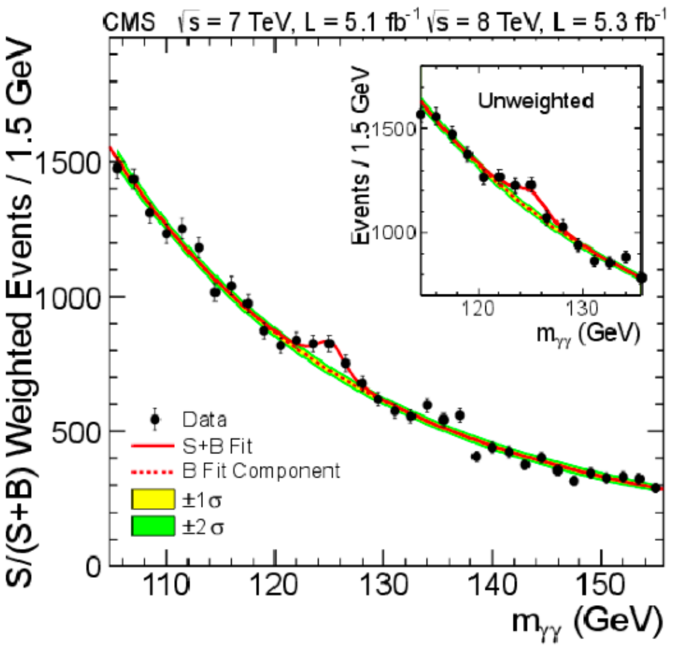
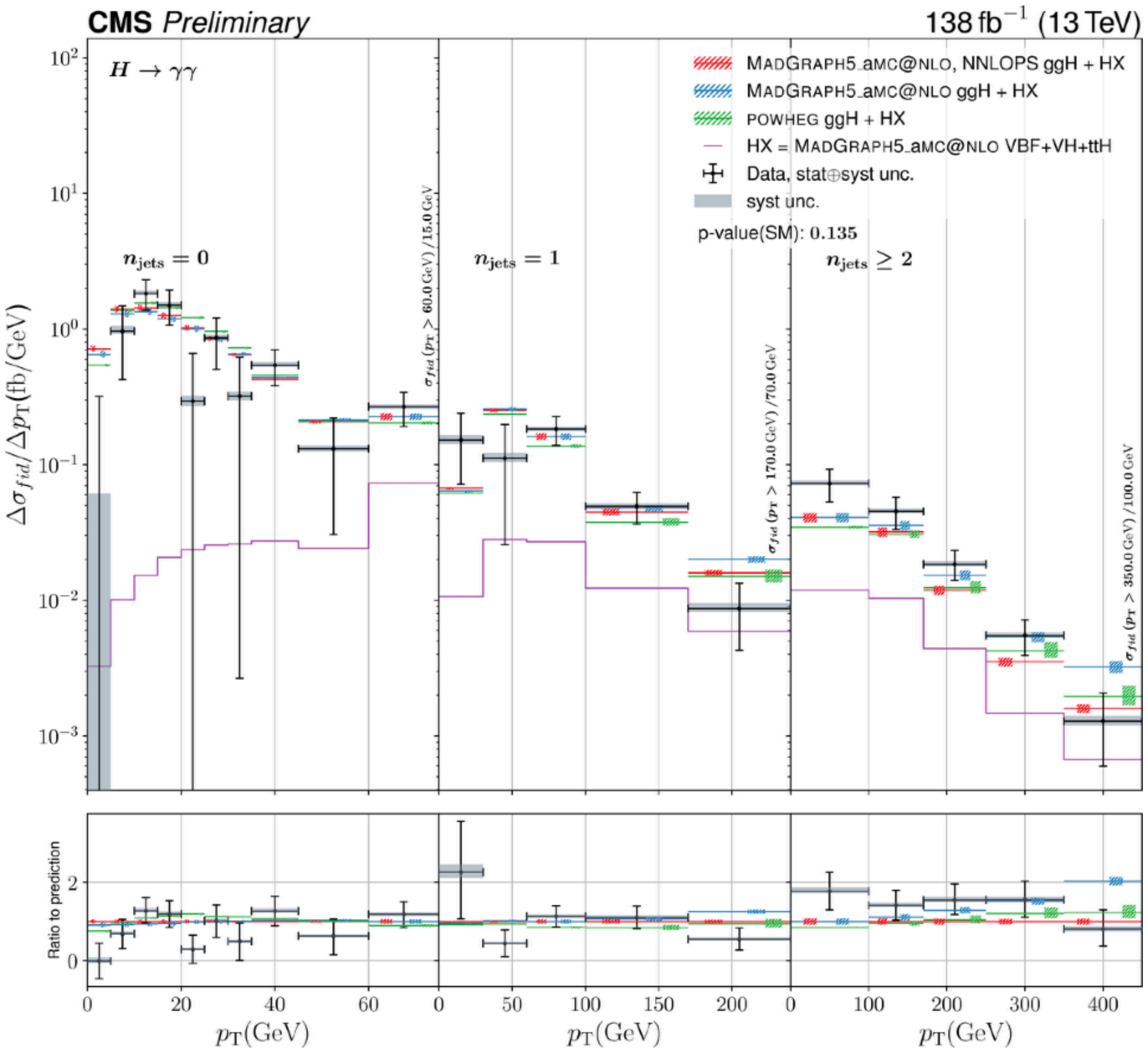
2012



2022



STXS and Fiducial Cross Sections Measurements

Mauro Donegà
ETH - Zürich

Disclaimer

- The most relevant/updated results from ATLAS and CMS about STXS and Fiducial Cross Sections have already been presented in previous talks this week

- Use this talk to show the ideas behind the measurements:
  How the results are obtained more than the plots themselves

- Personal non exhaustive selection of examples

It was 10 years ago…

Like often happens with birthdays it's a good time to look back at see what we've done so far and see what we're going to do next.

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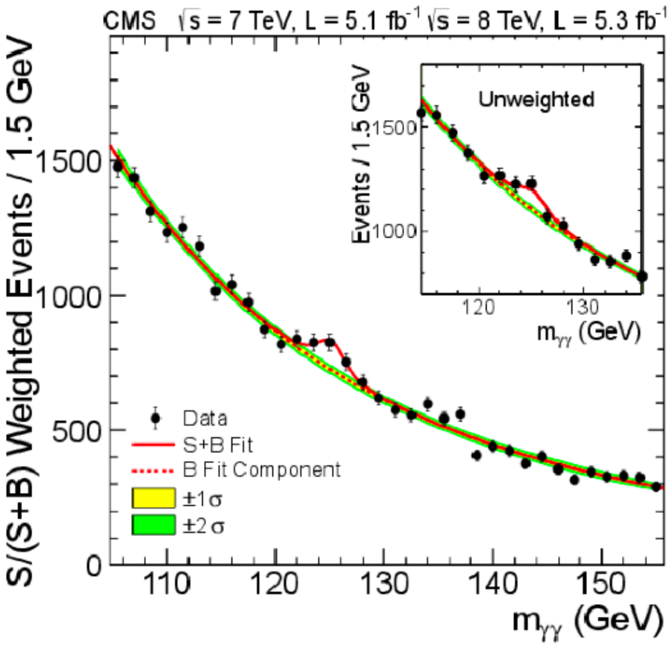
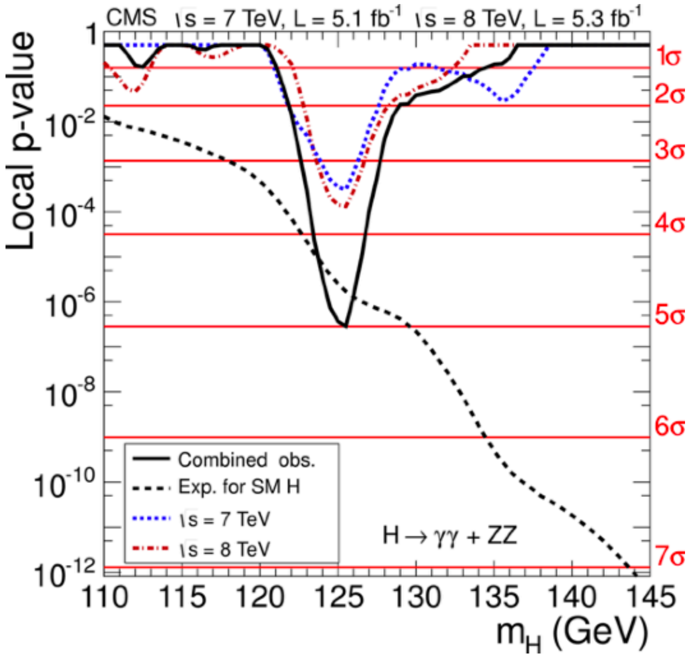
Discovery





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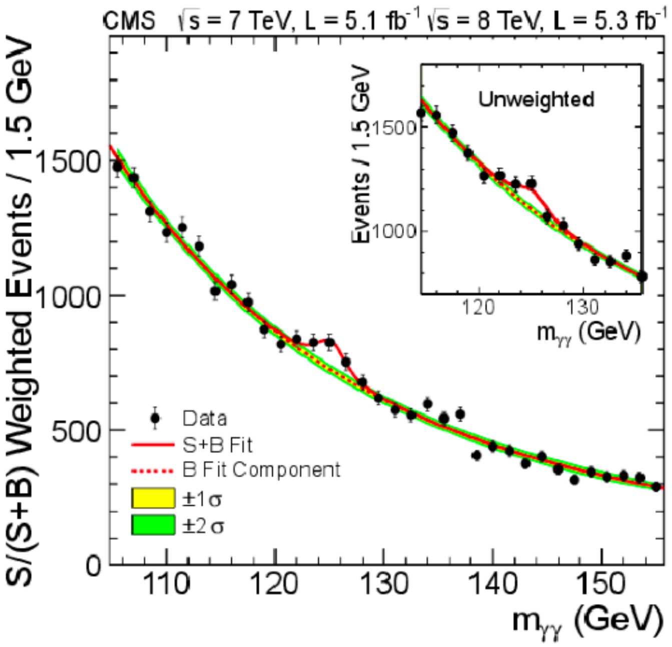

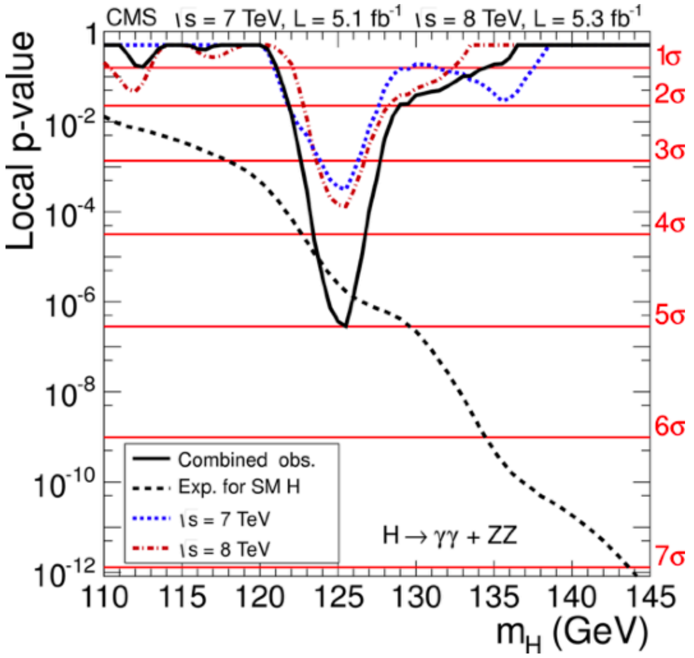

Quantum numbers:

- Spin 0
- m_H = 125.38 ± 0.11(stat) ± 0.08(syst) GeV (1 per mille)
- $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV (indirect from off-shell)
- Pure CP-odd excluded

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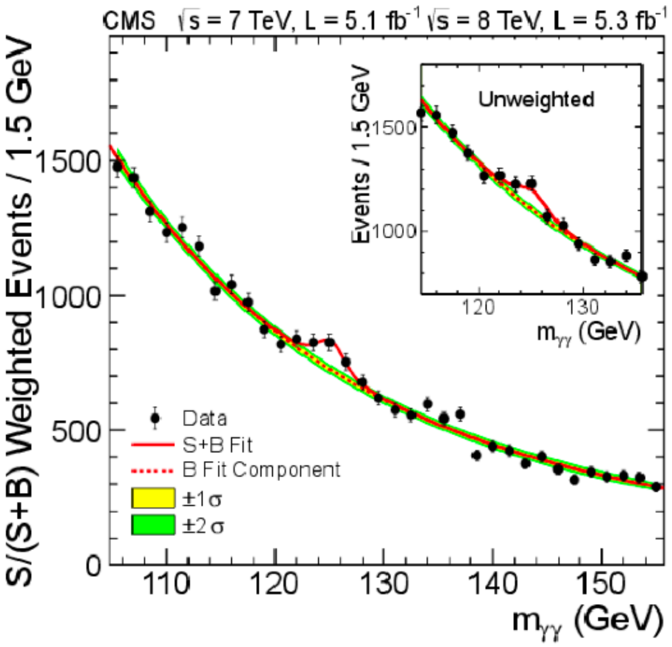

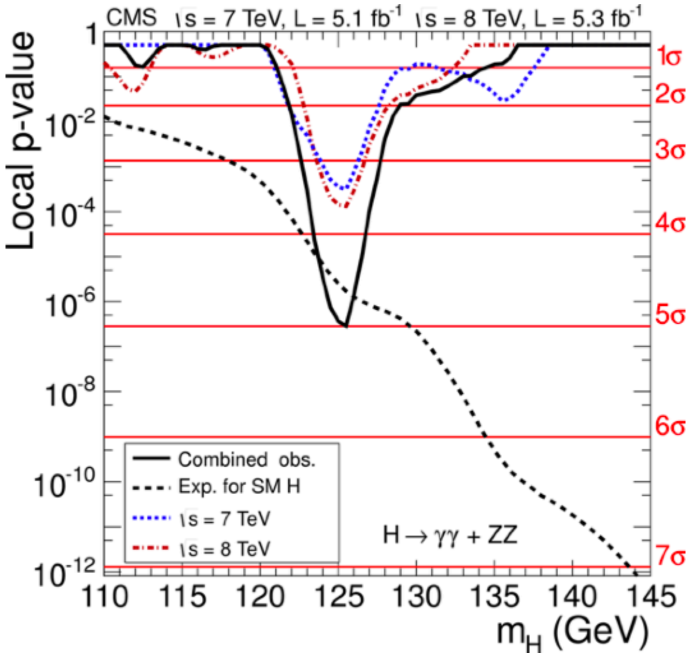

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We will never be able to confirm that it is the SM Higgs

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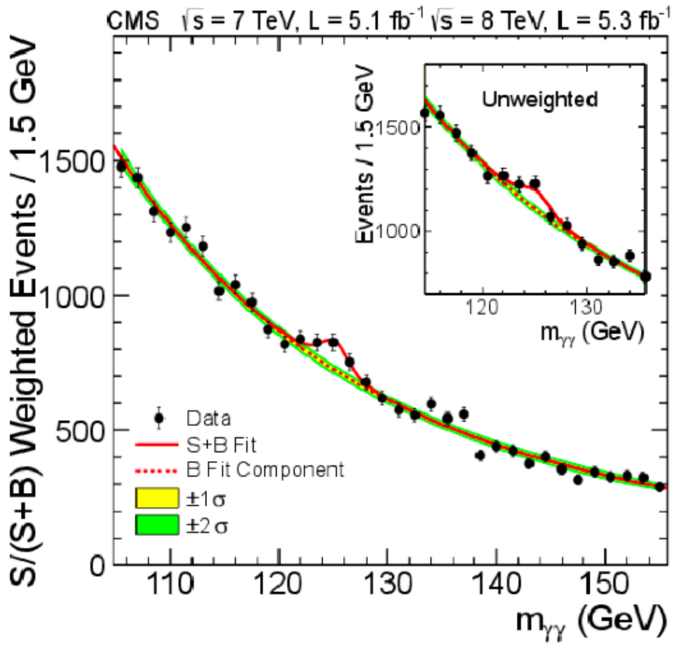
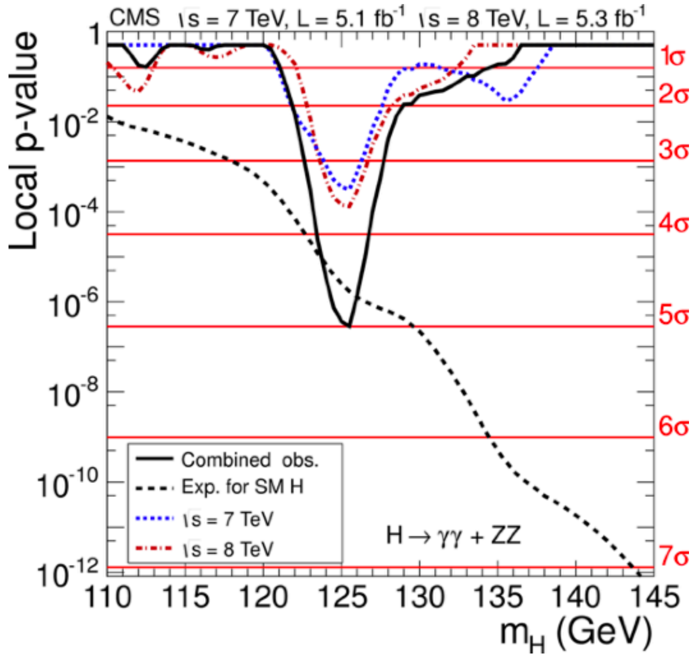
Discovery





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We will never be able to confirm that it is the SM Higgs
…but we can prove that it is not the SM Higgs

with "precision" measurements
and accurate theoretical predictions !

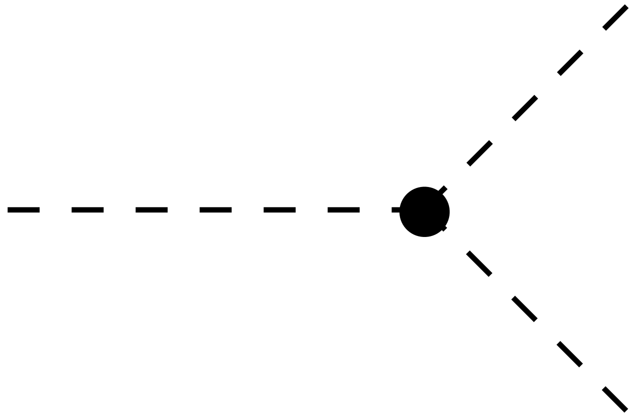
Why particle masses are interesting in high energy physics ?

At a multi-TeV collider one would expect that the mass of a particle o(100 GeV) should be essentially irrelevant: E >> m

Instead even at LHC energy the mass of a particle is not an irrelevant correction, it makes particle behave *qualitatively* differently:
  massless spin1 photon: 2 polarisation
  massive spin1 W/Z   : 3 polarisations

The Higgs mechanism fixes the "bookkeeping" of the spins for *spinning* massive particles

The Higgs boson itself has no spin: who's giving the mass to the Higgs ? …the Higgs

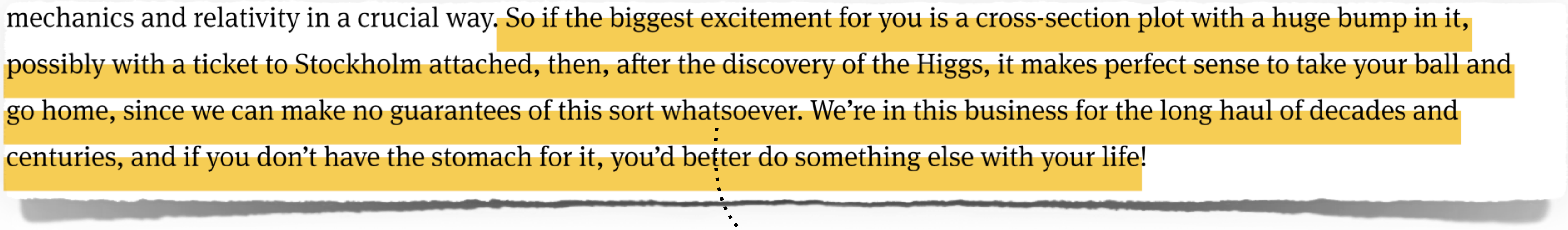


the only case with no change of
quantum numbers at the vertex.
Never seen before !

There is a lot to learn beyond finding the bump

In it for the long haul - N. Arkani Ahmed - CERN Courier

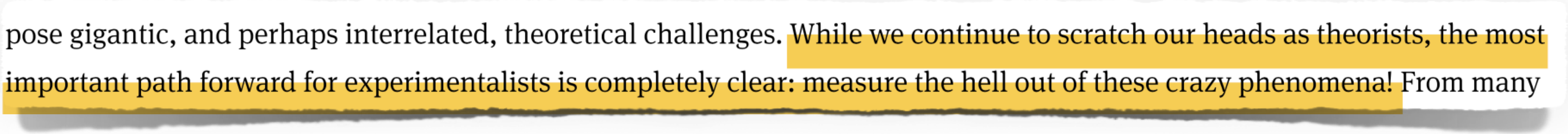
but if you don't look for it, you're not going to see it
LHC is a discovery machine



mechanics and relativity in a crucial way. So if the biggest excitement for you is a cross-section plot with a huge bump in it, possibly with a ticket to Stockholm attached, then, after the discovery of the Higgs, it makes perfect sense to take your ball and go home, since we can make no guarantees of this sort whatsoever. We're in this business for the long haul of decades and centuries, and if you don't have the stomach for it, you'd better do something else with your life!

“no loose theorem”… gone

message to experimentalists



pose gigantic, and perhaps interrelated, theoretical challenges. While we continue to scratch our heads as theorists, the most important path forward for experimentalists is completely clear: measure the hell out of these crazy phenomena! From many

There is a lot to learn studying the Higgs boson

Is this (not) the SM Higgs ?
e.g. Fit signal strengths, kappas, STXS, differential fiducial XS
(parametrize the effect of operators on observables - pT, njets, etc…)

Is the Higgs the only source of Electroweak Symmetry Breaking?
Is it a fundamental scalar or is part of a larger structure ?
e.g Search new Higgs, measure VBS $W_L W_L$.

Is it composite ? (pion like boson of a broken larger symmetry restored at some higher scale)
e.g measure couplings, self coupling/potential, STXS, differential fiducial XS

What is the shape of the Higgs potential (Higgs trilinear/quartic coupling)?
double Higgs production, high precision pT spectrum single Higgs, STXS, differential fiducial XS

Does the Higgs violate CP?
e.g. Full angular analysis of the HZZ, STXS, differential fiducial XS, $\Delta\phi_{jj}$ in VBF

Does the Higgs violate flavour ?
e.g. H—> tau mu

The more we know the more we want to know

After the discovery we started characterising the Higgs assuming:

1) the signal comes from only 1 particle
2) SM Higgs boson hypothesis 0^+ and in terms of its production and decay kinematics
3) narrow width approximation is valid (production/decay decoupled)

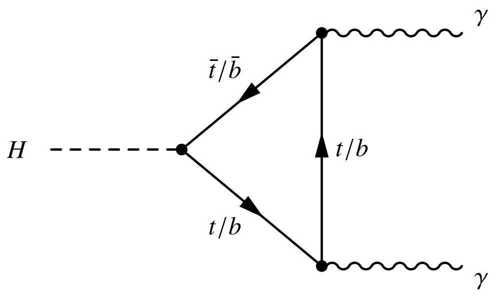
Signal strength modifier $$\mu = \frac{\sigma \cdot \mathrm{BR}}{\sigma^{SM} \cdot \mathrm{BR}^{SM}}$$

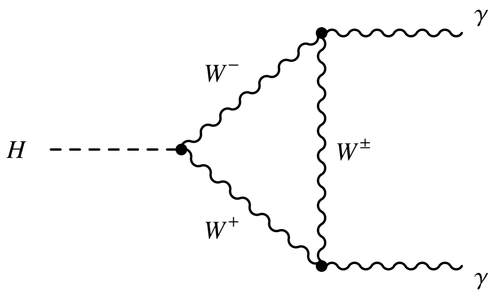
Then we moved to coupling modifiers (kappas) = multipliers at amplitude level

$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$$

$$\kappa_H^2 = \sum_j \mathrm{BR}^j_{\mathrm{SM}} \kappa_j^2 \qquad \Gamma_{\mathrm{H}} = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

Sensitive to interference effect in loops
e.g. negative interference between:





Hunting for BSM effects

BSM typically affects both the total number signal events and shapes.

gg—>H: SM top-loop production, BSM can contribute with any new strongly interacting particle to the Higgs-gluon coupling. Subtract the top-Yukawa comparing “ggF - ttH”

gg—>Hg: boosted ggF: in the tails of pT(H) where the number of SM events drops to o(permille), BSM easier to observe

VH: 2—>2 process. Boost from recoil on the V-boson. Enhance momentum-dependent BSM effects in couplings (SM VVH has no momentum dependence). Measure pTH, pTV, mVH

VBF: 2—> 3 allows to test several observables: modification to Higgs and gauge sectors, Lorentz structure of the VVH coupling, CP even/odd

ttH: 2—> 5: test of the top Yukawa, very challenging theoretical predictions / very challenging measurements

HVV: THE test of the SM

Hff: test of the SM Yukawa interaction

Invent new measurements
to probe the largest possible
phase space
with the highest precision

Starting point: signal strength modifier μ

Events are measured in analysis categories designed to optimise the signal extraction. The signal strength modifier in a category can be fitted from:

$$\#events^{cat} = \mu^{cat} \cdot \sum_{ij} \left[\left(Eff \cdot A^{SM} \right)^{cat}_{ij} \cdot \sigma_i^{SM} \cdot BR_j^{SM} \cdot L \right] + bkg^{cat}$$

BSM CAN AFFECT THE ACCEPTANCE

$$\boxed{A^{SM} \neq A(c_1 \ldots c_n)}$$

AND IN ANY CASE LIMITED BY SM PREDICTION ACCURACY

MEASURED

SM PREDICTIONS

FITTED SIGNAL STRENGTH MODIFIER

Theory interpretation $\mu^{cat} = \mu^{cat}(\underbrace{c_1, c_2, \ldots c_n}_{\text{THEORY PARAMETERIZATION}})$

Maximal information extracted at the price of the *maximal* model dependence (SM)

Better measurements

What properties should a measurement have ?

- it should allow to extract the maximal information from the data
- the extracted information should be as model independent as possible
- it should be presented in a way to allow for future/different re-interpretations of the data

Very practically: including new/different theoretical predictions in existing measurements is very time consuming —> decouple the measurements from their interpretations

Shift the theory dependence from the measurements to the interpretations

e.g. better SM modelling only affect the theory interpretation and it will not require to rerun the analysis; theory uncertainties are in the theory interpretation, not in the measurements

Different solutions have been developed (partially) fulfilling these requirements:

- Simplified Template Cross Sections (STXS)
- Fiducial Total/Differential Cross Sections

Simplified Template XSections: STXS

Les Houches 2015: https://arxiv.org/pdf/1605.04692.pdf

Goal: maximise the sensitivity of the measurements and minimise their theory dependence using the smallest number of partitions (bins) of the analysis phase space:

- measure of cross sections instead of signal strength modifiers
- measurements done in “simplified fiducial volumes” (bins)
- allow the use of MVA/ML for signal extraction
- combine all decay channels (i.e. look only at the production side)

The “bins” are chosen to:

- minimise the dependence on theoretical uncertainties folded into the measurements
- maximise experimental sensitivity
- isolation of possible BSM effects (e.g. in the tails)
- minimise the number of bins without loss of experimental sensitivity
  eventually increasing the number of bins with increasing datasets (staging)
  or merging them back in case of low stat
- Easy to combine: mutually exclusive kinematic bins;
  all agree on the same assumptions and bins boundaries;
  experiments will provide the covariance matrix among the bins

Simplified Template XSections: STXS

From signal strength modifiers

$$\forall\,\text{decay}\qquad \#\text{events}^{\text{cat}} = \mu^{\text{cat}}\cdot\sum_{i}\left[\left(\text{Eff}\cdot A^{\text{SM}}\right)_{i}^{\text{cat}}\cdot\sigma_{i}^{\text{SM}}\cdot BR^{\text{SM}}\cdot L\right] + \text{bkg}^{\text{cat}}$$

it's a simple extension to obtain the STXS

$$\forall\,\text{decay}\qquad \#\text{events}^{\text{cat}} = \sum_{\substack{\text{bin}\\ \text{STXS}}}\left[\underbrace{\mu_{\text{bin}}\,\sigma_{\text{bin}}^{\text{SM}}}_{\substack{\text{SM AS TEMPLATE}\\ \text{IN STXS BIN}}}\left(\text{Eff}\cdot A^{\text{SM}}\right)_{\text{bin}}^{\text{cat}}\cdot BR^{\text{SM}}\cdot L\right] + \text{bkg}^{\text{cat}}$$

kinematic properties still defined in terms of the full phase space, but STXS bins defined to minimise the theory uncertainties

Reduce dependence on theory uncertainties

Several aspects related to theory uncertainties:

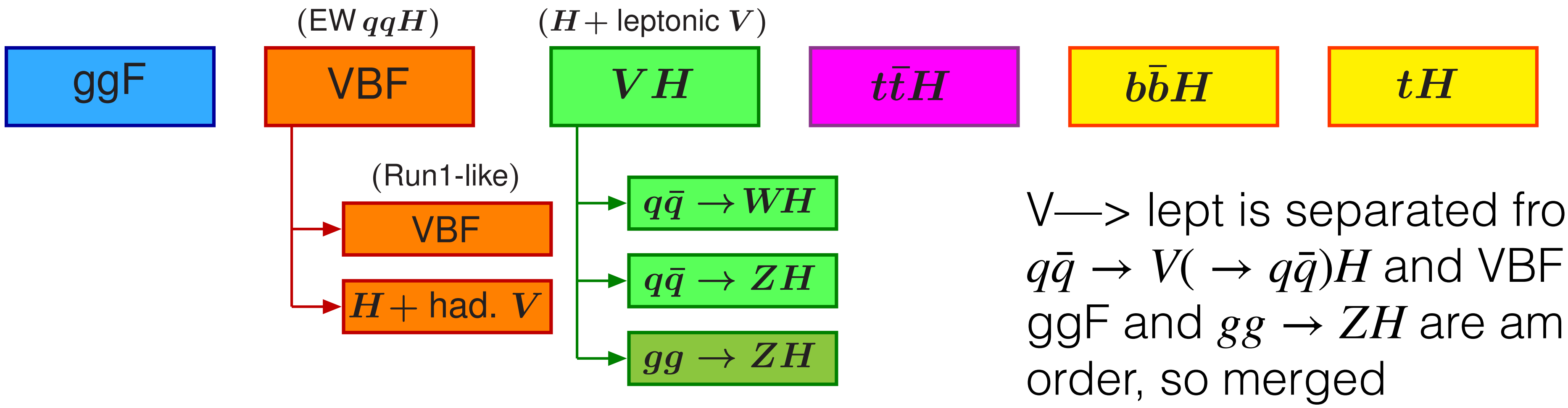
- avoid large variations of acceptance in one truth bin (introduce a direct dependence of the underlying theory distribution in the simulation) —> instead split the bins, if statistics (i.e. experimental sensitivity) allows it
- use of MVA is delicate: one has to check that the MVA selection is mapped in a specific region of phase space (ideally "close" to what would obtain with simple cuts)
- separate bins which are potentially sensitive to BSM: tails of the distribution / corners of the phase space

The measured analysis categories are unfolded to the STXS bins: possible model dependence from the theory used to compute the response matrix.

