

# Recommendations for the presentation of auxiliary information in BSM Higgs searches

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(for the HiggsBounds/HiggsSignals team:

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Higgs Boson (ATLAS Preliminary data)

Sonification by Domenico Vicinanza

$\text{♩} = 60$

16th Workshop of the LHCHSWG  
CERN, Geneva, 17 October 2019

1. Introduction
2. Exclusion limits from BSM Higgs searches
3. Measurements of the Higgs boson signal
4. Summary

# Introduction

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Specific model interpretations (BSM Higgs benchmark scenarios,  $\kappa$  fits, etc.) by ATLAS and CMS are nice and have their purpose, but:

**The main experimental result is the model-independent limit or measurement of the signal cross section.**

- Remaining **model-dependence** should be *transparent* and *unfoldable*.
- **Uncertainty correlations** with other limits or measurements should be *accessible*.

*If this is ensured:*

⇒ **Experimental results can be accurately reinterpreted in any BSM model.**

⇒ The theory community can then make *maximal use* of the LHC results!

Theory tools: **HiggsBounds+HiggsSignals**, **Lilith**, HEPfit, ...

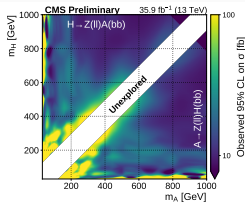
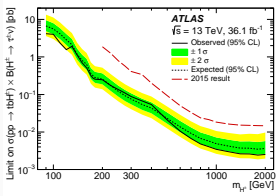
# HiggsBounds and HiggsSignals

Team: P. Bechtle, SH, T. Klingl, T. Stefaniak, G. Weiglein, J. Wittbrodt

## HiggsBounds

Confronts BSM Higgs sectors with **exclusion limits** from LEP, Tevatron and LHC Higgs searches.

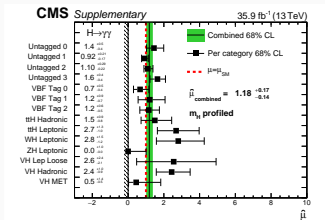
⇒ **excluded/allowed at 95% C.L.** ( $\chi^2_{\tau\tau}$  ...)



## HiggsSignals

Confronts BSM Higgs sectors with LHC Higgs **signal rate** and **mass measurements**.

⇒  $\chi^2$  (sep. for rates and mass)



Codes available at [GitLab](#) & [hepforge](#).

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## HiggsBounds

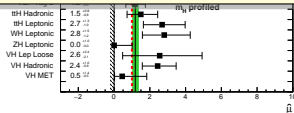
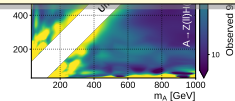
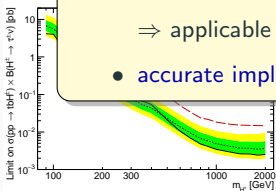
Confronts BSM Higgs sectors with

## HiggsSignals

Confronts BSM Higgs sectors

*Main purpose and aim of these tools:*

- Quick and convenient model testing tools for theorists;
- framework with minimal model-assumptions  
⇒ applicable to many BSM Higgs models;
- accurate implementation (incl. correlations, etc.) of public results;



Codes available at [GitLab](#) & [hepforge](#).

# Limits from BSM Higgs searches

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# Presentation of exclusion limits

## A general remark

Limits (*observed* and *expected*) should be presented as *function of all ( $N$ ) relevant parameters*:  $M_{\phi_i}$ ,  $\sigma$ 's of involved production modes,  $\Gamma_{\text{tot}}$ , ...

*If  $N$  too large to handle*: Make further assumptions, but try to make sure these can be undone in a reinterpretation (as well as possible).

