WG2 : FIDUCIAL/DIFFERENTIAL/SIMPLIFIED/TEMPLATE XS

Experimental results, developments, open points, discussions...

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Higgs Days @ Santander, 18-22 September, 2017

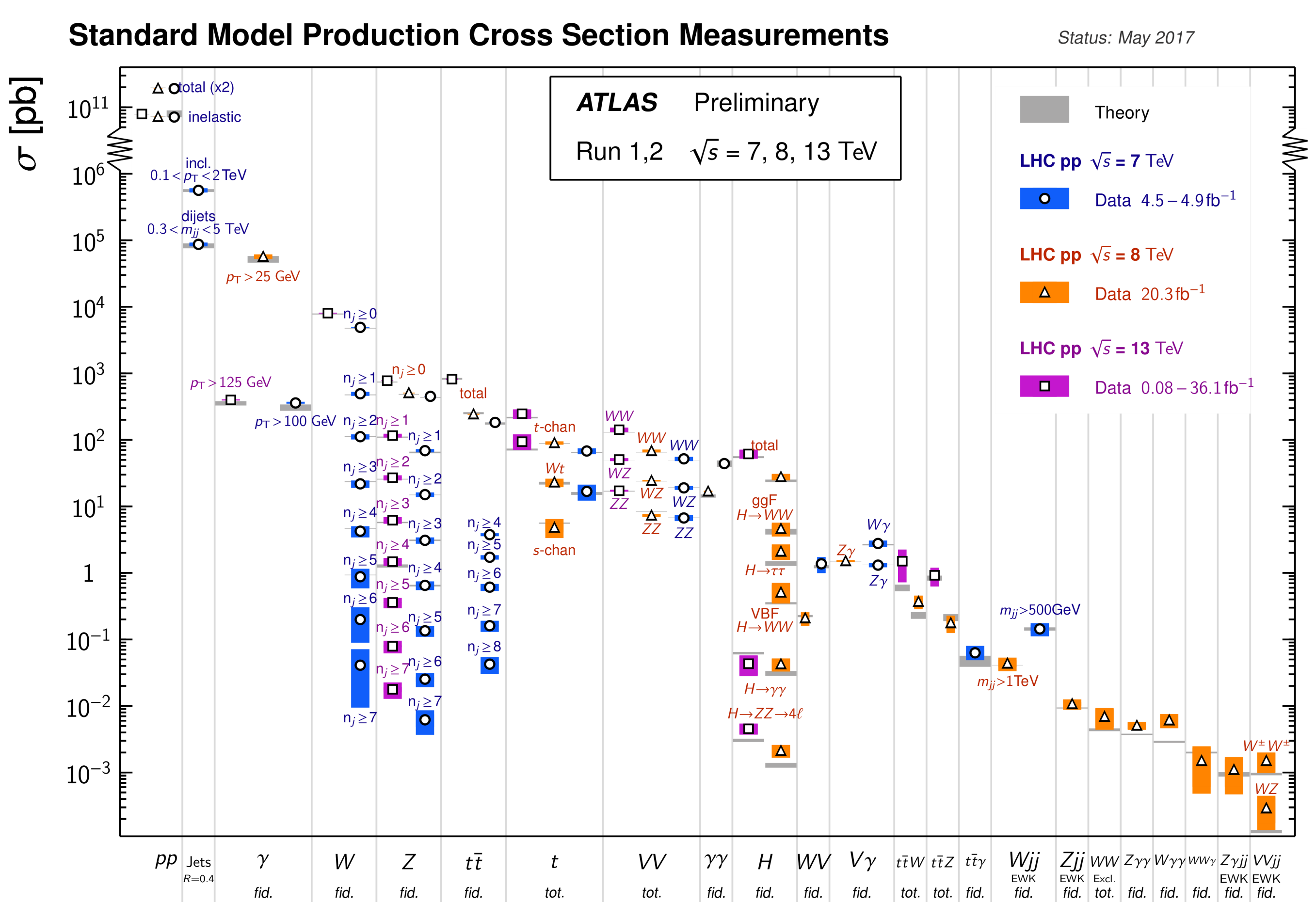
Preface

Higgs discovery: Triumph of LHC and its experiments @ Run 1

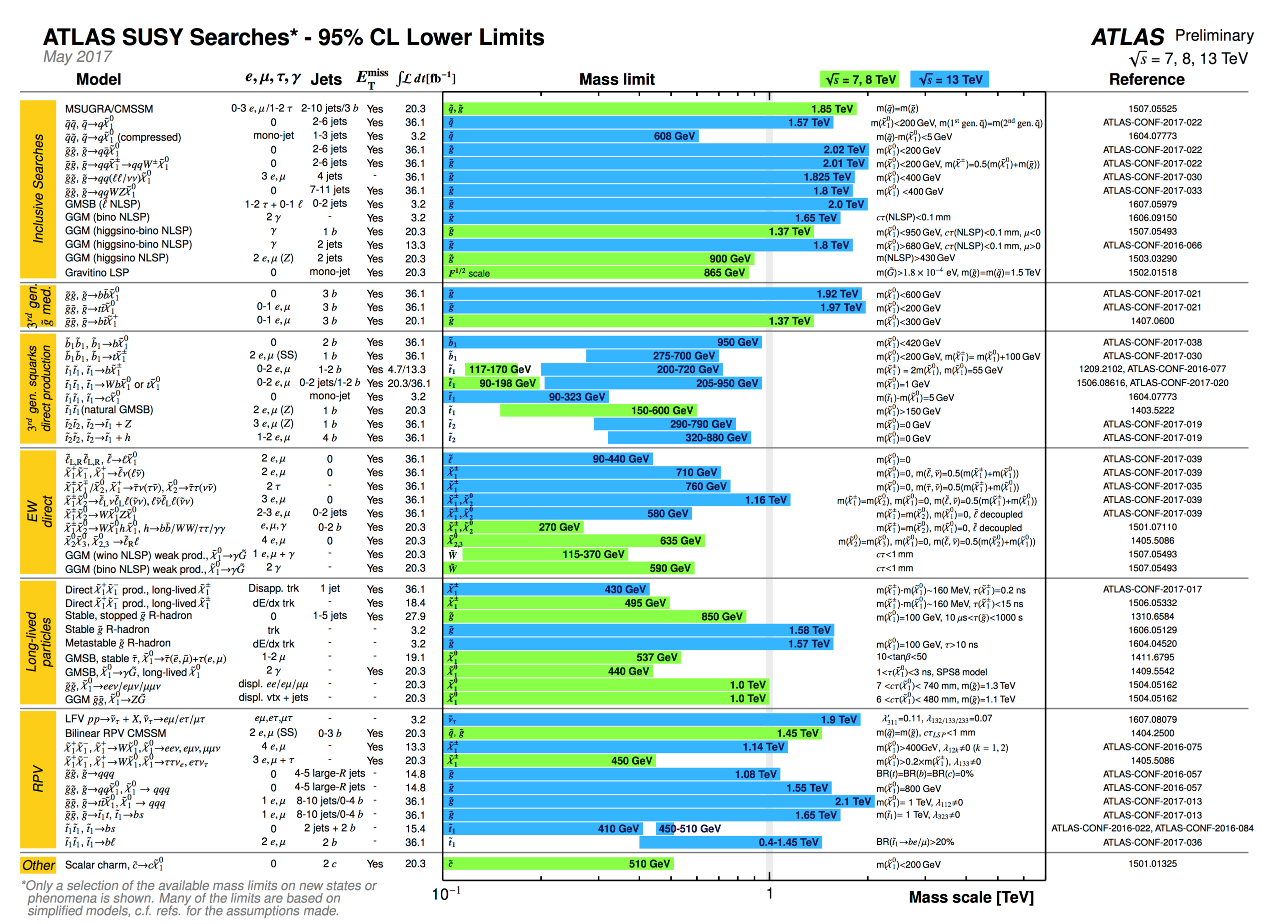
Excellence of LHC/experiments: Enabled rich physics program @13 TeV in Run 2

Plethora of SM measurements and searches for new physics:

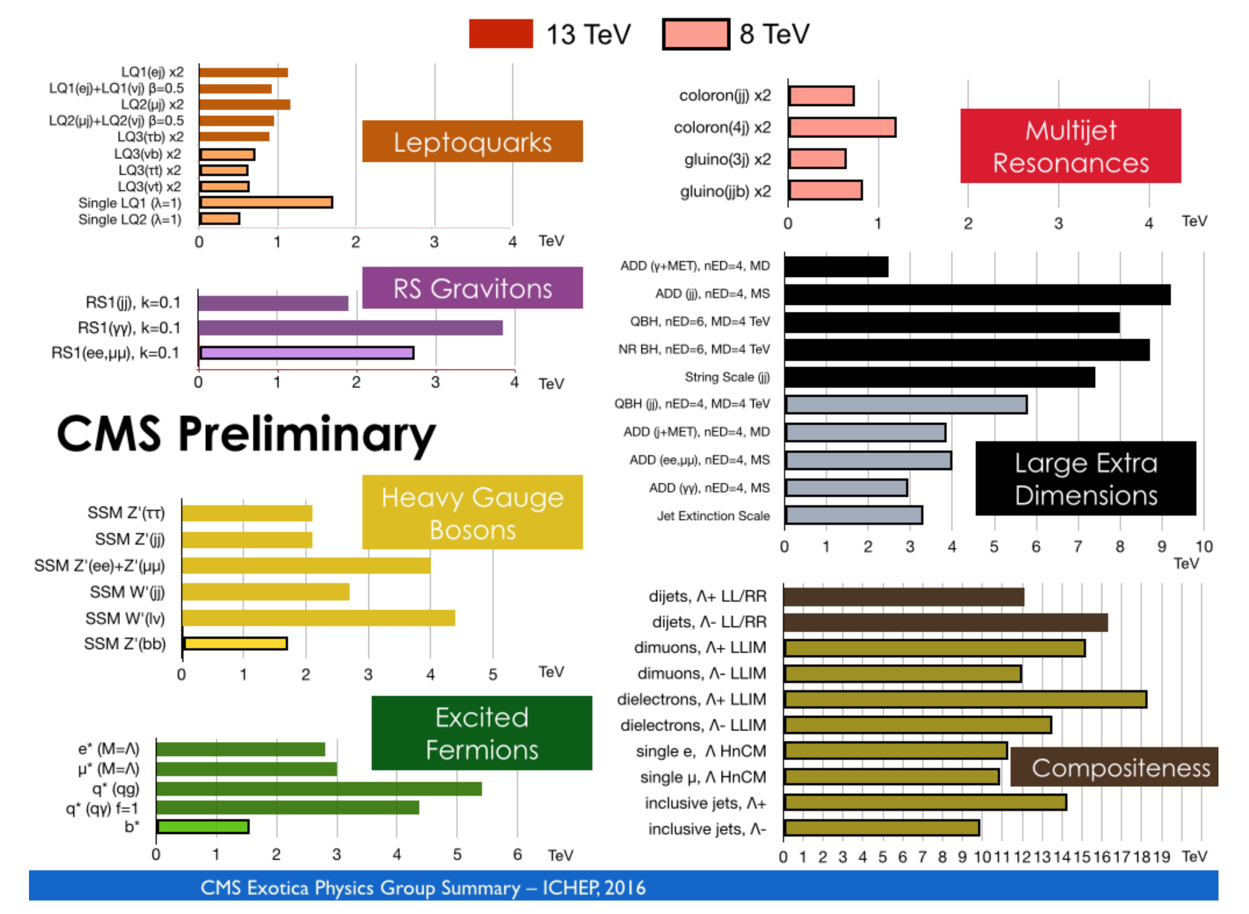
SM measurements



SUSY searches



Exotic searches



➡ No deviation from SM

➡ No indications for new physics phenomena

Run 2: Exploit the Higgs boson as a tool to probe for new physics

From measurements to interpretations...

LHC DATA

↓

Higgs boson measurements:

1. Characterisation of the SM Higgs boson
2. Search for BSM phenomena in Higgs physics

(as model-independent as possible)

- signal strengths
- simplified template XS
- Fiducial XS and differential distributions

↓

Interpretation of results:

1. Internally within experiments
2. externally by TH colleagues

(requires close EXP-TH interaction and recommendations)

- coupling strength modifiers
- pseudo-observables
- EFT approaches
- simplified/explicit BSM models

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LHC DATA

↓ Minimize theory dependence

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From measurements to interpretations...

LHC DATA

Minimize theory dependence

XS and distributions

Direct theory dependence

modifiers

EFT approaches

lified/explicit BSM models

Goals

Minimize dependence on theory systematics in measurements:

Clearer and systematically improvable treatment at interpretation level

(acceptance corrections, extrapolations to total xsec, ...)

Minimize model dependence in measurements:

Decouples measurements from discussions about specific models

(SM, linear/nonlinear EFT, BSM models, ...)

Measurements stay long-term useful:

Maximize usability of the LHC data

Allows easy (re)interpretation with different theory inputs/assumptions:

Improved theory predictions/uncertainties

(μi, κi, anomalous couplings, EFT coefficients, specific BSM scenarios, ...)

From measurements to interpretations…

LHC DATA

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Thin line between fiducial and simplified XS

Fiducial XS: **Optimized for max. theory independence**	**Simplified XS:** **Good sensitivity + reduced theory dependence**
• Minimize acceptance corrections	• Allow larger acceptance corrections
• Simple (rectangular) signal cuts	• Allow event categories, MVAs, ...
• "Exact" fiducial volume	• Abstracted/simplified fiducial volumes
• Fiducial in Higgs decay	• Inclusive in Higgs decay
• Targeted object definitions	• Common idealized object definitions
Agnostic to production modes	**Split by production mode**
(Single-)differential distributions **(overlapping events)**	**Split into mutually exclusive regions of phase space**
Mostly H → γγ, ZZ, (W W) **(by default no combination of channels)**	**Explicitly designed for combination of all decay channels**

- Complementary roles, but several common issues
  - Treatment of out-of-acceptance corrections, presentation of results, ...

Thin line between fiducial and simplified XS

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phase space

Explicitly designed for combination
of all decay channels

Simplified template cross sections are similar to differential signal strengths with pre-defined binning (based on SM assumptions).

- Complementary roles, but several common issues
  - Treatment of out-of-fiducial corrections, presentation of results, ...

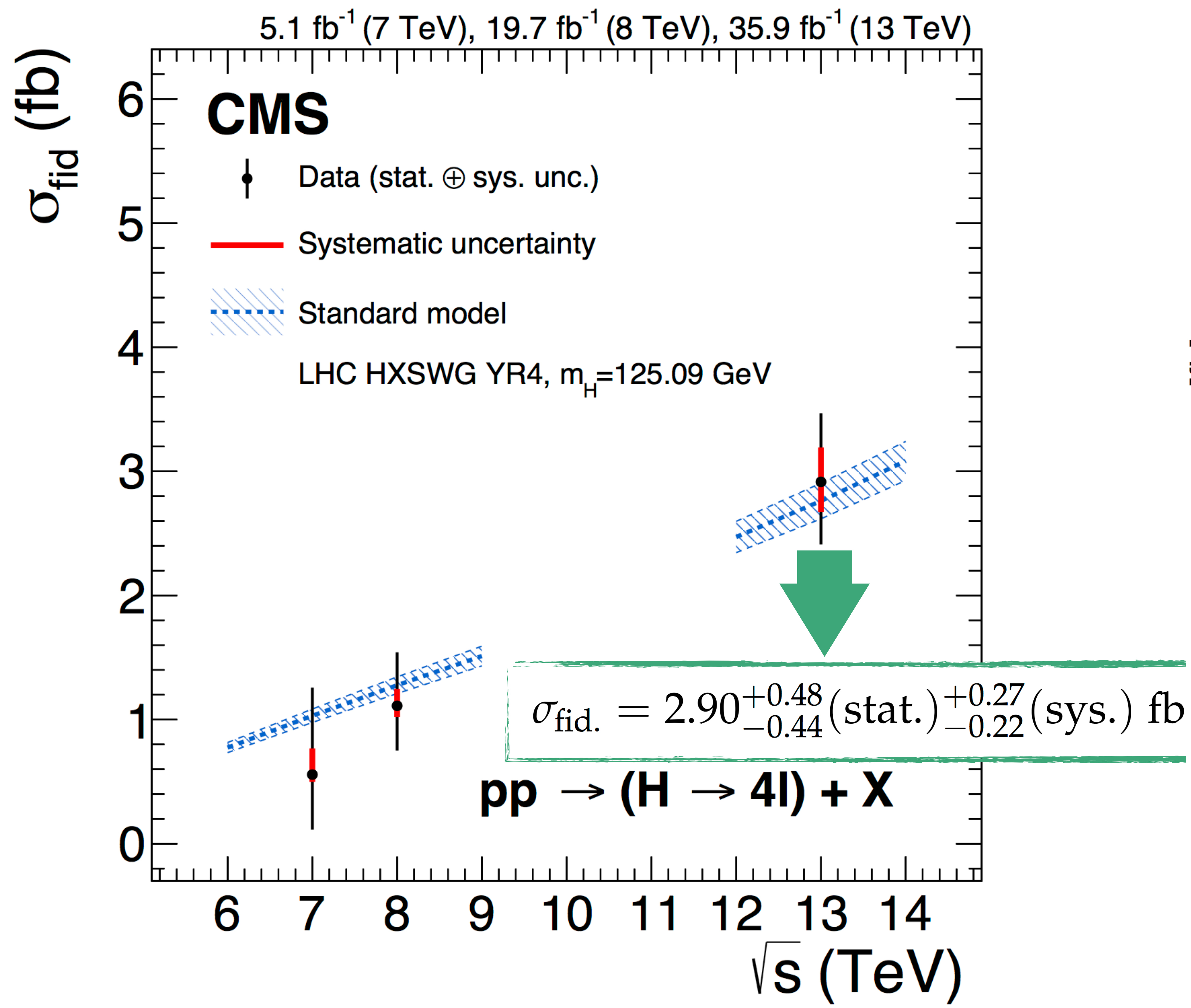
Fiducial cross sections and unfolded distributions

Latest fiducial XS measurements : H → 4ℓ

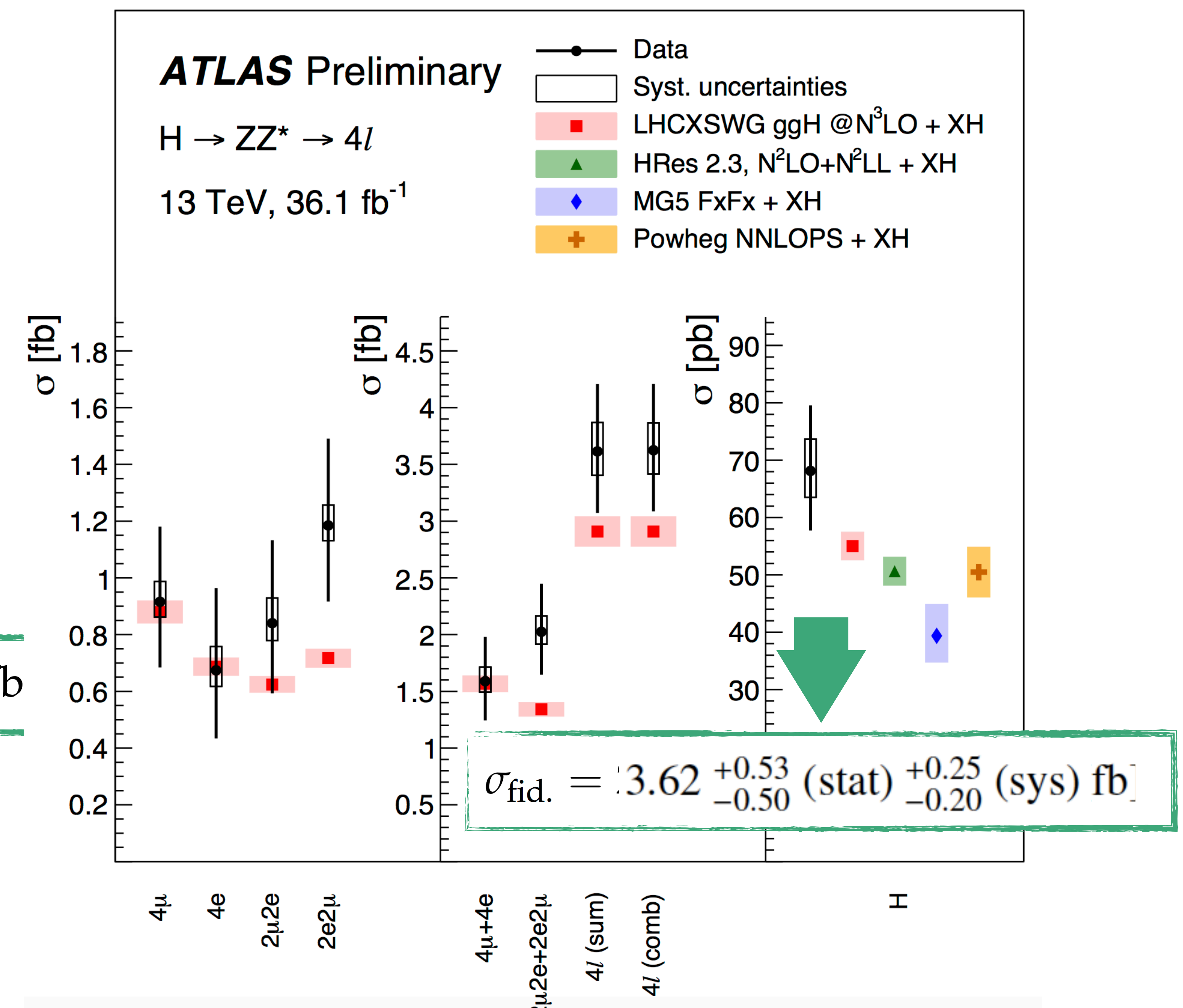
Measurements of fiducial cross sections:

- Not sensitive to production mechanism, expected to be dominated by gluon fusion

Fiducial XS @ 7, 8, 13 TeV



Fiducial XS @ 13 TeV



Compatible with theoretical estimates within existing uncertainties

Latest fiducial XS measurements : $H \to \gamma\gamma$

Measurements of fiducial cross sections:

