Experimental determinations of $\alpha_s(m_Z)$ from semi-inclusive hard processes

Introduction
pp measurements
EEC in e^+e^- (previous and open data)
FFs
Heavy quarks
Conclusion

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Special challenges in QCD workshop
GGI, Florence 08./09.01.2026

> “If we want things to stay as they are, things will have to change.”
> Giuseppe Tomasi di Lampedusa, The Leopard

Introduction

Google AI overview (27.12.2026):

“A semi-inclusive observable in particle and nuclear physics refers to a measurement where a specific subset of the final-state particles is detected in coincidence, while the remaining, unobserved part of the final state (denoted as "X") is summed or integrated over”

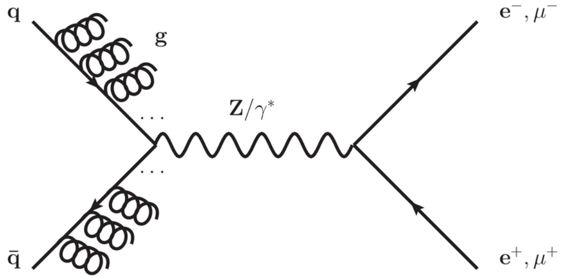
Inclusive: $\sigma_{tot}(e^+e^- \rightarrow \text{hadrons})$, $d\sigma^{DIS}/(dx dQ^2)$) (just counting)

Semi-inclusive: EEC (e^+e^-), TEEC (pp), NCDY, CCDY (partially measured: 2-particle correlations, lepton(s), …), SIDIS, ...

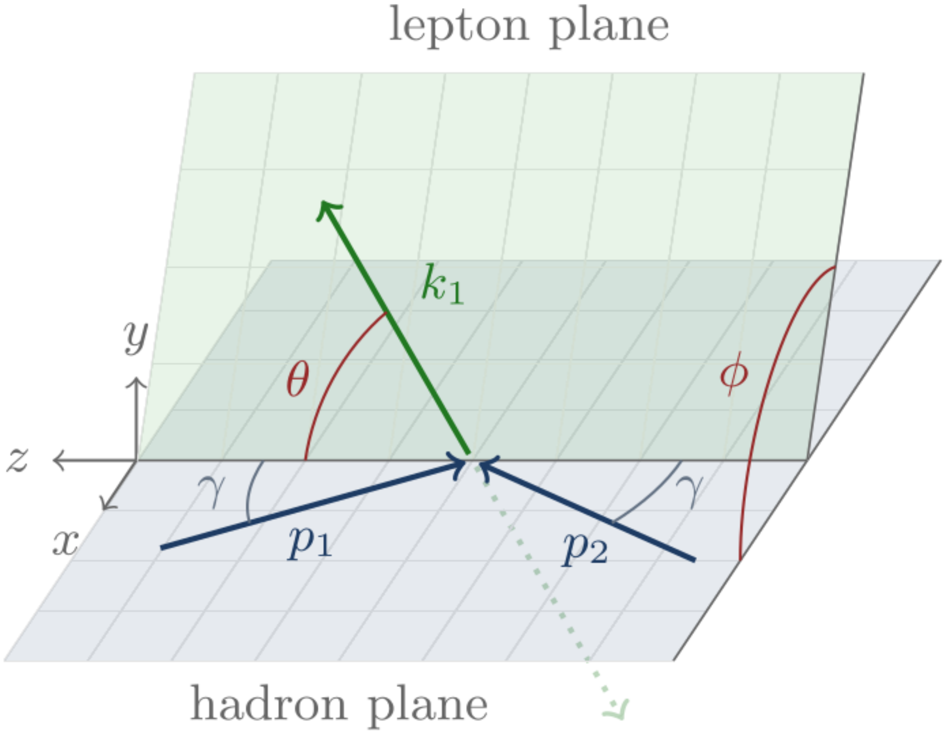
Exclusive: e.g. Thrust $T = 1/\Sigma_i|\mathbf{p}_i|\ \Sigma_i\ |\mathbf{p}_i\cdot\mathbf{n}|$ (all objects measured)

ATLAS NC Drell-Yan 8 TeV

pp → $l\bar{l}$ + X with $m_{l\bar{l}} \approx m_Z$



[R. Gould at al, JHEP 11 (2017) 003]



In Collins-Soper frame

$d\sigma/(dp_t dy dm_{l\bar{l}} d\cos\theta_l d\Phi_l) \sim$

$d\sigma^{(unpol)}/(dp_t dy dm_{l\bar{l}}) F(\theta_l,\Phi_l,A_i)$

i=0,…,7

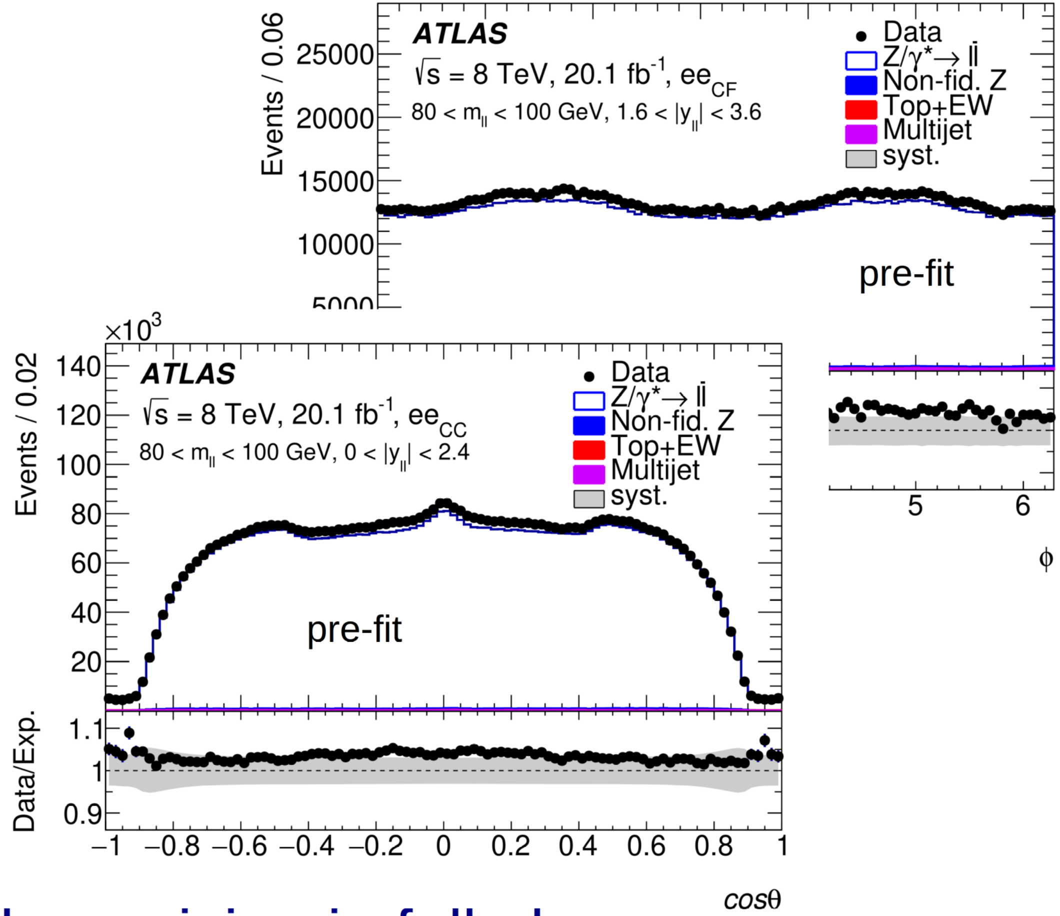
[ATLAS coll., Eur. Phys. J. C 84 (2024) 315]

Z decay and production “factorise” in Z cms, basis for high precision QCD analysis

ATLAS NC Drell-Yan 8 TeV

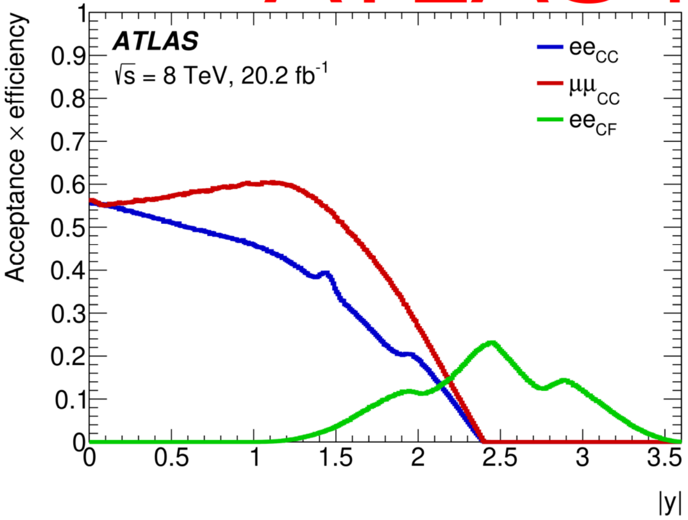
$$F(\theta_l,\Phi_l,A_i) = 3/(16\pi)\,\{$$
$$(1+\cos^2\theta_l) + \tfrac{1}{2}A_0\,(1-3\cos^2\theta_l)$$
$$+ A_1 \sin 2\theta_l \cos\Phi_l$$
$$+ \tfrac{1}{2}A_2 \sin^2\theta_l \cos 2\Phi_l$$
$$+ A_3 \sin\theta_l \cos\Phi_l + A_4 \cos\theta_l$$
$$+ A_5 \sin^2\theta_l \sin 2\Phi_l + A_6 \sin 2\theta_l \sin\Phi_l$$
$$+ A_7 \sin\theta_l \sin\Phi_l\,\}$$

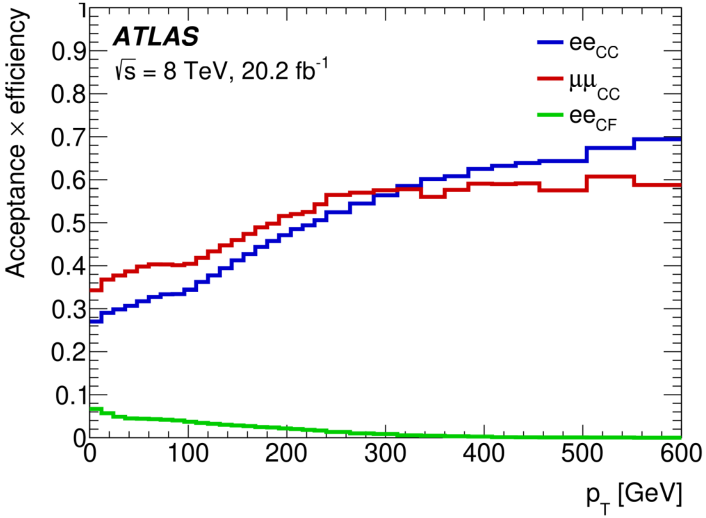
[ATLAS coll., Eur. Phys. J. C 84 (2024) 315]



