Higgs WG Summary

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HL-LHC June Workshop

Some Useful Information

- HL-LHC Workshop TWiki page
- WG2 TWiki page
- WG2 conveners: Maria Cepeda, Stefania Gori, Philip Ilten, Marumi Kado, Francesco Riva

- WG mailing list is hllhc-wg2@cern.ch
- mailing list membership constitutes the draft author list
- sign up and/or check the list here
- e-groups will be made shortly for each chapter of the report
- Overleaf document (ask for editing link)

- October 2017 CERN workshop
- April 2018 FNAL workshop
- this June 2018 CERN workshop

- list of WG2 (Higgs) meetings

Goals

- Higgs Yellow Report
  1. provide improved benchmarks
  2. provide a synthesis of the opportunities for Higgs physics at HL/HE-LHC
  3. provide a strong and as exhaustive as possible reference to the community
- this workshop
  1. the progress in each section (in particular HE projections)
  2. collect and discuss all areas where choices are needed
  3. organise integration of experimental results
  4. liaise between all participants to ensure good communication between authors

Yellow Report (YR) Outline

1. Introduction: Main goals and timeline
2. Precision Higgs physics
3. Di-Higgs production and Higgs self couplings
4. Other high energy probes
5. The higgs boson mass and width
6. Invisible decays of the Higgs boson
7. Higgs flavor and rare decays
8. Global view of Higgs couplings at the HL/HE-LHC
9. BSM Higgs

Wishlist Summary

- nice summary by Marianna, *et. al.* from May meeting
- legend: previous study, 2017 TDR study, to be done/expanded

	ATLAS	CMS	LHCb
couplings	✓✓✓	✓✓✓	
$\mathrm{d}\sigma/\mathrm{d}X$	✓✓	✓✓	
width	✓		
CPV	✓	✓✓	
rare decays	✓✓✓	✓✓	✓
exotic decays		✓	✓
di-Higgs	✓✓✓	✓✓✓	
additional scalars	✓✓	✓✓	(✓)

(✓) what about $B^+ \to K^+\chi(\mu\mu)$ from LHCb?

1. Precision Higgs physics
5. Higgs mass and width
8. Global view of Higgs couplings at the HL/HE-LHC

Precision Higgs Yellow Report Outline

- editors: **Predrag Milenovic** (CMS), **Michael Duehrssen-Deblin** (ATLAS), **Simone Alioli** (theory))

1. Channels reach in diboson decays, including fiducial and differential measurements
2. Channels reach in main Yukawa couplings, including fiducial and differential measurements
3. Special focus on direct and indirect probe of top Yukawa coupling (**Alessandro Calandri**)
4. Progress on TH uncertainties: what to expect?
5. Impact from PDFs and alphaS on Higgs measurements
6. Progress on Higgs specific MC (**Prestel**, **Hoeche**, **Maltoni**, **Alioli**)
7. HE Cross-sections (**Grazzini *et al.***)
8. Higgs couplings precision overview
9. Probes using differential distributions of CP sensitive observables (**Yu, Piccinini *et al.***)
10. Interpretation in terms of Composite Higgs models (**Vecchi**)
11. Interpretation in terms of SUSY models (**Wagner**, **Shah**)
12. Kappa-formalism and the nonlinear EFT (**Krause**, **Cata**)

Higgs Mass and Width Yellow Report Outline

- editors: **Meng Xiao** (CMS)

1. Theory review (**Melnikov**, **Caola**)
2. Measurement of the Higgs boson mass
3. Mass shift from the diphoton interference: constraints on the width (**Dixon**)
4. Direct constraints from the Higgs boson lineshape
5. Direct constraints from the Higgs boson lifetime measurements
6. Width from off-Shell higgs boson couplings
7. Width from the diphoton interference rate (**Z.Liu**)

Overview

- Higgs coupling measurements are a top priority from the 2013 European strategy, see talk by Tatsuya Nakada

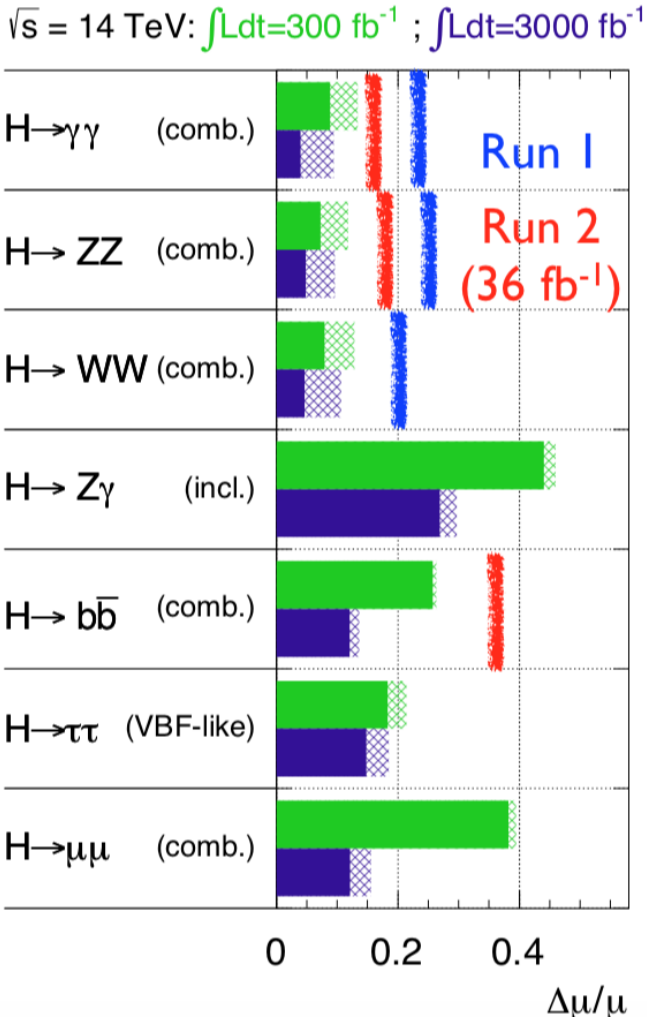
  *The discovery of the **Higgs boson** is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.*

- previous Run 1/2 analyses have shown projections were not accurate enough
- provide a new benchmark that is *accurate, not necessarily precise*, for the HL-LHC
- re-appraisal in several channels necessary
- provide a rough estimate for HE-LHC coupling measurements

Accurate, Not Necessarily Precise

- extrapolate from Run 2 analyses when possible
  - increased luminosity
  - increased centre-of-mass energy (14, 15 and 27 TeV)
  - reconstruction performance with new detector
  - different PU conditions (200)
  - different systematic scenarios
- agreement almost all systematics
  - theory uncertainties centralised by LHC Higgs XS working group, see talk by Fabrizio Caola
  - experimental uncertainties discussed in detail, see talk by Meenakshi Narain and Simone Griso

ATL-PHYS-PUB-2014-016

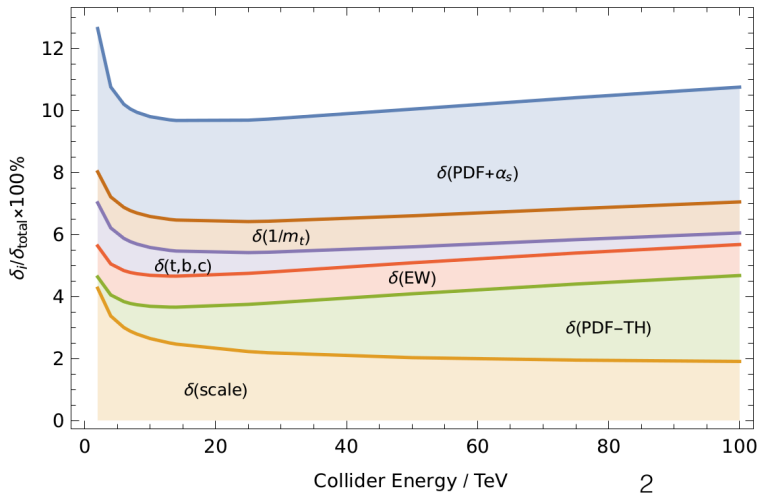


Theory Cross-sections and Uncertainties

- collaboration with LHC Higgs XS Working Group
- first meeting this week, common meetings to come
- provide cross sections (14 and 27 TeV)

