

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
- **NⁿLO corrs., NⁿLL 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, ...),
 $e^+e^- \rightarrow Z, W^+W^-, t\bar{t} \rightarrow 4j, 6j, \dots$ (m_W, m_t extractions)

+ **Unsolved aspects of QCD itself (confinement)**

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



(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:

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

+ Can incorporate in global fit to SM: ($c_1=1$ =LO, c_2, c_3 and most recently c_4 also known Baikov et al, 2012)

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

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

Parametric uncertainty from BRs $\propto |V_{\text{CKM}}|^2$
esp $\delta|V_{cs}| \sim 1.6\%$ must be reduced by factor ~ 3

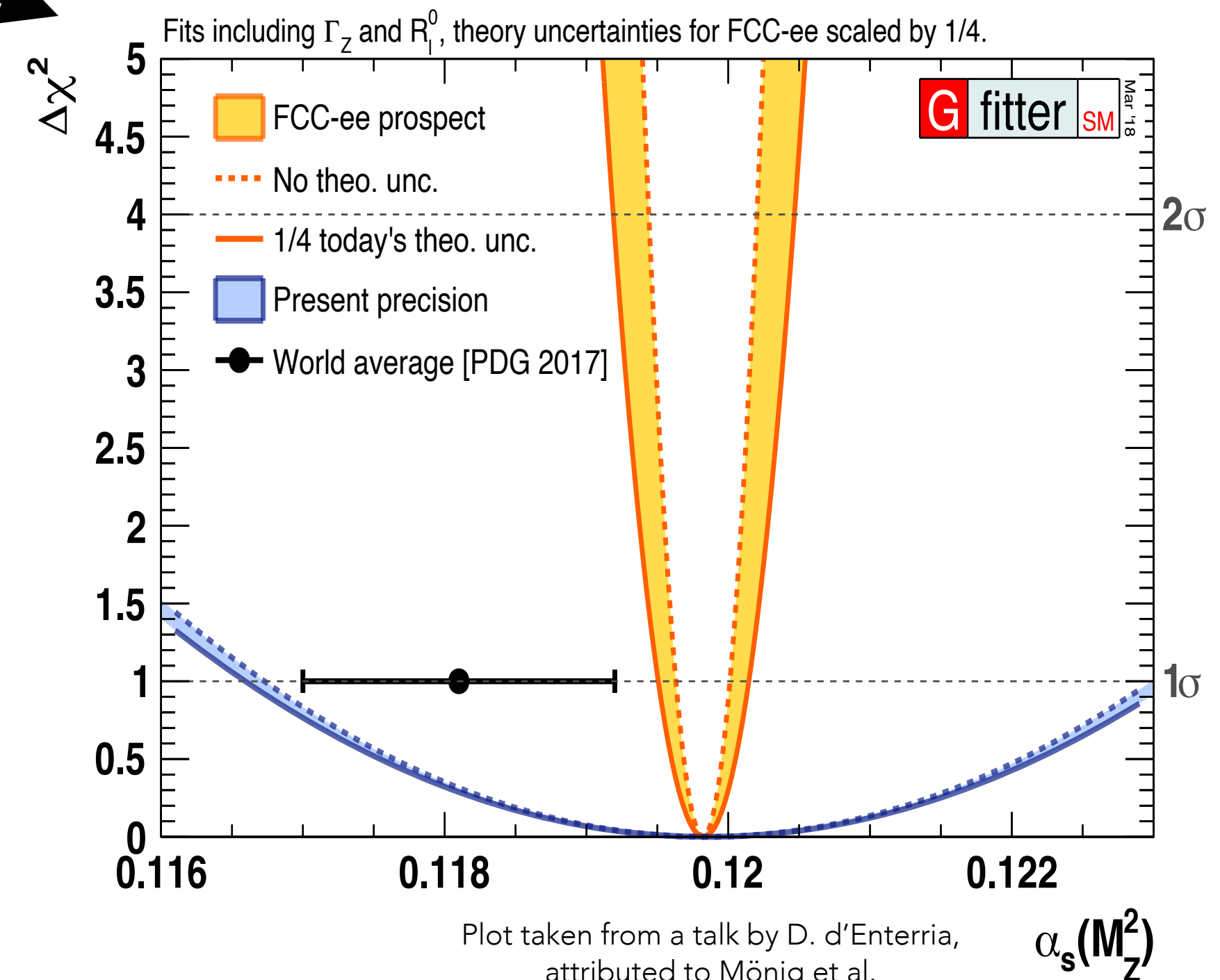
+ Hadronic τ decays

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

$$R_\tau = \frac{\Gamma(\tau \rightarrow \text{hadrons})}{\Gamma(\tau \rightarrow \nu_\tau e^- \bar{\nu}_e)}$$

also known to N³LO: **competitive(?)**

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



Perturbative Calculations for EE — MC Generators

(Slide adapted from A. Hoang)

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

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](https://arxiv.org/abs/1912.11050)), multi-parton coherence (cf eg arXiv:[1402.3186](https://arxiv.org/abs/1402.3186)), "direct" $n \rightarrow n + 2$ branchings (cf eg extra slides), subleading N_C , ...

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

Scaling studies with \sqrt{s} can play important role? \blacktriangleright Disentangle power corrections, α_s running, ...

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

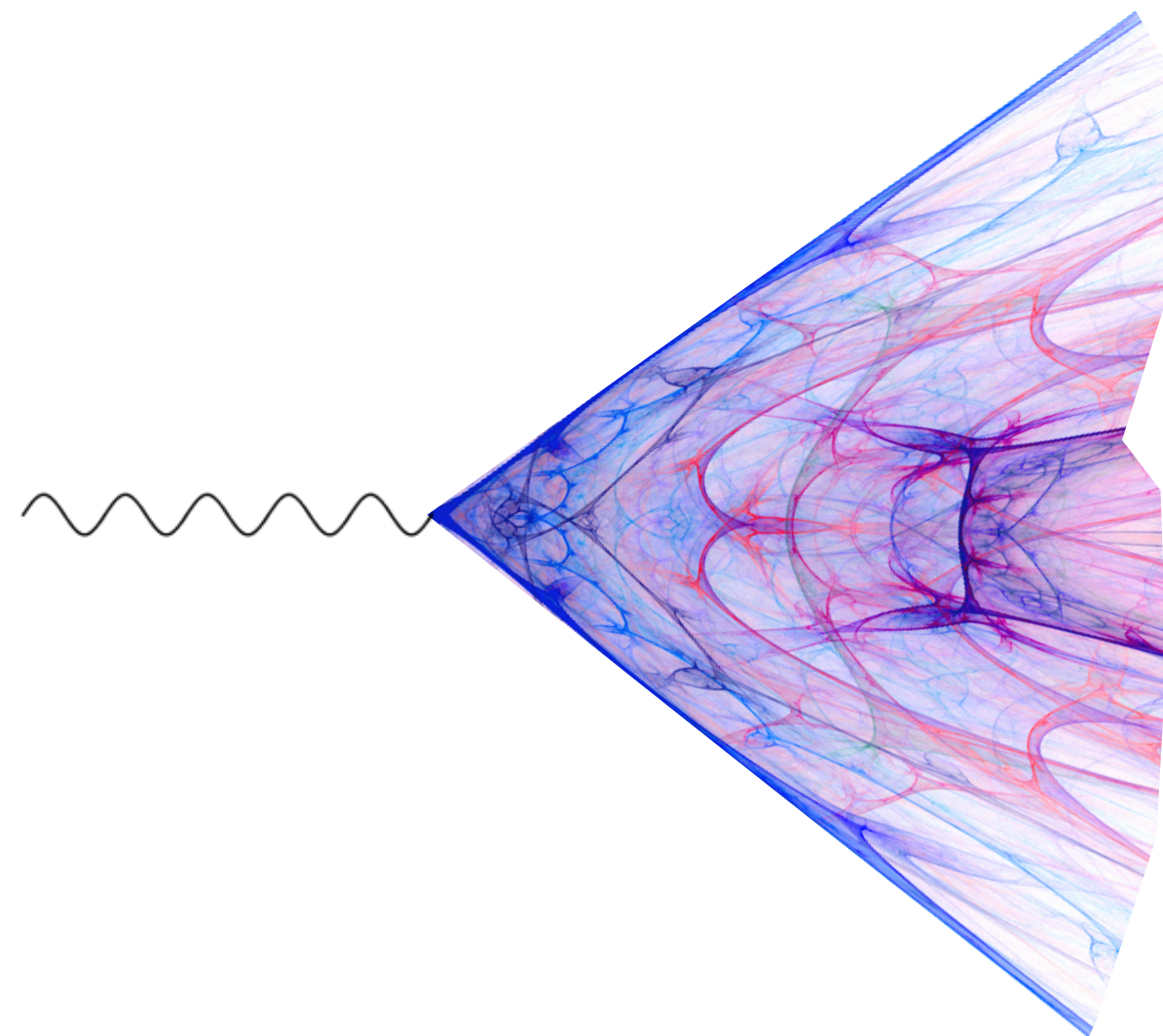
Requirements (?)

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

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



Hadronization & Non-Perturbative QCD Dynamics

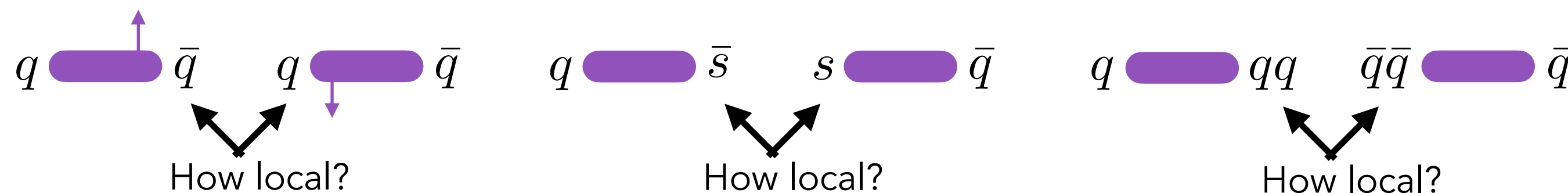


Confinement in QCD remains a fundamental and unsolved problem.

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 $\Lambda_{\text{QCD}} \sim \mathbf{100 \text{ MeV}}$ must be well resolved

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

How local is hadronisation?

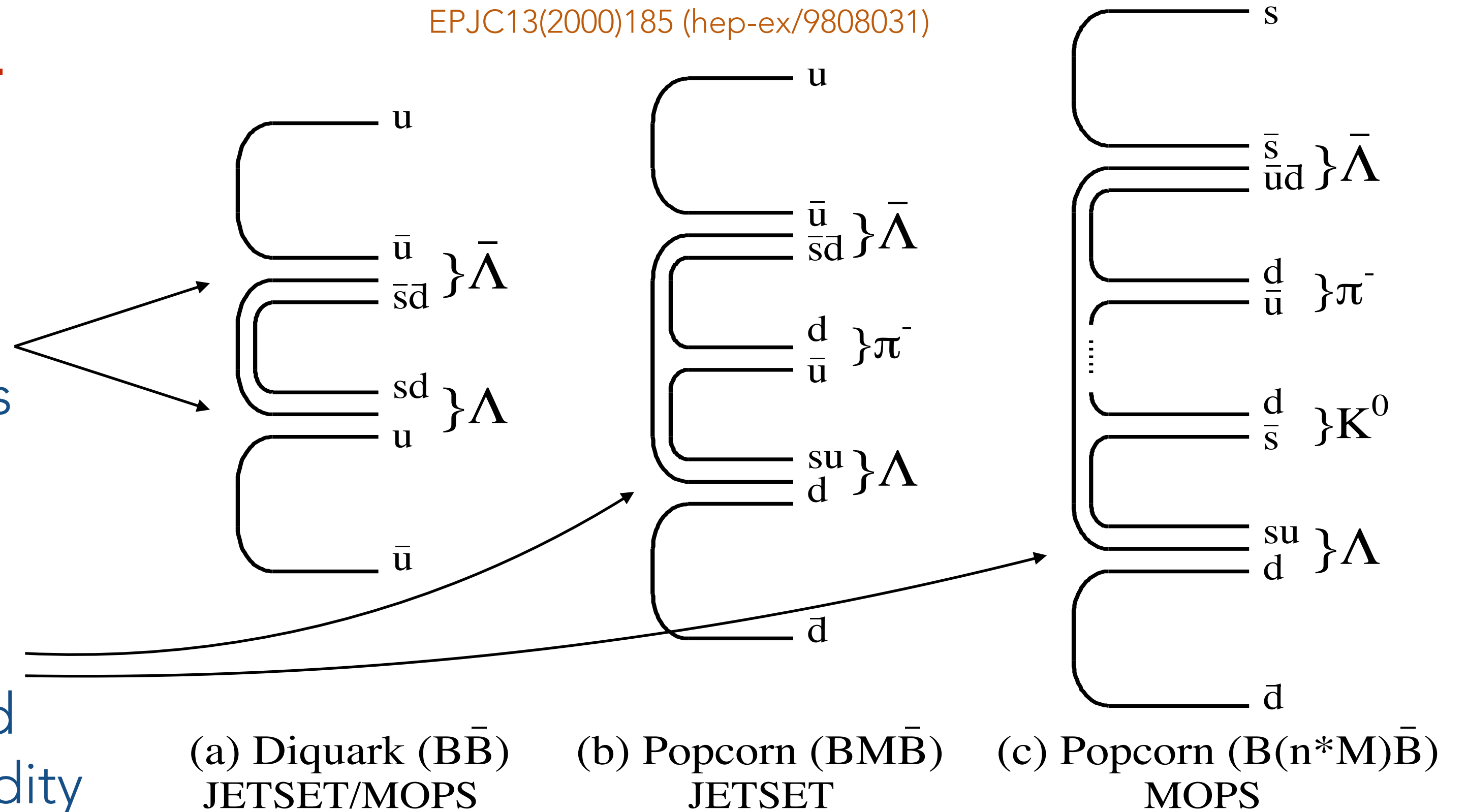
(see also FCC-ee QCD workshops & writeups)

