High energy probes and EFT at HE/HL LHC

18 June 2018

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On behalf of the ATLAS and CMS collaborations

Introduction

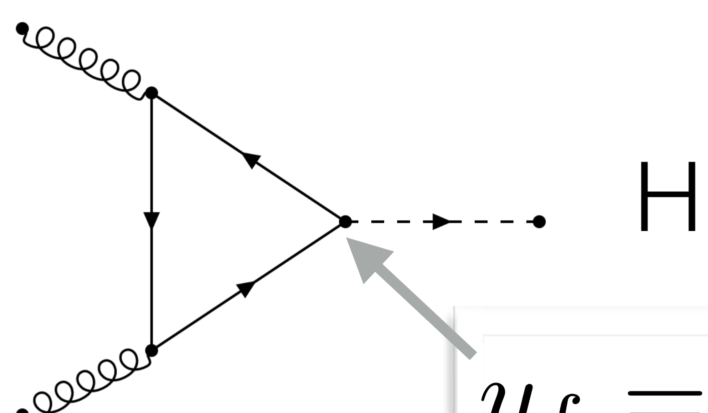
- **Precision era:** Looking for modifications of the standard model
  - Which manifest not per se in **total yields**, but rather in distortions of **(differential) spectra**, or in **tails**
- **EFT:** Adding operators to the SM Lagrangian
  - Dim 6 example: affects **differential Higgs cross sections**
  - Dim 8 example: affects **anomalous quartic gauge coupling** (aQGC) in **VBS**

Outline

- **Differential cross sections**
  - Attainable uncertainties on spectra at HL-LHC
  - Interpretations in terms of Higgs coupling modifiers
- **VBF/VBS**
  - EFT for VBS
  - Summary of results & projections

Introduction: Differential cross sections

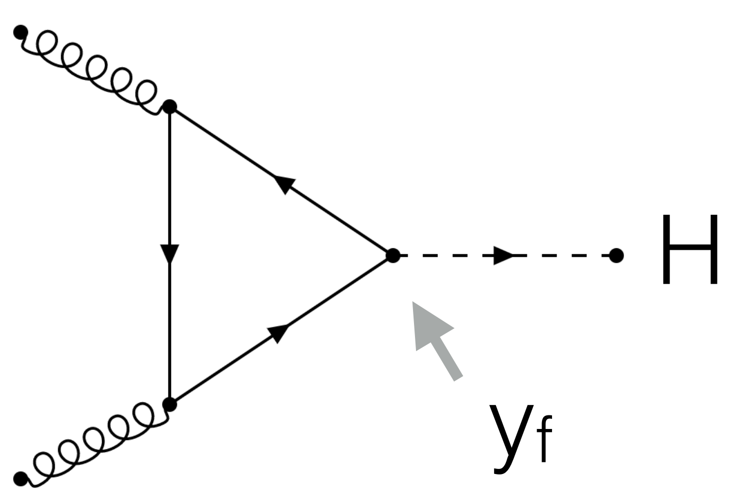
- What is so interesting about the **differential cross sections**?
  - Measures not only the **inclusive cross section**, but also the **shape** of the distribution
  - The **shape** may be tested versus its Standard Model expectation
  - Relatively small **coupling variations** lead to significant shape distortions



$$y_f = \kappa_f \cdot y_f^{SM}$$

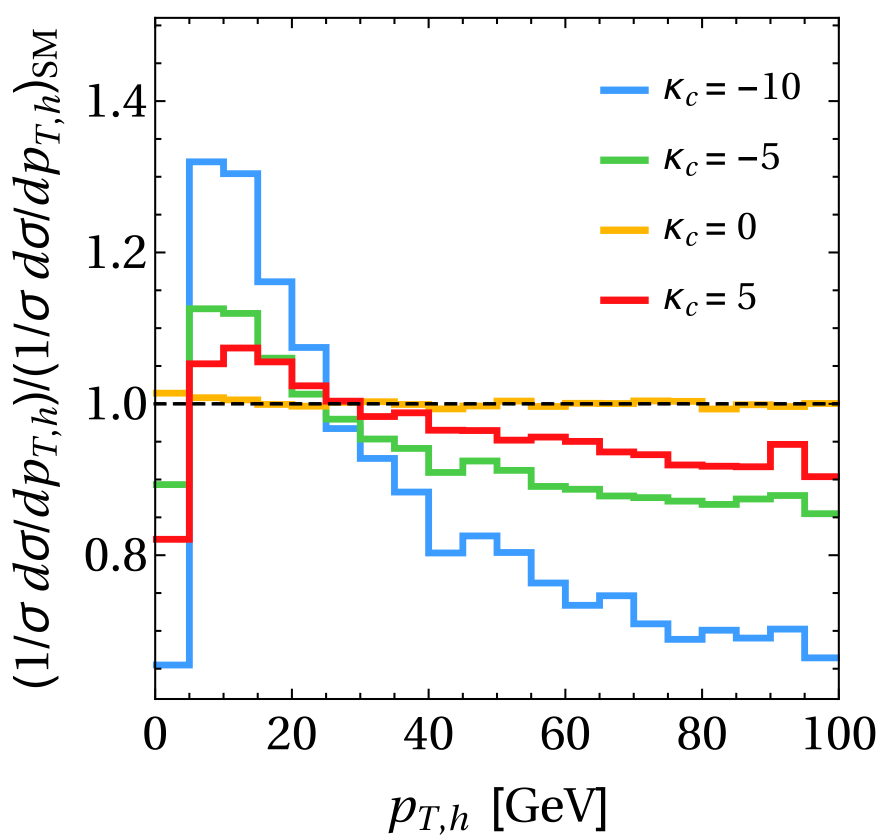
Introduction: Differential cross sections

- **Transverse momentum p_T^H**
  - Sensitivity to modifications of effective **Higgs Yukawa couplings** at low p_T
  - Sensitivity to **finite top mass effects** at high p_T

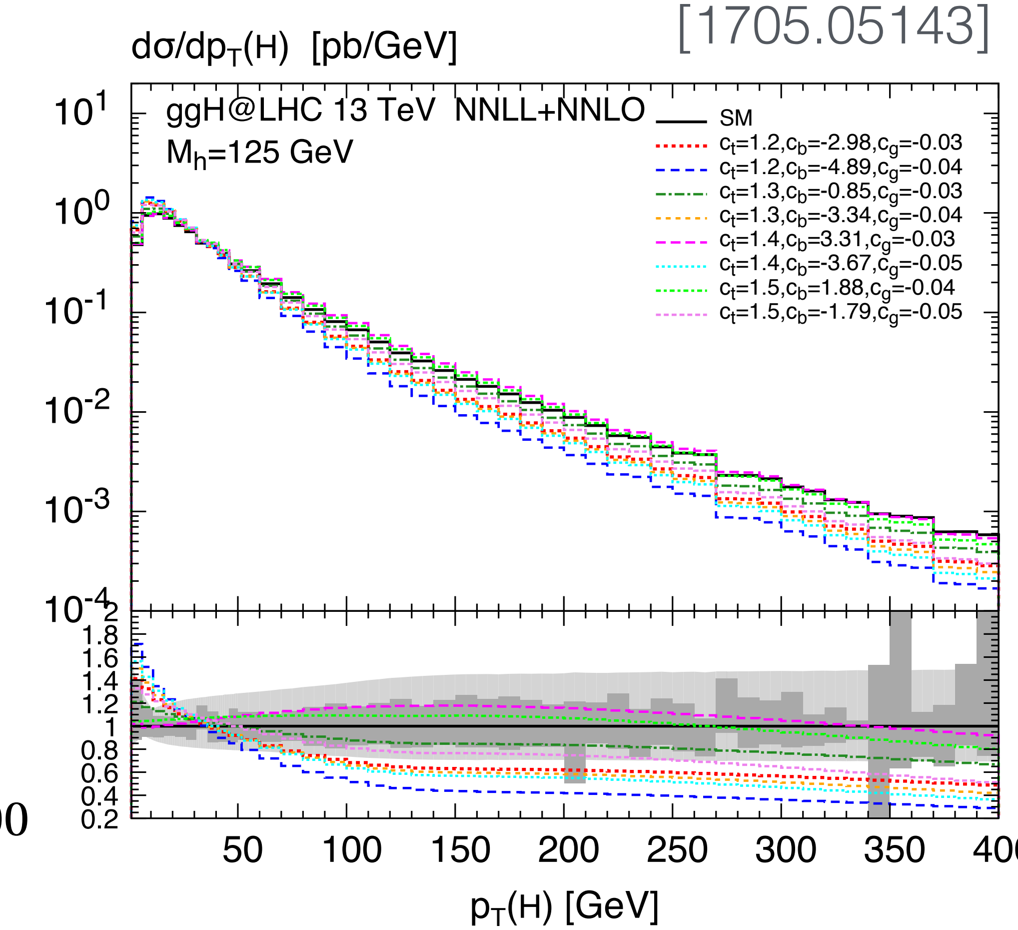


$$y_f = \kappa_f \cdot y_f^{SM}$$

Bishara, Haisch, Monni, Re (2016) [1606.09253]

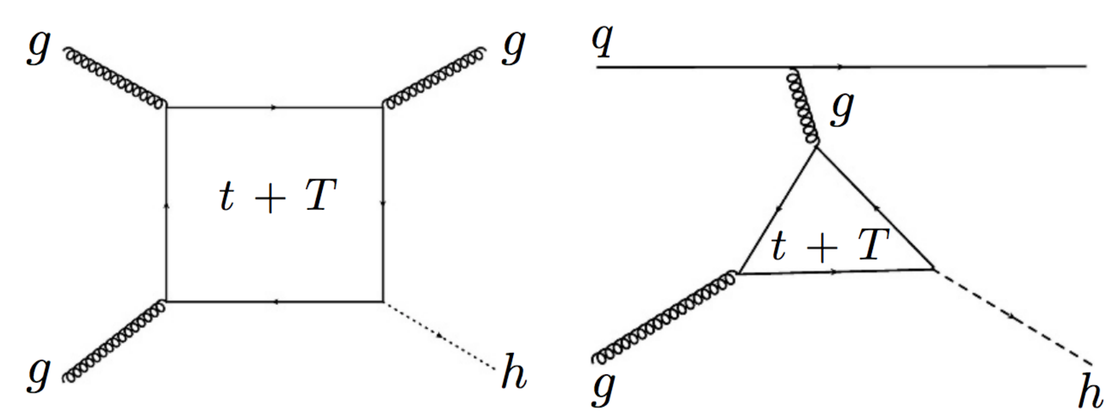


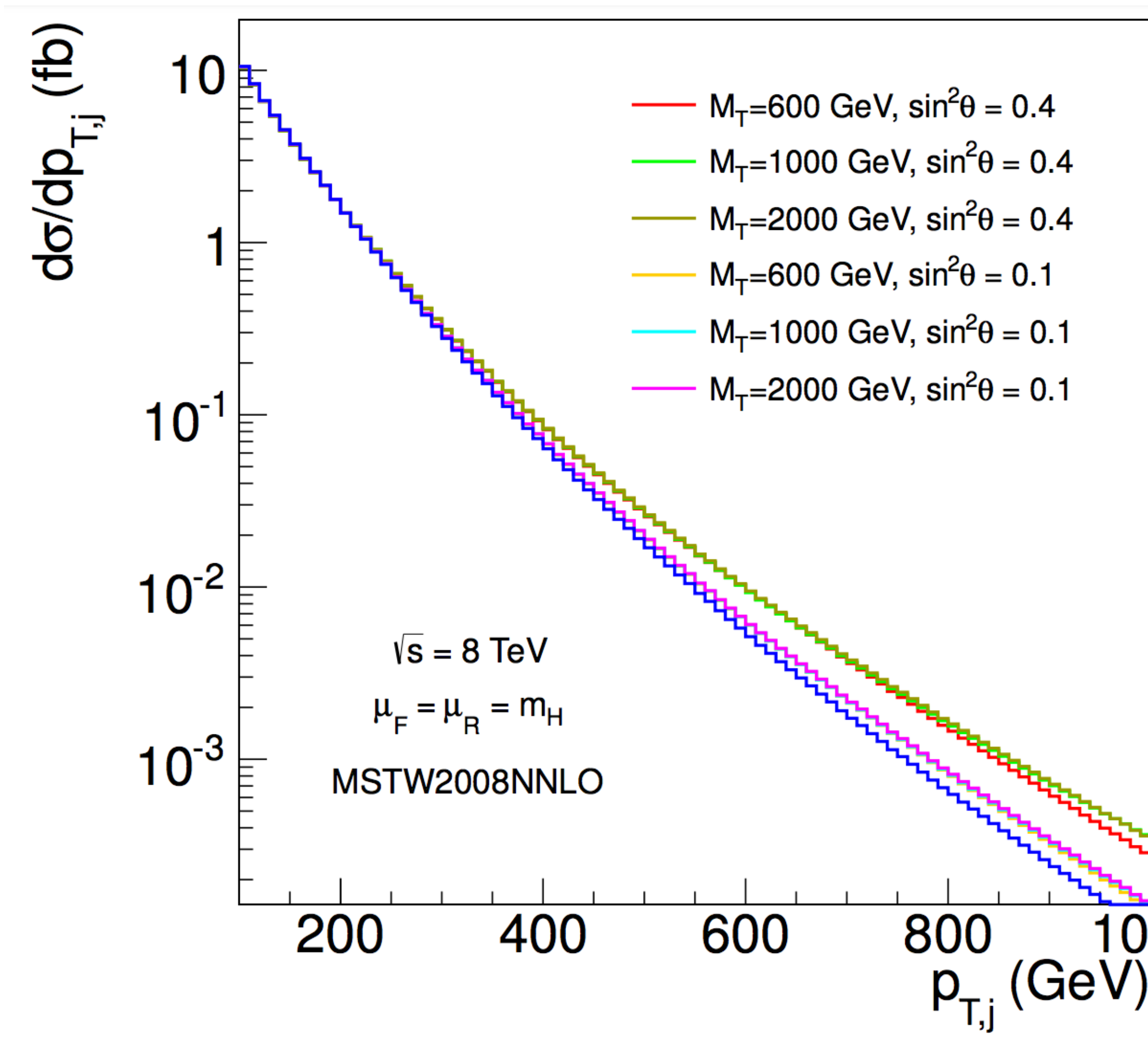
Grazzini, Ilnicka, Spira, Wiesemann (2017) [1705.05143]



Introduction: Differential cross sections

- **Jet multiplicity N_{jets}** & **p_T of the first jet p^T_{jet1}**
    - New physics in the loop, sensitivity at high p_T
- **Rapidity $|y^H|$**
    - Theory distribution mostly determined by the **gluon PDF**; possible test





Banfi, Martin, Sanz (2014) [1308.4771]

The current state

- Primary measurements of differential cross sections from **H to 2 photons** and **H to 4 leptons**

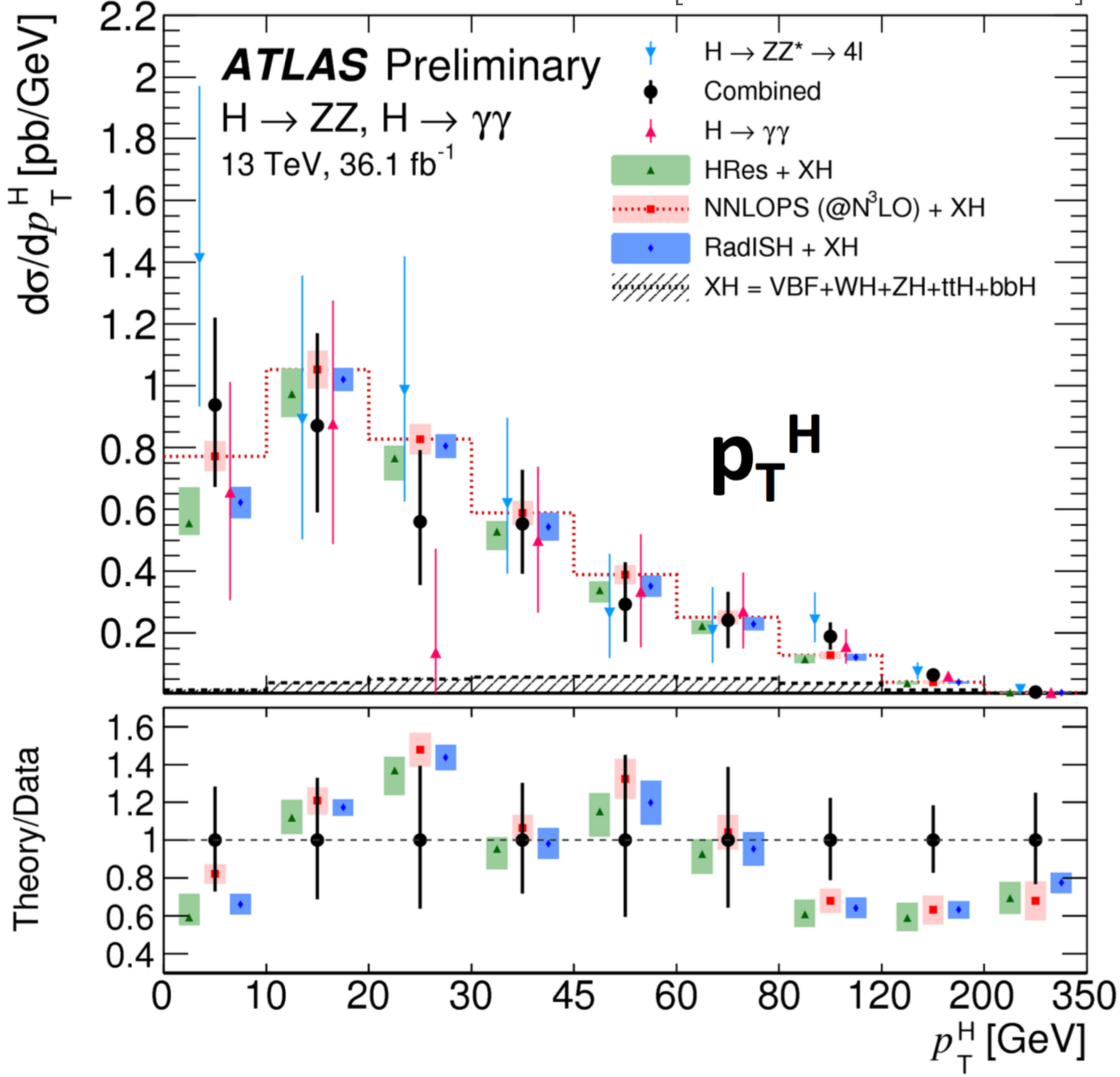
- Current state for **13 TeV**:

	ATLAS	CMS
$H \rightarrow \gamma\gamma$	p_T^H, N_{jets}, p^T_{jet1}, $\lvert y^H \rvert$ [1802.04146]	p_T^H, N_{jets} [CMS-PAS-HIG-17-015]
$H \rightarrow ZZ$	p_T^H, N_{jets} [1712.02304]	p_T^H, N_{jets}, p^T_{jet1} [JHEP 1711 (2017) 047]
Combination	✓ [ATLAS-CONF-2018-002]	

