Extracting strong coupling constant with energy correlators at CEPC

arXiv:2406.10946

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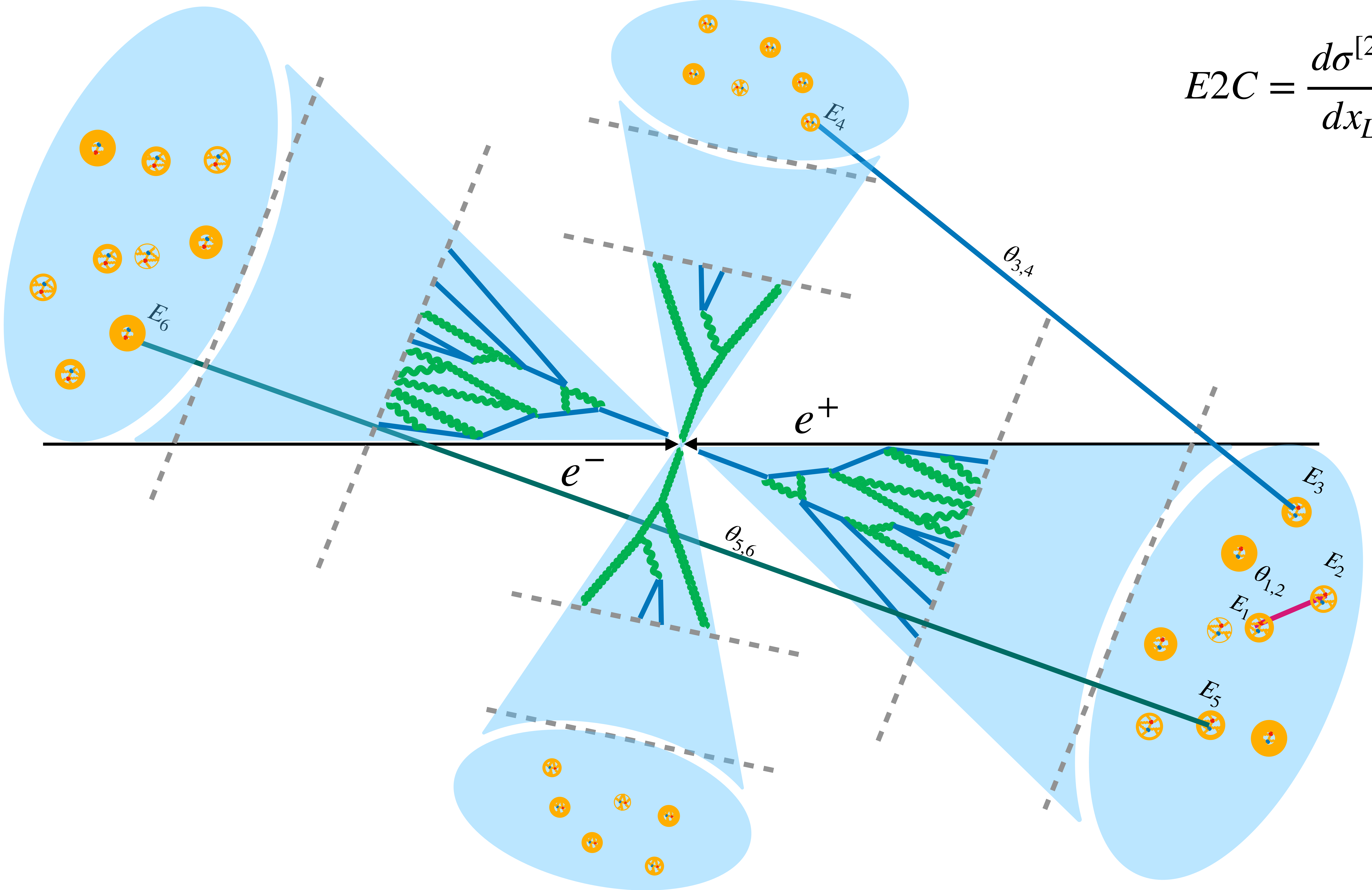
The 2024 international workshop on the high energy CEPC

Energy correlator in e^+e^- colliders



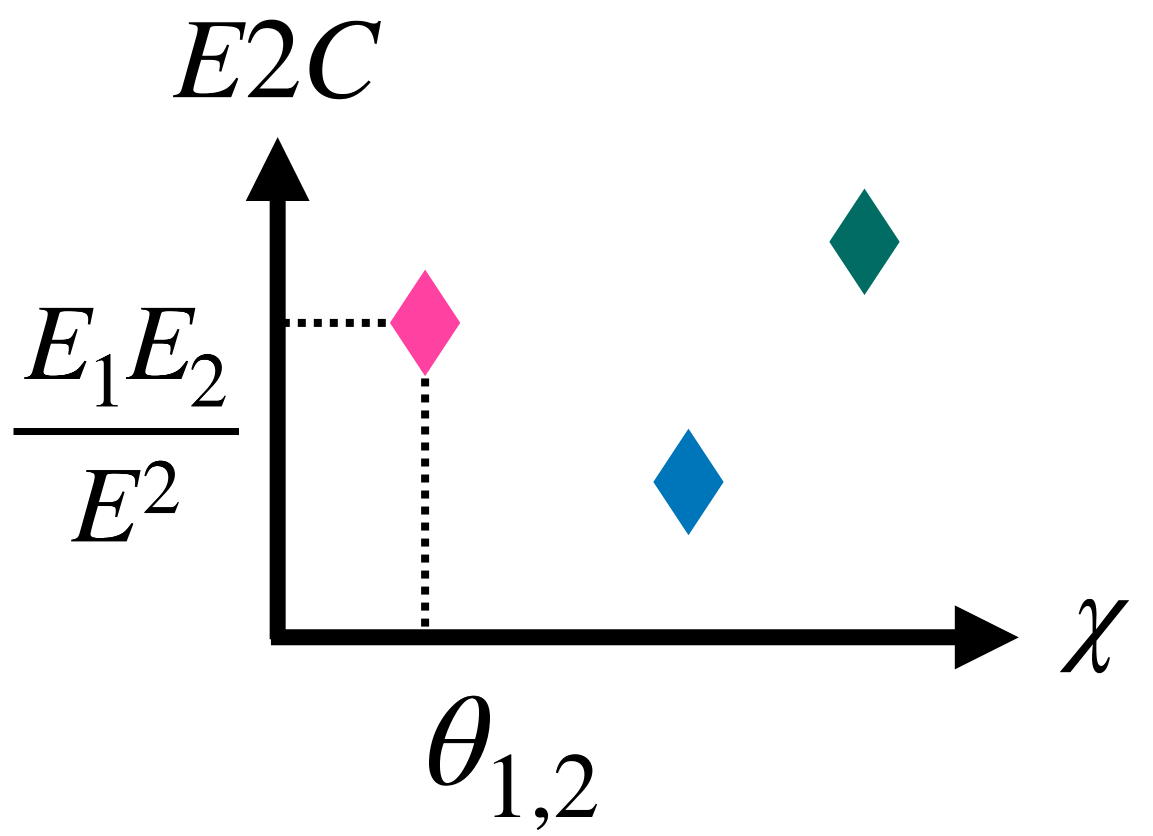
$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(\chi_{ij} - \theta_{ij})$$

