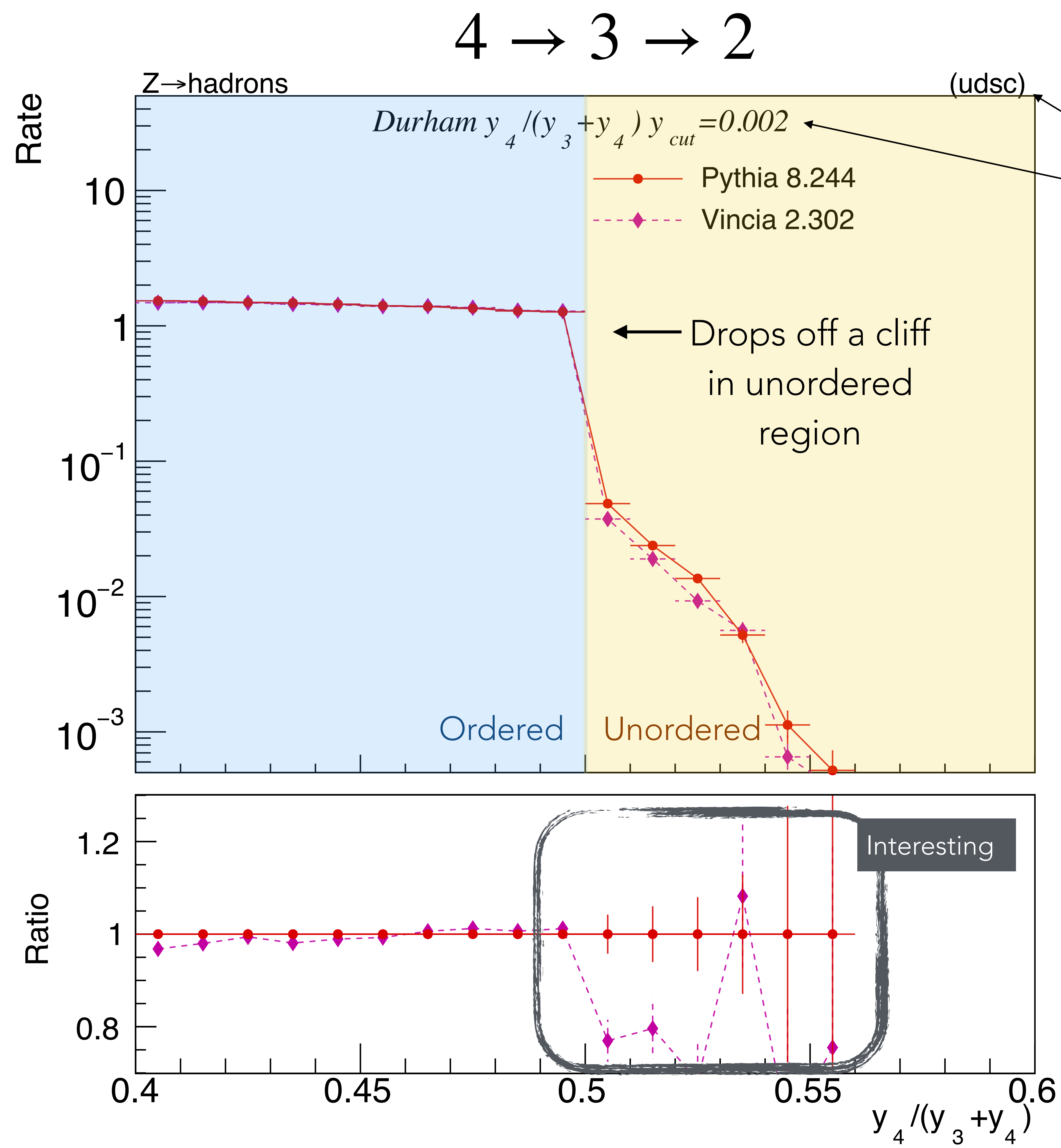
$$\frac{y_{34}}{y_{34} + y_{23}}$$

Rate normalised to total 4-jet rate

Off-the-shelf versions of Pythia and Vincia

Very similar results on individual jet rates.

Neither includes direct $2 \to 4$.