Example: Baryon-Antibaryon correlations

Diquark model:
strong correlations over short rapidity distances

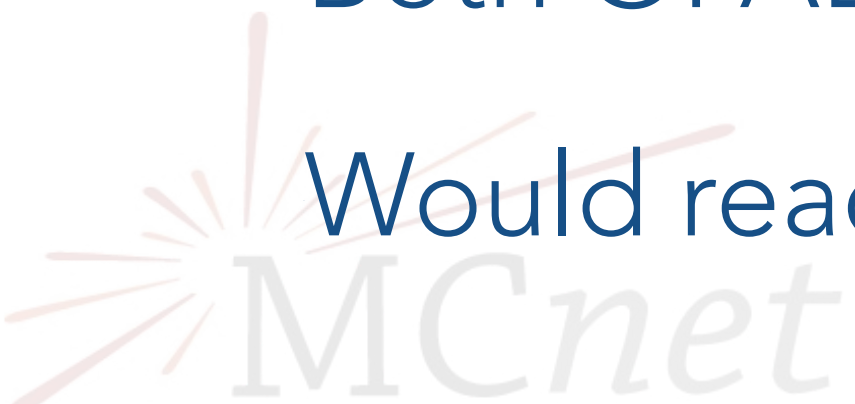
Popcorn/MOPS:
more complex and spread-out in rapidity

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



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

Would reach OPAL systematics at **100 \times LEP** (\rightarrow 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 \implies reference ee benchmarks

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

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, $\Lambda\Lambda$) **highly** non-local in string picture

LEP Puzzle: correlations \rightarrow **Fermi-Dirac radius** $\sim 0.1 \text{ fm} \ll r_p$ (both pp and $\Lambda\Lambda$; multiple expts)

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



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

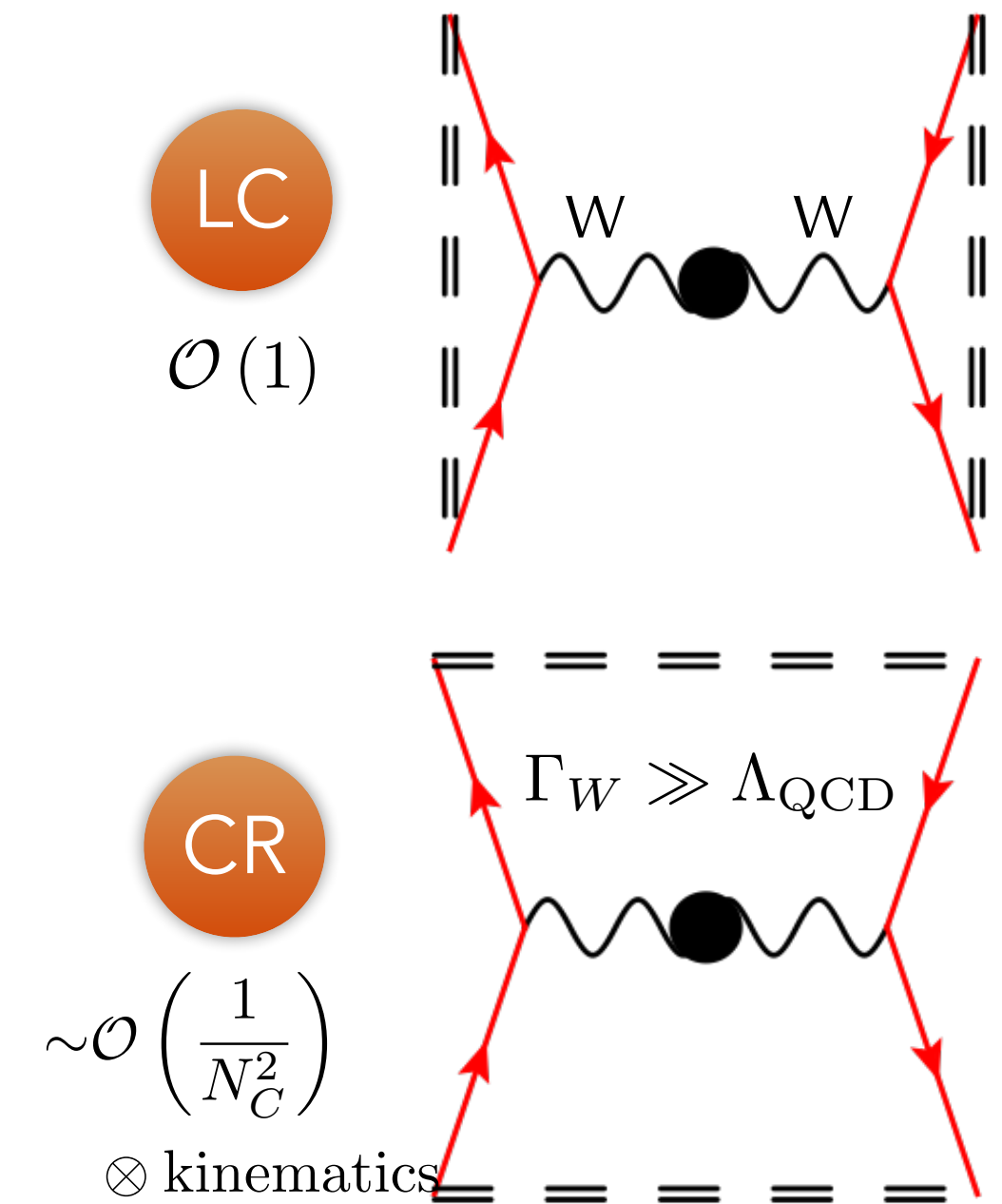
Fundamental to understanding & modeling hadronisation

Follow-up studies now underway at LHC.

High-stats ee ➤ other side of story

Also relevant in (hadronic) $ee \rightarrow tt$, and $Z \rightarrow 4$ jets

Little done for CEPC/FCC-ee (ILC?) so far ... (to my knowledge)
A lot of new models, scope to propose new observables, ...



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

Some overviews of recent models:
[arXiv:1507.02091](https://arxiv.org/abs/1507.02091) , [arXiv:1603.05298](https://arxiv.org/abs/1603.05298)

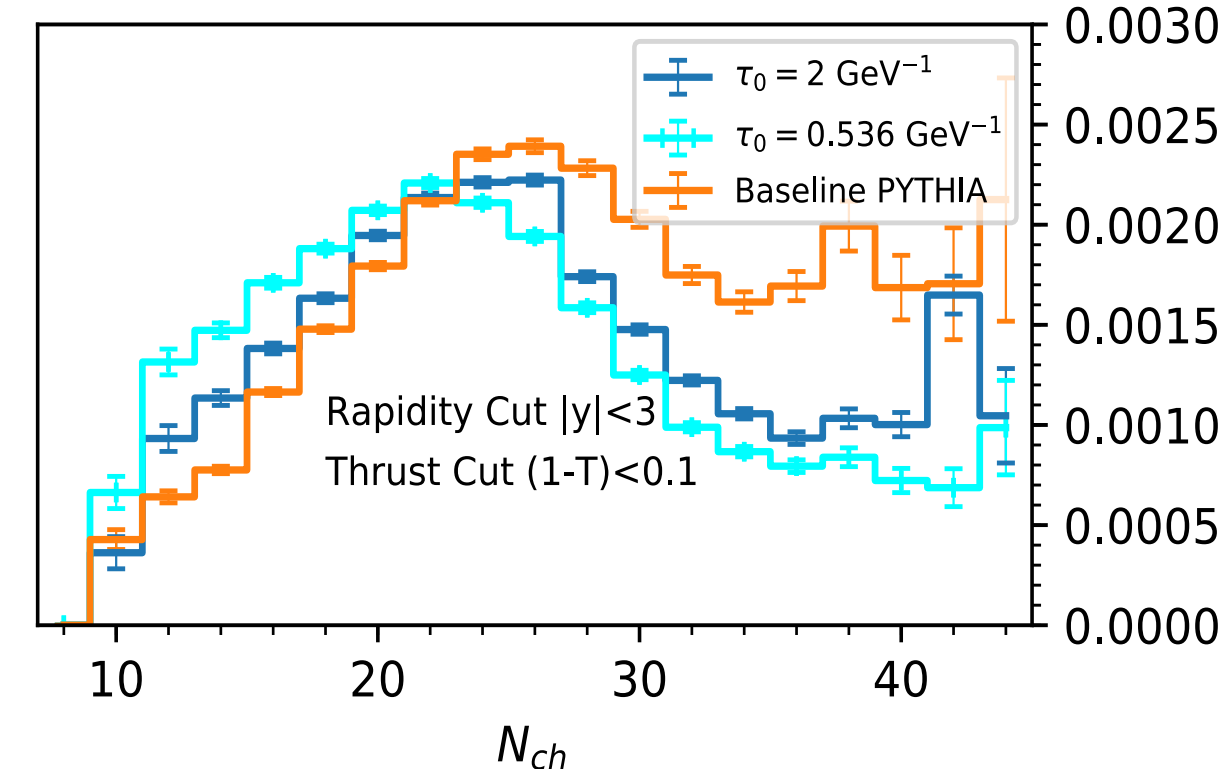
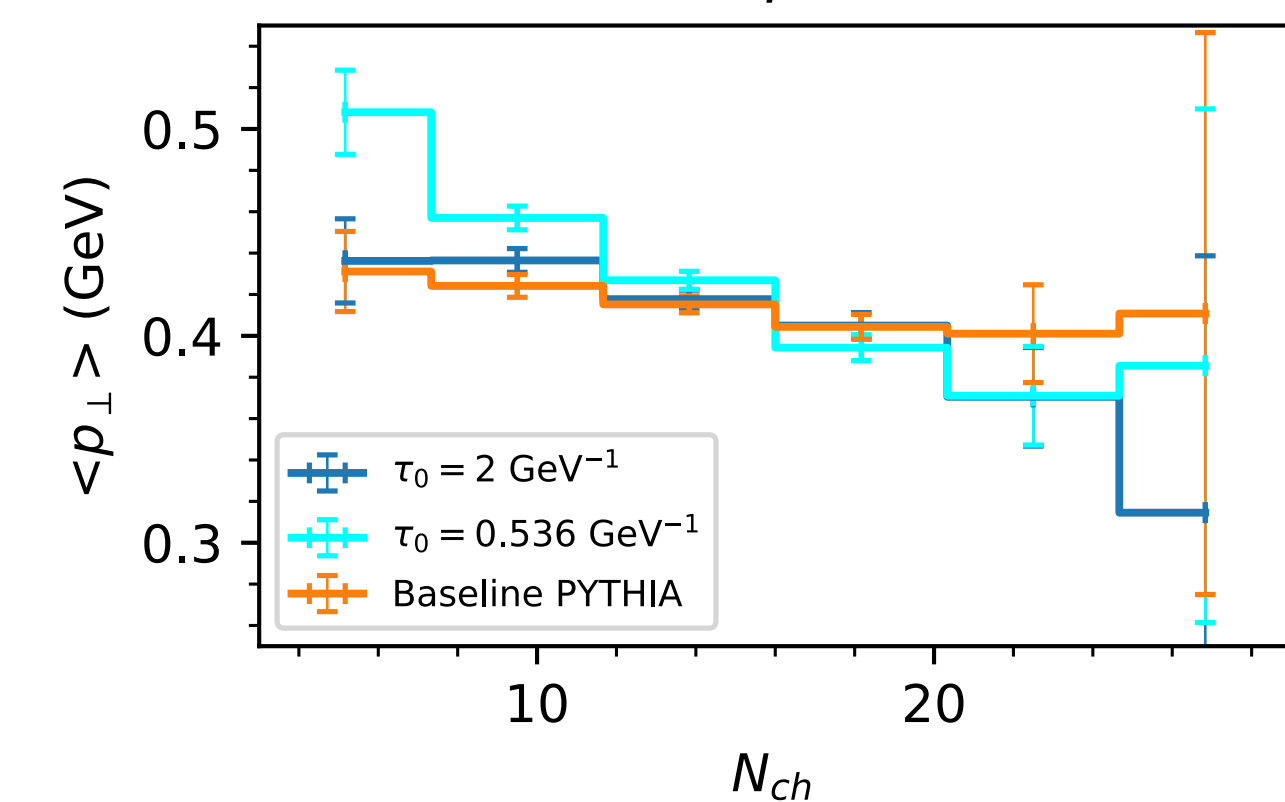
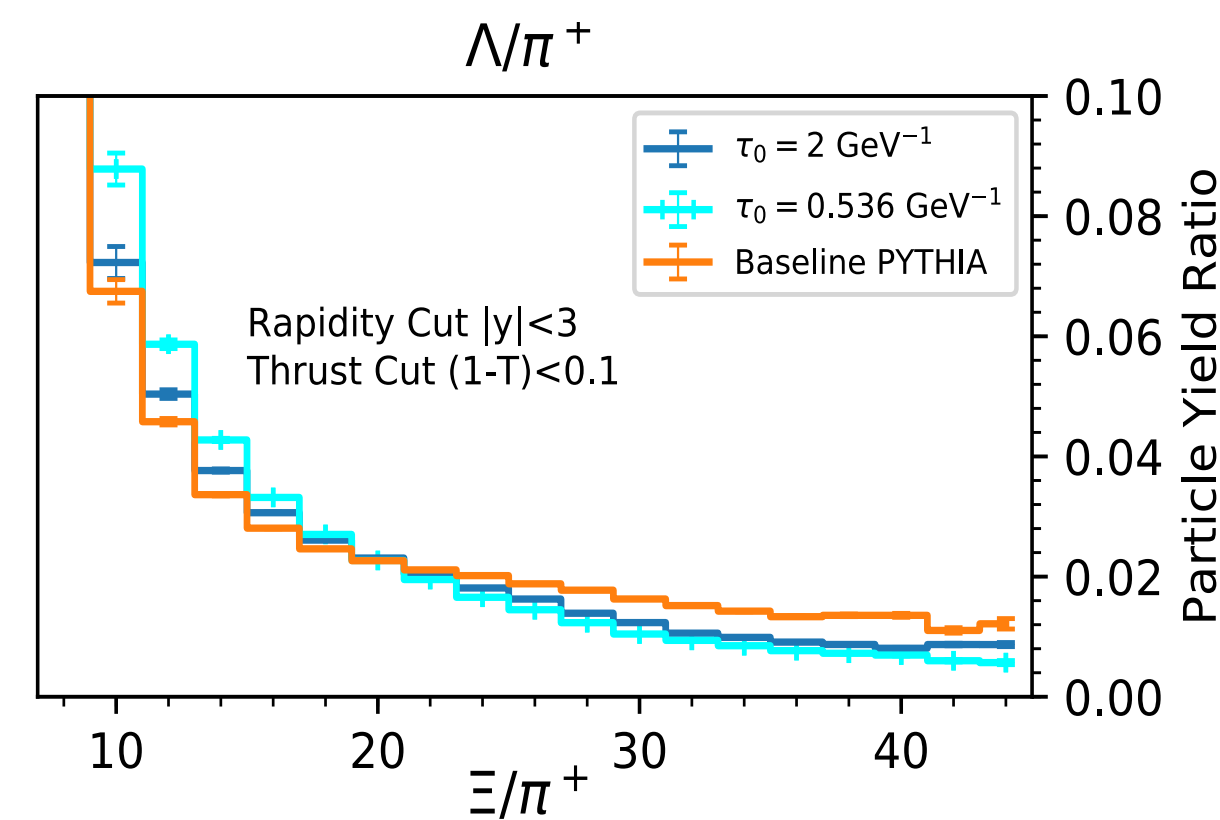
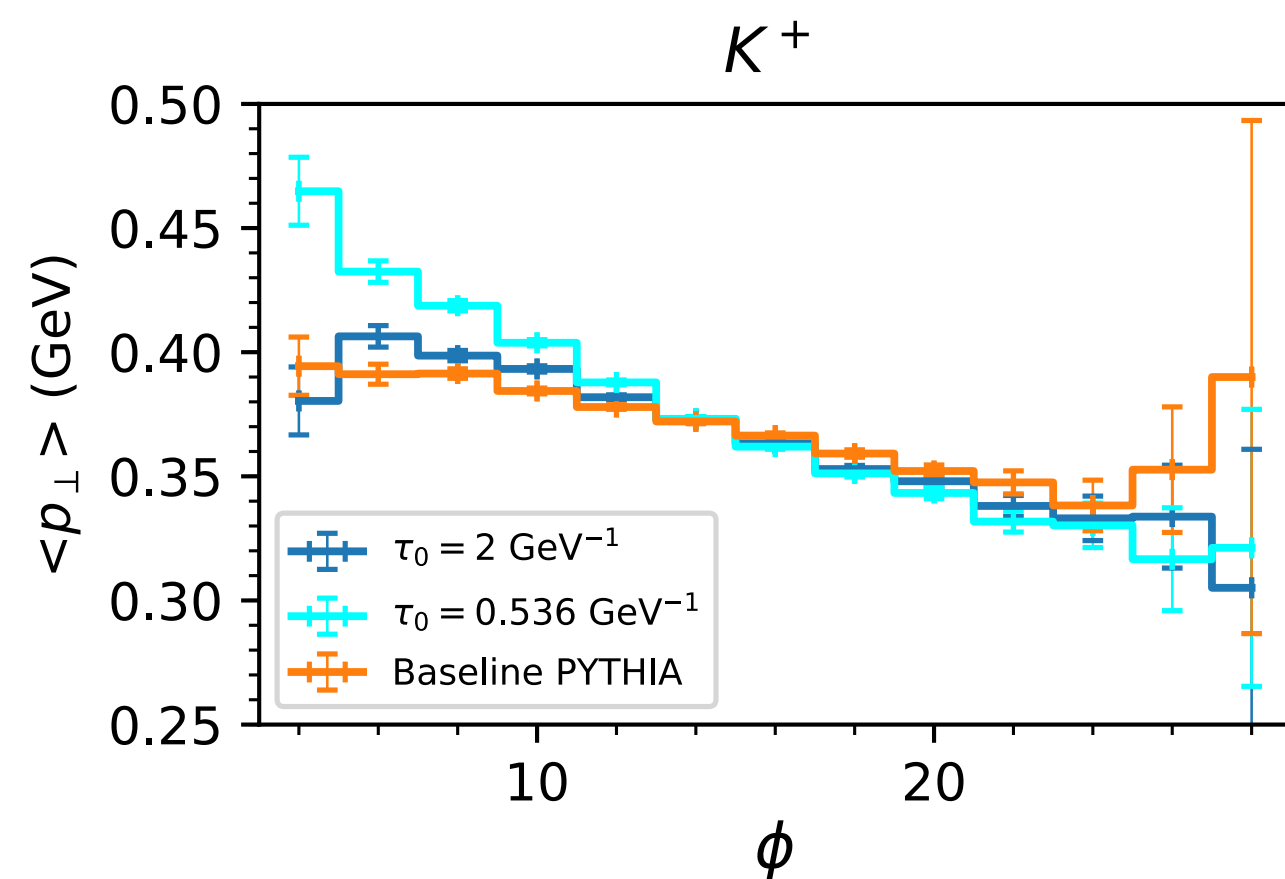
Example of further questions: String with time-dependent "Cooldown"

