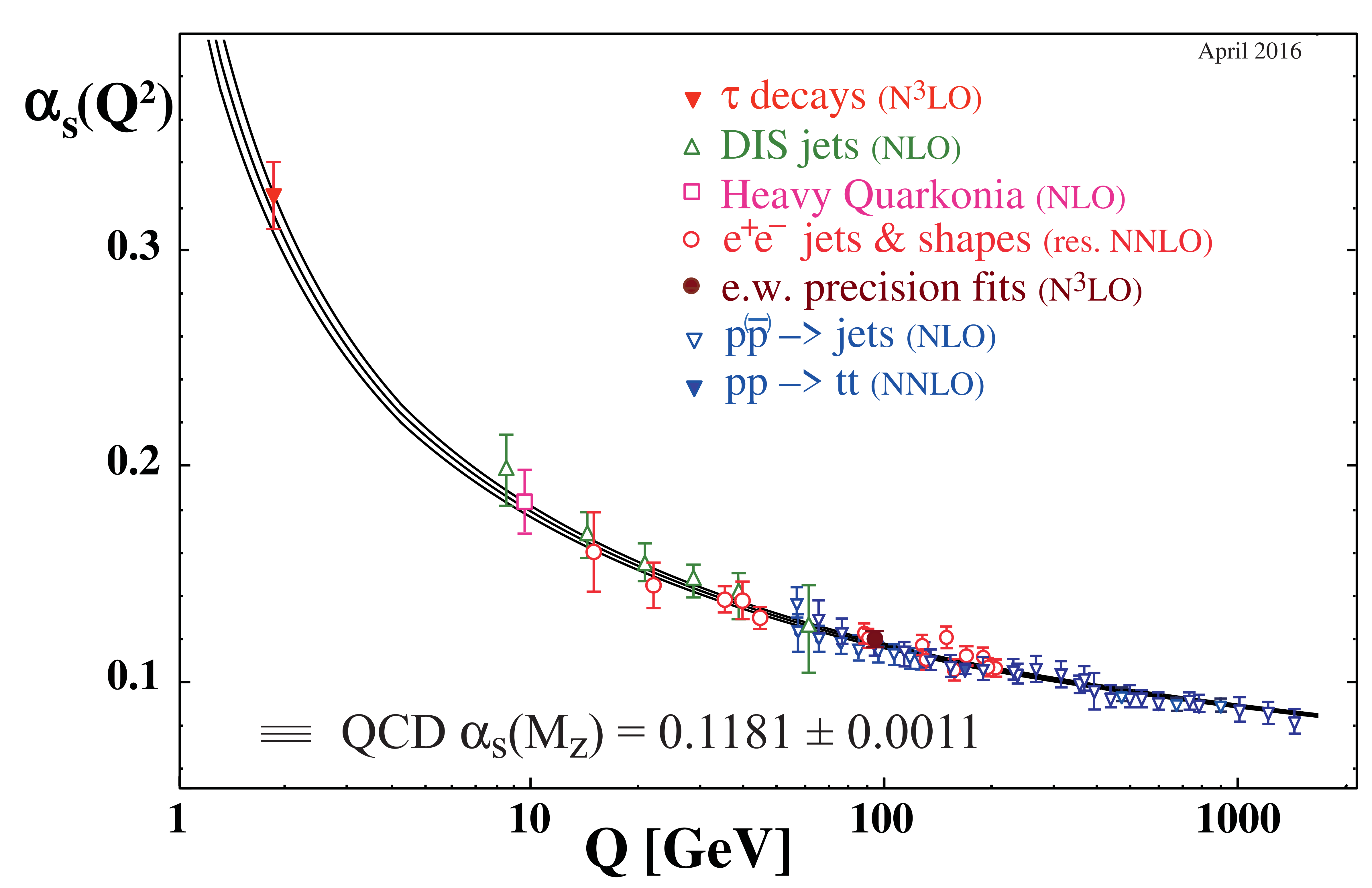
QCD across colliders and energy scales

Special colloquium in honour of the retirement of Siggi Bethke



Prof. Dr. Siegfried Bethke (Photo: A. Griesch/MPP)

Gavin Salam

Rudolf Peierls Centre for Theoretical Physics
& All Souls College, Oxford

Science and Technology Facilities Council

THE ROYAL SOCIETY

UNIVERSITY OF OXFORD

European Research Council
Established by the European Commission

particle physics

“big unanswered questions”

about fundamental particles & their interactions

(dark matter, matter-antimatter asymmetry,
nature of dark energy, hierarchy of scales…)

v.

“big answerable questions”

and how we go about answering them

(nature of Higgs interactions, validity of SM up to high scales,
lepton flavour universality, pattern of neutrino mixing, …)

The Lagrangian and Higgs interactions: two out of three qualitatively new!

$$\mathscr{L}_{\rm SM} = \cdots + |D_\mu \phi|^2 + \psi_i y_{ij} \psi_j \phi - V(\phi)$$

Gauge interactions, structurally like those in QED, QCD, EW, **studied for many decades** (but now with a scalar)

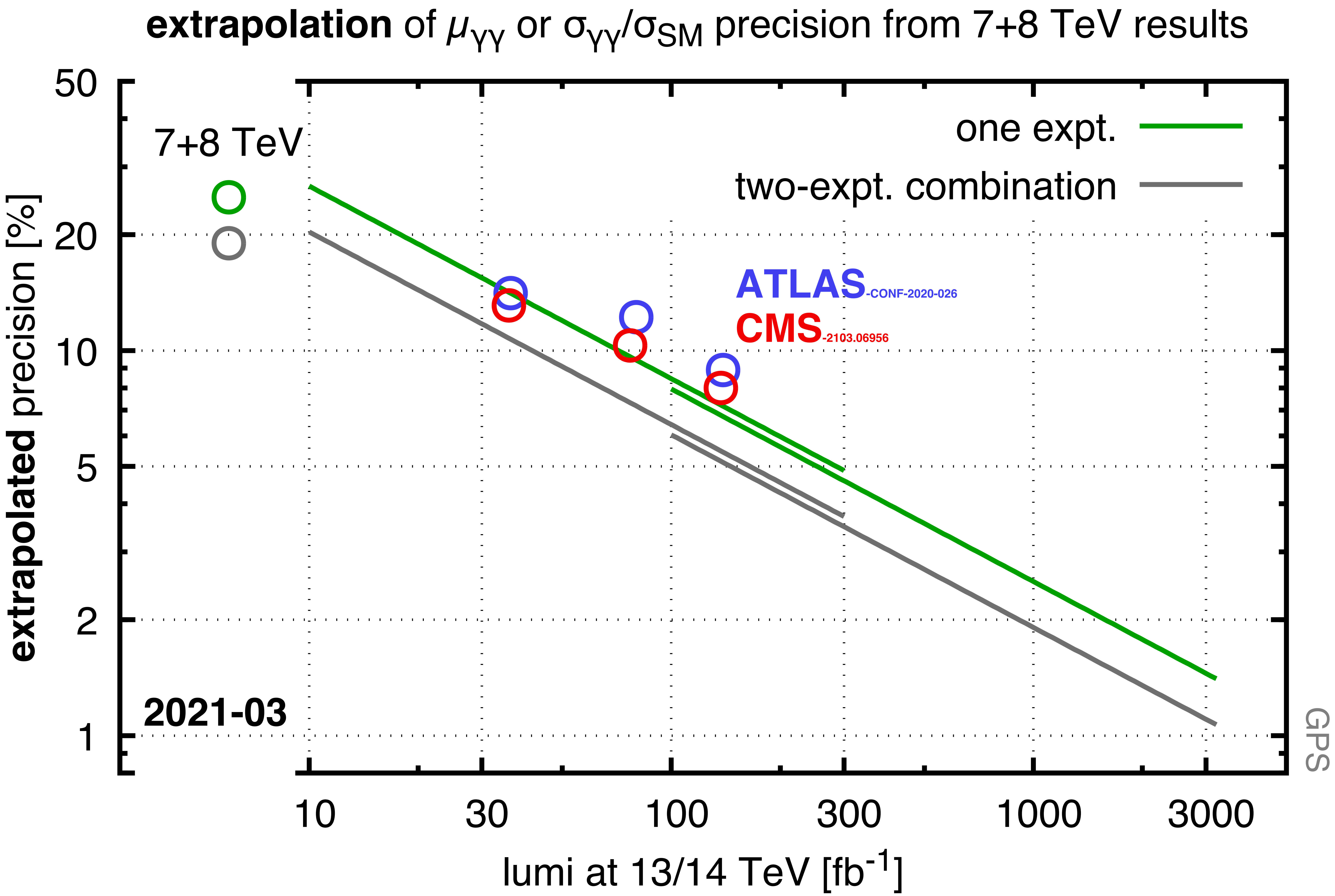
Yukawa interactions. Responsible for fermion masses, and induces "fifth force" between fermions. **Direct study started only in 2018!**

Higgs potential → self-interaction

Holds the SM together.

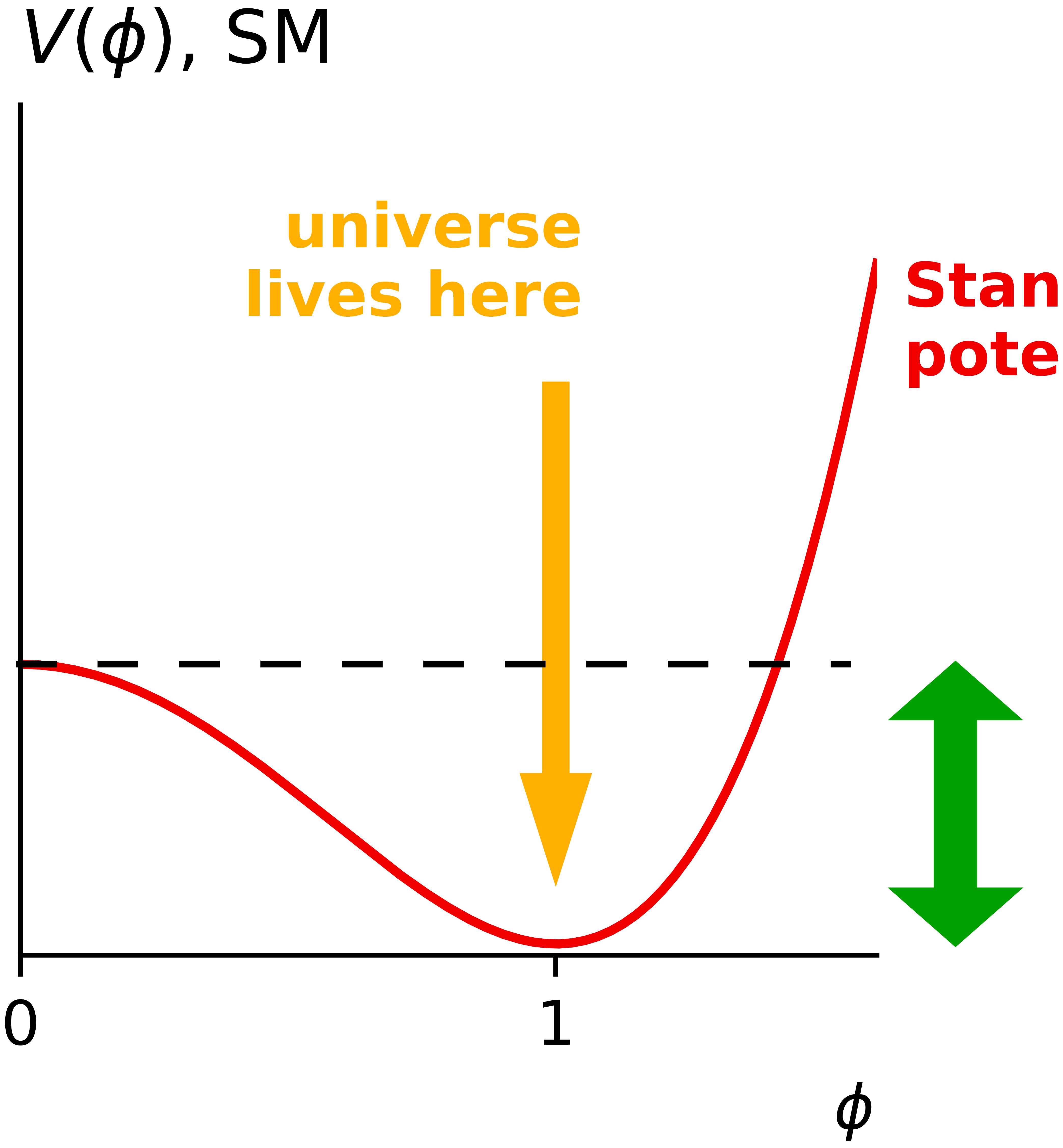
Unobserved

The LHC is increasingly a precision machine, even for Higgs physics



1% uncertainty on α_s
→ 2% uncertainty on
Higgs cross section

Higgs potential — huge energy densities

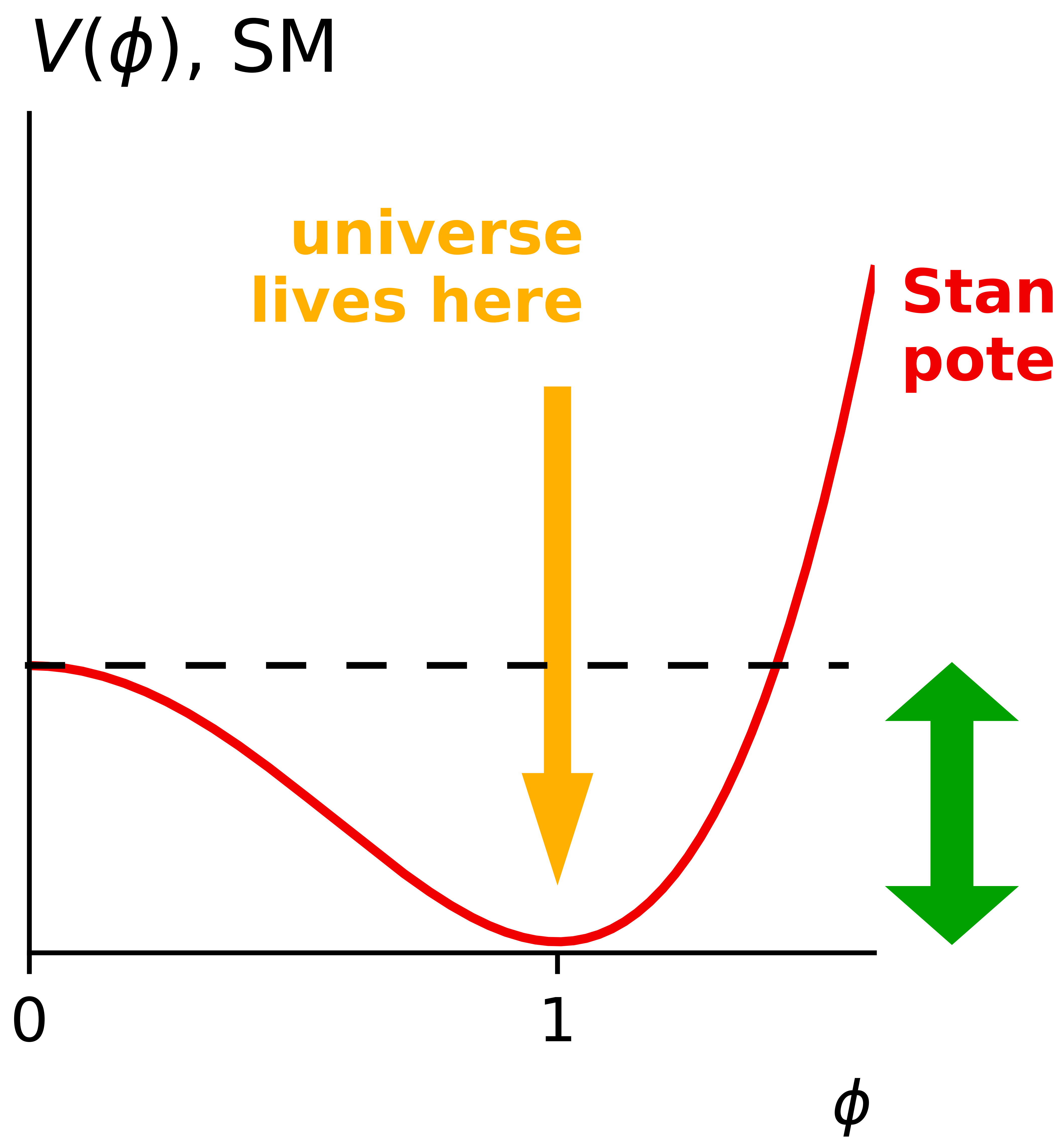


Energy density of 1.5×10^{10} GeV/fm^3

Mass density of 2.6×10^{28} kg/m^3

(fit $\gtrsim$ $10 \times$ sun's mass
into this auditorium)

Higgs potential — huge energy densities



Energy density of 1.5×10^{10} GeV/fm^3

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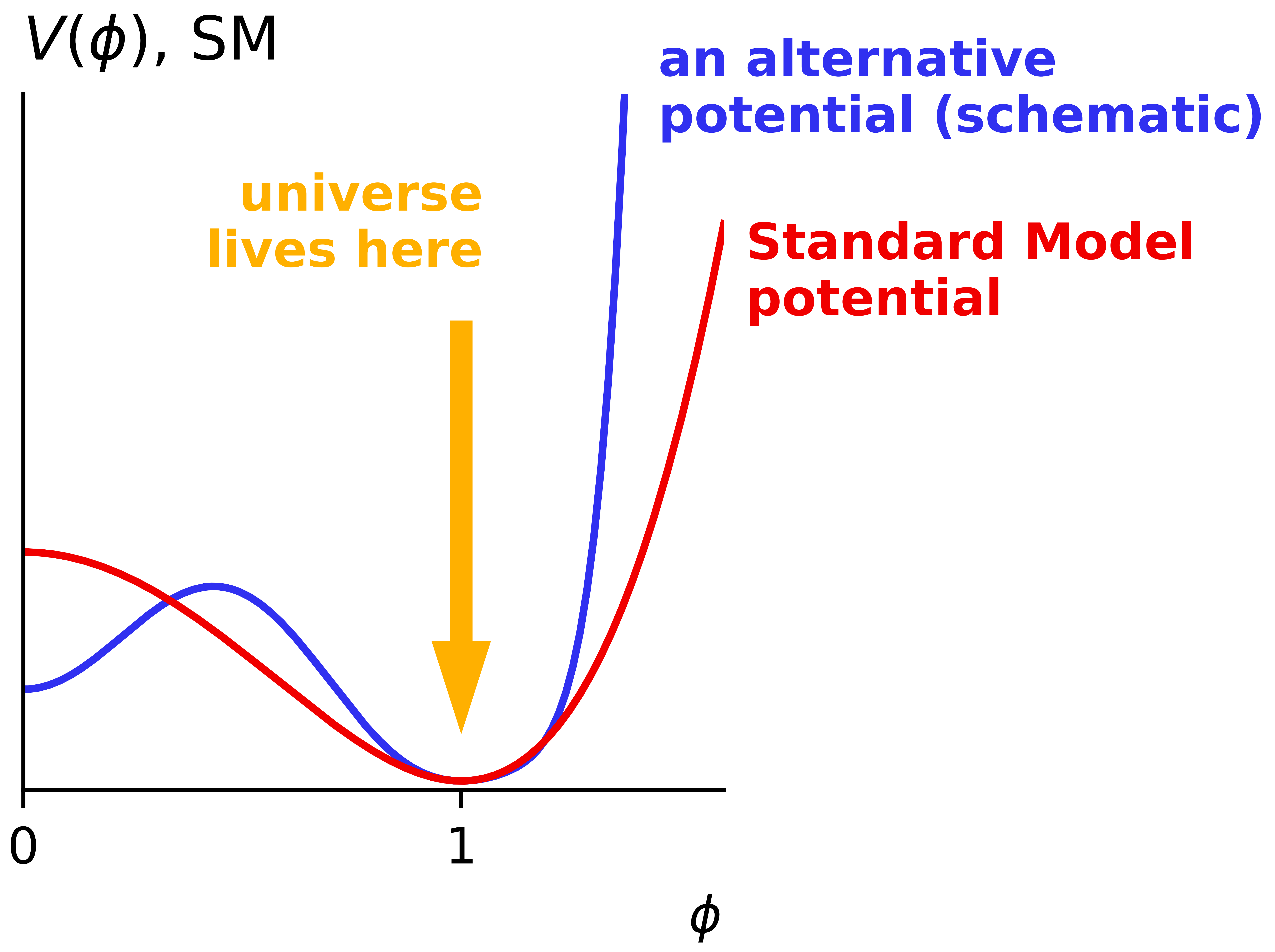
Higgs potential — huge energy densities — yet to be experimentaly confirmed



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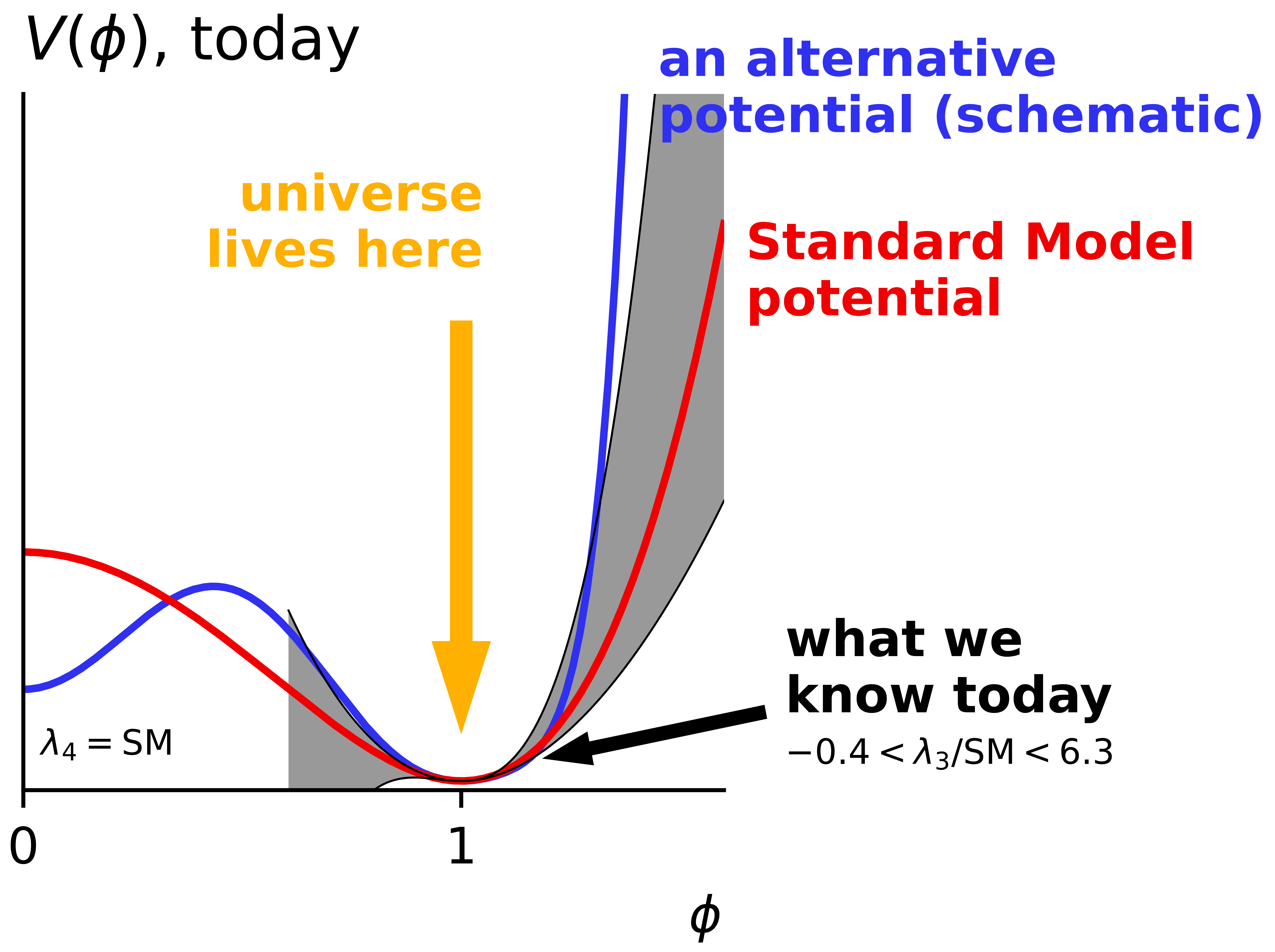
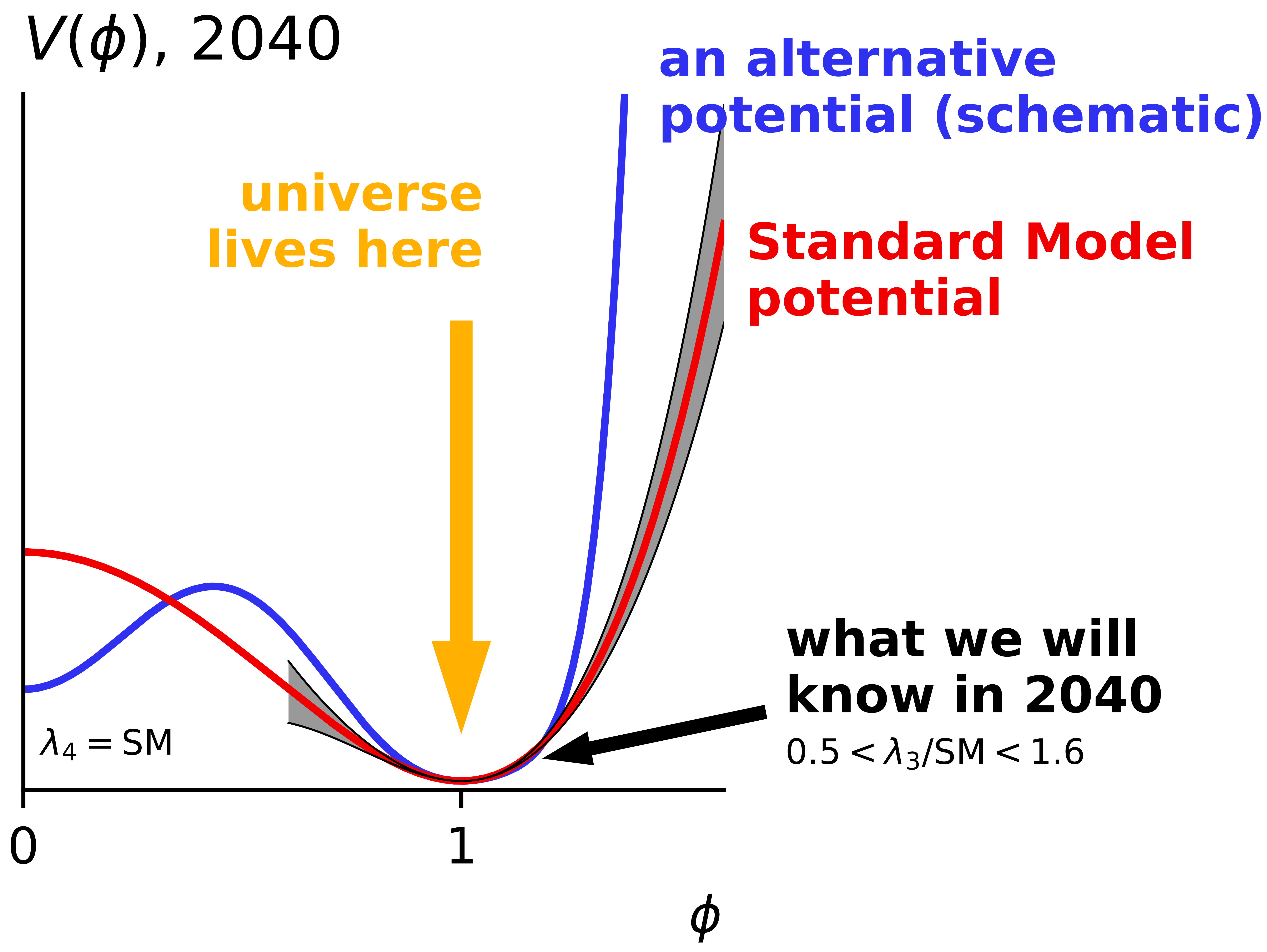
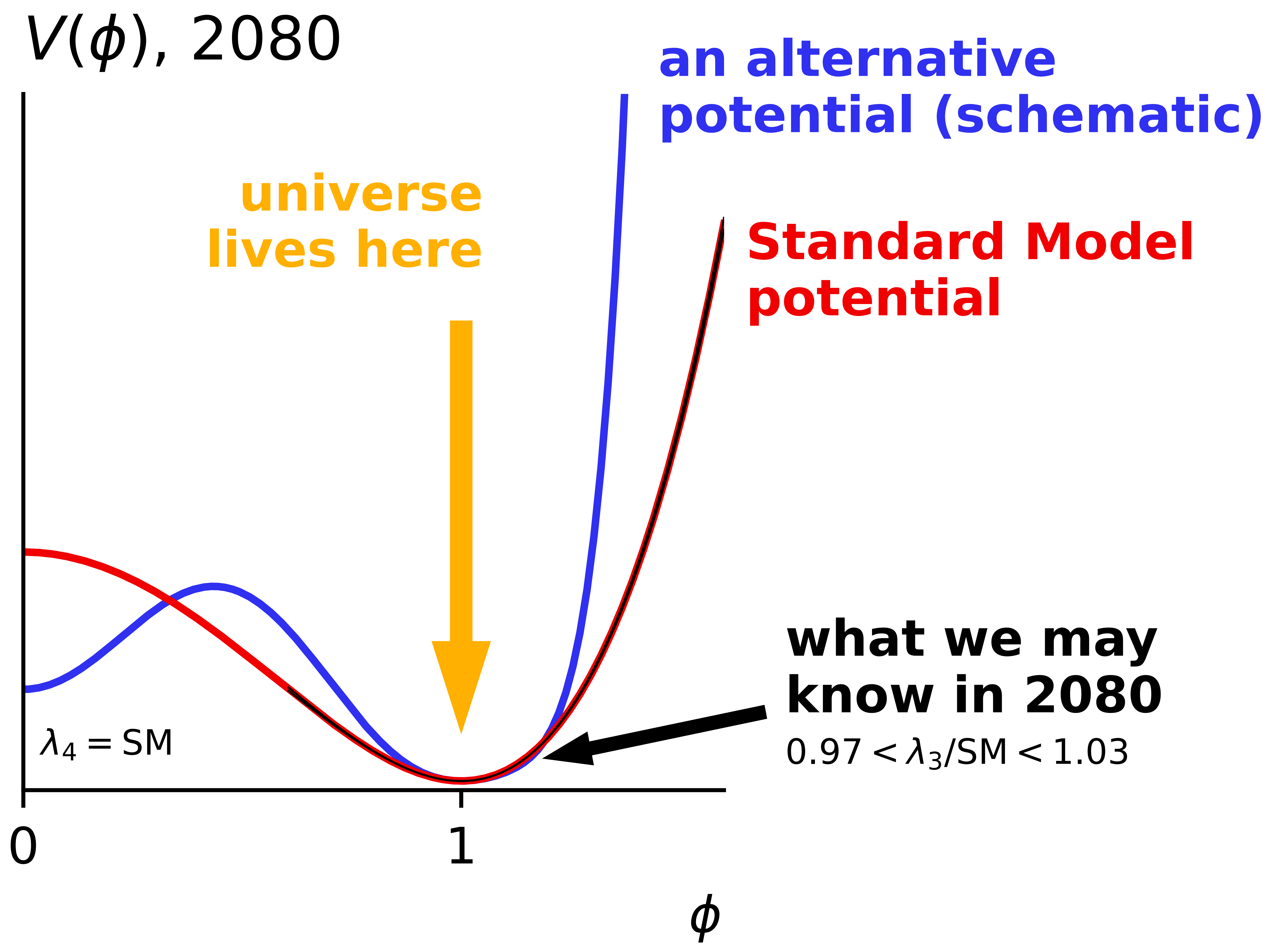