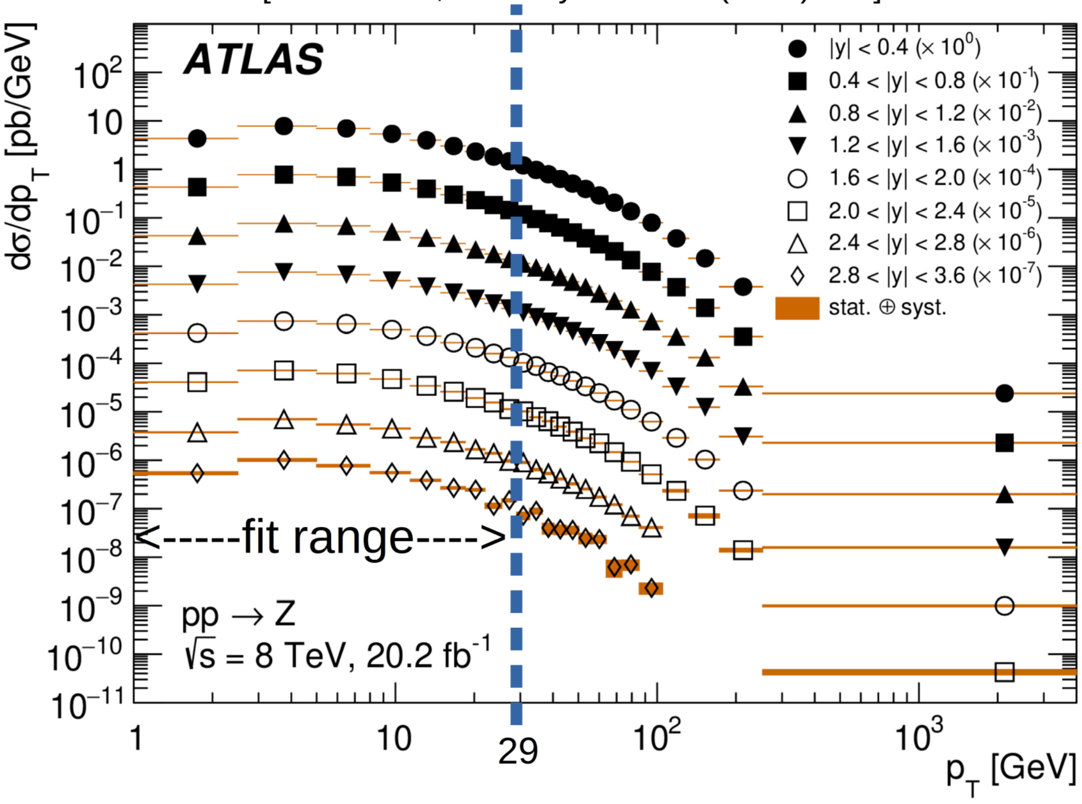
Extract A_i by template fits to polynomial terms in p_t-y bins: model exptl effects by detector MC ⇒ high precision in full phase space

ATLAS NC Drell-Yan 8 TeV

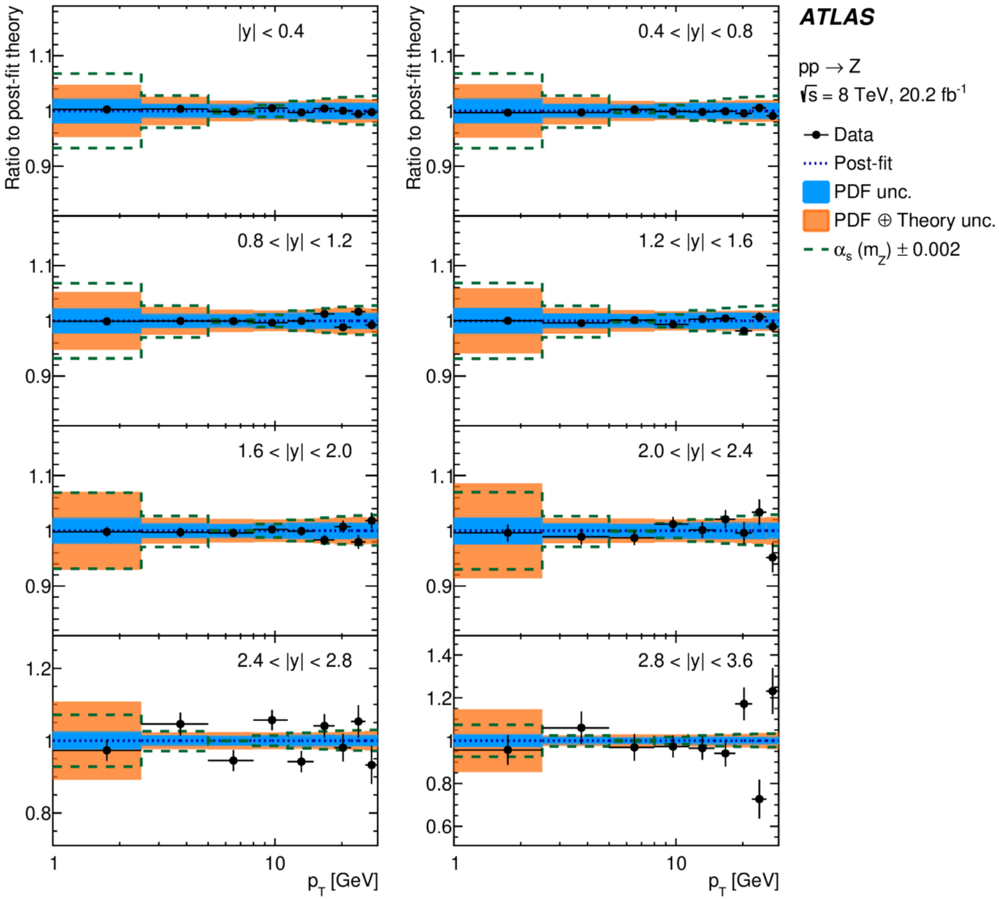




[ATLAS coll., Eur. Phys. J. C 84 (2024) 315]



ATLAS NC Drell-Yan 8 TeV



[ATLAS-STDM-2023-01, arXiv: 2309.12986]

QCD analysis: p_t spectrum of $l\bar{l}$ system ("Z") sensitive to $\alpha_S(m_Z)$

N3LO+N4LLa result (DYTURBO):

$\alpha_S(m_Z) = 0.1178 \pm 0.0004_{\mathrm{exp}} \pm 0.0005_{\mathrm{pdf}} \pm 0.0004_{\mathrm{scale}} \pm 0.0005_{\mathrm{other}} = 0.1178 \pm 0.0009_{\mathrm{tot}}$

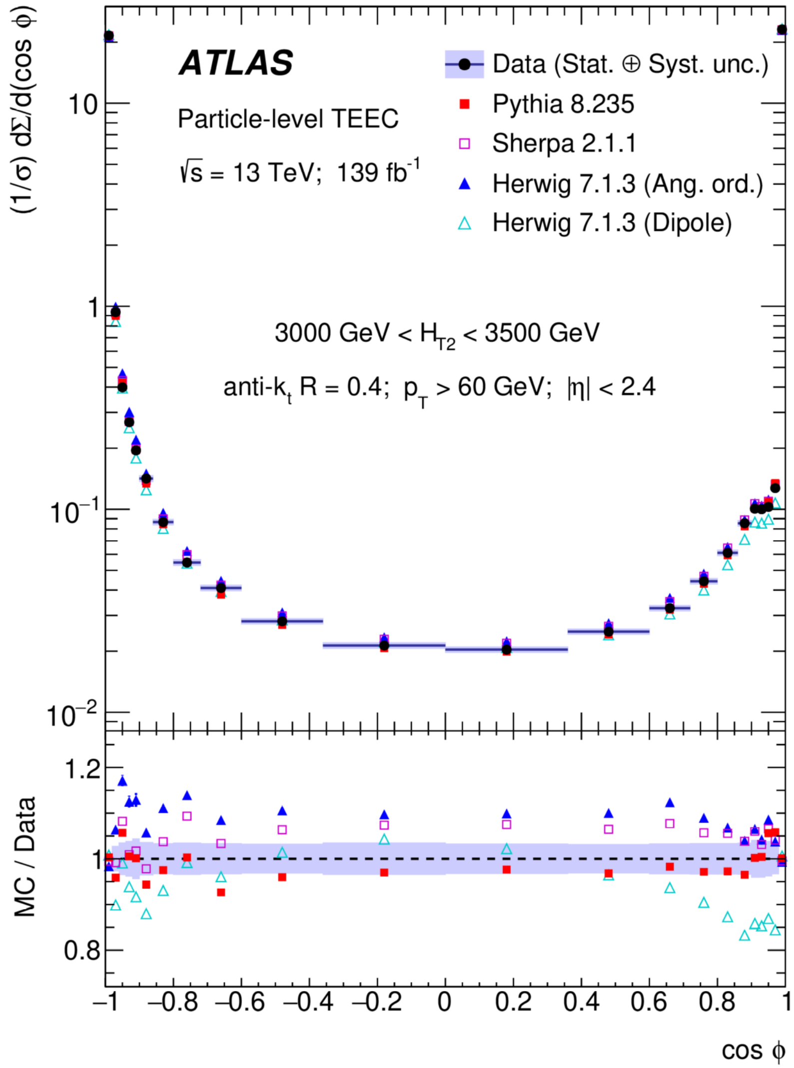
PDF parametrisation vs fit, non-pert model checked carefully (now under scrutiny)

Best $\alpha_S(m_Z)$ besides Lattice QCD!

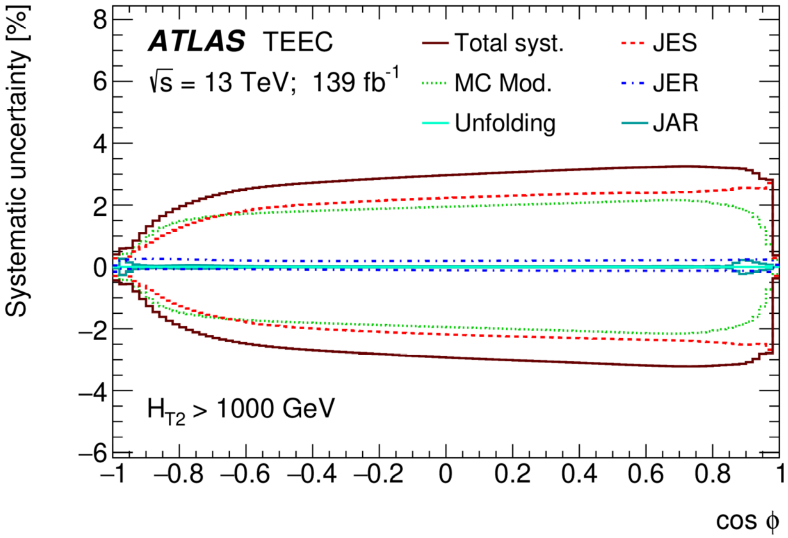
ATLAS TEEC 13 TeV

Anti-k_t R=0.4 jets, p_t > 60 GeV (460 GeV jet trigger), $H_{T2} = p_{t,1}+p_{t,2}$ > 1000 GeV

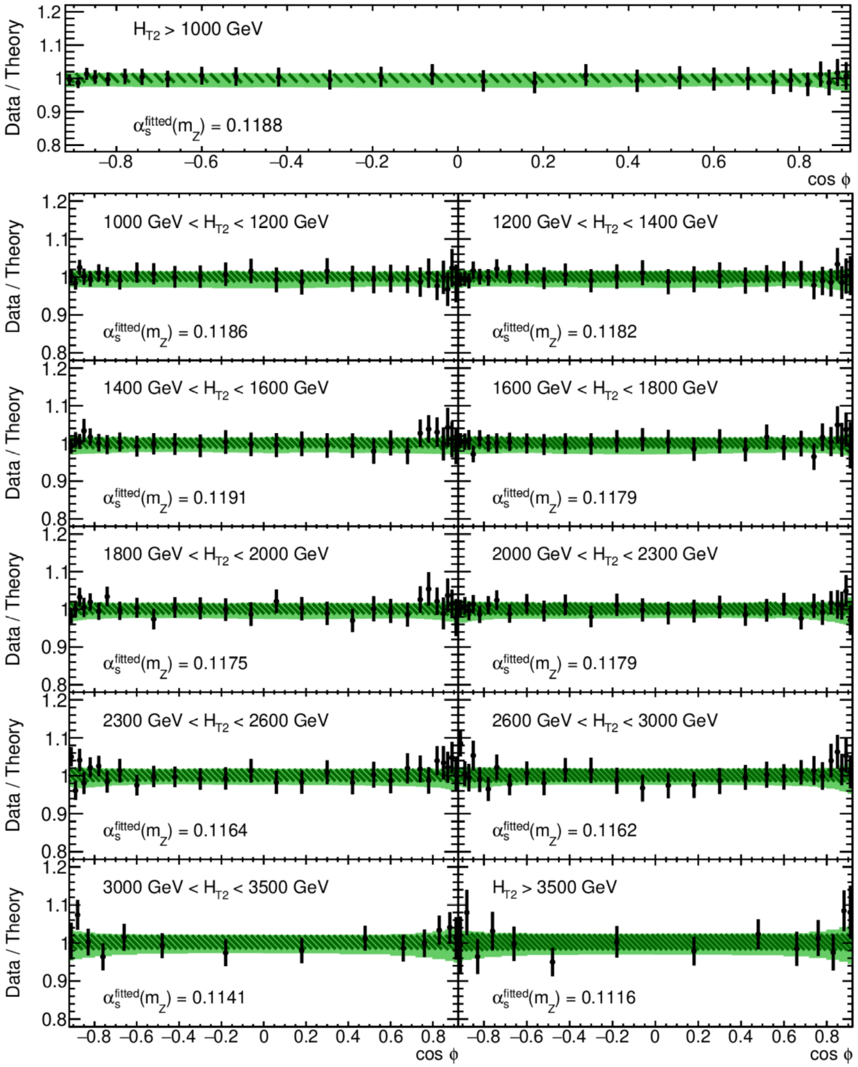
$1/\sigma\, d\sigma^{TEEC}/d\cos\Phi =$
$1/N\sum_{events}\sum_{jets}E_{t,i}E_{t,j}/(\sum_{jets}E_{t,i})\delta(\cos\Phi_{ij}-\cos\Phi)$