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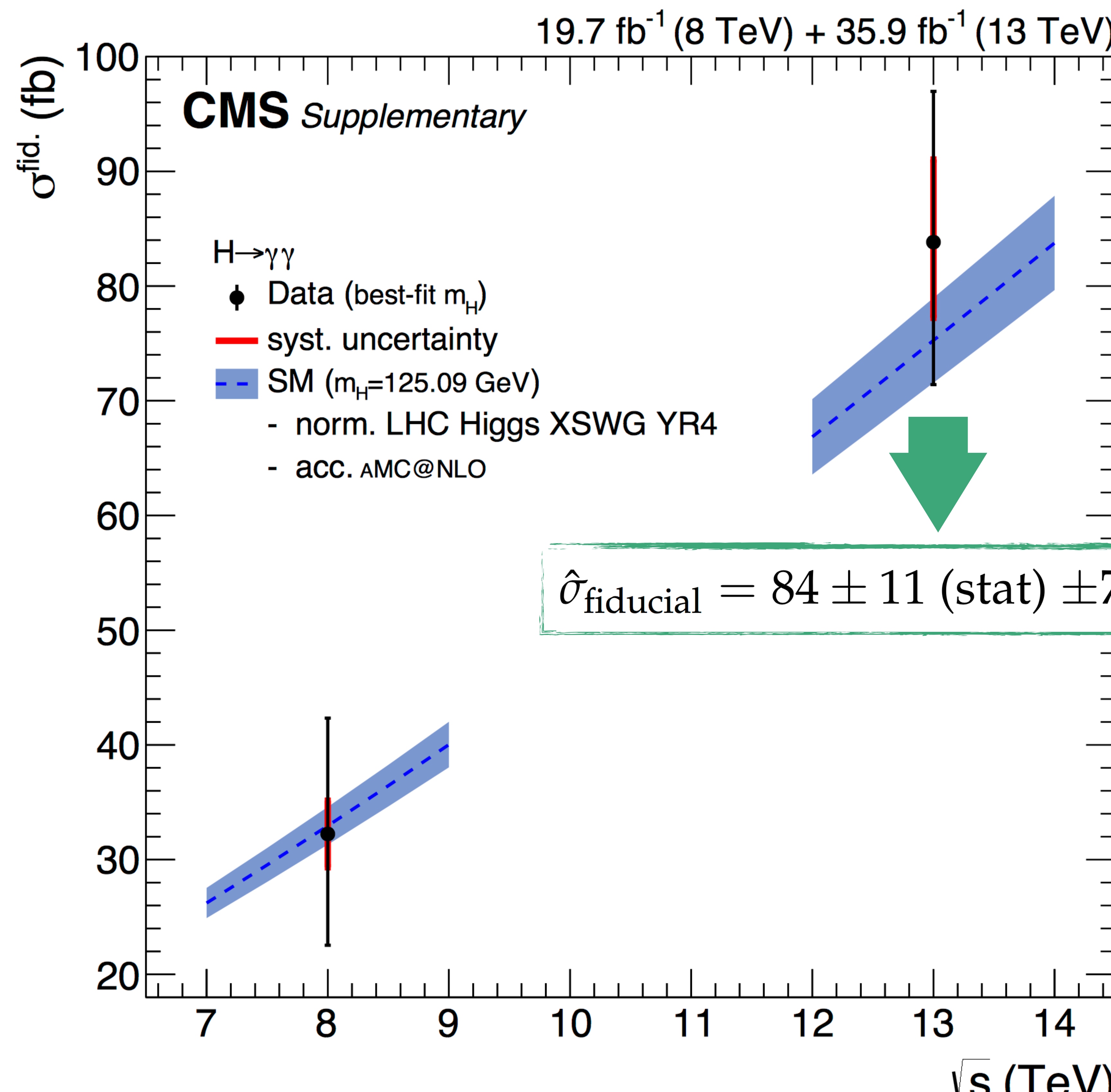
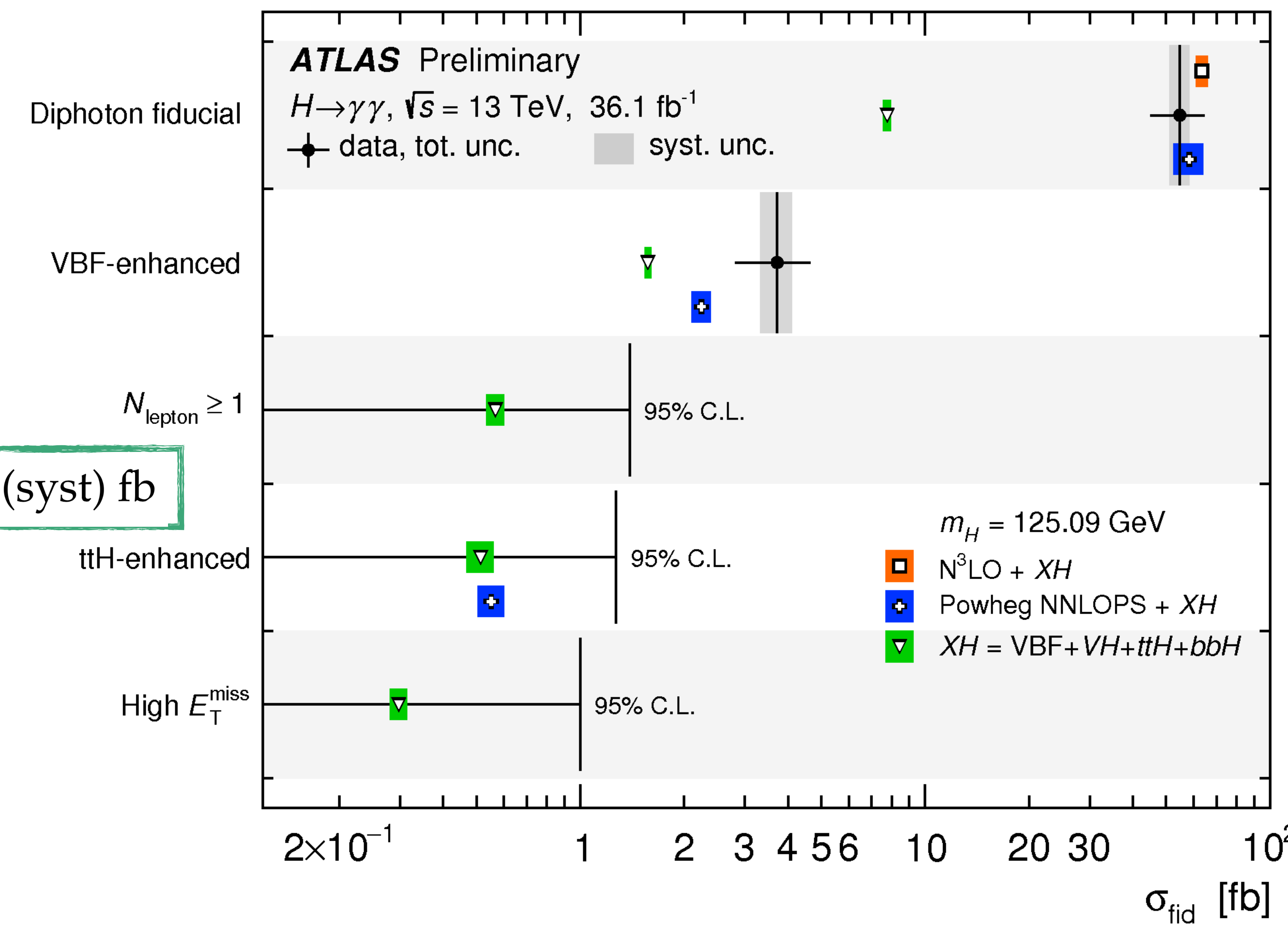
Fiducial XS @ 8, 13 TeV



$$\hat{\sigma}_{\text{fiducial}} = 84 \pm 11\ (\text{stat}) \pm 7\ (\text{syst})\ \text{fb}$$

Fiducial XS @ 13 TeV



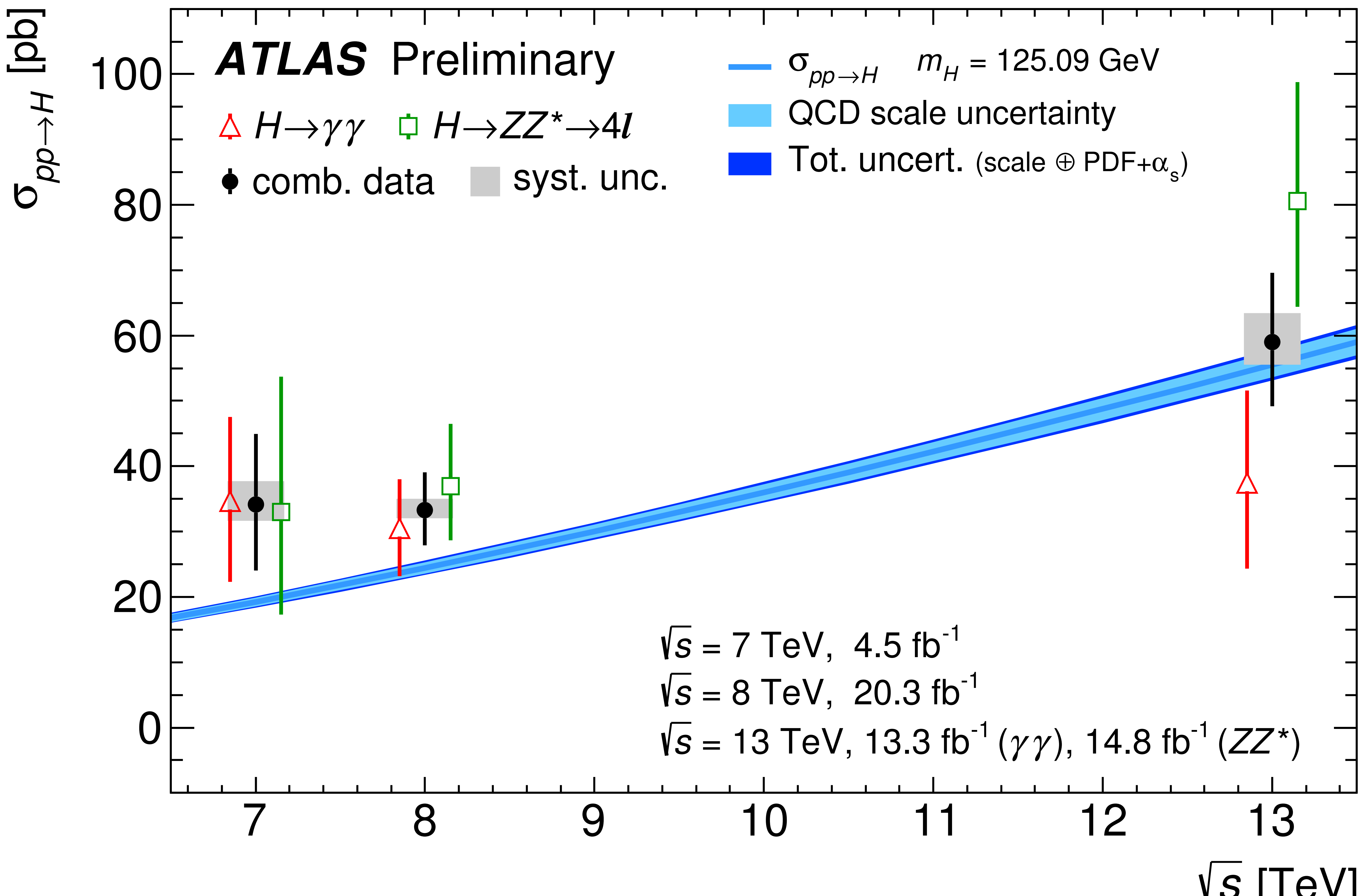
Compatible with theoretical estimates within existing uncertainties

Latest fiducial XS combination : H→γγ + H→ZZ→4l

Combined measurements of fiducial cross sections:

- Reasonable agreement among H → 4l and H → γγ for low statistics (13.3 fb^{-1} @ 13 TeV), p-value > 56%

H→γγ + H→ZZ→4l @ 7, 8, 13 TeV

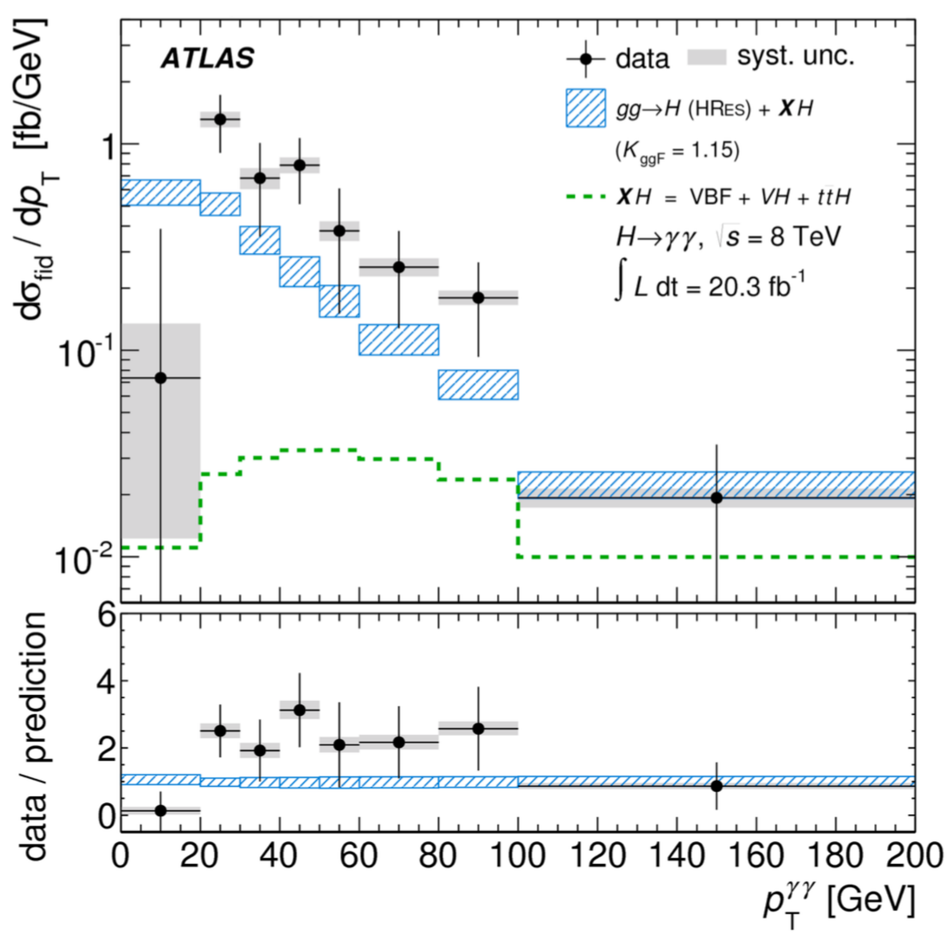


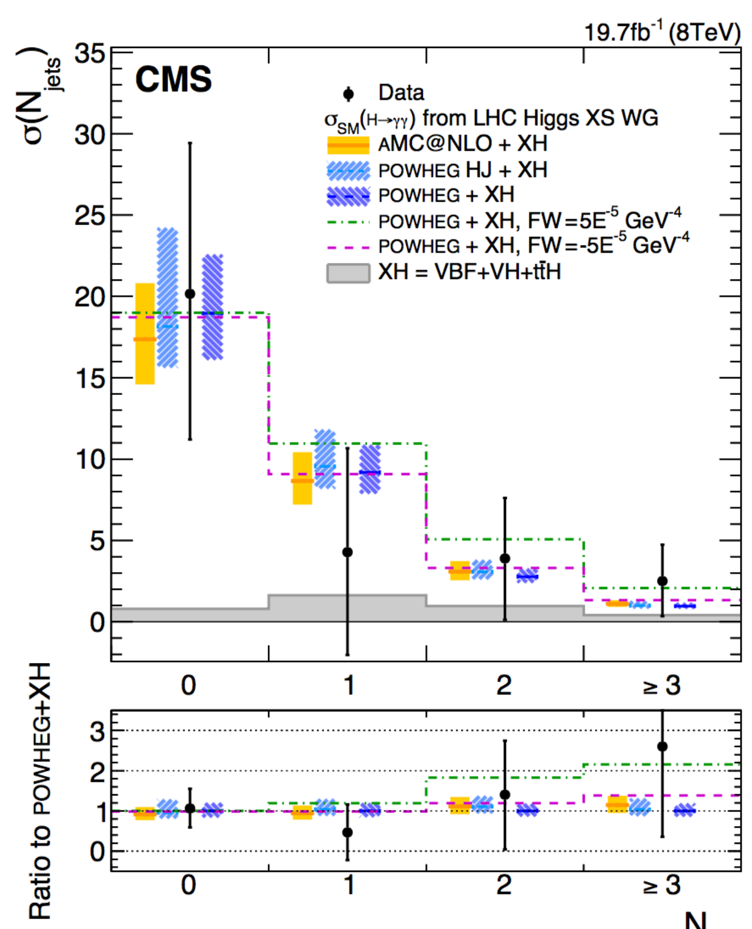
Compatible with theoretical estimates within existing uncertainties

Reminder: Differential fiducial XS in Run 1

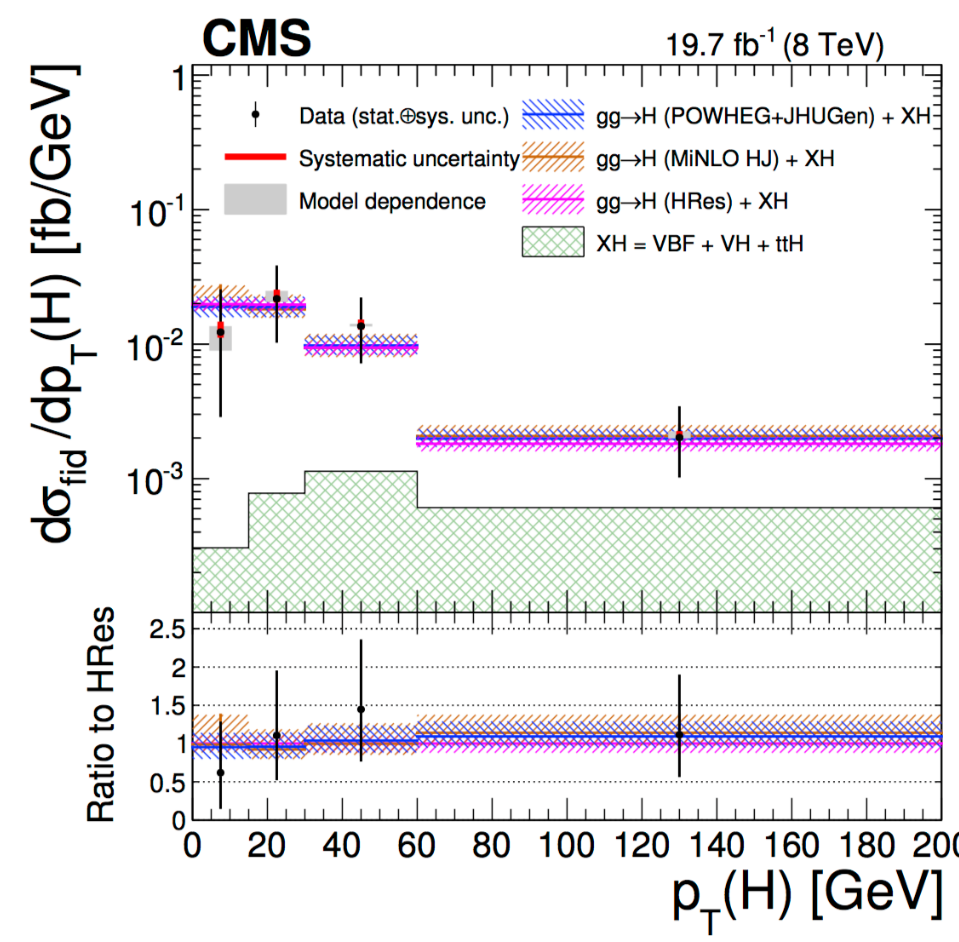
- **Differential fiducial XS @ 8 TeV for pT(H) in H → γγ, ZZ, W W channels:**
  - Sensitive to modelling of hard quark and gluon radiation, relative contributions of different production modes, BSM effects in the loops, etc.