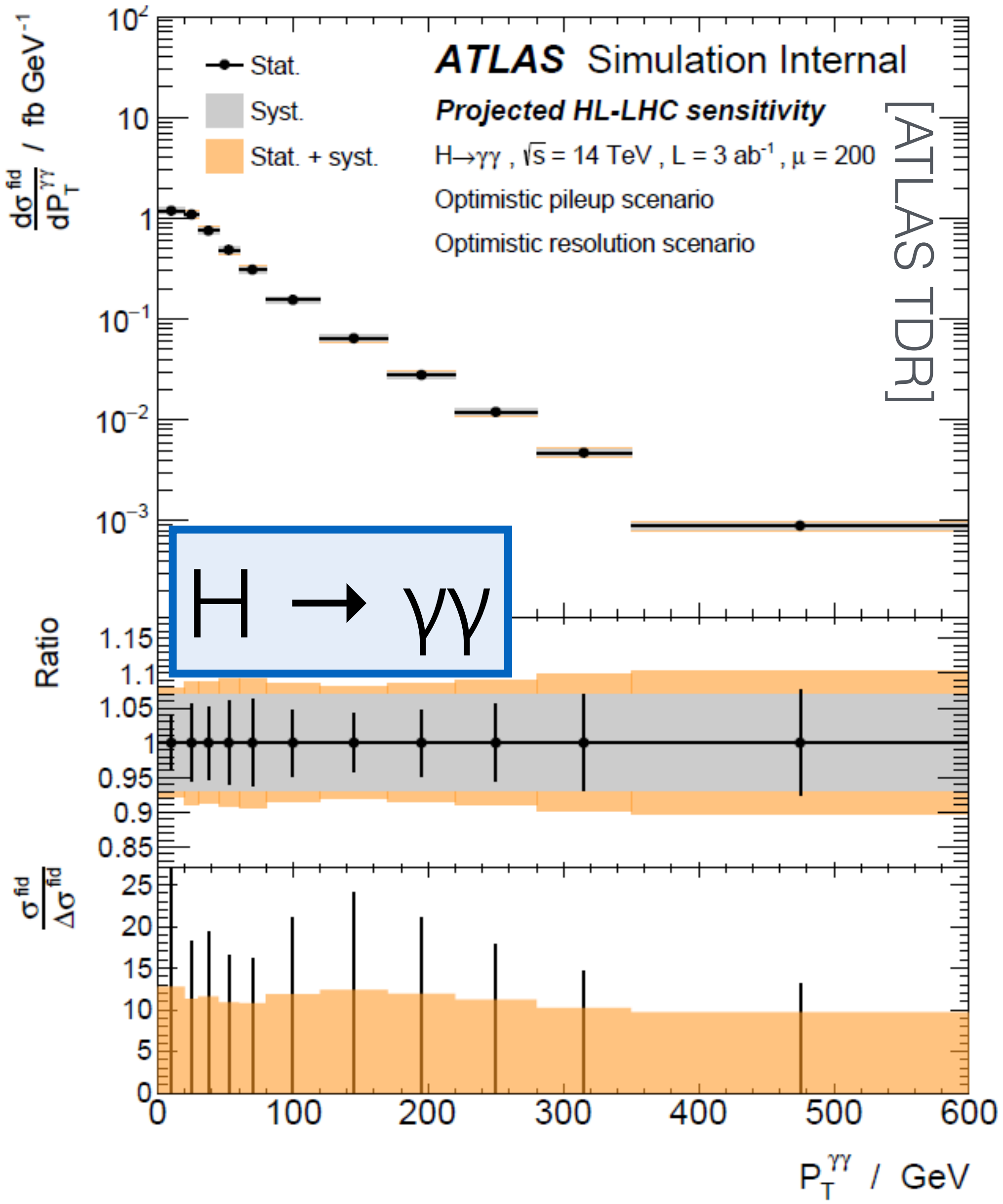
p_T^H: ATLAS

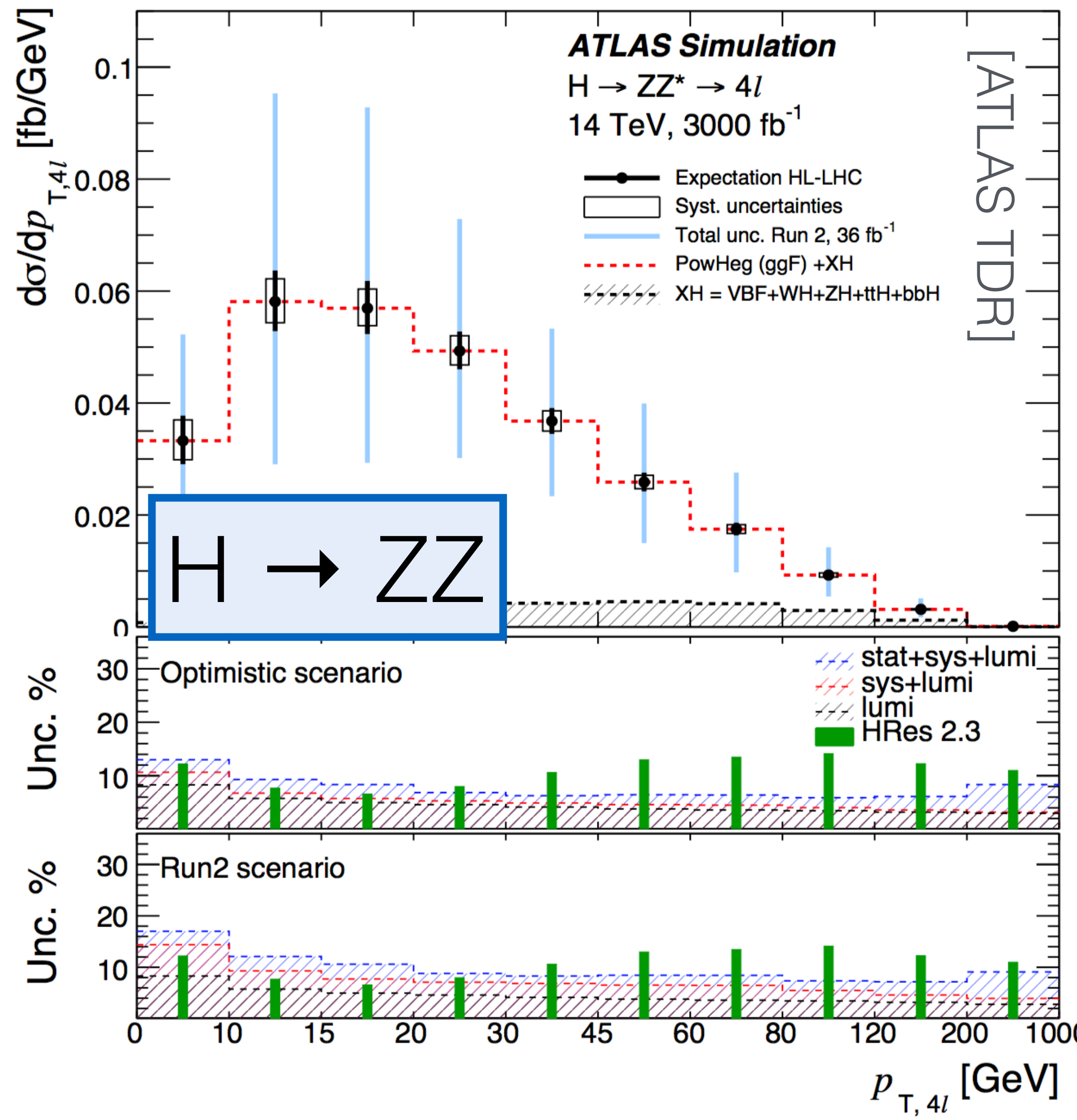
- Fleshed out combination from ATLAS
- Particular improvement in the low p_T region
- 20%-40% uncertainties, mostly statistically dominated

[ATLAS-CONF-2018-002]



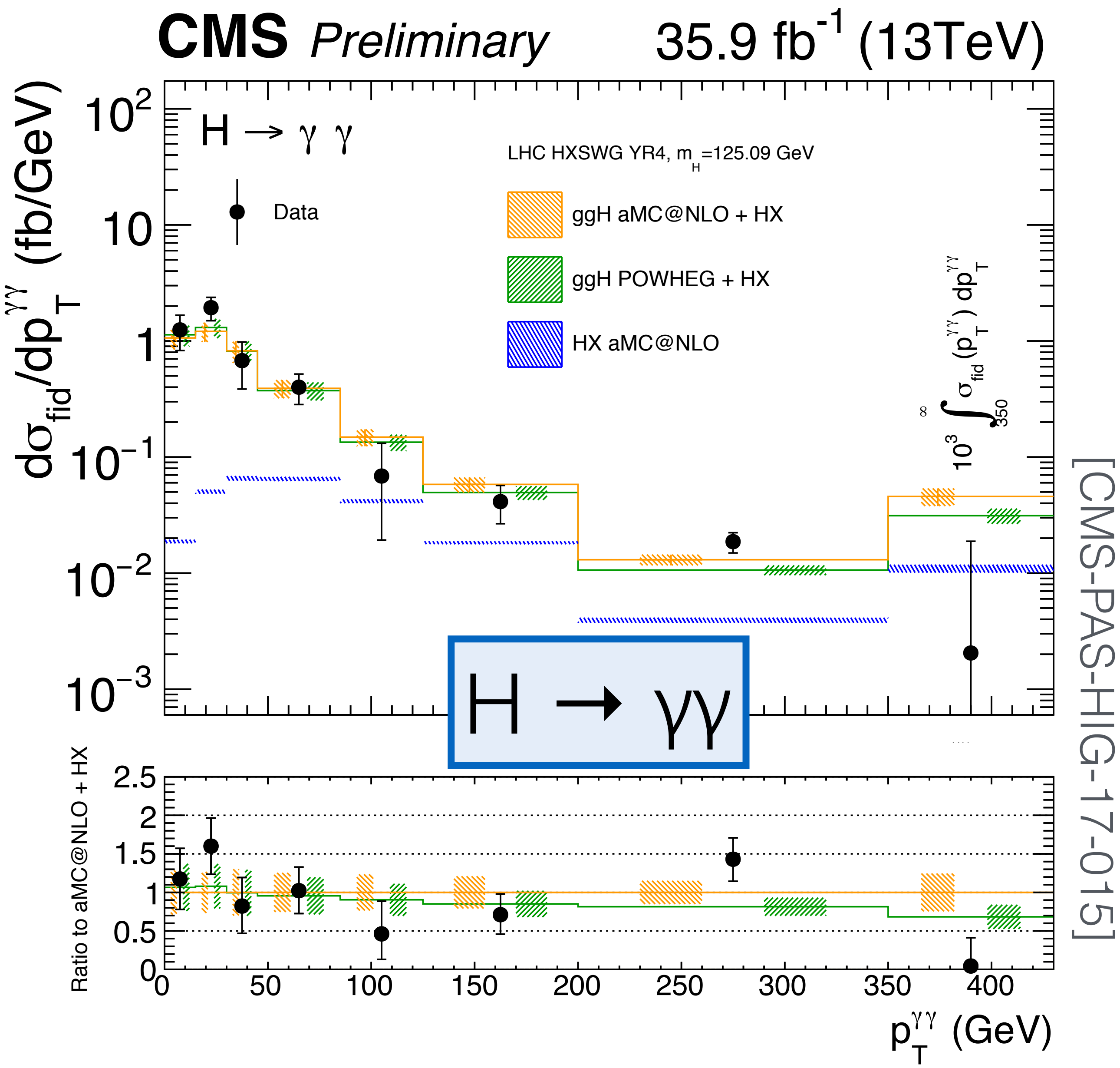
p_T^H: Projections from ATLAS

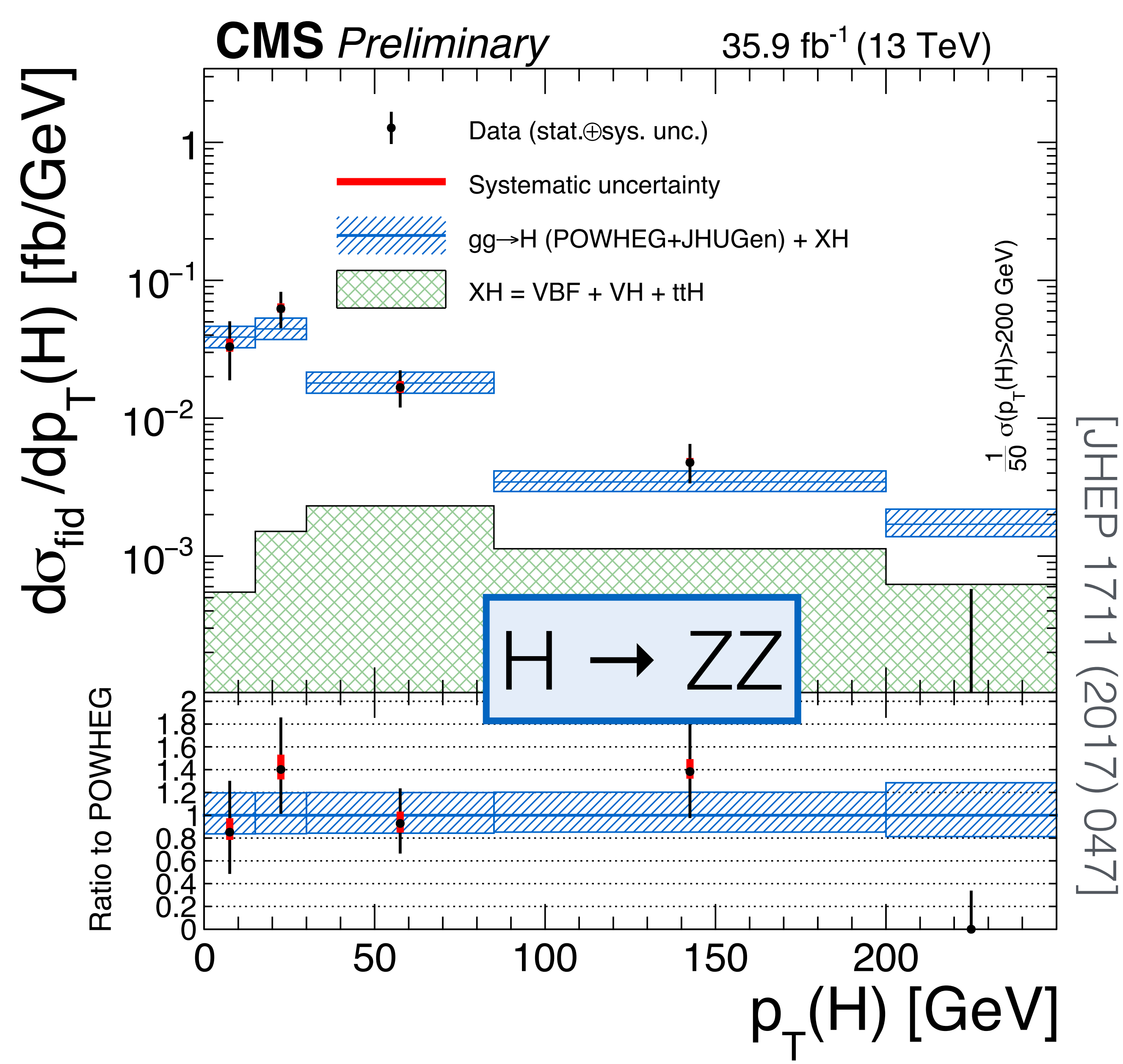




- ~5% uncertainties for H → γγ, between 5-10% for H → ZZ
- For H → γγ, Improvement by a factor of ~8-9, really close to $\sqrt{3000/36} \simeq 9$ (scaling only stat., assuming same syst.)
- **<5%** uncertainty achievable with a combination

p_T^H: CMS



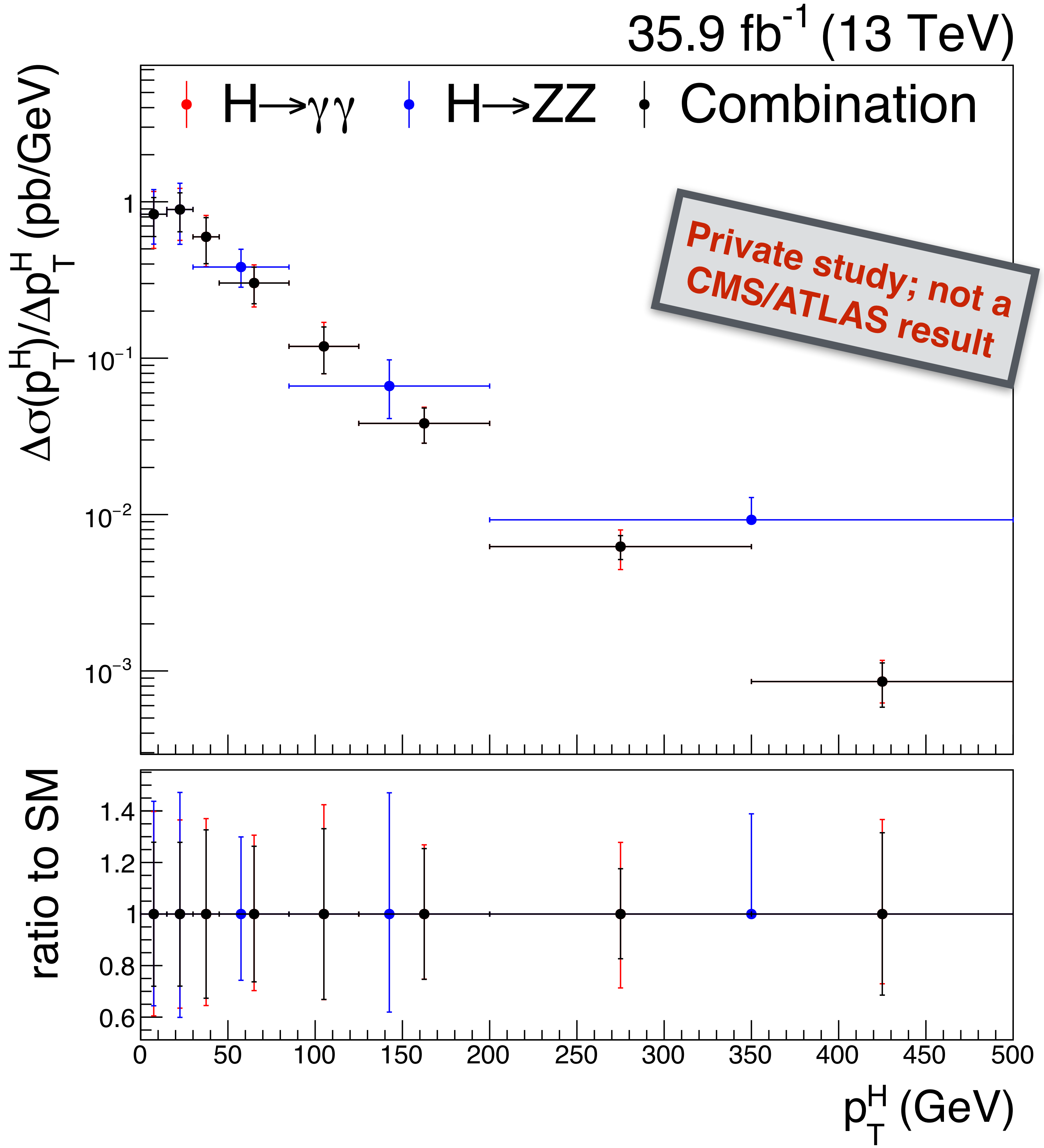


- Proper combination ongoing, but we can make an attempt:
  - Assume no correlations, and no bin-to-bin migrations

