TOWARDS GLOBAL INTERPRETATION:
AN EXPERIMENTALISTS' VIEW AND WISHES

Highlights from workshop(s) discussions, some personal views

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Ultimate Precision at Hadron Colliders, 25th Nov - 6th Dec 2019

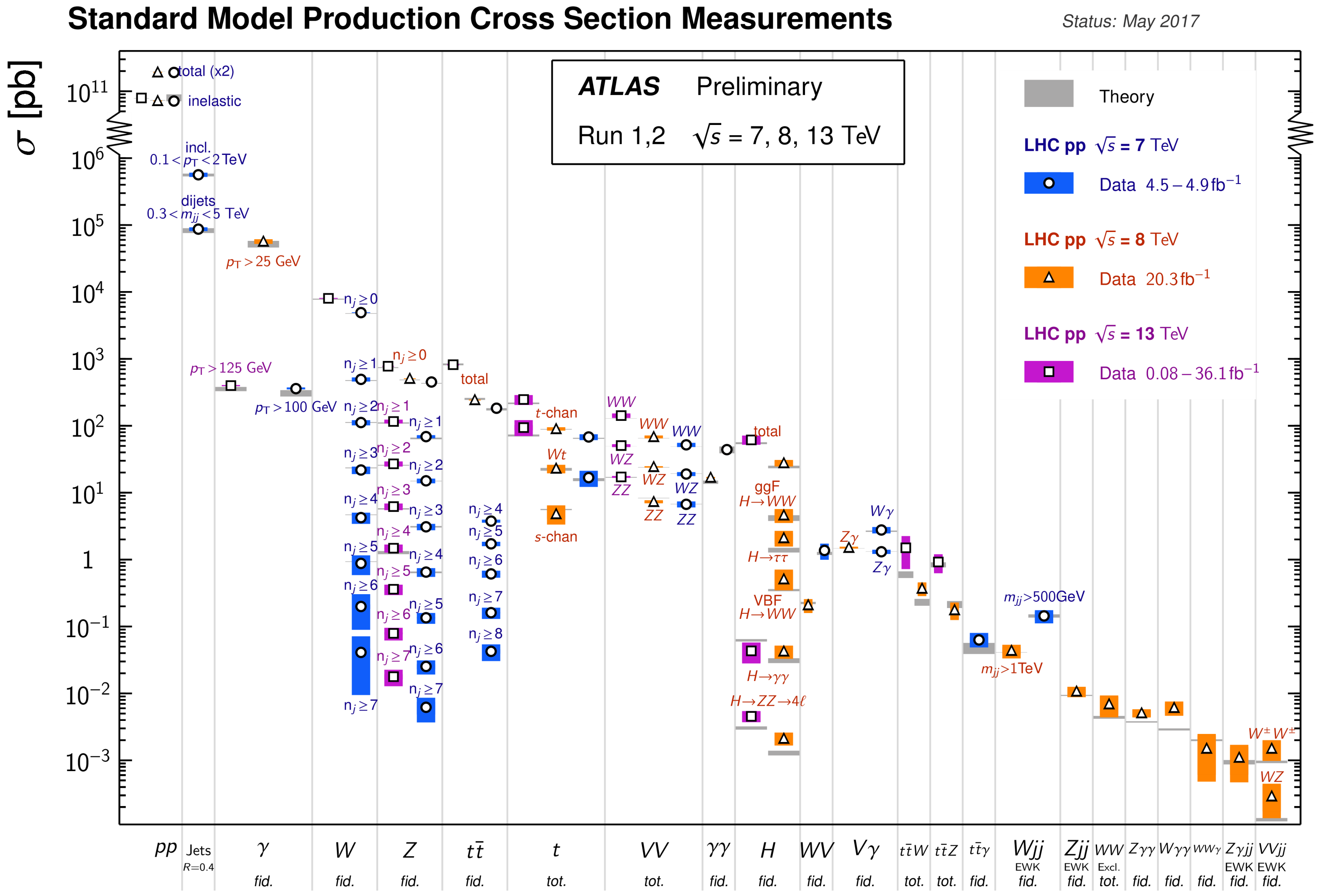
Preface

Excellence of LHC & its experiments: Enabled rich physics program @ 7/8/13 TeV

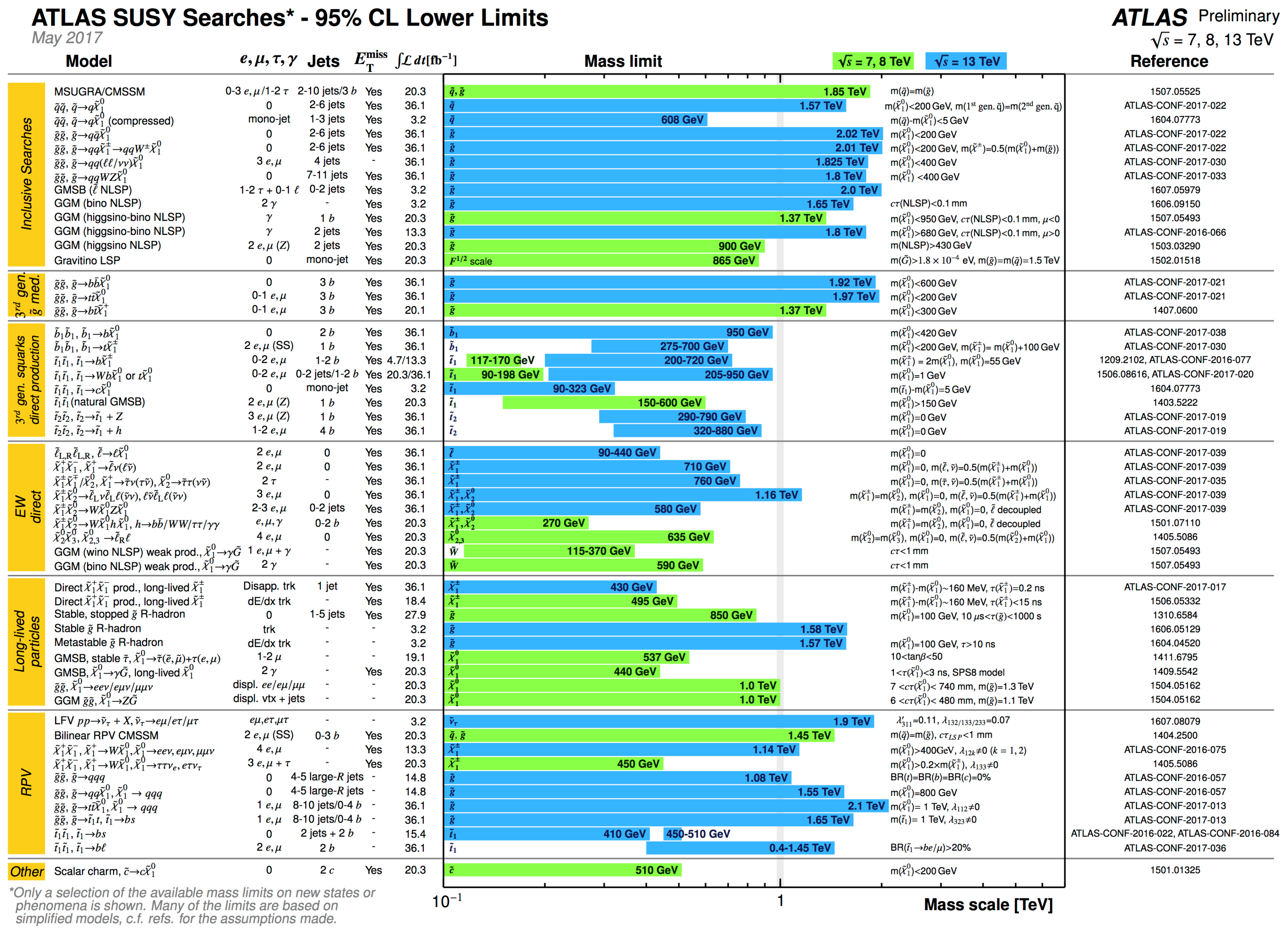
- **LHC**: effective bunch collision schemes, high machine availability.
- **Experiments**: very good performance at high pile-up, and detector operation efficiency.

Performed a plethora of SM measurements and searches for new physics:

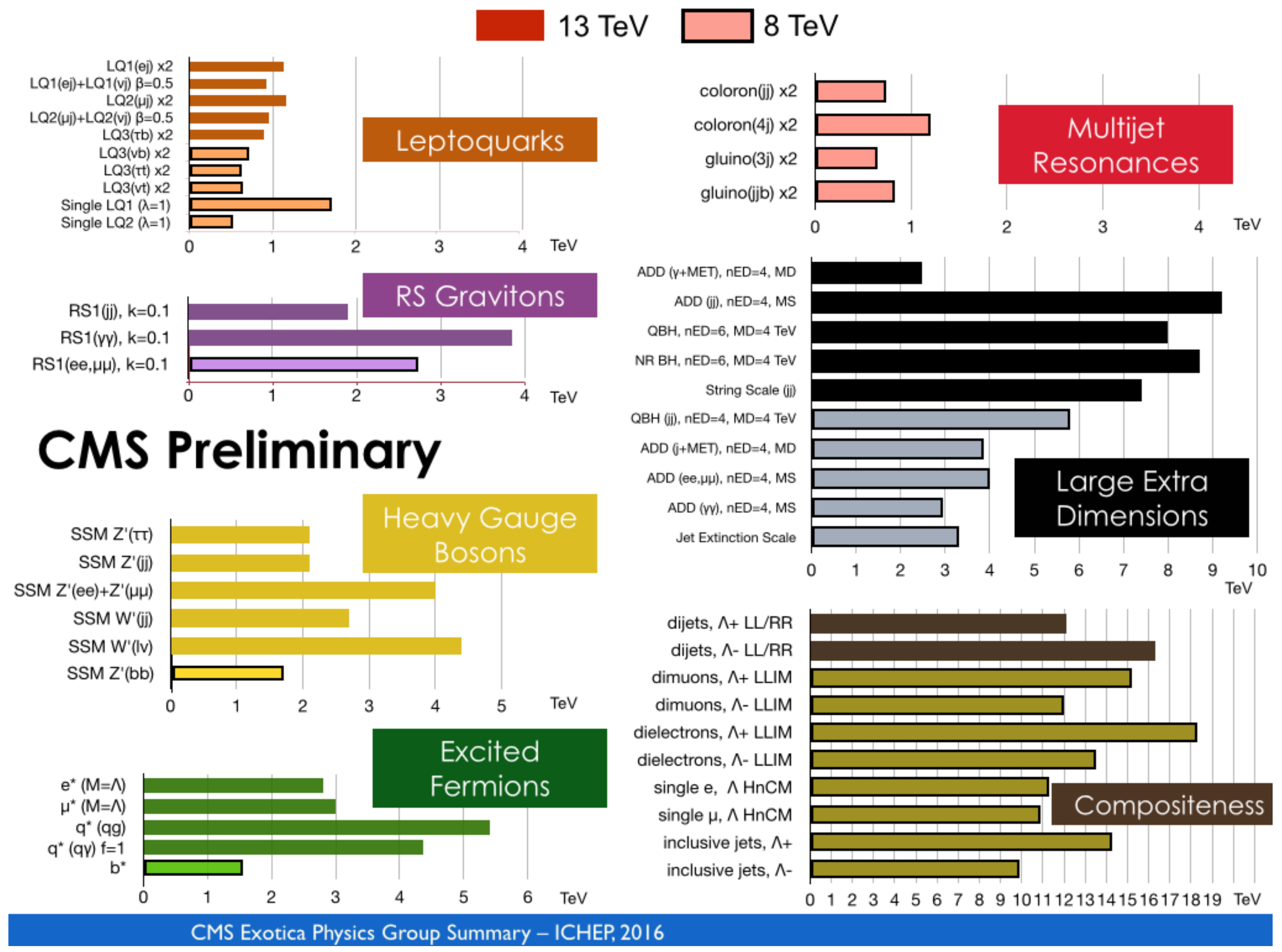
SM measurements



SUSY searches



Exotic searches



No deviation from SM

No indications for new physics phenomena

Need : LHC upgrade to fully exploit its potential and push the limits even further
Consistent global interpretation of wide spectrum of measurements

From measurements to (global) interpretations...

LHC DATA

Minimize theory dependence

Experimental measurements:

1. Characterisation of the SM processes and particles (EWK/TOP/HIG)
2. Search for BSM phenomena

(as model-independent as possible)

signal strengths

simplified template XS

Fiducial XS and differential distributions

Direct theory dependence

Interpretation of results:

1. Internally within experiments
2. externally by TH colleagues

(requires close EXP-TH interaction and recommendations)

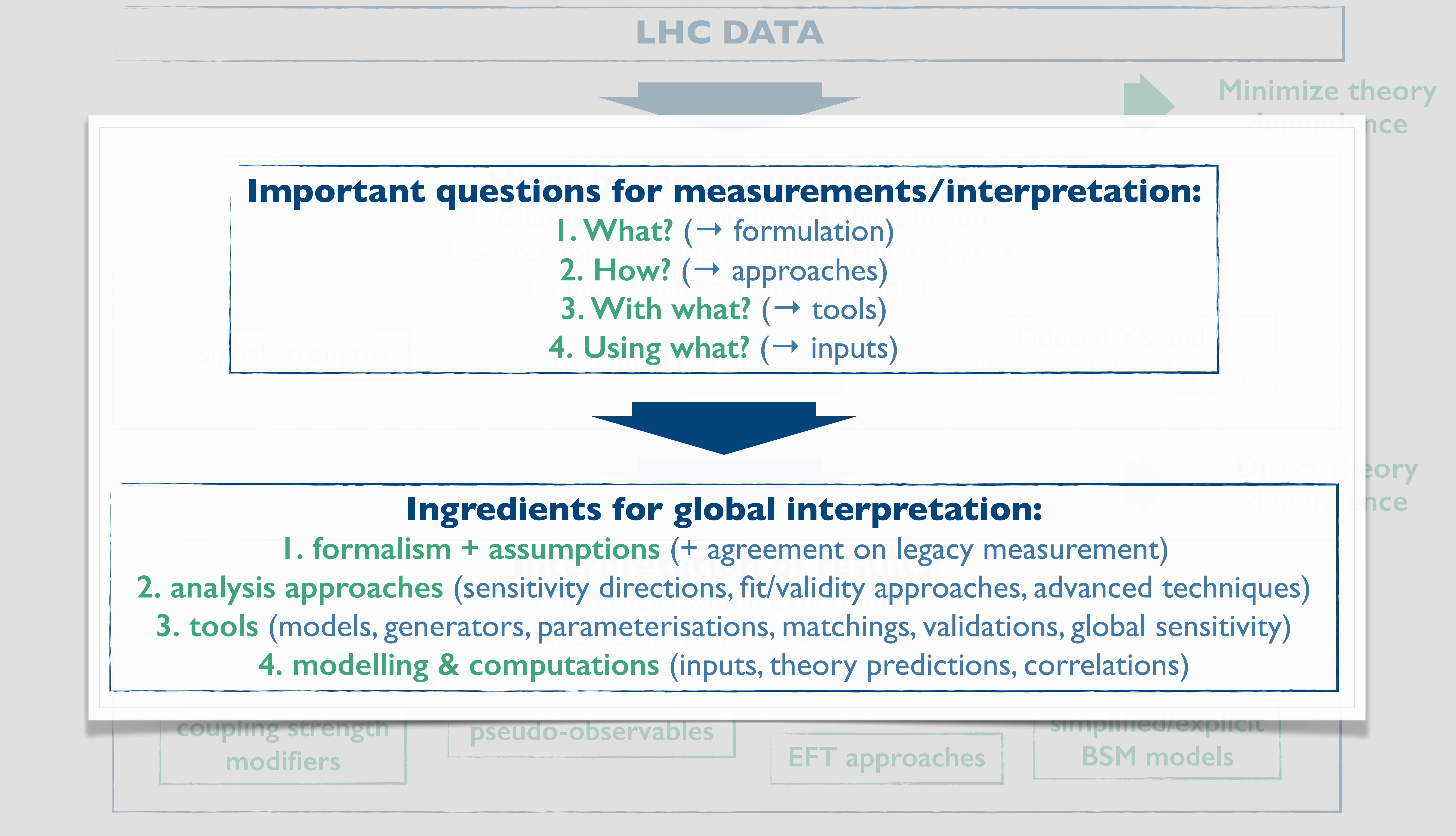
coupling strength modifiers

pseudo-observables

EFT approaches

simplified/explicit BSM models

From measurements to (global) interpretations...



Important questions for measurements/interpretation:

1. What? (→ formulation)
2. How? (→ approaches)
3. With what? (→ tools)
4. Using what? (→ inputs)

Ingredients for global interpretation:

1. **formalism + assumptions** (+ agreement on legacy measurement)
2. **analysis approaches** (sensitivity directions, fit/validity approaches, advanced techniques)
3. **tools** (models, generators, parameterisations, matchings, validations, global sensitivity)
4. **modelling & computations** (inputs, theory predictions, correlations)

> No phenomenon is a true phenomenon
> until it is an observed phenomenon.
> John A. Wheeler

Global interpretation:
Formalism, tools & approaches

- Motivation for global interpretations and some general aspects
- EFT formulation, assumptions, approaches
- EFT effects & necessary tools, towards global sensitivity

Effective Field Theory as a global approach

Effective Field Theory (EFT) - general ideas:

- **LHC results**: no new resonance, indicate scale of new physics as >> 1TeV
- **(SM)EFT approach**: only SM fields & symmetries are present at the accessible scale
  → valid QFT-based description of Nature

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

- Taylor expansion of Lagrangian in canonical dimensions:
  (large number of parameters)

$$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$$

C_i free parameters (Wilson coefficients)

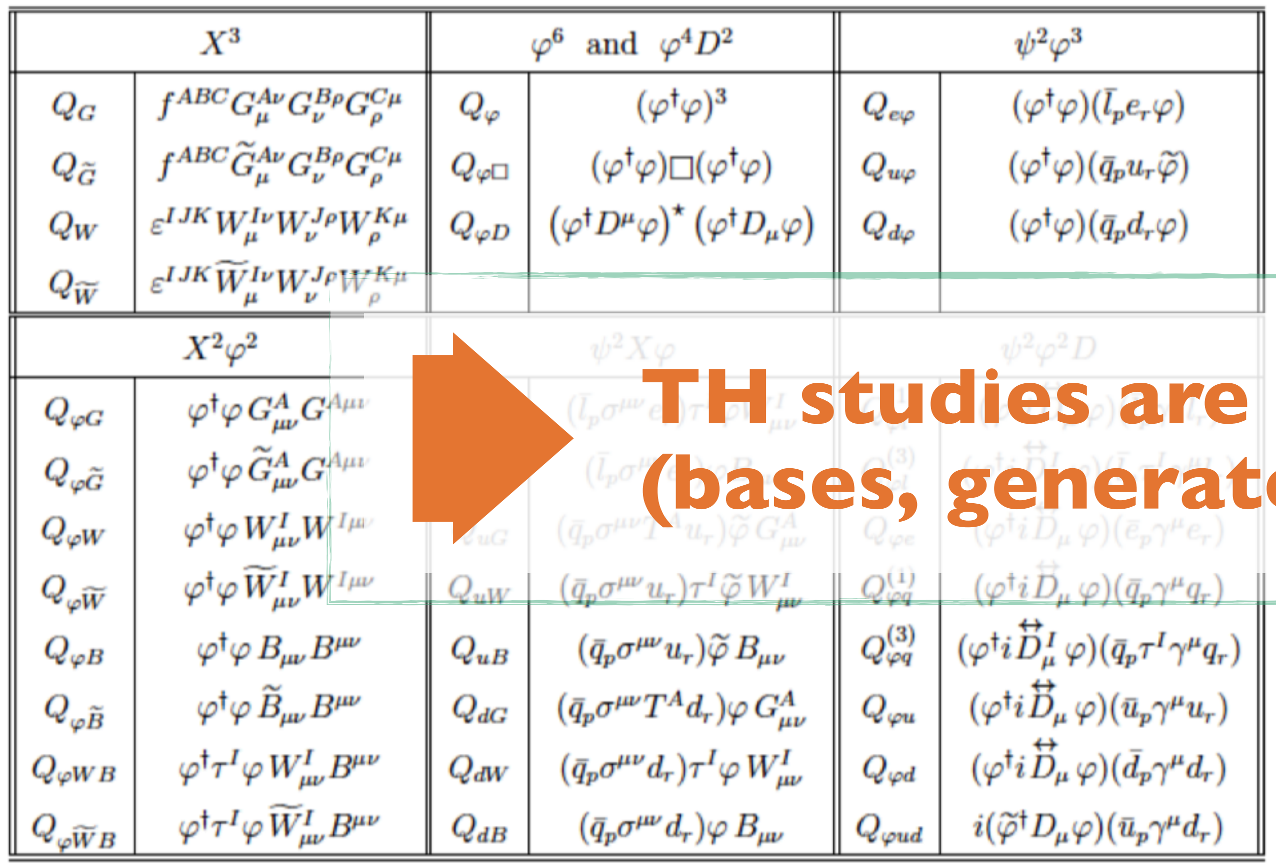
$\mathcal{O}_i$ invariant operators that form a complete, non redundant basis

EFT - possibilities:

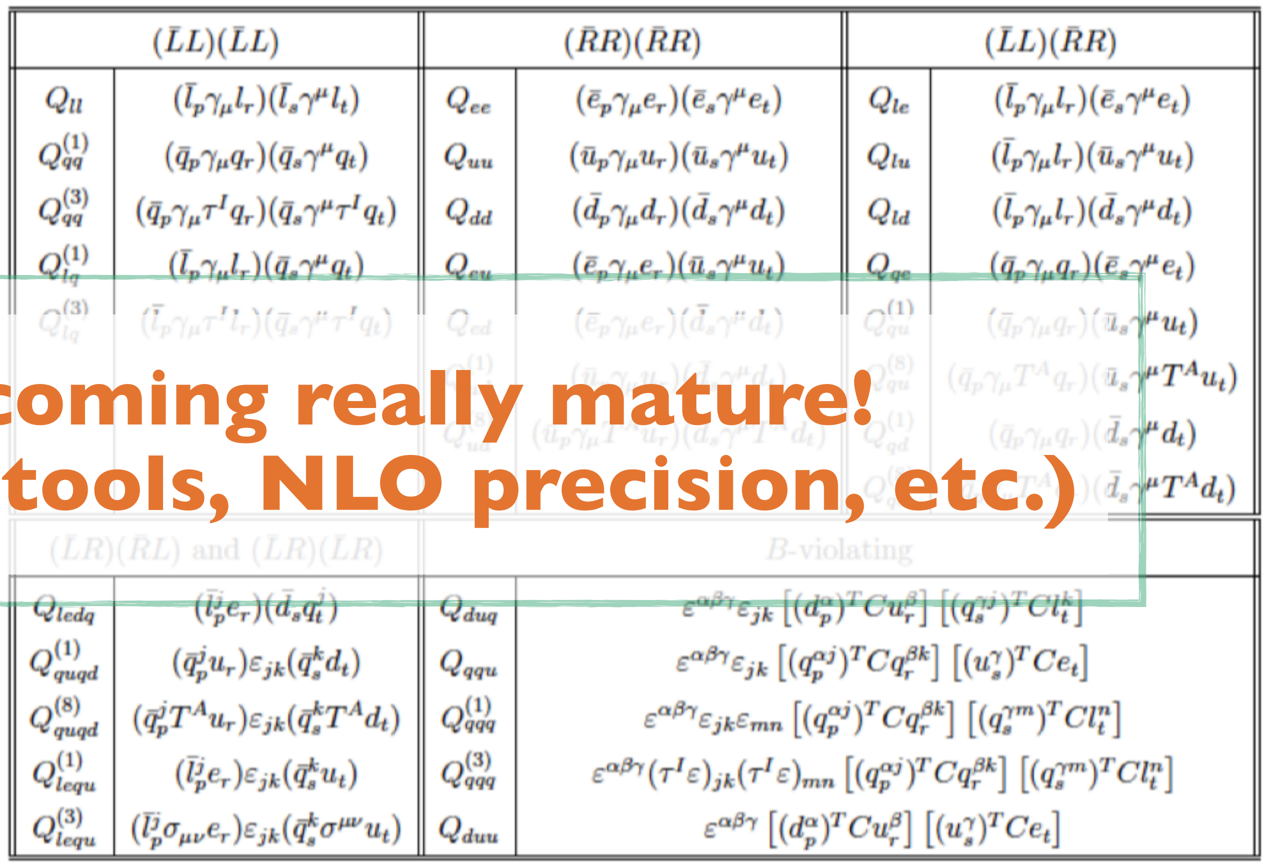
- **Allows:** to perform gauge invariant calculations & loops (systematically improvable with higher orders)
- **Use:** as a self-consistent "theory" and systematically probe its parameters
- **Approach:** choose a basis (SILH, Warsaw), retain all/relevant operators in measurement

SMEFT encodes BSM fingerprint on all processes consistently

Requires global fit of SMP/TOP/HIG measurements!



X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	[illegible]	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	[illegible]	[illegible]
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	[illegible]	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$



$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q^{(1)}_{lq}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q^{(3)}_{lq}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q^{(1)}_{ud}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q^{(1)}_{qd}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				[illegible]	[illegible] $(\bar{d}_s\gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating			
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$		
$Q^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$Q^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$	$Q^{(1)}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$	$Q^{(3)}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$		

TH studies are becoming really mature!
(bases, generatos, tools, NLO precision, etc.)

EFT models/generators/toolboxes

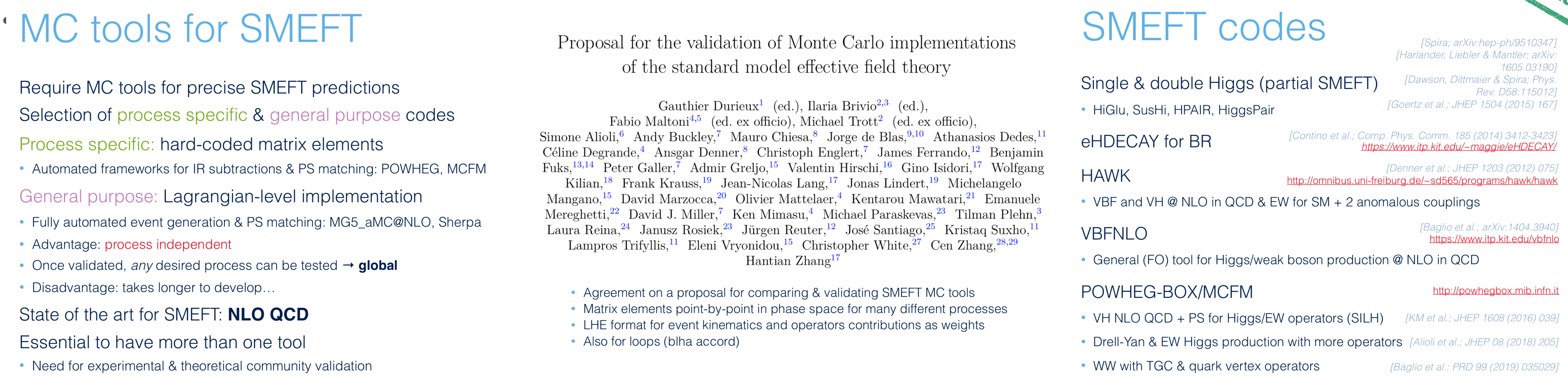
MC tools for SMEFT:

- **Hard-coded MEs:** POWHEG, MCFM; **Lagrangian-level implementation:** MG5_aMC@NLO, Sherpa
- **State of the art:** (N)NLO QCD for SM, NLO QCD for SMEFT, **LO@EFT or NLO@EFT?**

NLO@SMEFT:

- Non trivial EFT contributions could arise first at one-loop

K. Mimasu talk



MC tools for SMEFT

Require MC tools for precise SMEFT predictions

Selection of process specific & general purpose codes

Process specific: hard-coded matrix elements

- Automated frameworks for IR subtractions & PS matching: POWHEG, MCFM

General purpose: Lagrangian-level implementation

- Fully automated event generation & PS matching: MG5_aMC@NLO, Sherpa
- Advantage: process independent
- Once validated, *any* desired process can be tested → **global**
- Disadvantage: takes longer to develop…

State of the art for SMEFT: **NLO QCD**

Essential to have more than one tool

- Need for experimental & theoretical community validation

Proposal for the validation of Monte Carlo implementations
of the standard model effective field theory

Gauthier Durieux[1] (ed.), Ilaria Brivio[2,3] (ed.),
Fabio Maltoni[4,5] (ed. ex officio), Michael Trott[2] (ed. ex officio),
Simone Alioli,[6] Andy Buckley,[7] Mauro Chiesa,[8] Jorge de Blas,[9,10] Athanasios Dedes,[11] Céline Degrande,[4] Ansgar Denner,[8] Christoph Englert,[7] James Ferrando,[12] Benjamin Fuks,[13,14] Peter Galler,[7] Admir Greljo,[15] Valentin Hirschi,[16] Gino Isidori,[17] Wolfgang Kilian,[18] Frank Krauss,[19] Jean-Nicolas Lang,[17] Jonas Lindert,[19] Michelangelo Mangano,[15] David Marzocca,[20] Olivier Mattelaer,[4] Kentarou Mawatari,[21] Emanuele Mereghetti,[22] David J. Miller,[7] Ken Mimasu,[4] Michael Paraskevas,[23] Tilman Plehn,[3] Laura Reina,[24] Janusz Rosiek,[23] Jürgen Reuter,[12] José Santiago,[25] Kristaq Suxho,[11] Lampros Trifyllis,[11] Eleni Vryonidou,[15] Christopher White,[27] Cen Zhang,[28,29] Hantian Zhang[17]

- Agreement on a proposal for comparing & validating SMEFT MC tools
- Matrix elements point-by-point in phase space for many different processes
- LHE format for event kinematics and operators contributions as weights
- Also for loops (blha accord)

SMEFT codes

Single & double Higgs (partial SMEFT)

[Spira; arXiv:hep-ph/9510347]
[Harlander, Liebler & Mantler; arXiv:1605.03190]
[Dawson, Dittmaier & Spira; Phys. Rev. D58:115012]
[Goertz et al.; JHEP 1504 (2015) 167]

- HiGlu, SusHi, HPAIR, HiggsPair

eHDECAY for BR

[Contino et al.; Comp. Phys. Comm. 185 (2014) 3412-3423]
https://www.itp.kit.edu/~maggie/eHDECAY/

HAWK

[Denner et al.; JHEP 1203 (2012) 075]
http://omnibus.uni-freiburg.de/~sd565/programs/hawk/hawk

- VBF and VH @ NLO in QCD & EW for SM + 2 anomalous couplings

VBFNLO

[Baglio et al.; arXiv:1404.3940]
https://www.itp.kit.edu/vbfnlo

- General (FO) tool for Higgs/weak boson production @ NLO in QCD

POWHEG-BOX/MCFM

http://powhegbox.mib.infn.it

- VH NLO QCD + PS for Higgs/EW operators (SILH) [KM et al.; JHEP 1608 (2016) 039]
- Drell-Yan & EW Higgs production with more operators [Alioli et al.; JHEP 08 (2018) 205]
- WW with TGC & quark vertex operators [Baglio et al.; PRD 99 (2019) 035029]

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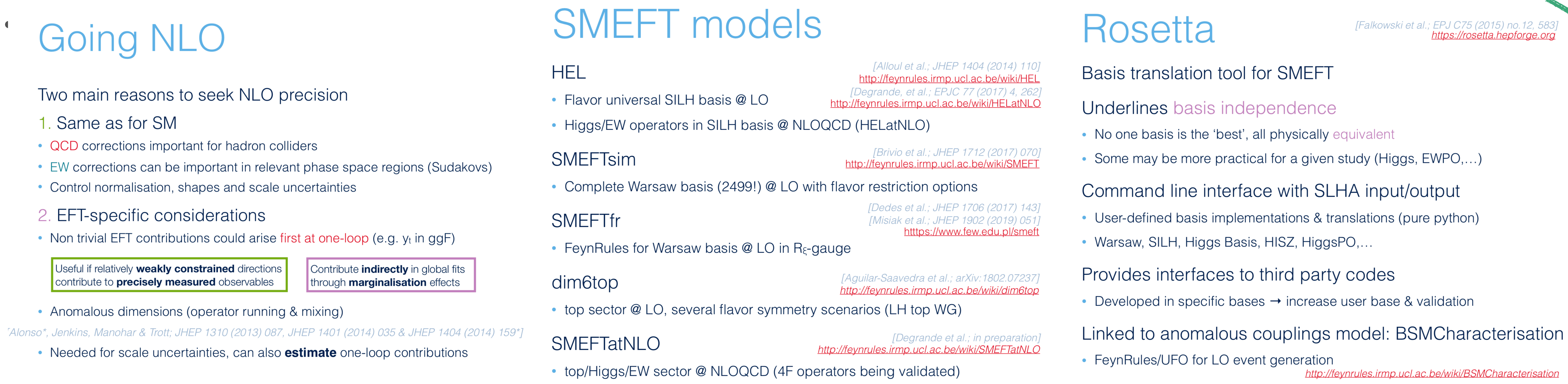
NLO@SMEFT:

K. Mimasu talk

- Non trivial EFT contributions could arise first at one-loop



Going NLO

Two main reasons to seek NLO precision

1. Same as for SM
   - QCD corrections important for hadron colliders
   - EW corrections can be important in relevant phase space regions (Sudakovs)
   - Control normalisation, shapes and scale uncertainties
2. EFT-specific considerations
   - Non trivial EFT contributions could arise first at one-loop (e.g. y_t in ggF)

Useful if relatively **weakly constrained** directions contribute to **precisely measured** observables

Contribute **indirectly** in global fits through **marginalisation** effects

- Anomalous dimensions (operator running & mixing)

Alonso*, Jenkins, Manohar & Trott; JHEP 1310 (2013) 087, JHEP 1401 (2014) 035 & JHEP 1404 (2014) 159*]

- Needed for scale uncertainties, can also **estimate** one-loop contributions

SMEFT models

HEL

[Alloul et al.; JHEP 1404 (2014) 110]
http://feynrules.irmp.ucl.ac.be/wiki/HEL
[Degrande, et al.; EPJC 77 (2017) 4, 262]
http://feynrules.irmp.ucl.ac.be/wiki/HELatNLO

- Flavor universal SILH basis @ LO
- Higgs/EW operators in SILH basis @ NLOQCD (HELatNLO)

SMEFTsim

[Brivio et al.; JHEP 1712 (2017) 070]
http://feynrules.irmp.ucl.ac.be/wiki/SMEFT

- Complete Warsaw basis (2499!) @ LO with flavor restriction options

SMEFTfr

[Dedes et al.; JHEP 1706 (2017) 143]
[Misiak et al.; JHEP 1902 (2019) 051]
htttps://www.few.edu.pl/smeft

- FeynRules for Warsaw basis @ LO in R_ξ-gauge

dim6top

[Aguilar-Saavedra et al.; arXiv:1802.07237]
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- top sector @ LO, several flavor symmetry scenarios (LH top WG)

SMEFTatNLO

[Degrande et al.; in preparation]
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

- top/Higgs/EW sector @ NLOQCD (4F operators being validated)

Rosetta

[Falkowski et al.; EPJ C75 (2015) no.12, 583]
https://rosetta.hepforge.org

Basis translation tool for SMEFT

Underlines basis independence

- No one basis is the 'best', all physically equivalent
- Some may be more practical for a given study (Higgs, EWPO,…)

Command line interface with SLHA input/output

- User-defined basis implementations & translations (pure python)
- Warsaw, SILH, Higgs Basis, HISZ, HiggsPO,…

Provides interfaces to third party codes

- Developed in specific bases → increase user base & validation

Linked to anomalous couplings model: BSMCharacterisation

- FeynRules/UFO for LO event generation

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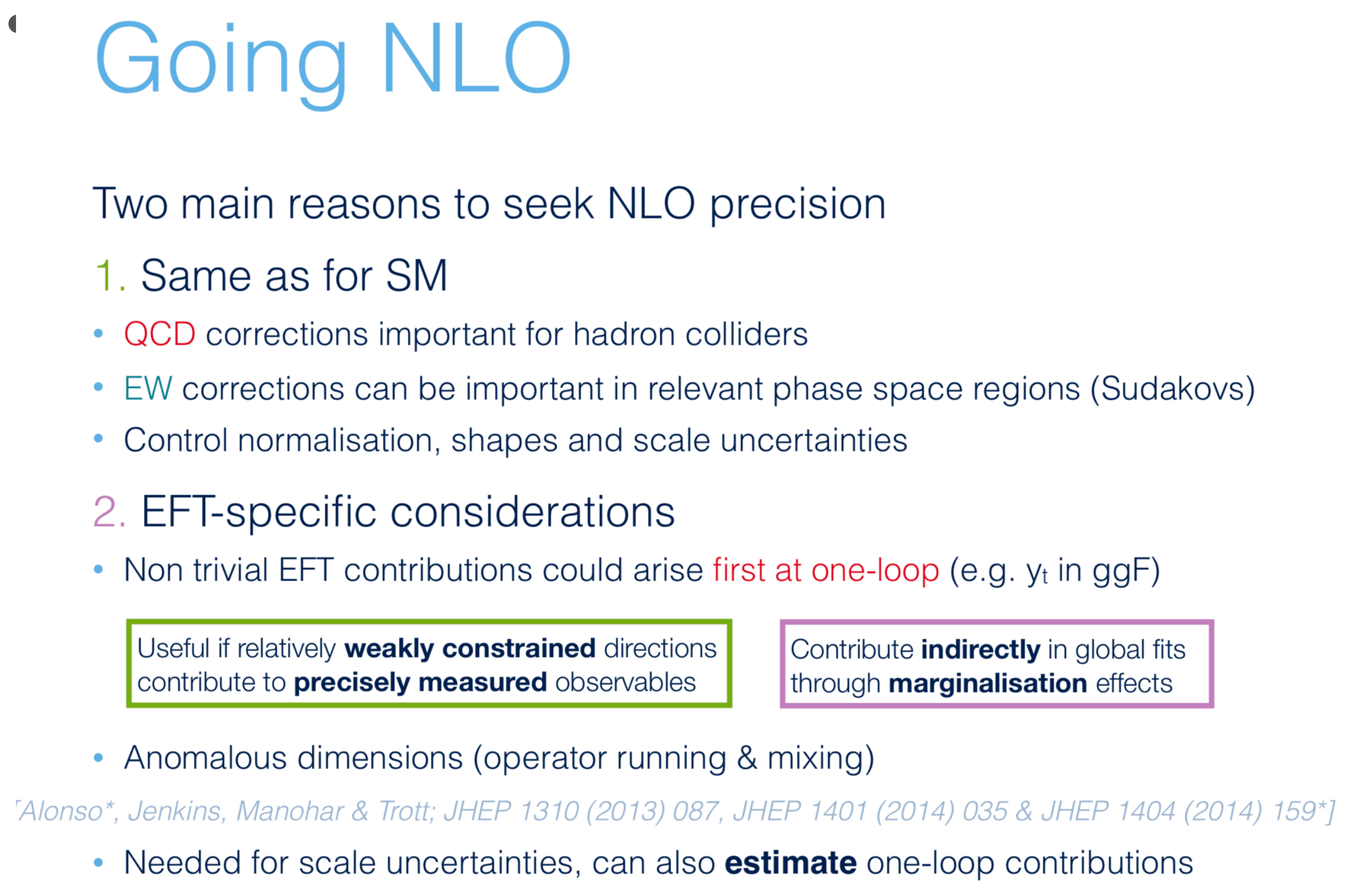

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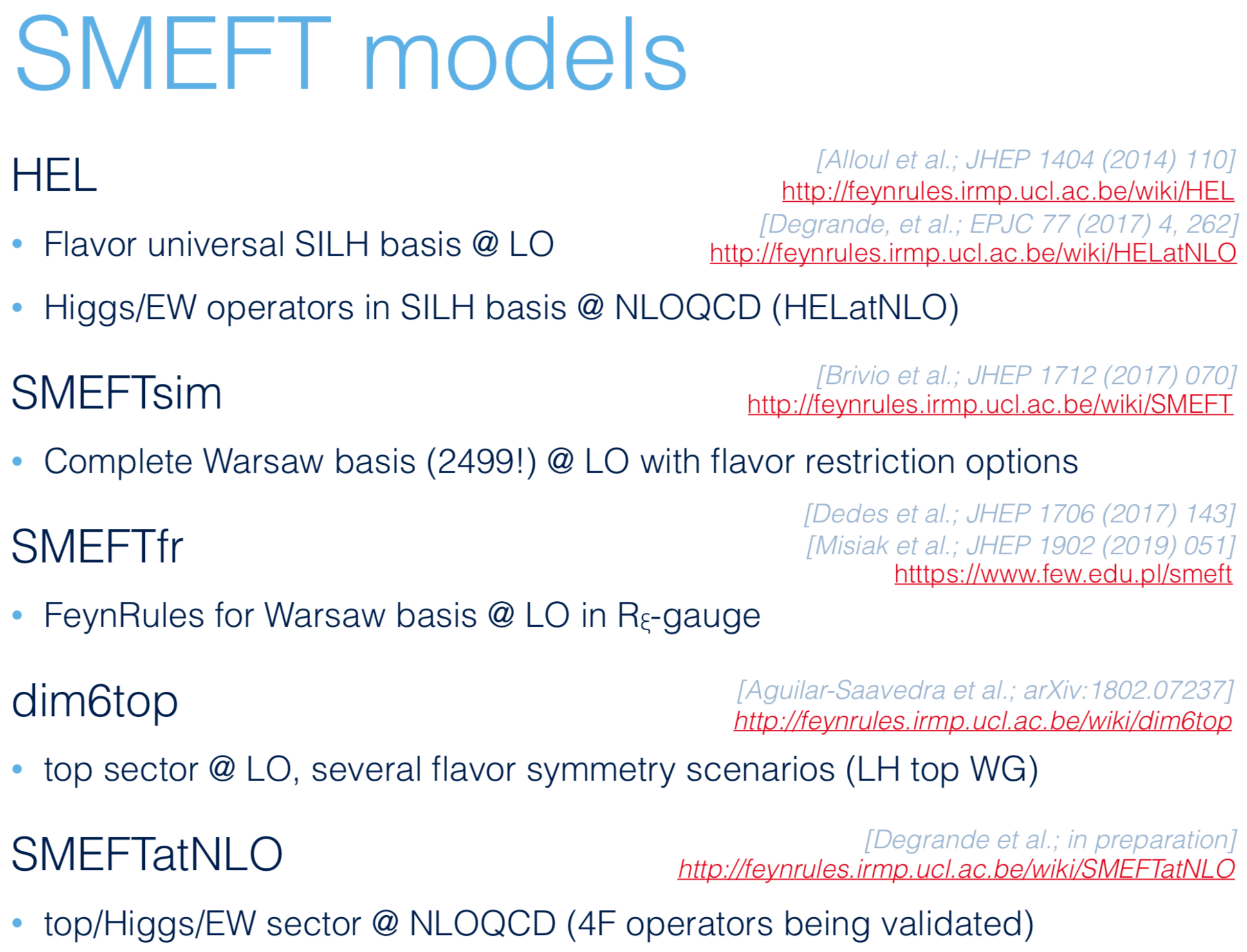

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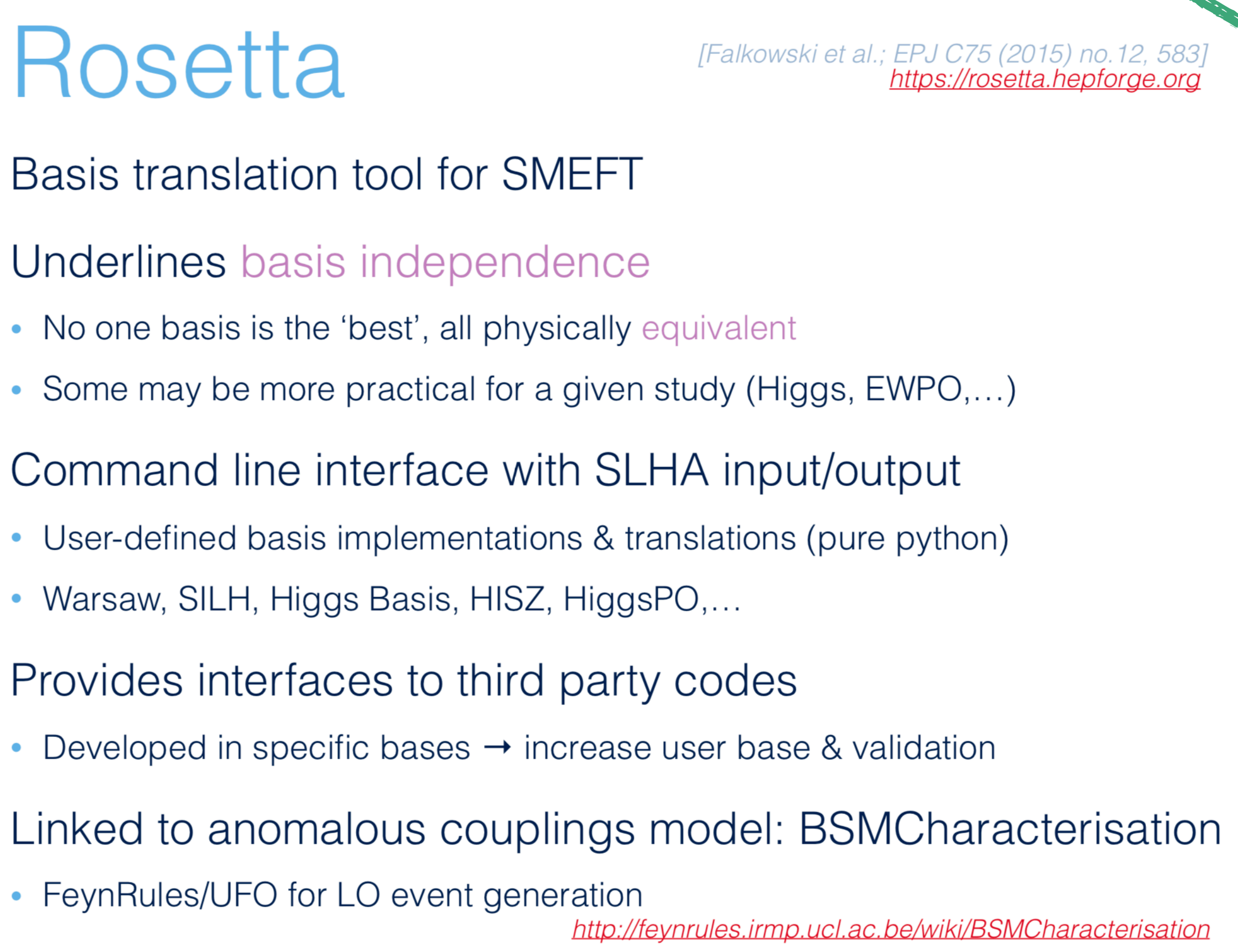

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Essential requirements:

Have more than one (harmonised) tools, validated by EXP & TH community

Optimised to handle large number of diagrams, vertices with up to 6 legs, etc.