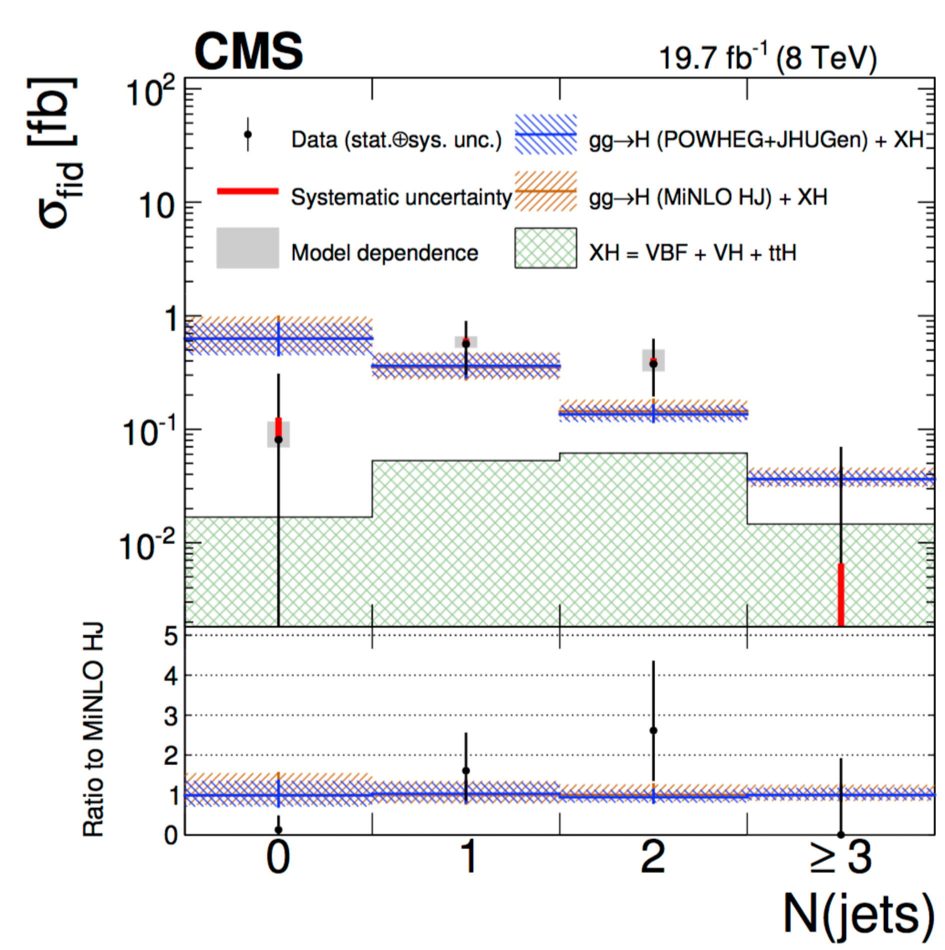
H→γγ



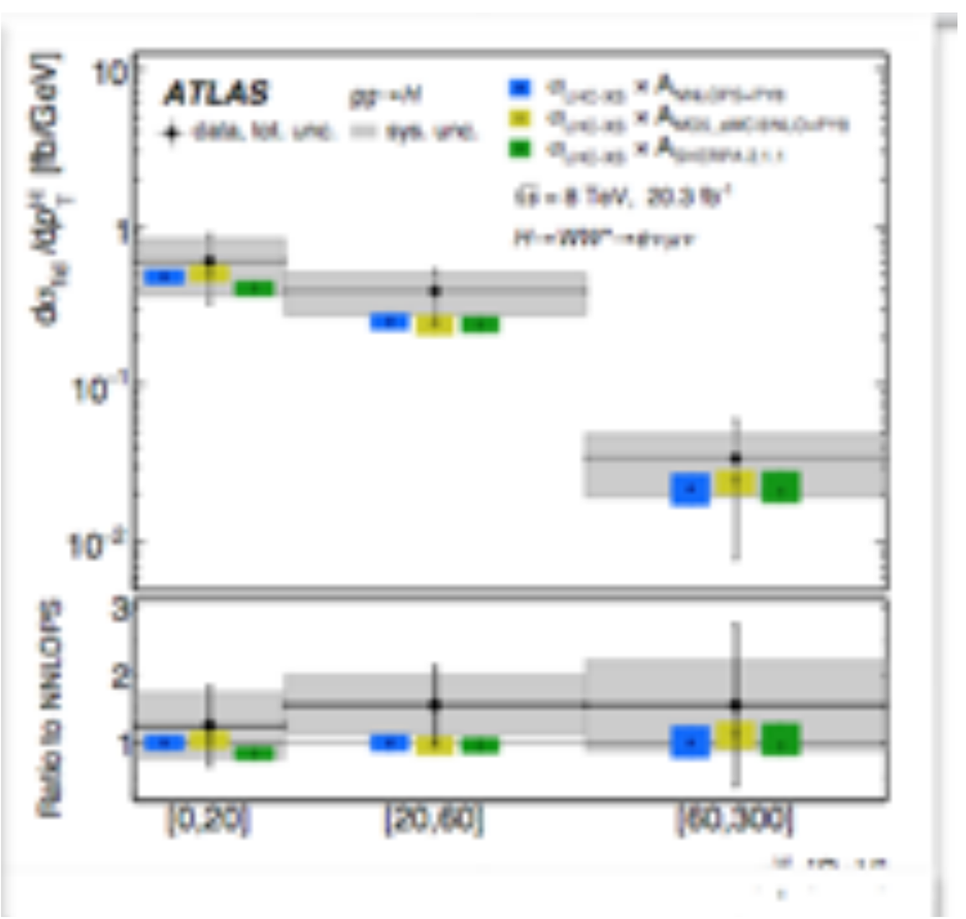


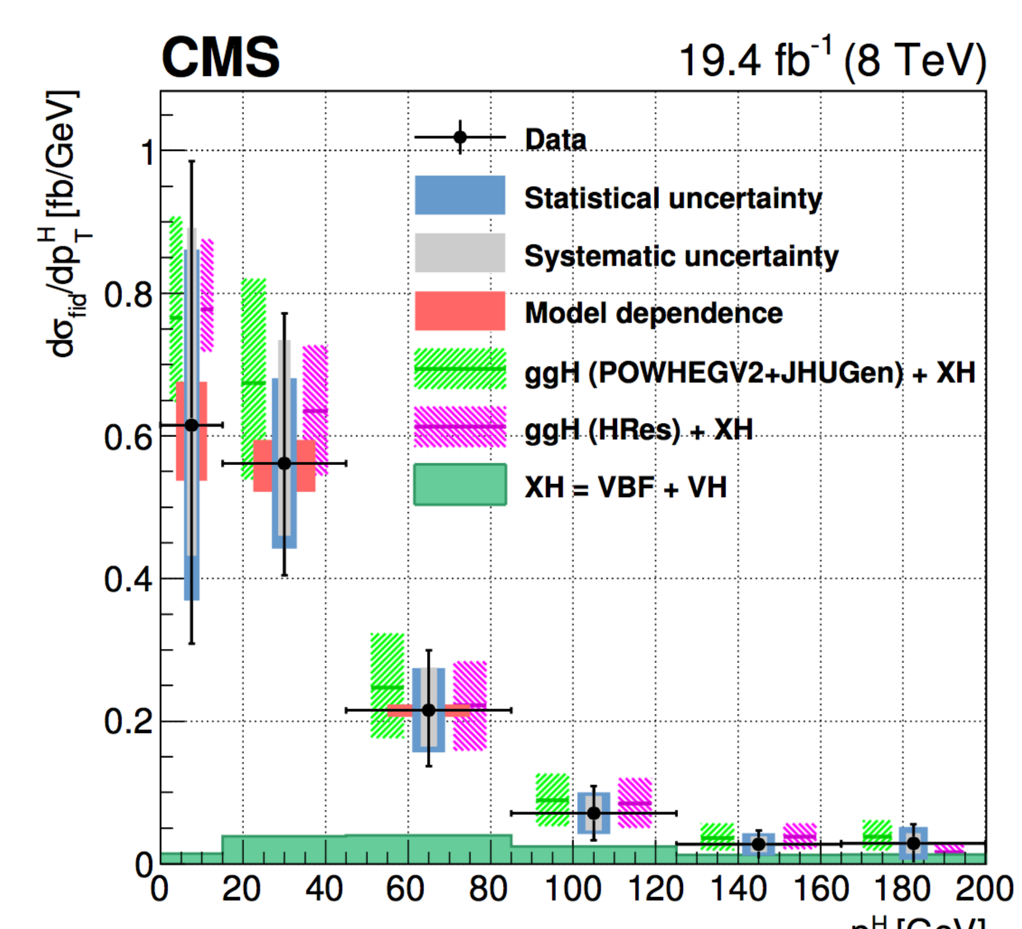
H→ZZ→4l





H→WW→2l2ν

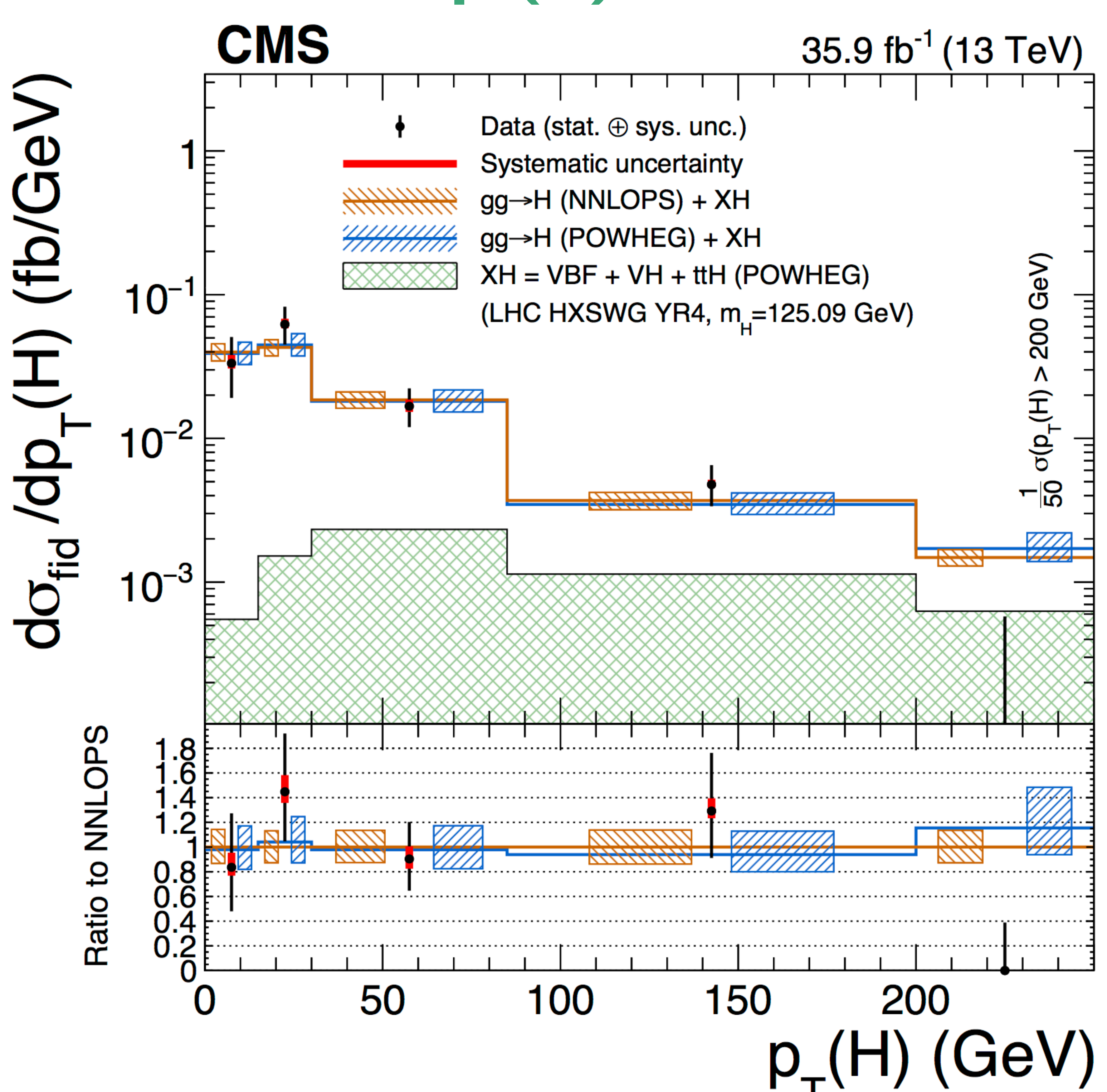




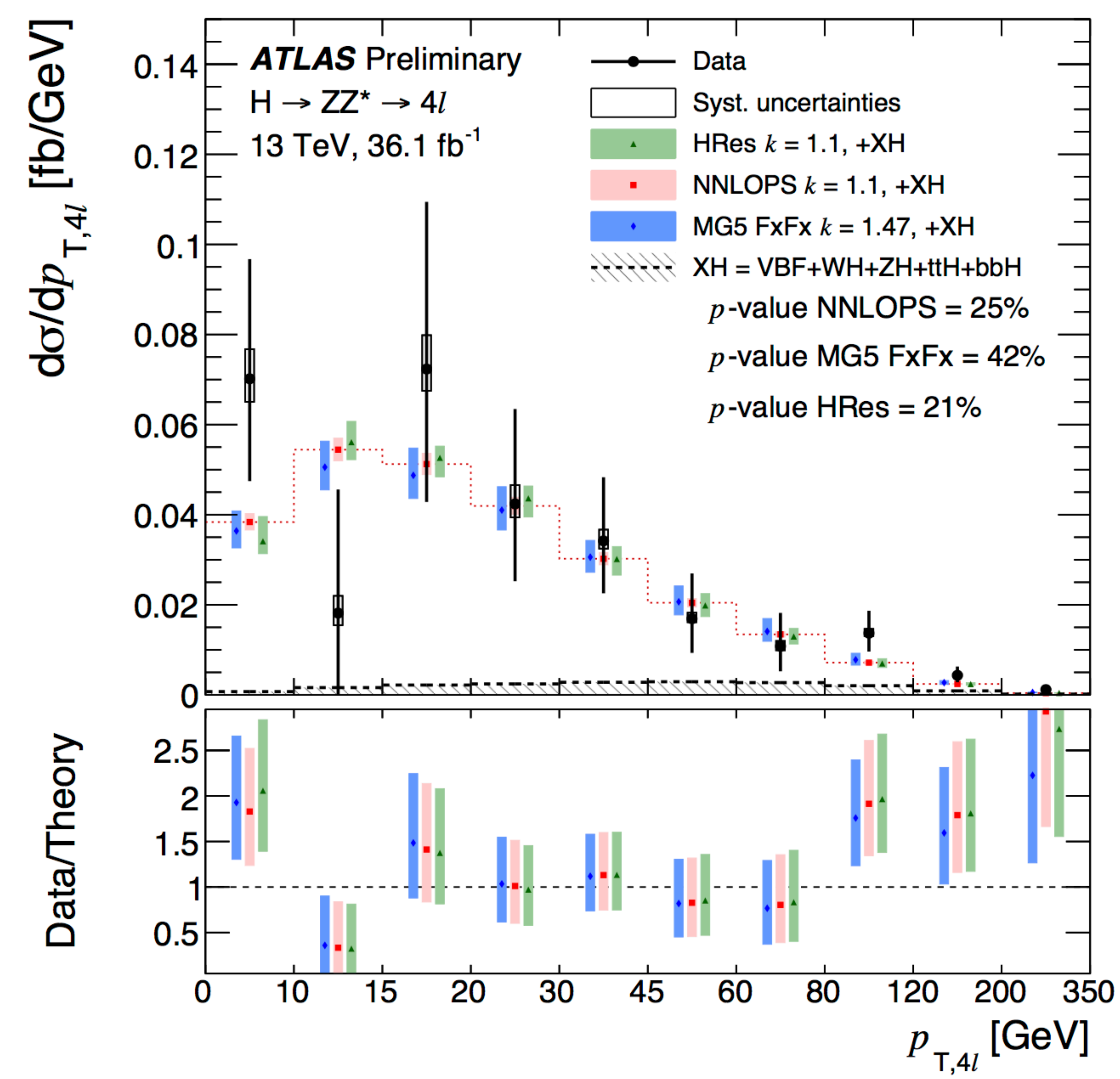
Latest differential fiducial XS : H → 4ℓ

- **Differential fiducial XS @ 13 TeV:**
  - Differential measurements for: p_T(4l), N(jets), p_T(jet), and also Y(4l), m_{34}, ...
  - Sensitive to modelling of hard quark and gluon radiation, relative contributions of different production modes, BSM effects in the loops, PDFs, etc.

p_T(4l) : CMS



p_T(4l) : ATLAS



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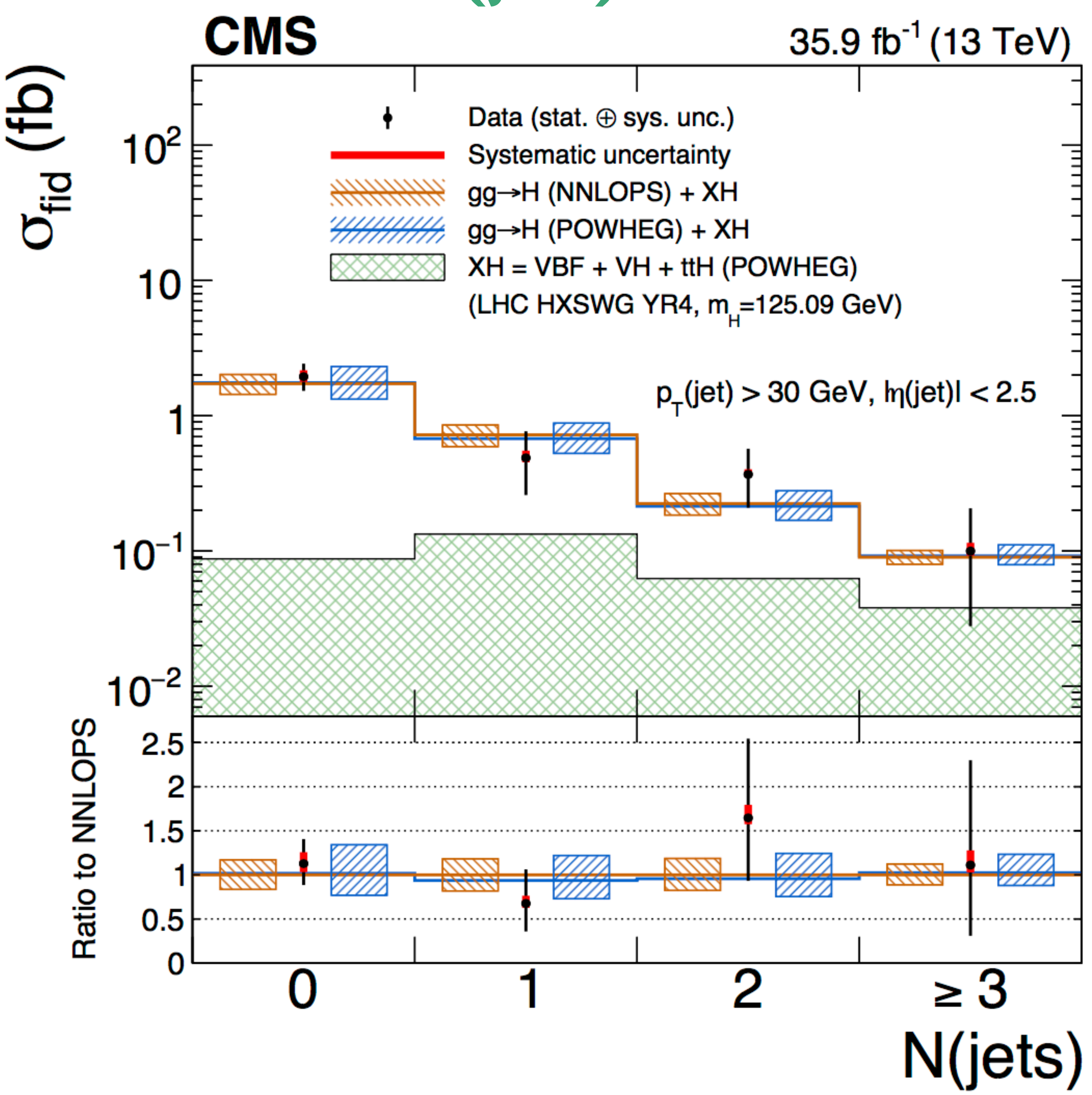
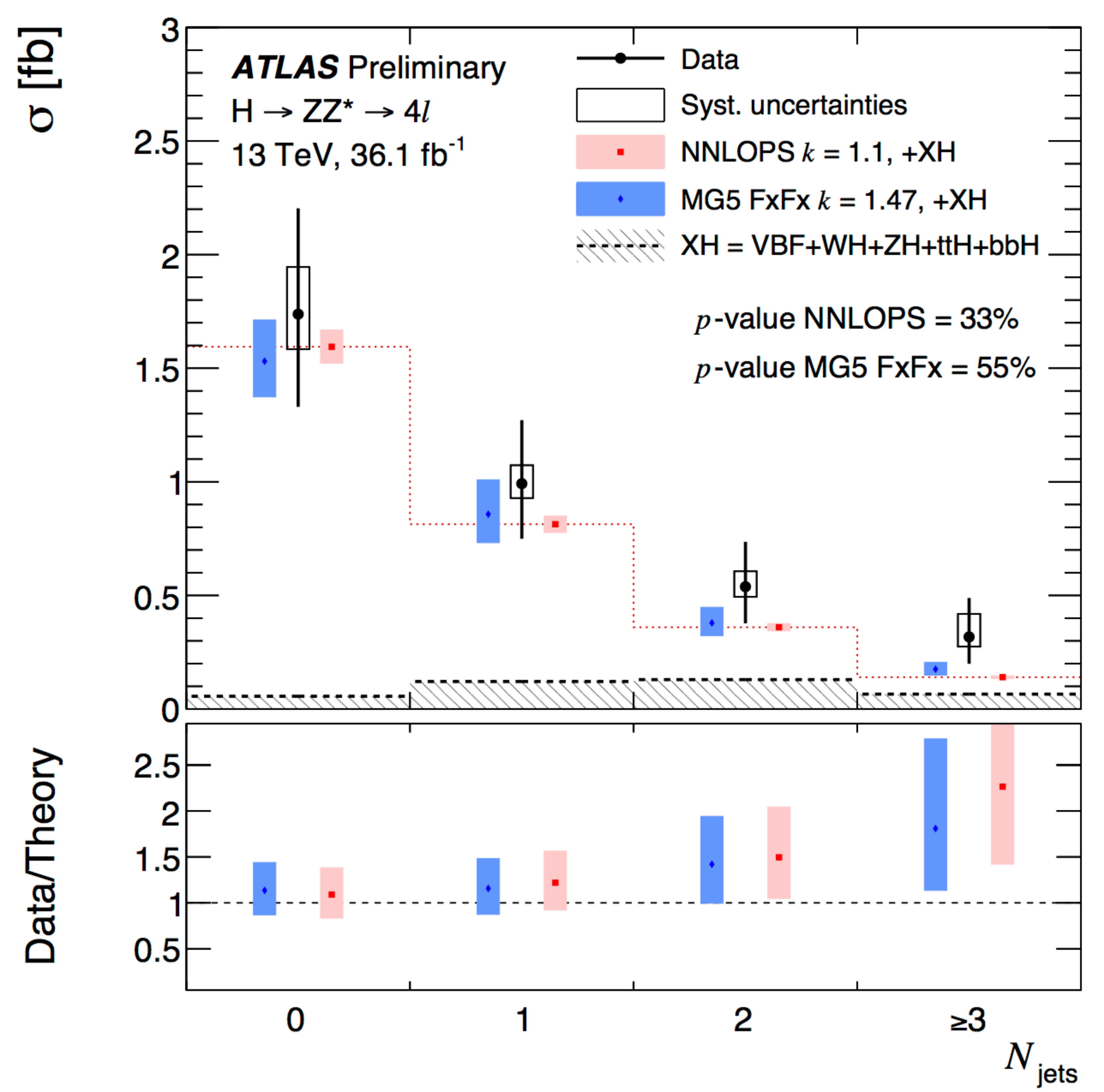
N(jets) : CMS



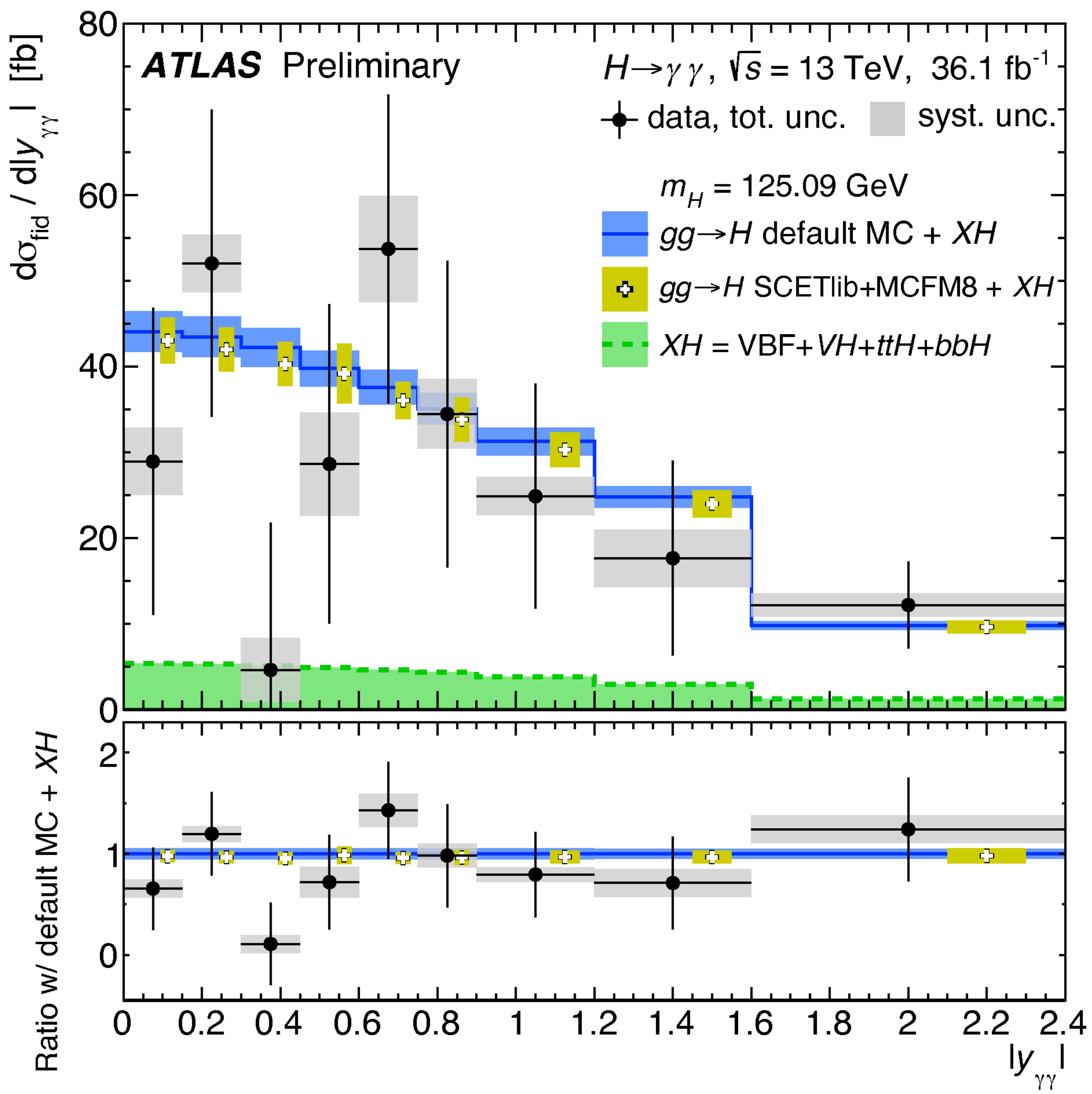
N(jets) : ATLAS



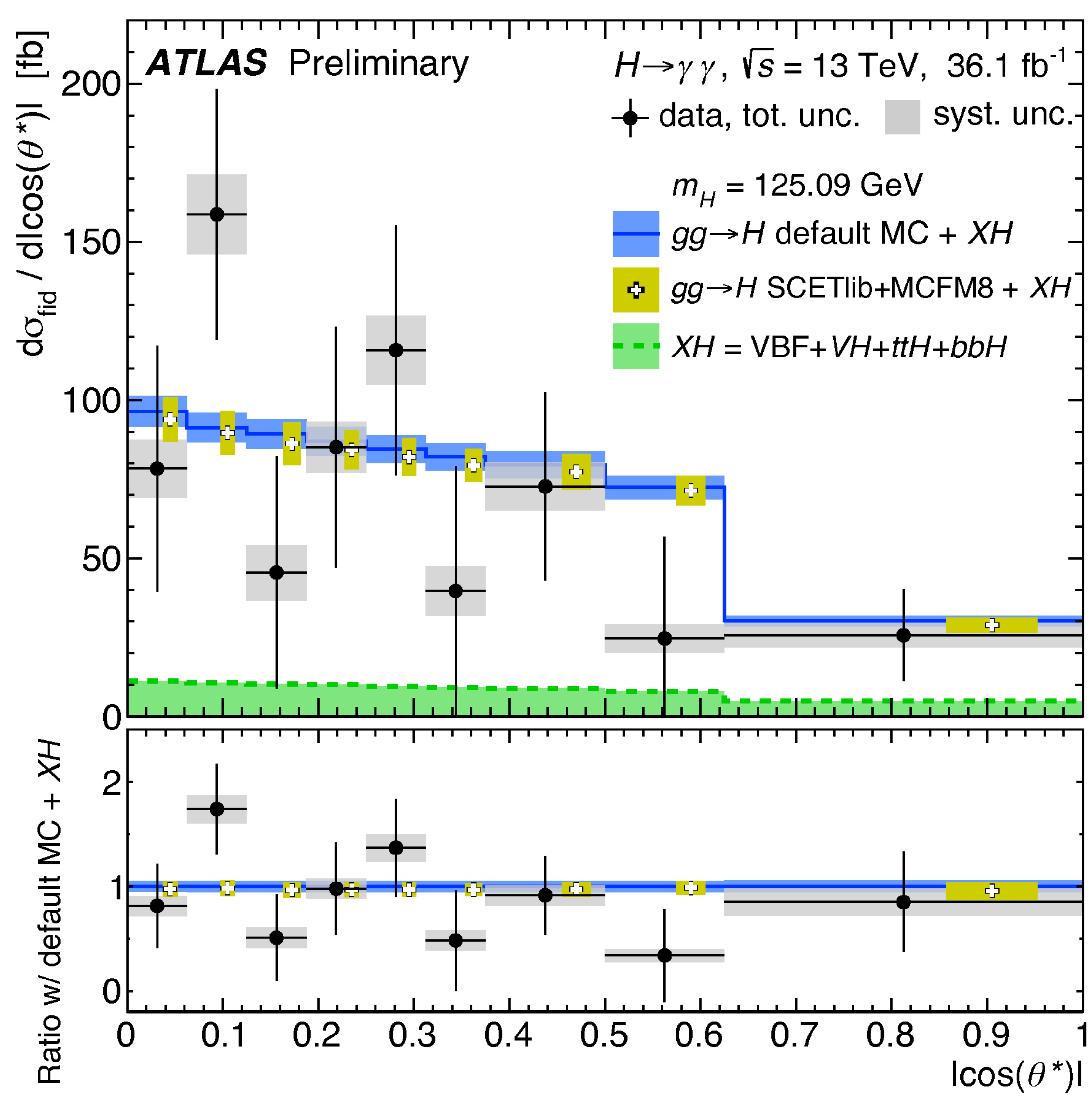
Latest differential fiducial XS : H → γγ

- **Differential fiducial XS @ 13 TeV:**
  - Differential measurements for: pT(γγ), N(jets), pT(jet), Y(γγ), |cosθ*|, Δφ(jj), ...
  - Sensitive to modelling of hard quark and gluon radiation, relative contributions of different production modes, BSM effects in the loops, PDFs, etc.