N. Hunt-Smith & PS arxiv:[2005.06219](https://arxiv.org/abs/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 \sim per-mille $\delta\alpha_s/\alpha_s$ accuracy

Stringent tests of new generation of **precision MC models** (higher-order shower kernels, NⁿLO merging, ...)

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

Interplays with EW & Higgs Physics Goals

Impact of (in)accurate MC predictions? \Leftrightarrow 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) \implies accurate starting point.

Reveal details of final states \Leftrightarrow disentangle strangeness, baryons, mass, spin ➔ **Needs: Good PID**

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

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



Extra Slides

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

Main Observable:

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

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

Kuhn: Conservative QCD scale variations $\rightarrow O(100 \text{ keV}) \rightarrow \delta\alpha_s \sim 3 \times 10^{-4}$

Comparable with the target for CEPC / FCC-ee

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

Can be calculated (after Higgs discovery) or use measured $\sin^2 \theta_{\text{eff}}$

Mönig (Gfitter) assuming $\Delta m_Z = 0.1 \text{ MeV}$, $\Delta \Gamma_Z = 0.05 \text{ MeV}$, $\Delta R_1 = 10^{-3}$

$\rightarrow \delta\alpha_s \sim 3 \times 10^{-4}$ ($\delta\alpha_s \sim 1.6 \times 10^{-4}$ without theory uncertainties)

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

Srebre & d'Enterria: huge improvement in BR(W_{had}) at FCC-ee (/CEPC?)

Combine with expected $\Delta \Gamma_W = 12 \text{ MeV}$ from LHC (high- m_T W) & factor-3 improvement in $|V_{cs}| \rightarrow$ 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% l_{pl} resolution (expected)

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

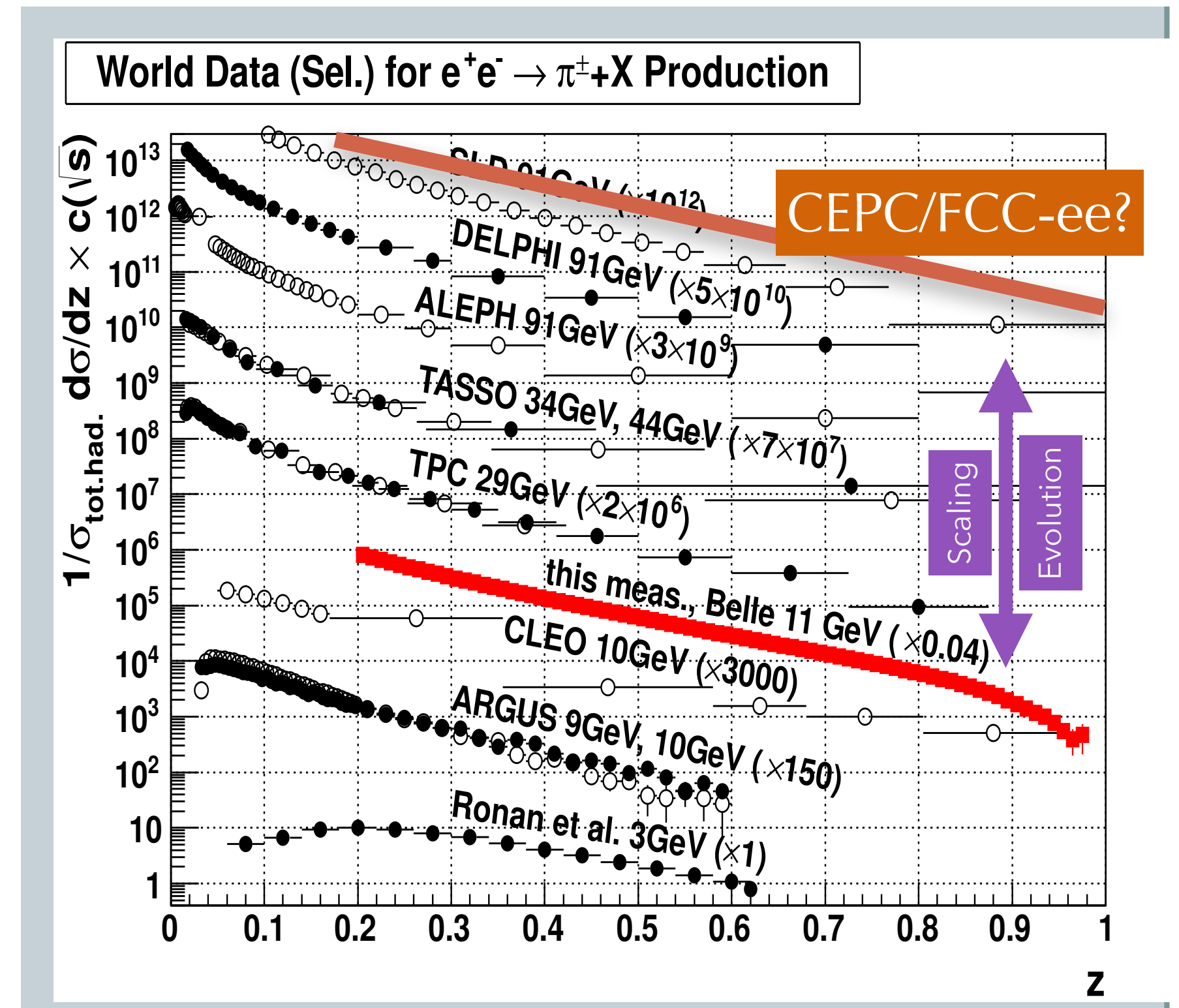
Will depend on Particle Identification capabilities.

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?