Aim for complete SMEFT@NLO (top/Higgs/EW sector with QCD@NLO)

EFT models/generators/toolboxes

Other Toolboxes for global interpretation:

- Wide spectrum of TH tools for statistical statistical inference on new physics models/parameters
- Implementation/parameterisation of observables, DB of legacy measurements with global likelihoods

K. Mimasu talk

smelli

[Aebischer et al.; EPJ C79 (2019) no.6, 509]
https://smelli.github.io

Project for global, public SMEFT likelihood

Wrapper around flavio tool **flavio**

- Initially developed for flavour physics observables [Straub; arXiv:1810:08132] https://flav-io.github.io
- EFT predictions for flavour, EWPO, LFV decays, lepton MDM, neutron EDM

Interface to Wilson tool **wilson** [Aebischer et al.; EPJ C78 (2018) no.12, 1026] https://wilson-eft.github.io

- Running SMEFT coefficients down to EW scale
- Based on DsixTools implementation [Celis et a.; EPJ C77 (2017) no.6, 405] https://dsixtools.github.io
- Matching to Weak Effective Theory below EW scale + running

"Full stack" suite of global EFT analysis software

- Common interface: Wilson coefficient exchange format (WCxf)

HEPfit

[de Blas et al.; arXiv: 1910.14012]
http://hepfit.roma1.infn.it

Open source library for model parameter inference

- Standard model & extensions (specifically SMEFT)

Bayesian statistical framework

- Markov-Chain Monte Carlo (MCMC) via Bayesian Analysis Toolkit [Caldwell et al.; Comp. Phys. Comm. 180 (2009) 2197]

Posterior distribution

$$P(\vec{\mathbf{x}}|D) = \frac{P(D|\vec{\mathbf{x}})P_0(\vec{\mathbf{x}})}{\int P(D|\vec{\mathbf{x}})P_0(\vec{\mathbf{x}})d\vec{\mathbf{x}}}$$

Likelihood, Prior & Bayesian evidence

- Metropolis-Hastings algorithm to sample parameter space from posterior

Observables

- Higgs signal strengths (LHC & Future lepton colliders incl. polarisation)
- EW precision data in (mZ, α, G_F) scheme
- Flavour observables
- BSM model-specific (incl. theoretical constraints)

WCxf

[Aebischer et al.; Comp. Phys. Comm. 232 (2018) 71-83]
https://wcxf.github.io

Community effort to uniformise input/output format

Specifically for interfacing SMEFT tools

- yaml, json formats for basis definition
- Rosetta-inspired translation functionality
- Predefined Warsaw, WET

EFT file

```
eft: SMEFT
sectors:
  dB=dL=0:
  dB=dL=1:
  dL=2:
```

WC file

```
eft: SMEFT
basis: Warsaw
scale: 1e16
values:
    Gtilde: 3.1e-6
    uphi11:
      Re: 0
      Im: 0.0001
```

Basis file

```
name: Warsaw
eft: SMEFT
sectors:
  dB=dL=0:
    G:
      real: true
    Gtilde:
      real: true
    W:
      real: true
    [...]
    uphi_11:
    uphi_12:
    uphi_13:
    [...]
```

Code	Import	Export
DsixTools	✓	✓
EOS	✓	
flavio	✓	✓
FlavorKit		✓
FormFlavor	✓	✓
wilson	✓	✓
SMEFT Feynman Rules	✓	✓
SMEFTsim	✓	
smelli	✓	✓
SPheno		✓
wcxf-python	✓	✓

Essential requirements:

Need flexible, entirely scalable, open source tools to pool knowledge & effort

Standardisation / harmonisation / uniformisation

(EXP) user friendly interfaces to global knowledge

EFT effects parameterisations

Two approaches to construct EFT signal model:

- **Full-sim @reco-level**: captures EFT acceptance effects, typical for optimised analyses & not unfolded
- **Fiducial @gen-level:** typical for simple analyses & comb., unfolded with SM acceptance assumptions

A.Gilbert talk (LHCHXSWG)

Sum of full-sim. signal PDFs

[1]

$$P_s(\mathbf{x}\,|\,c_j) = \sum_i a_i(c_j) \cdot p_i(\mathbf{x})$$

where:

- **i** runs over a set of fixed points in the EFT space
- **a_i** are normalisation coefficients
- **$p_i(\mathbf{x})$** are the pdfs for the fixed points - possibly from separate MC samples or matrix element reweighting of a smaller set of samples

Parameterise gen-level fiducial bins

[2]

$$P_s(\mathbf{x}\,|\,c_j) = \sum_k \left(p^k_{\mathrm{SM}}(\mathbf{x}) \cdot \sum_j c_j \mu_j^k \right)$$

where:

- **k** runs over fiducial bins at generator level
- **$p^k_{\mathrm{SM}}(\mathbf{x})$** is the SM reco.-level signal pdf for events in gen.-level bin **k**
- **μ_j^k** is a scaling constant for the effect of **c_j** on bin **k**

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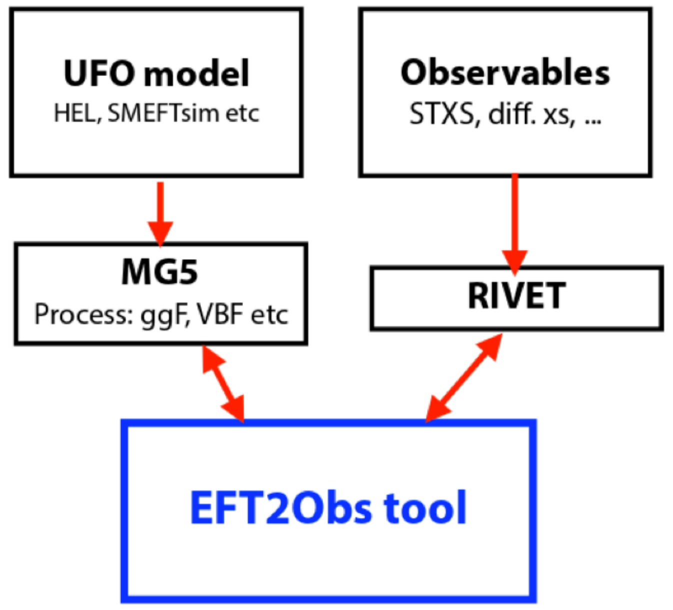
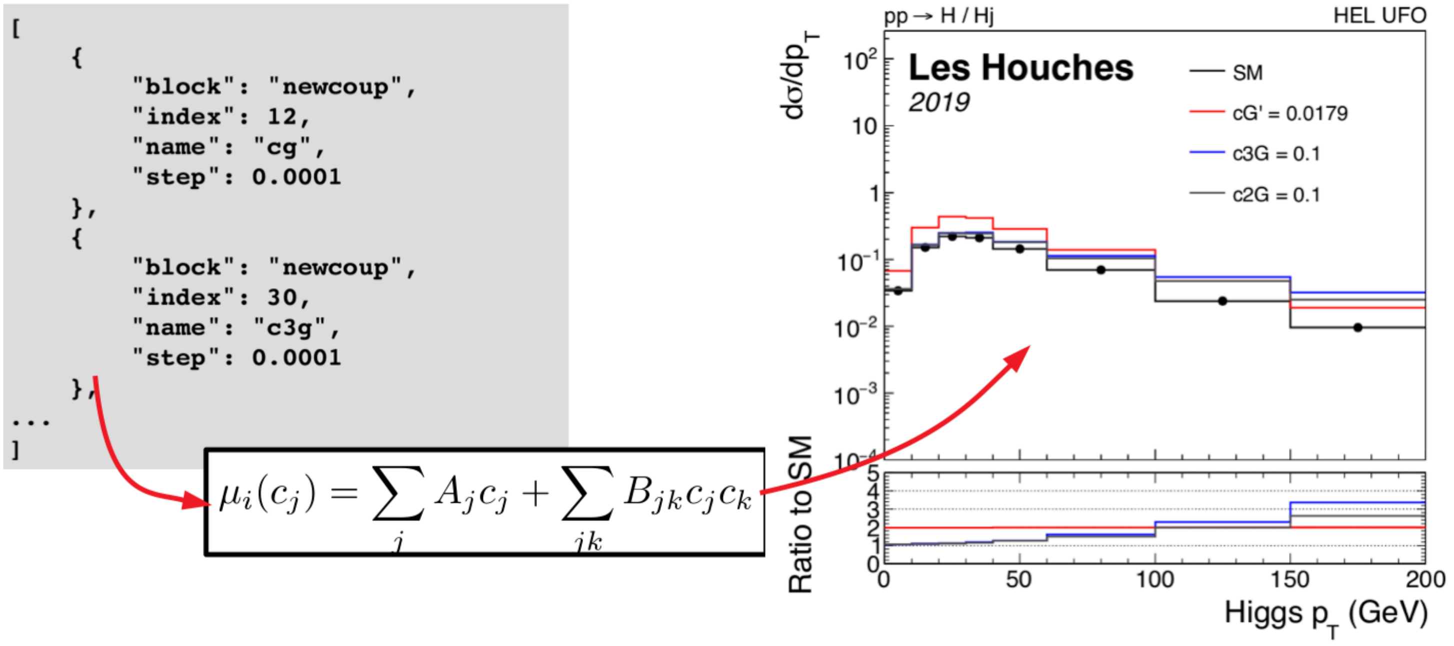
Several exp-built tools available :

- Exploiting MC computation of MEs and reweighting techniques
-

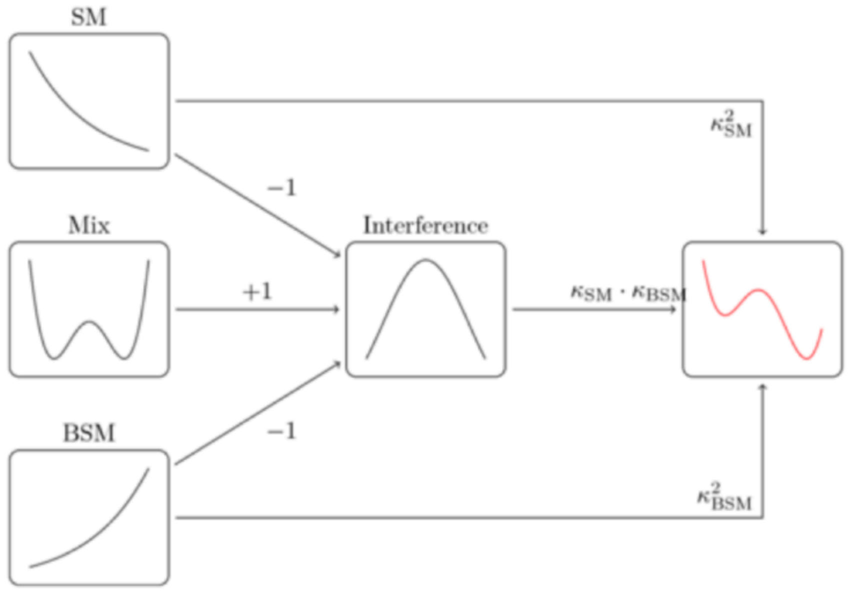
A.Gilbert talk (LHCHXSWG)

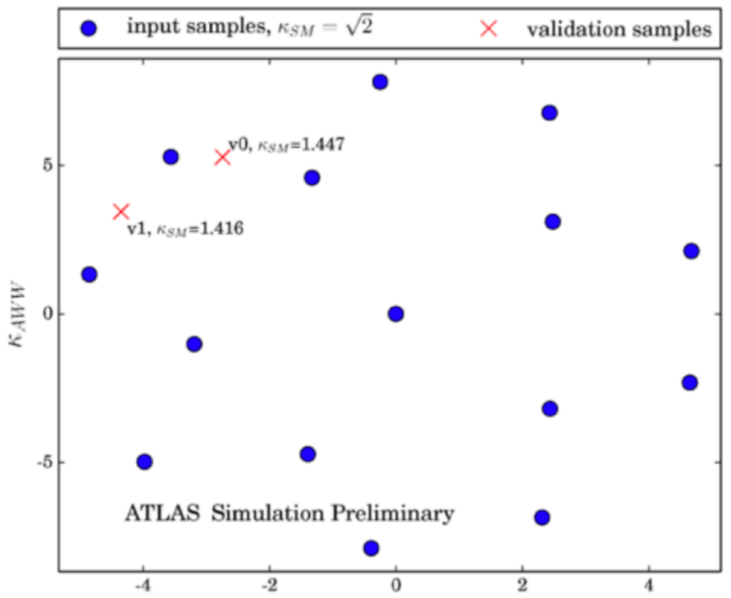


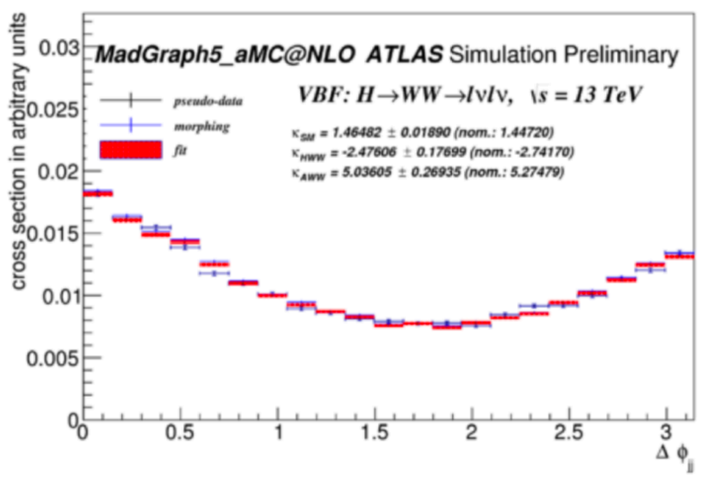


```
[
    {
        "block": "newcoup",
        "index": 12,
        "name": "cg",
        "step": 0.0001
    },
    {
        "block": "newcoup",
        "index": 30,
        "name": "c3g",
        "step": 0.0001
    },
...
]
```

$$\mu_i(c_j) = \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$







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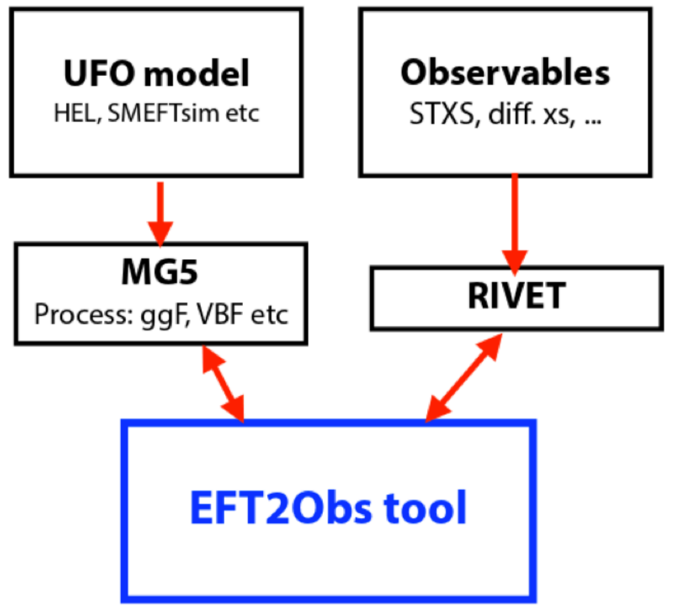


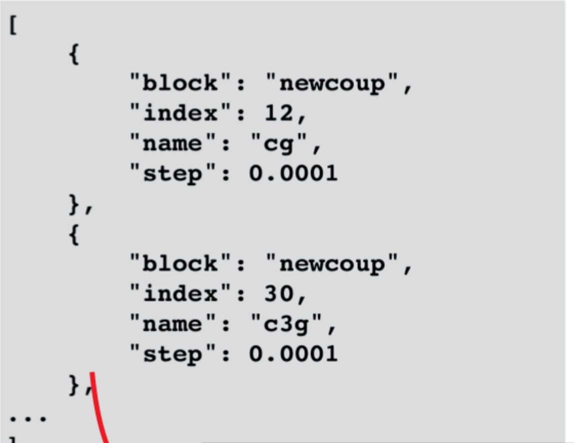
UFO model
HEL, SMEFTsim etc

Observables
STXS, diff. xs, ...

