Constraining cosmological models with the Effective Field Theory of Large-Scale Structures

Théo SIMON

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Based on arXiv:2210.14931

TS, Pierre Zhang and Vivian Poulin

[Cosmological inference from the EFTofLSS: the eBOSS QSO full-shape analysis]

PONT - 04/05/2023

The Effective Field Theory of Large-Scale Structures (EFTofLSS)

Main motivations

In **linear perturbation theory**, there are two popular ways to use LSS data:

1. Extract information from the full galaxy power spectrum:

$$P_g(z,k,\mu) \simeq \left[b_1(z) + f\mu^2\right]^2 P_m(z,k)$$

Kaiser '87

b_1: bias parameter, f: growth factor and $\mu = \hat{z} \cdot \hat{k}$

2. BAO angles + Redshift Space Distortion (RSD) information: BAO/$f\sigma_8$

LSS collaborations conventionally use the second method

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The galaxy power spectrum in the framework of the EFTofLSS:

$$P_g(k,\mu) \simeq \left[b_1 + f\mu^2\right]^2 P_m(k) = Z_1(\mu)^2 P_m(k)$$

We go from 1 to 10 free parameters

$$P_g(k,\mu) = Z_1(\mu)^2 P_{11}(k) + 2 Z_1(\mu) P_{11}(k) \left(c_{\rm ct} \frac{k^2}{k_{\rm M}^2} + c_{r,1}\mu^2 \frac{k^2}{k_{\rm R}^2} + c_{r,2}\mu^4 \frac{k^2}{k_{\rm R}^2} \right)$$
$$+ 2\int \frac{d^3q}{(2\pi)^3} Z_2(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q}, \mu)^2 P_{11}(|\boldsymbol{k}-\boldsymbol{q}|) P_{11}(q) + 6 Z_1(\mu) P_{11}(k) \int \frac{d^3q}{(2\pi)^3} Z_3(\boldsymbol{q}, -\boldsymbol{q}, \boldsymbol{k}, \mu) P_{11}(q)$$
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Carrasco++ [arXiv:1206.2926] ; Baumann++ [arXiv:1004.2488]
Senatore [arXiv:1406.7843] ; Perko++ [arXiv:1610.09321]

See Guido D'Amico's talk

The effective field theory of large-scale structures (EFTofLSS)

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$P_g(k,\mu)$ can be determined directly from $P_{11}(k) = P_m^{\rm lin}(k)$

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10 parameters

4 parameters b_i ($i = 1,2,3,4$) to describe the **galaxy bias** which arises from the one-loop contributions

3 parameters corresponding to **counterterms** (c_{ct} linear combination of a higher derivative bias and the dark matter sound speed, while $c_{r,1}$ and $c_{r,2}$ are the redshift-space counterterms)

3 parameters which describe **stochastic** terms

The effective field theory of large-scale structures (EFTofLSS)

Application to BOSS data

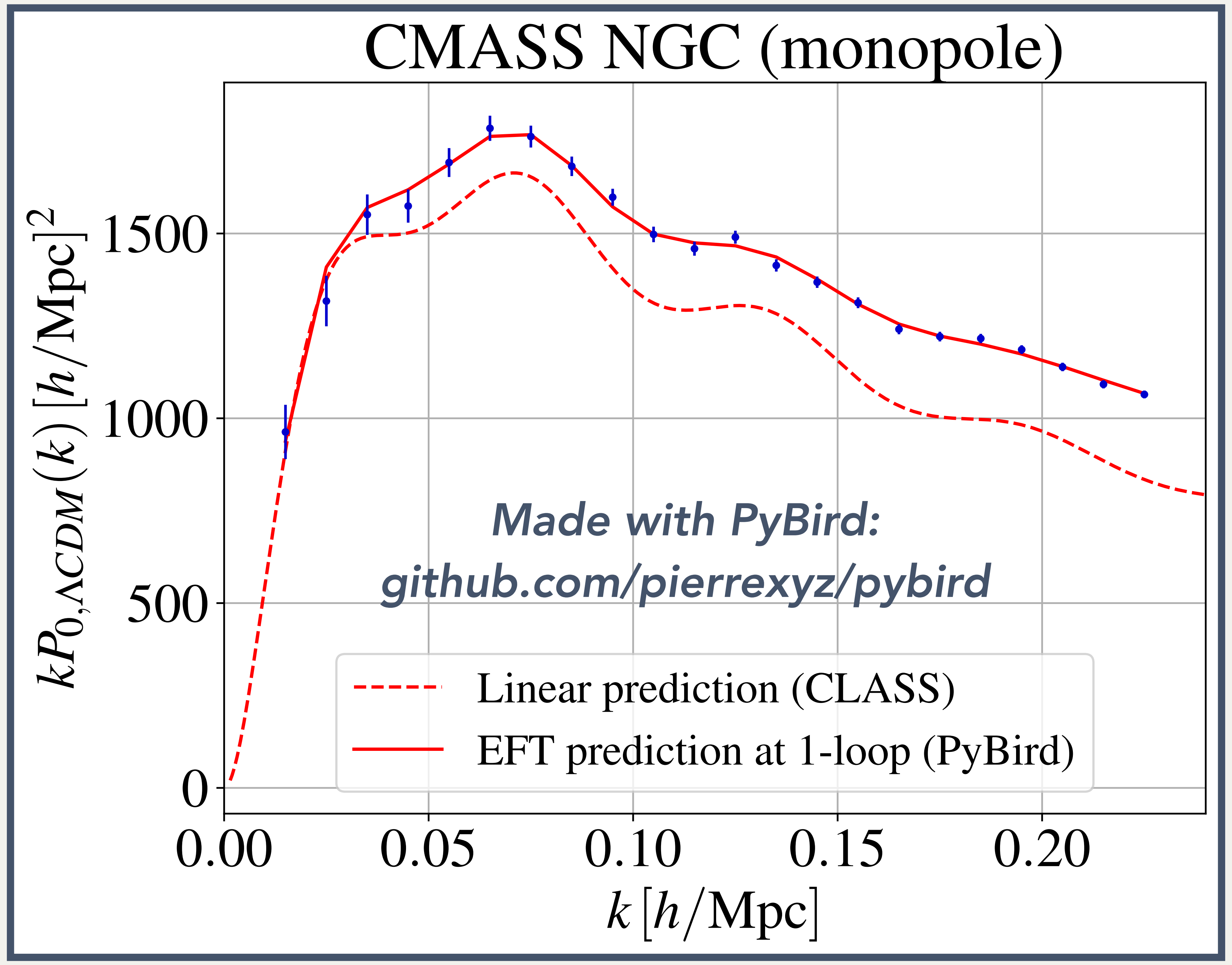
Galaxies selected in two redshift ranges:
→ LOWZ (SGC/NGC): $0.2 < z < 0.43$ ($z_{\rm eff} = 0.32$)
→ CMASS (SGC/NGC): $0.43 < z < 0.7$ ($z_{\rm eff} = 0.57$)

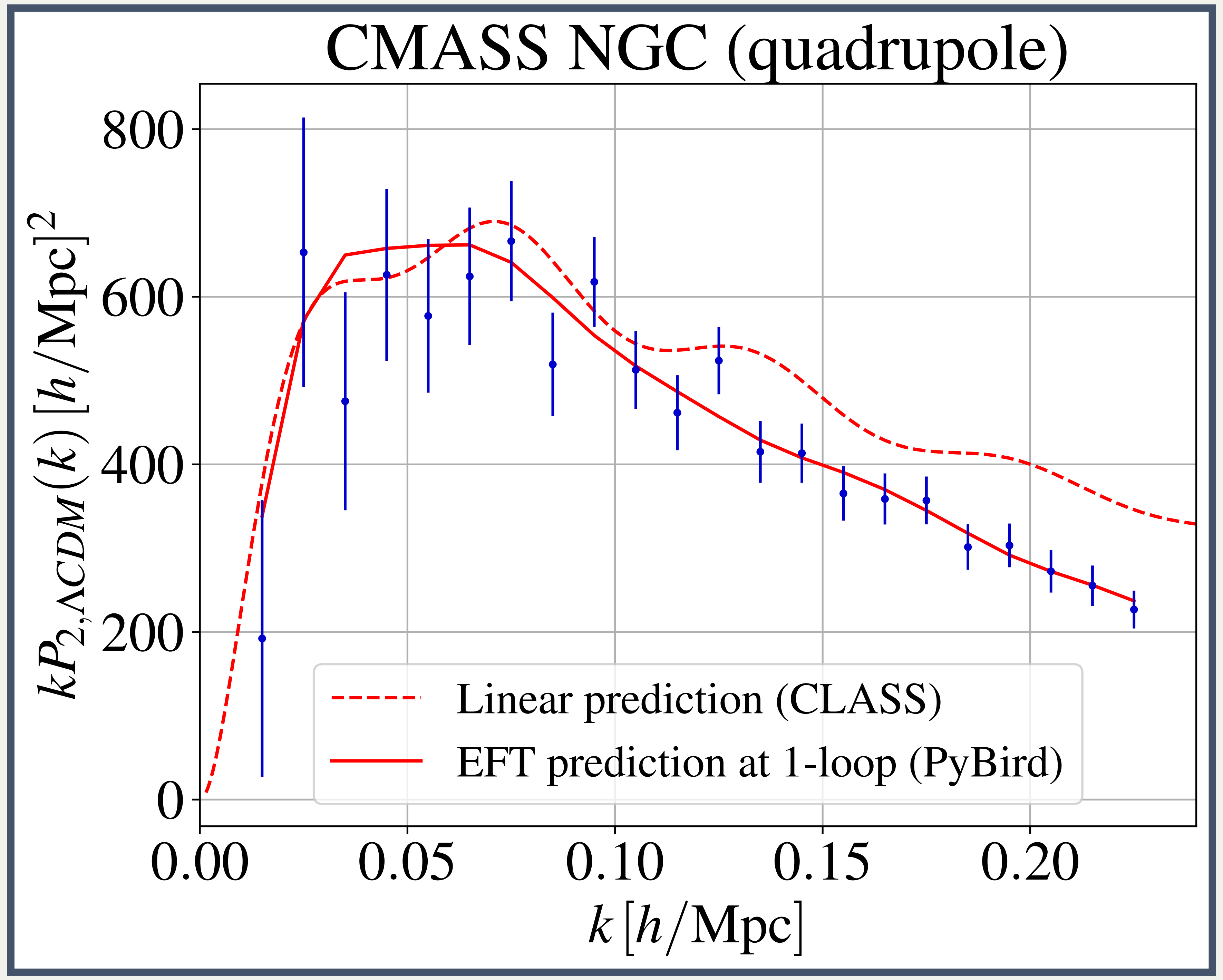
BOSS Collaboration [arXiv:1607.03155]