**Example:** Search for an additional SM-like Higgs boson decaying to  $\gamma\gamma$ .

**Parameters:**  $M_{\phi}$ ,  $\Gamma_{\text{tot}}$ ,  $\sigma_{pp \rightarrow \phi}$ ,  $\sigma_{pp \rightarrow \phi qq}$ ,  $\sigma_{pp \rightarrow W\phi}$ ,  $\sigma_{pp \rightarrow Z\phi}$ ,  $\sigma_{pp \rightarrow t\bar{t}\phi}$

**Usual assumption:**  $\sigma_i = \mu \cdot \sigma_i^{\text{SM}}$  (common signal strength modifier  $\mu$ )

$\Rightarrow$  Limit is set on  $\mu$  (or  $\sigma_{\text{tot}} = \sum_i \sigma_i$ ), as a function of  $M_{\phi}$  and  $\Gamma_{\text{tot}}/M_{\phi}$ .

$\Rightarrow$  Proper reinterpretation requires *signal efficiency/acceptance* for all production modes *as function of  $M_{\phi}$* .

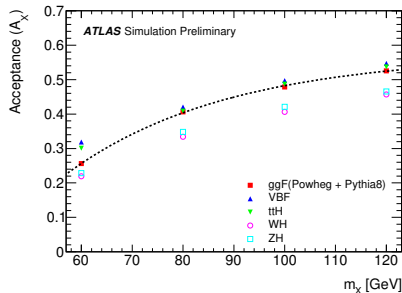
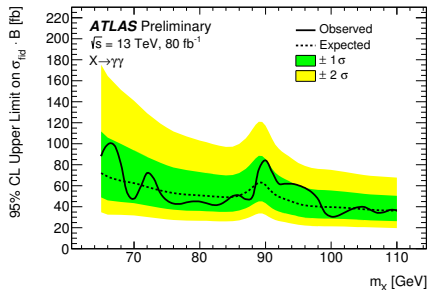


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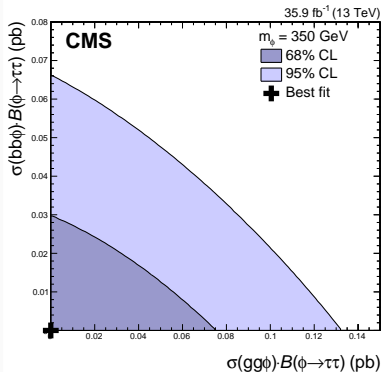
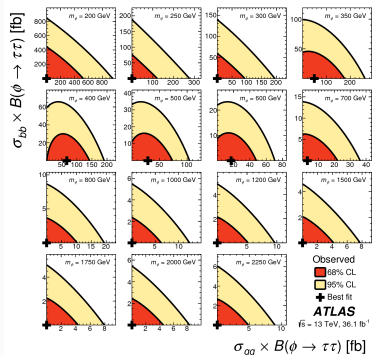
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[ATLAS-CONF-2018-025]

# Exclusion likelihood of BSM Higgs to $\tau^+\tau^-$ searches

- ATLAS and CMS published  $-2 \ln \mathcal{L}$  values for 13 TeV, 36  $\text{fb}^{-1}$  results (CMS also for 8 TeV),
- Narrow resonance ( $\phi$ ) toy model in three-dimensions:  $(m_\phi, \sigma_{gg\phi}, \sigma_{bb\phi})$ .



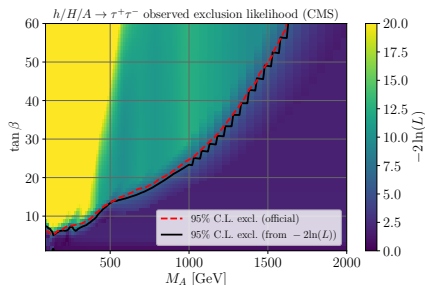
# Reproduction of exclusion likelihood for arbitrary models

- Likelihood information very useful for global BSM parameter fits,
- implemented in HiggsBounds with simple algorithm.

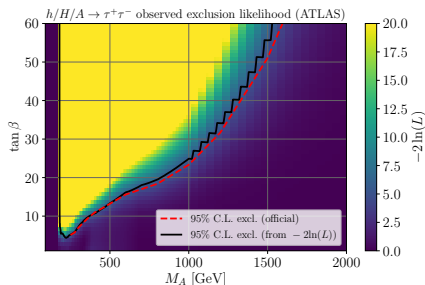
[Bechtle, SH, Stål, Stefaniak, Weiglein, 1507.06706]

Validation results in  $m_h^{mod+}$  scenario:

CMS 13 TeV, 36 fb<sup>-1</sup>



ATLAS 13 TeV, 36 fb<sup>-1</sup>



⇒ Very good reproduction of official 95% C.L. exclusion contour.