MG5
Process: ggF, VBF etc

RIVET

EFT2Obs tool



```
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    {
        "block": "newcoup",
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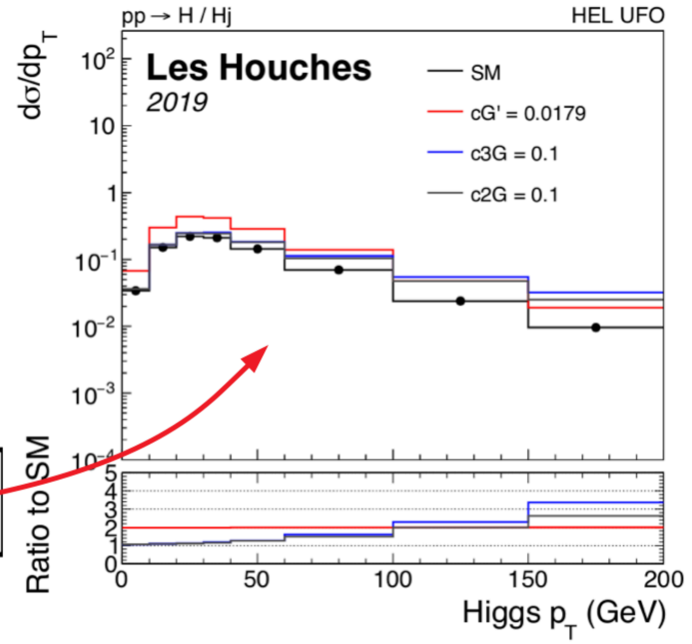

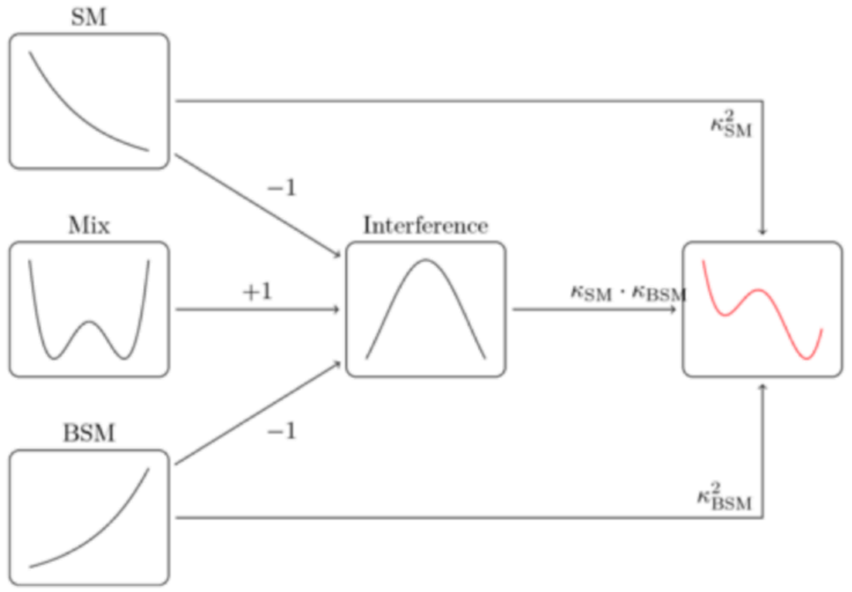

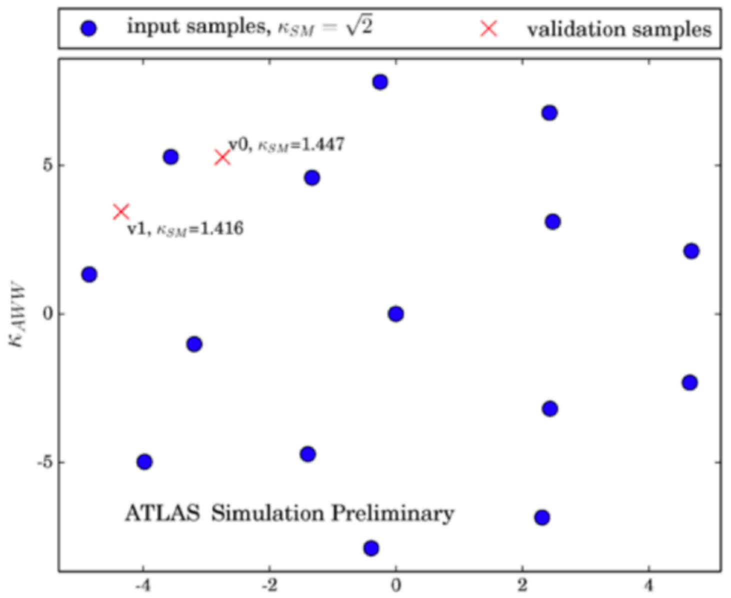

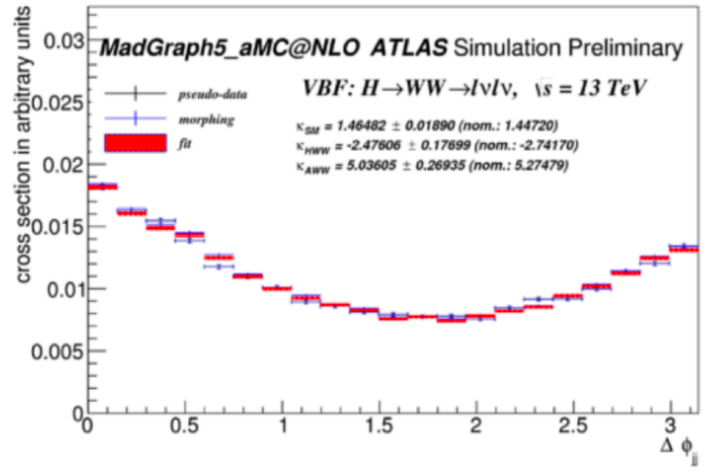

Need more general tool(s) for automatic parameterisation of effects of EFT operators (in sync. with existing similar TH tools).
Need interfacable event-by-event re-weighting tool based on analytic LO EFT MEs.

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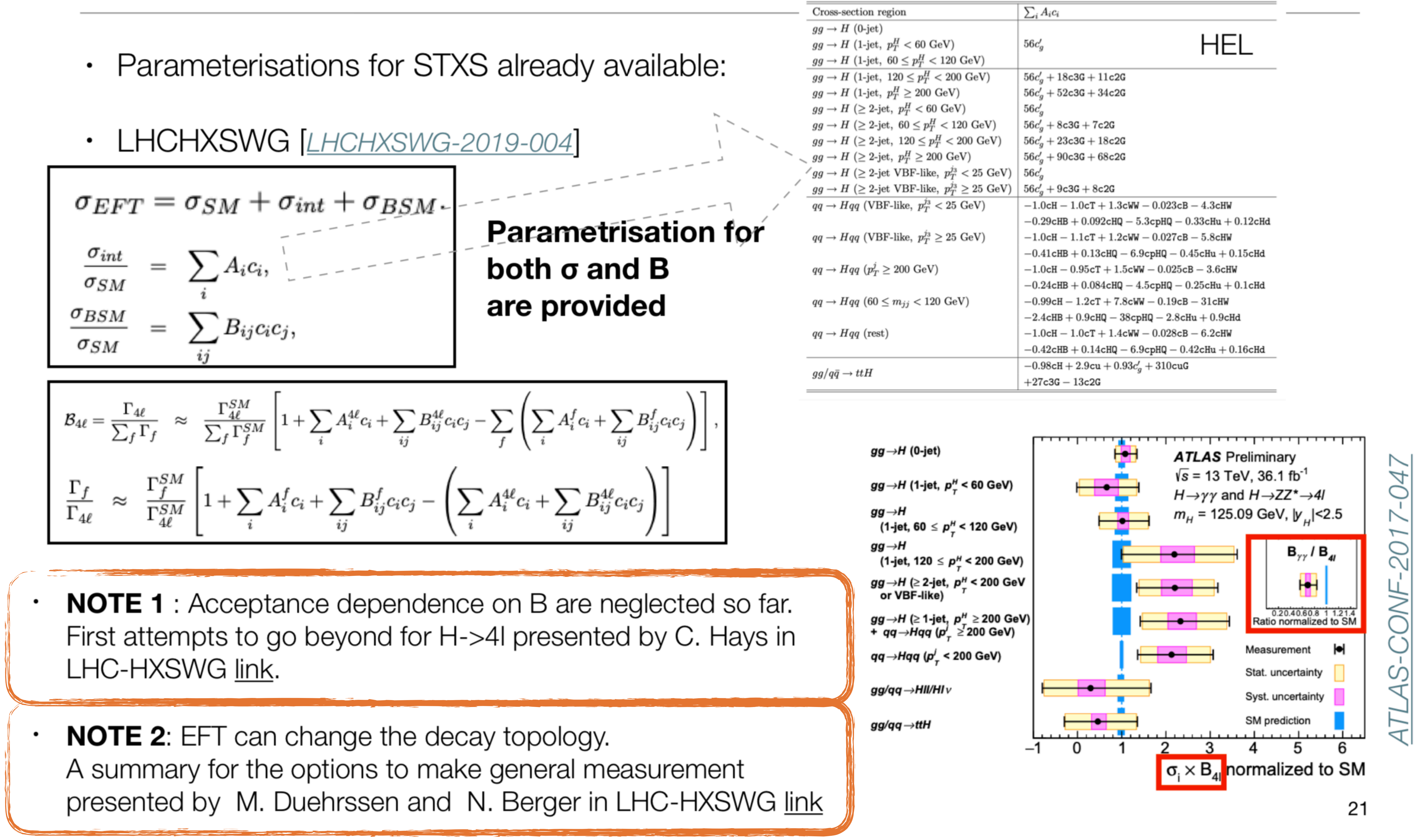
Caveats in exploiting combination of STXS measurements:

P. Francavilla talk



- Parameterisations for STXS already available:
- LHCHXSWG [LHCHXSWG-2019-004]

$$\sigma_{EFT} = \sigma_{SM} + \sigma_{int} + \sigma_{BSM}$$

$$\frac{\sigma_{int}}{\sigma_{SM}} = \sum_i A_i c_i,$$

$$\frac{\sigma_{BSM}}{\sigma_{SM}} = \sum_{ij} B_{ij} c_i c_j,$$

Parametrisation for both σ and B are provided

$$\mathcal{B}_{4\ell} = \frac{\Gamma_{4\ell}}{\sum_f \Gamma_f} \approx \frac{\Gamma_{4\ell}^{SM}}{\sum_f \Gamma_f^{SM}} \left[1 + \sum_i A_i^{4\ell} c_i + \sum_{ij} B_{ij}^{4\ell} c_i c_j - \sum_f \left(\sum_i A_i^f c_i + \sum_{ij} B_{ij}^f c_i c_j \right) \right],$$

$$\frac{\Gamma_f}{\Gamma_{4\ell}} \approx \frac{\Gamma_f^{SM}}{\Gamma_{4\ell}^{SM}} \left[1 + \sum_i A_i^f c_i + \sum_{ij} B_{ij}^f c_i c_j - \left(\sum_i A_i^{4\ell} c_i + \sum_{ij} B_{ij}^{4\ell} c_i c_j \right) \right]$$

HEL

Cross-section region	$\sum_i A_i c_i$
$gg \to H$ (0-jet) $gg \to H$ (1-jet, $p_T^H < 60$ GeV) $gg \to H$ (1-jet, $60 \leq p_T^H < 120$ GeV)	$56c'_g$
$gg \to H$ (1-jet, $120 \leq p_T^H < 200$ GeV)	$56c'_g + 18\mathtt{c3G} + 11\mathtt{c2G}$
$gg \to H$ (1-jet, $p_T^H \geq 200$ GeV)	$56c'_g + 52\mathtt{c3G} + 34\mathtt{c2G}$
$gg \to H$ ($\geq$ 2-jet, $p_T^H < 60$ GeV)	$56c'_g$
$gg \to H$ ($\geq$ 2-jet, $60 \leq p_T^H < 120$ GeV)	$56c'_g + 8\mathtt{c3G} + 7\mathtt{c2G}$
$gg \to H$ ($\geq$ 2-jet, $120 \leq p_T^H < 200$ GeV)	$56c'_g + 23\mathtt{c3G} + 18\mathtt{c2G}$
$gg \to H$ ($\geq$ 2-jet, $p_T^H \geq 200$ GeV)	$56c'_g + 90\mathtt{c3G} + 68\mathtt{c2G}$
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$qq \to Hqq$ (VBF-like, $p_T^{j3} < 25$ GeV)	$-1.0\mathtt{cH} - 1.0\mathtt{cT} + 1.3\mathtt{cWW} - 0.023\mathtt{cB} - 4.3\mathtt{cHW}$ $-0.29\mathtt{cHB} + 0.092\mathtt{cHQ} - 5.3\mathtt{cpHQ} - 0.33\mathtt{cHu} + 0.12\mathtt{cHd}$
$qq \to Hqq$ (VBF-like, $p_T^{j3} \geq 25$ GeV)	$-1.0\mathtt{cH} - 1.1\mathtt{cT} + 1.2\mathtt{cWW} - 0.027\mathtt{cB} - 5.8\mathtt{cHW}$ $-0.41\mathtt{cHB} + 0.13\mathtt{cHQ} - 6.9\mathtt{cpHQ} - 0.45\mathtt{cHu} + 0.15\mathtt{cHd}$
$qq \to Hqq$ ($p_T^j \geq 200$ GeV)	$-1.0\mathtt{cH} - 0.95\mathtt{cT} + 1.5\mathtt{cWW} - 0.025\mathtt{cB} - 3.6\mathtt{cHW}$ $-0.24\mathtt{cHB} + 0.084\mathtt{cHQ} - 4.5\mathtt{cpHQ} - 0.25\mathtt{cHu} + 0.1\mathtt{cHd}$
$qq \to Hqq$ ($60 \leq m_{jj} < 120$ GeV)	$-0.99\mathtt{cH} - 1.2\mathtt{cT} + 7.8\mathtt{cWW} - 0.19\mathtt{cB} - 31\mathtt{cHW}$ $-2.4\mathtt{cHB} + 0.9\mathtt{cHQ} - 38\mathtt{cpHQ} - 2.8\mathtt{cHu} + 0.9\mathtt{cHd}$
$qq \to Hqq$ (rest)	$-1.0\mathtt{cH} - 1.0\mathtt{cT} + 1.4\mathtt{cWW} - 0.028\mathtt{cB} - 6.2\mathtt{cHW}$ $-0.42\mathtt{cHB} + 0.14\mathtt{cHQ} - 6.9\mathtt{cpHQ} - 0.42\mathtt{cHu} + 0.16\mathtt{cHd}$
$gg/q\bar{q} \to ttH$	$-0.98\mathtt{cH} + 2.9\mathtt{cu} + 0.93c'_g + 310\mathtt{cuG}$ $+27\mathtt{c3G} - 13\mathtt{c2G}$

- **NOTE 1** : Acceptance dependence on B are neglected so far. First attempts to go beyond for H->4l presented by C. Hays in LHC-HXSWG link.

- **NOTE 2**: EFT can change the decay topology. A summary for the options to make general measurement presented by M. Duehrssen and N. Berger in LHC-HXSWG link

Need TH involvement to include decay information and tackle acc. effects in STXS.

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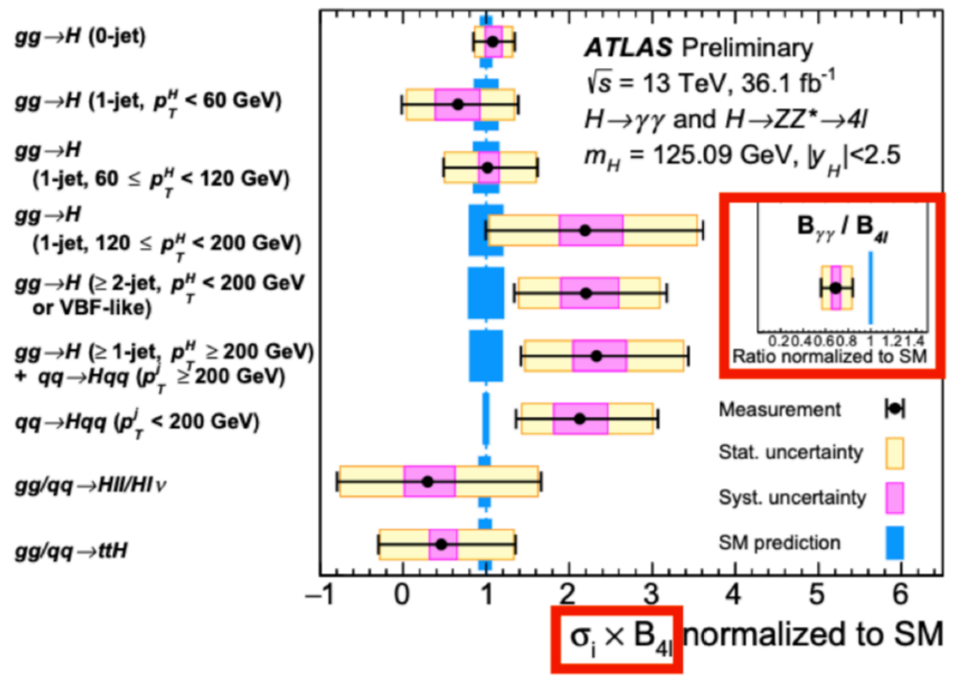

ATLAS-CONF-2017-047

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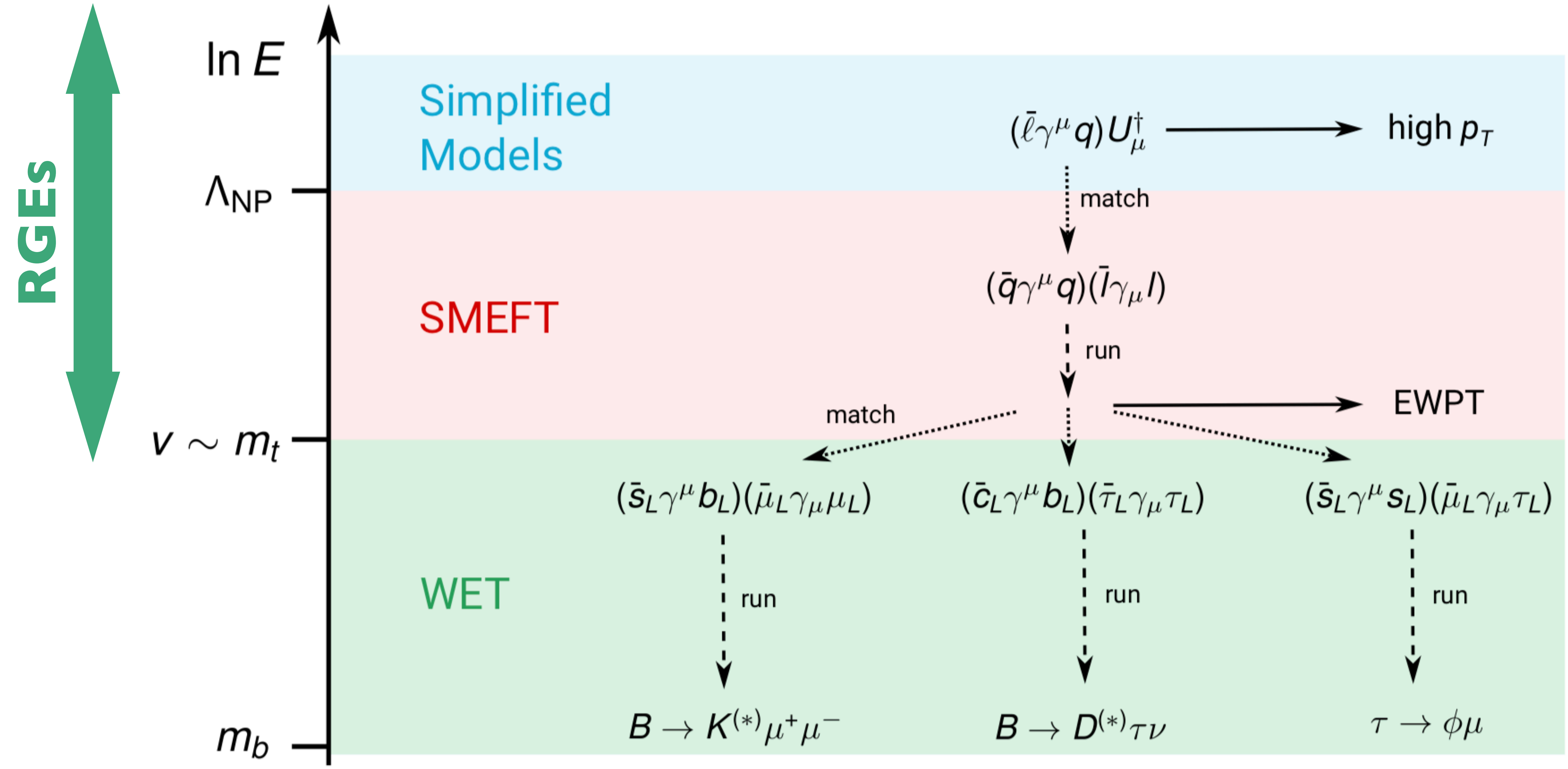
Need to also have publicly quoted EFT parameterisation of STXS bins by TH.

BSM-SMEFT matching

BSM-SMEFT - automated matching:

- Matching the EFT results with non-minimal BSM scenarios using automated tools,



BSM-SMEFT matching

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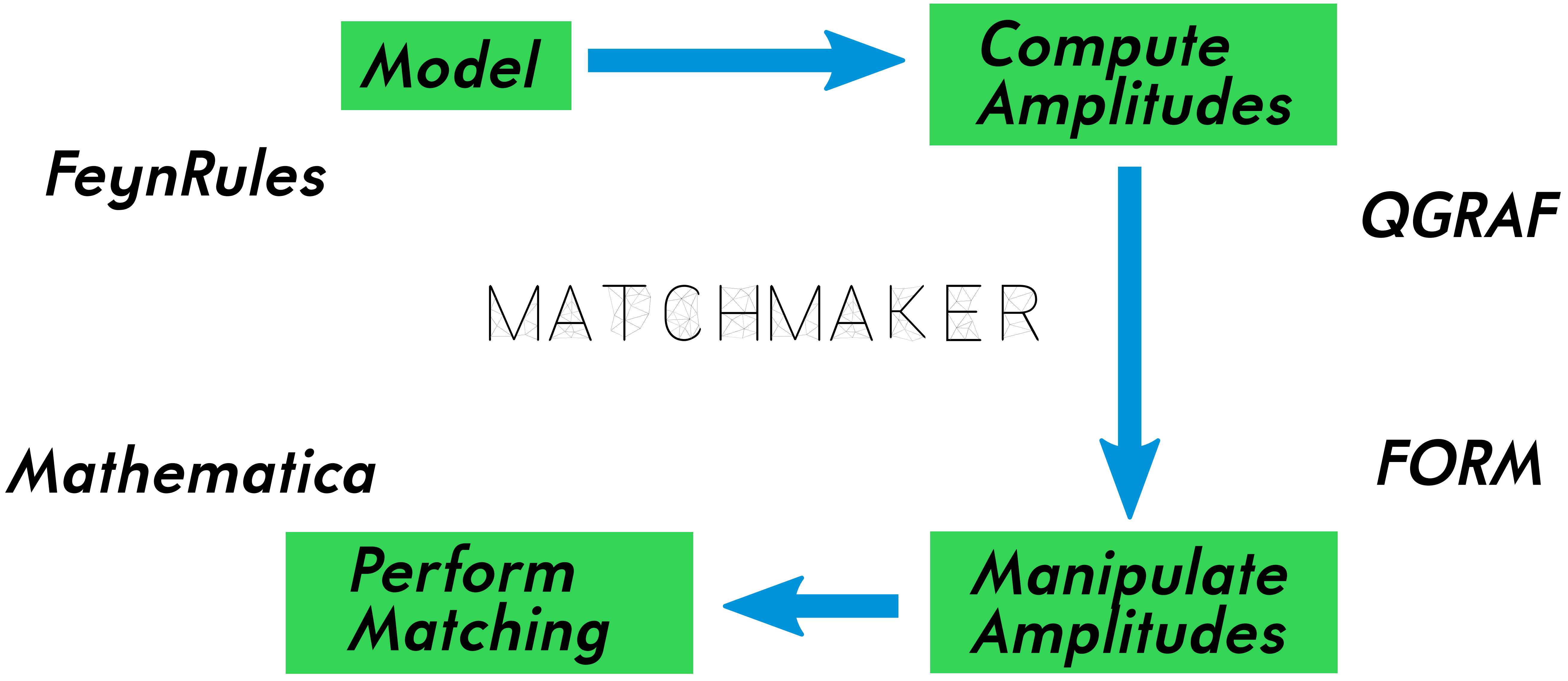
- **Goal**: obtain the full 1-loop UV/IR dictionary (**MATCHMAKER**: tree-level and dim-6 operators.)

MATCHMAKER

Anastasiou, AC, Lazopoulos, Santiago

A. Carmona talk (LHCHXSWG)



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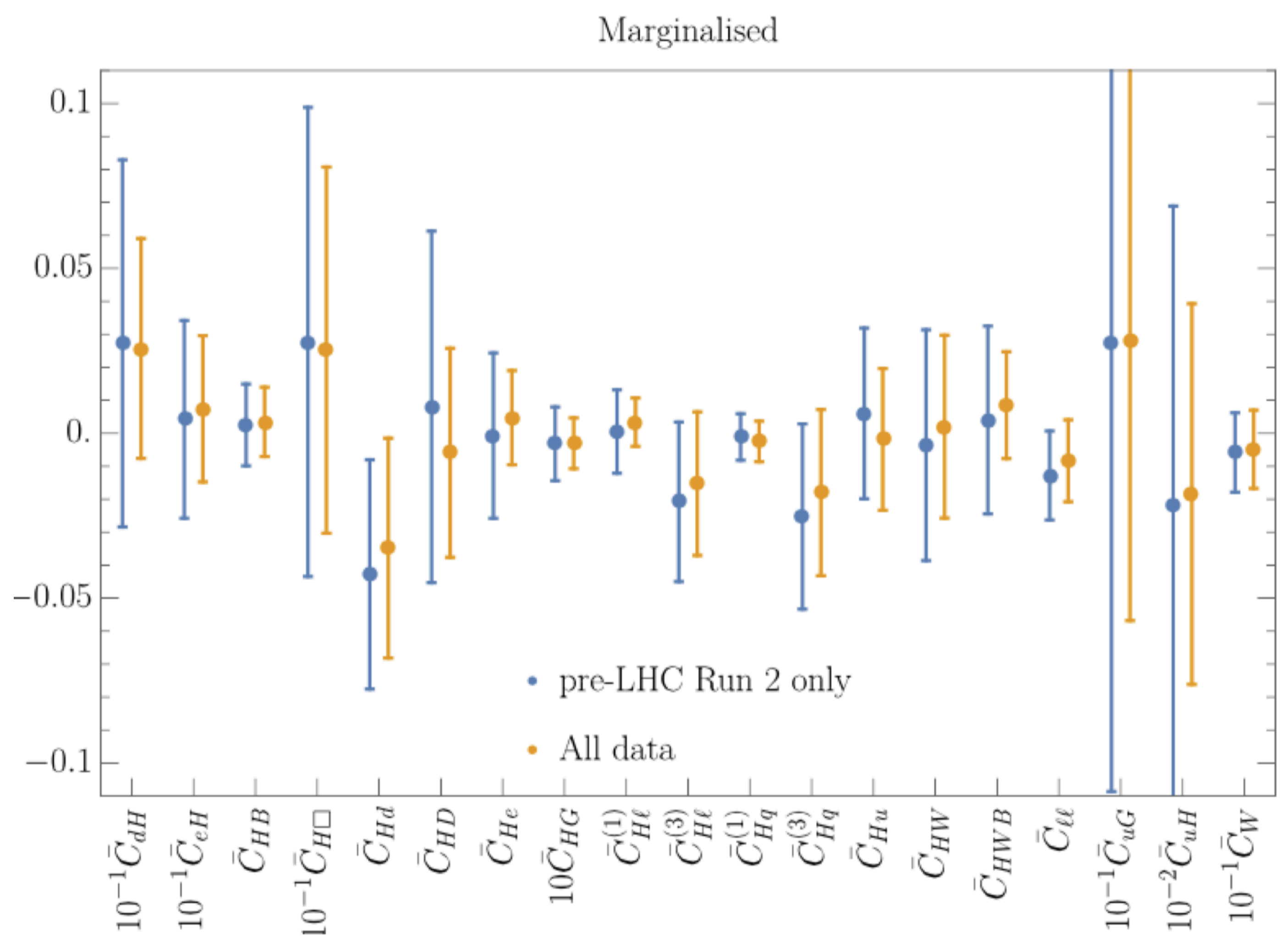
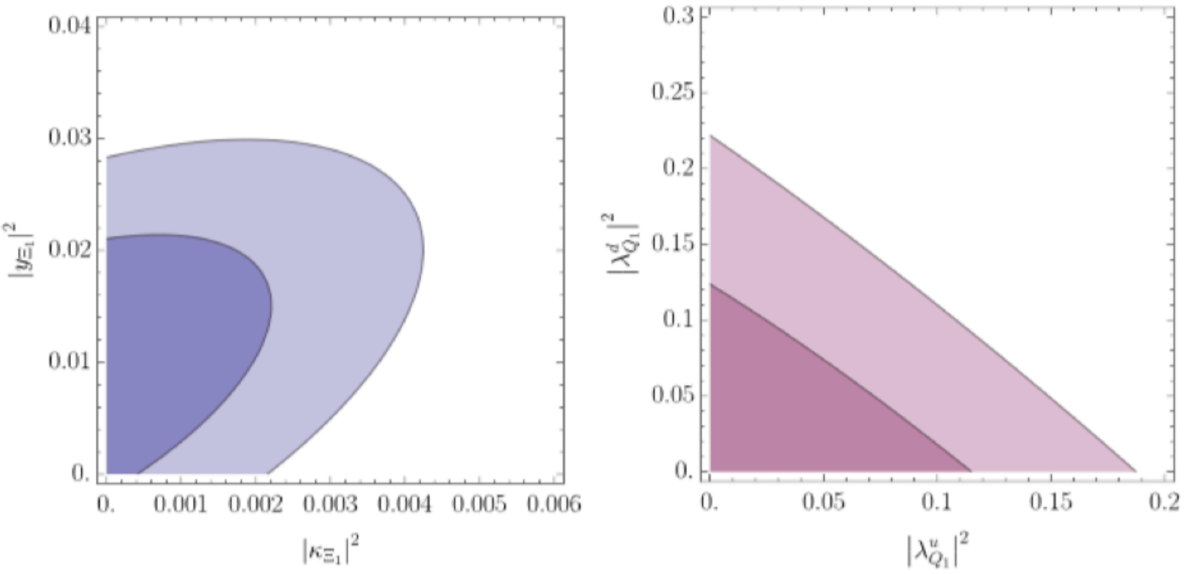
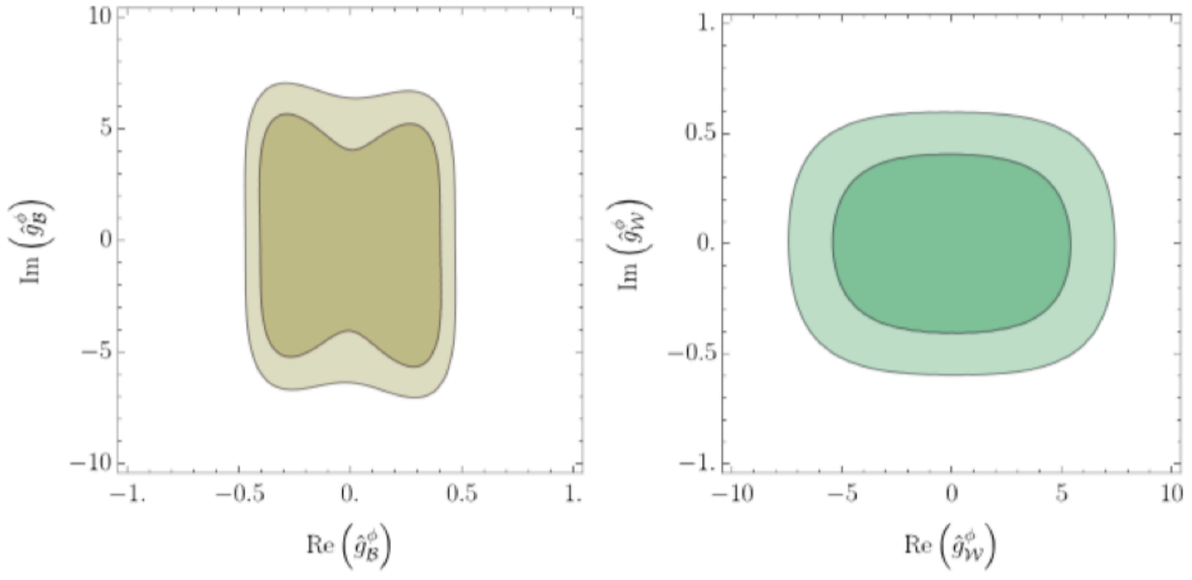


- Simplified models: **renormalisable SM extensions**

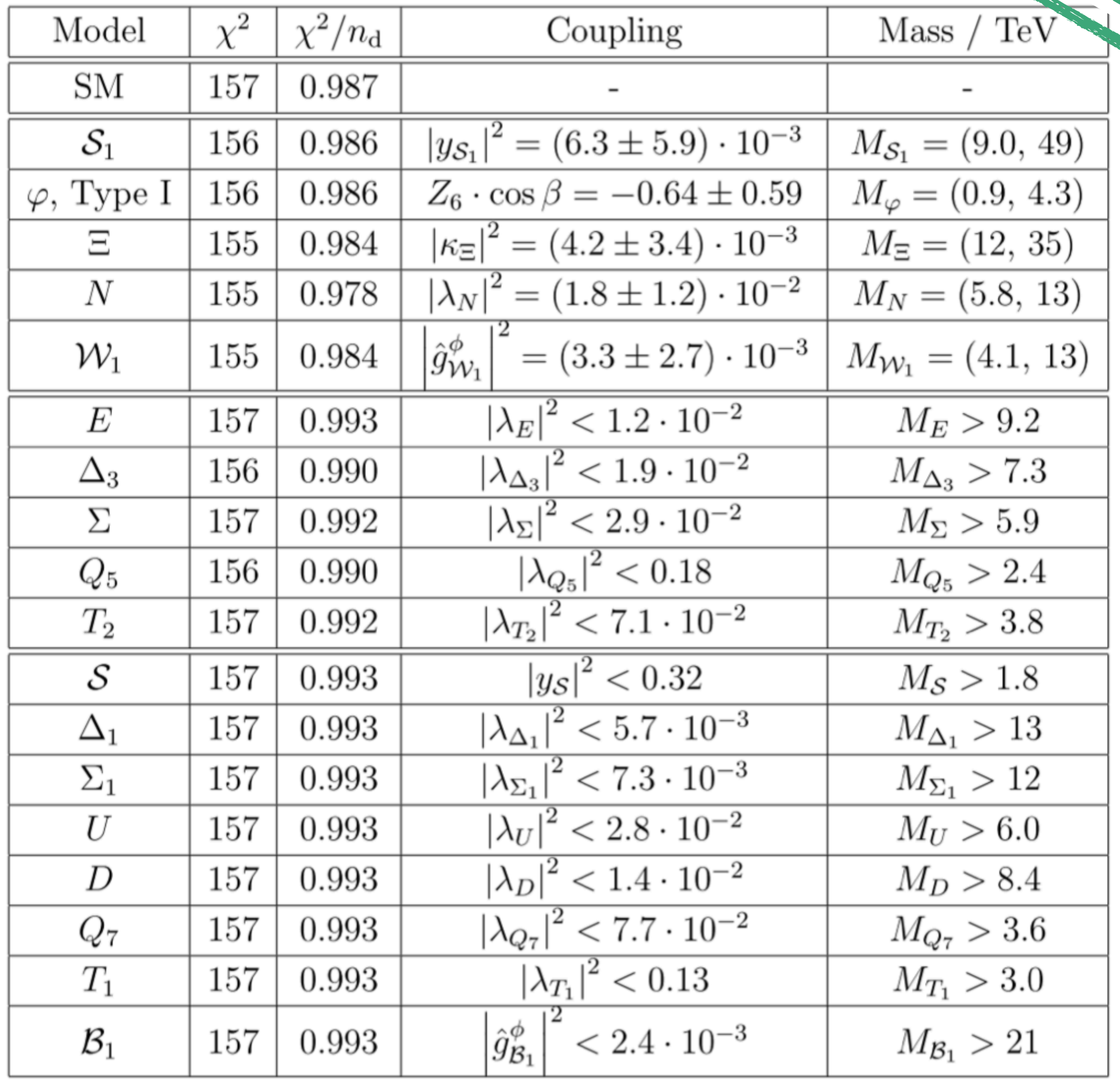
T. You talk



(a) Ξ_1 (b) Q_1



(c) $\mathcal{B}$, no ψ^4 operators (d) $\mathcal{W}$, no ψ^4 operators



Model	χ^2	$\chi^2/n_{\rm d}$	Coupling	Mass / TeV
SM	157	0.987	-	-
$\mathcal{S}_1$	156	0.986	$\lvert y_{\mathcal{S}_1}\rvert^2 = (6.3 \pm 5.9)\cdot 10^{-3}$	$M_{\mathcal{S}_1} = (9.0,\ 49)$