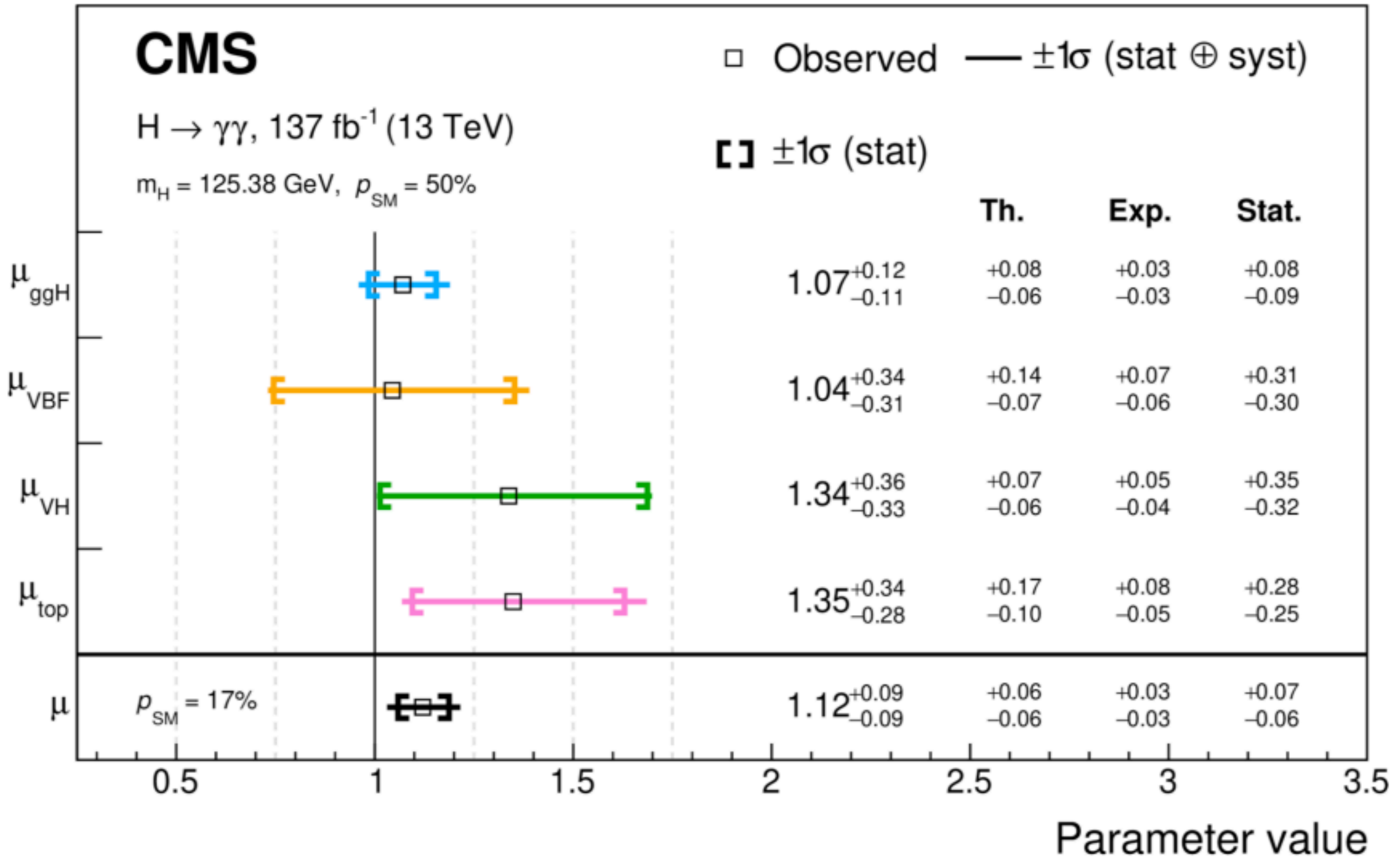
The definition of final states particles should be kept simple to allow to treat the Higgs boson as the "final state particle" —> this is what allows a simpler combination.

First step: stage 0

Basic splitting by production mechanism



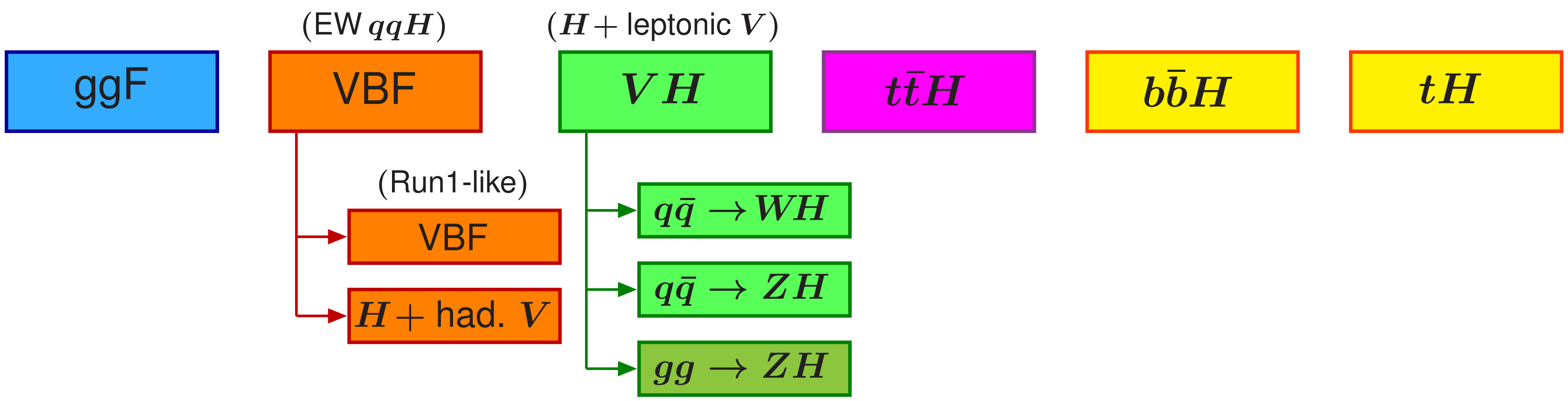
V—> lept is separated from V —>hadronic $q\bar{q} \rightarrow V(\rightarrow q\bar{q})H$ and VBF as well as ggF and $gg \rightarrow ZH$ are ambiguous at higher order, so merged



		Th.	Exp.	Stat.
μ_{ggH}	$1.07^{+0.12}_{-0.11}$	$^{+0.08}_{-0.06}$	$^{+0.03}_{-0.03}$	$^{+0.08}_{-0.09}$
μ_{VBF}	$1.04^{+0.34}_{-0.31}$	$^{+0.14}_{-0.07}$	$^{+0.07}_{-0.06}$	$^{+0.31}_{-0.30}$
μ_{VH}	$1.34^{+0.36}_{-0.33}$	$^{+0.07}_{-0.06}$	$^{+0.05}_{-0.04}$	$^{+0.35}_{-0.32}$
μ_{top}	$1.35^{+0.34}_{-0.28}$	$^{+0.17}_{-0.10}$	$^{+0.08}_{-0.05}$	$^{+0.28}_{-0.25}$
μ	$1.12^{+0.09}_{-0.09}$	$^{+0.06}_{-0.06}$	$^{+0.03}_{-0.03}$	$^{+0.07}_{-0.06}$

Staged approach

Stage 0



ggF

(EW qqH)
VBF
- (Run1-like) VBF
- $H+$ had. V

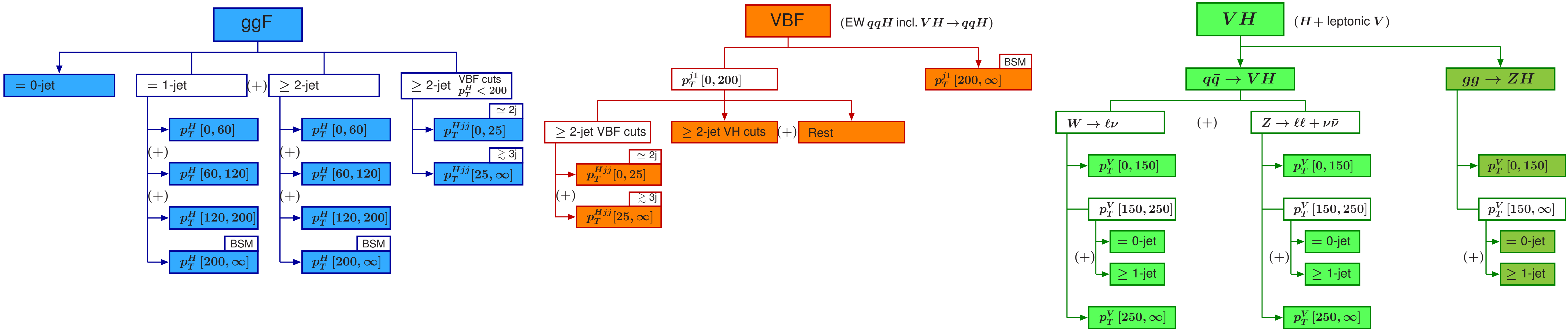
($H+$ leptonic V)
VH
- $q\bar{q} \to WH$
- $q\bar{q} \to ZH$
- $gg \to ZH$

$t\bar{t}H$

$b\bar{b}H$

tH

Stage 1 adds more granularity



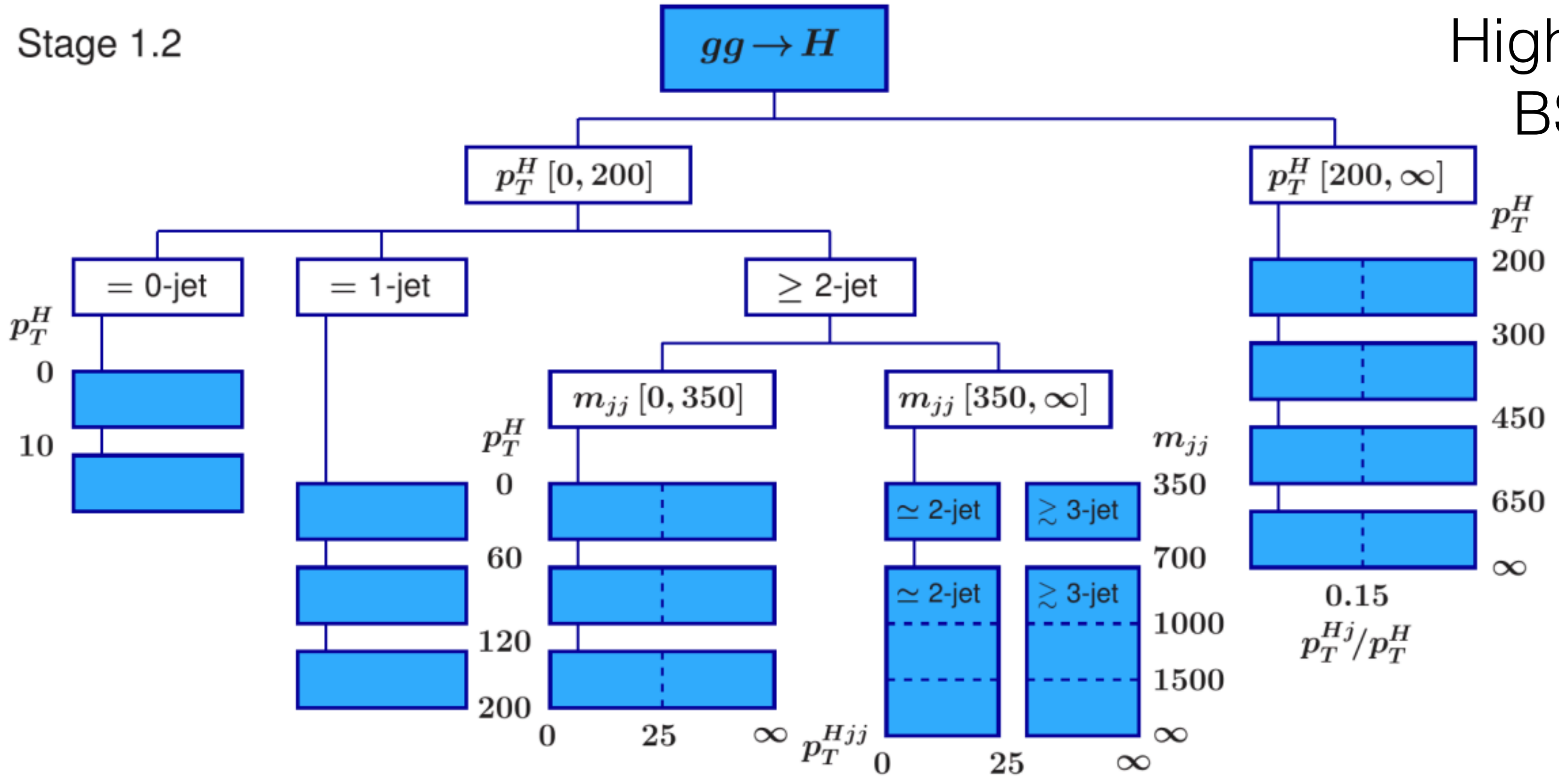
ggF
- $=$ 0-jet
- $=$ 1-jet
  - p_T^H $[0, 60]$
  - (+)
  - p_T^H $[60, 120]$
  - (+)
  - p_T^H $[120, 200]$
  - BSM p_T^H $[200, \infty]$
- (+)
- $\geq$ 2-jet
  - p_T^H $[0, 60]$
  - (+)
  - p_T^H $[60, 120]$
  - (+)
  - p_T^H $[120, 200]$
  - BSM p_T^H $[200, \infty]$
- $\geq$ 2-jet VBF cuts $p_T^H < 200$
  - $\simeq$ 2j $p_T^{Hjj} [0, 25]$
  - $\gtrsim$ 3j $p_T^{Hjj} [25, \infty]$

VBF (EW qqH incl. $VH \to qqH$)
- p_T^{j1} $[0, 200]$
  - $\geq$ 2-jet VBF cuts
    - $\simeq$ 2j $p_T^{Hjj} [0, 25]$
    - (+)
    - $\gtrsim$ 3j $p_T^{Hjj} [25, \infty]$
  - $\geq$ 2-jet VH cuts
  - (+)
  - Rest
- BSM p_T^{j1} $[200, \infty]$

VH ($H+$ leptonic V)
- $q\bar{q} \to VH$
  - $W \to \ell\nu$
    - p_T^V $[0, 150]$
    - p_T^V $[150, 250]$
      - $=$ 0-jet
      - (+)
      - $\geq$ 1-jet
    - p_T^V $[250, \infty]$
  - (+)
  - $Z \to \ell\ell + \nu\bar{\nu}$
    - p_T^V $[0, 150]$
    - p_T^V $[150, 250]$
      - $=$ 0-jet
      - (+)
      - $\geq$ 1-jet
    - p_T^V $[250, \infty]$
- $gg \to ZH$
  - p_T^V $[0, 150]$
  - p_T^V $[150, \infty]$
    - $=$ 0-jet
    - (+)
    - $\geq$ 1-jet

Simplified Template XSections

The latest results are presented in the STXS stage 1.2



High pT to enhance BSM sensitivity

Study QCD radiation

Important input to VBF ggF background

Simplified Template XSections

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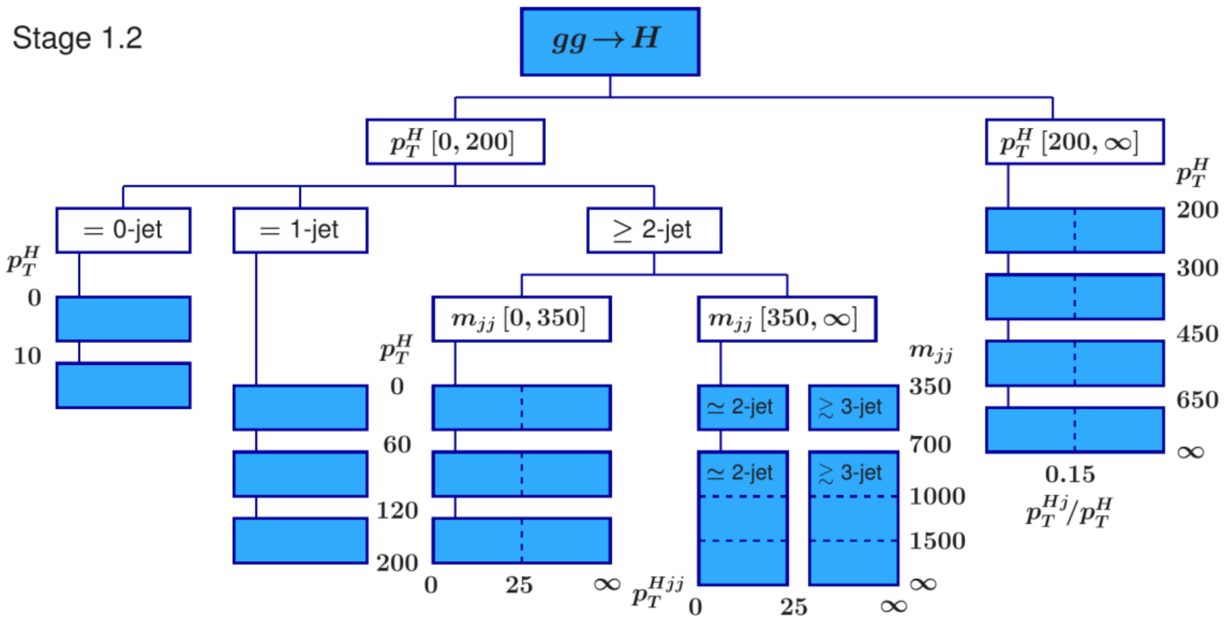
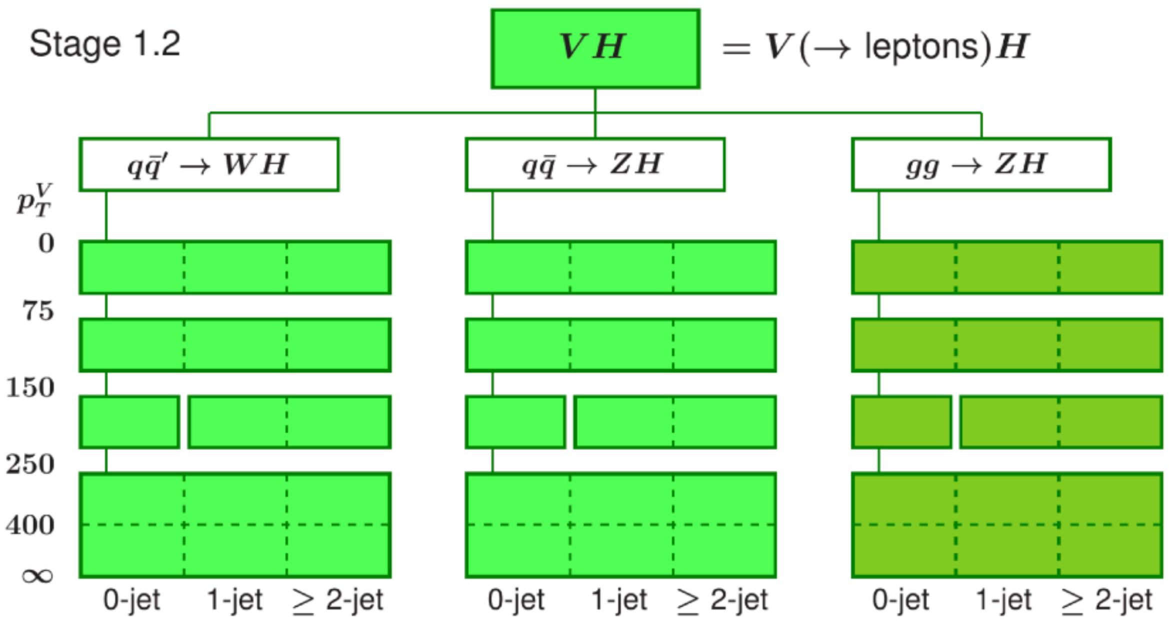
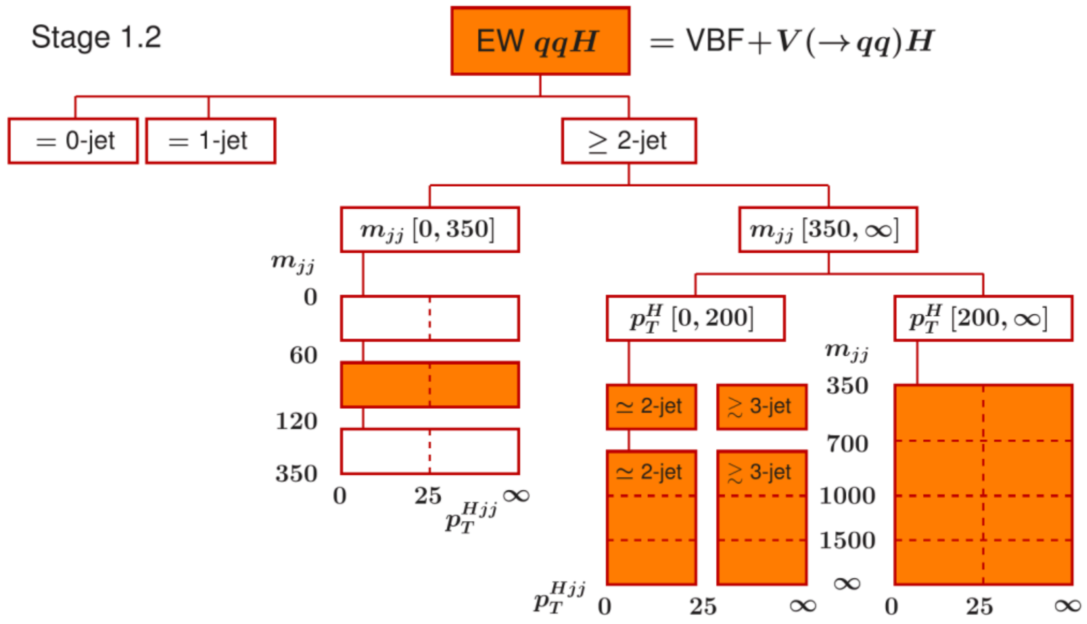
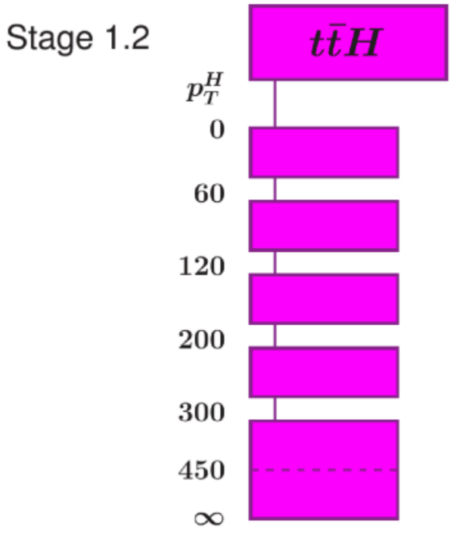
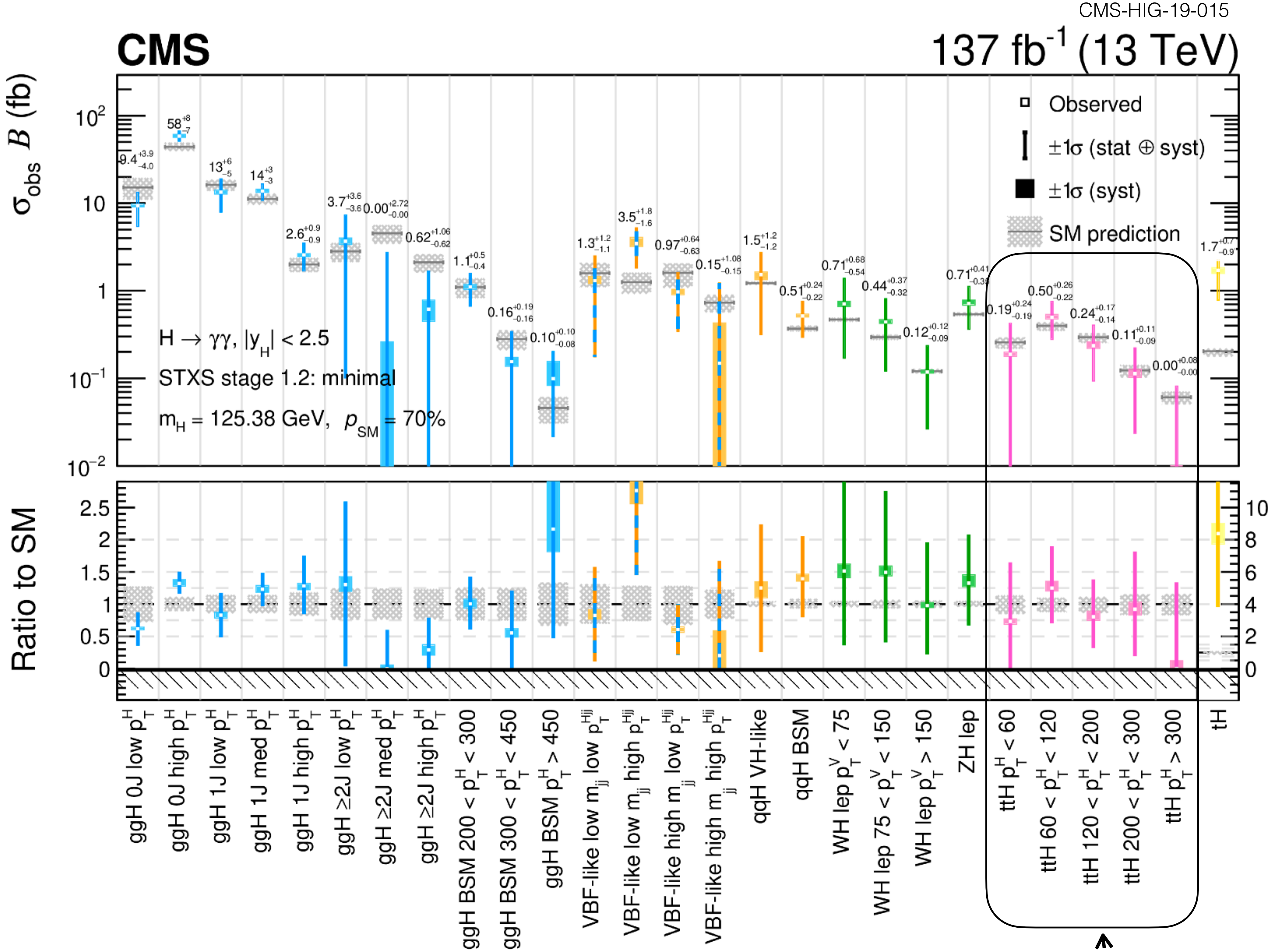