$$\chi_{ij} = [0° - 180°]$$

Small x_L: collinear limit

Middle x_L

Large x_L: back-to-back limit



Energy correlator in e^+e^- colliders

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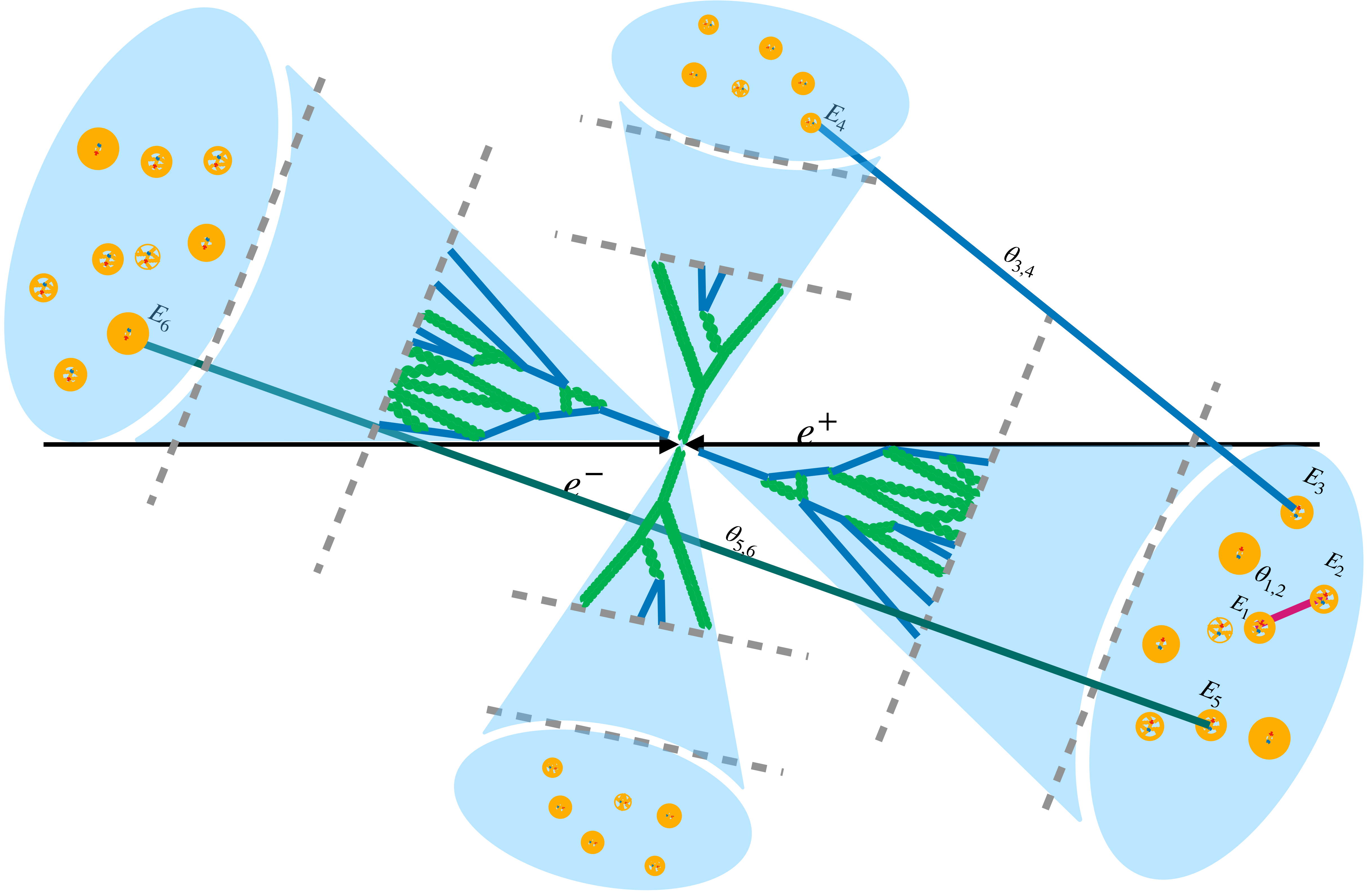
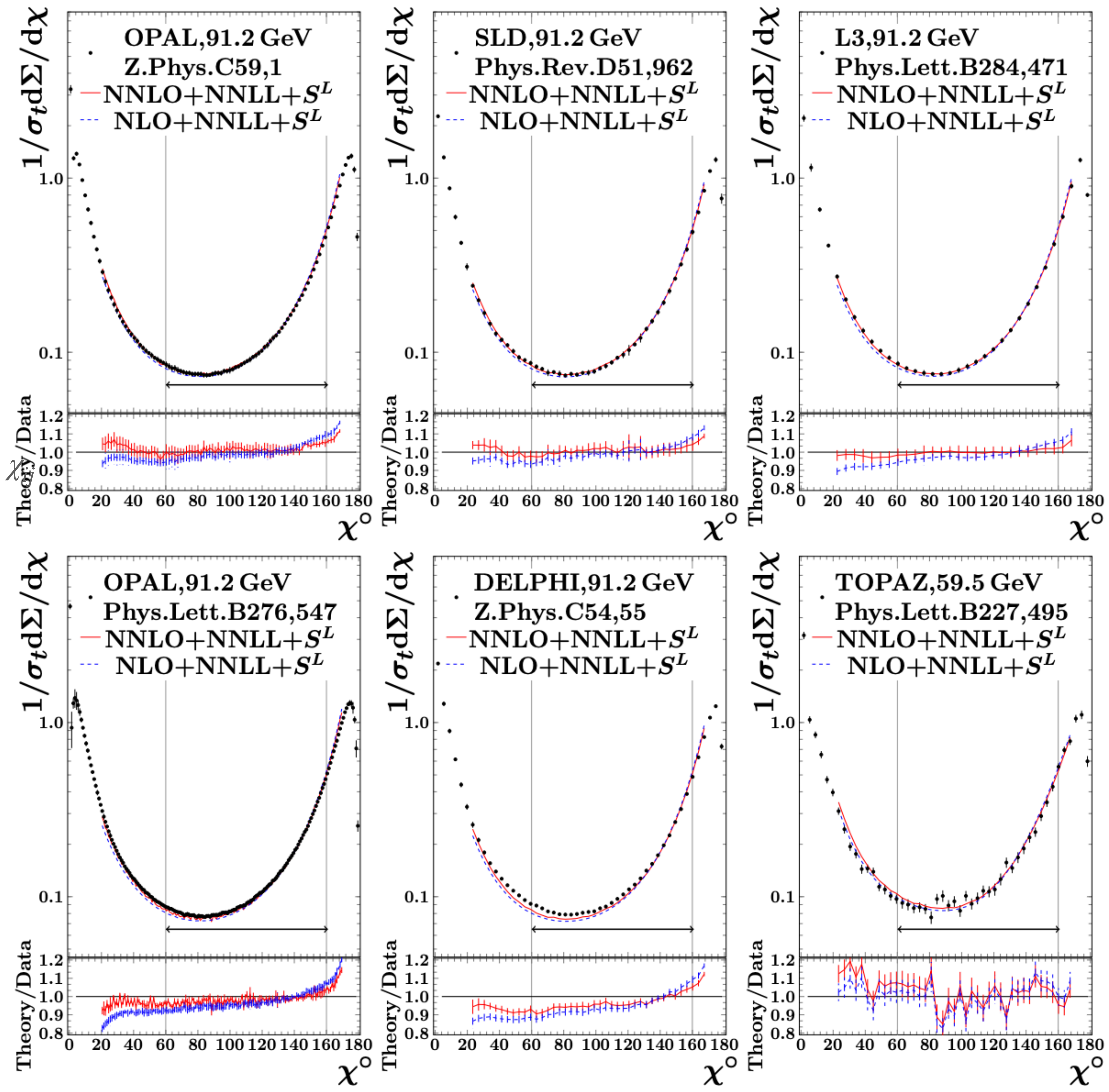
arxiv: 1804.09146