[ATLAS coll., JHEP 07 (2023) 85]



ATLAS TEEC



ATLAS

Particle-level TEEC

$\sqrt{s} = 13$ TeV; 139 fb^{-1}

anti-k_t R = 0.4

$p_T > 60$ GeV

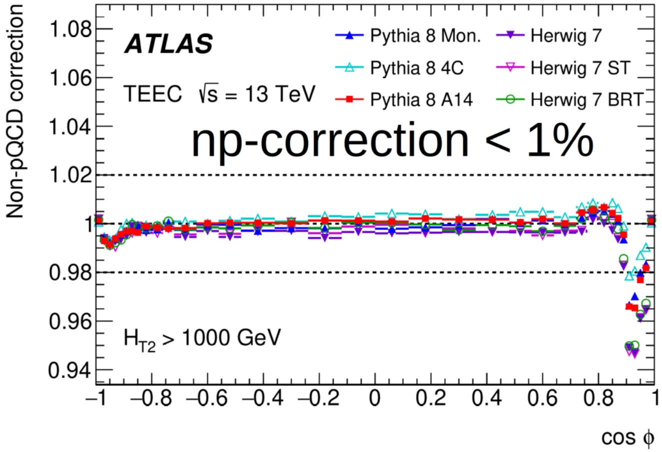
$|\eta| < 2.4$

$\mu_{R,F} = \hat{H}_T$

NNLO pQCD

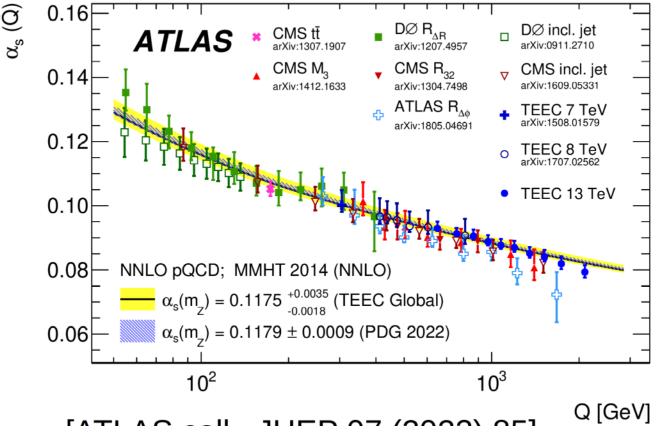
MMHT 2014 (NNLO)

- Exp. unc.
- ▨ Non-scale unc.
- 🟩 Theo. unc.



np-correction < 1%

TEEC (MMHT14):
$\alpha_s(m_Z) = 0.1175$
± 0.0001 (stat.)
± 0.0006 (exp.)
$^{+0.0032}_{-0.0011}$ (scale)
± 0.0011 (PDF)
± 0.0002 (np)
± 0.0005 (unf.)



[ATLAS coll., JHEP 07 (2023) 85]

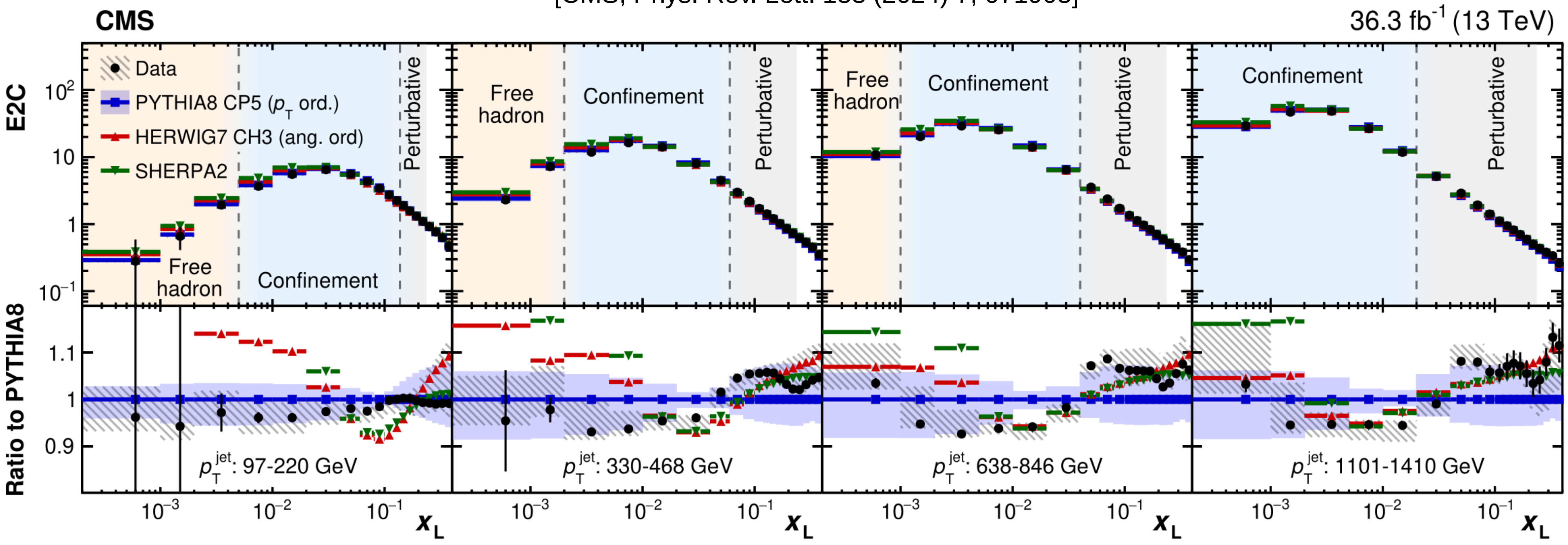
CMS EEC in jets at 13 TeV

Di-jets anti-kt R=0.4, $p_{t,jet}$ > 60, ... trigger, $p_{t,jet1,jet2}$ > 97 GeV, $|\eta_{jet}|<2.1$

$x_{L,ij} = \sqrt{(\Delta\eta_{ij})^2+(\Delta\phi_{ij})^2}$, $d\sigma/dx_L = 1/(\Delta x_L N)\sum_{events}\sum_{jets}\int_{bin} E_iE_j\,/E_{jet}^2\,\delta(x_L'-x_{L,ij})dx_L'$

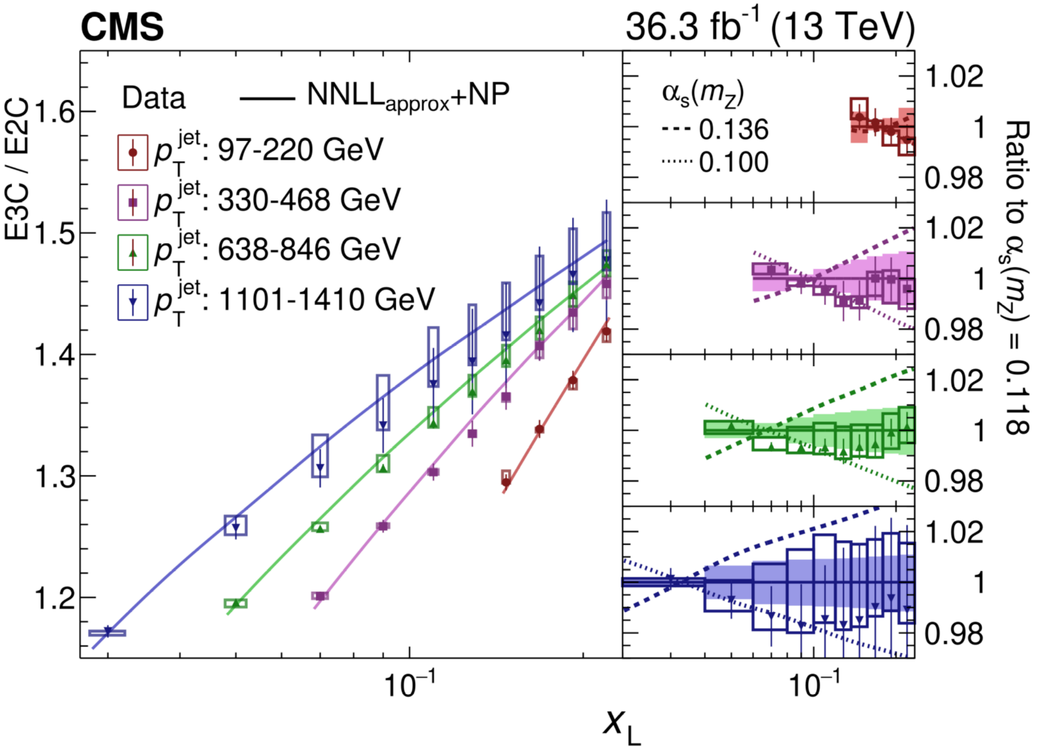
For E3C use largest x_L of triplet and weight $E_iE_jE_k\,/E_{jet}^3$

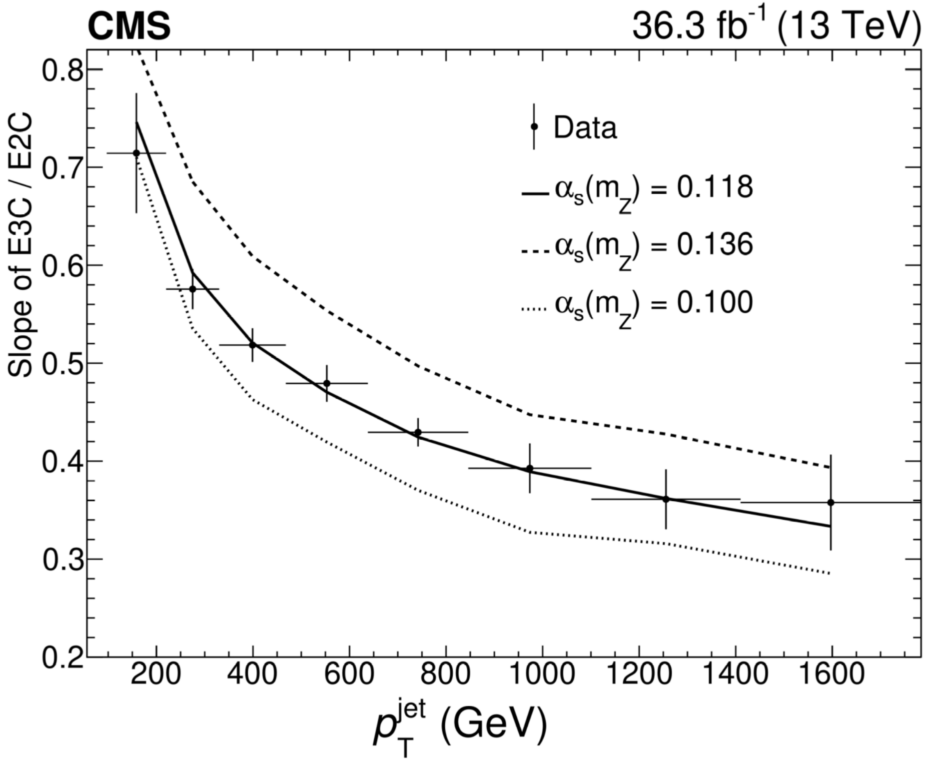
[CMS, Phys. Rev. Lett. 133 (2024) 7, 071903]



CMS EEC in jets at 13 TeV

$\alpha_s(m_Z) = 0.1229 \pm 0.0013_{\text{stat}} \pm 0.0030_{\text{exp}} \pm 0.0032_{\text{theo}}$ with NLO+NNLLa
E3C/E2C suppresses systematics (exp, pdf, …)

