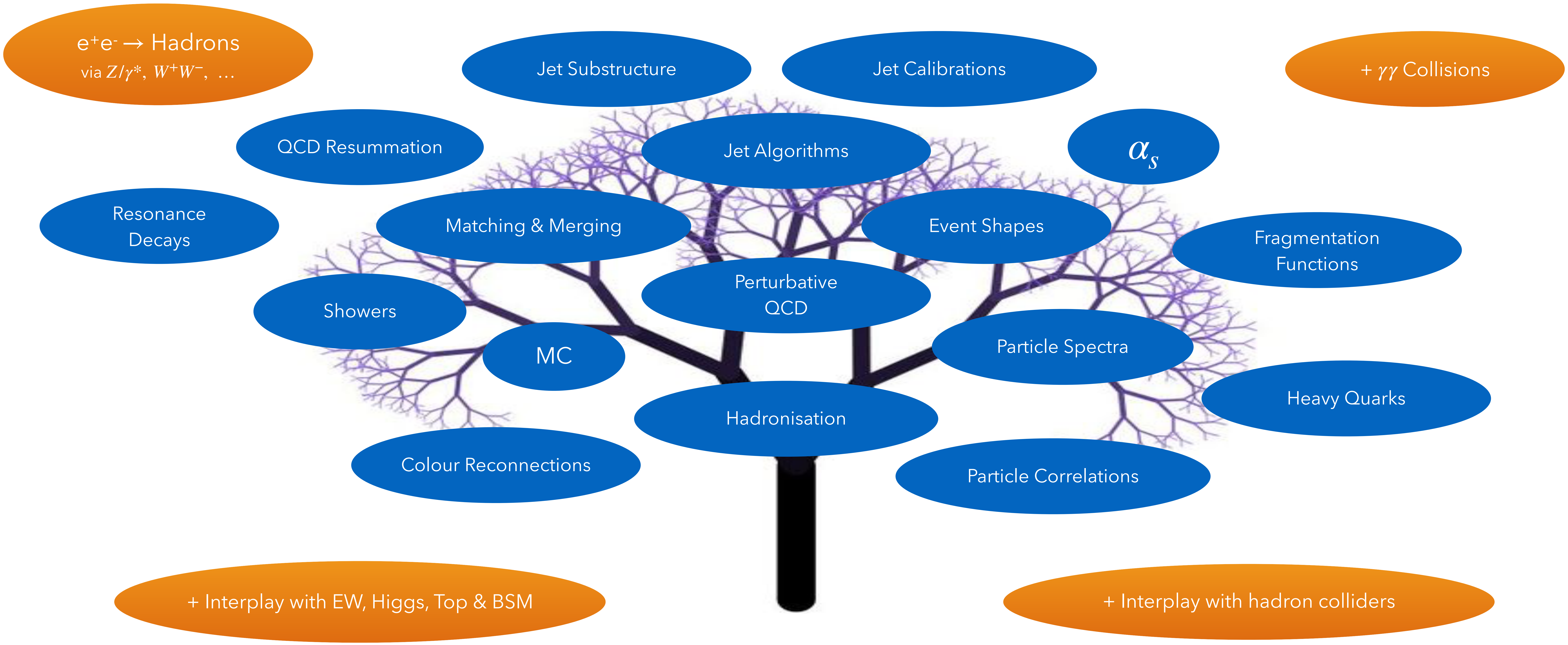
QCD Physics at (future) e^+e^- Colliders

Peter Skands (Monash University)



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IAS Program on High Energy Physics (HEP 2021), Hong Kong

QCD = Key piece at future ee, pp colliders

(Slide adapted from D. d'Enterria)

Though QCD is not *per se* the main driving force for future colliders,
QCD is crucial for many pp, ee measurements (signals & backgrounds):

- **High-precision α_s:** Affects all pQCD processes & precision observables
- **N^nLO corrs., N^nLL resummations:** Affects all precision x-sections & decays
- **Heavy-Quark/Quark/Gluon separation** (jet substructure, boosted topologies): needed for all precision SM measurements & BSM searches with final jets
- **Non-perturbative QCD:** Affects final states with jets: Parton Hadronisation (Fragmentation Uncertainties, Colour reconnection, …), $e^+e^- \to Z,\ W^+W^-,\ t\bar{t} \to 4j, 6j, \ldots$ (m_W, m_t extractions)

interplay

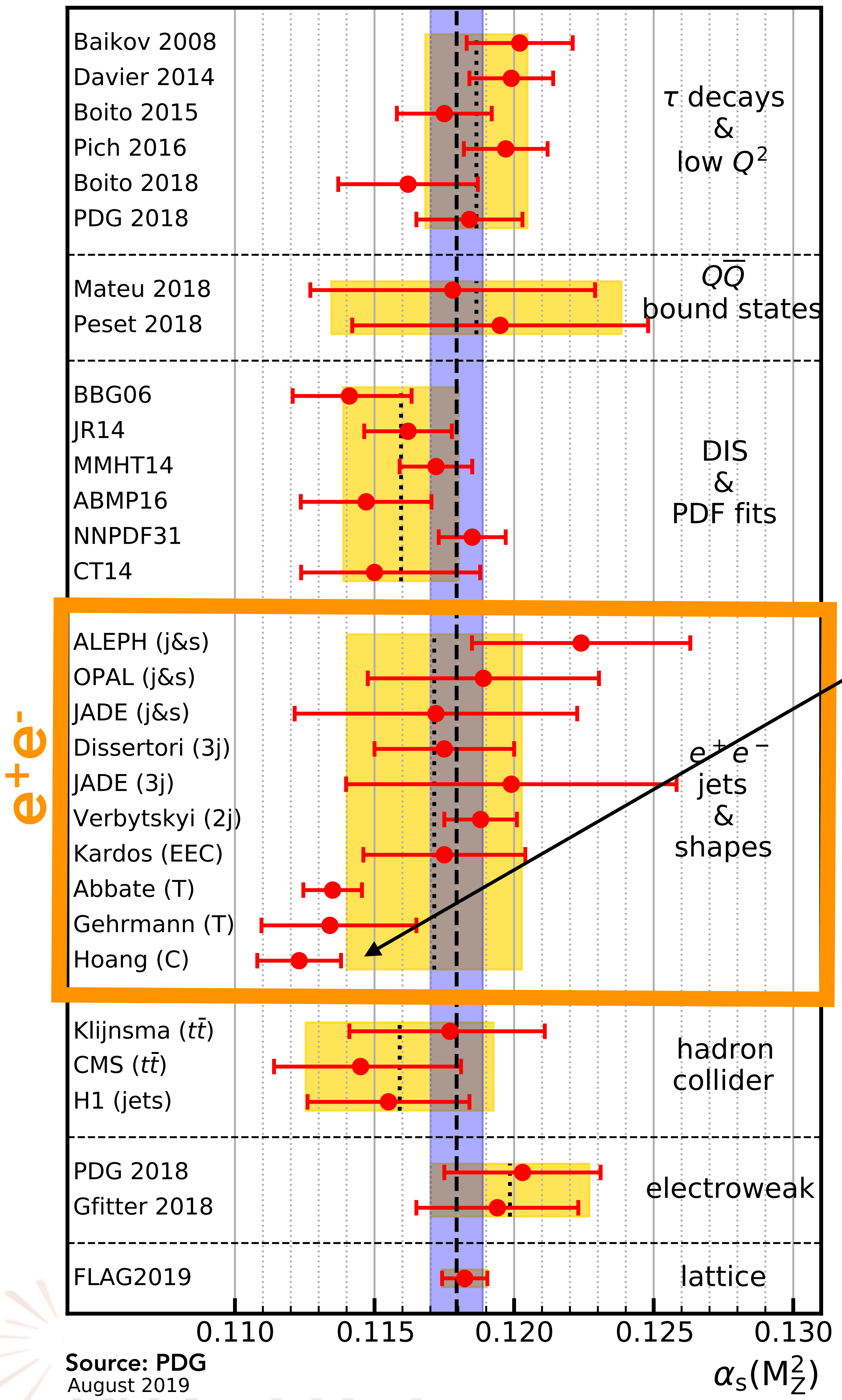
+ Unsolved aspects of QCD itself (confinement)

- Dynamics of confinement: Fundamental QCD, strings vs clusters vs ???

MCnet

Current state of the art for α_s from LEP

(see also FCC-ee QCD workshops & writeups)



Source: PDG
August 2019

LEP beams switched off Nov 2000; theory has kept evolving:

NNLO 3-jet calculations: Weinzierl, PRL 101, 162001 (2008), and Gehrmann-de-Ridder, Gehrmann, Glover, Heinrich (EERAD), CPC185(2014)3331

+ new resummations: E.g., SCET-based N3LL for C-parameter: Hoang et al, PRD91(2015)094018

$\Longrightarrow$ **Reanalyses: new $\alpha_s(m_Z)$ extractions**

E.g., 0.1123 ± 0.0015 from C-parameter @ NNLO + N³LL'

Note large spread among e^+e^- extractions

➤ PDG $\alpha_s(M_Z^2)$ from ee = 0.1171 ± 0.0031 $\qquad (\delta\alpha_s/\alpha_s)_{\mathrm{LEP}} \sim 2.6\,\%$

Compared with global = 0.1179 ± 0.0010 $\qquad (\delta\alpha_s/\alpha_s)_{\mathrm{PDG}} \sim 1\,\%$

CURRENT STATE OF THE ART: $\dfrac{\delta\alpha_s}{\alpha_s} \sim \mathcal{O}(1\%)$

α_s at FCC-ee / CEPC — Overview

(Apologies for not covering prospects specific to ILC)

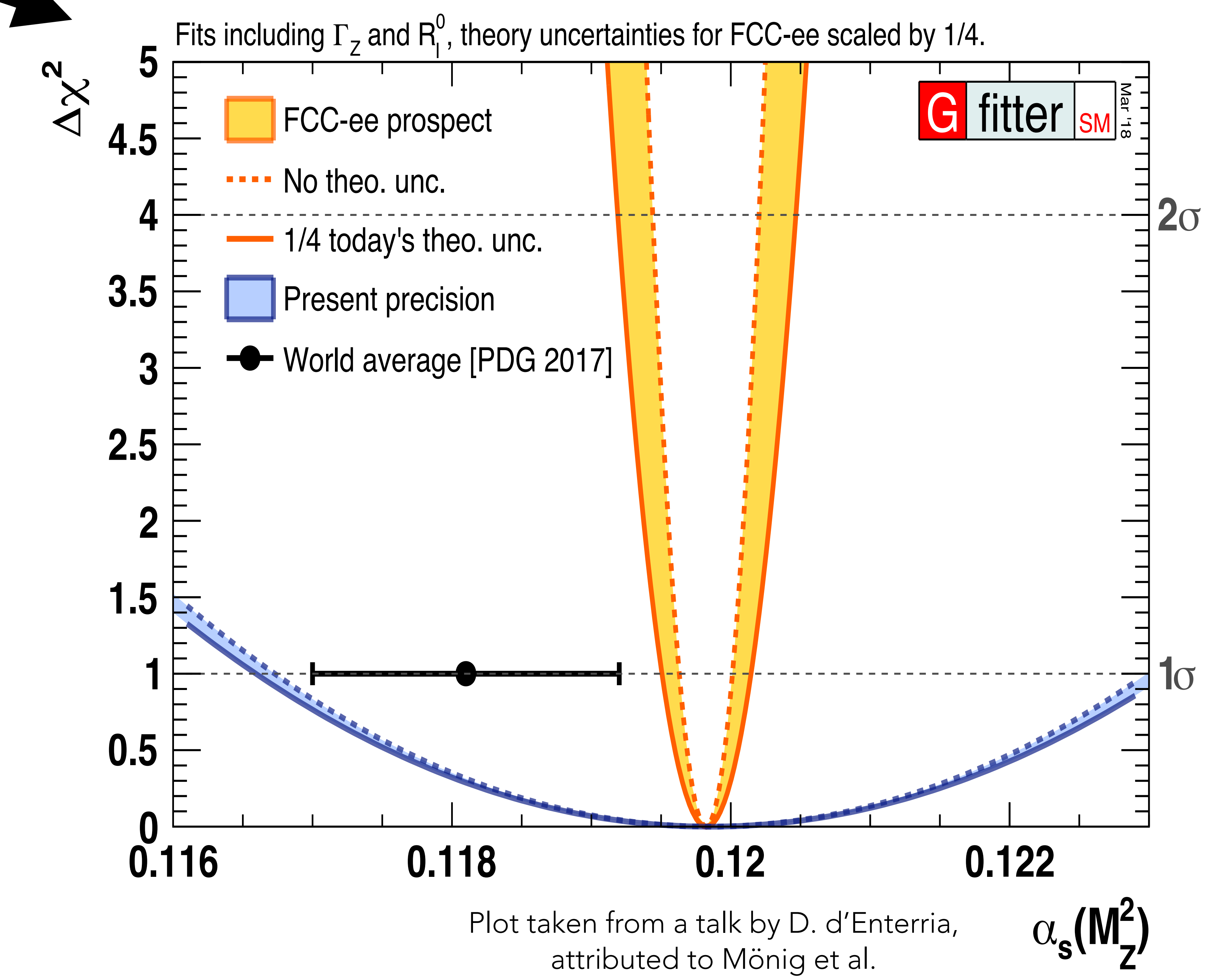
Hadronic Z decays

Theory: most precise = most inclusive. Total width Γ_Z (from threshold scan) & hadronic "R" ratio @ N³LO:

$$\frac{\Gamma(e^+e^- \to \text{hadrons})}{\Gamma(e^+e^- \to \mu^+\mu^-)} = R_{\rm EW}(Q)\left(1 + \sum_{n=1}^{\infty} c_i \left(\frac{\alpha_s}{2\pi}\right)^n + \mathcal{O}\left(\frac{\Lambda^4}{Q^4}\right)\right) \quad \Longrightarrow \frac{\delta\alpha_s}{\alpha_s} \sim \mathcal{O}(10^{-3})$$

(c_1=1=LO, c_2,c_3 and most recently c_4 also known Baikov et al, 2012)

+ Can incorporate in global fit to SM:



Plot taken from a talk by D. d'Enterria, attributed to Mönig et al.