Multipoles of the galaxy power spectrum, obtained through a **Legendre** polynomials ($\mathscr{L}_\ell$) decomposition:

$$P_g(z,k,\mu) = \sum_{\ell \text{ even}} \mathscr{L}_\ell(\mu) P_\ell(z,k)$$

→ the two main contributions to $P_g(z,k,\mu)$ are the **monopole** ($\ell = 0$) and the **quadrupole** ($\ell = 2$)





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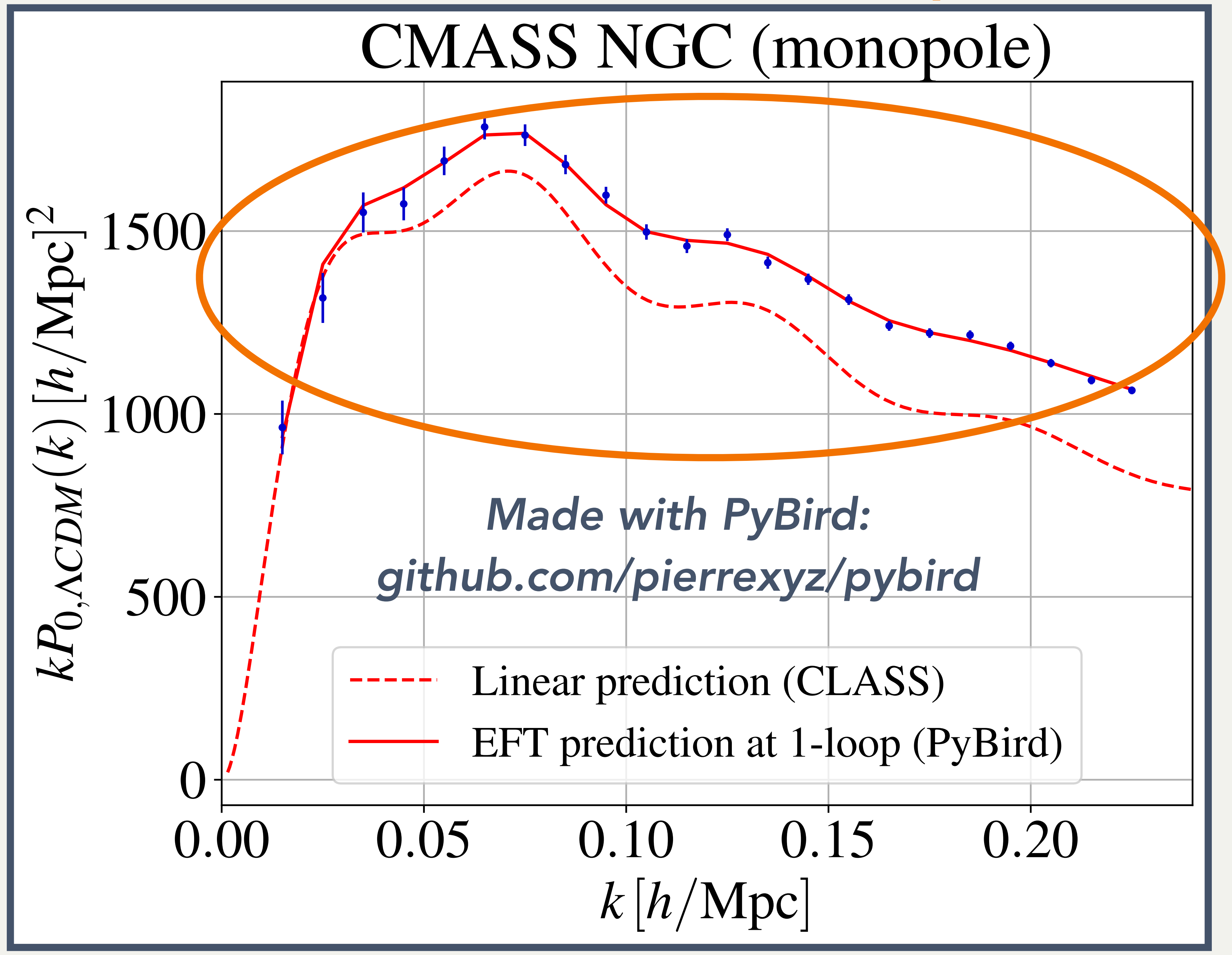
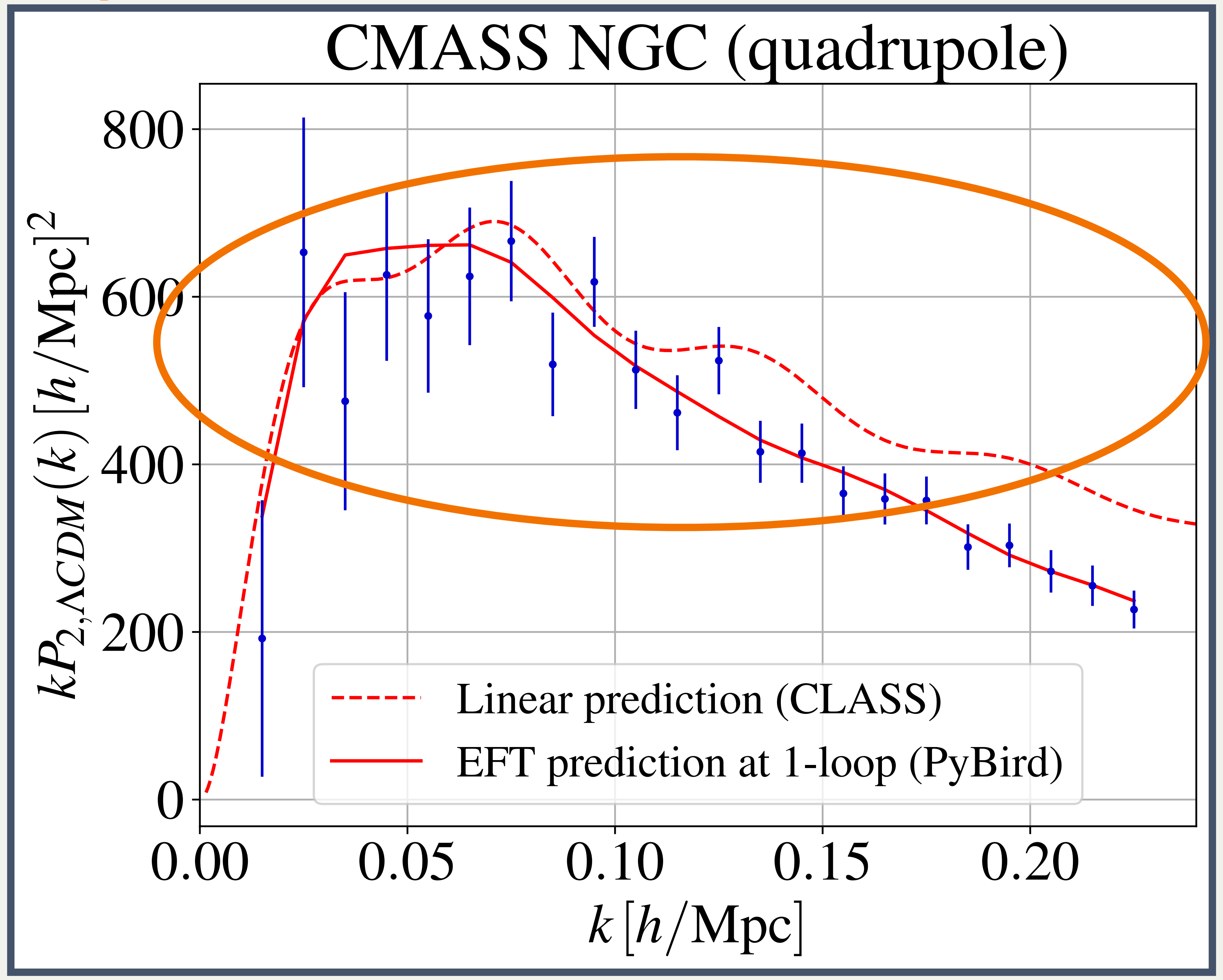
Improvement in precision!