p_T^H: CMS

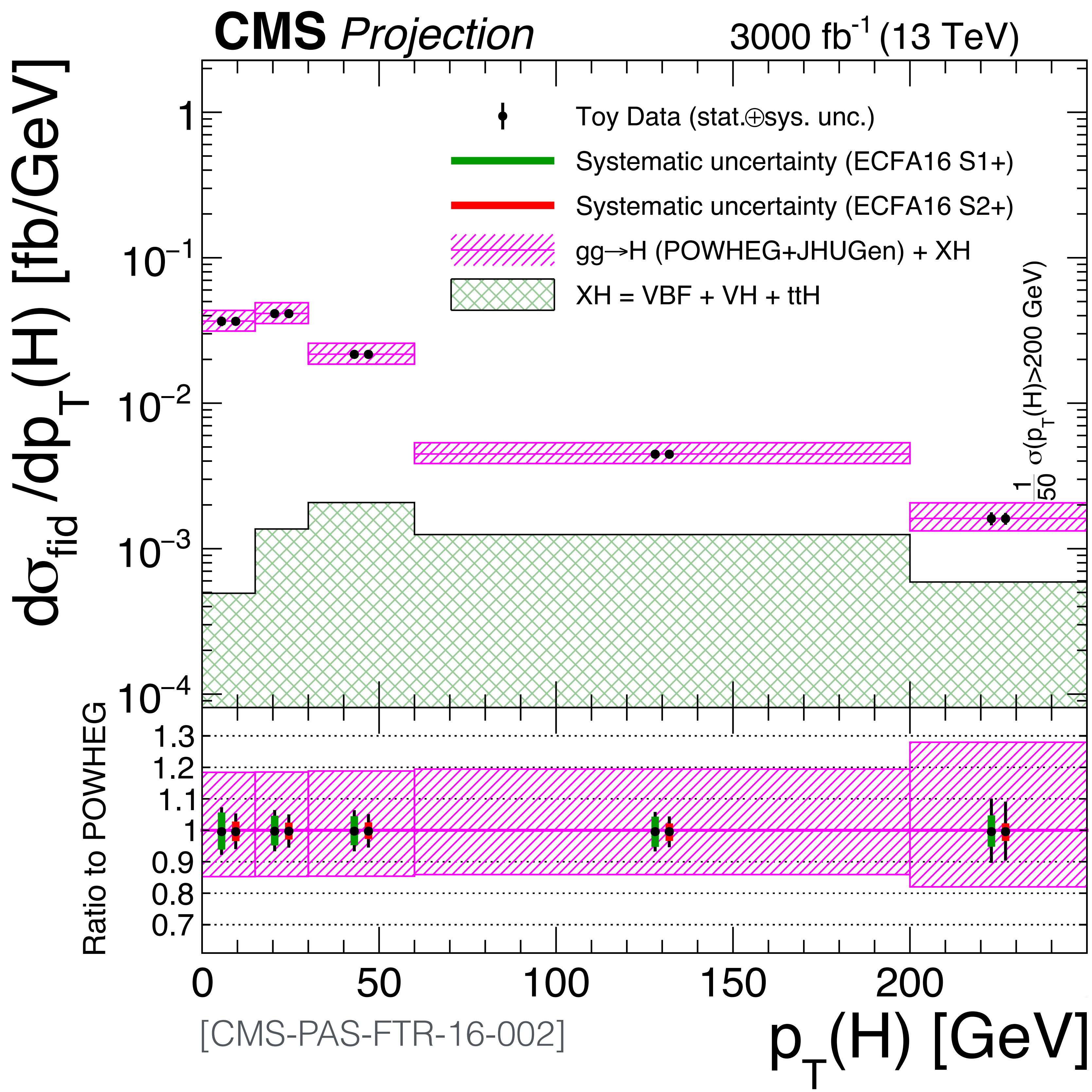
DISCLAIMER: NOT A PROPER COMBINATION; BALLPARK ESTIMATE

- Doing a very basic combination
  - No bin-to-bin correlations/migrations
  - Simple χ2 fit (entries weighted by uncertainty)
  - This is **not** a proper combination and **not** a CMS result
  - This study indicates a similar pattern to ATLAS: **20-30% statistically dominated uncertainties**



p_T^H: Projections from CMS

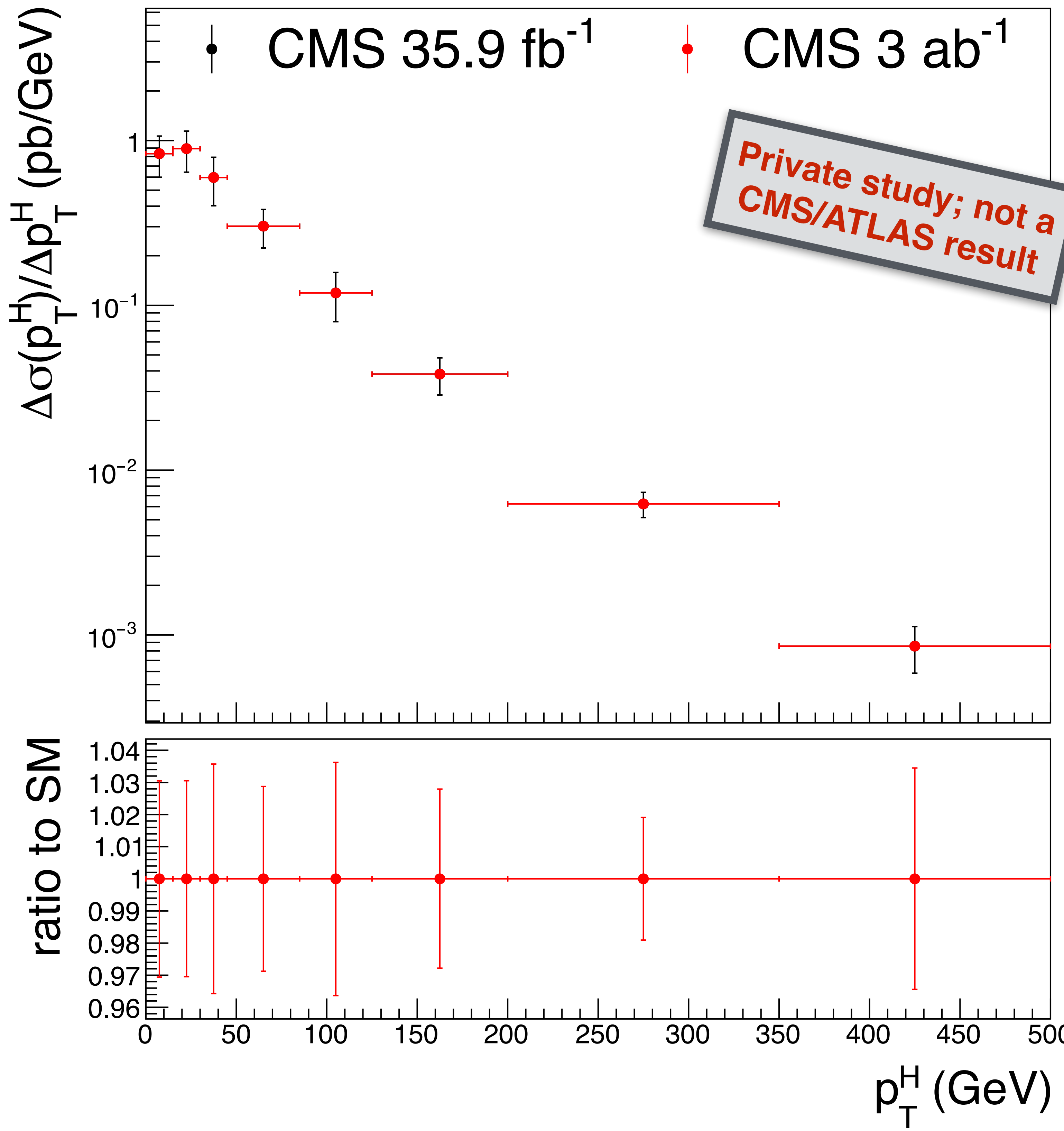
- Projection available for **H → ZZ**
  - 5-10% uncertainties, comparable to ATLAS H → ZZ



[CMS-PAS-FTR-16-002]

p_T^H: Projections from CMS

- No proper projection for the **combination** yet, but simply scaling observed uncertainties by $\sqrt{35.9/3000}$
- Moved central values to SM expectation
- Yields **~3%** uncertainties (a bit by construction of course), comparable to the ATLAS projections



Remarks on p_T^H

- Uncertainties of the **order of a few percent** seem achievable for HL-LHC, with $\mathcal{O}(10)$ bins up to p_T 350 GeV
- Currently, uncertainties are very **statistically dominated**
    - Differentials are not hit as hard by the '*systematics wall*'
    - Good motivation to combine results from both experiments
- Possibility to improve further by including more decay channels in the combination: $H \rightarrow WW$, $VH \rightarrow bb$ (planned by ATLAS), (boosted) $H \rightarrow bb$, etc.

Couplings: κ_t vs. c_g

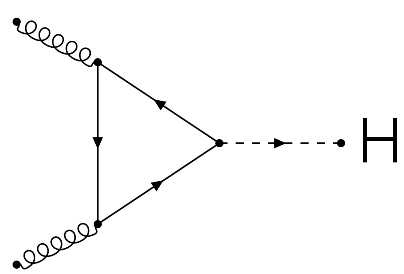
- p_T spectrum can be used to fit **κ_t vs. c_g**

  - Modify Lagrangian:

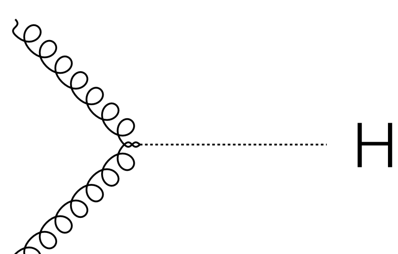
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\alpha_S}{\pi v} c_g h G^a_{\mu\nu} G^{a,\mu\nu}$$

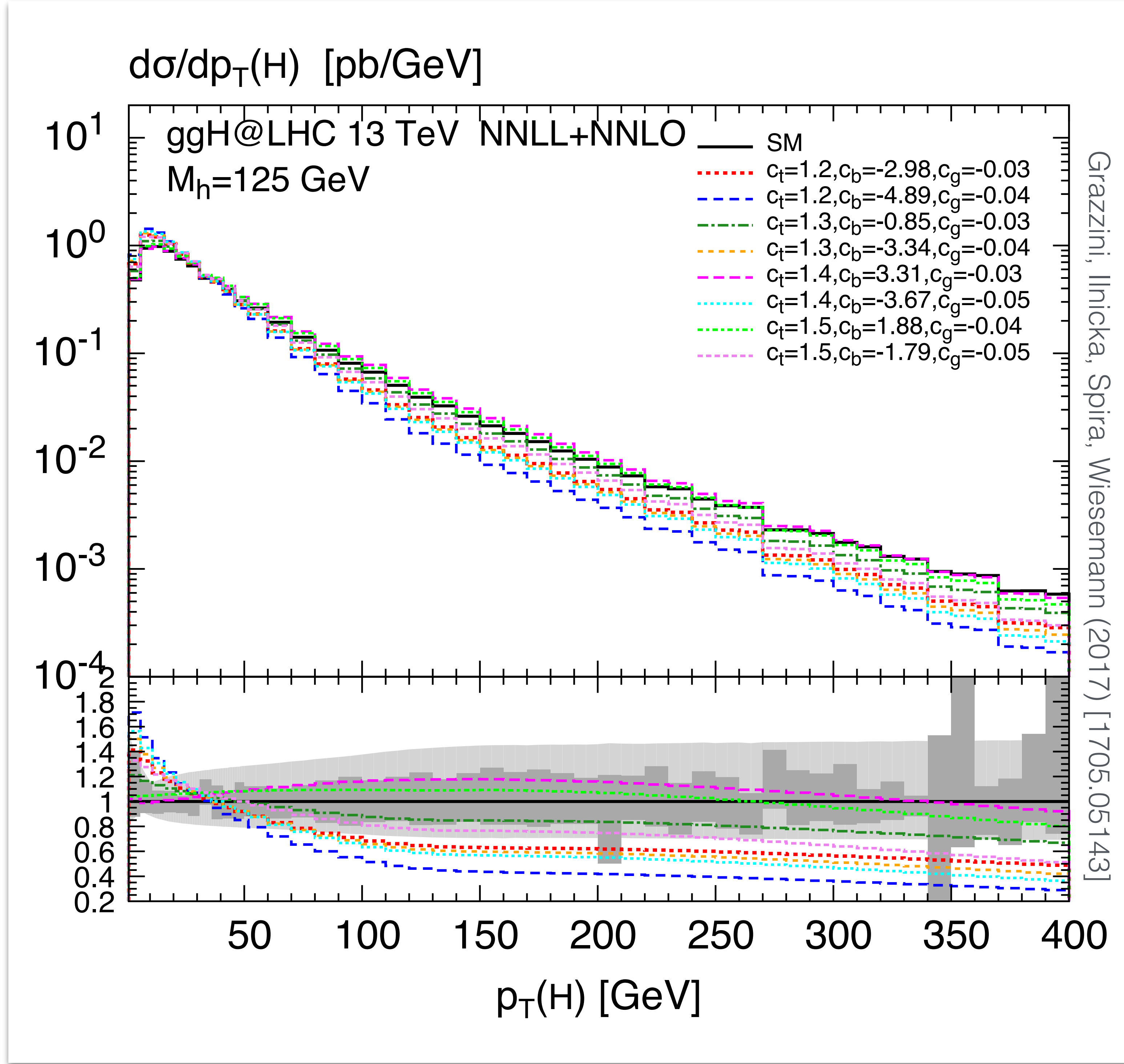
(dim-6)

($\kappa_t = 1$, $c_g = 0$) ~ SM,



($\kappa_t = 0$, $c_g = \sim 1/12$) ~ point-like coupling of the Higgs to gluons





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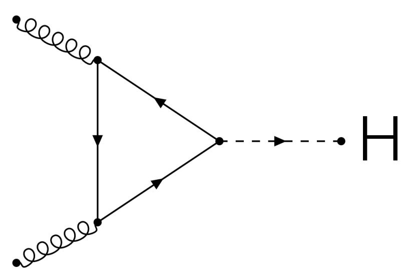
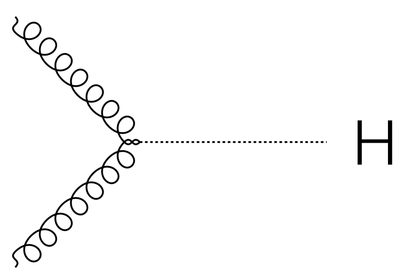
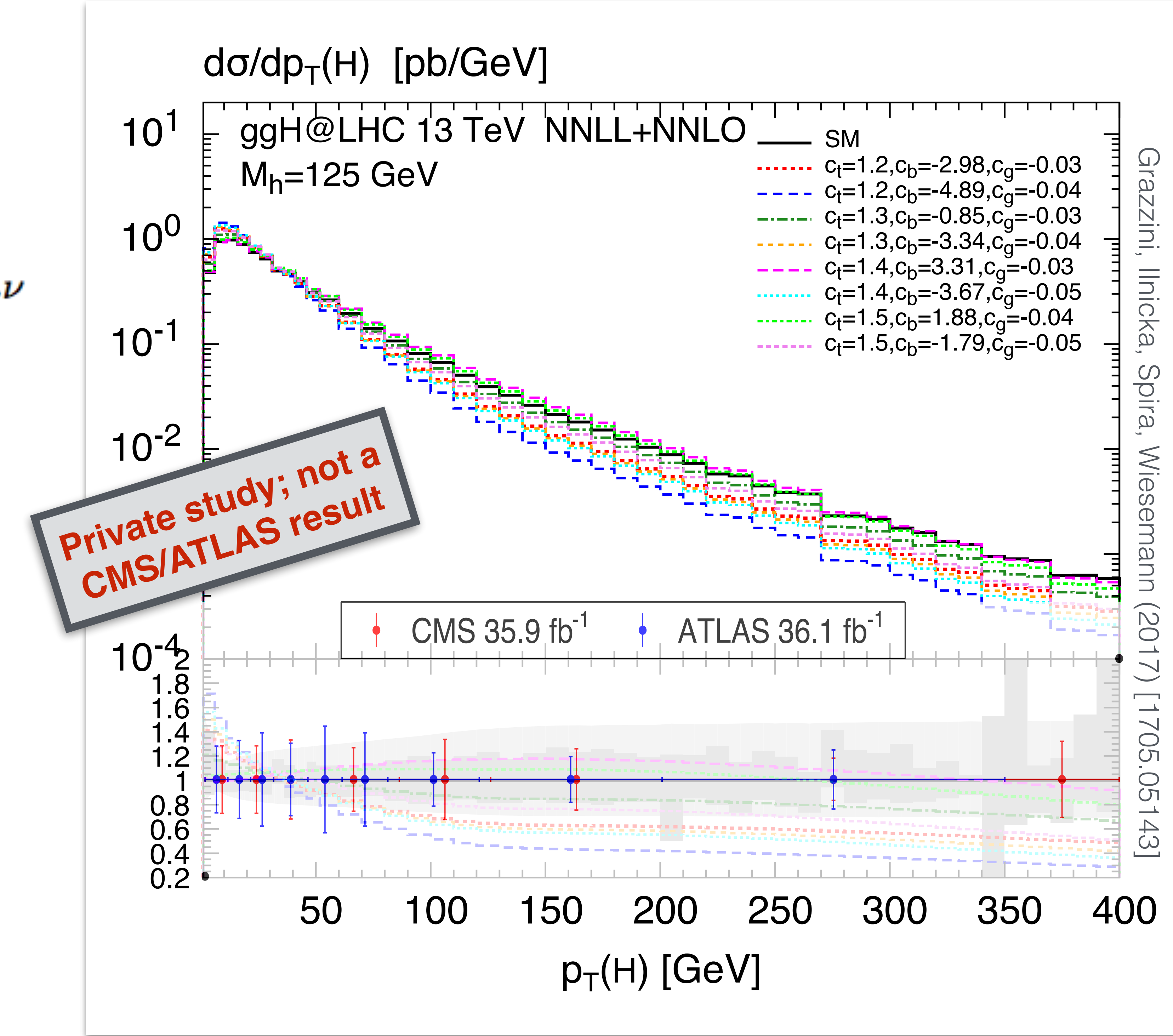


($\kappa_t = 0$, $c_g = 0.007$) ~ point-like coupling of the Higgs to gluons





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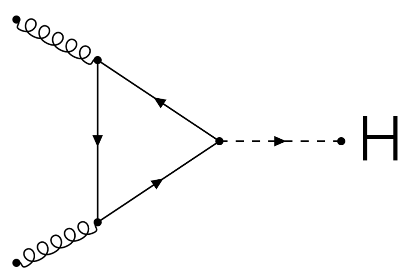

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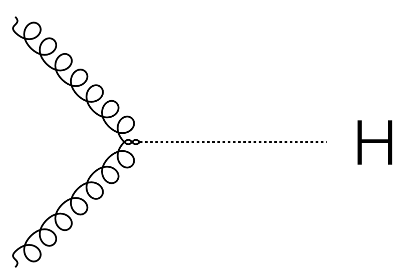