+ Hadronic W decays (+ Γ_W from thresh. scan)

Similar TH accuracy + **Huge** increase over LEP ($10^4 \to 10^8$): **can be competitive**

Parametric uncertainty from BRs $\propto |V_{\rm CKM}|^2$

esp **$\delta|V_{cs}|$~1.6%** must be reduced by factor ~ 3

+ Hadronic τ decays

Expect O(10^{11}) τ decays from $Z \to \tau^+\tau^-$

$$R_\tau = \frac{\Gamma(\tau \to \text{hadrons})}{\Gamma(\tau \to \nu_\tau e^- \bar{\nu}_e)}$$ also known to N³LO: **competitive**(?)

Need to control **non-perturbative** $(\Lambda/m_\tau)^2 \sim 1\,\%$ effects

Multi-purpose MC generators (Herwig, Pythia, Sherpa, Whizard) can simulate all aspects of particle production and decay

Well developed machinery from LHC with NLO matching as standard

Just change initial state…

+ no initial-state colour

→ less modelling of colour neutralisation needed

and pick what you need!

Not so fast …

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

MC Generators — How precise are they?

For hadronic Z decays, for an observable involving a scale Q:

e.g., Q could be a jet- or event-shape resolution scale

Parton showers sum all-orders "**LL**" corrections $\propto \alpha_s^n \ln^{n+1}(Q^2/m_Z^2)$

+ For some simple inclusive observables, also "**NLL**" $\propto \alpha_s^n \ln^n(Q^2/m_Z^2)$

(Showers do include further all-orders aspects, like exact energy and momentum conservation, not accounted for in this counting.)

NLO matching only corrects the **first hard radiation**, not parton-shower dynamics.

Missing higher-order terms can in part be **compensated** for by MC-specific α_s choices and **tuned hadronisation parameters**.

But the presence of this ambiguity makes it difficult to use MCs as "precision" tools.

Hadronisation corrections scale differently with $\sqrt{s}$: $(\Lambda/Q)^n$ vs $\ln^n(Q^2/s)$

Resolve ambiguity by high-precision measurements of same set of observables for several different $\sqrt{s}$? (Nice studies from LEP 1 vs 2 but suffered from low stats off Z pole.)

Studies of ILC/FCC-ee/CEPC capabilities needed.

Can achieve good statistics all the way from $\sqrt{s}$=**250 GeV to 10 GeV** (via ISR from Z pole ~ 10 events / GeV at LEP; requires FWD coverage) → full perturbative range + connect with B factories

MC Generators ➤ Next Generation

Slide from A. Hoang (CEPC Workshop, Oct 2020)

- 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

double emssion

amplitude evolution (full coherence,

non-global logs, color reconnection)

Li, Skands '16

Höche Prestel' 14, '15

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!

Opportunities & Requirements

New generation of highly precise MC models by 2030.

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

For all other cases, expect (N)NLO matched and merged with next-generation showers.

Tests and Validations

Need benchmark observables sensitive to **subtle differences beyond LL**.

E.g., multi-parton correlations (e.g., triple-energy correlations cf eg arXiv:1912.11050), multi-parton coherence (cf eg arXiv:1402.3186), "direct" $n \to n+2$ branchings (cf eg extra slides), subleading N_C, …

+ Giga-Z/Tera-Z ➤ statistics to focus on small but "clean" corners of phase space

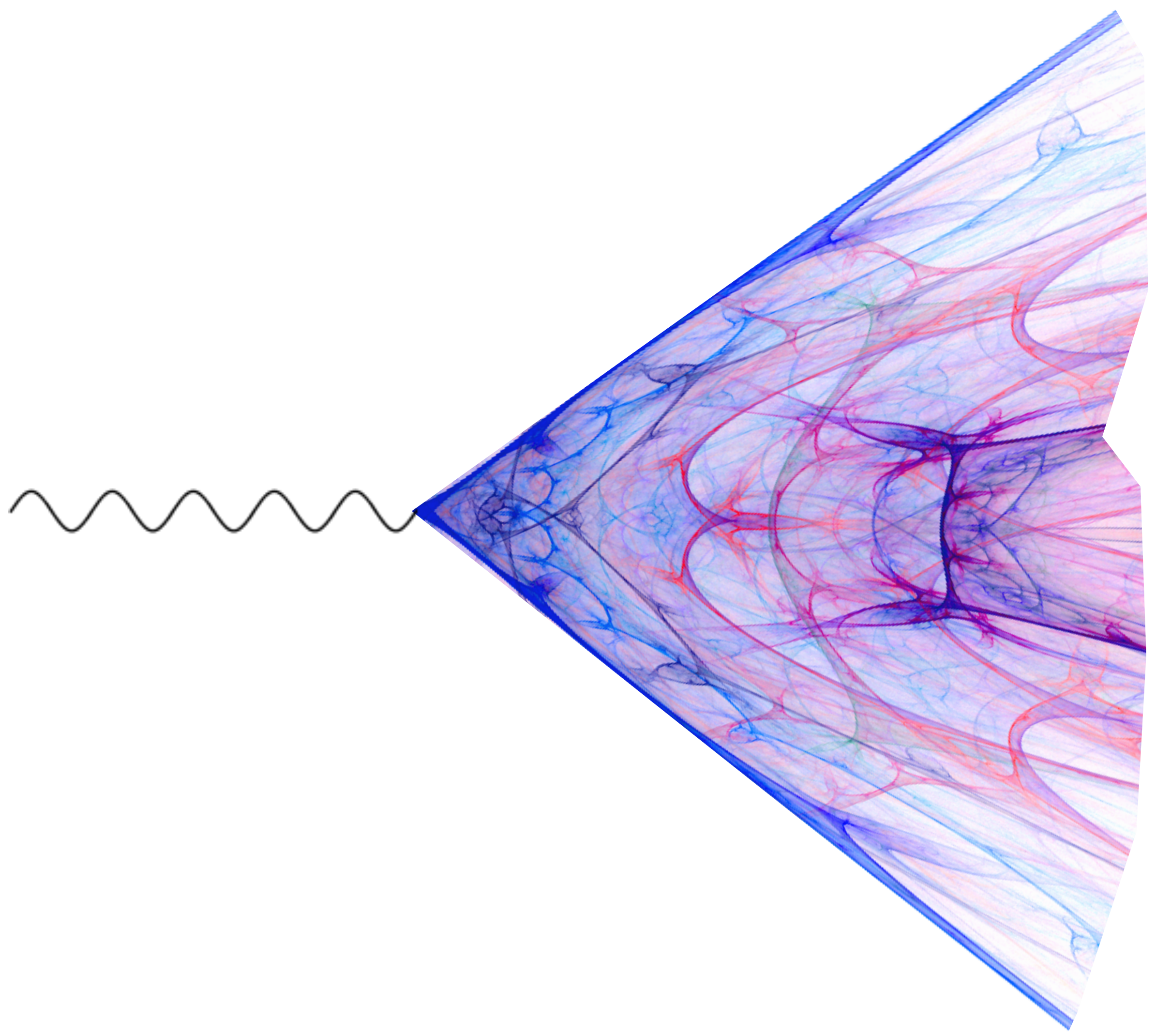
Scaling studies with $\sqrt{s}$ can play important role? ➤ Disentangle power corrections, α_s running, …

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?

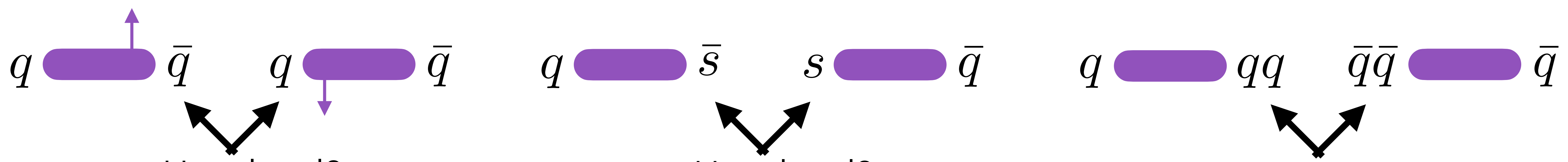


Confinement in QCD remains a fundamental and unsolved problem.

Affects all final states with jets: fragmentation uncertainties, colour reconnections, …

+ interesting (stringy) physics in its own right

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



Relative **momentum kicks** of order Λ_{QCD} ~ **100 MeV** must be well resolved

Must be able to tell **which hadrons are which** (strangeness, baryon number, spin) ➤ **PID**

How local is hadronisation?

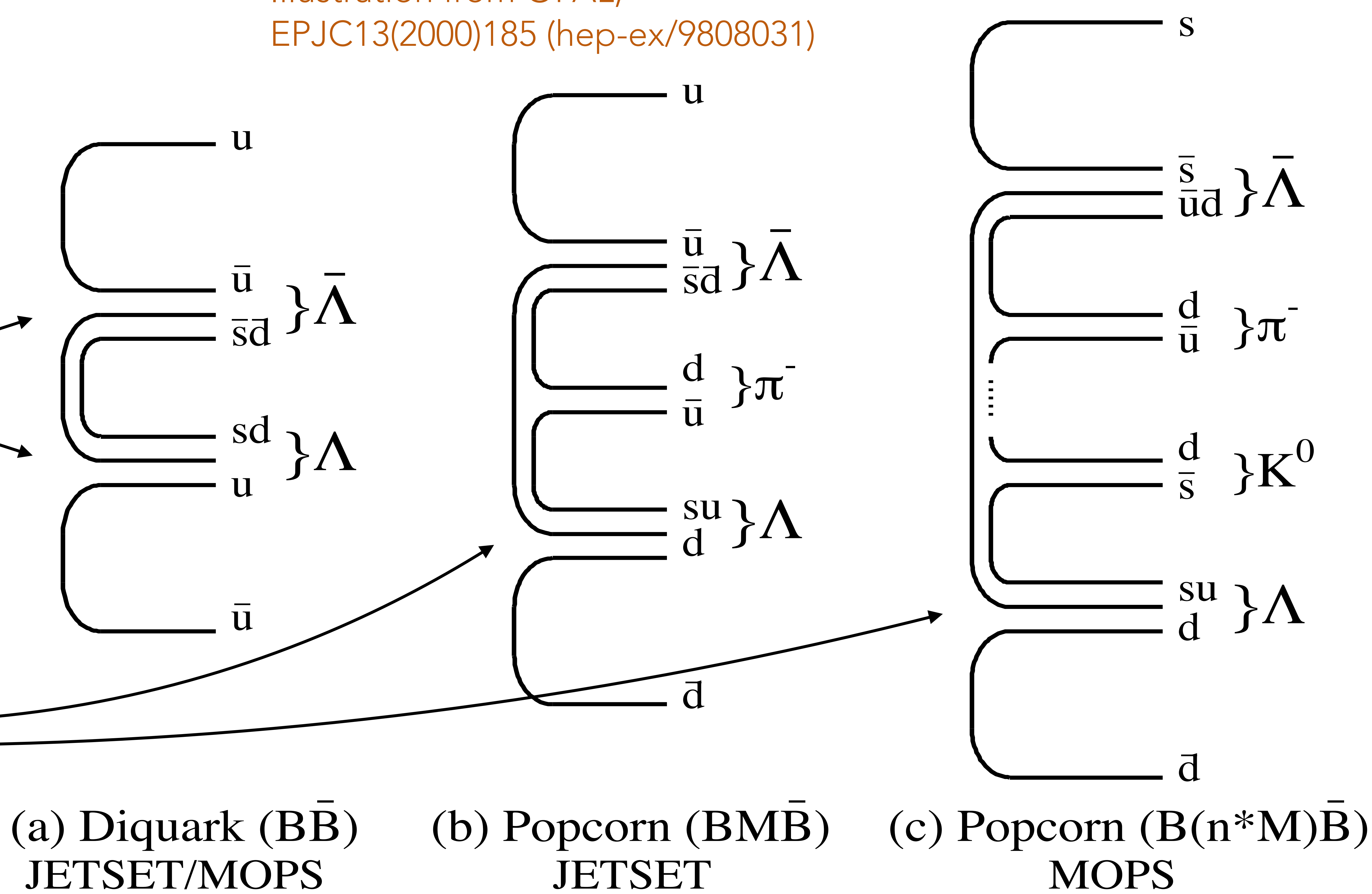
(see also FCC-ee QCD workshops & writeups)

Illustration from OPAL, EPJC13(2000)185 (hep-ex/9808031)

Example: Baryon-Antibaryon correlations

Diquark model:
strong correlations over short rapidity distances

Popcorn/MOPS:
more complex and spread-out in rapidity



Both OPAL measurements were statistics-limited (OPAL 1993, 1998)

Would reach OPAL systematics at **100 × LEP** (→ 1000 with better detector?)