# Likelihoods from other BSM Higgs searches?

So far, BSM  $\phi \rightarrow \tau^+ \tau^-$  searches and  $h_{125} \rightarrow \text{inv.}$  have published likelihoods.

**Which search channel's likelihood is the most wanted?**

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**Which search channel's likelihood is the most wanted?**

$\Rightarrow$  **The answer is model-dependent.**

Some good candidates (*theory-biased!*):

Channel	relevant parameters	BSM model
$pp \rightarrow b\bar{b}\phi, \phi \rightarrow b\bar{b}$	$M_\phi, \sigma(pp \rightarrow \phi), \sigma(pp \rightarrow b\bar{b}\phi)$	MSSM, 2HDM
$pp \rightarrow \phi \rightarrow t\bar{t}$	$M_\phi, g_{Ht\bar{t}}, g_{At\bar{t}}, \Gamma_{\text{tot}}$	MSSM, 2HDM
$pp \rightarrow \phi \rightarrow ZZ, W^+W^-$	$M_\phi, \mu_{pp \rightarrow \phi}, \mu_{\text{VBF}, \text{V}\phi}, (\Gamma_{\text{tot}})$	singlet extensions
$pp \rightarrow \phi \rightarrow h_{125}h_{125}$	$M_\phi, \sigma(pp \rightarrow \phi \rightarrow h_{125}h_{125}), (\Gamma_{\text{tot}})$	singlet extensions
$pp \rightarrow \phi_2 \rightarrow Z\phi_1$	$M_{\phi_1}, M_{\phi_2}, \sigma(pp \rightarrow \phi_2 \rightarrow Z\phi_1)$	2HDM
$pp \rightarrow t b\phi^\pm, \phi^\pm \rightarrow tb$	$M_{\phi^\pm}, \sigma(pp \rightarrow t b\phi^\pm \rightarrow t b t b)$	MSSM, 2HDM
...	...	...

# Higgs signal measurements

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# Presentation of Higgs signal measurements

## Experiments should (continue to) provide:

- measurements as **signal strength ( $\mu$ )**, **STXS** and **fiducial XS**  
→ allows for useful cross checks.
- **signal efficiencies** (or signal composition) of relevant Higgs subprocesses for *each* measurement [assuming a SM Higgs boson],
- reference value of **SM Higgs prediction** for *each* measurement,
- **correlation-matrices** (ideally: separately for exp. and theo.),
- allow for *negative values* of the measured cross section.  
→ “*unbiased estimator*”.
- provide measurements for fixed Higgs mass (possibly various(?), but not only  $M_H$ -profiled!).

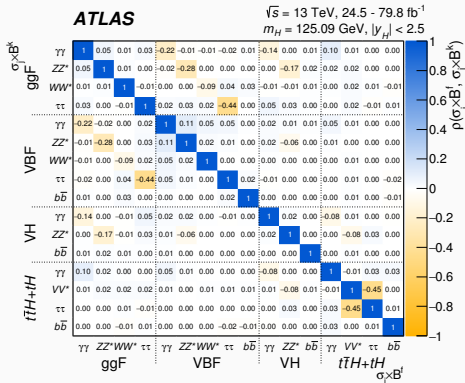
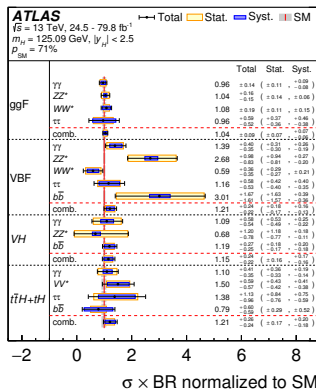
## Data should be provided in digitized form with sufficient accuracy.