φ, Type I	156	0.986	$Z_6 \cdot \cos\beta = -0.64 \pm 0.59$	$M_{\varphi} = (0.9,\ 4.3)$
Ξ	155	0.984	$\lvert\kappa_{\Xi}\rvert^2 = (4.2 \pm 3.4)\cdot 10^{-3}$	$M_{\Xi} = (12,\ 35)$
N	155	0.978	$\lvert\lambda_N\rvert^2 = (1.8 \pm 1.2)\cdot 10^{-2}$	$M_N = (5.8,\ 13)$
$\mathcal{W}_1$	155	0.984	$\left\lvert\hat{g}^{\phi}_{\mathcal{W}_1}\right\rvert^2 = (3.3 \pm 2.7)\cdot 10^{-3}$	$M_{\mathcal{W}_1} = (4.1,\ 13)$
E	157	0.993	$\lvert\lambda_E\rvert^2 < 1.2\cdot 10^{-2}$	$M_E > 9.2$
Δ_3	156	0.990	$\lvert\lambda_{\Delta_3}\rvert^2 < 1.9\cdot 10^{-2}$	$M_{\Delta_3} > 7.3$
Σ	157	0.992	$\lvert\lambda_{\Sigma}\rvert^2 < 2.9\cdot 10^{-2}$	$M_{\Sigma} > 5.9$
Q_5	156	0.990	$\lvert\lambda_{Q_5}\rvert^2 < 0.18$	$M_{Q_5} > 2.4$
T_2	157	0.992	$\lvert\lambda_{T_2}\rvert^2 < 7.1\cdot 10^{-2}$	$M_{T_2} > 3.8$
$\mathcal{S}$	157	0.993	$\lvert y_{\mathcal{S}}\rvert^2 < 0.32$	$M_{\mathcal{S}} > 1.8$
Δ_1	157	0.993	$\lvert\lambda_{\Delta_1}\rvert^2 < 5.7\cdot 10^{-3}$	$M_{\Delta_1} > 13$
Σ_1	157	0.993	$\lvert\lambda_{\Sigma_1}\rvert^2 < 7.3\cdot 10^{-3}$	$M_{\Sigma_1} > 12$
U	157	0.993	$\lvert\lambda_U\rvert^2 < 2.8\cdot 10^{-2}$	$M_U > 6.0$
D	157	0.993	$\lvert\lambda_D\rvert^2 < 1.4\cdot 10^{-2}$	$M_D > 8.4$
Q_7	157	0.993	$\lvert\lambda_{Q_7}\rvert^2 < 7.7\cdot 10^{-2}$	$M_{Q_7} > 3.6$
T_1	157	0.993	$\lvert\lambda_{T_1}\rvert^2 < 0.13$	$M_{T_1} > 3.0$
$\mathcal{B}_1$	157	0.993	$\left\lvert\hat{g}^{\phi}_{\mathcal{B}_1}\right\rvert^2 < 2.4\cdot 10^{-3}$	$M_{\mathcal{B}_1} > 21$

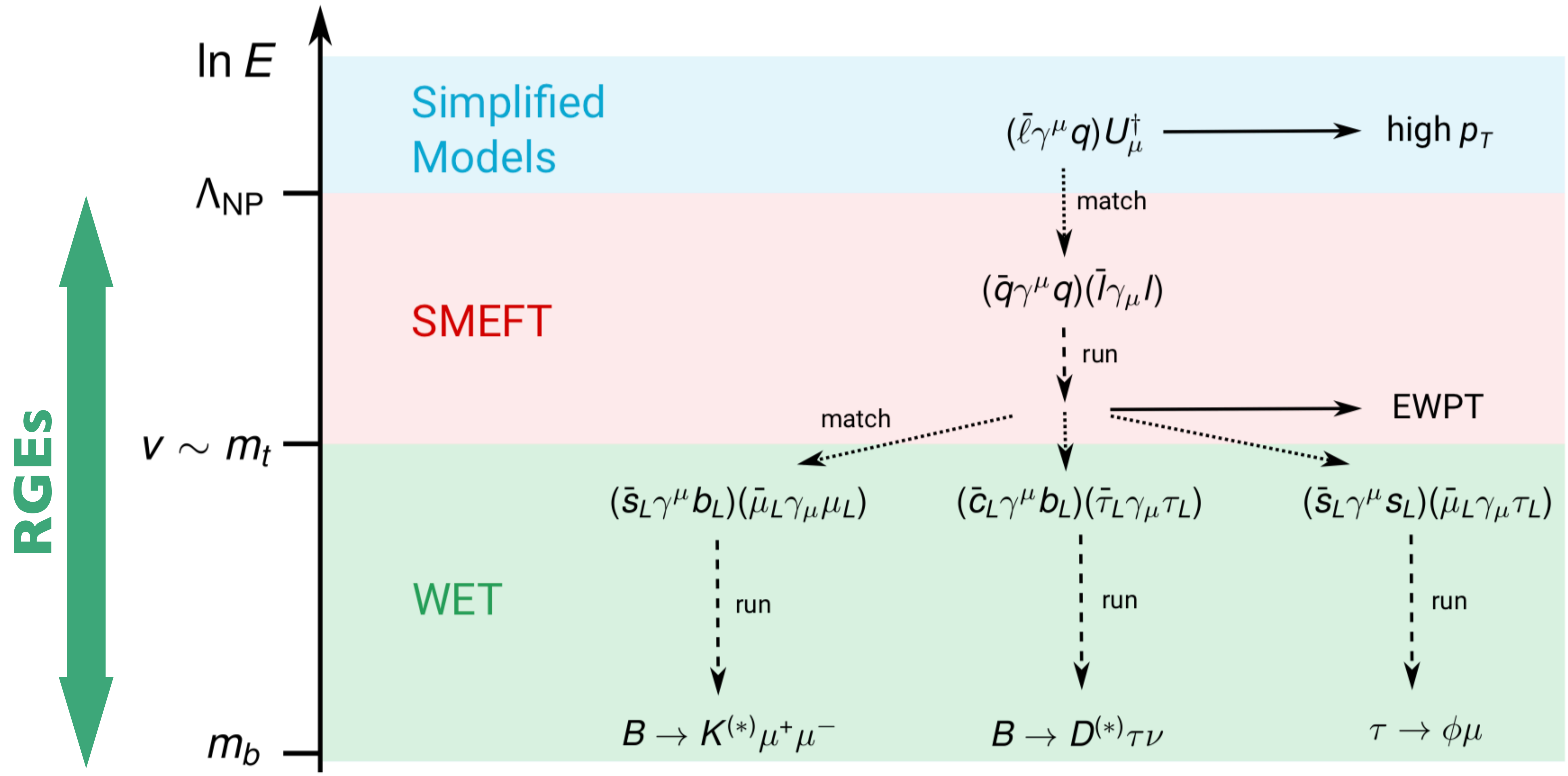
Potentially useful further developments by TH:

- Possibly extend to other EFTs variations (e.g. HEFT), treatment of light degrees of freedom, ...
- Automated matching with NLO SMEFT with 2-loop RGEs/ADs (need development)

SMEFT-LEFT matching & global sensitivity

SMEFT matching to Low-energy EFT:

- Running/matching SMEFT coefficients down to EW scale (and to Weak Effective Theory below EW scale)



$\ln E$

Λ_{NP}

$v \sim m_t$

m_b

RGEs

Simplified Models

$(\bar{\ell}\gamma^\mu q)U^\dagger_\mu$ → high p_T

match

SMEFT

$(\bar{q}\gamma^\mu q)(\bar{l}\gamma_\mu l)$

run

→ EWPT

match

WET

$(\bar{s}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$

$(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\tau_L)$

$(\bar{s}_L\gamma^\mu s_L)(\bar{\mu}_L\gamma_\mu\tau_L)$

run

run

run

$B \to K^{(*)}\mu^+\mu^-$

$B \to D^{(*)}\tau\nu$

$\tau \to \phi\mu$

Importance for global sensitivity:

- Allow to exploit constraints from low-energy direct/indirect probes

SMEFT-LEFT matching & global sensitivity

SMEFT matching to Low-energy EFT:

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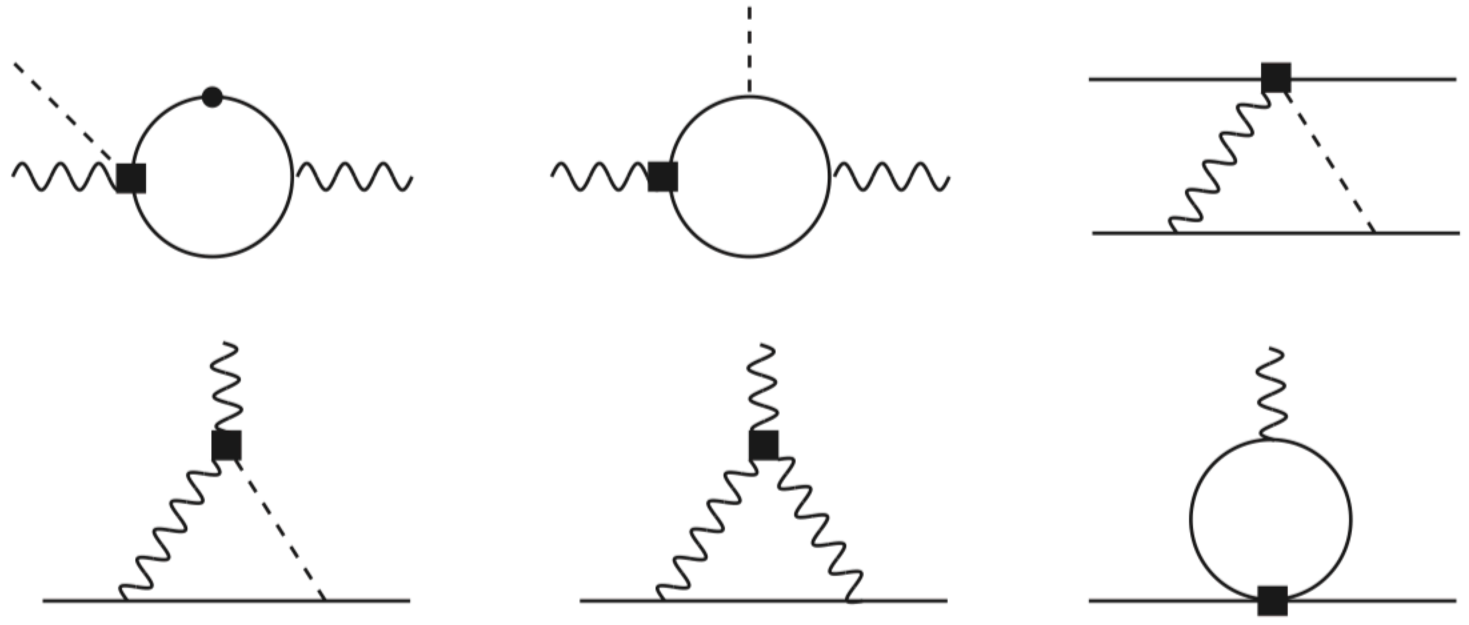
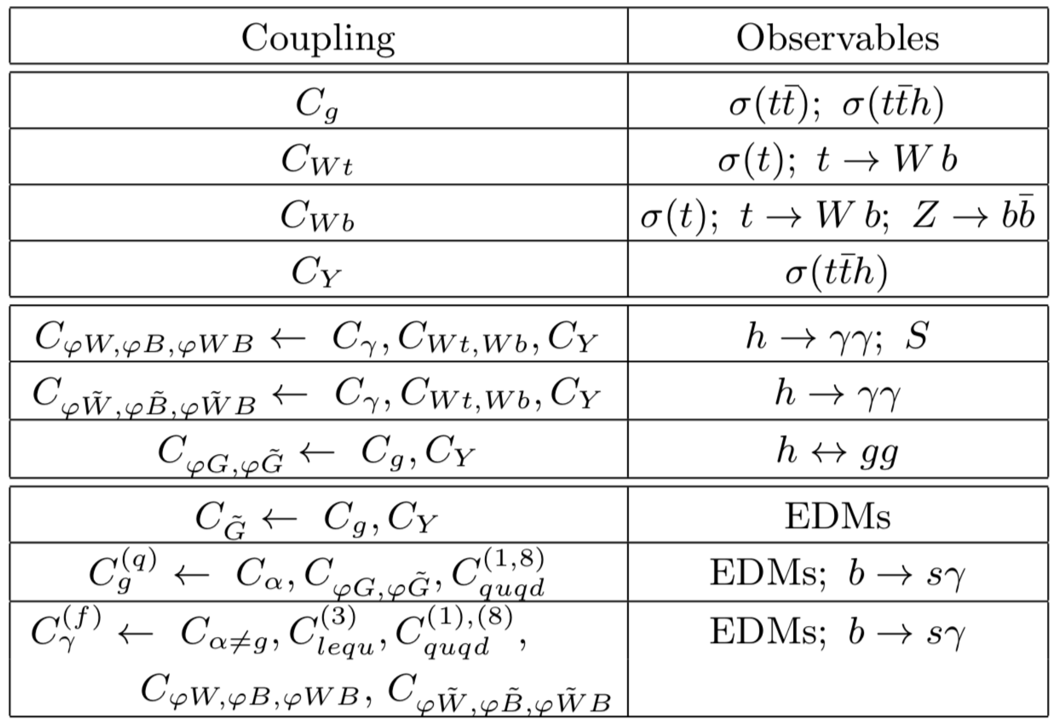
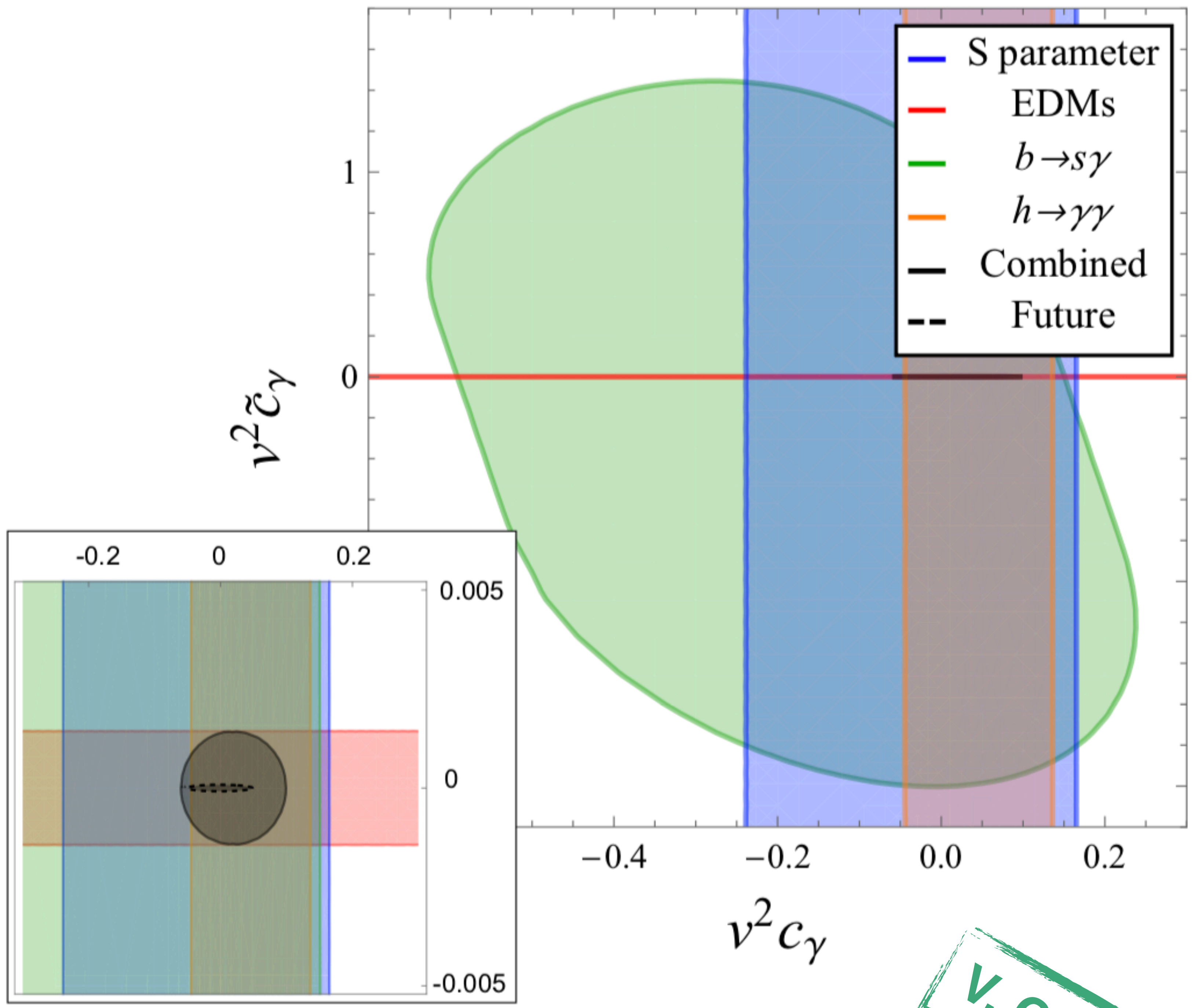




Coupling	Observables
C_g	$\sigma(t\bar{t});\ \sigma(t\bar{t}h)$
C_{Wt}	$\sigma(t);\ t \to W\,b$
C_{Wb}	$\sigma(t);\ t \to W\,b;\ Z \to b\bar{b}$
C_Y	$\sigma(t\bar{t}h)$
$C_{\varphi W,\varphi B,\varphi WB} \leftarrow\ C_\gamma, C_{Wt,Wb}, C_Y$	$h \to \gamma\gamma;\ S$
$C_{\varphi\tilde{W},\varphi\tilde{B},\varphi\tilde{W}B} \leftarrow\ C_\gamma, C_{Wt,Wb}, C_Y$	$h \to \gamma\gamma$
$C_{\varphi G,\varphi\tilde{G}} \leftarrow\ C_g, C_Y$	$h \leftrightarrow gg$
$C_{\tilde{G}} \leftarrow\ C_g, C_Y$	EDMs
$C_g^{(q)} \leftarrow\ C_\alpha, C_{\varphi G,\varphi\tilde{G}}, C_{quqd}^{(1,8)}$	EDMs; $b \to s\gamma$
$C_\gamma^{(f)} \leftarrow\ C_{\alpha\neq g}, C_{lequ}^{(3)}, C_{quqd}^{(1),(8)},$ $C_{\varphi W,\varphi B,\varphi WB}, C_{\varphi\tilde{W},\varphi\tilde{B},\varphi\tilde{W}B}$	EDMs; $b \to s\gamma$



V. Cirigliano et al.

Importance for global sensitivity:

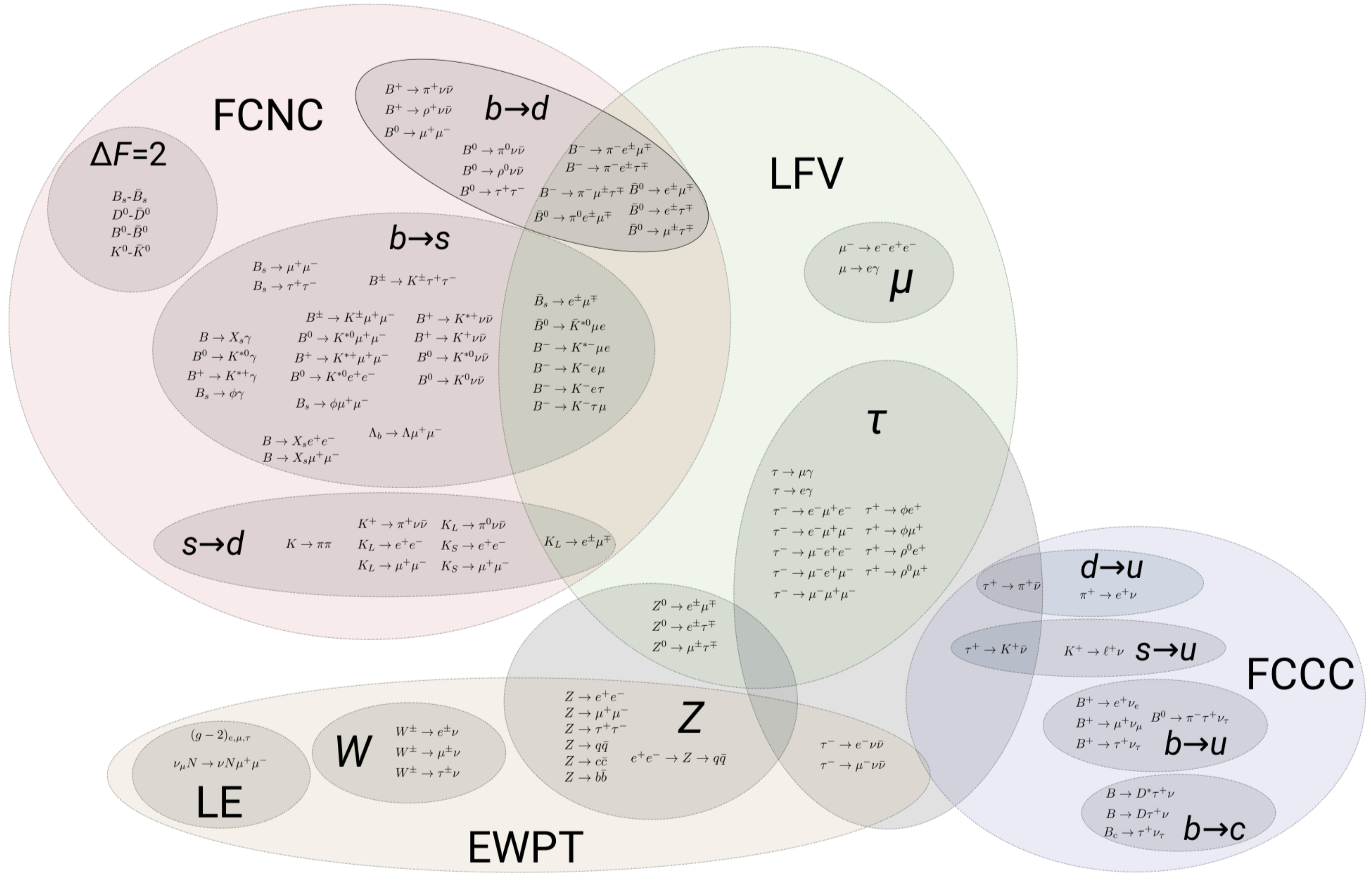
- Allow to exploit constraints from low-energy direct/indirect probes
  - neutron & atomic/molecular EDMs as probes of chirality-flipping TOP-HIG couplings, etc.

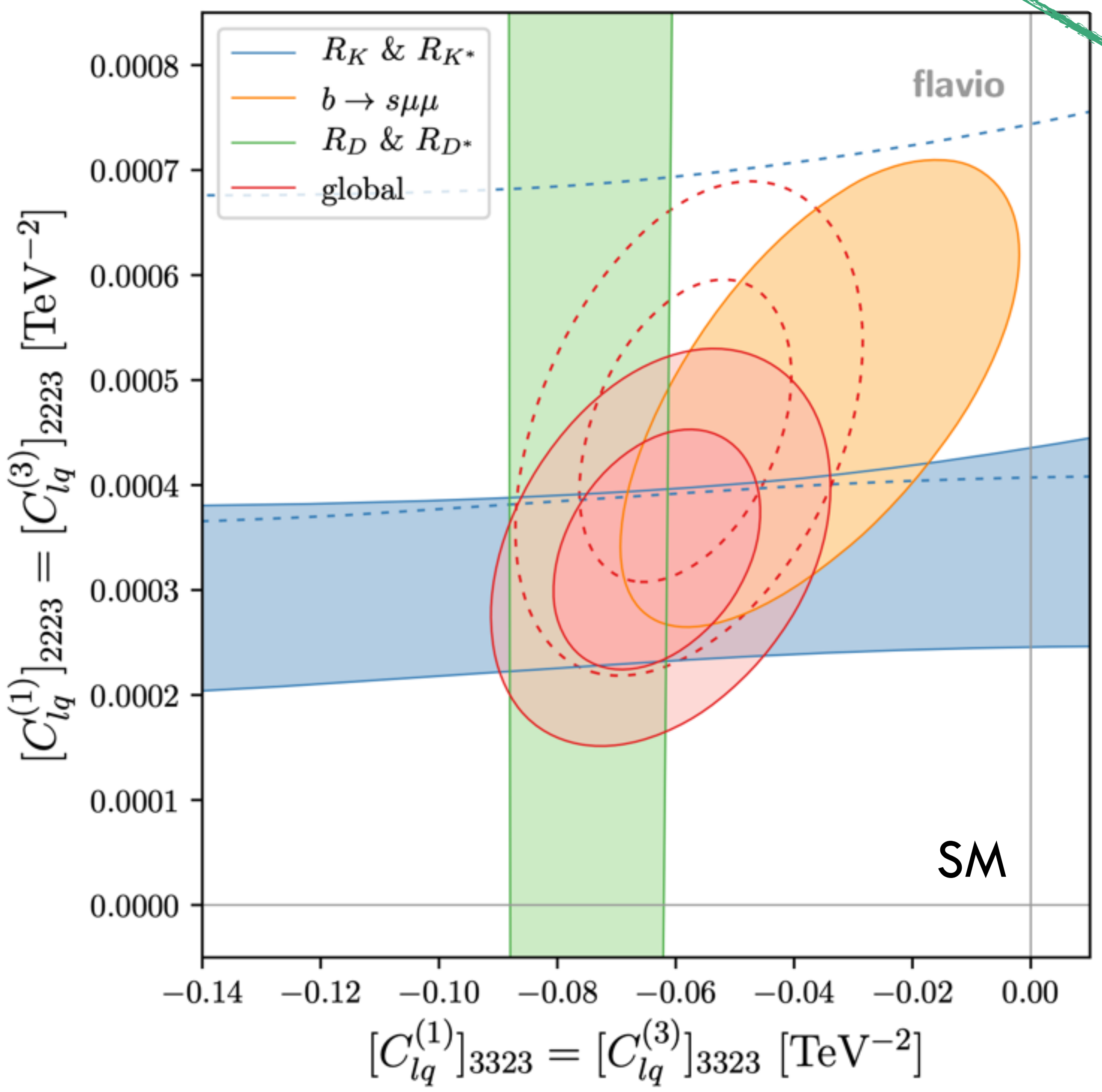
SMEFT-LEFT matching & global sensitivity

SMEFT matching to Low-energy EFT:

- Running/matching SMEFT coefficients down to EW scale (and to Weak Effective Theory below EW scale)

So far, 265 Observables Aebischer et al. 1810.07698





D. M. Straub et al.

Importance for global sensitivity:

- Allow to exploit constraints from low-energy direct/indirect probes
  - neutron & atomic/molecular EDMs as probes of chirality-flipping TOP-HIG couplings, etc.
  - flavour observables (b → sγ, b → sll) as probes of flat directions in the LEP/LHC sensitivity.

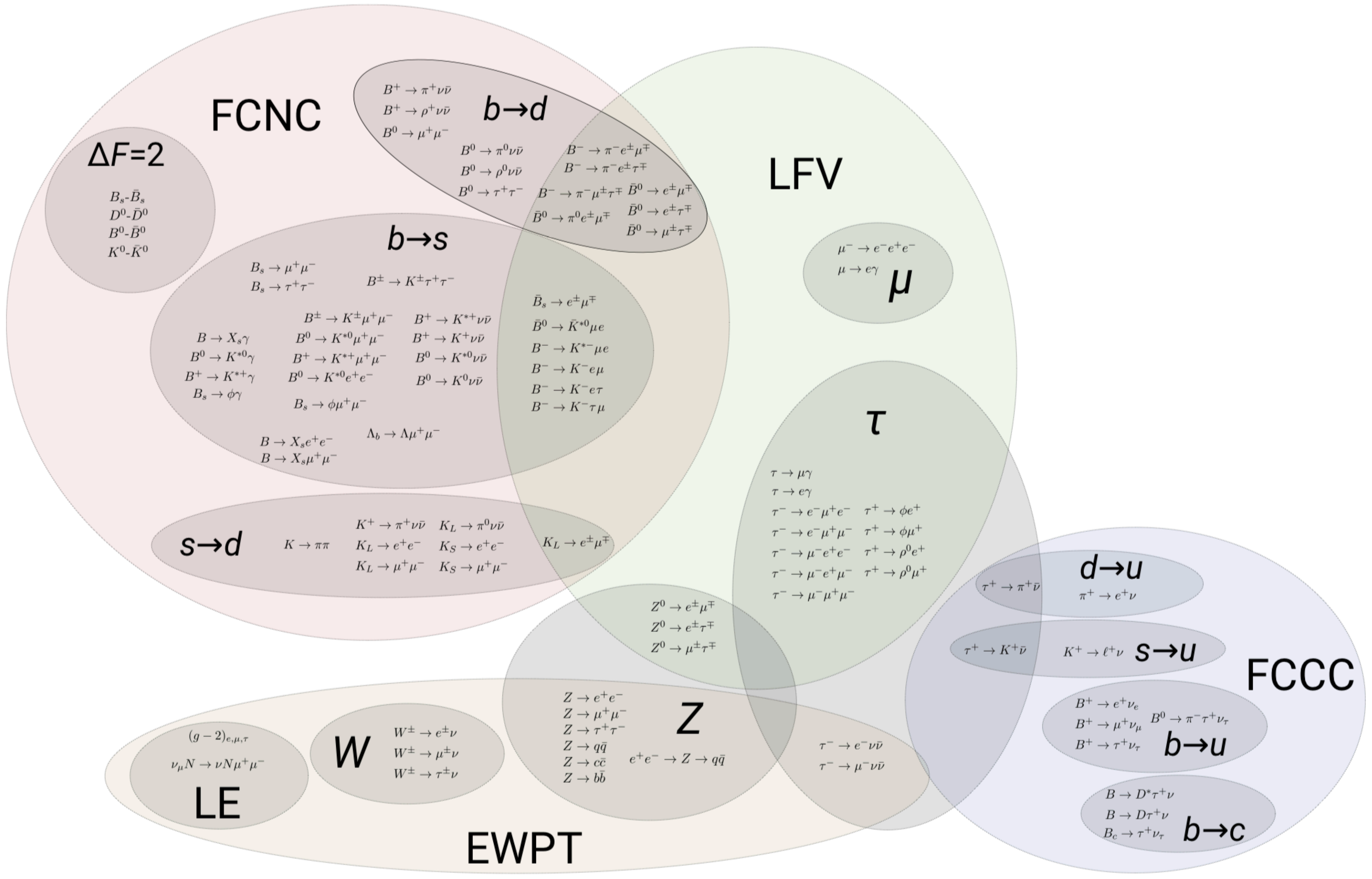
SMEFT-LEFT matching & global sensitivity

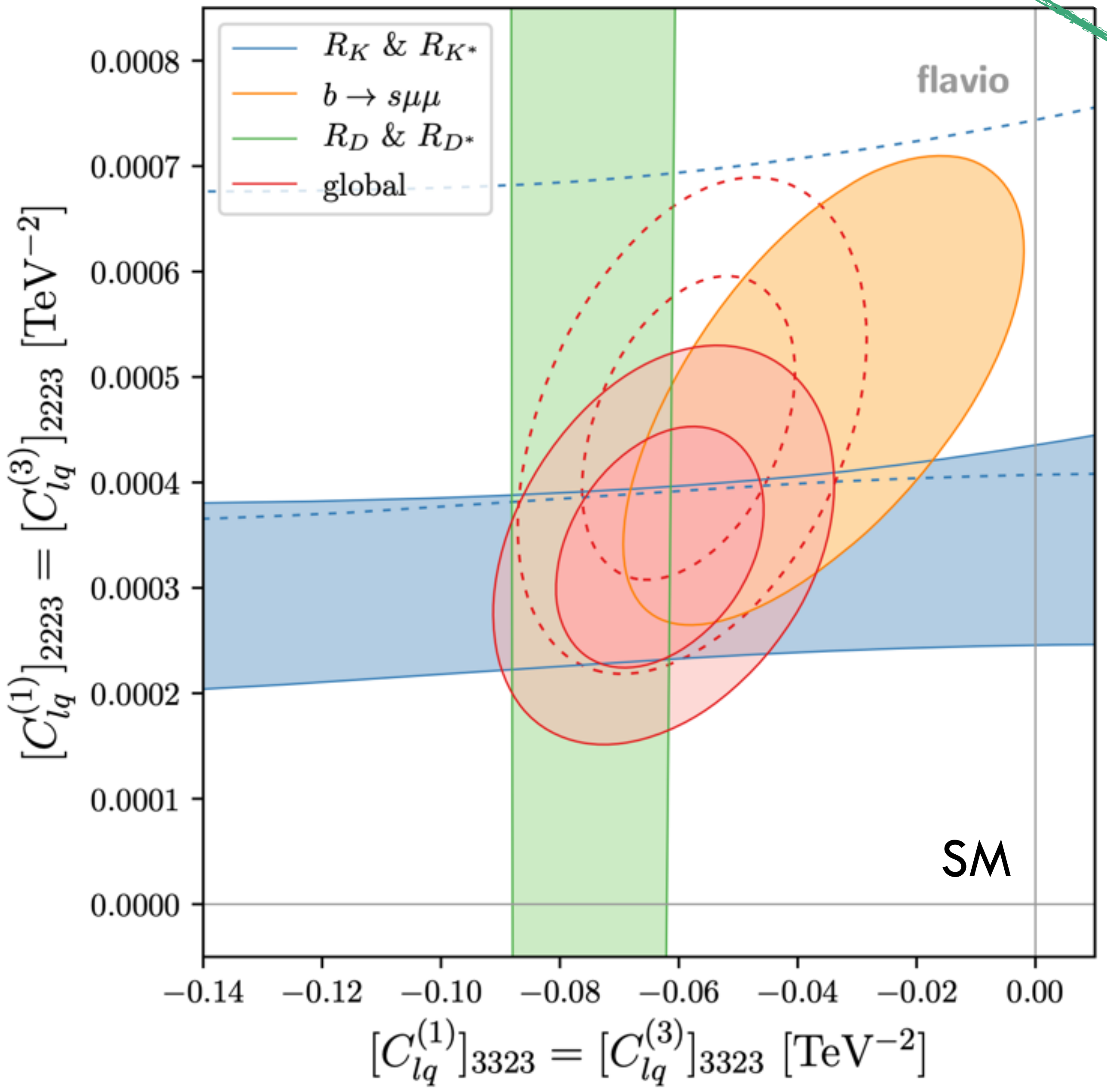
SMEFT matching to Low-energy EFT:

- Running/matching SMEFT coefficients down to EW scale (and to Weak Effective Theory below EW scale)

D. M. Straub et al.

So far, 265 Observables Aebischer et al. 1810.07698





Desired further developments by TH:

- Systematic computation of 2-loop RGEs/ADs for NLO improved SMEFT - LEFT/WET matching

Indirectly required/motivated:

- More sensitive EDM searches and improved lattice QCD & nuclear structure calculations
- **S**ystematic study of flavour observables that help with new constraints in global fits.

> Good tests kill flawed theories; we remain alive to guess again.
> Sir Karl Raimund Popper

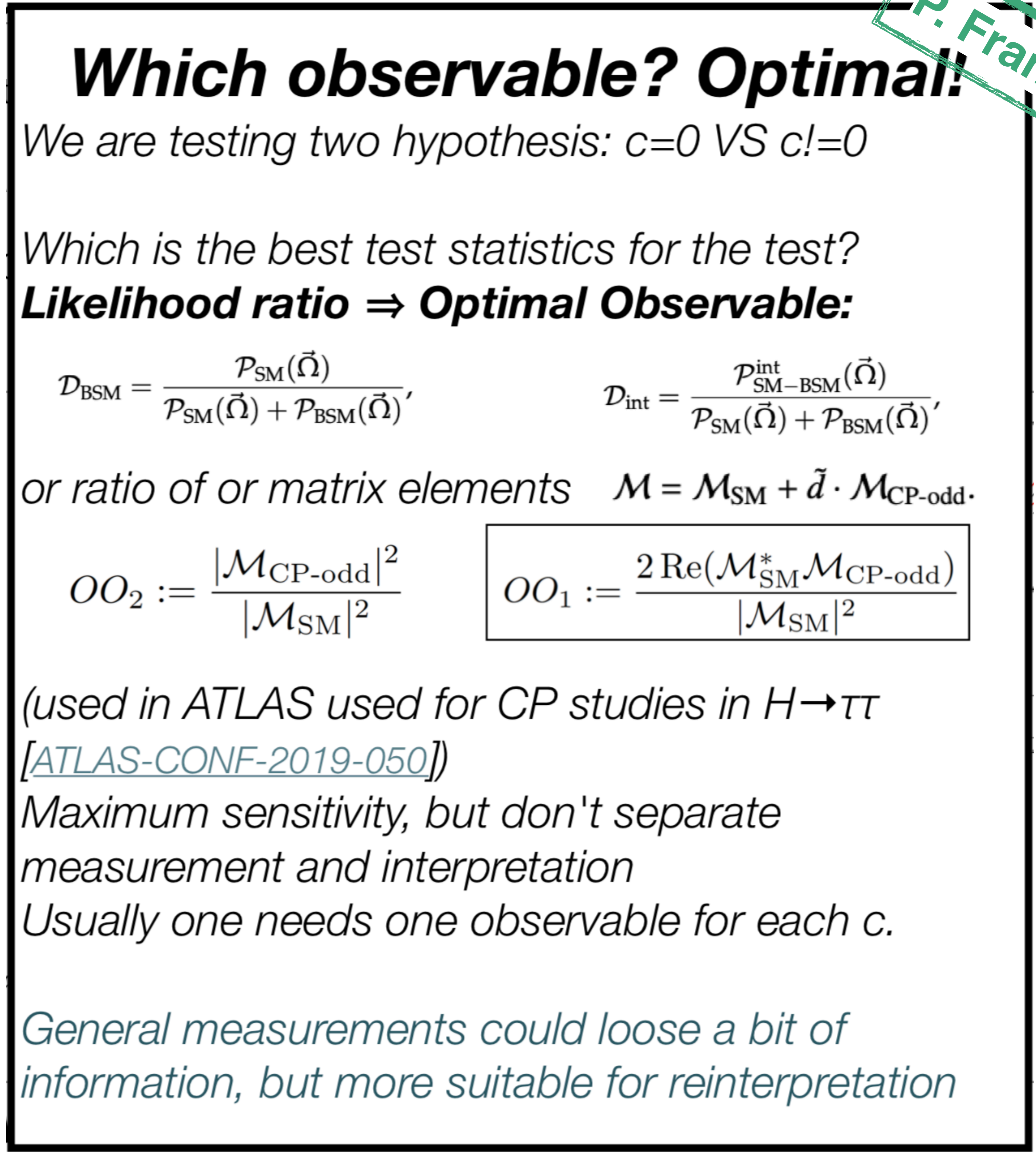