Y(γγ) : ATLAS



|cos(θ*)| : ATLAS



Latest differential fiducial XS : H → γγ

- **Differential fiducial XS @ 13 TeV:**
  - Differential measurements for: $p_T(\gamma\gamma)$, N(jets), p_T(jet), Y(γγ), |cosθ*|, Δφ(jj), ...
  - ...erent production modes,

Differences between ATLAS and CMS

Definition of the fiducial-level objects and fiducial phase space

Treatment in case of observables with poor resolution

Treatment of the model (in)dependance and unfolding strategies

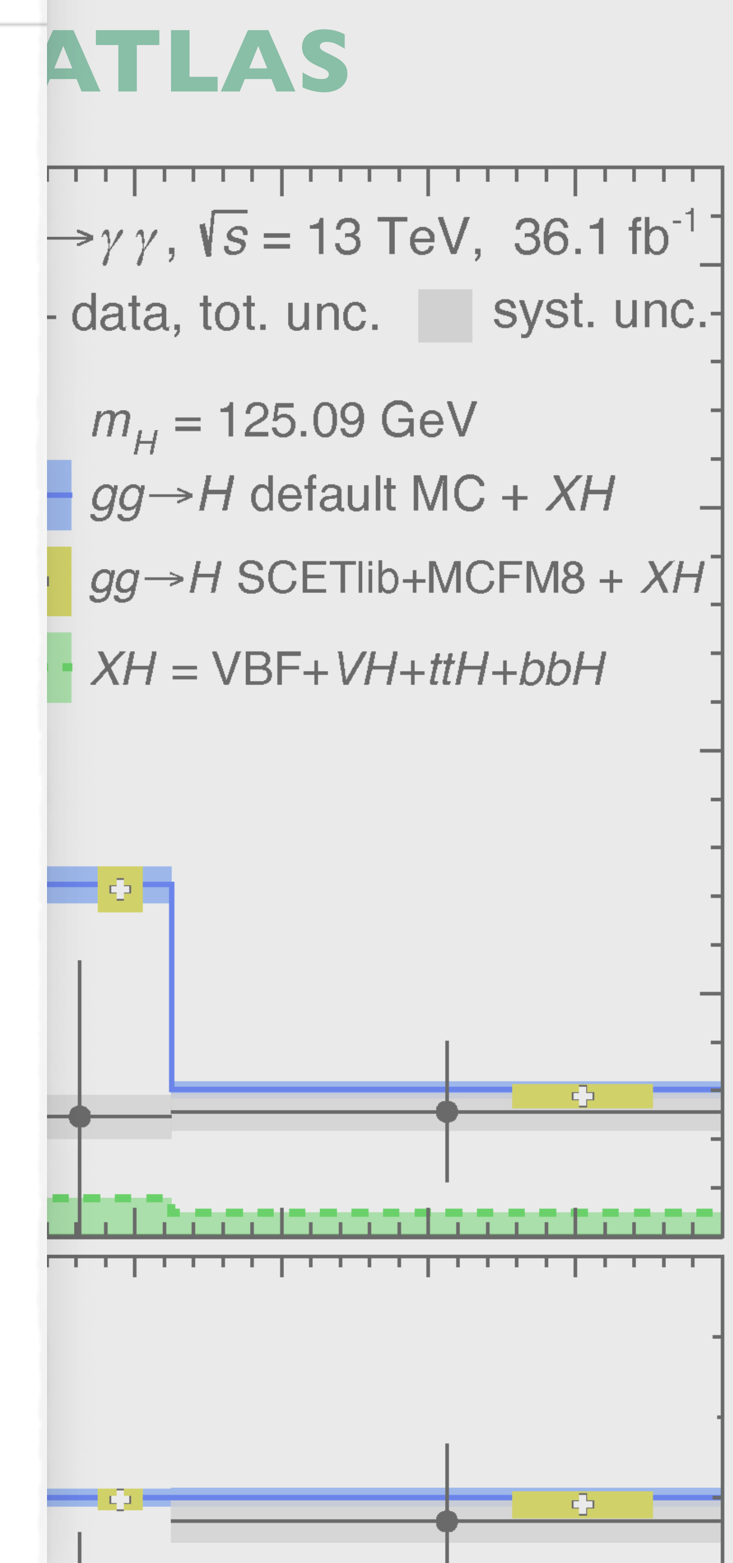
Choice of the alternative models,
Treatment of the out-of-acceptance contributions

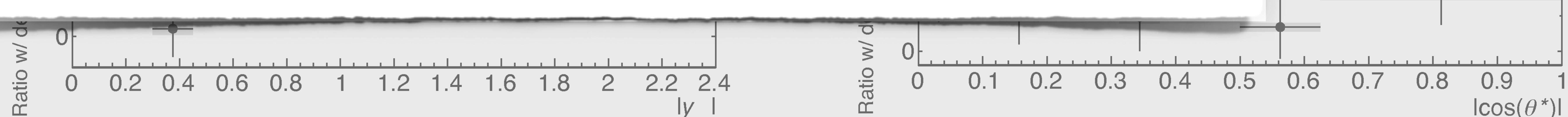
Choice of observables and harmonisation of binning

Production or decay-level observables, binning criteria, etc.

Presentation of the results, and how to provide information to theorists

Correlation matrices, availability in HEP, etc.





Choice of differential observables and binning

Core Results / Nice to have

Observables considered:

- **1D distributions**:
  p_T(H), N(jets), |Y(H)|, p_T(jet 1),
  p_T(jet 2), |p_T(H) - p_T(jet 1)|, |Y(H) - Y(jet 1)|, |Y(jet 1) - Y(jet 2)|, M_{jj}.
- **2D distributions**: **p_T(H) x N(jets), p_T(H) x |Y(H)|.**

Additional ideas/wishes?

Still need to agree on the exact set of **1D/2D** variables.

Binning:

- Need to have aligned coarse bin boundaries
- Criteria for bin boundaries related to the uncertainty on the expected yields
  - ATLAS: having > 2 sigma expected significance in each bin,
  - CMS: somewhat stronger requirement on the exp. signal yield uncertainty,

  Exceptions: overflow or boundary bins., match STXS boundaries if possible (for convenience)

Experiments have agreed (or are about to agree) on the bin boundaries.

Choice of binning boundaries

XYZ aligned boundaries
possible finer boundaries

Possible binning scenarios (ATLAS/CMS)

- Binning for $p_T(H)$:

H→γγ: 0 10 15 20 30 45 60 80 100 120 155 200 260 350

H→4l: 0 10 15 20 30 45 60 80 100 120 155 200 260 350

- Binning for |y(H)|:

H→γγ: 0 0.15 0.3 0.45 0.6 0.75 0.9 1.2 1.6 2 2.5

H→4l: 0 0.15 0.3 0.45 0.6 0.75 0.9 1.2 1.6 2 2.5

- Binning for p_T(lead jet):

Jet Definition anti-kt dR=0.4, 30 GeV, need to decide on centrality

H→γγ: 30 40 55 75 95 120 200 350

H→4l: 30 40 55 75 95 120 200 350

- Discussion on other observables and binning is ongoing…

Definition of fiducial region

Fiducial regions:

- **Too many differences** in ATLAS and CMS analyses/regions (p_T and η cuts, isolation, etc.):

  ➡ There is no need to aim the same fiducial phase space definitions.

- Combined measurement with different fiducial definitions:
  - **by extrapolation to the full phase space with restriction |y(H)| < 2.5**
    Easiest, additional model dependence, makes sense for $H \rightarrow \gamma\gamma$ + $H \rightarrow 4l$ combination.
    Fiducial with |y(H)| < 2.5 is interesting as it's experimentally accessible part of phase space.

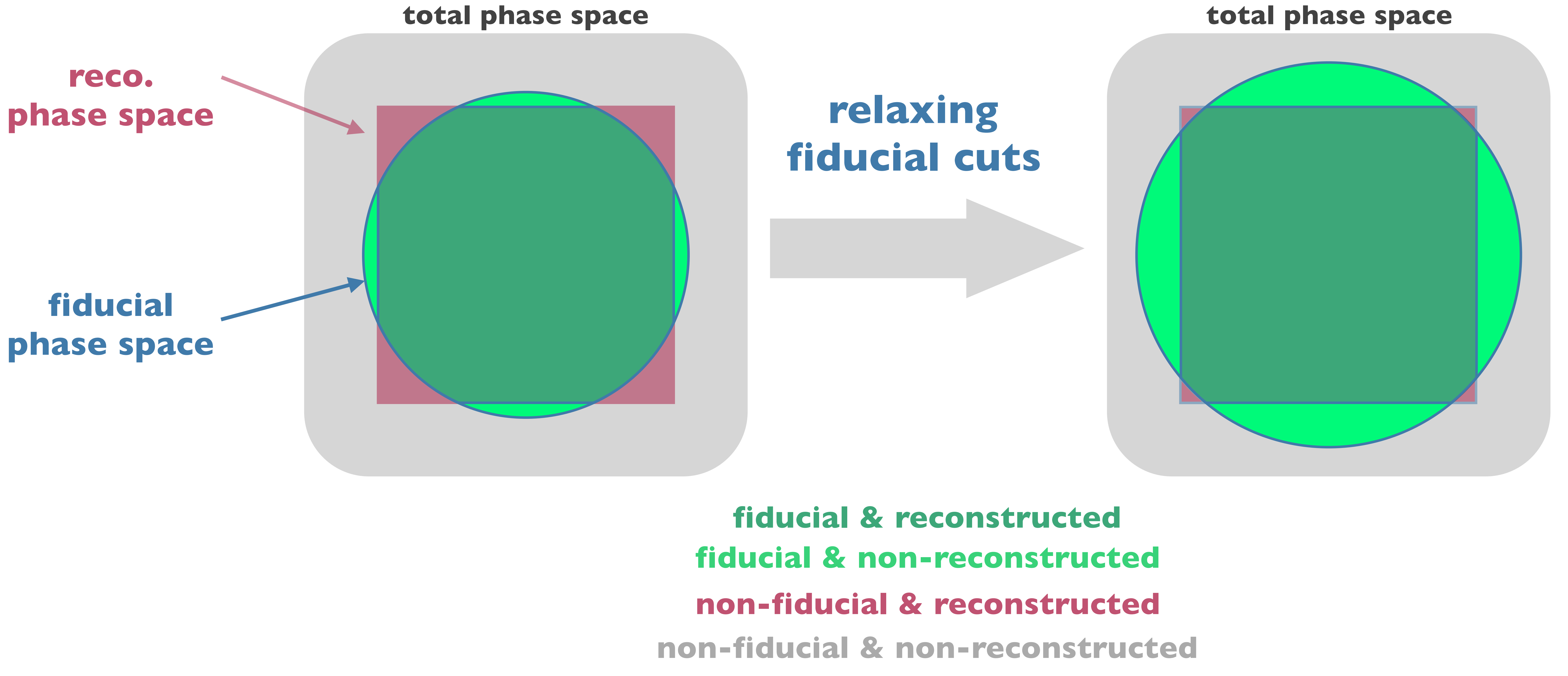
  Any comment?

  Might also consider combination:
  - **in "common" part or the "minimal enclosing" part of the phase space**
    Not easy to find for different channels, less add. model dependence,
    makes sense for individual $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$ - **proposal that this is not an initial priority.**

Fiducial requirements & observables with poor resolution

To be studied in each analysis:

- How to define the fiducial phase space when observables used to define the signal region have **poor experimental resolution** (missing $\mathbf{E_T}$, jet $\mathbf{p_T}$, etc.)?
  - Effects of migration of signal events can be large
  - Subtraction of non-fiducial signal events is model dependent
- Study if relaxing fiducial requirements can reduce model dependence.



Aspects of fiducial measurements agreed/discussed

Signal definitions:

- Perform measurement for the processes via the Higgs resonance.
  Subtract non-resonant contributions in **pp→(H→)γγ, pp→(H→)ZZ→4l, pp→(H→)WW→2l2ν**
- Measurement for the fiducial **pp→4l** and **pp→2l2ν** production also important in the long term.

Out-of-acceptance contributions:

- Arise from imperfect experimental resolution. Related directly to the model dependance.
  Experiments aim to agree on the common approach how to subtract it from the signal.

Other aspects discussed:

- **Model dependance:** From variation of relative fraction of SM production modes within exp. constraints.
- **Treatment of m(H):** Aim to agree weather to fix m(H) as as ext. parameter, or to float it as a nuisance.
- **Unfolding:** Desirable to be able to use likelihood fits with embedded response matrix.

Aspects of fiducial measurements agreed/discussed

Results and their presentation:

- Comparisons to theory predictions: **follow (post-)YR4 prescriptions** (e.g. use **N^3LO QCD** for the ggH normalisation, and **NNLO+NNLL** QCD for shape).
- Presentation of central values, uncertainties, correlations to be in line with STXS presentation (see later).

Approaches to combination:

- **by extrapolation to the full phase space with restriction |y(H)| < 2.5.** Easiest, some additional model dependence, makes sense for H→γγ + H→4l combination.

Combined measurements:

- Individual channels: **H→4l, H→γγ** (also **H→WW** for **p_T(H) and N(jets) if/once available**)
- Combined all together: **H→4l + H→γγ** (**+ H→WW** for **p_T(H) and N(jets) if/once available**)

Simplified template (ST) XS

Thin line between fiducial and simplified XS

Fiducial XS: Optimized for max. theory independence	**Simplified XS:** Good sensitivity + reduced theory dependence
• Minimize acceptance corrections • Simple (rectangular) signal cuts • "Exact" fiducial volume • Fiducial in Higgs decay • Targeted object definitions	• Allow larger acceptance corrections • Allow event categories, MVAs, ... • Abstracted/simplified fiducial volumes • Inclusive in Higgs decay • Common idealized object definitions
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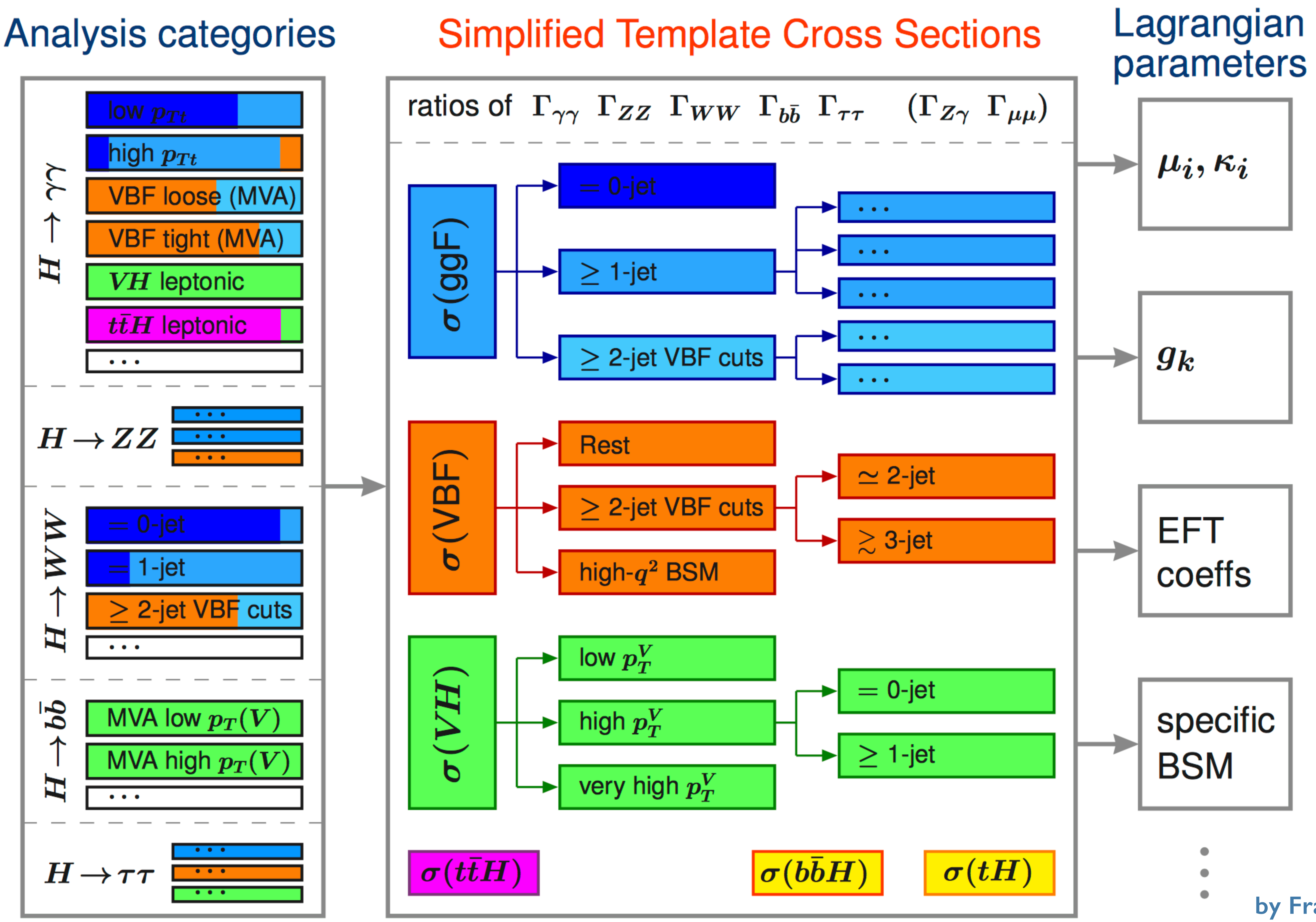
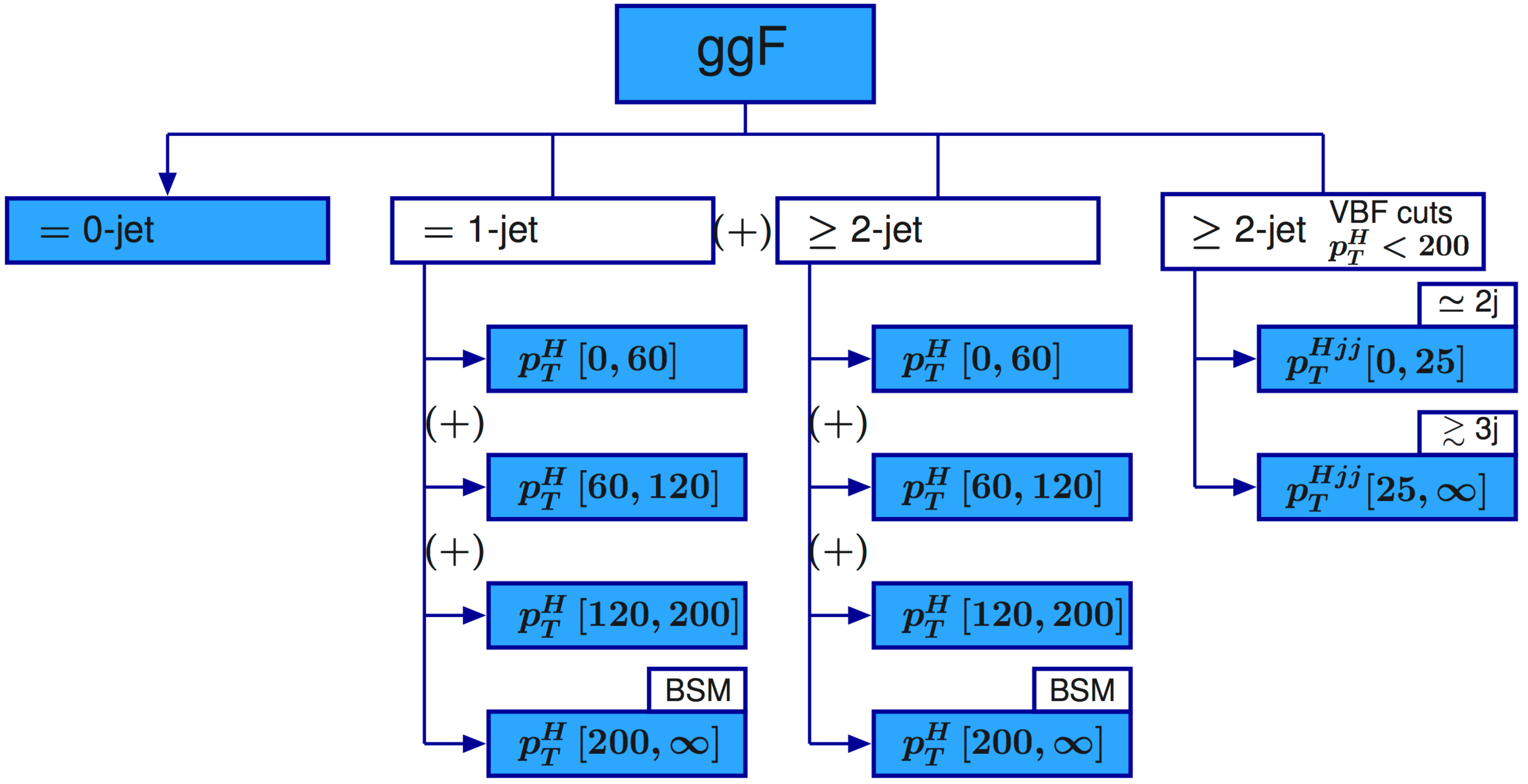
  - Treatment of out-of-fiducial corrections, presentation of results, ...