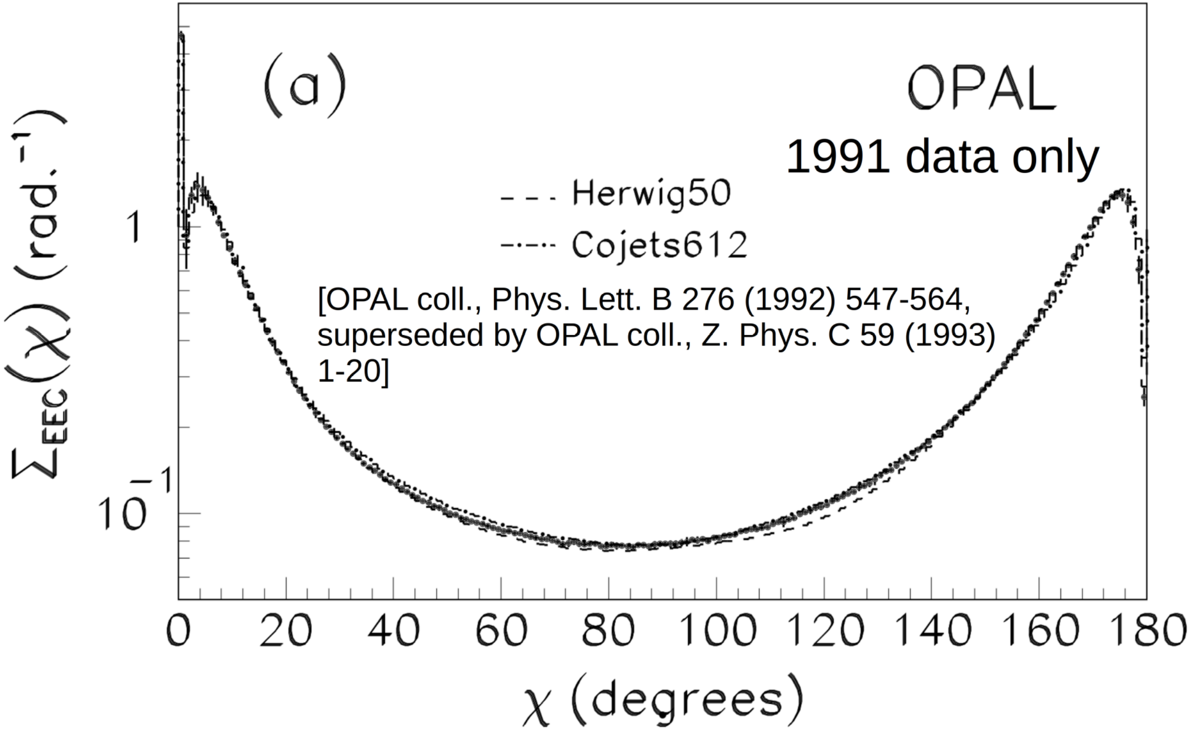




EEC in e^+e^-

EEC: energy weighted distribution of angles between particle pairs

$$d\Sigma/d\chi = 1/(\Delta\chi N) \int_{\text{bin}} \Sigma_{\text{events}}\Sigma_{ij}\, E_iE_j/E_{\text{vis}}^2\, \delta(\chi'-\theta_{ij})\, d\chi'$$



1991 data only

[OPAL coll., Phys. Lett. B 276 (1992) 547-564, superseded by OPAL coll., Z. Phys. C 59 (1993) 1-20]

Trigger efficiency: >99.9%
Exptl corrections: <10% except $\chi \approx 0$ or 180°
Track ang. res.: <0.1mrad (x-y), <10mrad (r-z)
ECAL cells 40x40mrad^2 (3.3^{o2})
Bin-by-bin unfolding to hadron level: τ<300ps, no ISR

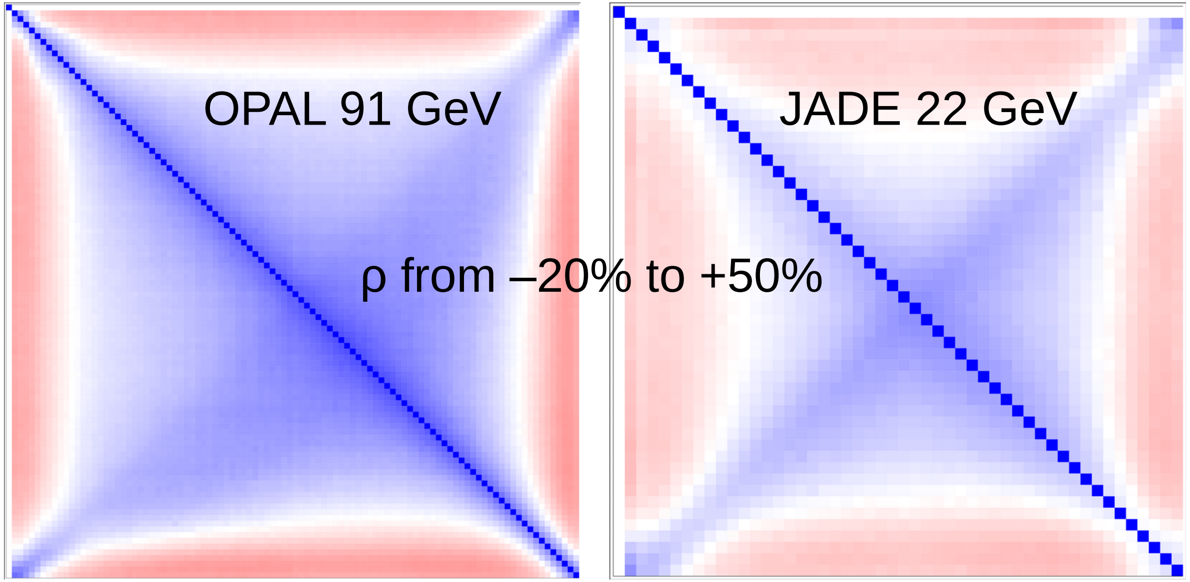
EEC global fit NNLO+NNLL

Experiment	$\sqrt{s}$, GeV, data	$\sqrt{s}$, GeV, MC	Events
SLD [47]	91.2(91.2)	91.2	60000
OPAL [50]	91.2(91.2)	91.2	336247
OPAL [51]	91.2(91.2)	91.2	128032
L3 [48]	91.2(91.2)	91.2	169700
DELPHI [49]	91.2(91.2)	91.2	120600
TOPAZ [52]	59.0 – 60.0(59.5)	59.5	540
TOPAZ [52]	52.0 – 55.0(53.3)	53.3	745
TASSO [53]	38.4 – 46.8(43.5)	43.5	6434
TASSO [53]	32.0 – 35.2(34.0)	34.0	52118
PLUTO [58]	34.6(34.6)	34.0	6964
JADE [54]	29.0 – 36.0(34.0)	34.0	12719
CELLO [57]	34.0(34.0)	34.0	2600
MARKII [56]	29.0(29.0)	29.0	5024
MARKII [56]	29.0(29.0)	29.0	13829
MAC [55]	29.0(29.0)	29.0	65000
TASSO [53]	21.0 – 23.0(22.0)	22.0	1913
JADE [54]	22.0(22.0)	22.0	1399
CELLO [57]	22.0(22.0)	22.0	2000
TASSO [53]	12.4 – 14.4(14.0)	14.0	2704
JADE [54]	14.0(14.0)	14.0	2112

[Kardos, SK, Somogyi, Tulipant, Verbytskyi,
Eur. Phys. J. C 78 (2018) 6, 498]