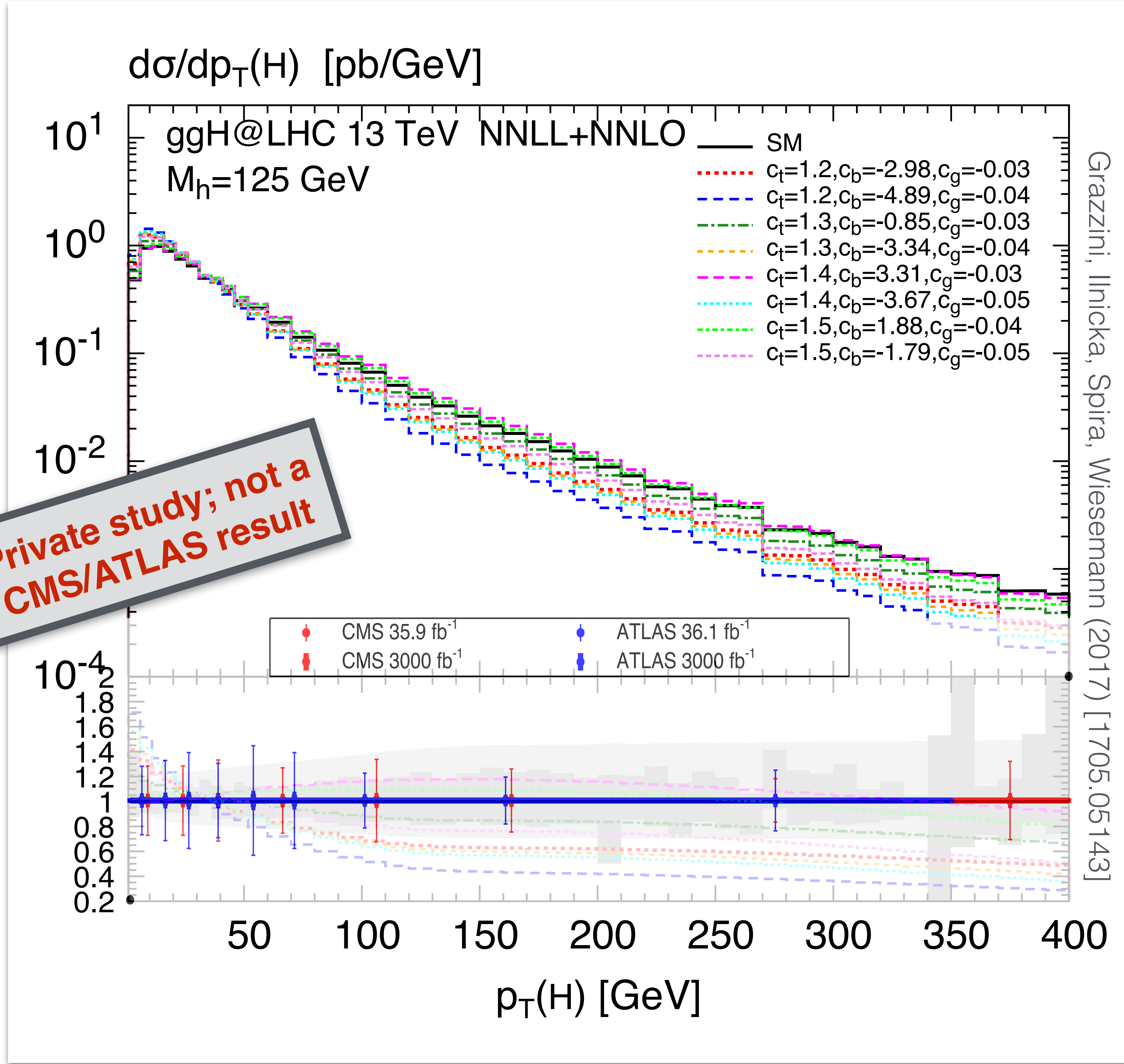

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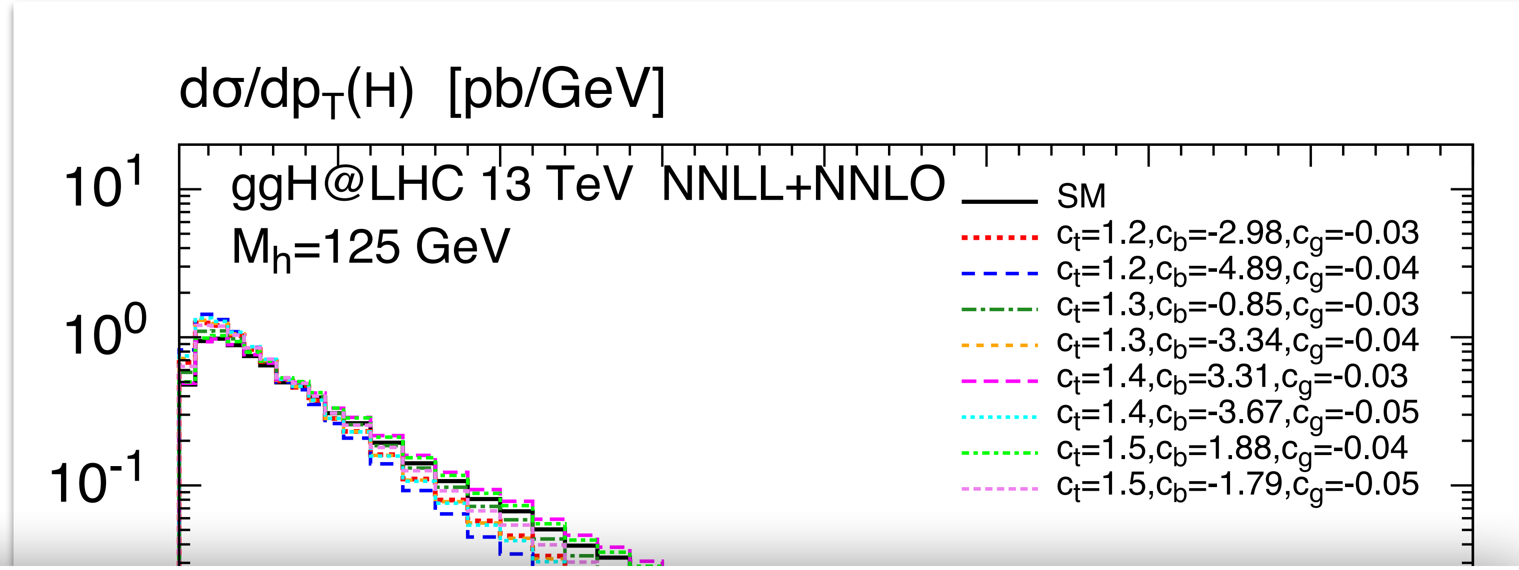

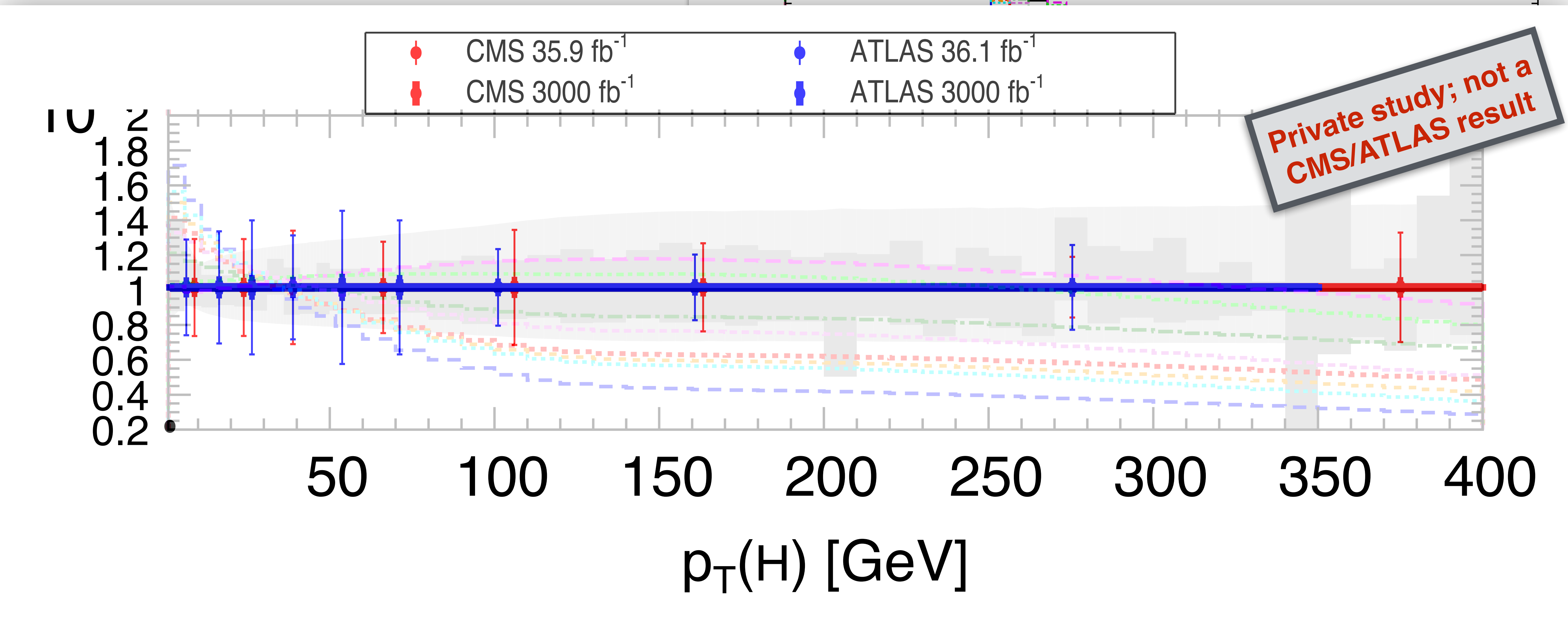

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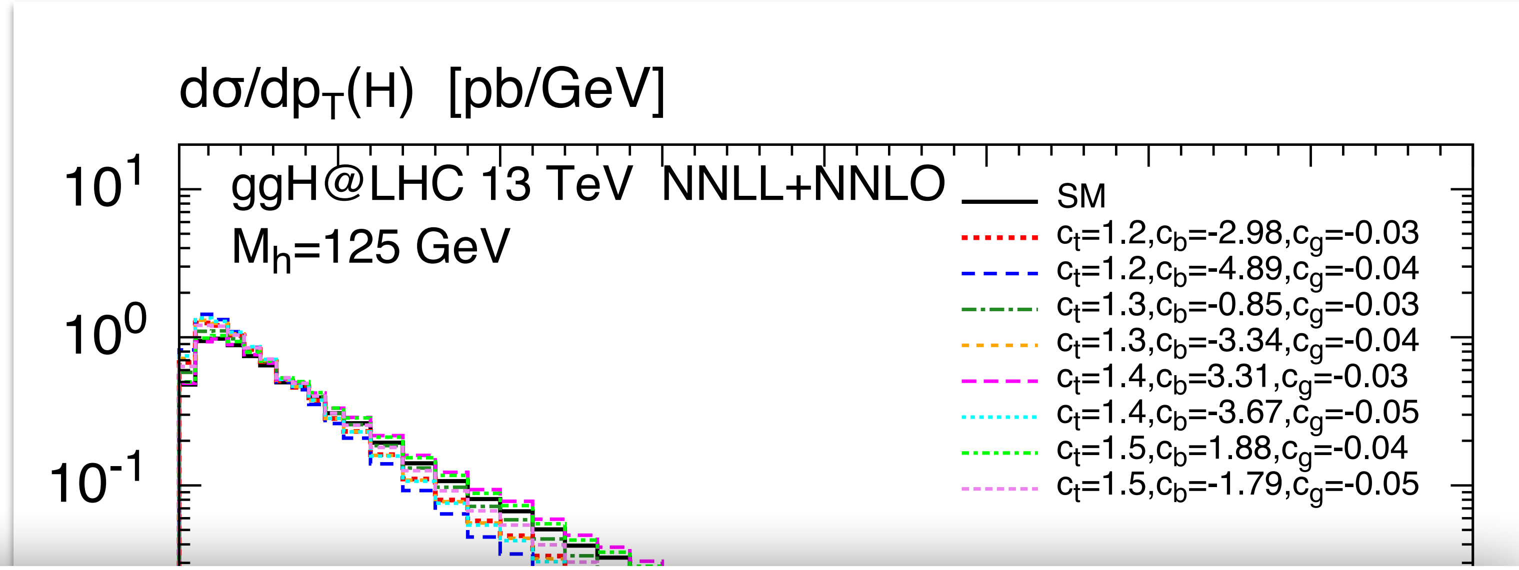

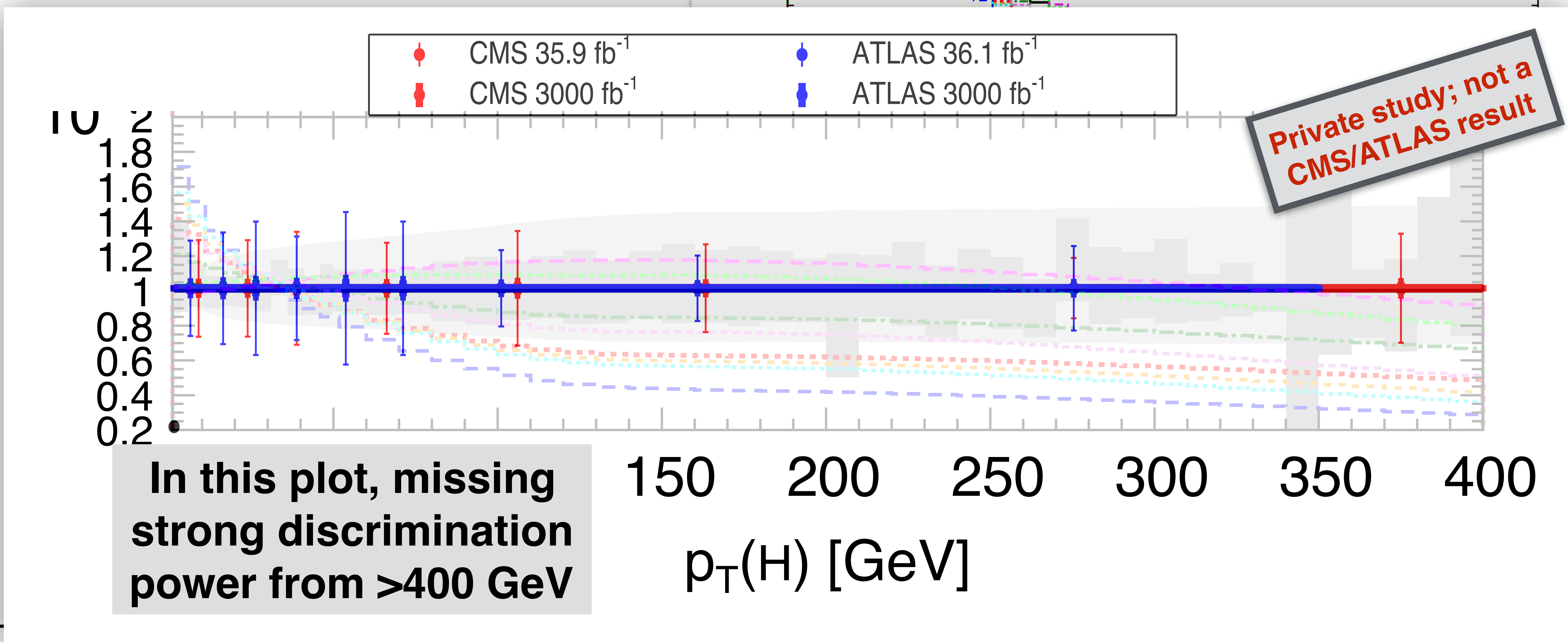

VBS / VBF

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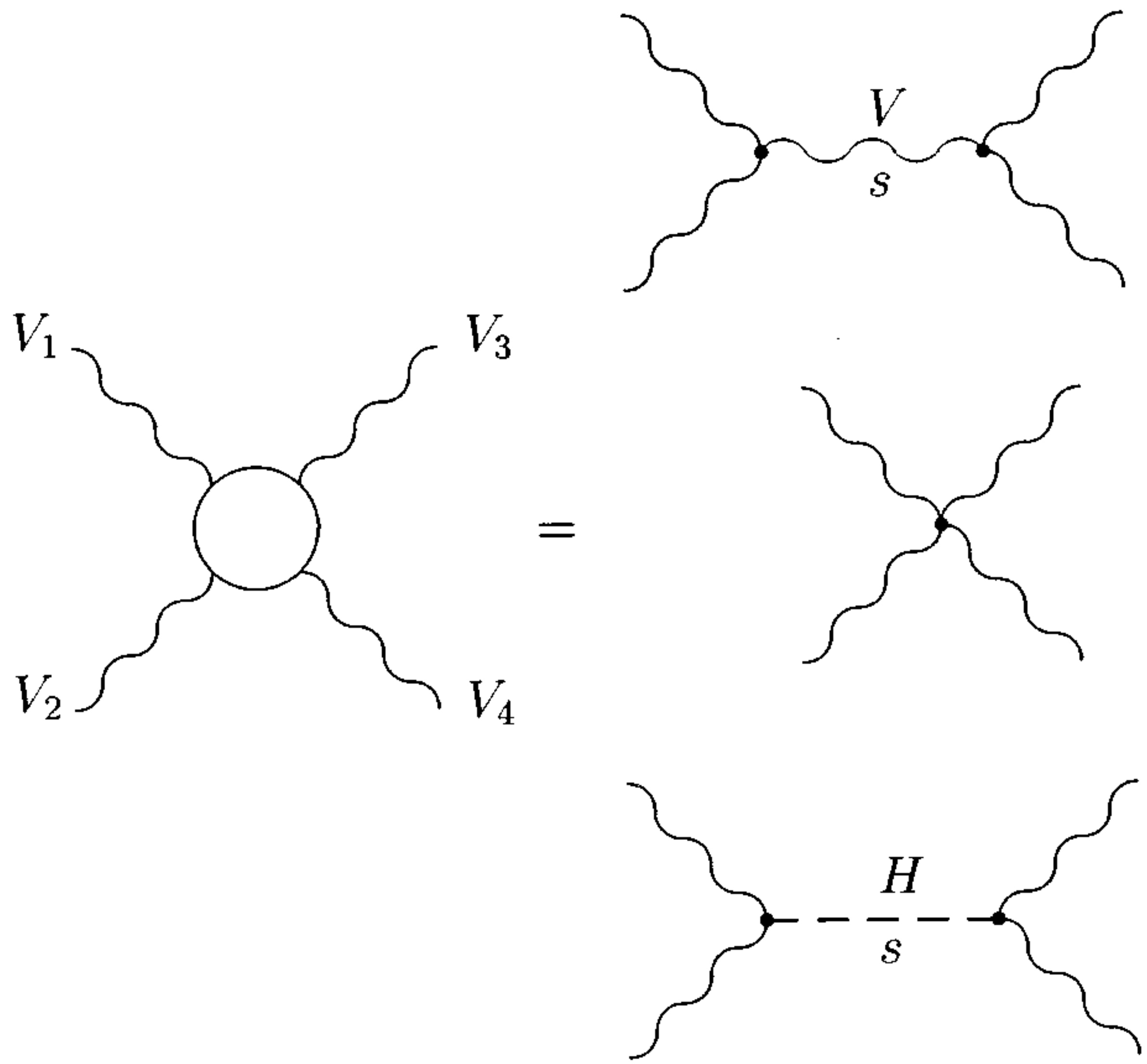
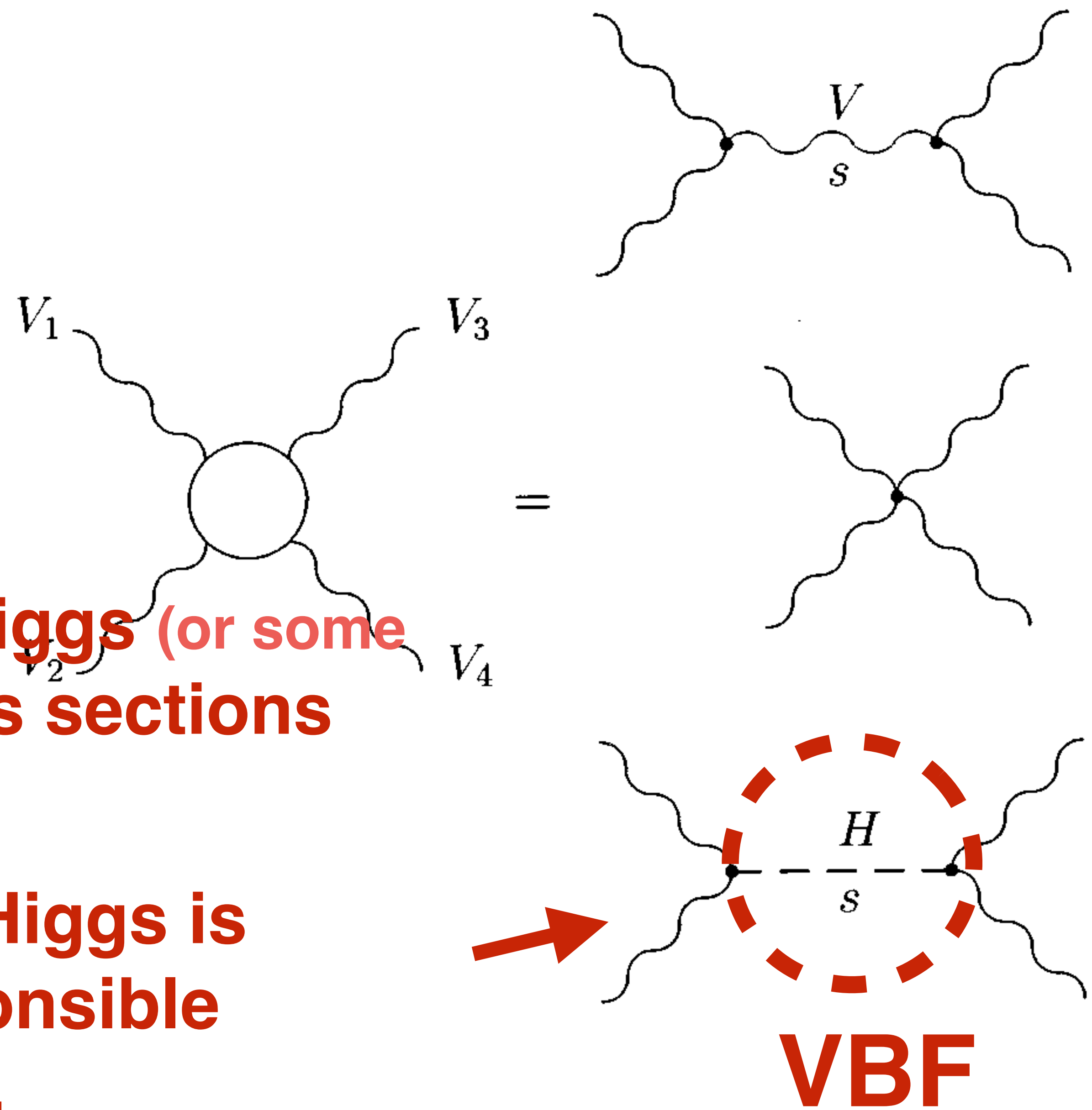