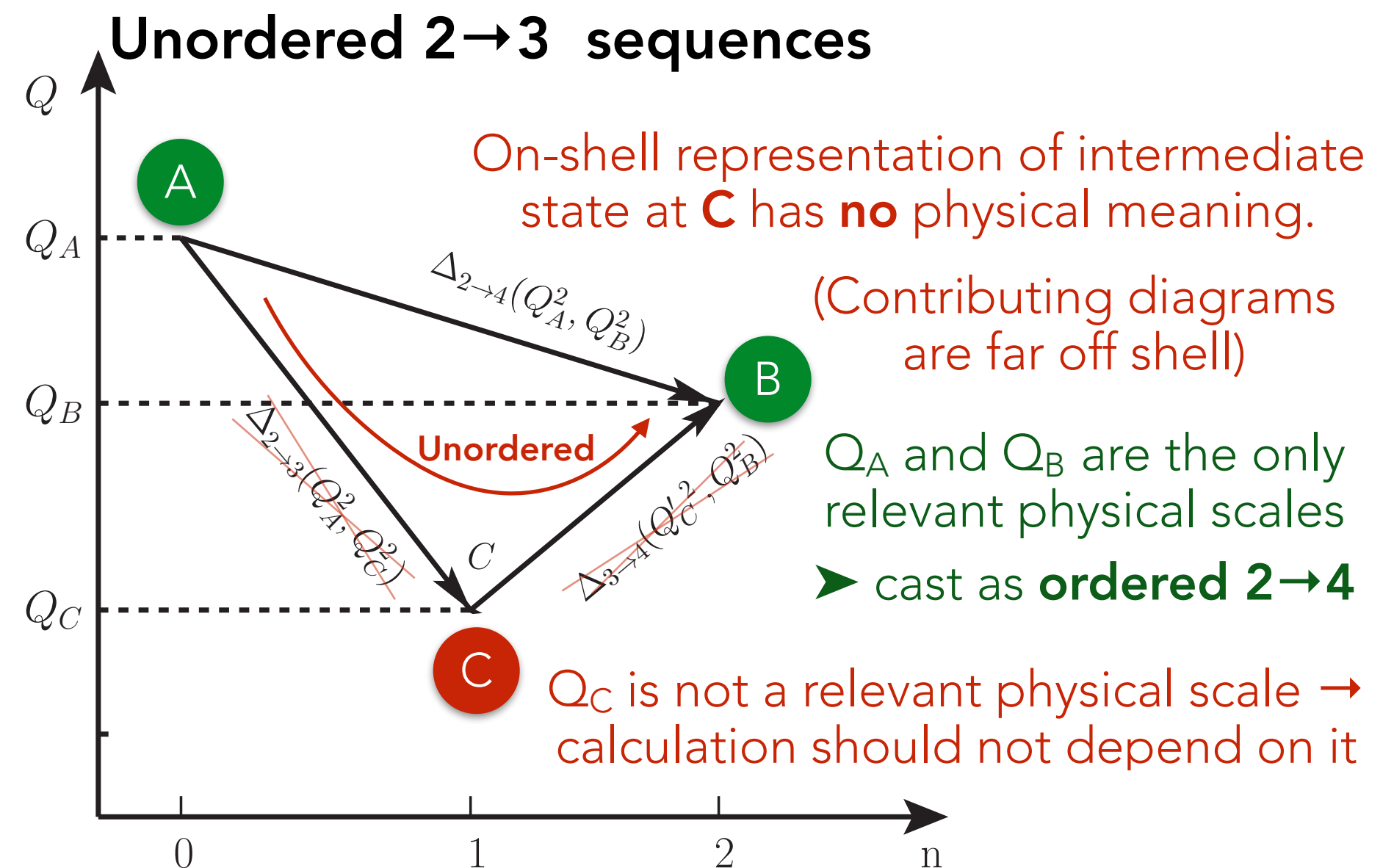
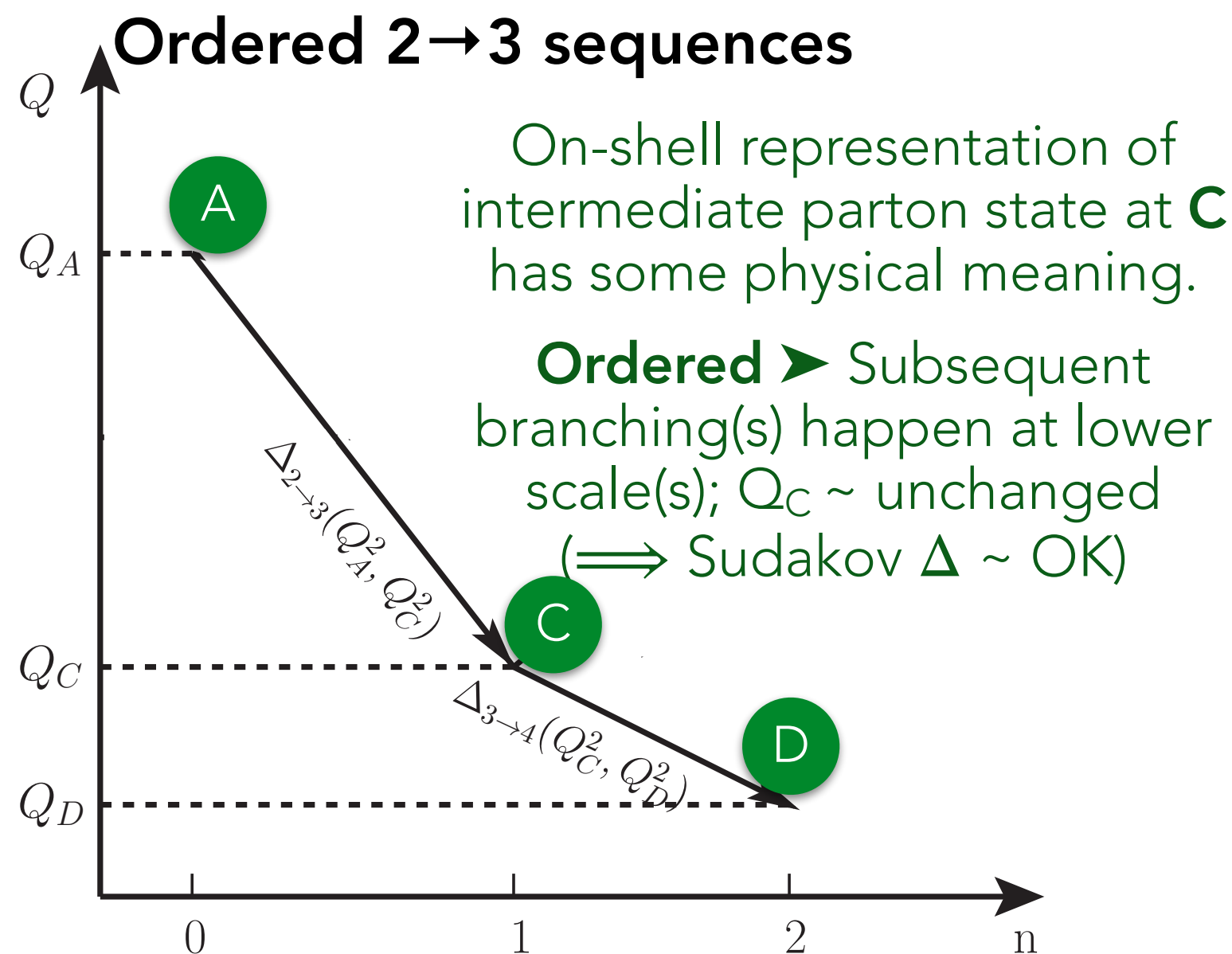
Li & PS, *PLB* 771 (2017) 59 (arXiv:1611.00013) + ongoing work

Elements

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

Ordered clustering sequences \Rightarrow iterated $2 \rightarrow 3$ (+ virtual corrections \sim differential K-factors)

Unordered clustering sequences \Rightarrow direct $2 \rightarrow 4$ (+ in principle higher $2 \rightarrow n$, ignored for now)



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

... but in **unordered region** let 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)

$$\frac{d\Delta(Q_0^2, Q^2)}{dQ^2} = \int d\Phi_{\text{ant}} \left[\delta(Q^2 - Q^2(\Phi_3)) a_3^0 \right. \\ \left. \times \left(1 + \frac{a_3^1}{a_3^0} + \sum_{s \in a, b} \int_{\text{ord}} d\Phi_{\text{ant}}^s R_{2 \rightarrow 4} s_3' \right) \Delta(Q_0^2, Q^2) \right. \\ \left. + \sum_{s \in a, b} \int_{\text{unord}} d\Phi_{\text{ant}}^s \delta(Q^2 - Q^2(\Phi_4)) R_{2 \rightarrow 4} s_3 s_3' \Delta(Q_0^2, Q^2) \right]$$

(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:

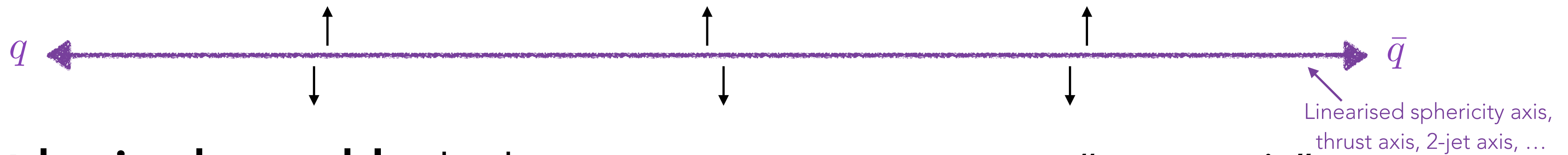
$$\frac{d}{dQ^2} \Delta(Q_0^2, Q^2) = \int \frac{d\Phi_3}{d\Phi_2} \delta(Q^2 - Q^2(\Phi_3)) (a_3^0 + a_3^1) \Delta(Q_0^2, Q^2) \\ + \int \frac{d\Phi_4}{d\Phi_2} \delta(Q^2 - Q^2(\Phi_4)) a_4^0 \Delta(Q_0^2, Q^2), \quad (3)$$

poles → poles

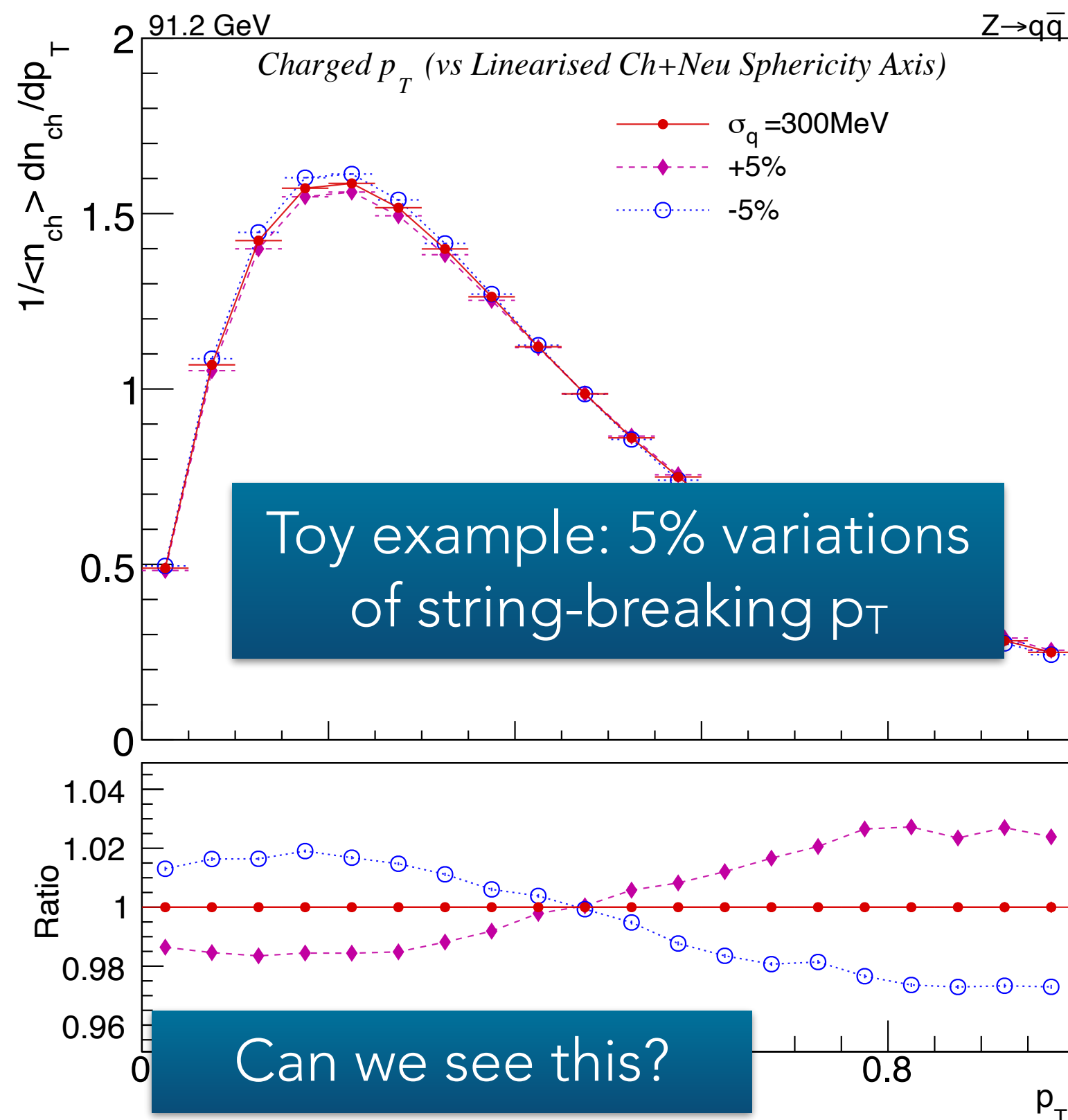
But on this form, the pole
cancellation happens
between the two integrals

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

Transverse Fragmentation \Leftrightarrow Momentum Resolution

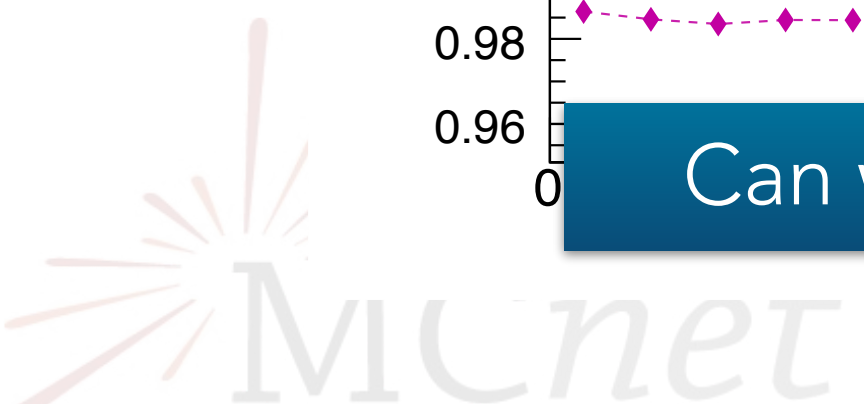
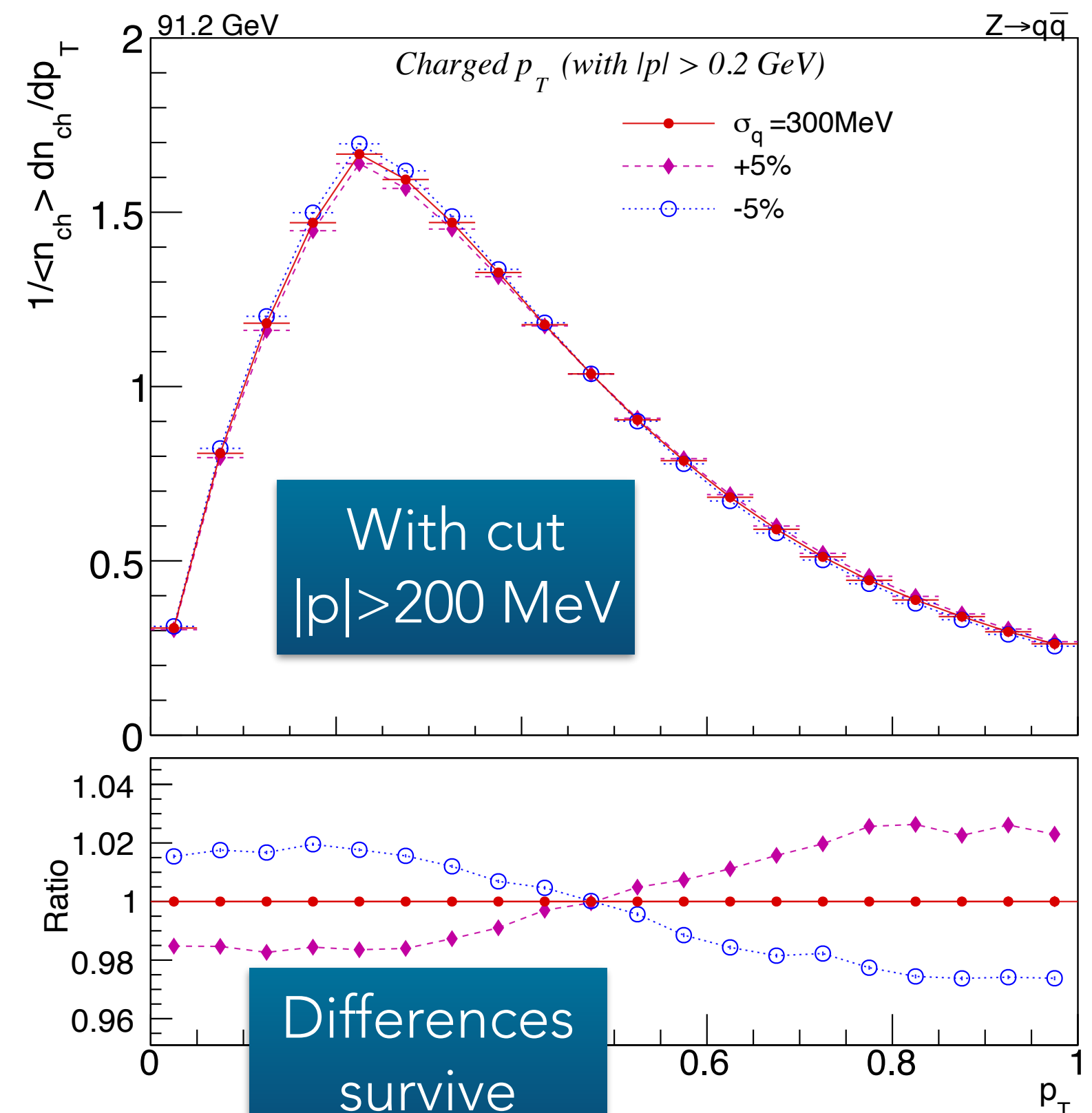


Most basic observable: hadron p_T spectra, transverse to "event axis"



Toy Example

Perturbatively dominated power-law tail



Effects of order $\Lambda_{QCD} \sim 100 \text{ MeV} \leftrightarrow$ Coverage for $|p| < \Lambda_{QCD}$?

p_T kicks from hadronisation

Pythia \sim Gaussian $\sim 300 \text{ MeV}$ (+ ρ decays)

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

To check this, look for pions with $|p| < 300 \text{ MeV}$

► 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?