EFT : process modelling & analysis approaches

- TH process modelling & necessary/available precision
- EFT analysis approaches & results presentation

Advanced techniques

Analysis based on optimised discriminants :

- MEM-based LRs for hypothesis discrimination for well reconstructed final states
- ML-based LR estimators proposed (applicable to wider set of analysis?)



Which observable? Optimal!

We are testing two hypothesis: c=0 VS c!=0

Which is the best test statistics for the test?
Likelihood ratio ⇒ Optimal Observable:

$$\mathcal{D}_{\rm BSM} = \frac{\mathcal{P}_{\rm SM}(\vec{\Omega})}{\mathcal{P}_{\rm SM}(\vec{\Omega})+\mathcal{P}_{\rm BSM}(\vec{\Omega})}, \qquad \mathcal{D}_{\rm int} = \frac{\mathcal{P}^{\rm int}_{\rm SM-BSM}(\vec{\Omega})}{\mathcal{P}_{\rm SM}(\vec{\Omega})+\mathcal{P}_{\rm BSM}(\vec{\Omega})},$$

or ratio of or matrix elements $\mathcal{M} = \mathcal{M}_{\rm SM} + \tilde{d}\cdot\mathcal{M}_{\text{CP-odd}}.$

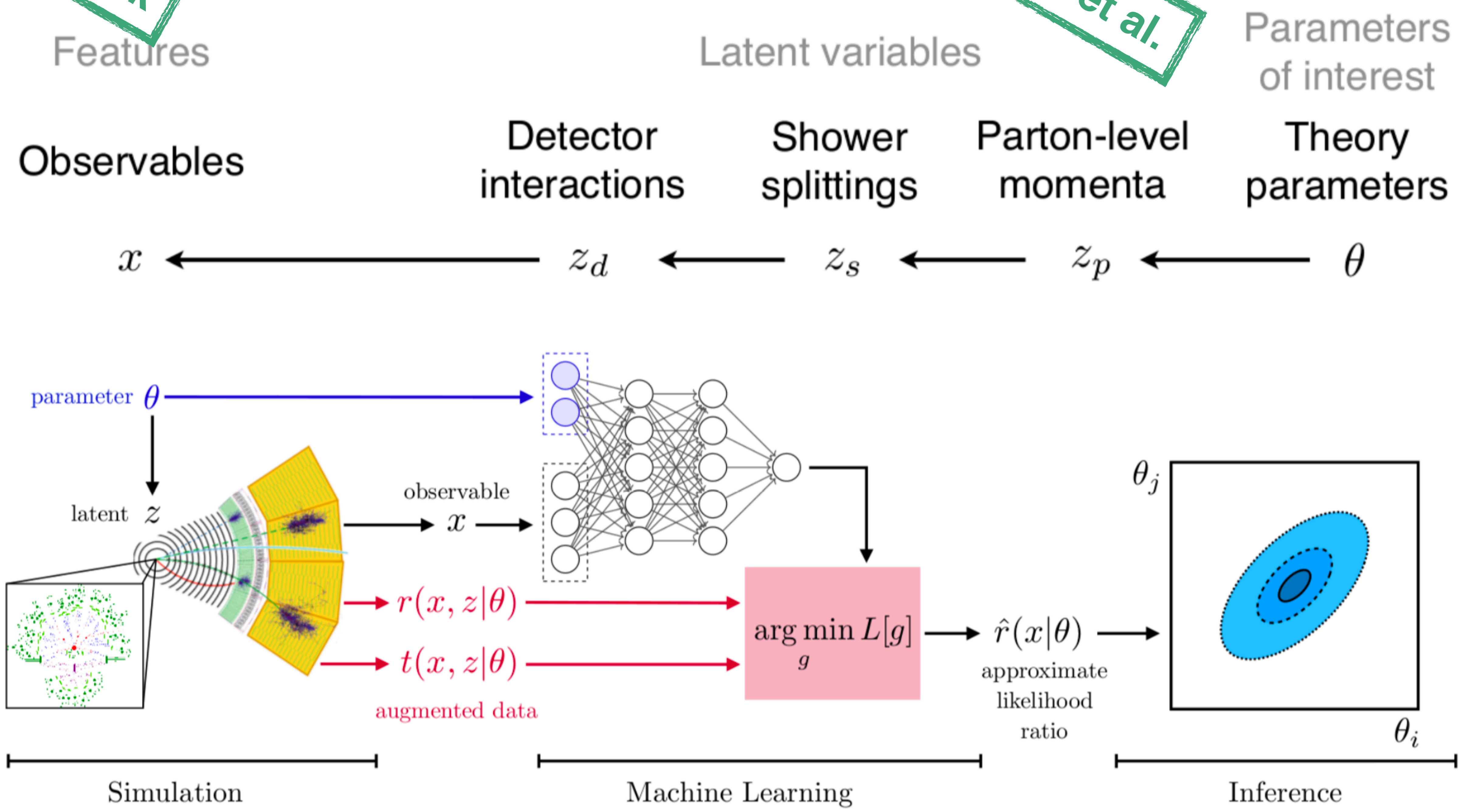
$$OO_2 := \frac{|\mathcal{M}_{\text{CP-odd}}|^2}{|\mathcal{M}_{\rm SM}|^2} \qquad \boxed{OO_1 := \frac{2\,{\rm Re}(\mathcal{M}^*_{\rm SM}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\rm SM}|^2}}$$

(used in ATLAS used for CP studies in H→ττ [ATLAS-CONF-2019-050])
Maximum sensitivity, but don't separate measurement and interpretation
Usually one needs one observable for each c.

General measurements could loose a bit of information, but more suitable for reinterpretation

P. Francavilla talk

G. Louppe et al.



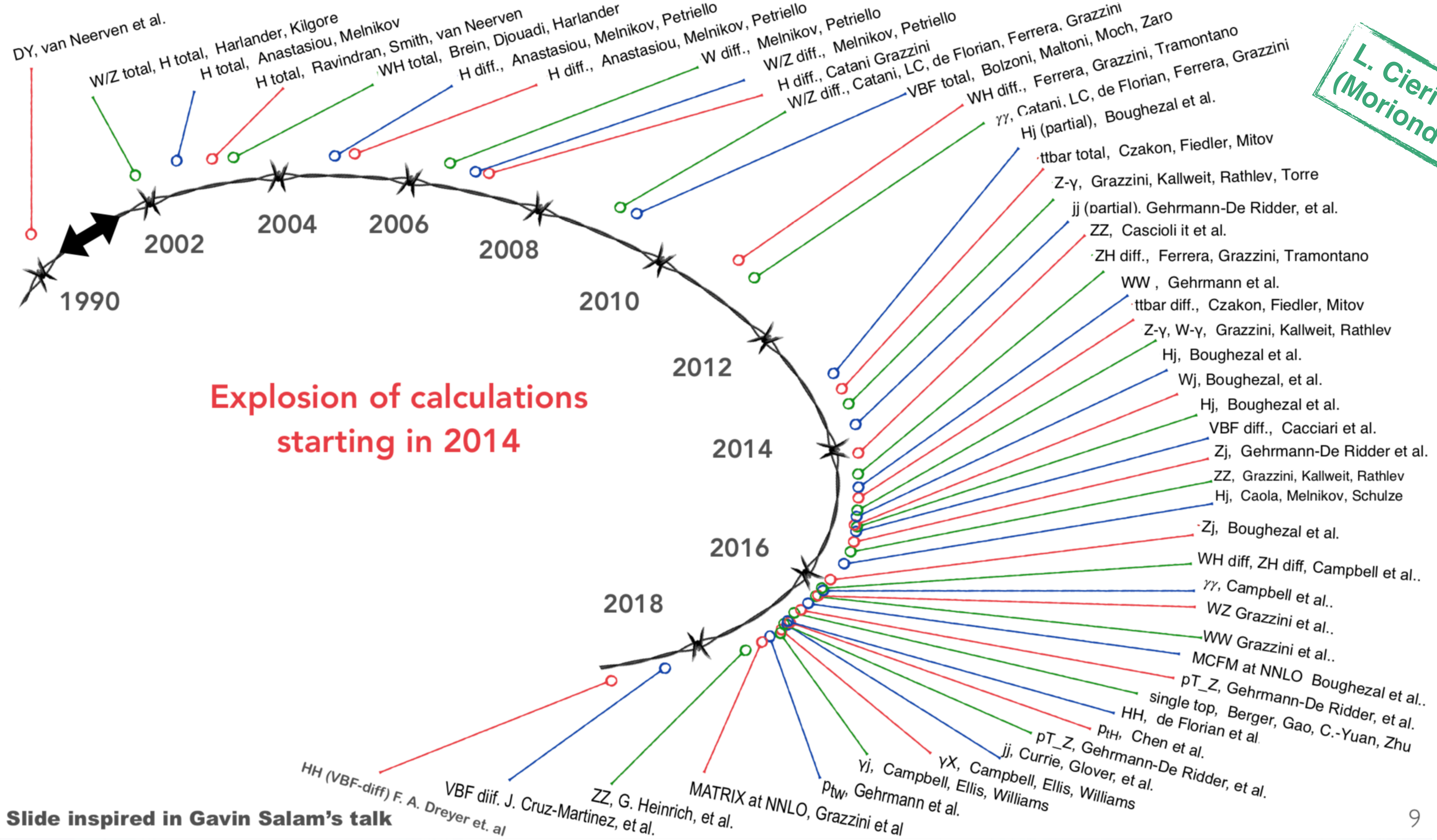
Further developments/discussion with TH:

- Can we converge to optimised analyses and to present measurements in their unfolded distr.

N^{3}LO "revolution" towards HL-LHC?

Progress in higher-order pQCD computations:

- "NNLO revolution" becoming "NNLO standard" during recant years



Explosion of calculations starting in 2014

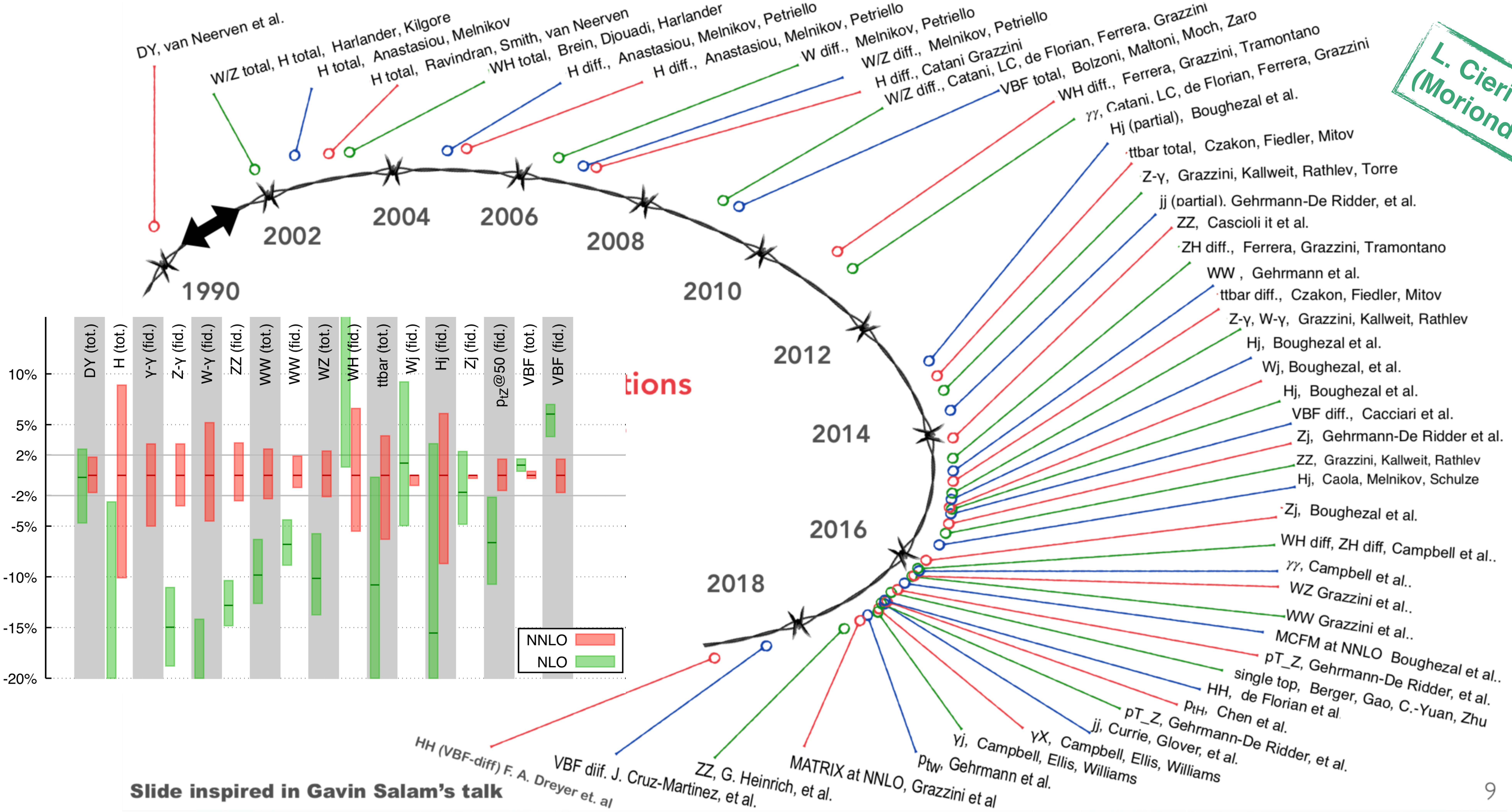
L. Cieri talk (Moriond'19)

Slide inspired in Gavin Salam's talk

N^3LO "revolution" towards HL-LHC?

Progress in higher-order pQCD computations:

- "NNLO revolution" becoming "NNLO standard" during recant years



L. Cieri talk (Moriond'19)

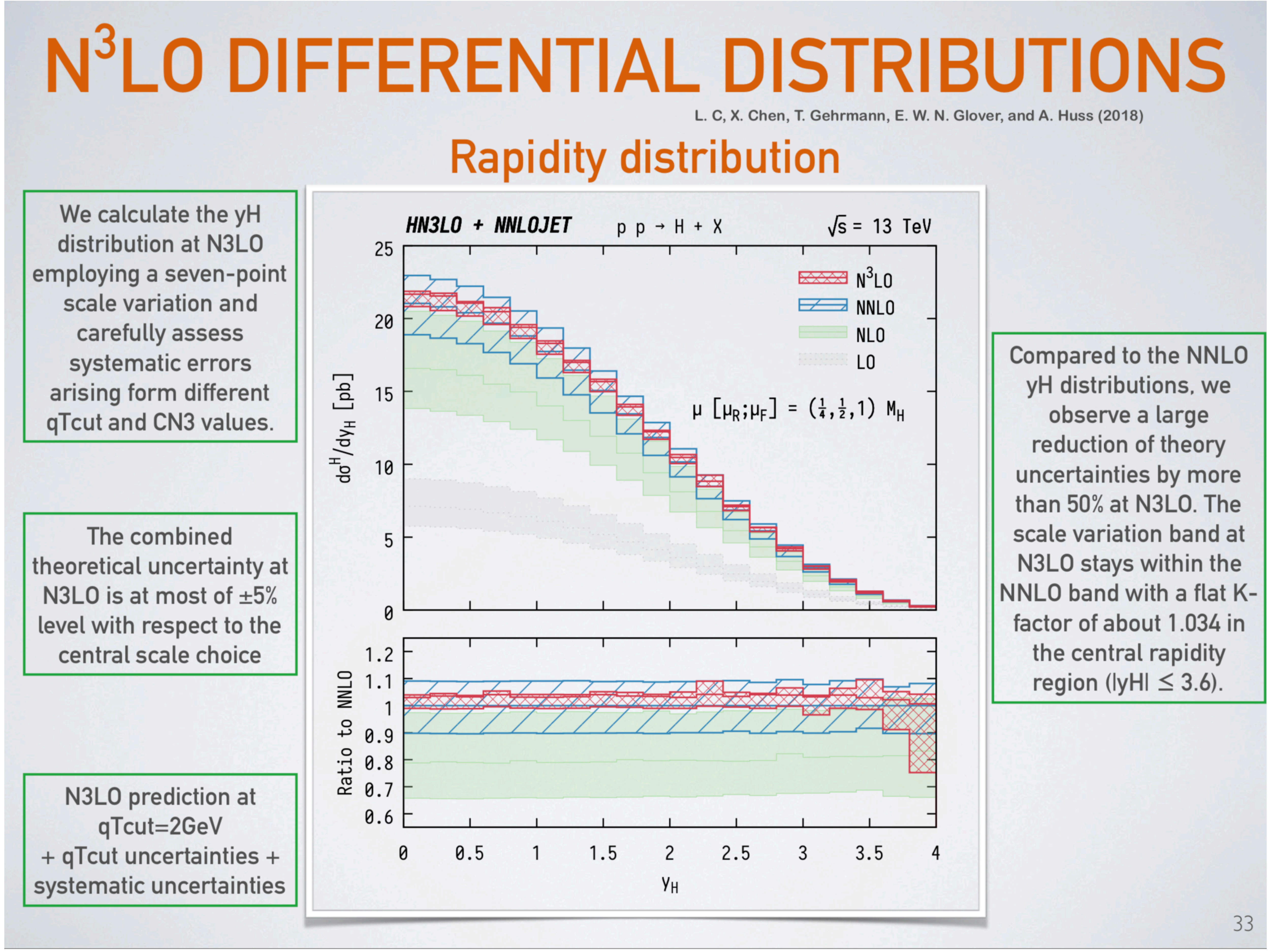
Slide inspired in Gavin Salam's talk

N^3LO "revolution" towards HL-LHC?

Progress in higher-order pQCD computations:

- "NNLO revolution" becoming "NNLO standard" during recant years
- Important progress in NNNLO computation methods for differential observables (e.g. Higgs rapidity)
  - Important reduction of ~50% in TH uncertainty from NNLO

L. Cieri talk (Moriond'19)



N^3LO DIFFERENTIAL DISTRIBUTIONS

L. C, X. Chen, T. Gehrmann, E. W. N. Glover, and A. Huss (2018)

Rapidity distribution

We calculate the yH distribution at N3LO employing a seven-point scale variation and carefully assess systematic errors arising form different qTcut and CN3 values.

The combined theoretical uncertainty at N3LO is at most of ±5% level with respect to the central scale choice

N3LO prediction at qTcut=2GeV + qTcut uncertainties + systematic uncertainties

Compared to the NNLO yH distributions, we observe a large reduction of theory uncertainties by more than 50% at N3LO. The scale variation band at N3LO stays within the NNLO band with a flat K-factor of about 1.034 in the central rapidity region (|yH| ≲ 3.6).

N^3LO "revolution" towards HL-LHC?

Progress in higher-order pQCD computations:

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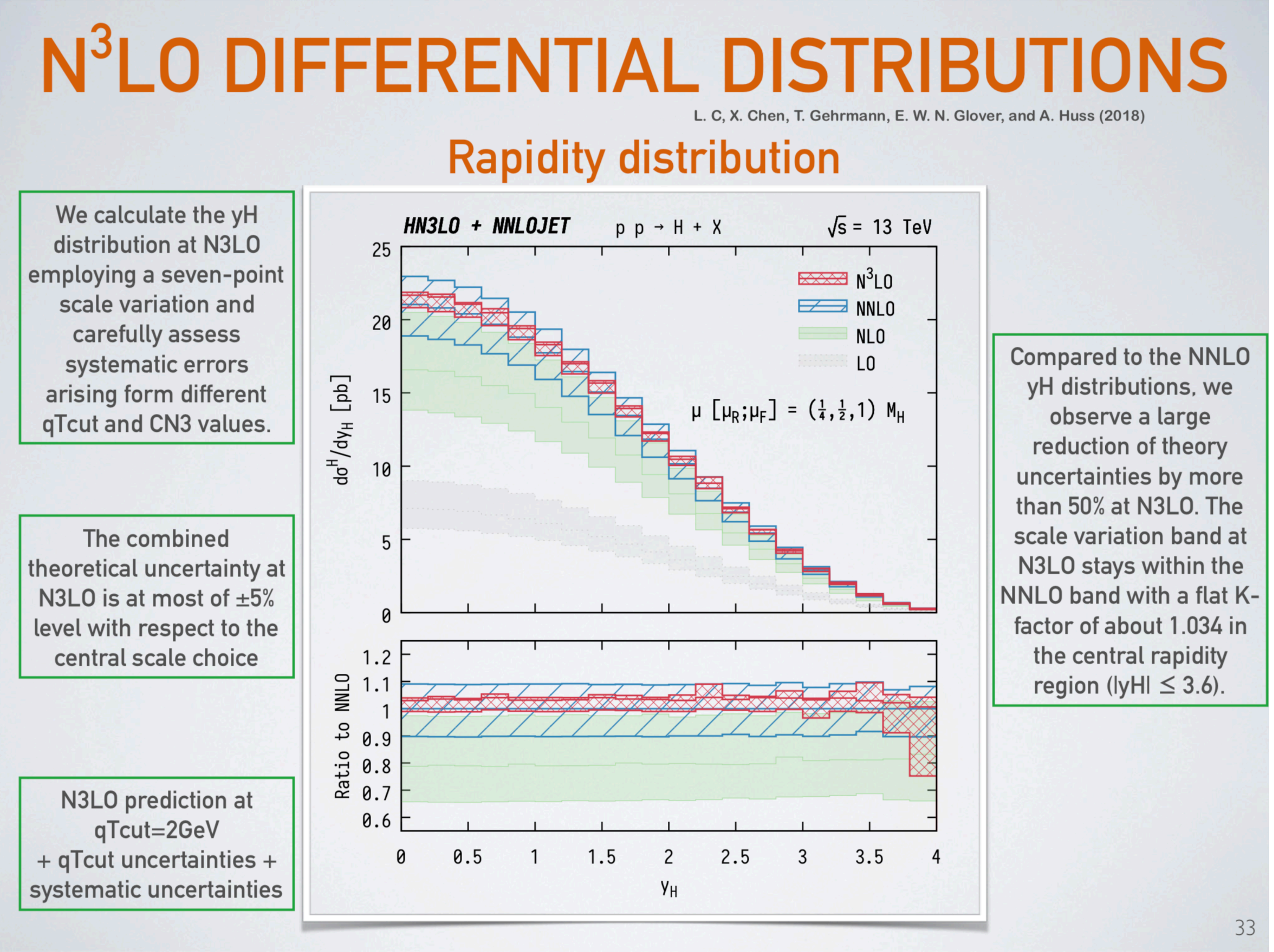

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Are we on brink of a new "revolution" in next 10 years?

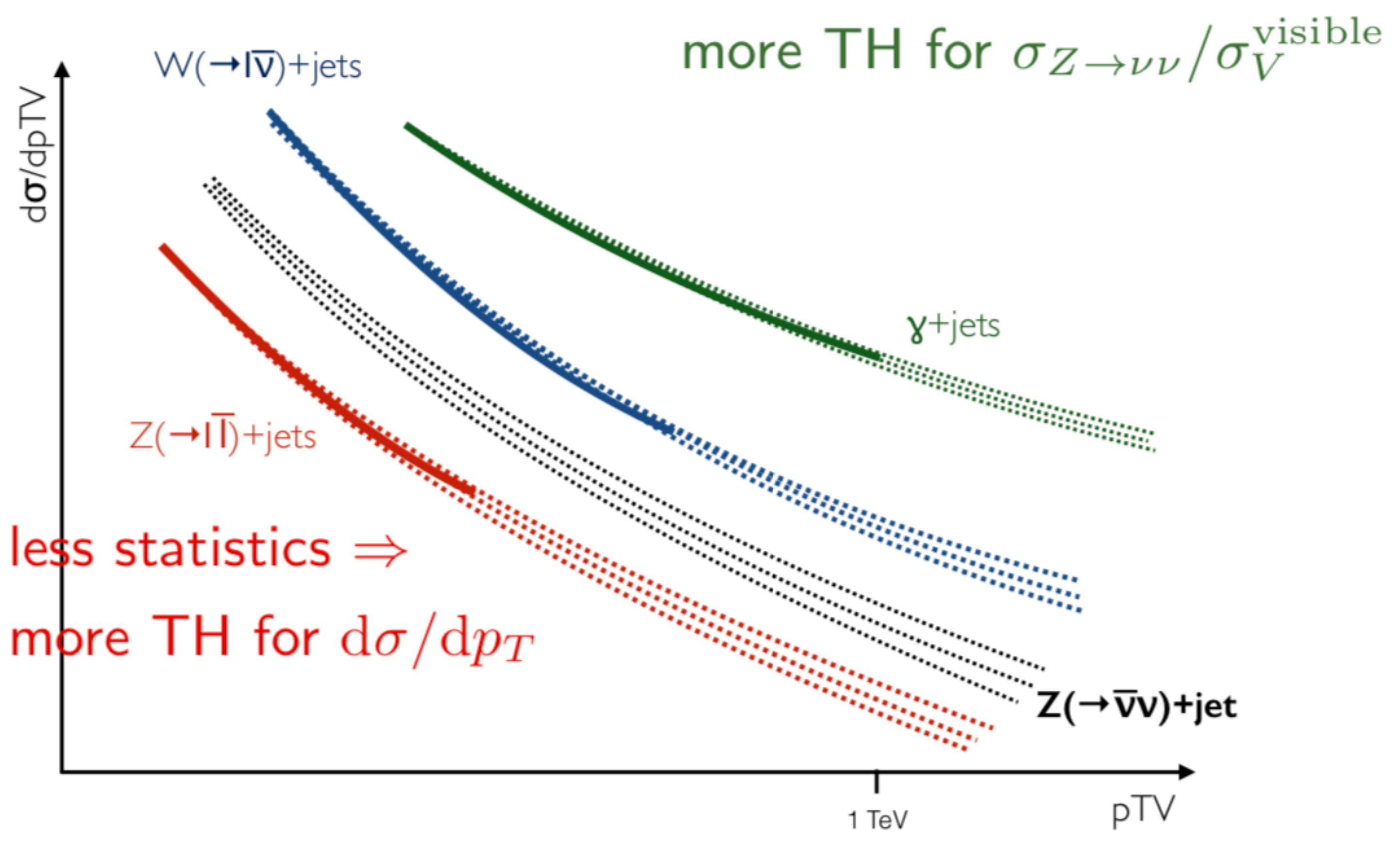
Hope TH colleagues will make this dream come true...

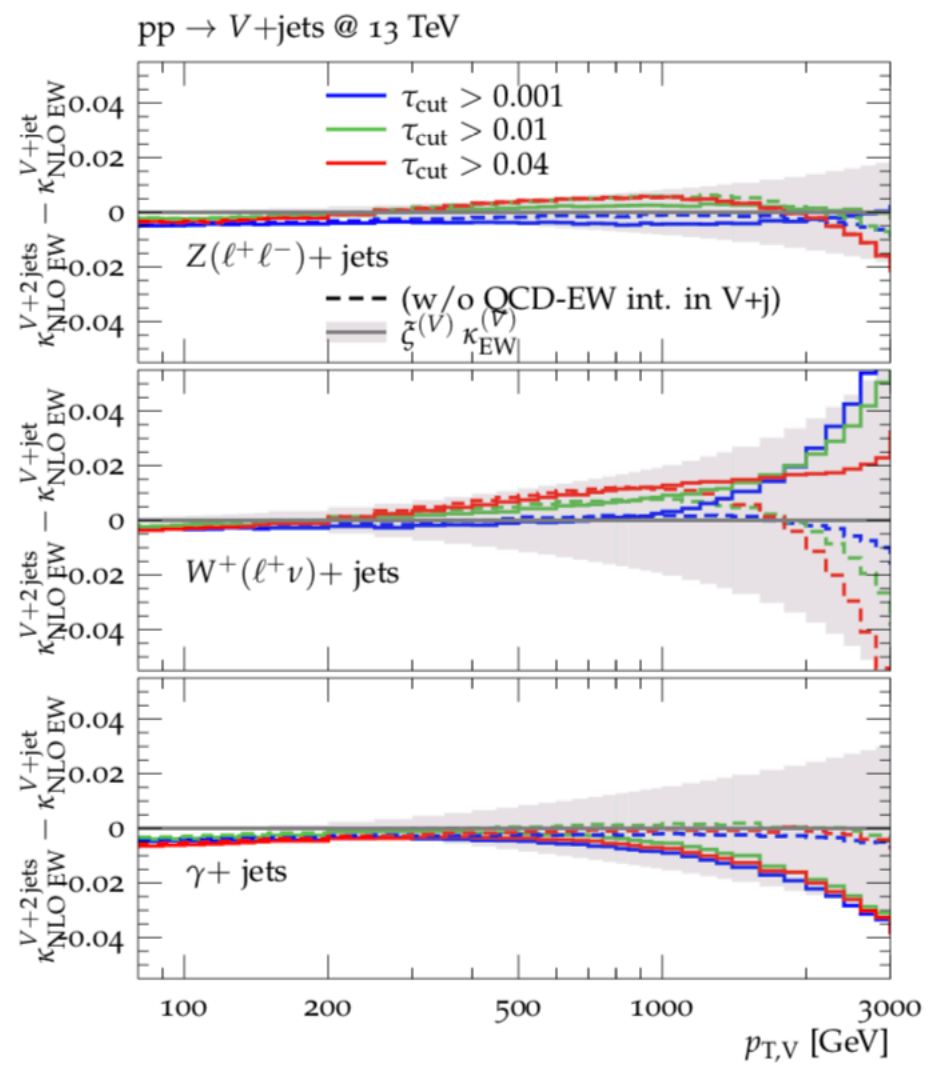
Precision modelling: correlations & data-driven methods

Exploiting correlations:

- Correlations among: observables in each measurement, measurements in each experiment, all experiments
- Correlations between SR & CRs: crucial for applying precision TH to data-driven BKG determinations

S. Pozzorini talk





Data from visible $Z/W/\gamma+$jet processes + theory extrapolation

- simultaneous profile likelyhood fit of 3 backgrounds + signal
- exploits theory for $\sigma_{Z\to\nu\nu}/\sigma_V^{\text{visible}}$ ratios and $\mathrm{d}\sigma/\mathrm{d}p_T$ shape

prior theory uncertainties and their correlations are crucial!

- QCD uncertainty model confirmed by NNLO calculations
- overall uncertainty at 1 TeV $\lesssim 5\%$ in distributions and $\lesssim 2\%$ in ratios
- reduction of TH uncertainty crucial for high-statistics monojet searches!

Need close TH-EXP interaction & guidance for:

- Clear understanding of dominant sources of TH corrections
- Building model for TH uncertainties with correlations across processes
(e.g. exploit the idea of Idea of quasi-universality of higher-order QCD corrections)

Inputs for global fit: PDFs

PDFs: Important ingredients in (HL-)LHC measurements

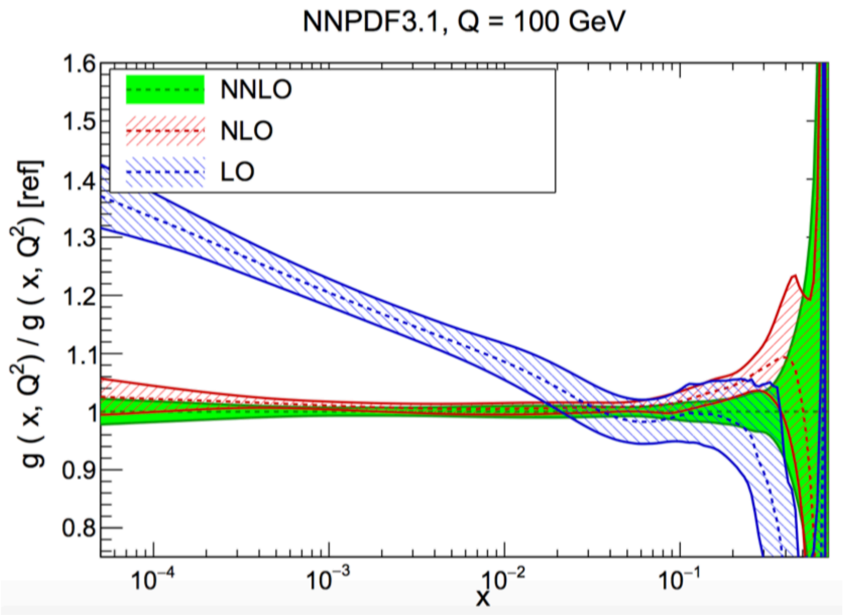
- The N(eural)N(etwork)PDFs : LHC data provide powerful constrain (especially at large x, large inv. mass)

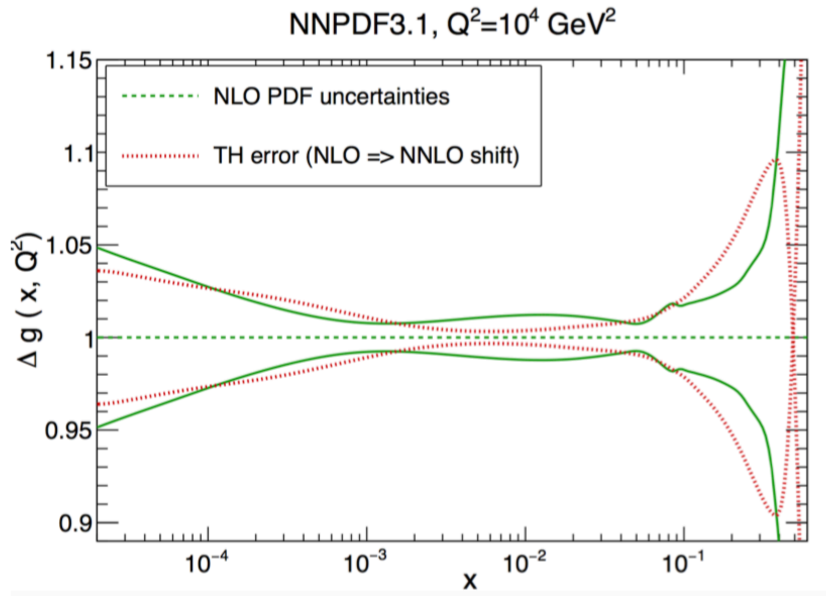
HOW TO MAKE PDFS MORE ACCURATE?