VBS / VBF

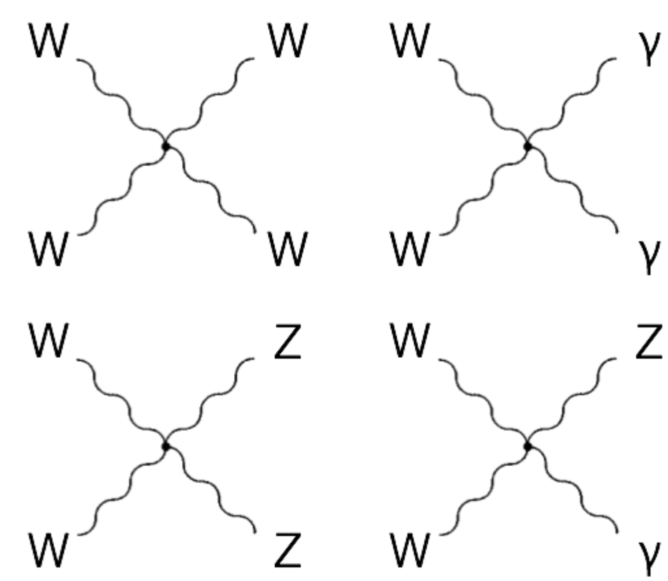


Without the Higgs (or some other NP)**, cross sections diverge**

- **Not sure if Higgs is <u>solely</u> responsible**
- **Explore high energy, see if Higgs preserves unitarity at all energies**

VBS / VBF

***Quartic Gauge Coupling*, only few diagrams allowed in the SM:**



Any other couplings would be NP

Parametrizable via EFT

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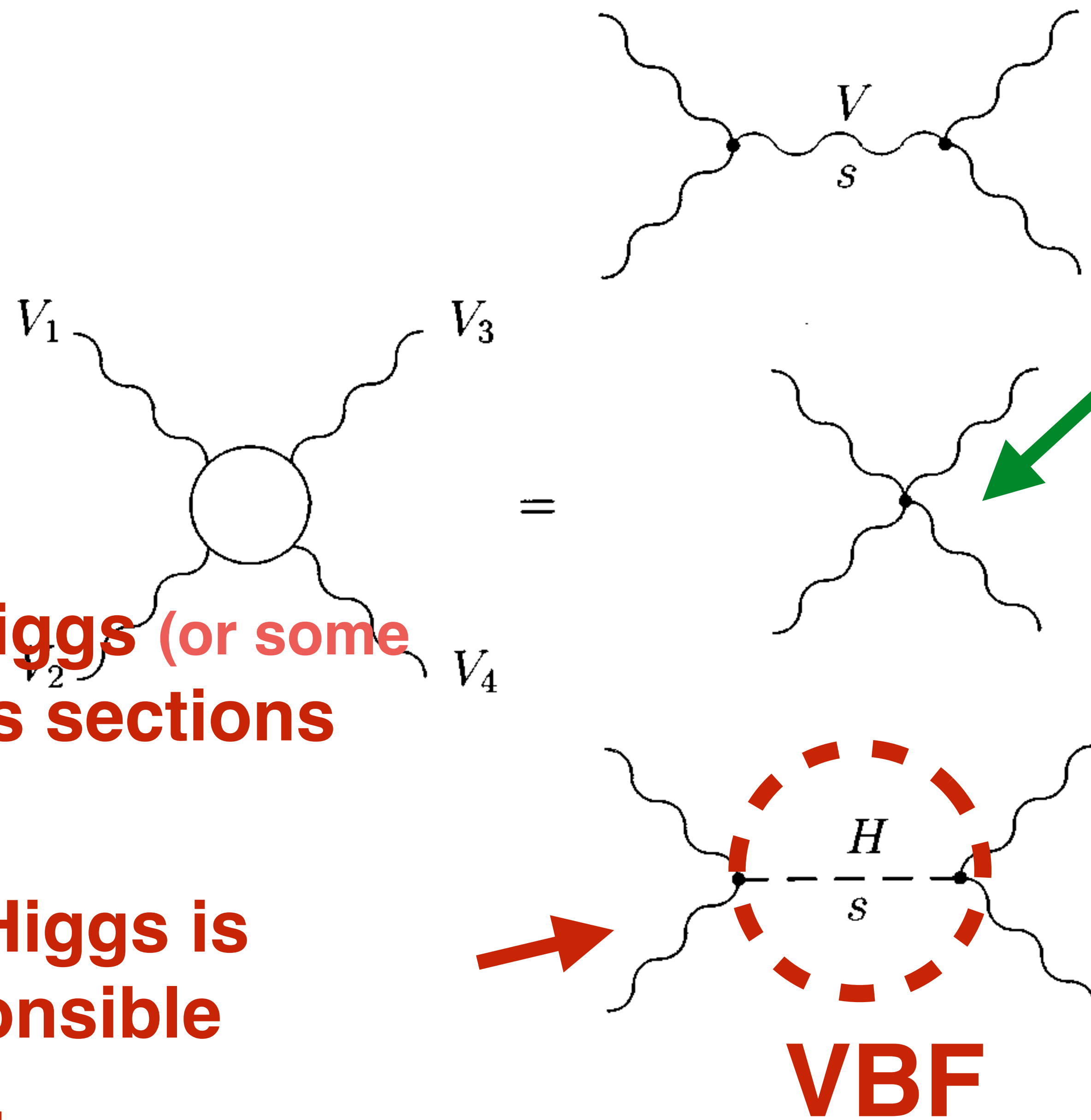

EFT approach

- Add higher dimension operators to the SM Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c^{(8)}}{\Lambda^2}\mathcal{O}_j^{(8)} + \ldots$$

  - Compare measurements under $\mathcal{L}$ vs. $\mathcal{L}_{\mathrm{SM}}$, look for NP!

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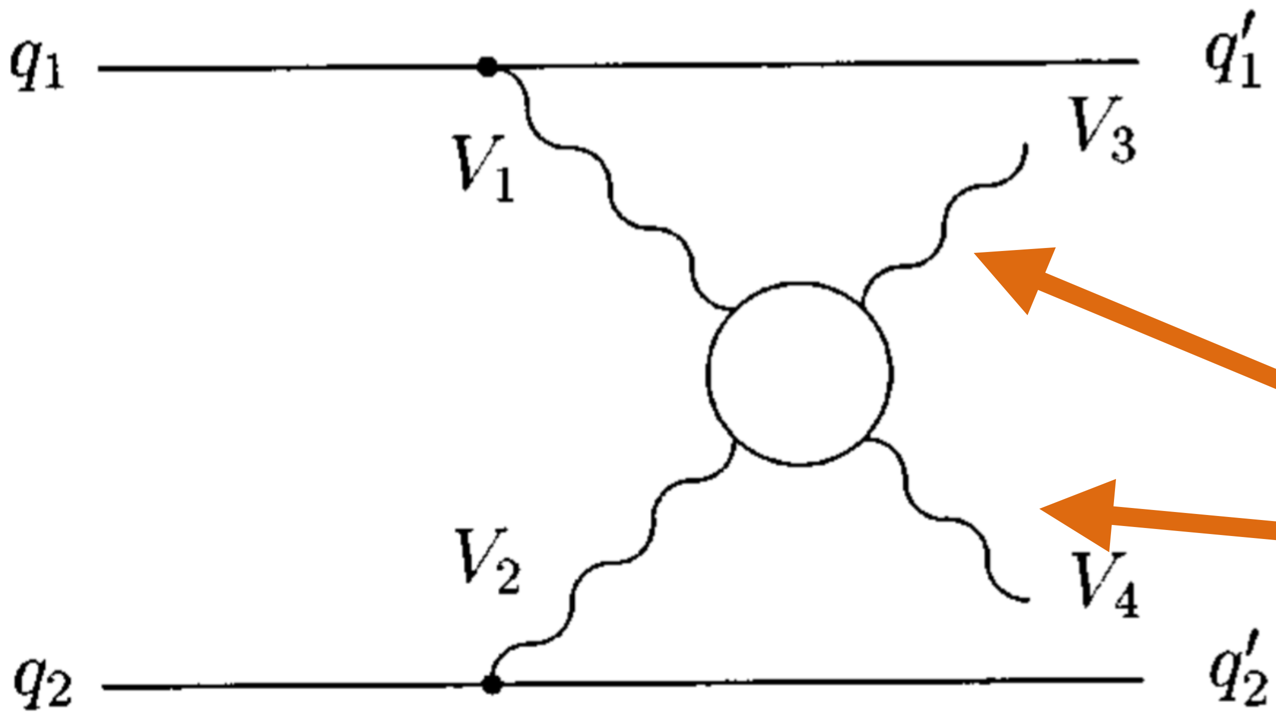
  - Compare measurements under $\mathcal{L}$ vs. $\mathcal{L}_{\mathrm{SM}}$, look for NP!

- **dim-8 operators** needed to induce (anomalous) QGC without TGC vertices
  - Modifications of existing SM vertices, and newly allowed vertices

[Rauch, 1610.08420]

	$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$	$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$	$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$
$WWWW$	X	X		X		
$WWZZ$	X	X	X	X	X	
$ZZZZ$	X	X	X	X	X	X
$WWZ\gamma$		X	X	X	X	
$WW\gamma\gamma$		X	X	X	X	
$ZZZ\gamma$		X	X	X	X	X
$ZZ\gamma\gamma$		X	X	X	X	X
$Z\gamma\gamma\gamma$				X	X	X
$\gamma\gamma\gamma\gamma$				X	X	X