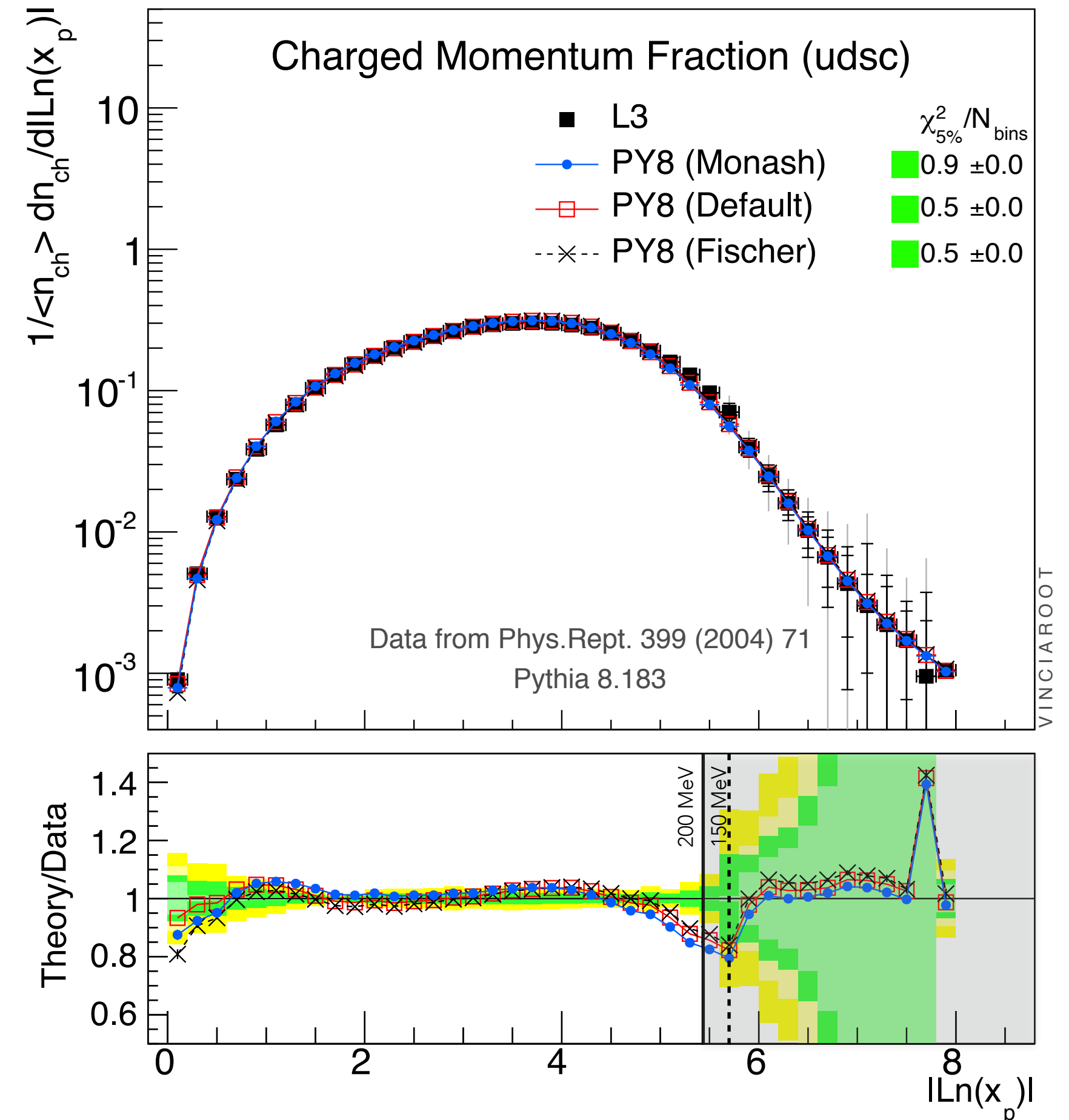
Mismodelled resonance decays?

Cut at $|p| = 200 \text{ MeV}$ makes this tough to examine clearly

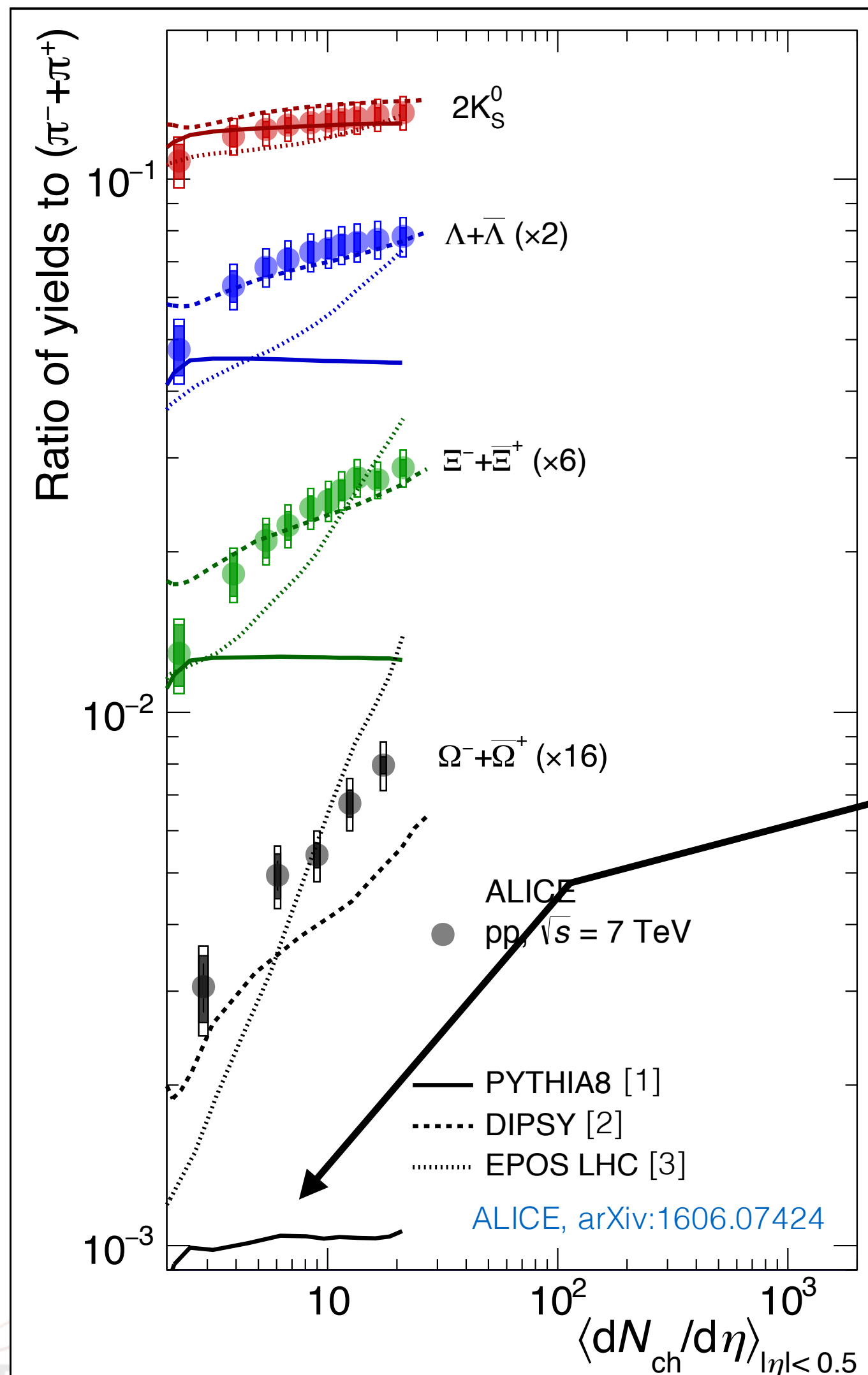
3 hits down to $\sim 50 \text{ MeV}$?

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 $\pm 20\%$)

$e^+e^- \rightarrow WW$: 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:

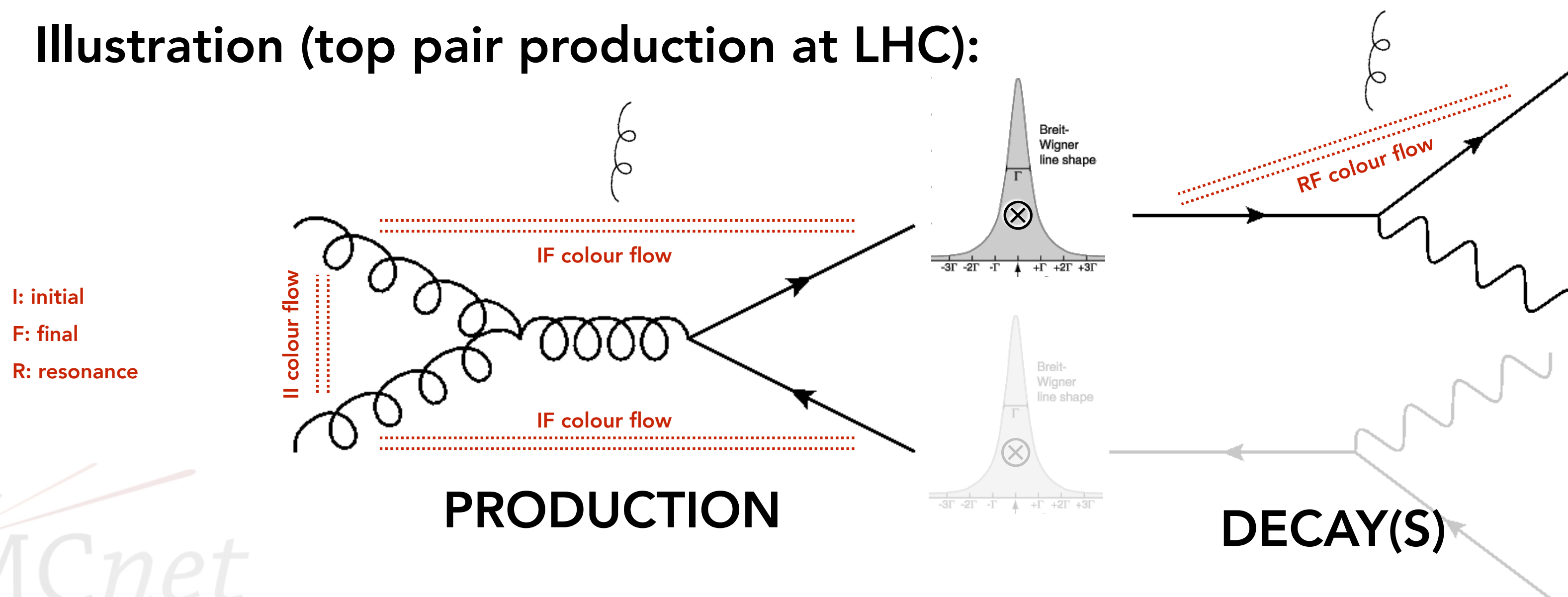
Independent Breit-Wigners for each of the W bosons, with running widths.