# Example: Validation tests with latest ATLAS combination

$(\kappa_V, \kappa_F)$  and  $(\kappa_g, \kappa_\gamma)$  using  $\mu$  input from ATLAS combination:

[ATLAS, 1909.02845]

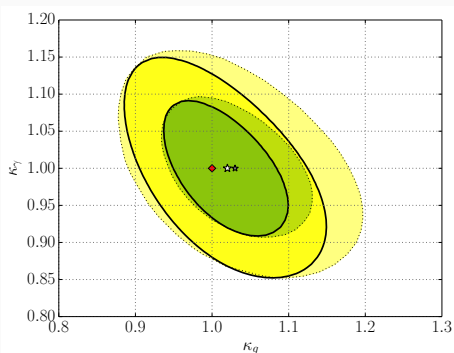
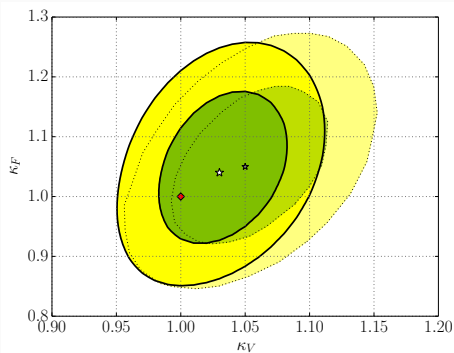


TH uncertainty included?!

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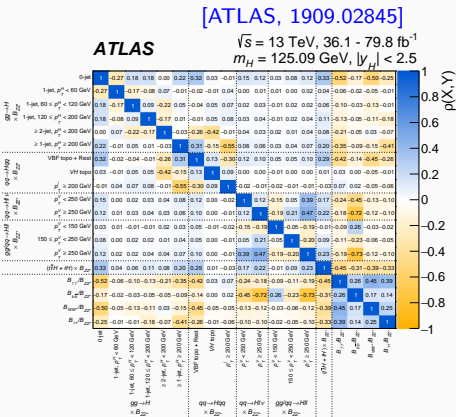
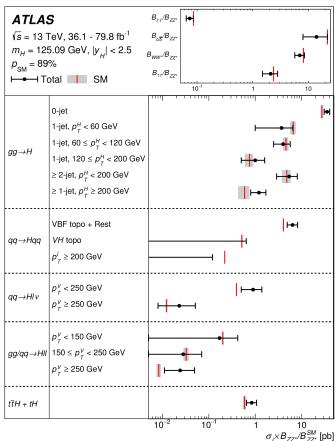
[ATLAS, 1909.02845]



darker: HiggsSignals, lighter: ATLAS

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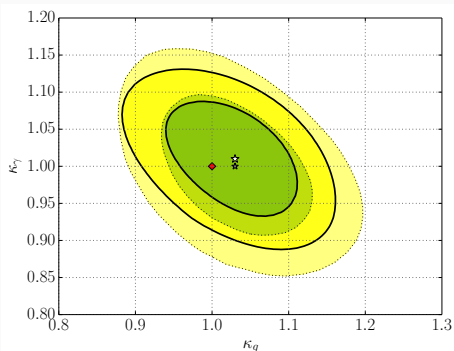
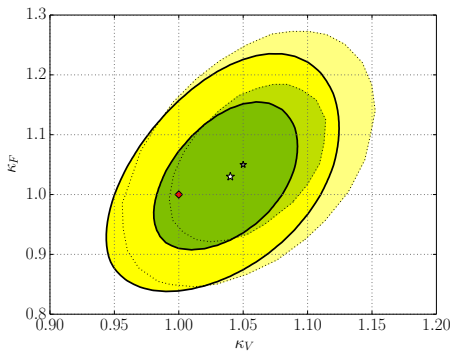


TH uncertainties not included?!