Widely measured



Previous α_S extraction using Energy correlators

arxiv: 1804.09146

Experiments: e^+e^- collisions

CM energy : 14 - 91.2 GeV

Theory: NNLO + NNLL

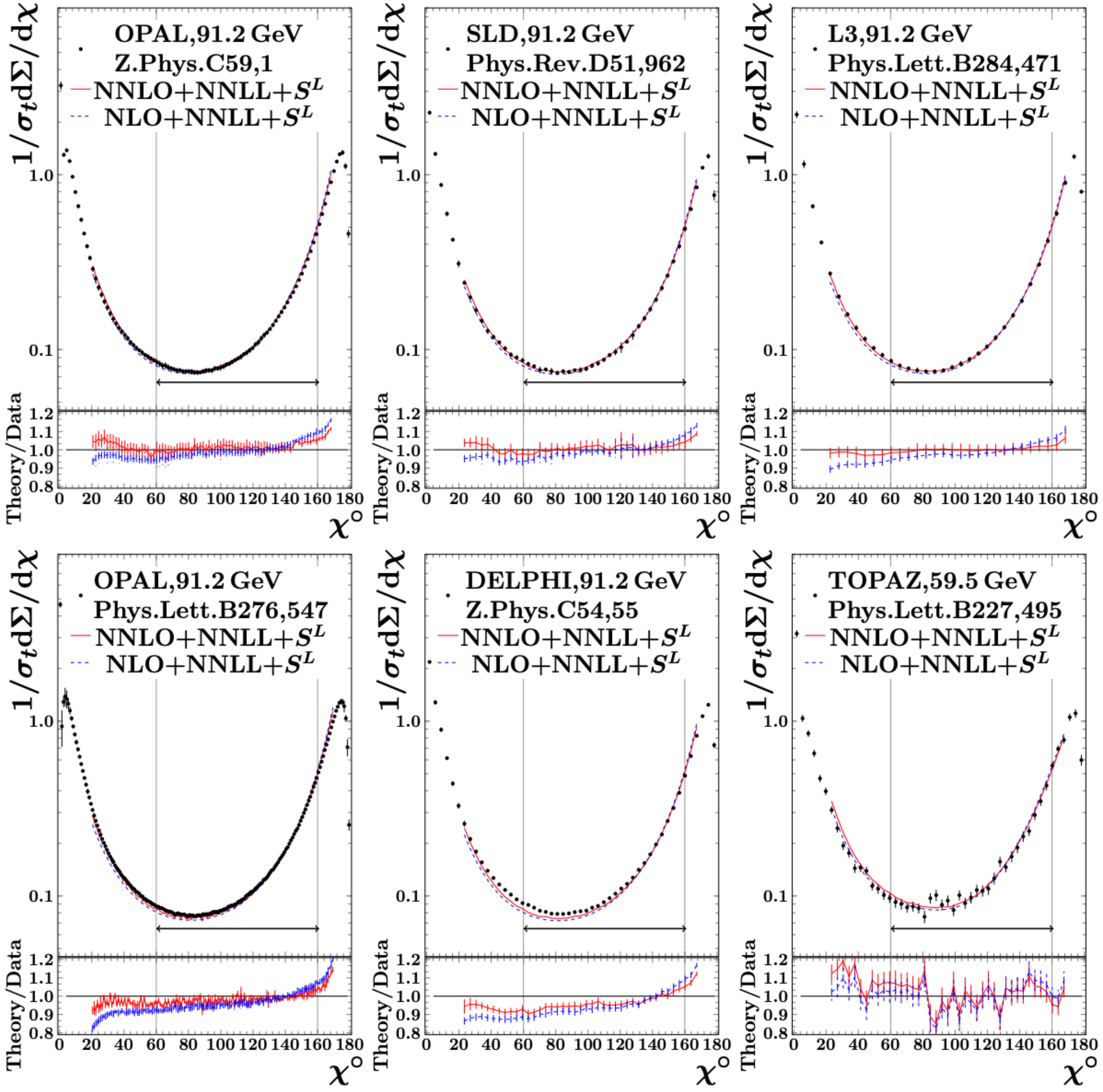
Hadronization model: HERWIG and SHERPA

Extraction range: $60^\circ - 160^\circ$

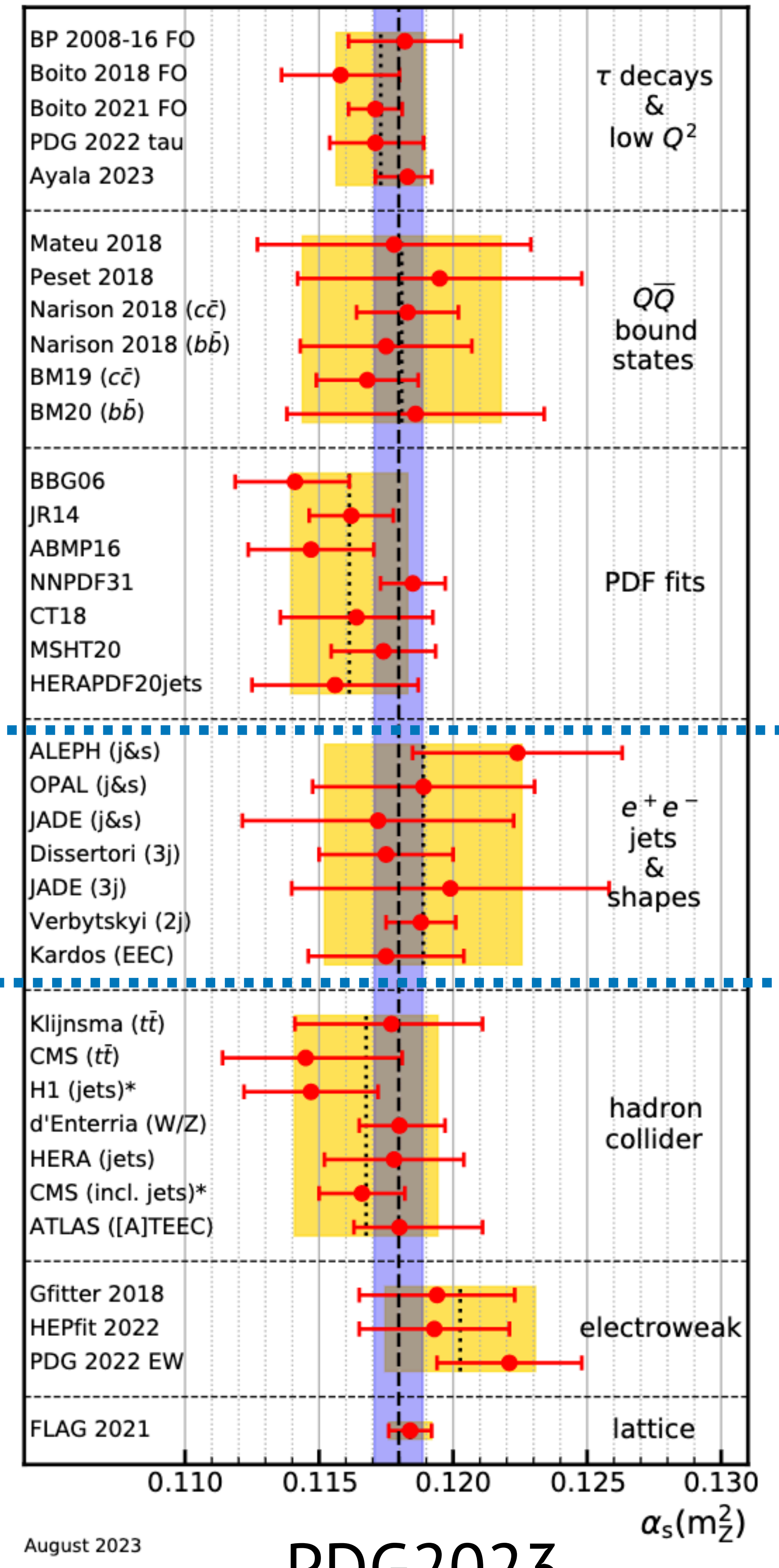
(lack of collinear region)

$\alpha_S(M_Z) = 0.11750 \pm 0.00287$(comb.)

Dominant uncertainty : Hadronization&Theory



Previous α_S extractions using event shape observable



PDG2023

0.1173 ± 0.0009

0.1181 ± 0.0011

0.1161 ± 0.0014

0.1189 ± 0.0017
lowest sensitivity

0.1168 ± 0.0014

0.1203 ± 0.0016

Distinct phase space:

- sensitive to soft and collinear physics

Limitation:

Significant theory uncertainty:

- high uncertainty due to resummation

Substantial hadronization uncertainty:

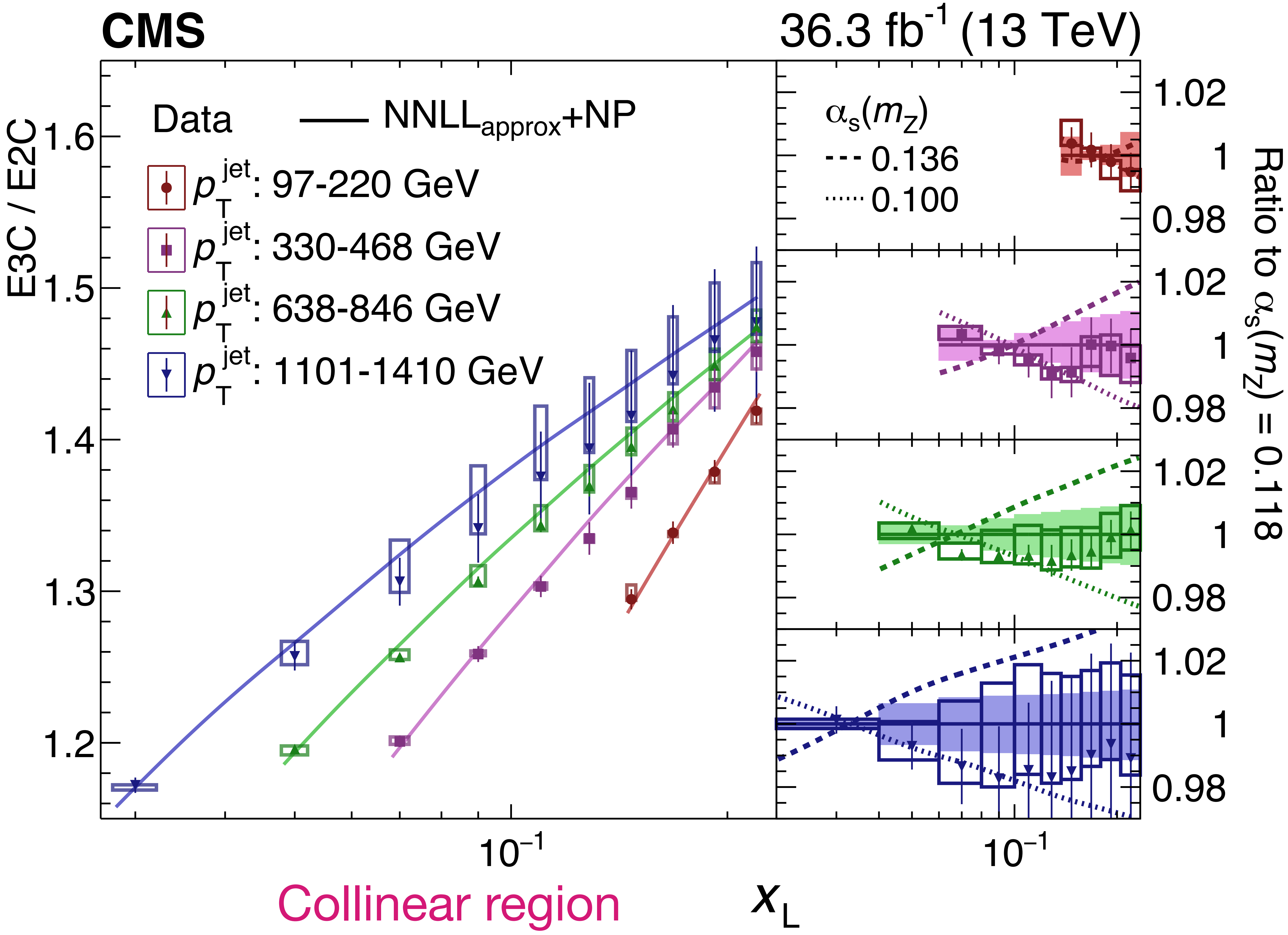
- Large hadronization correction

α_S extraction using E3C/E2C in CMS experiment

2402.13864

$$E3C = \frac{d\sigma^{[3]}}{dx_L} = \sum_{i,j,k}^{n} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k}))$$