- decide on theory systematic scenarios for HL/HE-LHC
  - similar predictions as arXiv:1610.07922
  - consider possible future theory development
  - define scale variation, PDF, α_s, *etc.* uncertainty
  - one baseline scenario and one optimistic scenario

talk by Fabrizio Caola



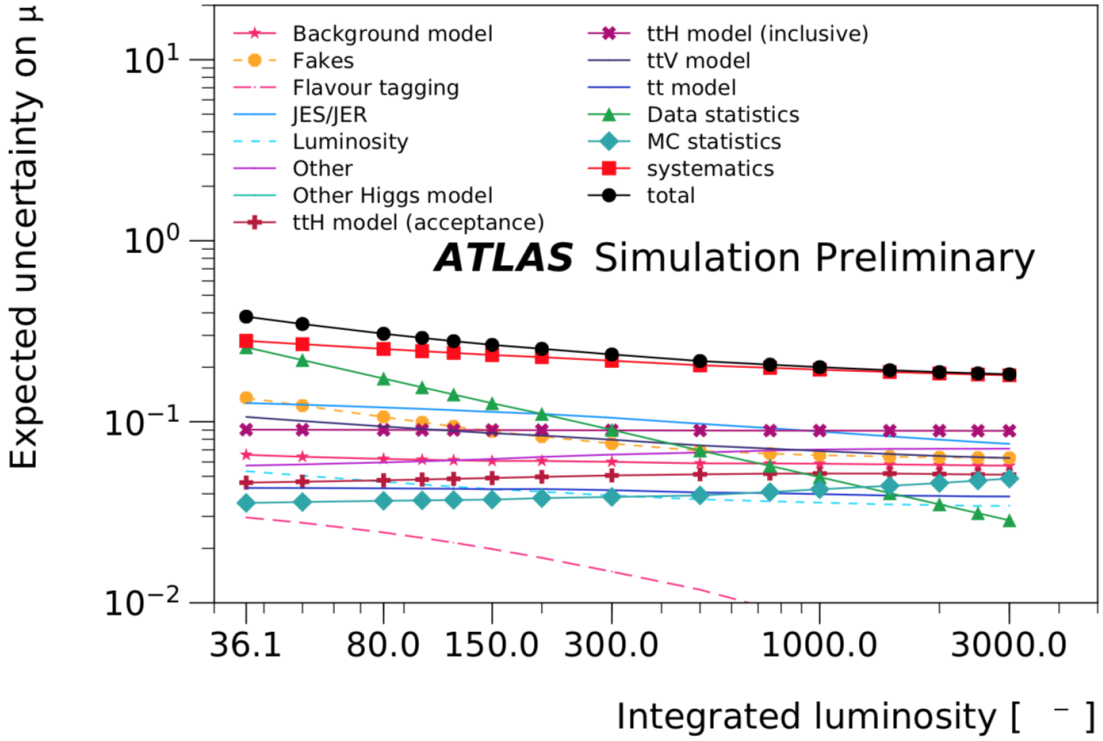
- **essentially done but needs to be written down**

Experimental Wishlist and Uncertainties

- uncertainties discussed in detail in two dedicated meetings and during this workshop, *e.g.* talk by Meenakshi Narain and Simone Griso
- dominant uncertainties identified and discussed with experts
  - signal modelling at all levels, *e.g.* cross-sections, Monte Carlo
  - Background modelling (WW, t and V+jets mostly)
  - jet energy scale and resolution
  - photon energy scale and resolutionesolution (and scale), w
  - flavor tagging
- some uncertainty improvements automatically handled in profiling
  - validity of model needs to be confirmed by collaborations
- wishlist, *e.g.* *possible* studies, discussed and solidified

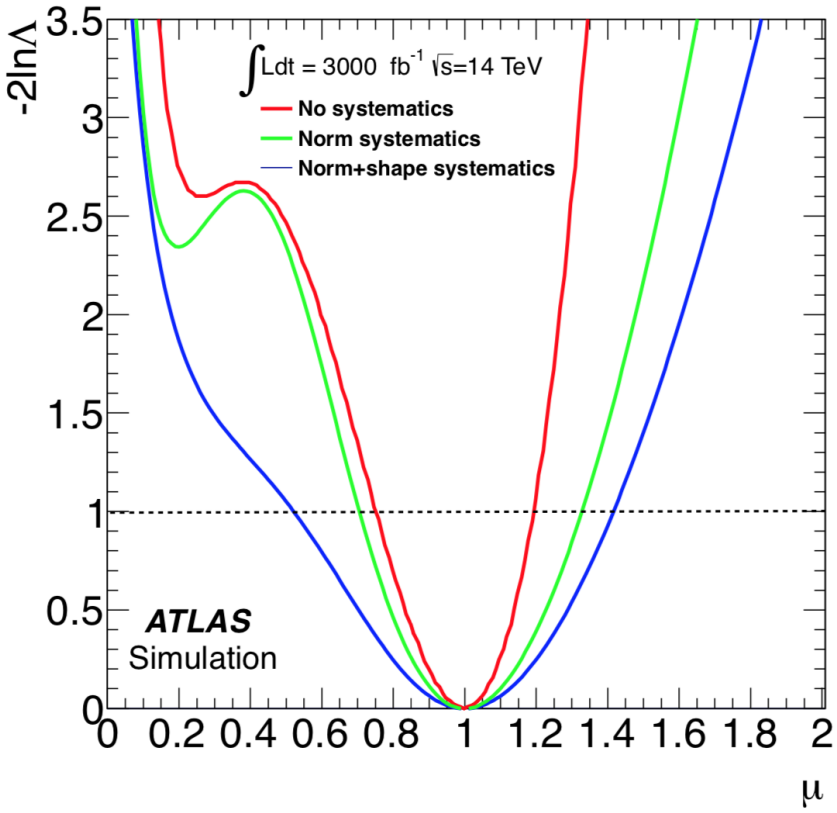
Practical Example

- extrapolate expected sensitivty from current framework
  - already can see change in hierarchy
  - many uncertainties can be constrained by data
  - theory and experimental uncertainties via prescriptions
  - 1% luminosity uncertainty



Mass Width

- we do want a mass prediction, even if use case not entirely clear
- projections of direct width measurements
- fiducial ratio measurement $\gamma\gamma/4\ell$ for width
- constraints on width and mass shift from $\gamma\gamma$ interference
- discuss off-shell Higgs measurements on the width
- provide synthesis of all the measurements



HE-LHC Considerations

- high energy running scenario specified (27 TeV and 15 ab^{-1}), but detectors are not
- experiments will perform basic extrapolation (energy and luminosity, not pile-up and detector performance) for a few analyses *e.g.* HH
- projections will rely on combined theory and experimental input
- high energy studies have been organised within sections, needs reinforcement

Remarks

- overall couplings benchmark using the main channels combination
- provide an ATLAS-CMS combined statement about the couplings
- more specific discussions in the YR on specific questions
  - how precisely top yukawa can be measured directly (ttH and tH analyses)
  - access charm Yukawa ($VH(cc)$, rare decays, differential)
  - effort on lighter Yukawas (rare decays, differential, WH charge asymmetry)

3 Di-Higgs production and Higgs self couplings

Yellow Report Outline

- editors: **Cadamuro** (CMS), **Wardrope** (ATLAS), **Riembau** (theory)

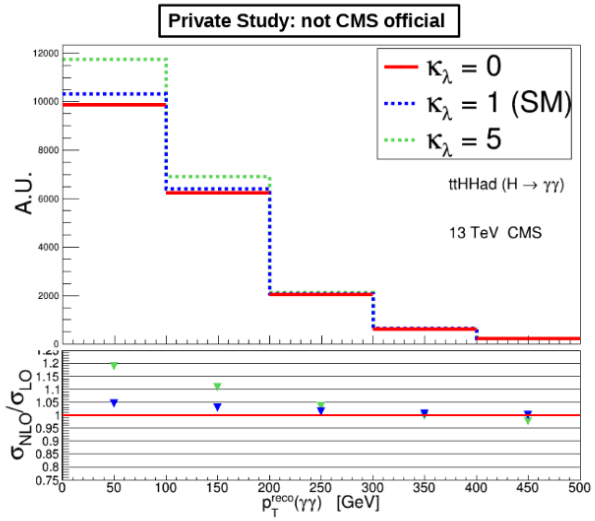
1. SM calculation (**Dawson**, **Heinrich *et al.***)
2. Double Higgs measurements and trilinear coupling (ATLAS and CMS)
3. Indirect probes of the trilinear coupling through differential distributions measurements (CMS)
4. Indirect probes through single Higgs boson production (**Maltoni**, **Pagani**, **Zanderighi *et. al***, **Englert**; see di-Higgs meeting)
5. HE prospects (**Goncalves** and **Plehn**, **Homiller** and **Meade**)
6. Theory implications, including a critical view of the validity of direct and indirect trilinear couplings measurements (**di Vita**, **Riembau**, **Vanthalon**; see di-Higgs meeting)

Differential Distributions

- see talk by Jonathon Langford (based on arXiv:1709.08649):

Signal extraction and interpretation

Signal yield varies w/ κ_λ



$p_T(H)$ for ttH → bjj bjj $\gamma\gamma$

1. **Uncertainties for differential cross-sections**: ttH and VH @HL-LHC
2. **Sensitivity to κ_λ**
   - 1D likelihood scan with κ_λ as POI
   - 2D scan of κ_λ vs κ_t?