Examples: H→γγ



First pT(H) spectrum of H→γγ in ttH

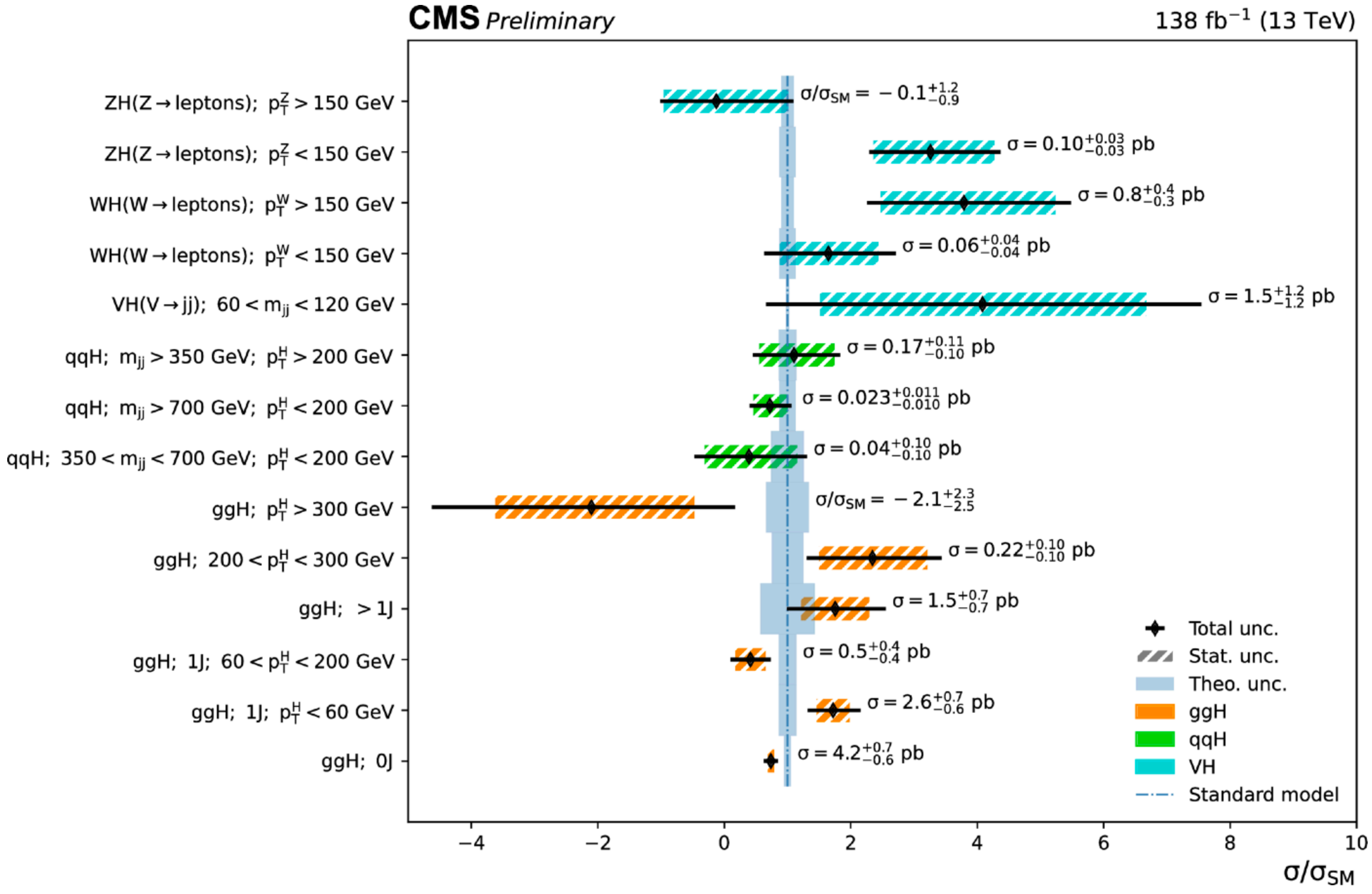
Heavy use of MVAs to extract the signal

Examples: H→WW

BR(H→WW) ~22%, BR(H→WW→eμ $\nu\nu$) ~1%

Signal extracted with a 2D fit (m_T, m_{ll})

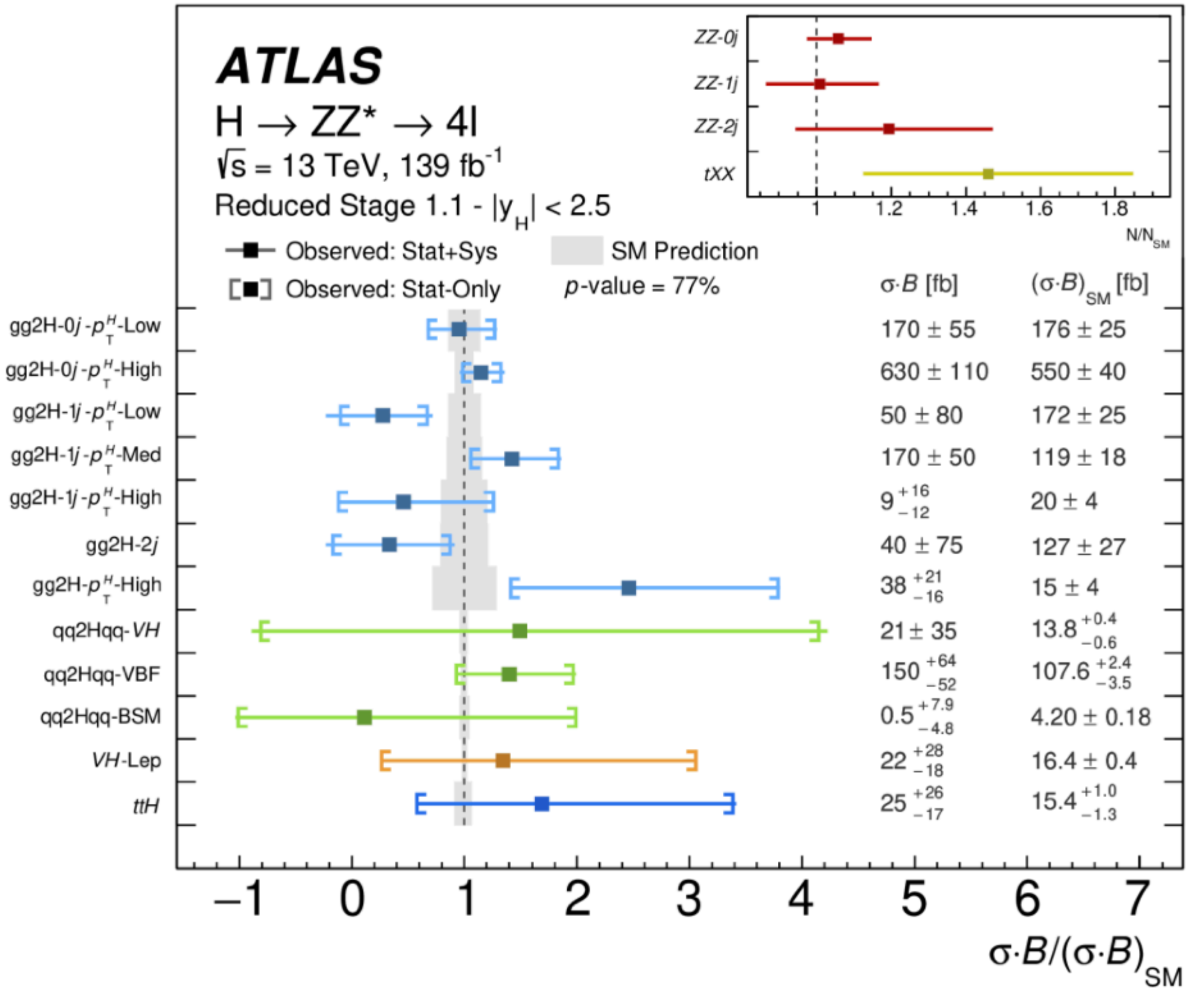
Large WW, top bkg and fake lepton backgrounds

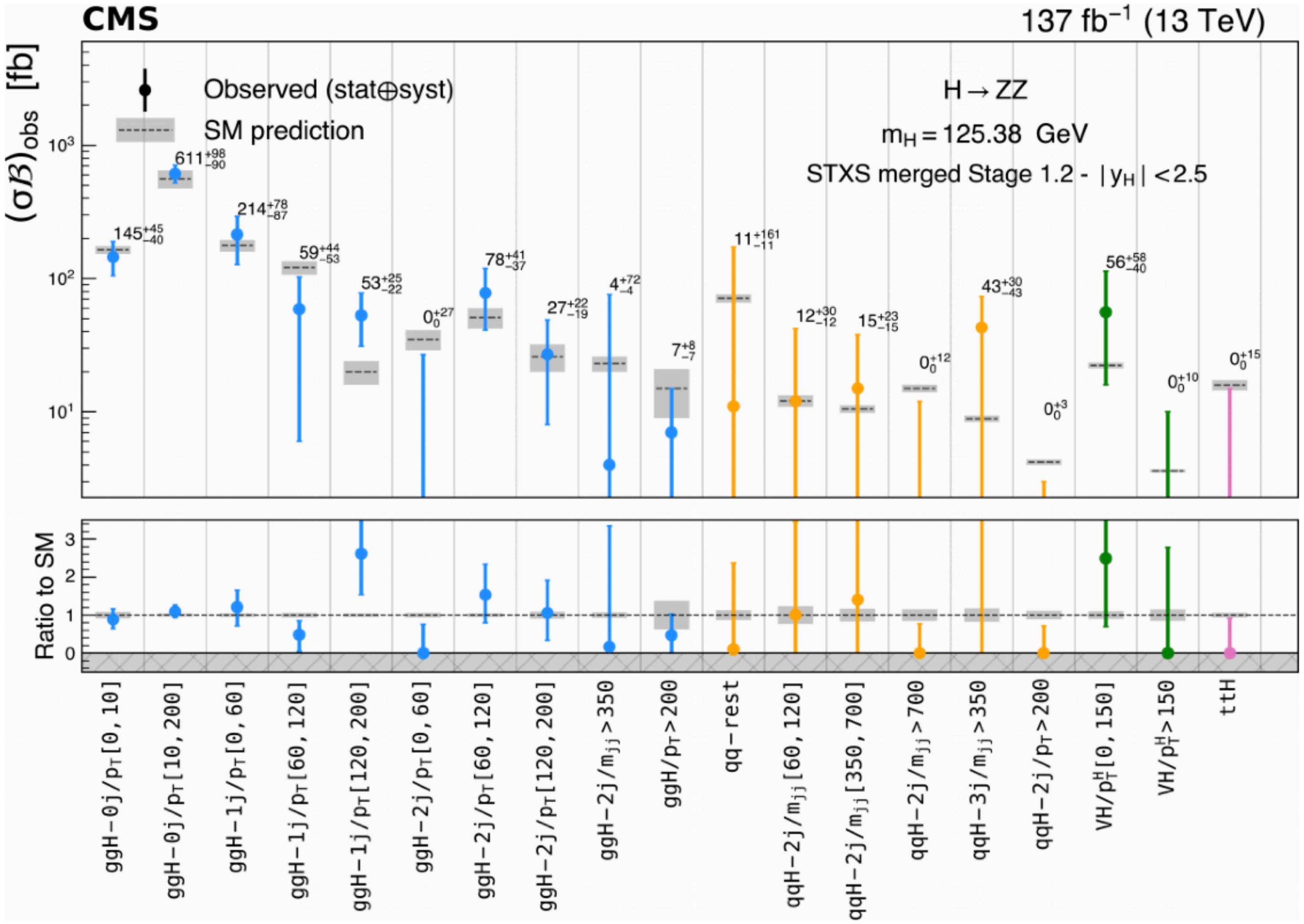


CMS-PAS-HIG-20-013

H→ZZ→4leptons

Golden channel but low statistics:
- signal extraction classifiers: DNN (ATLAS), MELA (CMS)
- merge STXS bins





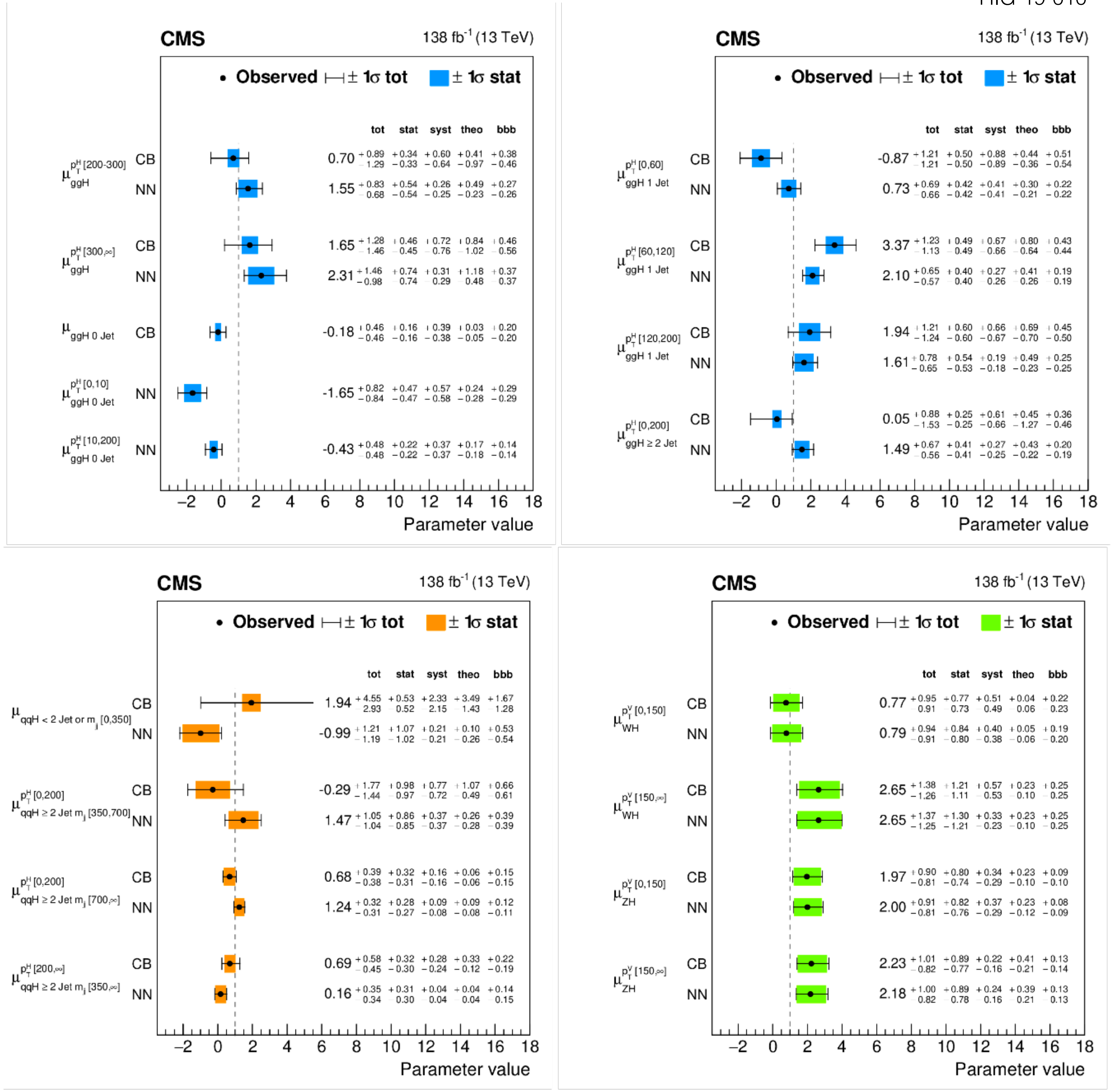
Examples: H→$\tau\tau$

Leptonic decay

Large BR ~6%
  explore low cross section
    production modes

Signal extraction
  CB = cut based
  NN = Neural Net

HIG-19-010

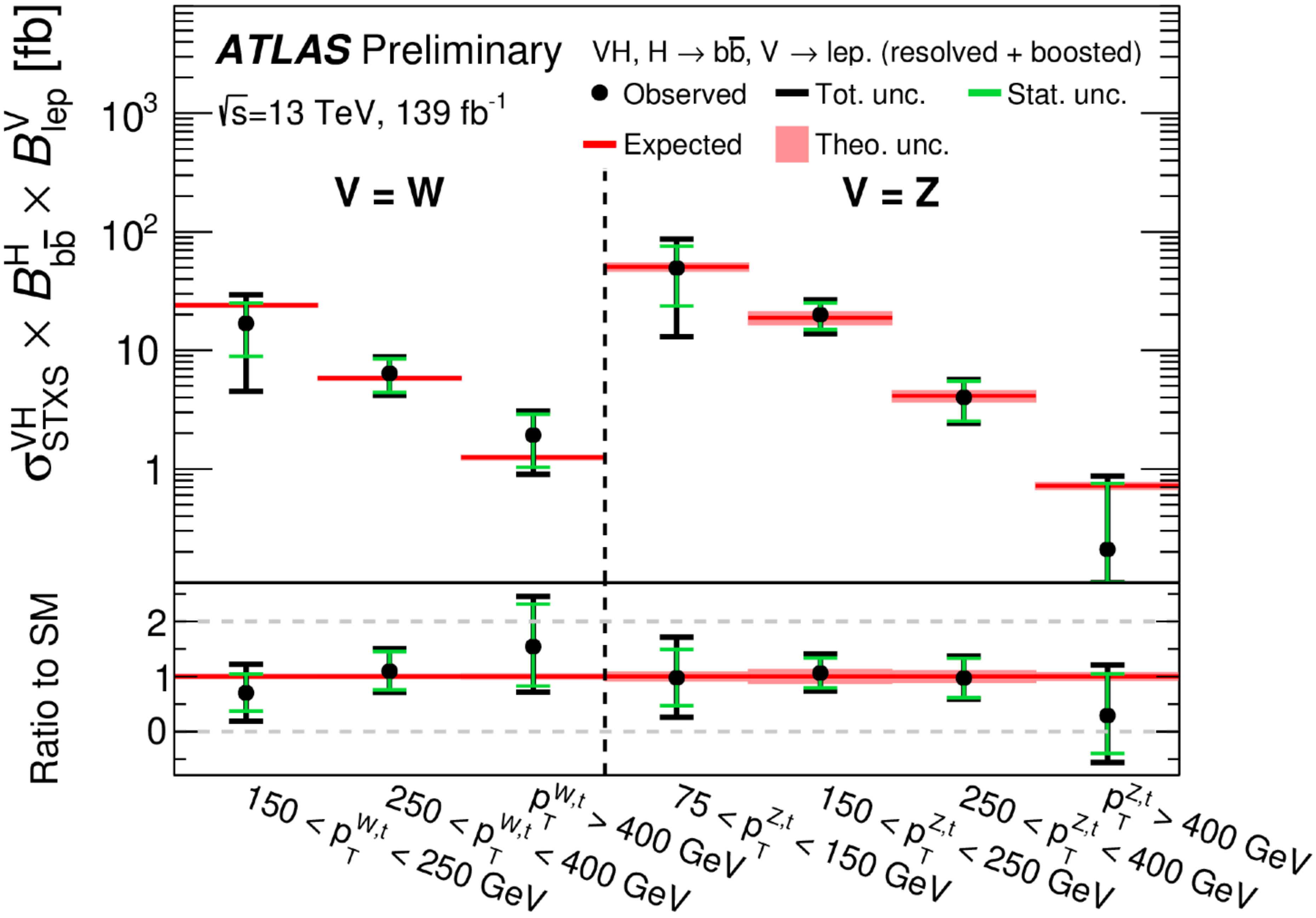


Examples: H→bb

Resolved analysis: signal extraction fit BDT classifier

Explores boosted topologies pT >400 GeV (still low stat)

ATLAS-CONF-2021-051



STXS combination and EFT interpretation

ATLAS-CONF-2021-053

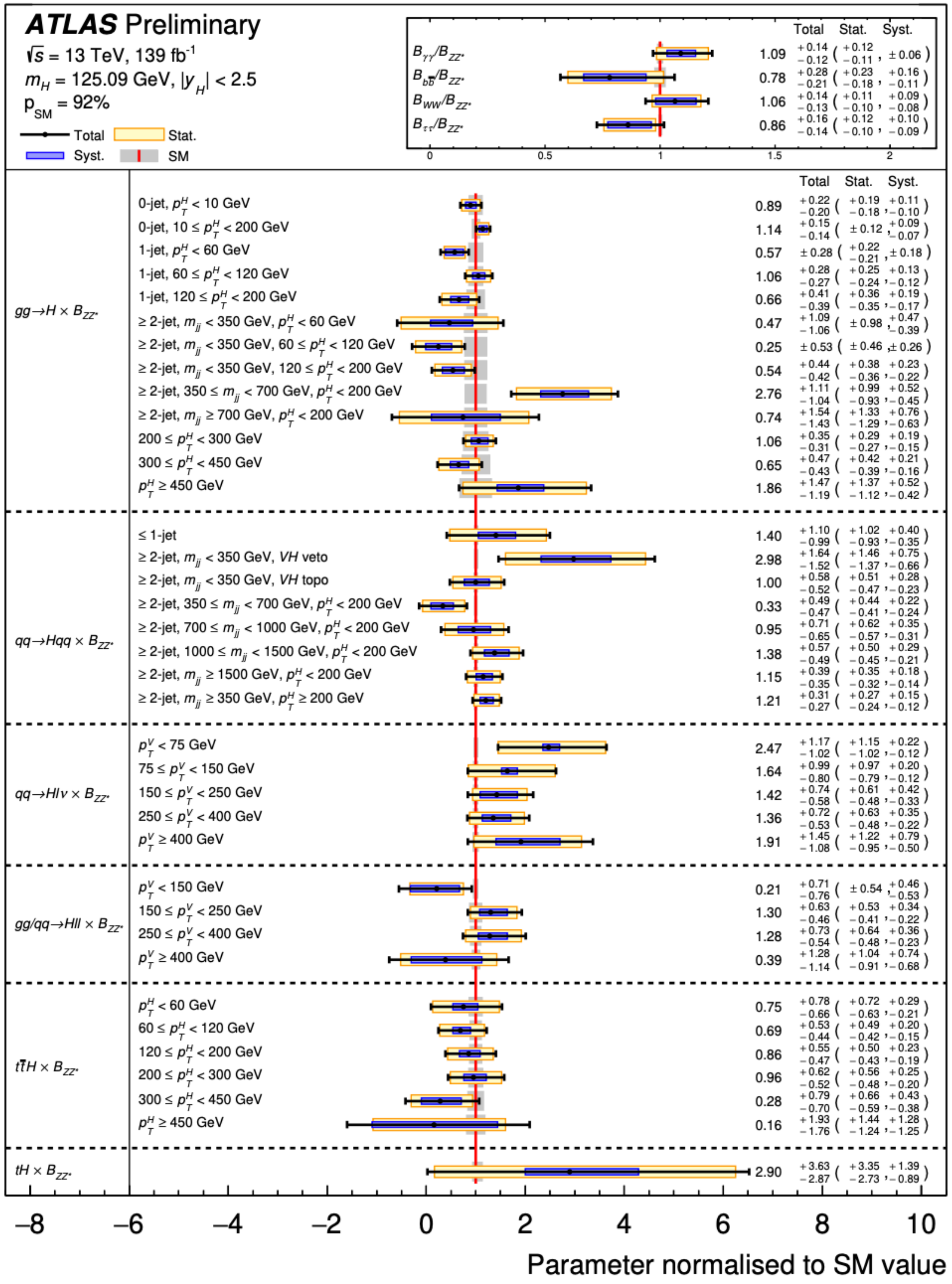
H→γγ, ZZ, WW, ττ, bb, Zγ

Single analyses have limited sensitivity in some bins, statistical gain from combining.

Theory dependence:

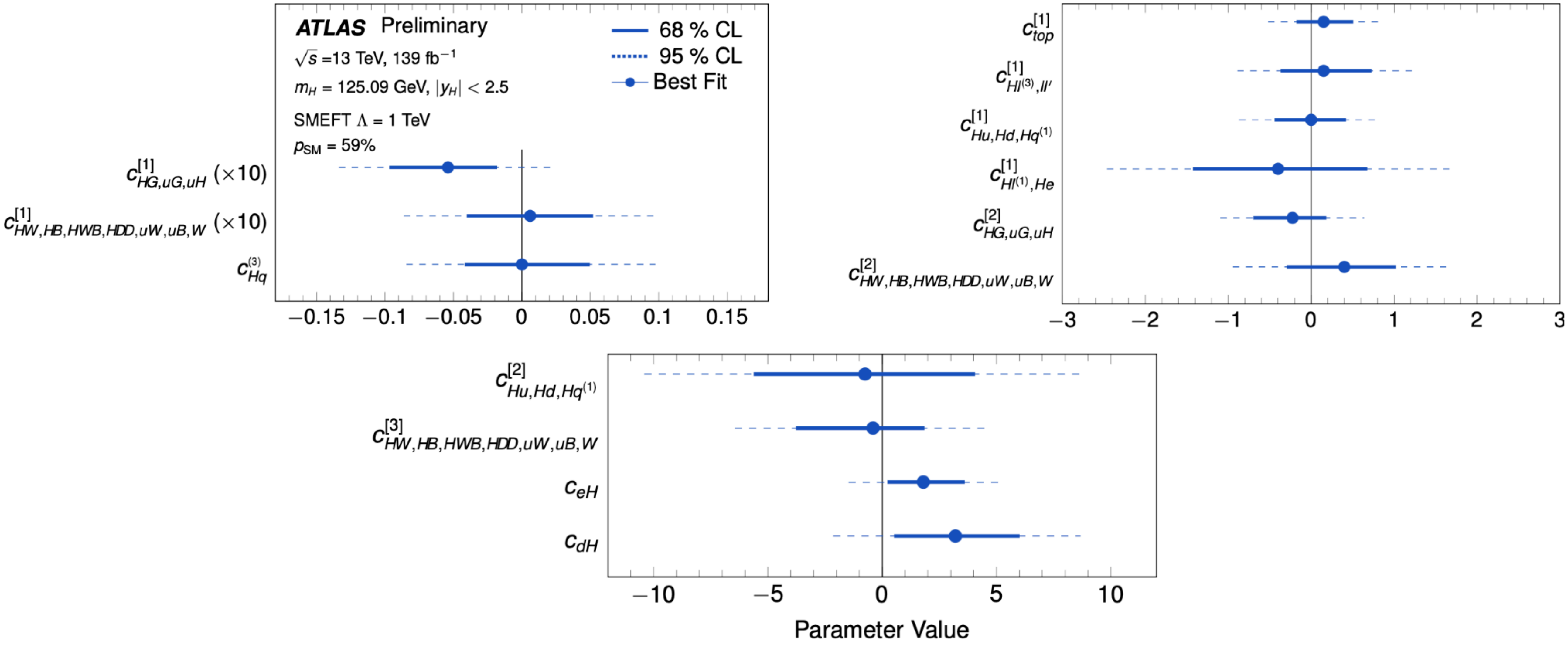
-Smaller theory dependence than total cross section, because (eff x Acc) are computed on smaller regions

- Assumptions about the kinematics within a given STXS region lead to some model-dependence, which can be reduced further by using a finer splitting of the phase space —> in future with larger statistics



STXS combination and EFT interpretation

13 EFT selected dim6 operators (Warsaw basis) impacting Higgs interactions.
Fit the coefficients of a modified basis (data do not contain enough information to constrain all original coefficients) essentially removing flat directions and grouping operators with similar effects.



Inclusive vs. Fiducial Cross Sections

Nomenclature:
Inclusive production cross section: “no detector”, i.e. full 4π acceptance
Fiducial production cross section: measure in the phase space allowed by the acceptance of the detector
Total / *Differential*: one number / measured in bins of an observable (spectrum)

Yellow Report 4: https://cds.cern.ch/record/2227475

Inclusive cross section

- extrapolate to full phase space 4π into regions not measured / removed by the analysis to be able to compare the results with theory
  —> model dependence in the extrapolation

Fiducial cross sections provide the maximal model independence:

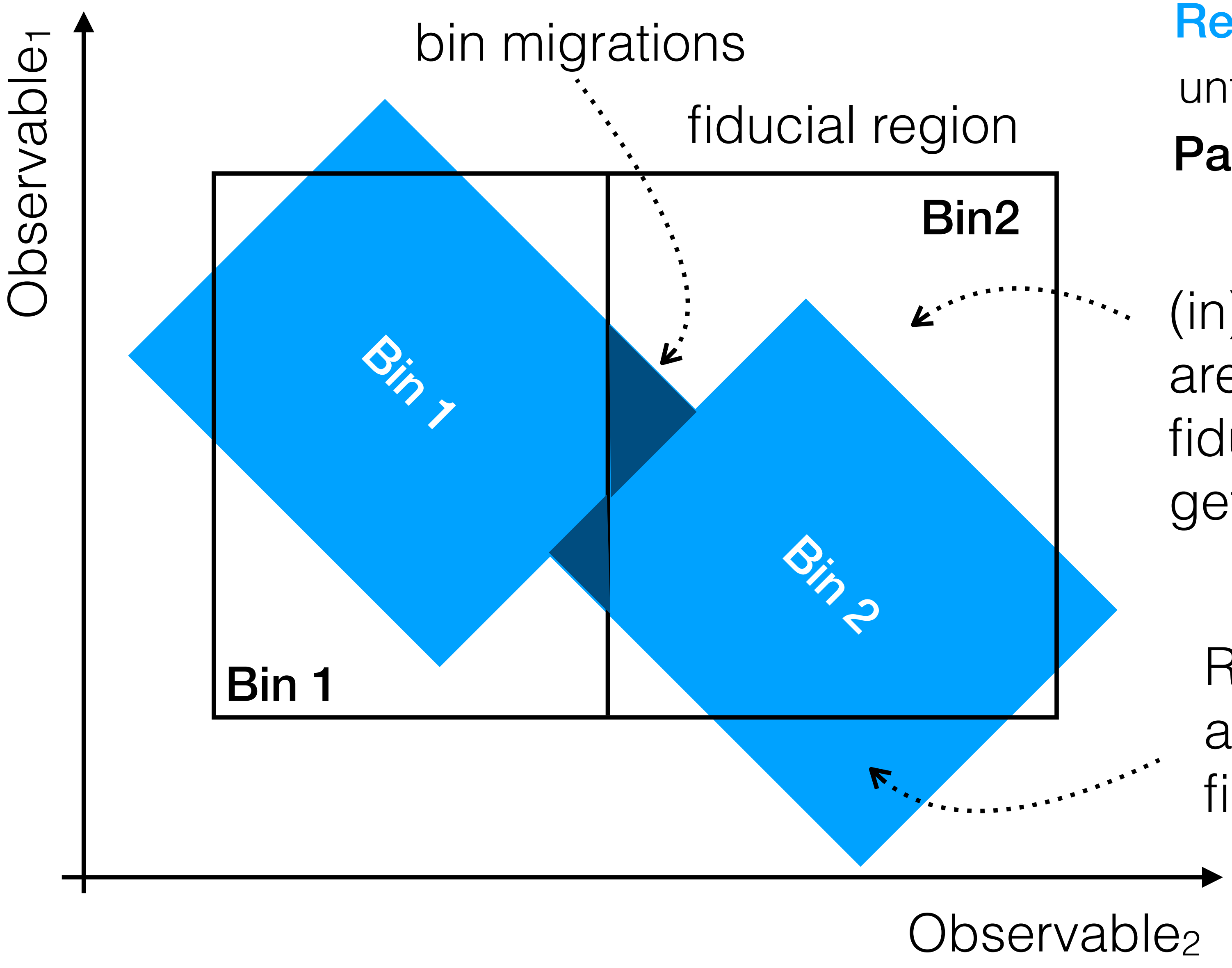
- define a fiducial phase space (“detector” acceptance) where you measure the cross section
- avoid large extrapolations: accounts for efficiencies and migrations
  inside <—> outside acceptance coming from resolution effects
  bin <—> bin migrations
- unfold the measurement to particle level
- factorise the experimental from the theoretical uncertainties

Using the fiducial cross sections, the comparison with theoretical predictions (SM or any BSM) is obtained by correcting the cross section by the (new) acceptance (fraction of signal events at particle level entering the analysis according to the new model)

—> maximise results re-interpretability

Fiducial phase space

Full Phase space (e.g. 2 dimensions)



Reconstructed bins
unfolded to
Particle level bins

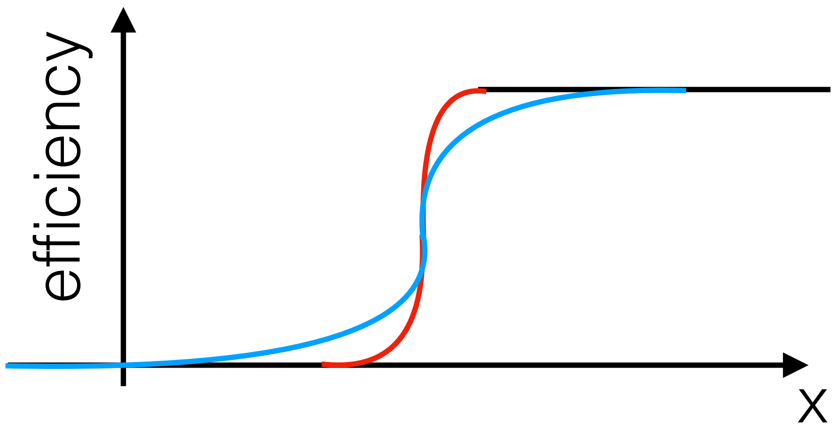
(in)Efficiency: events that are generated *inside* the fiducial region, but don't get reconstructed

Reconstructed events that are generated *outside* the fiducial region

Reduced by choosing an appropriate fiducial phase space

Fiducial phase space

To limit the model dependence (i.e. the extrapolation from the measured phase space to the fiducial phase space) we need to define a fiducial region as close as possible to the measured one



The choice of the fiducial region takes into account:
- detector acceptance $(p_T, \eta, \dots)$
- trigger selection (low resolution online cuts)
- analysis selection cuts (higher resolution offline cuts)

Any selection at reconstruction level has to be mimicked at particle level: keep it simple !