+ Many related questions, including …

(see also FCC-ee QCD workshops & writeups)

Strangeness and **kinematic** (p_T, rapidity) correlations

How local is strangeness conservation? (Similar to baryon correlations)

Especially **interesting** given LHC discoveries of **strangeness enhancements** and collective effects in high-multiplicity pp environments $\Longrightarrow$ reference *ee* benchmarks

And **test universality** in ee context eg in "hairpin" gluon jets ($Z \to b\bar{b}g$ for $x_G \sim 1$), $Z \to qq'\bar{q}\bar{q}'$, and $WW \to q\bar{q}'q''\bar{q}'''$

Gluon fragmentation — without Underlying Event

E.g., using double-tagged $b\bar{b}g$ events (limited event sample at LEP)

Colour-octet neutralisation? Zero-charge gluon jet + rapidity gaps on either side

Connections to Colour reconnections, glueballs, …

Leading (high-x) baryons in g jets?

Bose-Einstein Correlations & **Fermi-Dirac** Correlations

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

LEP Puzzle: correlations → Fermi-Dirac radius ~ 0.1 fm $\ll r_p$ (both pp and ΛΛ; multiple exps)

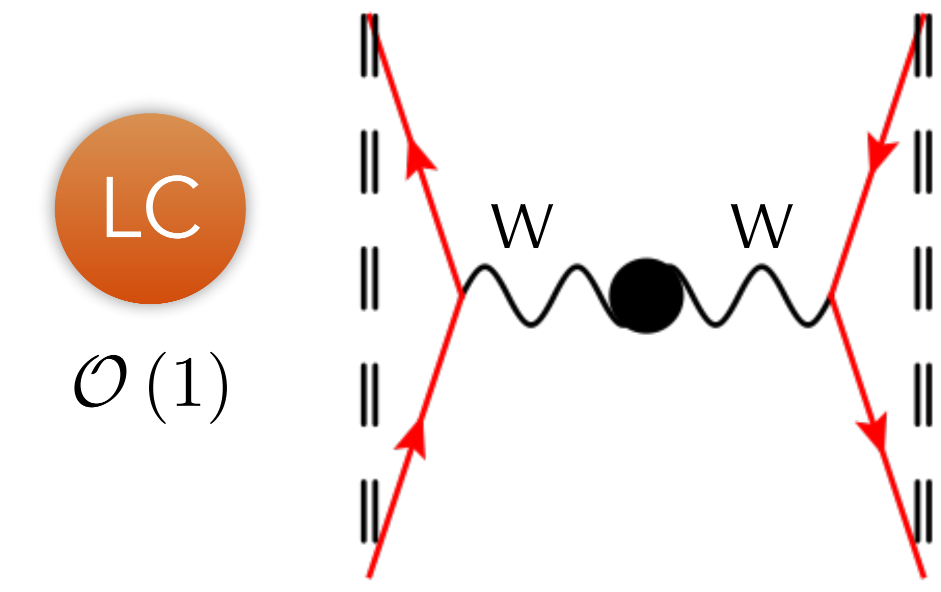
Spin/helicity correlations ("screwiness"?), multiply-heavy hadrons, exotics, nuclei, …

Colour Reconnections

(see also FCC-ee QCD workshops & writeups)

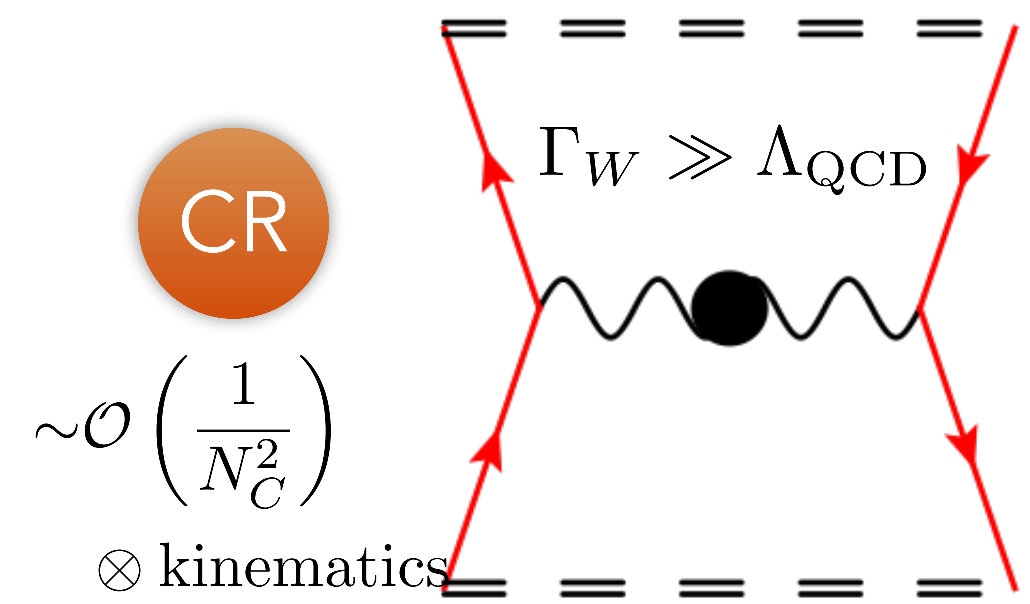
At LEP 2: hot topic (by QCD standards)**: "string drag" effect on W mass**

- 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 WW for m_W measurement** ➤ input as constraint to make **sensitive measurements of CR in hadronic WW**



Has become even hotter topic at LHC

- 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 (ILC?) so far … (to my knowledge)
A lot of new models, scope to propose new observables, …

Some overviews of recent models:
arXiv:1507.02091 , arXiv:1603.05298

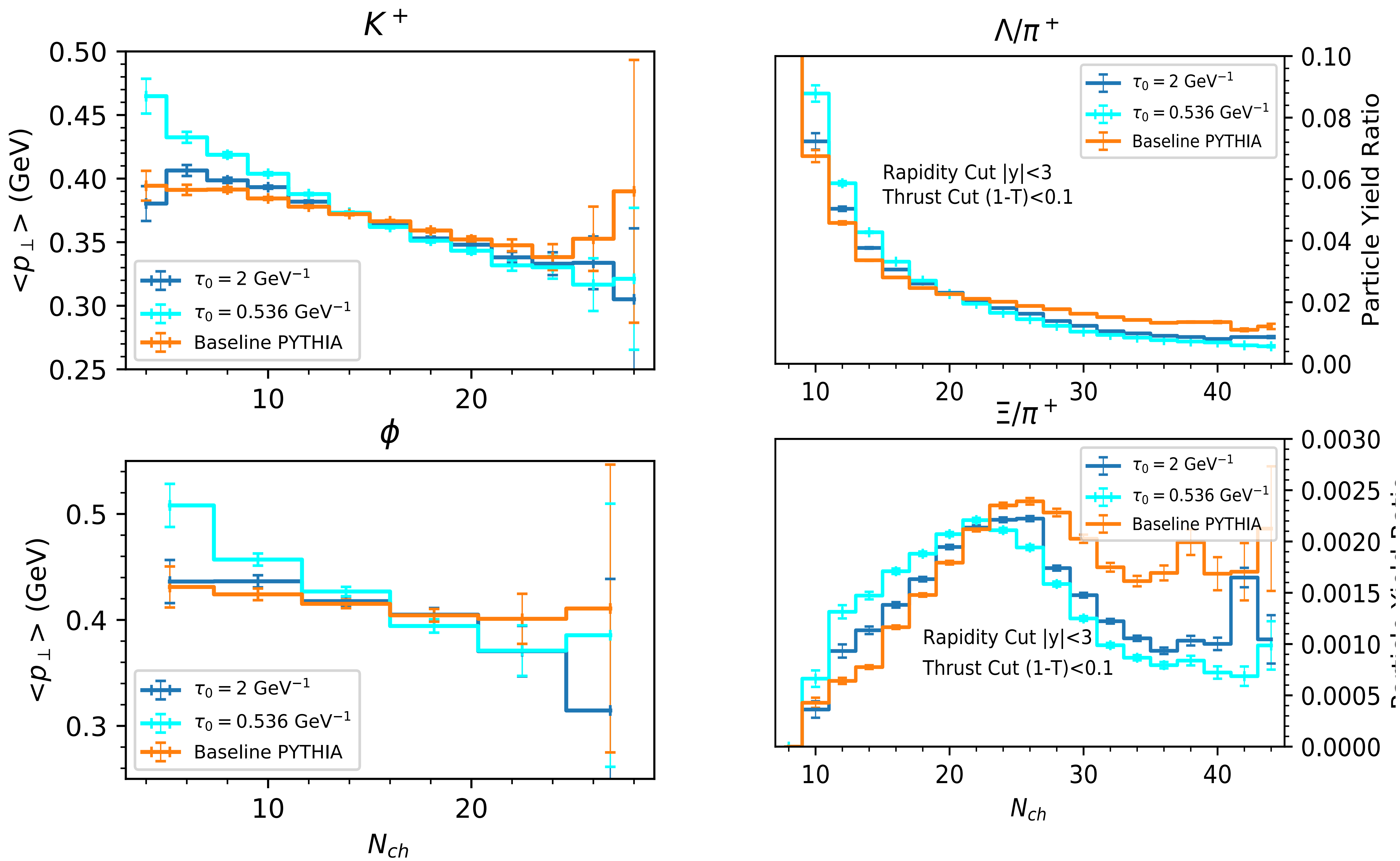
Example of further questions: String with time-dependent "Cooldown"

N. Hunt-Smith & PS arxiv:2005.06219

Toy model constrained to have same average string tension as Pythia's "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 Giga-Z/ Tera-Z

Precision QCD at Future e^+e^- Machines

Perturbative QCD: High Precision

Measurements of α_s with ~ per-mille $\delta\alpha_s/\alpha_s$ accuracy

Stringent tests of new generation of **precision MC models** (higher-order shower kernels, N^nLO merging, …)

➥ **Needs: fine jet substructure resolution & flavour tagging**

Interplays with EW & Higgs Physics Goals

Impact of (in)accurate MC predictions? ⇔ Identify & *communicate* crucial areas.

Nonperturbative QCD: High Resolution

Confinement will presumably still rank among the major unsolved problems in physics

Studies of **Hadronisation** = **Trial by fire** not just for any post-LHC sophisticated MC models, but also for any future systematically improvable approximation (or solution) to full QCD.

+ Precision pQCD (above) $\Longrightarrow$ accurate starting point.

Reveal details of final states ⇔ disentangle strangeness, baryons, mass, spin ➥ **Needs: Good PID**

Measure $\mathcal{O}(\Lambda_{\mathrm{QCD}}) \sim 100$ *MeV effects* with high precision ➥ **Needs: Good Momentum Resolution**

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

Extra Slides

Precision α_s at CEPC / FCC-ee

(see also FCC-ee QCD workshops & writeups)

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

Main Observable:

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

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

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 $\qquad g_{A,f} \to \sqrt{1+\Delta\rho_f}\, g_{A,f} \qquad \sin^2\theta_W \to \sqrt{1+\Delta\kappa_f}\,\sin^2\theta_W = \sin^2\theta_{\rm eff}^f,$

- 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?