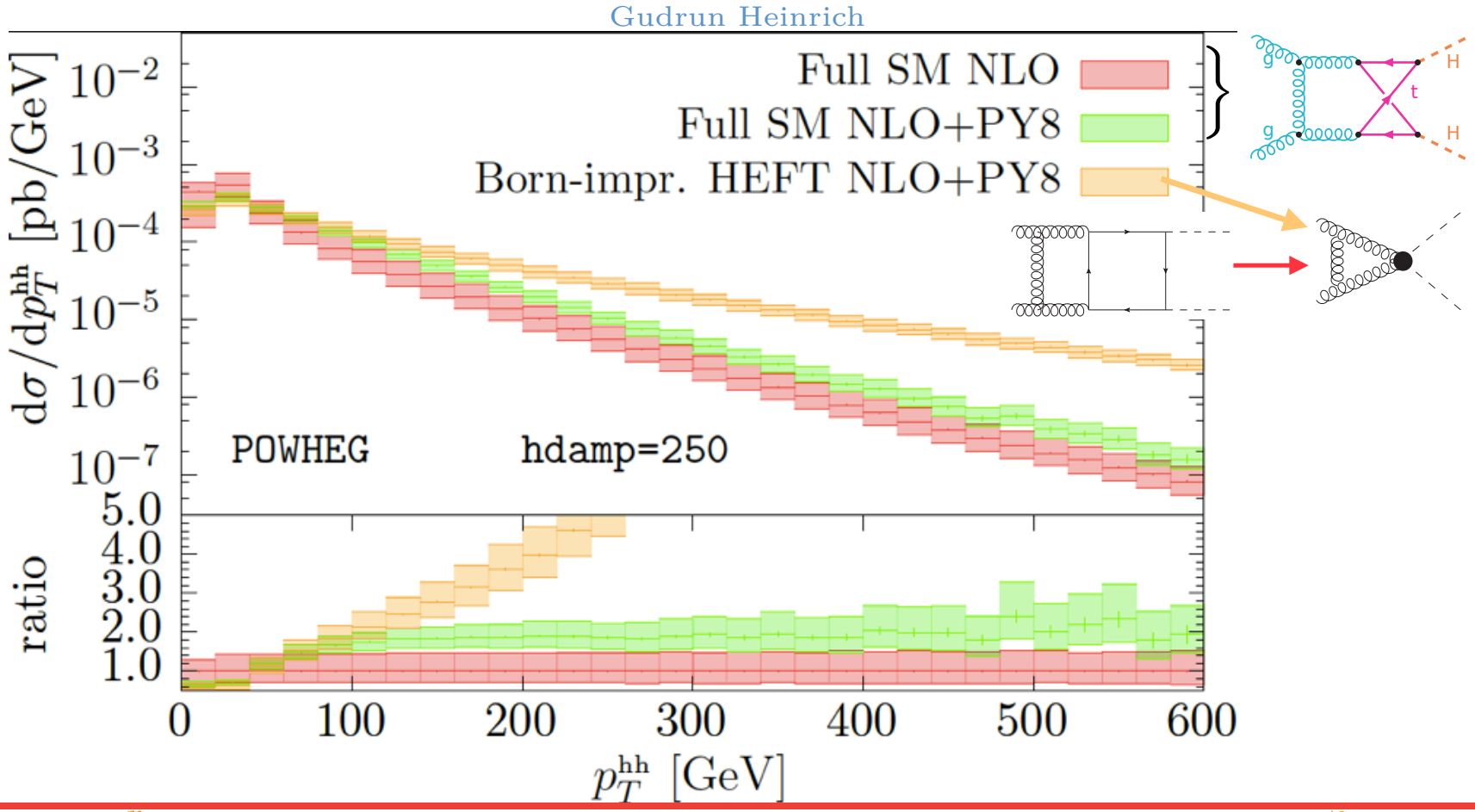
Important towards final sensitivity

- Systematics
  - experimental: YR2018
  - theoretical
- Theoretical assumptions
  - only λ_3 variations
  - impact of EW unc close to SM
  - role of QCD higher order effects

3. **Combination with HH**
   - 1D κ_λ scan, increased sensitivity
   - global fit: constraints from standard single-Higgs measurements

Mass Effects vs Parton Shower Effects

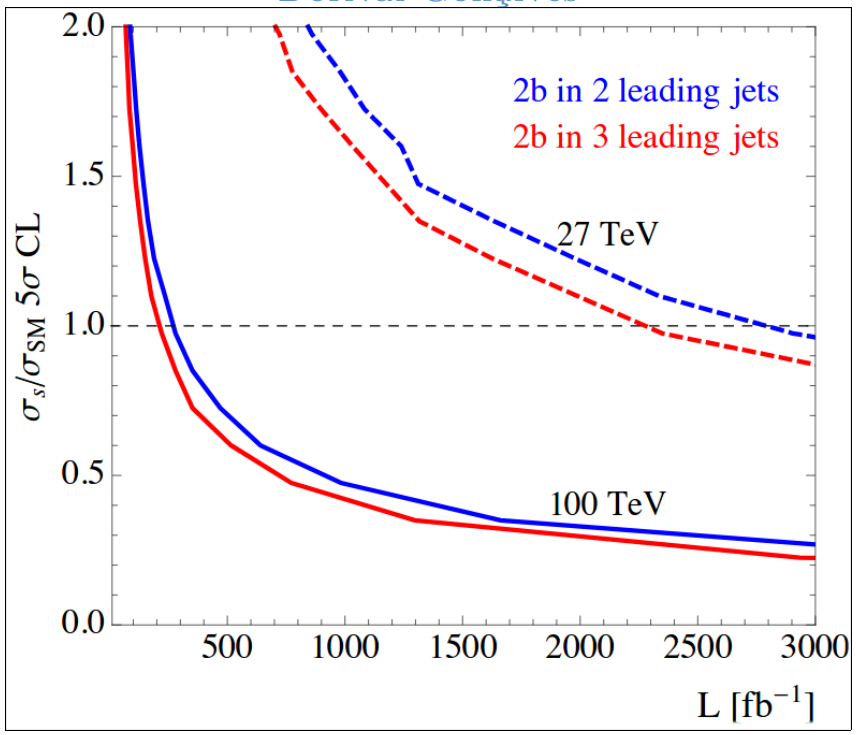
- for details see talk by Gudrun Heinrich
- shower effects are large but orders of magnitude less than Born-improved HEFT



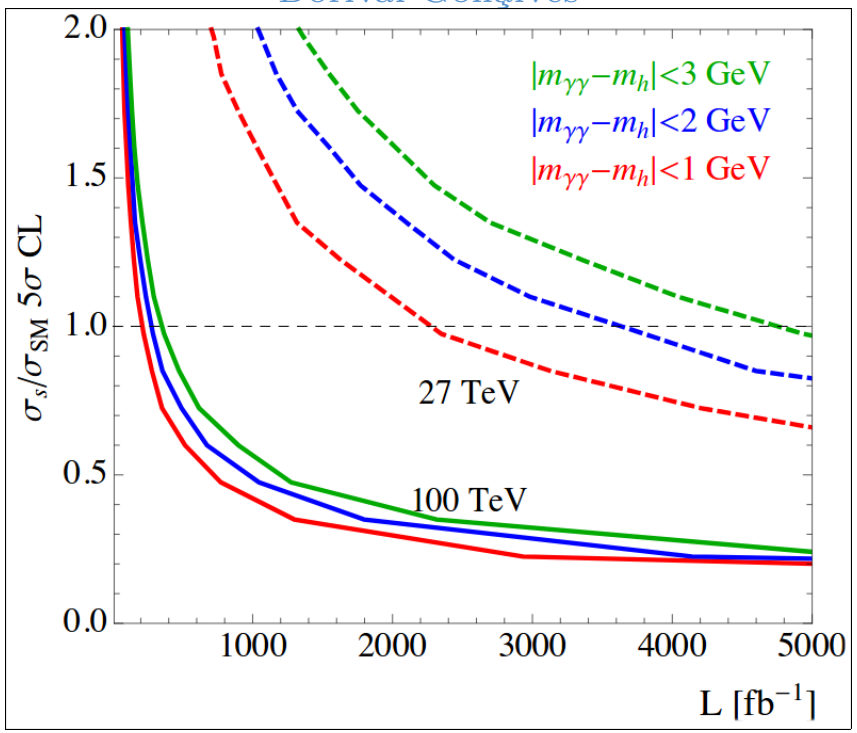
High Energy

- HH discovery at 27TeV requires 2.3ab^{-1} (rather than 2.8ab^{-1}) and 0.2ab^{-1} at 100 TeV
- photon and jet mass resolution critical for detector design
- see talk by Dorival Gonąlves based on arXiv:1802.04319

Dorival Gonąlves



Dorival Gonąlves



4 Other high energy probes

Yellow Report Outline

- editors: **Francesco Riva** (theory)

1. Measuring Offshell couplings
2. tth differential measurements (**Maltoni**, **Vryonodou**)
3. WH/ZH at high energy/luminosity (**Spannovski**, **Mcccoulough**)
4. WW/WZ at high energy/luminosity (**Elias-Miro**, **Panico**, **Azatov**)
5. VBF longitudinal VBS and di-Higgs (**Rojo**, **Bishara**, **Contino**)
6. Same-sign WW scattering (**Kalinowski**, **Kozow**, **Pokorski**, **Rosiek**, **Szleper**, **Tkaczyk**)

Overview

- tails of energy distributions, *e.g.* p_{T} and m, become interesting when $\delta_{\mathrm{stat}} \gg \delta_{\mathrm{syst}}$
  - for the HL-LHC this translates to a linear improvement
- some BSM-EFT effects grow with energy, $\sim E^2/\Lambda^2$
  - going from 100 GeV to 1 TeV increases effect by $\mathcal{O}(100)$
  - new distributions become avialable with high statistics