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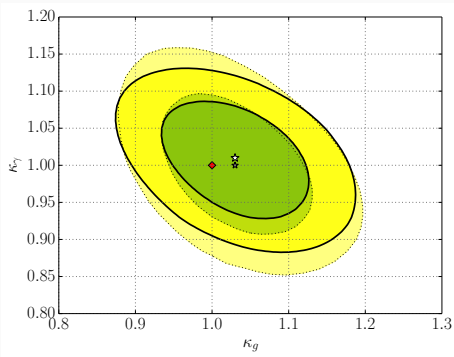
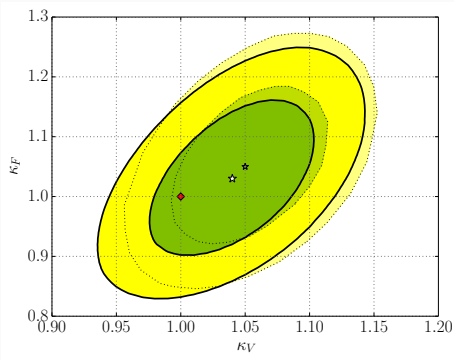


Without SM theory uncertainties (THU).

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$(\kappa_V, \kappa_F)$  and  $(\kappa_g, \kappa_\gamma)$  using **STXS input** from ATLAS combination:

[ATLAS, 1909.02845]

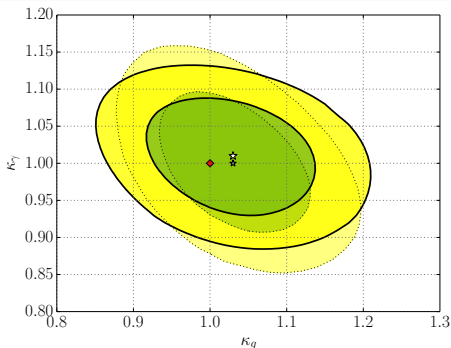
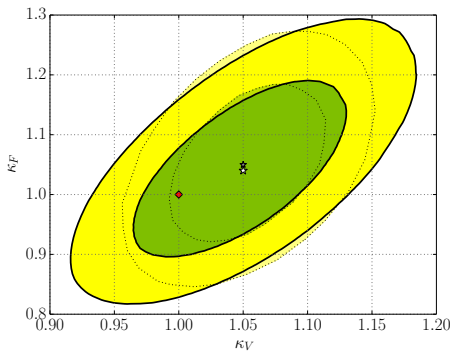


**SM THU only added on diagonal elements (uncorrelated).**

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[ATLAS, 1909.02845]

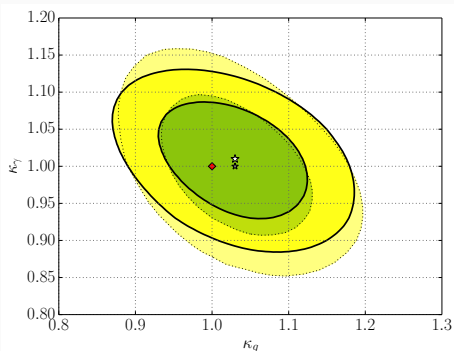
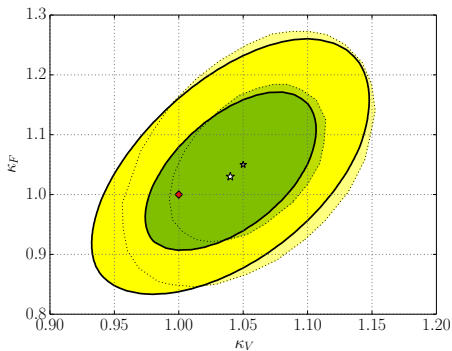