Made with PyBird: github.com/pierrexyz/pybird



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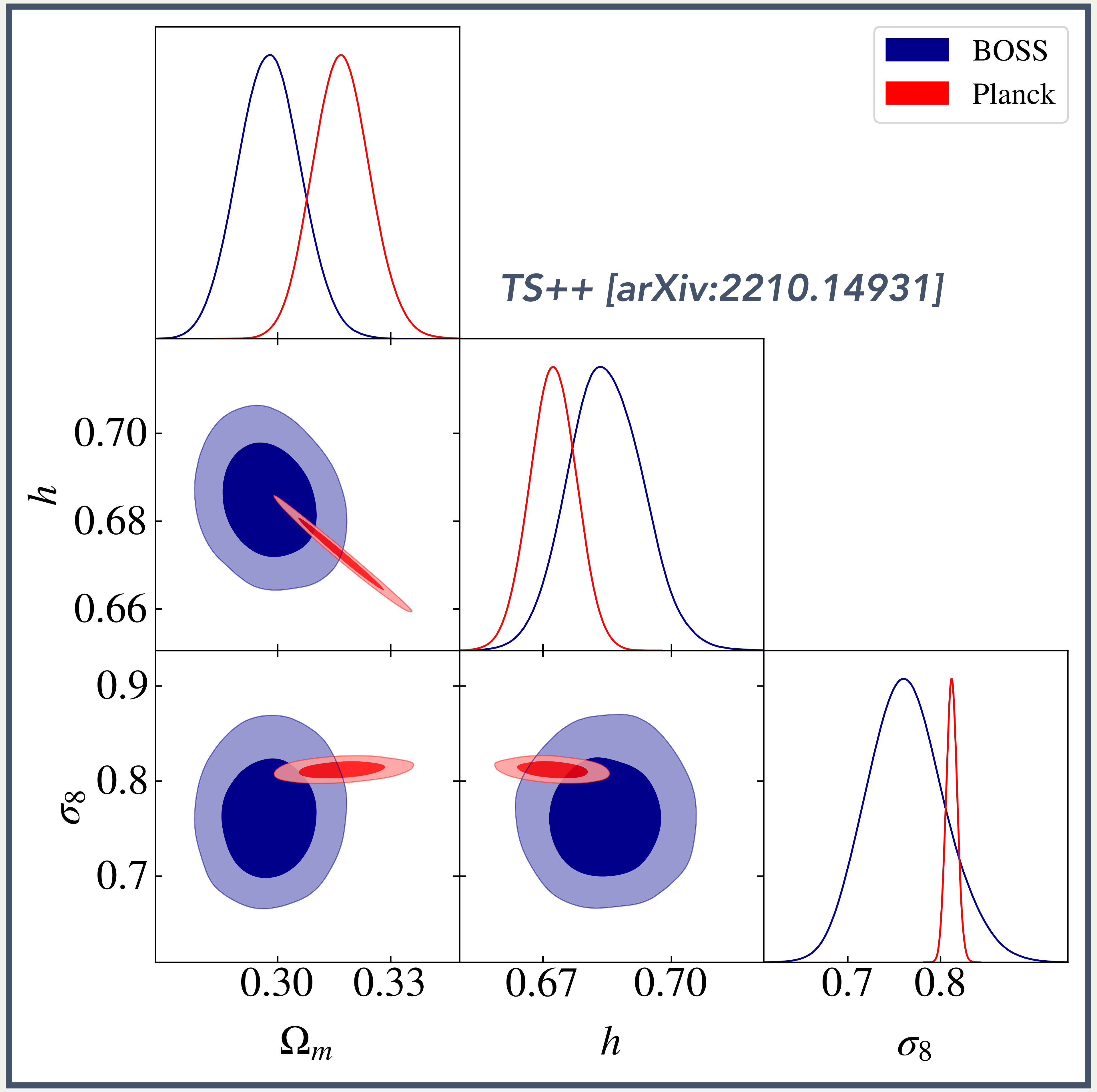
Application to BOSS data



The EFTofLSS analysis of BOSS data allows to determine Ω_m and h with a **precision of only** $10\,\%$ **and** $60\,\%$ lower than Planck

See also D'Amico++ [arXiv:1909.05271] ; Philcox++ [arXiv:2002.04035]

On the consistency of EFTofLSS

The EFT prior issue

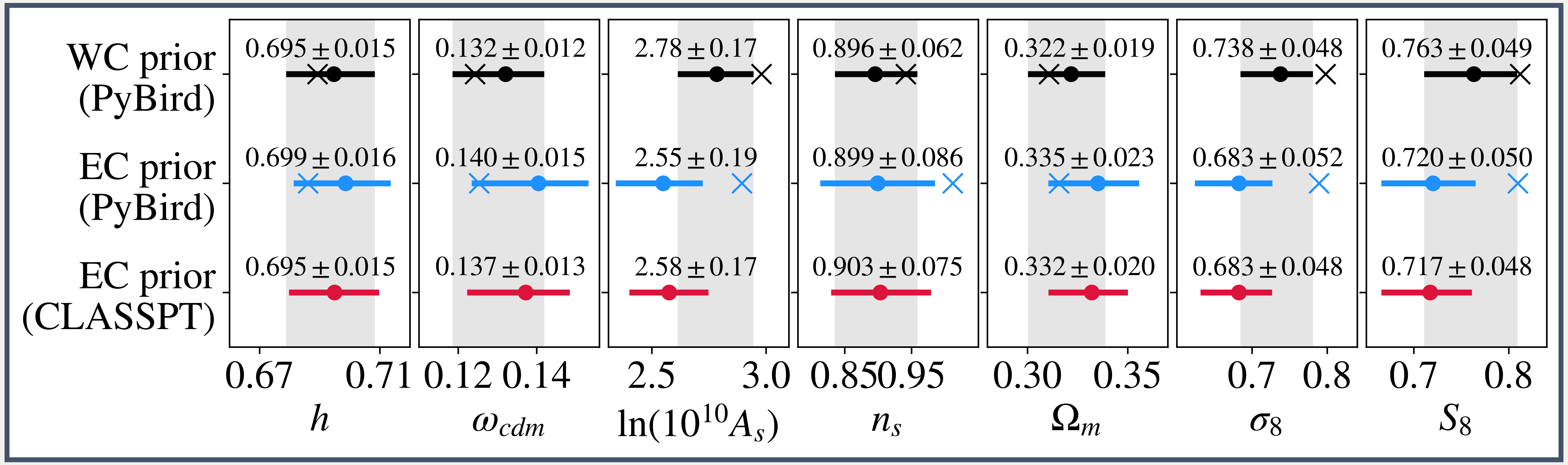
There are **two main codes** in the literature with **two different parametrizations**:

→ ***CLASS PT*** with the **EC** parametrization *Chudaykin++ [arXiv:2004.10607]*

→ ***PyBird*** with the **WC** parametrization *D'Amico++ [arXiv:2003.07956]*

(+ **Velociraptor** *Chen++ [arXiv:2005.00523]*)

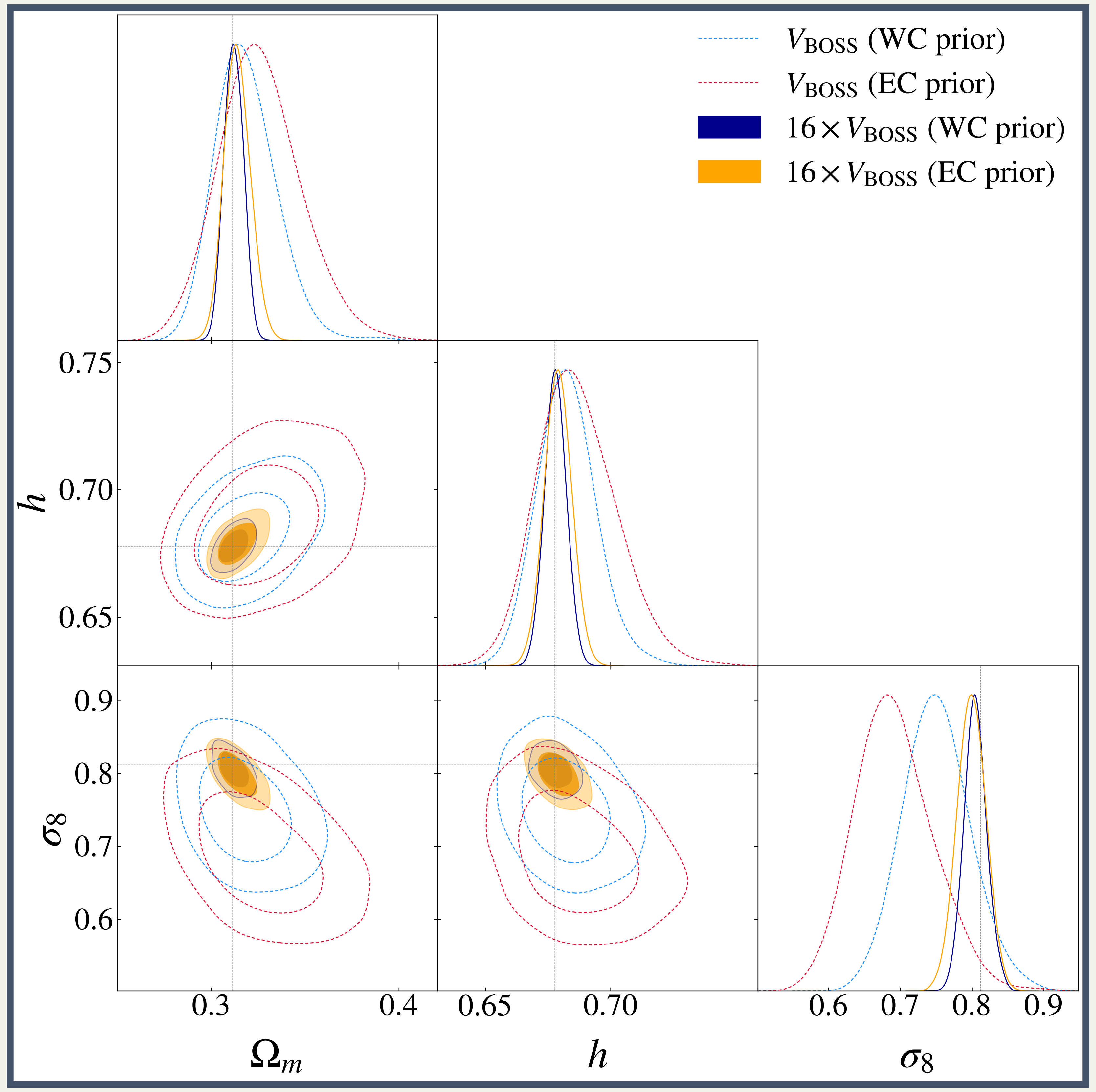
→ these two codes use **two different sets of priors** on EFT parameters



TS++ [arXiv:2208.05929]