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):



Interleaved Resonance Decays

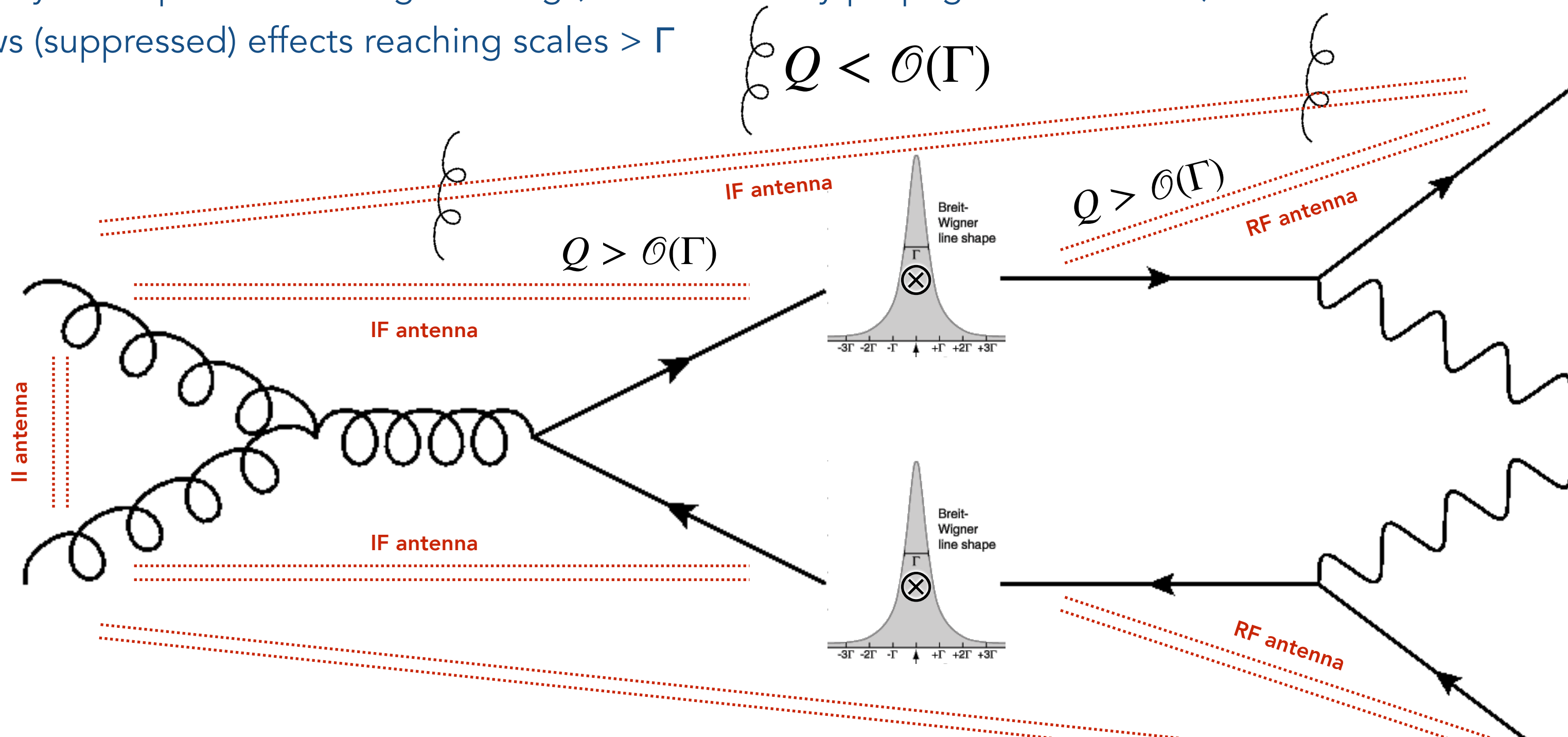
Decays of unstable resonances introduced in shower evolution at an average scale $Q \sim \Gamma$

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 $> \Gamma$ $\left\{ Q < \mathcal{O}(\Gamma) \right\}$



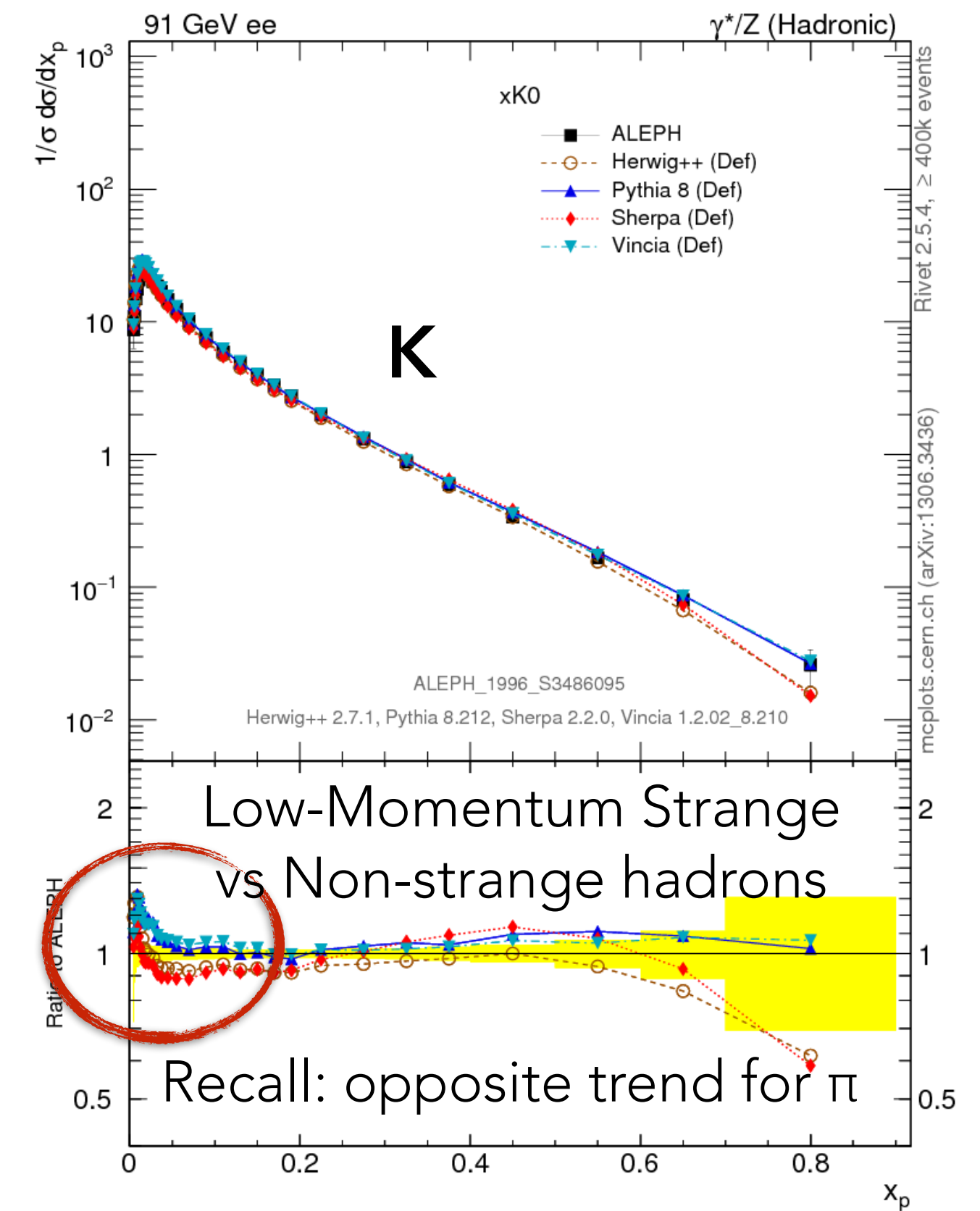
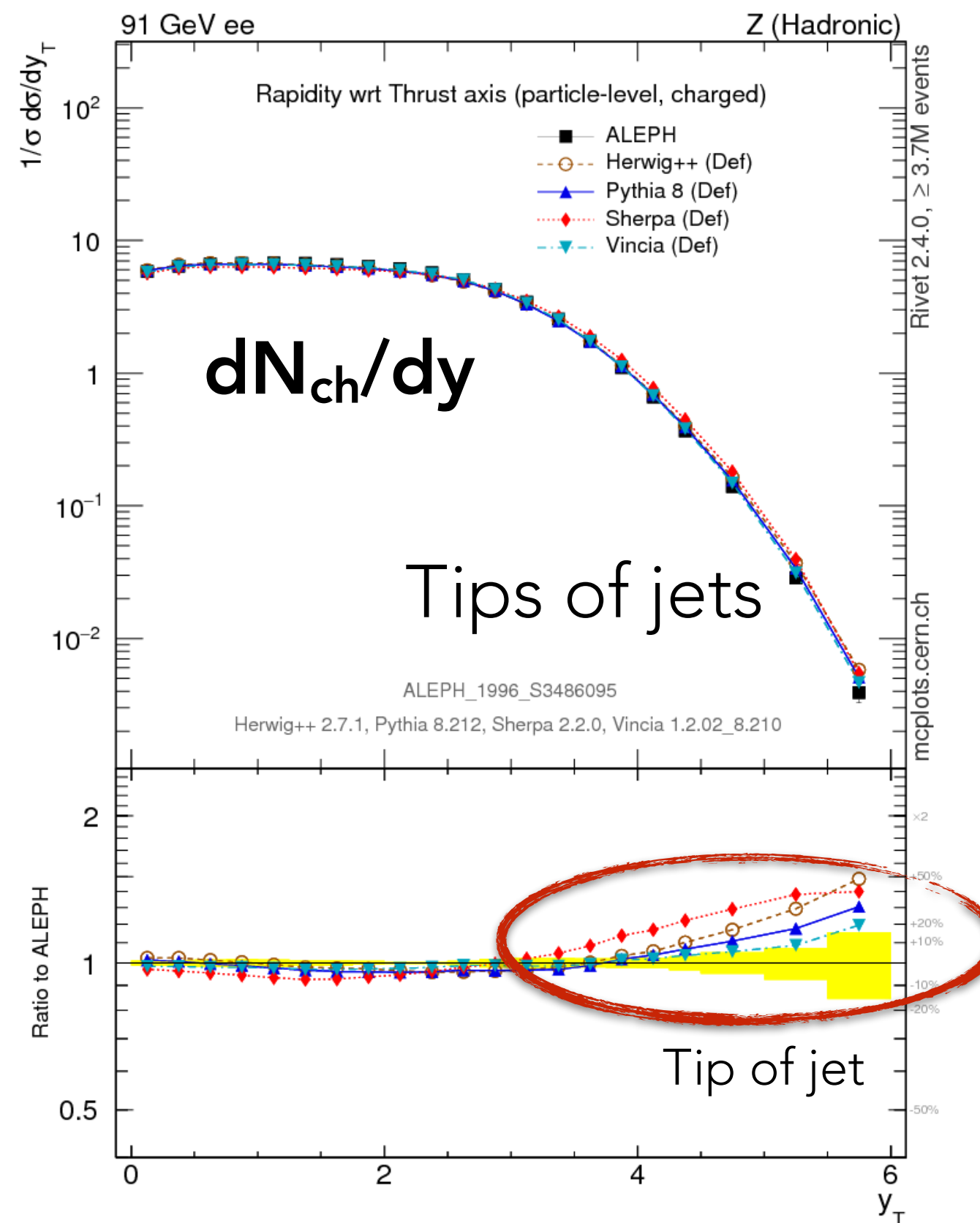
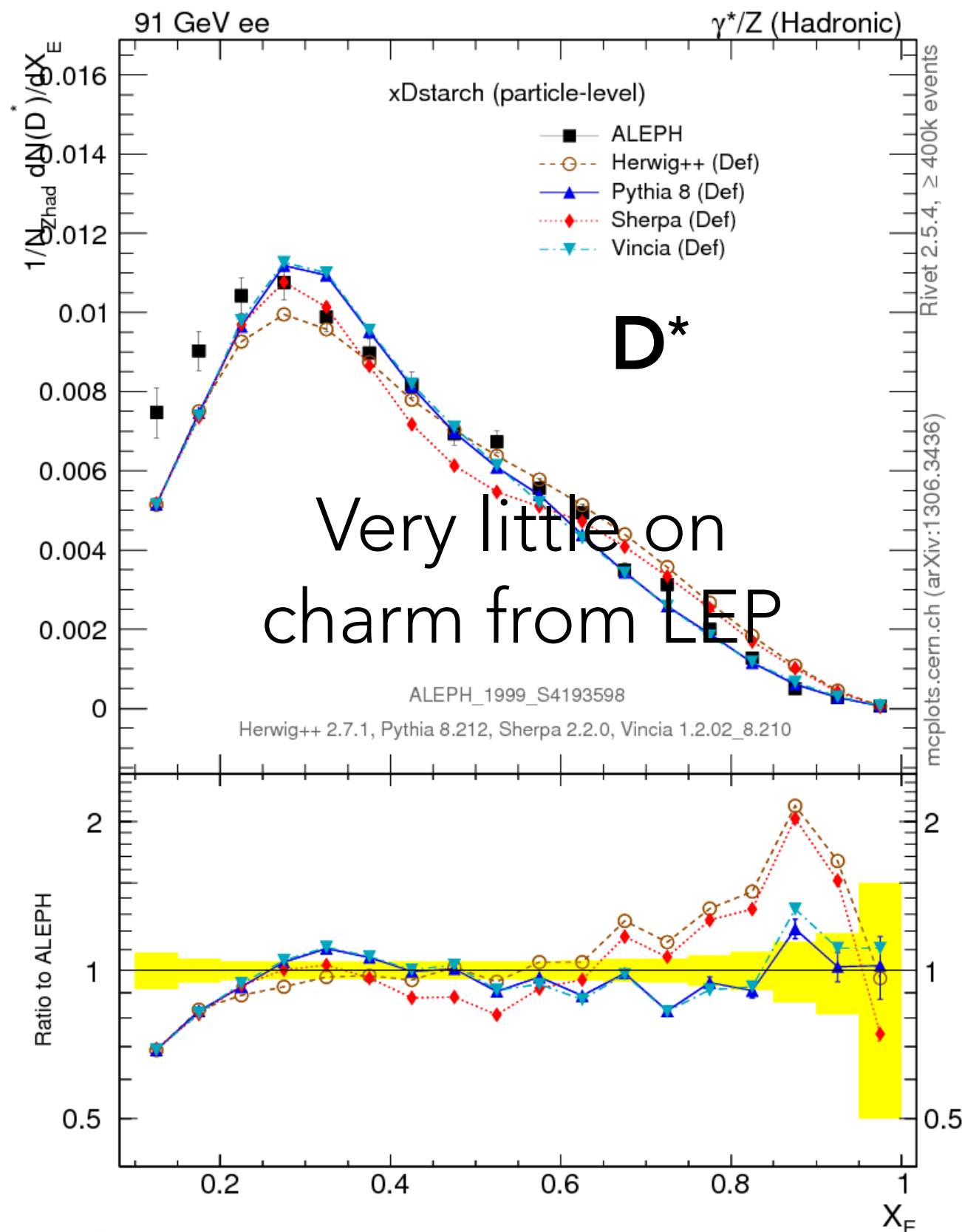
Automatically provides a natural treatment of finite- Γ effects.