Jet substructure



Collinear region

Benefit of taking ratio

- Exp sys: ~ 8% => ~ 3%
- Hadronization factors: ~5-35% => ~2%

α_S extraction using E3C/E2C in CMS experiment

2402.13864

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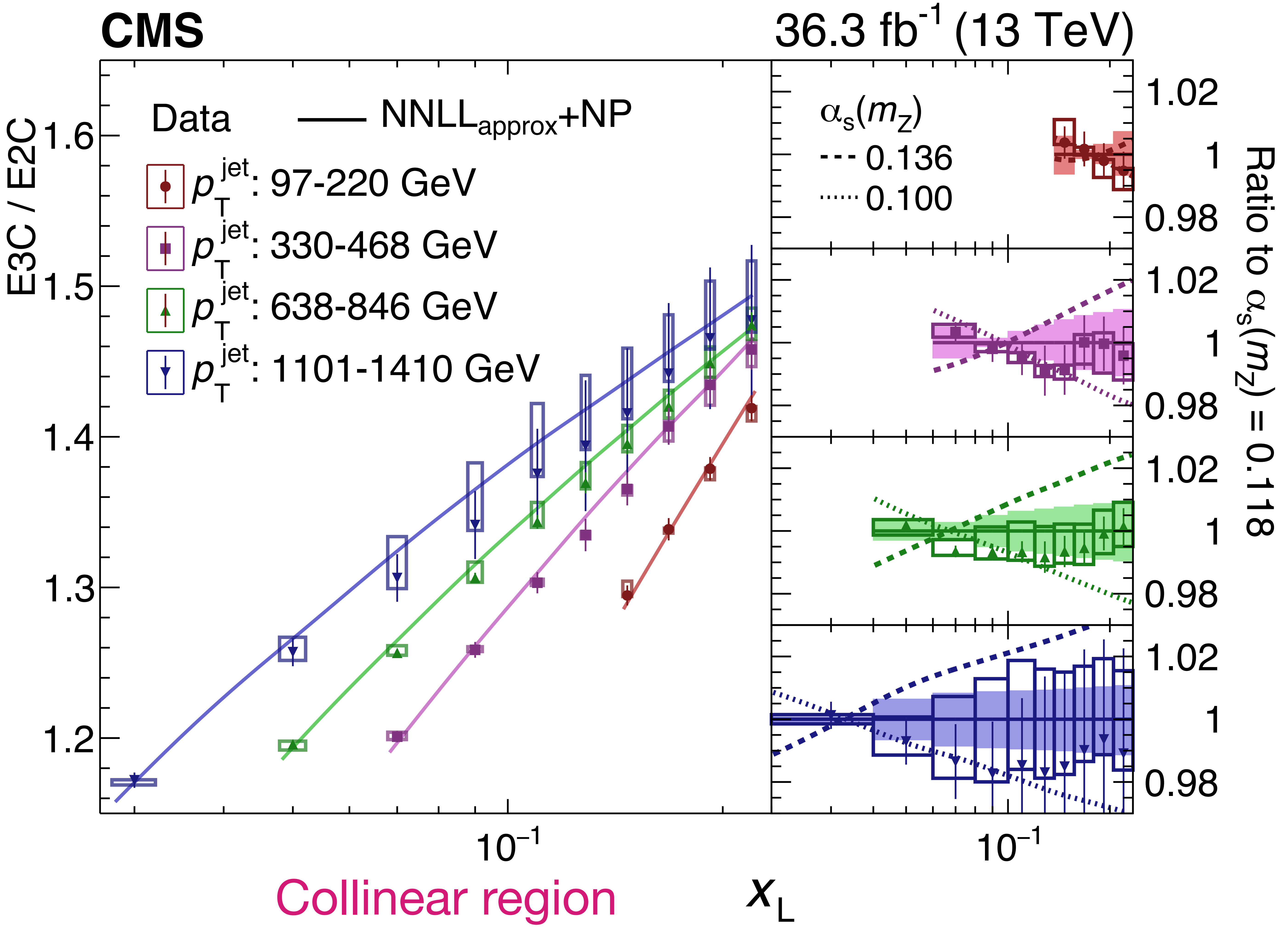