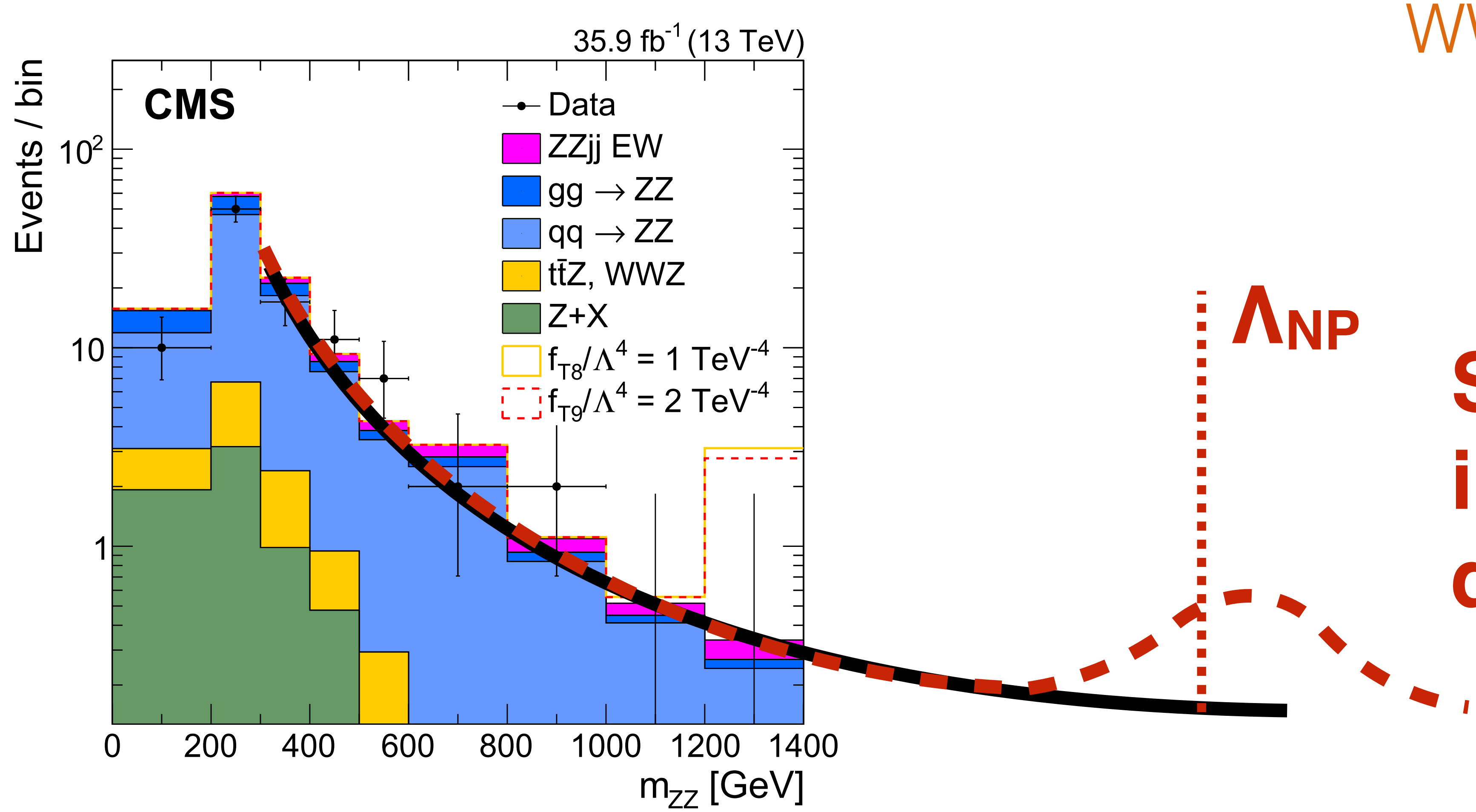
Experimental aspects of VBS



Very forward jet, large Δη

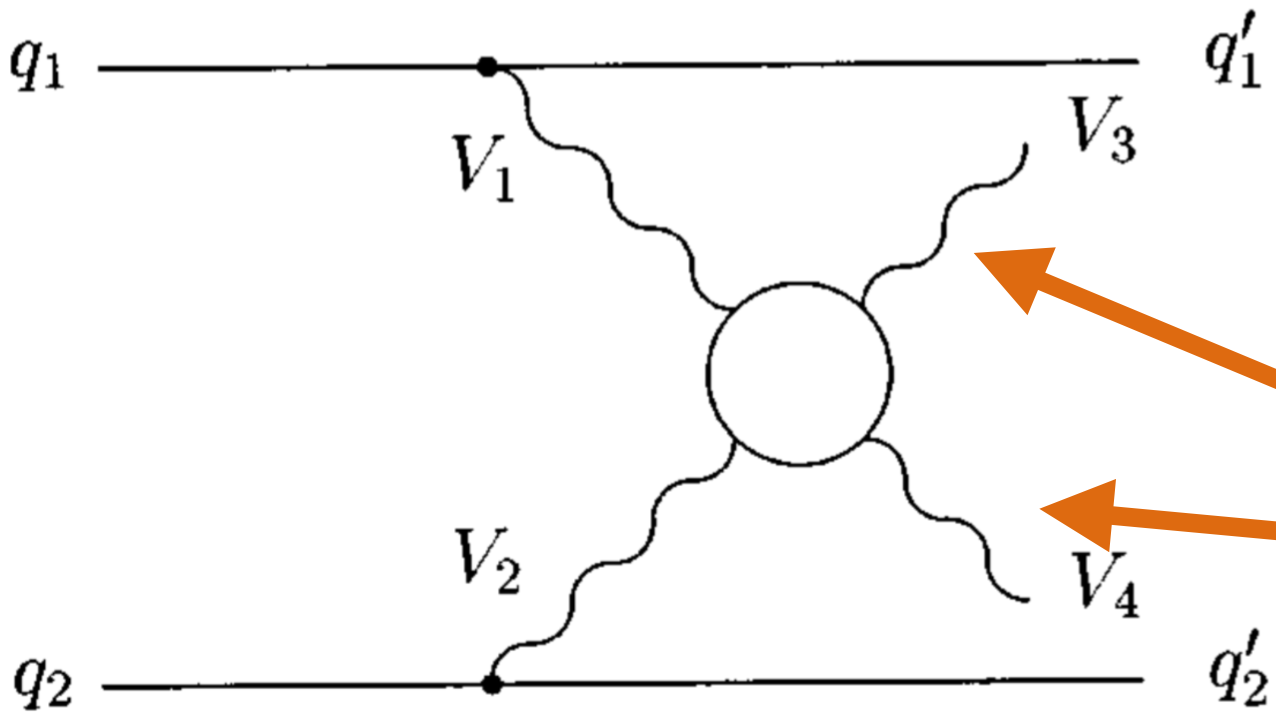
Rather central w.r.t. backgrounds

Main decay channels: WW, WZ, ZZ



See NP effects in tails of distributions

Experimental aspects of VBS



Very forward jet, large Δη

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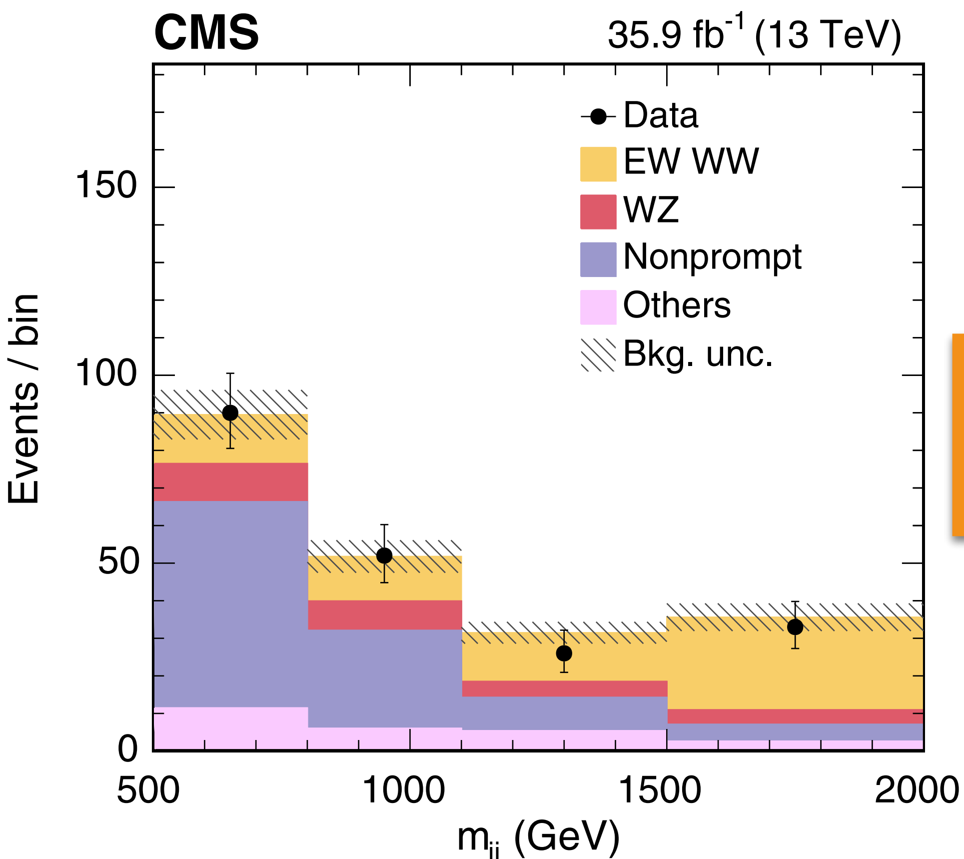
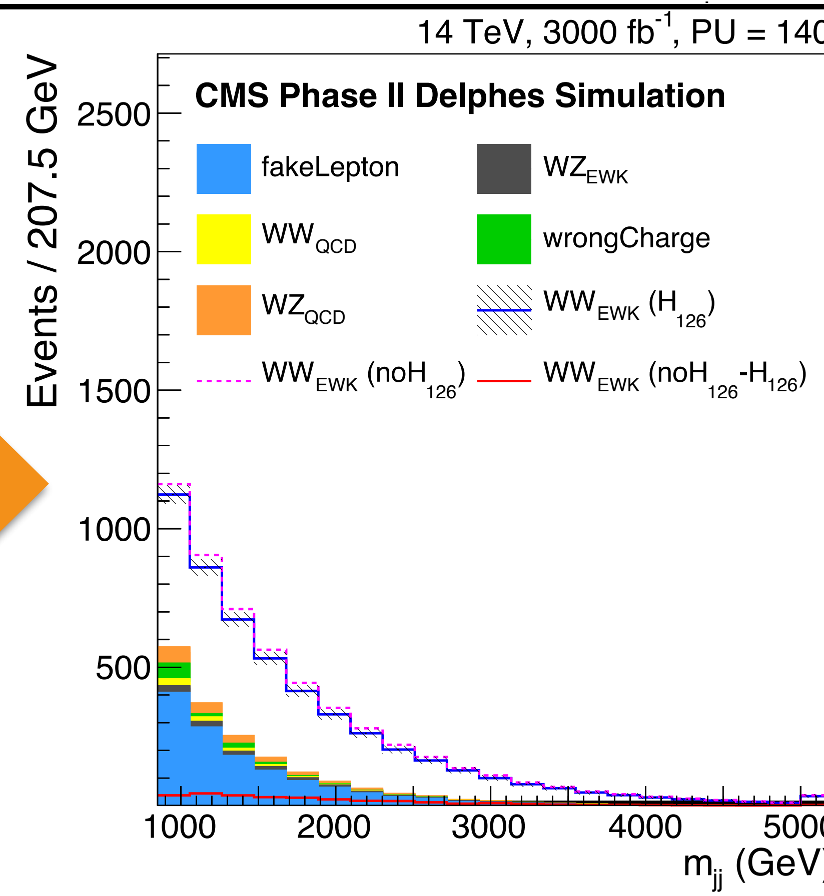
Main decay channels: WW, WZ, ZZ

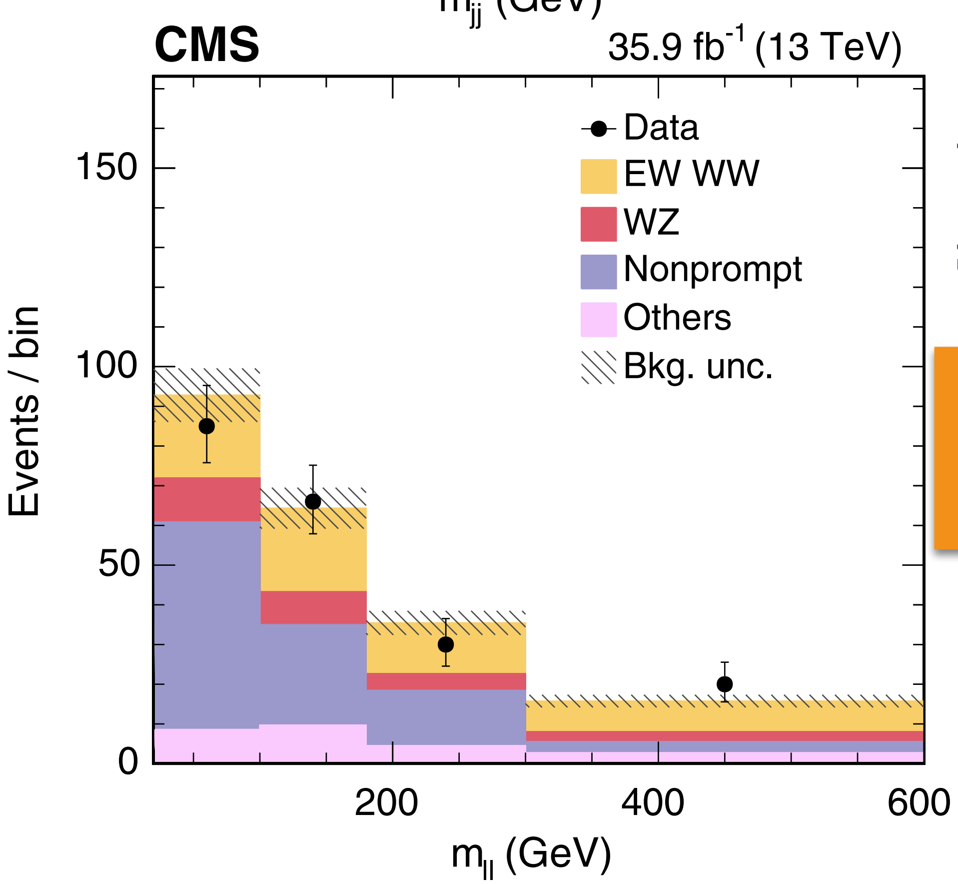
- Currently statistically limited at high energy
- General prospects of HL LHC:
  - Better statistics in the tail
  - Better forward coverage
  - Availability of differential cross sections
  - Harsh pileup conditions

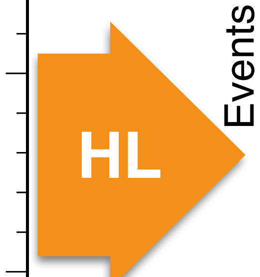
VBS: Same-sign WW → lνlν

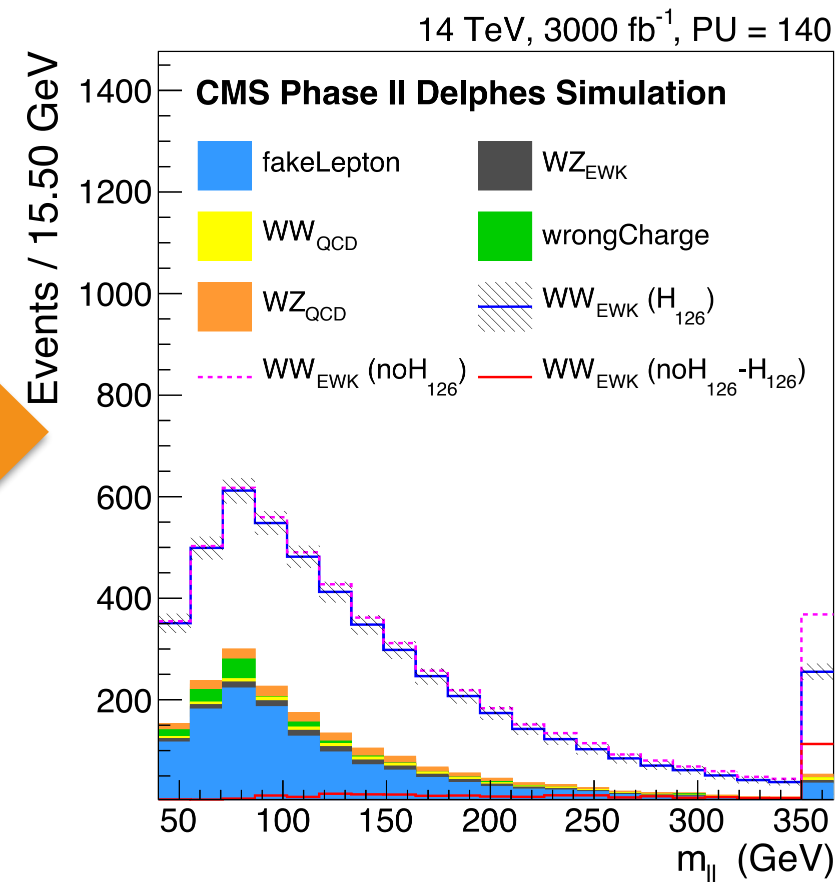




[PRL 120, 081801 (2018)]







[CMS PAS SMP-14-008]

- ssWW largest σ_{EW}/σ_{QCD}
- Recent **5.5** (5.7) **σ observed** (expected) significance by CMS
- Increased reach projected at HL-LHC

VBS: Same-sign WW → lvlv

ATLAS @ 3000 fb^{-1}

model	300 fb^{-1}	3 ab^{-1}
f_{S0}/Λ^4	10 TeV^{-4}	4.5 TeV^{-4}

5σ discovery values

[ATLAS-PHYS-PUB-2013-006]

95% CLs @ 3000 fb^{-1}

	Phase I (TeV $^{-4}$)	Phase II (TeV $^{-4}$)	Phase I aged (TeV $^{-4}$)	Run-I results (TeV $^{-4}$)
S_0	2.47	2.49	2.85	43 [12]
S_1	8.19	8.25	9.45	131 [12]
M_0	1.88	1.76	2.03	4.6 [38]
M_1	2.54	2.38	2.72	1.7 [38]
M_6	3.78	3.54	4.05	69 [12]
M_7	3.42	3.24	3.75	73 [12]
T_0	0.17	0.17	0.19	3.4 [39]
T_1	0.078	0.070	0.080	2.4 [12]
T_2	0.25	0.23	0.25	7.1 [12]

[CMS PAS SMP-14-008]

95% CLs @ 35.9 fb^{-1}

	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
f_{S0}/Λ^4	[−7.7, 7.7]	[−7.0, 7.2]
f_{S1}/Λ^4	[−21.6, 21.8]	[−19.9, 20.2]
f_{M0}/Λ^4	[−6.0, 5.9]	[−5.6, 5.5]
f_{M1}/Λ^4	[−8.7, 9.1]	[−7.9, 8.5]
f_{M6}/Λ^4	[−11.9, 11.8]	[−11.1, 11.0]
f_{M7}/Λ^4	[−13.3, 12.9]	[−12.4, 11.8]
f_{T0}/Λ^4	[−0.62, 0.65]	[−0.58, 0.61]
f_{T1}/Λ^4	[−0.28, 0.31]	[−0.26, 0.29]
f_{T2}/Λ^4	[−0.89, 1.02]	[−0.80, 0.95]

[PRL 120, 081801 (2018)]

- Projected limits on dim-8 operators show much stronger constraints

VBS: Same-sign WW → lvlv

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model	300 fb^{-1}	3 ab^{-1}
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5σ discovery values

[ATLAS-PHYS-PUB-2013-006]

Forward tracking upgrades: **15%** precision improvement of cross section

[ATL-PHYS-PUB-2017-023]

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	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
f_{S0}/Λ^4	[−7.7, 7.7]	[−7.0, 7.2]
f_{S1}/Λ^4	[−21.6, 21.8]	[−19.9, 20.2]
f_{M0}/Λ^4	[−6.0, 5.9]	[−5.6, 5.5]
f_{M1}/Λ^4	[−8.7, 9.1]	[−7.9, 8.5]
f_{M6}/Λ^4	[−11.9, 11.8]	[−11.1, 11.0]
f_{M7}/Λ^4	[−13.3, 12.9]	[−12.4, 11.8]
f_{T0}/Λ^4	[−0.62, 0.65]	[−0.58, 0.61]
f_{T1}/Λ^4	[−0.28, 0.31]	[−0.26, 0.29]
f_{T2}/Λ^4	[−0.89, 1.02]	[−0.80, 0.95]

[PRL 120, 081801 (2018)]

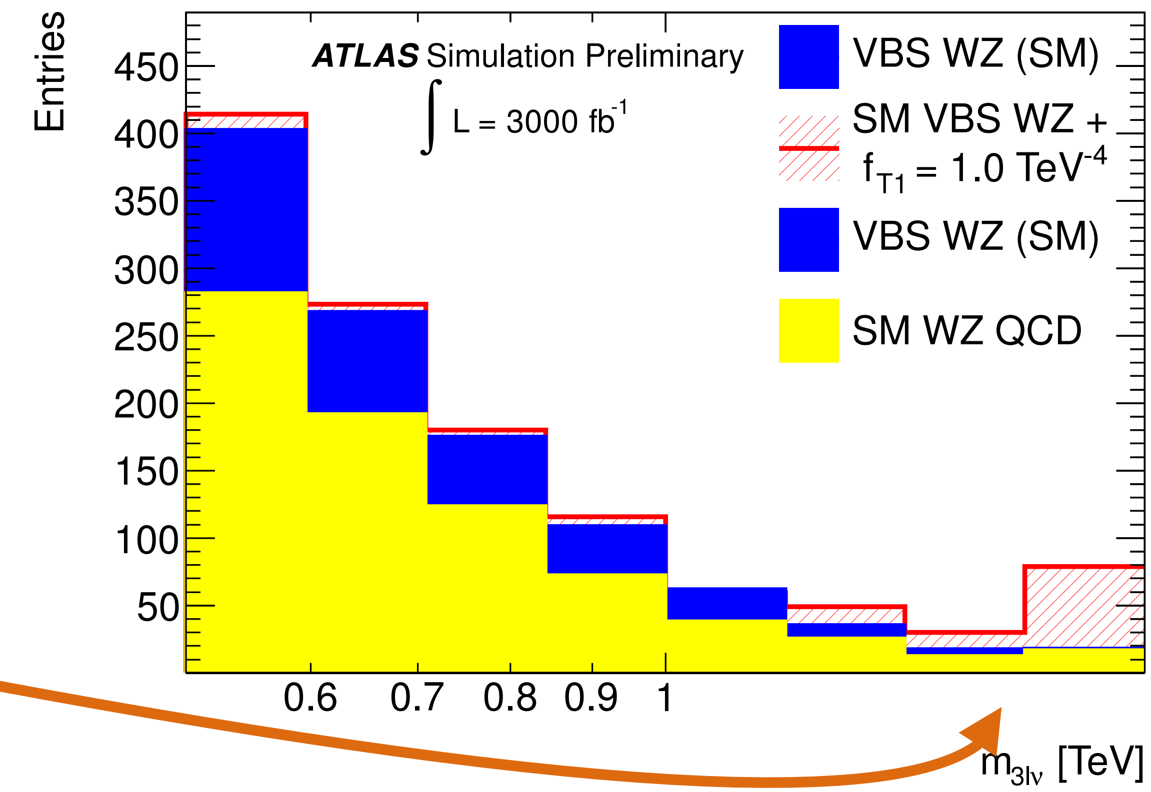
- Projected limits on dim-8 operators show much stronger constraints

VBS: WZ → lνll

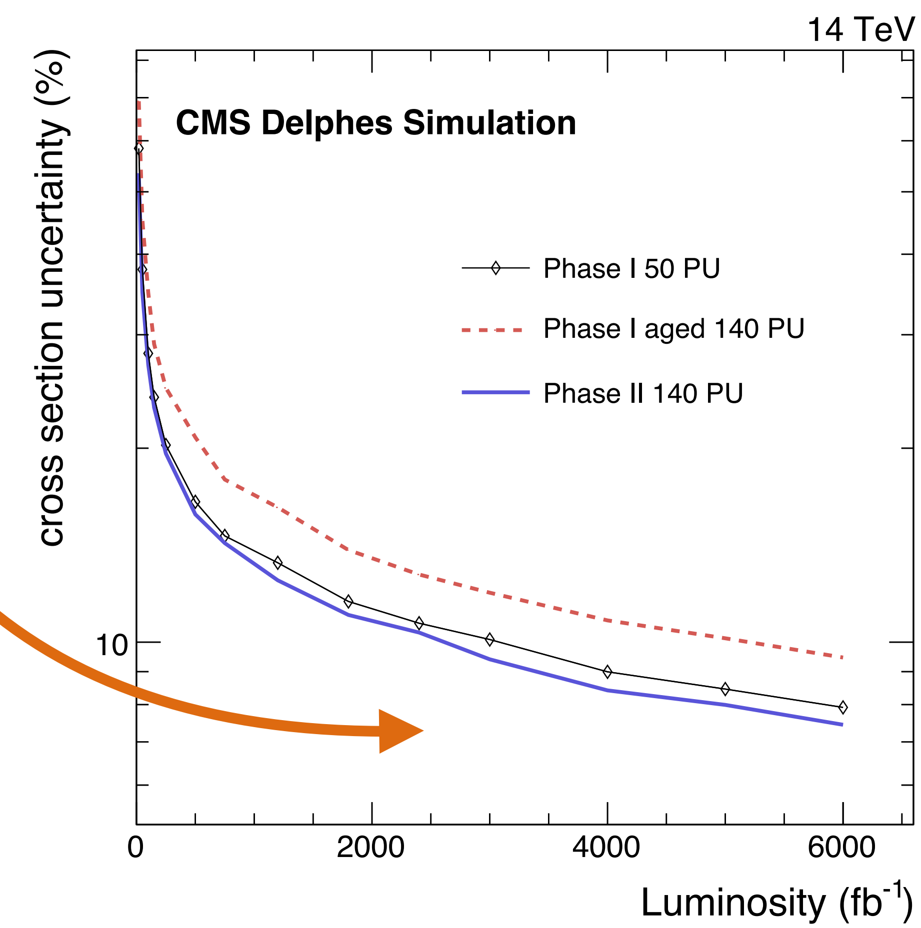
- Larger σ than VBS ZZ, while still able to construct m_{VV}
- Attainable sensitivity in the tails at high lumi
- Much better precision on the cross section
- 5σ discovery values:

[ATLAS-PHYS-PUB-2013-006]

	300 fb^{-1}	3000 fb^{-1}
f_{T1}/Λ^4	1.3 TeV^{-4}	0.6 TeV^{-4}



[ATLAS-PHYS-PUB-2013-006]

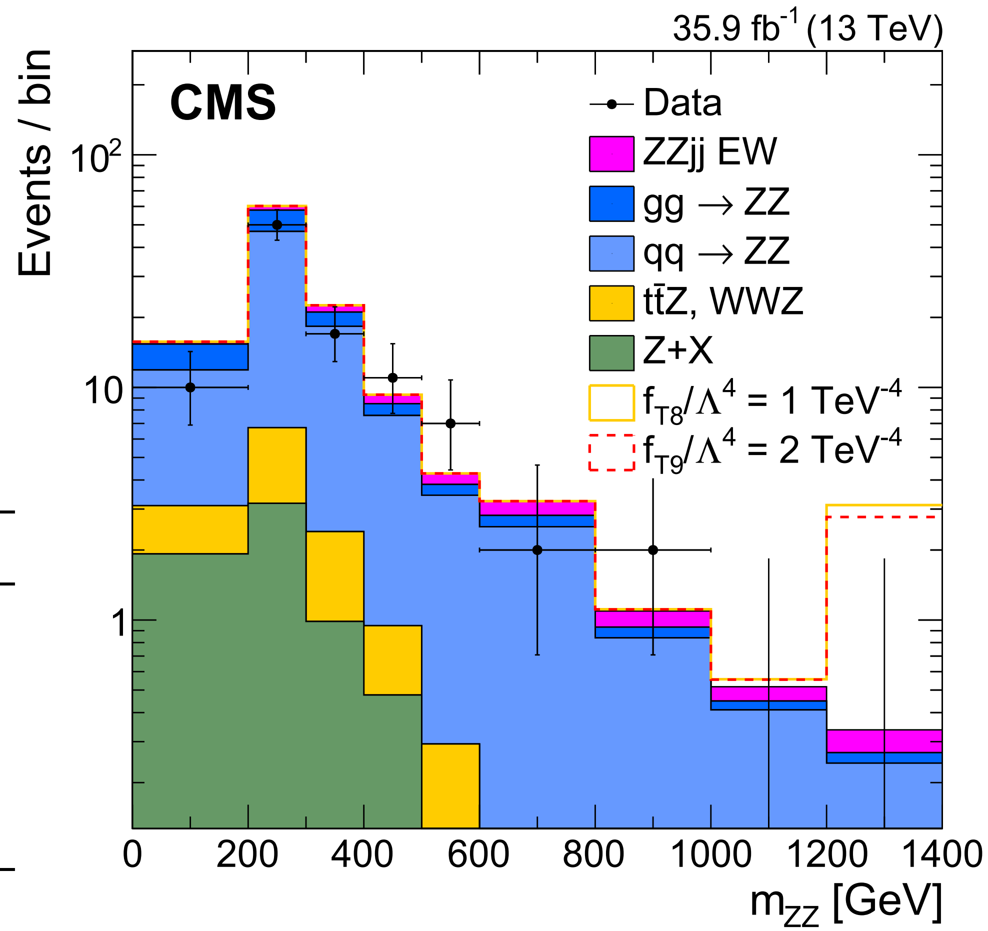


[CMS PAS SMP-14-008]