Small y_{cut} = 0.002 ($\leftrightarrow k_\perp \sim 4\,\mathrm{GeV}$) to maximise statistics

Excluded $Z \to b\bar{b}$ to avoid contamination from B decays

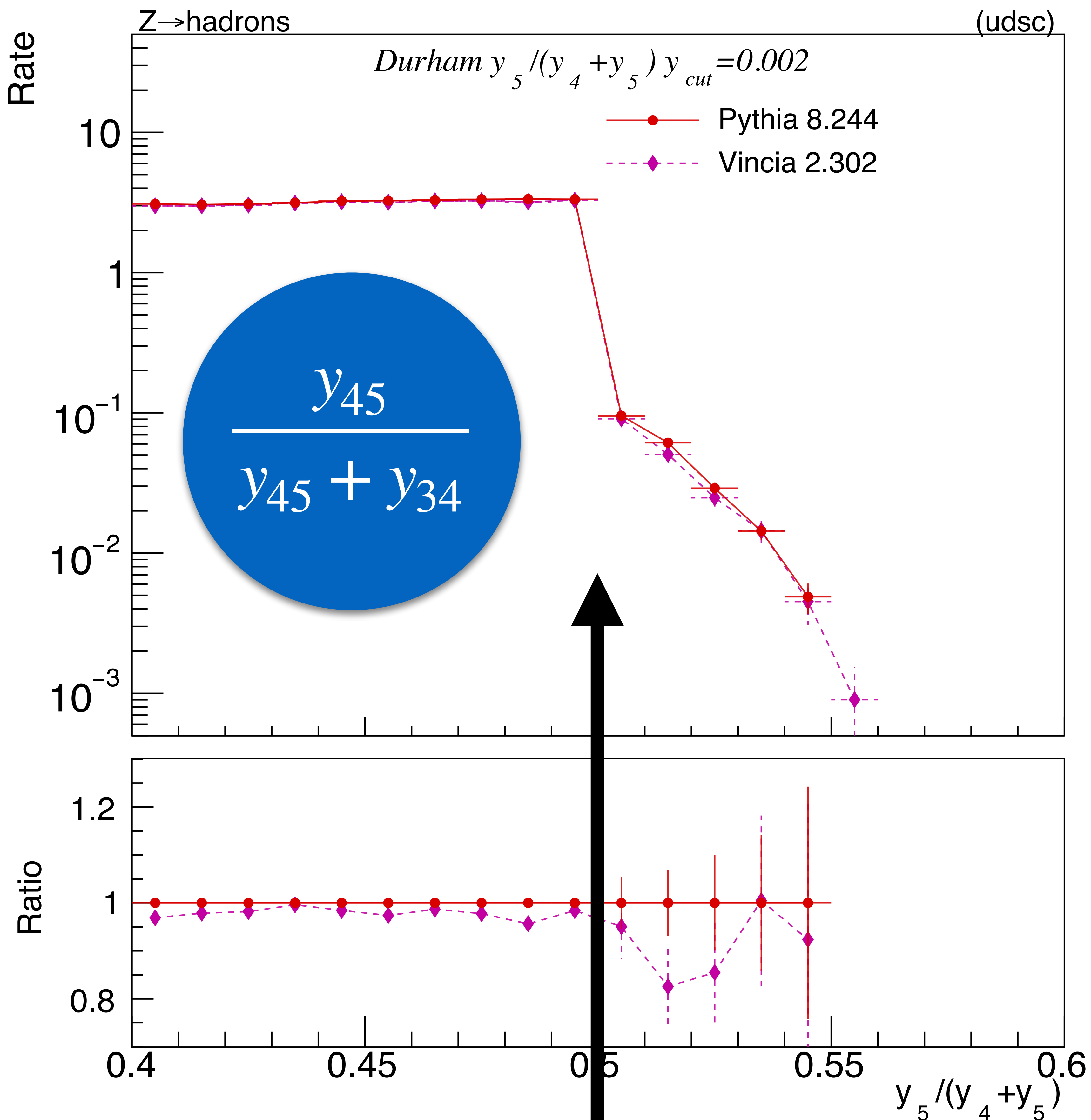
4M events (~ LEP 1)

(did not check the "interference" version of this observable here)

Q: could also be done for jet (sub)structure at the **LHC**?