Avoid when possible the use of MVA or make sure that you can mimic their behaviour reasonable well with simple cuts

Out of the fiducial phase space contributions (Out Of Acceptance - OOA) are treated as background and subtracted before unfolding (same shape as the fiducial signal)

Fiducial phase space is different for each final state !
(see later how to combine fiducial cross sections)

Fiducial Cross Sections

$$\overrightarrow{\#events}\left(\overset{\substack{\text{RECO}\\\text{LEVEL}}}{Obs}\right) = \sum_i \left[\overset{\substack{\text{PARTICLE}\\\text{LEVEL}}}{\vec{\sigma}\,(Obs_i)} \cdot \underset{\substack{\uparrow\\\text{efficiencies and}\\\text{resolution effects}}}{R_{ij}} \cdot L \right] + \overrightarrow{bkg}\,(Obs)$$

FIDUCIAL CROSS SECTIONS

INCLUDE ACCEPTANCE :

$$\vec{\sigma} = \vec{\sigma}\,(\underbrace{c_1, c_2, \ldots, c_n}_{\text{THEORY PARAMETRIZATION}})$$

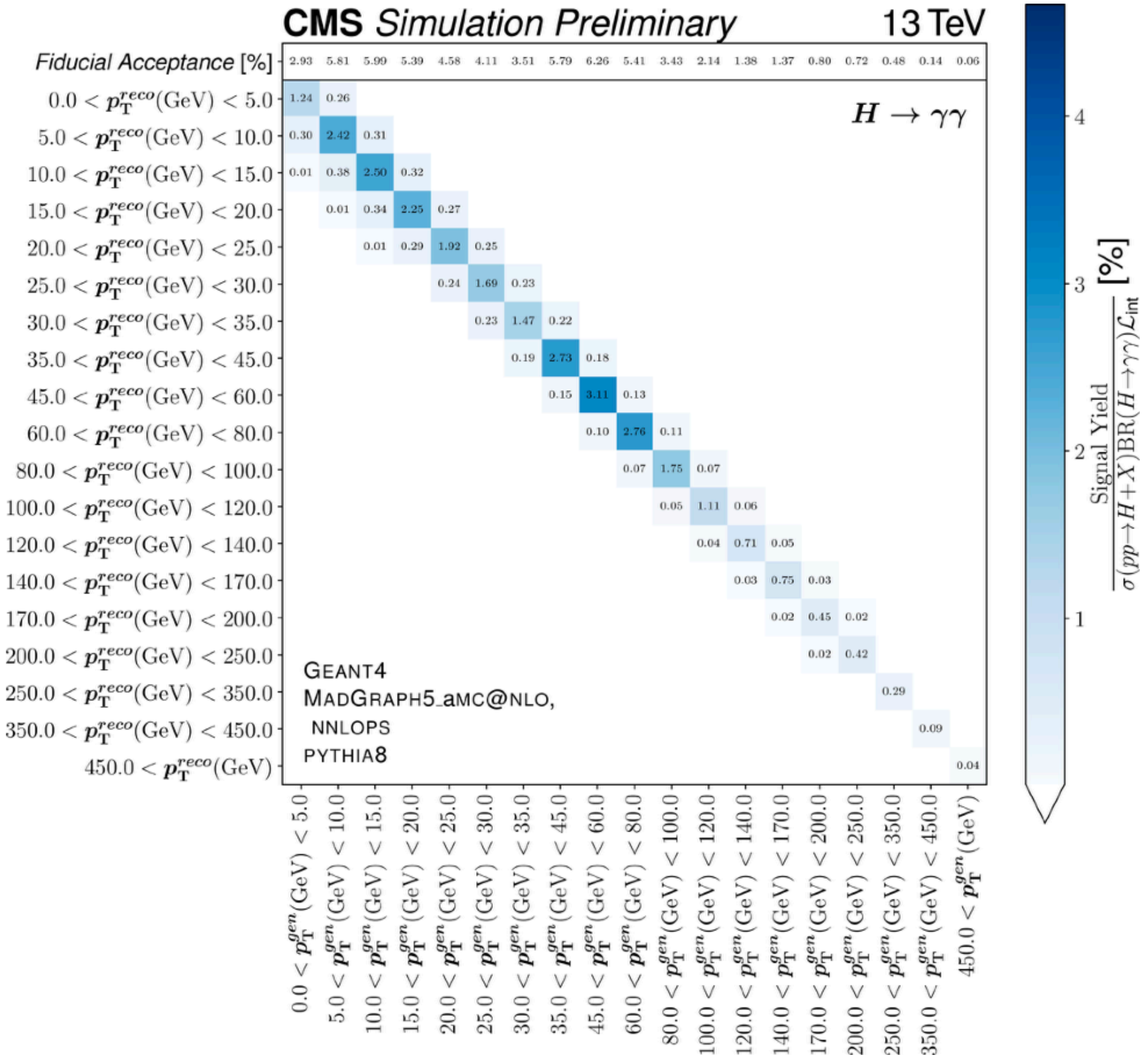
MEASURED

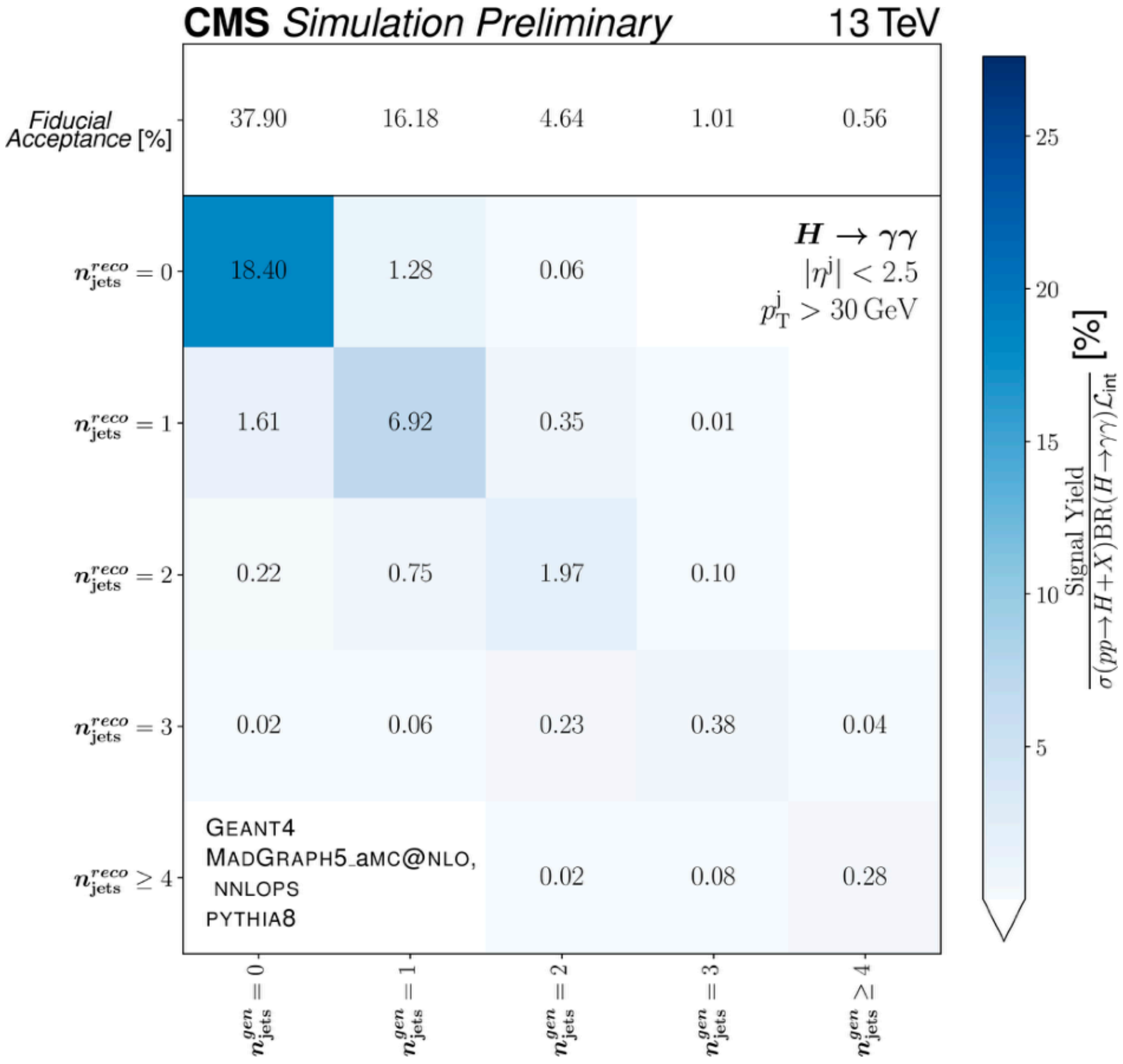
RESPONSE MATRIX = P(RECO VALUE i , TRUE VALUE j)

FROM MONTE CARLO SIMULATIONS

$$\sum_i R_{ij} = P(\text{RECO ANYWHERE} \mid \text{TRUE VALUE } j) = \varepsilon ff_j$$

Fiducial Cross Sections





Fiducial Cross Sections

$$\overrightarrow{\#\text{events}}\,(\overset{\substack{\text{RECO}\\ \text{LEVEL}\\ \downarrow}}{\text{Obs}}) = \sum_i \Big[\vec{\sigma}\,(\overset{\substack{\text{PARTICLE}\\ \text{LEVEL}\\ \downarrow}}{\text{Obs}_i}) \cdot \underset{\substack{\uparrow\\ \text{efficiencies and}\\ \text{resolution effects}}}{R_{ij}} \cdot L\Big] + \overrightarrow{\text{bkg}}\,(\text{Obs})$$

FIDUCIAL CROSS SECTIONS

<u>INCLUDE ACCEPTANCE</u> :

$$\vec{\sigma} = \vec{\sigma}\,(\underbrace{c_1, c_2, \dots, c_n}_{\text{THEORY PARAMETRIZATION}})$$

Acceptance:

- Inclusive cross section measurement: we correct for the acceptance, introducing the model dependence coming from the theory (e.g. SM) used to compute it
- Fiducial cross sections: the acceptance is in the “fiducial cross section” vector (we “don’t correct” for the acceptance) —> no model dependence on it
- Re-usability: whoever wants to compare the prediction of a new model with data needs to re-introduce the acceptance computed on the new model

Residual model dependence

Unfolding / Response matrix:

Move from reconstruction level (x) to particle level (y) (after parton showering, generally defined as particles with $c\tau > 10\text{mm}$)

$$R_{ij}(c) = \int d\phi\ \rho_j(\phi | c)\varepsilon_{ij}(\phi)$$

signal distribution

efficiencies

Model dependence if the response matrix depends on the theory parameters (c).

One can reduce the model dependence by:

- making small bins
  (flat ρ within the bin)
- having flat efficiency within the bins
  (flat ε within the bin)

Signal shape:

take as an example a shape analysis fitting a mass peak. The shape of the signal depends on its kinematics and the kinematics can depend on the parameters of the theory

Background:

the signal extraction removes the background component
model dependence if the theory parameters affect the background normalisation or its shape

STXS are not fiducial differential cross sections

Fiducial cross sections:

- are optimised for maximal theory independence
- acceptance corrections are minimised by using simple selection cuts
  avoid if possible the use of MVA/ML
- measurements are unfolded to a phase space as close as possible to the fiducial volume measured
- almost completely insensitive to the production mode
  (good for model independence but, e.g for the SM it translates into a maximal sensitivity to ggF and very limited to the other production modes)

STXS:

- allows the use of MVAs at the cost of having larger acceptance corrections
- are inclusive in Higgs decay —> simplify the combination of bins
- are agnostic to the details of the production modes (kinematic bins)

Observables vs. physics

Fiducial XSections are measured as a function of different observables sensitive to different theory parameters:

QCD radiation:

$p_T(H)$, N_{jets},

one jet observable $p_T(j_{leading})$, $Y(j_{leading})$,

two jets observables $p_T(j_{\text{sub-eading}})$,$Y(j_{\text{sub-eading}})$

proton PDF

$|Y(H)|$

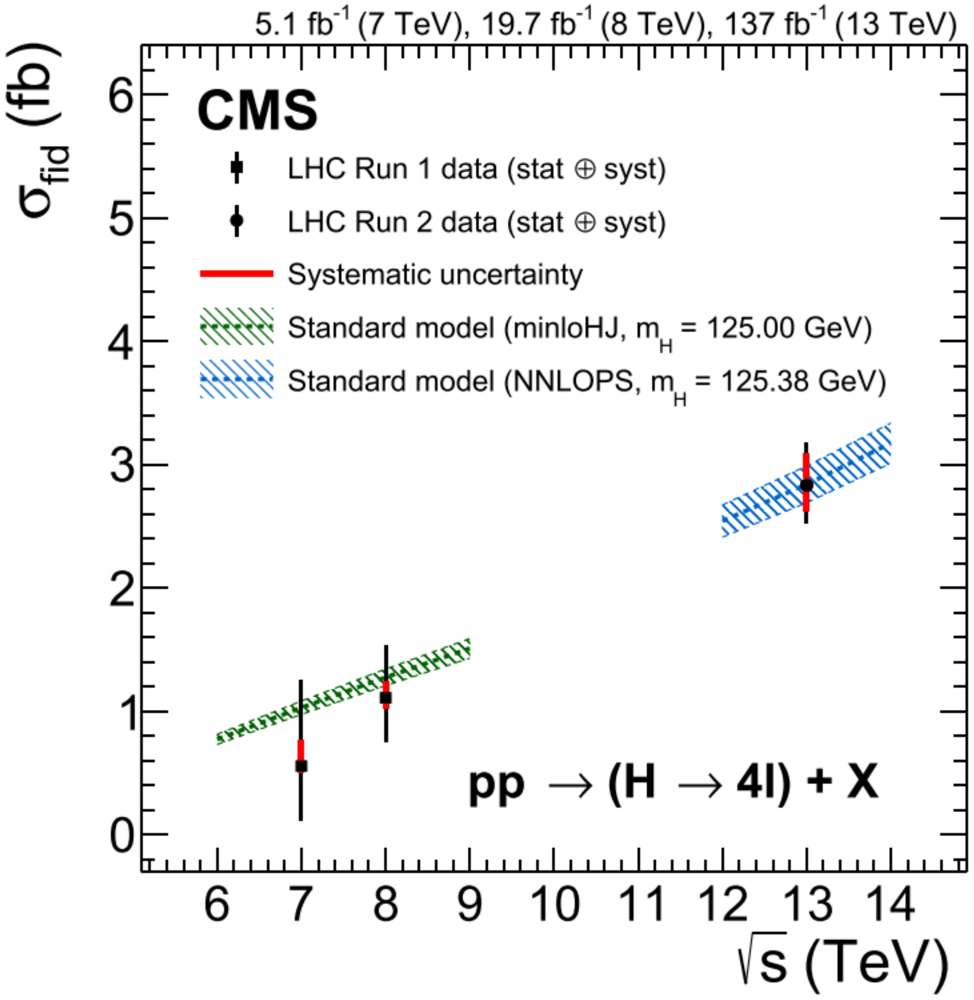
VBF production

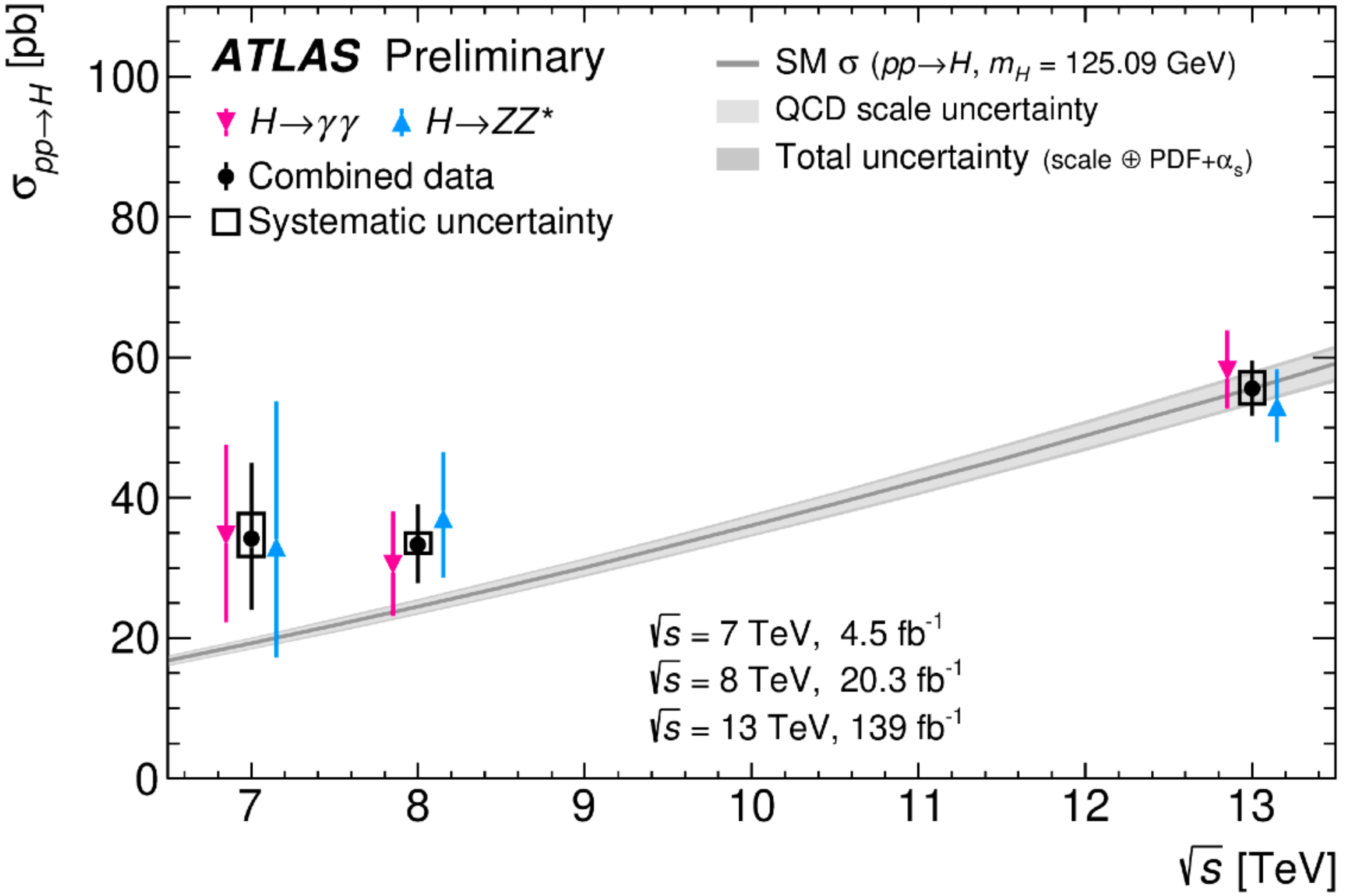
two jets observables $|\Delta\phi(H,j_0j_1)|$, $|\overline{\eta}(j_0j_1)-\eta(H)|$, $M(j_0j_1)$

spin, CP:

$|\cos(\vartheta^*)|$, $|\Delta\phi(j_0,j_1)|$

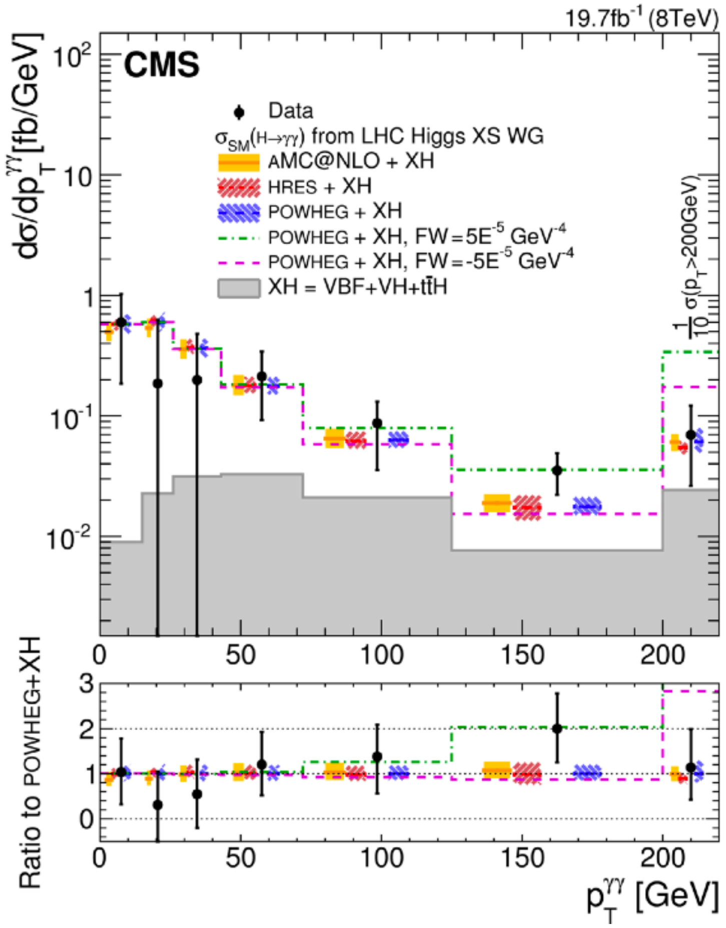
Fiducial Total Cross Sections Example: H→ZZ→4leptons





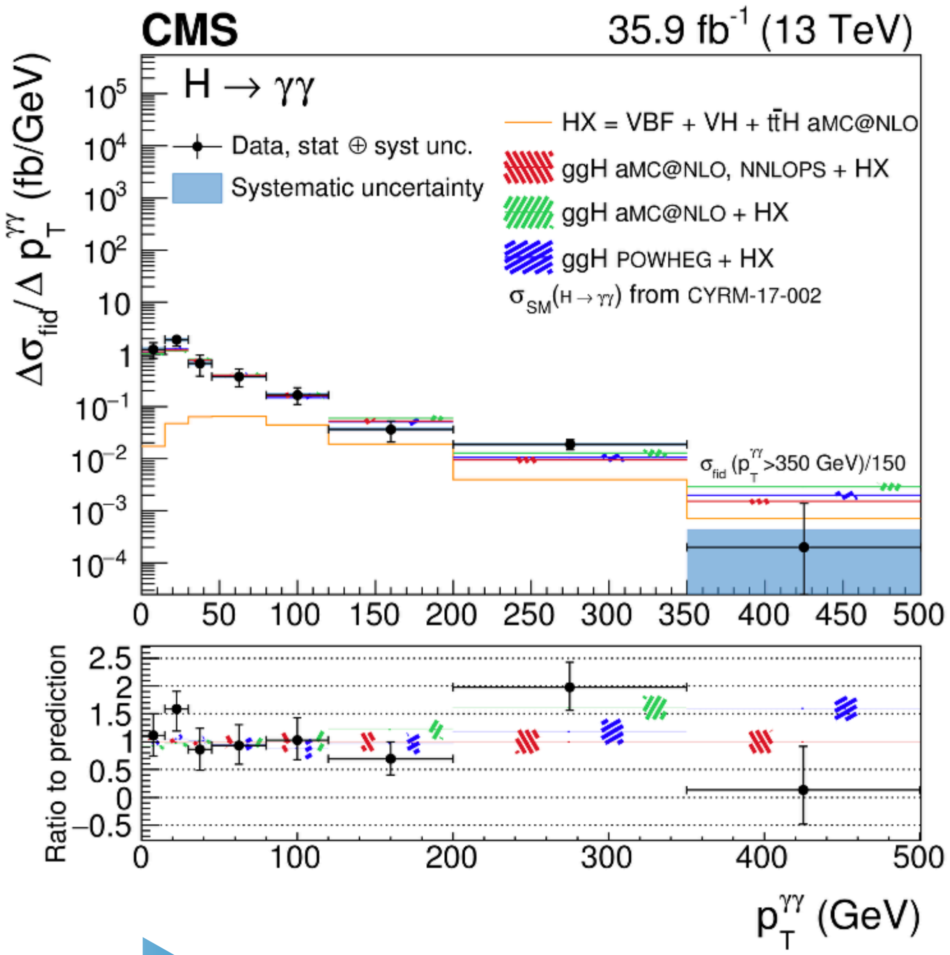
Evolution: fiducial differential production cross section H→γγ