Detailed study based on NNLO+NNLL,
np corrections with MC or DMW

Data carefully selected, stat. correlations
due to normalisation from MC

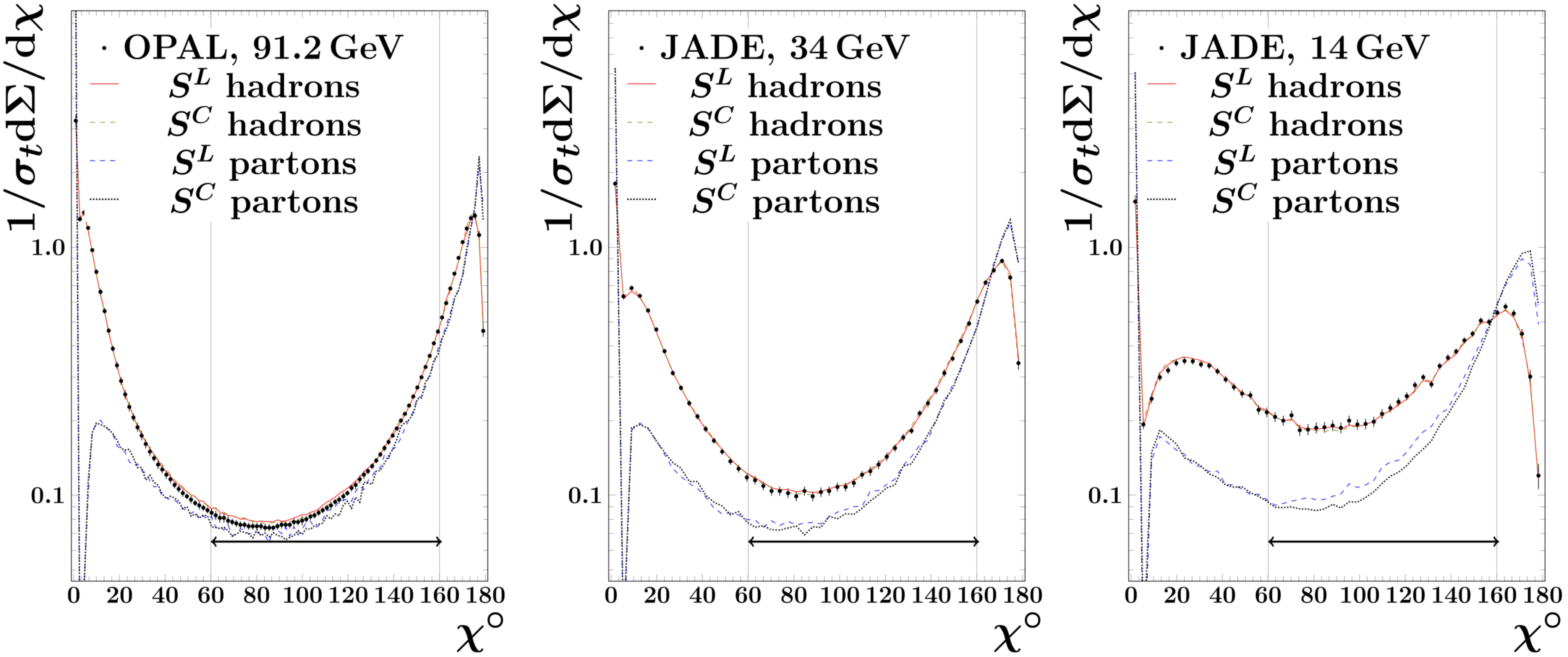


ρ from –20% to +50%

EEC global fit: MC vs data

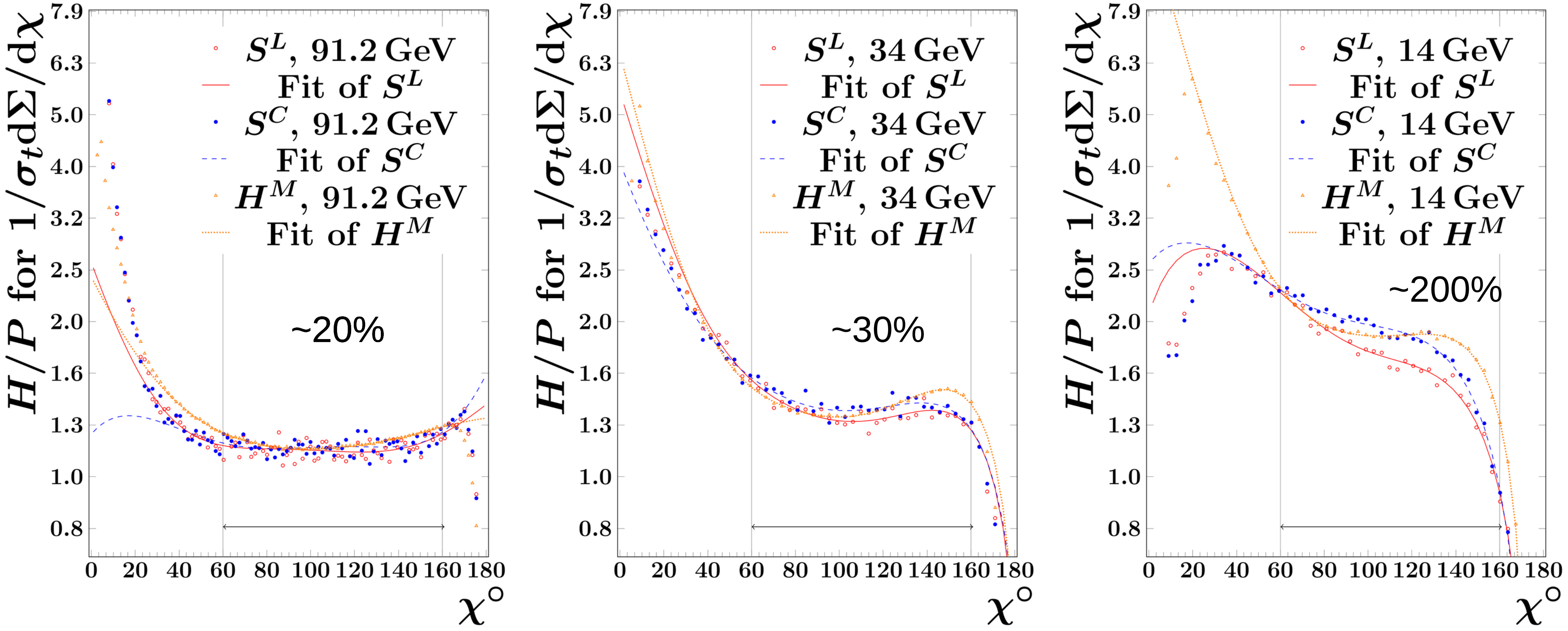
[Kardos, SK, Somogyi, Tulipant, Verbytskyi,
Eur. Phys. J. C 78 (2018) 6, 498]

Compare modern MC to data, e.g.
SHERPA 2.2.4 MENLOPS 2→2 at NLO

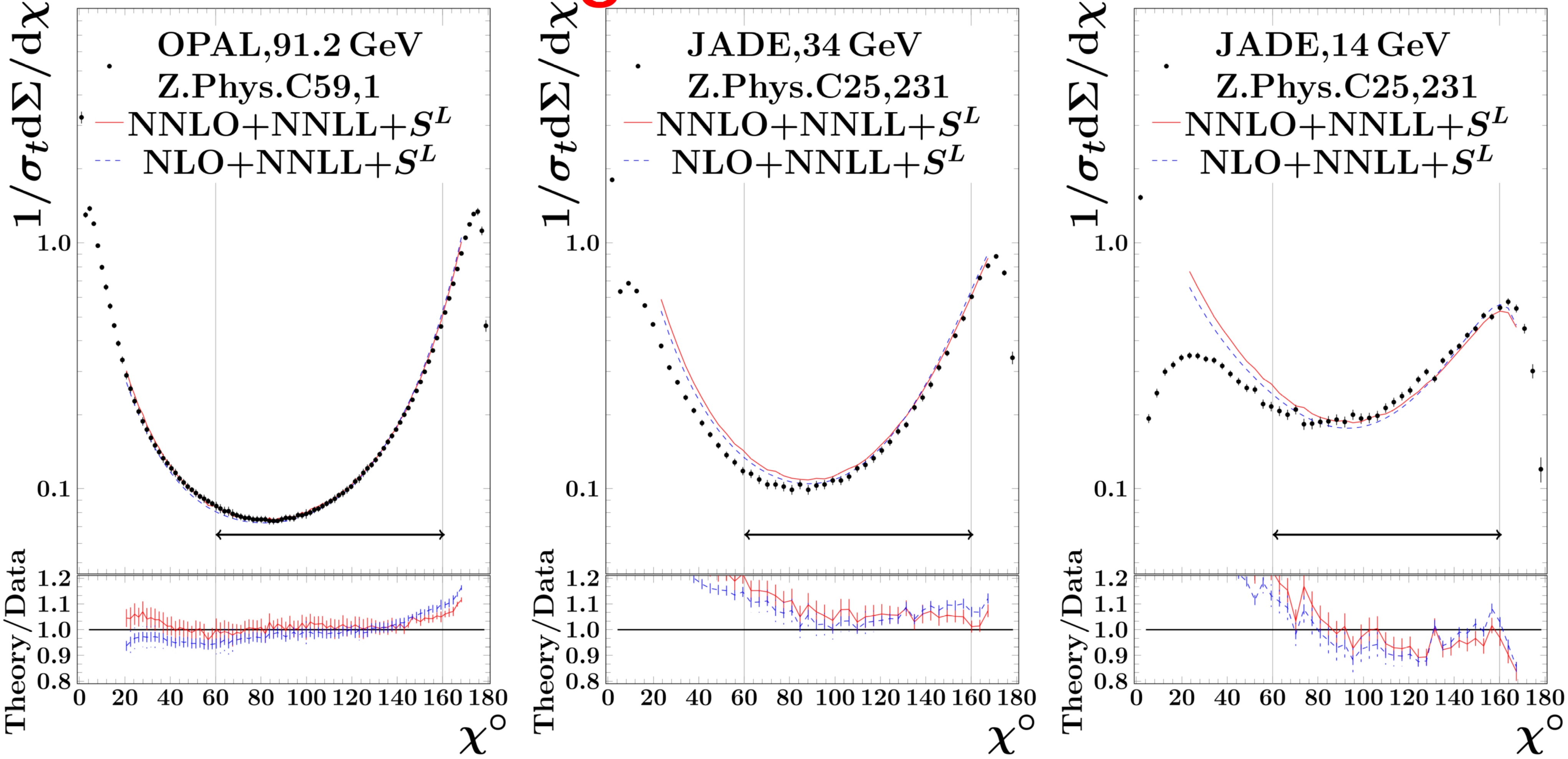


EEC global fit: MC np corr.

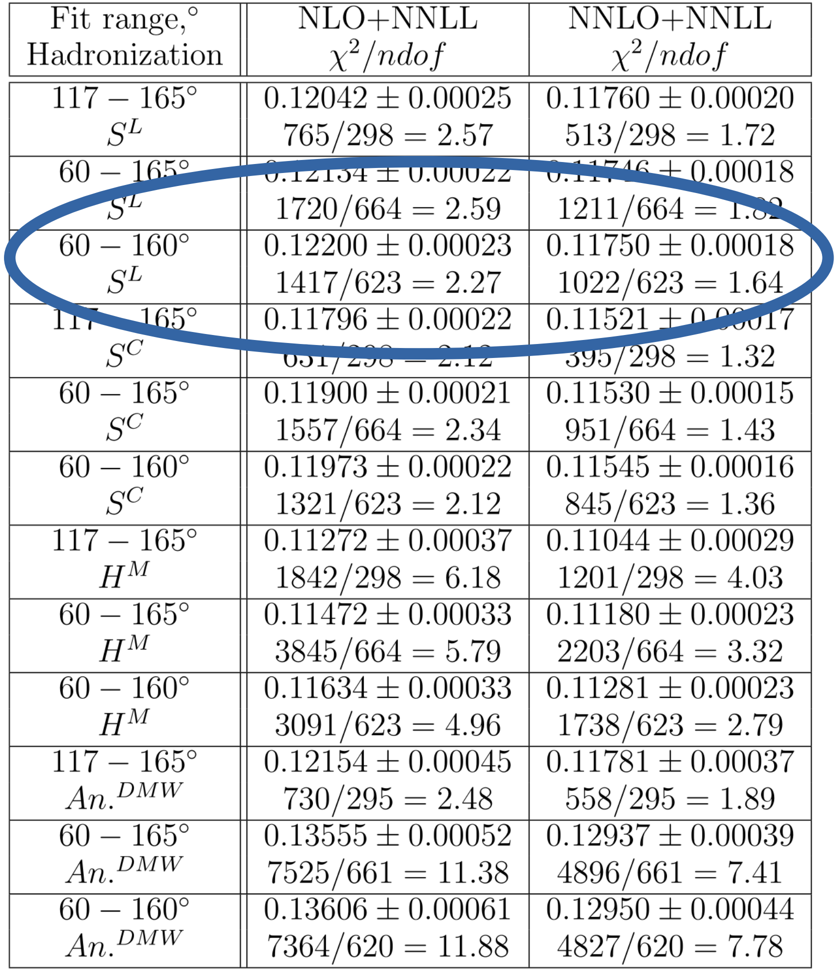
[Kardos, SK, Somogyi, Tulipant, Verbytskyi,
Eur. Phys. J. C 78 (2018) 6, 498]



EEC global fit: results



EEC global fit: results



Fit range,° Hadronization	NLO+NNLL $\chi^2/ndof$	NNLO+NNLL $\chi^2/ndof$
117 – 165° S^L	0.12042 ± 0.00025 $765/298 = 2.57$	0.11760 ± 0.00020 $513/298 = 1.72$
60 – 165° S^L	0.12134 ± 0.00022 $1720/664 = 2.59$	0.11746 ± 0.00018 $1211/664 = 1.82$
60 – 160° S^L	0.12200 ± 0.00023 $1417/623 = 2.27$	0.11750 ± 0.00018 $1022/623 = 1.64$
117 – 165° S^C	0.11796 ± 0.00022 $631/298 = 2.12$	0.11521 ± 0.00017 $395/298 = 1.32$
60 – 165° S^C	0.11900 ± 0.00021 $1557/664 = 2.34$	0.11530 ± 0.00015 $951/664 = 1.43$
60 – 160° S^C	0.11973 ± 0.00022 $1321/623 = 2.12$	0.11545 ± 0.00016 $845/623 = 1.36$
117 – 165° H^M	0.11272 ± 0.00037 $1842/298 = 6.18$	0.11044 ± 0.00029 $1201/298 = 4.03$
60 – 165° H^M	0.11472 ± 0.00033 $3845/664 = 5.79$	0.11180 ± 0.00023 $2203/664 = 3.32$
60 – 160° H^M	0.11634 ± 0.00033 $3091/623 = 4.96$	0.11281 ± 0.00023 $1738/623 = 2.79$
117 – 165° $An.^{DMW}$	0.12154 ± 0.00045 $730/295 = 2.48$	0.11781 ± 0.00037 $558/295 = 1.89$
60 – 165° $An.^{DMW}$	0.13555 ± 0.00052 $7525/661 = 11.38$	0.12937 ± 0.00039 $4896/661 = 7.41$
60 – 160° $An.^{DMW}$	0.13606 ± 0.00061 $7364/620 = 11.88$	0.12950 ± 0.00044 $4827/620 = 7.78$

$\alpha_s(m_Z) = 0.11750 \pm 0.00018_{\text{exp.}} \pm 0.00102_{\text{np}}$
$\pm 0.00257_{\text{ren.}} \pm 0.00078_{\text{res.}}$

(exp error scaled by $\sqrt{\chi^2/\text{ndof}}=1.28 \Rightarrow \pm 0.00014_{\text{exp.}}$)

DMW: $S_{NP} = \exp(-\tfrac{1}{2}a_1 b^2)(1-2a_2 b)$,
χ^2/ndof larger for larger fit ranges