$$\sigma = \alpha_s^p \sigma_0 + \alpha_s^{p+1}\sigma_1 + \alpha_s^{p+2}\sigma_2 + \mathcal{O}(\alpha_s^{p+3})$$

- Standard global PDF fits based on fixed-order QCD calculations
- So far PDF sets only account for experimental error. Error associated with truncation of perturbative series ignored
- ➡ **NNLO theoretical predictions for observables entering PDF fits**
- ➡ **Fast interface with NNLO codes**
- ➡ **Photon PDF and inclusion of EW corrections**
- ➡ **Inclusion of theory uncertainties**

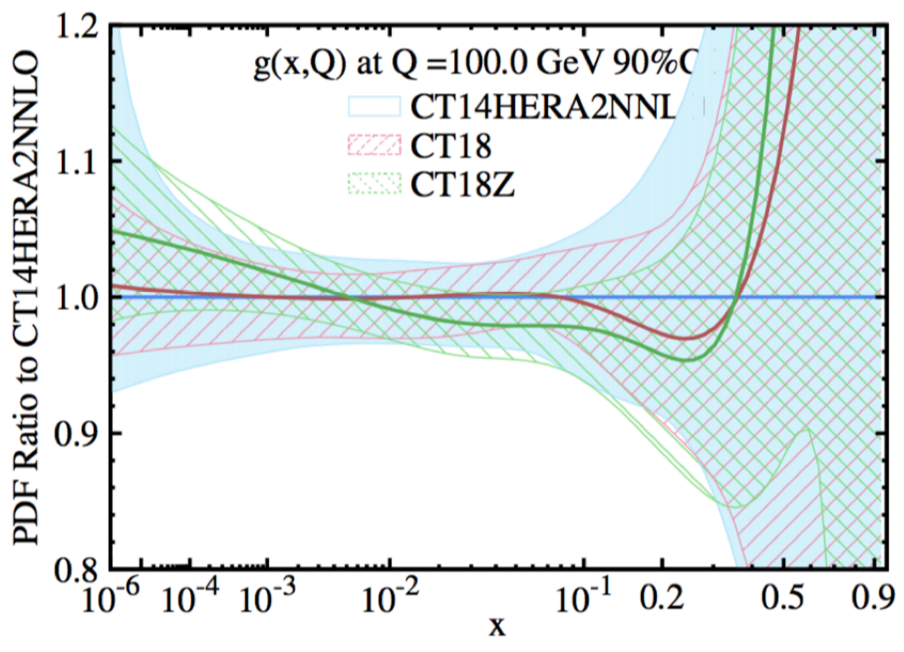
C. Voisey's talk

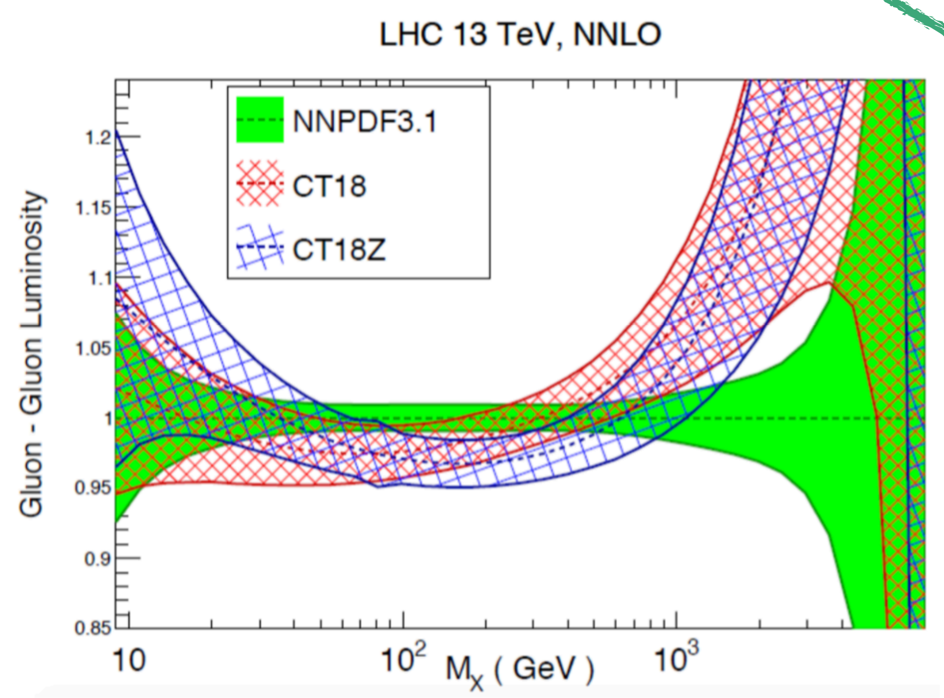




A COMPARISON AMONG GLOBAL FITS

M. Ubiali talk





CTEQ-TEA collaboration, arXiv: 1908.11394

P. Nadolsky's talk

- **NNPDF3.1** **(2017)** - gluon softer at large x and with ~30% uncertainty reduction
- **CT18** **(2019)** - gluon harder at large x and milder uncertainty reduction

- CT18 releases separate CT18Z set that includes W and Z precision measurements at 7 TeV due to data tension
- Differences in datasets? Or theory: fitted versus perturbative charm? Methodology?

Need sustained TH effort in order to:

- Understand the differences between the latest fits (NNPDF3.1 and CT18) and obtain more accurate PDFs

Interplay between EFT & PDFs

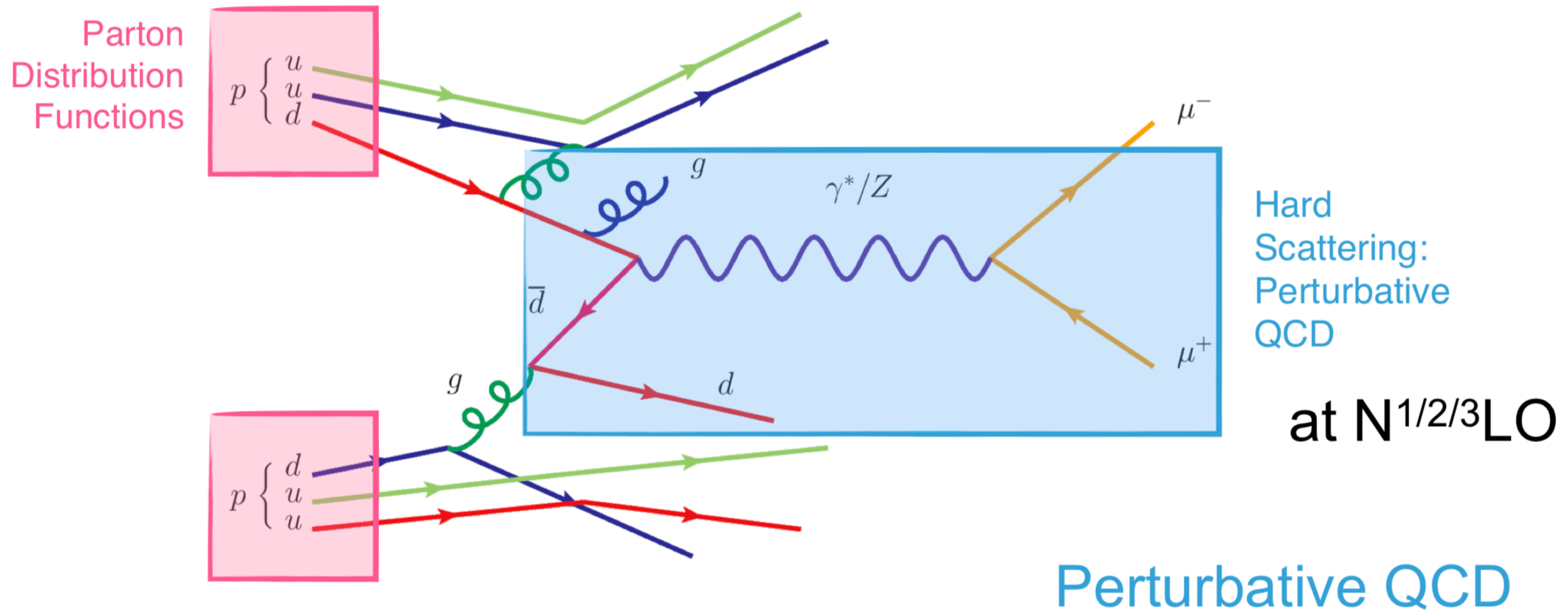
PDFs: Important ingredients in (HL-)LHC measurements

- The N(eural)N(etwork)PDFs : LHC data provide powerful constrain (especially at large x, large inv. mass)
- PDF are process universal but model dependent

PDFs importance in global interpretation

- Effect on gluon PDFs larger than for quark PDFs
-

C. Degrande talk



at $N^{1/2/3}LO$

Perturbative QCD

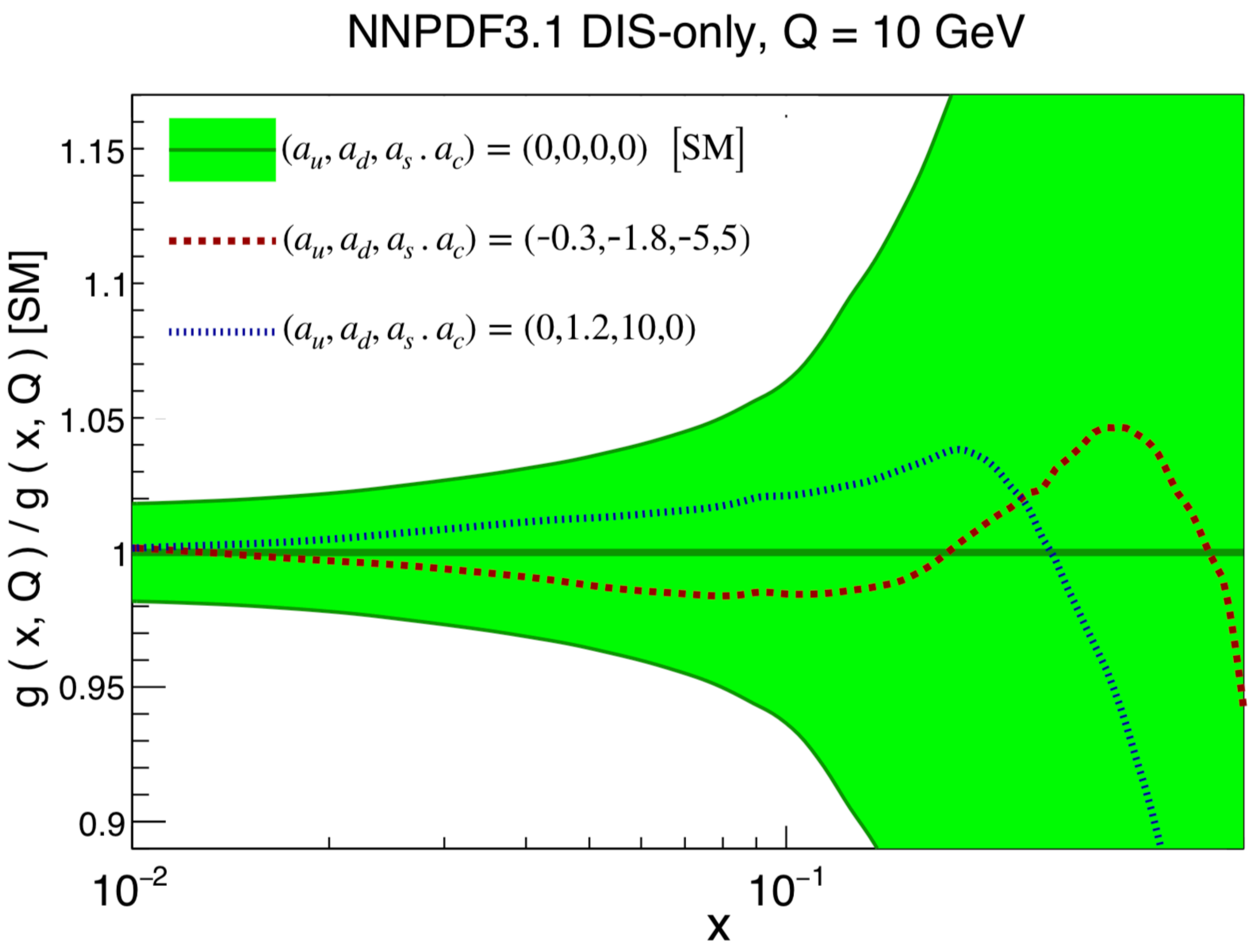
$$d\sigma^{pp\to ab} = \sum_{i,j} \boxed{f_i^{\mathrm{SMEFT}} \otimes f_j^{\mathrm{SMEFT}}} \otimes \boxed{d\hat{\sigma}^{ij\to ab}} + \dots \qquad f_i(x,\mu)$$

∋LHC

SMEFT

data

PDF are process universal but model dependent



Deviation within uncer. but large uncertainty (DIS only)

Important interplay between PDF and EFT
Need close TH-EXP interaction

Interplay between EFT & PDFs

PDFs: Important ingredients in (HL-)LHC measurements

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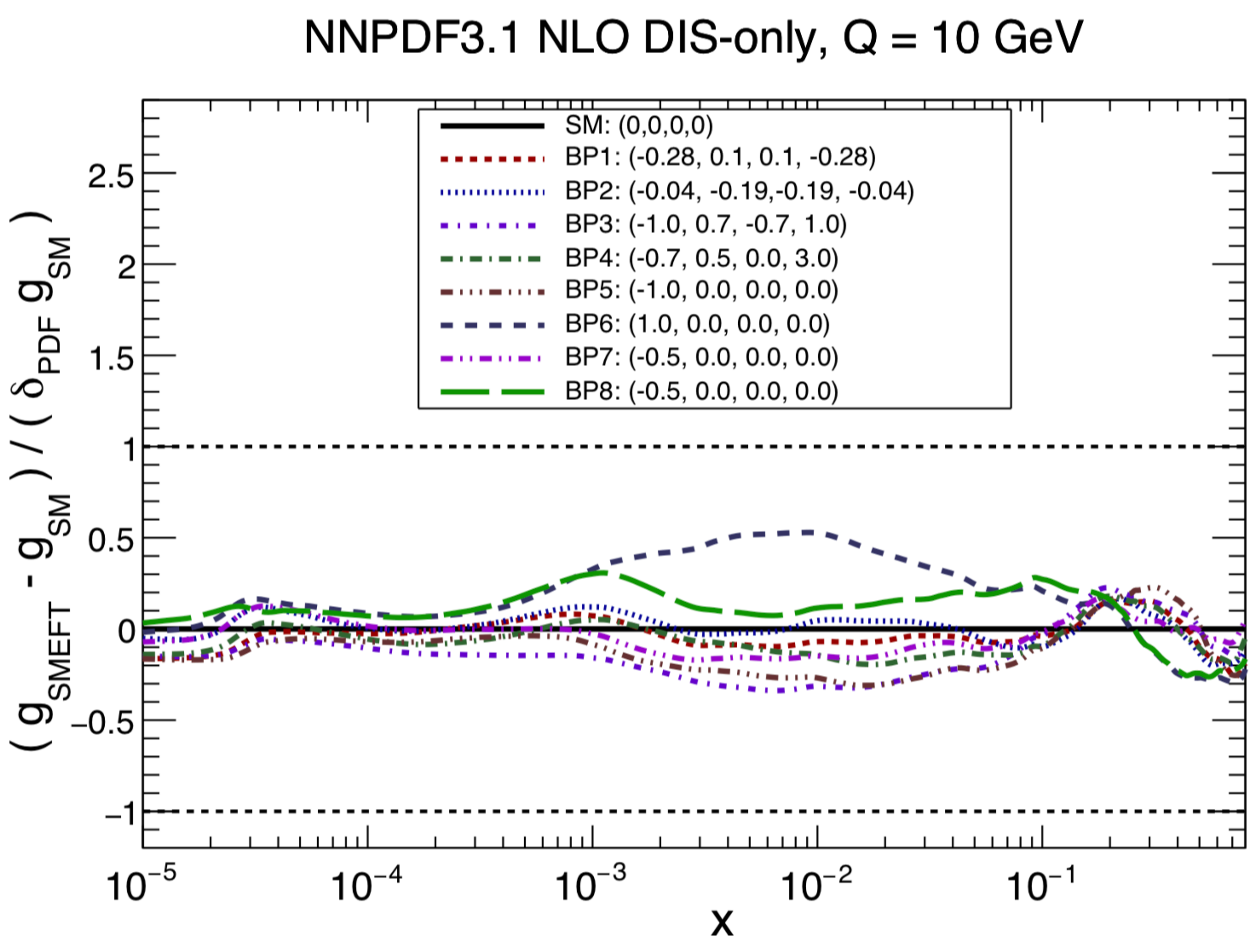
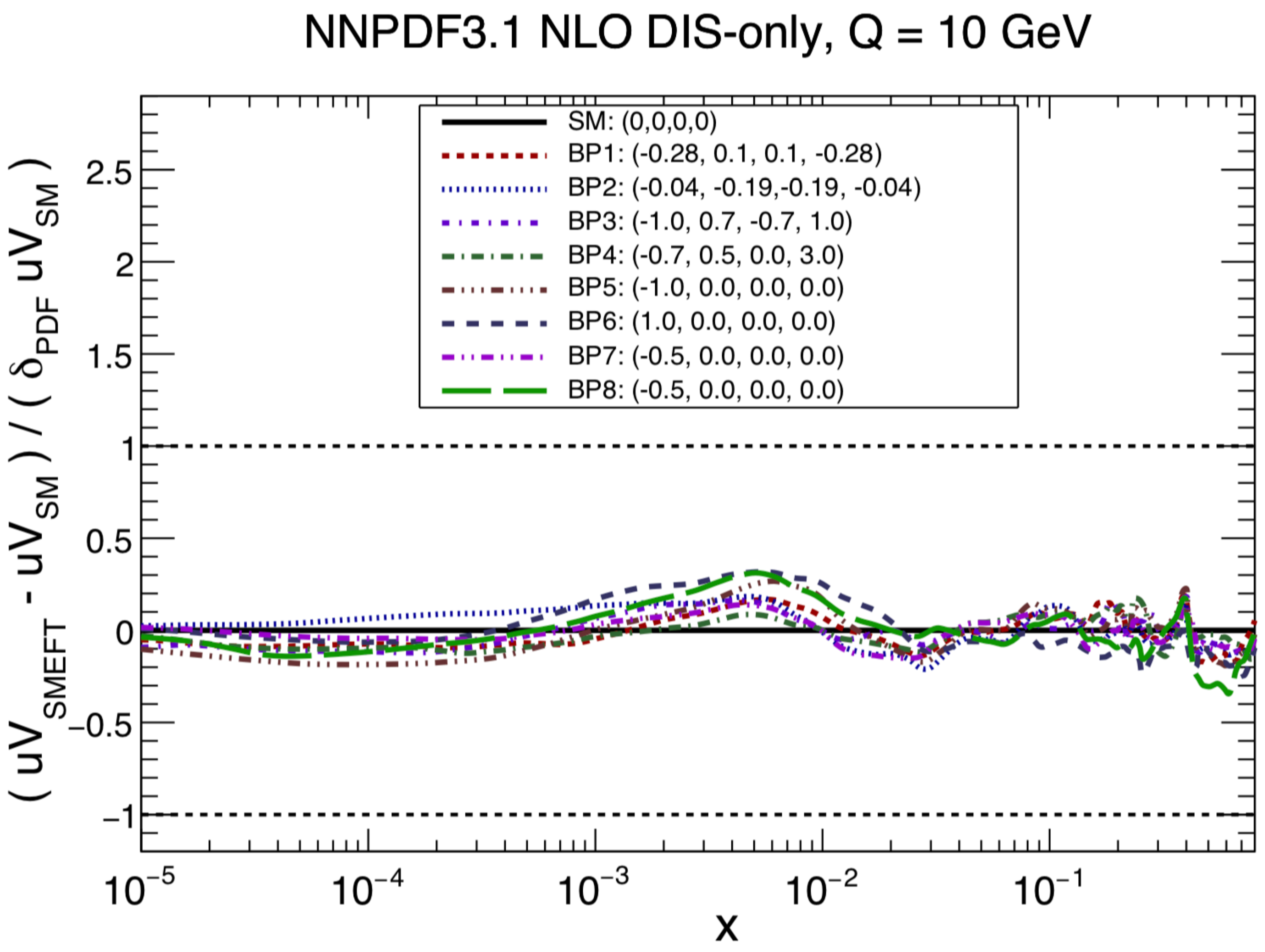
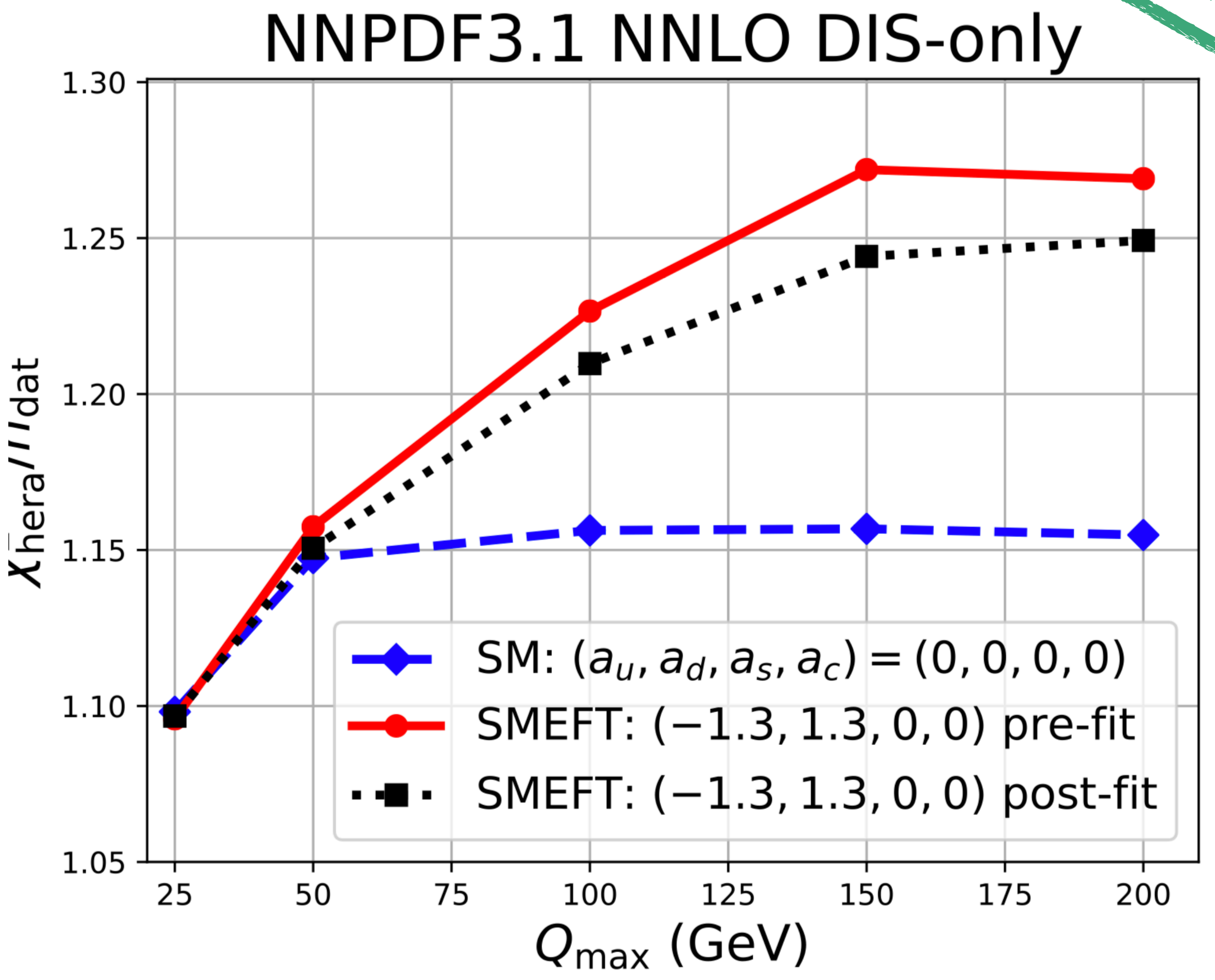
C. Degrande talk


NNPDF3.1 NLO DIS-only, Q = 10 GeV


NNPDF3.1 NLO DIS-only, Q = 10 GeV


NNPDF3.1 NNLO DIS-only

C
de

σ_{4F}

Important interplay between PDF and EFT
Need close TH-EXP interaction

Exploiting process/operator interplays : TOP-HIG

E.Vryonidou talk

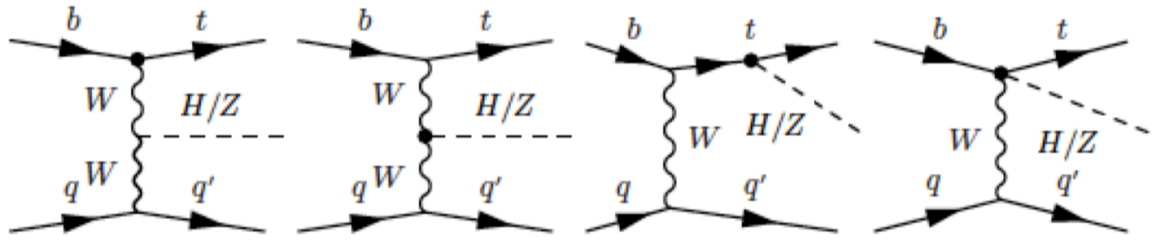
EFT fits largely ignore the interplay between top and Higgs:

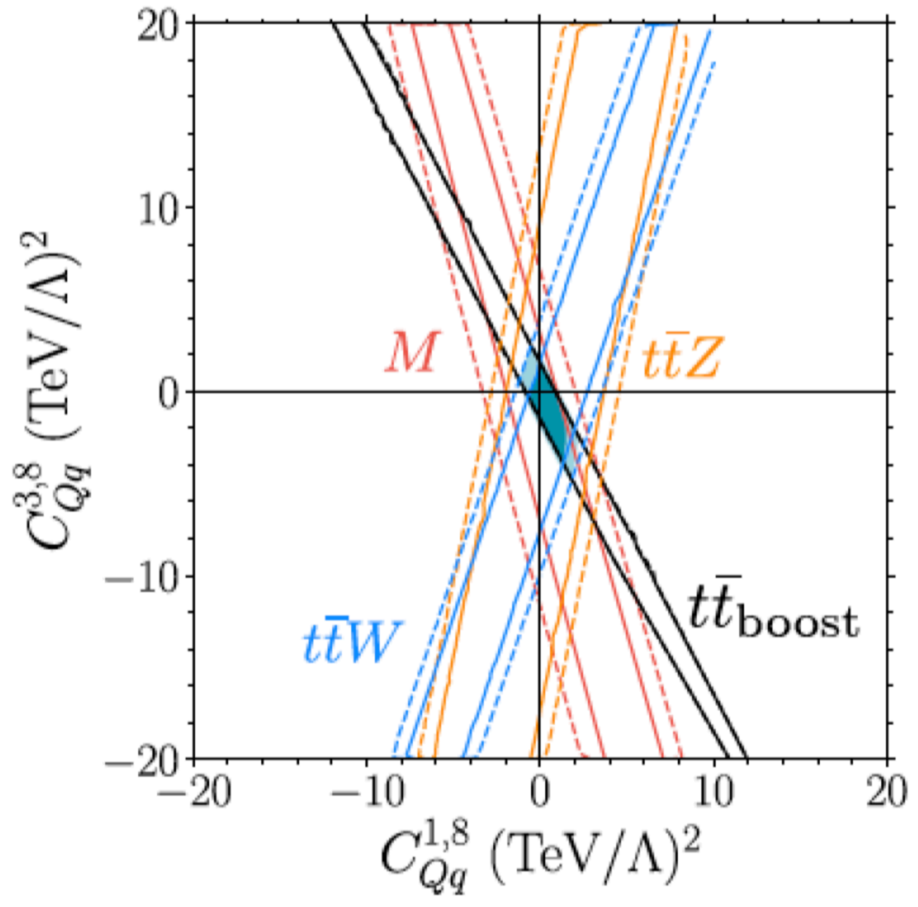
- Should we and/or can we avoid the messy picture?

Breaking degeneracies:

- Important impact of differential information, extract maximal information from combination/interplay

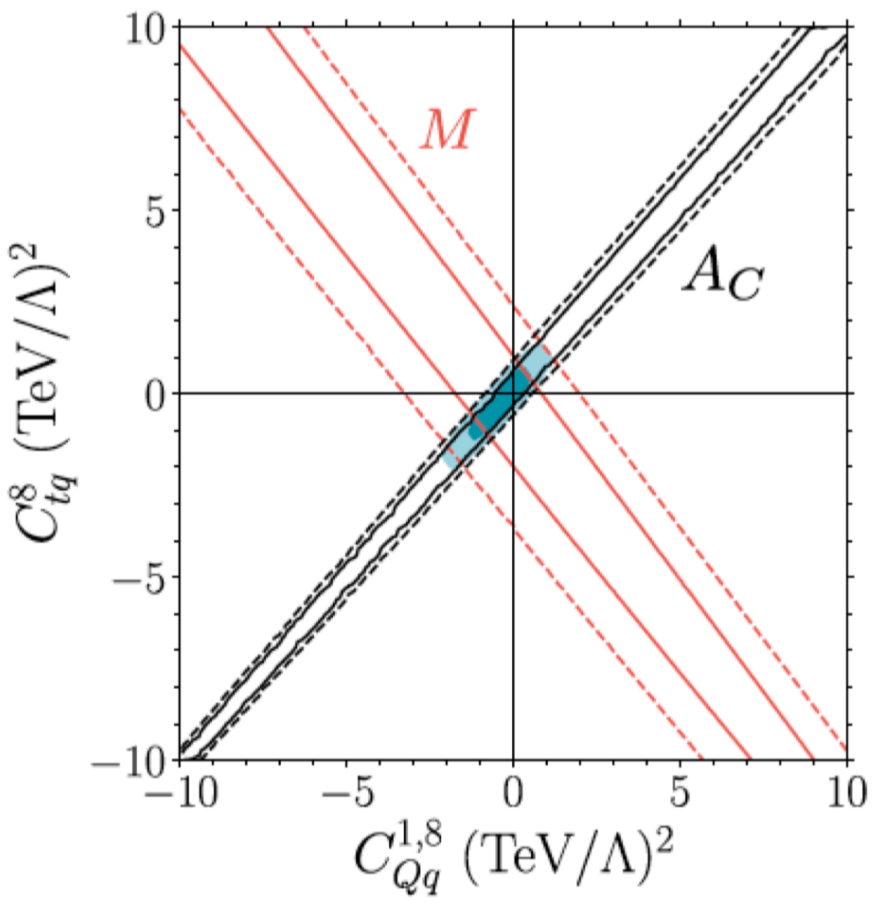
tZj/tHj example





$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$$

$$O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i)$$



$$O_{tq}^{8} = (\bar{q}_i\gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t)$$

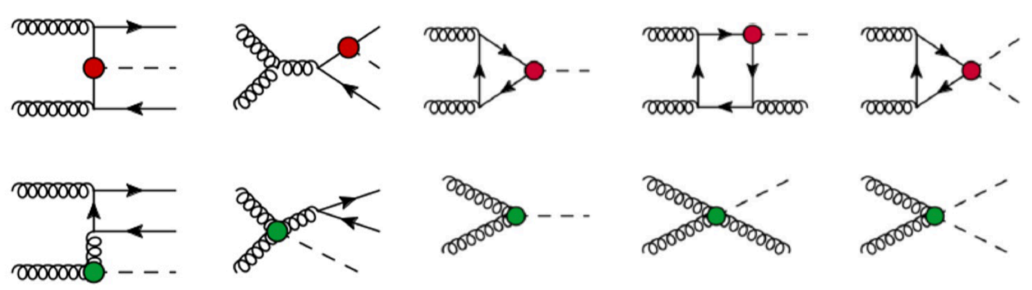
$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$$

ttH + H, H+j to break degeneracy

$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2\left(\phi^\dagger\phi\right)G^A_{\mu\nu}G^{A\mu\nu}\,,$$

(cf. k_t, k_g)



ttH

H, H+j, HH

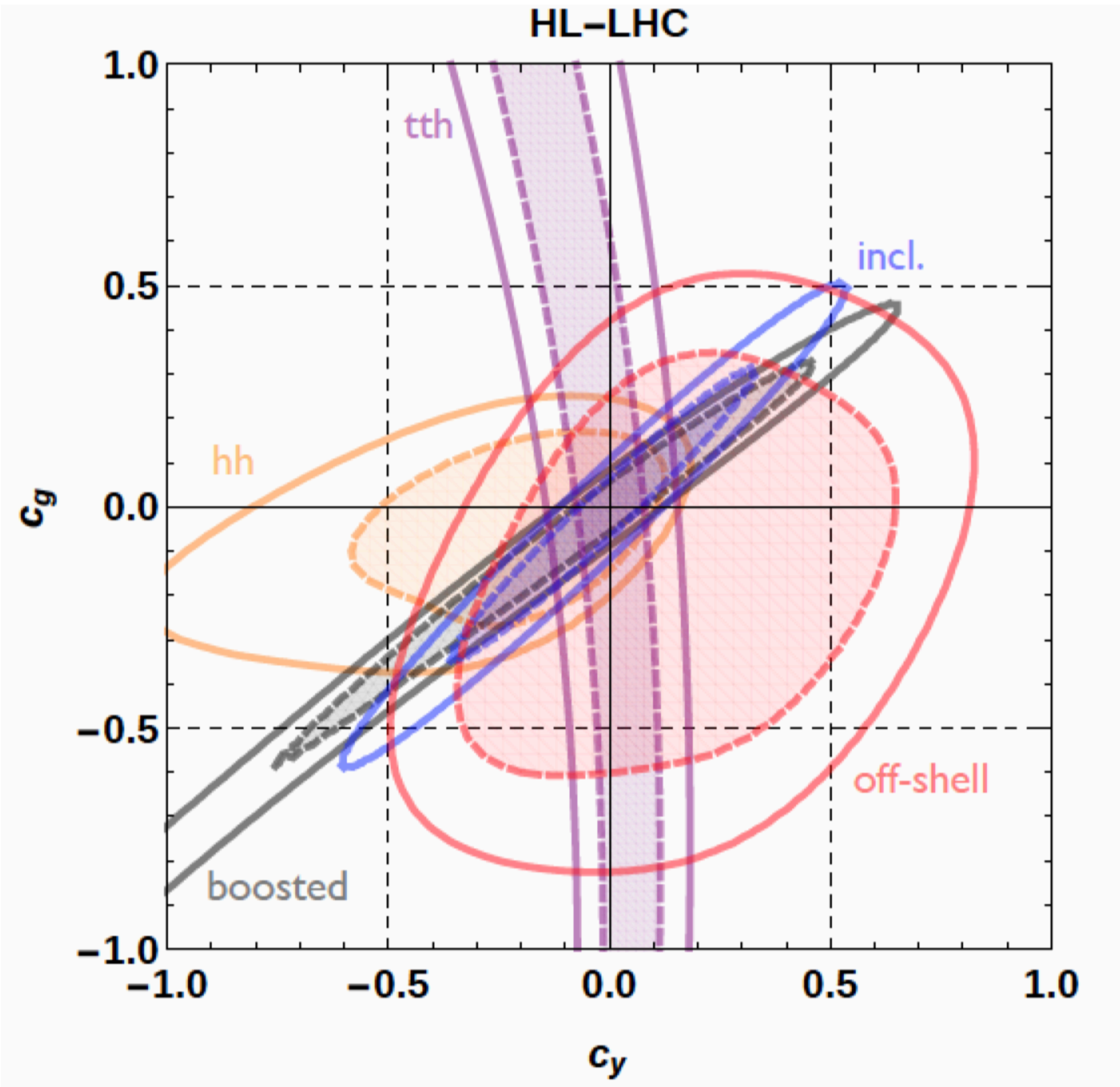
$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$

$$O_{\phi G} = y_t^2\left(\phi^\dagger\phi\right)G^A_{\mu\nu}G^{A\mu\nu}$$

Lots of processes

Combination:

- inclusive H
- boosted Higgs
- ttH
- HH
- off-shell Higgs



Exploiting process/operator interplays : TOP-HIG

E.Vryonidou talk

HZ in gluon fusion : source of info. on top and Z / Higgs couplings

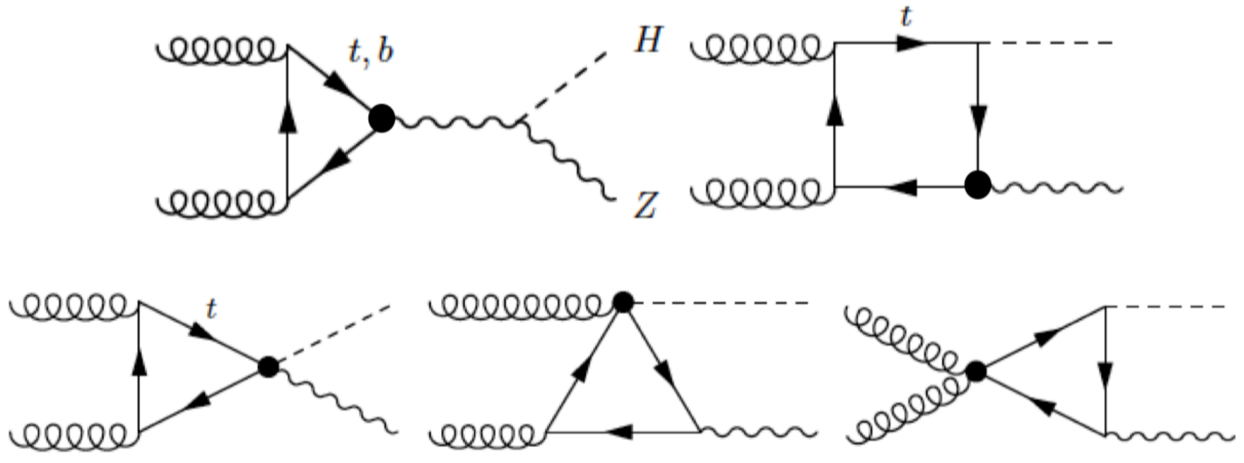
$$O^{(3)}_{\varphi Q} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

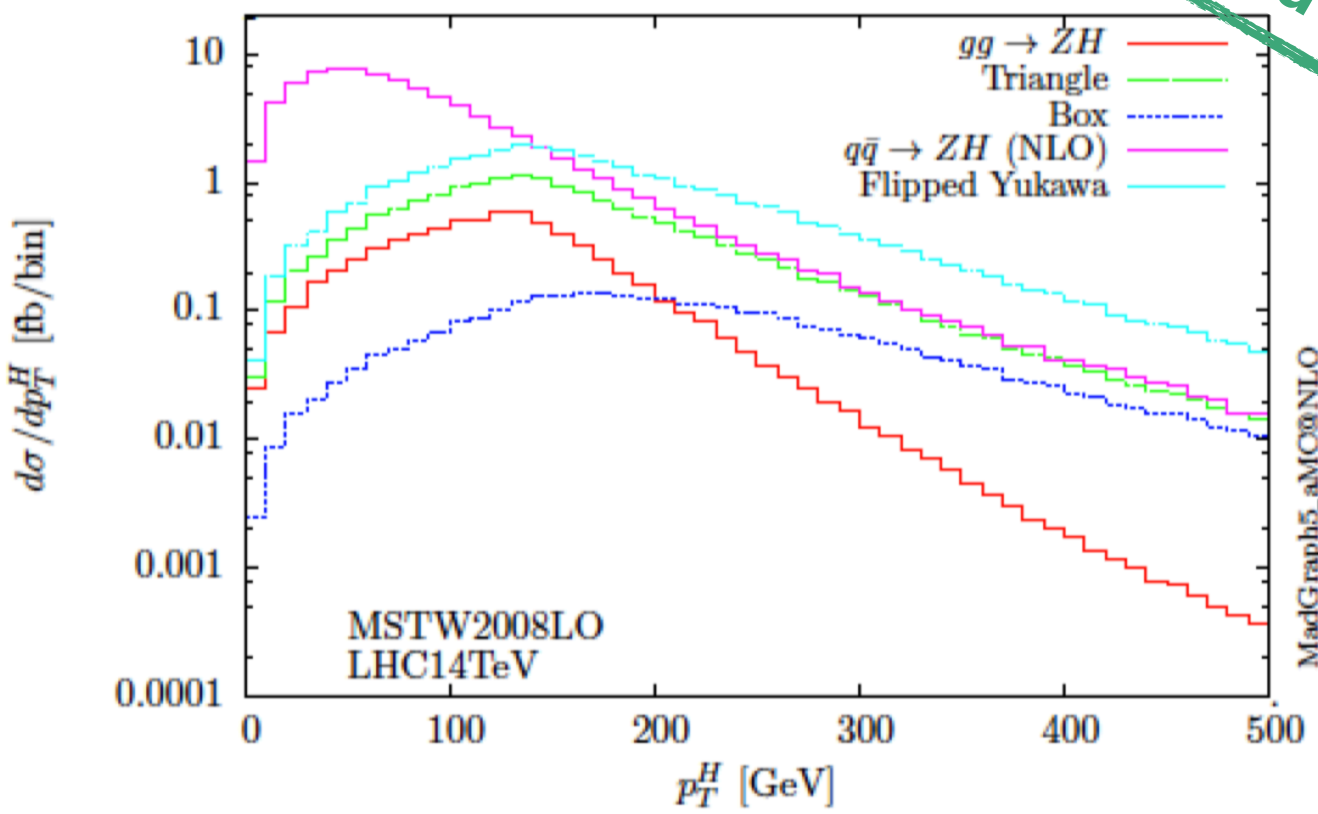
$$O^{(1)}_{\varphi Q} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)(\bar{Q}t)\,\tilde{\phi}$$





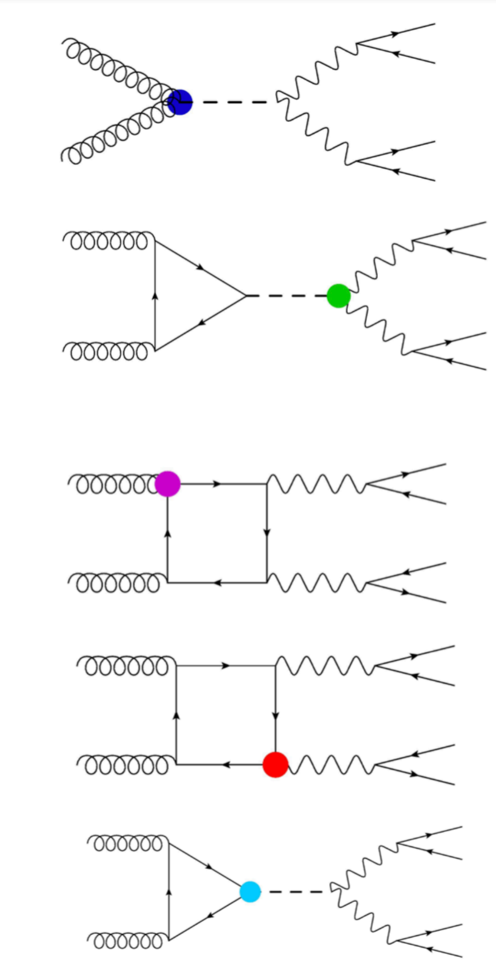
Off-shell Higgs production : source of information on ttZ

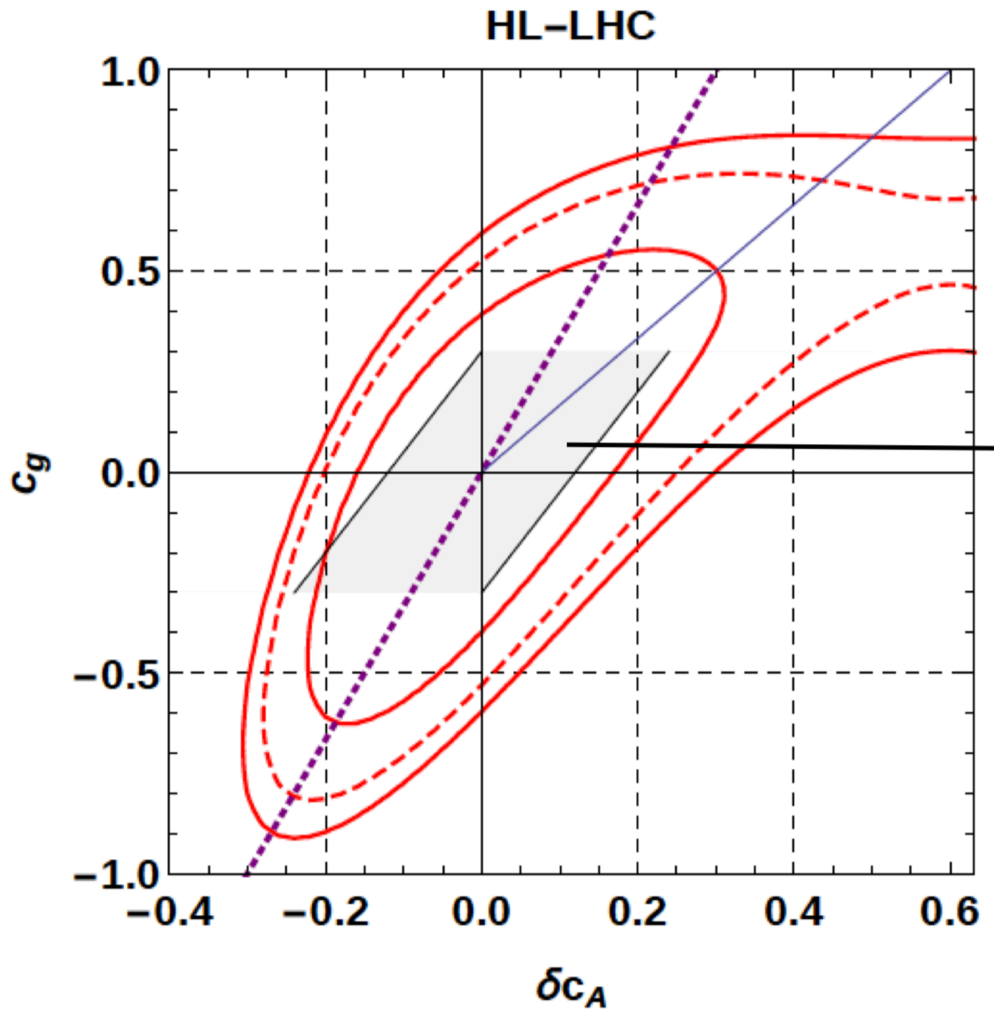
Higgs operators

$\mathcal{O}_{\varphi G}$	cpG	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) G^{\mu\nu}_A\, G^A_{\mu\nu}$	$\mathcal{O}_{\varphi W}$	cpW	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W^{\mu\nu}_I\, W^I_{\mu\nu}$
$\mathcal{O}_{\varphi B}$	cpBB	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu}\, B_{\mu\nu}$	$\mathcal{O}_{\varphi WB}$	cpWB	$(\varphi^\dagger\tau_I\varphi)\, B^{\mu\nu}W^I_{\mu\nu}$
$\mathcal{O}_{\varphi}$	cp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$	$\mathcal{O}_{\varphi d}$	cdp	$\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$
$\mathcal{O}_{\varphi D}$	cpDC	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$			

Top operators