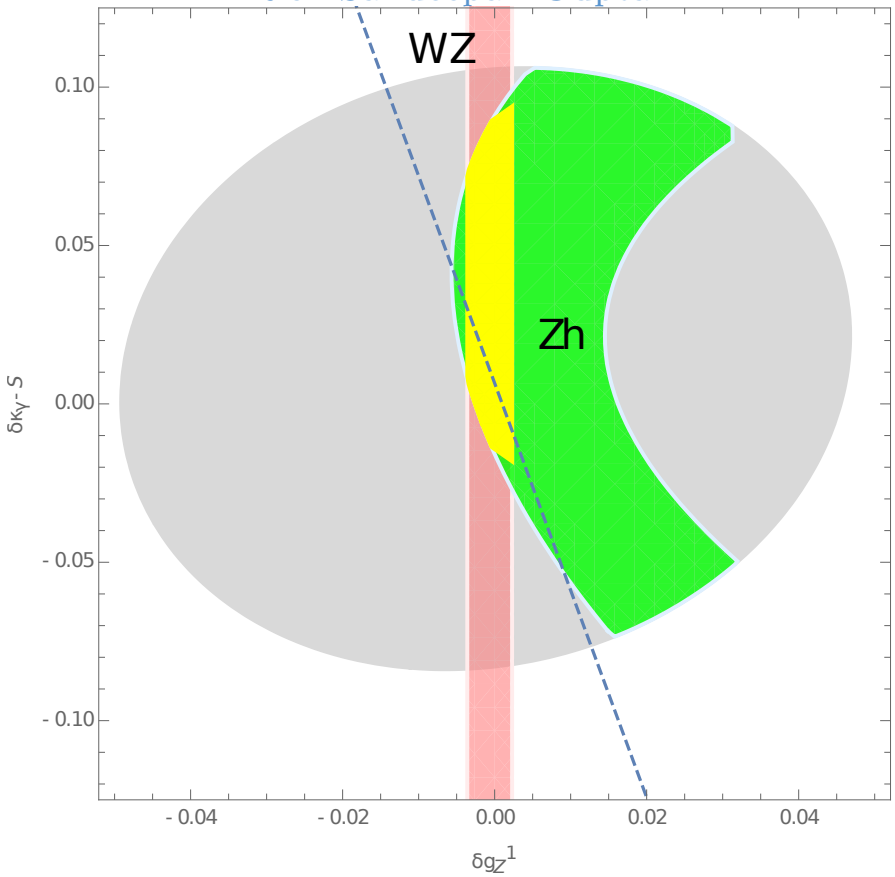
Vector and Higgs

- see talk by Rick Sandeepan Gupta
- VV and HV processes are connected by symmetry and constrain the same high energy observables

$$\Phi \equiv \begin{pmatrix} G^+ \\ \frac{H+iG}{\sqrt{2}} \end{pmatrix}$$

- BSM in HZ with $Z \to \ell\ell$ and $H \to bb$
- $ZH \to G^0 H$
- what about $Z \to \nu\nu$ and WH? VH mass distributions?

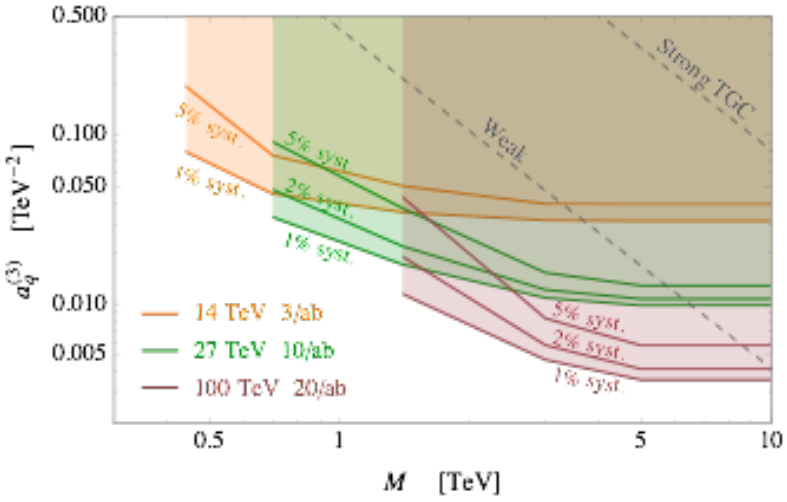
Rick Sandeepan Gupta



Double Vector Bosons

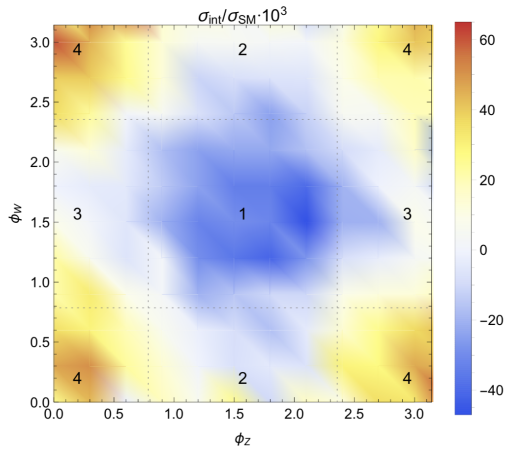
- $WW \to G^+G^-$
- $WZ/\gamma \to G^+G^0$
- BSM in longitudinal vectors
  - WZ/WW semi-leptonic
  - systematics in polar angle distributions?

arXiv:1712.01310



- BSM in transverse vectors
  - $WZ/W\gamma$ leptonic/semi-leptonic
  - systematics in azimuthal distributions?

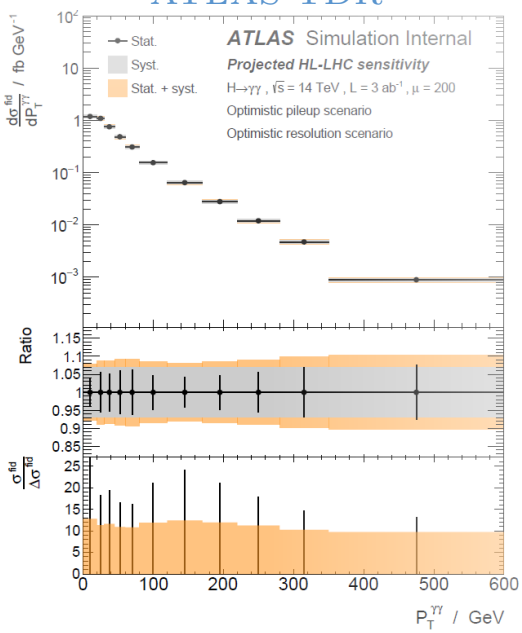
Azatov, Elias-Miro, Reyimuaji, Venturini



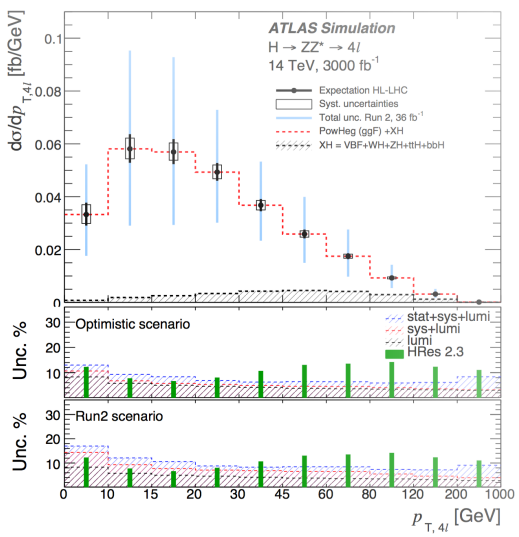
Top BSM and VBF

- p_{T} spectrum sensitive new physics, see talk by Thomas Klijnsma
- projected 5% uncertainty for $\gamma\gamma$, $5-10\%$ for ZZ, $< 5\%$ combined
- better to consider single overflow bin?

ATLAS-TDR



ATLAS-TDR



- study on ttH differential measurements by Maltoni and Vryonodou
- study on $WW \to HHWW$ by Rojo, Bishara, and Contino

7 Higgs flavor and rare decays

Yellow Report Outline

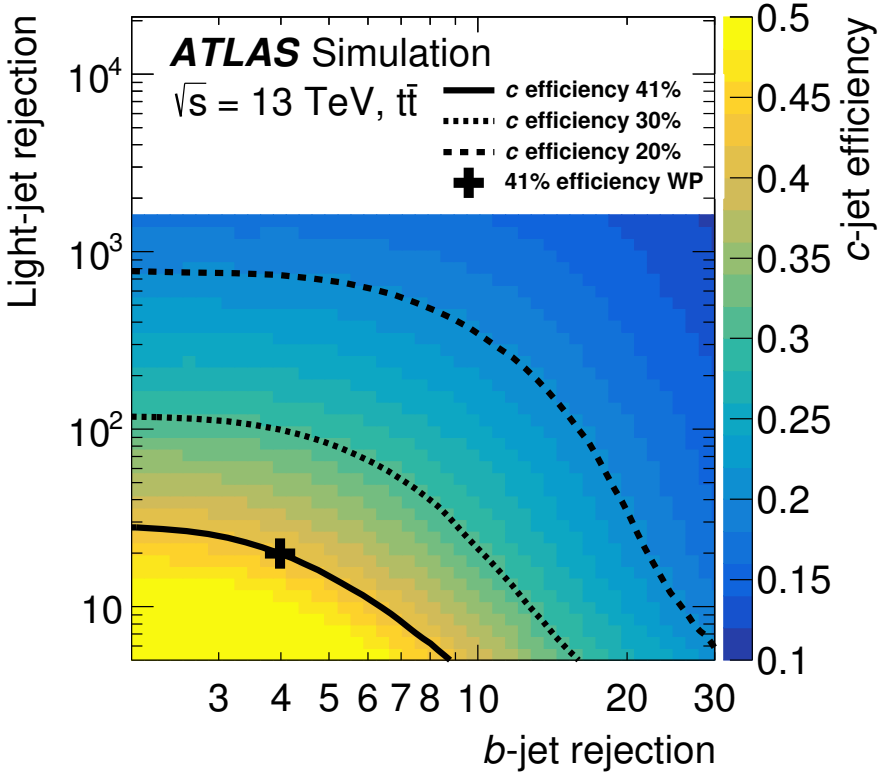
- editors: **Kostas Nikopoulos** (ATLAS), **Alexander Schmidt** (CMS), **Lorenzo Sestini** (LHCb), **Yotam Soreq** (theory)