HIG-14-016



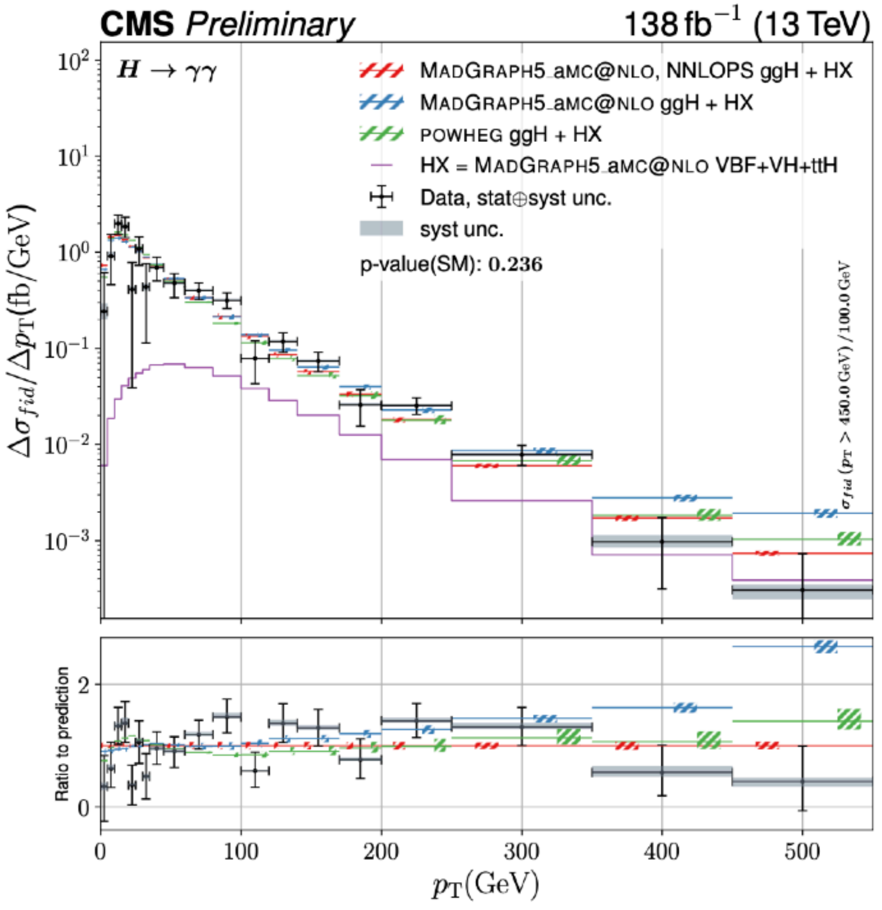
Run 1

HIG-17-025



2016

HIG-19-016

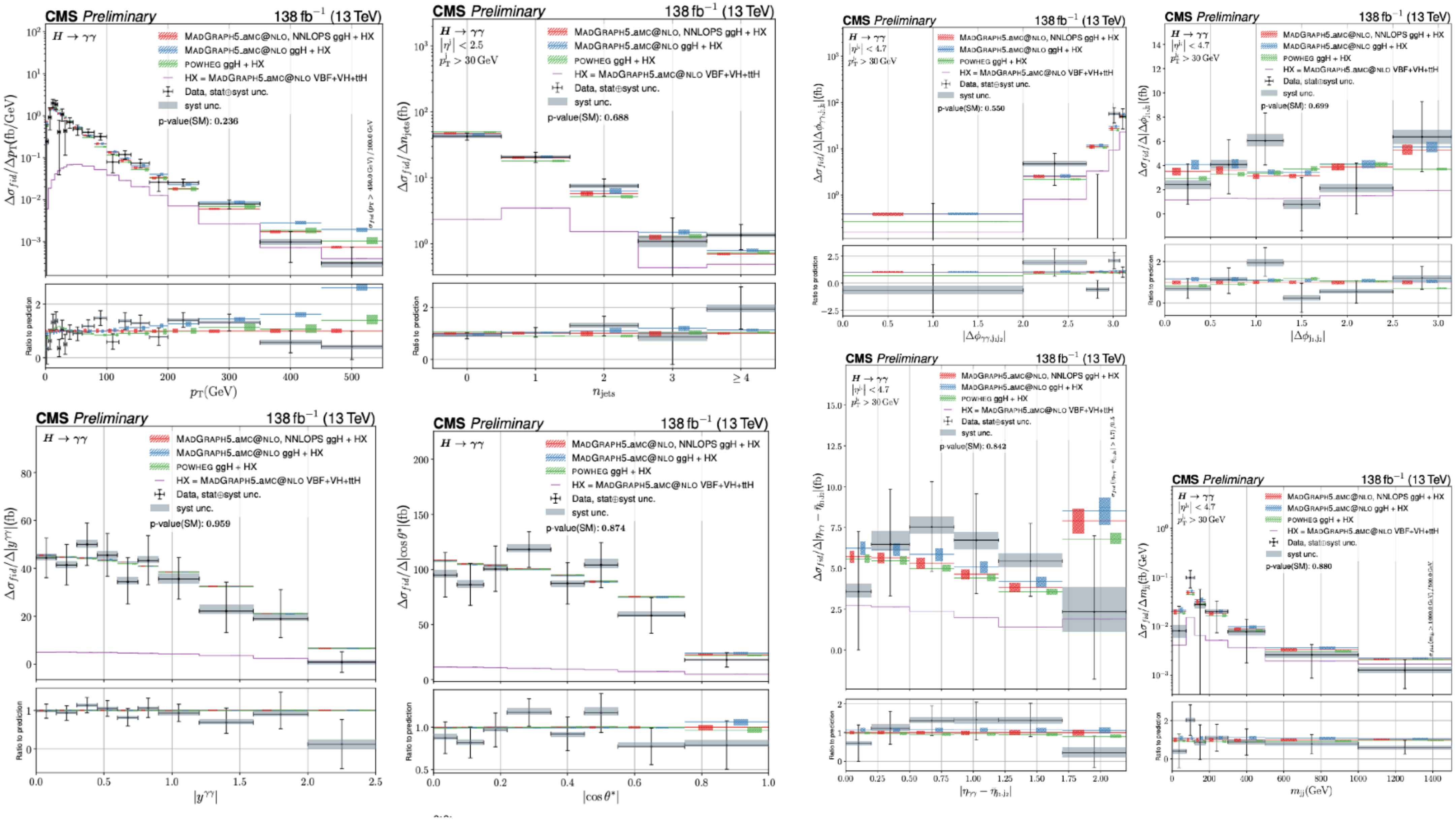


Full Run 2

Example: H→γγ

Large statistics and excellent resolution allow to sample the phase space in all sorts of ways.
~25 1D cross sections and ~5 2D cross sections

HIG-19-016



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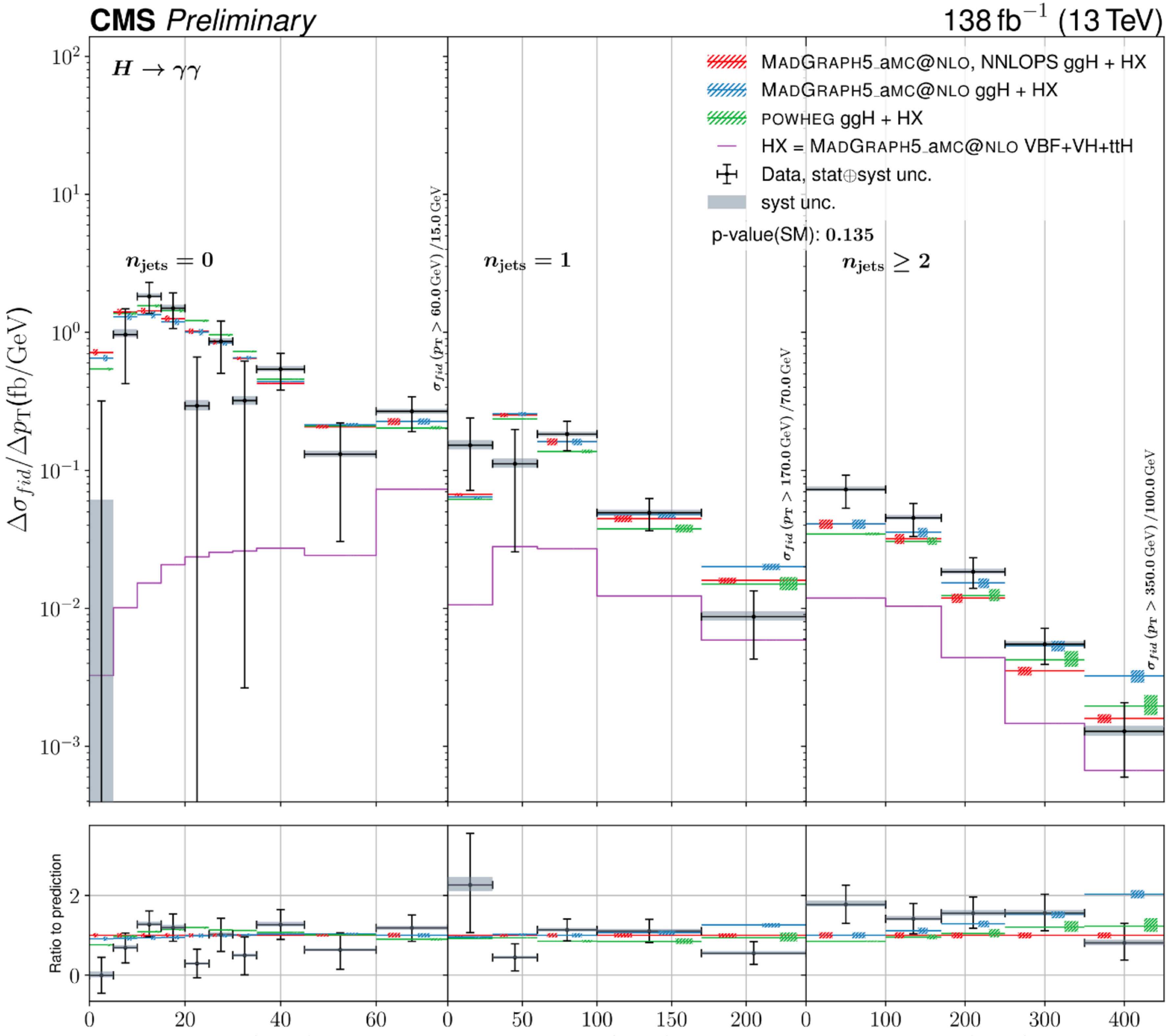
Multidimensional fiducial xsections

Number of dimensions limited by the available statistics

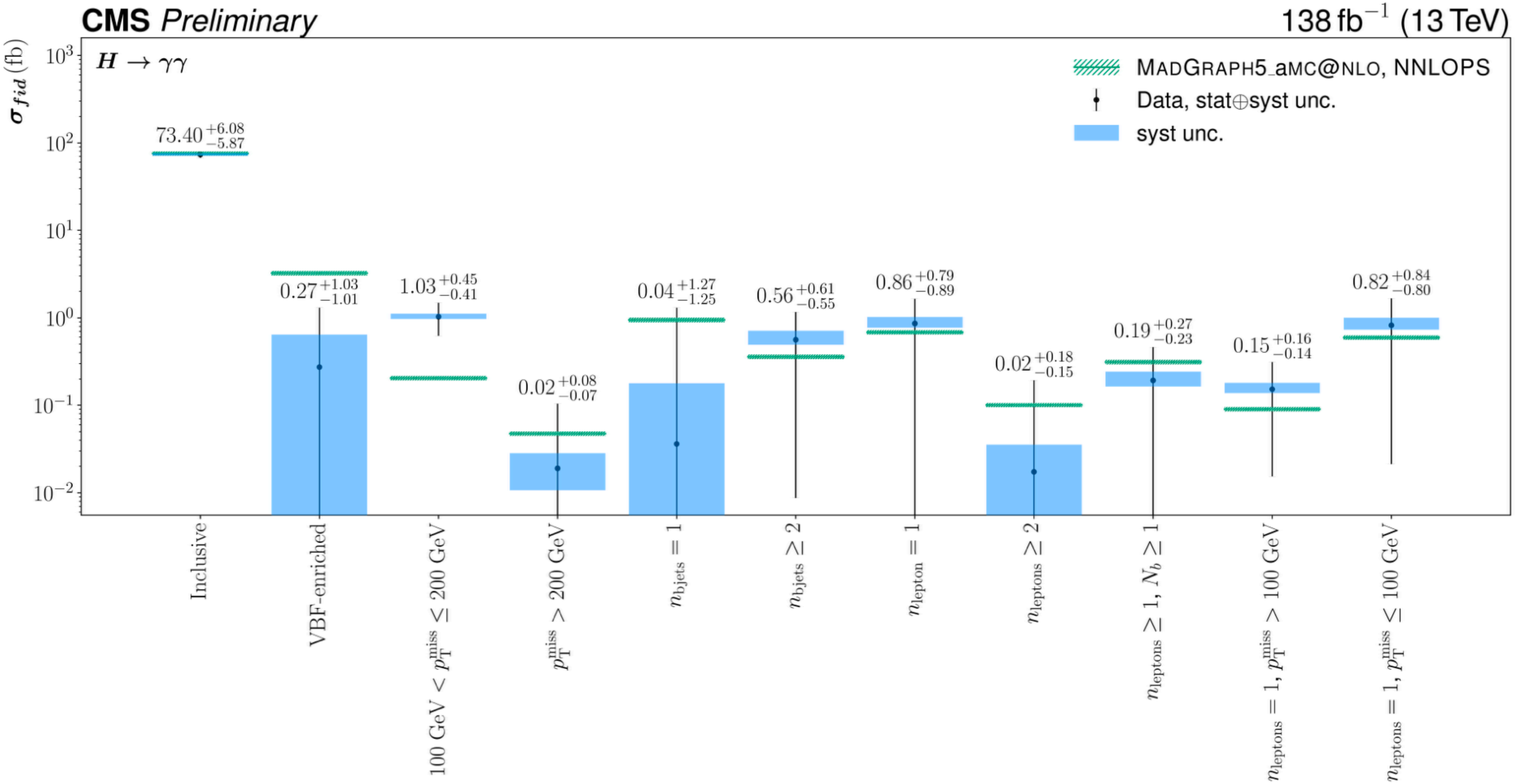
HIG-19-016



Dedicated regions

Also probed dedicated regions of the fiducial phase space

HIG-19-016



Example: H→WW

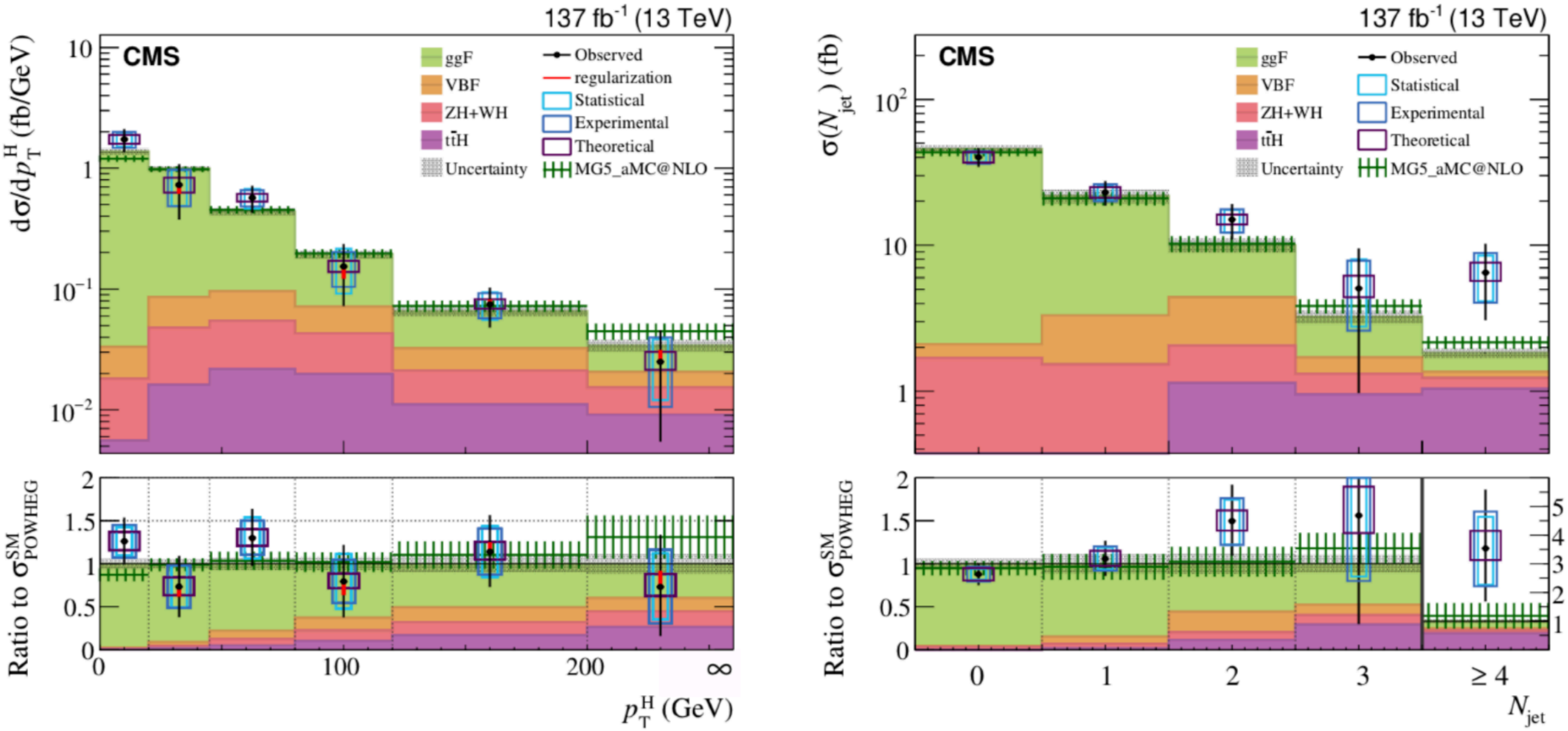
BR(H→WW) ~22%, BR(H→WW→eμ $\nu\nu$) ~1%

Signal extracted with a 2D fit (m_T, m_{ll})

Large WW, top bkg and fake lepton backgrounds

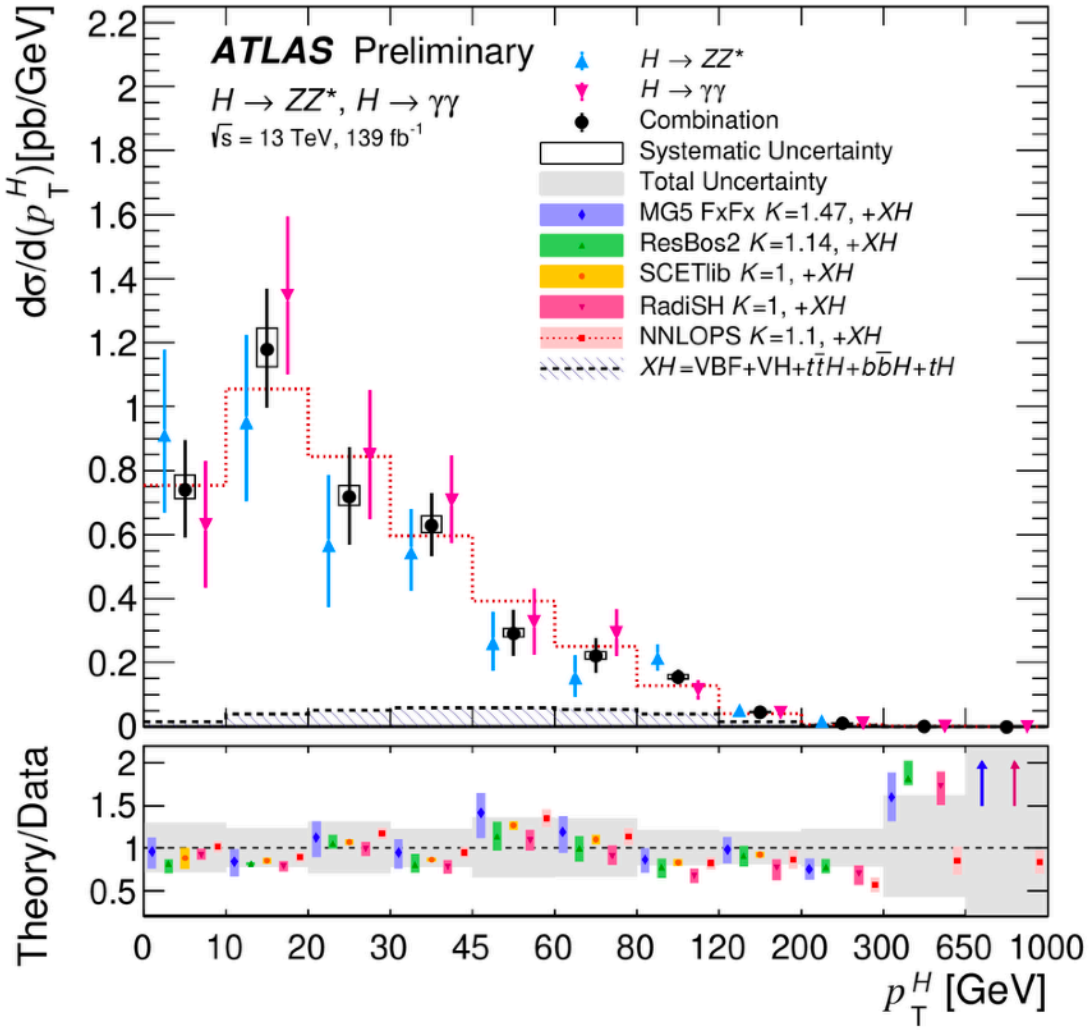
Neutrinos in the final state severely affects pT(H) measurement —> Regularised unfolding

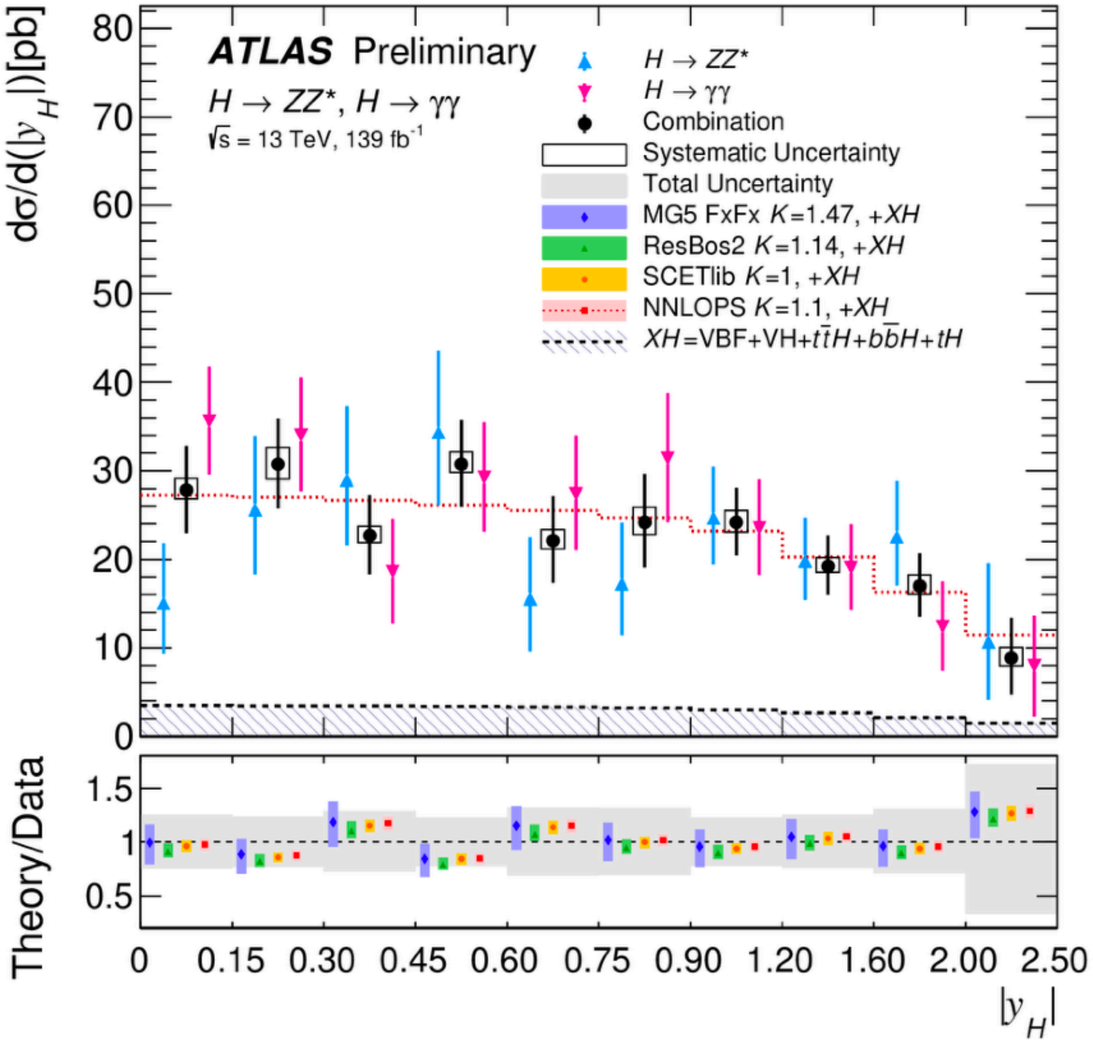
CMS-HIG-19-002



Combination spectra: H→ZZ→4leptons + H→γγ

The diphoton and H—>4l differential production cross sections all probe different phase spaces. So they are first extrapolated to 4π (introduce a model dependence!) and then combined by fitting simultaneously the signal component in the observable bins.

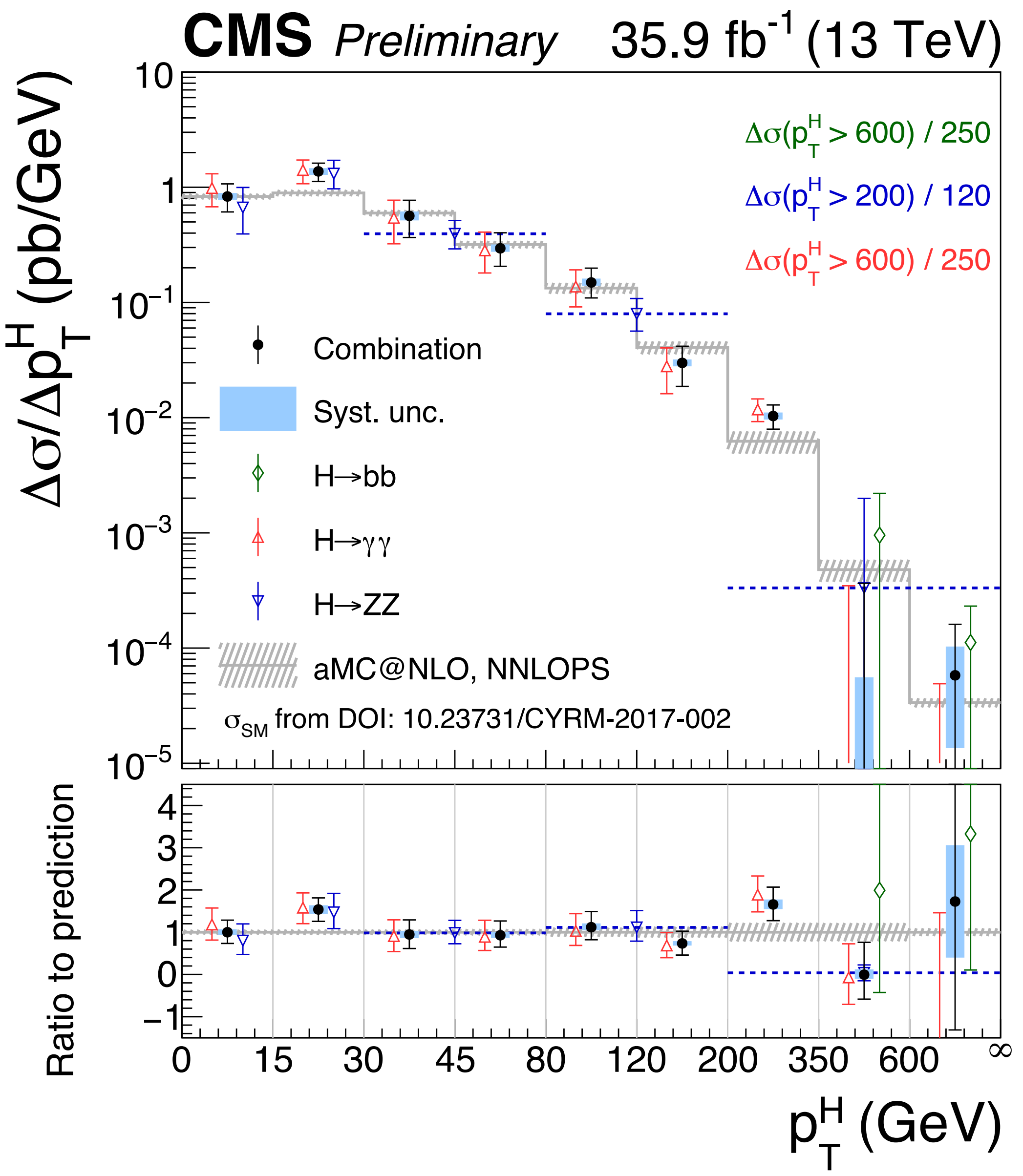




Combination spectra: H→ZZ→4leptons + H→γγ+ggH→bb

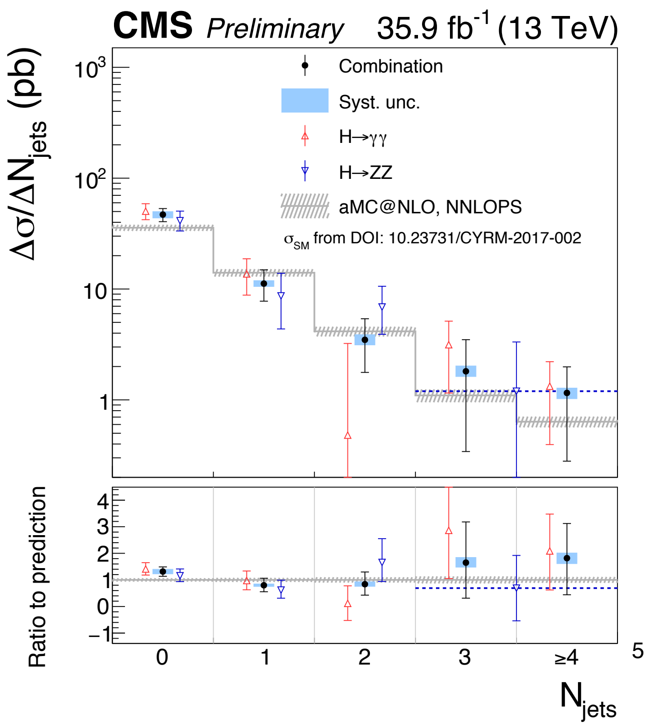
Older example: diphoton, H—>4l and boosted ggH—>bb differential production cross sections.

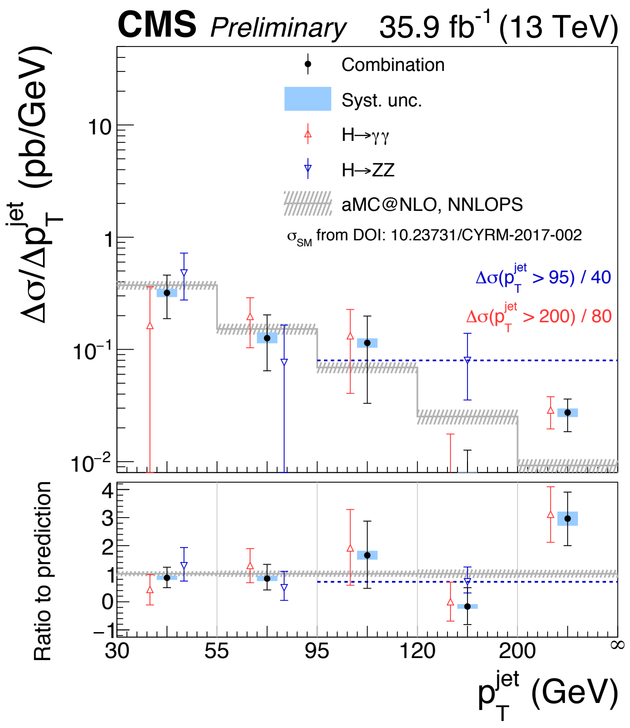
First extrapolated to 4π and then combined by fitting simultaneously the signal component in the observable bins.