STXS framework



by Frank Tackmann

ggH binning (stage 1)

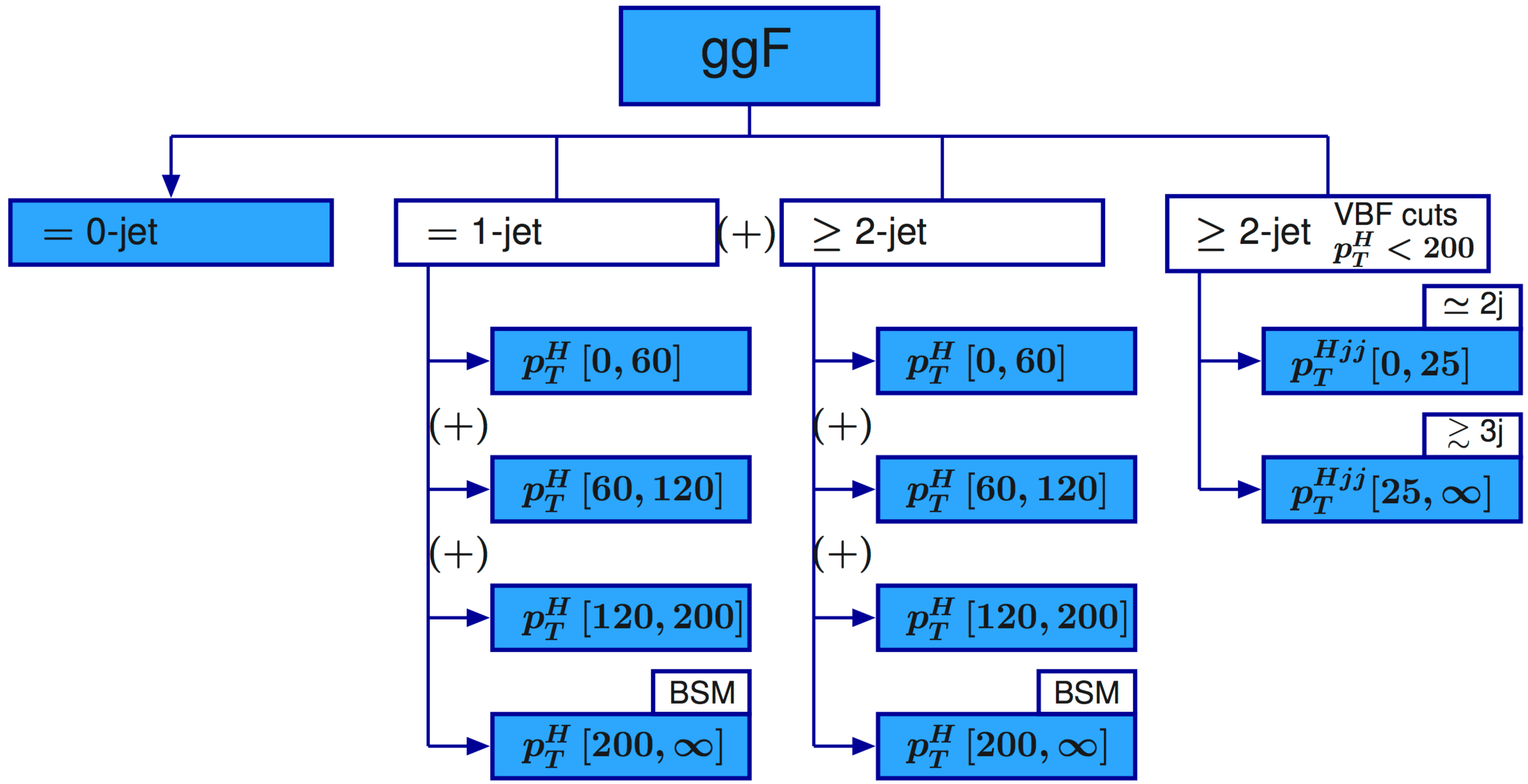


by Frank Tackmann

Initial choice of the binning:

- Jet bins motivated by experimental analyses
- High $p_T(H)$ bins target boosted categories (e.g. ττ, bb) and BSM overflow
- VBF-like cuts to constrain ggH contribution in VBF categories

ggH binning (stage 1)

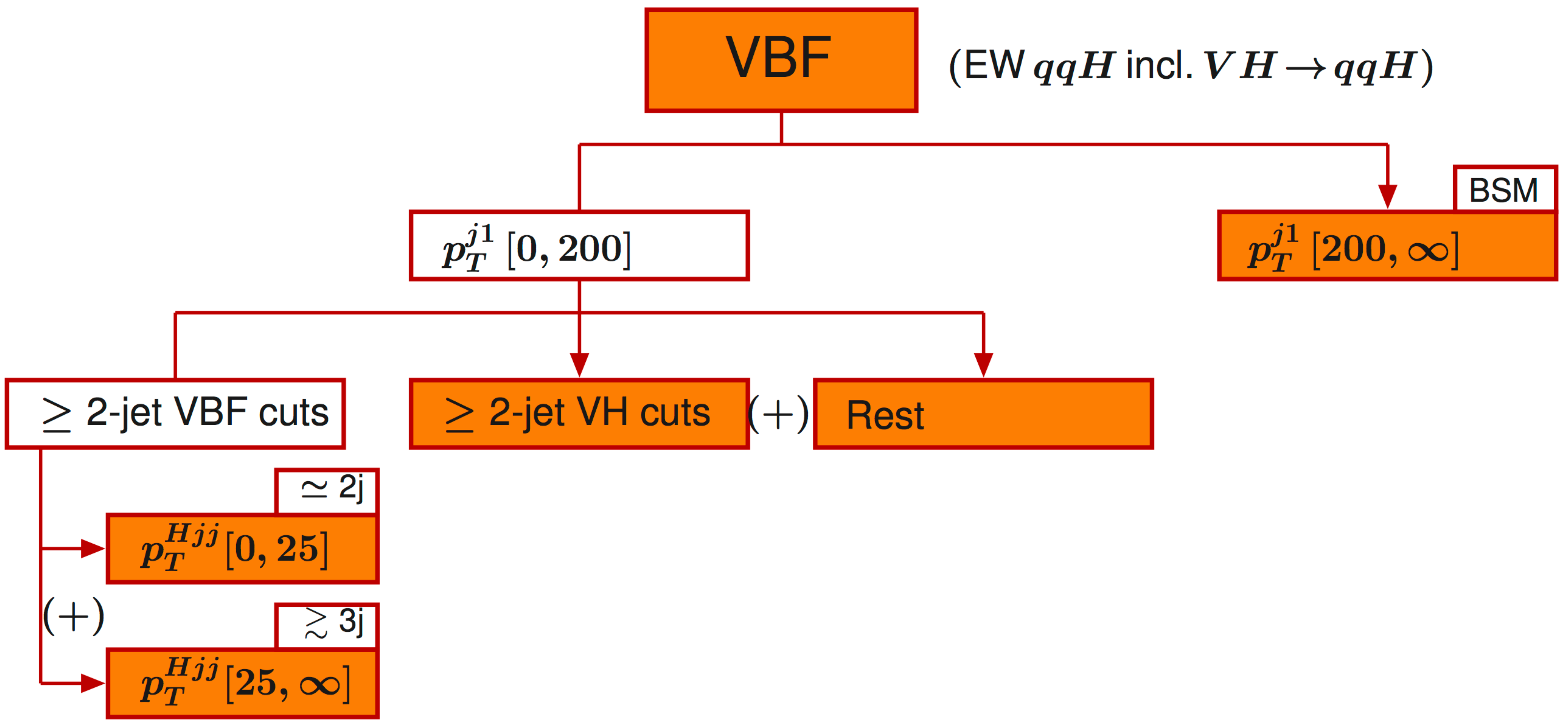


by Frank Tackmann

Proposed updates in the choice of the binning:

- Split highest $p_T(H)$ bins into [200, 500] and [500, ∞] to have a dedicated bin for boosted H → bb
- Also allow for possibly split at $2m_{top}$ into [200, 350] and [350, 500] GeV
- Thinking about options to further resolve low-p_T region
  - One option is to split the 0-jet bin into $p_T(H) \lesssim$ 10..20 GeV

VBF binning (stage 1)

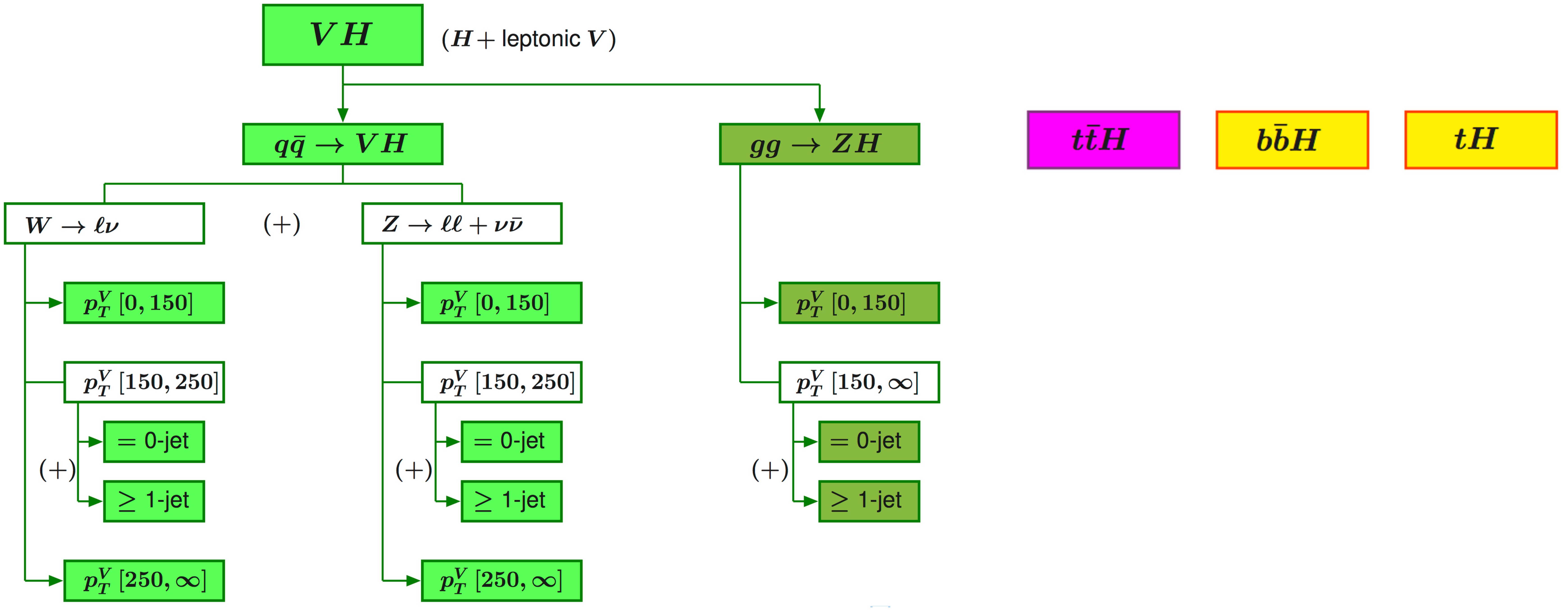


by Frank Tackmann

Choice of the binning:

- VBF defined as electroweak qqH production
  - including usual VBF process and VH with hadronic V decays
- First split by $p_T(j_1)$
  - **VBF topology cuts**: m_{jj} > 400 GeV and $\Delta\eta_{jj}$ > 2.8 (no other cuts)
  - **V (→ jj)H topology cuts**: 60 GeV < m_{jj} < 120 GeV
  - **Rest**: Everything not passing above (including events with < 2 jets)

VH / ttH / bbH / tH binning (stage 1)



VH binning:

by Frank Tackmann

- "VH" is defined as pp → V (→ leptons)H process
  - split into qq→ W (→ lν)H, qq→ Z(→ ll, νν)H, and gg → Z(→ ll, νν)H

ttH / tH binning:

- Consider splitting by p_T(H) into [0, 200] and [200, ∞], and by p_T(top) into [0, 300] and [300, ∞],
  - to separately target non-boosted and boosted H or top analyses

bbH binning:

- No experimental sensitivity/distinction from ggH, so merged with ggH

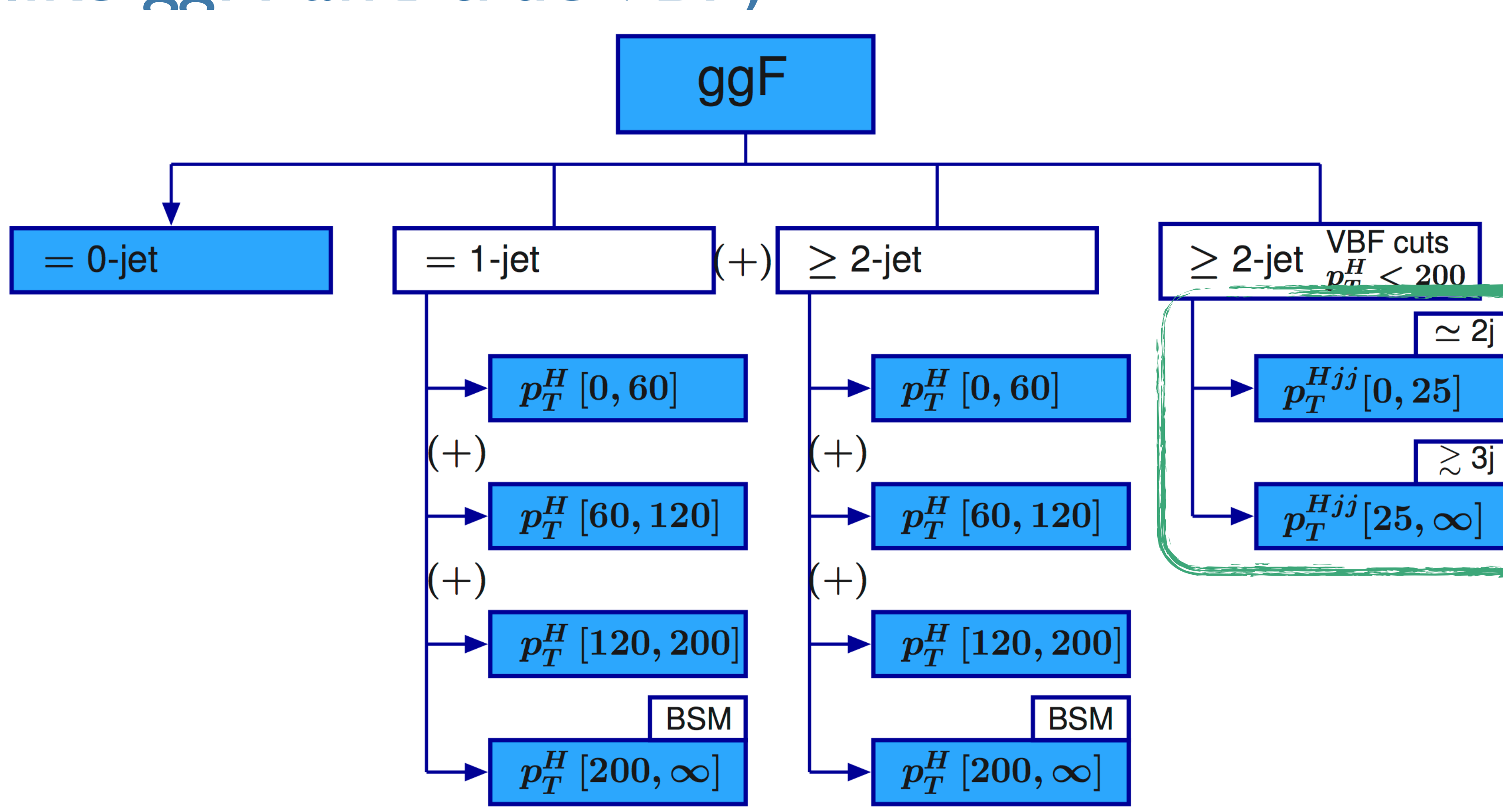
Binning and experimental challenges

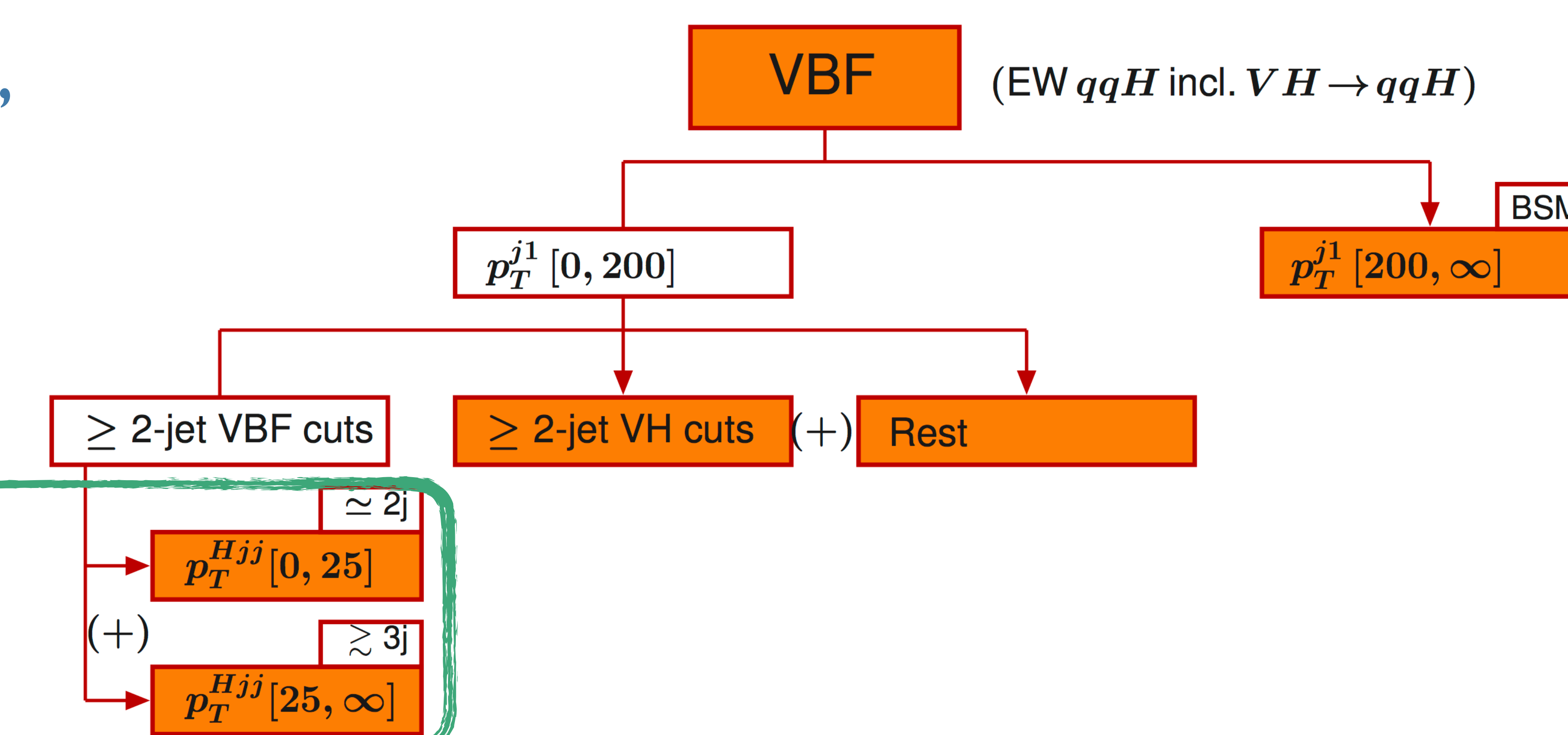
Defined different stages for each production mode :

- Stage 0: Closest correspondence to Run 1
- Stage 1: Considered "minimal" splitting for Run 2 (more coarse scenario for early measurements)
- …

Bin merging at early Run-2 measurements:

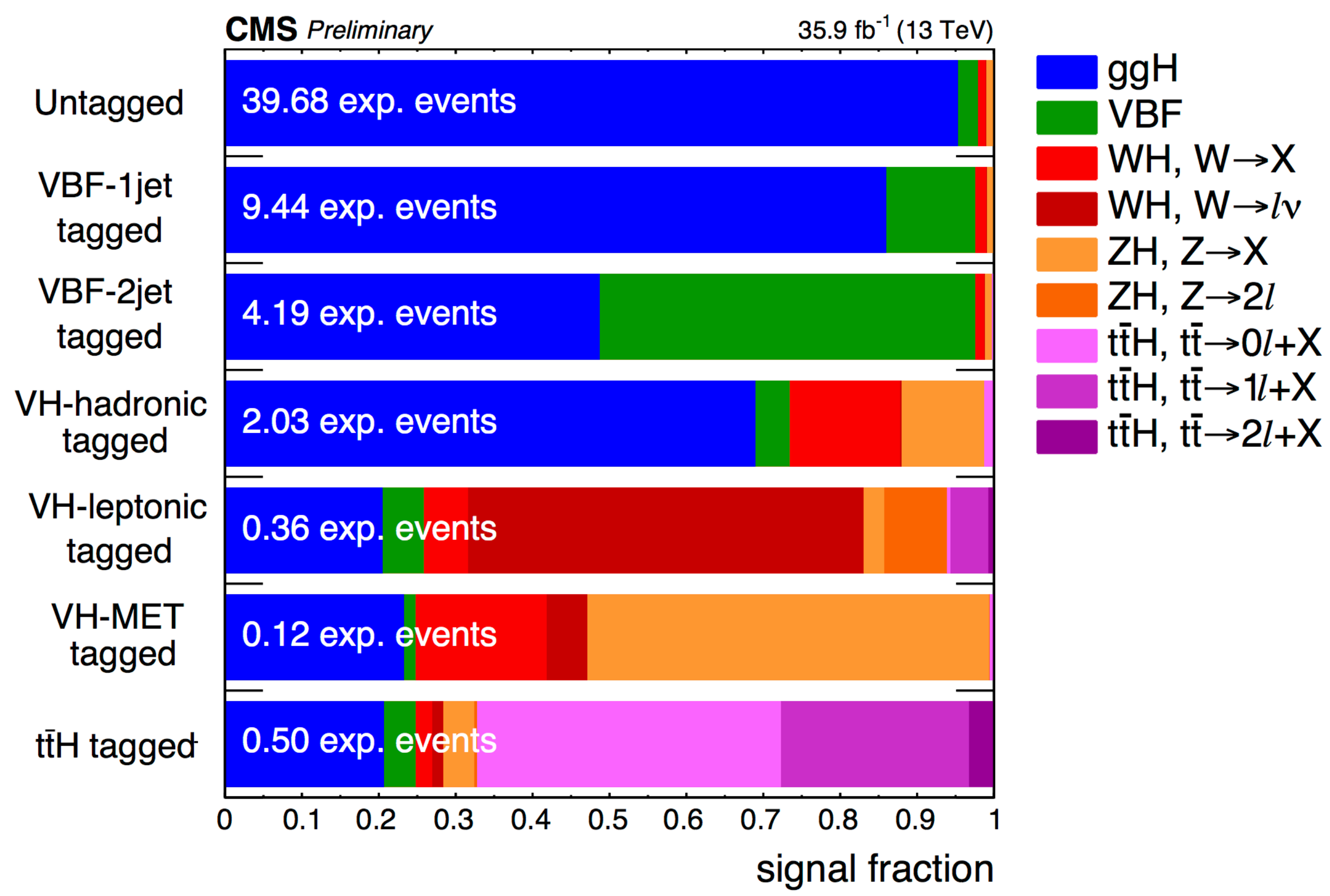
- Truth bins with no sensitivity from experimental measurement
  (e.g. no matching experimental selection or not (yet) enough statistics)
- Heavily correlated
  (any bins that can not be disentangled from measurement,
  e.g. VBF-like ggH and true VBF)