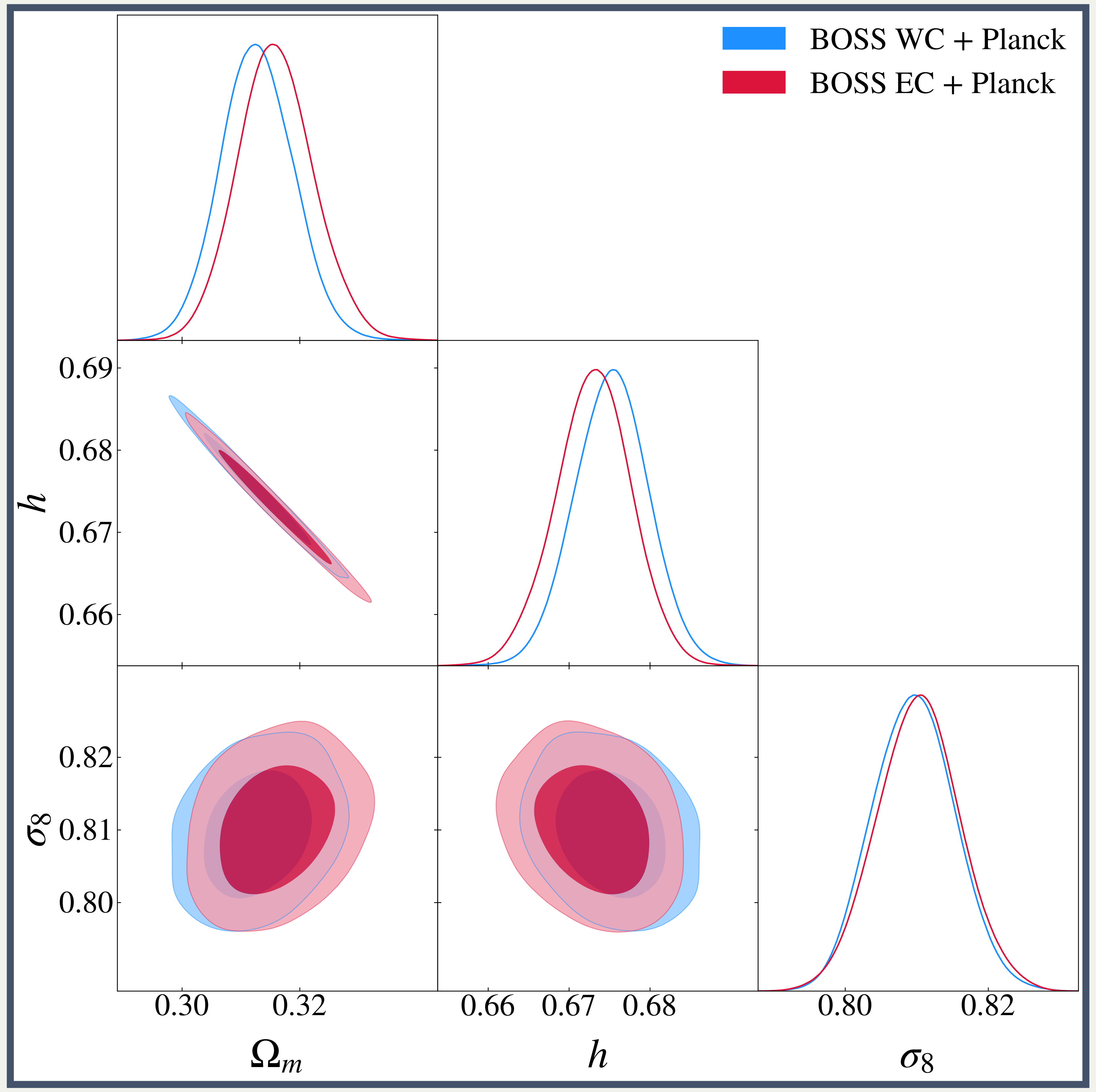
On the consistency of EFTofLSS

How to overcome this problem?



We find good consistency for:

- a larger volume of data (future experiments like DESI or EUCLID)
- a combination with Planck data



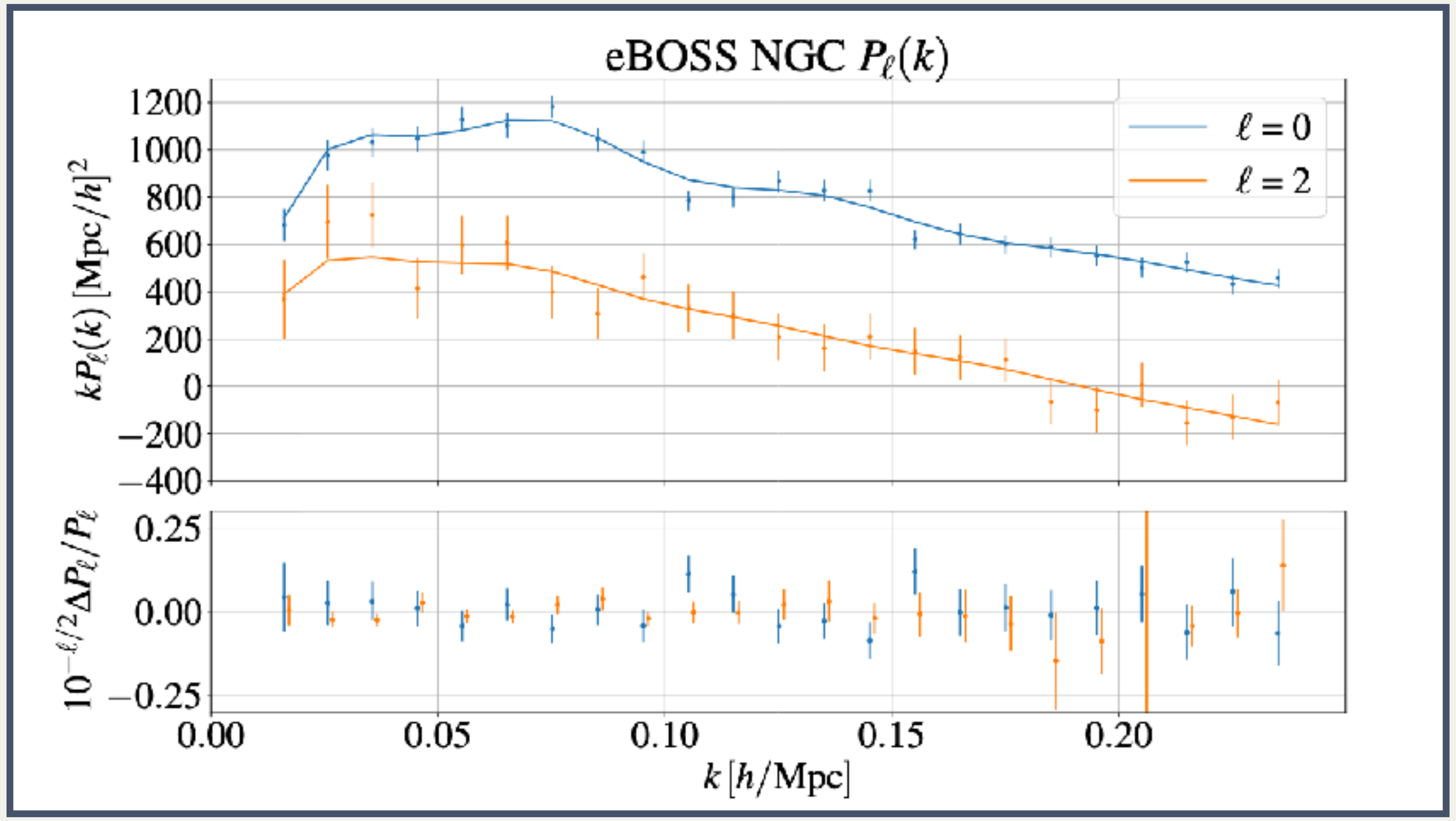
TS++ [arXiv:2208.05929]

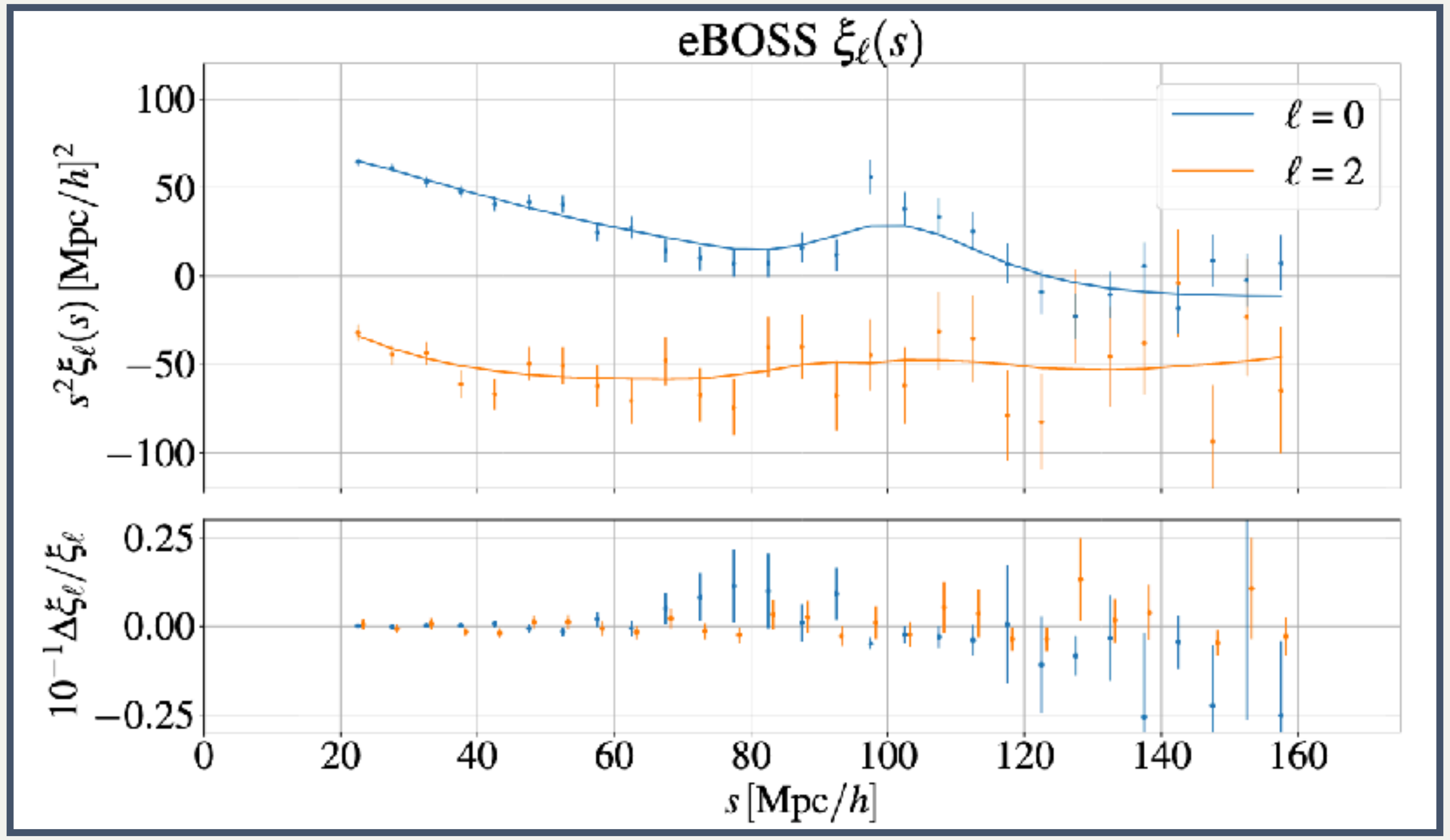
Work in progress: profile likelihood of the EFTofLSS analysis of BOSS data