H→γγ, H→4l, ggH→bb

$$\mathcal{L}(\vec{\Delta\sigma}|\vec{\theta}) = \prod_{m=1}^{n_c} \mathcal{L}_m(\vec{\Delta\sigma}|\vec{\theta}) \cdot \mathrm{pdf}(\vec{\theta})$$





Physics models: Interpretation

BSM physics can leave the total Higgs total production cross section unchanged w.r.t SM, but still distort the differential spectra.

Basic idea:

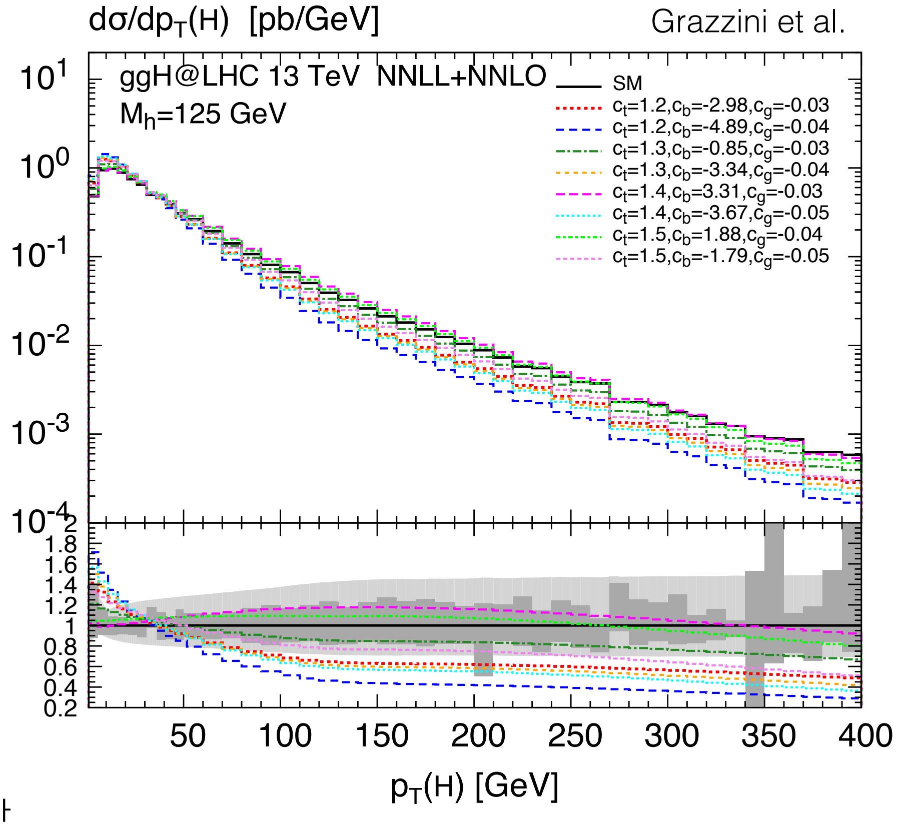
“parametrization”
write xsec(couplings)

Theory predictions:
couplings modifications (kt, kb, kc, kg)
or EFT coefficients

Fit xsec to data
and extract parameters

Examples:

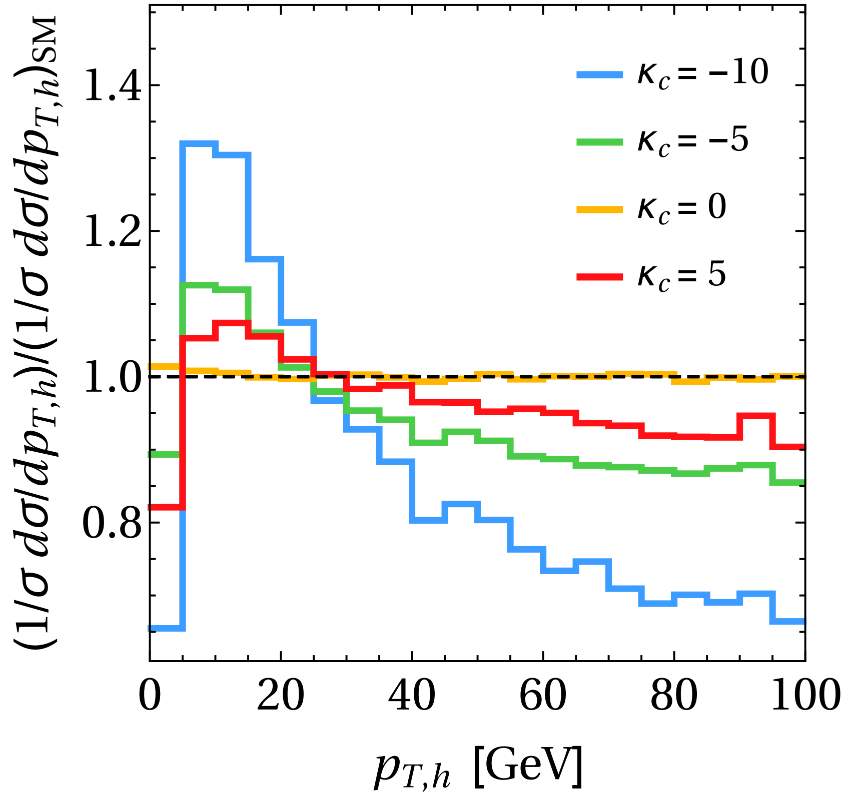
How the pT spectrum changes changing k_t, k_g, k_b



Grazzini et al.

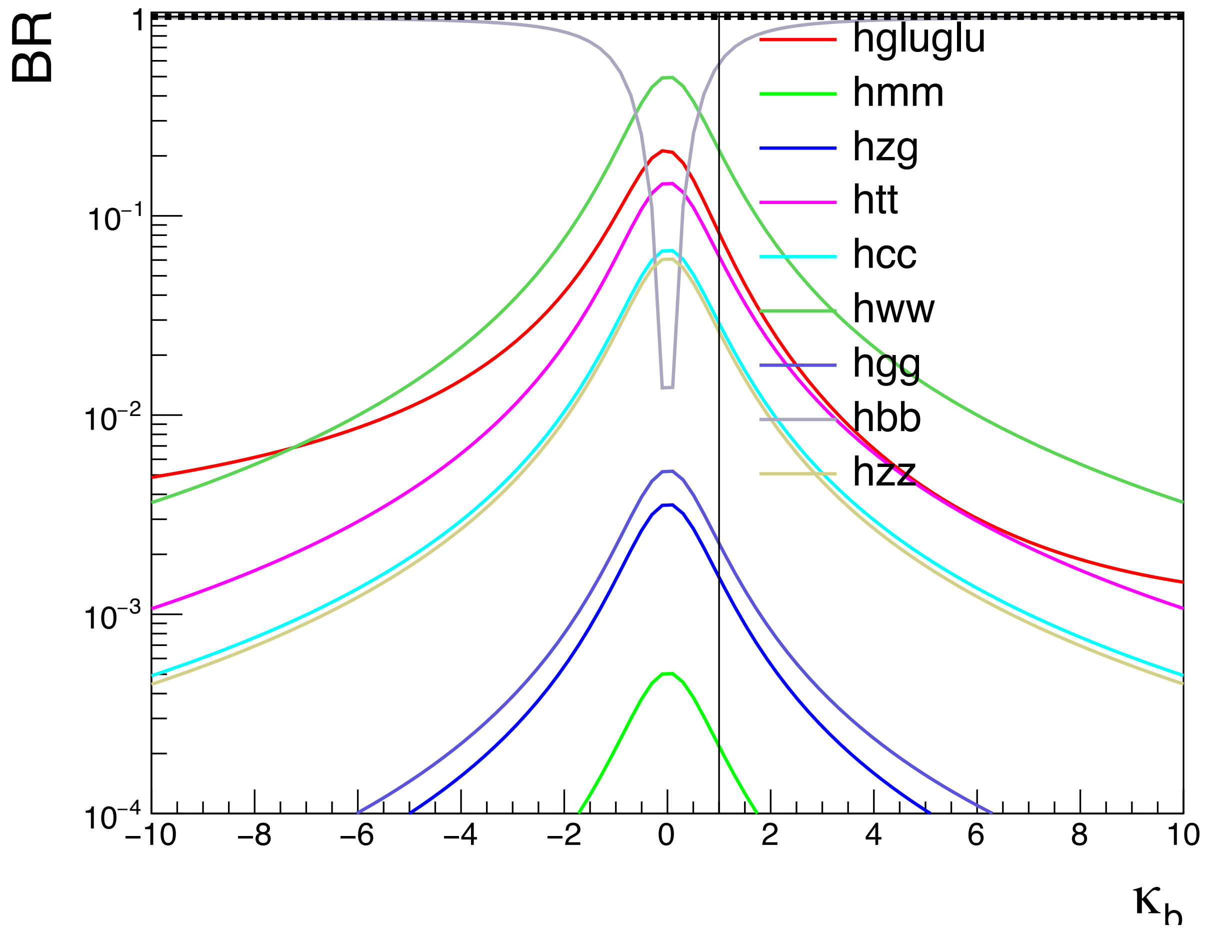
How the pT spectrum changes changing k_b, k_c

Haisch et al.



Interpretations and fits

Inclusive cross sections are already very sensitive to couplings !
In this case changing k_b immediately saturates the full width Γ

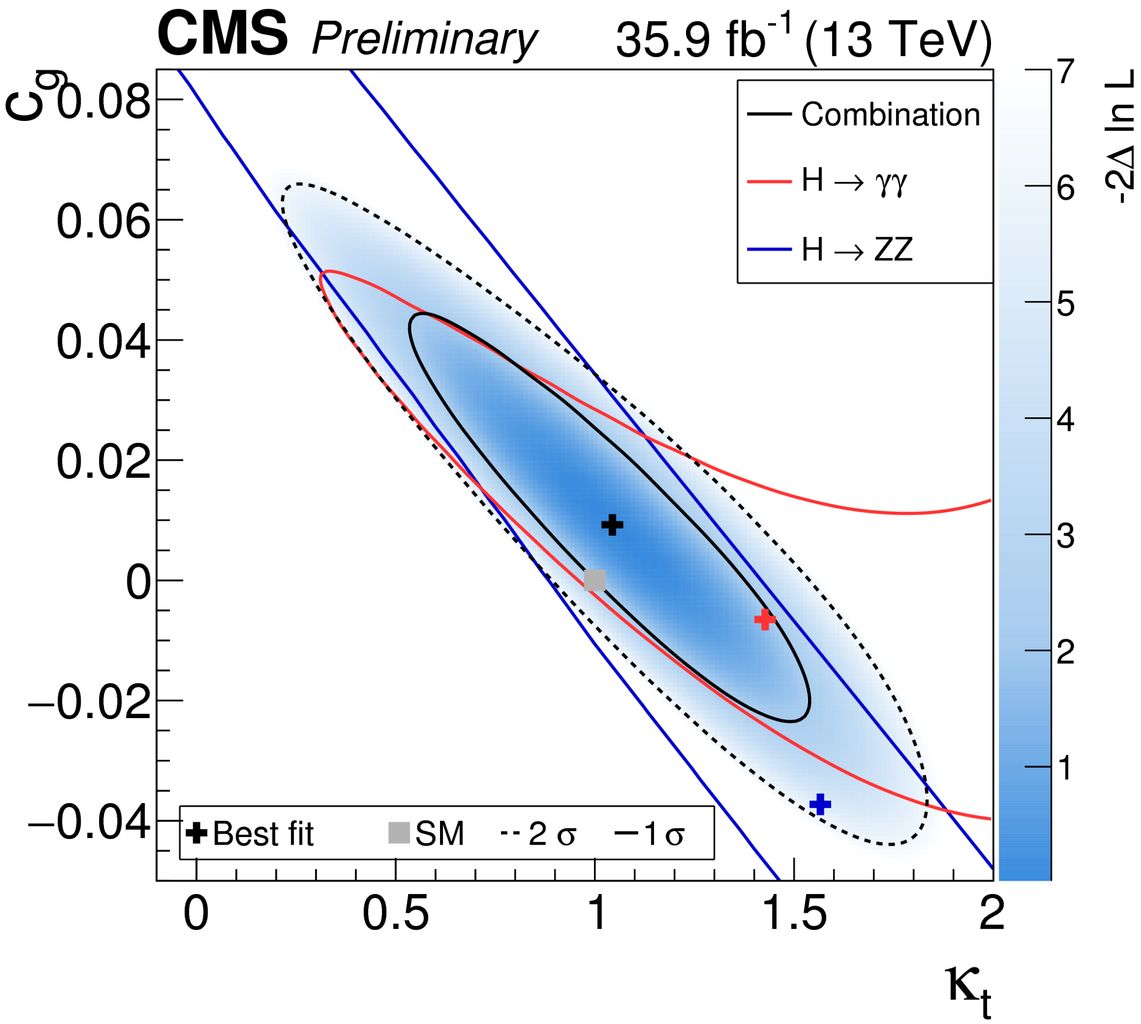


The most general parametrization to be fitted on data is: xsec(couplings) x BR (couplings)

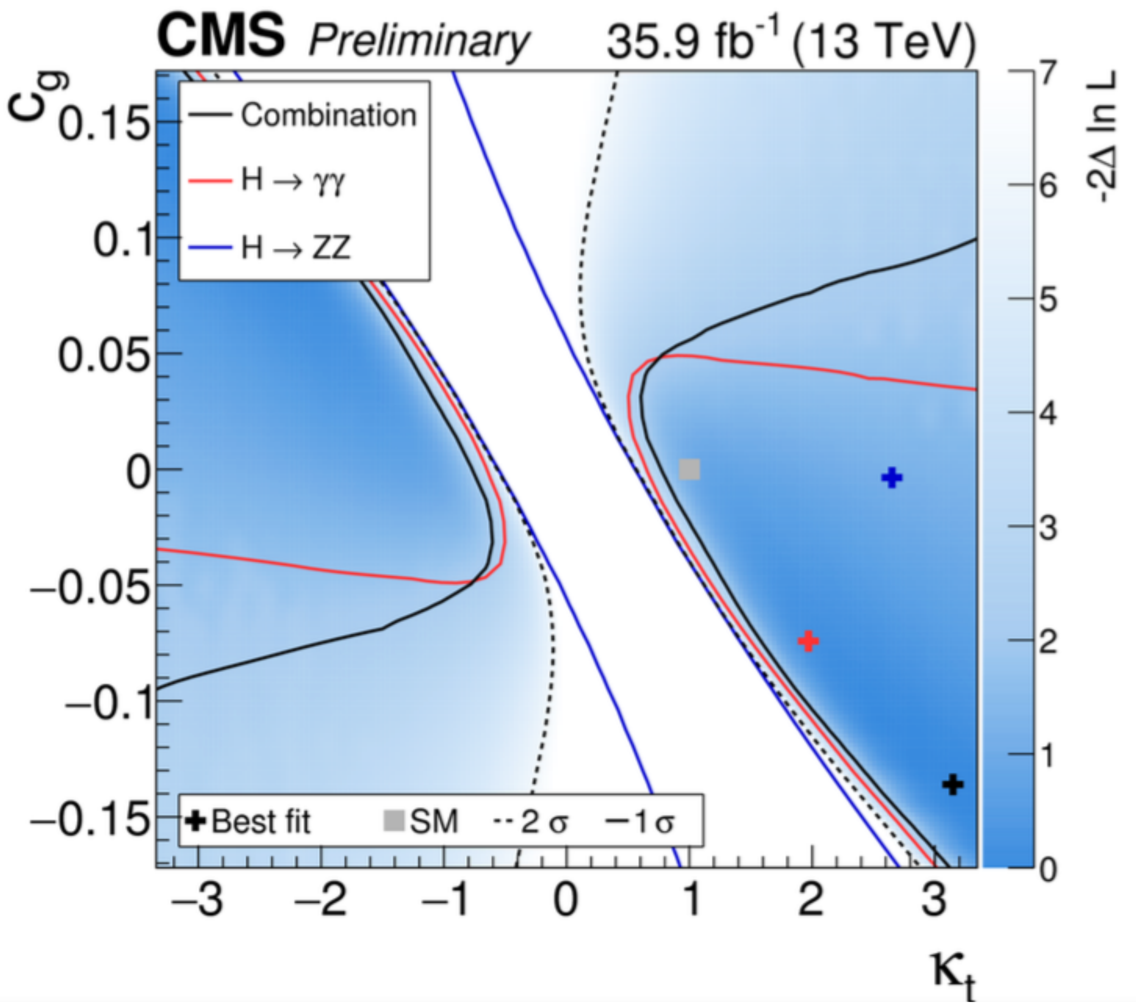
Interpretations and fits: k_t, c_g, k_b

$$12c_g + \kappa_t \simeq 1$$

Fit k_t, c_g
Assume no BSM contributions

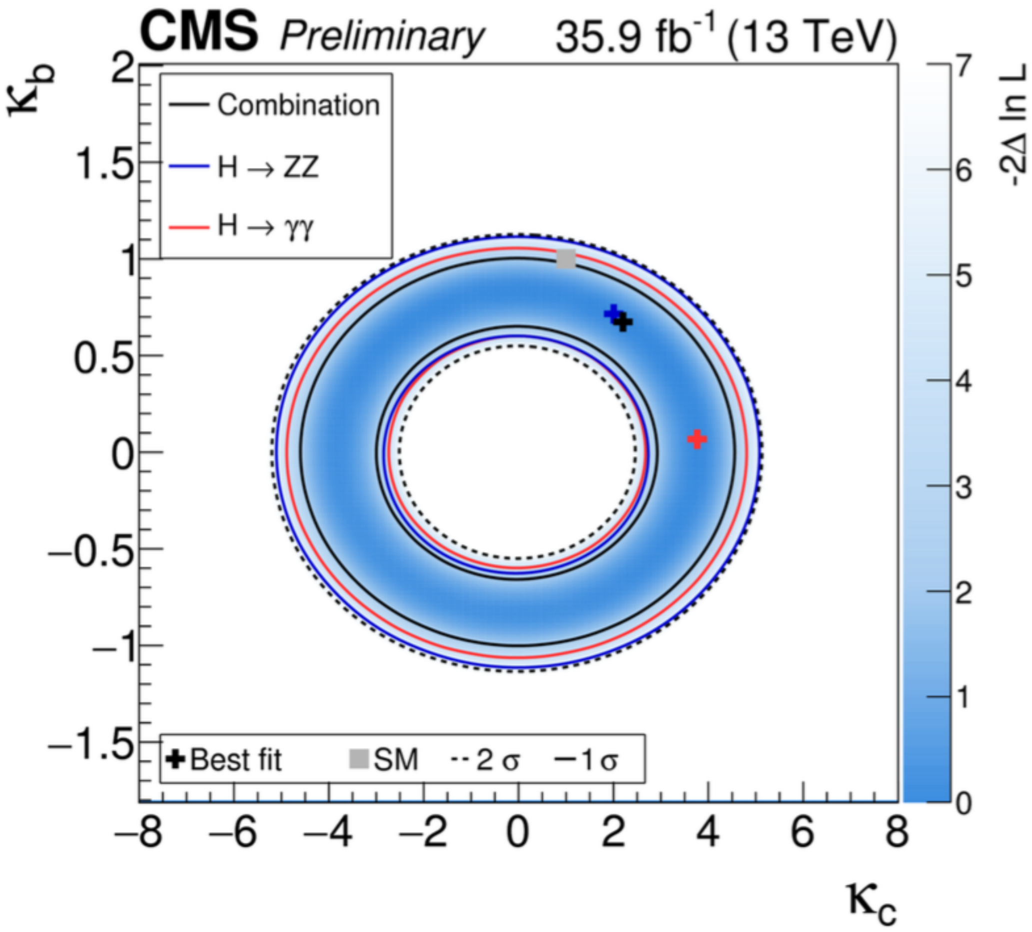


Fit k_g, c_g, and $BR_{\gamma\gamma,4l}$ (k_t, c_g)
Profile overall normalisation and total width



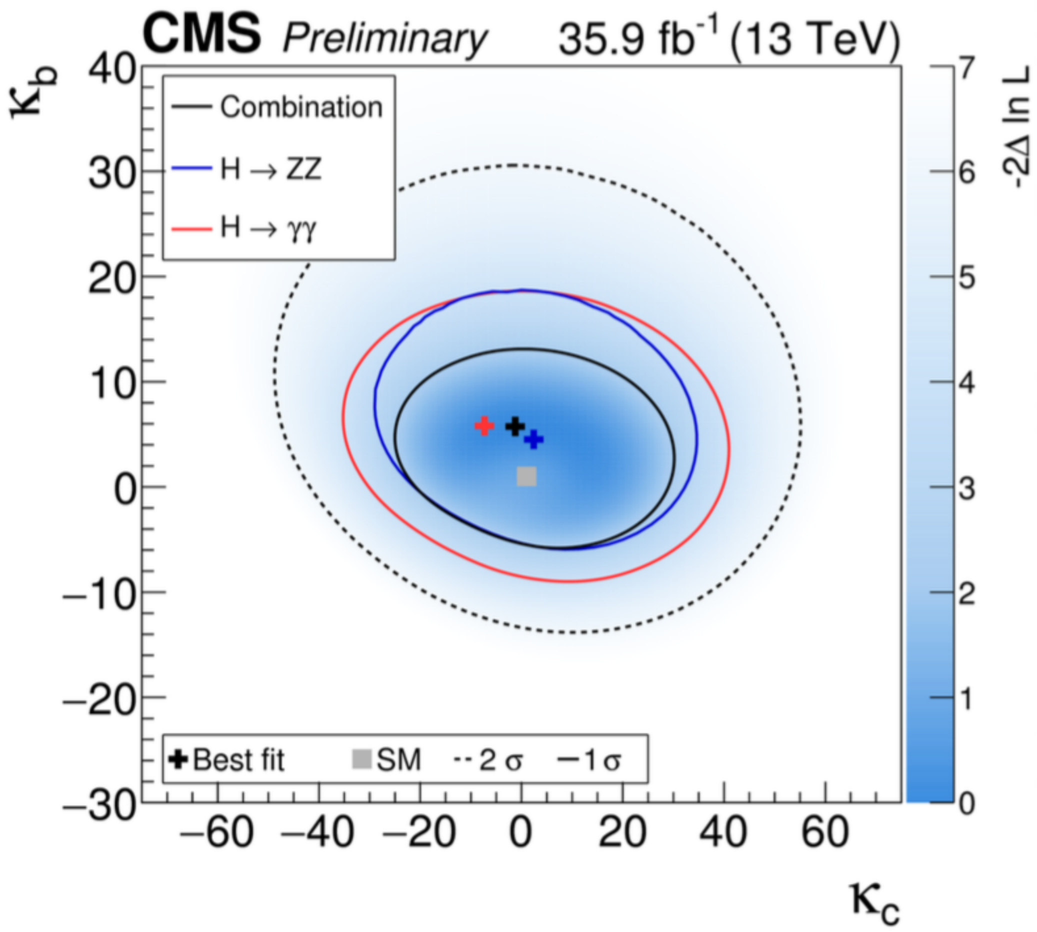
Interpretations and fits: k_b, k_c

Fit k_b, k_c, and use $BR_{\gamma\gamma,4l}$ (k_b, k_c)
Assume no BSM contributions



Shape + Normalization fit

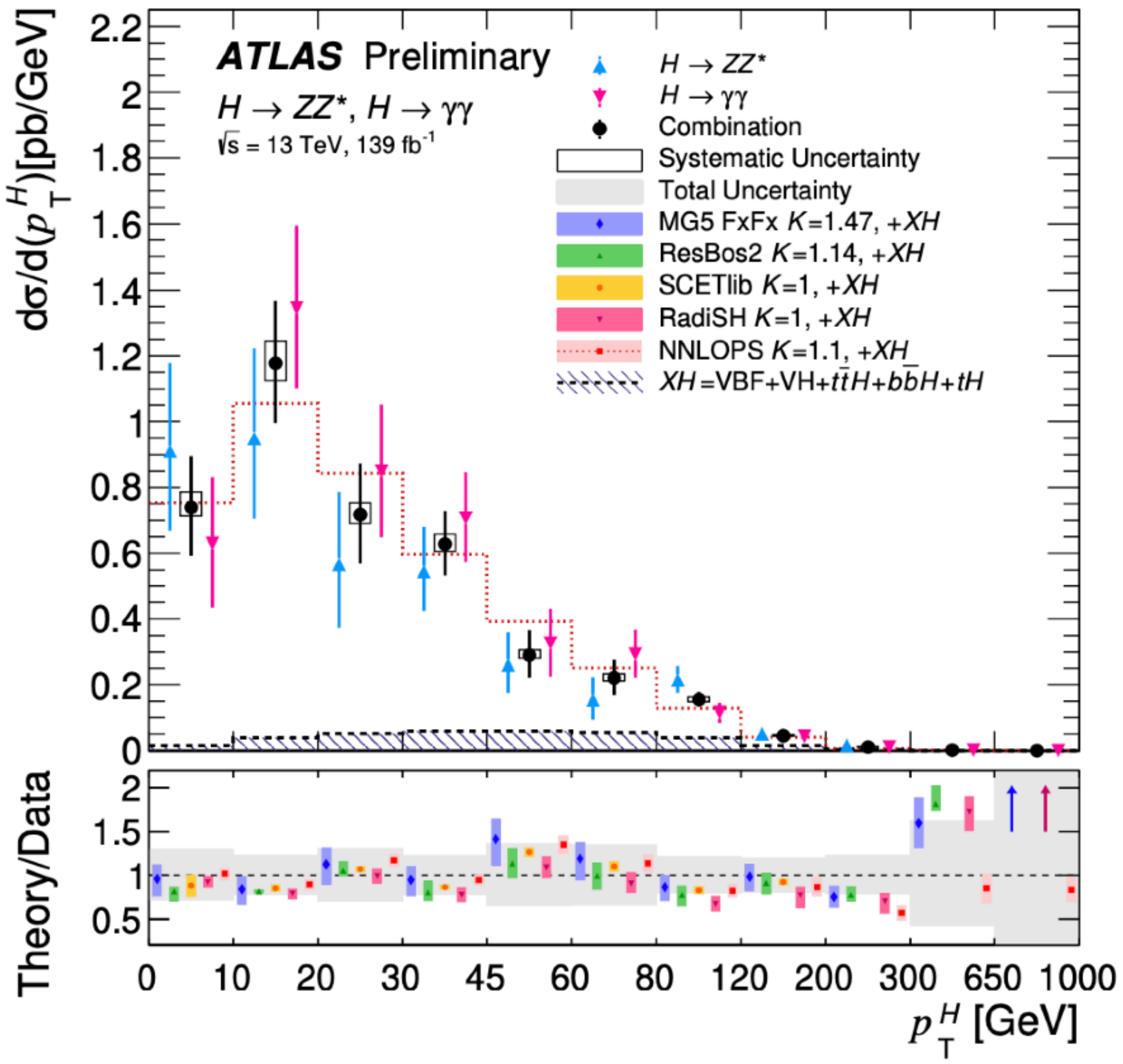
Fit k_b, k_c, and fit $BR_{\gamma\gamma}$, BR_{4l}
Profile overall normalization and total width

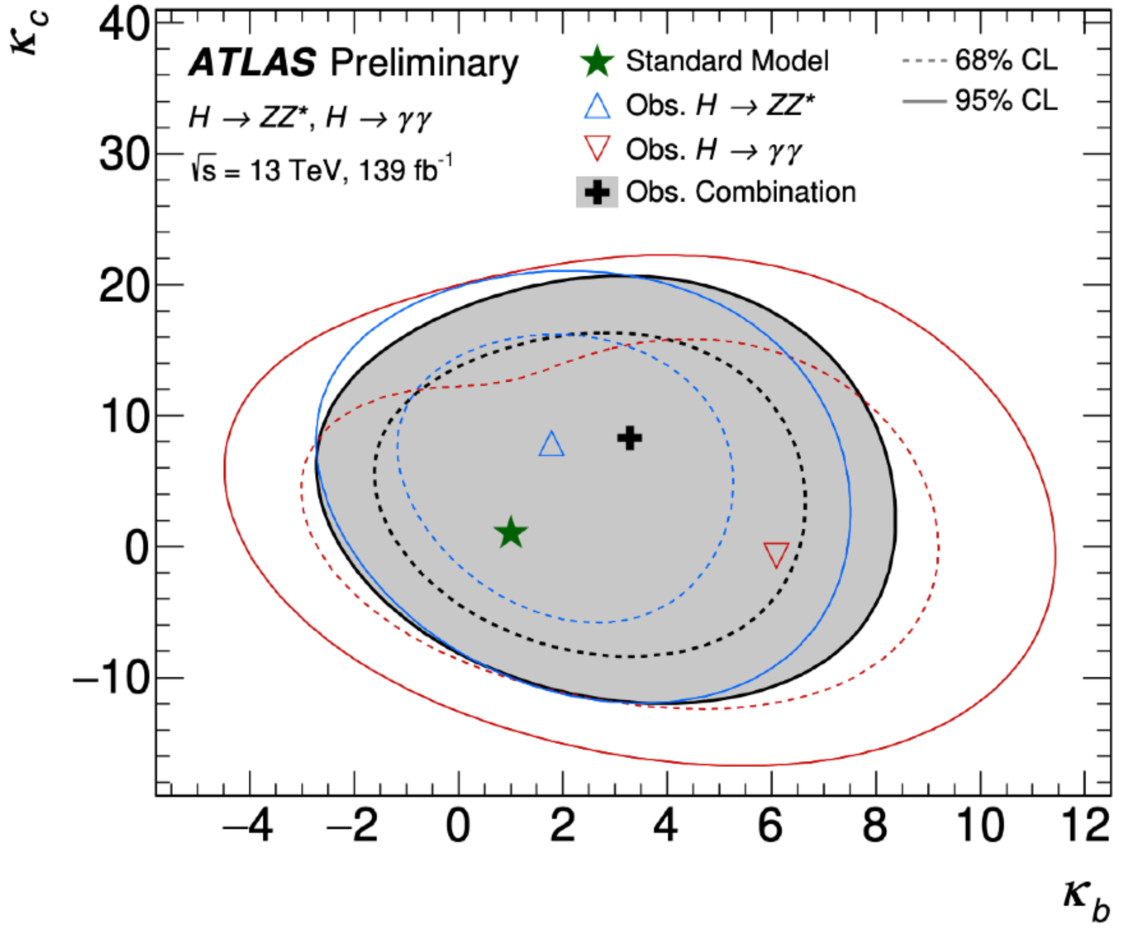


Shape only fit

Interpretations and fits: k$_b$, k$_c$

Same procedure by ATLAS with full Run2 statistics



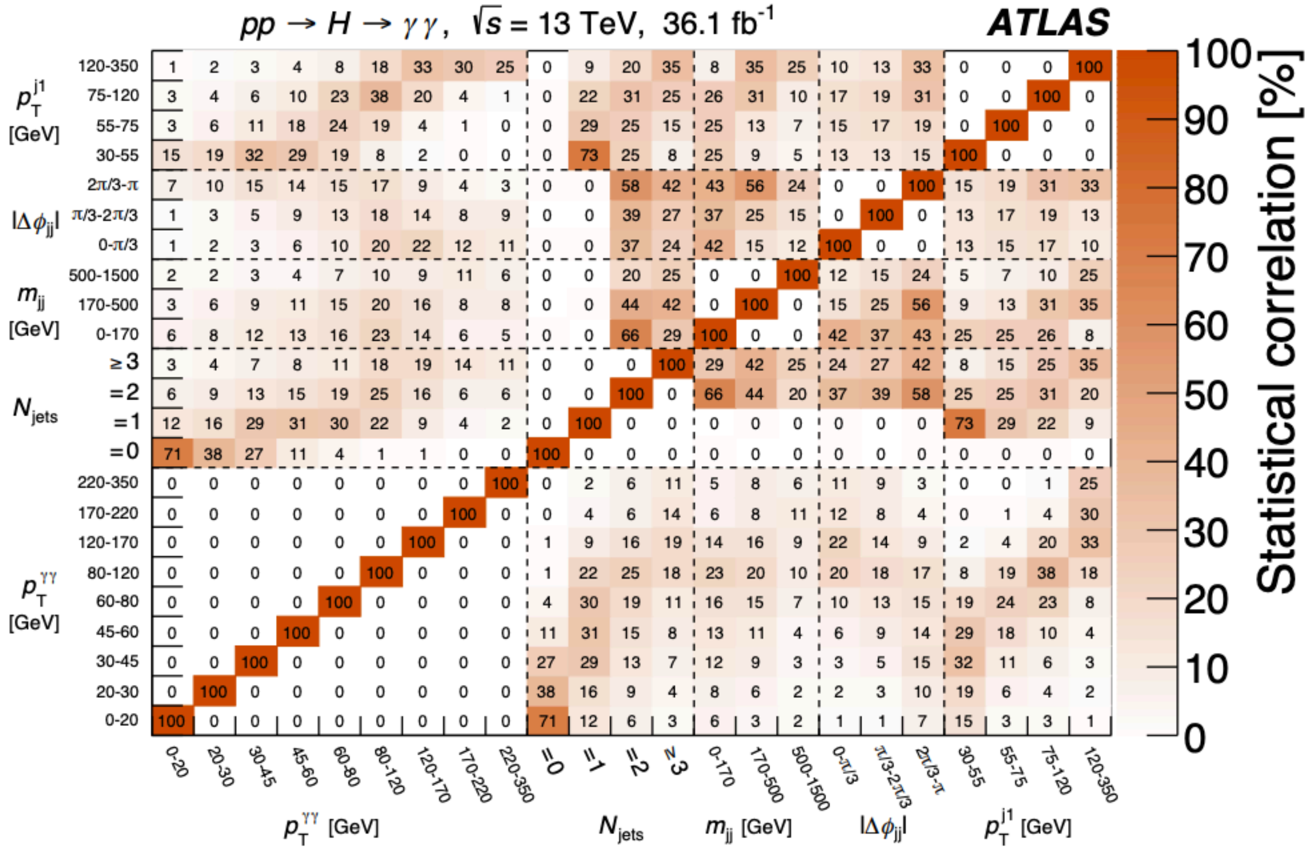


Fit n fiducial differential xsec

Search for anomalous couplings (a CP-odd component) that change event rates, kinematics and jet spectra.