**SM THU added using correlations of inclusive XS (not binned).**

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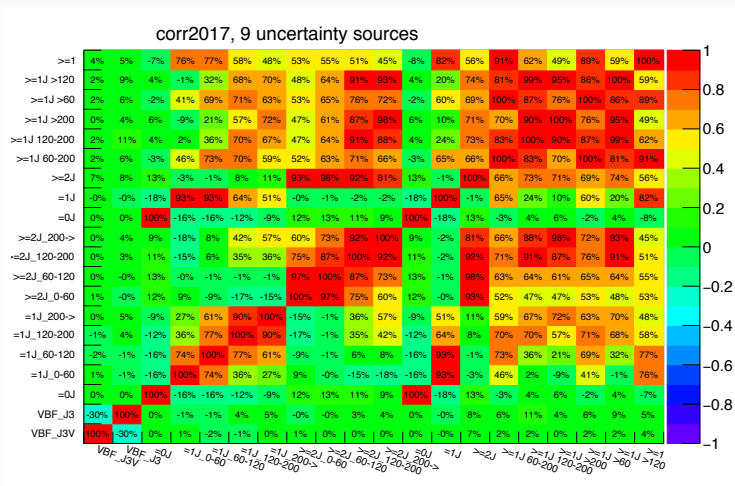
$(\kappa_V, \kappa_F)$  and  $(\kappa_g, \kappa_\gamma)$  using STXS input from ATLAS combination:

[ATLAS, 1909.02845]



**SM THU added using correlations of STXS ggF bins (next slide).**

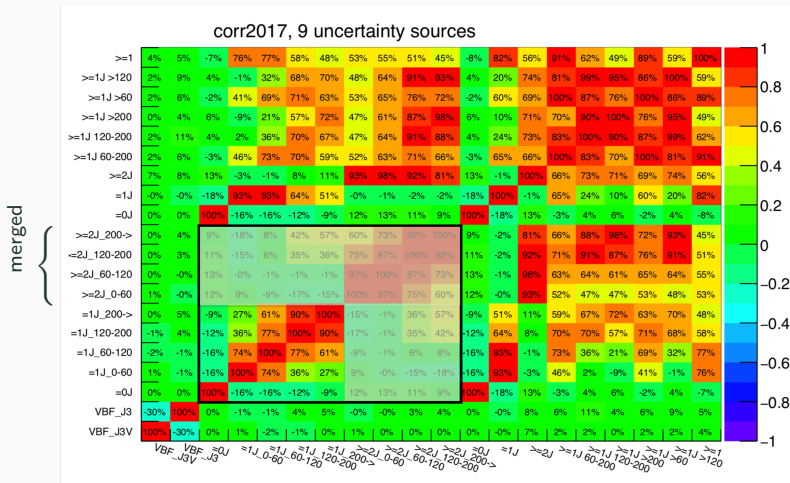
# Example: Validation tests with latest ATLAS combination



<https://indico.cern.ch/event/618048/>, see WG1 meeting follow-up (pdf).

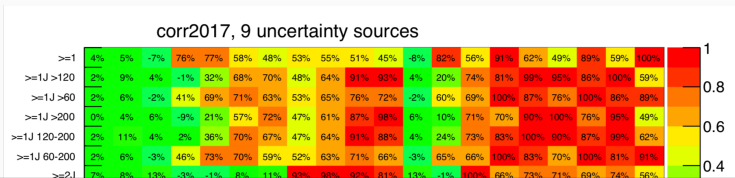


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<https://indico.cern.ch/event/618048/>, see WG1 meeting follow-up (pdf).

# Example: Validation tests with latest ATLAS combination



merged

Theory-uncertainty correlation matrix for the STXS framework (used by ATLAS+CMS+theory) is highly desirable!

- Correlation information must be retained after bin merging,
- Needed for all production modes (not only ggF).

Until we have this “official” matrix, experiments could release the correlation matrix used in their analysis.

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# Summary

*Experimentalists put an enormous amount of work into their analyses.*

⇒ Make sure **impact and legacy of experimental results** is **maximal!**

⇒ **Limits and measurements** must be *re-interpretable* for theorists.

- *Limits as function of all relevant parameters*; with assumptions on signal composition, reinterpretation requires **signal efficiencies**.
- ideally, *exclusion likelihoods* in addition to of hard 95% C.L. limits.
- ... and of course for **expected** and **observed**.
- **125 GeV Higgs measurements**: *different formats* ( $\mu$ , STXS,  $\sigma_{\text{fid}}$ ), *signal efficiencies* and *correlations* are crucial for accurate implementation.

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Thanks for your attention!