VBS: ZZ → llll

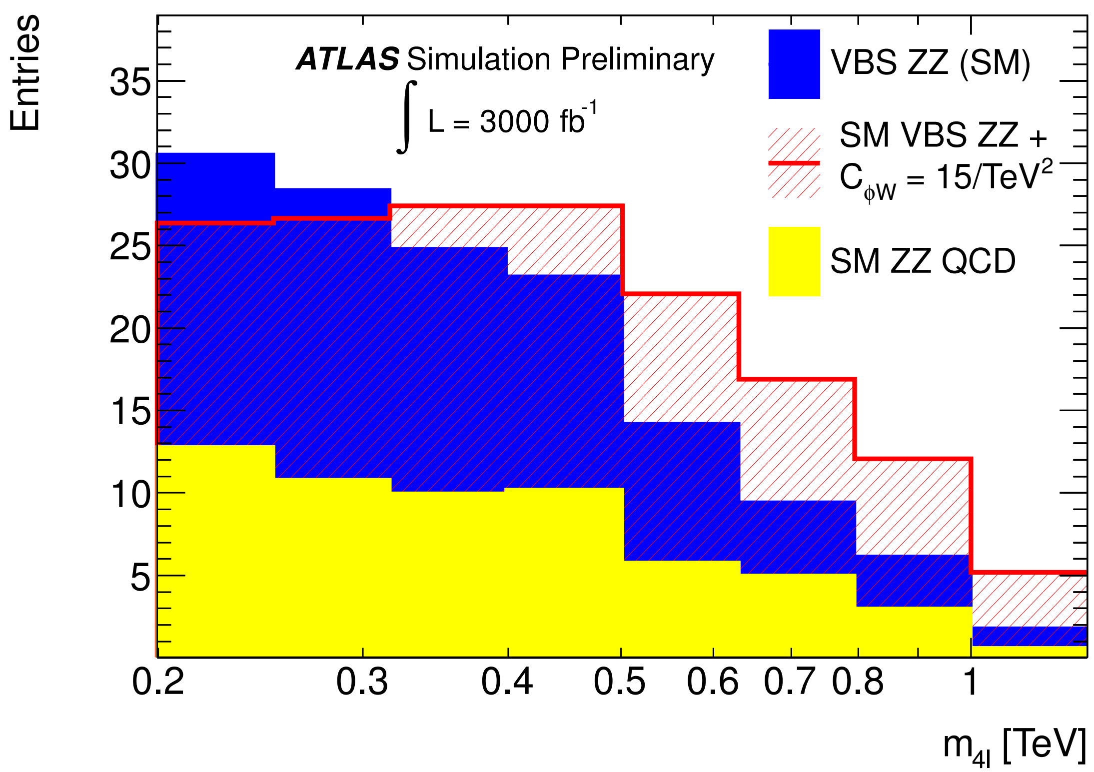
- Fully reconstructable final state
- 13 TeV CMS result, reaching up to m_{ZZ} ~1600 GeV

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper
f_{T0}/Λ^4	−0.53	0.51	−0.46	0.44
f_{T1}/Λ^4	−0.72	0.71	−0.61	0.61
f_{T2}/Λ^4	−1.4	1.4	−1.2	1.2
f_{T8}/Λ^4	−0.99	0.99	−0.84	0.84
f_{T9}/Λ^4	−2.1	2.1	−1.8	1.8

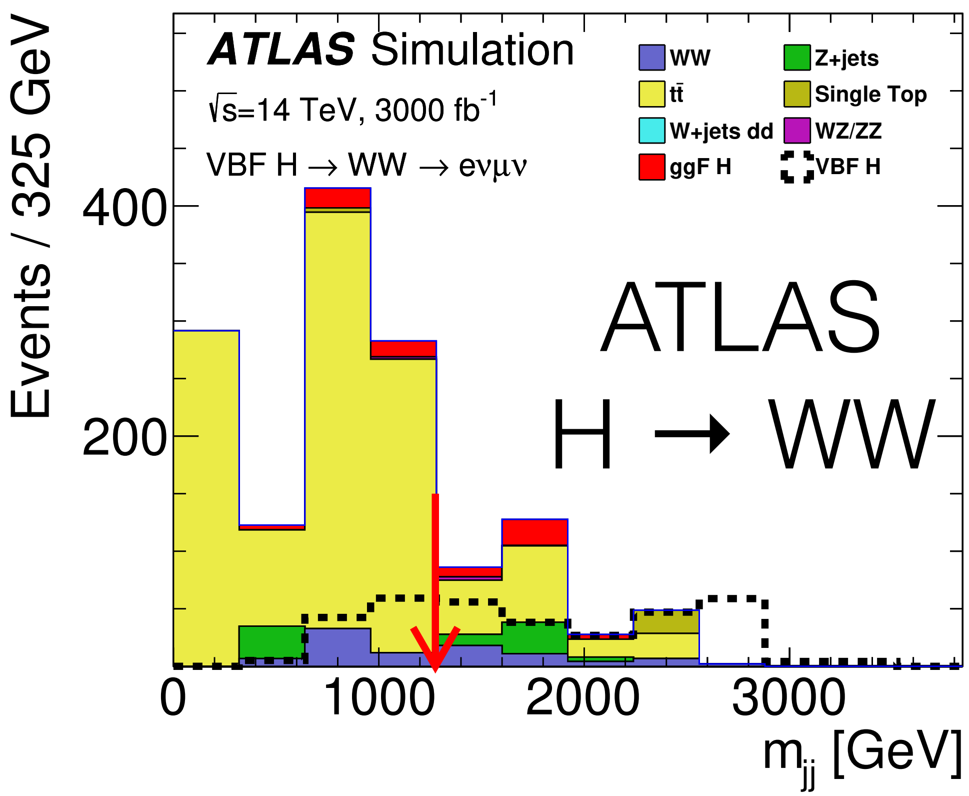


- Projection from ATLAS

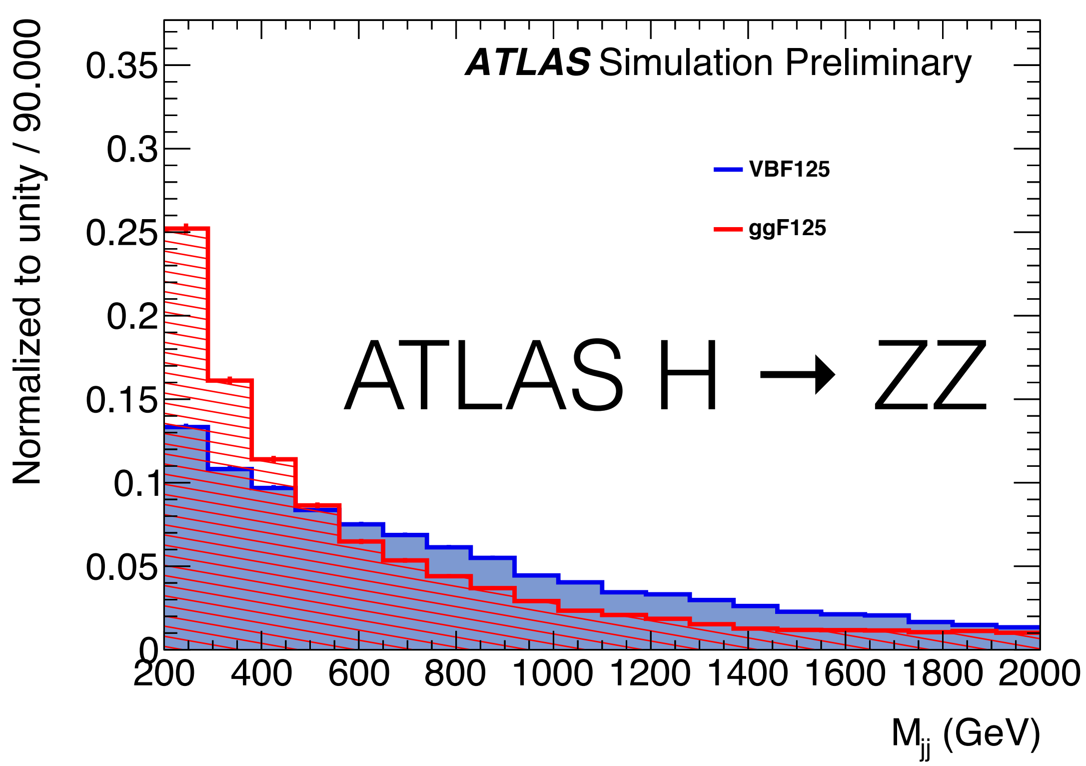
  (m_{jj} > 1 TeV)

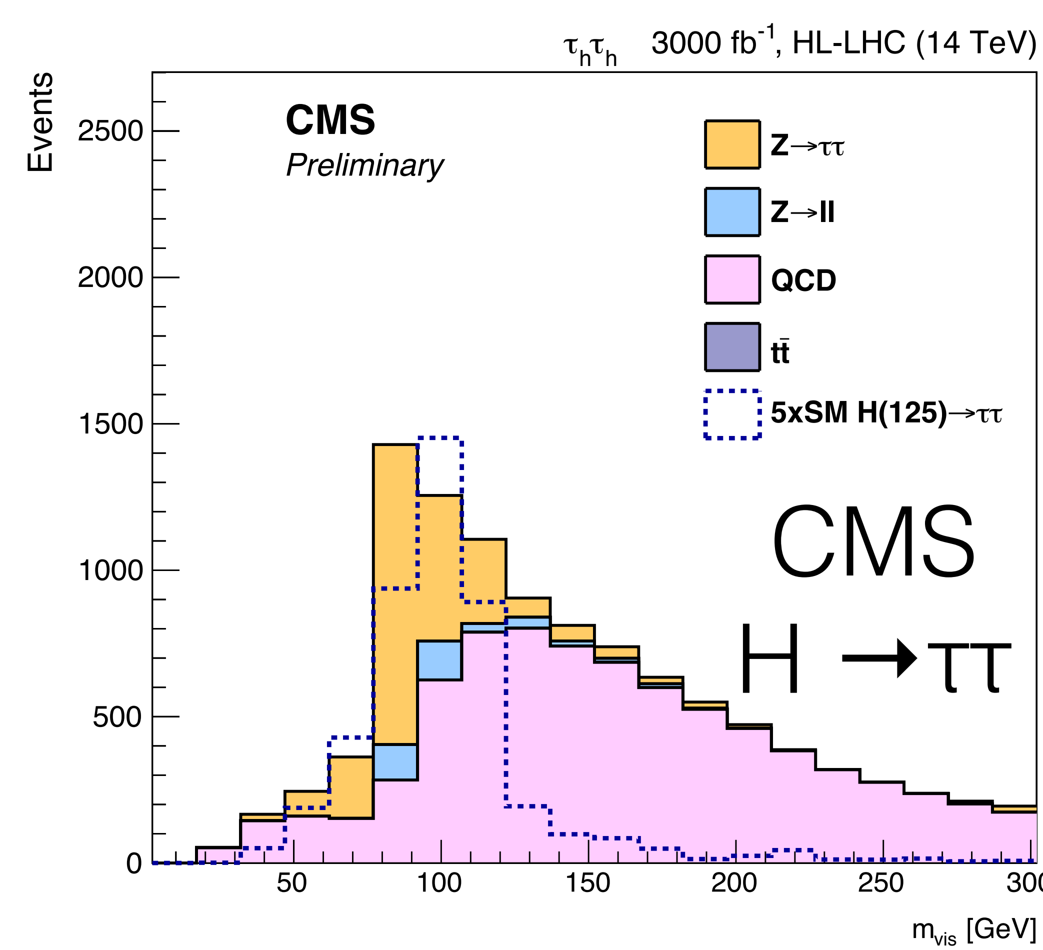


VBF



- Projections for VBF
  - Good for precision measurements of the Higgs signal strength, and couplings to other particles





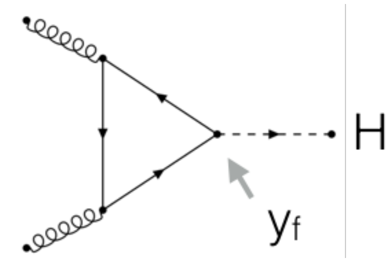
Conclusion

- HL-LHC opens up some interesting avenues for NP-searches at high energy
  - Deviations in **differential spectra** at high pT can be fitted to Higgs coupling modifiers, e.g. κ_t/c_g
  - NP-potential in the tails of **VBS**
- **EFT** in both cases a good framework for interpretation
  - Interpretation by theorists or experimentalists?
- Both cases currently **limited by statistics**
  - 3 ab^{-1} of data opens up possibilities for new measurements, and would provide competitive limits on Higgs couplings

Back up

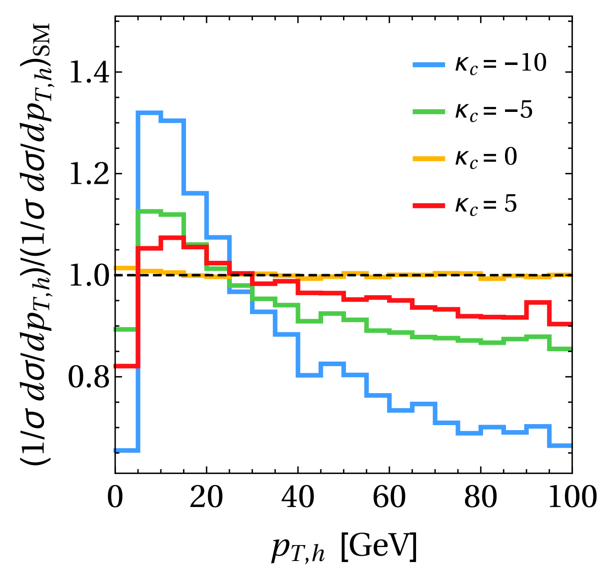
Introduction

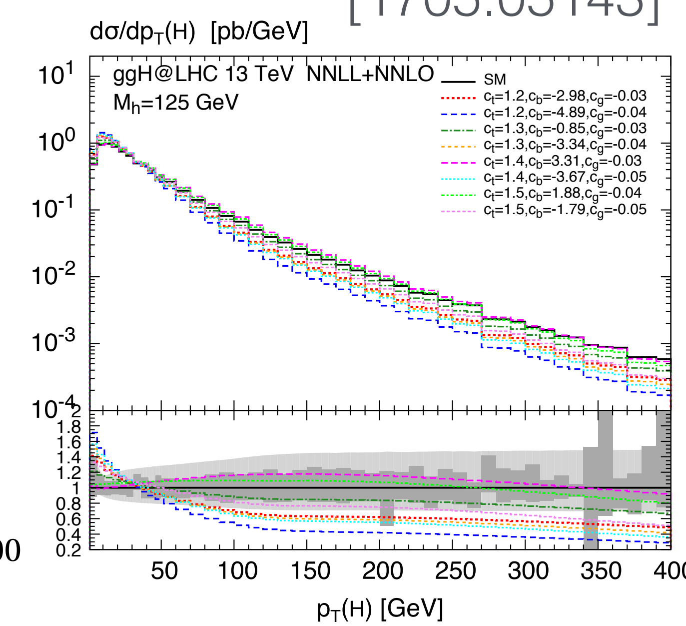
- **Transverse momentum p_T^H**
  - Sensitivity to modifications of effective Higgs Yukawa couplings
  - Sensitivity to finite top mass effects
- **Jet multiplicity N_{jets} & p_T of the first jet p^T_{jet1}**
  - New physics in the loop, sensitivity at high p_T
- **Rapidity $|y^H|$**
  - Theory distribution mostly determined by the gluon PDF; possible test

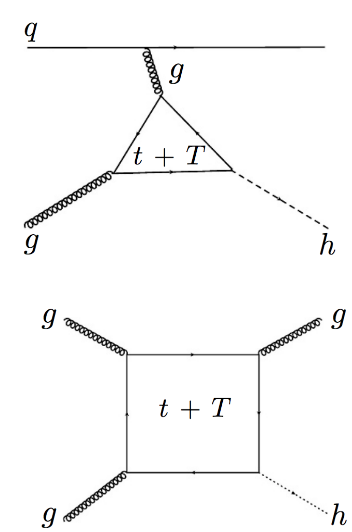


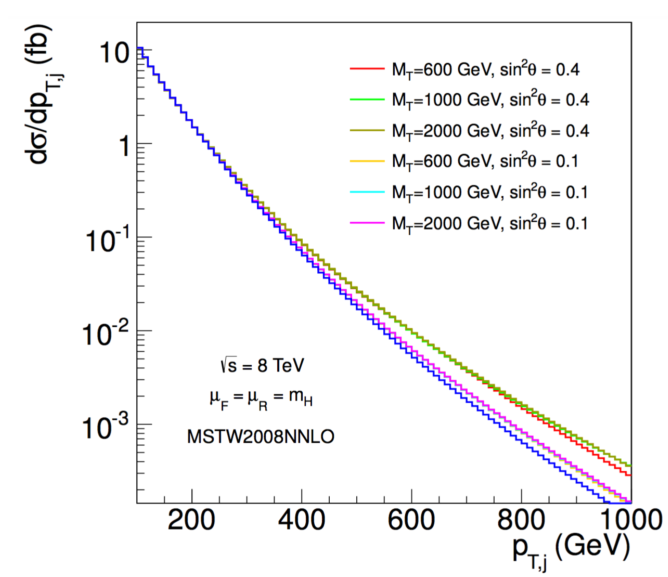
Grazzini, Ilnicka, Spira, Wiesemann (2017) [1705.05143]

Bishara, Haisch, Monni, Re (2016) [1606.09253]