Higgs potential — huge energy densities — yet to be experimentaly confirmed



Higgs potential — huge energy densities — yet to be experimentaly confirmed

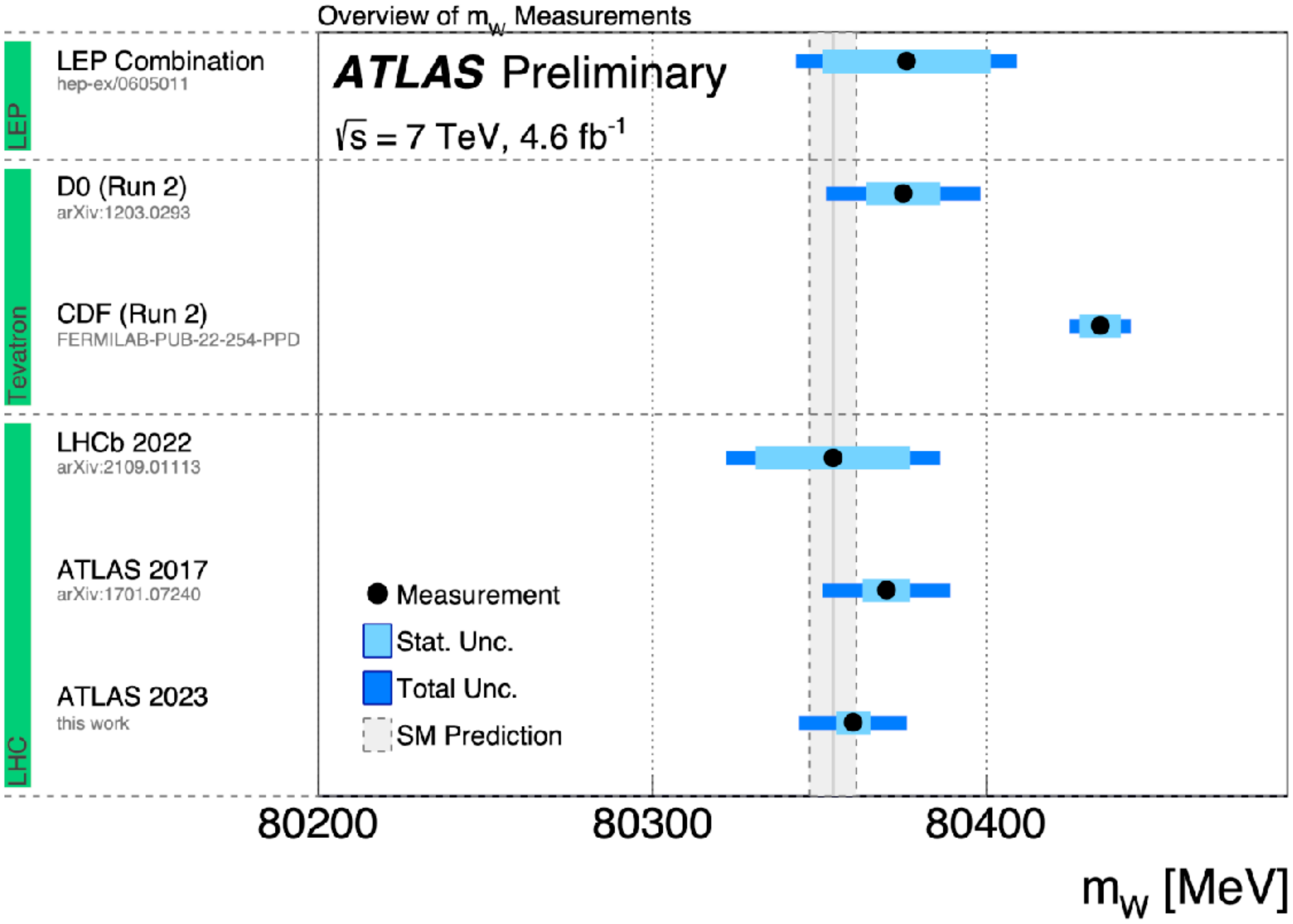


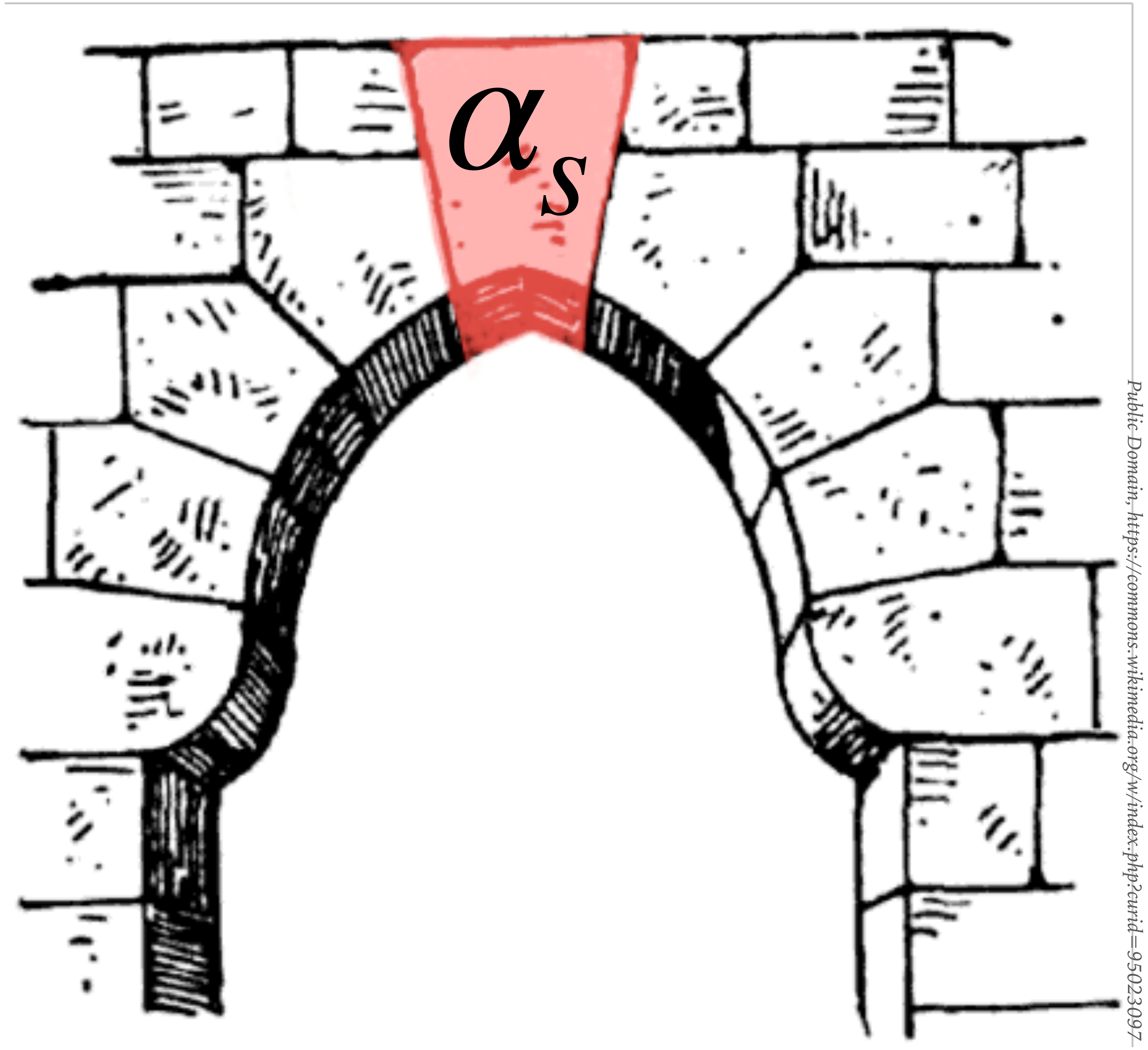
ATLAS 2209.10910 (HH→bbττ) systematics [highest expected sensitivity]

Table 4: Breakdown of the relative contributions to the uncertainty in the extracted signal cross-sections, as determined in the likelihood fit (described in Section 8) to data. They are obtained by fixing the relevant nuisance parameters in the likelihood fit, subtracting the square of the obtained uncertainty in the fitted signal cross-section from the square of the total uncertainty, taking the square root, and then dividing by the total uncertainty. The sum in quadrature of the individual components differs from the total uncertainty due to correlations between uncertainties in the different groups.

Uncertainty source	Non-resonant HH	Resonant $X \to HH$ 300 GeV	500 GeV	1000 GeV
Data statistical + floating normalisation	81%	76%	90%	93%
Data statistical	81%	76%	90%	93%
$t\bar{t}$ and Z + HF normalisations	4%	8%	3%	5%
Systematic	58%	65%	43%	37%
MC statistical	28%	44%	33%	18%

Do we know how to do precision physics at hadron colliders?





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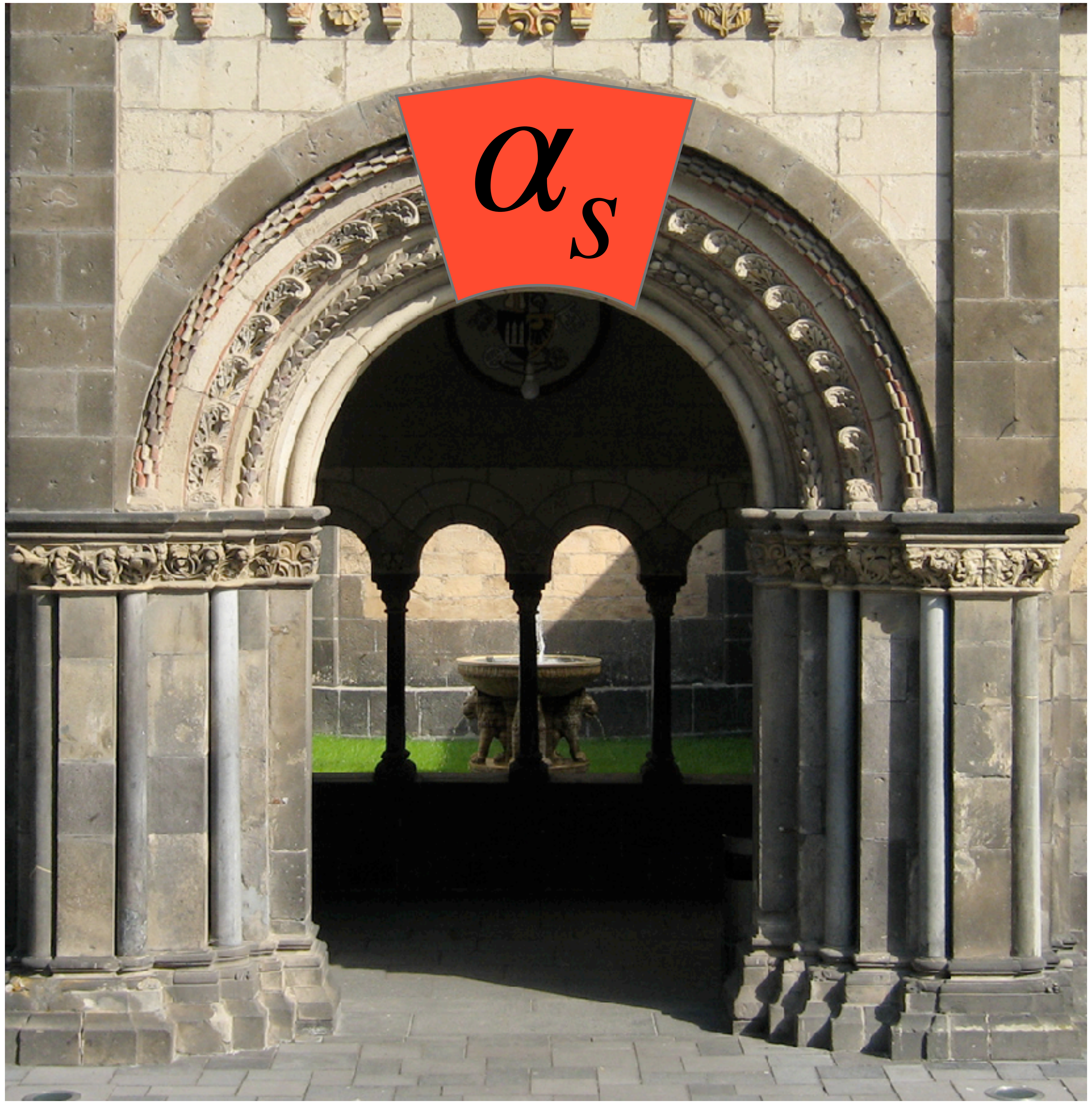
the strong coupling

Maria Laach



https://de.wikipedia.org/wiki/Abtei_Maria_Laach#media/Datei:Maria_Lach_05.jpg

the strong coupling

HD-PY 92/13
OPAL-CR093
October 23, 1992

TESTS OF QCD *

Siegfried Bethke §
Physikalisches Institut, University of Heidelberg
Philosophenweg 12
D-6900 Heidelberg, Germany

The final world average is thus quoted to be

$$\boxed{\alpha_s(M_{Z^0}) = 0.118 \pm 0.007},$$

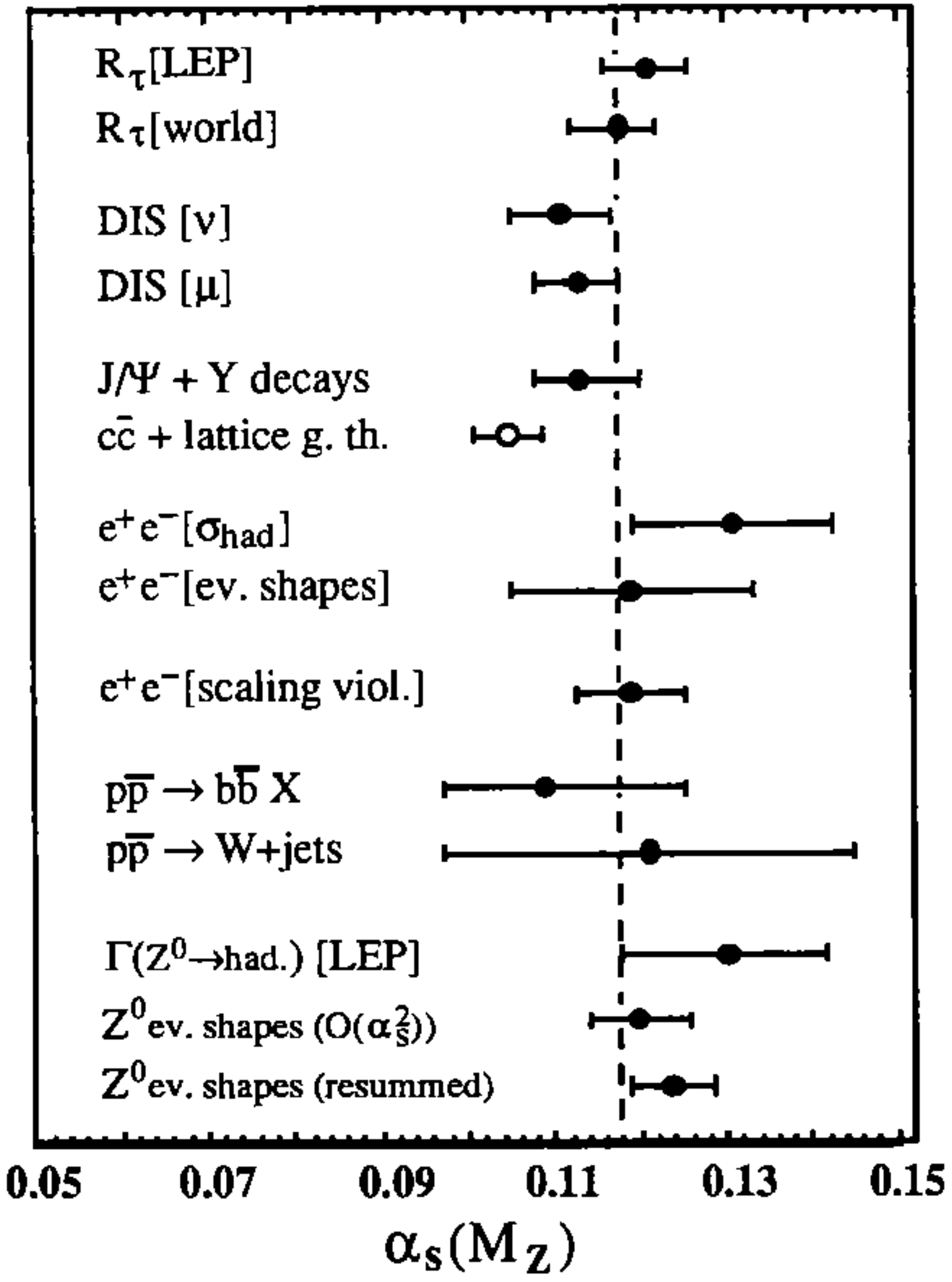


Fig. 31. Summary of measurements of $\alpha_s(M_{Z^0})$.

HD-PY 92/13
OPAL-CR093
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Gerne hätt ich fortgeschrieben
aber es ist liegen blieben.

Johann Wolfgang Goethe

A Summary of alpha-s measurements
Siegfried Bethke (Heidelberg U.), Stefano Catani (CERN) (1992)
Contribution to: 27th Rencontres de Moriond: QCD and High-energy Hadronic Interacti
pdf cite claim reference search 1 citation

1992

Summary of α^-s measurements
Siegfried Bethke (Aachen, Tech. Hochsch.) (Oct, 1994)
Published in: Nucl.Phys.B Proc.Suppl. 39BC (1995) 198 • Contribution to: Summer Sc Aspects of Collider Physics, High-energy Physics: QCD Workshop 94, Summer School on Hadronic Aspects of Collider Physics, 105-121
pdf DOI cite claim reference search 31 citations

1994

Status of alpha-s measurements
Siegfried Bethke (Aachen, Tech. Hochsch.) (1995)
Contribution to: 30th Rencontres de Moriond: QCD and High-energy Hadronic Interactions
pdf links cite claim reference search 0 citations

1995

Experimental tests of asymptotic freedom
Siegfried Bethke (Aachen, Tech. Hochsch.) (Sep, 1996)
Published in: Nucl.Phys.B Proc.Suppl. 54 (1997) 314-326 • Contribution to: High-energy P Euroconference on Quantum Chromodynamics (QCD 96), 314-324 • e-Print: hep-ex/9609014 [hep-ex]
pdf DOI cite claim reference search 39 citations

1996

QCD tests at e+ e- colliders
Siegfried Bethke (Aachen, Tech. Hochsch.) (Sep, 1997)
Published in: Nucl.Phys.B Proc.Suppl. 64 (1998) 54-62 • Contribution to: High-Energy Phys Euroconference on Quantum Chromodynamics: QCD 97: 25th Anniversary of QCD • e-Print: hep-ex/9710030 [hep-ex]
pdf DOI cite claim reference search 32 citations

1997

Jet physics at LEP and world summary of alpha(s)
S. Bethke (Aachen, Tech. Hochsch.) (Sep, 1998)
Contribution to: RADCOR 1998, 243-260 • e-Print: hep-ex/9812026 [hep-ex]
pdf cite claim reference search 36 citations

1998

Determination of the QCD coupling α_s
S. Bethke (Munich, Max Planck Inst.) (Apr, 2000)
Published in: J.Phys.G 26 (2000) R27 • e-Print: hep-ex/0004021 [hep-ex]
pdf DOI cite claim reference search 261 citations

2000

α_s 2002
Siegfried Bethke (Munich, Max Planck Inst.) (Nov, 2002)
Published in: Nucl.Phys.B Proc.Suppl. 121 (2003) 74-81 • Contribution to: QCD 02, 74 ex/0211012 [hep-ex]
pdf DOI cite claim reference search 101 citations

2002

α_s at Zinnowitz 2004
Siegfried Bethke (Munich, Max Planck Inst.) (Jul, 2004)
Published in: Nucl.Phys.B Proc.Suppl. 135 (2004) 345-352 • Contribution to: 7th DESY Elementary Particle Theory: Loops and Legs in Quantum Field Theory, 345-352 • e-Print: hep-ex/0407021 [hep-ex]
pdf DOI cite claim reference search 131 citations

2004

Experimental tests of asymptotic freedom
Siegfried Bethke (Munich, Max Planck Inst.) (Jun, 2006)
Published in: Prog.Part.Nucl.Phys. 58 (2007) 351-386 • e-Print: hep-ex/0606035 [hep-
pdf DOI cite claim reference search 388 citations

2006

The 2009 World Average of alpha(s)
Siegfried Bethke (Munich, Max Planck Inst.) (Aug, 2009)
Published in: Eur.Phys.J.C 64 (2009) 689-703 • e-Print: 0908.1135 [hep-ph]
pdf DOI cite claim reference search 561 citations

2009

Review of Particle Physics (RPP)
Particle Data Group • J. Beringer (LBL, Berkeley) et al. (2012)
Published in: Phys.Rev.D 86 (2012) 010001
DOI cite claim reference search 9,066 citations

2011

Review of Particle Physics
Particle Data Group • K.A. Olive (Minnesota U.) et al. (2014)
Published in: Chin.Phys.C 38 (2014) 090001
links DOI cite claim reference search 9,091 citations

2013

Review of Particle Physics
Particle Data Group • C. Patrignani (Bologna U. and INFN, Bologna) et al. (Oct 3, 2016)
Published in: Chin.Phys.C 40 (2016) 10, 100001
pdf links DOI cite claim reference search 6,794 citations

2015

Determination of the strong coupling constant $\alpha_s(m_Z)$ from measurem total cross section for top-antitop quark production
Thomas Klijnsma (Zurich, ETH), Siegfried Bethke (Munich, Max Planck Inst.), Günther Dis Gavin P. Salam (CERN and Paris, LPTHE) (Aug 24, 2017)
Published in: Eur.Phys.J.C 77 (2017) 11, 778 • e-Print: 1708.07495 [hep-ph]
pdf DOI cite claim reference search 36 citations

2017

Pre-2019 summaries of α_s
Siegfried Bethke (Munich, Max Planck Inst.) (Jul 9, 2019)
Published in: PoS ALPHAS2019 (2019) 001 • Contribution to: alphas-2019, 7-12, alp
pdf DOI cite claim reference search 0 citations