5-Jet Events

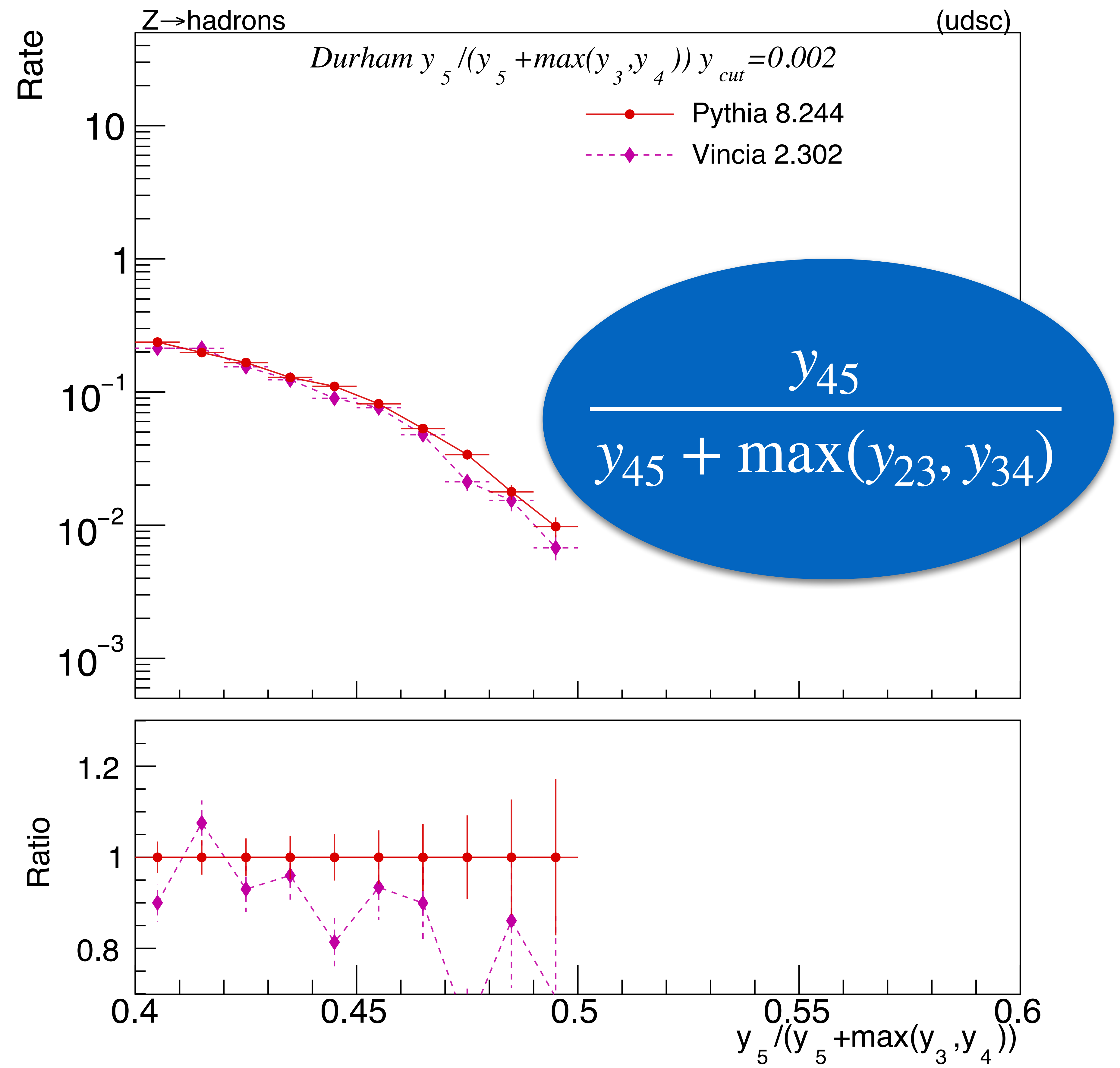
$5 \to 4 \to 3$



Same structure for $3 \to 5$ as for $2 \to 4$.

(➜ Combine to increase statistics?)

$5 \to 4 \to 3 \to 2$



Limited power to probe $2 \to 5$

(in this way) but worth an attempt?

Suggested by Pier Monni, cf also 1912.11050

Generalisation of usual EEC, with relatively simple log structure.

Sensitive to triple-collinear?

I so far took a look at two triple-energy correlators:

"Equilateral": all angles equal

"Planar": two angles equal, the last one twice as large.