MCnet

Fragmentation Functions

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

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

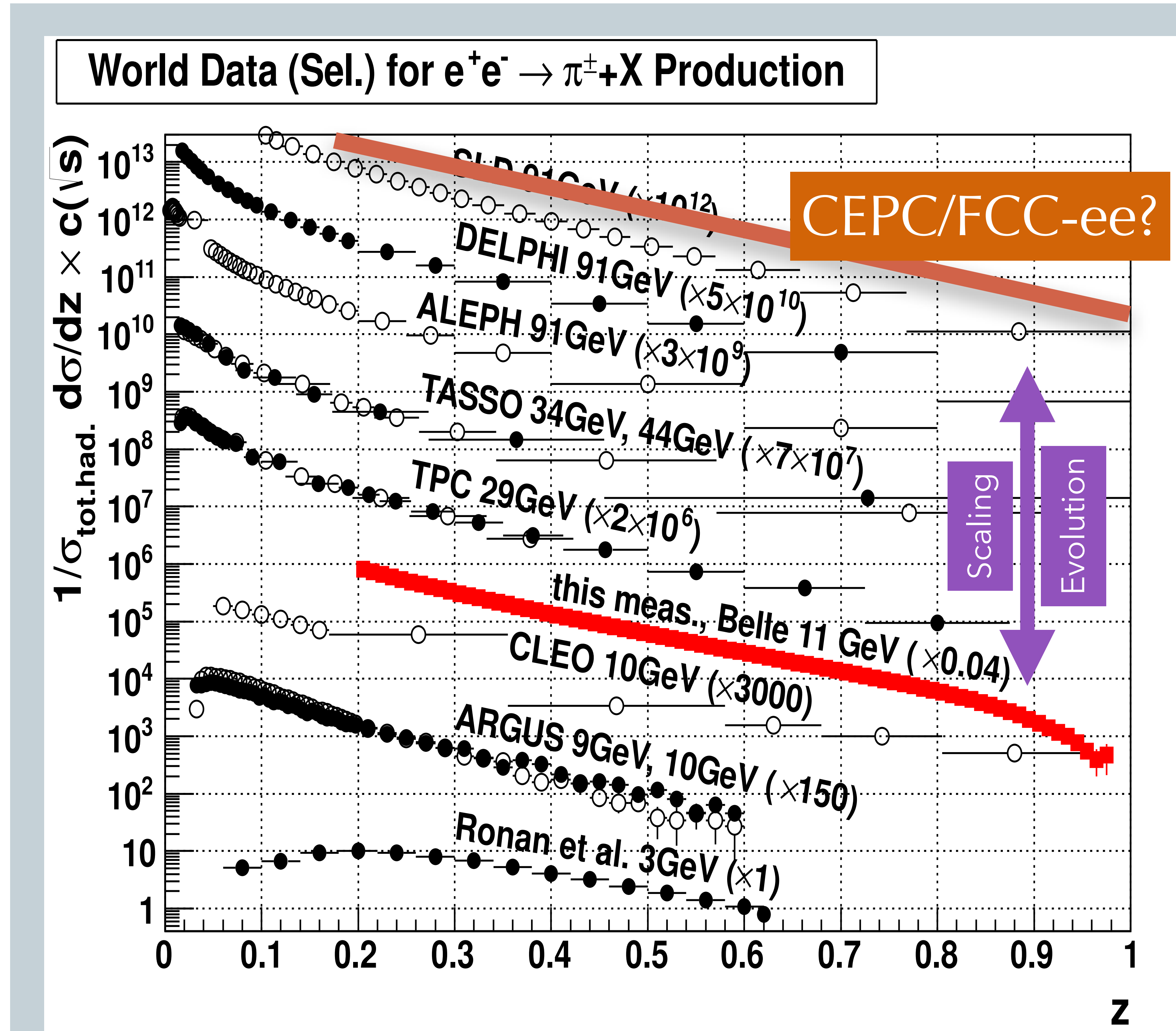
Precision of TH and EXP big advantage

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% |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,…

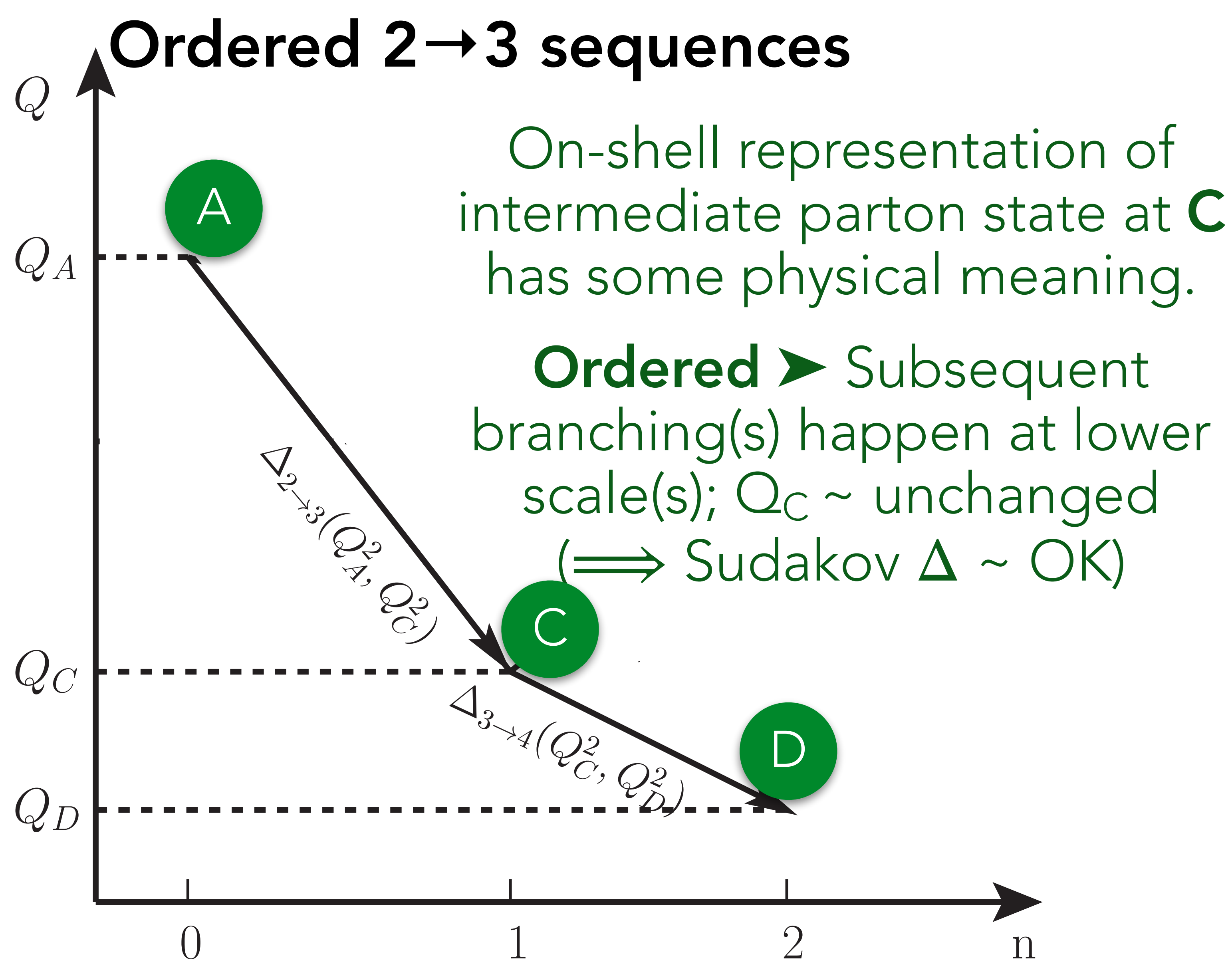
Second-Order Shower Kernels?

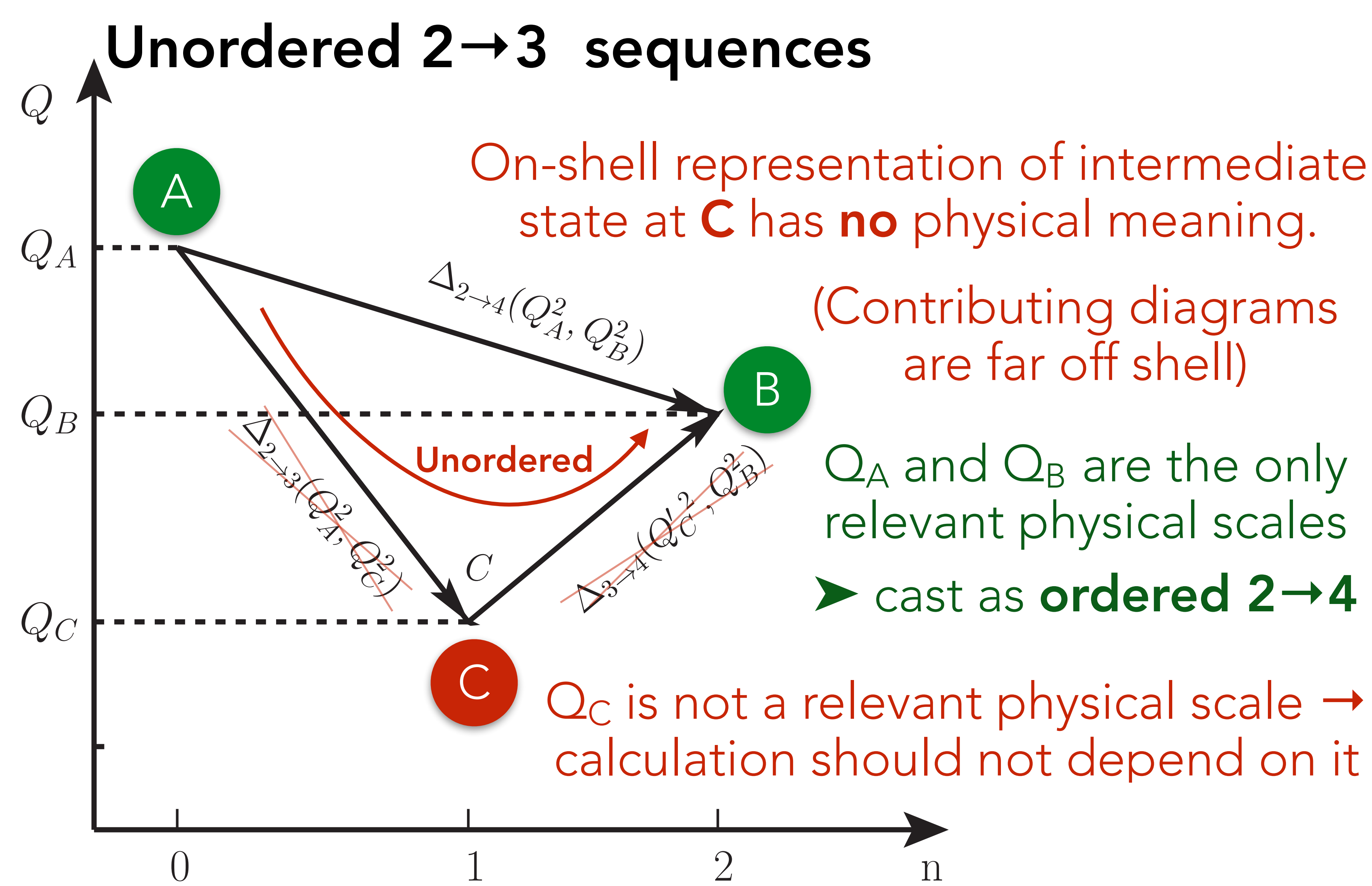
Li & PS, ***PLB* 771 (2017) 59** (arXiv:1611.00013) + ongoing work

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)





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)

$$\frac{d\Delta(Q_0^2,Q^2)}{dQ^2} = \int d\Phi_{\mathrm{ant}} \Bigg[\delta(Q^2 - Q^2(\Phi_3))\, a_3^0 \times \left(1 + \frac{a_3^1}{a_3^0} + \sum_{s\in a,b} \int_{\mathrm{ord}} d\Phi^s_{\mathrm{ant}}\, R_{2\to4}\, s'_3 \right) \Delta(Q_0^2,Q^2)$$

$$+ \sum_{s\in a,b} \int_{\mathrm{unord}} d\Phi^s_{\mathrm{ant}}\, \delta(Q^2 - Q^2(\Phi_4)) R_{2\to4}\, s_3\, s'_3\, \Delta(Q_0^2,Q^2) \Bigg]$$

(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:

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

$$+ \int \frac{d\Phi_4}{d\Phi_2}\, \delta(Q^2 - Q^2(\Phi_4))\, a_4^0\, \Delta(Q_0^2,Q^2)\,, \quad (3)$$