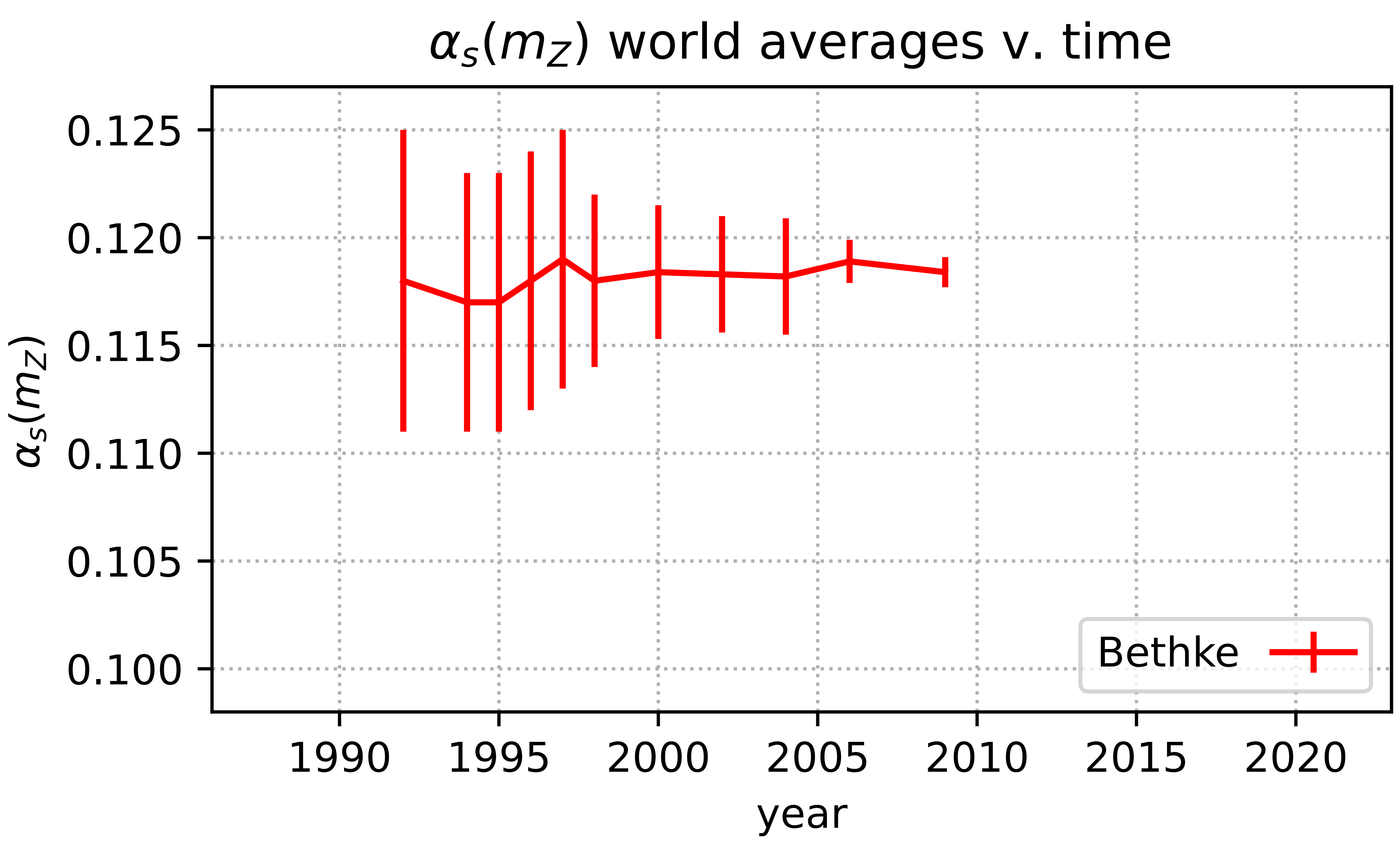
2019

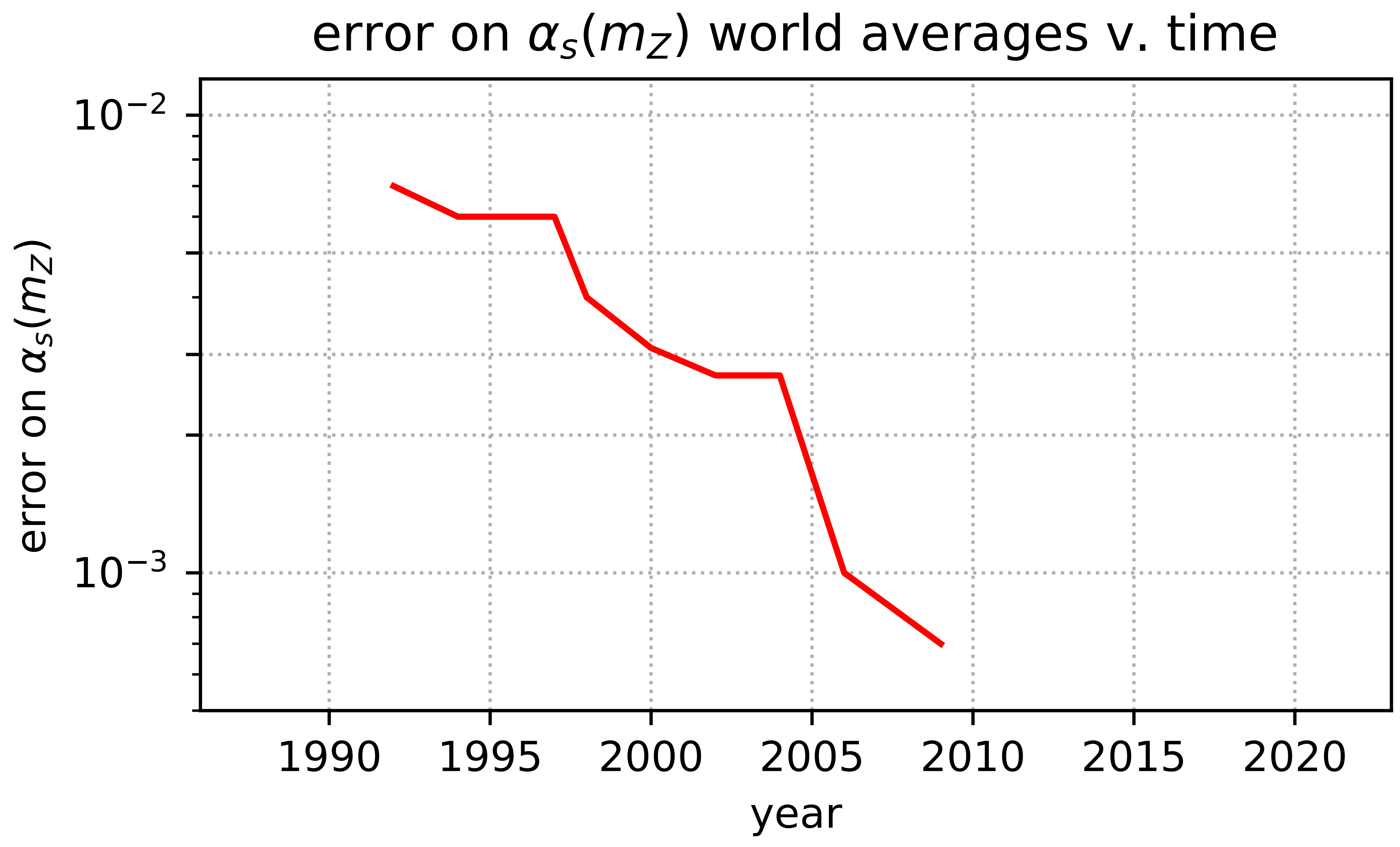
Three decades of the strong coupling

Uncertainty has gone down by an order of magnitude to ~ 0.8%

central value has stayed stable, today

$\alpha_s(m_Z) = 0.1179 \pm 0.0009$





Sources of improvement

- data (LEP, DIS,~LHC)
- better theory (e.g. NNLO, N3LL)
- better computers (e.g. for lattice)

Challenges

- how to handle spread of error estimates (e.g. when systematic dominated)

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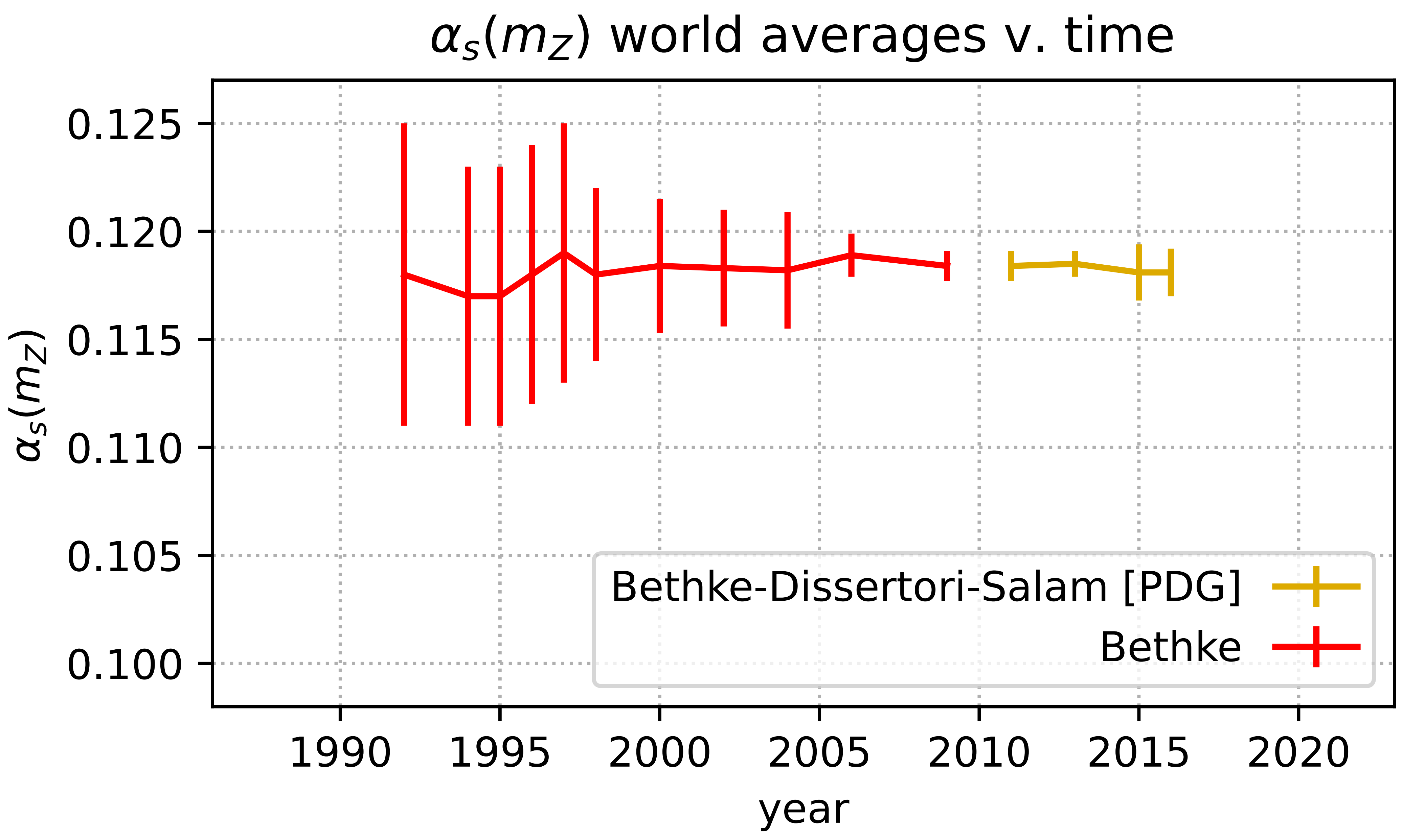

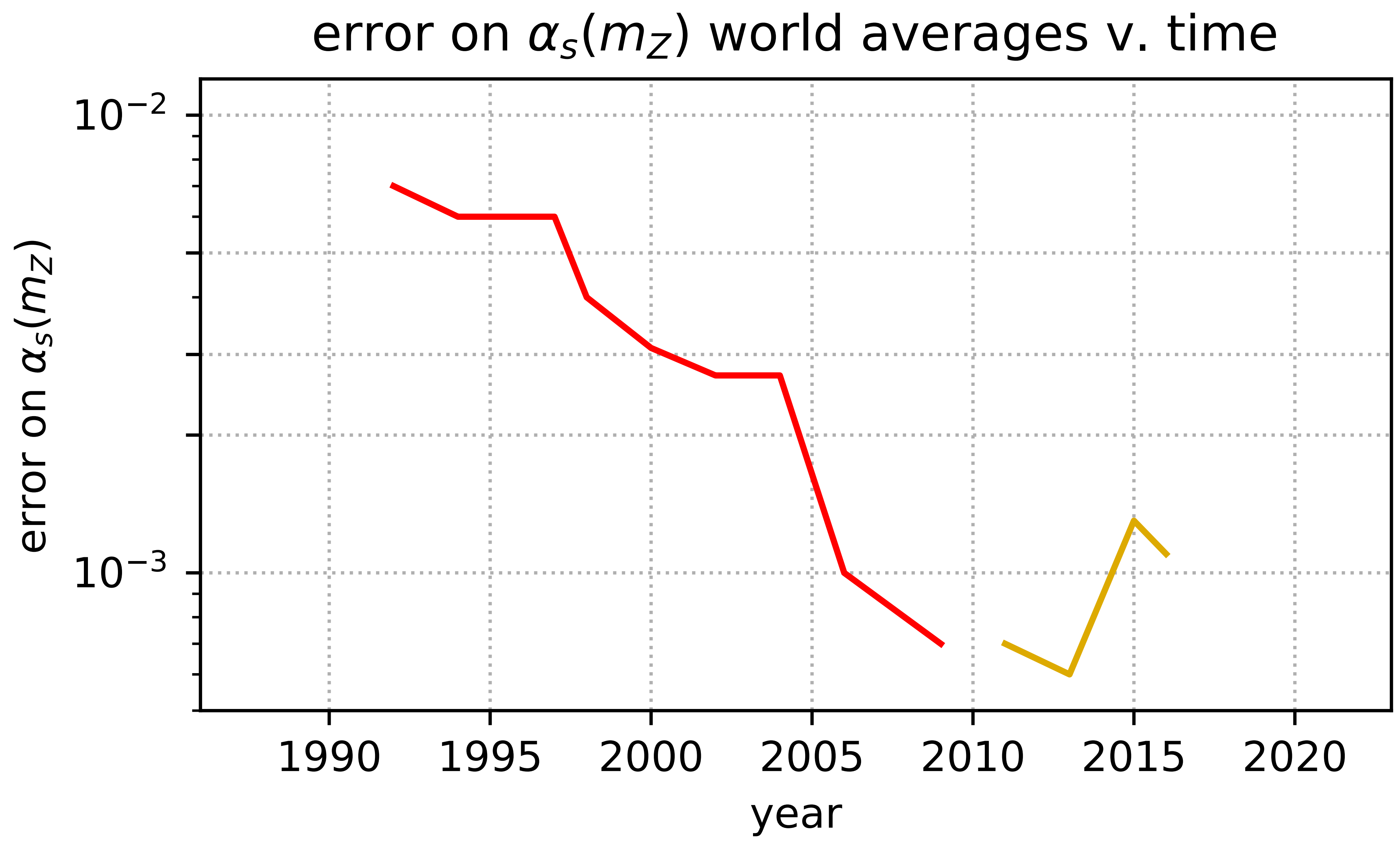

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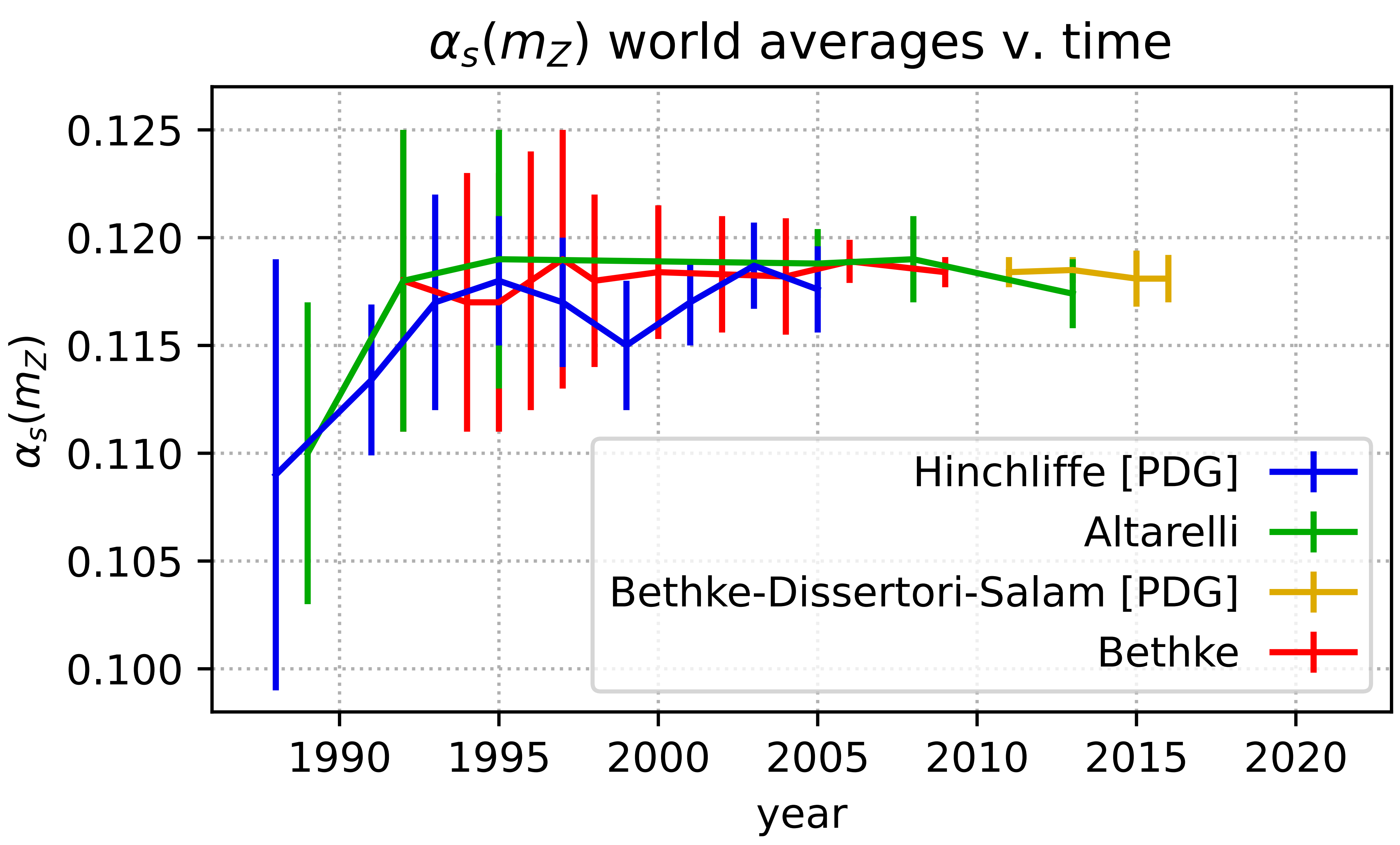

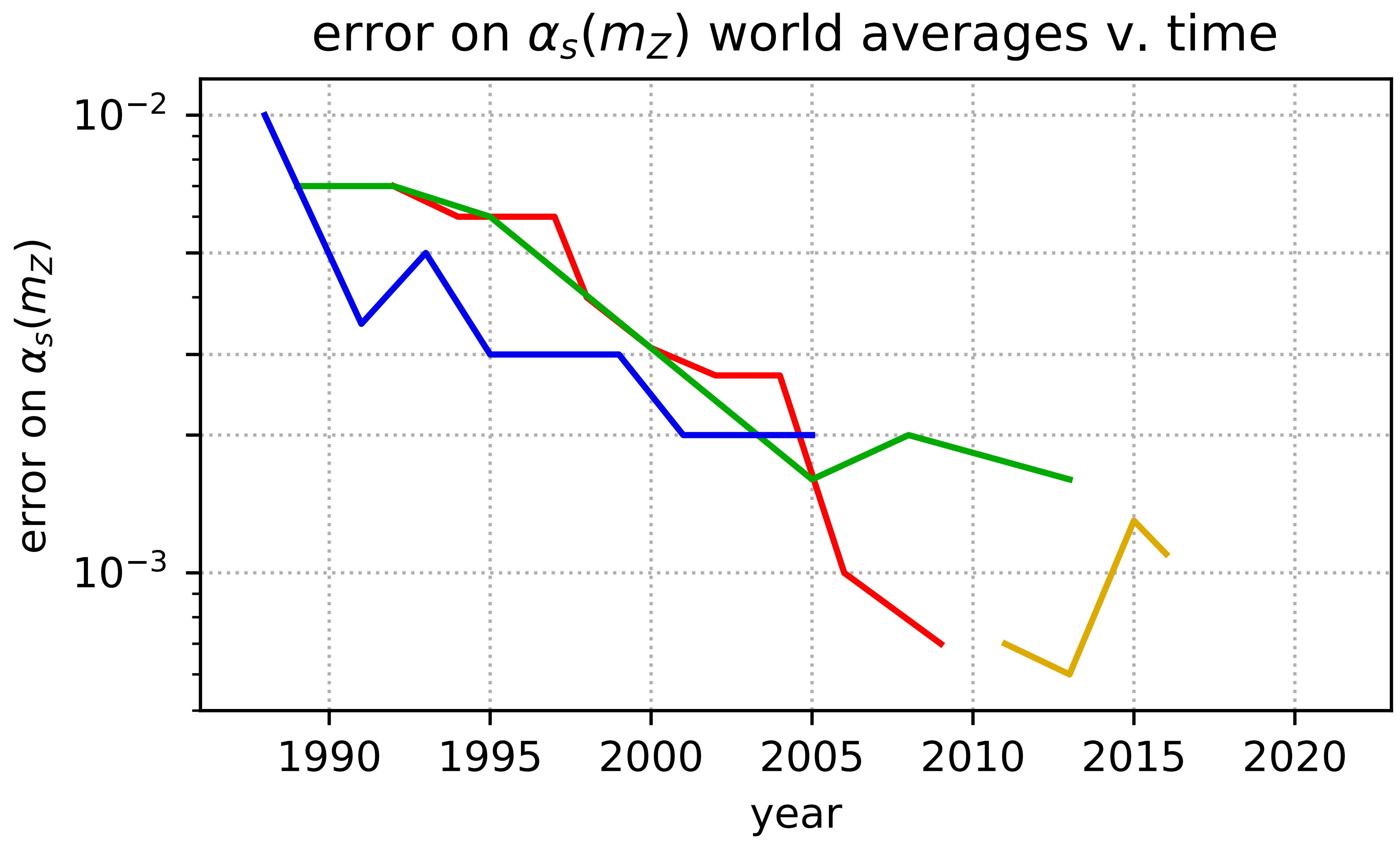

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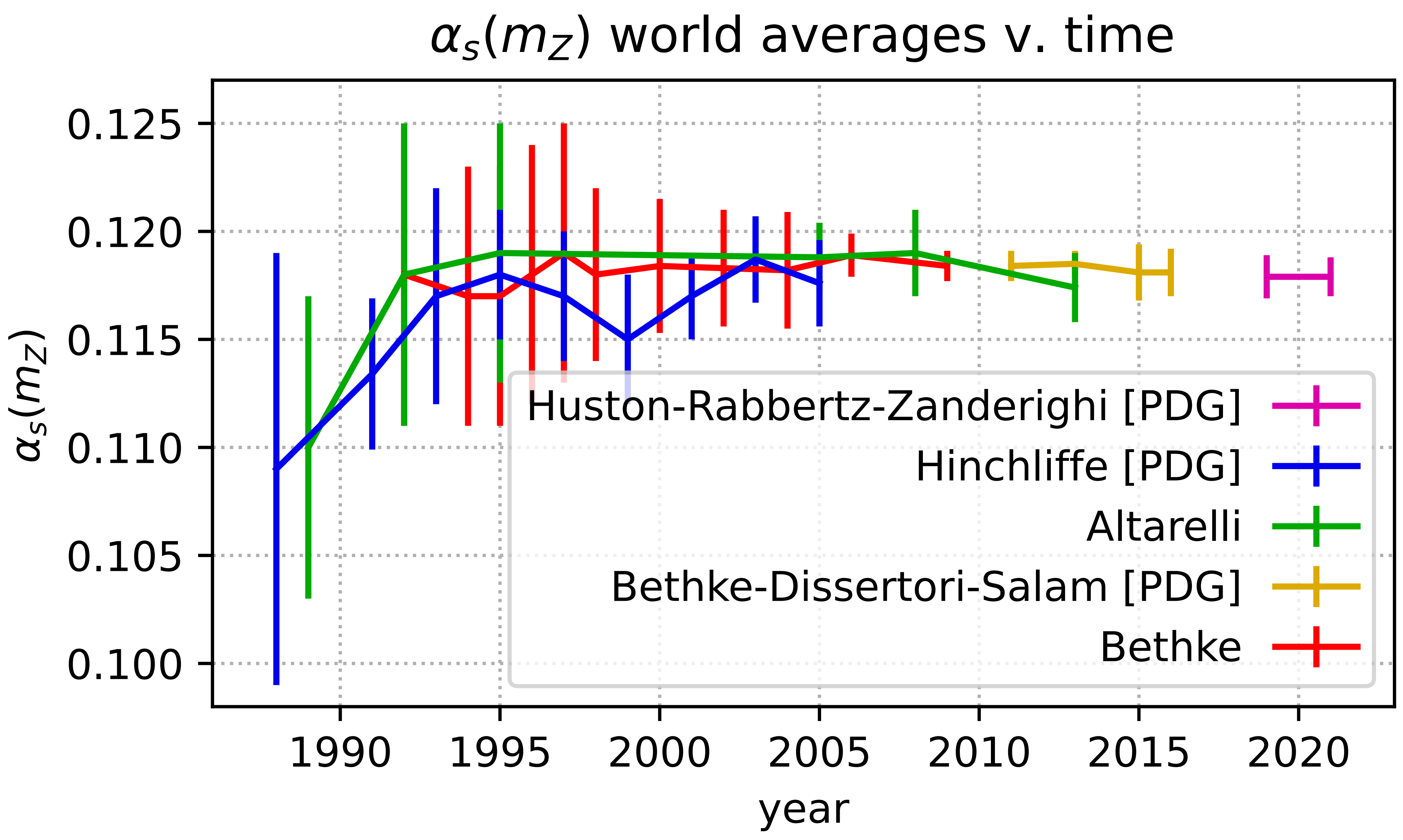
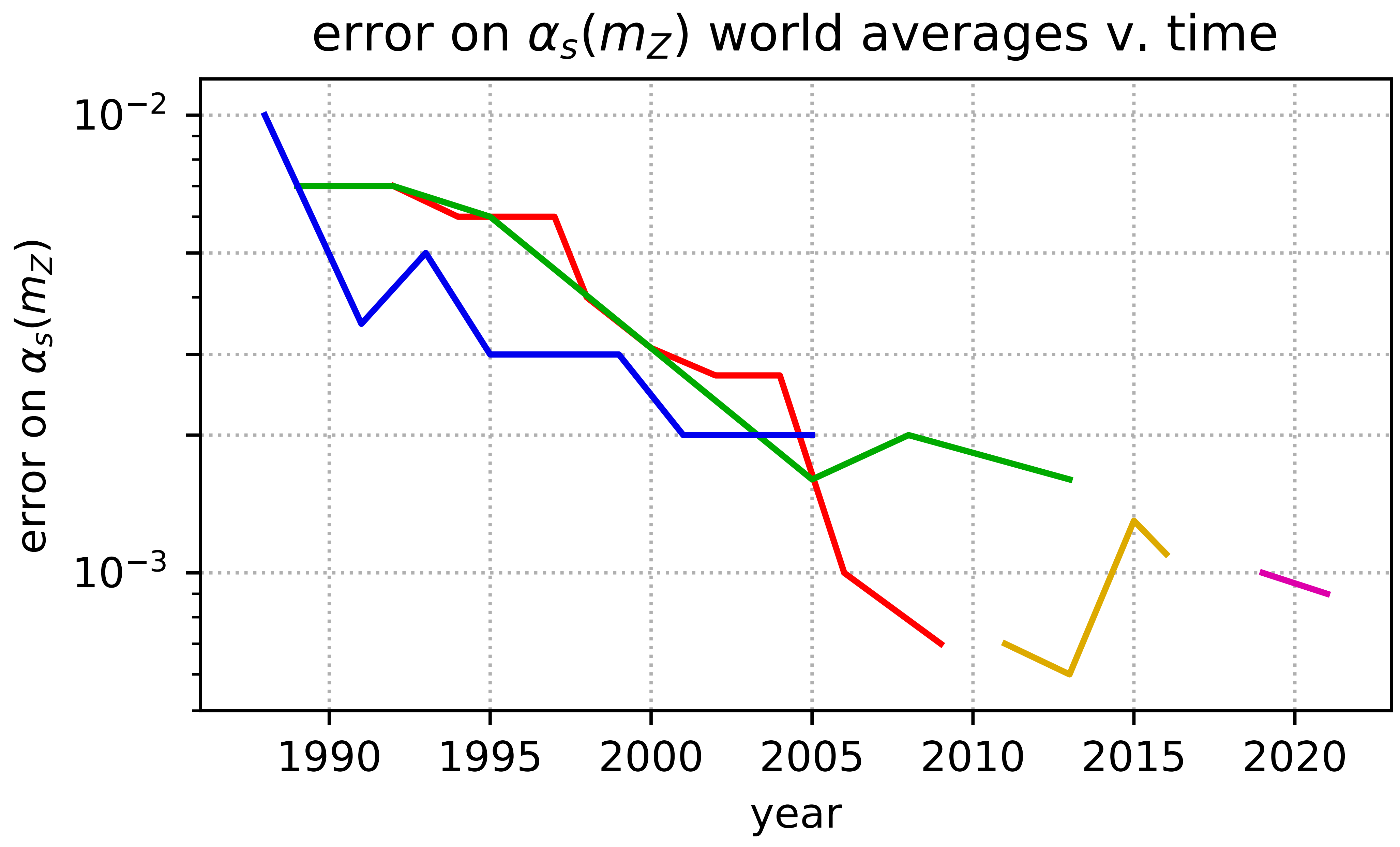