1. Flavor aspects Yukawa modifications in flavor models (**Bishara**)
2. Exclusive Higgs decays (**Soreq**)
3. Flavor tagging (charm and strange) (**Schlaffer**)
4. LFV decays of the Higgs
5. Yukawa constraints from Higgs distributions (**Soreq**)
6. CP violation in Higgs couplings (τ, ttH) (**Harnik**)

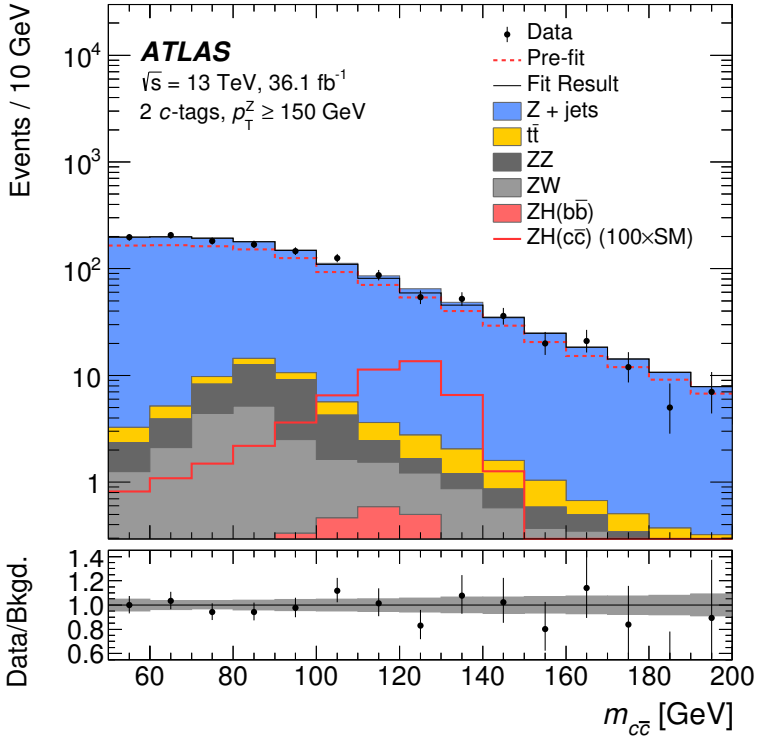
Higgs to Inclusive Charm

- see talk by Elliot Reynolds for more details
- ATLAS measurement of $ZH \to \ell\ell cc$: arXiv:1802.04329
- current limit is roughly 100× SM
- projection now available, roughly 6× SM

arXiv:1802.04329



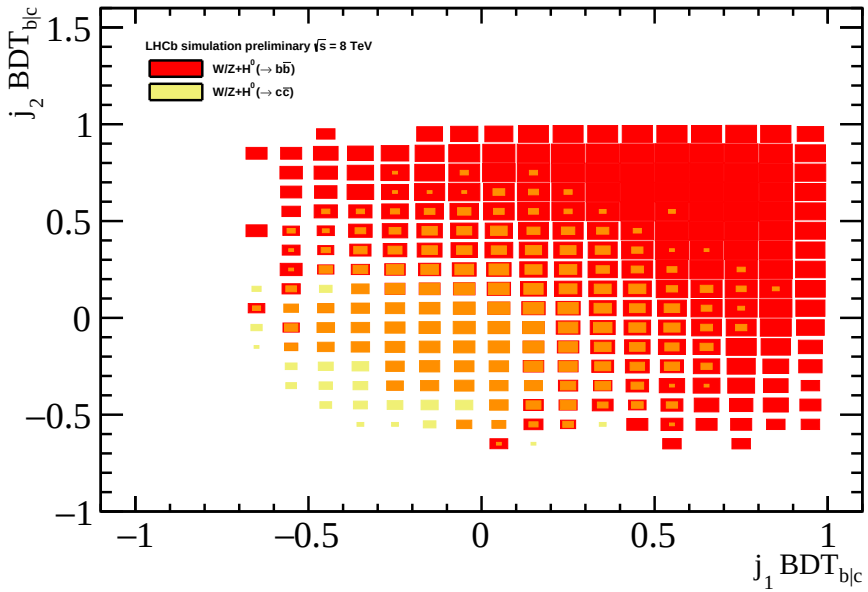
arXiv:1802.04329



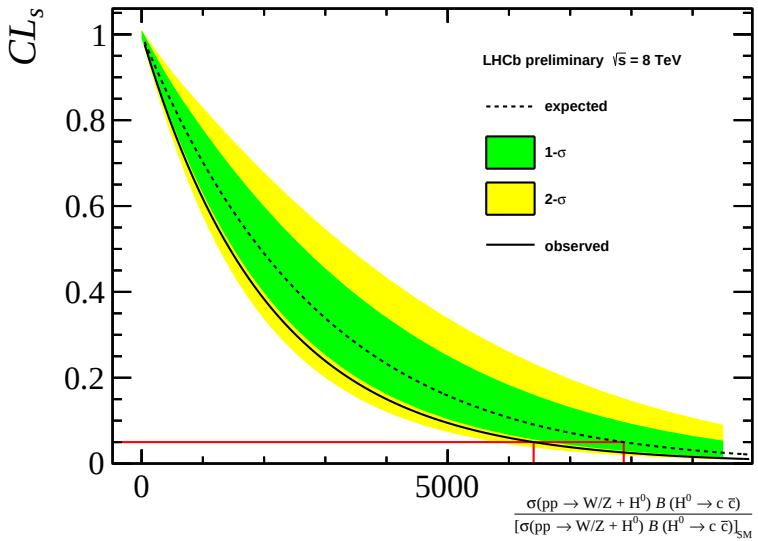
Higgs to Inclusive Charm

- LHCb measurement of $VH \to cc\ell$: LHCb-CONF-2016-006
- current limit is roughly 6400× SM
- rough projection of 4× SM
- detailed study underway including $H \to bb$

LHCb-CONF-2016-006



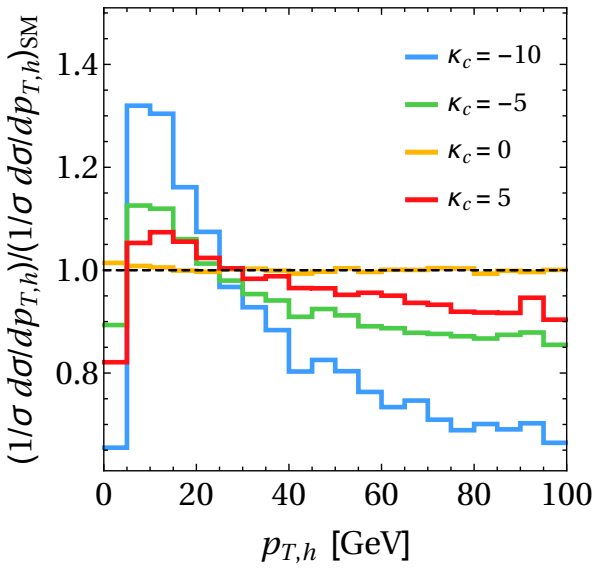
LHCb-CONF-2016-006



Differential Cross-sections

- see talk by Thomas Klijnsma
- p_T spectrum sensitive to couplings (low) and top mass (high)
- rapidity spectrum depends on gluon PDF