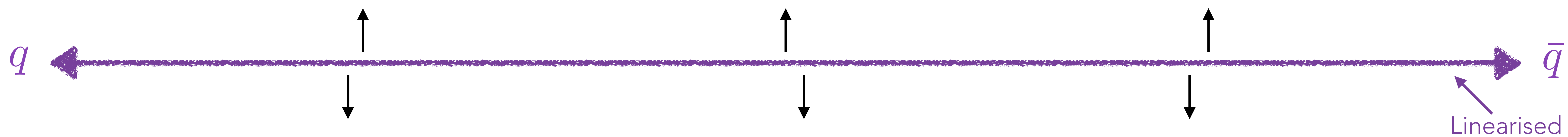
poles

poles

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

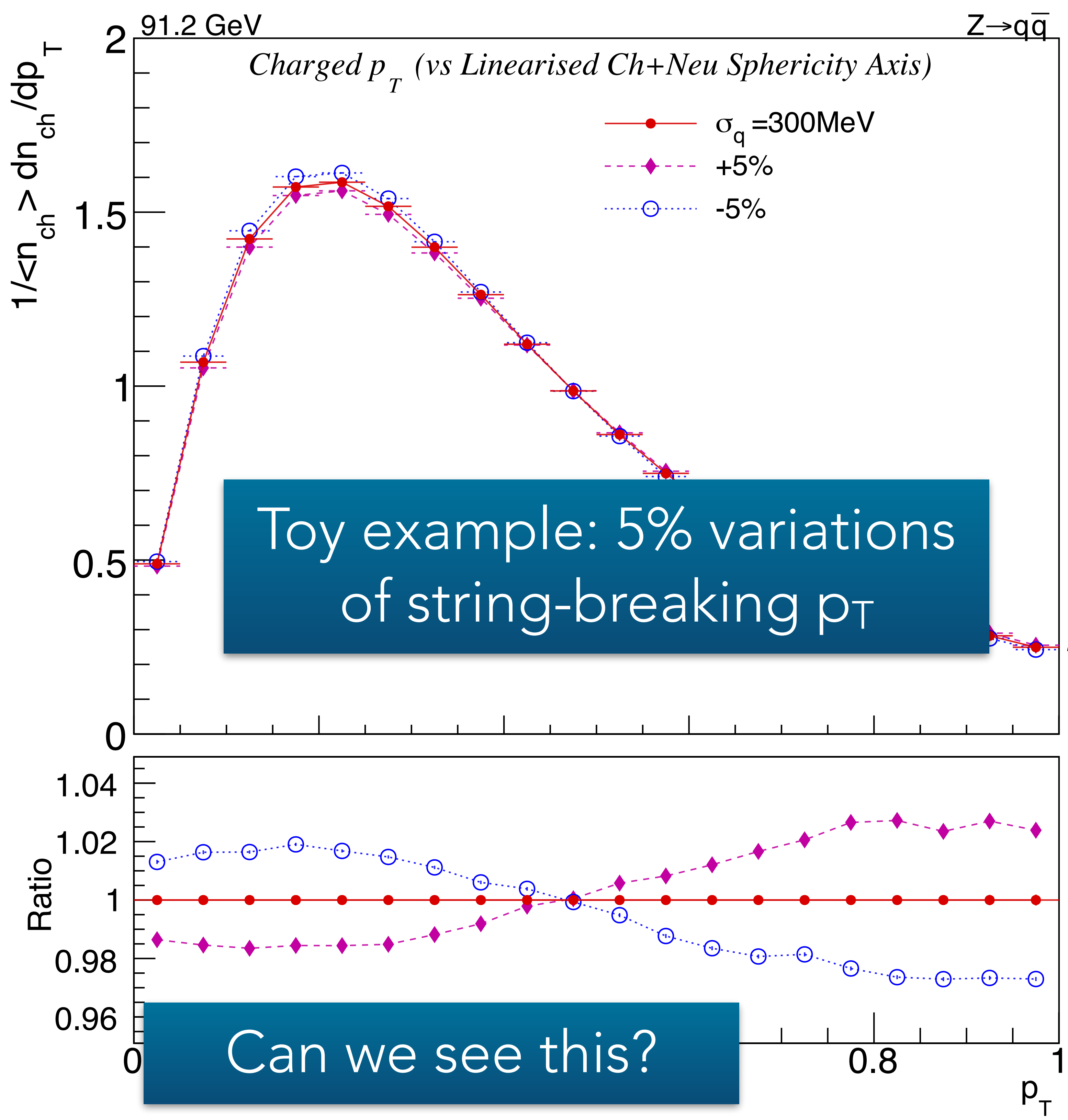
Limited manpower but expect this in PYTHIA within the next ~ 2 years.

Transverse Fragmentation ⇔ Momentum Resolution



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

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

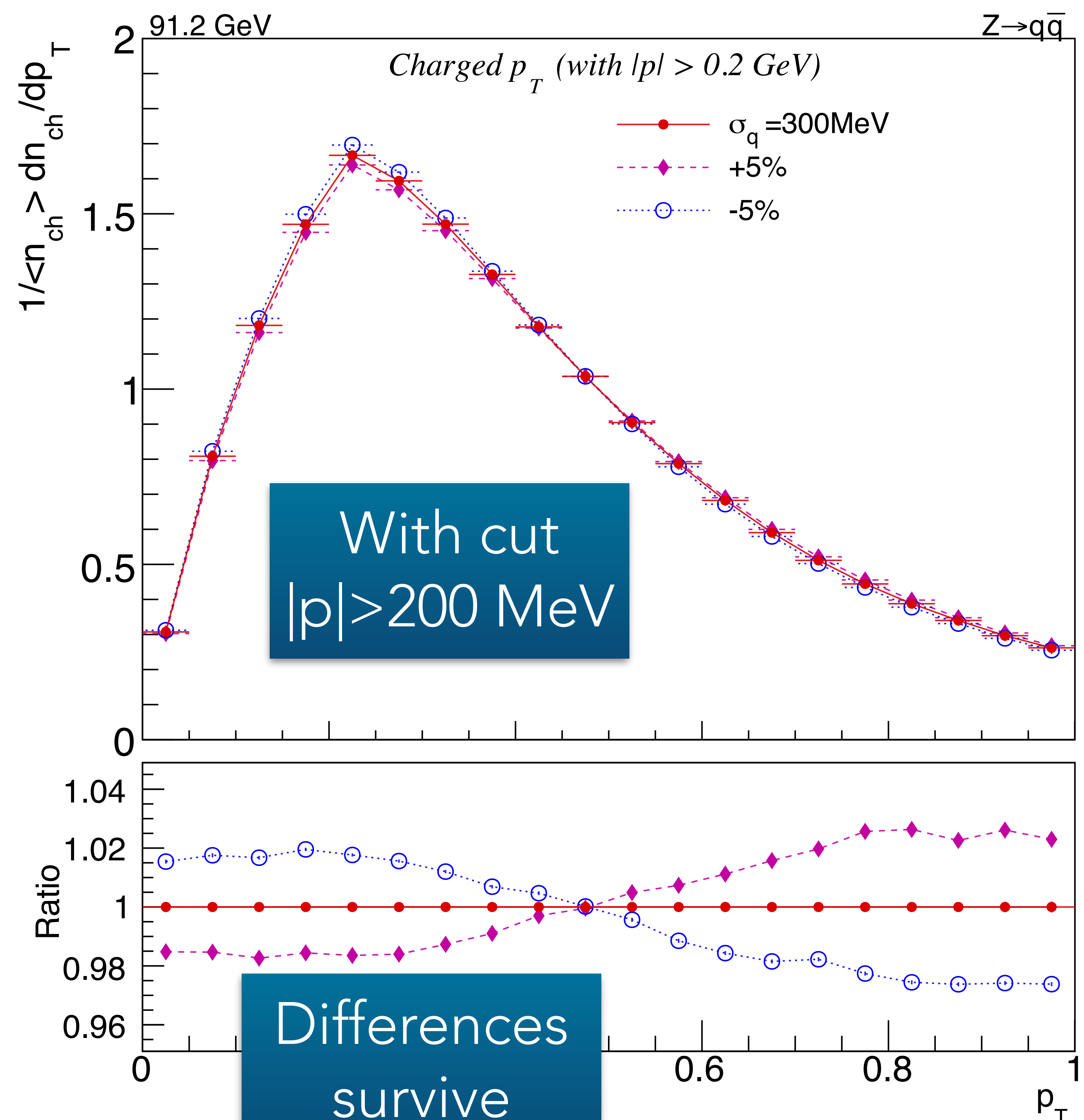


Toy example: 5% variations of string-breaking p_T

Can we see this?

Toy Example

Perturbatively dominated power-law tail



With cut |p|>200 MeV

Differences survive

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?

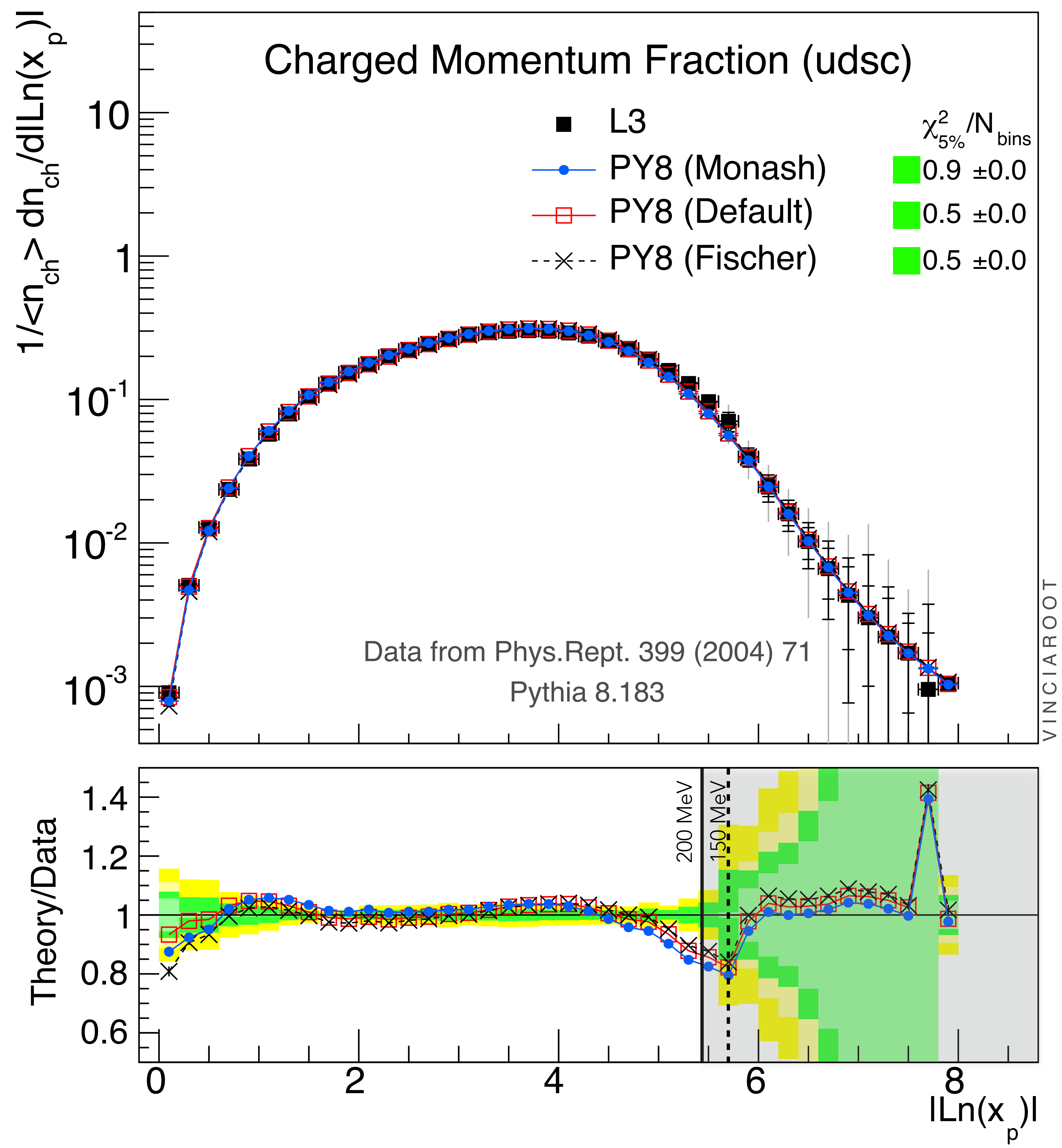
Mismodelled resonance decays?