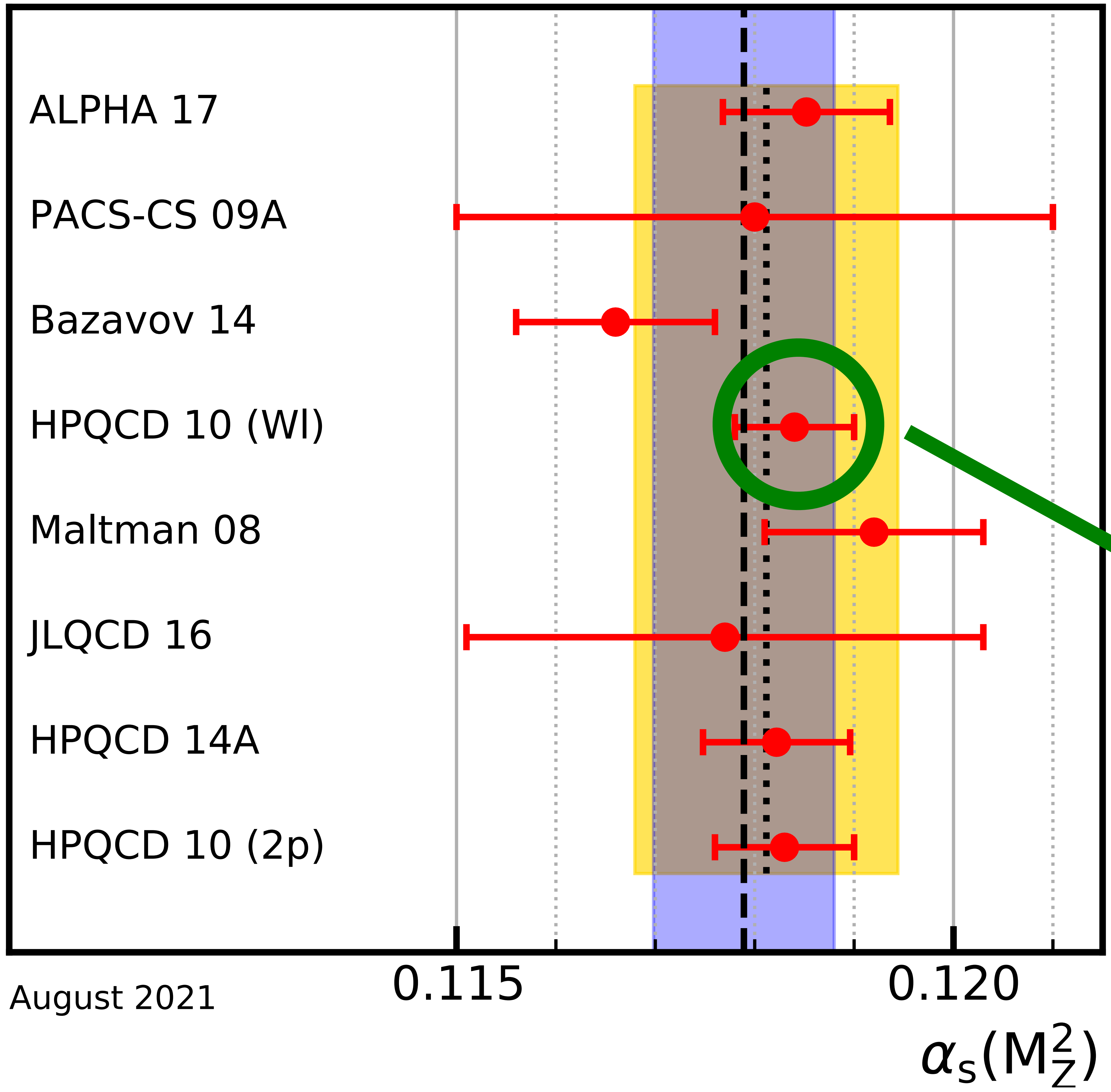
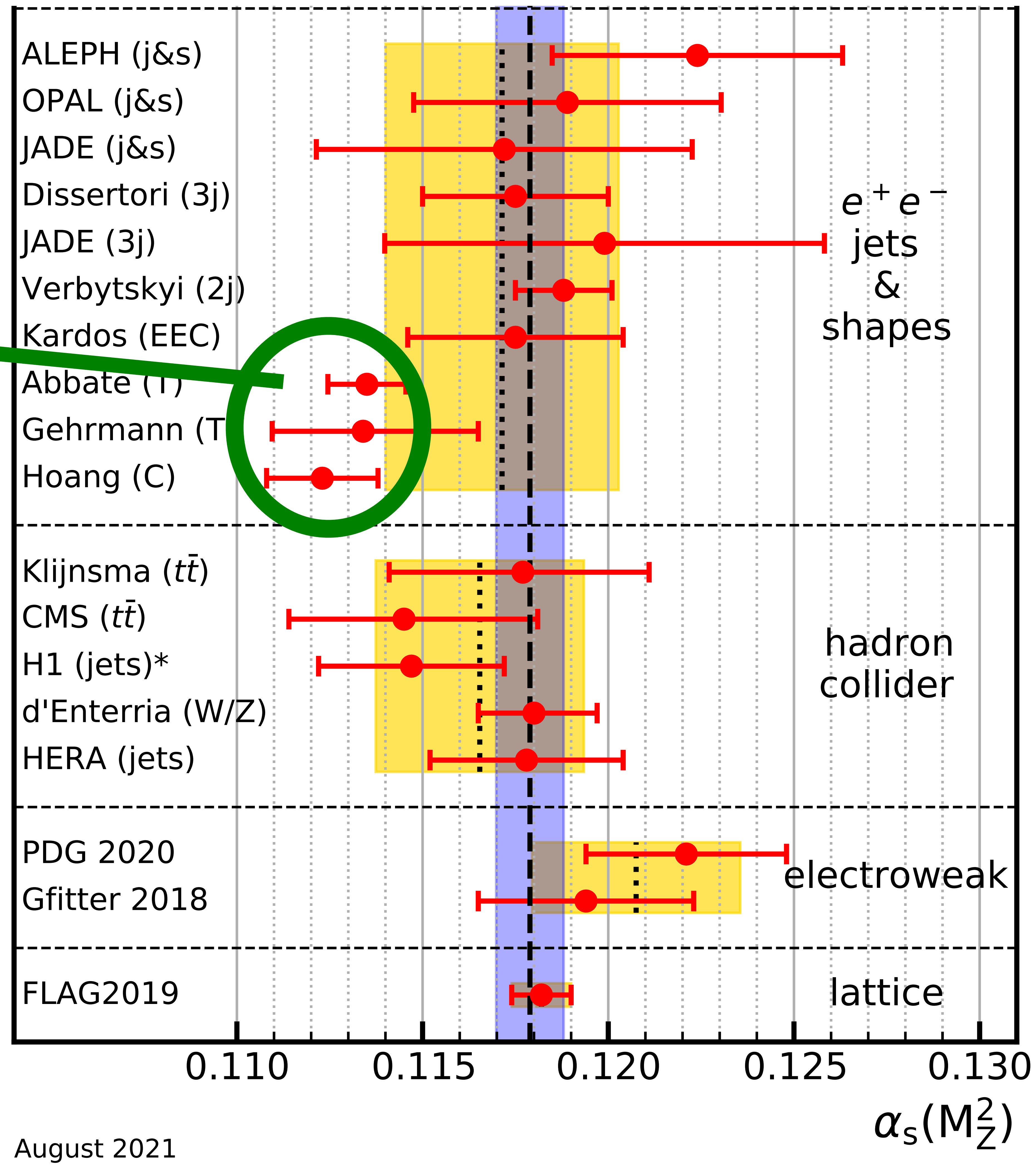
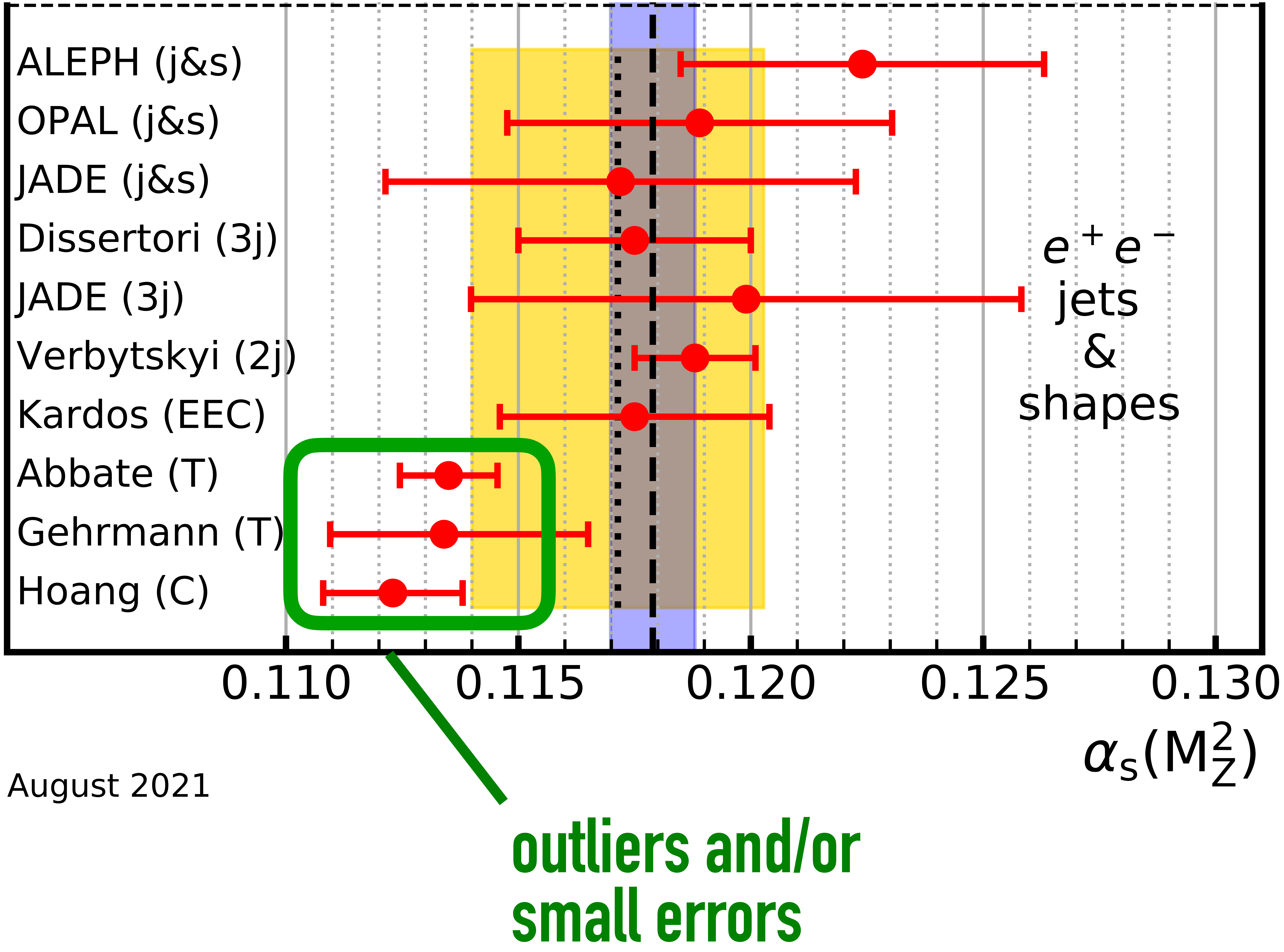


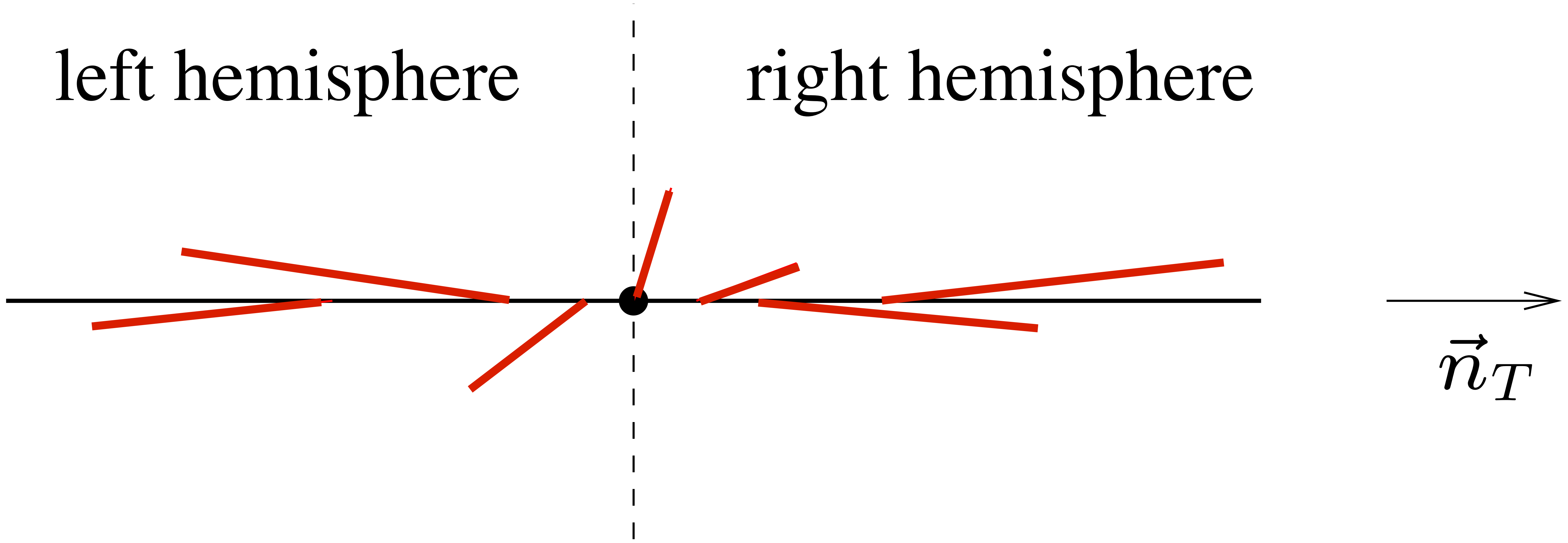
Figure 9.5: Lattice determinations that enter the FLAG2019 average. The yellow (light shaded) band and dotted line indicates the average value for this sub-field. The dashed line and blue (dark shaded) band represent the final world average value of $\alpha_s(M_Z^2)$. [a]

outliers and/or small errors



Event shapes





thrust $T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i . \vec{n}|}{\sum_i |\vec{p}_i|}\,, \qquad \tau = 1 - T\,,$

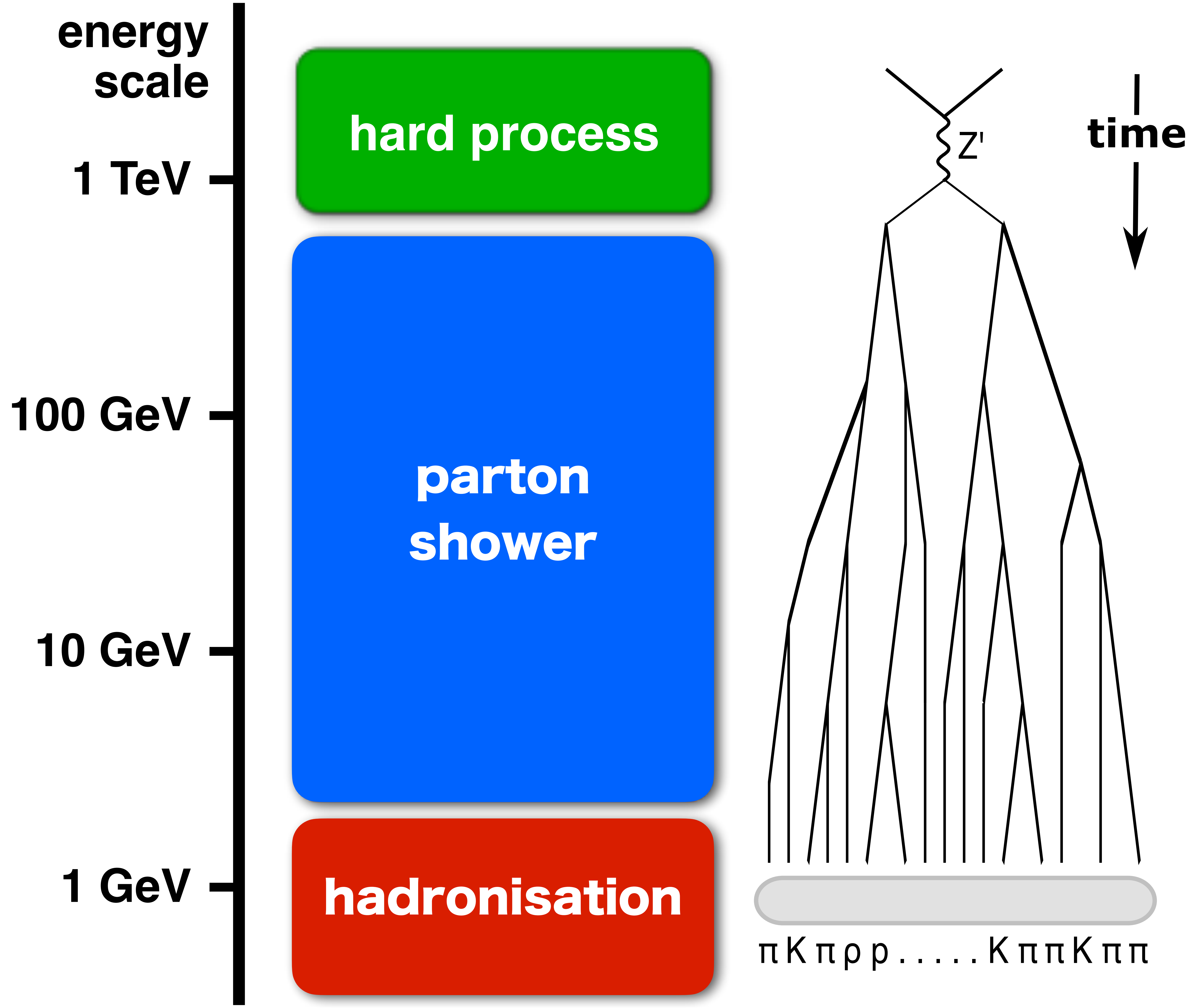
C-parameter $C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2\theta_{ij}}{\left(\sum_i |\vec{p}_i|\right)^2}\,,$

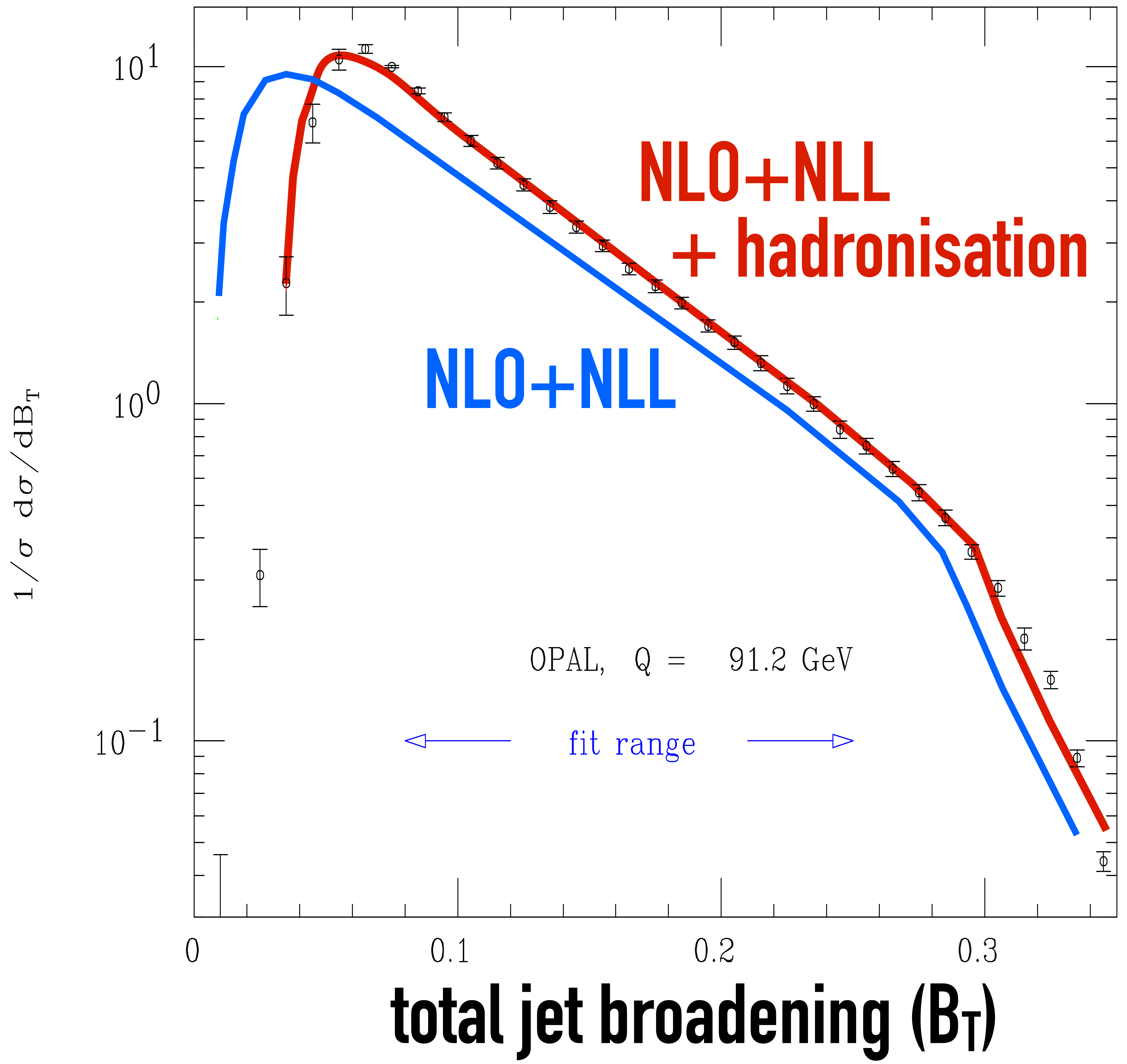
jet-mass $\rho = \frac{\left(\sum_{i \in \text{hemisphere}} p_i\right)^2}{\left(\sum_i E_i\right)^2}\,,$

broadening $B_T = \frac{\sum_i p_{ti}}{\sum_i |\vec{p}_i|}\,.$

event shapes measure amount of radiation relative to simple $e^+e^- \to q\bar{q}$ event

non-perturbative physics & hadronisation: the bane of quantitative collider QCD





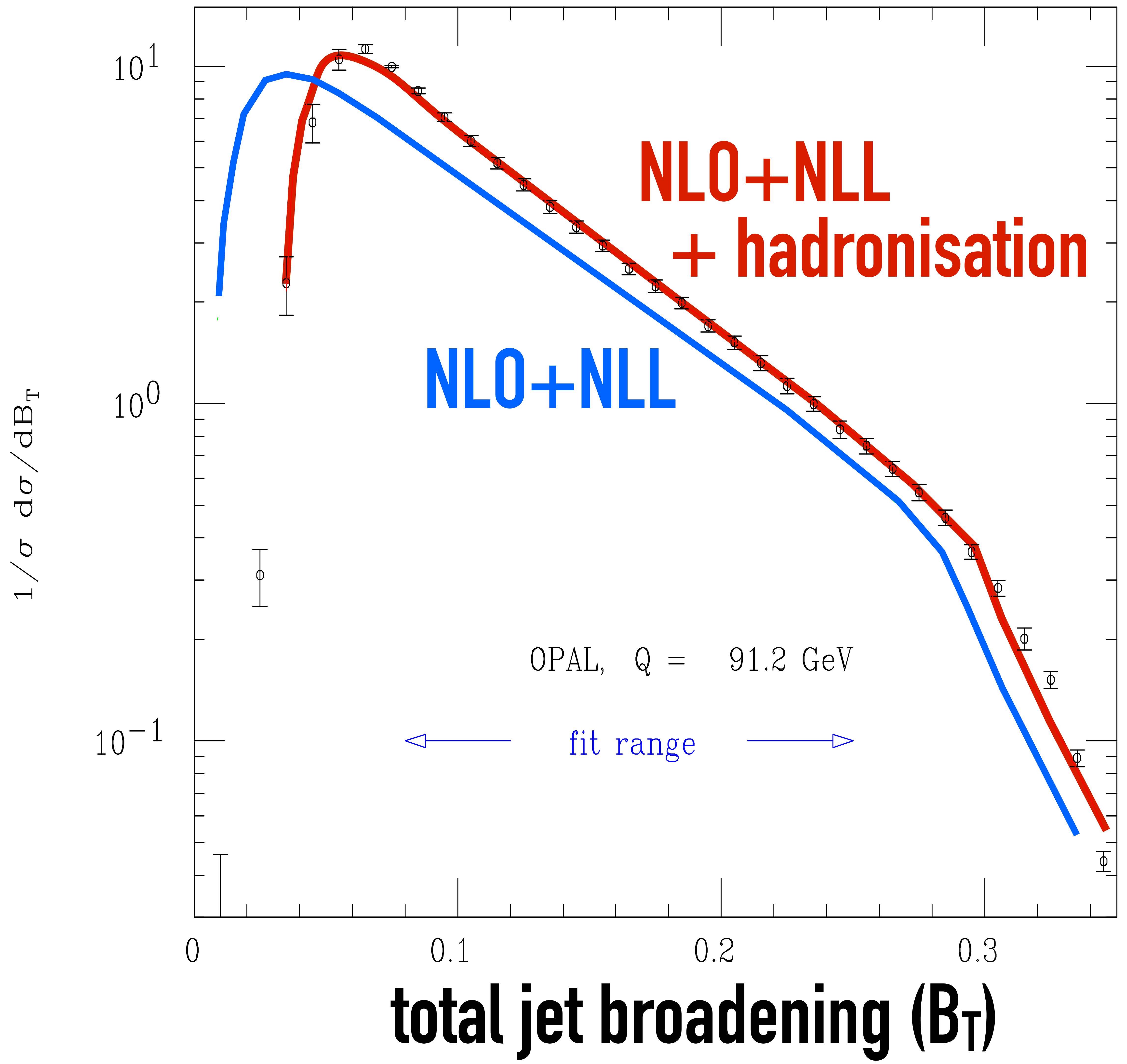
non-perturbative physics & hadronisation: the bane of quantitative collider QCD

c. 1995, theorists proposed analytical approaches to quantifying hadronisation (Dokshitzer, Marchesini & Webber; Beneke & Braun; Manohar & Wise; Korchemsky & Sterman).