arXiv:1606.09253



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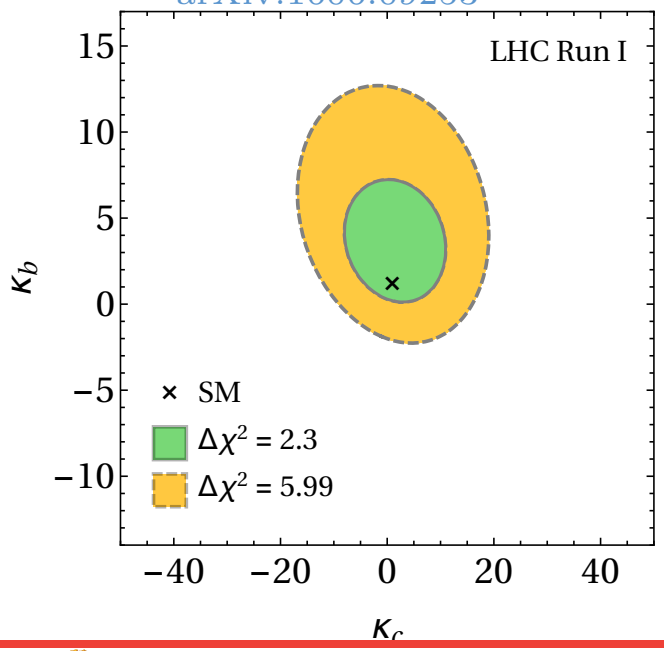
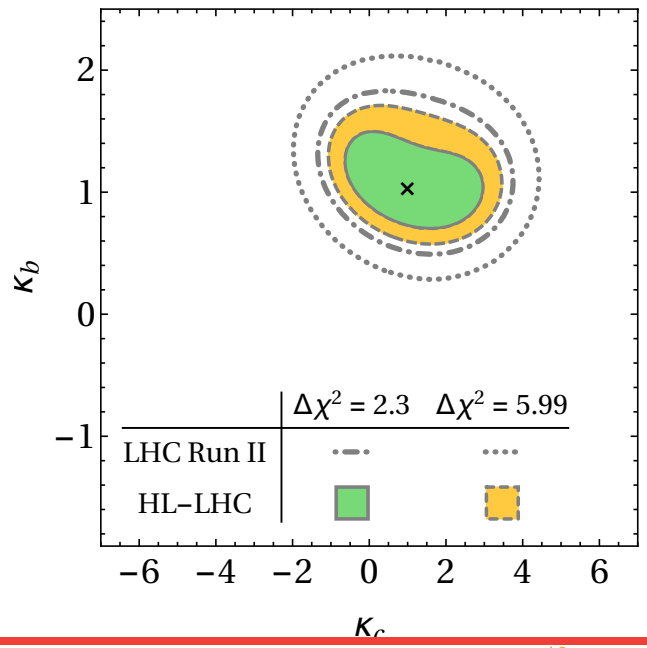
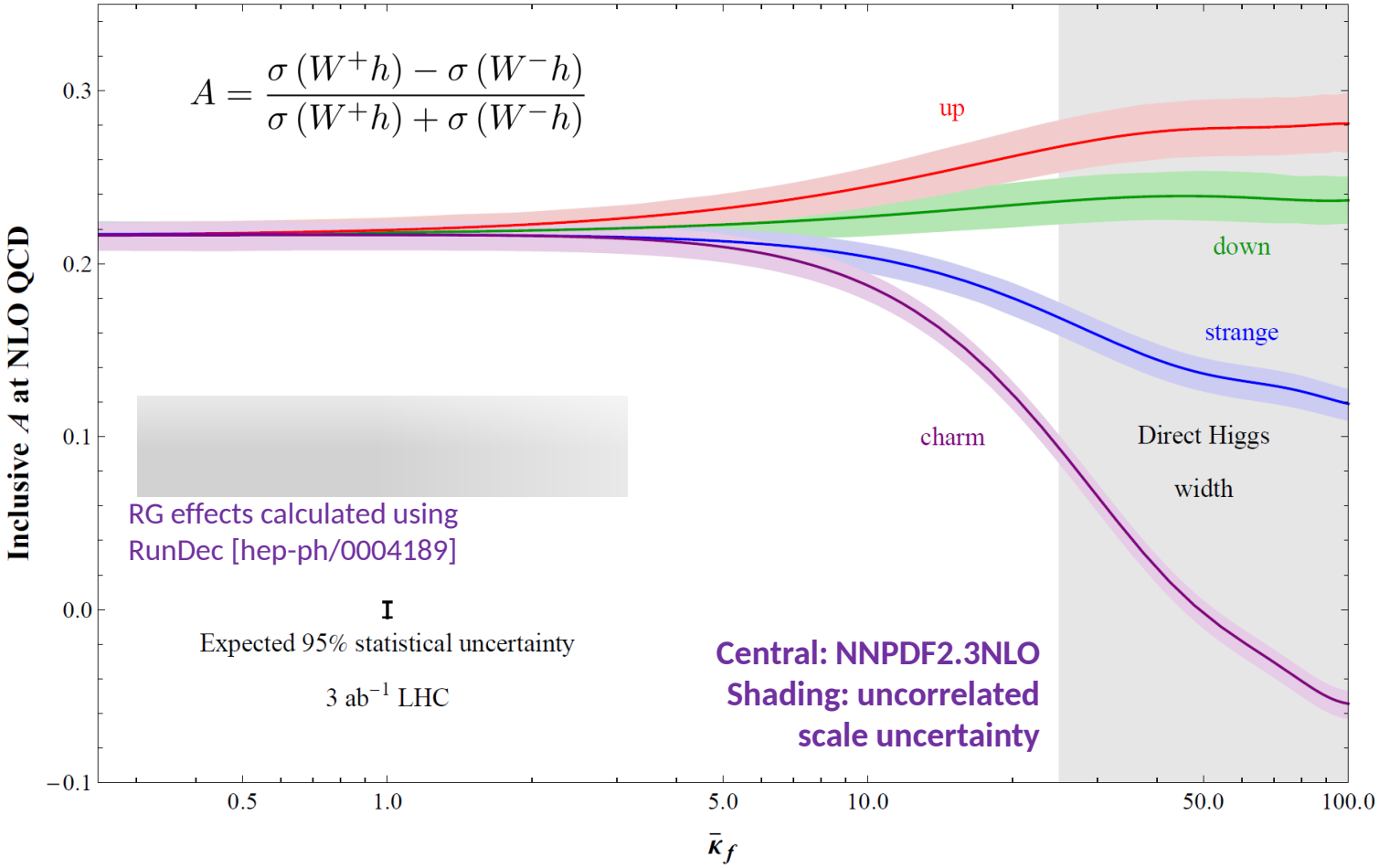




Charge Asymmetry

- see talk by Felix Yu for theory overview on Higgs flavour

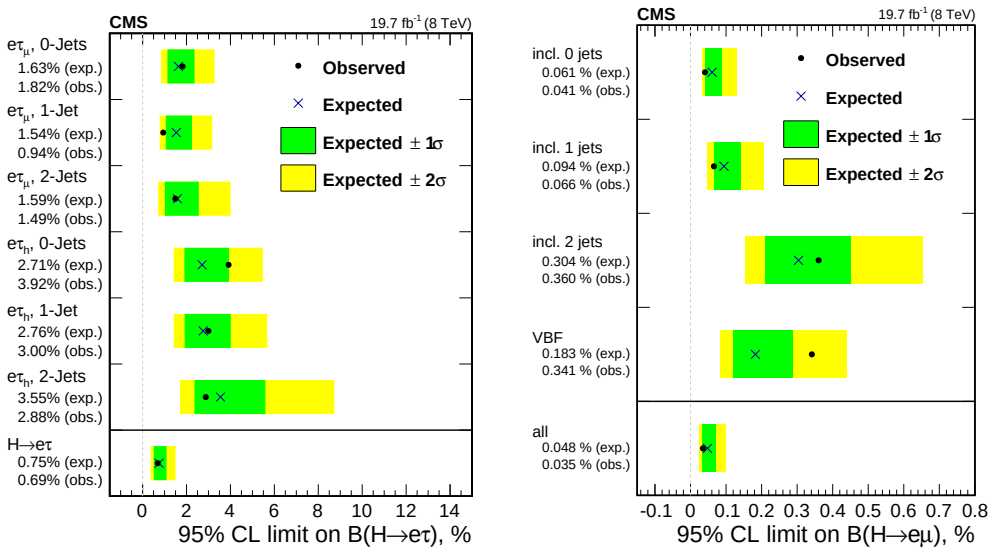
Felix Yu



Lepton Flavour Violation

- search by CMS for $H \to \tau\mu$ and $H \to \tau e$ arXiv:1712.07173
- search by CMS for $H \to e\mu$ and $H \to e\tau$: arXiv:1607.03561
- projections of results underway

arXiv:1607.03561



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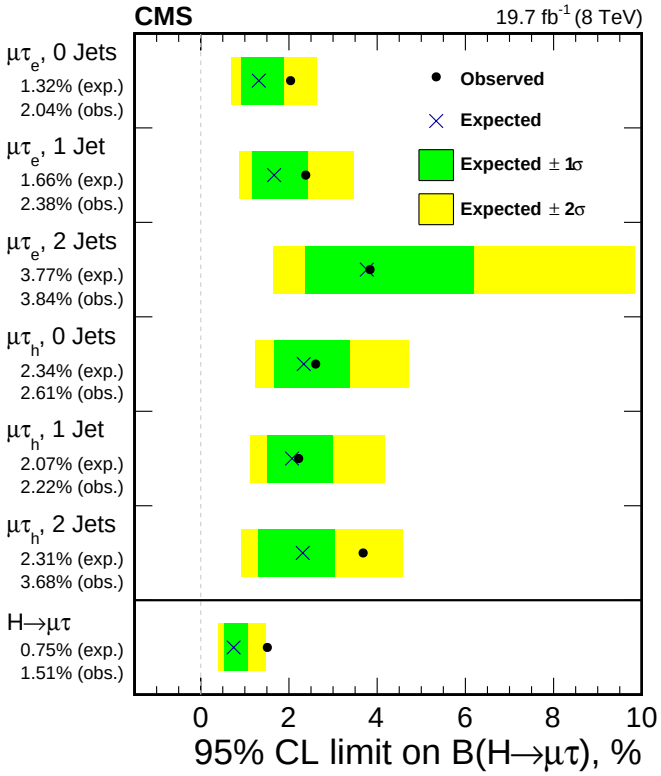
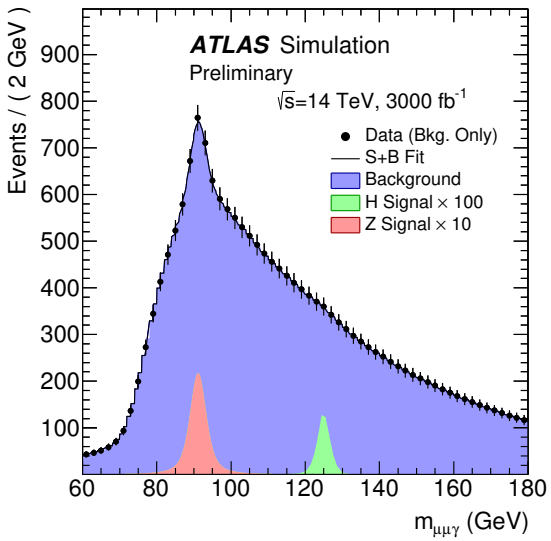