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

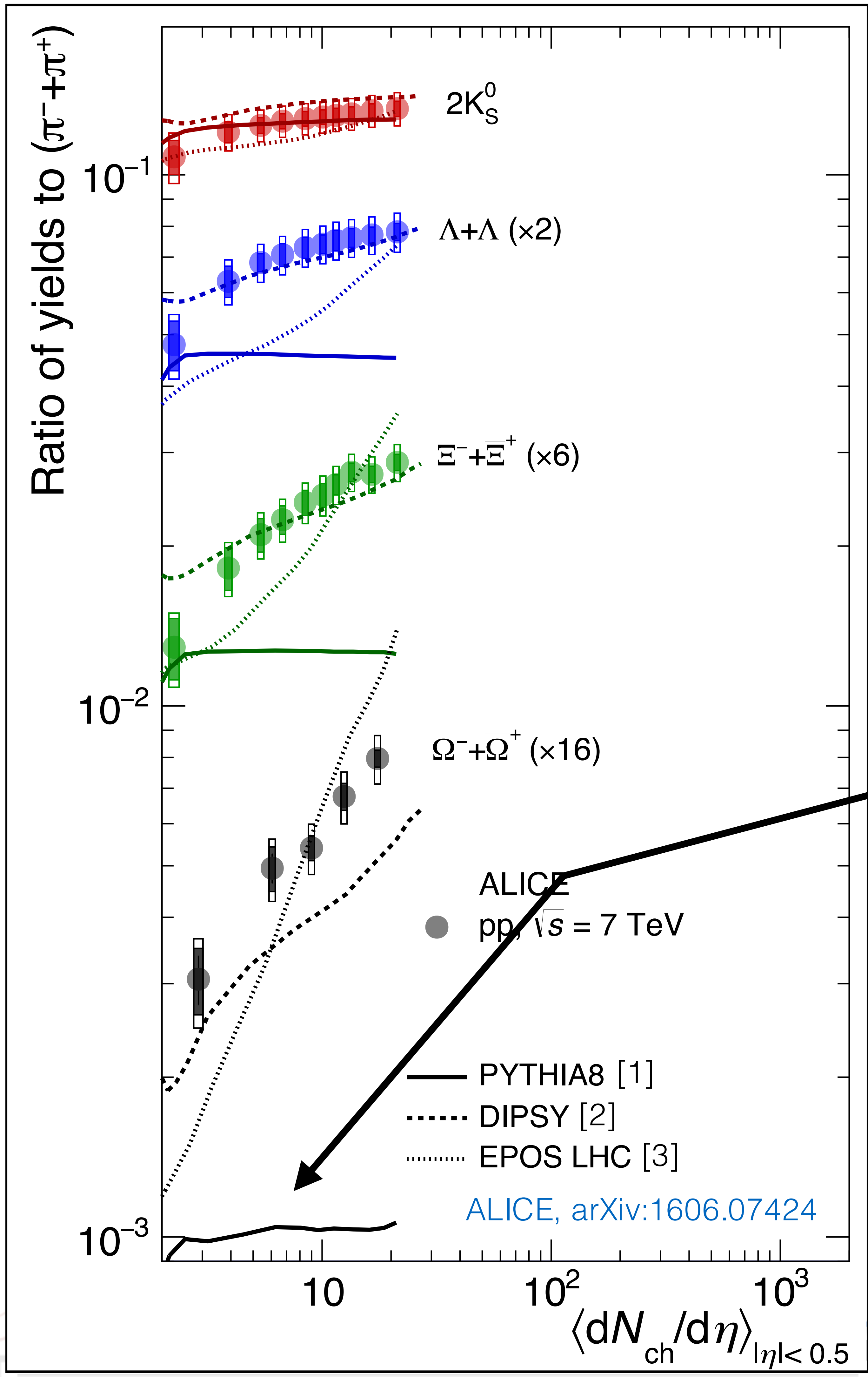
3 hits down to ~ 50 MeV ?

Special runs / setups with lower thresholds?

Example from LEP



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%)

$e^+e^- \to WW$: 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.

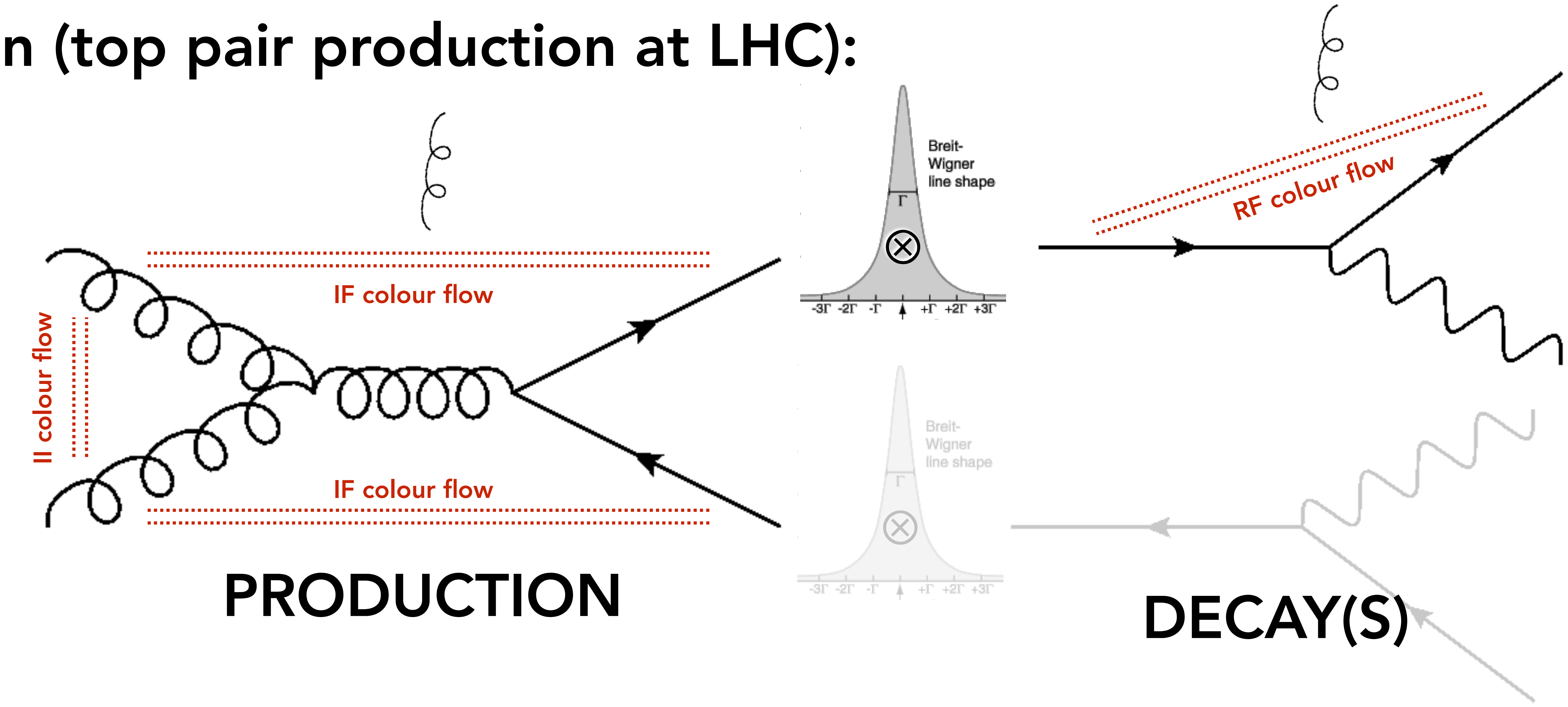
4-fermion ME used to generate correlated kinematics for the W decays.

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):