$$\delta V \sim \frac{c_V \alpha_0}{Q}$$

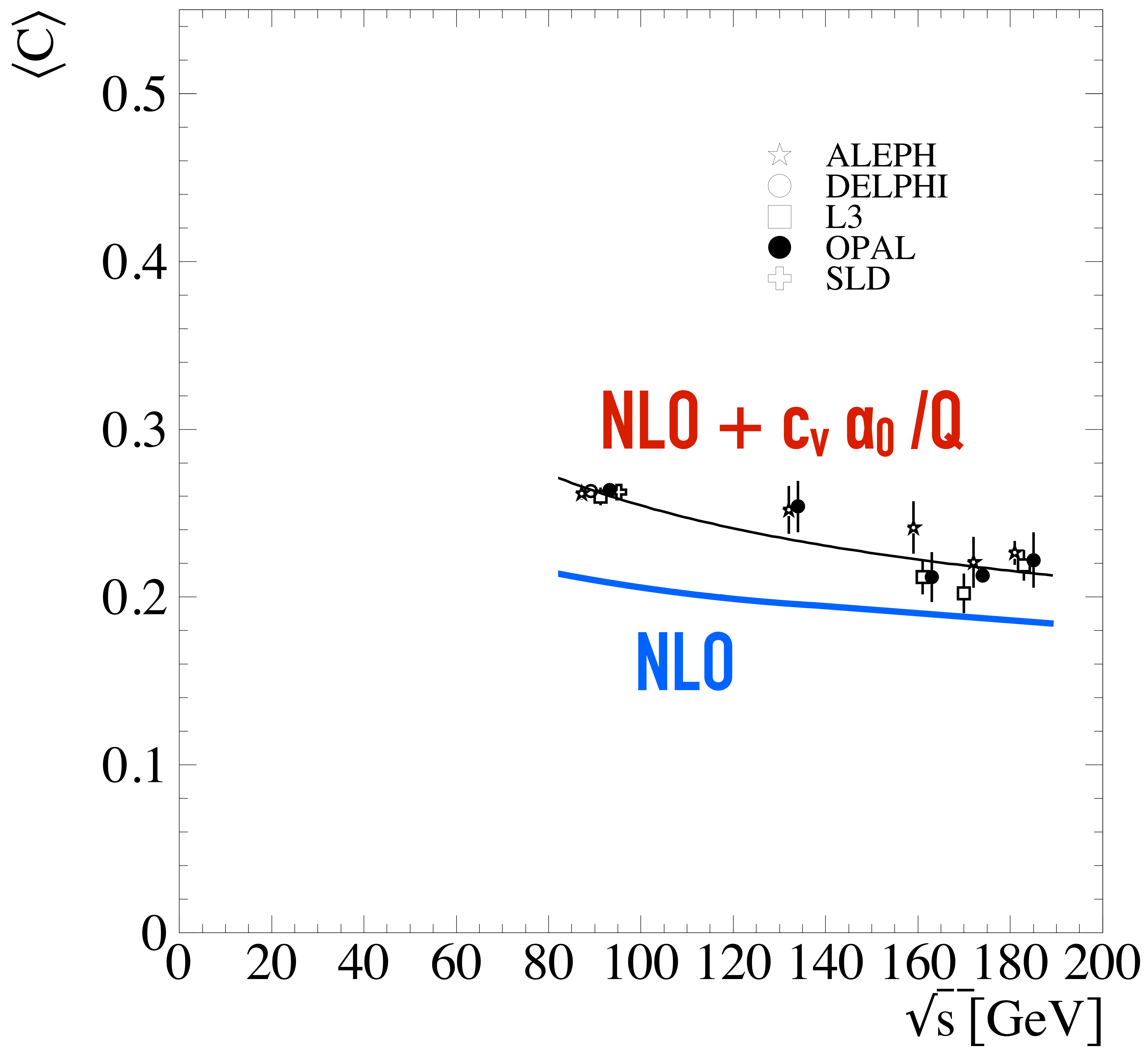
Did they match data?
Two key features to check:

- universality of α_0 across many shapes
- scaling with centre-of-mass energy Q



Only LEP had measured full range of event shapes

but LEP did not have enough lever-arm in Q



The JADE Experiment at the PETRA e^+e^- collider - history, achievements and revival

S. Bethke[1*] and A. Wagner[2*]

JADE experiment: 1979 – 1986 at DESY
[JApan-Deutschland-England]

“So the original JADE data were preserved **[except] the JADE luminosity files.** […] A worldwide search […] found a printed version […] on green recycling paper and too faint for scanning […] the numbers had to be typed in a tedious effort into a text file. Only 5 typing errors were found and corrected by a checksum routine.”

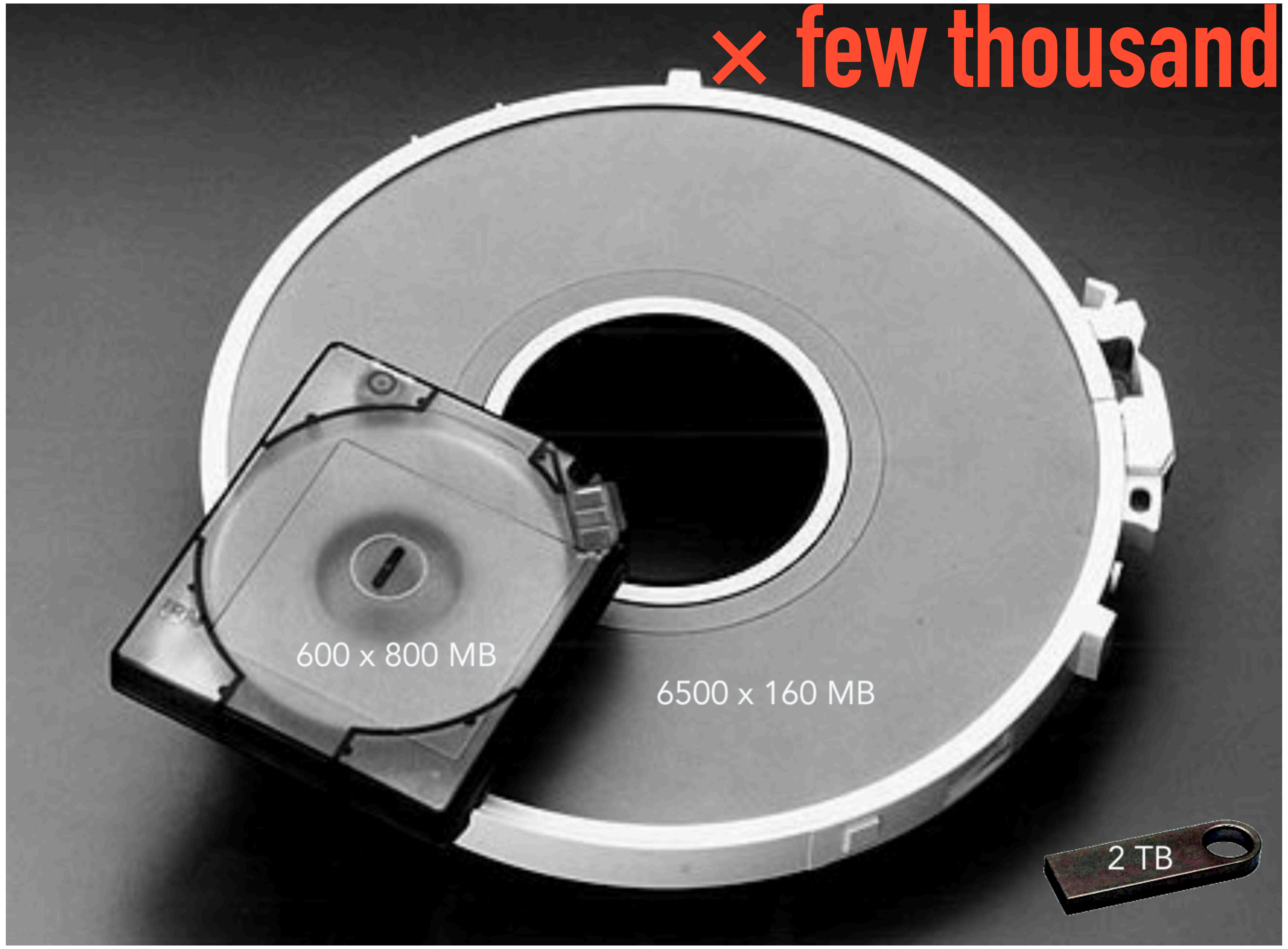


Fig. 22 The JADE data were originally stored on about 6500 IBM tapes, later converted and written to about 600 IBM3490 cartridges, and nowadays conveniently fit onto a single 2 TB USB memory stick.

Bethke & Wagner, 2208.11076

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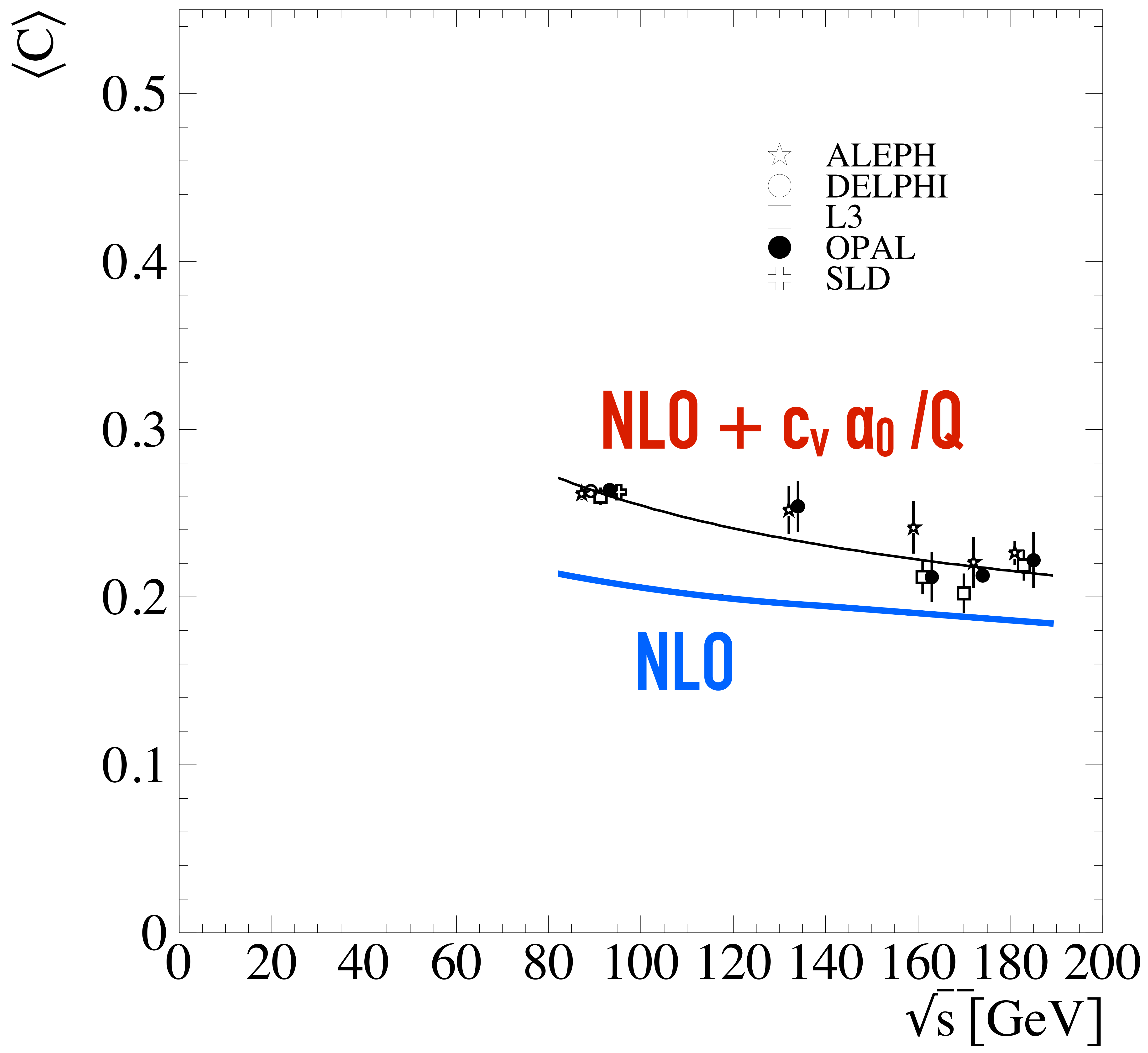
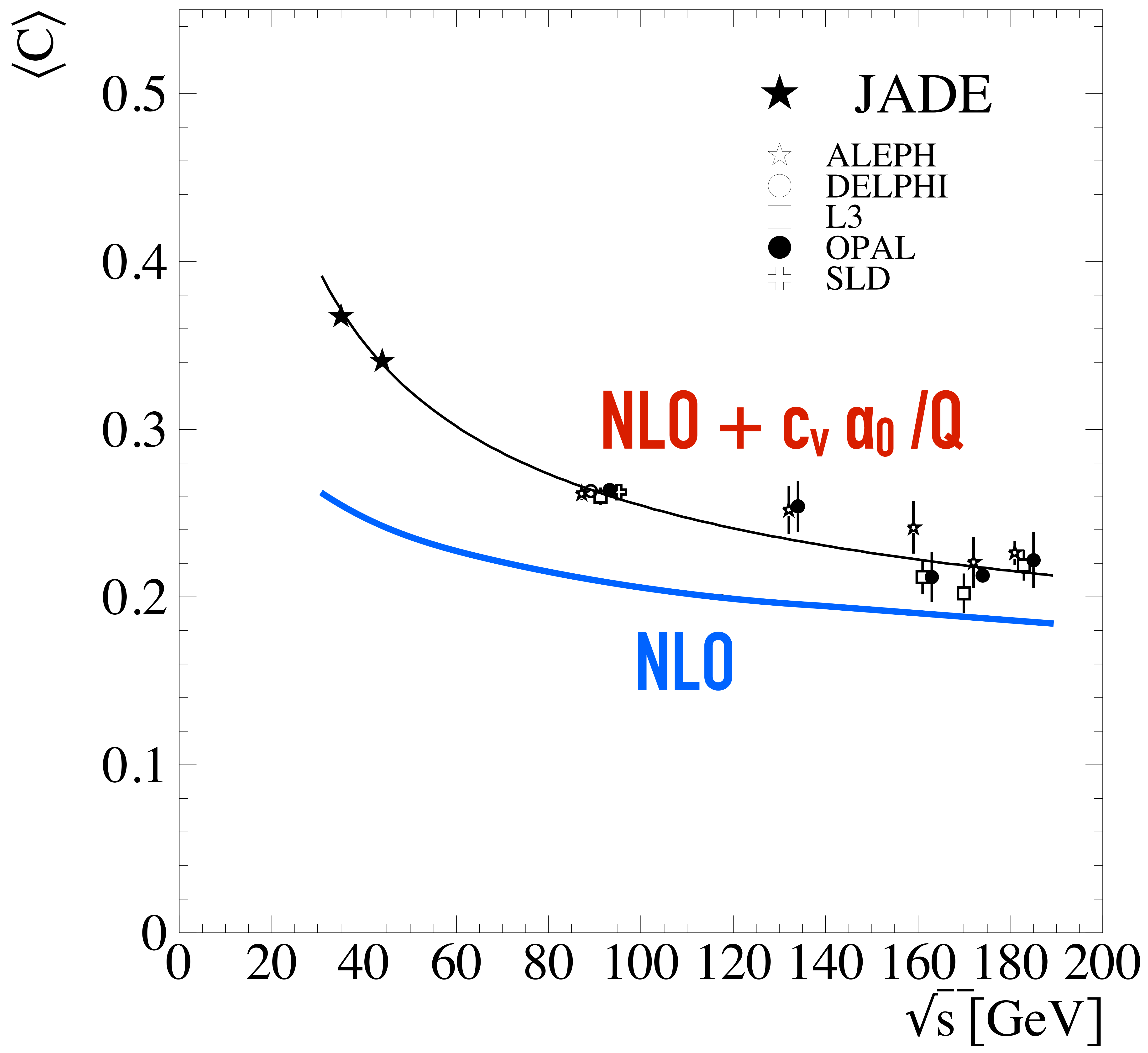


JADE Collab, hep-ex/9903009

Adding in the JADE data played major role in confirming the simple theoretical picture



JADE data + fits

(a)	$\langle 1-T \rangle$	$\langle M_H^2/s \rangle$	$\langle B_T \rangle$	$\langle B_W \rangle$	$\langle C \rangle$	average
$\alpha_S(M_{Z^0})$	**0.1198**	**0.1141**	**0.1183**	**0.1190**	**0.1176**	**0.1177**
Q range [GeV]	13-183	14-183	35-183	35-183	35-183	
$\bar{\alpha}_0(2\text{ GeV})$	**0.509**	**0.614**	**0.442**	**0.392**	**0.451**	**0.473**

JADE collab., hep-ex/9903009

"In March 2022, the members of the JADE collaboration unanimously decided to release all JADE data and software to be publicly accessible as "open data" and maintained within the CERN open data initiative [104]. The implementation of JADE data, software and documentation into this environment is currently in progress."

Bethke & Wagner, 2208.11076

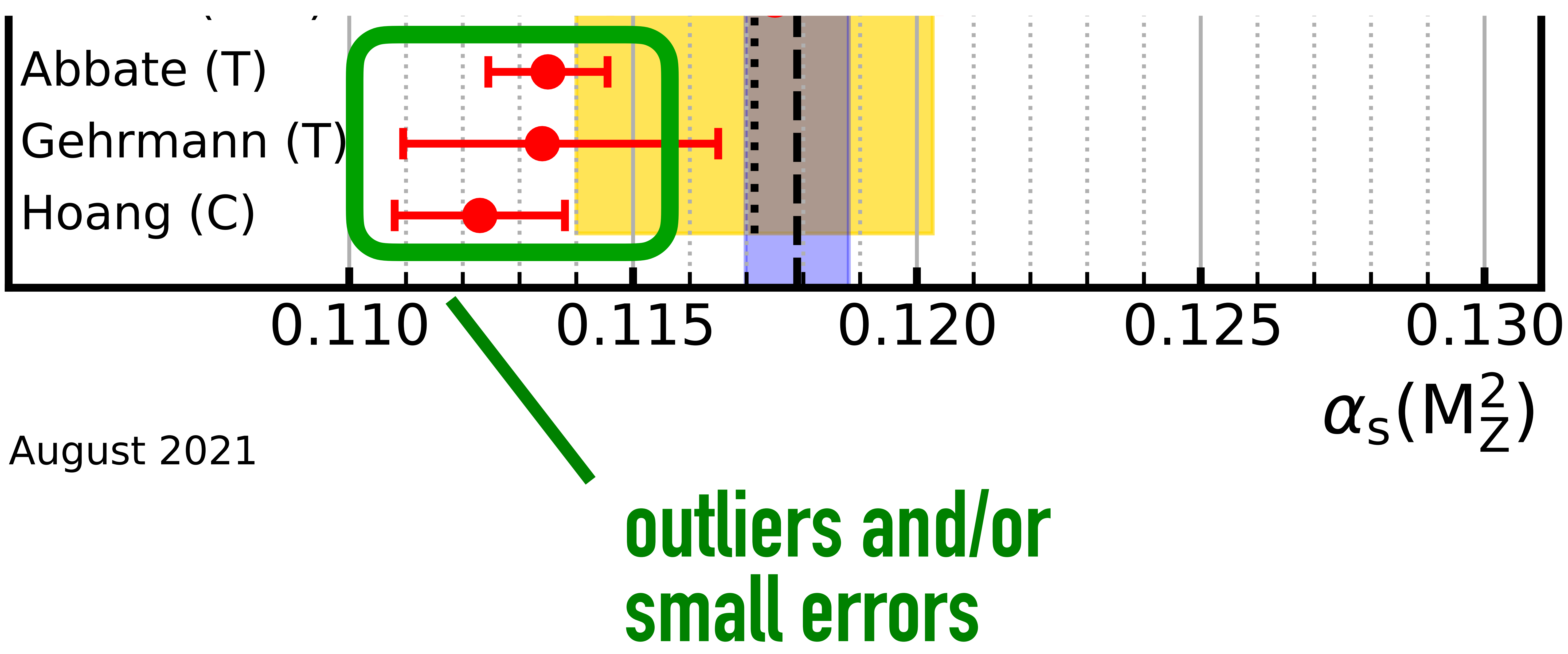
cf. ongoing work by Verbytskyi @ MPI

World average: $\alpha_s(m_Z) = 0.1179 \pm 0.0009$

Thrust: $\alpha_s(m_Z) = 0.1135 \pm 0.0002_{\text{exp}} \pm 0.0005_{\text{hadr}} \pm 0.0009_{\text{pert}}$ 1006.3080

C-parameter: $\alpha_s(m_Z) = 0.1119 \pm 0.0006_{\text{exp+had}} \pm 0.0013_{\text{pert}}$ 1501.04111

NNLO + N3LL **+ 1/*Q***



non-perturbative shift as f^n of C

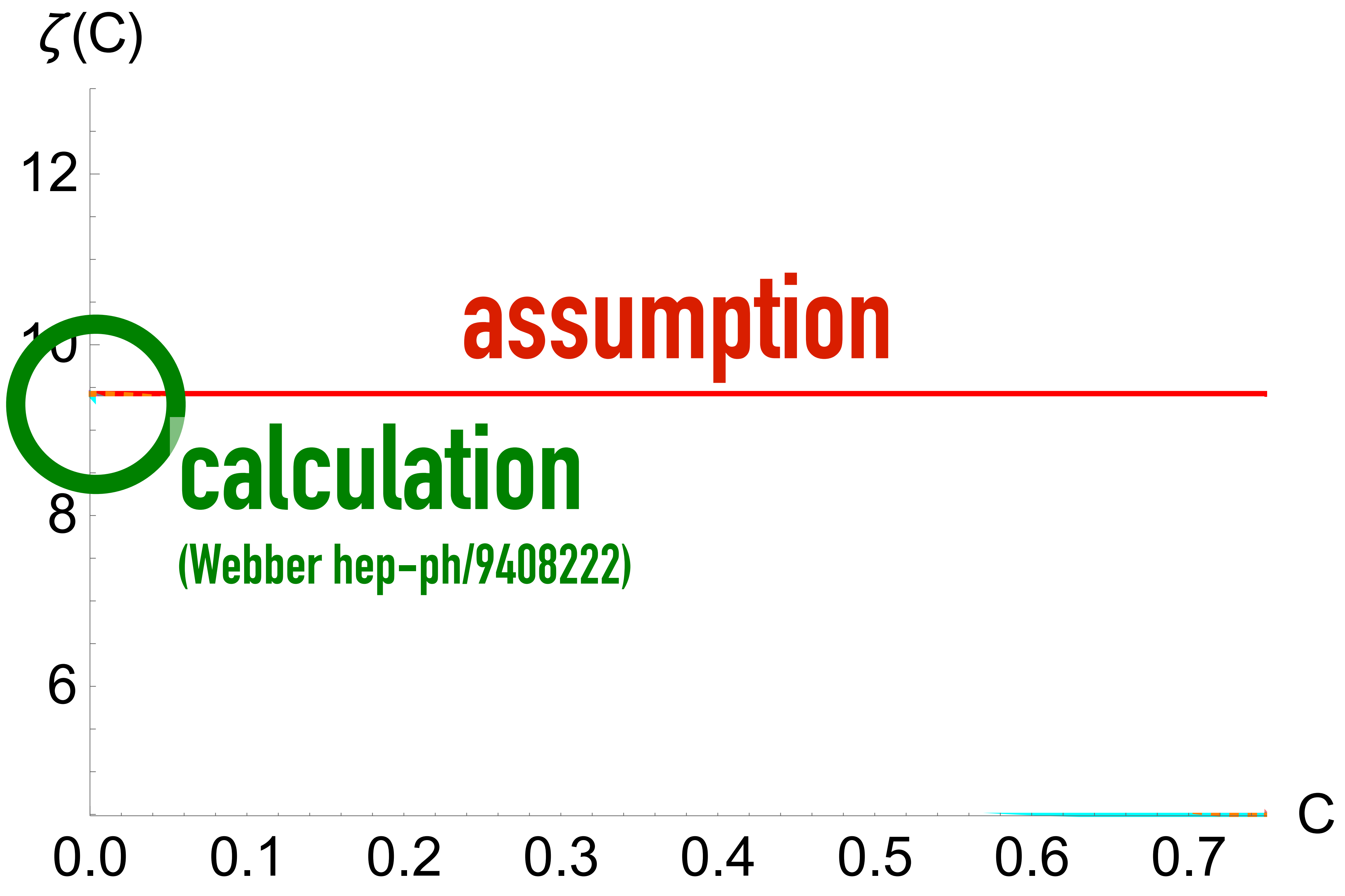


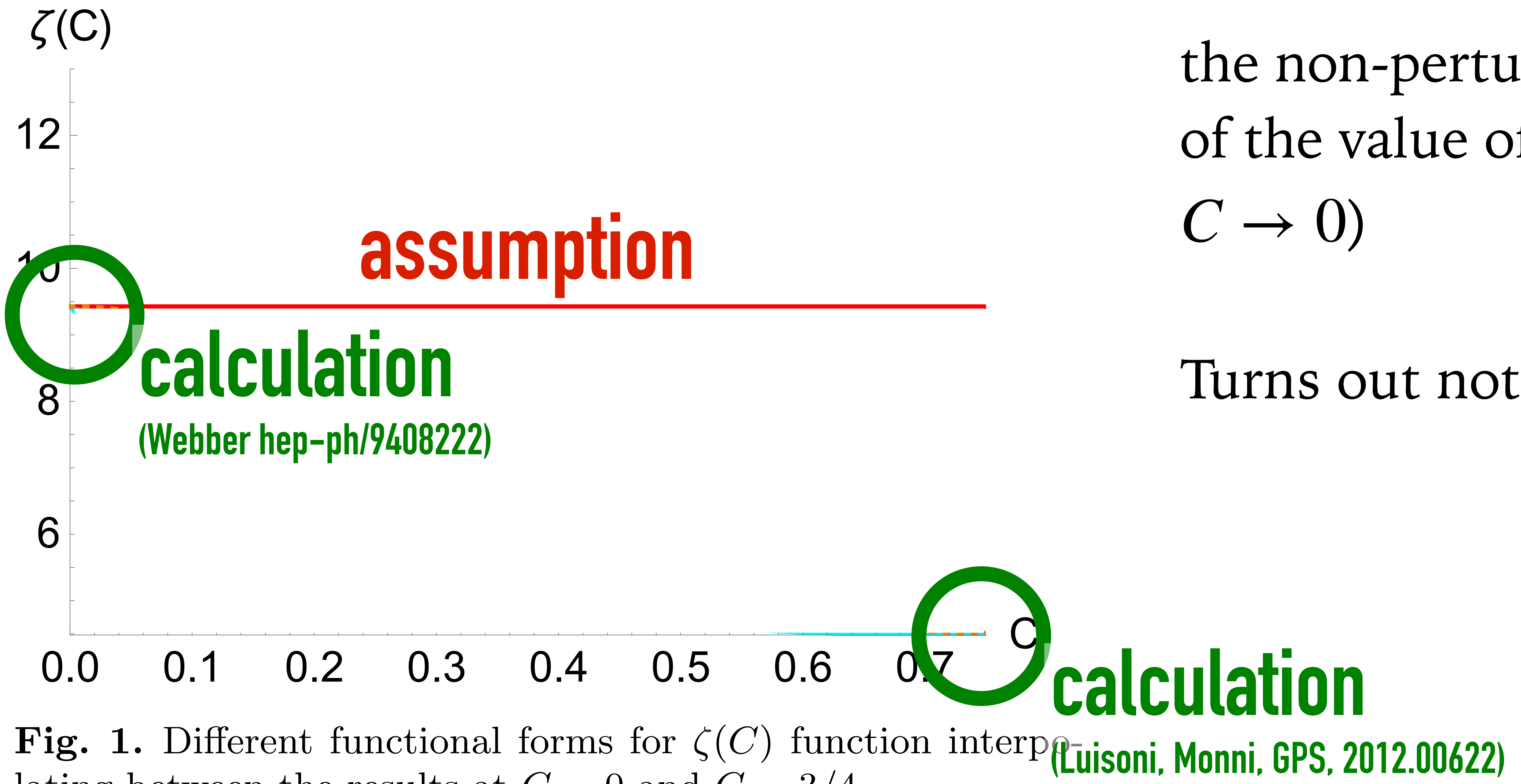
Fig. 1. Different functional forms for $\zeta(C)$ function interpolating between the results at $C = 0$ and $C = 3/4$.