Collinear region

Jet substructure

$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

major source

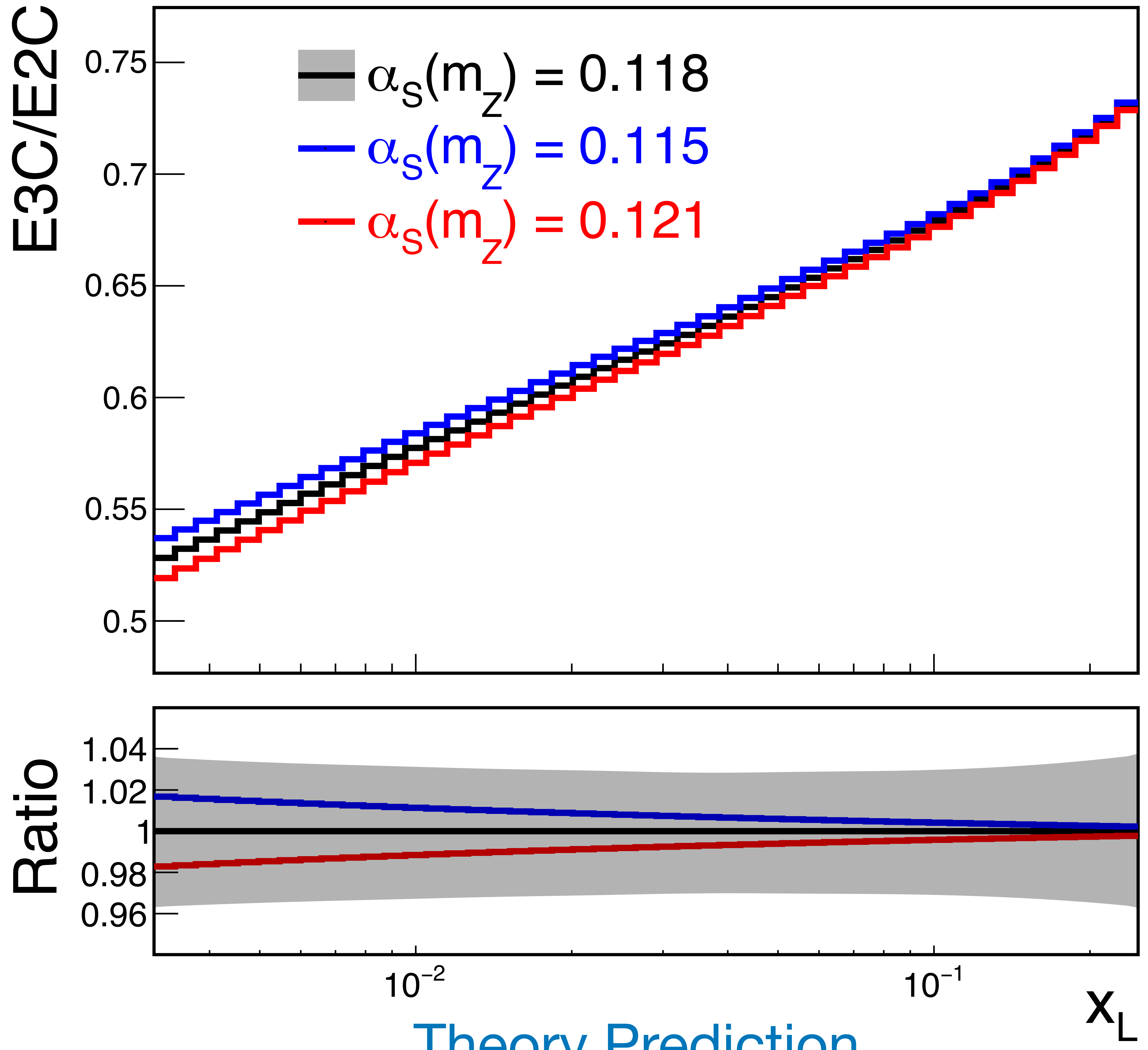
Covariance matrix

QCD scale of NNLLapprox

Neutral hadron energy scale

Uncertainty ~ 4%,
most precise from jet-substructure to date

E3C/E2C at e^+e^- collisions: Theoretical prediction



Theory Prediction

Phase space: 2307.07510

Experiments: e^+e^- collisions

CM energy : 91.2 GeV

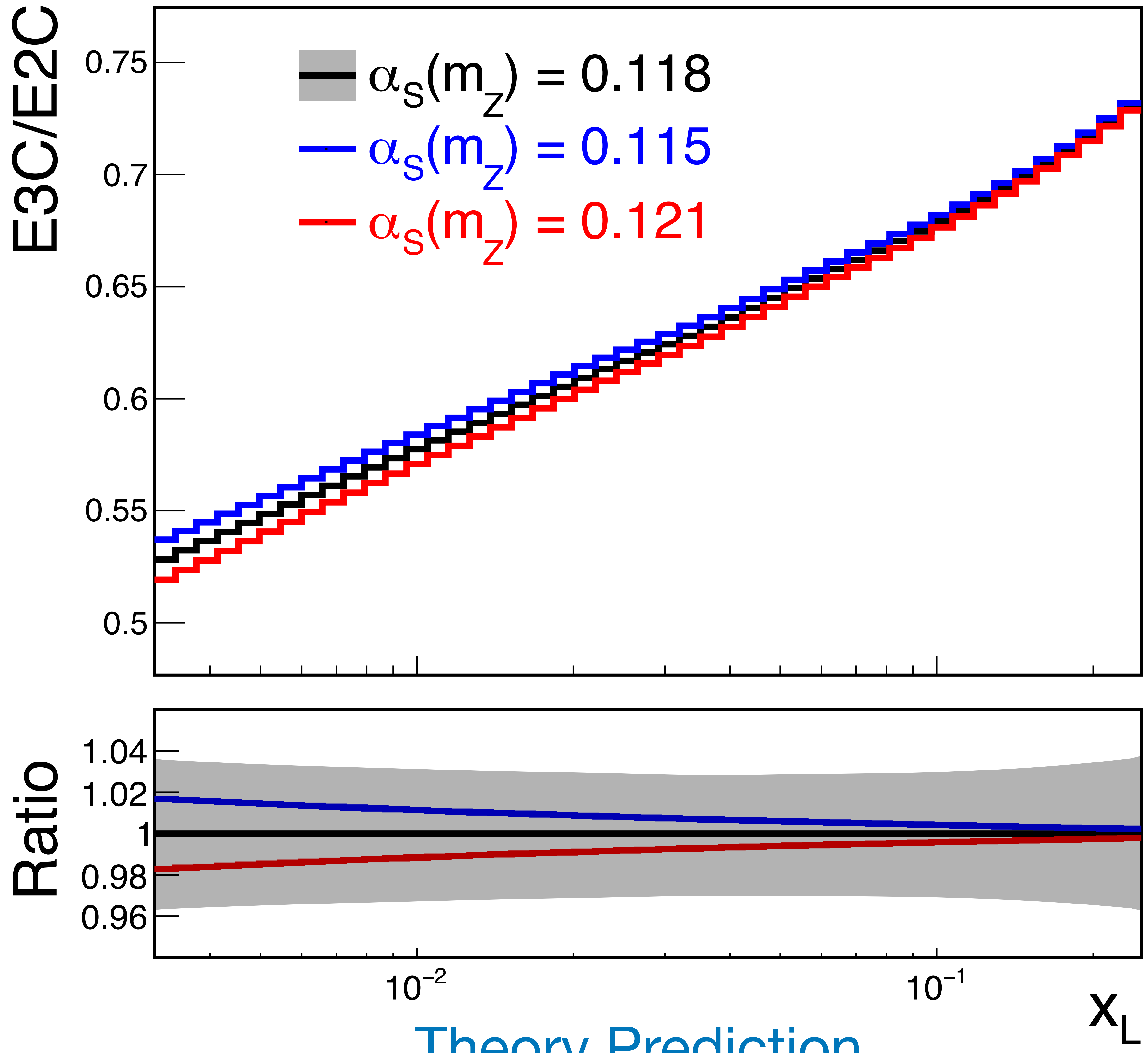
Theory: NLO + NNLL

range: $6° - 60°$ ($x_L = [0.003 - 0.25]$)

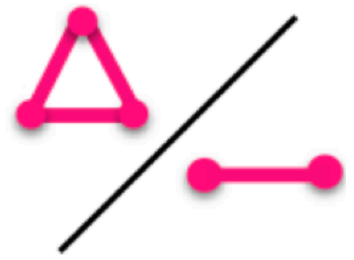
Sufficient statistic

Never been used for $\alpha_S(m_Z)$ extraction

E3C/E2C at e^+e^- collisions: Theoretical prediction



Theory Prediction



$\propto \alpha_S(Q) \ln x_L + O(\alpha_s^2)$

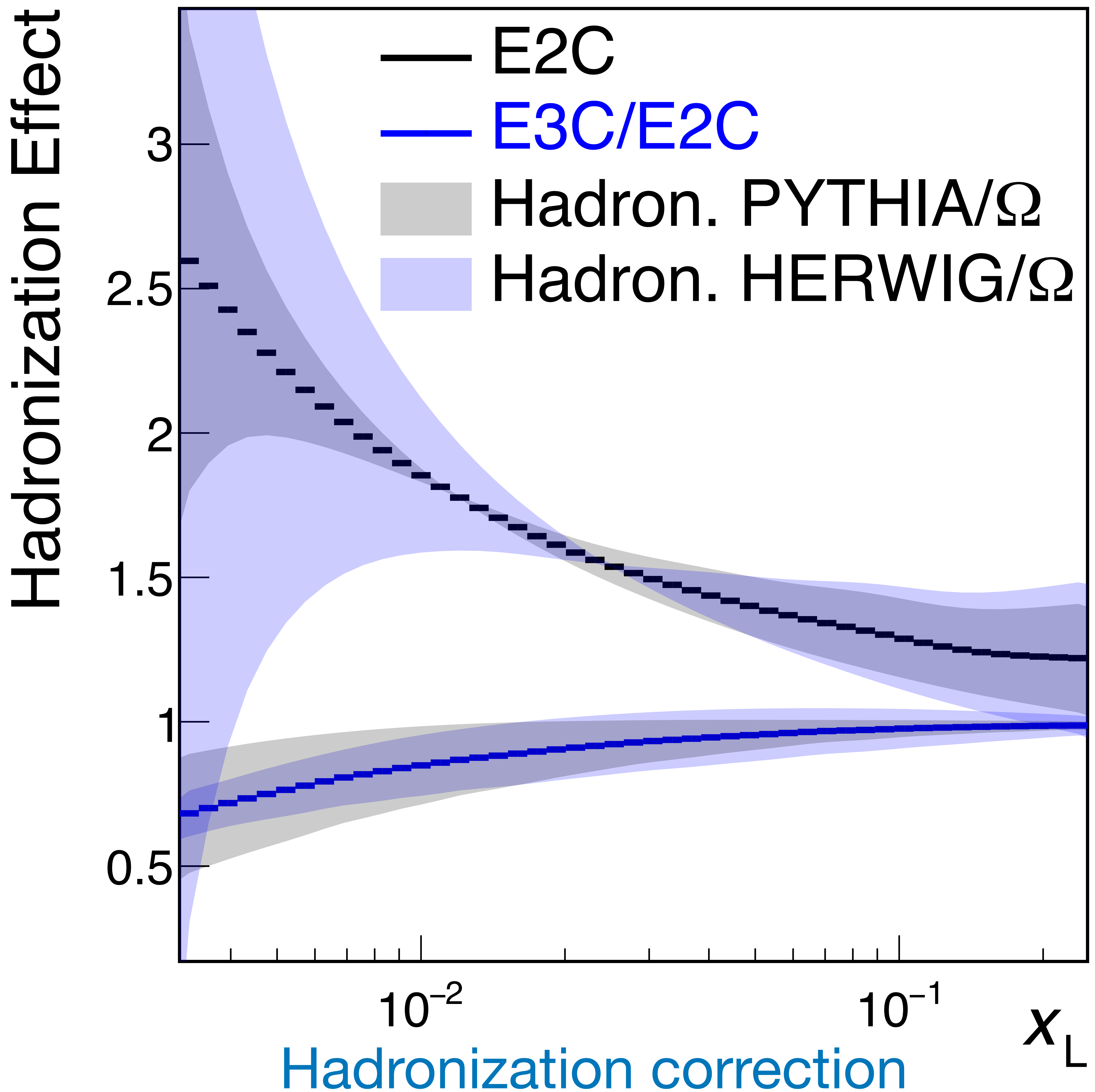
$\alpha_S(m_Z) \uparrow$, Slope $\uparrow$

Theory uncertainty:

- 3% in scale
- Flat shape

Expected low theory uncertainty

E3C/E2C at e^+e^- collisions: Hadronization correction



Hadronization correction

Nominal: Ω : Analytical model (2405.19396)