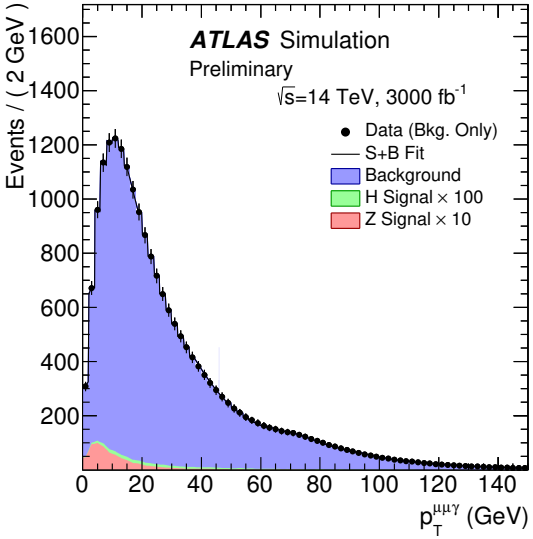
$H \to J/\psi\gamma$

- search by ATLAS for $H/Z \to Q\bar{Q}\gamma$: arXiv:1501.03276
- projections by ATLAS for HL-LHC: ATL-PHYS-PUB-2015-043
- no plans for CMS or LHCb projections

	$\mathcal{B}(H \to J\psi\gamma)$	$\mathcal{B}(Z \to J/\psi\gamma$
SM	2.9×10^{-6}	8.0×10^{-8}
Run 1	1.5×10^{-3}	2.6×10^{-6}
HL-LHC	4.4×10^{-5}	4.4×10^{-7}

ATL-PHYS-PUB-2015-043





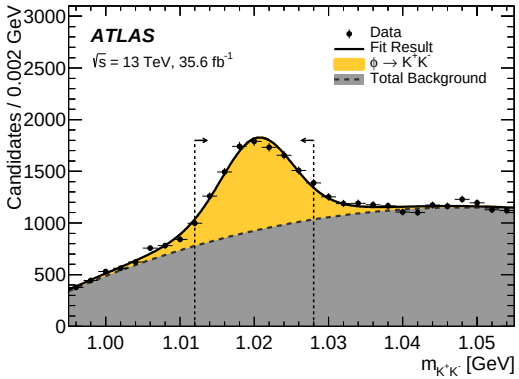
$H \to \phi\gamma$ and $H \to \rho\gamma$

- search by ATLAS for $H/Z \to \rho/\phi\gamma$: arXiv:1712.02758
- ATLAS projections are underway
- no plans for CMS or LHCb projections

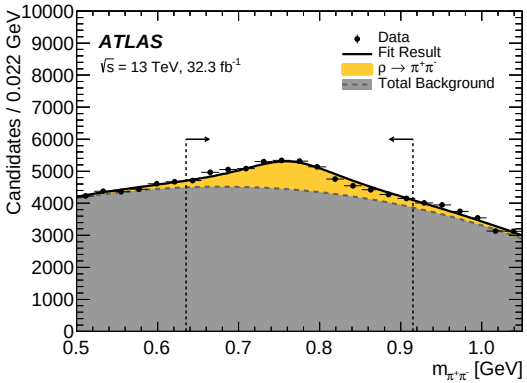
	$\mathcal{B}(H \to \phi\gamma)$	$\mathcal{B}(Z \to \phi\gamma$
SM	2.3×10^{-6}	1.0×10^{-8}
Run 2	4.8×10^{-4}	9.0×10^{-7}

	$\mathcal{B}(H \to \rho\gamma)$	$\mathcal{B}(Z \to \rho\gamma$
SM	1.7×10^{-5}	4.2×10^{-8}
Run 2	8.8×10^{-4}	2.5×10^{-5}

arXiv:1712.02758



arXiv:1712.02758



6 Invisible Decays

8 BSM Higgs

Invisible Decays Yellow Report Outline

- editors: **Anne Marie Magnan** (CMS), **Benjamin Nachman** (ATLAS)

1. Main channels for direct searches
2. Interpretation and combination with precision Higgs boson measurements (**Stefaniak**, **Robens**)
3. Higgs portal interpretations (**Stefaniak**, **Robens**)

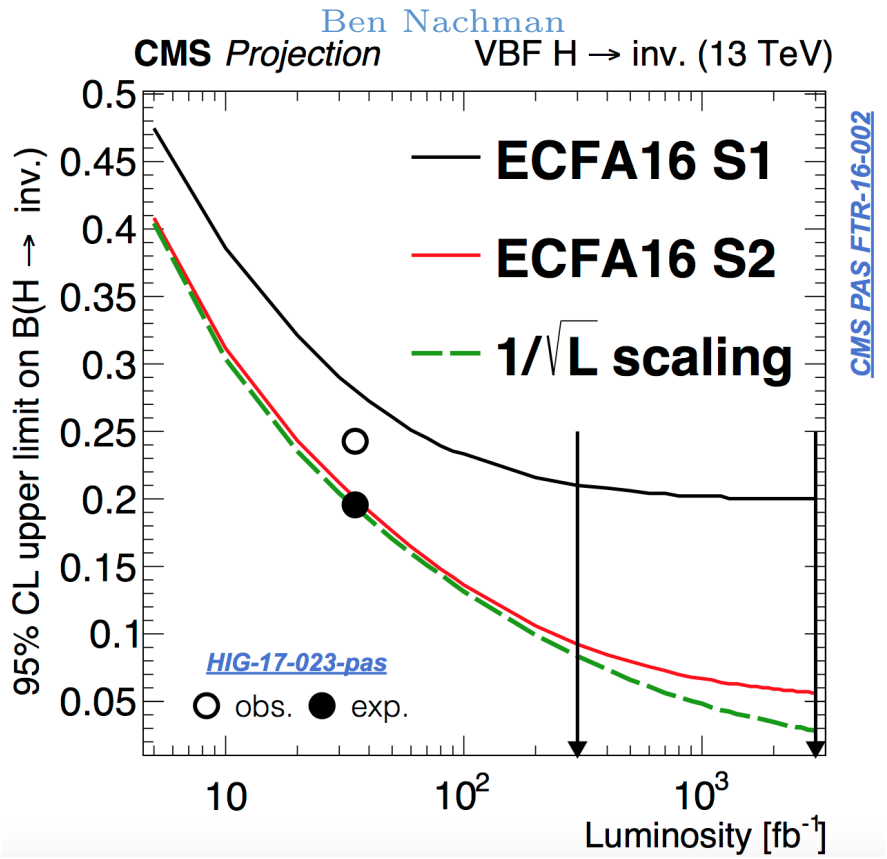
BSM Higgs Yellow Report Outline

- BSM editors: **Martin Flechl** (CMS), **Lei Zhang** (ATLAS), **Martino Borsato** (LHCb), **Stefania Gori** (theory)

1. Searches for additional Higgs bosons in fermionic final states (τ, b, μ, and t)
2. Searches for additional Higgs bosons in diboson final states
3. Searches for intermediate mass Higgs bosons (60 GeV – 120 GeV) (**Heinemeyer**)
4. Searches for low mass Higgs bosons (up to 60GeV)
5. Covering the MSSM and 2HDMs (**J.M.No**)
6. Covering Twin Higgs models (**Redigolo**)
7. Interference effects in heavy Higgs searches (**M. Carena**, **Z.Liu**)
8. New techniques for reconstructing highly boosted heavy Higgs bosons (**Klimek**)
9. Exotic decays of the Higgs boson (**D.Curtin**, **Z.Liu**, **A.Thamm**, **L.T.Wang**)