critical assumption in those high-precision fits:

the non-perturbative shift is independent of the value of the observable (valid when $C \to 0$)

Turns out not be true

non-perturbative shift as f^n of C



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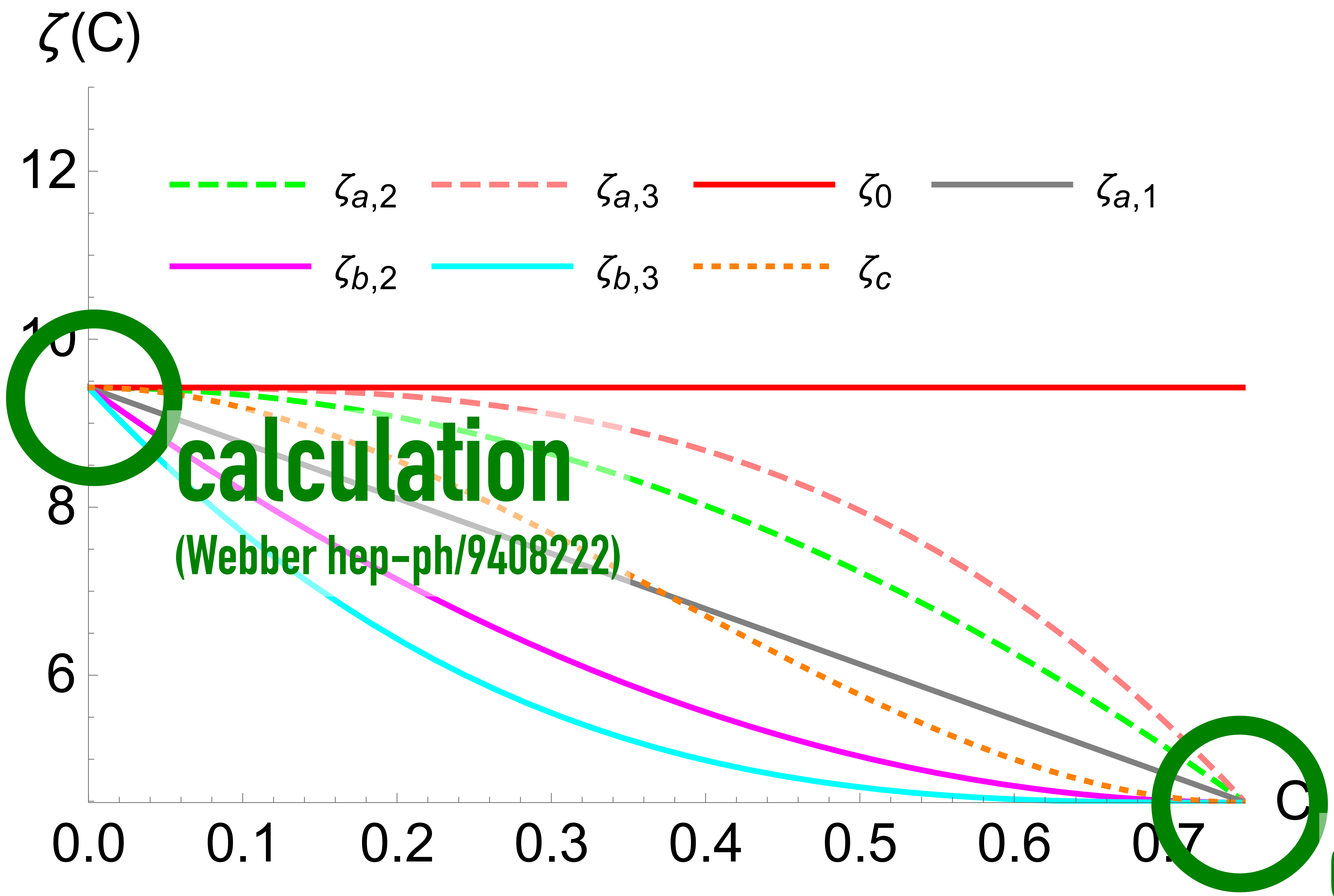
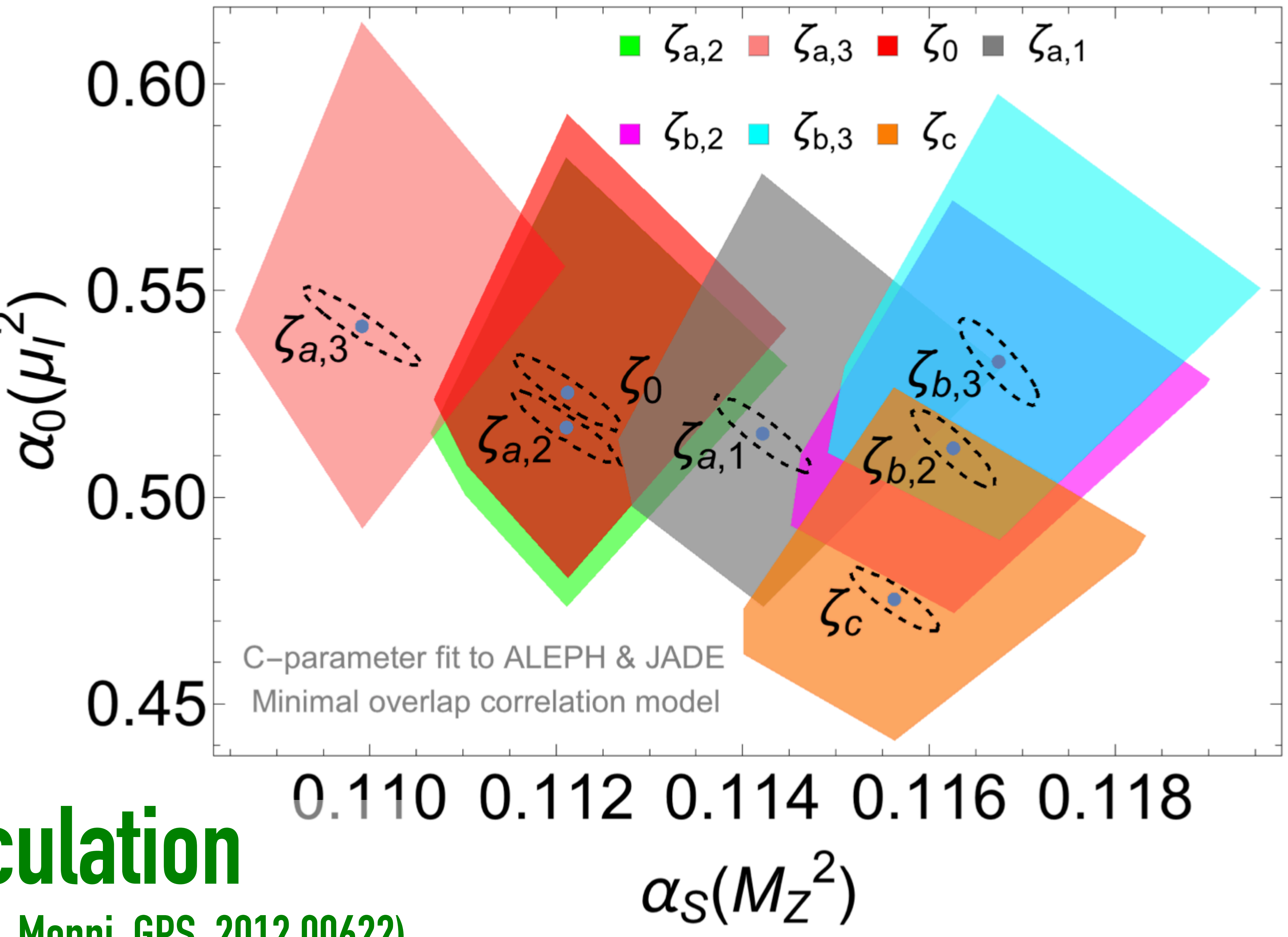


Fig. 1. Different functional forms for $\zeta(C)$ function interpolating between the results at $C = 0$ and $C = 3/4$.

fit results with different interpolations



(Luisoni, Monni, GPS, 2012.00622)

non-perturbative shift as f^n of C

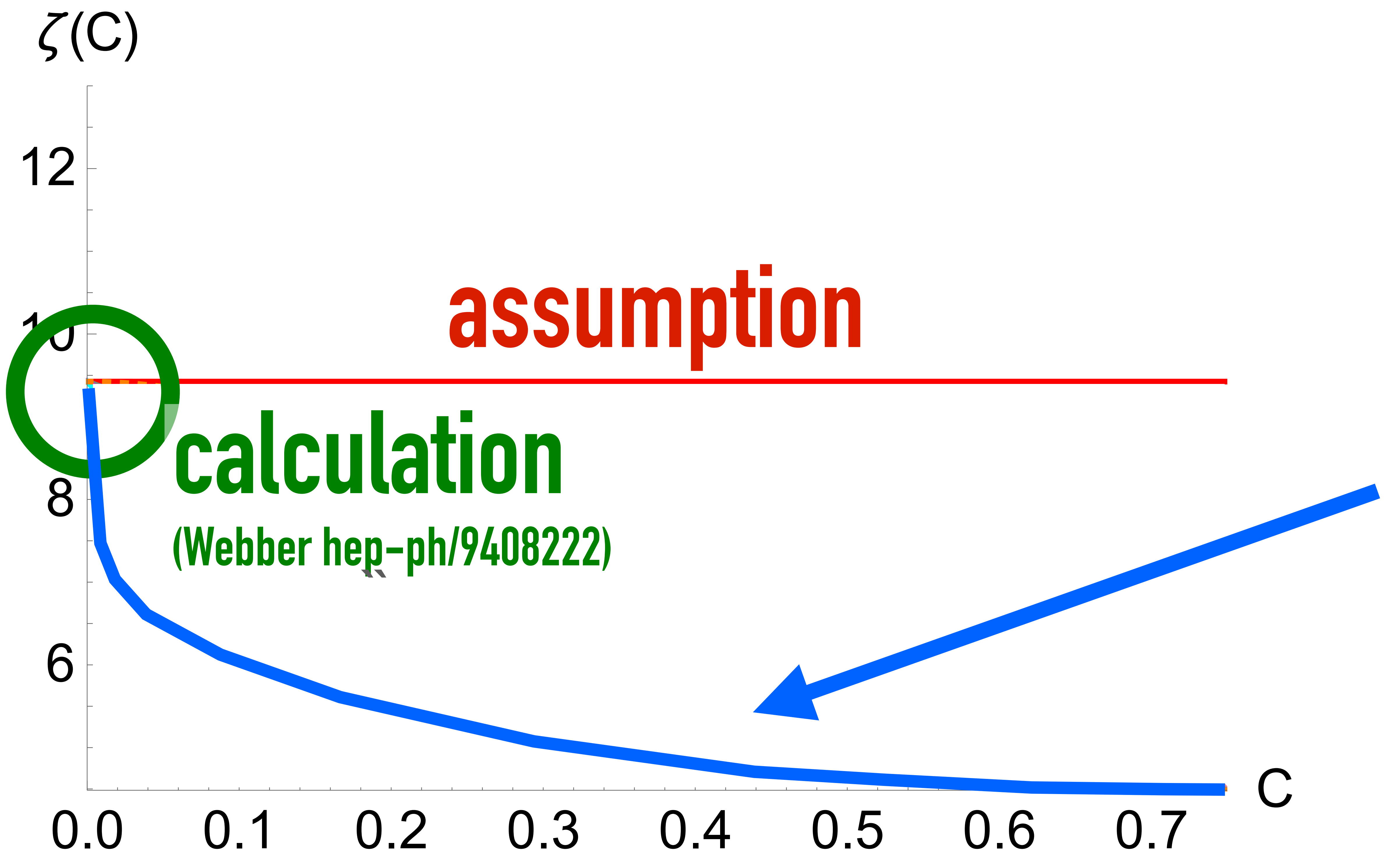


Fig. 1. Different functional forms for $\zeta(C)$ function interpolating between the results at $C = 0$ and $C = 3/4$.

full calculation

Caola, Ferrario Ravasio, Limatola, Melnikov, Nason, Ozcelik, 2204.02247

non-perturbative shift as f^n of C

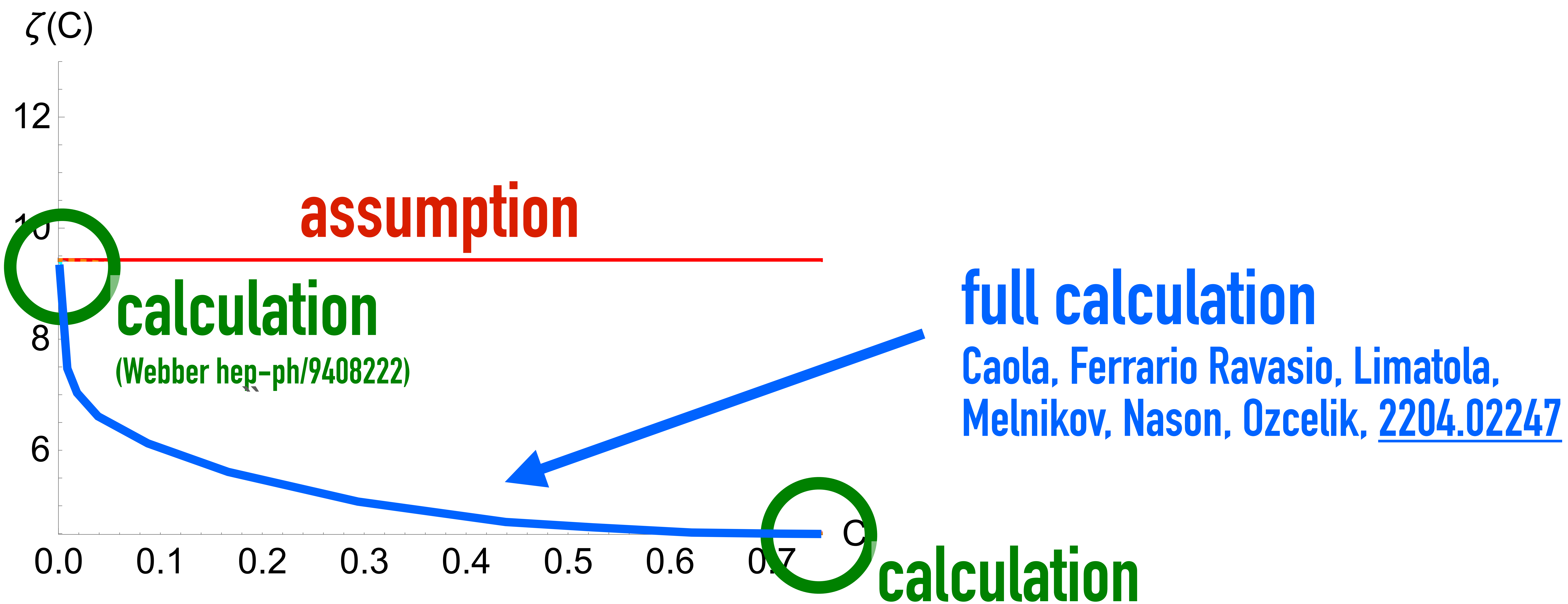
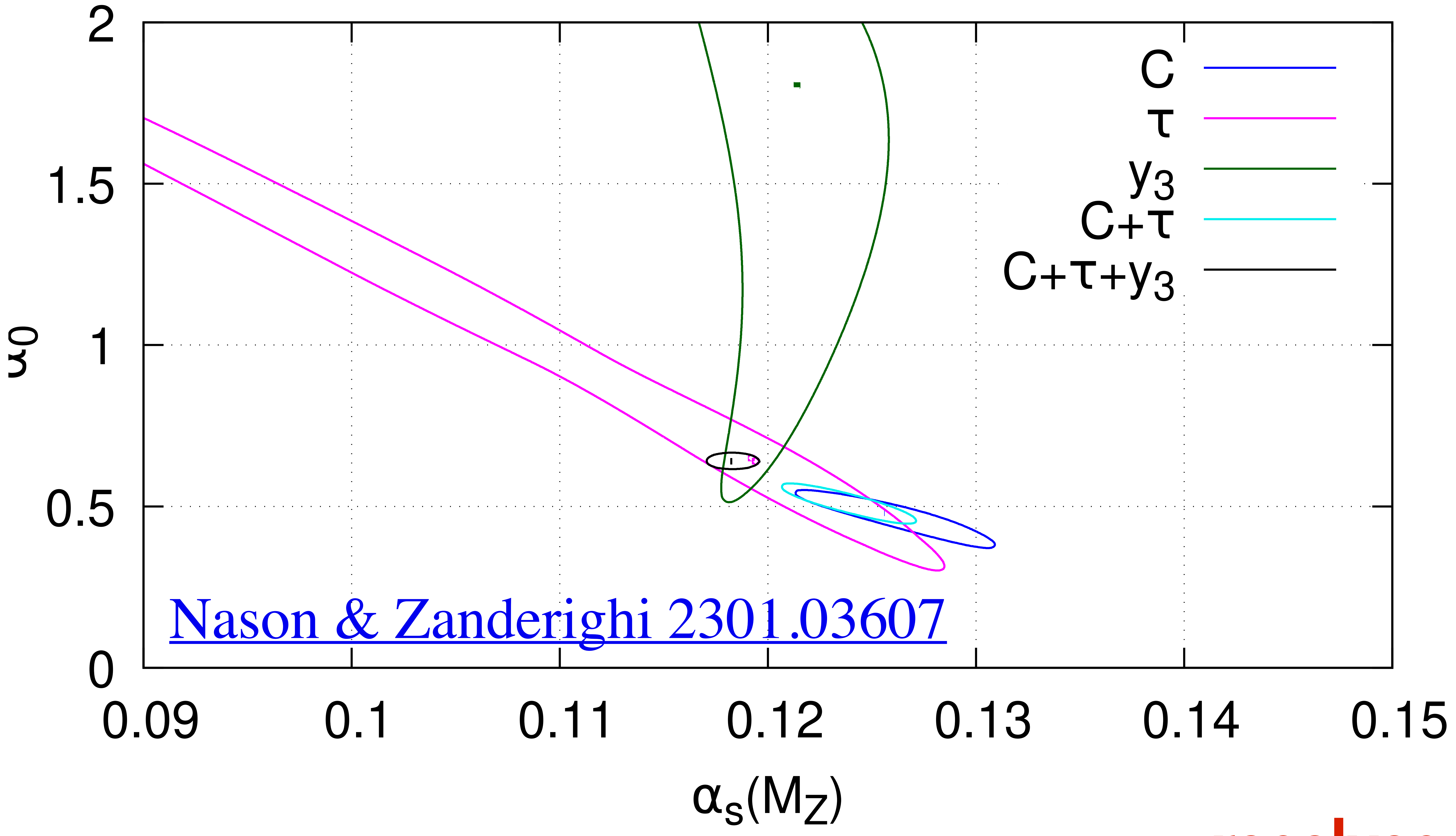


Fig. 1. Different functional forms for $\zeta(C)$ function interpolating between the results at $C = 0$ and $C = 3/4$.

Fits with full (1st-order) non-perturbative correction



fits restricted to 3-jet region, NNLO + 1/Q

fixed 1/Q: $\alpha_s = 0.1132$

full 1/Q: $\alpha_s = 0.1182$

"variations of our procedure can lead easily to differences of the order of a percent"

resolves a long-standing tension

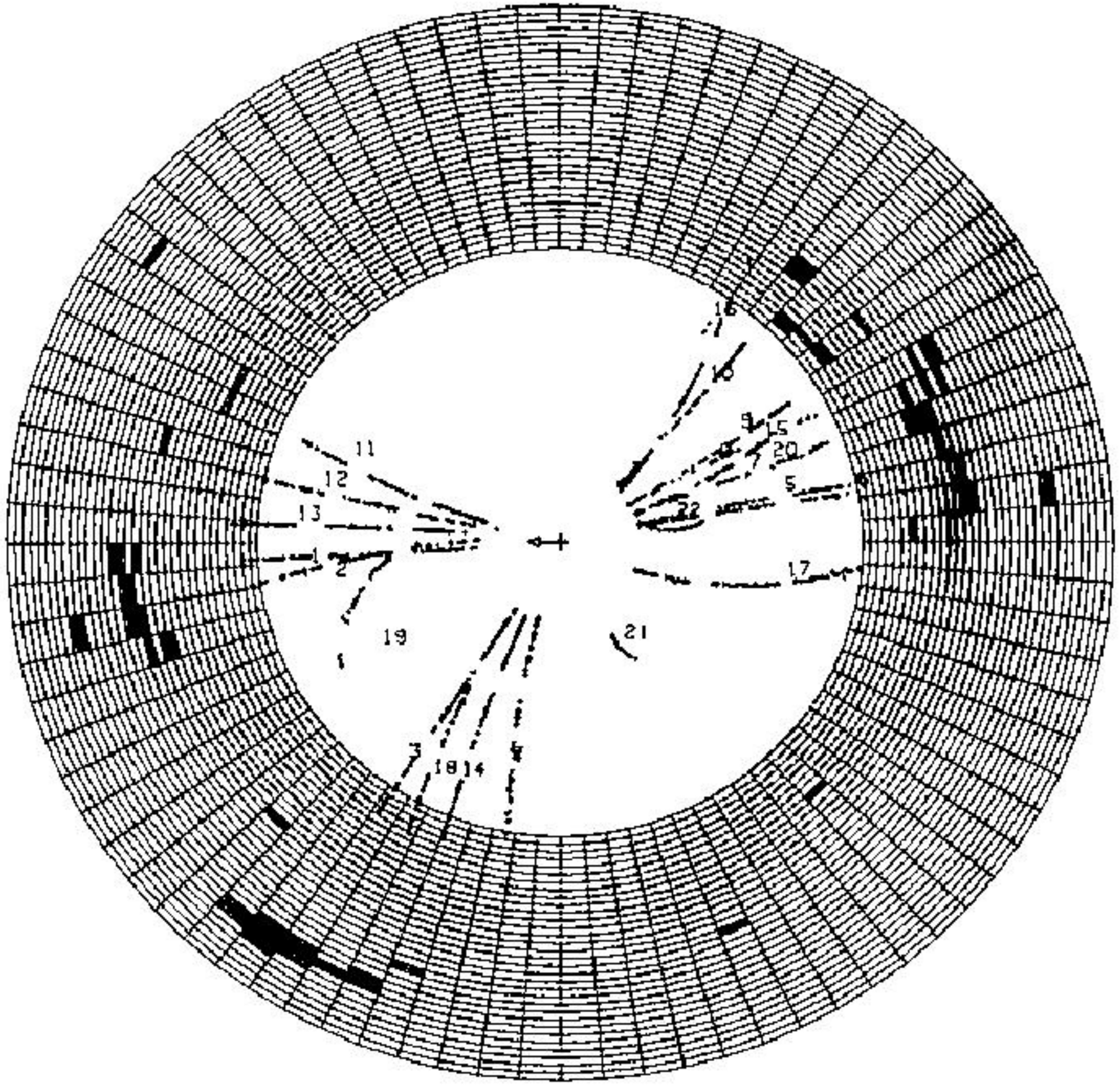
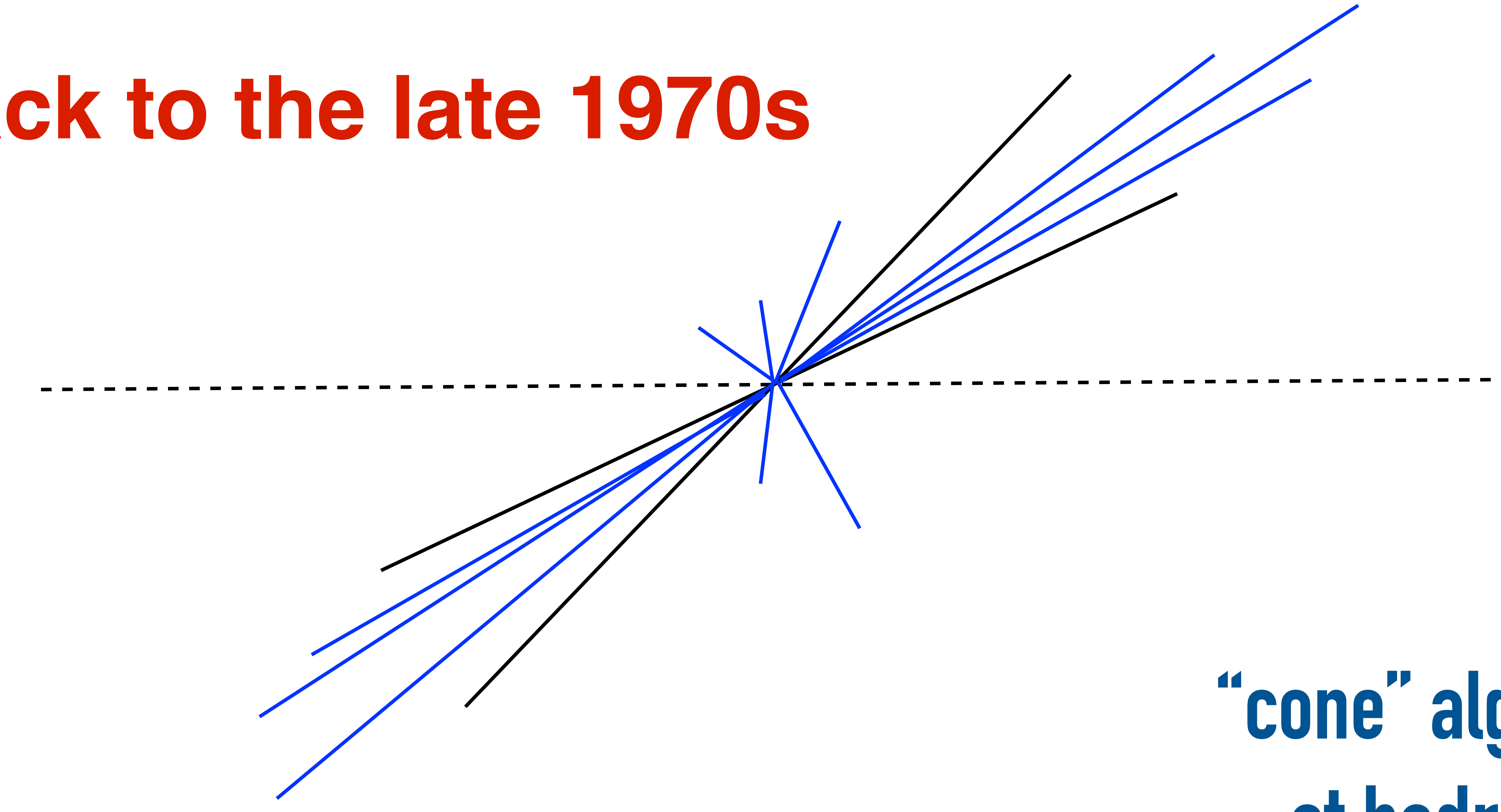


Fig. 10 3-jet event recorded at $E_{cm} = 33$ GeV, displayed as projection of hits in the central Jet-chamber to the plane perpendicular to the beam axis (central cross), and in a perspective view of the lead-glass counters. Those counters hit by particles are filled in black.