Expect in next Pythia release (8.304)

Plenty of other interesting detailed features

(plots from mcplots.cern.ch)

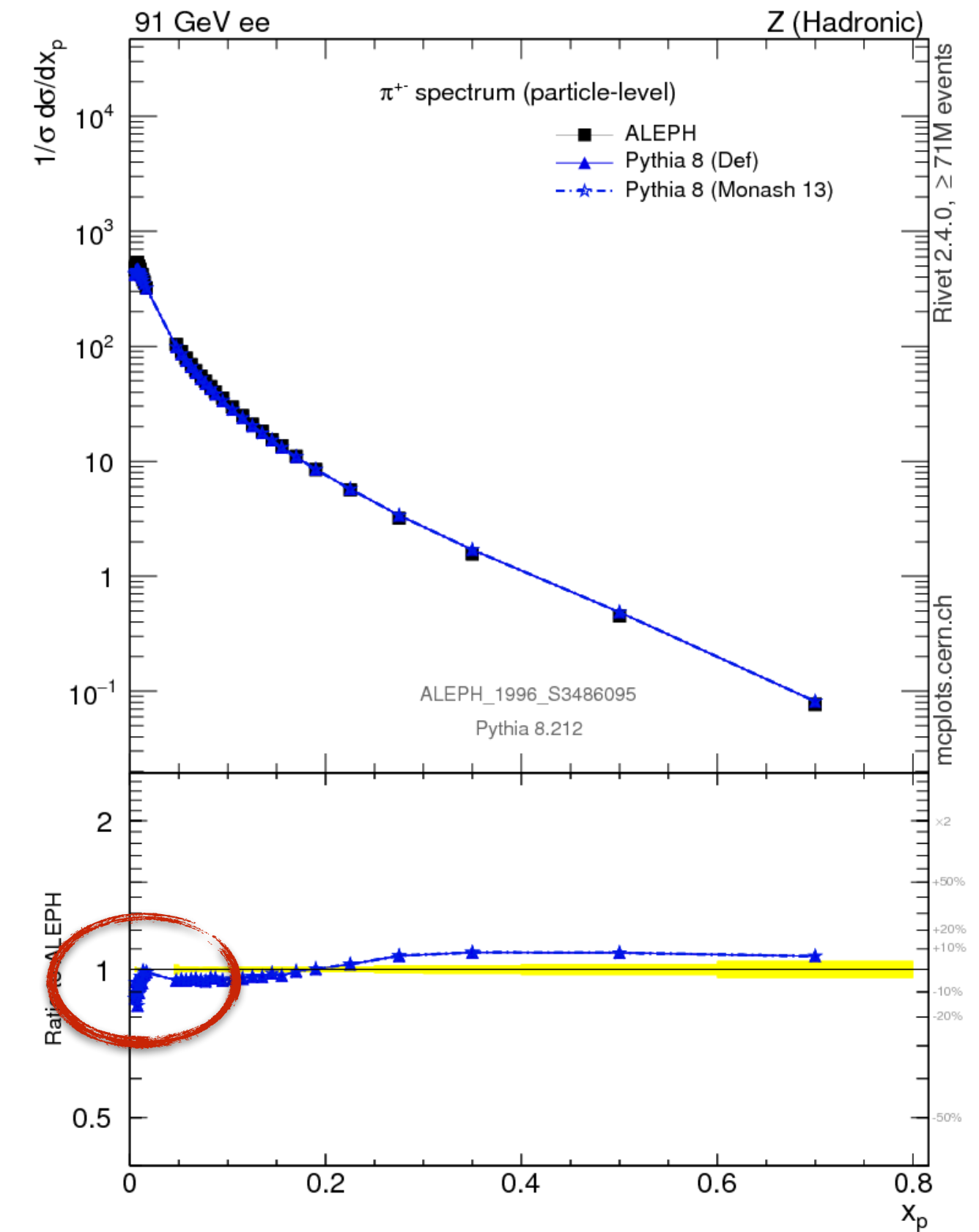
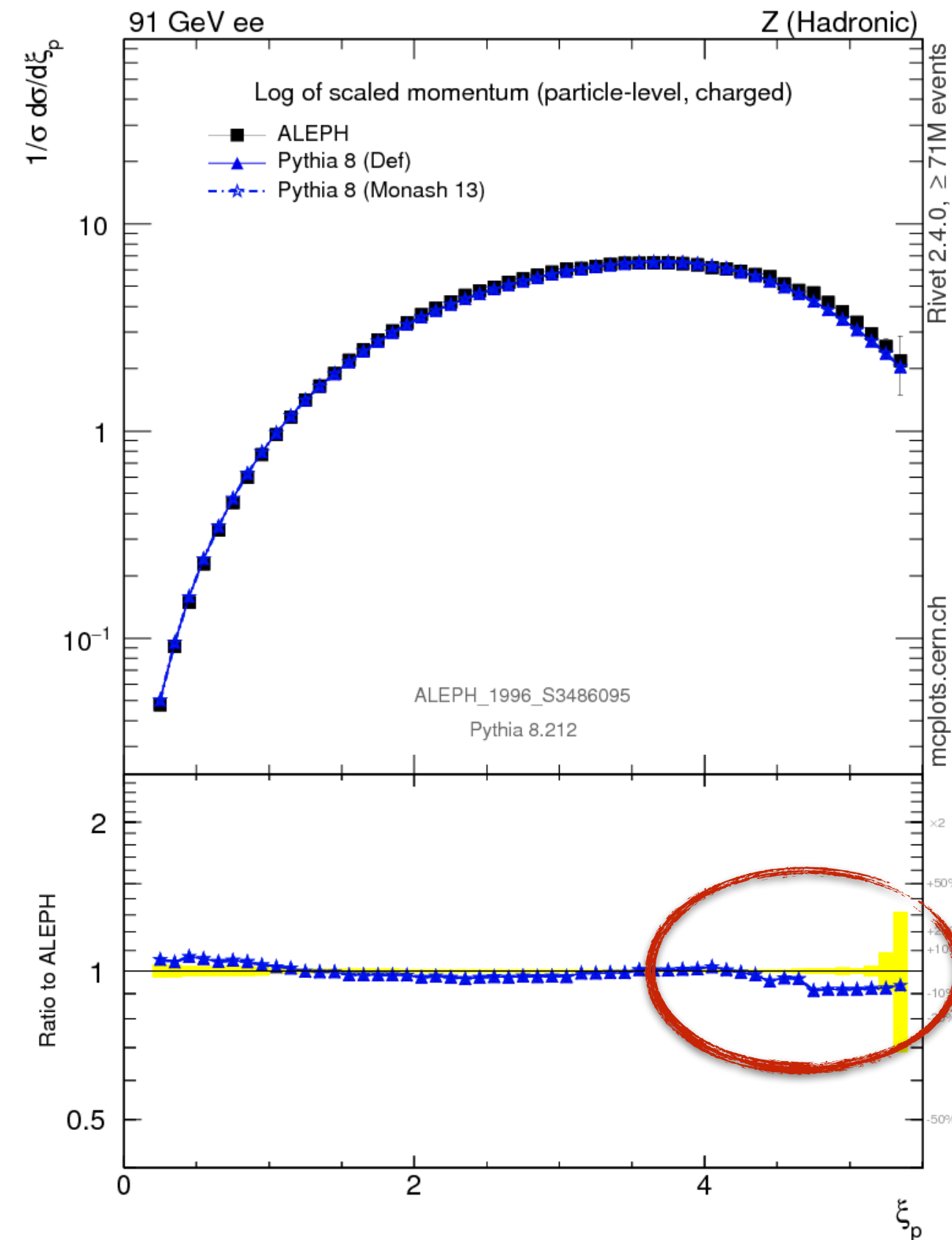
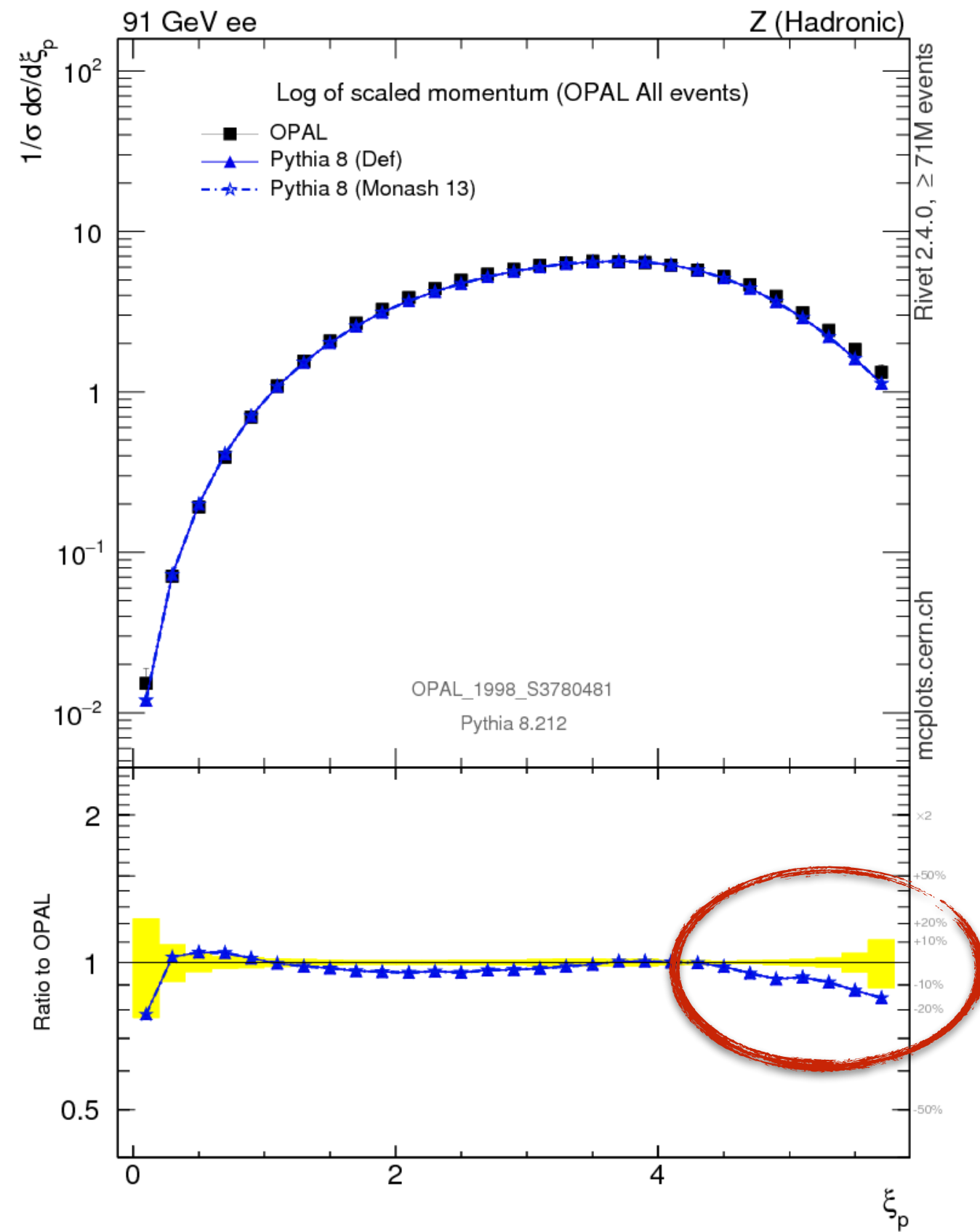
Just a few examples



Capabilities for hadrons from decays ($\pi^0, \eta, \eta', \rho, \omega, K^*, \phi, \Delta, \Lambda, \Sigma, \Sigma^*, \Xi, \Xi^*, \Omega, \dots$)

+ **heavy-flavour** hadrons

Very challenging; conflicting measurements from LEP



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 ($Z \rightarrow bbg$)

(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 \rightarrow 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 $X \rightarrow qq$ vs $X \rightarrow gg$



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
Dominated for $r \gtrsim 0.2 \text{ fm}$

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 $> \kappa$** favours “early” production of quark-antiquark pairs?

+ Pre-steady-state thermal effects from a (rapidly) **expanding string?** Berges, Floerchinger, and Veruogopalan JHEP 04(2018)145)

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

Handles to split degeneracies

$H \rightarrow gg$ vs $Z \rightarrow qq$

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

Requires good $H \rightarrow gg$ vs $H \rightarrow bb$;

Driven by Higgs studies requirements?