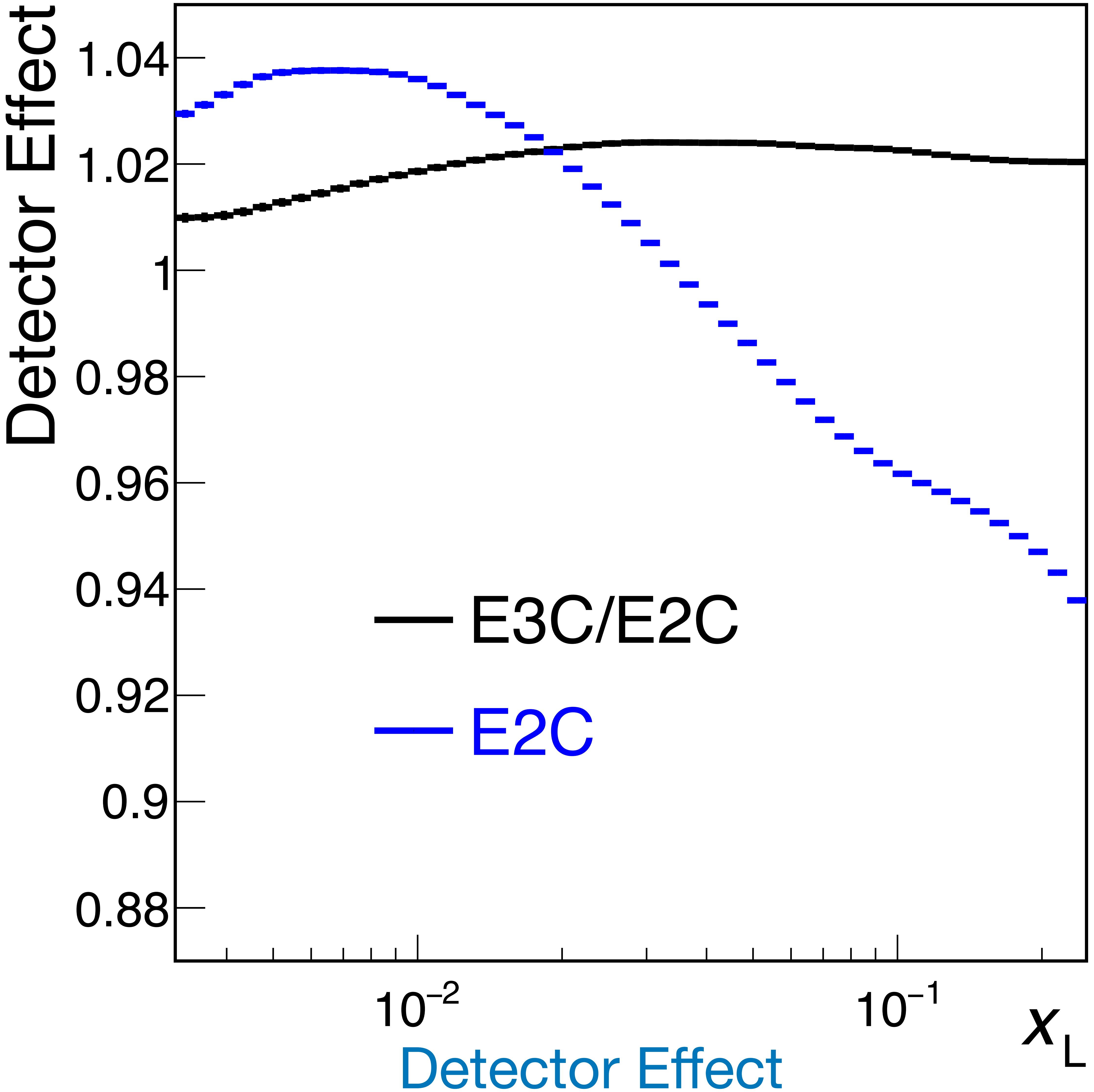
Variation: PYTHIA: lund string model
HERWIG: cluster model

Taking ratio

Hadronization correction ↓

Hadronization uncertainty ↓

E3C/E2C at e^+e^- collisions: Detector effect



Detector Effect

Delphes simulation using CEPC setting

Energy resolution:

ECAL: $16\,\%/\sqrt{E}$

HCAL: $50\,\%/\sqrt{E}$

Space resolution:

Charged particle: 0.1mrad (E>10GeV)

Taking ratio

Scale: Reduced from ~10% to ~2%

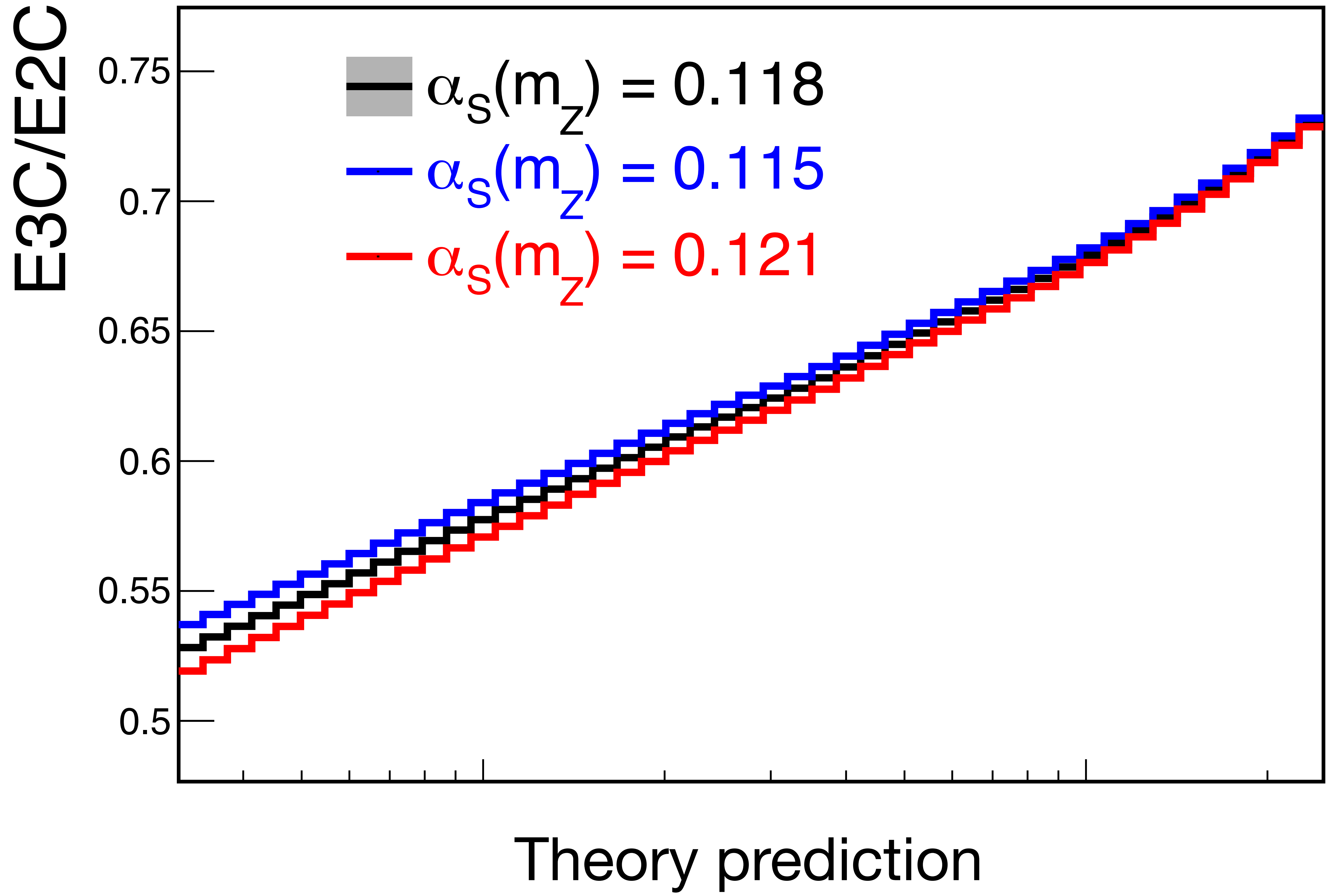
Shape: From steep to flat

Associated exp. uncertainty will also reduced

Expected sensitivity of α_S extraction using χ^2 tool

$$\chi^2\left(\alpha_s,\vec{\theta}\right) = \left(\vec{v}_{\text{th}}\left(\vec{\theta},\alpha_s\right) - \vec{v}_{data}(\vec{\theta})\right)^T V^{-1}_{\text{data}}\left(\vec{v}_{\text{th}}\left(\vec{\theta},\alpha_s\right) - \vec{v}_{data}(\vec{\theta})\right) + \sum_i \theta_i^2 .$$