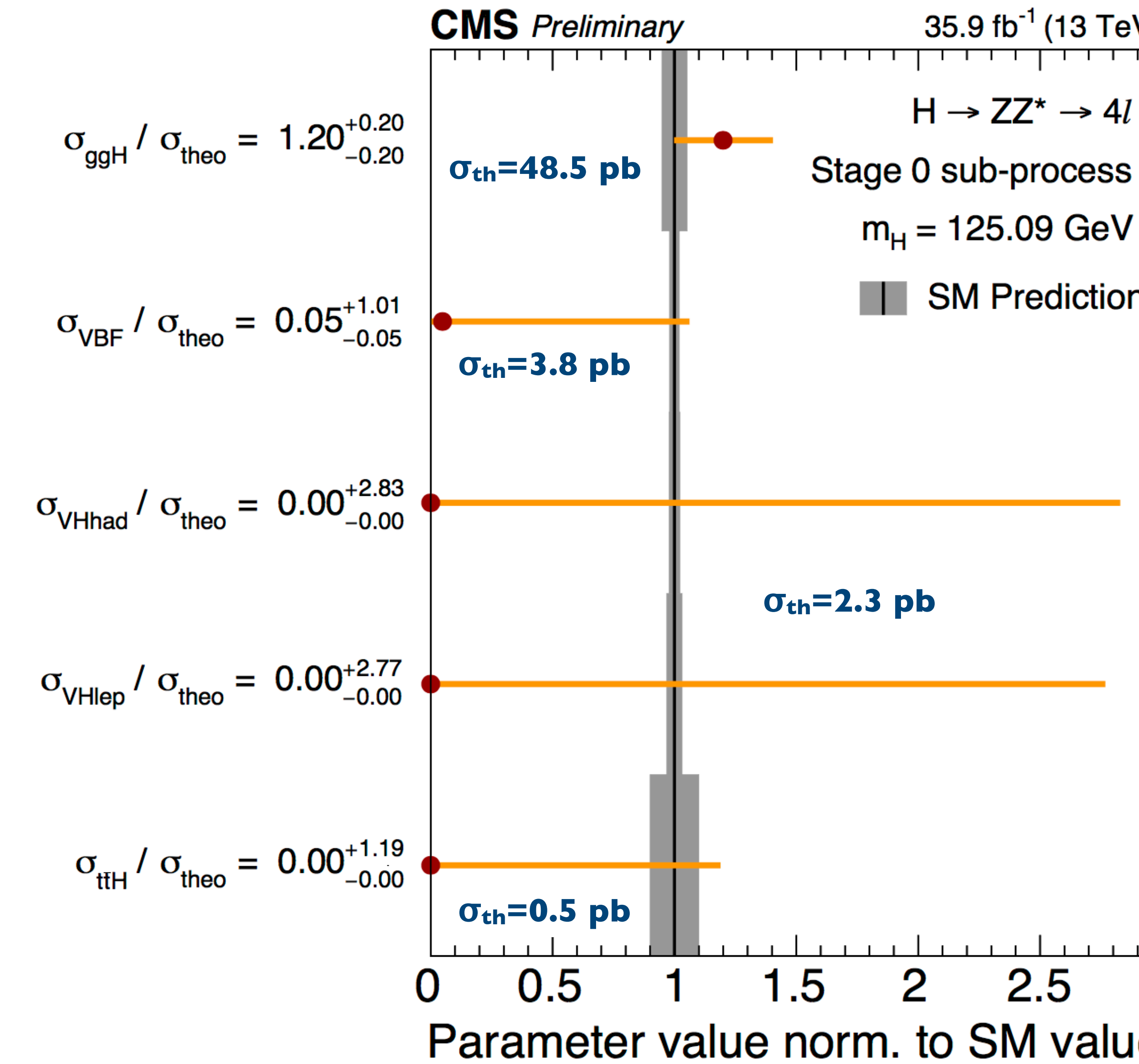




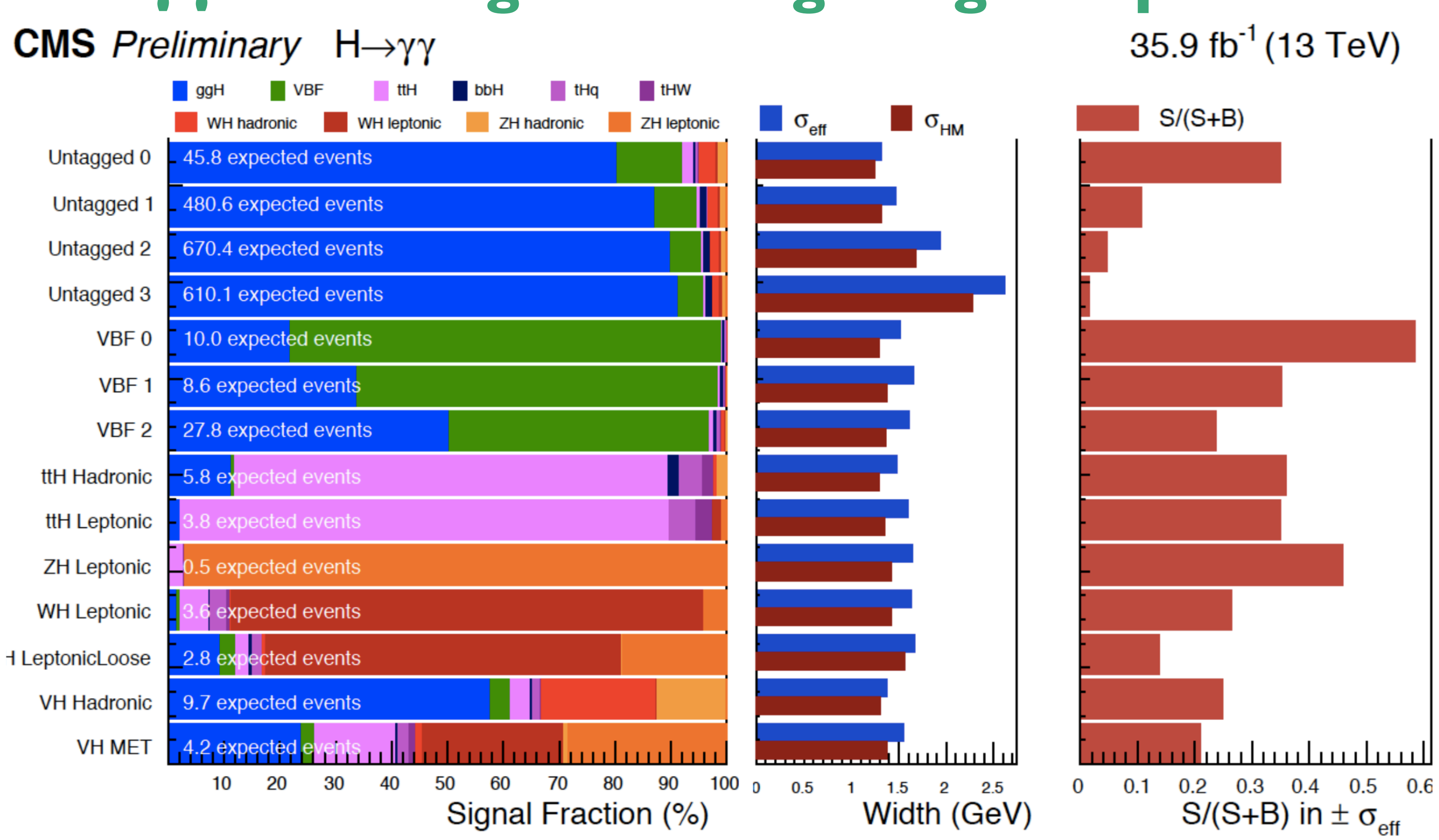
Early Run-2 results (stage 0): H → γγ and H → 4l

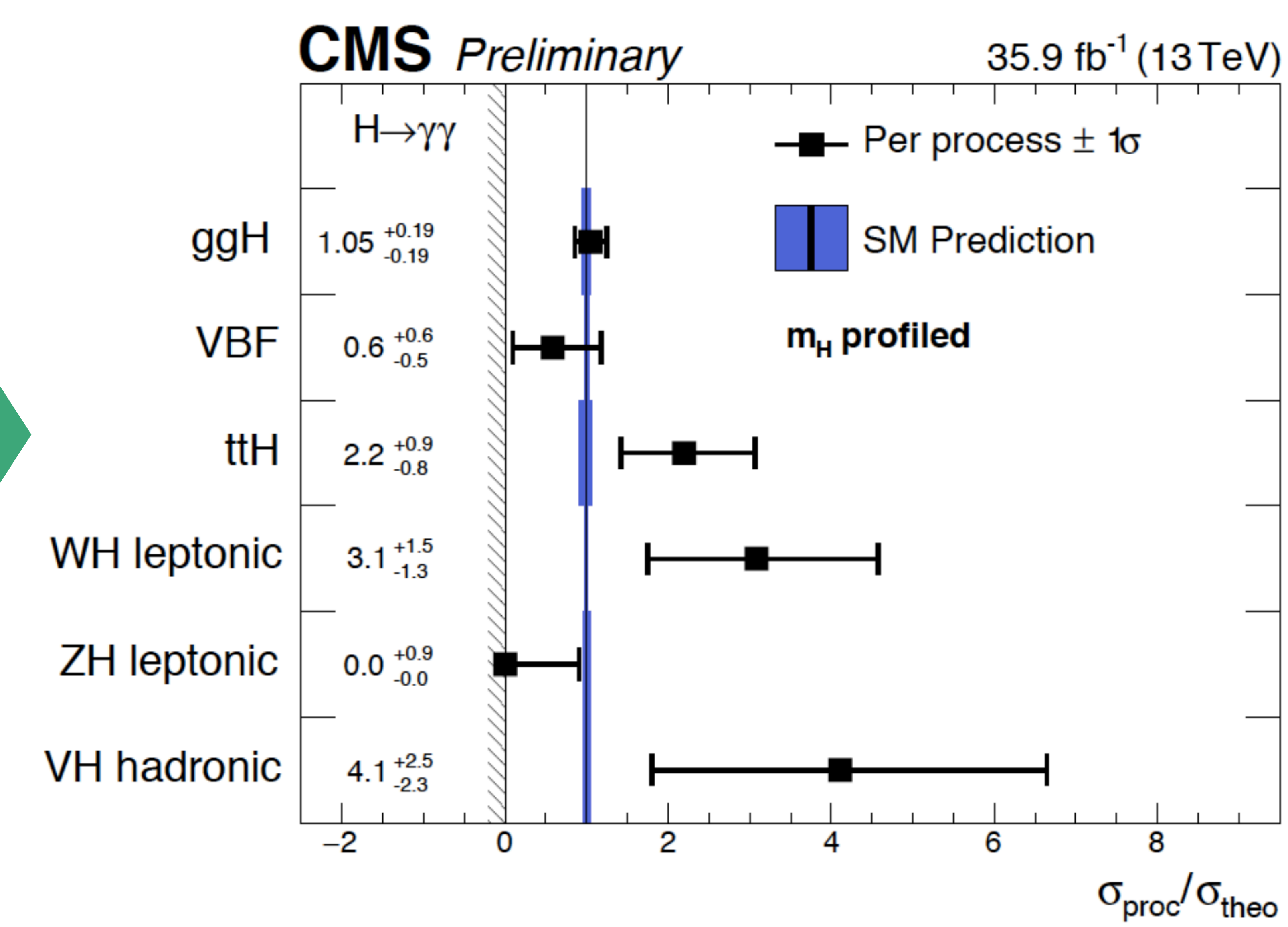
H→4l: 7 categories targeting 5 prod. modes:





H→γγ: 14 categories targeting 5/6 prod. modes:





Early Run-2 results (stage 1) : H → γγ

Kinematic regions for stage-1 + intermediate merging:

ATLAS

Process	Measurement region	Stage 1 region
ggH + $gg \to Z(\to qq)H$	0-jet	0-jet
	1-jet, $p_T^H < 60\,GeV$	1-jet, $p_T^H < 60\,GeV$
	1-jet, $60 \leq p_T^H < 120\,GeV$	1-jet, $60 \leq p_T^H < 120\,GeV$
	1-jet, $120 \leq p_T^H < 200\,GeV$	1-jet, $120 \leq p_T^H < 200\,GeV$
	$\geq$ 1-jet, $p_T^H > 200\,GeV$	1-jet, $p_T^H > 200\,GeV$
		$\geq$ 2-jet, $p_T^H > 200\,GeV$
	$\geq$ 2-jet, $p_T^H < 200\,GeV$ or VBF-like	$\geq$ 2-jet, $p_T^H < 60\,GeV$
		$\geq$ 2-jet, $60 \leq p_T^H < 120\,GeV$
		$\geq$ 2-jet, $120 \leq p_T^H < 200\,GeV$
		VBF-like, $p_T^{Hjj} < 25\,GeV$
		VBF-like, $p_T^{Hjj} > 25\,GeV$
$qq' \to Hqq'$ (VBF + VH)	$p_T^j < 200\,GeV$	$p_T^j < 200\,GeV$, VBF-like, $p_T^{Hjj} < 25\,GeV$
		$p_T^j < 200\,GeV$, VBF-like, $p_T^{Hjj} \geq 25\,GeV$
		$p_T^j < 200\,GeV$, VH-like
		$p_T^j < 200\,GeV$, Rest
	$p_T^j > 200\,GeV$	$p_T^j > 200\,GeV$
VH (leptonic decays)	VH leptonic	$q\bar{q} \to ZH$, $p_T^Z < 150\ GeV$
		$q\bar{q} \to ZH$, $150\ GeV < p_T^Z < 250\ GeV$, 0-jet
		$q\bar{q} \to ZH$, $150\ GeV < p_T^Z < 250\ GeV$, $\geq$ 1-jet
		$q\bar{q} \to ZH$, $p_T^Z > 250\ GeV$
		$q\bar{q} \to WH$, $p_T^W < 150\ GeV$
		$q\bar{q} \to WH$, $150\ GeV < p_T^W < 250\ GeV$, 0-jet
		$q\bar{q} \to WH$, $150\ GeV < p_T^W < 250\ GeV$, $\geq$ 1-jet
		$q\bar{q} \to WH$, $p_T^W > 250\ GeV$
		$gg \to ZH$, $p_T^Z < 150\ GeV$
		$gg \to ZH$, $p_T^Z > 150\ GeV$, 0-jet
		$gg \to ZH$, $p_T^Z > 150\ GeV$, $\geq$ 1-jet
top-associated production	top	$t\bar{t}H$
		tHW
		$tHqb$
$b\bar{b}H$	merged w/ ggH	$b\bar{b}H$

Group together the BSM bins
- Not enough stats for ggH 1 vs. 2 jets
- No ggH/VBF discrimination

Group together ggH 2-jet bins
- Not enough stats for for $p_T(H)$ splits
- VBF-like ambiguous with real VBF

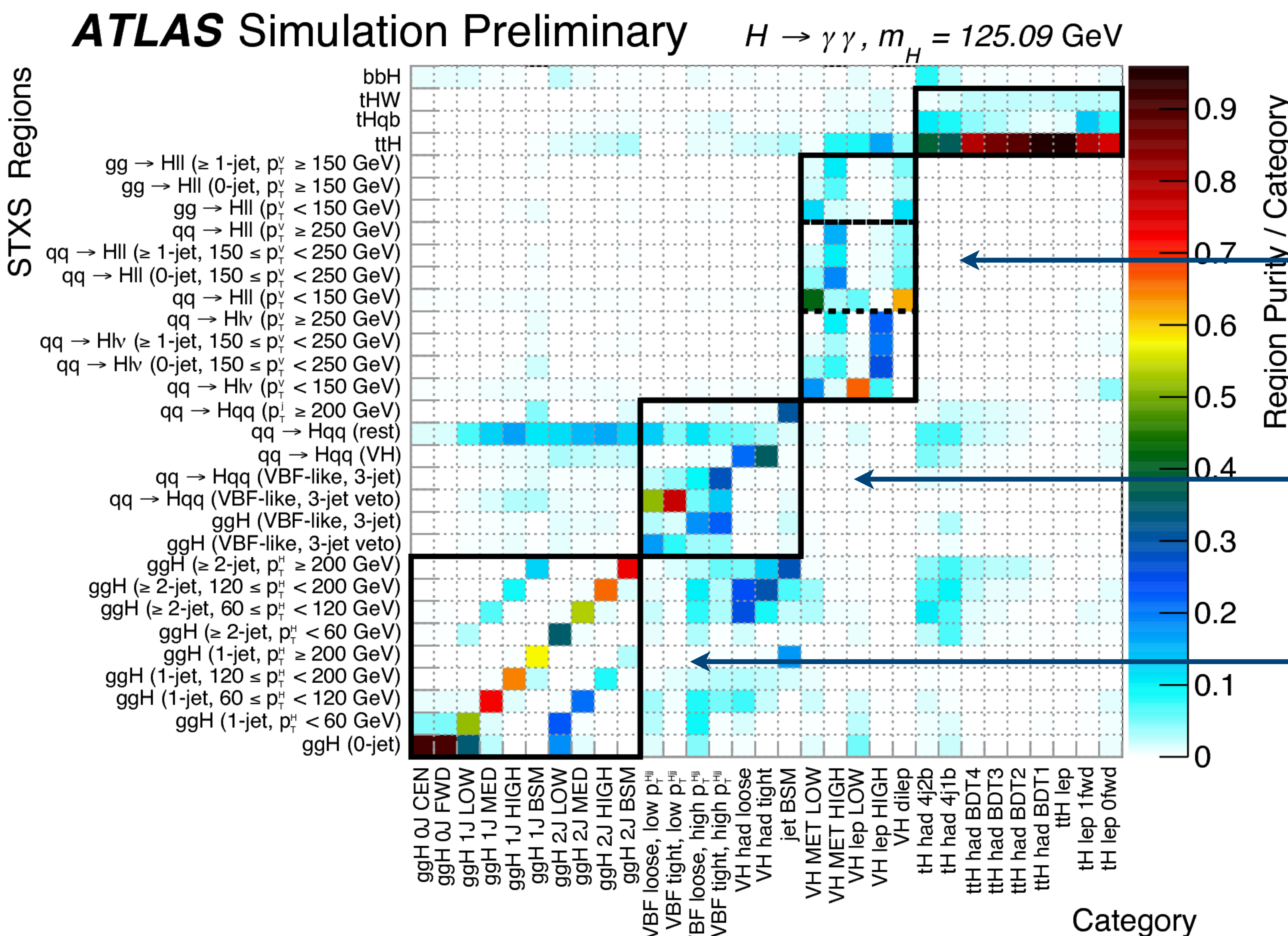
Group together VBF bins
- Group "VBF_REST" and "VH2JET" with better- measured VBF-like bins

Group together VH-lep bins
- Not enough stats for $p_T(V)$, N(jets) splits

Group tH with ttH
Group bbH with ggH

Early Run-2 results (stage 1) : H → γγ

Signal fraction in reco. categories, originating from given stage-1 bins:



bbH, ttH, tH

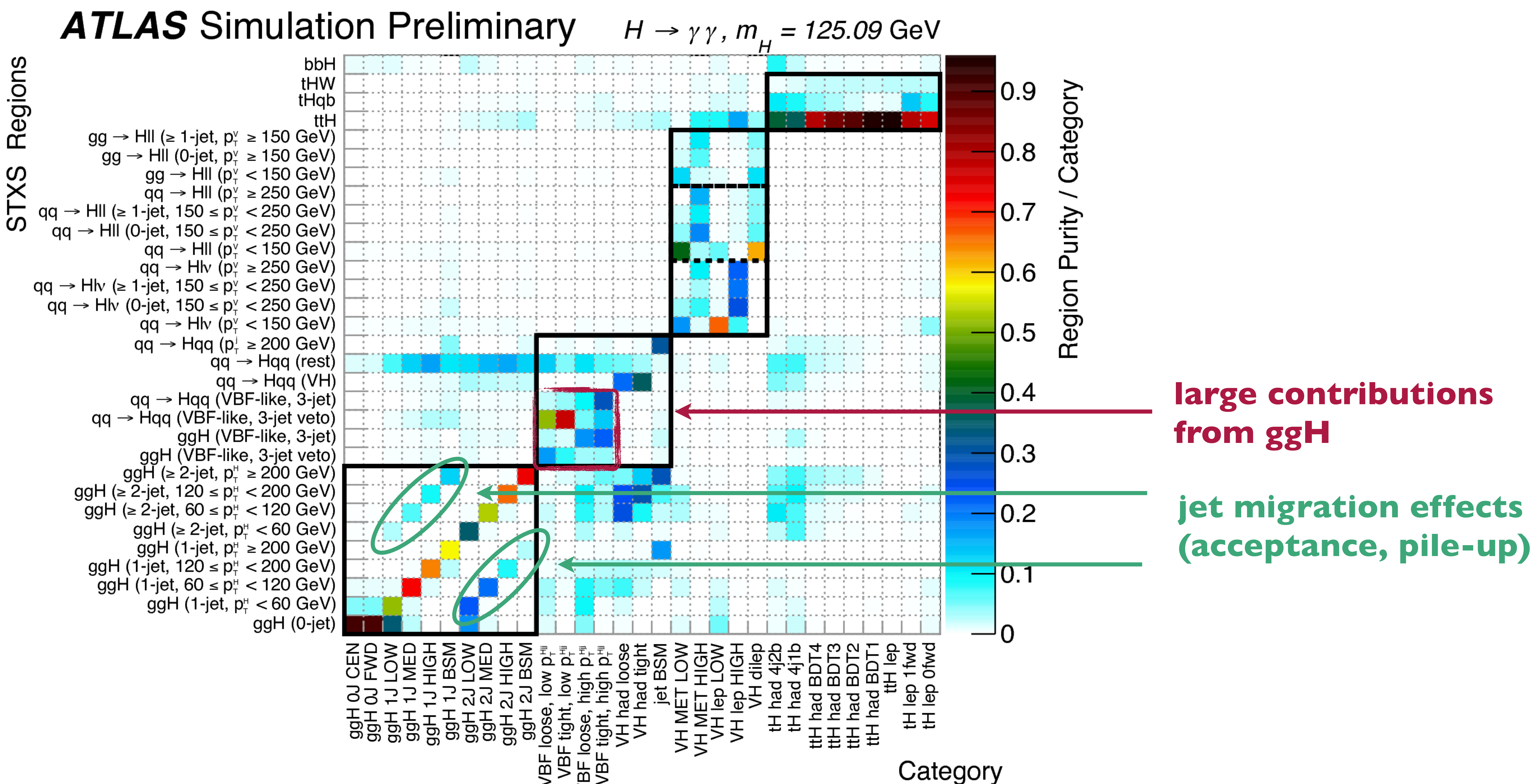
VH leptonic (WH, ZH)

VBF + VH hadronic

untagged (ggH dominated)