$\mathcal{O}_{t\varphi}$	ctp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{Q}\,t\,\tilde{\varphi} + \text{h.c.}$	$\mathcal{O}_{tW}$	ctW	$i(\bar{Q}\tau^{\mu\nu}\,\tau_I\,t)\,\tilde{\varphi}\,W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tG}$	ctG	$ig_S\,(\bar{Q}\tau^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu} + \text{h.c.}$	$\mathcal{O}_{tB}$	-	$i(\bar{Q}\tau^{\mu\nu}\,t)\,\tilde{\varphi}\,B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}^{(3)}_{\varphi Q}$	cpQ3	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\,\tau_I\varphi)(\bar{Q}\,\gamma^\mu\,\tau^I Q)$	$\mathcal{O}_{tZ}$	ctZ	$-\sin\theta_W\mathcal{O}_{tB} + \cos\theta_W\mathcal{O}_{tW}$
$\mathcal{O}^{(-)}_{\varphi Q}$	cpQM	$\mathcal{O}^{(1)}_{\varphi Q} - \mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$	cpt	$i(\varphi^\dagger\,\overleftrightarrow{D}_\mu\,\varphi)(\bar{t}\,\gamma^\mu\,t)$





4-parameter fit:

c_t, c_g, c_V, c_A

Constraint from gg to ZH
Englert et al arXiv:1603.05304

Constraints on ttZ couplings competitive with ttZ process

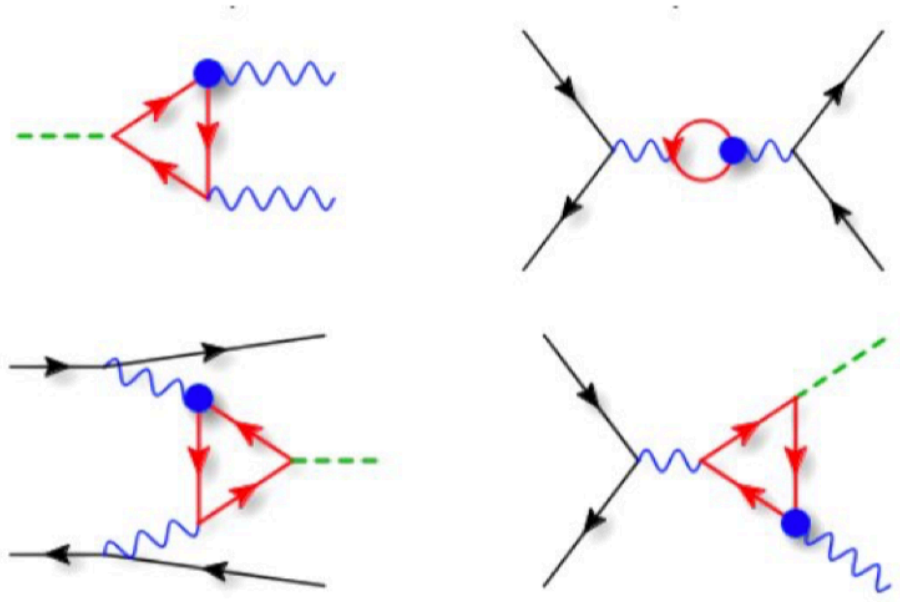
Need close TH-EXP interaction: to enlighten interplays

Loops for tree-level processes

E.Vryonidou talk

processes interplay and one-loop contributions

- Process interplay breaks degeneracies, one-loop process contributions can be important (with limited information on top couplings one-loop Higgs processes can be significantly modified)



+

$$
\begin{aligned}
O_{t\varphi} &= \bar{Q} t \tilde{\varphi}\, (\varphi^\dagger \varphi) + h.c.,\\
O^{(3)}_{\varphi Q} &= (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{Q}\gamma^\mu \tau^I Q),\\
O_{\varphi tb} &= (\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{t}\gamma^\mu b) + h.c.,\\
O_{tB} &= (\bar{Q}\sigma^{\mu\nu} t)\, \tilde{\varphi} B_{\mu\nu} + h.c.,\\
O_{\varphi t} &= (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t),\\
O^{(1)}_{\varphi Q} &= (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q),\\
O_{tW} &= (\bar{Q}\sigma^{\mu\nu}\tau^I t)\, \tilde{\varphi} W^I_{\mu\nu} + h.c.,
\end{aligned}
$$

+ **Current constraints from top LHC measurements**

Poor knowledge of top couplings leads to uncertainties on Higgs measurements at the LHC:

	$\gamma\gamma$	γZ	bb	WW*	ZZ*
gg	(-100%,1980%)	(-88%,200%)	(-40%,48%)	(-40%,47%)	(-40%,46%)
VBF	(-100%,1880%)	(-88%,170%)	(-6.1%,5.3%)	(-6.8%,6.7%)	(-8.8%,9.2%)
WH	(-100%,1880%)	(-88%,170%)	(-5.5%,4.2%)	(-6.1%,5.6%)	(-7.8%,7.9%)
ZH	(-100%,1880%)	(-87%,170%)	(-6.5%,5.9%)	(-7.1%,7.1%)	(-9.4%,9.9%)

loop-induced

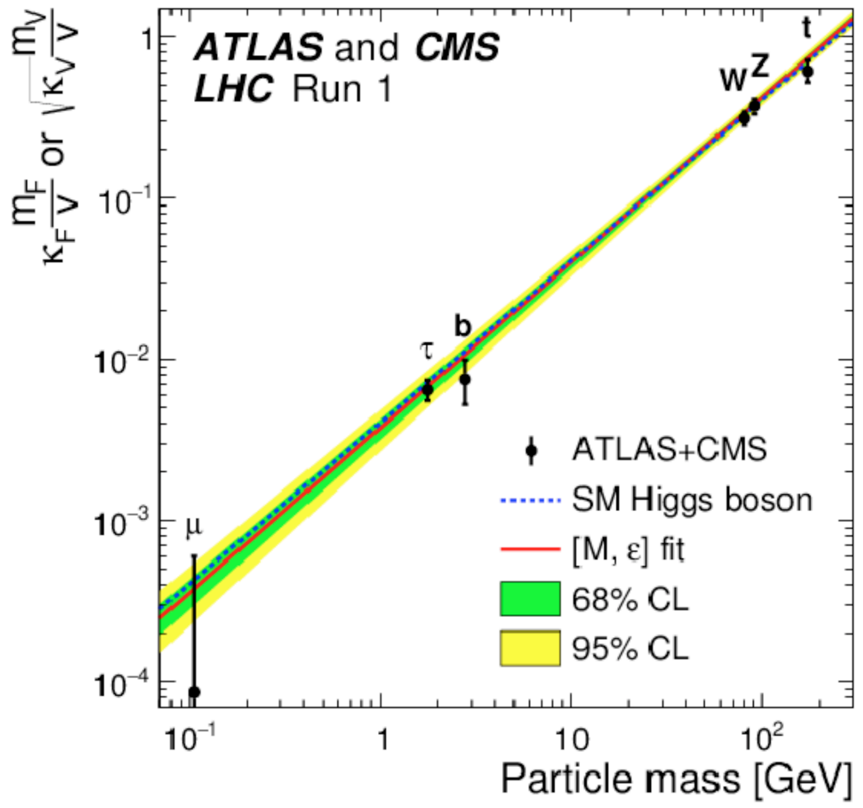
tree-level

Need close TH-EXP interaction: to include one-loop effects

Instead of a summary…

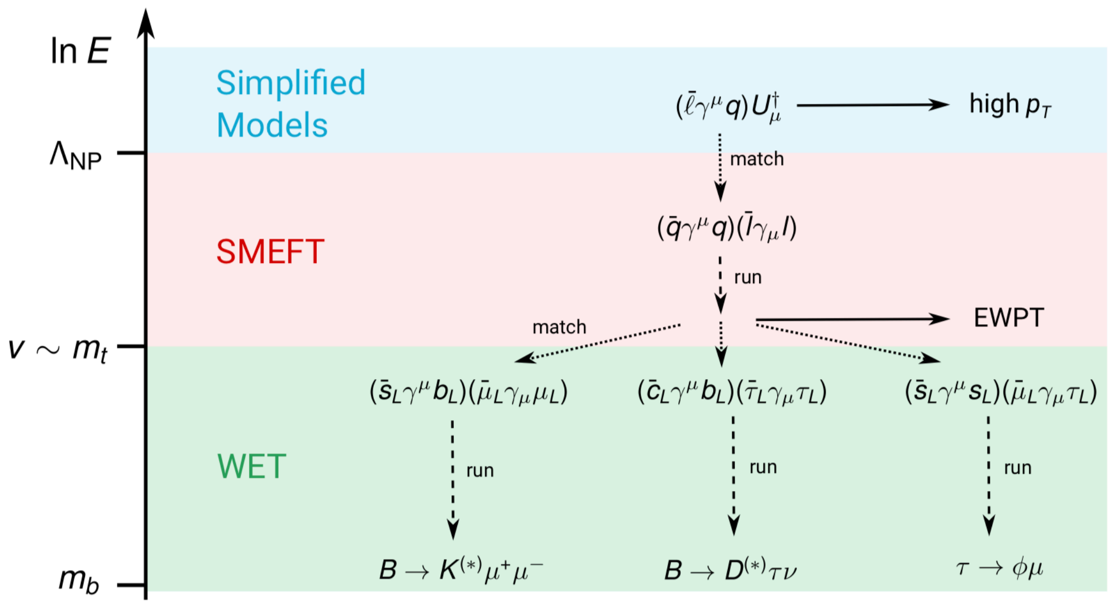
Measurements @ 7, 8, 13 TeV confirmed the immense potential of LHC

- Understanding of the true **nature of SM of particles physics** is one of the central subjects in the particles physics today



EFT offers one of the most important global approaches:

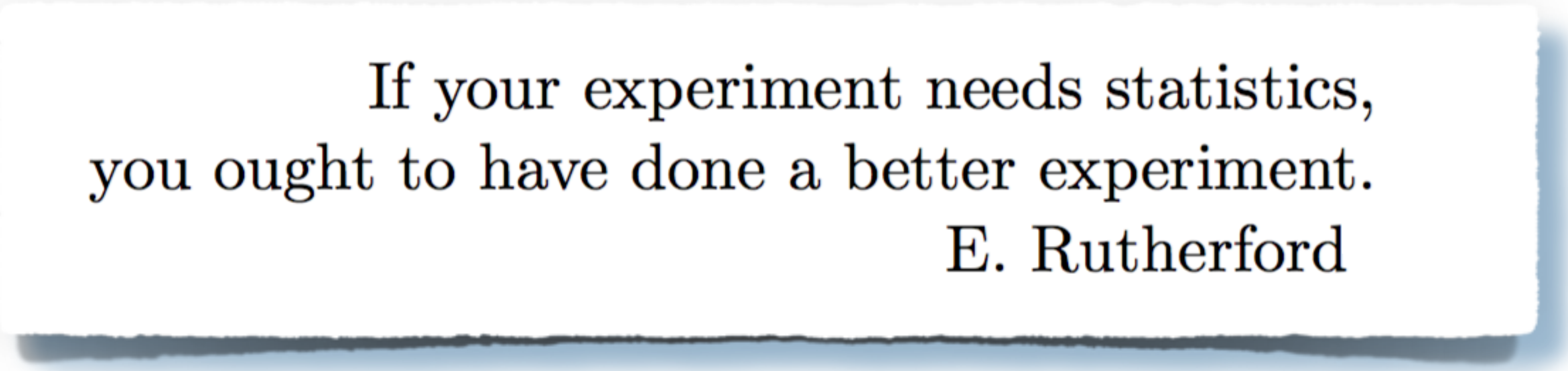
- **SMP/TOP/HIG** already perform high-precision measurements.
  TH studies & tools are becoming mature and ready to be used in global EFT fit!
- TH and EXP need to continue working together

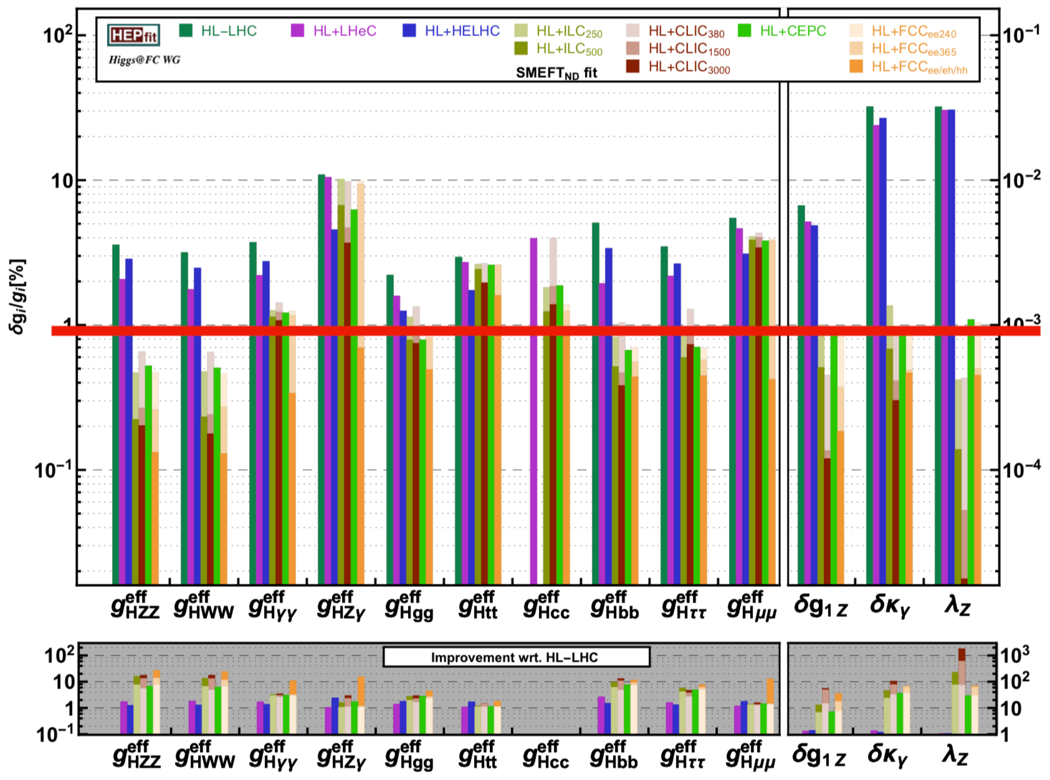


HL-LHC will enable full discovery potential

- Major effort of the community of theoretical and experimental physicists is required (and is already ongoing)
- Estimates of the HL-LHC performance are extremely encouraging

Next-generation accelerators & experiments are key to our understanding of Nature

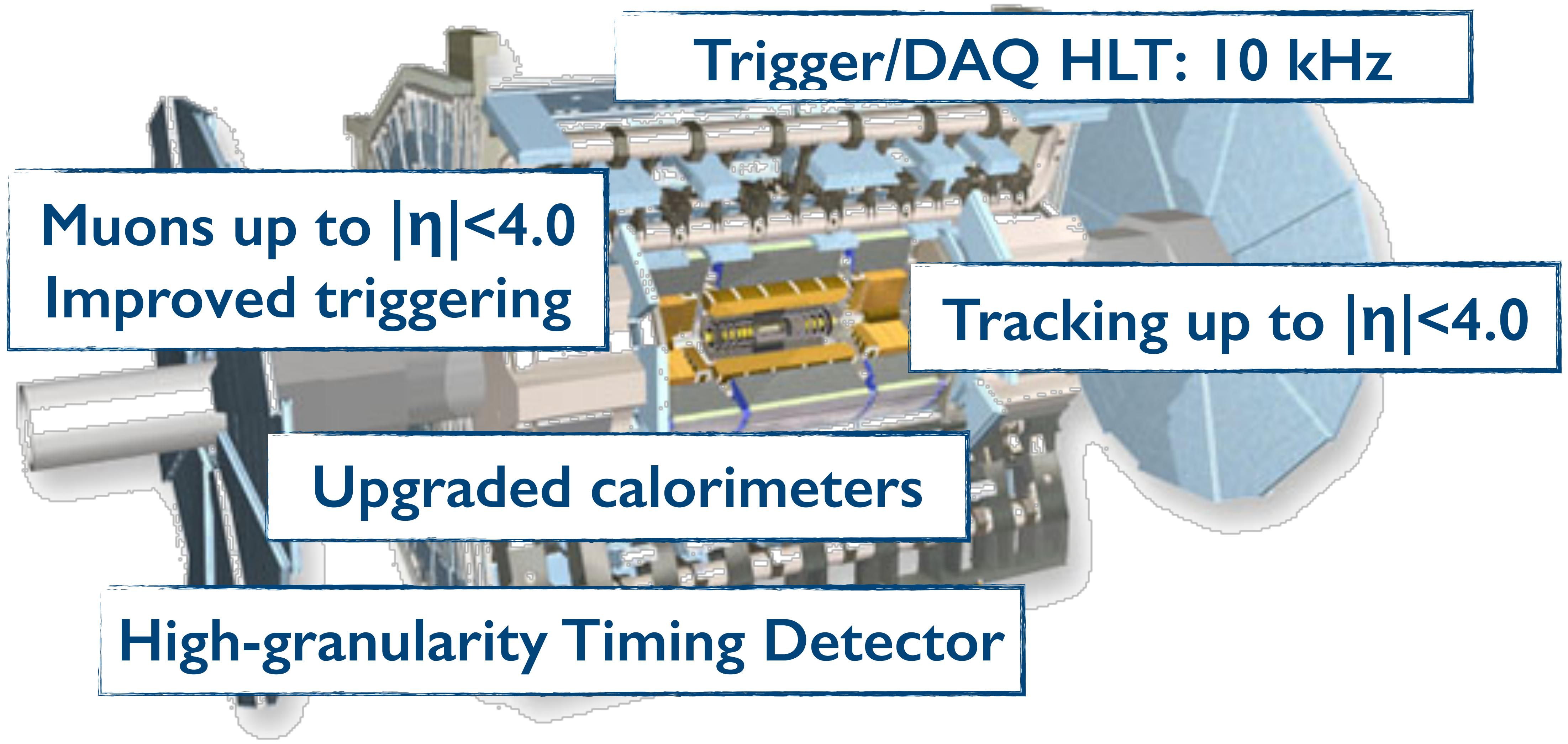

If your experiment needs statistics,
you ought to have done a better experiment.
E. Rutherford



1% magic threshold

Additional material

Upgraded detectors @ HL-LHC



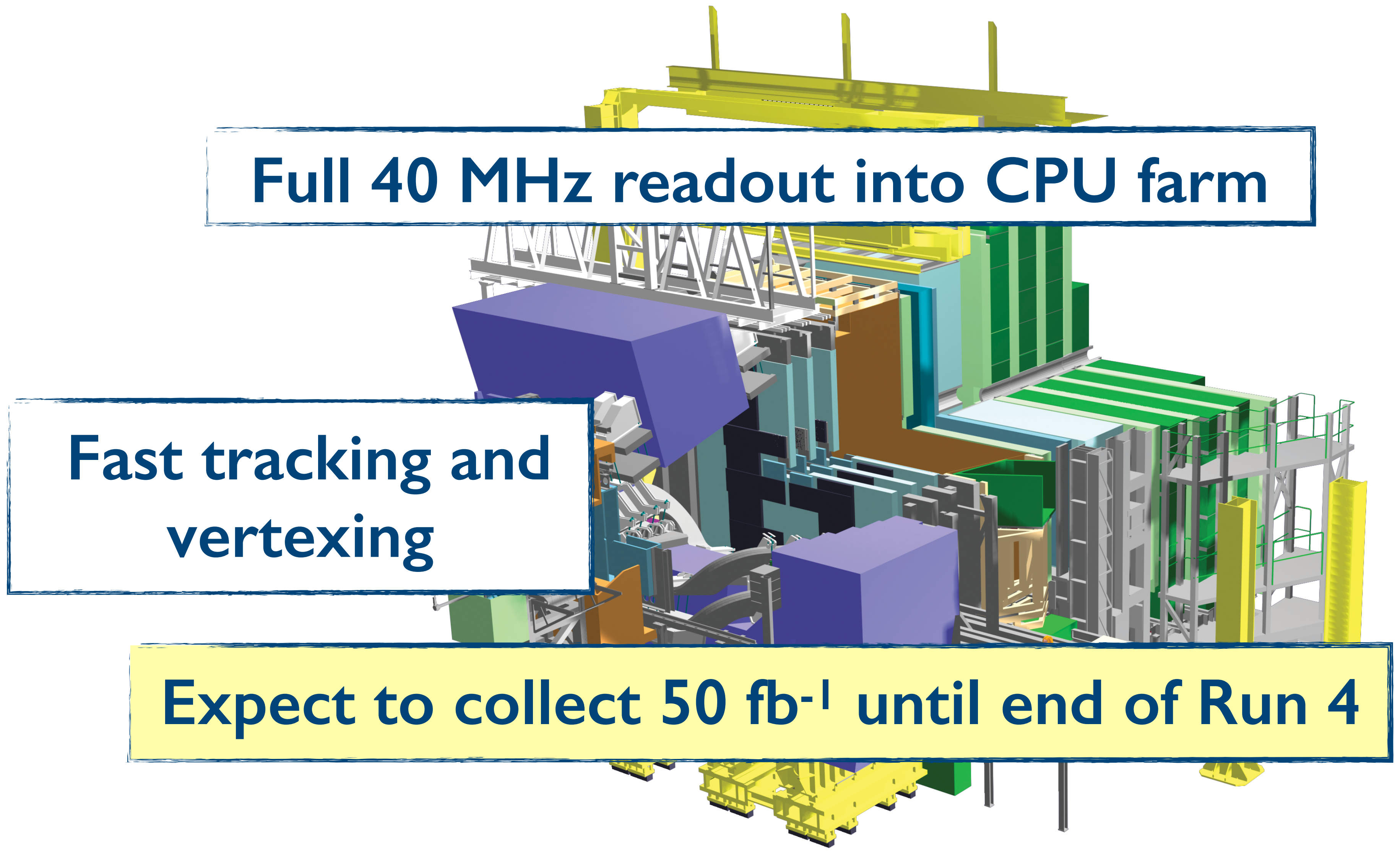
Trigger/DAQ HLT: 10 kHz

Muons up to |η|<4.0
Improved triggering

Tracking up to |η|<4.0

Upgraded calorimeters

High-granularity Timing Detector

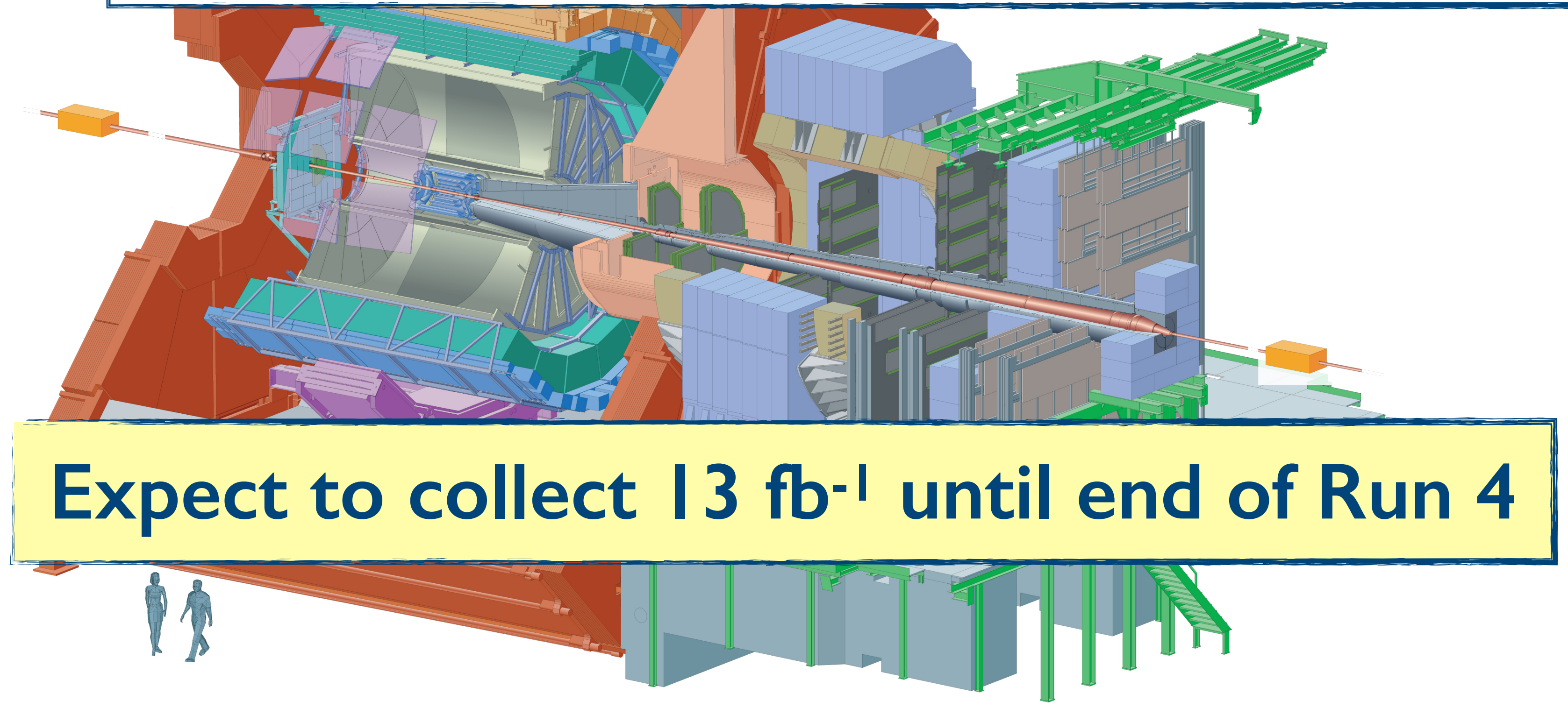


Full 40 MHz readout into CPU farm

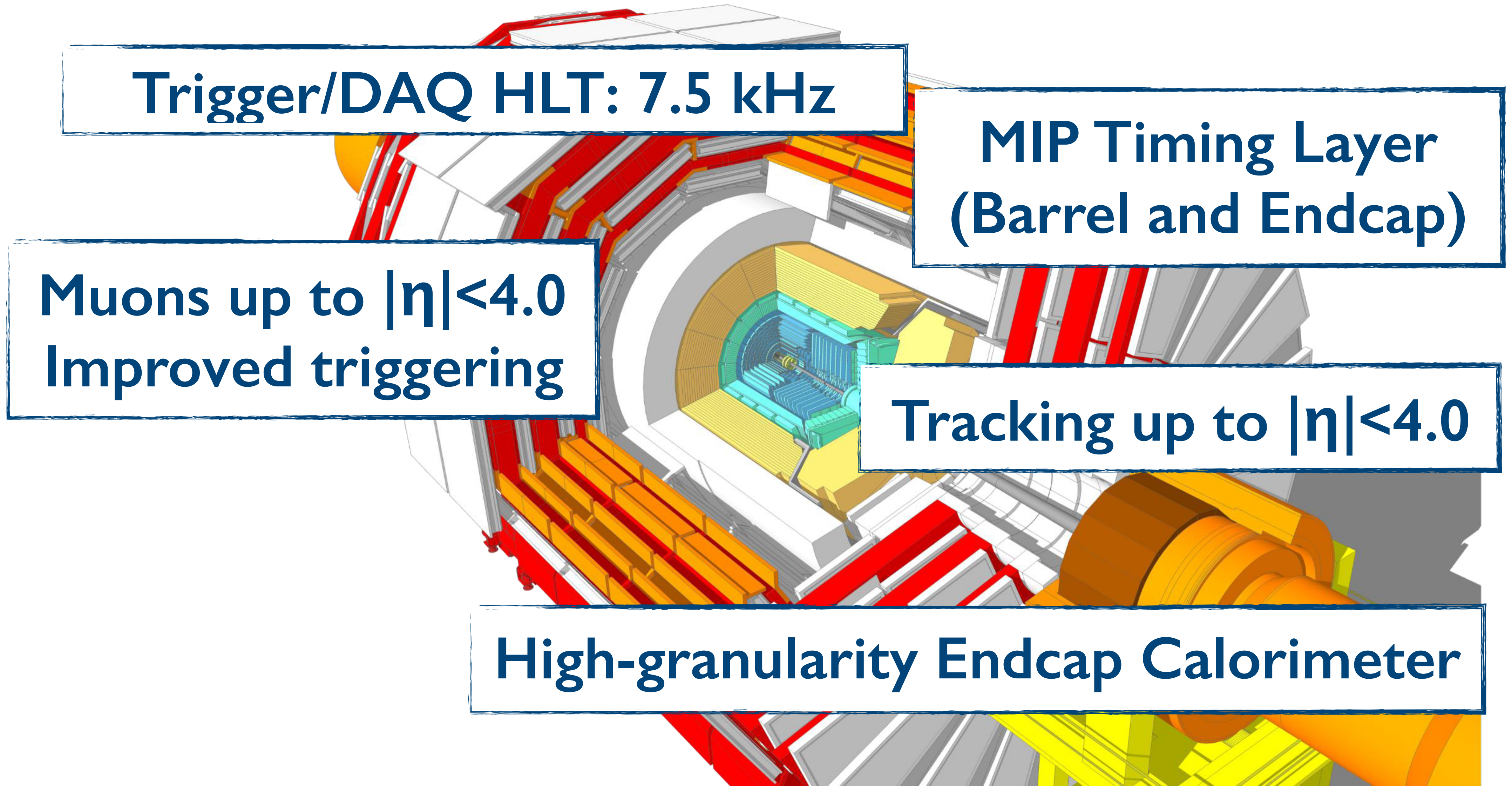
Fast tracking and
vertexing

Expect to collect 50 fb^{-1} until end of Run 4

Major upgrade during LS2:
Forward Interaction Trigger, Inner Tracking System, Muon Forward Tracker



Expect to collect 13 fb^{-1} until end of Run 4



Trigger/DAQ HLT: 7.5 kHz

MIP Timing Layer
(Barrel and Endcap)

Muons up to |η|<4.0
Improved triggering

Tracking up to |η|<4.0

High-granularity Endcap Calorimeter

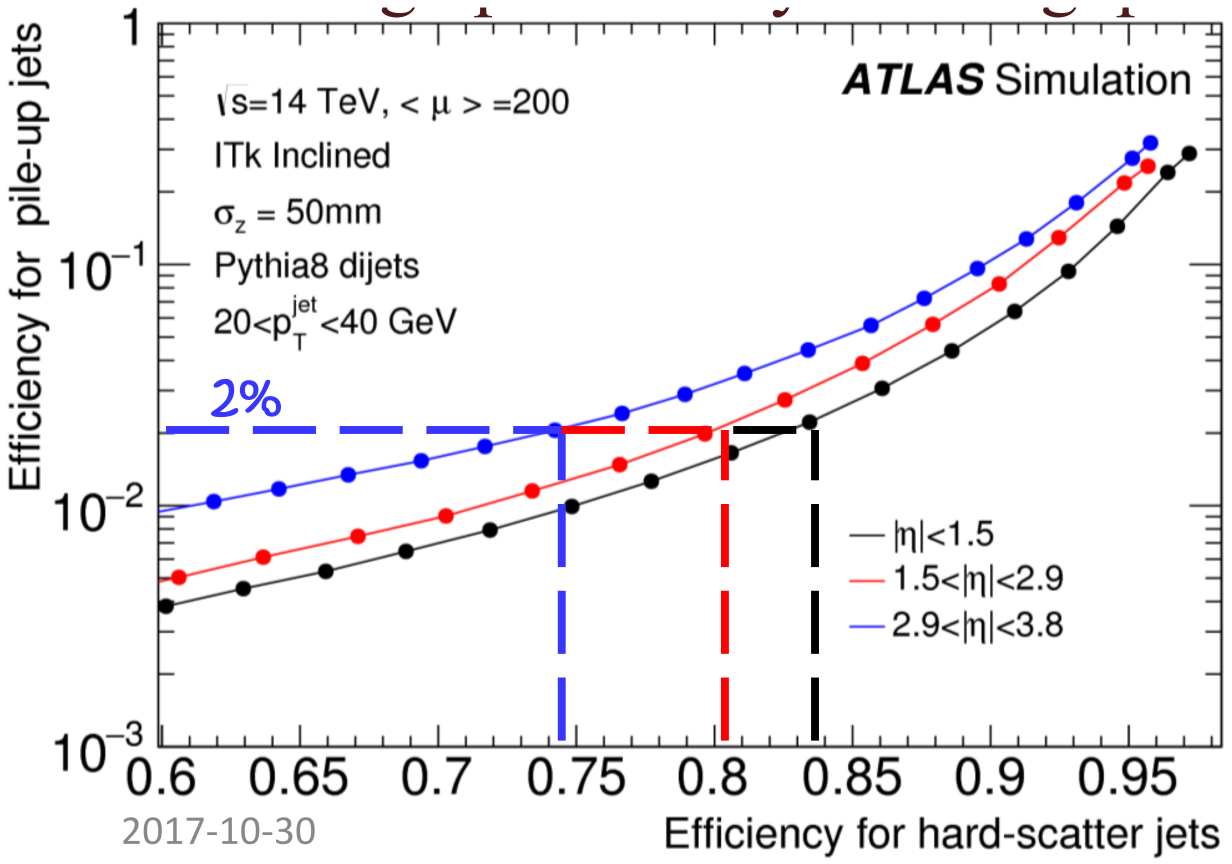
Experiments' TDRs

Detectors performance @ HL-LHC

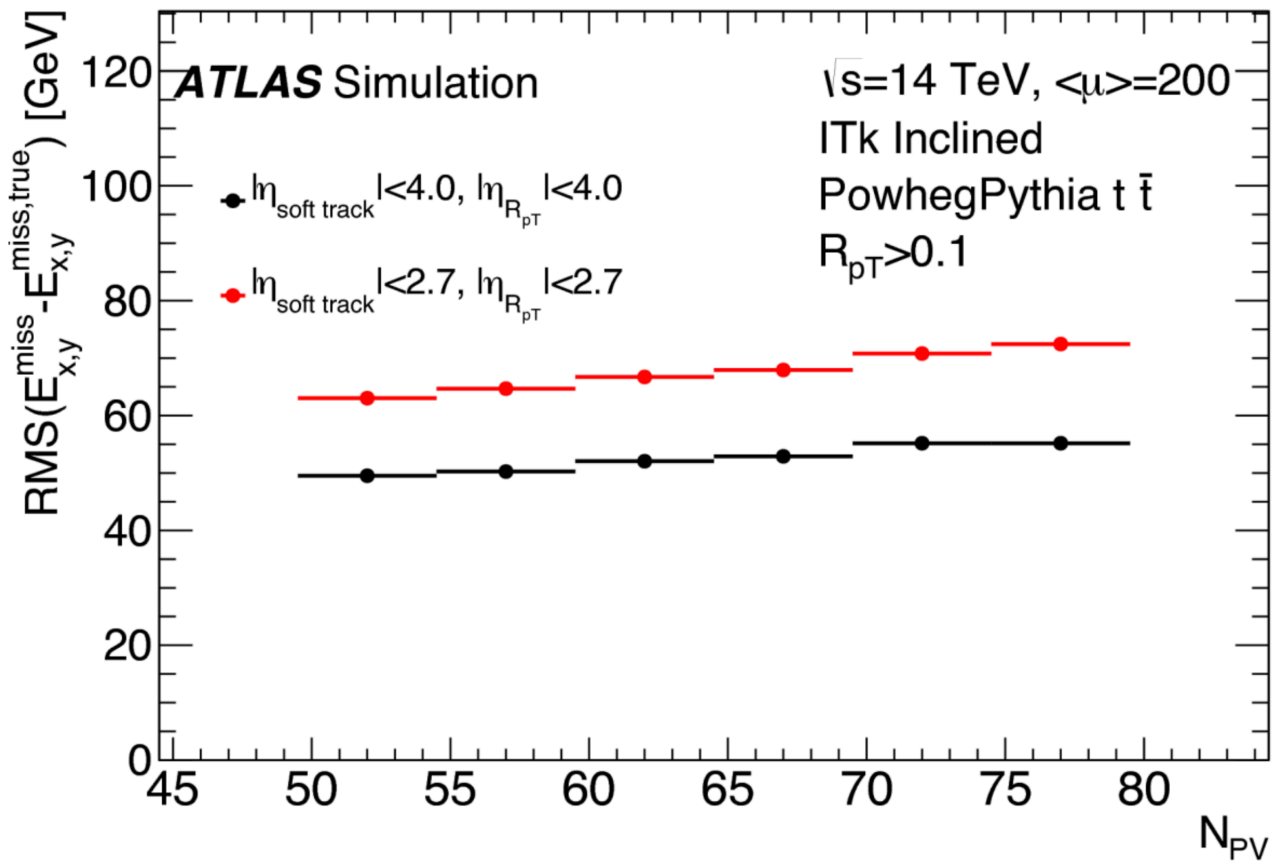
Detector performance after Phase-2 upgrades:

- Effective pileup mitigation
- Overall performance similar or better than during Run 2
- Extended capabilities with new algorithms

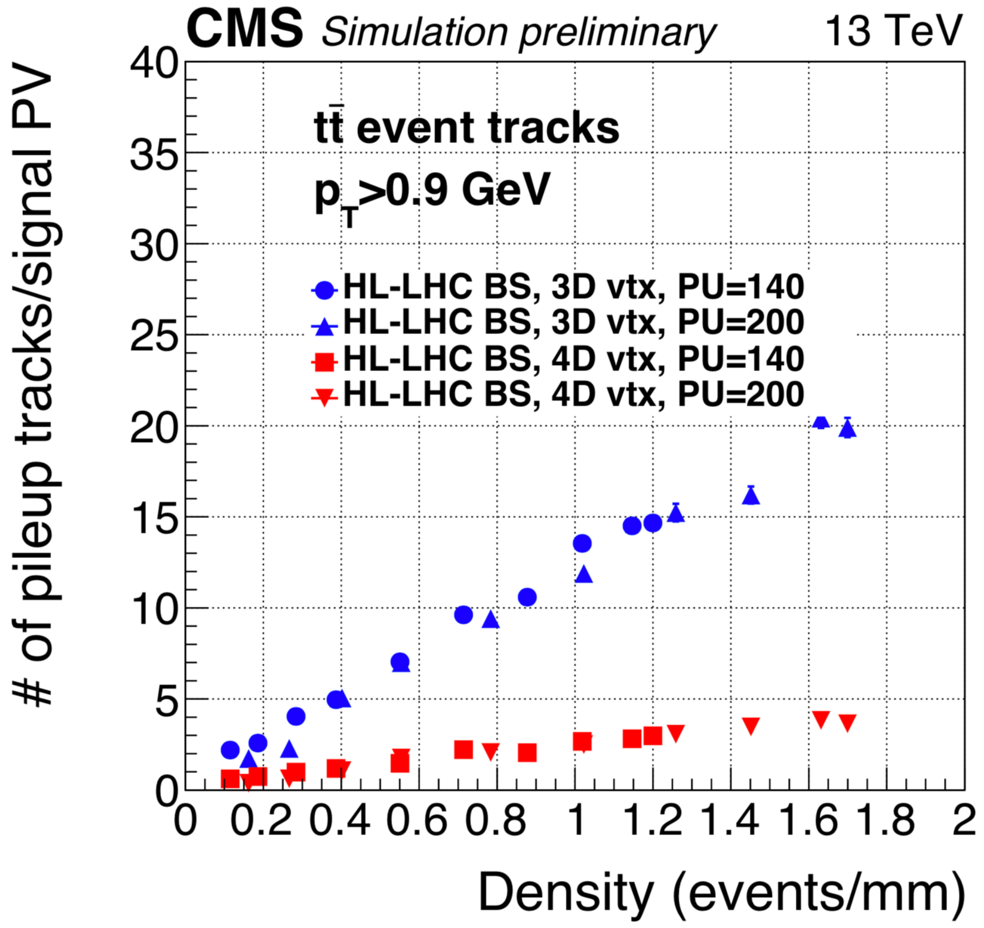
Jets



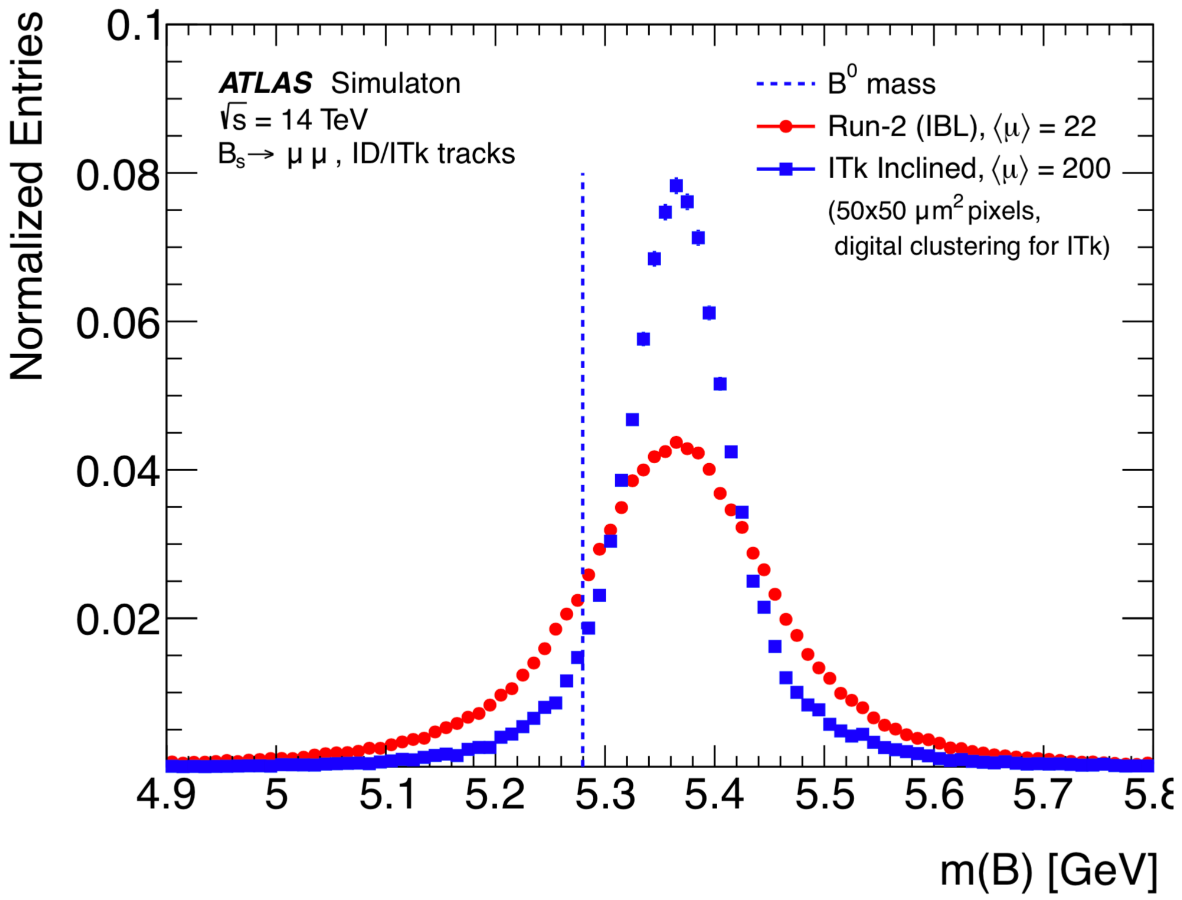
MET resolution



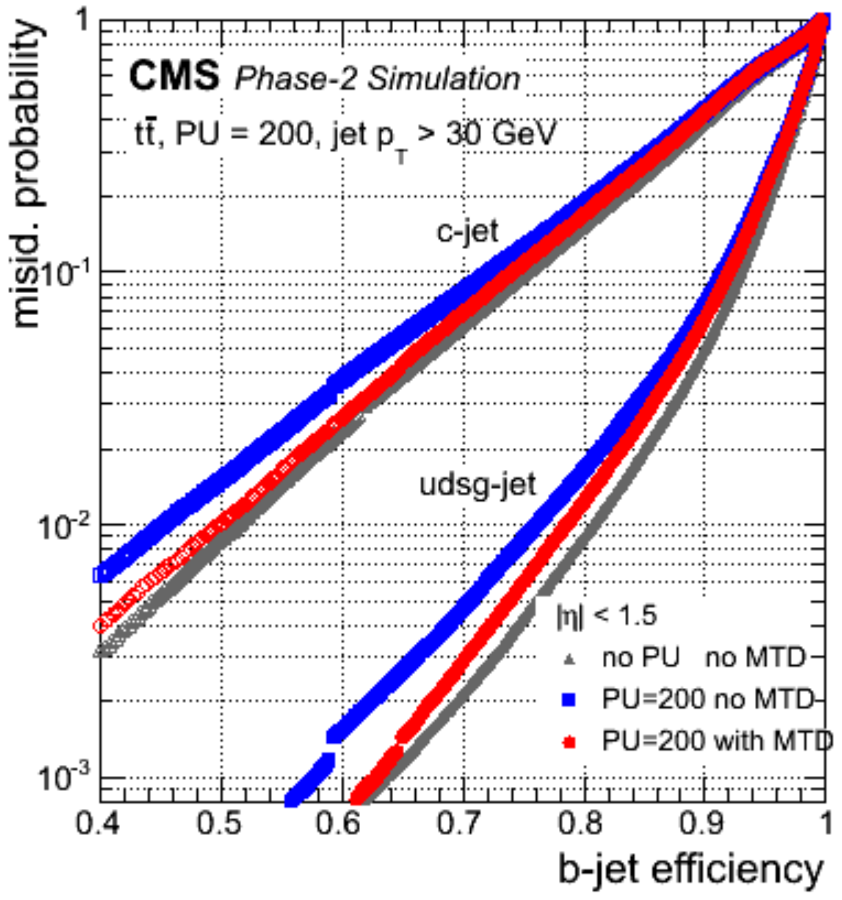
Pile-up suppression



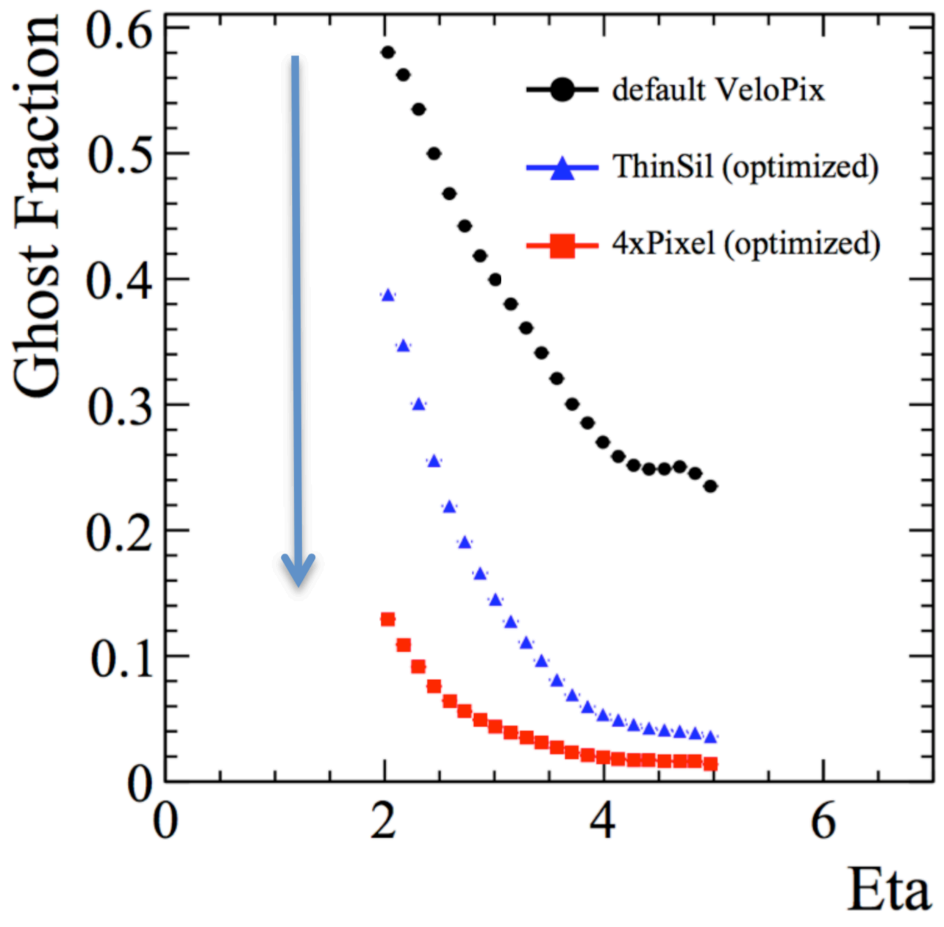
Mass resolution



B-tagging



LHCb Vertex Locator



Systematics recommendations & extrapolation methodology

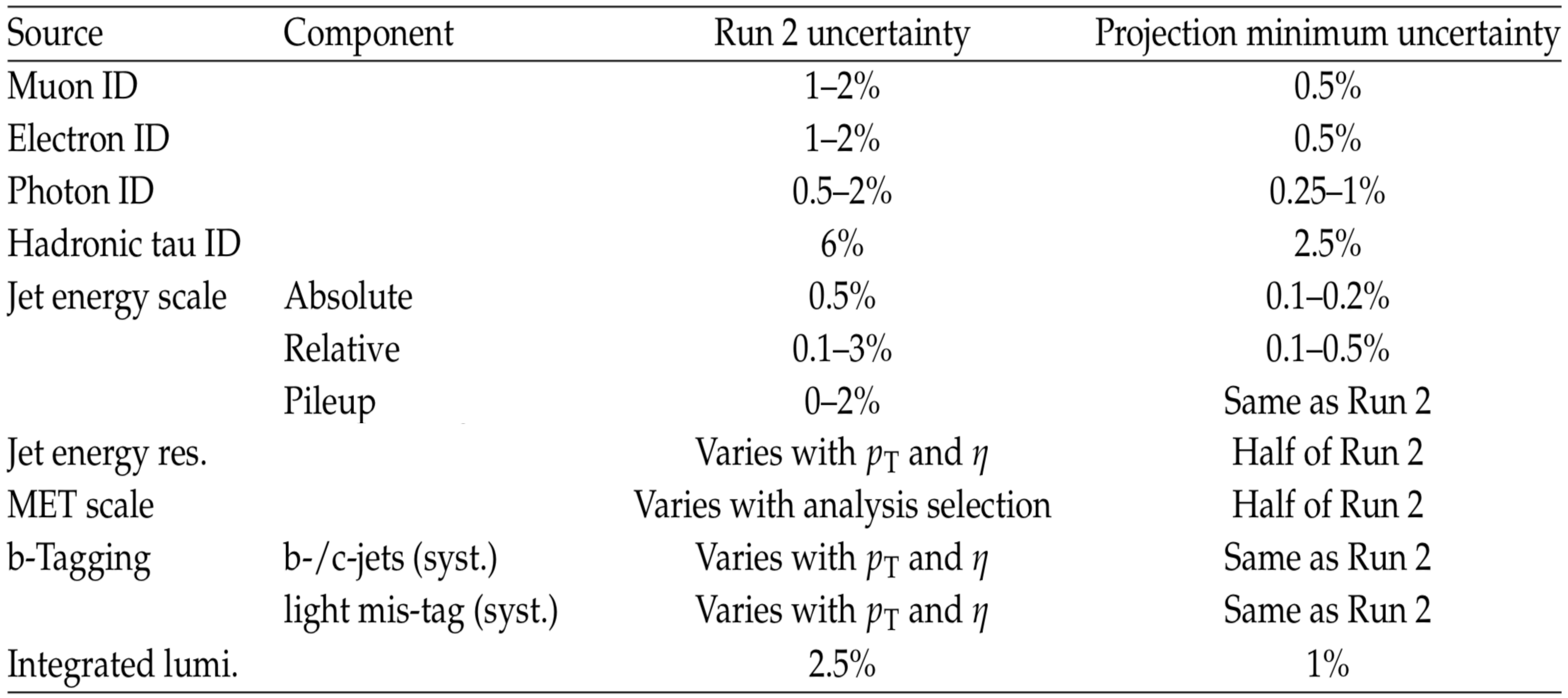
General:

- Systematic uncertainties will be limiting factor for a wide range of measurements
- Assume similar detector & trigger performances
- Aim for as realistic assumptions as possible

Theoretical uncertainties:

- Build upon existing/recent TH progress/studies