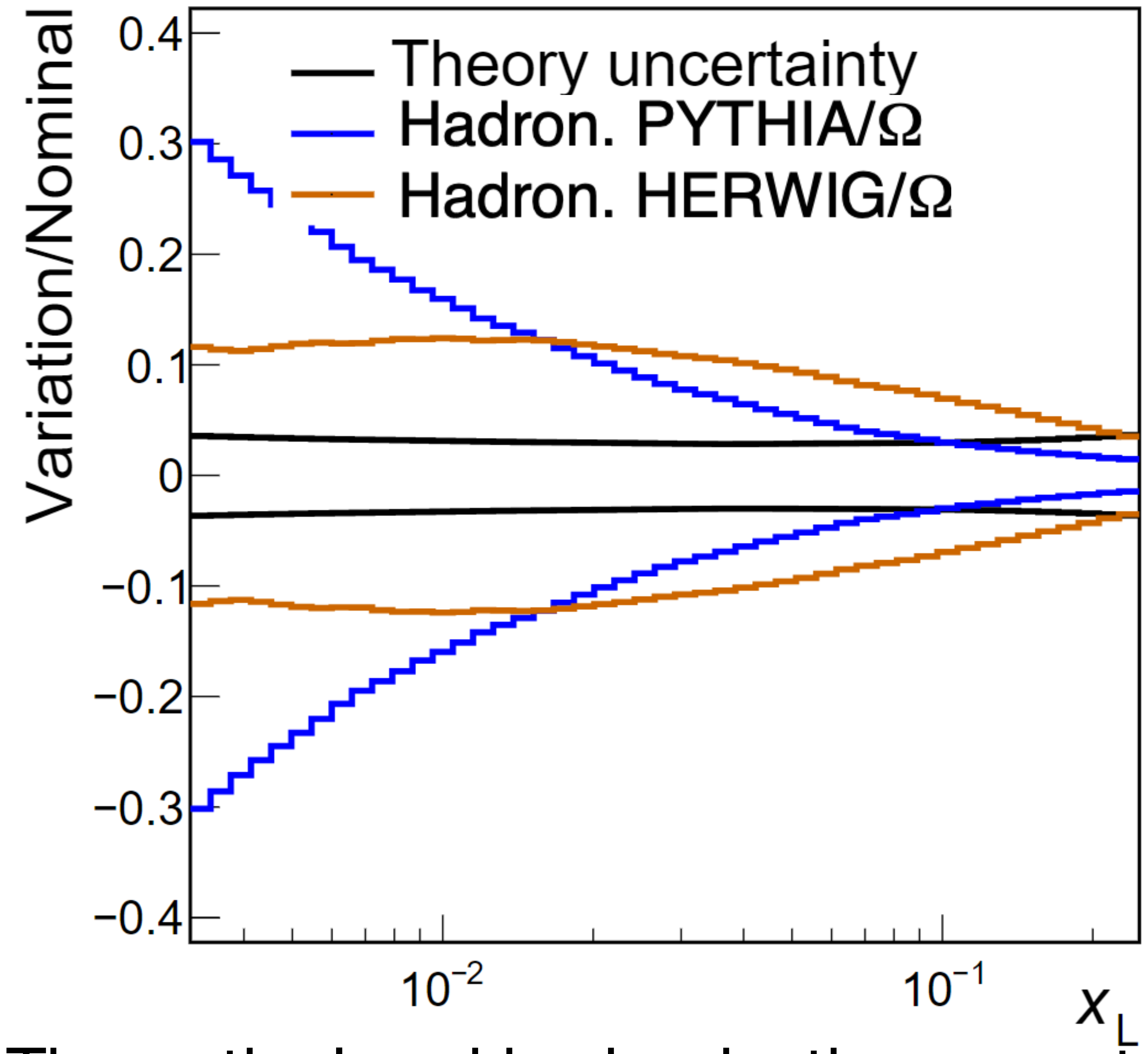
$\vec{v}_{\text{th}}$: Theory prediction for different $\alpha_s(m_Z)$



Expected sensitivity of α_S extraction using χ^2 tool

$$\chi^2\left(\alpha_s, \vec{\theta}\right) = \left(\vec{v}_{\text{th}}\left(\vec{\theta}, \alpha_s\right) - \vec{v}_{data}(\vec{\theta})\right)^T V^{-1}_{\text{data}} \left(\vec{v}_{\text{th}}\left(\vec{\theta}, \alpha_s\right) - \vec{v}_{data}(\vec{\theta})\right) + \sum_i \theta_i^2 .$$

$\vec{\theta}$: Nuisance parameter to considered theory uncertainty and hadronization uncertainty

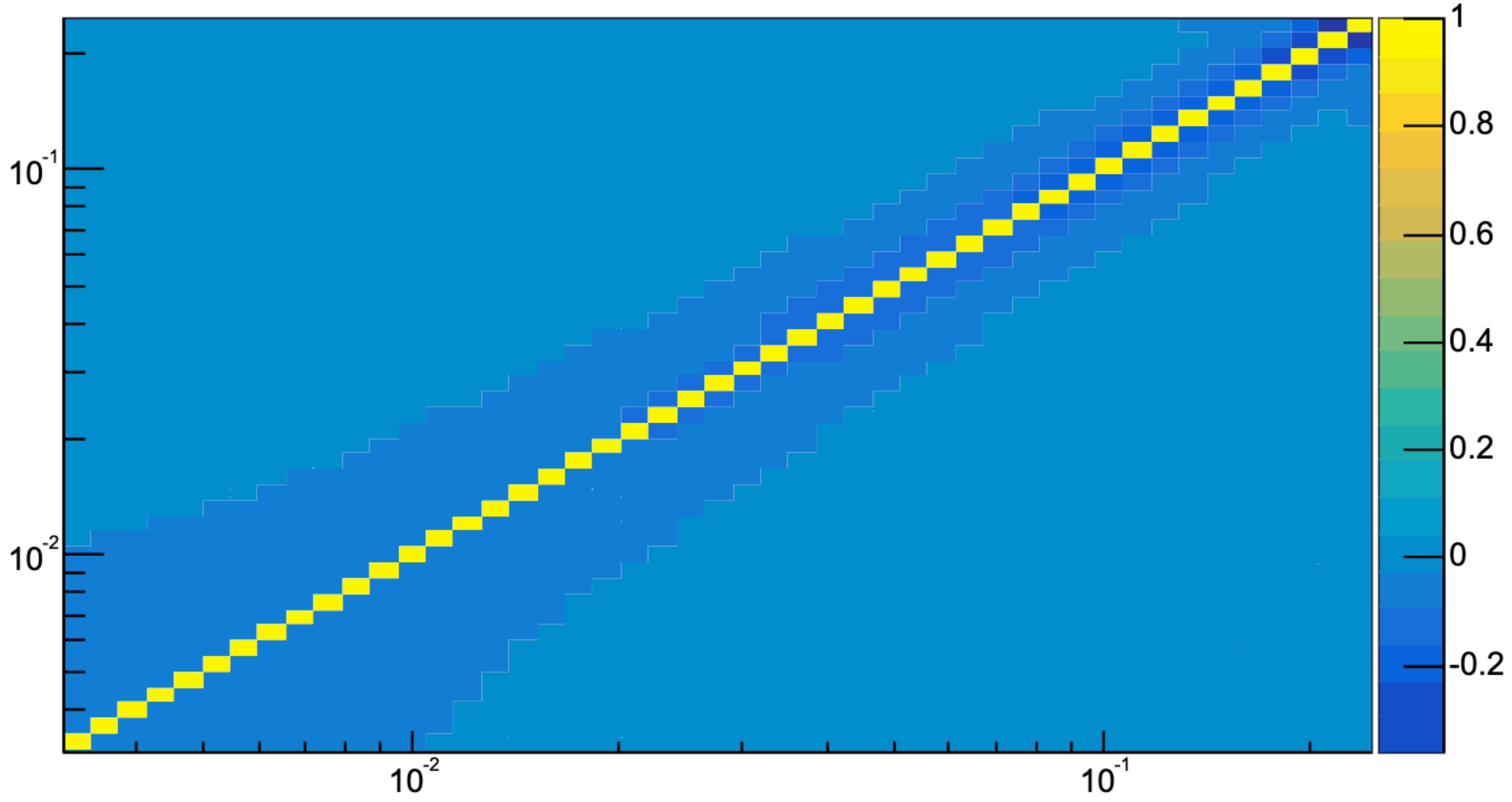


Theoretical and hadronization uncertainty

Expected sensitivity of α_S extraction using χ^2 tool

$$\chi^2\left(\alpha_s, \vec{\theta}\right) = \left(\vec{v}_{\text{th}}\left(\vec{\theta}, \alpha_s\right) - \vec{v}_{data}(\vec{\theta})\right)^T V_{\text{data}}^{-1}\left(\vec{v}_{\text{th}}\left(\vec{\theta}, \alpha_s\right) - \vec{v}_{data}(\vec{\theta})\right) + \sum_i \theta_i^2 .$$