QCD jets

how do you project particles into "jets" in a way that makes sense experimentally & in perturbative QCD?

Jet definitions dated back to the late 1970s



Sterman and Weinberg,
Phys. Rev. Lett. 39, 1436 (1977):

To study jets, we consider the partial cross section $\sigma(E,\theta,\Omega,\varepsilon,\delta)$ for e^+e^- hadron production events, in which all but a fraction $\varepsilon \ll 1$ of the total e^+e^- energy E is emitted within some pair of oppositely directed cones of half-angle $\delta \ll 1$, lying within two fixed cones of solid angle Ω (with $\pi\delta^2 \ll \Omega \ll 1$) at an angle θ to the e^+e^- beam line. We expect this to be measur-

$$\sigma(E,\theta,\Omega,\varepsilon,\delta) = (d\sigma/d\Omega)_0\,\Omega\left[1 - (g_E^2/3\pi^2)\left\{3\ln\delta + 4\ln\delta\,\ln 2\varepsilon + \frac{\pi^3}{3} - \frac{5}{2}\right\}\right]$$

"cone" algorithms were favourite at hadron colliders until late 2000's, but very difficult to make infrared safe

SISCone: first infrared/collinear safe cone algorithm [Soyez & GPS, 0704.0292]

Algorithm 2 Procedure for establishing the list of all stable cones (protojets). For simplicity, parts related to the special case of multiple cocircular points (see footnote 7) are not shown. They are a straightforward generalisation of steps 6 to 13.

```
1: For any group of collinear particles, merge them into a single particle.
2: for particle i = 1...N do
3:    Find all particles j within a distance 2R of i. If there are no such particles, i forms
      a stable cone of its own.
4:    Otherwise for each j identify the two circles for which i and j lie on the circumference.
      For each circle, compute the angle of its centre C relative to i, ζ = arctan Δφ_iC/Δy_iC.
5:    Sort the circles found in steps 3 and 4 into increasing angle ζ.
6:    Take the first circle in this order, and call it the current circle. Calculate the total
      momentum and checkxor for the cones that it defines. Consider all 4 permutations
      of edge points being included or excluded. Call these the "current cones".
7:    repeat
8:       for each of the 4 current cones do
9:          If this cone has not yet been found, add it to the list of distinct cones.
10:         If this cone has not yet been labelled as unstable, establish if the in/out status
            of the edge particles (with respect to the cone momentum axis) is the same as
            when defining the cone; if it is not, label the cone as unstable.
11:      end for
12:      Move to the next circle in order. It differs from the previous one either by a
         particle entering the circle, or one leaving the circle. Calculate the momentum for
         the new circle and corresponding new current cones by adding (or removing) the
         momentum of the particle that has entered (left); the checkxor can be updated by
         XORing with the label of that particle.
13:   until all circles considered.
14: end for
15: for each of the cones not labelled as unstable do
16:   Explicitly check its stability, and if it is stable, add it to the list of stable cones
      (protojets).
17: end for
```

Algorithm 3 The disambiguated, scalar $\tilde{p}_t$ based formulation of a Tevatron Run-II type split–merge procedure [6], with overlap threshold parameter f and transverse momentum threshold $p_{t,\min}$. To ensure boost invariance and IR safety, for the ordering variable and the overlap measure, it uses of $\tilde{p}_{t,\text{jet}} = \sum_{i\in\text{jet}} |p_{t,i}|$, *i.e.* a scalar sum of the particle transverse momenta (as in a 'p_t' recombination scheme).

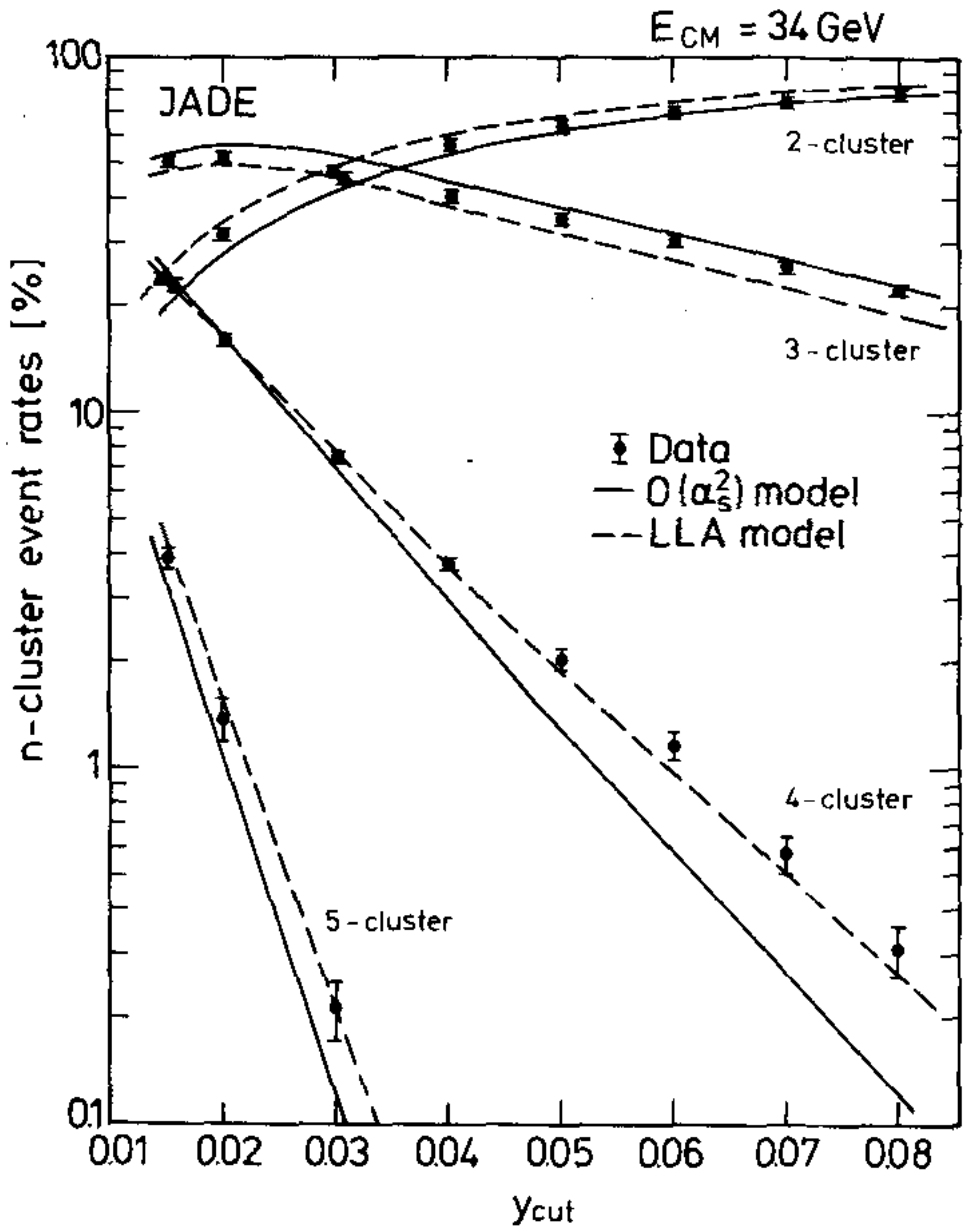
```
1: repeat
2:    Remove all protojets with p_t < p_t,min.
3:    Identify the protojet (i) with the highest p̃_t.
4:    Among the remaining protojets identify the one (j) with highest p̃_t that shares
      particles (overlaps) with i.
5:    if there is such an overlapping jet then
6:       Determine the total p̃_t,shared = Σ_{k∈i&j} |p_t,k| of the particles shared between i and
         j.
7:       if p̃_t,shared < f p̃_t,j then
8:          Each particle that is shared between the two protojets is assigned to the one to
            whose axis it is closest. The protojet momenta are then recalculated.
9:       else
10:         Merge the two protojets into a single new protojet (added to the list of protojets,
            while the two original ones are removed).
11:      end if
12:      If steps 7–11 produced a protojet that coincides with an existing one, maintain
         the new protojet as distinct from the existing copy(ies).
13:   else
14:      Add i to the list of final jets, and remove it from the list of protojets.
15:   end if
16: until no protojets are left.
```

unappealingly complex

Experimental Studies on Multijet Production in e^+e^- Annihilation at PETRA Energies

Z. Phys. C – Particles and Fields 33, 23–31 (1986)

JADE Collaboration



the JADE algorithm

For all pairs of particles k and l of an event, the scaled invariant mass squared $y_{kl} = M_{kl}^2/E_{vis}^2$ is calculated, where E_{vis} is the total visible energy of an event*. The two particles with the smallest value of y_{kl} are replaced by a pseudoparticle or "cluster" of four-momentum $(p_k + p_l)$. This procedure is repeated until all y_{kl} exceed a certain threshold value y_{cut},

the first complete, infrared & collinear safe jet algorithm — remarkably simple

PHYSICS LETTERS B
Volume 213, number 2
20 October 1988

EXPERIMENTAL INVESTIGATION OF THE ENERGY DEPENDENCE OF THE STRONG COUPLING STRENGTH

JADE Collaboration

S. BETHKE [a,1], J. ALLISON [b], K. AMBRUS [a], R.J. BARLOW [b], W. BARTEL [c], C.K. BOWDERY [d], S.L. CARTWRIGHT [e,2], J. CHRIN [b], D. CLARKE [e], A. DIECKMANN [a], I.P. DUERDOTH [b], G. ECKERLIN [a], E. ELSEN [a], R. FELST [c], A.J. FINCH [d], F. FOSTER [d], T. GREENSHAW [f], J. HAGEMANN [f], D. HAIDT [c], J. HEINTZE [a], G. HEINZELMANN [f], K.H. HELLENBRAND [a,3], P. HILL [g], G. HUGHES [d], H. KADO [2], K. KAWAGOE [h], C. KLEINWORT [f], G. KNIES [c], T. KOBAYASHI [h], S. KOMAMIYA [a,4], H. KREHBIEL [c], J. von KROGH [a], M. KUHLEN [f], F.K. LOEBINGER [b], A.A. MACBETH [b], N. MAGNUSSEN [c,5], R. MARSHALL [e], R. MEINKE [c], R.P. MIDDLETON [e], M. MINOWA [h], P.G. MURPHY [b], B. NAROSKA [c], J.M. NYE [d], J. OLSSON [c], F. OULD-SAADA [f], A. PETERSEN [f,6], R. RAMCKE [f], H. RIESEBERG [3], D. SCHMIDT [c,5], H. v.d. SCHMITT [a], L. SMOLIK [a], U. SCHNEEKLOTH [f,2], J.A.J. SKARD [g,7], J. SPITZER [a], P. STEFFEN [c], K. STEPHENS [b], A. WAGNER [a], I.W. WALKER [d], P. WARMING [b,8], G. WEBER [f], M. ZIMMER [a] and G.T. ZORN [g]

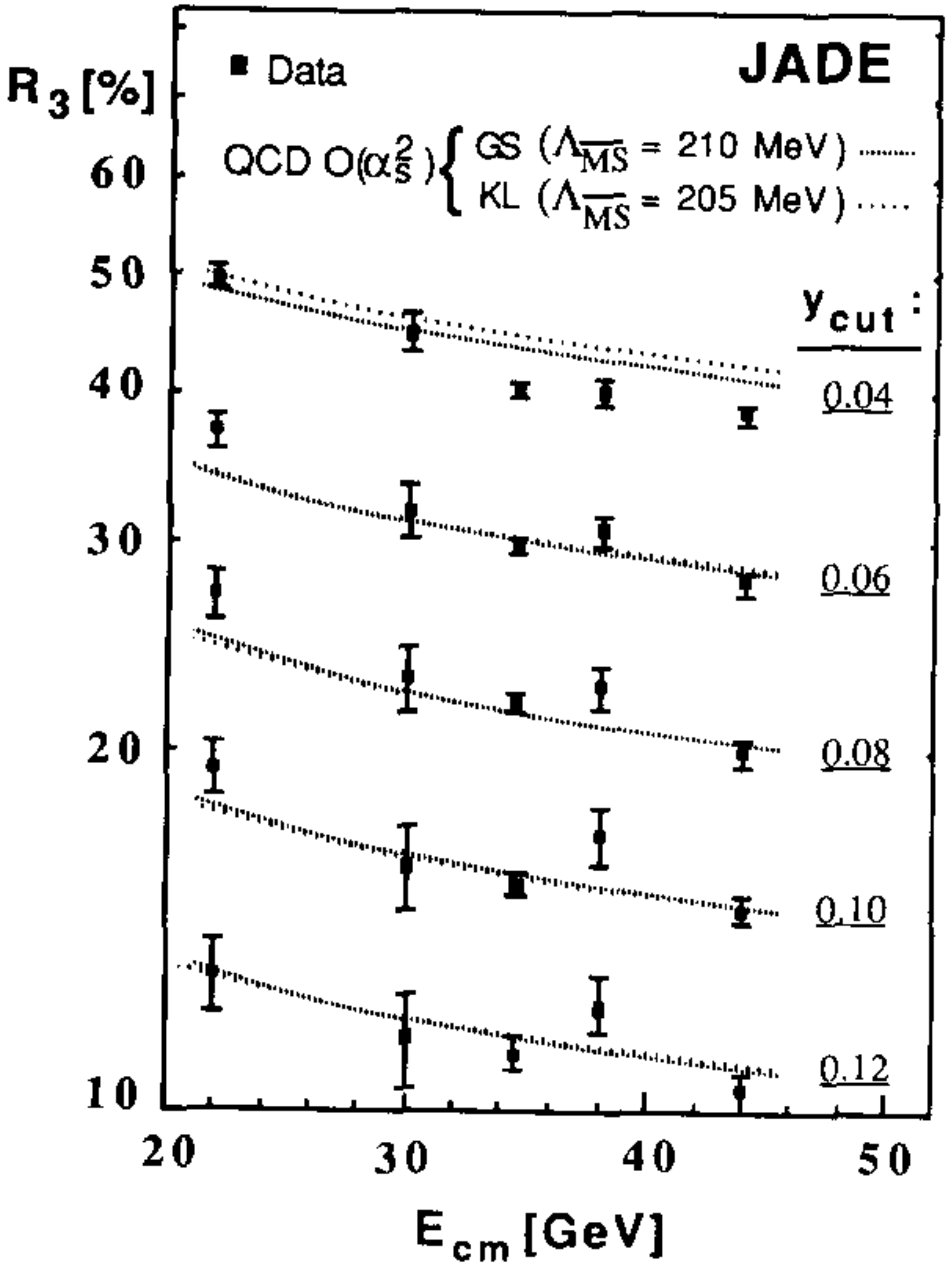


Fig. 2. Three-jet event rates at different centre of mass energies for various values of y_{cut}, together with the direct predictions of the complete second-order perturbative QCD calculations of Gottschalk and Shatz (GS) and of Kramer and Lampe (KL).

characteristics of the JADE algorithm

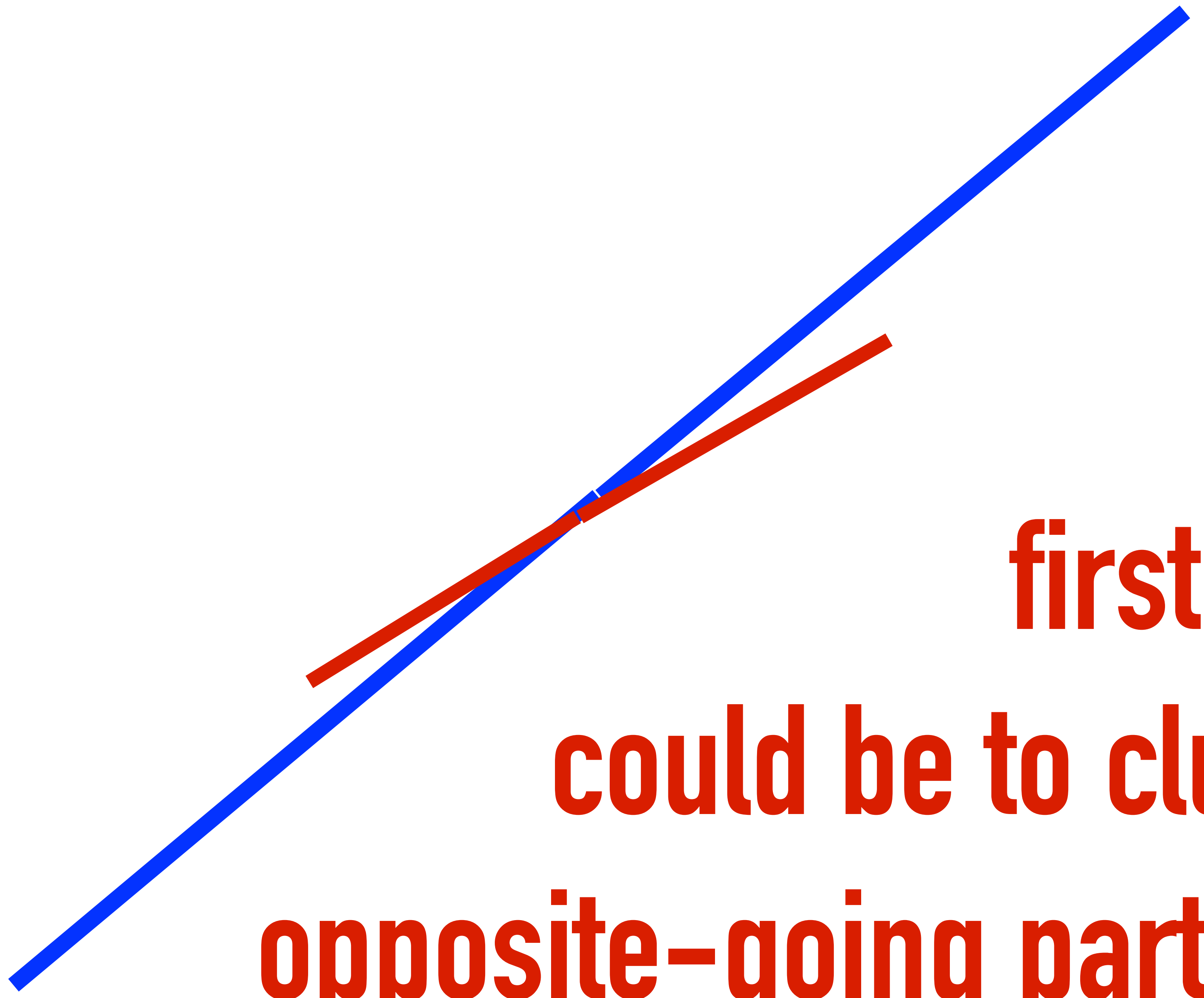
Jet cross sections at leading double logarithm in $e^+ e^-$ annihilation
Brown & Stirling, PLB 1990

It was, however, conjectured by Smilga [8] that the two-jet fraction would exponentiate:

$$f_2 = \exp\left(-\frac{C_F\alpha_s}{\pi}\ln^2 y\right). \qquad (37)$$

[carrying out the explicit calculation] we obtain

$$f_2 = 1 - \frac{C_F\alpha_s}{\pi}\ln^2 y + \frac{1}{2!}\left(\frac{C_F\alpha_s}{\pi}\right)^2 \ln^4 y \boxed{\left(\frac{5}{6}\right)}.$$



first step
could be to cluster
opposite-going particles

JET STUDIES WORKSHOP
ST. JOHN'S COLLEGE, DURHAM.
DECEMBER 1990

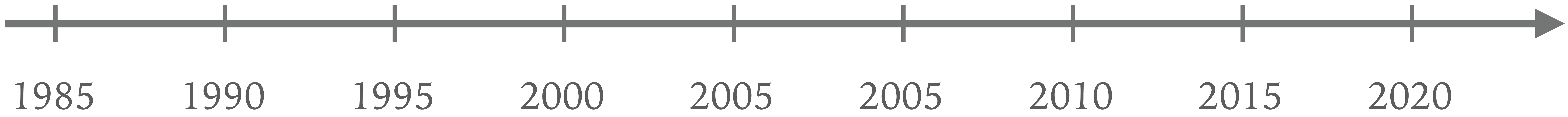
JADE algorithm descendants: modify pairwise distance

Durham k_t-algorithm: $d_{ij} = \min(E_i^2, E_j^2)(1 - \cos\theta_{ij})$

Catani, Dokshitzer, Olsson, Turnock, Webber

JADE

$d_{ij} = E_i E_j (1 - \cos\theta_{ij})$



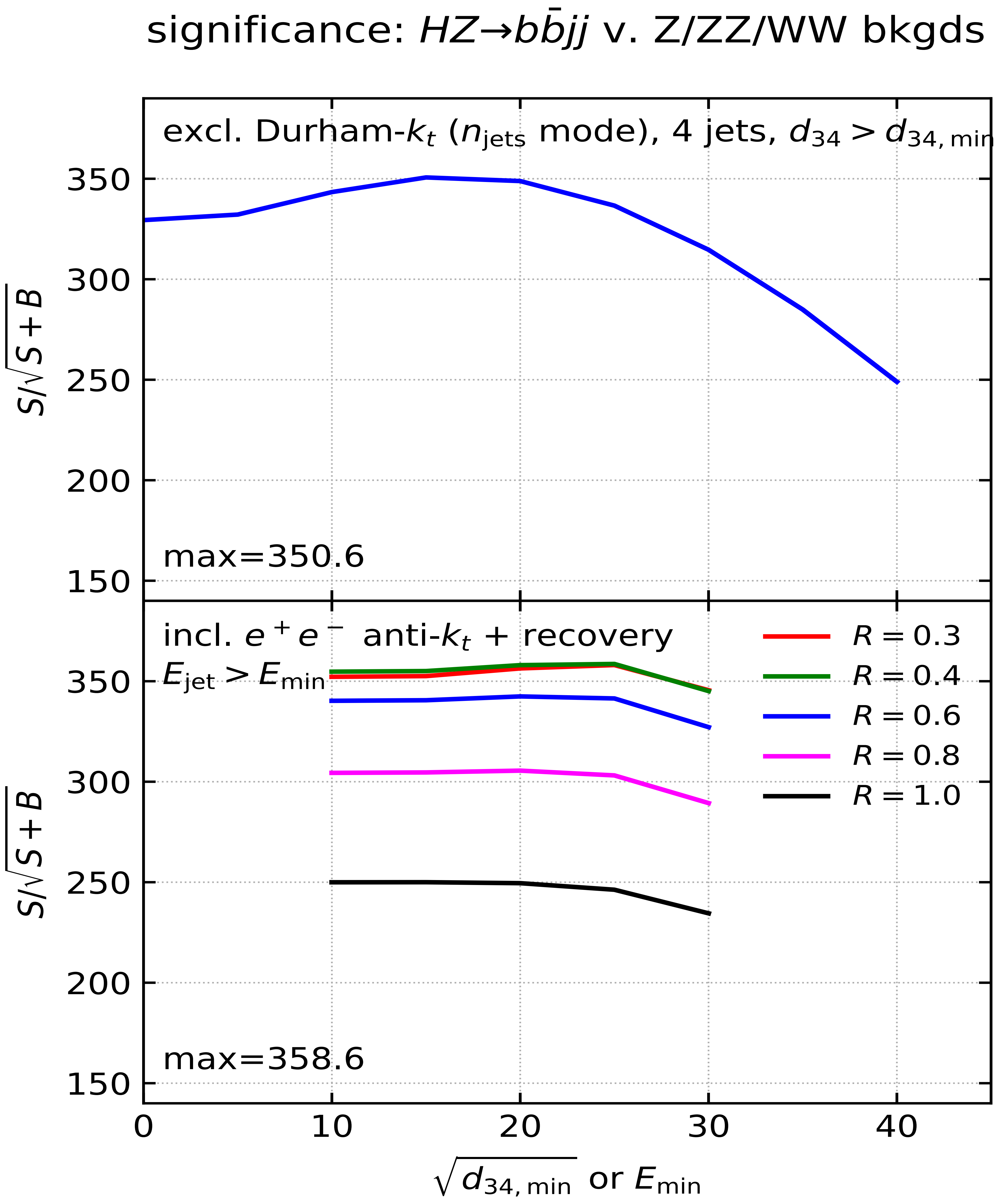
Durham-k_t algorithm: widely used at LEP, good performance for FCCee

FCC $e^+e^- \to HZ \to bbjj$ analysis

illustration of impact of d_{34} cut

- too small a limit on d_{34} leads to enhanced background
- too large a limit cuts out large fraction of signal
- One can scan over d_{34} cut to optimise $S/\sqrt{S+B}$
- A modern analysis might use the event-by event d_{34} value as a ML input (or full jet momenta)