I: initial
F: final
R: resonance



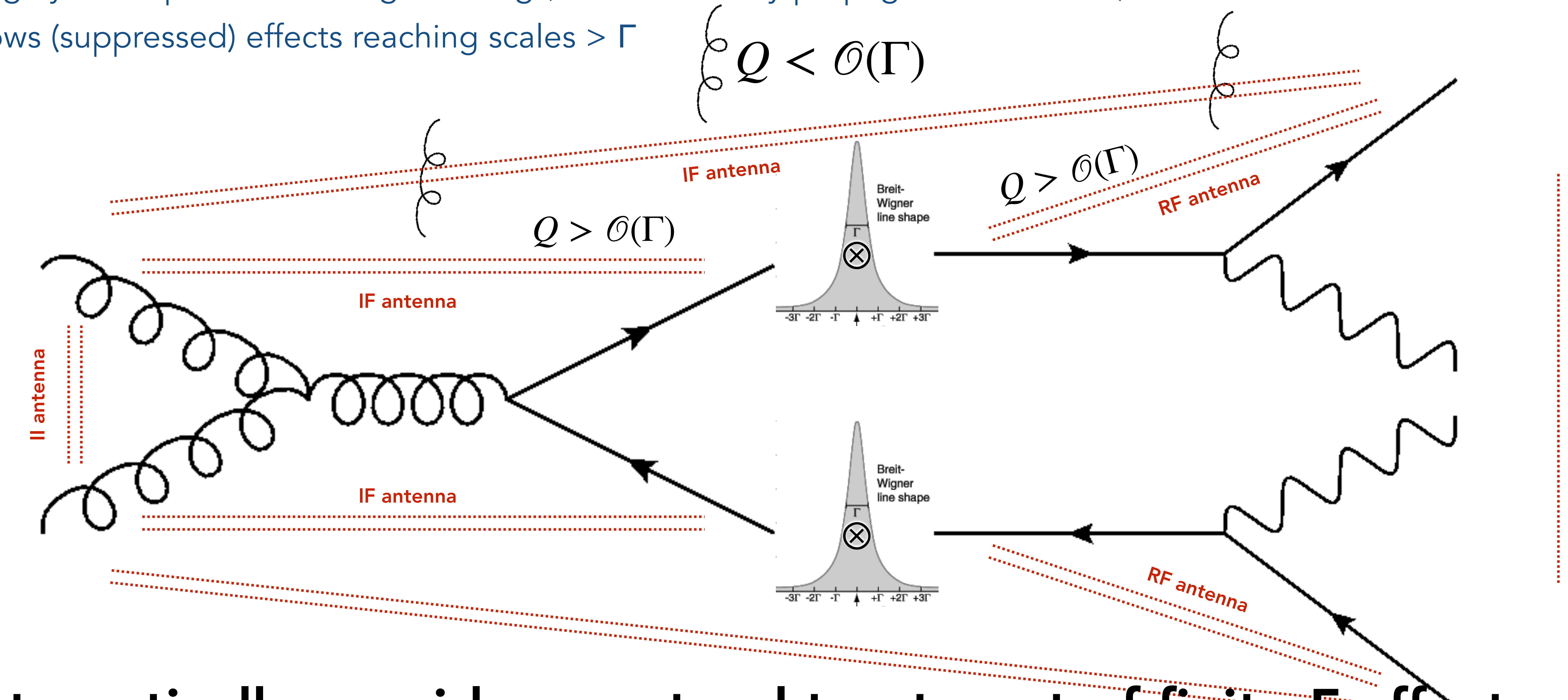
Interleaved Resonance Decays

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



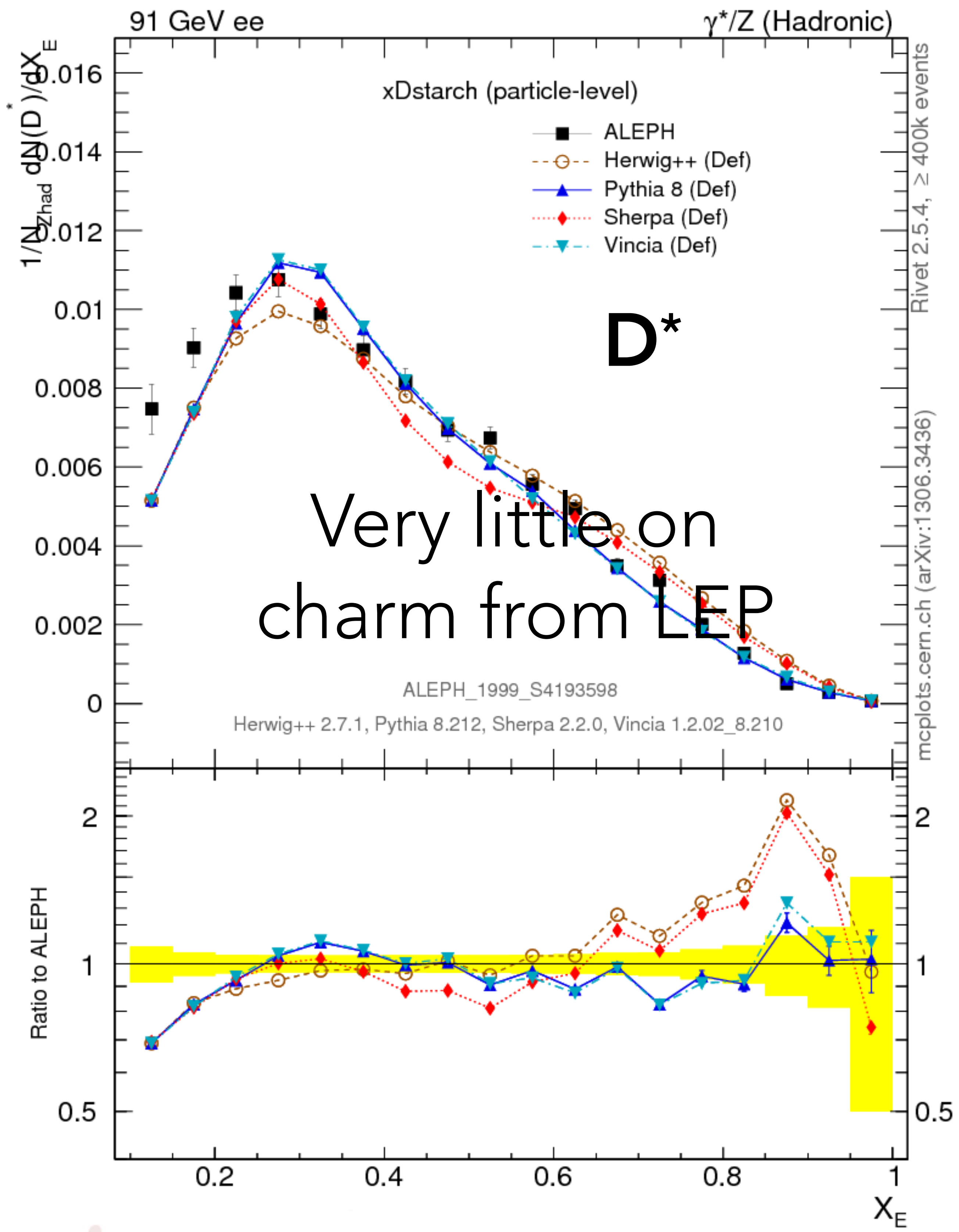
Automatically provides a natural treatment of finite-Γ effects.

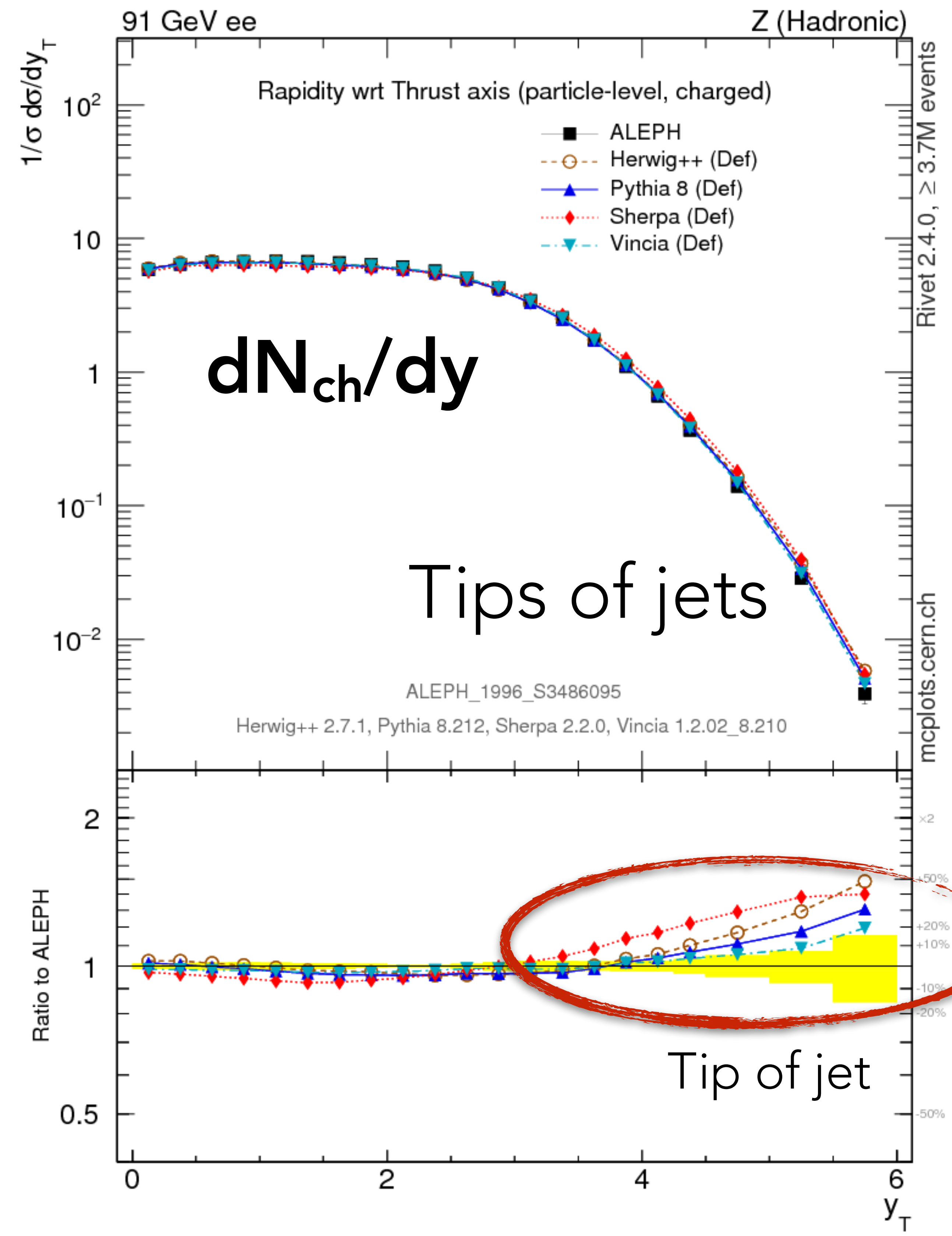
Expect in next Pythia release (8.304)

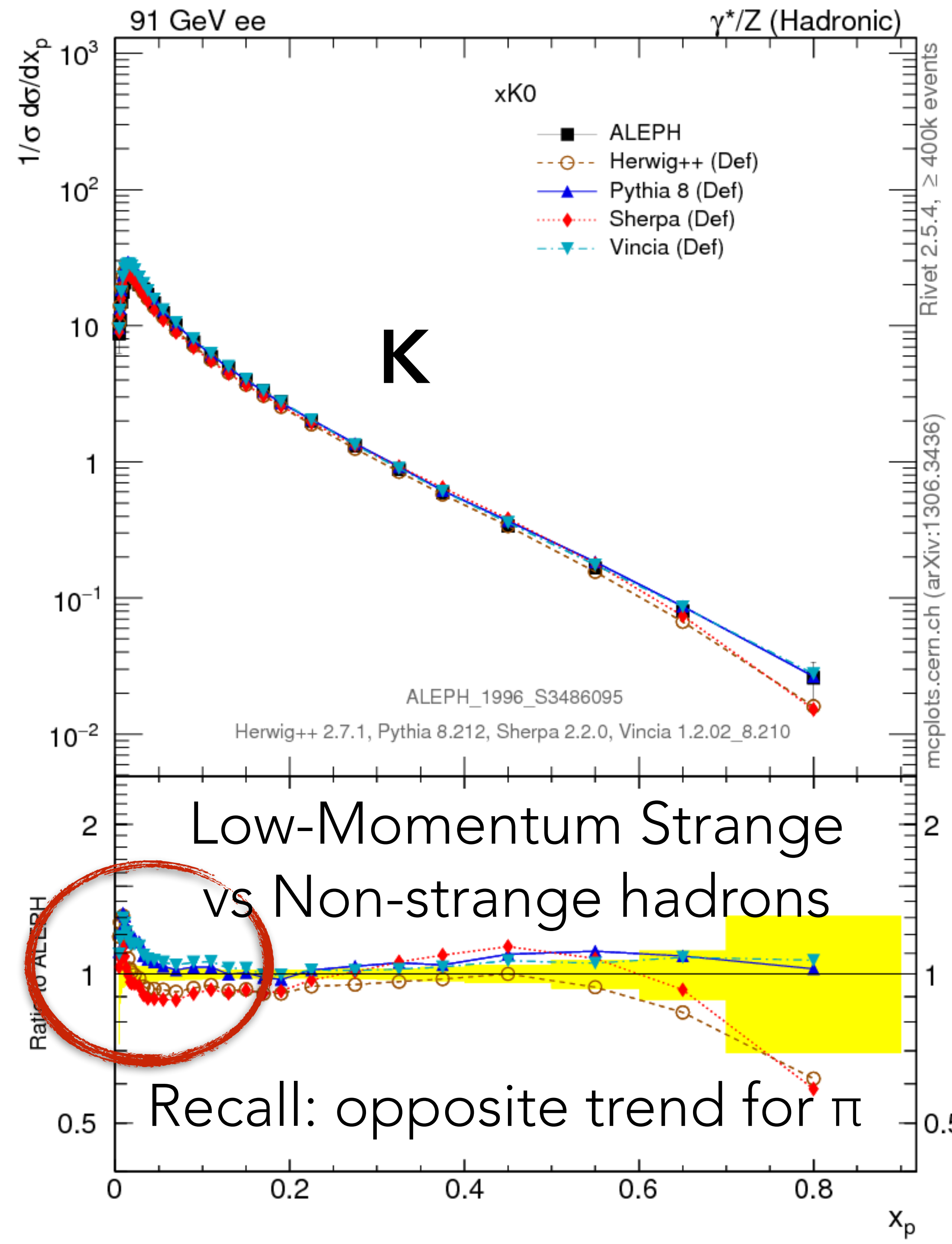
Plenty of other interesting detailed features

(plots from mcplots.cern.ch)

Just a few examples







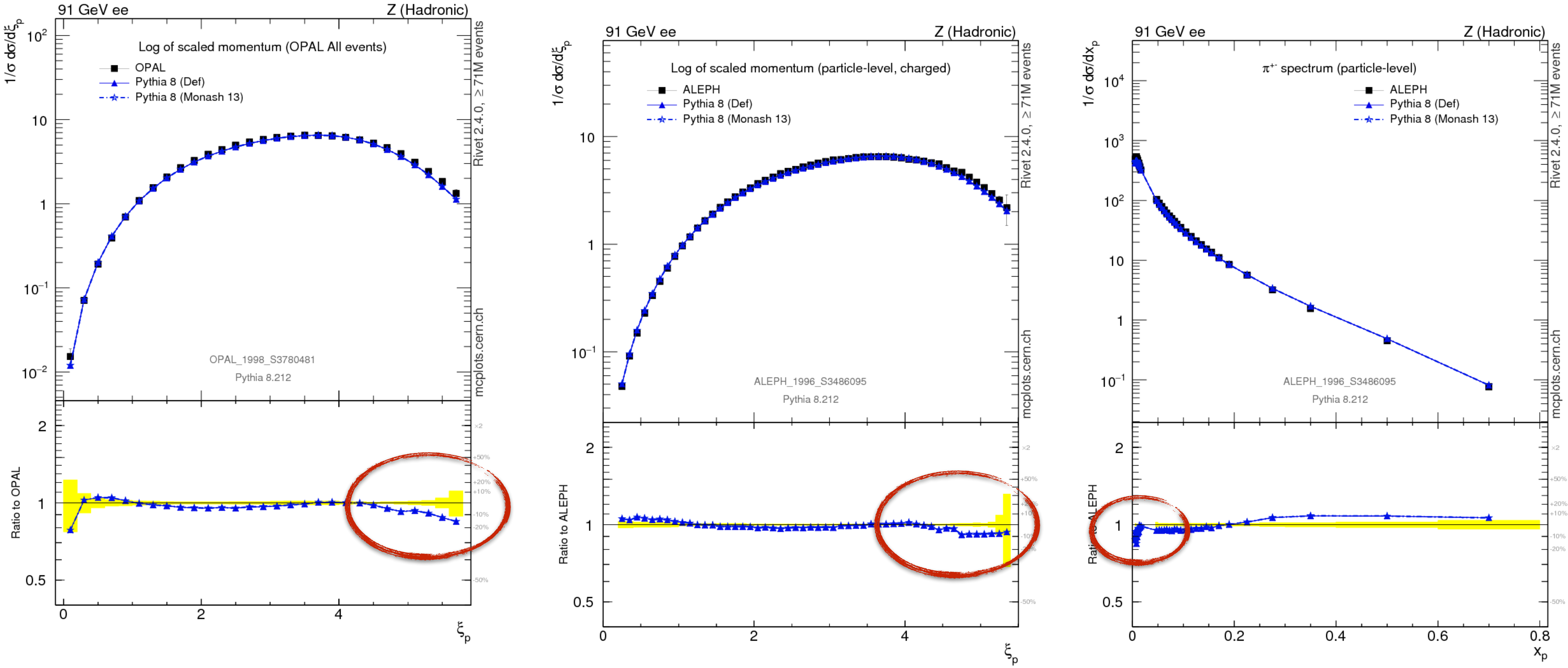
Capabilities for hadrons from decays (π^0, η, η', ρ, ω, K^*, ϕ, **Δ**, Λ, Σ, Σ^*, Ξ, Ξ^*, Ω, …)

\+ **heavy-flavour** hadrons

Very challenging; conflicting measurements from LEP

L3?