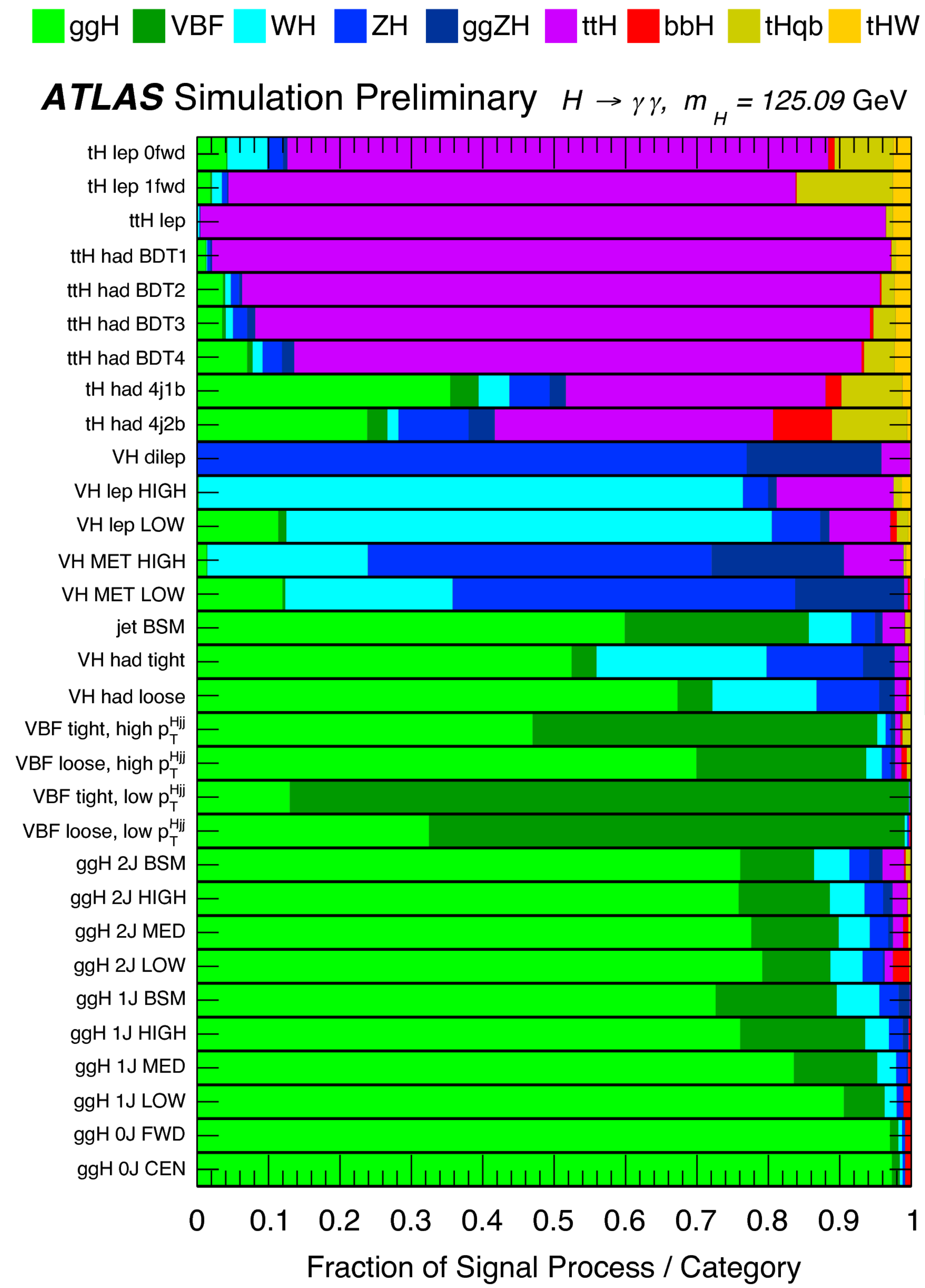
Early Run-2 results (stage 1) : H → γγ

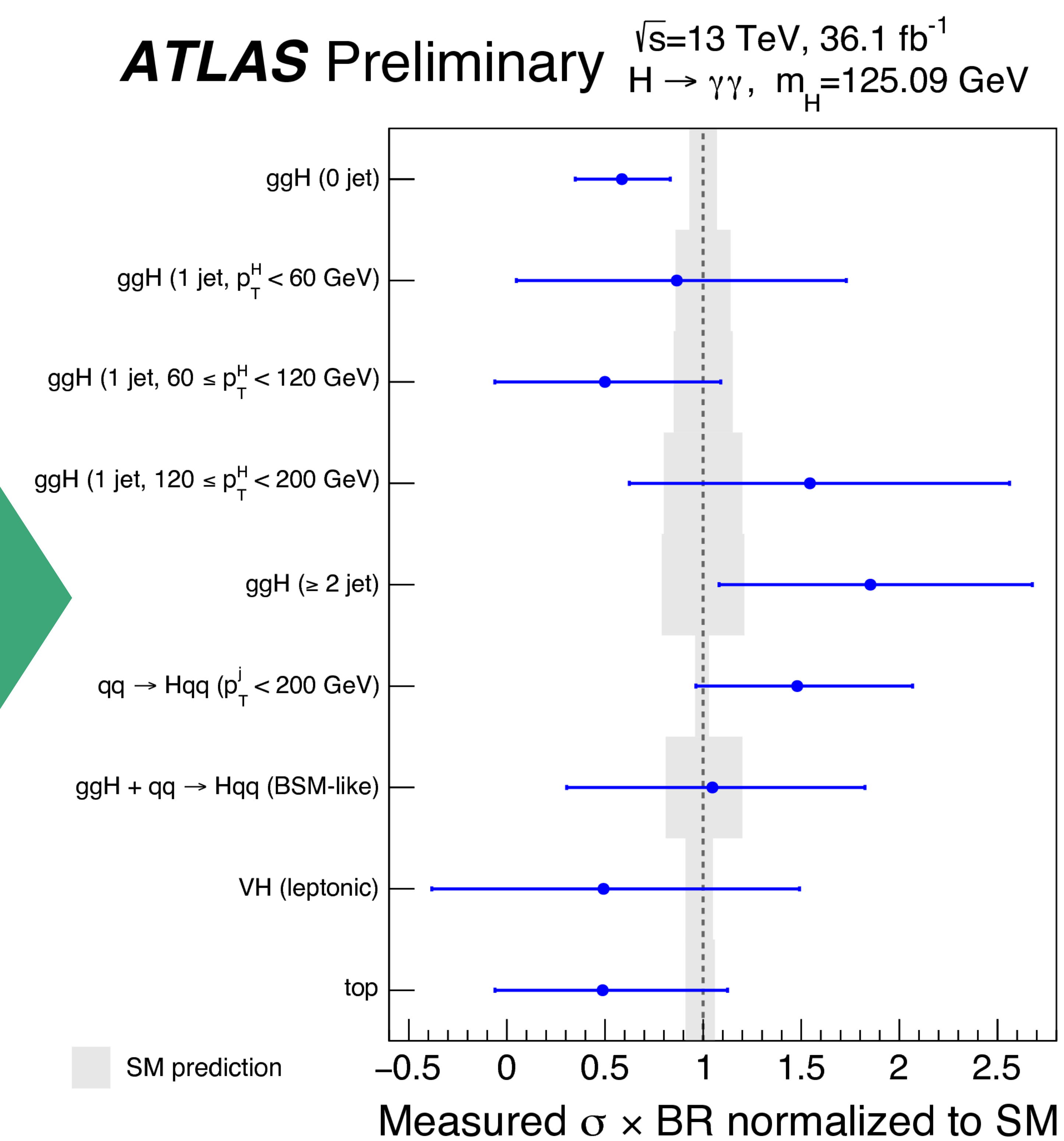
Signal fraction in reco. categories, originating from given stage-1 bins:

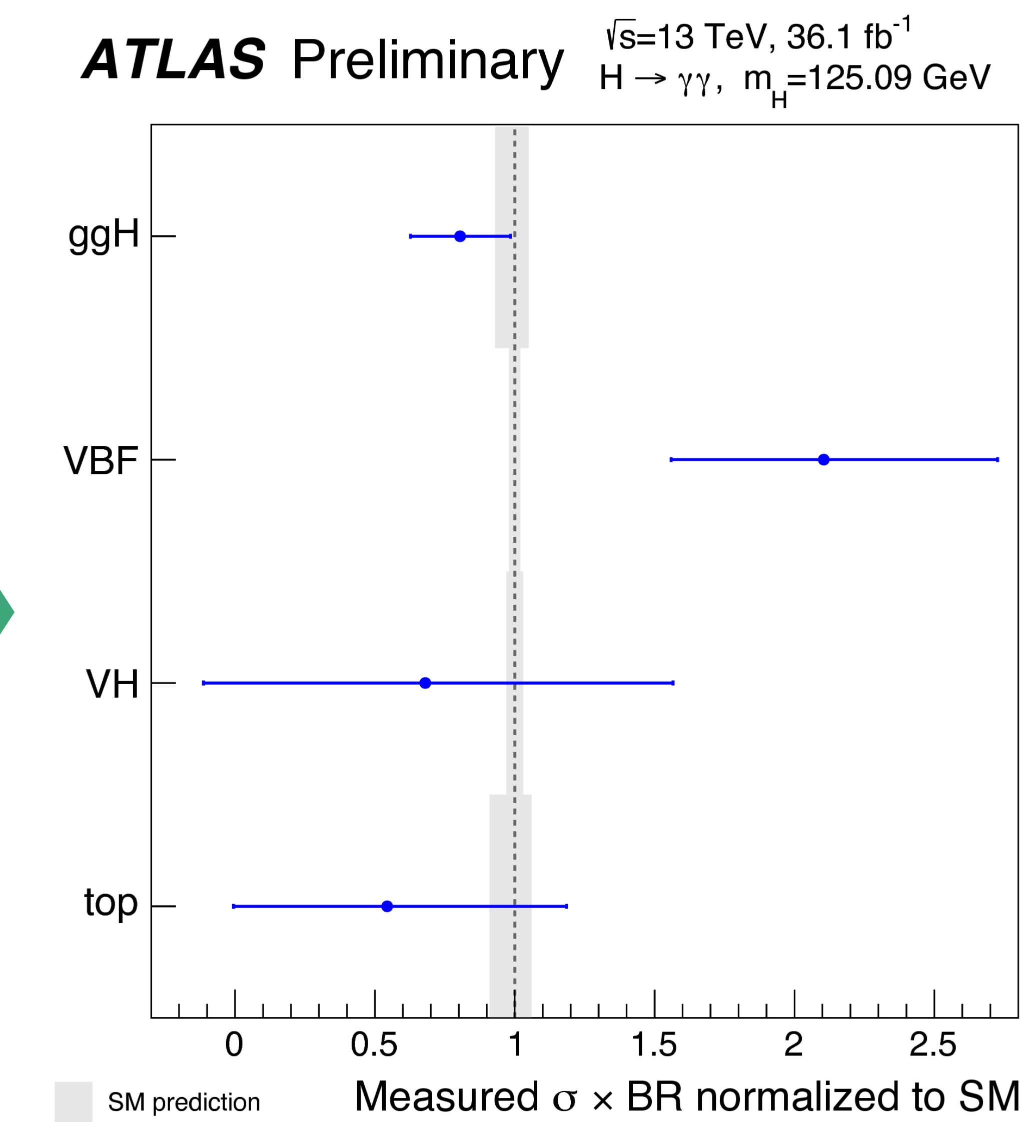


Early Run-2 results (stage 1) : H → γγ

H→γγ: 31 category targeting 9 stage-1 bins:



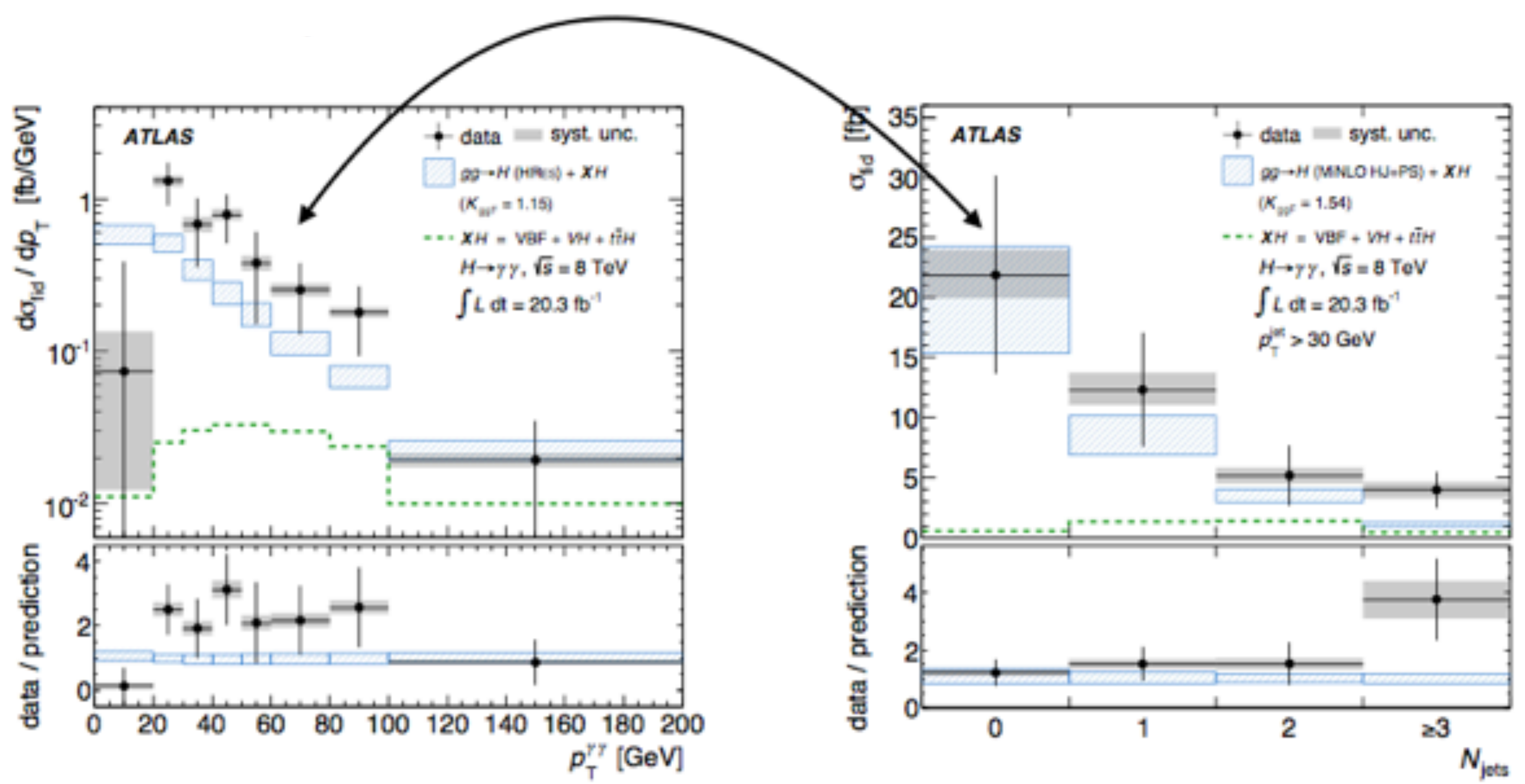




Going beyond:
Exploiting the cross section measurements…

Exploiting differential XS: First examples...

- A combined analysis of several fiducial observables offers a unique probe to constrain NP effects
  - Complementary and more model independent to the simplified template XS (limited to a subset of channels)
  - Requires theory predictions which match the experimental sensitivity and determination of **statistical correlations between observables**.



- Exploiting several distributions with individually modest sensitivity can lead to stronger limits
- Consider also double-differential distributions

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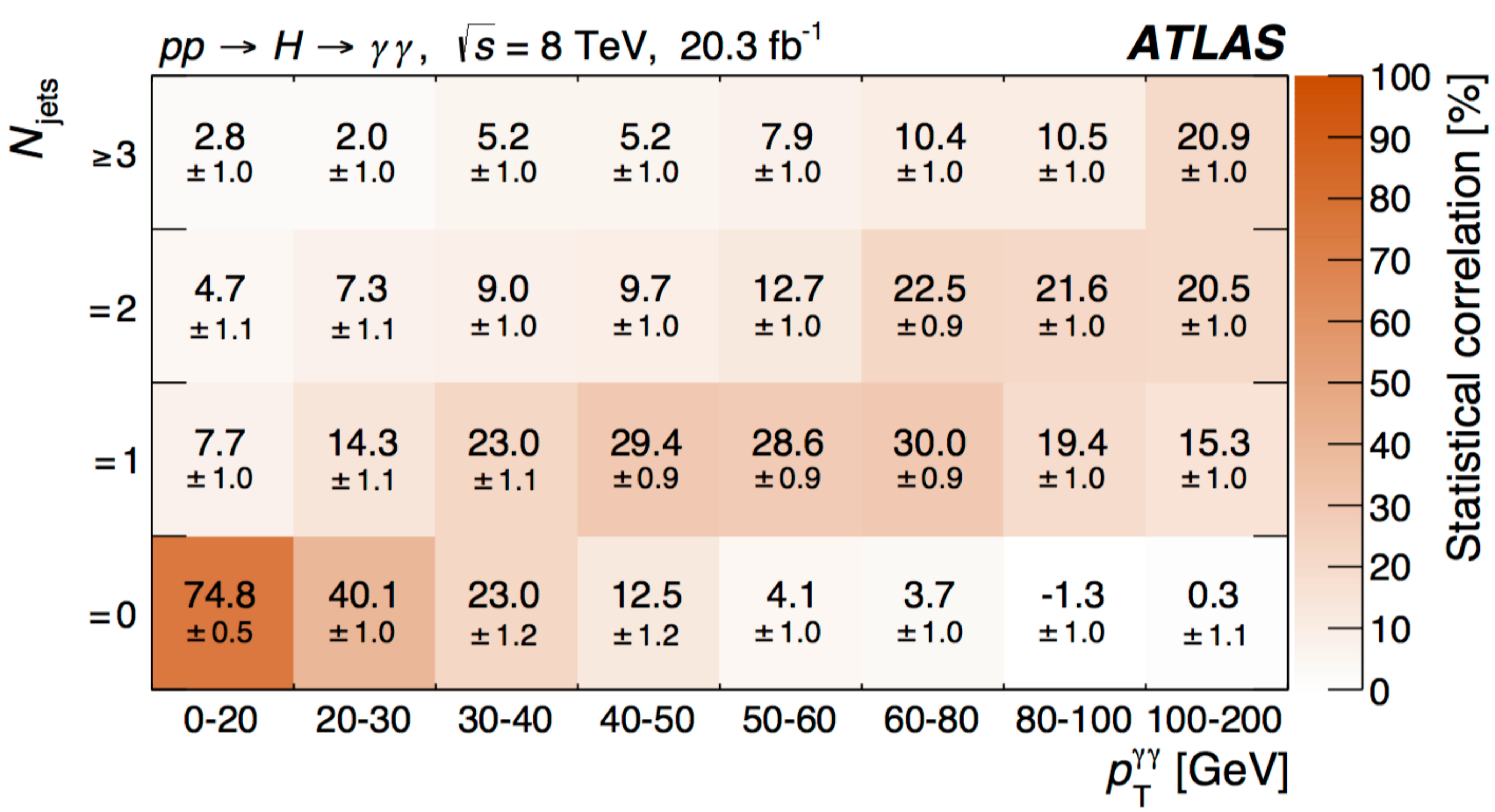
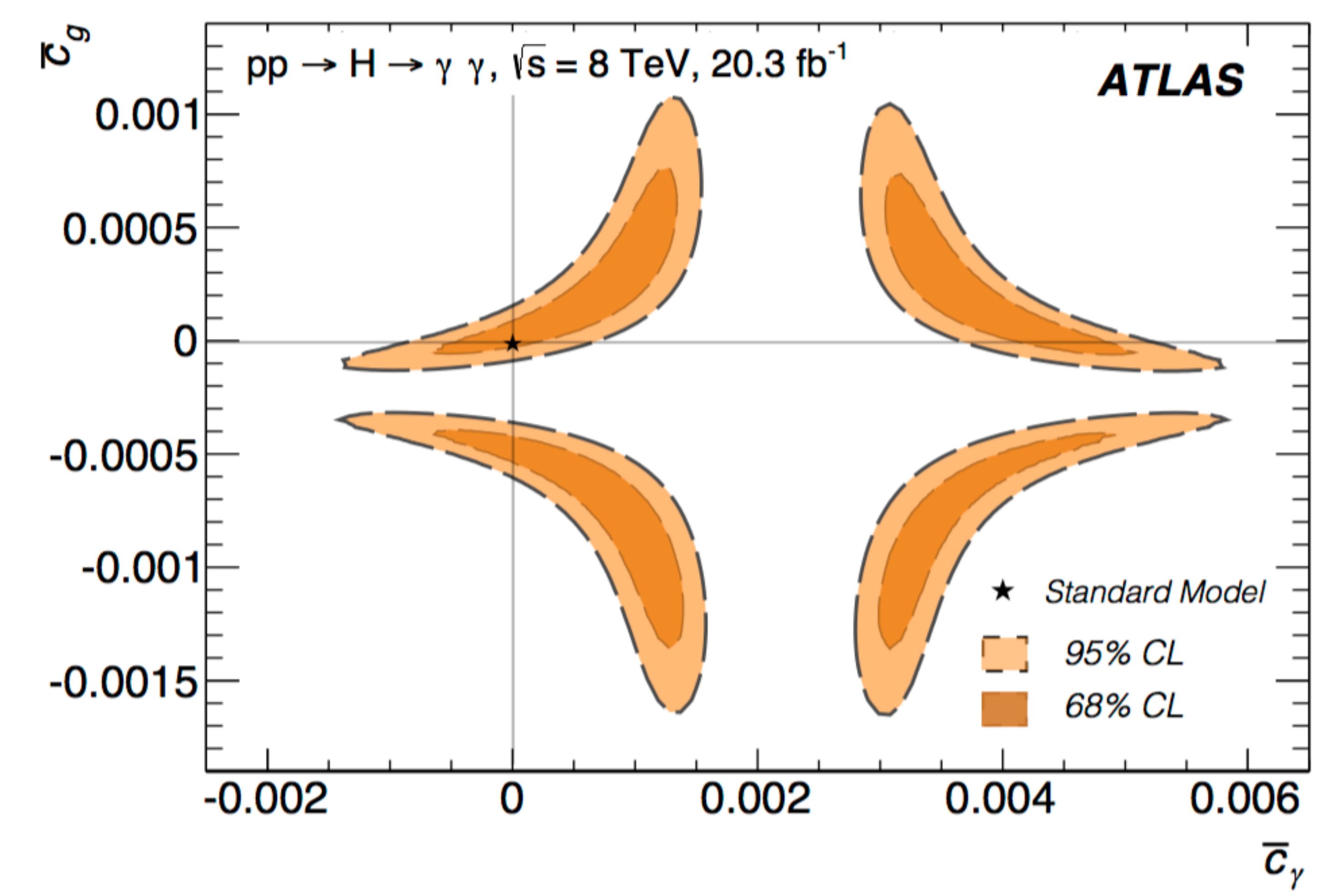
Example: limits on sub-set of Willson's coefficients





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- Consider also double-differential distributions