EFTofLSS applied to eBOSS QSO data

- **343 708 quasars** selected in the redshift range $0.8 < z < 2.2$
- $z_{\mathrm{eff}} = 1.5$
- 2 skycuts: NGC and SGC

eBOSS Collaboration [arXiv:2007.08991]





TS++ [arXiv:2210.14931]

Determination of the cut-off scale $k_{\rm max}$ of the one-loop prediction

The next-to-next-to-leading order (NNLO) terms

At **one-loop order**, the galaxy power spectrum reads:

$$P_g(k,\mu) = Z_1(\mu)^2 P_{11}(k) + 2 Z_1(\mu) P_{11}(k) \left(c_{\rm ct} \frac{k^2}{k_{\rm M}^2} + c_{r,1}\mu^2 \frac{k^2}{k_{\rm M}^2} + c_{r,2}\mu^4 \frac{k^2}{k_{\rm M}^2} \right)$$
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One can add the **NNLO terms** (*i.e.*, the dominant two-loop terms):

$$P_{\rm NNLO}(k,\mu) = \frac{1}{4} b_1 \left(c_{r,4} b_1 + c_{r,6} \mu^2 \right) \mu^4 \frac{k^4}{k_{\rm R}^4} P_{11}(k)$$

Zhang++ [arXiv:2110.07539]

If the contribution of $P_{\rm NNLO}(k,\mu)$ becomes **too large,** the one-loop prediction is **not accurate enough** → this determines the **cut-off scale** $k_{\rm max}$ of the prediction

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2 new EFT terms

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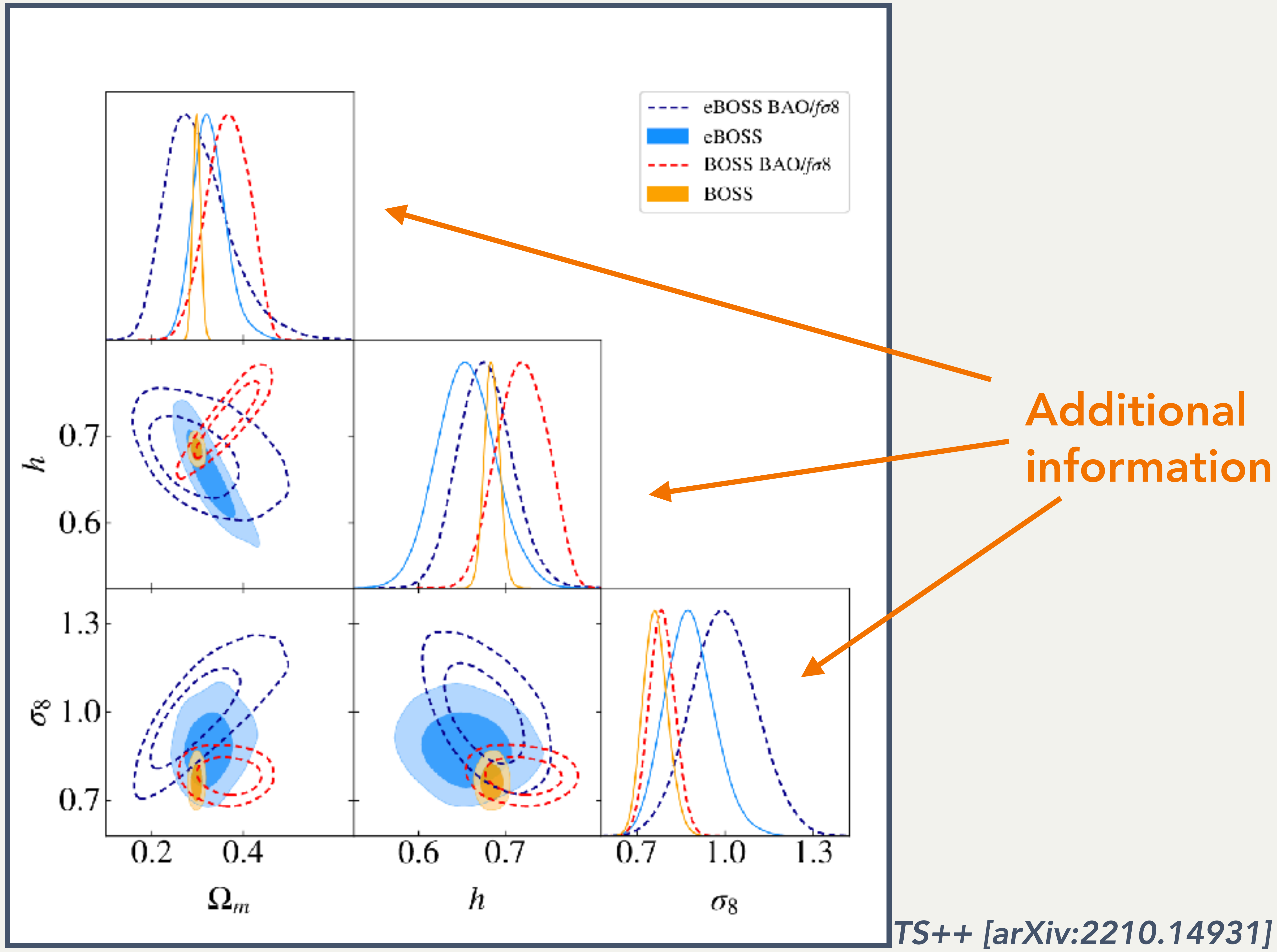
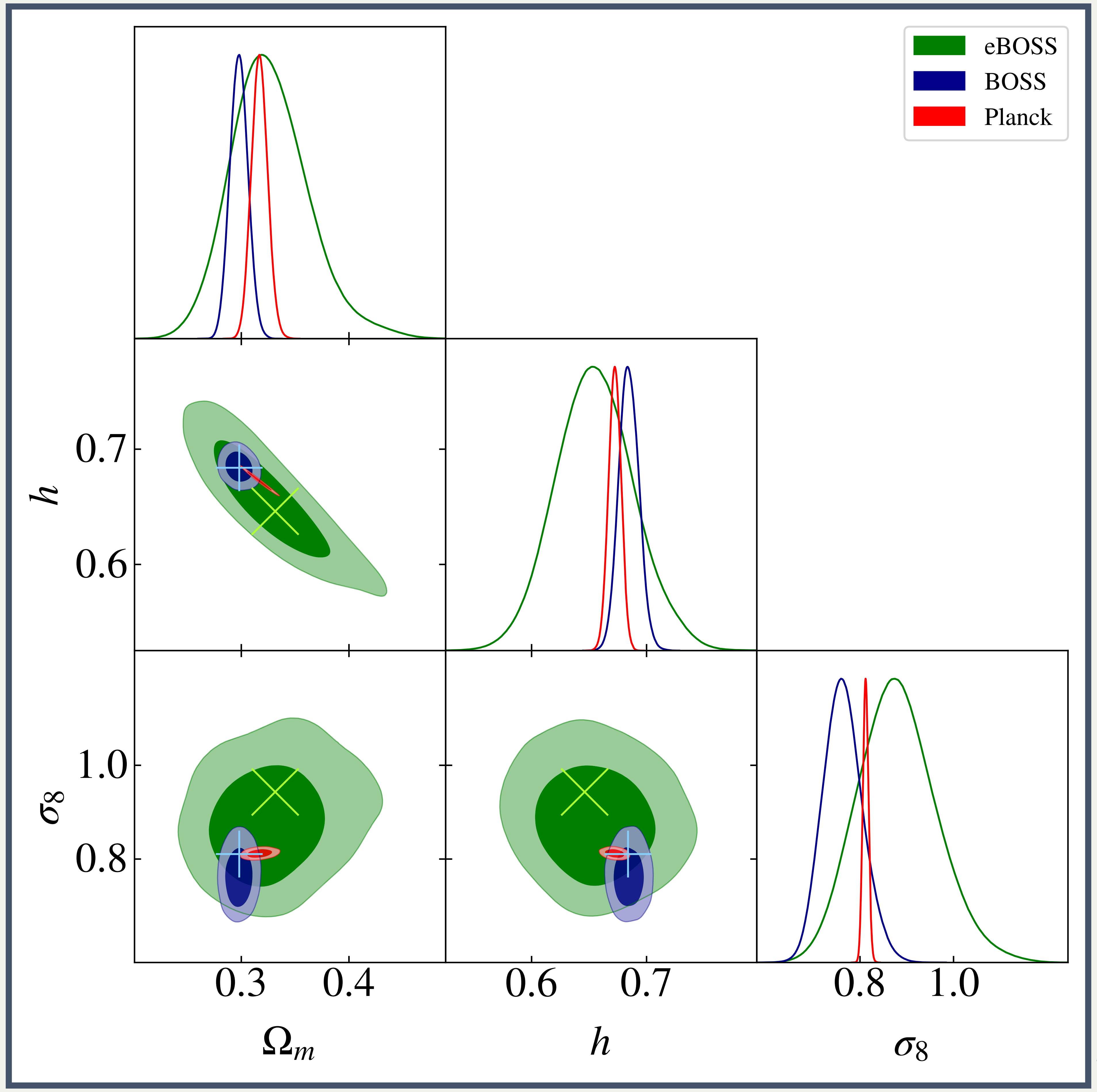
BAO/$f\sigma_8$ vs EFTofLSS