V_{data}: Covariance matrix derived from pseudo data

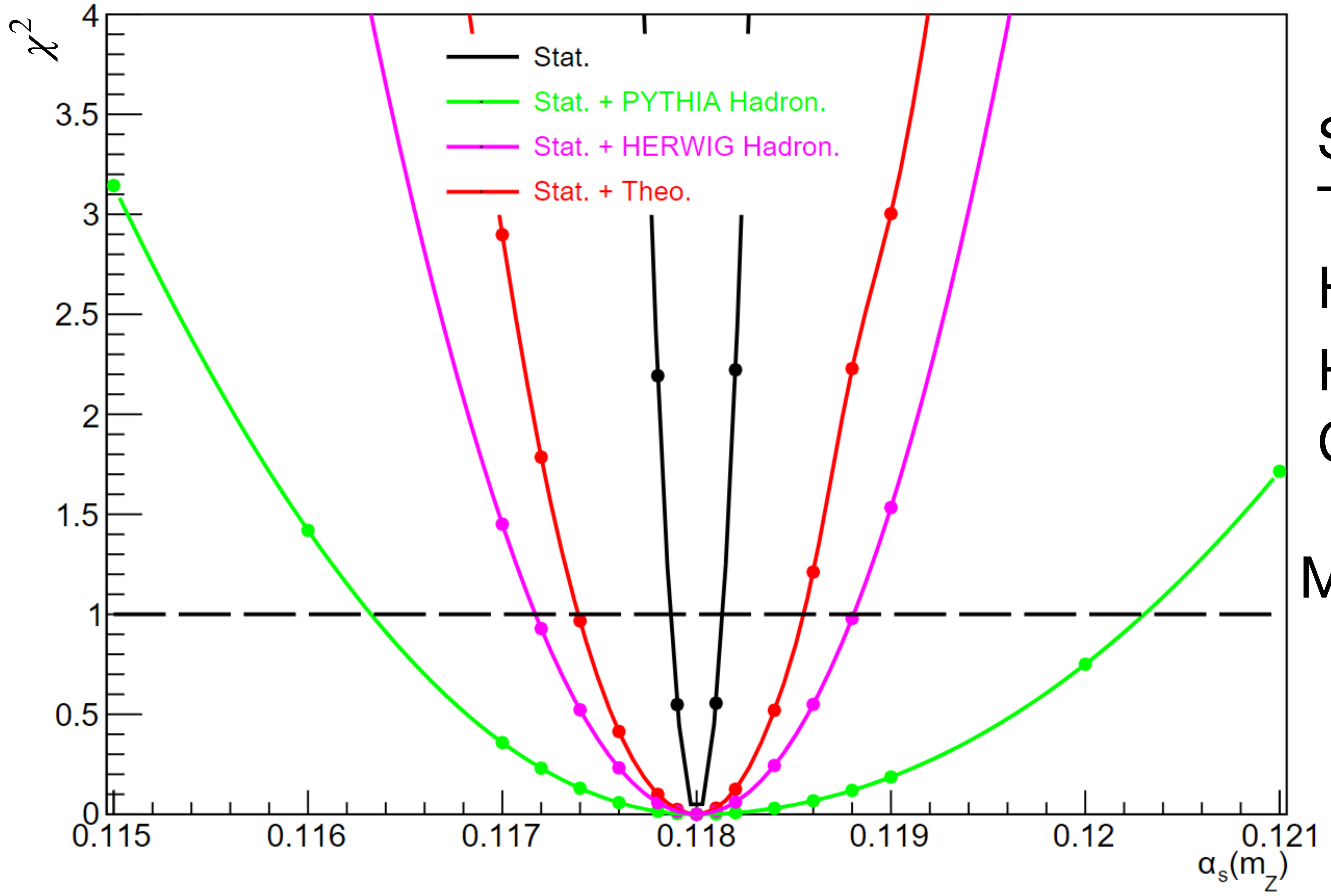


Correlation matrix derived from PYTHIA

Expected sensitivity of α_S extraction using χ^2 tool

$$\chi^2\left(\alpha_s,\vec{\theta}\right) = \left(\vec{v}_{\text{th}}\left(\vec{\theta},\alpha_s\right) - \vec{v}_{data}(\vec{\theta})\right)^T V_{\text{data}}^{-1}\left(\vec{v}_{\text{th}}\left(\vec{\theta},\alpha_s\right) - \vec{v}_{data}(\vec{\theta})\right) + \sum_i \theta_i^2 .$$

$\mathscr{L}$ = 40 pb^{-1} (similar to the data used in arxiv: 1804.09146)



Stat : +0.000134 -0.000135

Theo : +0.000534 -0.000594

Hadron. PYTHIA/Ω: +0.002300 -0.001670

Hadron. HERWIG/Ω : +0.000797 -0.000819

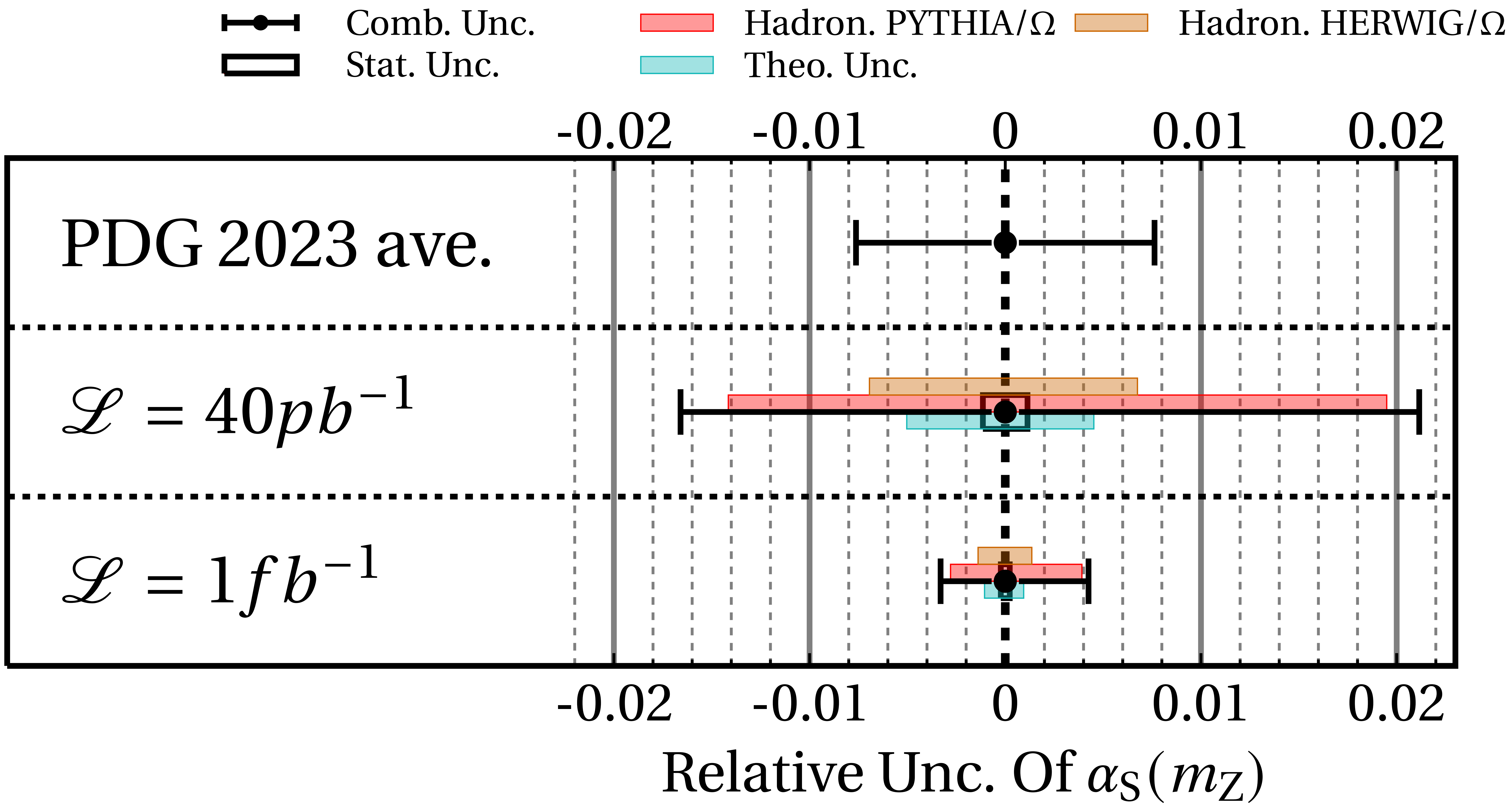
Combined : +0.002496 -0.001958

More sensitive than using EEC alone for extraction

$$\alpha_S(M_Z) = 0.11750 \pm 0.00287\text{(comb.)}$$

arxiv: 1804.09146

Expected sensitivity of α_S extraction



2% for $40pb^{-1}$ (1 minute)

0.4% for 1 fb^{-1} (0.5 hours)

Summary

- E3C/E2C in collinear region at e^+e^- colliders has substantial advantages:
  - Never been explored before
  - Reduced theoretical uncertainty in α_S extraction
  - Reduced hadronization effects
  - Minimal dependence on detector response
- Precision can reached:
  - 2% precision under $40pb^{-1}$(1 minute collection in CEPC)
  - 0.4% precision under $1fb^{-1}$(0.5 hours collection in CEPC)