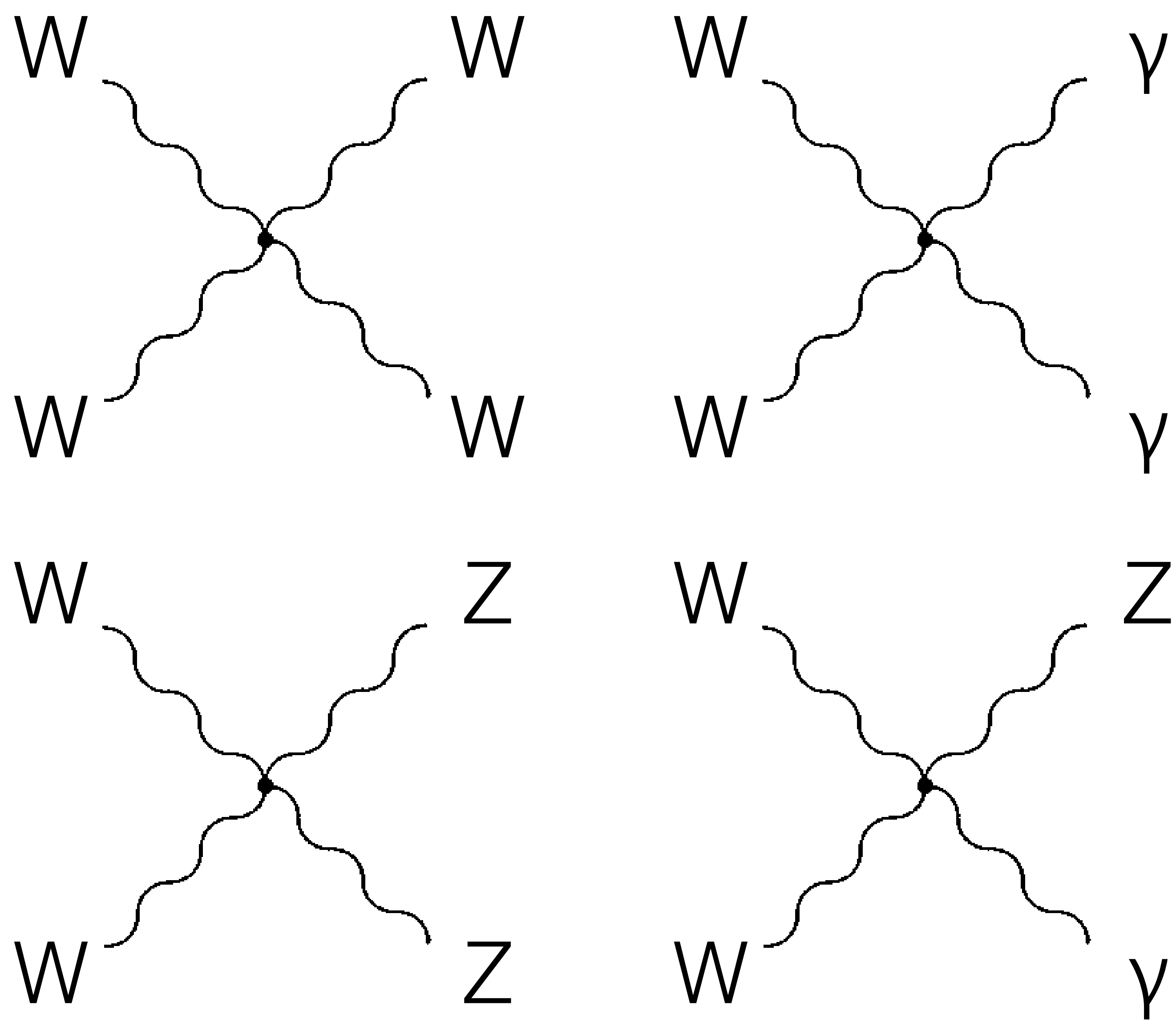








Banfi, Martin, Sanz (2014) [1308.4771]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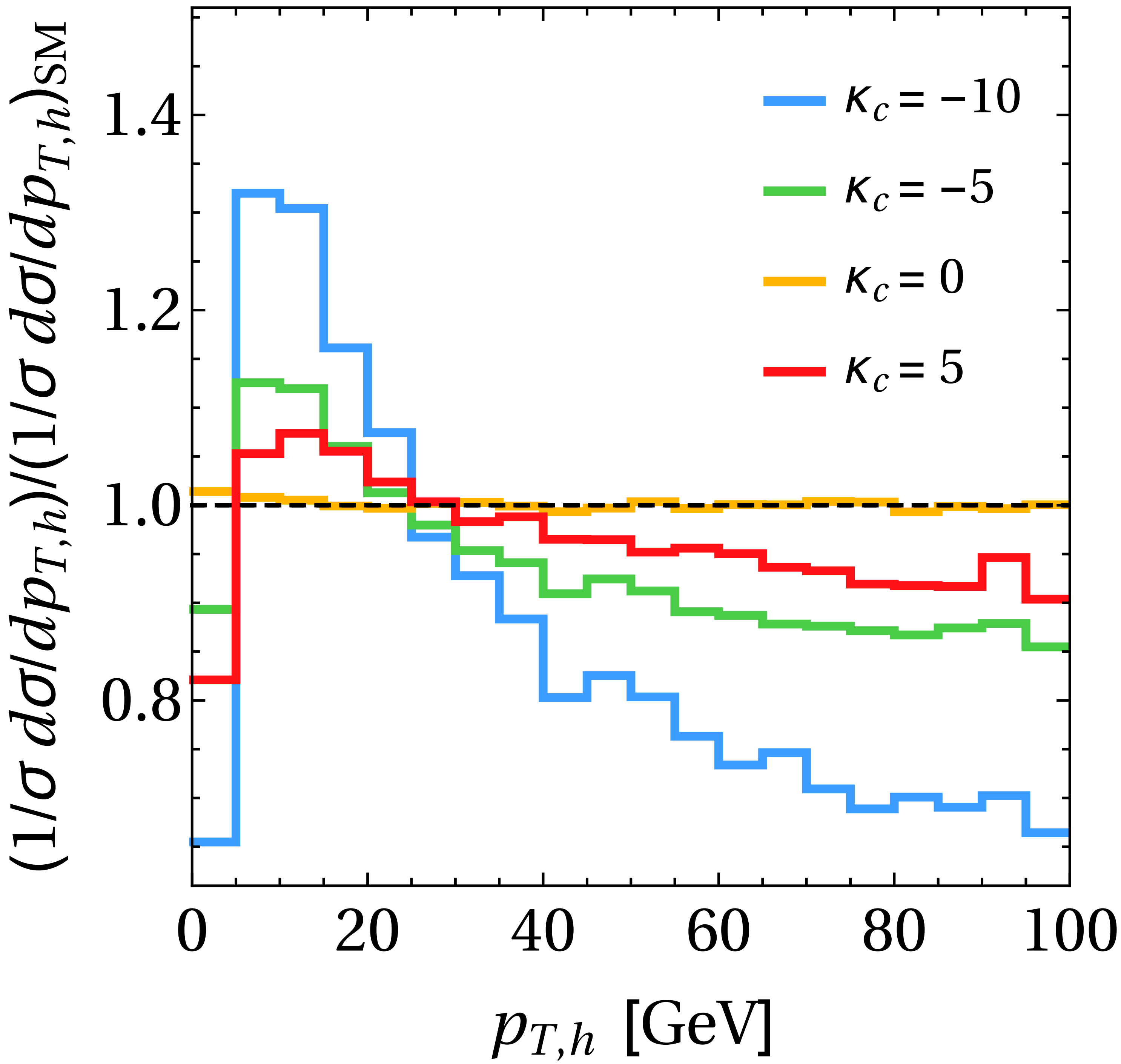
Couplings: κ_b vs. κ_c

- Can use the p_T spectra to fit κ_b vs. κ_c
  - Simply vary κ_b vs. κ_c until the spectrum matches the observed spectrum the best
  - What can we do with this at 3 ab^{-1}?

Bishara, Haisch, Monni, Re (2016) [1606.09253]



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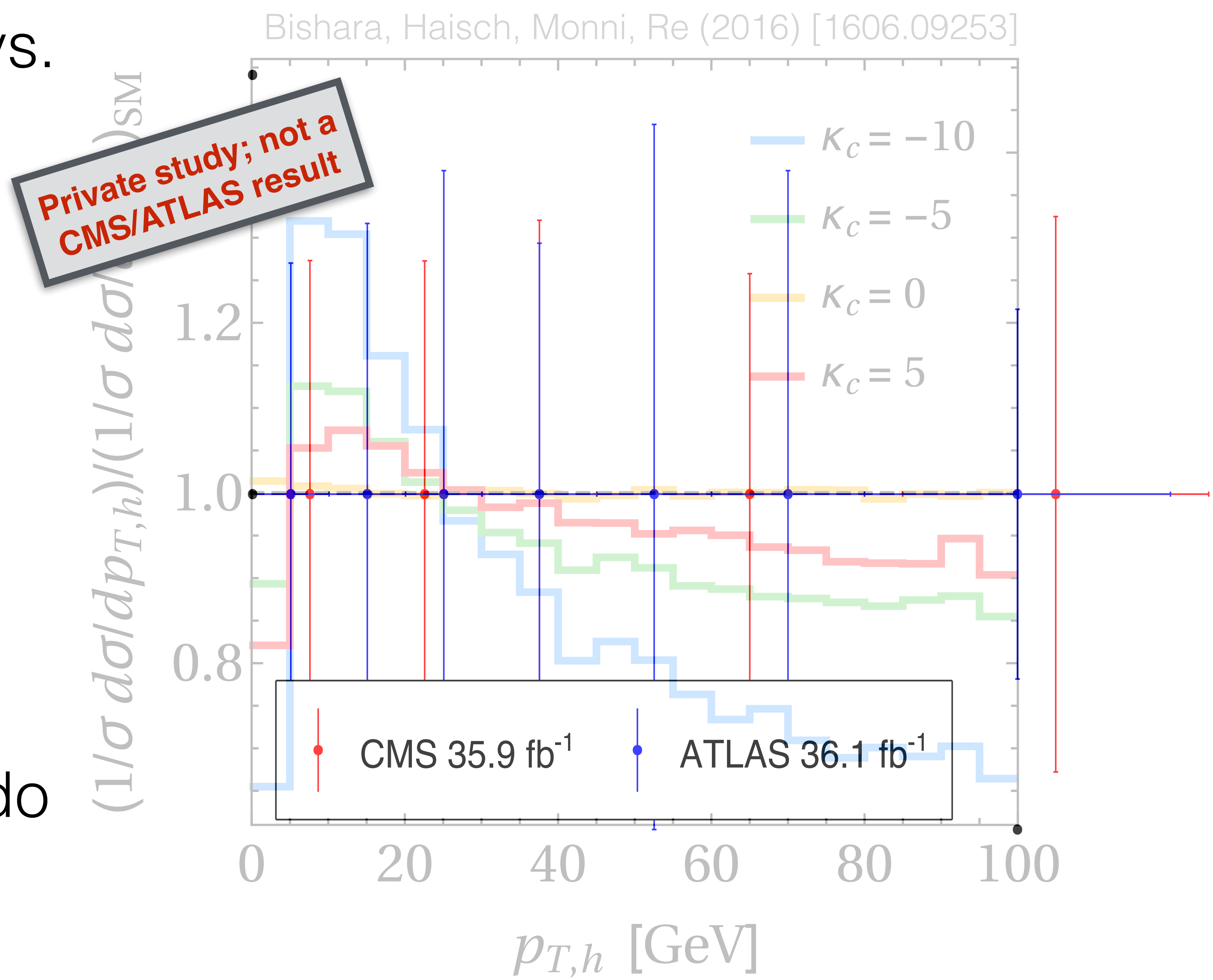

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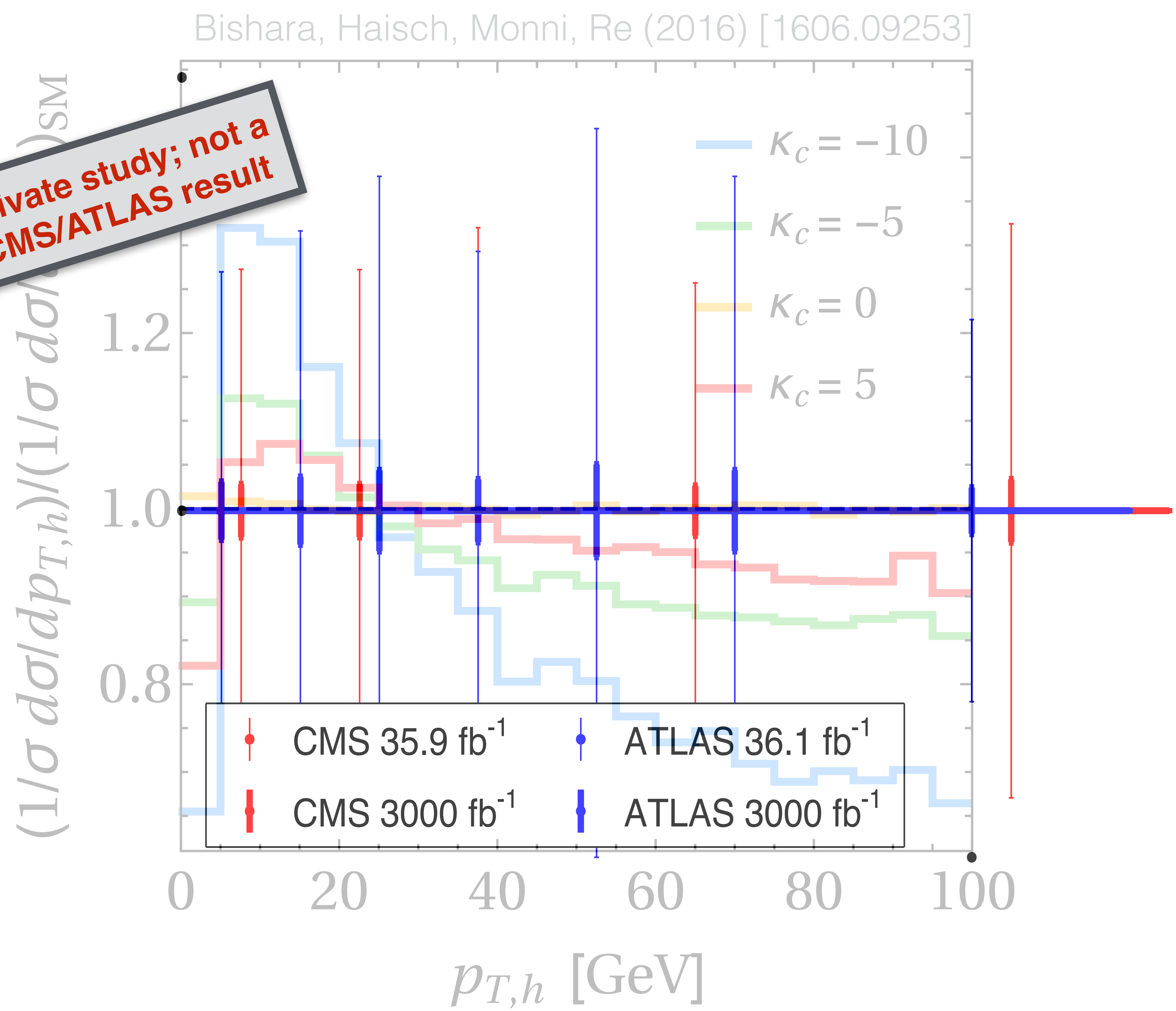
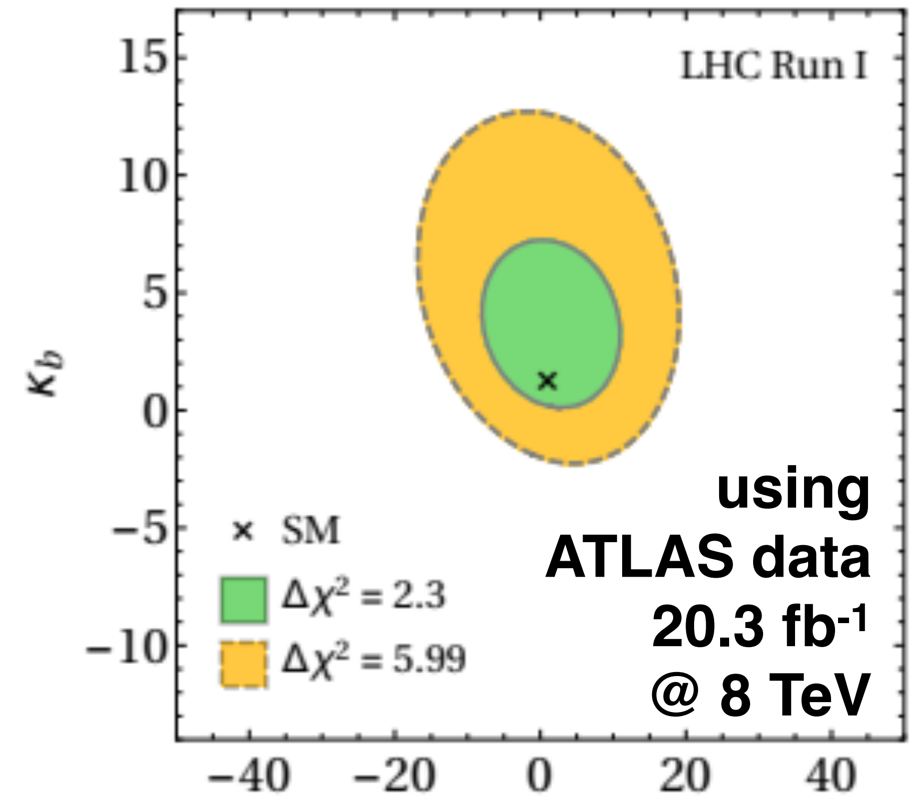


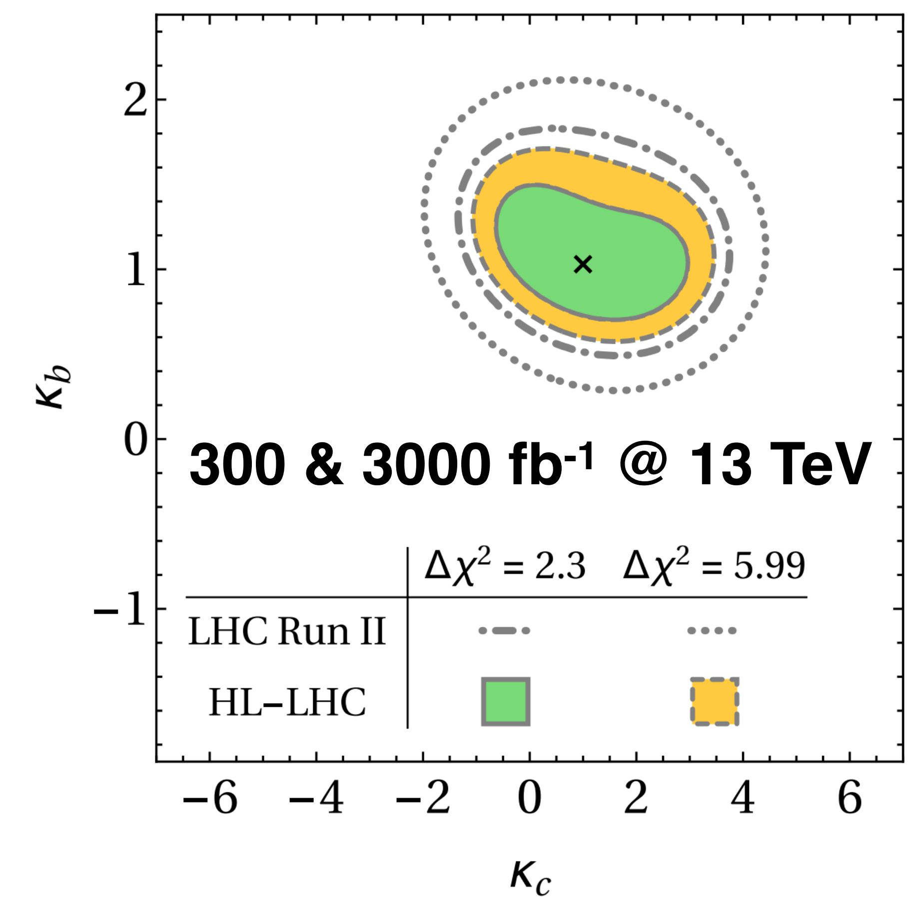
Couplings: κ_b vs. κ_c

- Theorist fit on ATLAS combined pT-specturm indicates κ_c sensitivity of order [-10, 10] @ 68% CL
- Projections*:
  - ~[-1.5 , 4.0] @ 300 fb^{-1}
  - ~[-0.5 , 3.0] @ 3000 fb^{-1}

*: Some side notes:

- Optimistic projections for theory uncertainties
- Assuming also H → WW
- Correlations taken from 8 TeV case





Bishara, Haisch, Monni, Re (2016) [1606.09253]