TS++ [arXiv:2210.14931]

- For **eBOSS**, the error bars of Ω_m and σ_8 are reduced by a factor ~ 2.0 and ~ 1.3
- For **BOSS**, the error bars of Ω_m and h are reduced by a factor ~ 5.4 and ~ 3.2

LSS data vs Planck

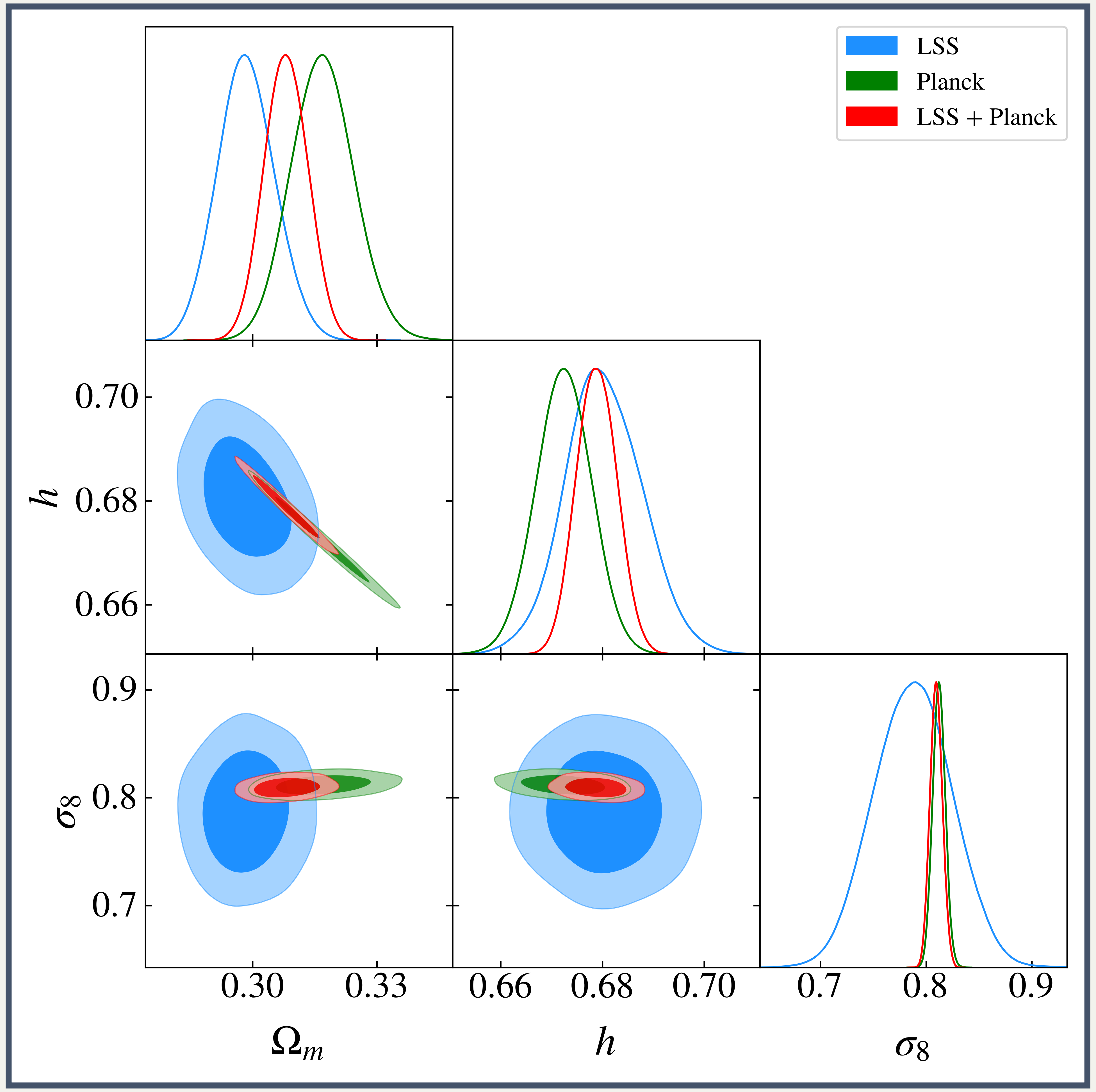


TS++ [arXiv:2210.14931]

- **eBOSS, BOSS and Planck are consistent** at $\lesssim 1.8\sigma$ on all cosmological parameters
- h is $\sim 1\sigma$ lower for eBOSS than for BOSS, while σ_8 is $\sim 1.5\sigma$ higher
- The h and σ_8 Planck values are in-between those of BOSS and eBOSS

→ **there is no tension between Planck and BOSS/eBOSS**

LSS data combined with Planck



LSS: eBOSS + BOSS + ext-BAO + Pantheon

(***ext-BAO***: 6dF & MGS (SDSS) data)

- **Compared to Planck alone**, the constraints on Ω_m and h are **improved by** $\sim 30\,\%$
- σ_8 and A_s are not significantly impacted

TS++ [arXiv:2210.14931]

Extensions to ΛCDM: curvature density fraction Ω_k

- With LSS data only, we find Ω_k **compatible with zero curvature at** 1.3σ
- The EFT analysis **significantly improves the constraints** on Ω_k by $\sim 50\,\%$ compared to the conventional BAO/$f\sigma_8$ analysis
- The combination of LSS and Planck leads to a **strong constraint** and excludes the (slightly favored) negative values of Ω_k

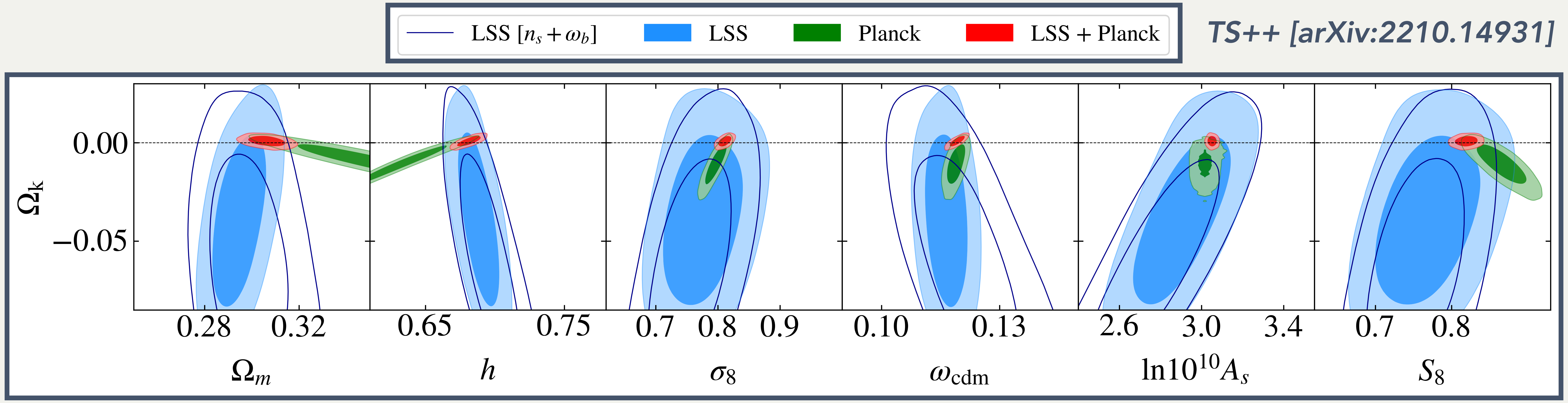
LSS:

$\Omega_k = -0.039^{+0.028}_{-0.029}$

LSS+Planck:

$\Omega_k = 0.0008^{+0.0018}_{-0.0017}$

TS++ [arXiv:2210.14931]

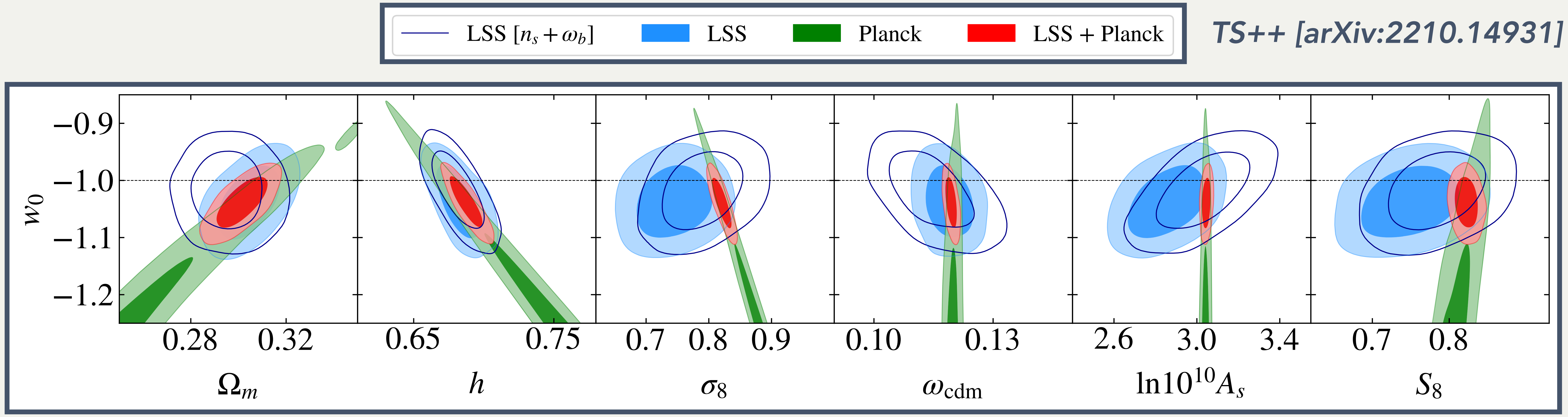


Extensions to ΛCDM: dark energy equation of state w_0

- With the LSS data only, we find **no evidence for a universe with $w_0 \neq -1$**
- The EFT analysis **improves the constraints** on w_0 by $\sim 20\,\%$ compared to the conventional BAO/$f\sigma_8$ analysis
- The addition of LSS data select values of w_0 close to −1, located in the 2σ region reconstructed from Planck data