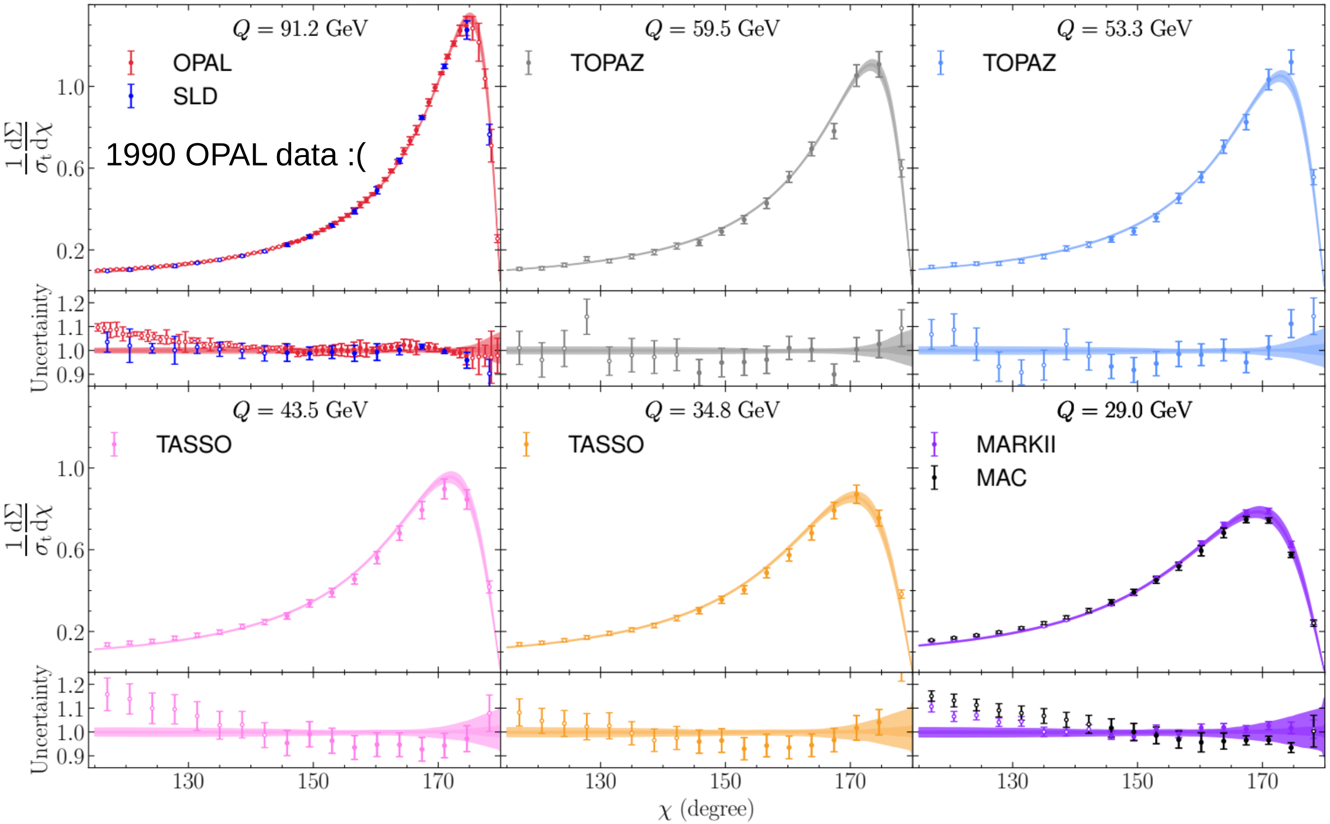
"Hence we conclude that away from the back-to-back region, the analytic model cannot fully account for hadronization effects."

NLO+NNLL:

$\alpha_s(m_Z) = 0.12200 \pm 0.00023_{\text{exp.}} \pm 0.00113_{\text{np}} \pm 0.00433_{\text{ren.}}$
$\pm 0.00293_{\text{res.}}$

EEC global fits in e^+e^-

[Kong, Penttala, Zhang, arXiv:2410.21435]



1990 OPAL data :(

SOA theory prediction

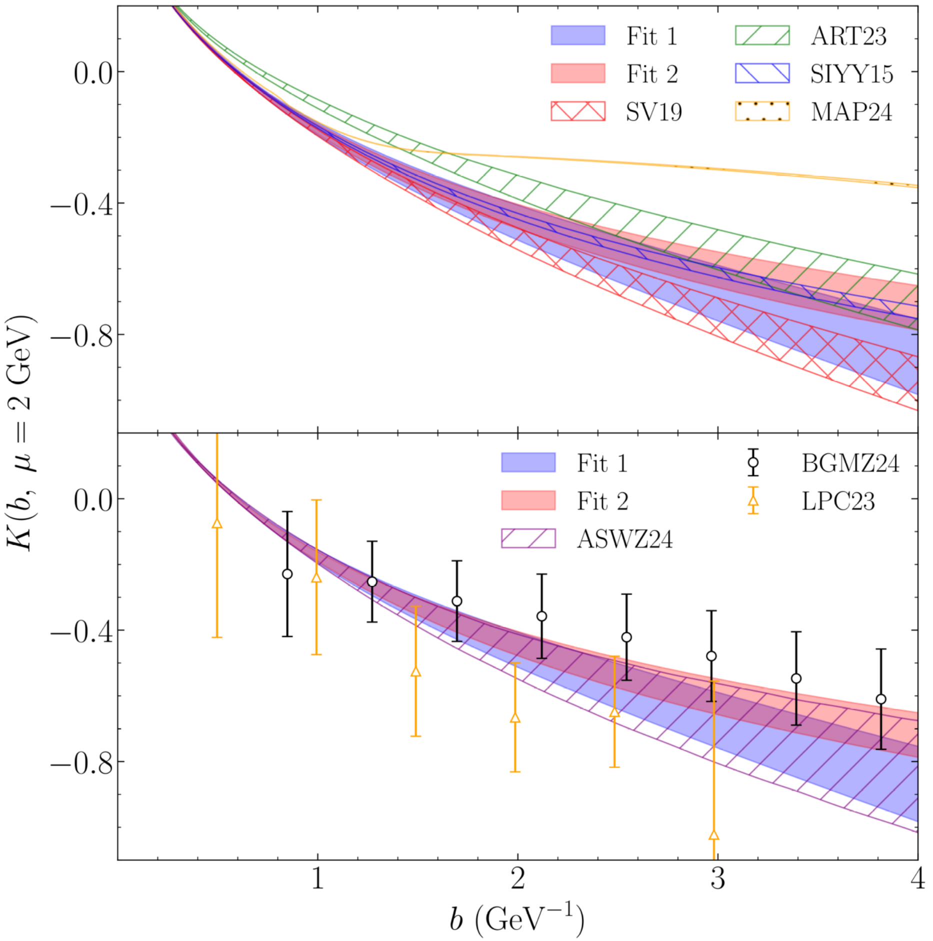
NNLO+N3LL resum.
fit range: χ in $[145^o, 175^o]$

np effects from TMD factorisation in N3LL

$\alpha_S(m_Z) = 0.1193 \pm 0.0009_{exp}$
$\pm 0.0011_{theo}$

(exp error smaller w.r.t. pg14 due to missing stat. corr?)

EEC global fits in e^+e^-



Extraction of CS kernel from NNLO+N3LL+TMDnp EEC fits

Fit 1 and Fit 2: different CS kernel parametrisations

Consistent with “phenomenological extractions” (upper plot) and Lattice QCD extractions (lower plots)

[Kong, Penttala, Zhang, arXiv:2410.21435]

ALEPH open data

[EPA, arXiv: 2505.11828,
(DELPHI arXiv:2510.18762)]

EEC, reco - EEC fake

Step 1: Remove Fakes

→ **EEC Matched** →

Correct for detector resolution, energy smearing in 2D

Step 2: Unfold

E_iE_j/E-θ_L bins

→ **Unfolded EEC** →

Project the 2D distribution to 1D

Step 3: Construct the final observable

→ **Projected EEC** →

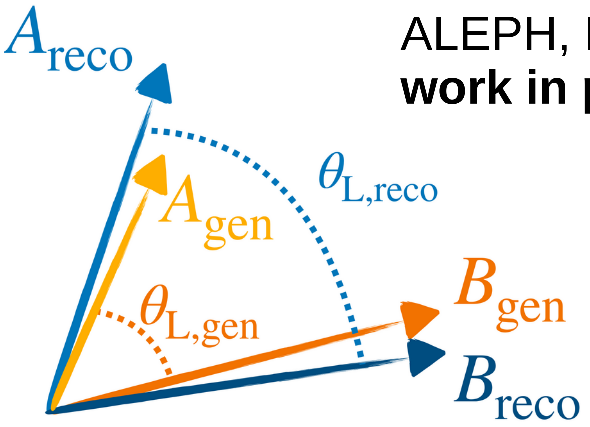
Correct the observable to the “truth level”

Step 4: Corrections

matching fakes,
binning correction,
matching efficiency,
event selection efficiency

→ **Fully-Corrected EEC**

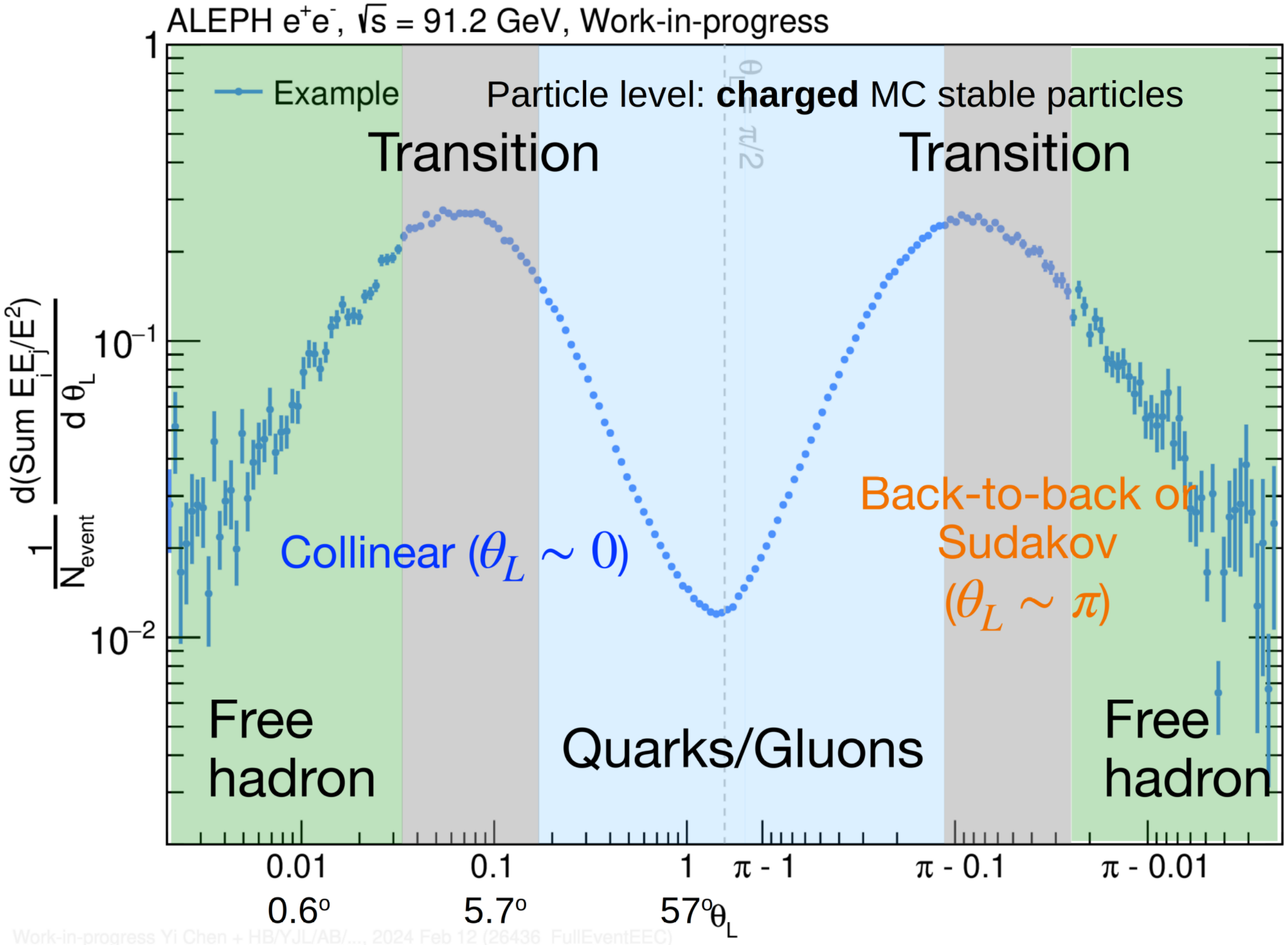
ALEPH, DELPHI open data analyses
work in progress



Particle level: **charged** MC stable particles
CF typical LEP EEC analysis:
bin-by-bin in θ_L correction by ratio
particle level MC w/o ISR no cuts to
detector level MC with ISR and all cuts
Particle level: **all** MC stable particles (τ>300ps)

ALEPH open data

[EPA, arXiv: 2505.11828]



ALEPH detector

track ang. resolution
~OPAL (or better)
0.1(10)mrad x-y(r-z)