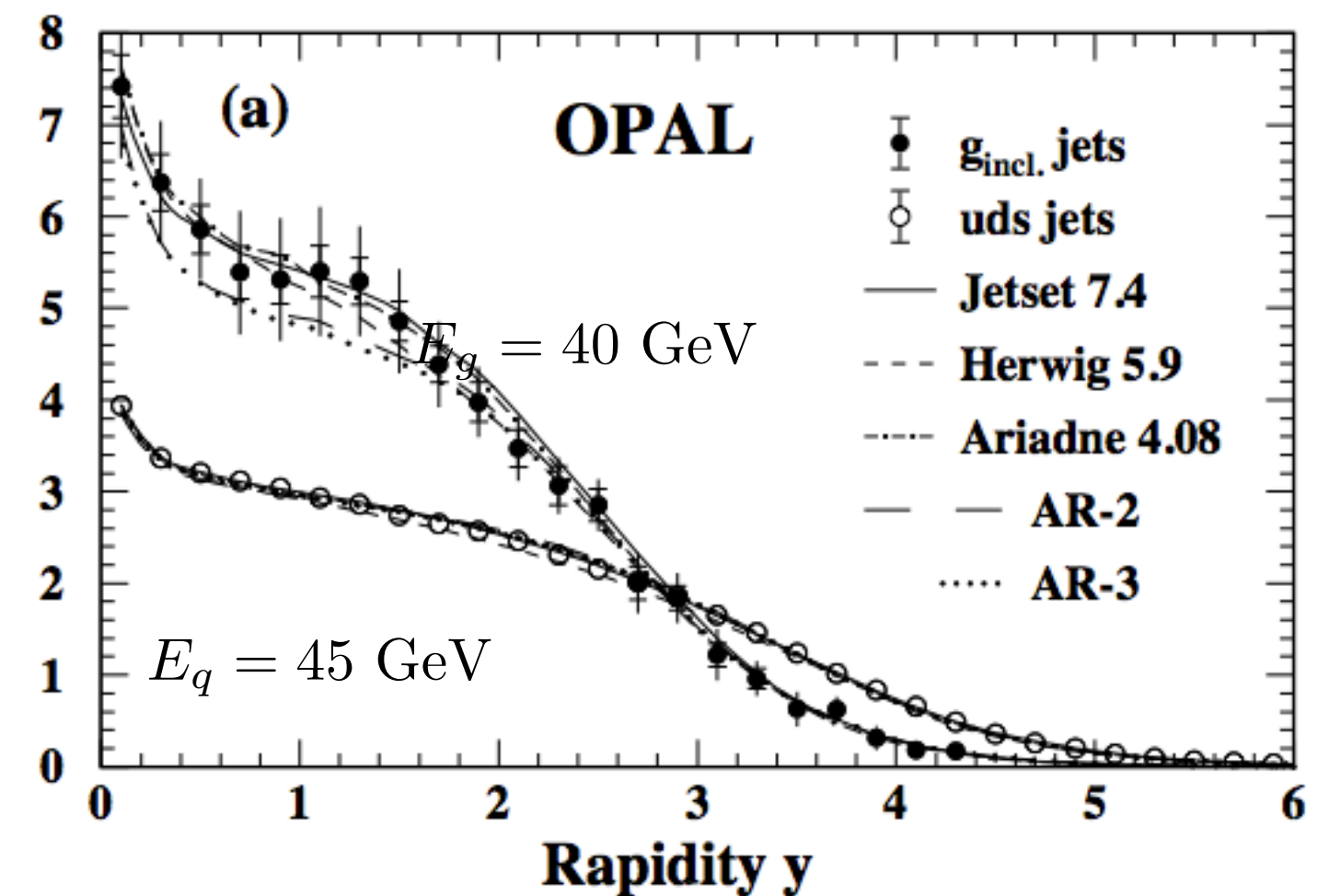
$Z \rightarrow bbg$ vs $Z \rightarrow qq(g)$

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

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

($R \sim 0.1$ also useful for jet substructure)

$\frac{1}{N} \frac{dn_{ch.}}{dy}$



Scaling: radiative events \rightarrow Forward Boosted

Scaling is **slow**, logarithmic \rightarrow 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

(Also useful for FFs & general scaling studies)

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

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

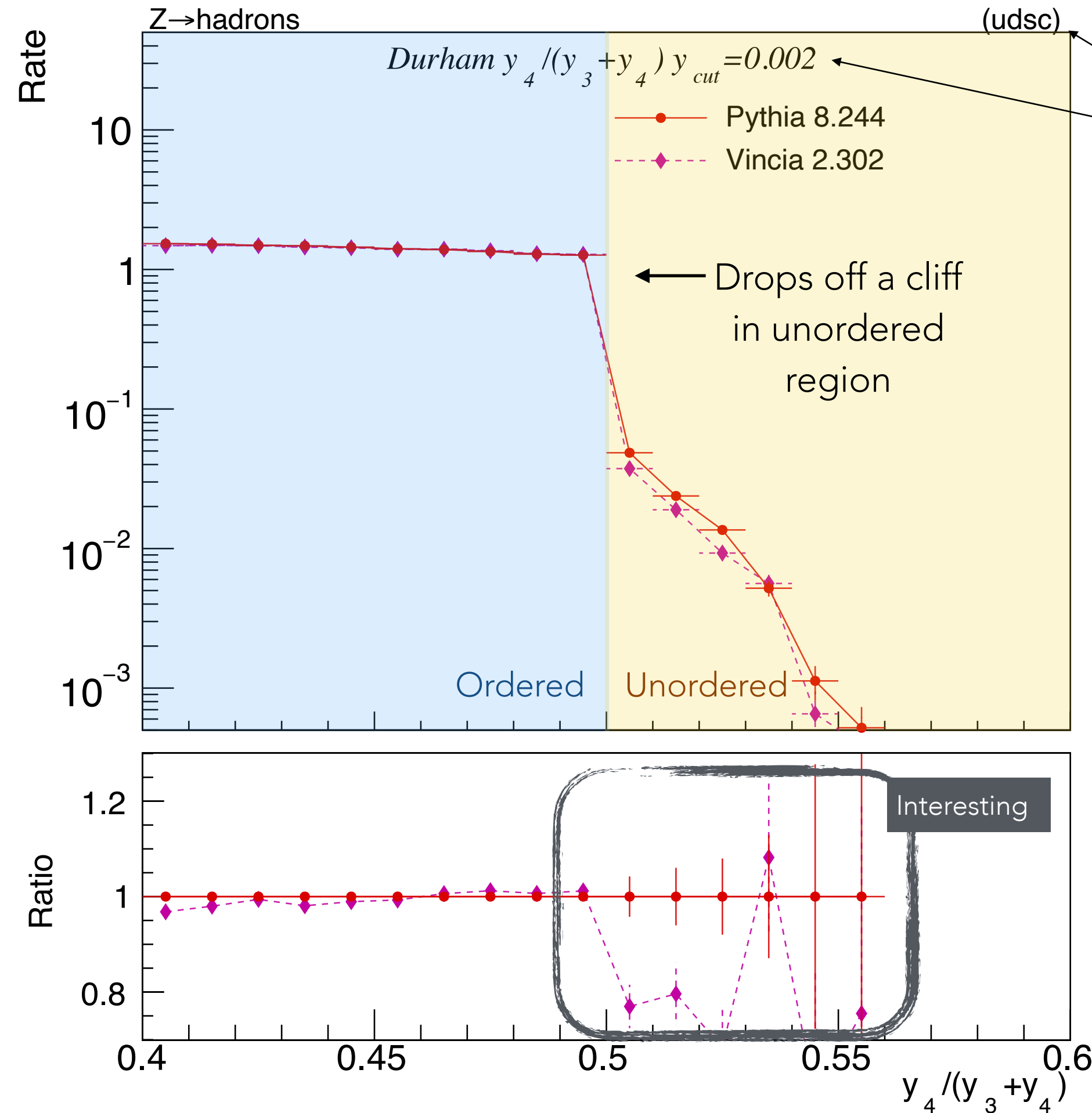
Rate normalised to total 4-jet rate

Off-the-shelf versions of Pythia and Vincia

Very similar results on individual jet rates.

Neither includes direct $2 \rightarrow 4$.

$4 \rightarrow 3 \rightarrow 2$



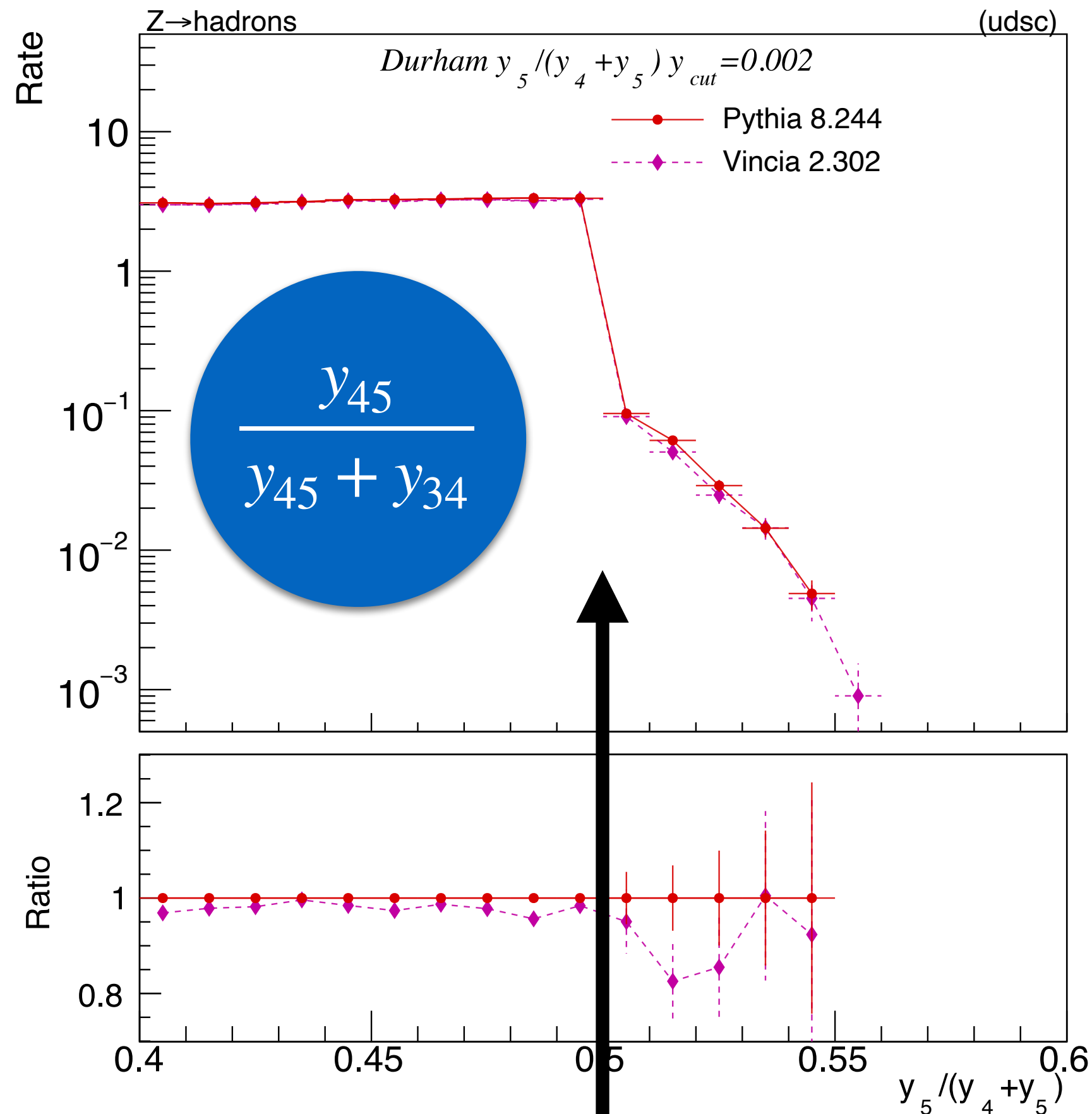
Small $y_{cut} = 0.002$
 ($\leftrightarrow k_{\perp} \sim 4$ GeV) to maximise statistics
 Excluded $Z \rightarrow b\bar{b}$ to avoid contamination from B decays
 4M events (\sim LEP 1)

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

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

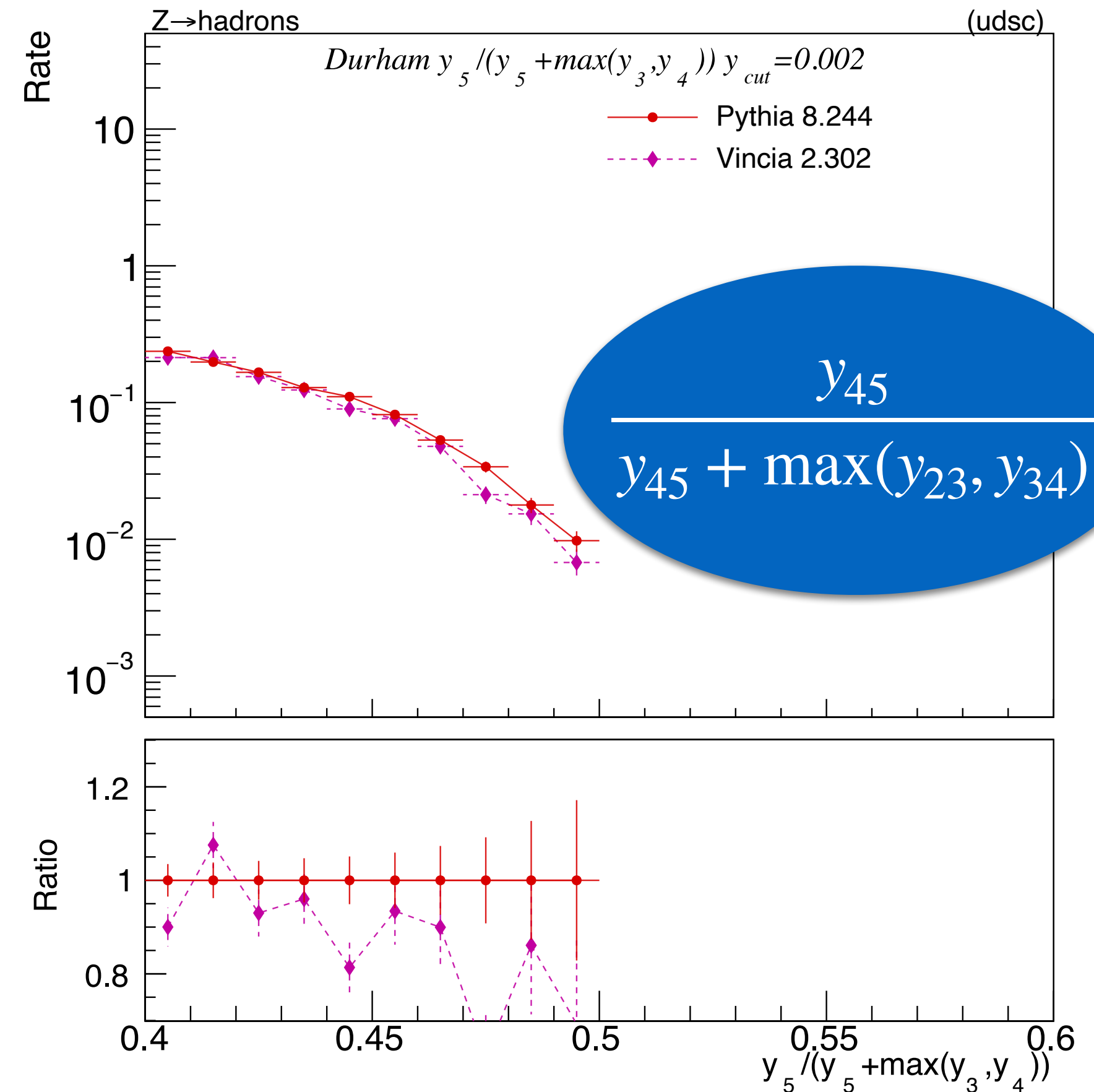
5-Jet Events

5 → 4 → 3



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

5 → 4 → 3 → 2



Limited power to probe 2 → 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.