LSS:
$w_0 = -1.038 \pm 0.041$

LSS+Planck:
$w_0 = -1.039 \pm 0.029$



TS++ [arXiv:2210.14931]

Extensions to ΛCDM: total neutrino mass $\sum m_\nu$

- The LSS constraint derived in this work is **only** $\sim 10\,\%$ **weaker than the Planck constraint** ($\sum m_\nu = 0.241 eV$)

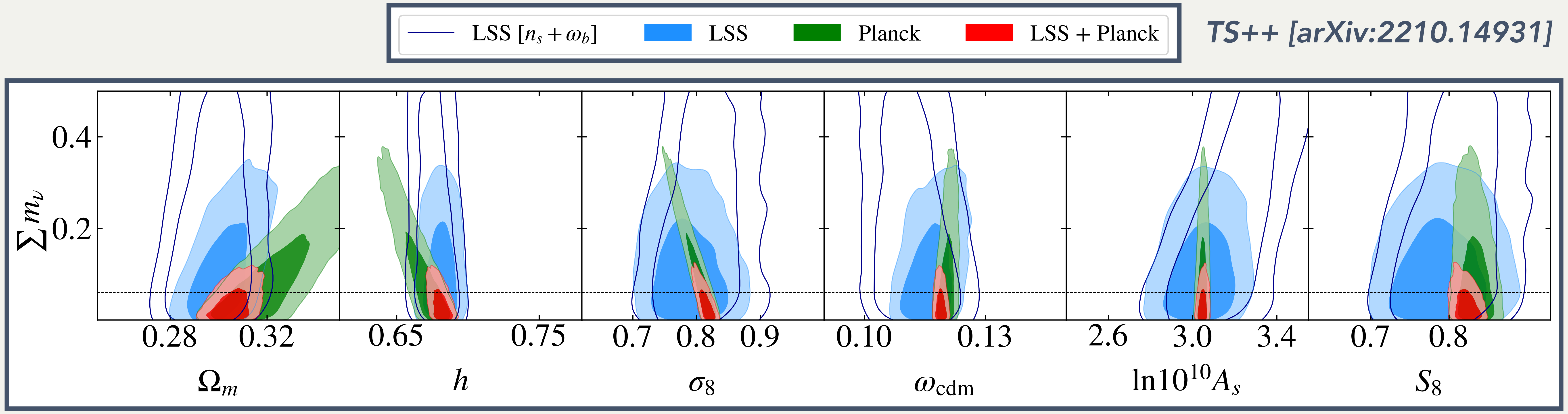
- The EFT analysis **significantly improves the constraints** on $\sum m_\nu$ (by a factor of ~ 18) over the conventional BAO/$f\sigma_8$ analysis ($\sum m_\nu = 4.84 eV$)

  Palanque-Delabrouille++ [arXiv:1911.09073]

- This analysis **disfavors the inverse hierarchy** at $\sim 2.2\sigma$ & is **competitive to the Lyman-α constraints**

LSS:
$\sum m_\nu < 0.274 eV$

LSS+Planck:
$\sum m_\nu < 0.093 eV$



TS++ [arXiv:2210.14931]

Extensions to ΛCDM: effective number of relativistic species N_{eff}

- The value of ΔN_{eff} is **compatible with the standard model**
- Unlike EFTofLSS, **the conventional BAO/$f\sigma_8$ analysis is unable to constrain this parameter**
- The addition of the LSS data **improves** the results of Planck alone by $\sim 25\,\%$

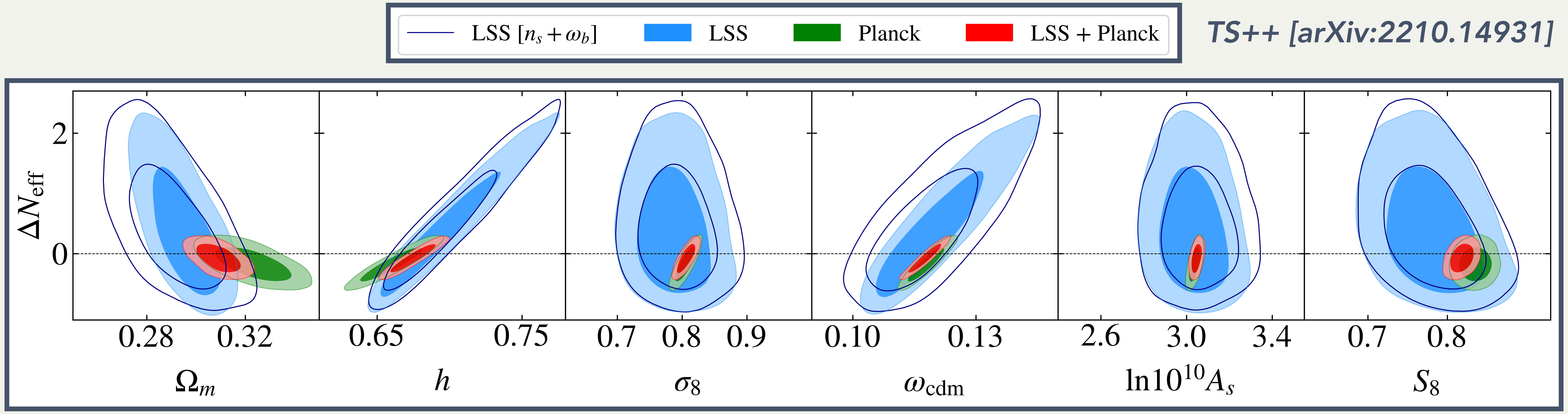
TS++ [arXiv:2210.14931]

LSS:

$\Delta N_{\text{eff}} = 0.40^{+0.44}_{-0.91}$

LSS+Planck:

$\Delta N_{\text{eff}} = -0.07^{+0.15}_{-0.16}$



Conclusion

- The EFTofLSS is a novel method that provides an **accurate description of LSS data at a controlled precision**
- Constraints from LSS data are **competitive with CMB data**
- EFTofLSS allows to highlight that **there is no tension** between current BOSS/eBOSS data and Planck data (but not in tension with weak lensing neither)
- Data are consistent with ΛCDM at $\lesssim 1.3\sigma \rightarrow$ Strong constraints on canonical extensions to ΛCDM
  e.g. LSS+Planck: $\sum m_\nu < 0.093 e$V
- EFTofLSS provides **interesting constraints on non-trivial extensions** of the ΛCDM model:
  → see [TS et al. '22, arXiv:2203.07440] for **Decaying Cold Dark Matter**
  → see [TS et al. '22, arXiv:2208.05930] for **Early Dark Energy**

Thanks for your attention

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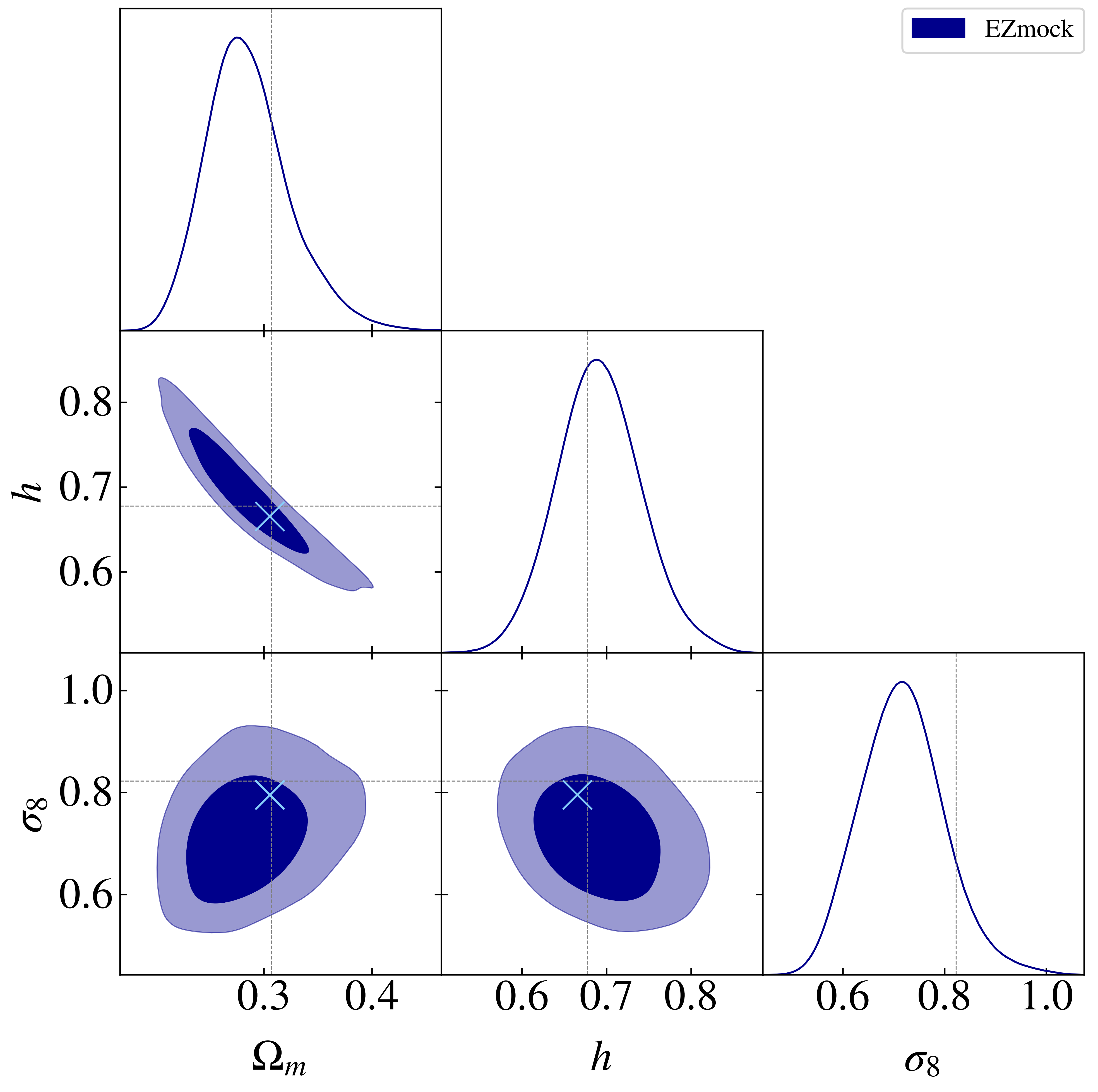
PONT - 04/05/2023