Fit to 5 differential cross sections:
pT(γγ), Njets, mjj, |Δφjj |, pT(j1)

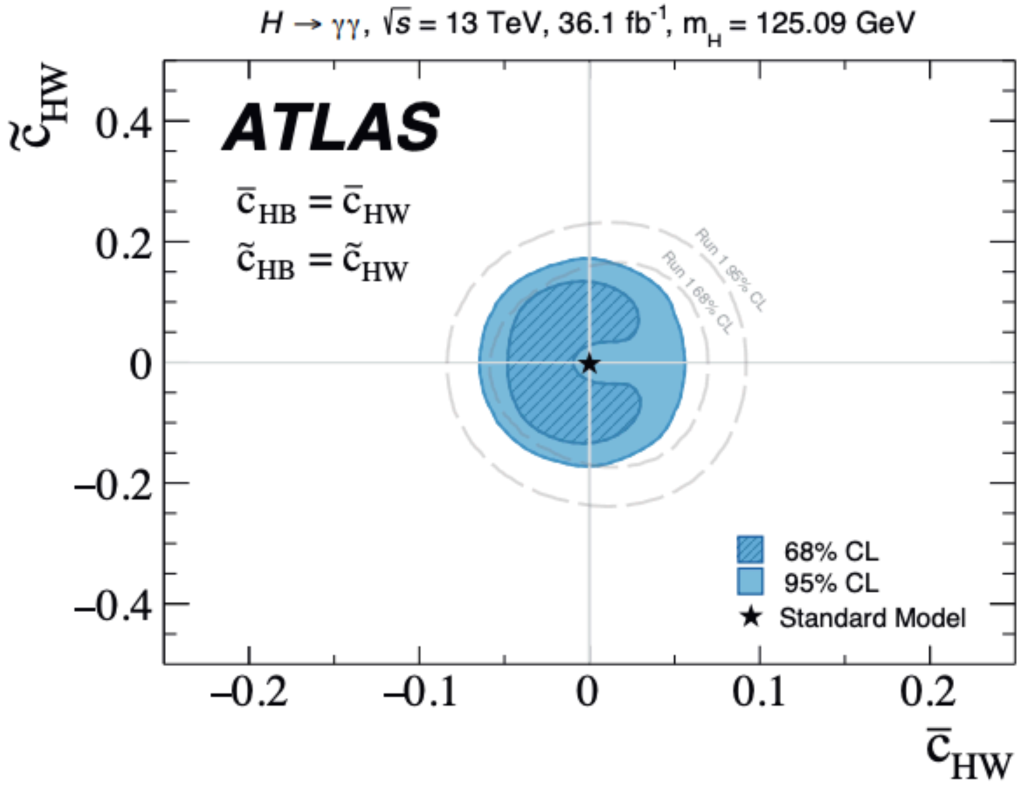
$$\mathcal{L} = \frac{1}{\sqrt{(2\pi)^k\,|C|}} \exp\left(-\frac{1}{2}\left(\vec{\sigma}_{\rm data} - \vec{\sigma}_{\rm pred}\right)^T C^{-1} \left(\vec{\sigma}_{\rm data} - \vec{\sigma}_{\rm pred}\right)\right)$$



		$p_T^{\gamma\gamma}$ [GeV]									N_{jets}				m_{jj} [GeV]			$\|\Delta\phi_{jj}\|$			p_T^{j1} [GeV]			
		0-20	20-30	30-45	45-60	60-80	80-120	120-170	170-220	220-350	=0	=1	=2	≥3	0-170	170-500	500-1500	0-π/3	π/3-2π/3	2π/3-π	30-55	55-75	75-120	120-350
p_T^{j1} [GeV]	120-350	1	2	3	4	8	18	33	30	25	0	9	20	35	8	35	25	10	13	33	0	0	0	100
	75-120	3	4	6	10	23	38	20	4	1	0	22	31	25	26	31	10	17	19	31	0	0	100	0
	55-75	3	6	11	18	24	19	4	1	0	0	29	25	15	25	13	7	15	17	19	0	100	0	0
	30-55	15	19	32	29	19	8	2	0	0	0	73	25	8	25	9	5	13	13	15	100	0	0	0
$\|\Delta\phi_{jj}\|$	2π/3-π	7	10	15	14	15	17	9	4	3	0	0	58	42	43	56	24	0	0	100	15	19	31	33
	π/3-2π/3	1	3	5	9	13	18	14	8	9	0	0	39	27	37	25	15	0	100	0	13	17	19	13
	0-π/3	1	2	3	6	10	20	22	12	11	0	0	37	24	42	15	12	100	0	0	13	15	17	10
m_{jj} [GeV]	500-1500	2	2	3	4	7	10	9	11	6	0	0	20	25	0	0	100	12	15	24	5	7	10	25
	170-500	3	6	9	11	15	20	16	8	8	0	0	44	42	0	100	0	15	25	56	9	13	31	35
	0-170	6	8	12	13	16	23	14	6	5	0	0	66	29	100	0	0	42	37	43	25	25	26	8
N_{jets}	≥3	3	4	7	8	11	18	19	14	11	0	0	0	100	29	42	25	24	27	42	8	15	25	35
	=2	6	9	13	15	19	25	16	6	6	0	0	100	0	66	44	20	37	39	58	25	25	31	20
	=1	12	16	29	31	30	22	9	4	2	0	100	0	0	0	0	0	0	0	0	73	29	22	9
	=0	71	38	27	11	4	1	1	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0
$p_T^{\gamma\gamma}$ [GeV]	220-350	0	0	0	0	0	0	0	0	100	0	2	6	11	5	8	6	11	9	3	0	0	1	25
	170-220	0	0	0	0	0	0	0	100	0	0	4	6	14	6	8	11	12	8	4	0	1	4	30
	120-170	0	0	0	0	0	0	100	0	0	1	9	16	19	14	16	9	22	14	9	2	4	20	33
	80-120	0	0	0	0	0	100	0	0	0	1	22	25	18	23	20	10	20	18	17	8	19	38	18
	60-80	0	0	0	0	100	0	0	0	0	4	30	19	11	16	15	7	10	13	15	19	24	23	8
	45-60	0	0	0	100	0	0	0	0	0	11	31	15	8	13	11	4	6	9	14	29	18	10	4
	30-45	0	0	100	0	0	0	0	0	0	27	29	13	7	12	9	3	3	5	15	32	11	6	3
	20-30	0	100	0	0	0	0	0	0	0	38	16	9	4	8	6	2	2	3	10	19	6	4	2
	0-20	100	0	0	0	0	0	0	0	0	71	12	6	3	6	3	2	1	1	7	15	3	3	1

HIGG-2016-21

Correlations between the observables determined from an ensemble of 100,000 bootstrapped data sets which are each reanalyzed using an unbinned maximum-likelihood fit of the diphoton invariant mass spectrum to extract the correlations.

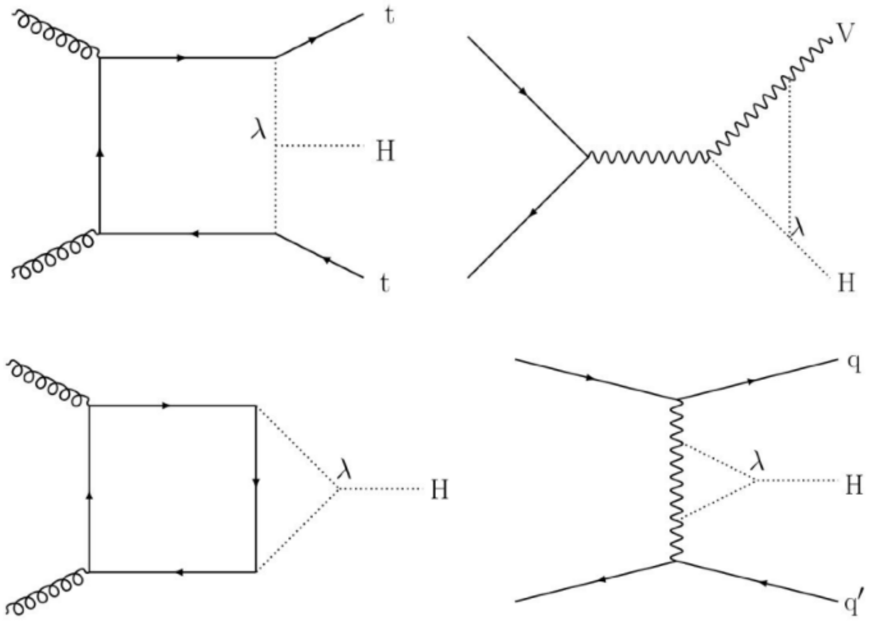


The resampling will not work with e.g. H—>ZZ where the background is limited.

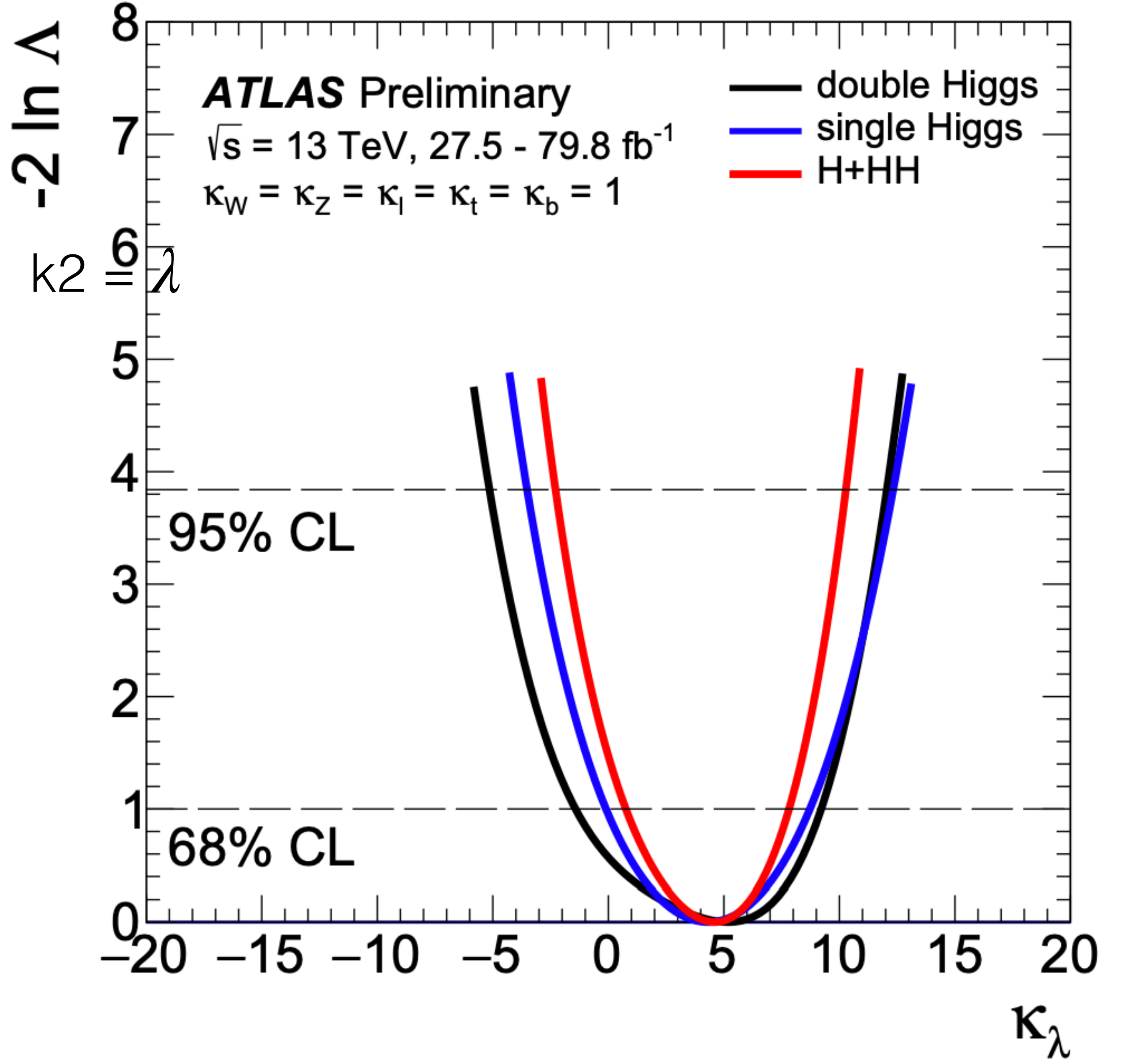
Sensitivity to HH production

Higher order corrections introduce a dependence on λ of total xsec, BR and pT(H)

Inclusive production cross sections
+ decay branching ratios
+ differential cross sections

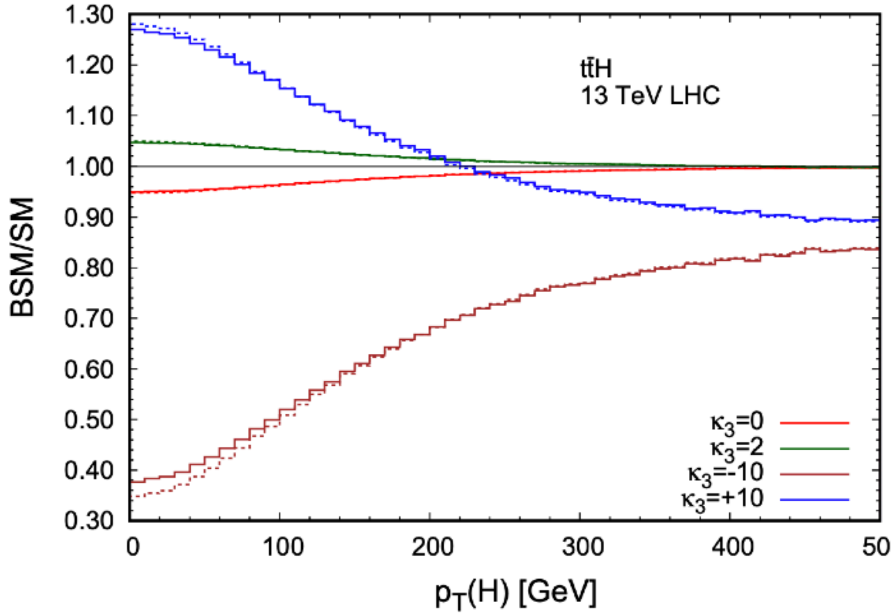


ATLAS-CONF-2019-049



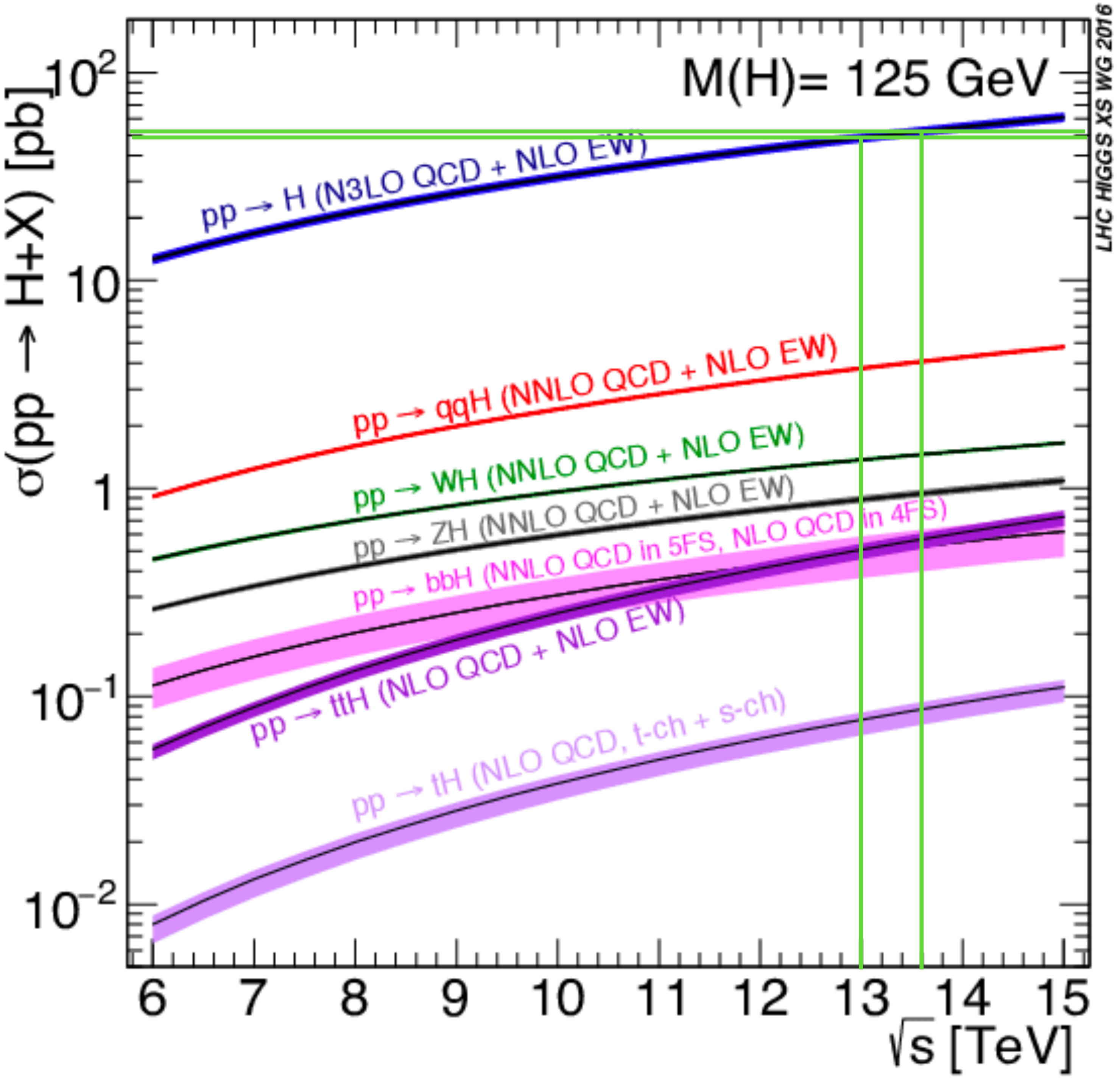
k2 = λ

Eur. Phys. J. C (2017) 77 :887



k$_3$ = λ

Run 3: Higgs production @ 13.6TeV



√s [TeV]	ggF (N3LO QCD + NLO EW) [pb]
13.0	4.851E+01
13.5	5.153E+01

Integrated Luminosity:
Run 2 ~ 140/fb
Run 3 ~ 300/fb

Anything new for Run 3 ?

…on top of re-doing the same with larger datasets

STXS:

- LHC HWG is moving towards the preparation of the stage 1.3
  - this may include
    - finer binning
    - larger coverage at high pT
    - bins sensitive to CP (e.g. $\Delta\phi_{jj}$ in VBF)

Fiducial cross sections:

- produce interpretations multiplying the likelihoods of each measurement in its own phase space
  - this removes the model dependent extrapolation to 4π needed to combine spectra

Summary

We have gone a long way from the discovery of the Higgs boson to the measurements of its properties in all sorts of ways.

The measurements techniques keep improving, the interpretation frameworks becomes more and more refined.

Still we are only entering Run 3 and the path to the full HL-LHC measurements will last for about two more decades (two more reasons to celebrate)

From the experimentalist side, in for the long haul means also detector operation, calibrations, computing, etc.. It a huge collective effort that has to be sustained for a very long time !

So far this Higgs looks a lot like the SM Higgs… but maybe it's not,
and it's up to (dis)prove it !

Bibliography

ATLAS

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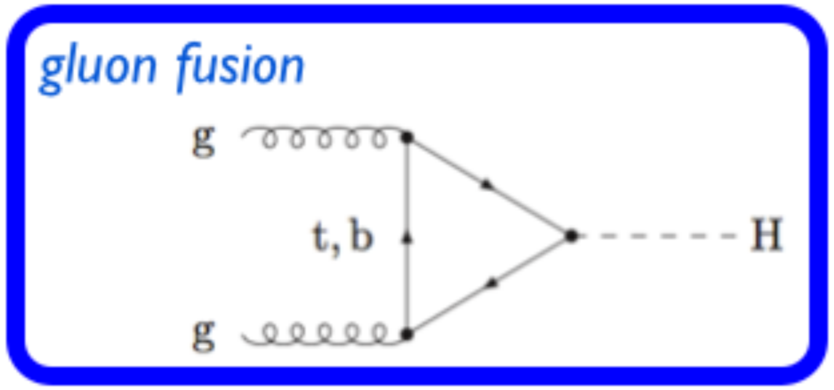
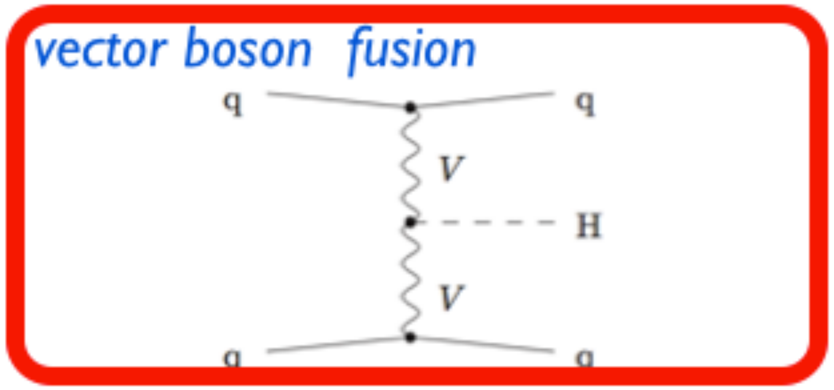
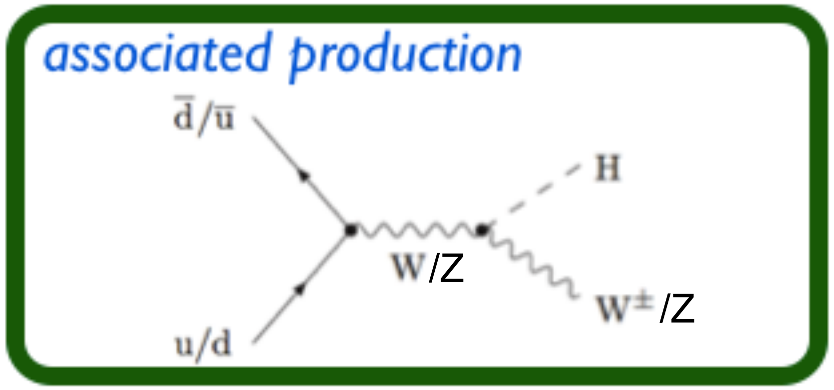
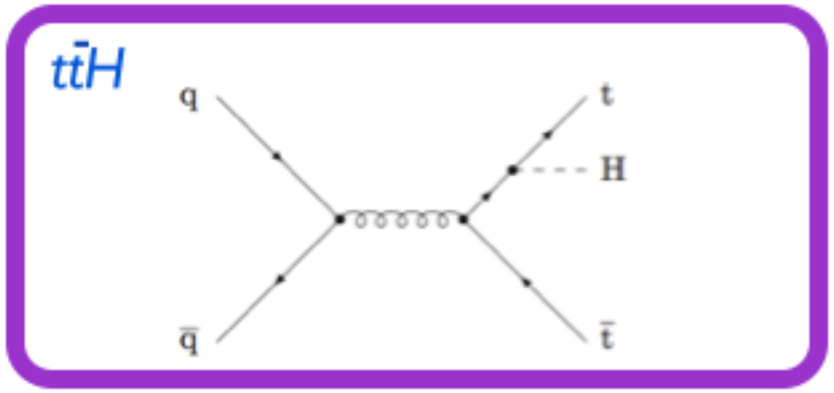
Extra material

Production modes: recap









What we expect to see is what we use to setup our analyses:

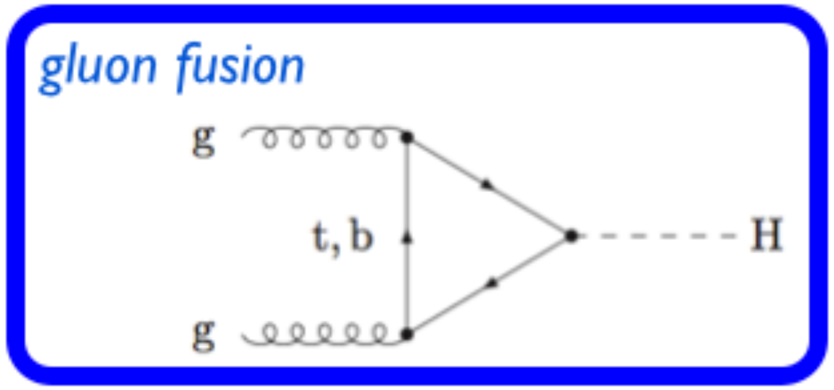
ggF:
- largest cross section
- no extra jet activity

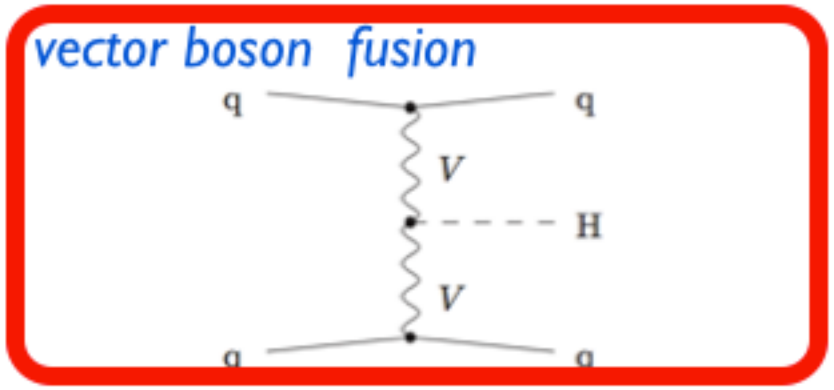
VBF:
- harder pT spectrum
- two high eta jets (large rapidity gap no colorflow)