Cacciari, GPS & Soyez 2022



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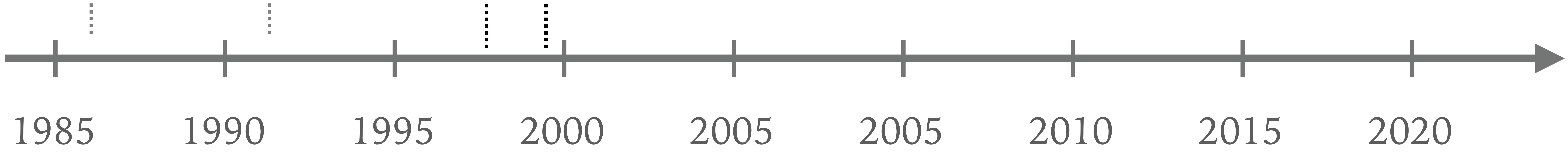
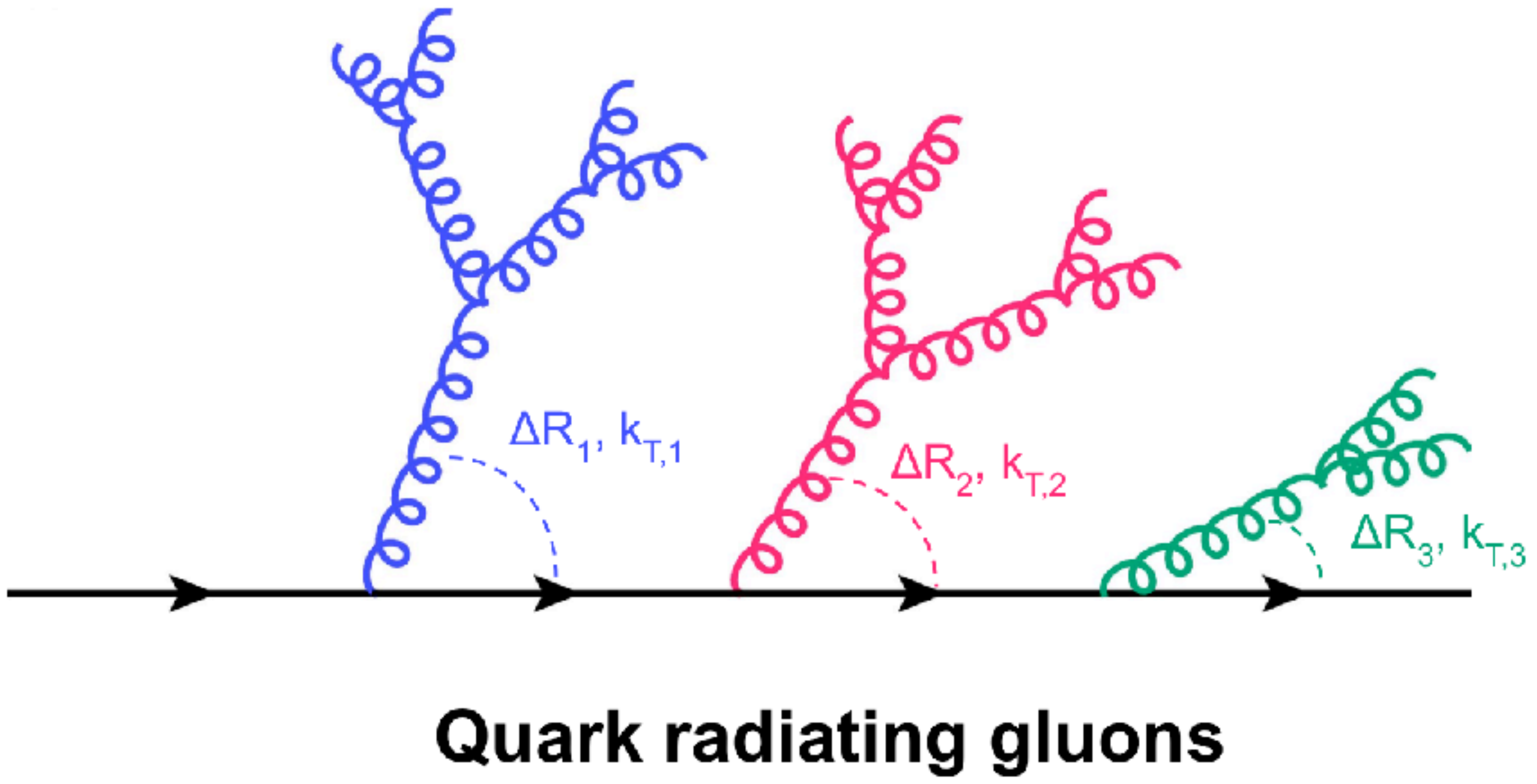
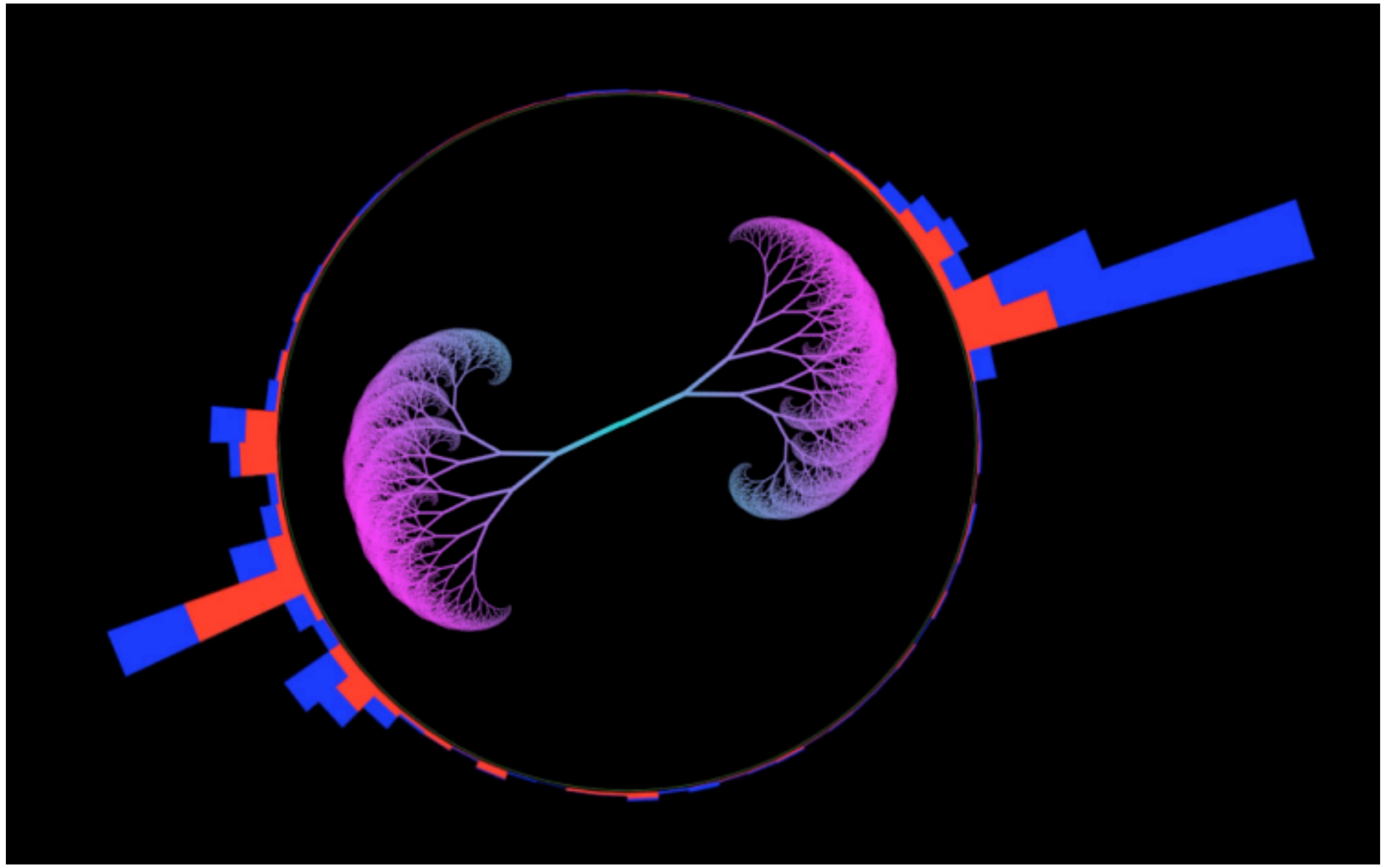


Cambridge/Aachen algorithm: best for substructure





https://cms.cern/news/fractal-tree-quarks-and-gluons

based on "Lund plane" concept for declustering and analysing the C/A sequence
Dreyer, GPS & Soyez, 1807.04758

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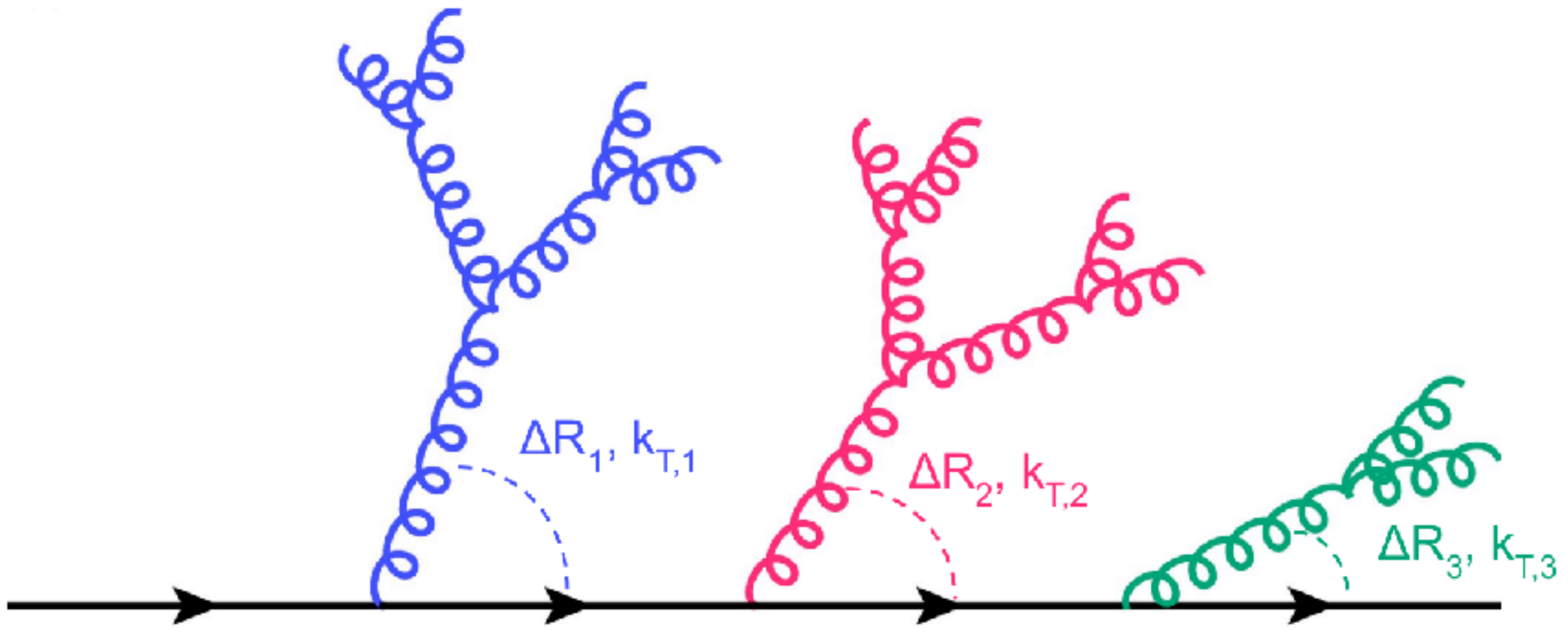
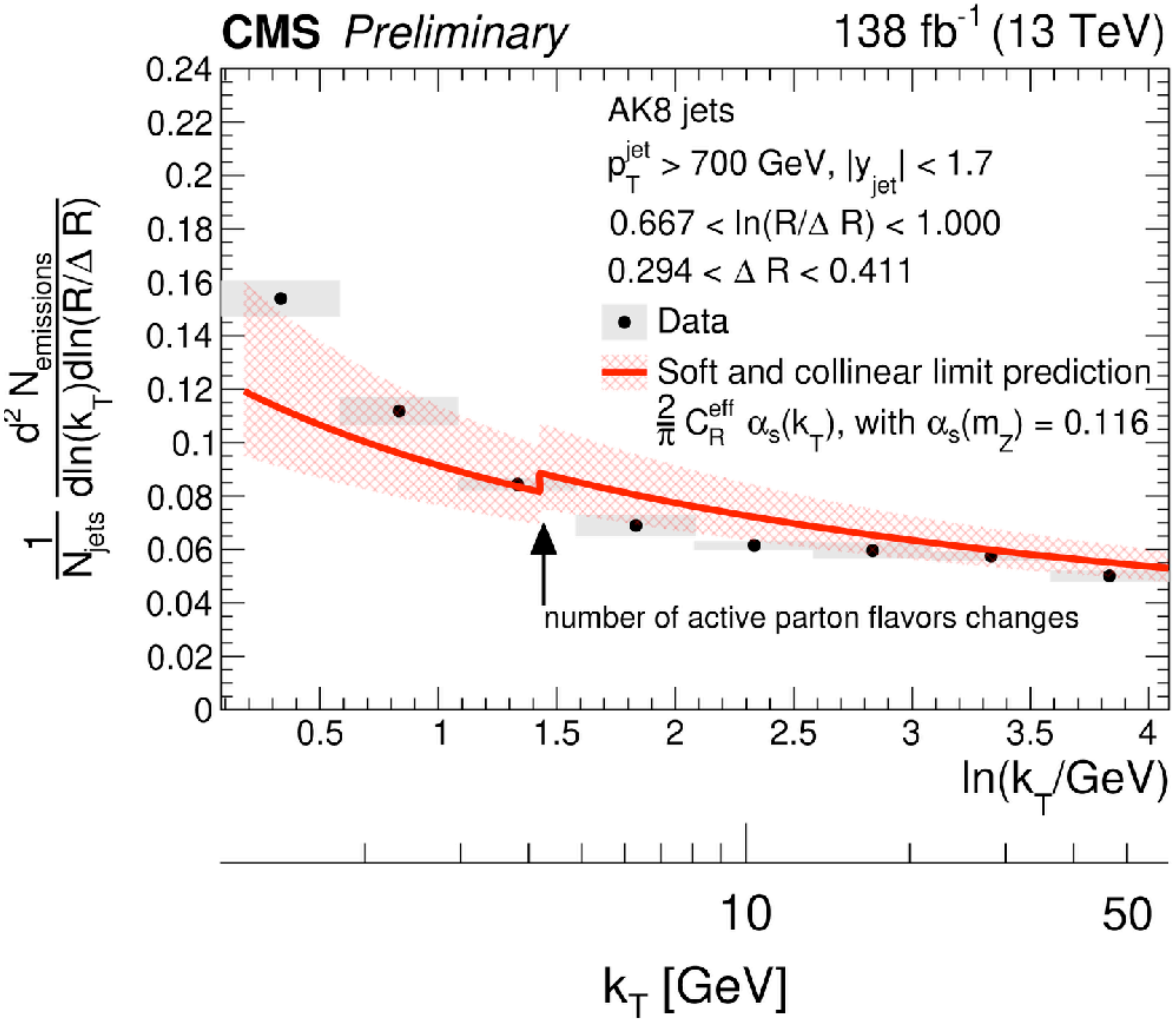


Quark radiating gluons

https://cms.cern/news/fractal-tree-quarks-and-gluons

based on "Lund plane" concept,
Dreyer, GPS & Soyez, [1807.04758](1807.04758)

measurements also by ALICE and ATLAS



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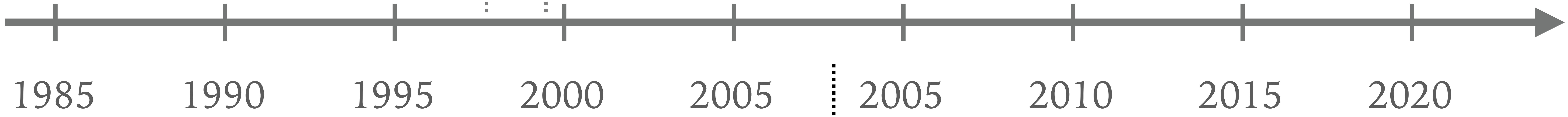
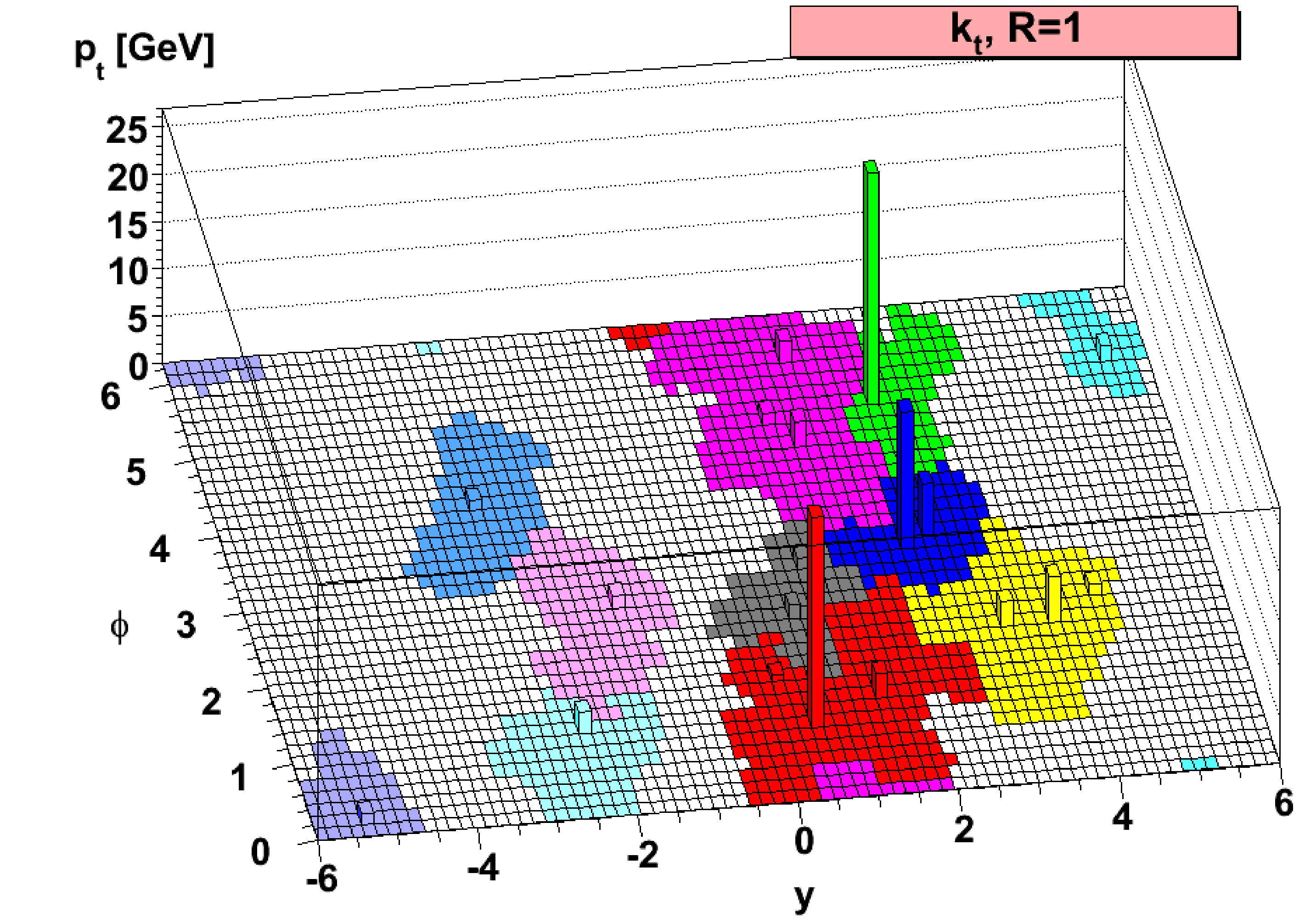
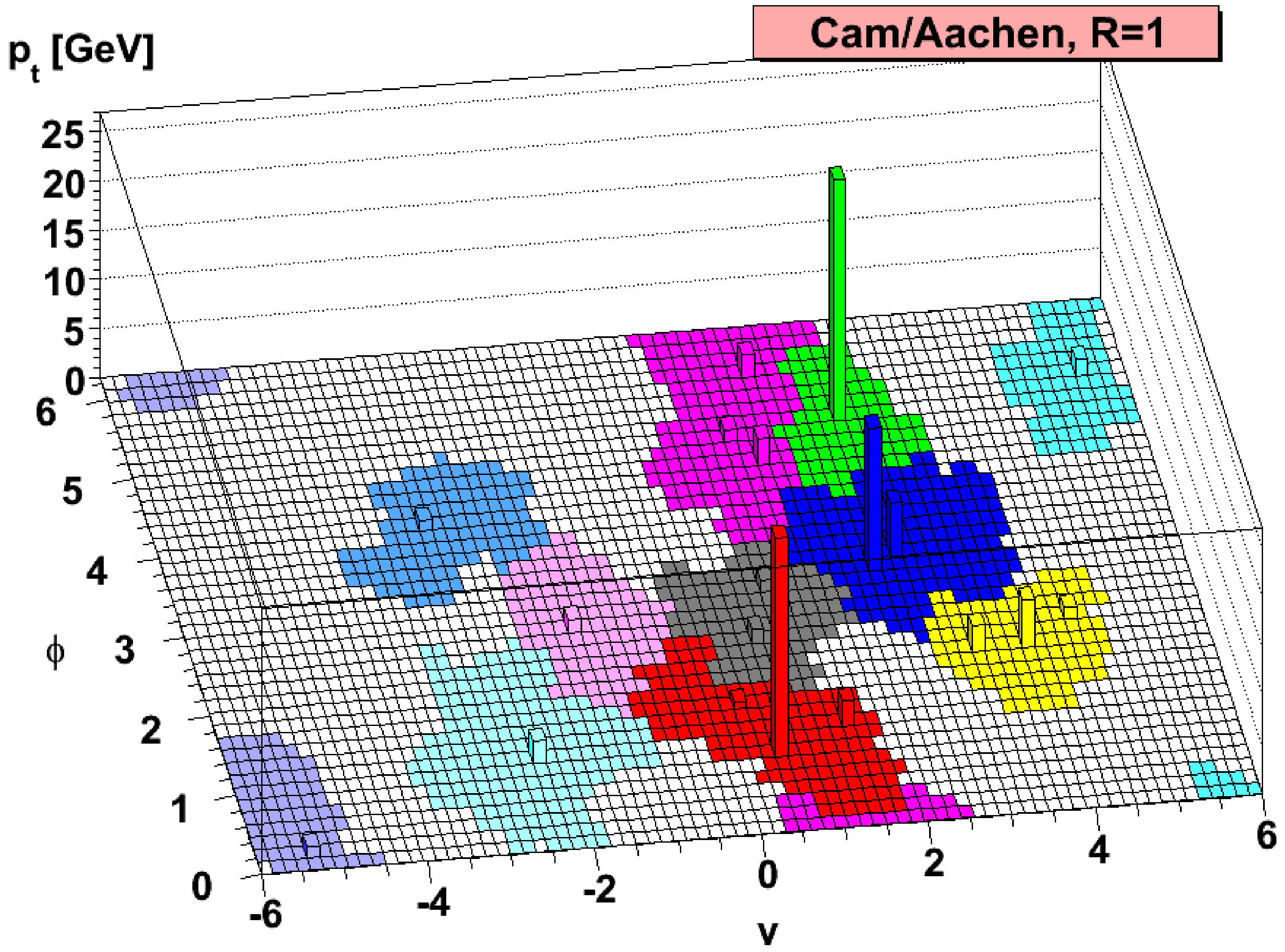


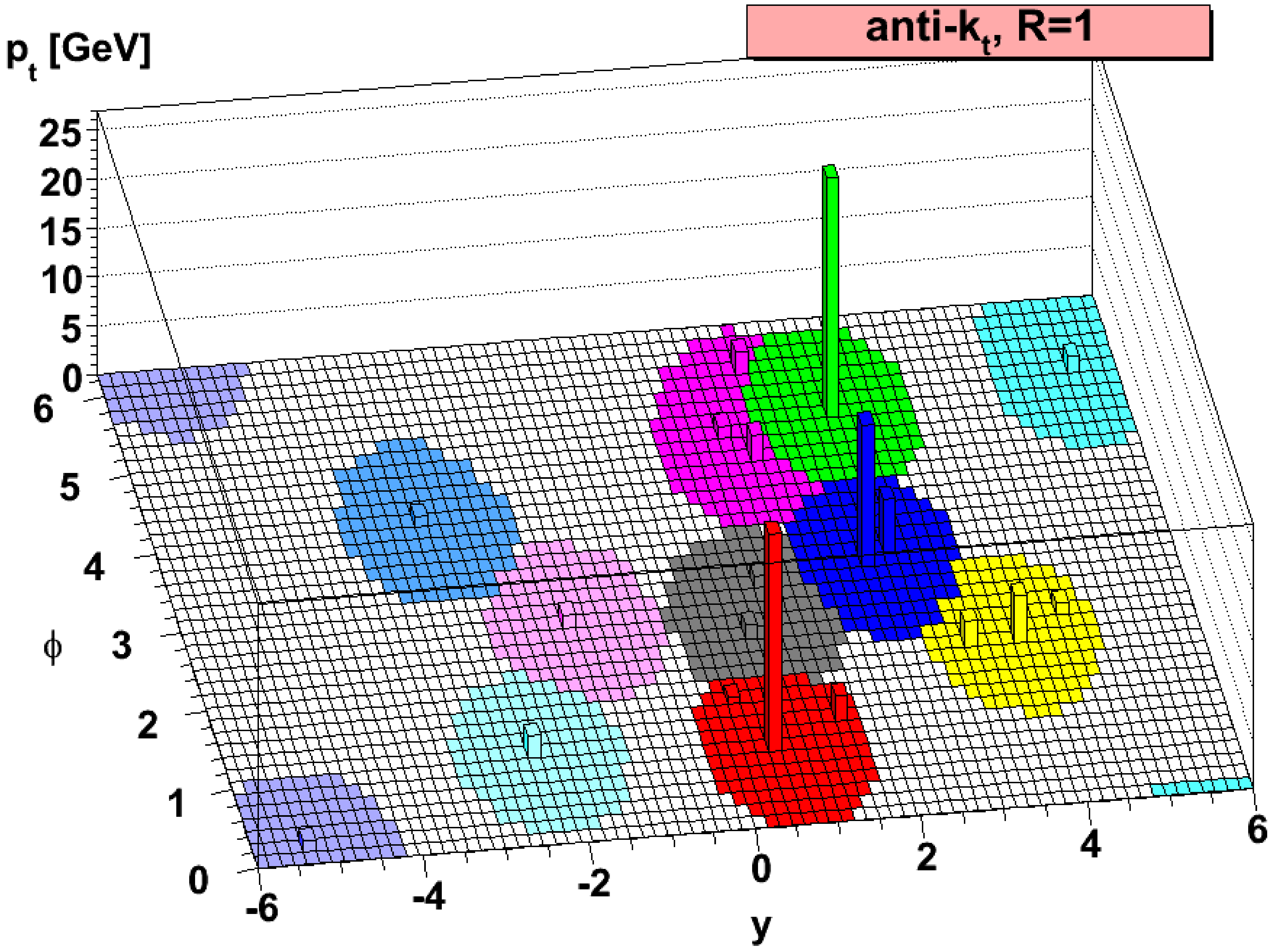
anti-k_t algorithm: $d_{ij} = (1 - \cos\theta_{ij}) / \max(E_i^2, E_j^2)$

Cacciari, Soyez, GPS

anti-k_t algorithm: circular jets made it default LHC choice







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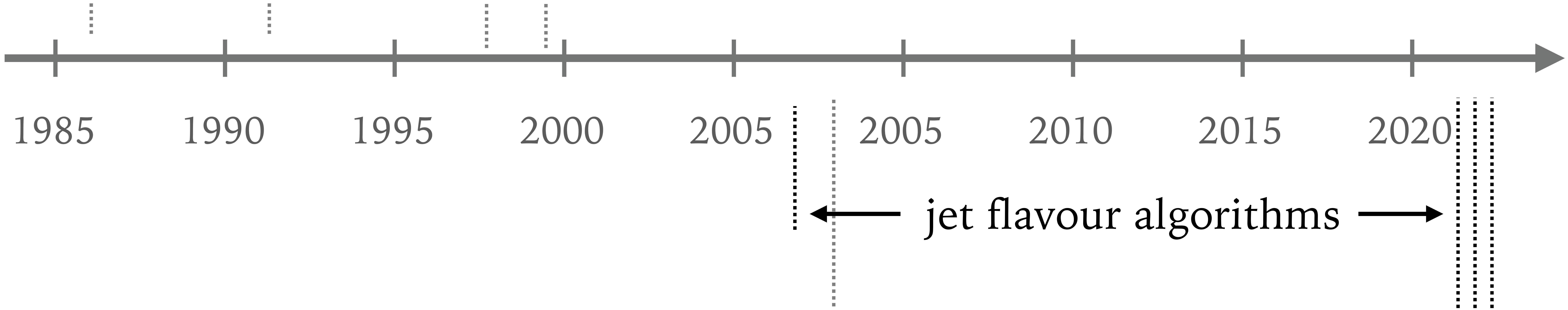

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Cacciari, Soyez, GPS

jet flavour algorithms: one of today's frontiers in jet finding

- can you make the "flavour" infrared and collinear safe (e.g. is it a quark-jet or a gluon-jet) & keep other good properties of standard jet algorithms
- early work: Banfi, GPS & Zanderighi, hep-ph/0601139
- Recent work:
  - Caletti, Larkoski, Marzani, Reichelt, 2205.01109 & 2205.01117
  - Czakon, Mitov, Poncelet, 2205.11879
  - Gauld, Huss, Stagnitto, 2208.11138
  - Caola, Grabarczyk, Hutt, GPS & Scyboz, Thaler, to appear soon
- **common theme: "undesirable" JADE property of clustering particles going in opposite directions turns out to be essential for flavoured pairs in order to make flavour IRC safe.**

conclusions

Concluding remarks

- Siggi's efforts & ideas pervade particle physics
  - Value of data preservation
  - Simplicity of pairwise clustering in jet physics
  - Care in bringing together different elements in the field as with strong-coupling world averages
- We should look forward to his wisdom continuing to advance the field!