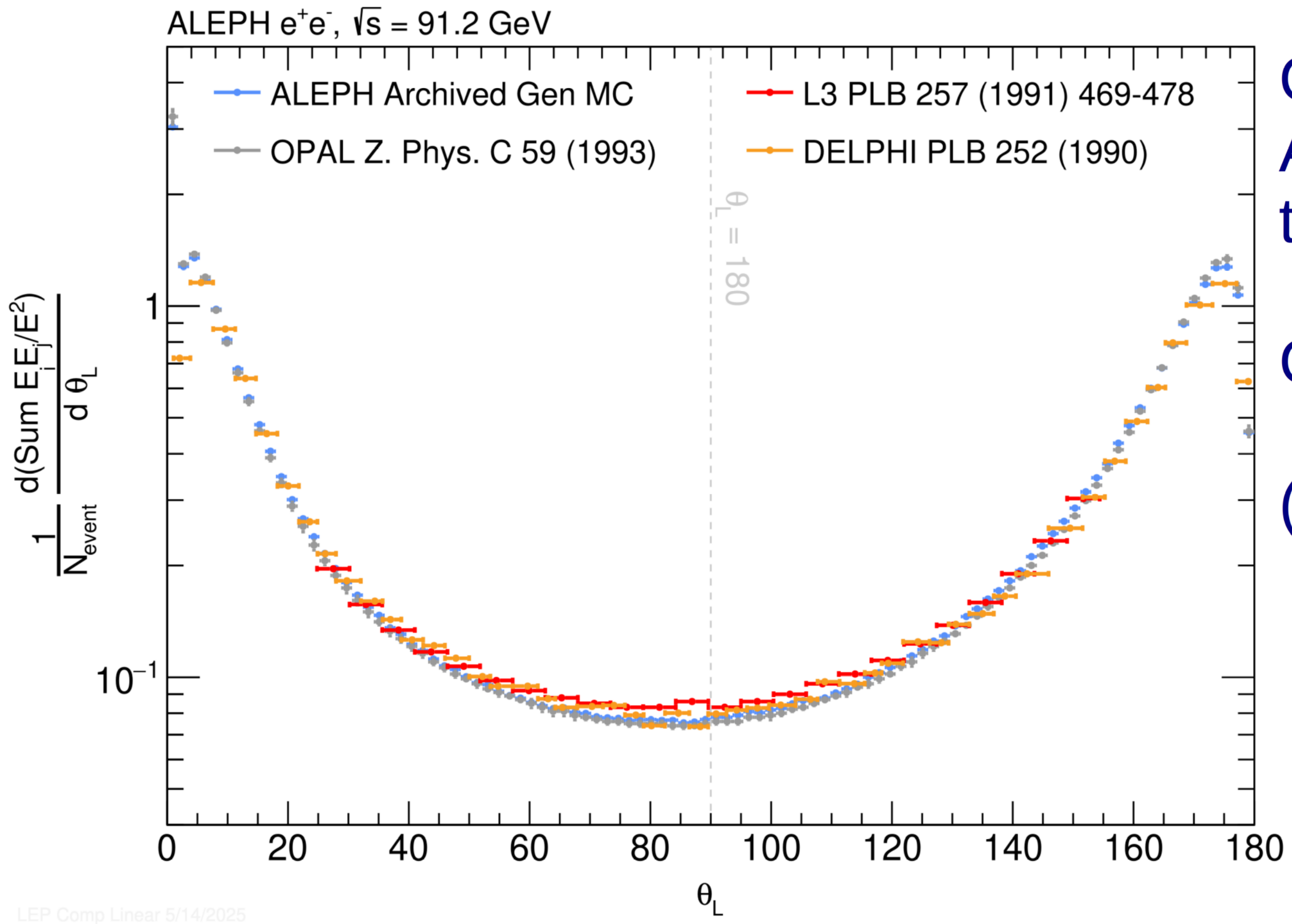
ECAL 0.9°x0.9° cells

mom. resolution (x-y)

1	10	100	[GeV]
0.5	0.8	6	[%]

ALEPH open data

[EPA, arXiv: 2505.11828]



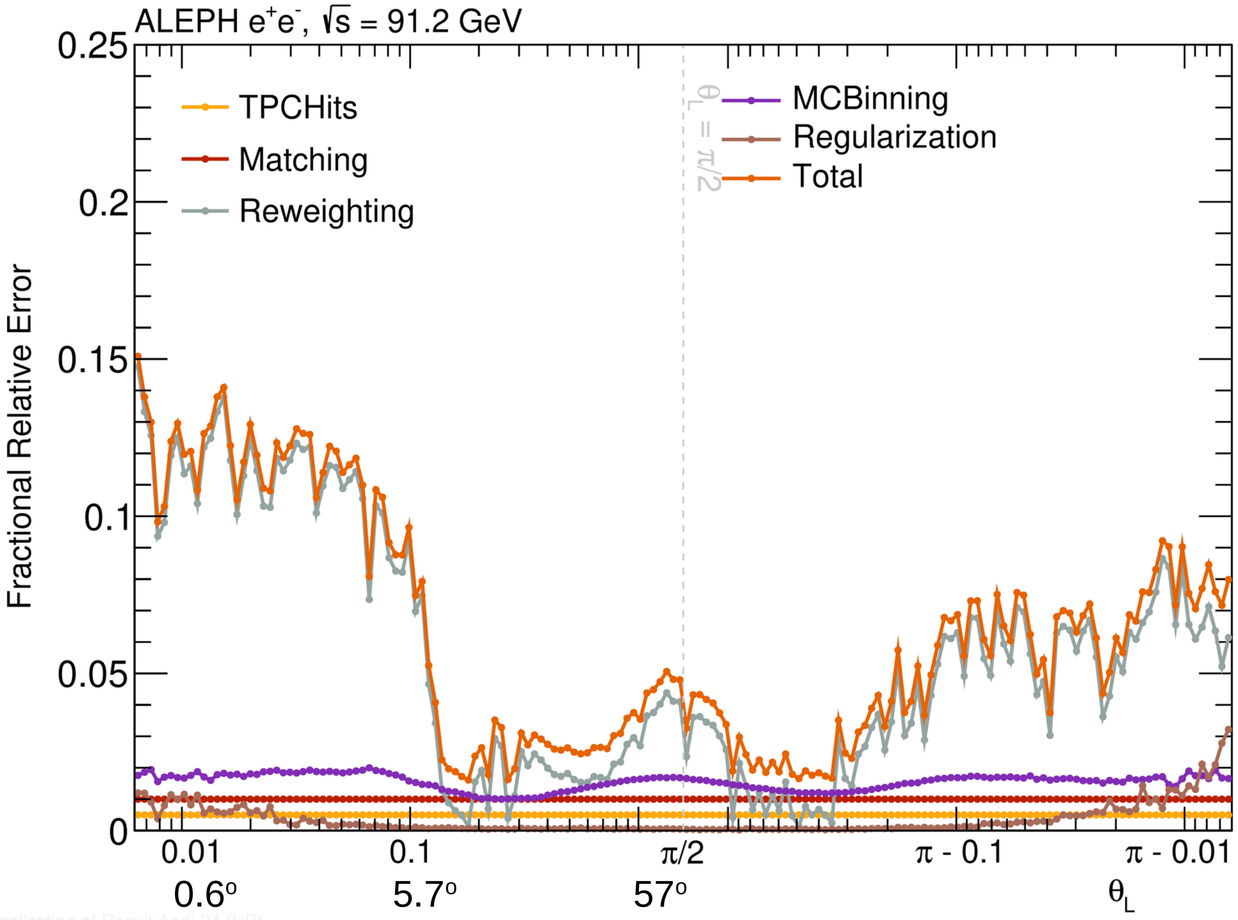
Comparison of archived ALEPH MC particle level to legacy results

Good agreement

(but tension with L3 result?)

ALEPH open data

[EPA, arXiv: 2505.11828]



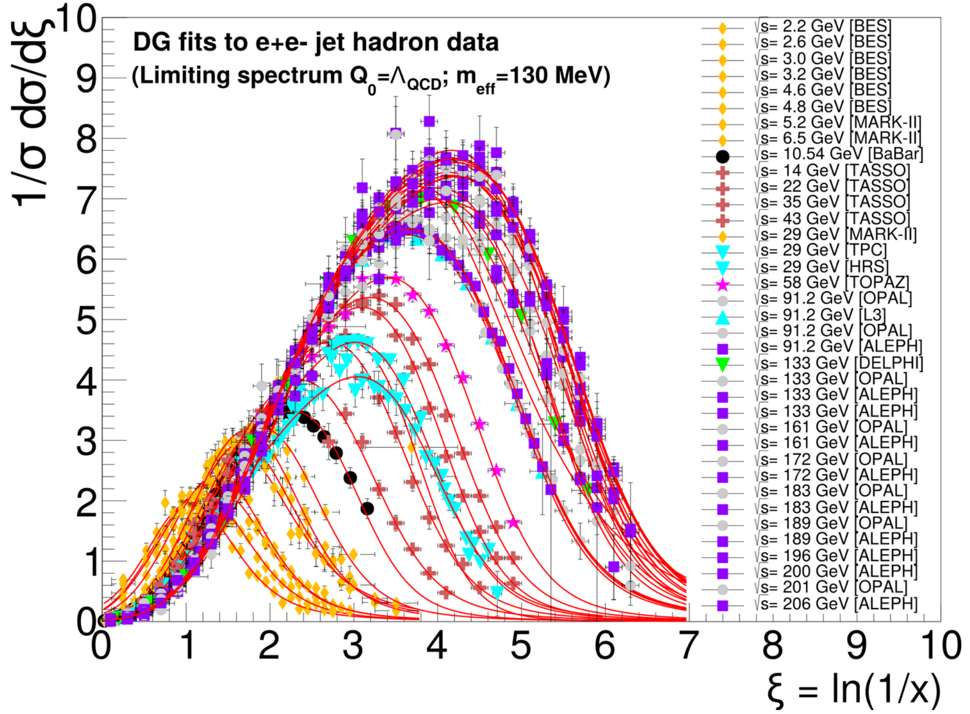
Error budget consistent with legacy LEP measurements

OPAL 1993: 2-5% total (stat+exptl) error for χ bins in [0.9°,179.1°]

Reweighting: MC model dependence of unfolding, done by reweighting archived MC to data. OPAL 1993 used tracks or cluster only, OPAL 2004 used HERWIG as alternative exptl correction, LEP1 event shape errors still ~1-5%

Fragmentation functions in e^+e^-

Fragmentation Functions in e^+e^-



Charged hadrons momentum spectra $x = 2E_h/\sqrt{s}$, $\xi = \ln(1/x)$, distribution is $1/\sigma d\sigma^h/d\xi$

FF: $D_{a,h}(z,Q)$, $z = p_h/p_a$, $Q = \sqrt{s}$

Distorted Gaussian model:

$D \approx C(\alpha_S(t))\exp(\int^t \gamma(\alpha_S(t'))dt')$

$t = \ln(Q)$, NNLO*+NNLL evolution of $\gamma(\alpha_S(t'))$

With c, b, (t) tags: study heavy quark fragmentation

$\alpha_s(m_Z) = 0.121 \pm 0.001_{exp} \pm 0.002_{theo}$

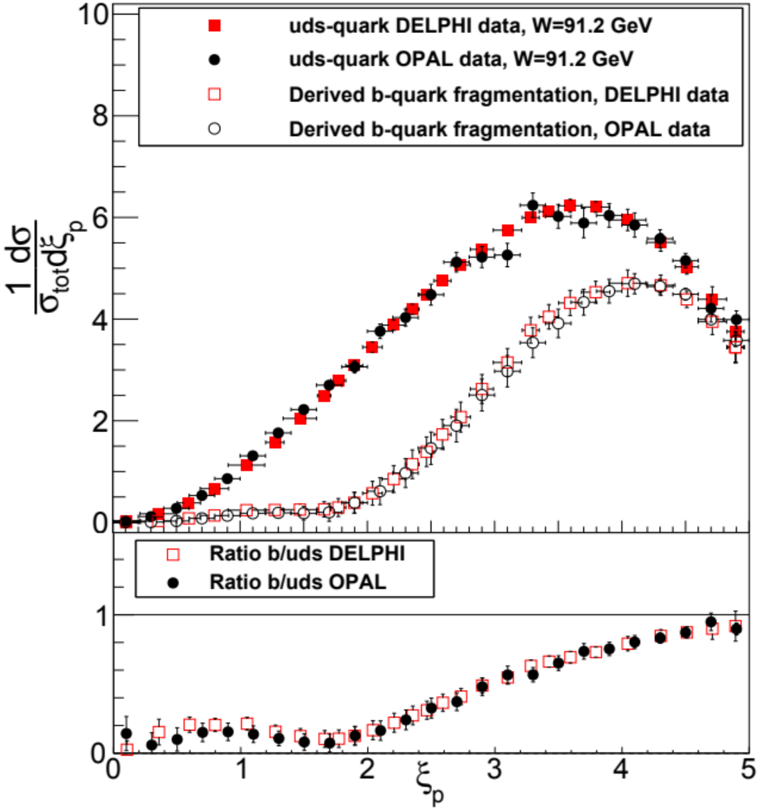
[R. Perez-Ramos, D. d'Enterria, arxiv: 2203.08271]