Determination of the cut-off scale $k_{\max}$ of the one-loop prediction

The EZmock



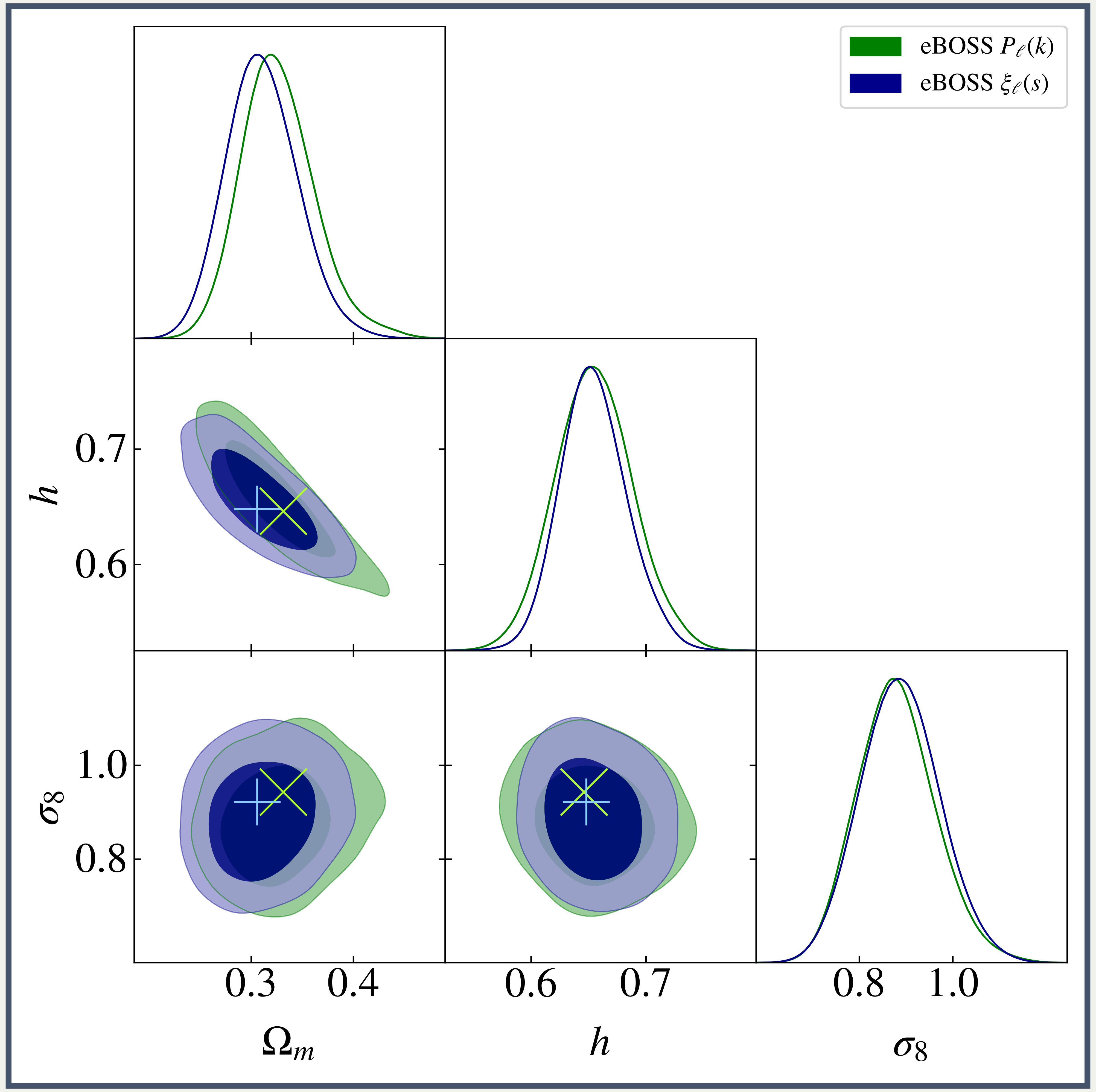
- **EZmock**: mocks that are built to simulate eBOSS observational characteristics

  Chuang++ [arXiv:1409.1124]

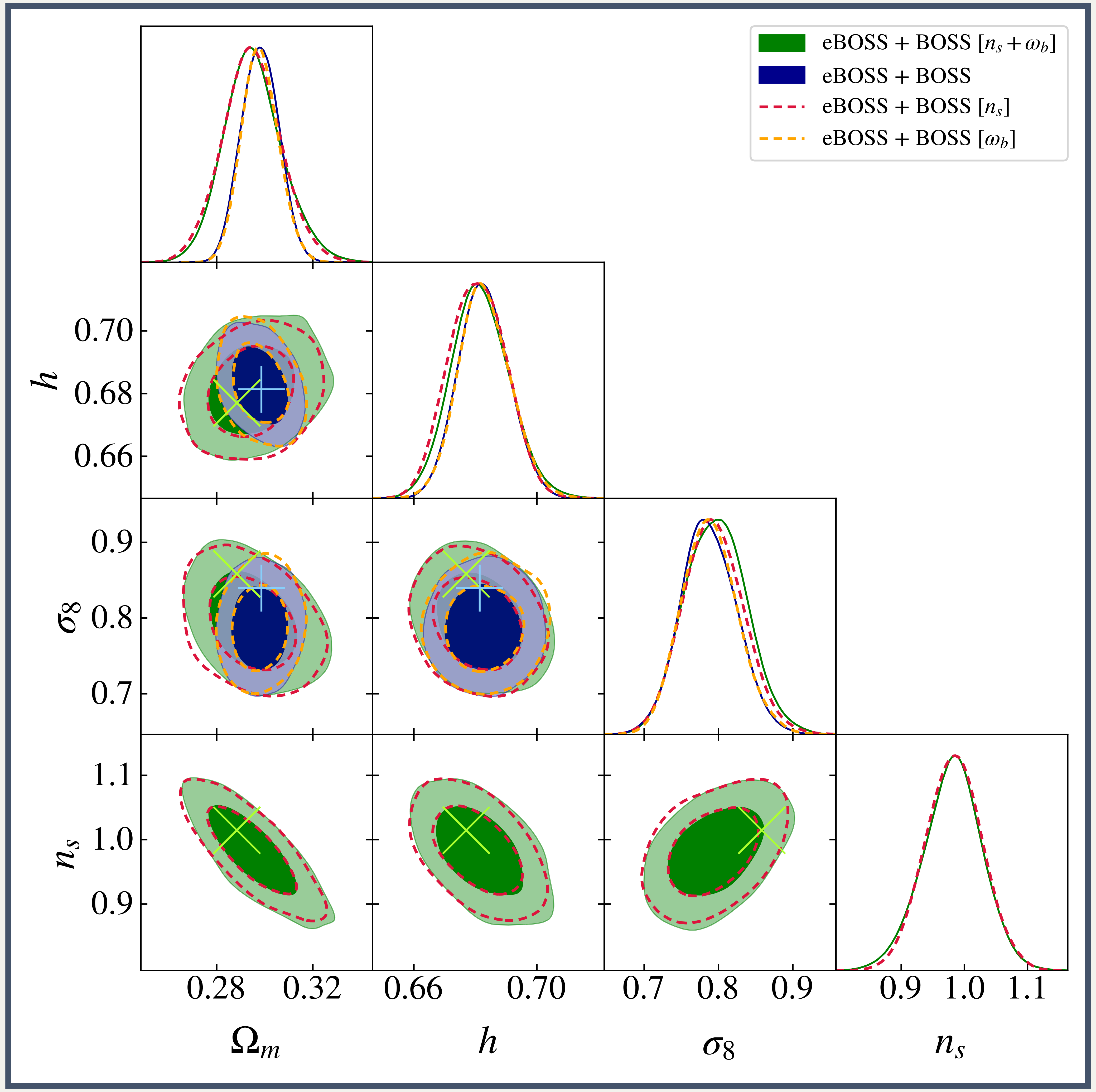
- Up to $k_{\max} = 0.24h\,\mathrm{Mpc}^{-1}$, the best-fit values of the cosmological parameters are shifted with respect to the truth of the simulations by $\lesssim 1/3 \cdot \sigma$

TS++ [arXiv:2210.14931]

eBOSS $P_\ell(k)$ vs eBOSS $\xi_\ell(k)$



Variation of n_s and ω_b



- We impose a uninformative large flat prior on n_s, while we impose a BBN Gaussian prior on ω_b
- The variation of ω_b within the BBN prior has a negligible impact on the cosmological results: we have a relative shift of $\lesssim 0.04\sigma$
- The variation of n_s within a uninformative large flat prior leads to a relative shift $\lesssim 0.4\sigma$

Dark energy equation of state $w_0 \geq -1$

- One can see that this new prior shifts the 2D posteriors inferred from the LSS data in a non-negligible way, while it remains globally stable for the LSS + Planck
- For these analyses, $\Delta\chi^2 = 0$ with respect to ΛCDM, since we obtain best-fit values of $w_0 = -1$

LSS:
$w_0 < -0.932$

LSS+Planck:
$w_0 < -0.965$