Experiment Projections

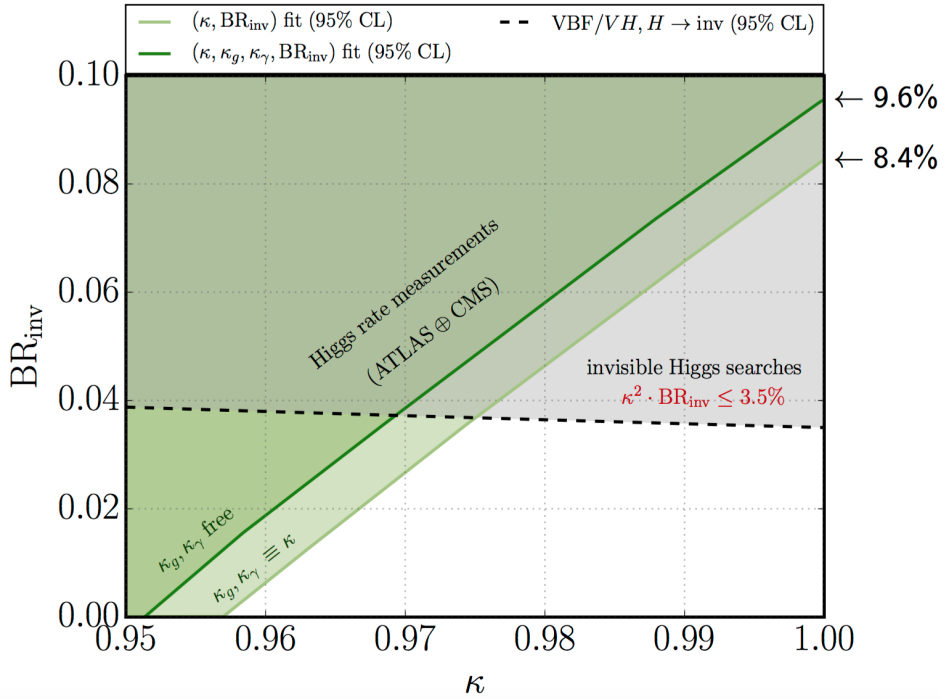
- see talk by Ben Nachman
- two different scenarios
  - theory uncertainty drops by 50%, experimental uncertainty drops with luminosity up to a bound
  - experimental uncertainties are not bounded
- challenges include systematics, trigger, pile-up, quark-gluon tagging, and vertexing
- timing information can provide benefits



Precision and Invisible

- see talk by Tim Stefaniak
- theory interpretations in terms of minimal Higgs portal, standard model plus complex scalar singlet, *etc.*
- what to assume for the Higgs couplings and Higgs invisible decays at the HE-LHC?

Tim Stefaniak



Experimental Projections

- see overview of projections in talk by Lei Zhang

Lei Zhang

	Topic	CMS	ATLAS	LHCb
Exotic decays	Invisible	✔		
	LFV	✔		
	Displaced 4jets/4μ	✔		
Additional scalars	A->Zh	✔	✔	
	ττ	✔	✔	
	μμ		✔	✔
	ZZ	(+ZZ→llqq)	✔	
	WW		✔	
	γγ low mass	✔		

Legend:

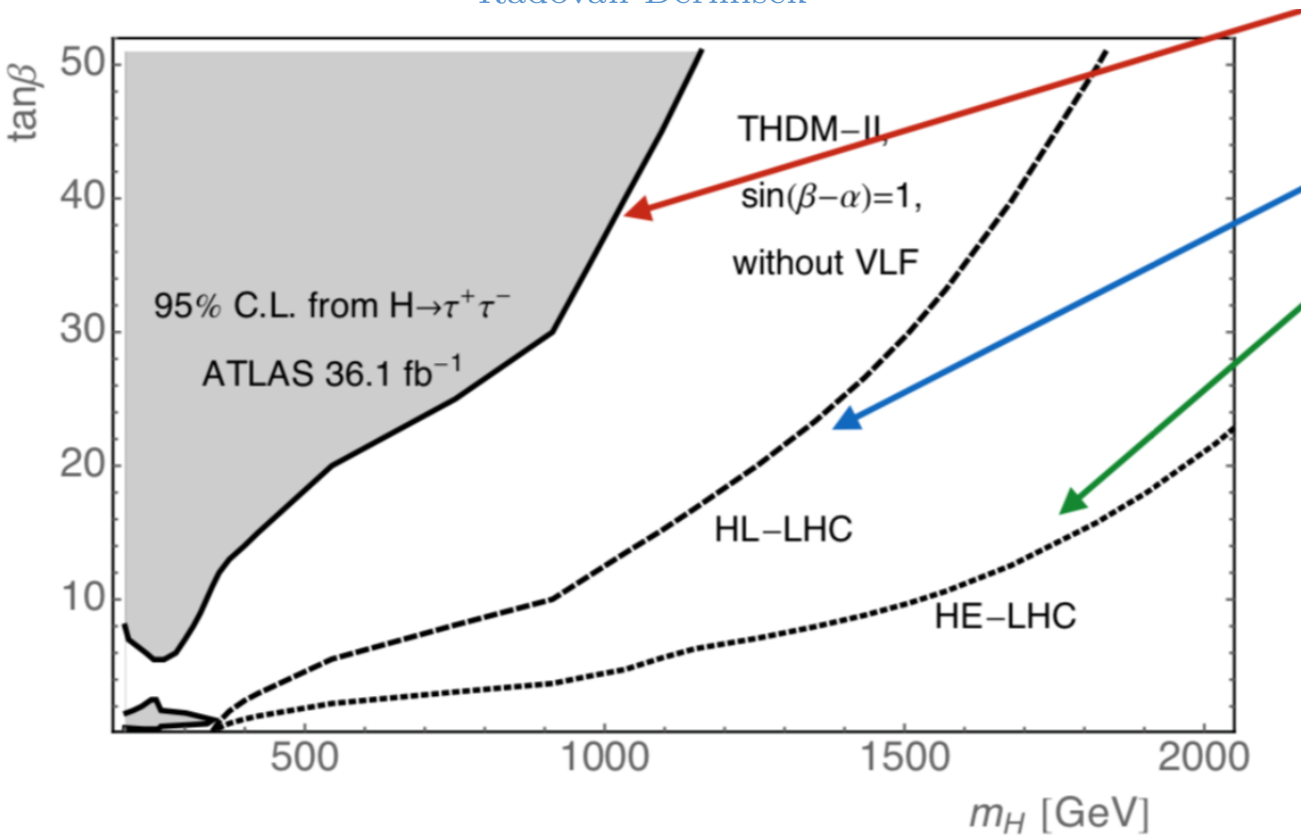
Past studies,

Wishlist for 2018

MSSM and 2HDM

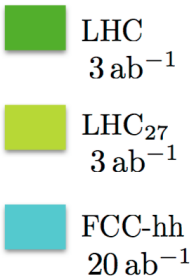
- overview of theory status given in talk by Andrea Thamm and talk by Sven Heinemeyer
- new heavy Higgs phenomenology projections in talk by Radovan Dermisek

Radovan Dermisek

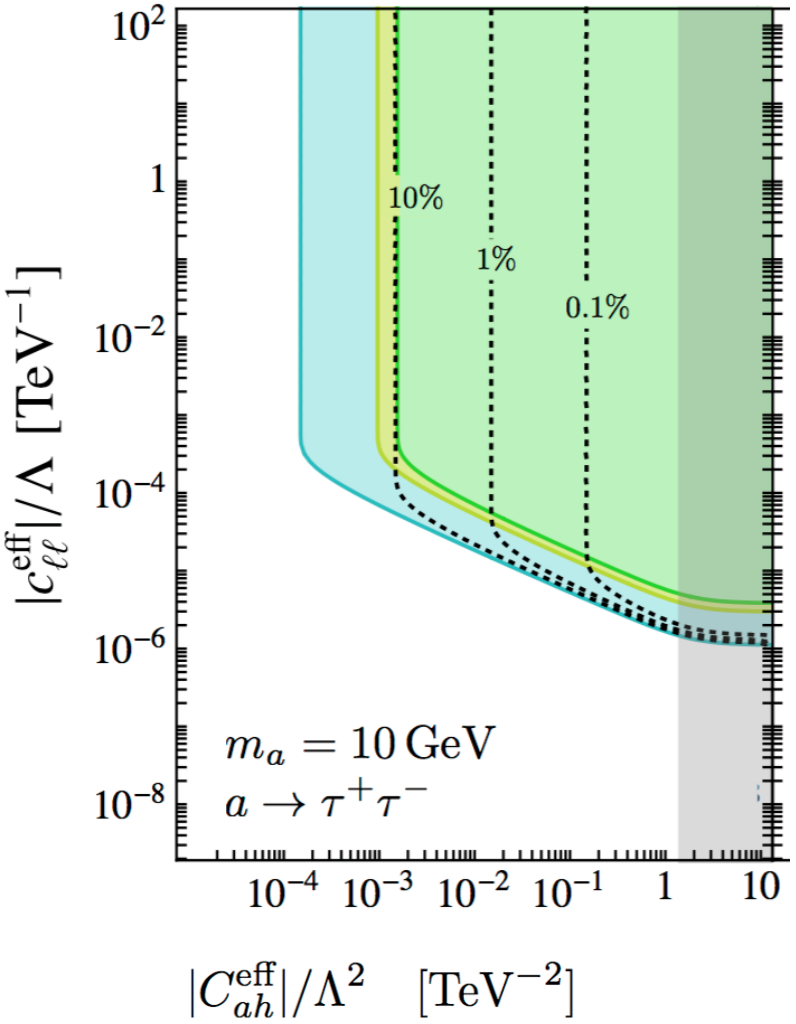


Exotic Higgs Decays

- updates on phenomenology study given in talk by Andrea Thamm
- considers $H \to aa$, here $m(a) = 10\text{GeV}$



talk by Andrea Thamm



Conclusions

Final Remarks

- we have our work cut out for us!
- need to be efficient but also rely on common sense
- modus operandi of *accurate but not necessarily precise*
- individual meetings per section and sub-section begining
- discussion from this workshop has been very useful
- communication between theory and experiment is critical
- writing should be happening now, very rough drafts are fine!