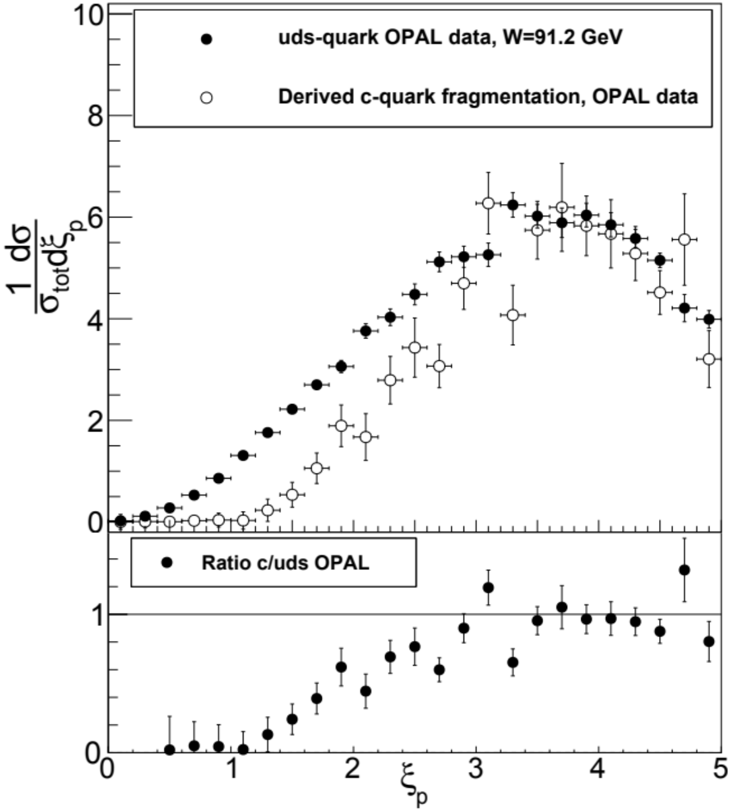
Bonus track: heavy quarks

Fragmentation Functions in e^+e^-

Heavy quark Q fragmentation: dead cone effect

[SK, Ochs, Perez Ramos, Phys. Rev. D 107(2023) 9, 094039]





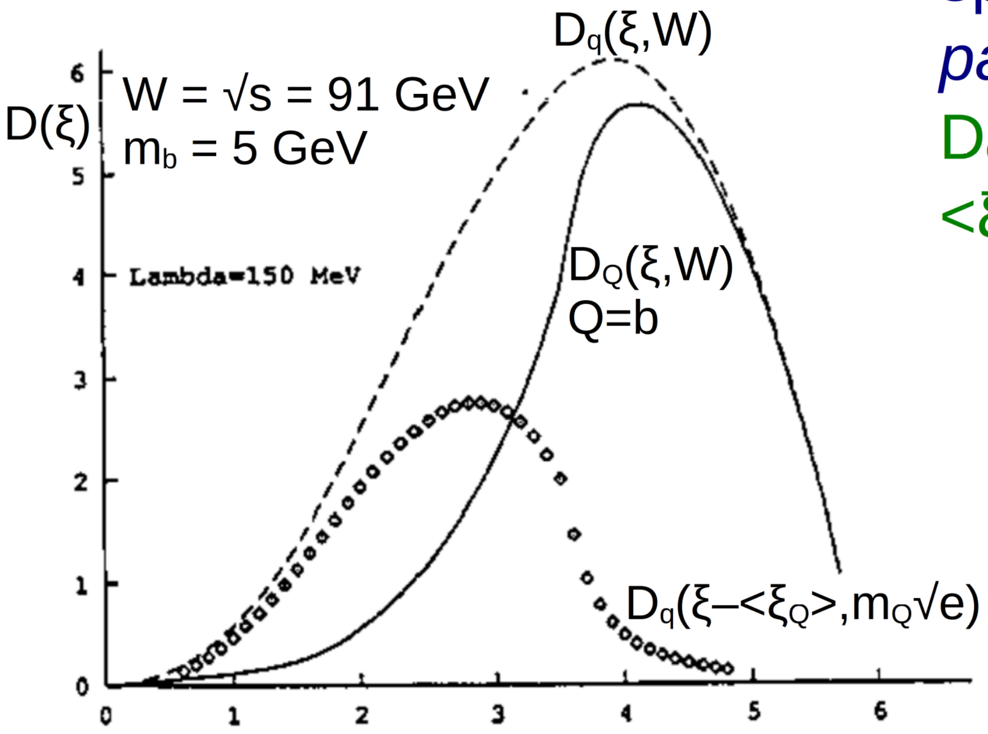
b,c-quark measurements corrected for B,C hadron decays

Fragmentation of Q with $\beta_Q < 1$ different from light q

Impact on
Q jet modelling
Q tagging

From original dead cone prediction

$e^+e^- \to b\bar{b} + X$

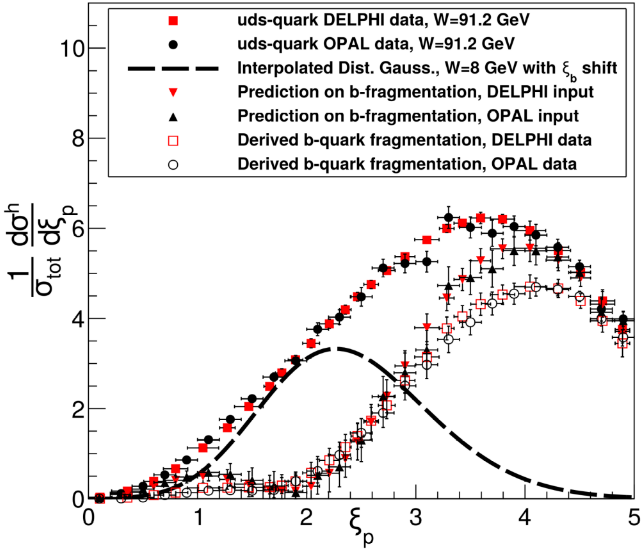


[Dokshitzer, Khoze, Troyan,
J. Phys. G17 (1991) 1481, 1602]

$\xi = \log(1/x)$
$x = 2p/\sqrt{s}$

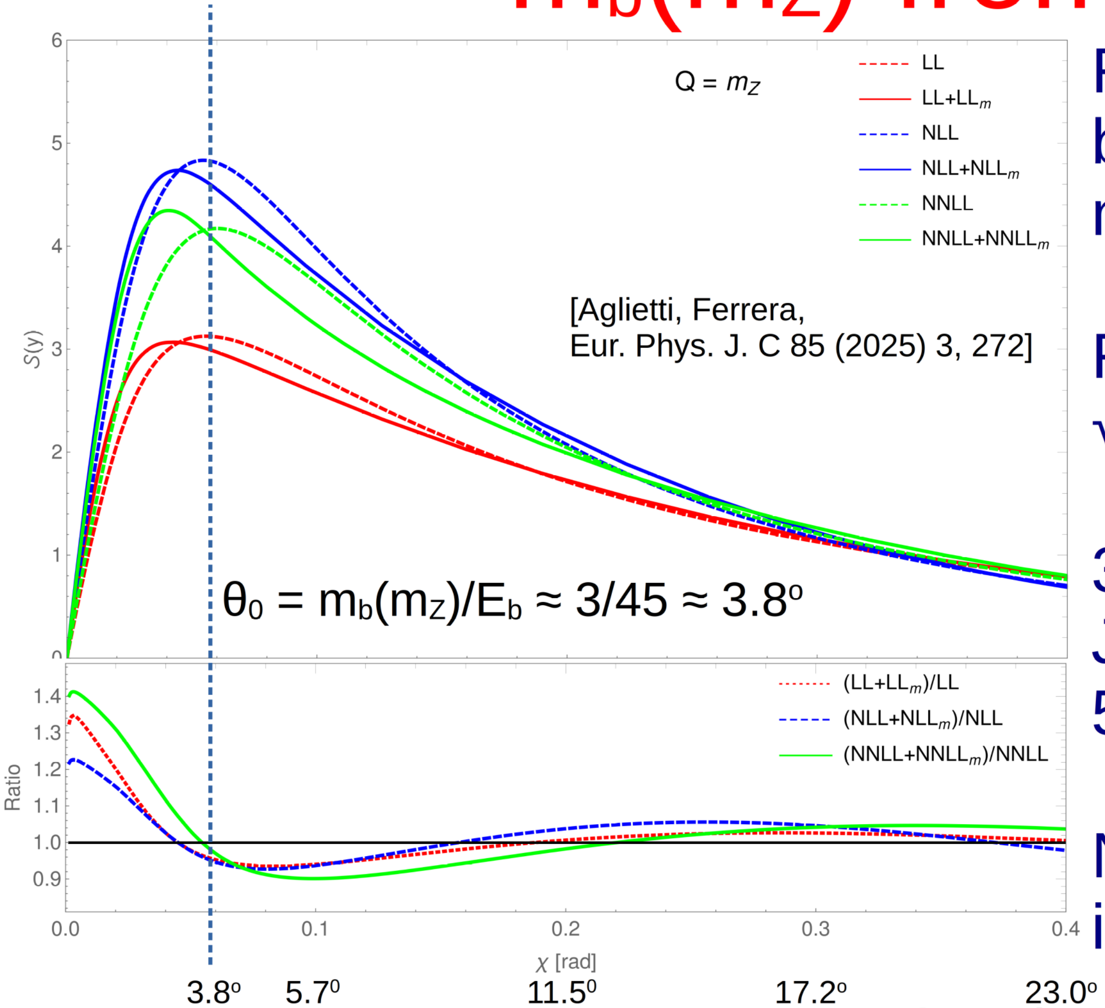
QCD MLLA prediction for momentum spectra $D_Q(\xi)$ of *accompanying particles* in heavy quark jets

$D_Q(\xi,W) = D_q(\xi,W) - D_q(\xi - \langle\xi_Q\rangle, m_Q\sqrt{e})$
$\langle\xi_Q\rangle = \ln(1/\langle x_Q\rangle)$



[SK, Ochs, Perez Ramos,
Phys. Rev. D 107(2023) 9, 094039]

$m_b(m_Z)$ from EEC?



[Aglietti, Ferrera,
Eur. Phys. J. C 85 (2025) 3, 272]

$\theta_0 = m_b(m_Z)/E_b \approx 3/45 \approx 3.8^o$

Resummation for EEC in the back-to-back region with quark mass effects

Ratio shows ~5-10% effect at $\sqrt{s}=m_Z$ (~20-30% at $\sqrt{s}=30$ GeV)

3-jet ratios (Durham $y_{cut}=0.01$, JADE $y_{cut}=0.02$) typically have 5% effect

Needs $e^+e^- \to b\bar{b}g$ at NNLO, ideally NLO$_m$ MC with PS$_m$

Conclusions

- Semi-inclusive:
  - good sensitivity to $\alpha_s(m_Z)$ with small exptl systematics
  - good control over theory predictions / systematics
- $p_{t,Z}$ at LHC:
  - most precise $\alpha_s(m_Z)$ except Lattice (under scrutiny)
- EECs
  - precise $\alpha_s(m_Z)$, testing ground for theory
  - connection of np correction between semi-inclusive observables
  - Sensitivity to quark masses

$m_b(m_Z)$ from jets