Exploiting differential XS: First examples…

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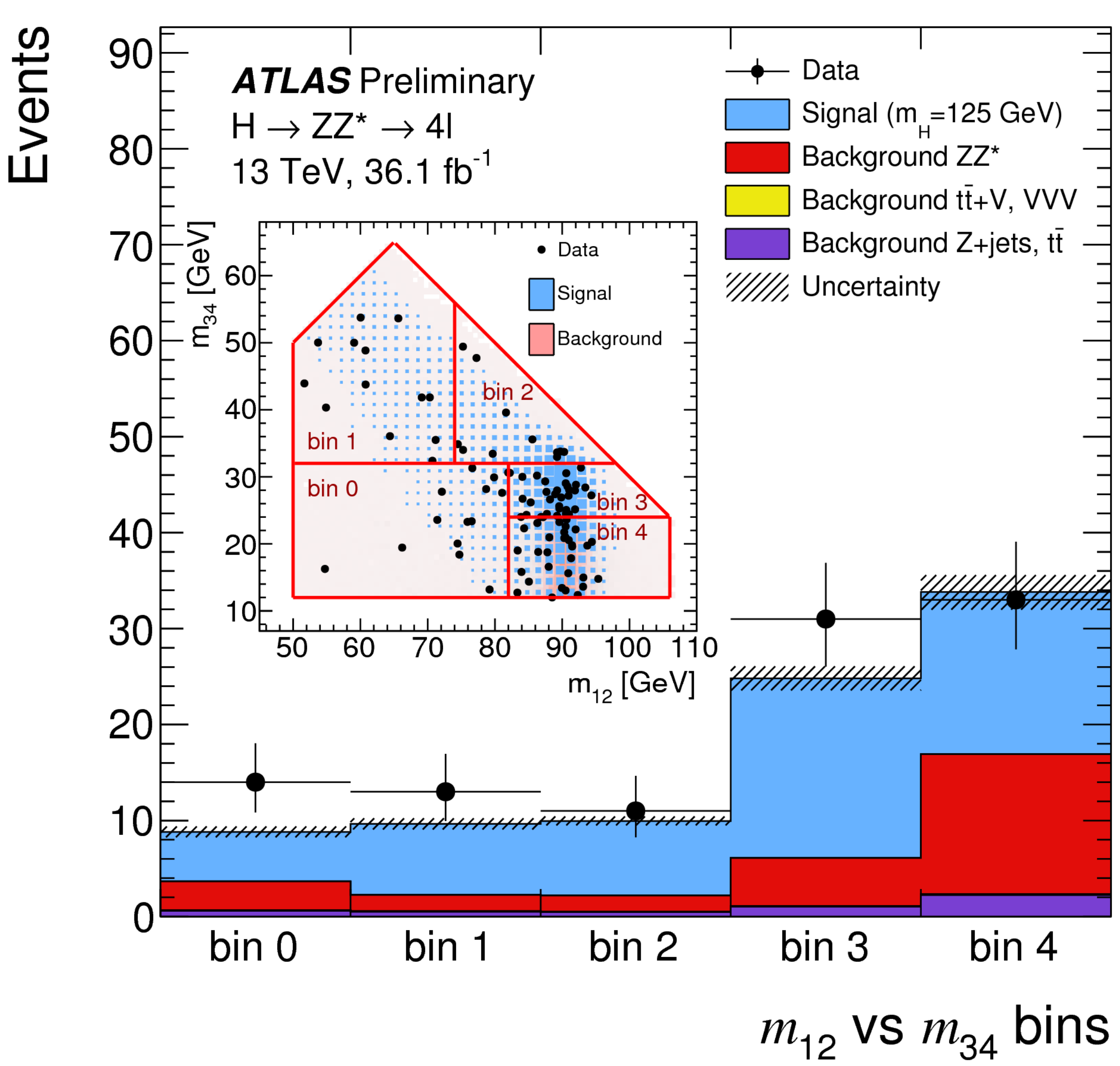
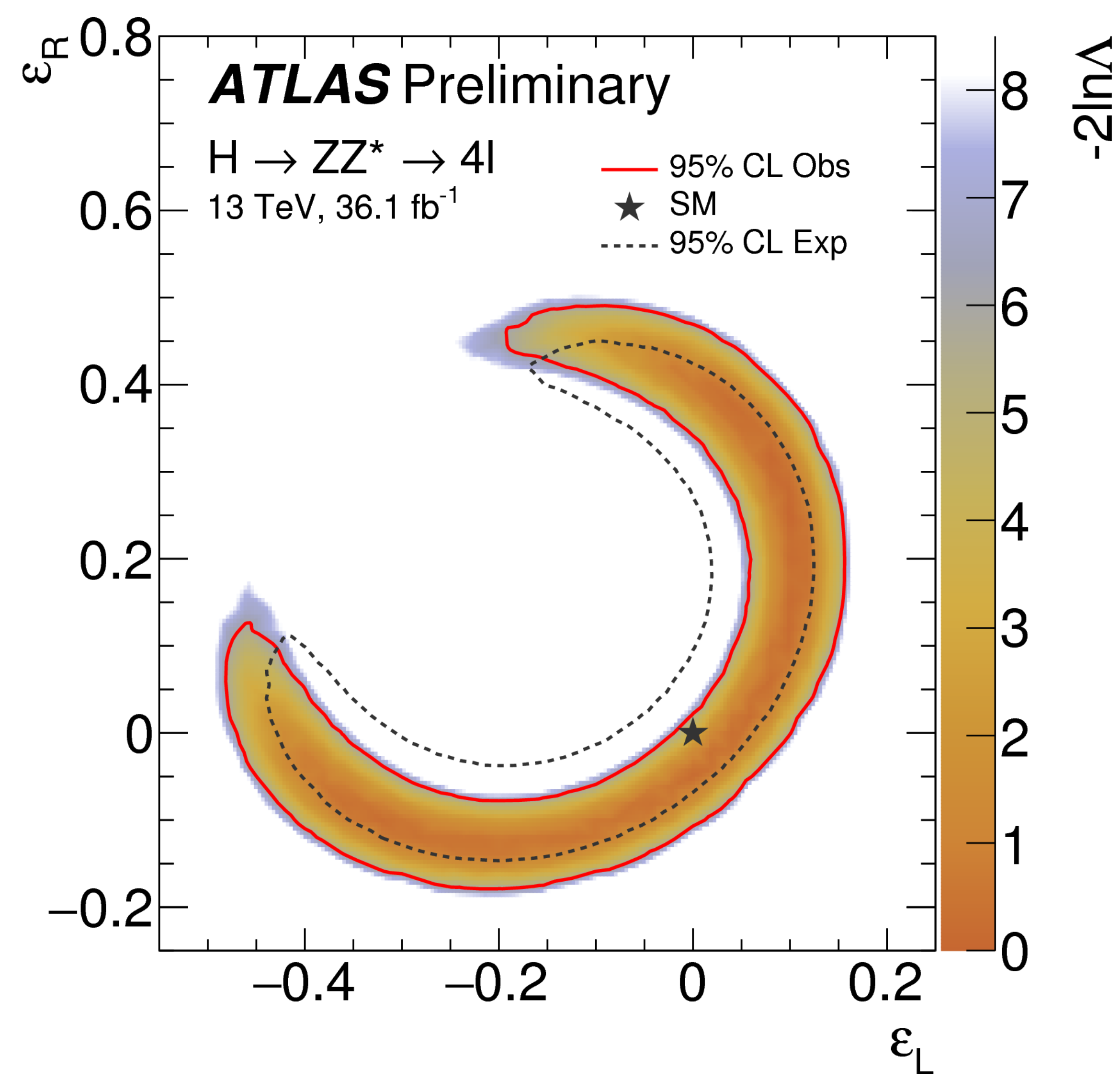
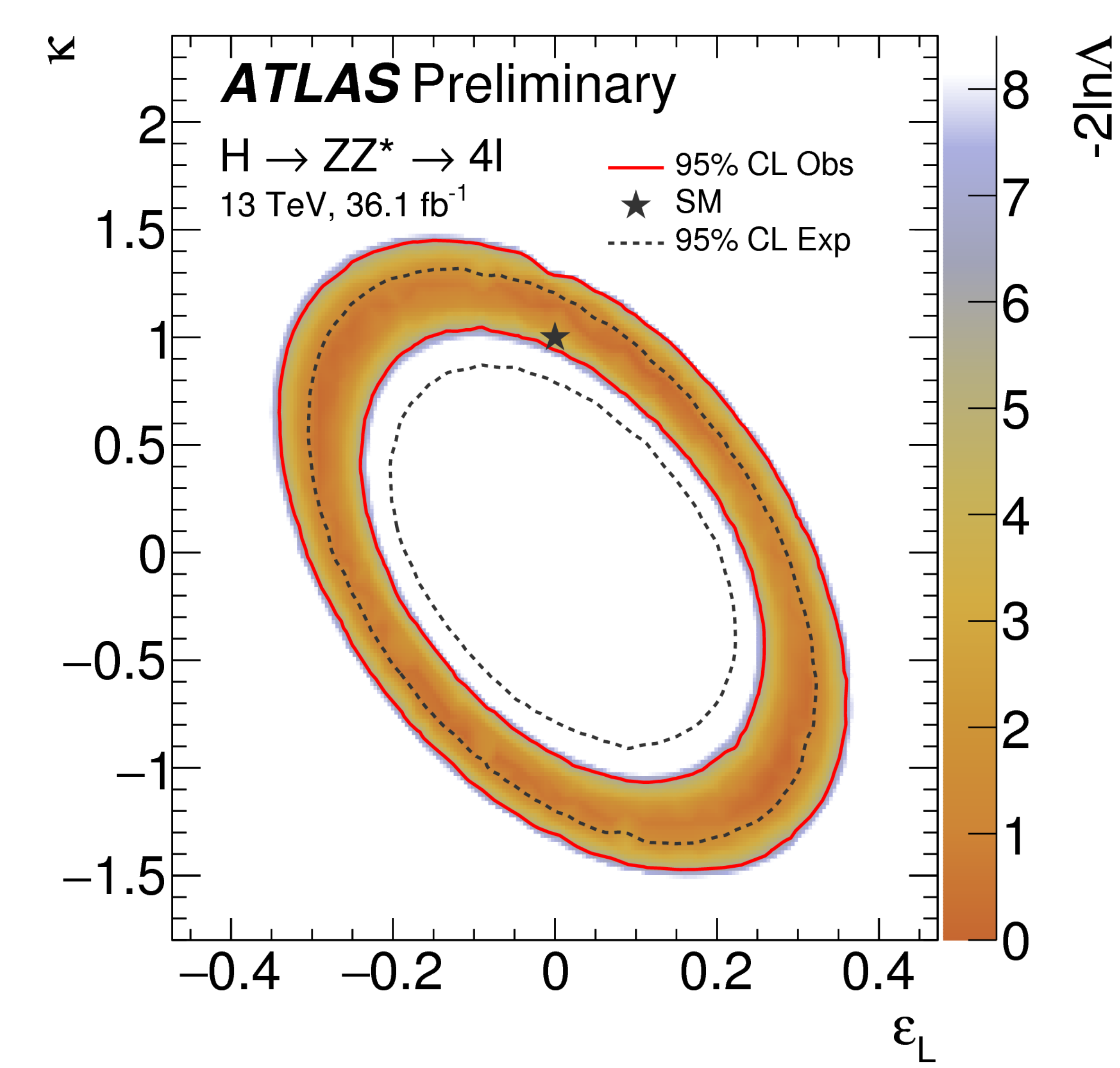
Example: limits on pseudo-observables







- Exploiting several distributions with individually modest sensitivity can lead to stronger limits
- Consider also double-differential distributions

Towards (more complete) BSM/EFT interpretations

Higgs & NP effects:

- New particles and/or new production modes → change of kinematics of H(125)
- May be tested via measured Fid/Diff. and also ST cross sections
  (internally by experiment, or externally by TH colleagues)

➡ **Need to facilitate BSM/EFT tests based on ST/Fid/Diff XS measurements**

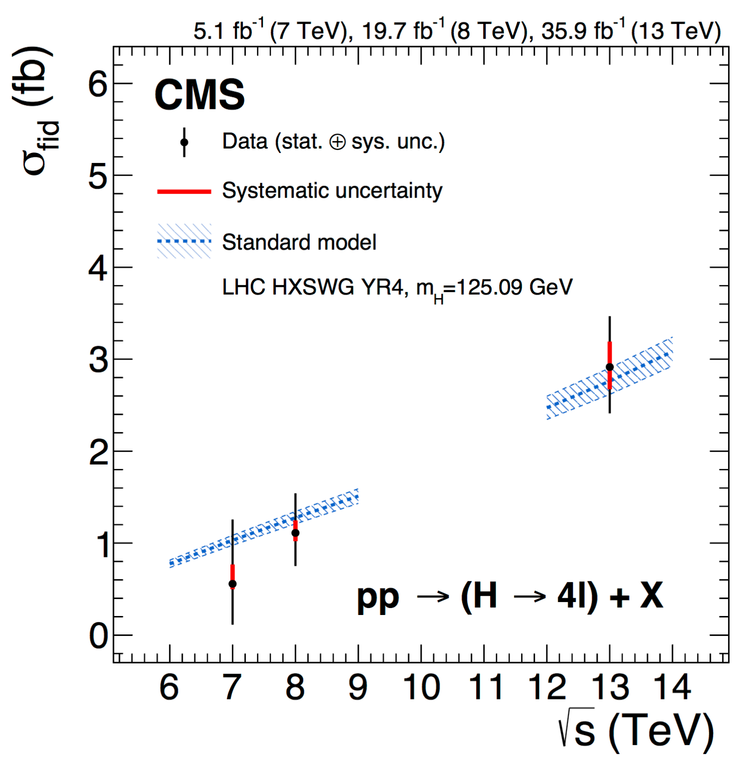
General tasks:

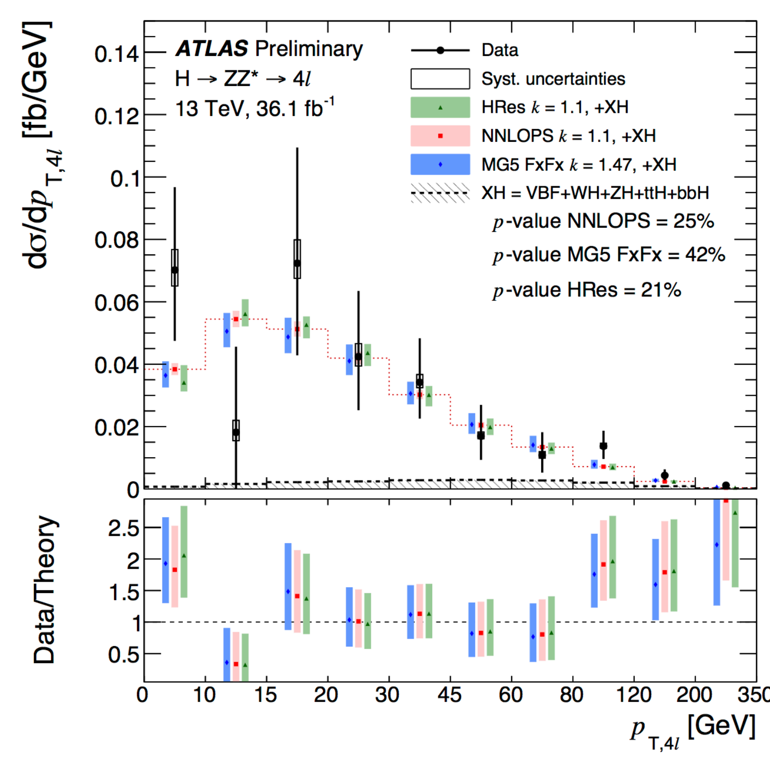
- **Fid/Diff XS:** Study **sensitive observables** and agree on required info/measurements to be published
  (minimal set of 1D and 2D observables, their correlations, etc.)
- **ST XS:** Include bins with decay-level information.
- **ST XS:** Compare **direct reach to EFT** (via dedicated analyses with e.g. BDT/ME discriminants)
  with interpretation via ST/Fid/Diff XS measurements.
- **Fid/Diff/ST XS:** **Provide tools** (e.g. Rivet?) and agree on **how to provide exp. results externally**
- Determine a limited number of **interpretation frameworks** to complement ST/Fid/Diff. XS analyses
  (agree on the common benchmark BSM/EFT, to be used internally/externally)

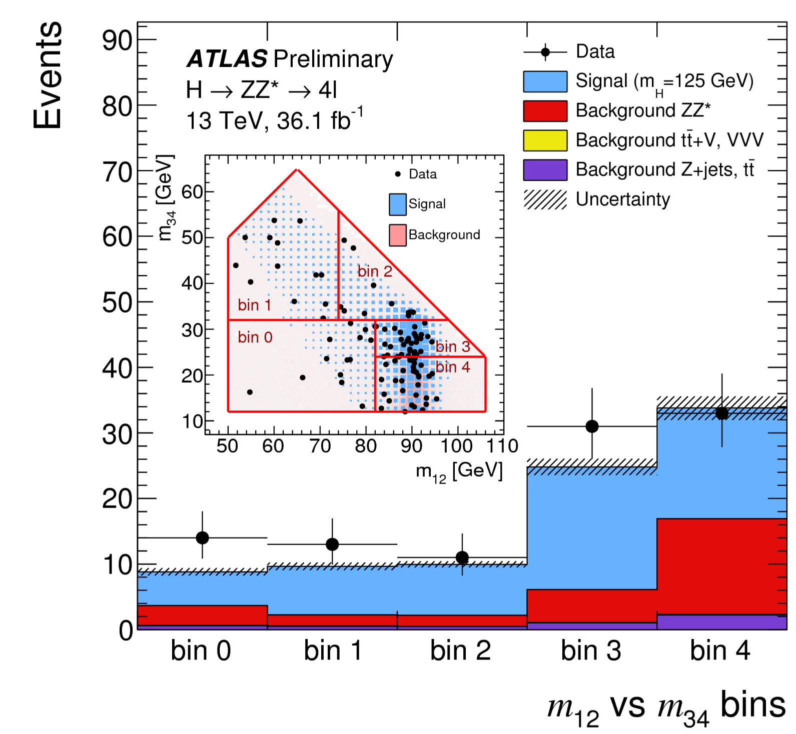
Next steps…

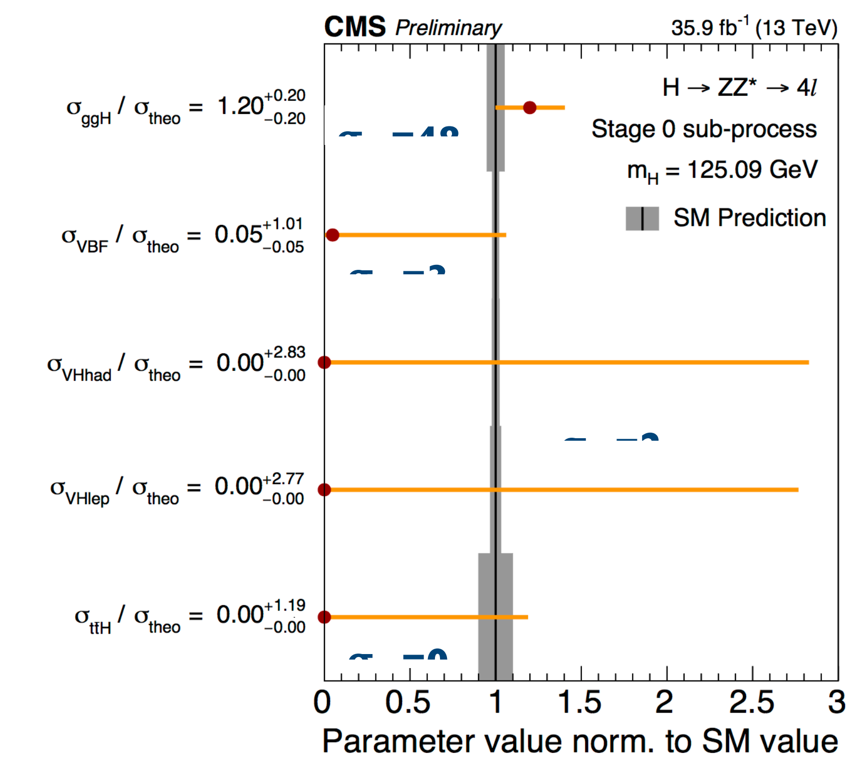
Understanding of the true nature of Higgs boson is one of the central subjects in the particles physics today

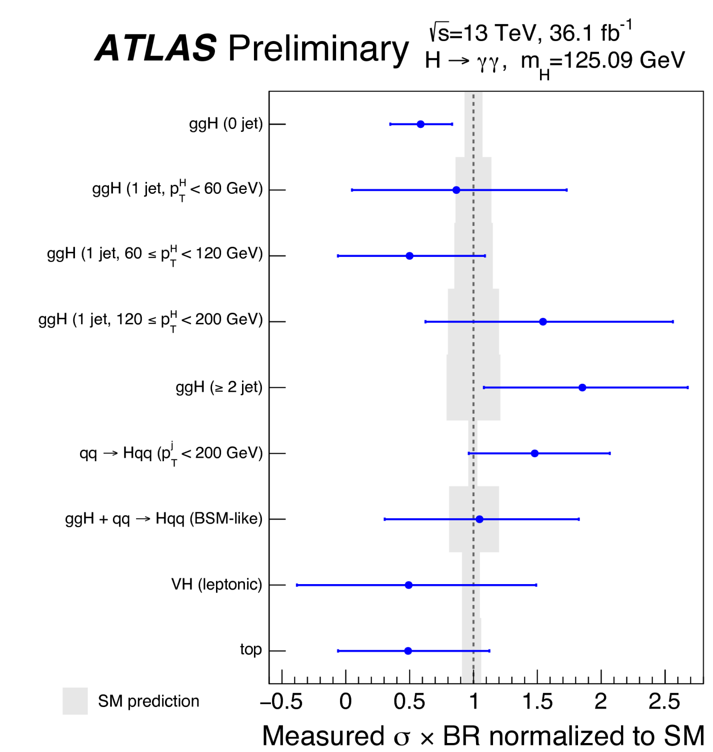
- Future measurements @ 13/14 TeV and later @ HL-LHC could provides us with some hints, where Higgs boson might be a portal to the new physics phenomena.











Several important ways to interpret the measurements

- TH and EXP need to continue working together to be able to exploit maximum from the available data
- Also need to harmonise approaches between experiments.

Common effort within EXP/TH groups is the key

- Need to continue with the synergy among similar efforts (HXS WG2, Les Houches, HiggsTools, etc.)
- Plan for a common document/note with Fid/Diff/ST XS recommendations.

Additional material

Theory uncertainties

Two aspects to theory (TH) uncertainties:

- Residual TH uncertainties related to "unfolding"
  (of experimental event categories to STXS bins)
- Uncertainties in interpretation of the measured STXS bins
  (when bins with diff. sensitivities are merged)

Need for coherent treatment:

- Implementation in terms of ±100% correlated or uncorrelated nuisance parameters
  - Parameterize individual sources within ggH, VBF, and VH uncertainties separately
    (identify/differentiate sources, evaluate their correlations, etc.)
  - Consider QCD and EWK contributions, proper correlation with inclusive cross section, etc.
- One goal is for interpretations to be able to easily use different predictions
  (work ongoing with Les Houches and LHCHXSWG colleagues, focus on stage-1 parametrization)

How to Provide Experimental Results

Assume Gaussian behavior is a good approximation :

- **Case 1: Provide full O(30)-dimensional covariance matrices separated by**
  - Statistical uncertainties
  - Total experimental systematic uncertainties (interesting for better understanding)
  - Combined theoretical uncertainties, and separately specific theoretical uncertainties (that might have to be correlated between the measurement and the interpretation)

- **Case 2: Keep the subset of nuisance parameters unprofiled**
  (those where uncertainties that might be correlated between measurement and interpretation, and where the effect of a given uncertainty after profiling cannot be reasonably expressed as a covariance matrix)

- **In case Gaussian approx. is not good for single STXS bin:** Provide (parametrized) likelihood for these bins
  (Could be expected e.g. for weakly constrained bins)

Validation:

- **Experiments will have to test if interpretations with these inputs possible**
  (compare to interpretations using full likelihoods)