(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?

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

(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

Example of recent reexamination of String Basics

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)

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 $H \to bb$**;

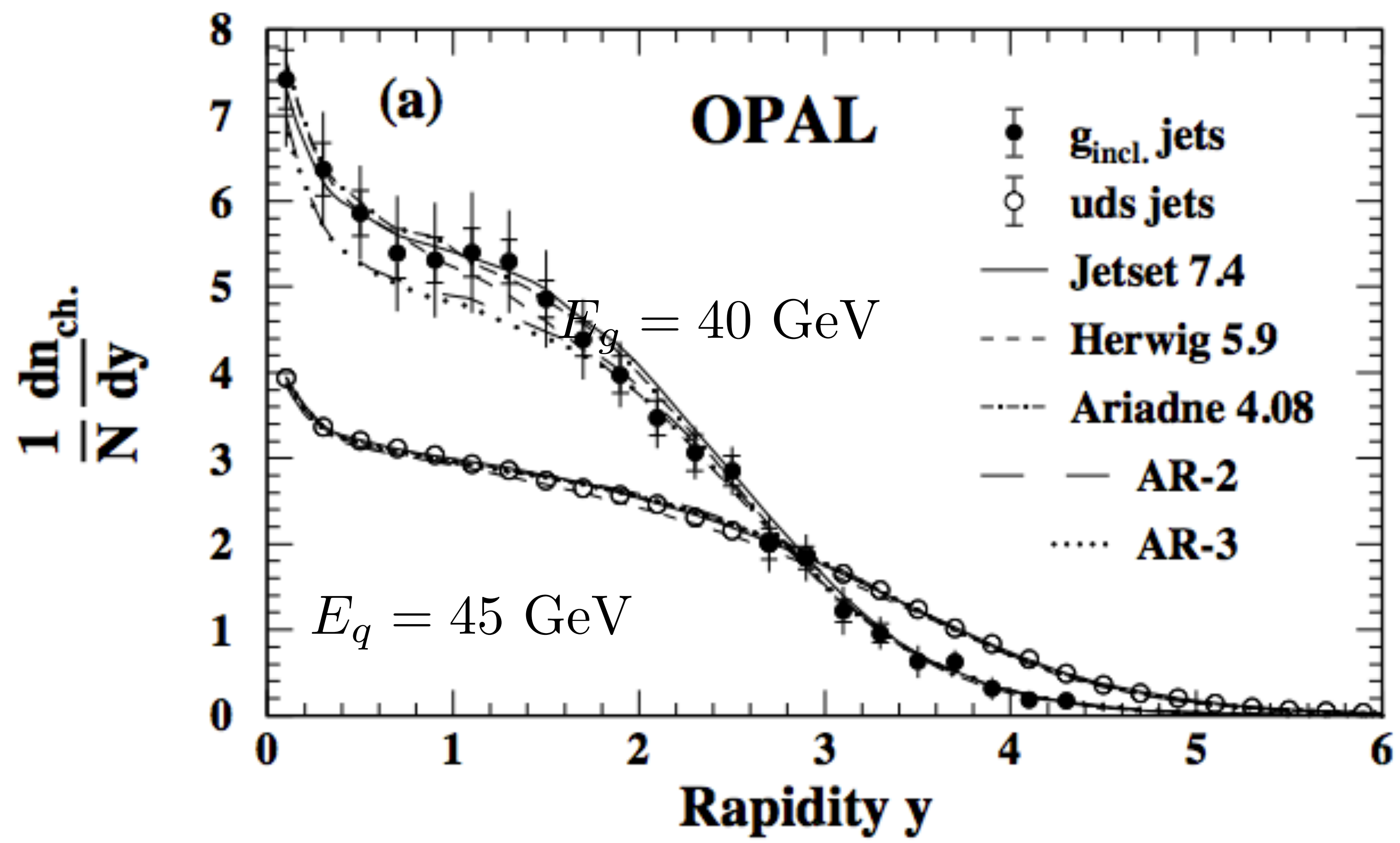
Driven by Higgs studies requirements?

$Z \to bbg$ 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

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

Useful benchmarks could be $E_{CM} \sim 10$ (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)

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

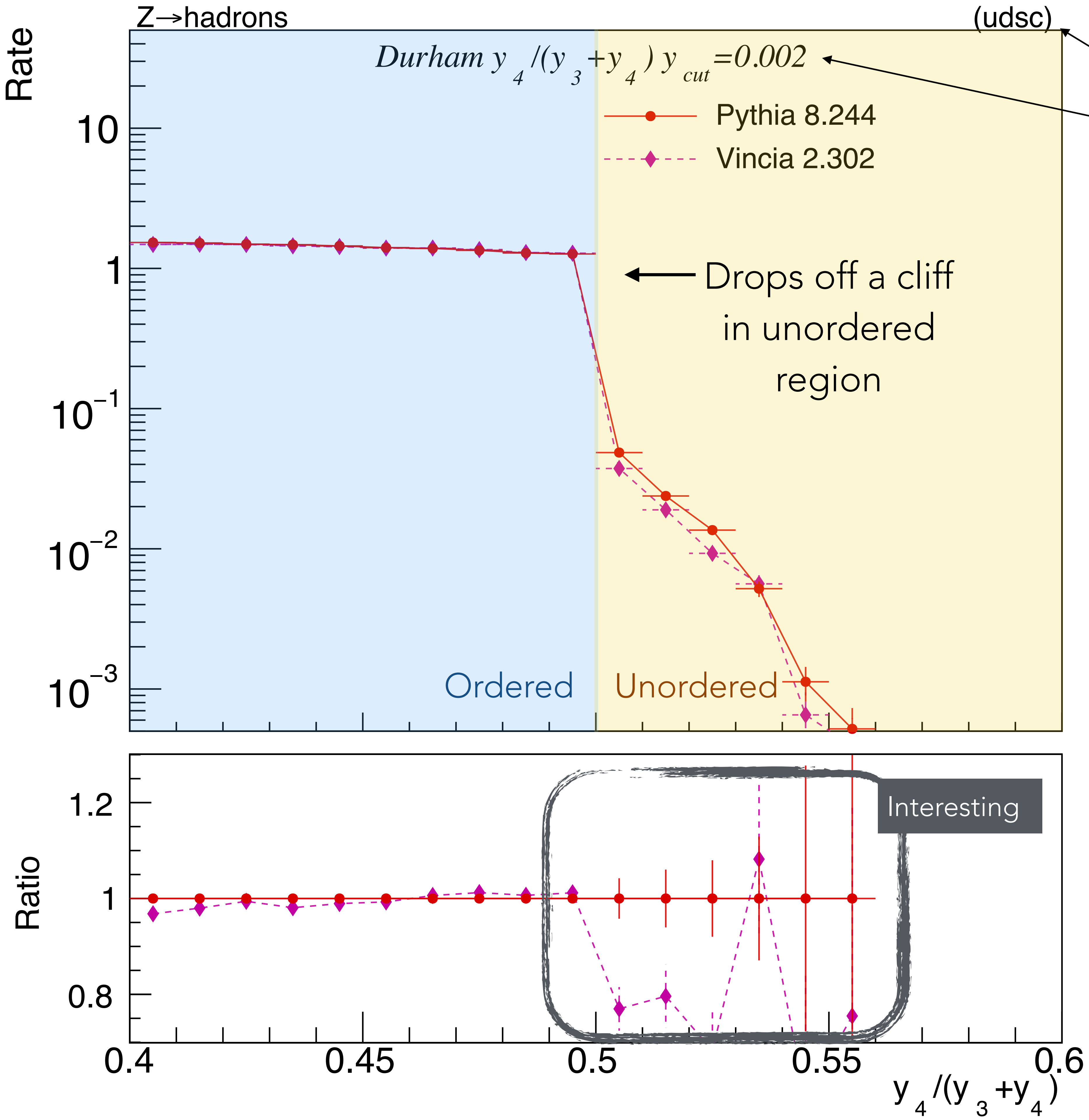
Rate normalised to total 4-jet rate

Off-the-shelf versions of Pythia and Vincia

Very similar results on individual jet rates.

Neither includes direct $2 \to 4$.

$4 \to 3 \to 2$



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

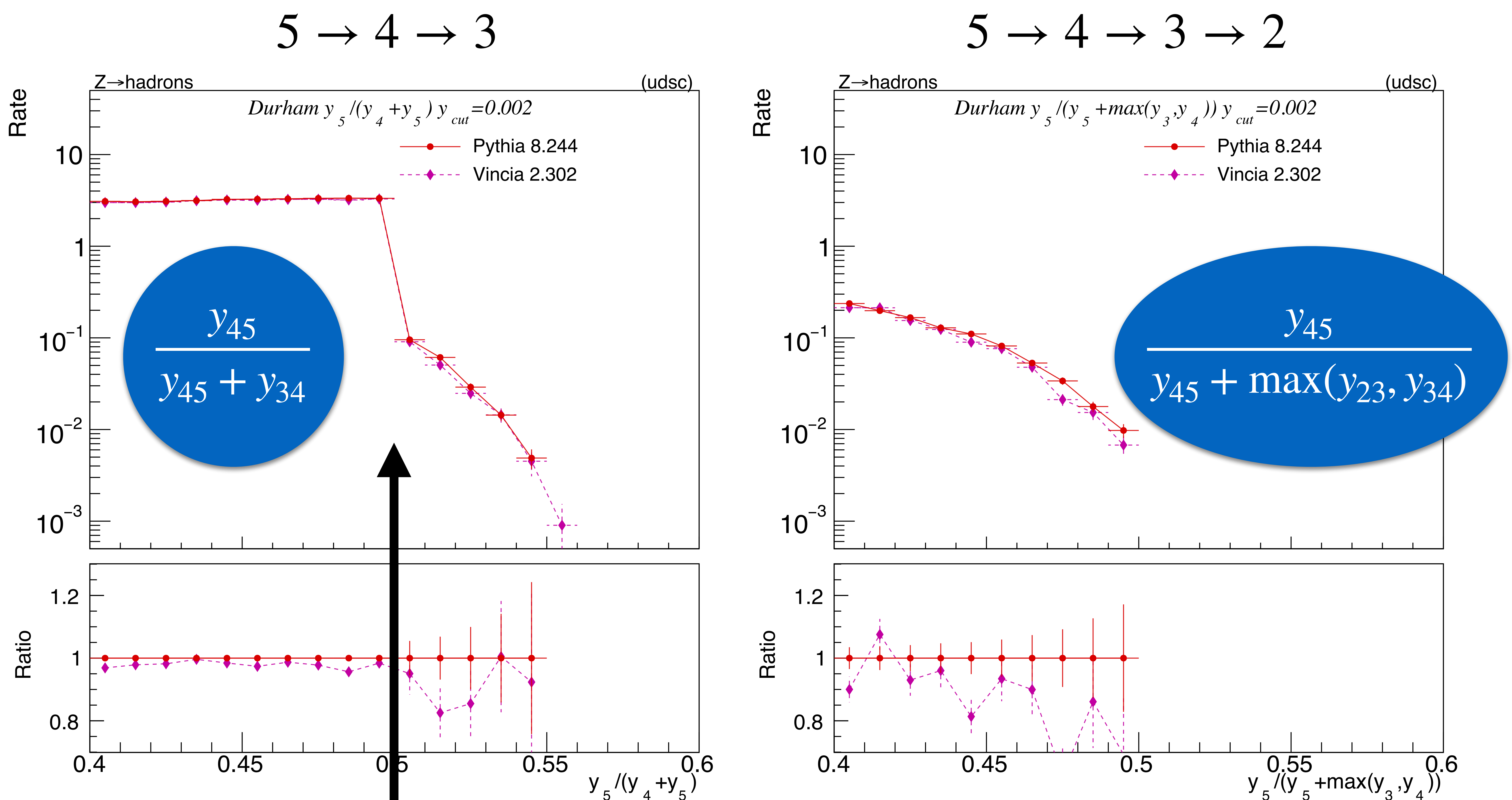
Excluded $Z \to b\bar{b}$ to avoid contamination from B decays

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



Same structure for $3 \to 5$ as for $2 \to 4$.
(➜ Combine to increase statistics?)

Limited power to probe $2 \to 5$
(in this way) but worth an attempt?

Triple-Energy Correlations

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.