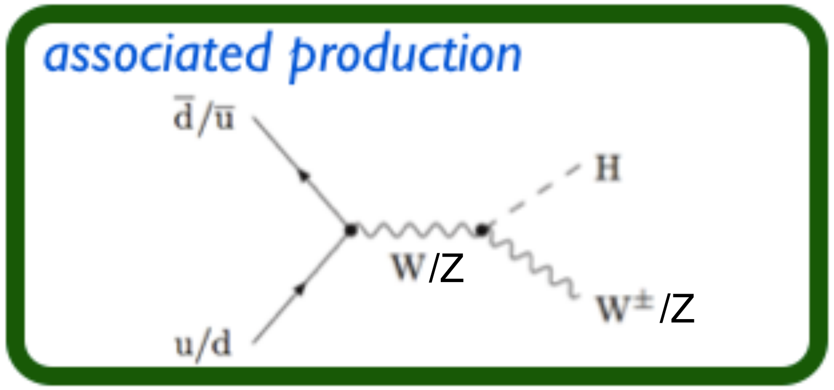
VH:
- tag on the presence of the W/Z
- pT spectrum similar to VBF

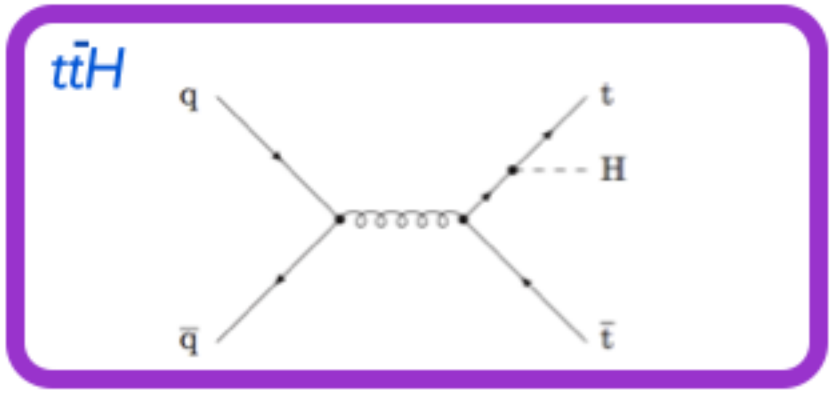
ttH:
- busy environment influence the isolation
- tag on the tops (high pT leptons, b-jets, #jets)

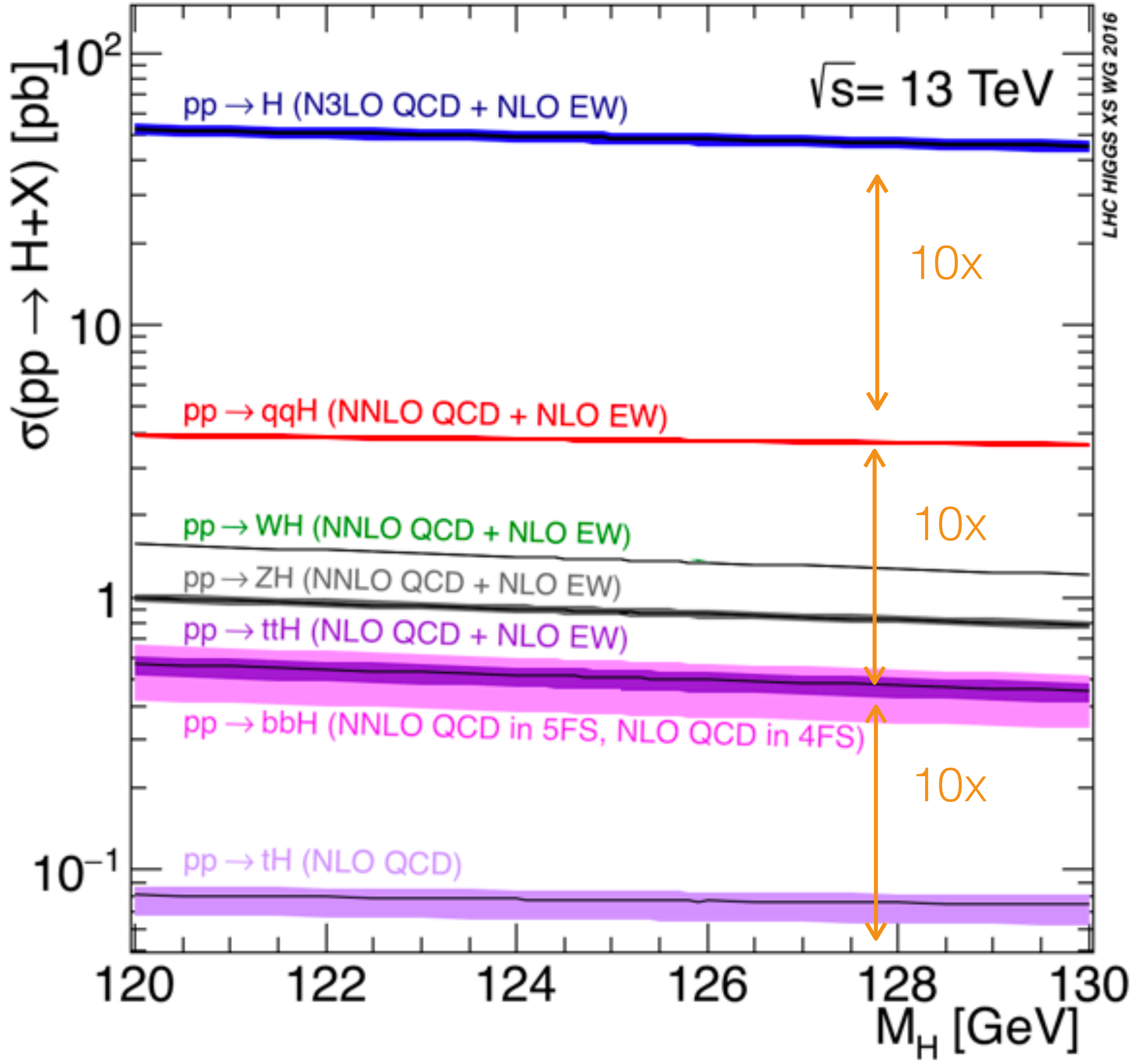
Production modes: recap


gluon fusion

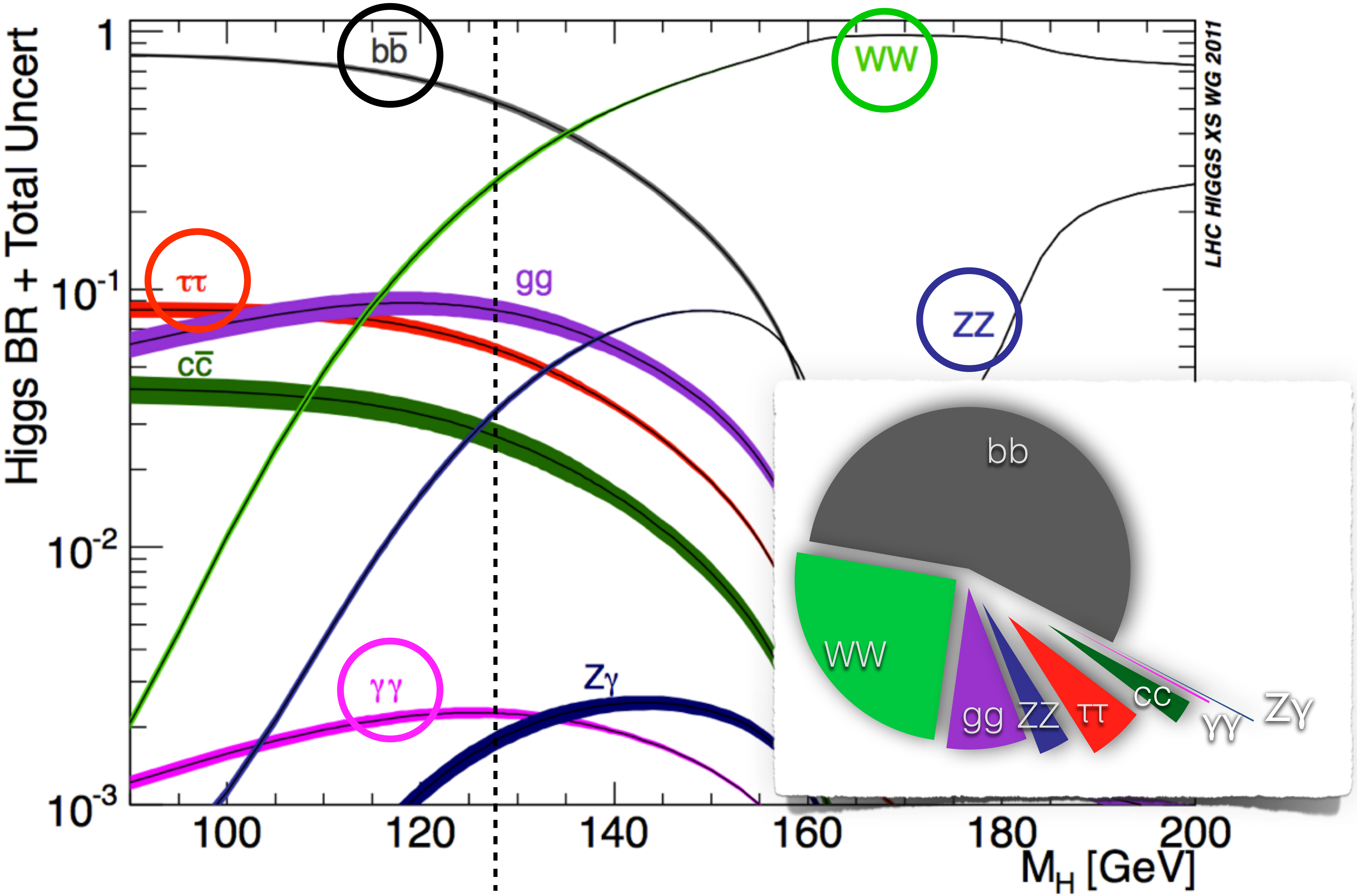

vector boson fusion


associated production


$t\bar{t}H$

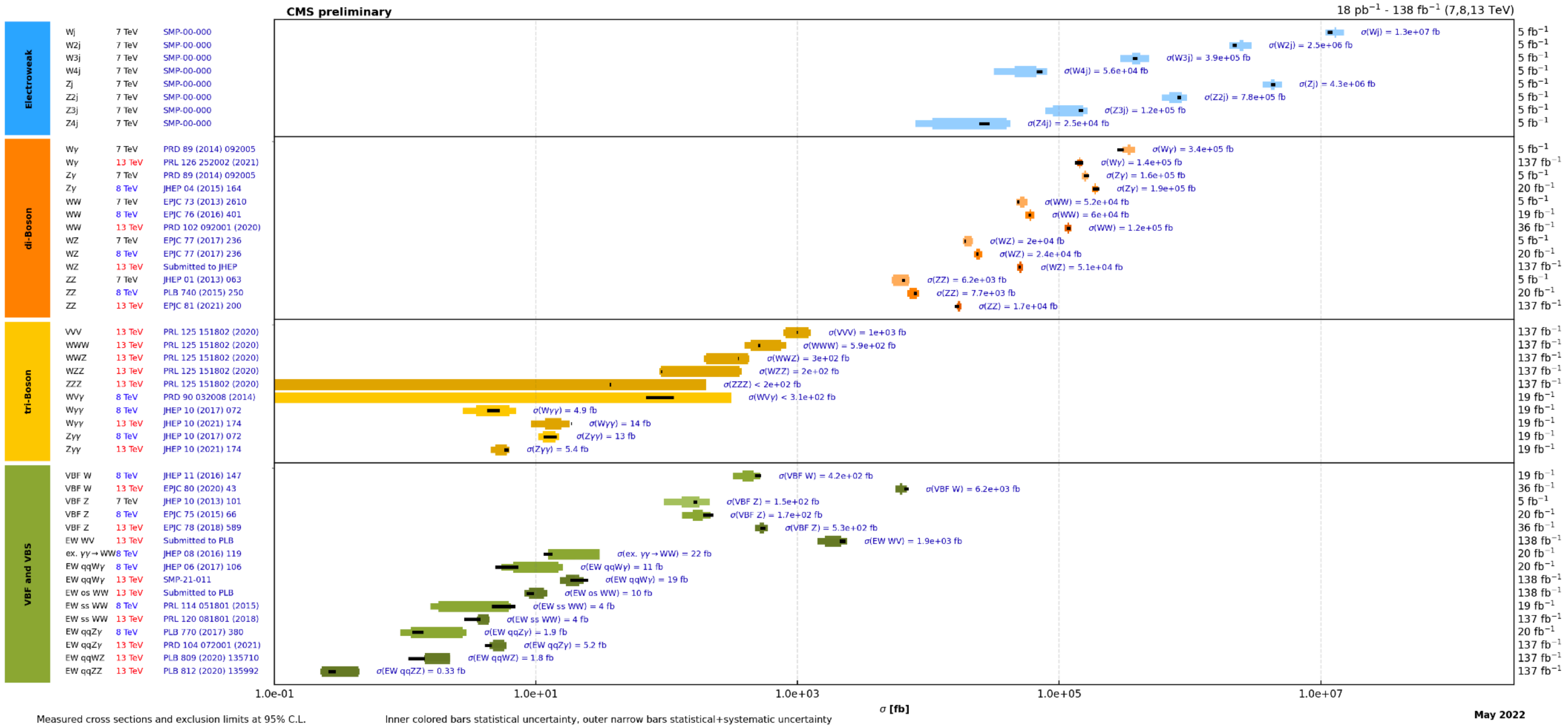


Decay modes: recap



Before going after the Higgs boson…

Overview of CMS cross section results



Measured cross sections and exclusion limits at 95% C.L.
See here for all cross section summary plots

Inner colored bars statistical uncertainty, outer narrow bars statistical+systematic uncertainty
Light colored bars: 7 TeV, Medium bars: 8 TeV, Dark bars: 13 TeV, Black bars: theory prediction

Analysis categories

Categorizing events allows the analysis to achieve better sensitivity / better parameters constraints. The reason is that you can make more accurate assumptions on how to model the data in one category (locally) than on the overall sample (globally).

Assume you have large enough statistics, the significance (see later in this lecture) is

given by $Z = \frac{S}{\sqrt{B}}$

Now, suppose you data in two categories: $Z_i = \frac{S_i}{\sqrt{B_i}}$ i = 1,2 (S_i, B_i>0)

The combined statistical significance of the two categories is: $Z_{cat} = \sqrt{\frac{S_1^2}{B_1} + \frac{S_2^2}{B_2}}$

The statistical significance of the signal without categories is: $Z = \frac{S_1 + S_2}{\sqrt{B_1 + B_2}}$

(total Signal = S_1+S_2, Total background B_1+B_2)

If you compare the two: $Z_{cat}^2 - Z^2 = \frac{S_1^2}{B_1} + \frac{S_2^2}{B_2} - \frac{(S_1 + S_2)^2}{B_1 + B_2} = \frac{B_1 B_2}{B_1 + B_2}\left(\frac{S_1}{B_1} - \frac{S_2}{B_2}\right)^2$

which is always > 0 unless S1/B1 = S2/B2. From a statistics point of view you always improve your analysis sensitivity by categorising the events.

k-framework

$$\begin{aligned}\mathcal{L} = {} & \boxed{\kappa_3} \frac{m_H^2}{2v} H^3 + \boxed{\kappa_Z} \frac{m_Z^2}{v} Z_\mu Z^\mu H + \boxed{\kappa_W} \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\ & + \boxed{\kappa_g} \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\mu\nu} H + \boxed{\kappa_\gamma} \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \boxed{\kappa_{Z\gamma}} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\ & - \left(\boxed{\kappa_t} \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \boxed{\kappa_b} \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \boxed{\kappa_\tau} \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H\end{aligned}$$

Coupling modifiers: $\boxed{\kappa_i}$

Deviation from 1
indicates New Physics

i = V, (same modifier for W and Z)
W, Z,
f, (same modifier for all fermions)
l, q, (one modifier for all leptons and another one for all quarks)
u-type quarks, d-type quarks,
b, top, g, γ,τ

(in particular k_g (gluon) in *production* means not resolving the top loop
kγ (photon) in *decay* means not resolving the top/W loop)

$$(\sigma \cdot \mathcal{B})\,(x \rightarrow \mathrm{H} \rightarrow f\!f) = \frac{\sigma_x \cdot \Gamma_{f\!f}}{\Gamma_{\mathrm{tot}}}$$

σ_x = production cross section (ggH, VBF, VH, ttH)
$\Gamma_{f\!f}$ = partial decay width into final state ff: WW, ZZ,γγ,bb,ττ
Γ_{tot} = total width accounting for a possible BSM partial decay width

$$\Gamma_{\mathrm{tot}} = \sum \Gamma_{f\!f} + \Gamma_{\mathrm{BSM}}$$

k-framework

	Loops	Interference	Effective scaling factor	Resolved scaling factor
Production				
$\sigma(\mathrm{ggH})$	✓	g-t	κ_{g}^2	$1.04\kappa_{\mathrm{t}}^2 + 0.002\kappa_{\mathrm{b}}^2 - 0.038\kappa_{\mathrm{t}}\kappa_{\mathrm{b}}$
$\sigma(\mathrm{VBF})$	—	—		$0.73\kappa_{\mathrm{W}}^2 + 0.27\kappa_{\mathrm{Z}}^2$
$\sigma(\mathrm{WH})$	—	—		κ_{W}^2
$\sigma(\mathrm{qq/qg} \to \mathrm{ZH})$	—	—		κ_{Z}^2
$\sigma(\mathrm{gg} \to \mathrm{ZH})$	✓	Z-t		$2.46\kappa_{\mathrm{Z}}^2 + 0.47\kappa_{\mathrm{t}}^2 - 1.94\kappa_{\mathrm{Z}}\kappa_{\mathrm{t}}$
$\sigma(\mathrm{ttH})$	—	—		κ_{t}^2
$\sigma(\mathrm{gb} \to \mathrm{WtH})$	—	W-t		$2.91\kappa_{\mathrm{t}}^2 + 2.31\kappa_{\mathrm{W}}^2 - 4.22\kappa_{\mathrm{t}}\kappa_{\mathrm{W}}$
$\sigma(\mathrm{qb} \to \mathrm{tHq})$	—	W-t		$2.63\kappa_{\mathrm{t}}^2 + 3.58\kappa_{\mathrm{W}}^2 - 5.21\kappa_{\mathrm{t}}\kappa_{\mathrm{W}}$
$\sigma(\mathrm{bbH})$	—	—		κ_{b}^2
Partial decay width				
Γ^{ZZ}	—	—		κ_{Z}^2
Γ^{WW}	—	—		κ_{W}^2
$\Gamma^{\gamma\gamma}$	✓	W-t	κ_{γ}^2	$1.59\kappa_{\mathrm{W}}^2 + 0.07\kappa_{\mathrm{t}}^2 - 0.67\kappa_{\mathrm{W}}\kappa_{\mathrm{t}}$
$\Gamma^{\tau\tau}$	—	—		κ_{τ}^2
Γ^{bb}	—	—		κ_{b}^2
$\Gamma^{\mu\mu}$	—	—		κ_{μ}^2
Total width for $\mathcal{B}_{\mathrm{BSM}} = 0$				
Γ_{H}	✓	—	κ_{H}^2	$0.58\kappa_{\mathrm{b}}^2 + 0.22\kappa_{\mathrm{W}}^2 + 0.08\kappa_{\mathrm{g}}^2 +$ $+ 0.06\kappa_{\tau}^2 + 0.026\kappa_{\mathrm{Z}}^2 + 0.029\kappa_{\mathrm{c}}^2 +$ $+ 0.0023\kappa_{\gamma}^2 + 0.0015\kappa_{\mathrm{Z}\gamma}^2 +$ $+ 0.00025\kappa_{\mathrm{s}}^2 + 0.00022\kappa_{\mu}^2$

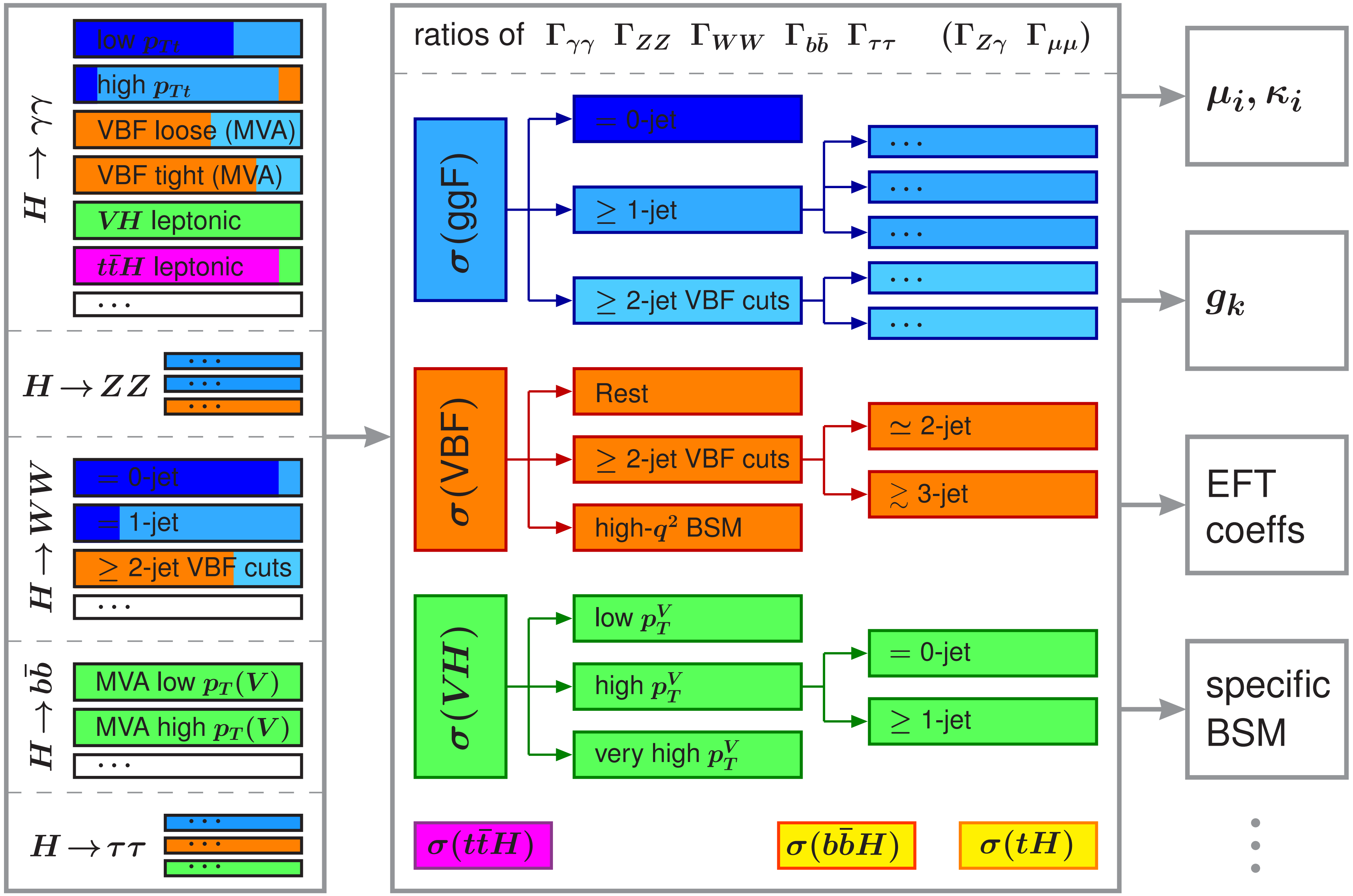
Computed for 13 TeV at m_H=125.09 GeV

Initial step

“standard” analyses
optimised for
μ and kappas

STXS

output to be used
for further
interpretation



The specific decay mode enters the fit through its partial decay width (ratio of BR to remove the unknown total width)

Unfolding

When measuring cross sections, unfolding means “undoing” the bin migrations due to finite resolution of the detector.
Move from reconstruction level (x) to particle level (y) (after parton showering, generally defined as particles with cτ > 10mm)

It boils down to extract f_{true} inverting $x_i = \sum_j R_{ij} y_j$

where R_{ij} is the detector response matrix.

The inversion can be implemented with a least square estimation:

$$\chi^2 = \sum_i \sum_j [y_i - x_i] V^{-1}1_{ij} [y_j - x_j]$$

Unfolding

Typically two approaches:

bin-by-bin corrections

write the inversion as $y_i = C_i x_i$ where $C_i = y_i^{MC} / x_i^{MC}$

y are the reco yields and x are true yields from simulations (ignore the information from neighbouring bins to invert migrations)

—> unsafe for very non diagonal response matrices

likelihood inversion

replace the $\chi 2$ with the full likelihood $\chi^2 \rightarrow -2 \log L(y, x)$

—> fit directly the true quantities

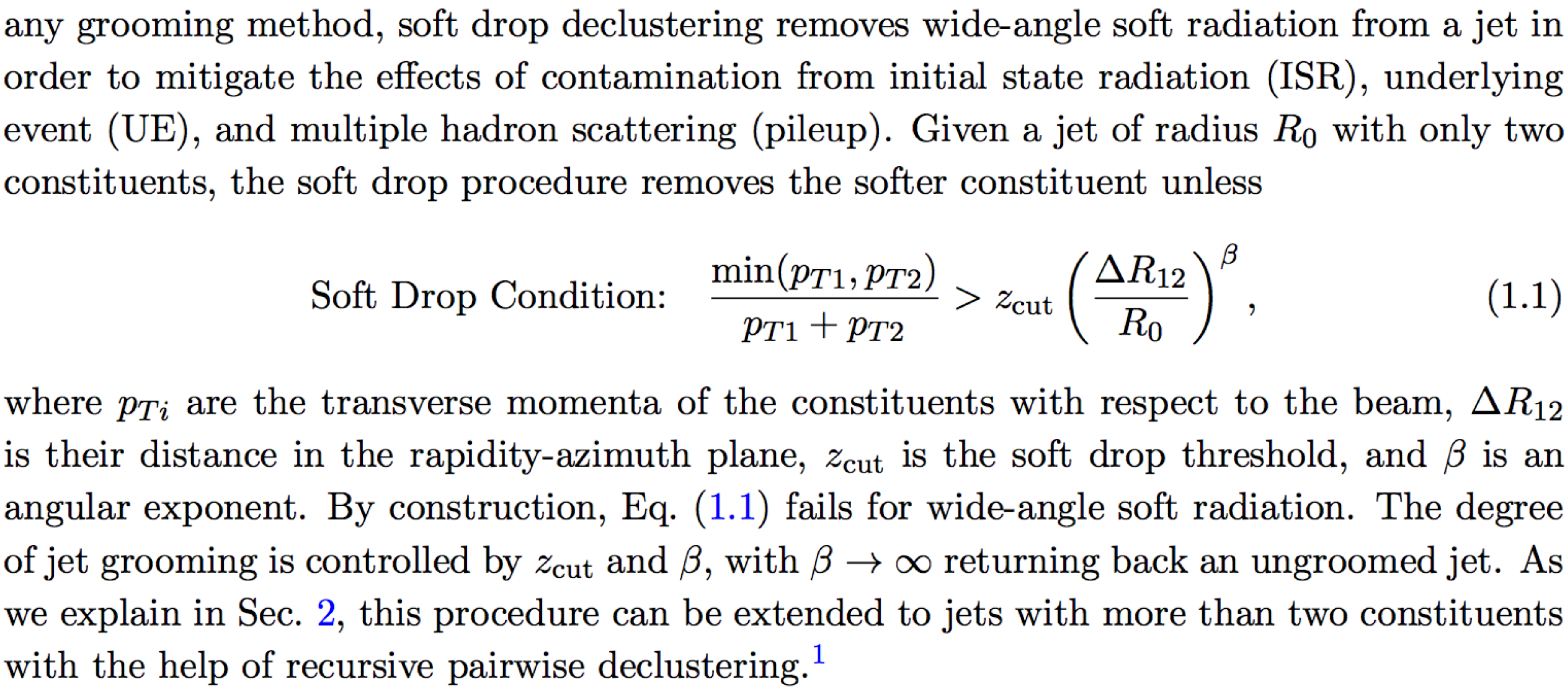
In both cases when R_{ij} has large off-diagonal elements, i.e. too small compared to the detector resolution, fluctuations of x get amplified by them resulting in a huge variance of y.

To smooth this large statistical fluctuation one can add a regularisation term at the price of introducing a bias in the measurement

$$\chi^2 = \sum_i \sum_j [y_i - x_i] V^{-1}1_{ij} [y_j - x_j] + \tau \sum_i \sum_j y_i k_{ij} y_j$$

ggH→bb

“Soft Drop declustering”



any grooming method, soft drop declustering removes wide-angle soft radiation from a jet in order to mitigate the effects of contamination from initial state radiation (ISR), underlying event (UE), and multiple hadron scattering (pileup). Given a jet of radius R_0 with only two constituents, the soft drop procedure removes the softer constituent unless

$$\text{Soft Drop Condition:} \quad \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}, \tag{1.1}$$

where p_{Ti} are the transverse momenta of the constituents with respect to the beam, ΔR_{12} is their distance in the rapidity-azimuth plane, z_{cut} is the soft drop threshold, and β is an angular exponent. By construction, Eq. (1.1) fails for wide-angle soft radiation. The degree of jet grooming is controlled by z_{cut} and β, with $\beta \to \infty$ returning back an ungroomed jet. As we explain in Sec. 2, this procedure can be extended to jets with more than two constituents with the help of recursive pairwise declustering.[1]