- Assume a scaling down by a constant factor
  - QCD calculations (1/2), understanding of PDFs (1/3), top p_T (1/2), etc.

Expected experimental systematic uncertainties



Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
Jet energy res.		Varies with p_{T} and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_{T} and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_{T} and η	Same as Run 2
Integrated lumi.		2.5%	1%

Experimental uncertainties:

- Estimates of ultimately achievable accuracy based on the upgraded Phase-2 detectors studies (TDRs).
- Assumption that sufficiently large simulation samples will be available.

arXiv:1810.03639

Ultimate precision for PDFs @ HL-LHC

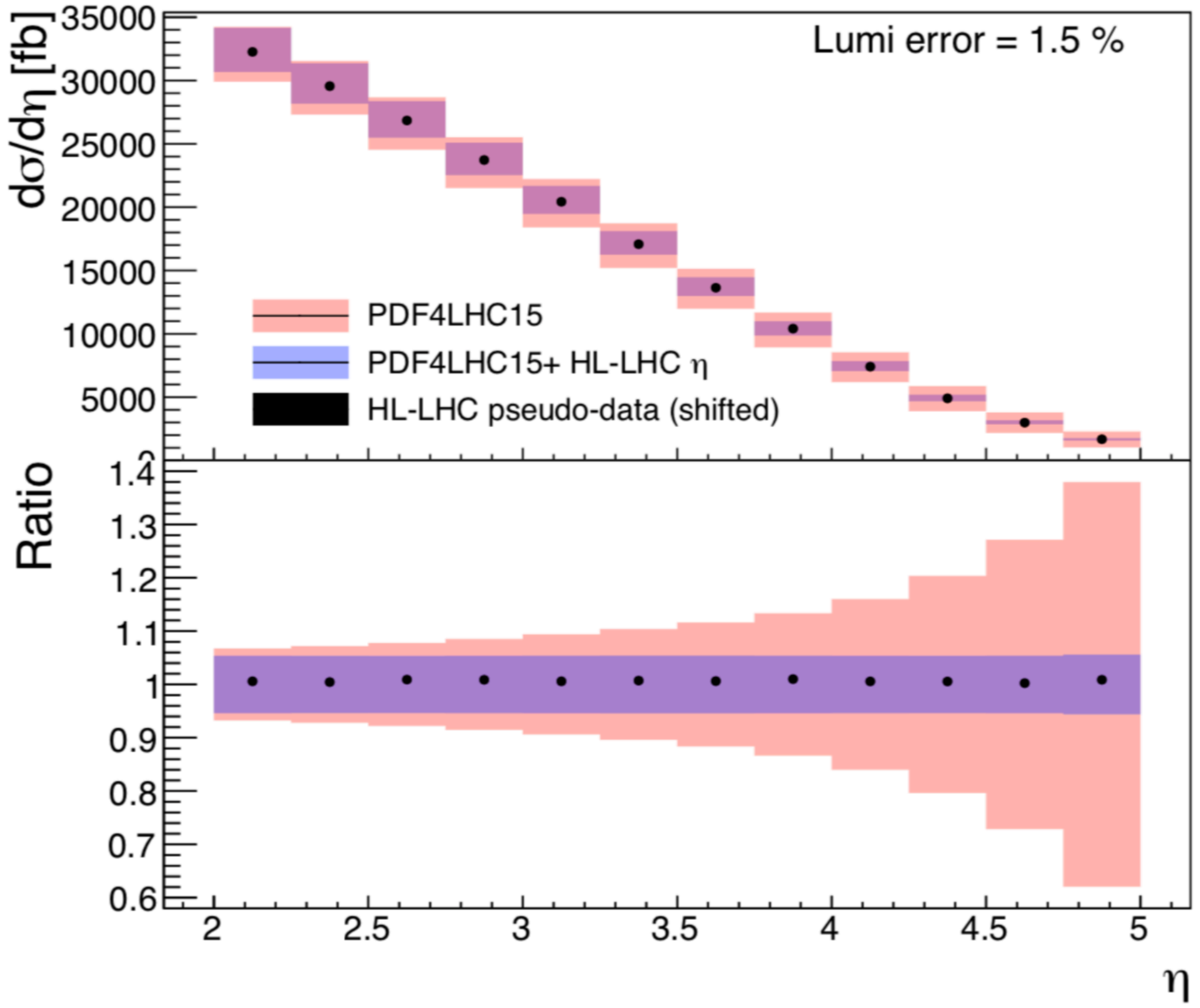
Knowledge of PDFs required to extract:

- fundamental couplings from cross section measurements
- predict the tails of SM distributions at large Q2
- probe the existence of new physics at high scales

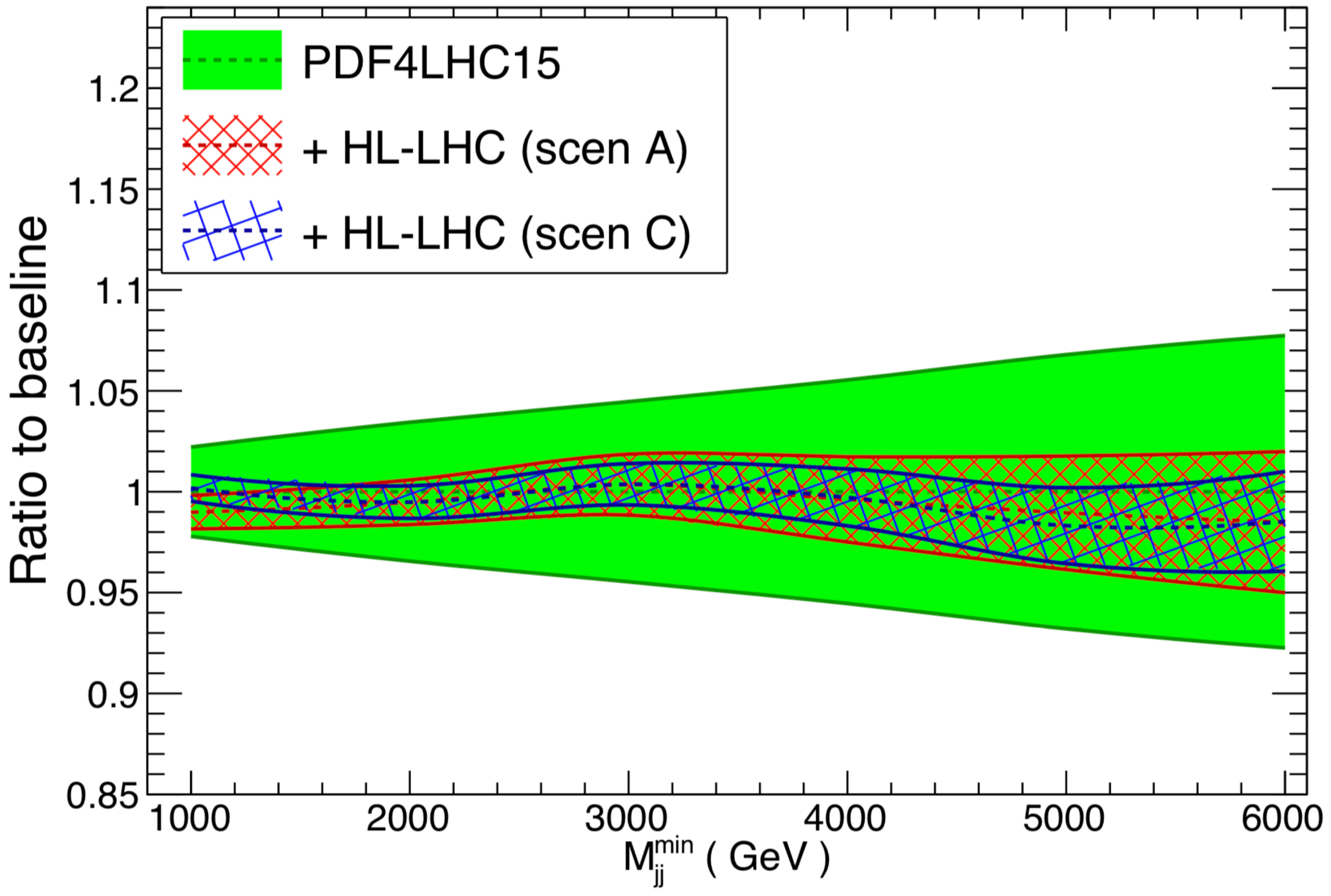
Estimate of PDFs constraints:

- Based on precision differential measurements of processes with: jets, top quarks, photons and EW gauge bosons
- Improvement from use of LHCb data, and access to large rapidities in ATLAS and CMS

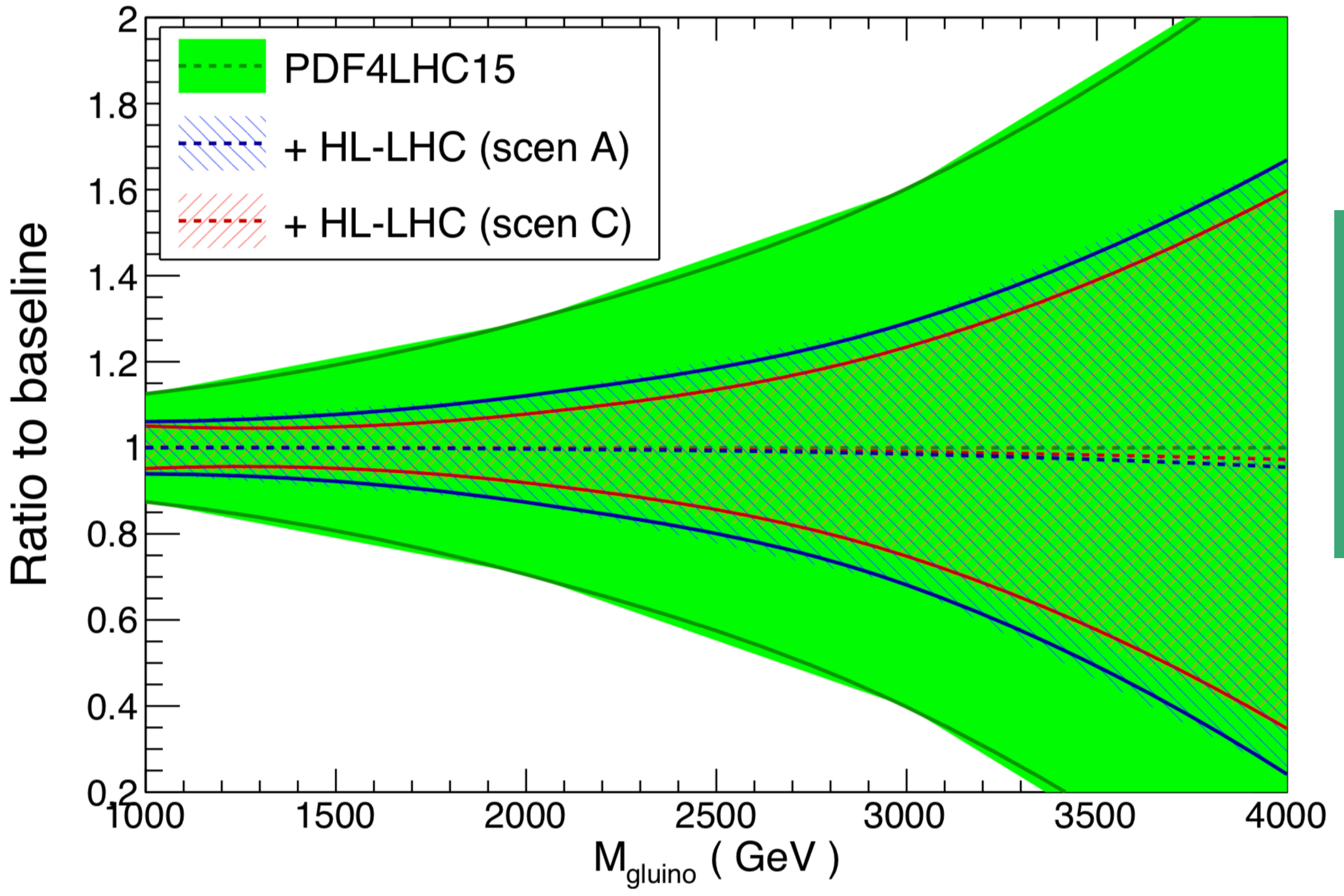
Example W+c data



Di-jet production



Gluino pair production



Improvement by factor ~2-4 (by ~5 at large x)

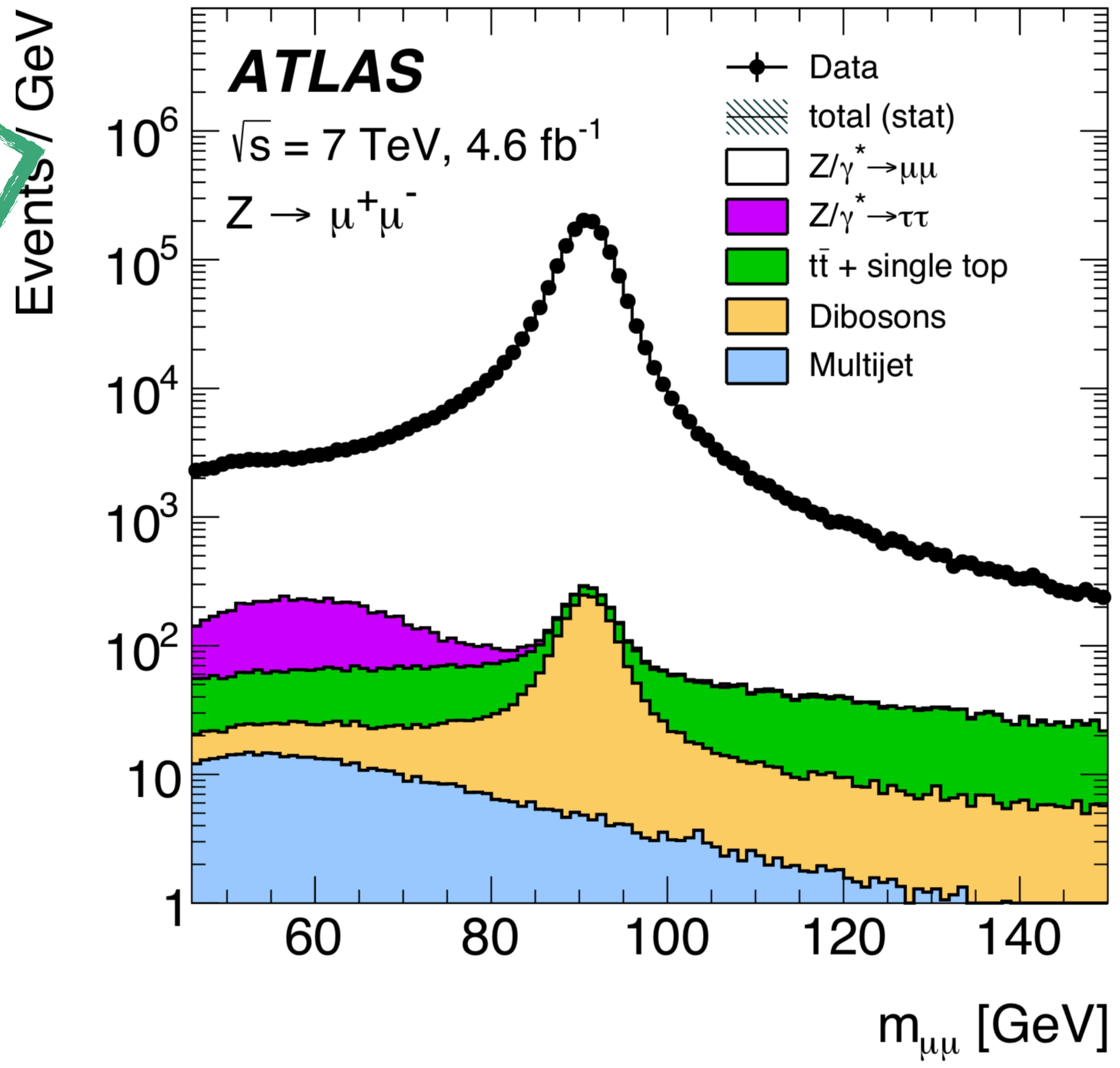
Precision cross sections, EWK mixing $\sin^2\theta_W$

arXiv:1612.03016
arXiv:1806.02184

Ultimate precision for cross sections:

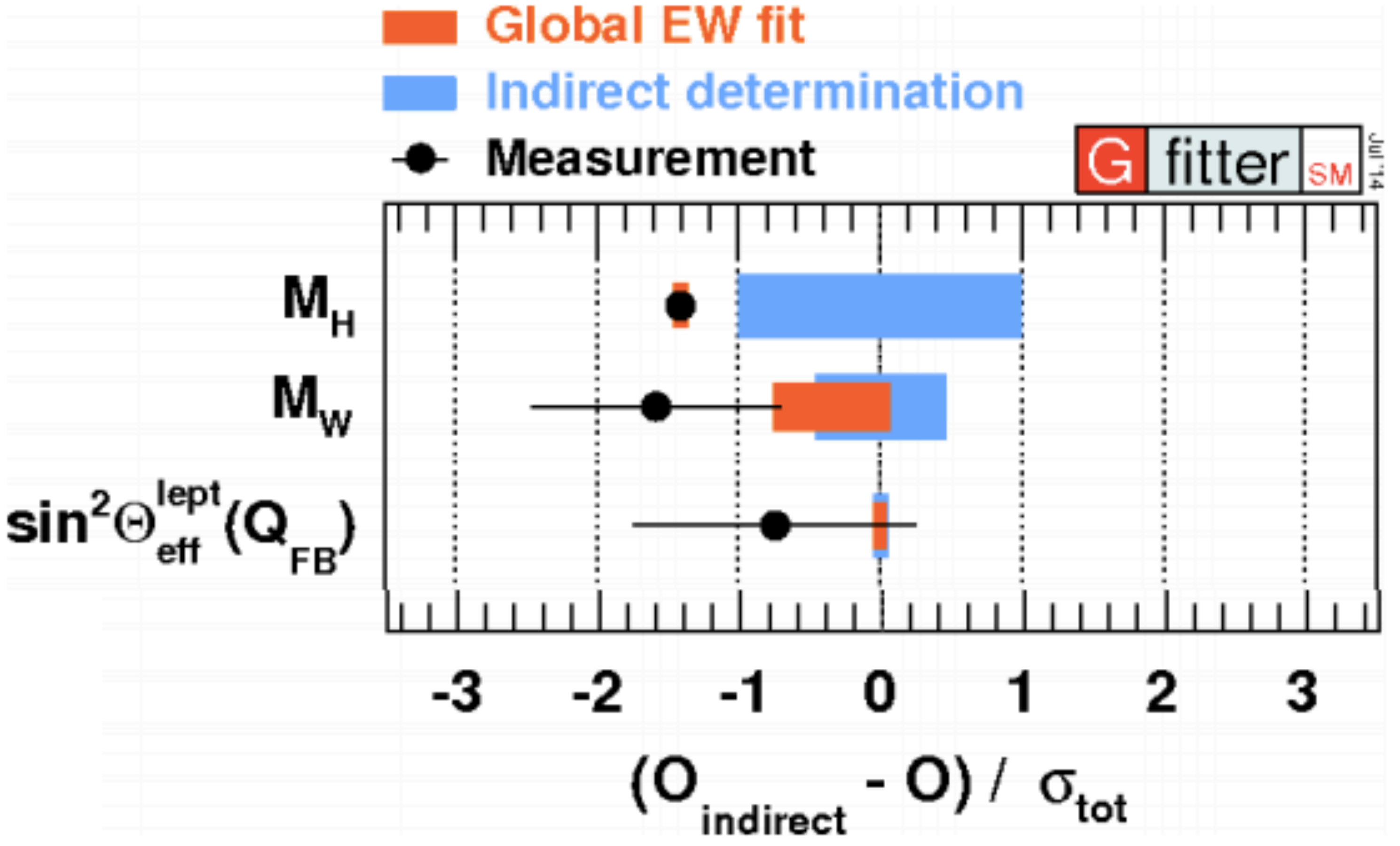
- @LHC: $\sigma(Z \rightarrow \mu\mu) = 502.2 \pm 0.3$ (stat) ± 1.7 (syst) ± 9.0 (lumi)
  - single dominant uncertainty : luminosity ~2%
- **Measurement @HL-LHC:**
  - Improved lumi. detectors, refined VdM scans, use of low-PU runs
- Once measured at (sub-)percent level, use Z cross section to help luminosity measurement.

Target luminosity uncertainty: 1%



Electroweak mixing $\sin^2\theta_W$:

- Total uncertainty likely reduced by a factor of 3 @ HL-LHC
- Individual measurements reach current world-combination uncer
  - Strong benefit from tracker/muon system coverage
  - Complementary ATLAS (electron) and CMS (muon) measurements
- Study effect of improved PDFs



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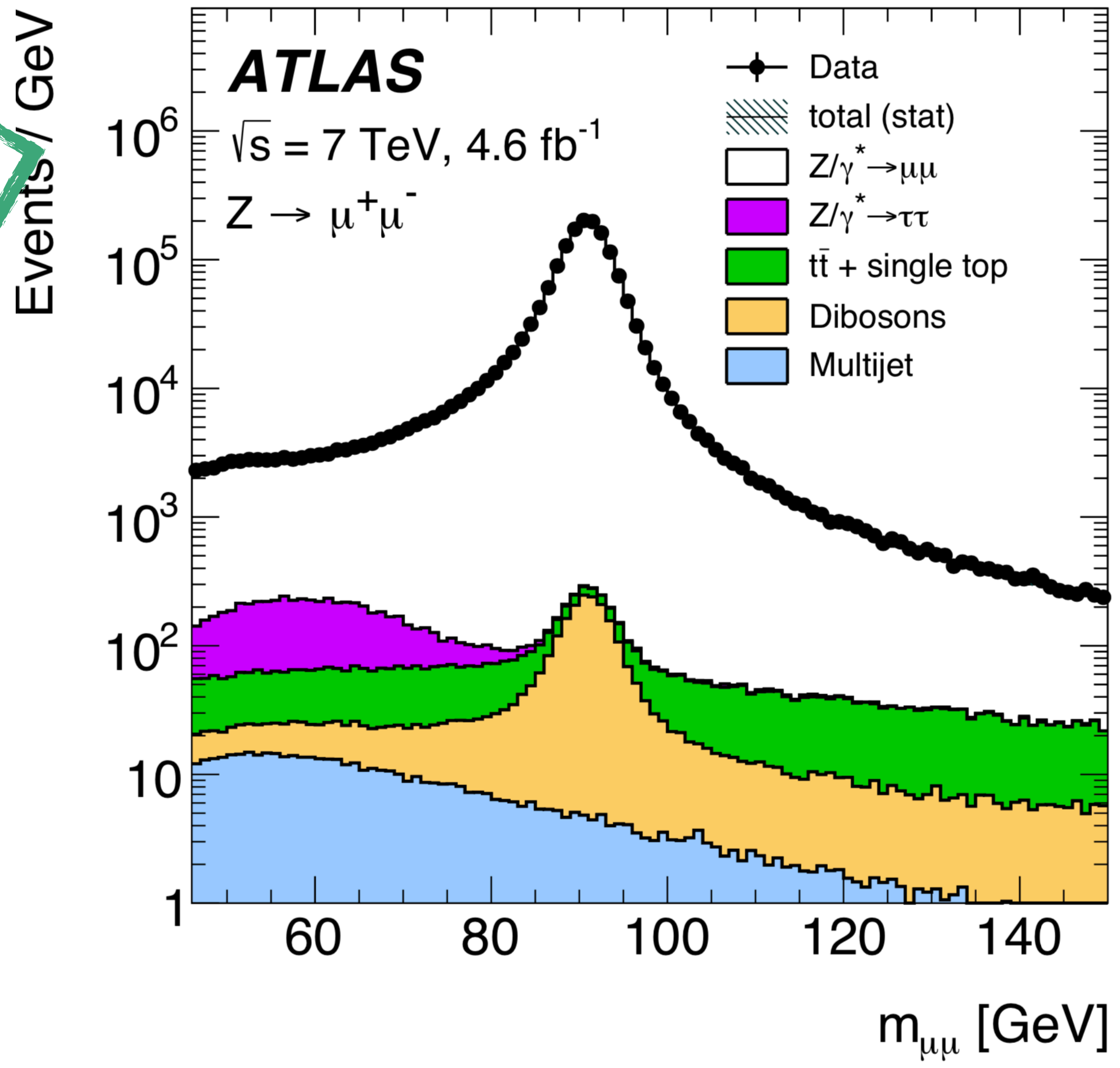
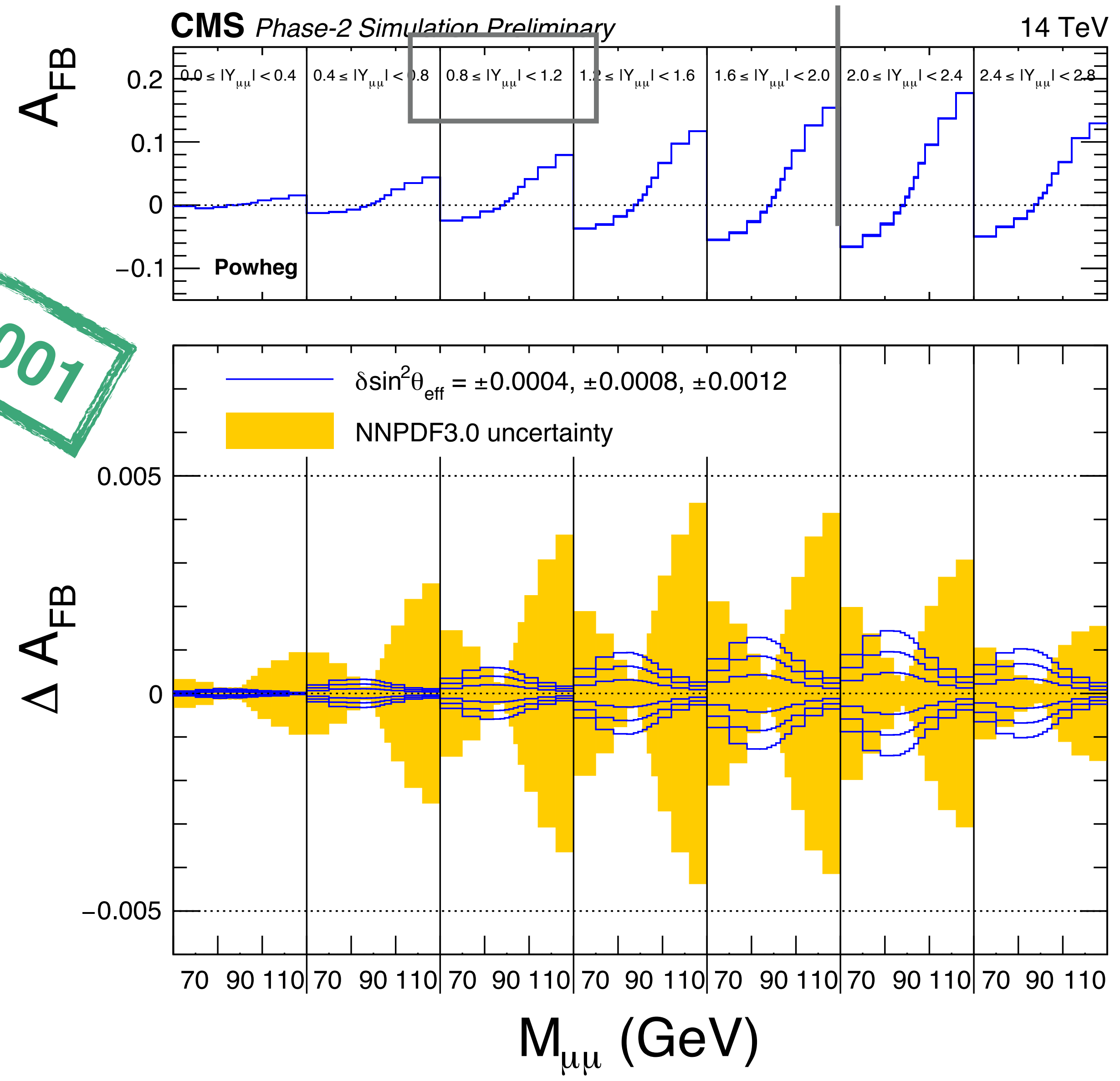


CMS-FTR-17-001



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- Individual measurements reach current world-combination uncertainty
  - Strong benefit from tracker/muon system coverage
  - Complementary ATLAS (electron) and
    CMS (muon) measurements
- Study effect of improved PDFs

Ultimate precision for W mass

arXiv:1701.07240
ATL-PHYS-PUB-2018-026

W mass measurement:

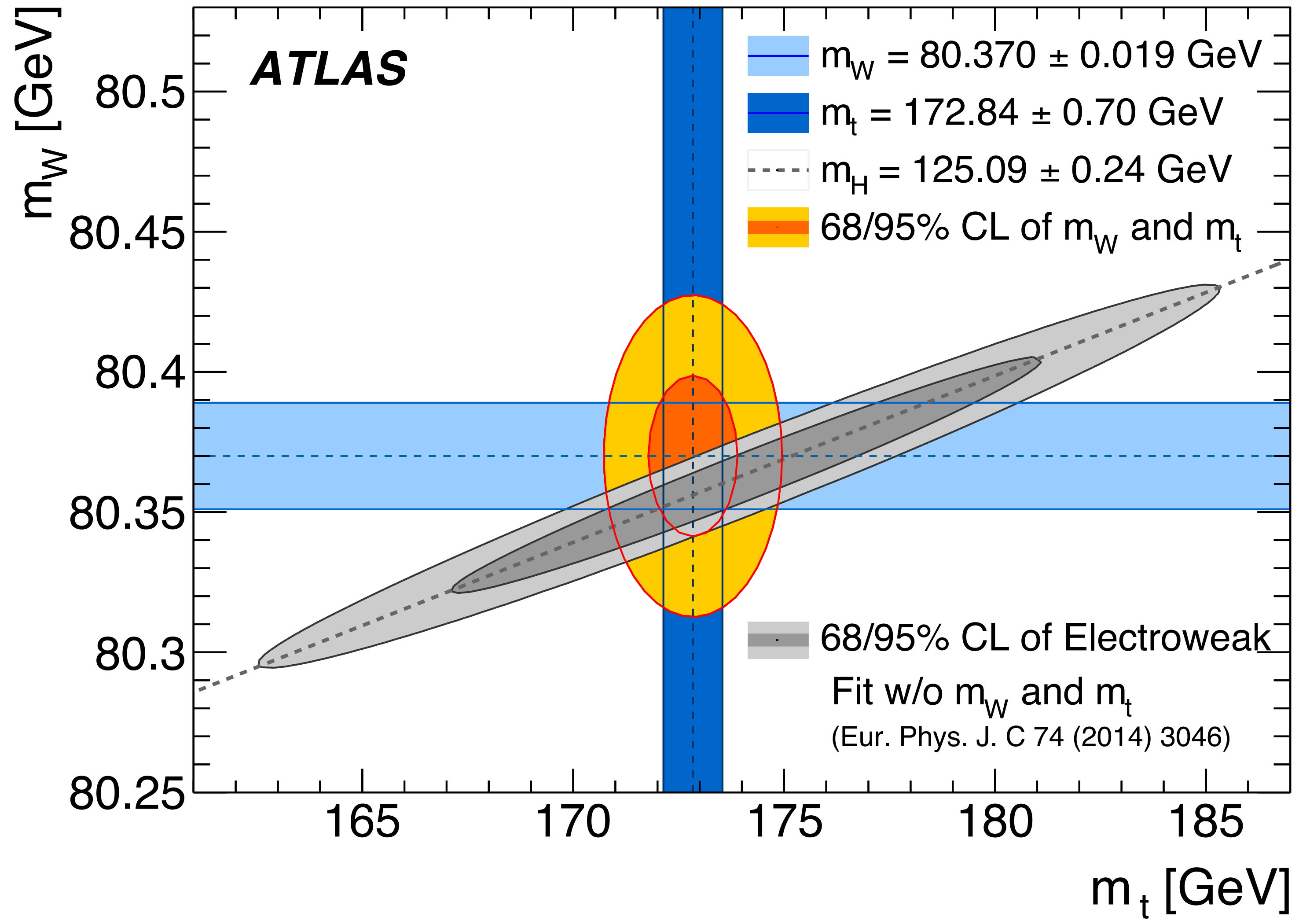
- Improved knowledge of the W mass - key target of HL-LHC
- Current dominant uncertainty from PDFs
  - limit PDF sensitivity via extended leptonic coverage |η| < 4
- Required optimal reconstruction of missing transverse momentun
  - low-pile-up runs are a necessity

Precision @HL-LHC:

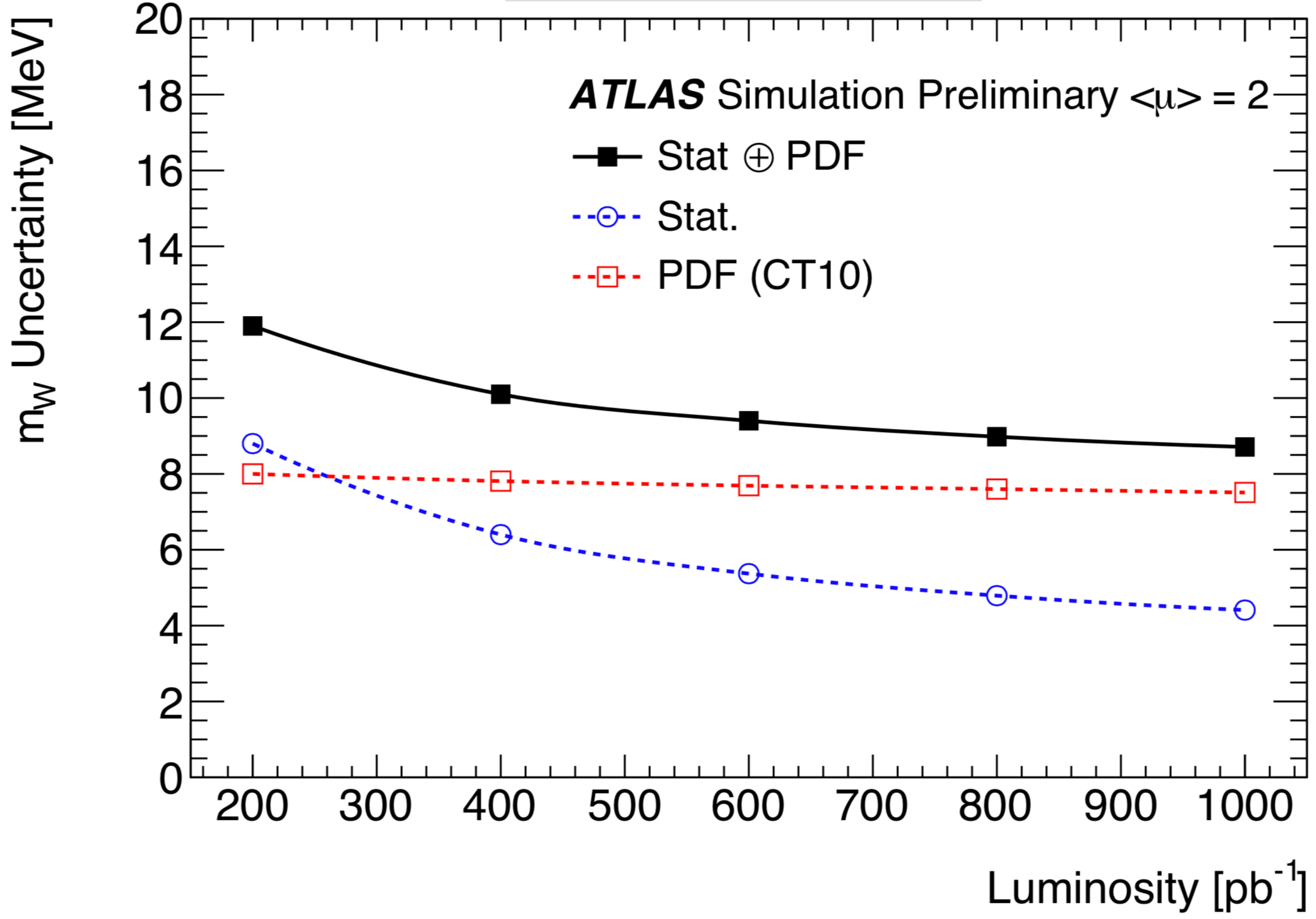
- Low-PU runs (with μ~2)
  - run 1 week: statistical precision **~9 MeV**
  - run 5 weeks: statistical precision **~4 MeV**
- Systematics with HL-LHC ultimate PDF **~4 MeV**

overall target of Δm_W = ±6 MeV

Latest m_W result @LHC



Gluino pair production



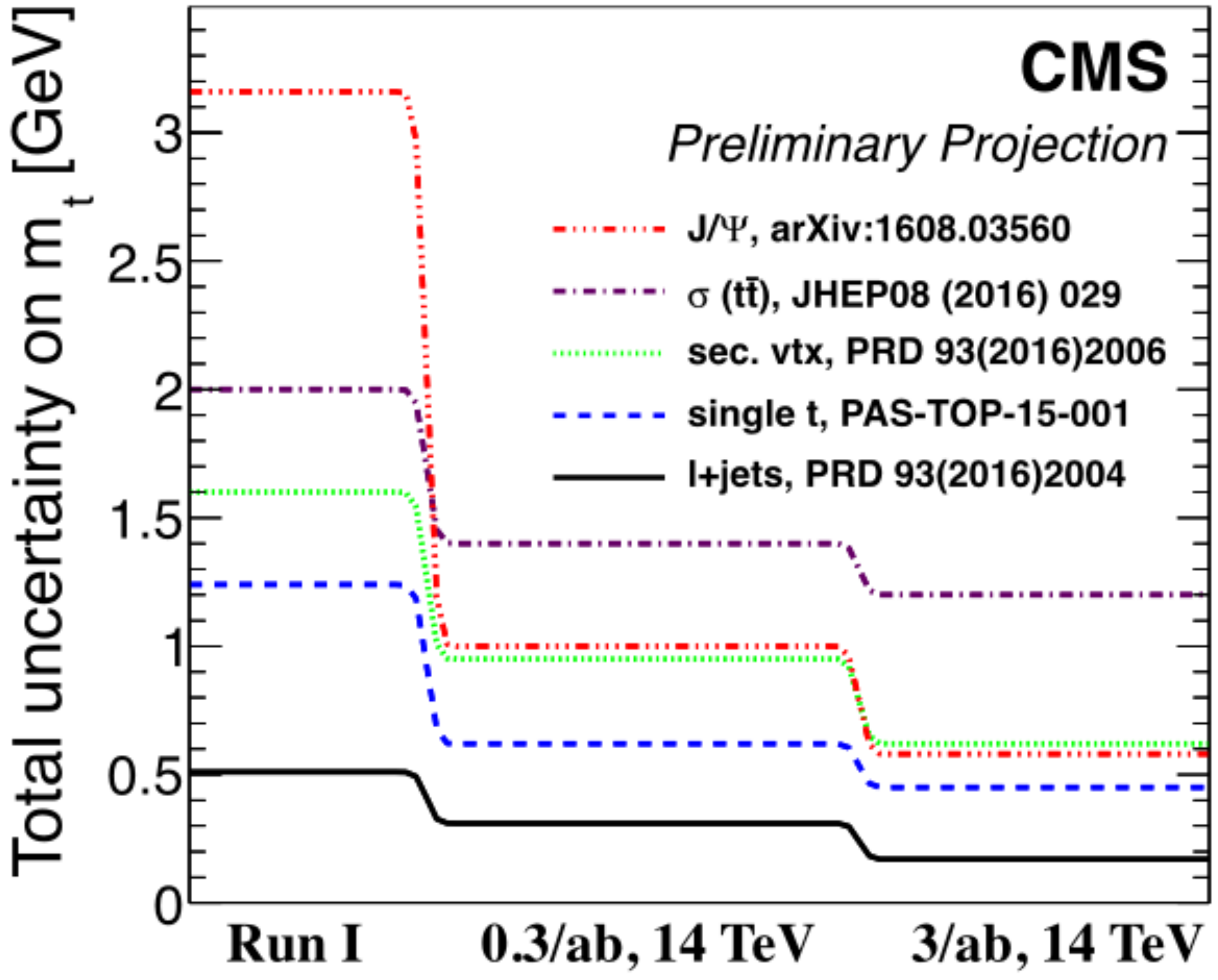
CMS FTR-18-005

Ultimate precision for top mass

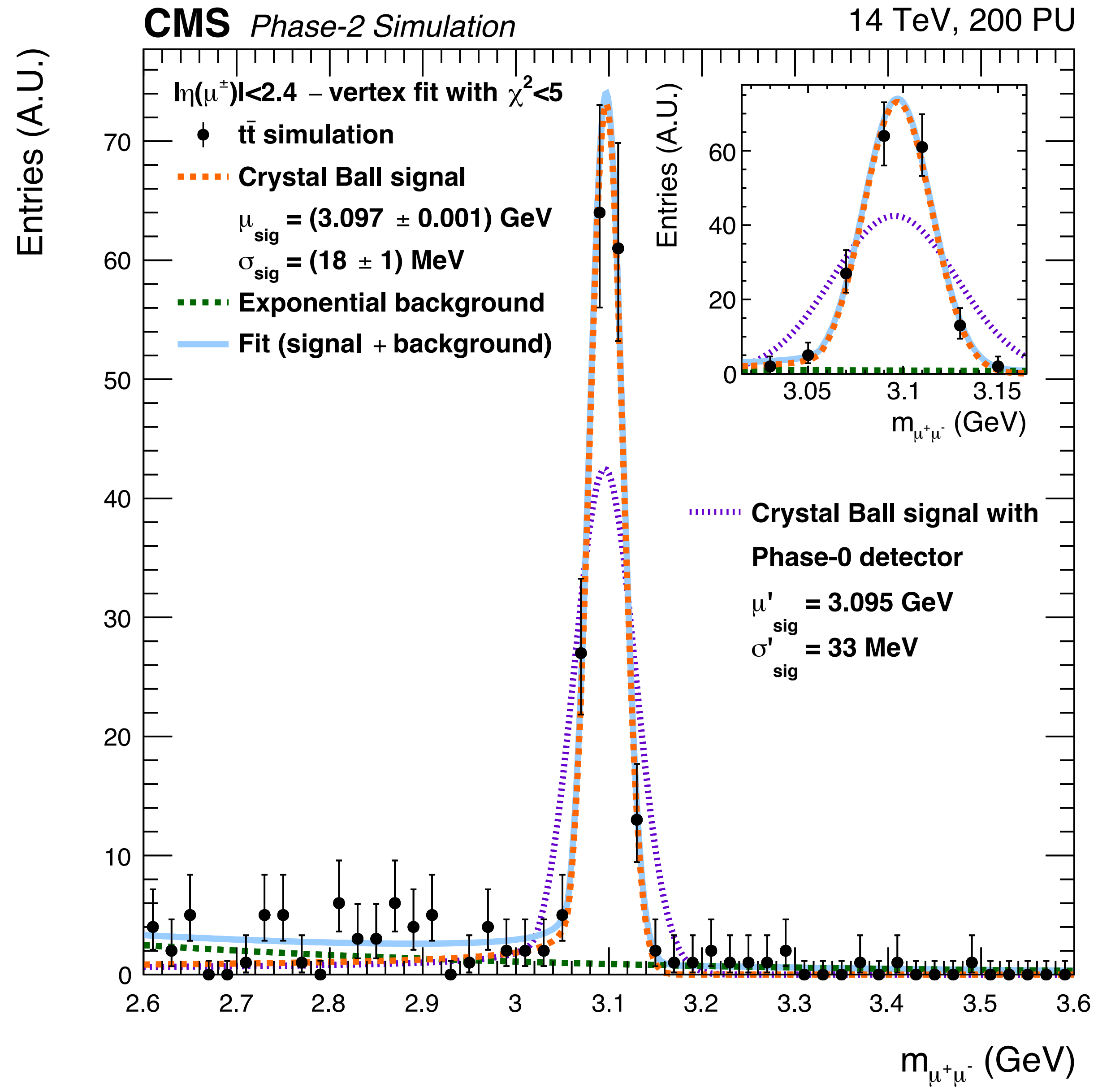
Top mass measurement @HL-LHC:

- Improved uncertainty through more statistics, calibration, better modelling, etc.
- Require future theoretical developments for interpretation in terms of a theoretically well defined mass
- Several methods available

Precision for different methods



"J/ψ method" (t→bW→J/ψlνX)



Precision for different methods

Method:	$t\bar{t}$ lepton+jets	t-channel single top	$m_{SV\ell}$	J/ψ	$\sigma_{t\bar{t}}$
Δm_{top} (GeV):	0.17	0.58	0.62	0.45	1.2

- cross-section (m_{pole})
- secondary vertex
- single top
- J/ψ method
- ℓ+jets

expect Δm_{TOP} < ±0.2 GeV

Anomalies in "Flavour" Physics

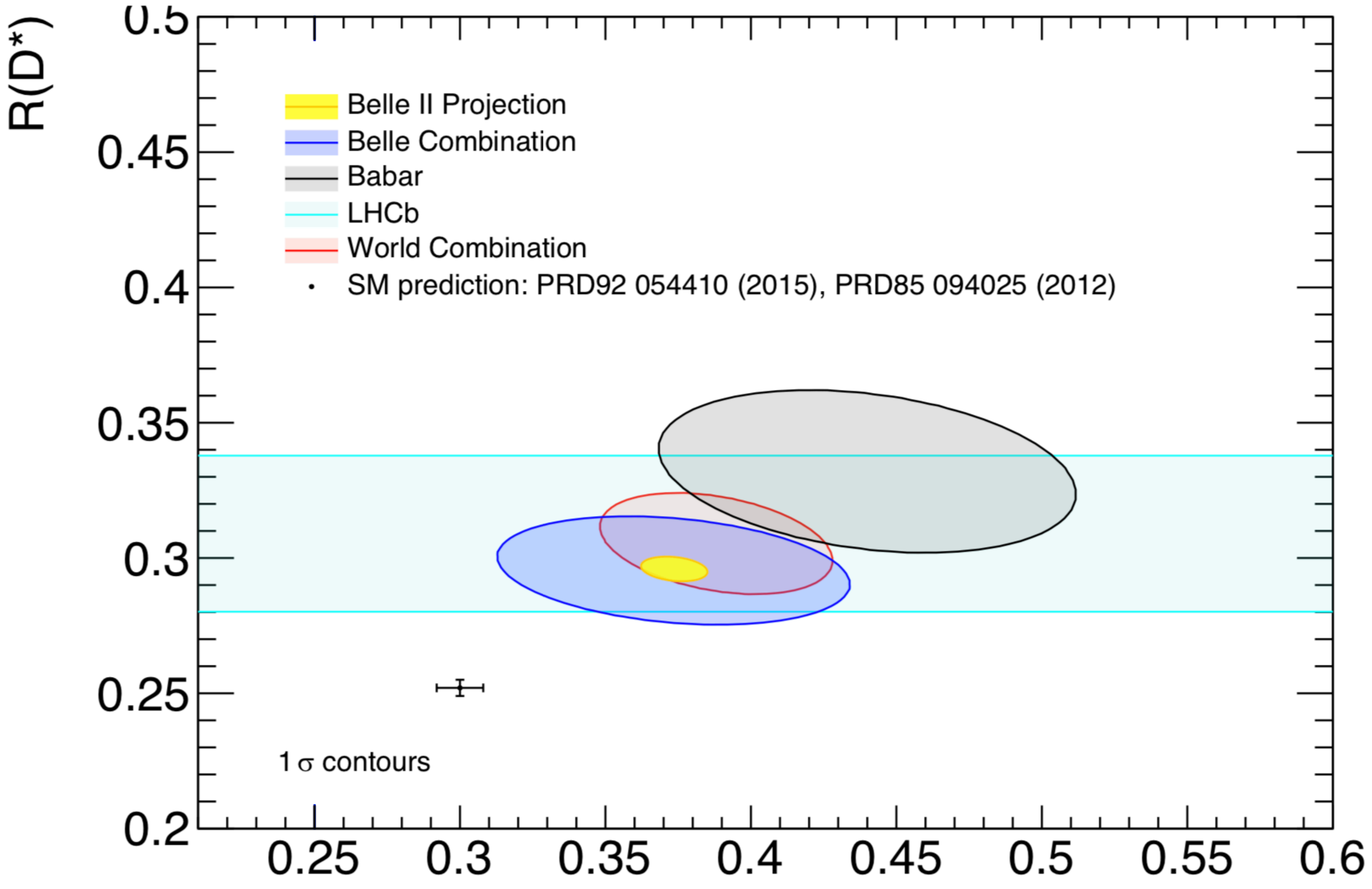
Flavour anomalies - low-q^2 :

- Asymmetry between **e** and **μ** in decay width $\mathbf{B \to K^{(*)}\ell^+\ell^-}$
  - observed by LHCb, but not by Belle, BaBar
- Asymmetry between **τ** and **μ/e** in decay width $\mathbf{B \to D^{(*)}\ell^+\ell^-}$
  - incompatibility with SM (by LHCb, Belle, BaBar)

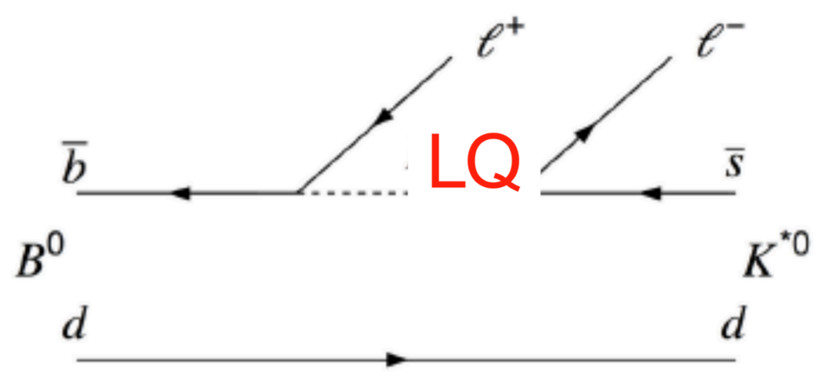
Flavour anomalies - high-q^2 :

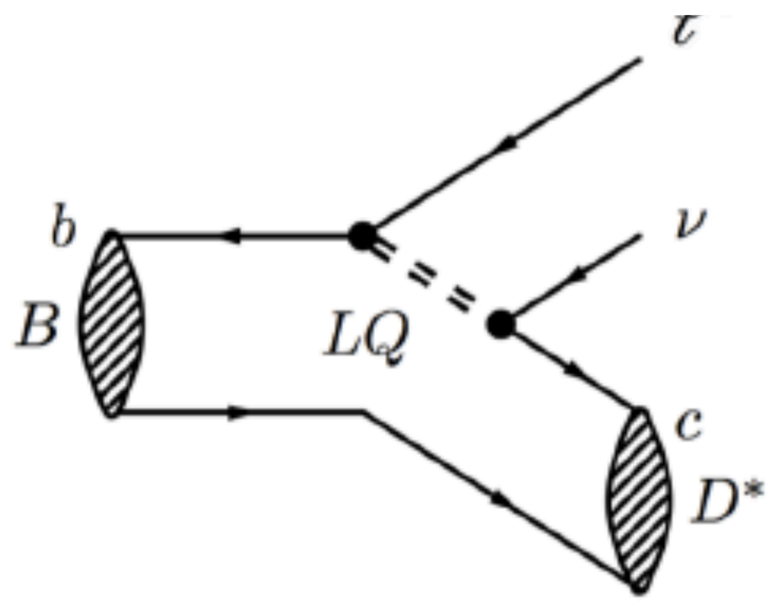
- **R(K*) & b → s $\ell^+\ell^-$**
  - Minimally flavour violating Z' ruled out (res. searches)
- **R(D) / R(D*) & b → c τ ν**
  - Good fits for W' vector, scalar, or vector LQ

Flavour anomalies & LHCb



Flavour anomalies & Lepto-Quarks





CMS-FTR-18-008

Anomalies in "Flavour" Physics

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- Asymmetry between **τ** and **μ/e** in decay width $\mathbf{B \to D^{(*)}\ell^+\ell^-}$
  - incompatibility with SM (by LHCb, Belle, BaBar)

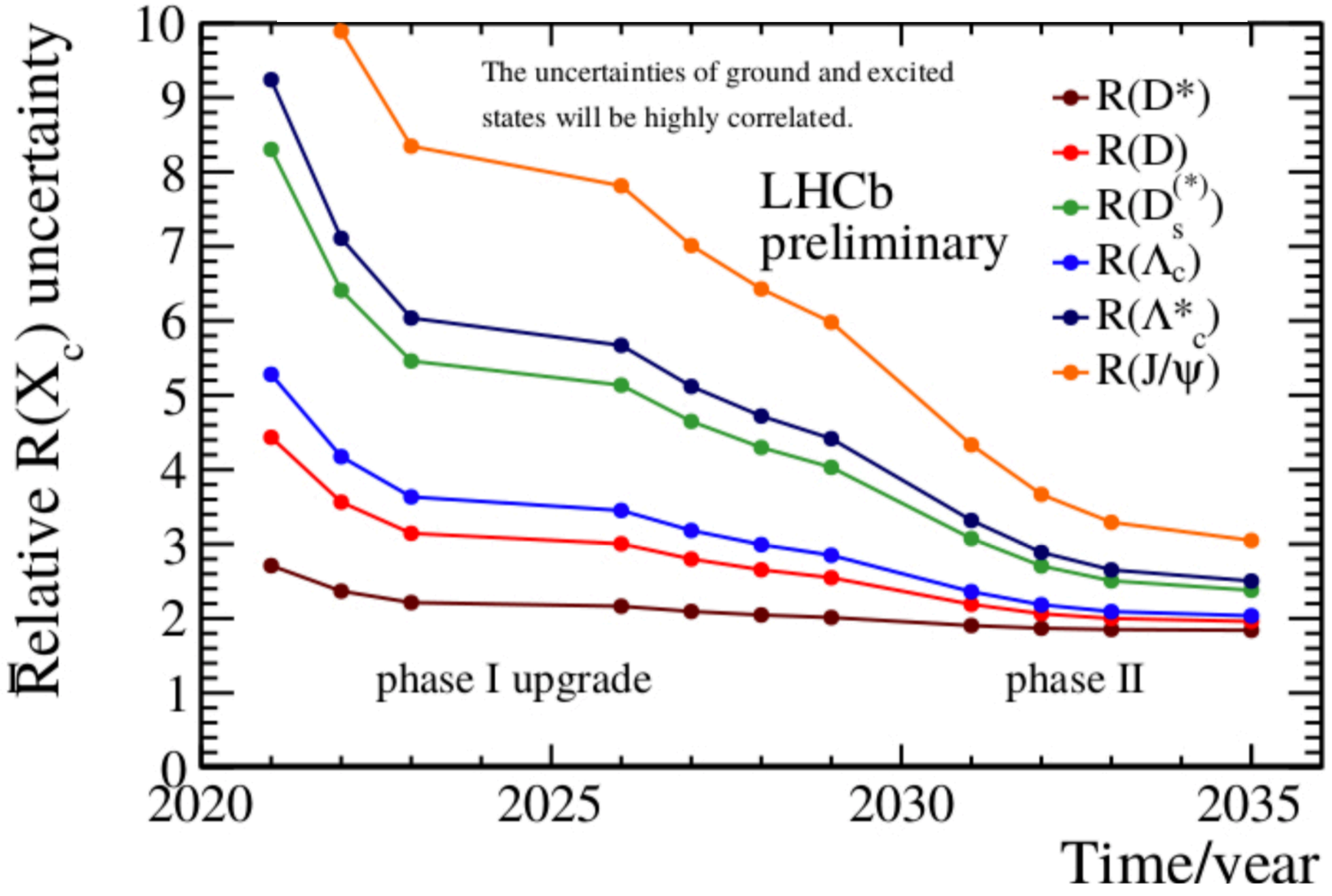
LHCb able to measure in several channels

Flavour anomalies - high-q^2 :

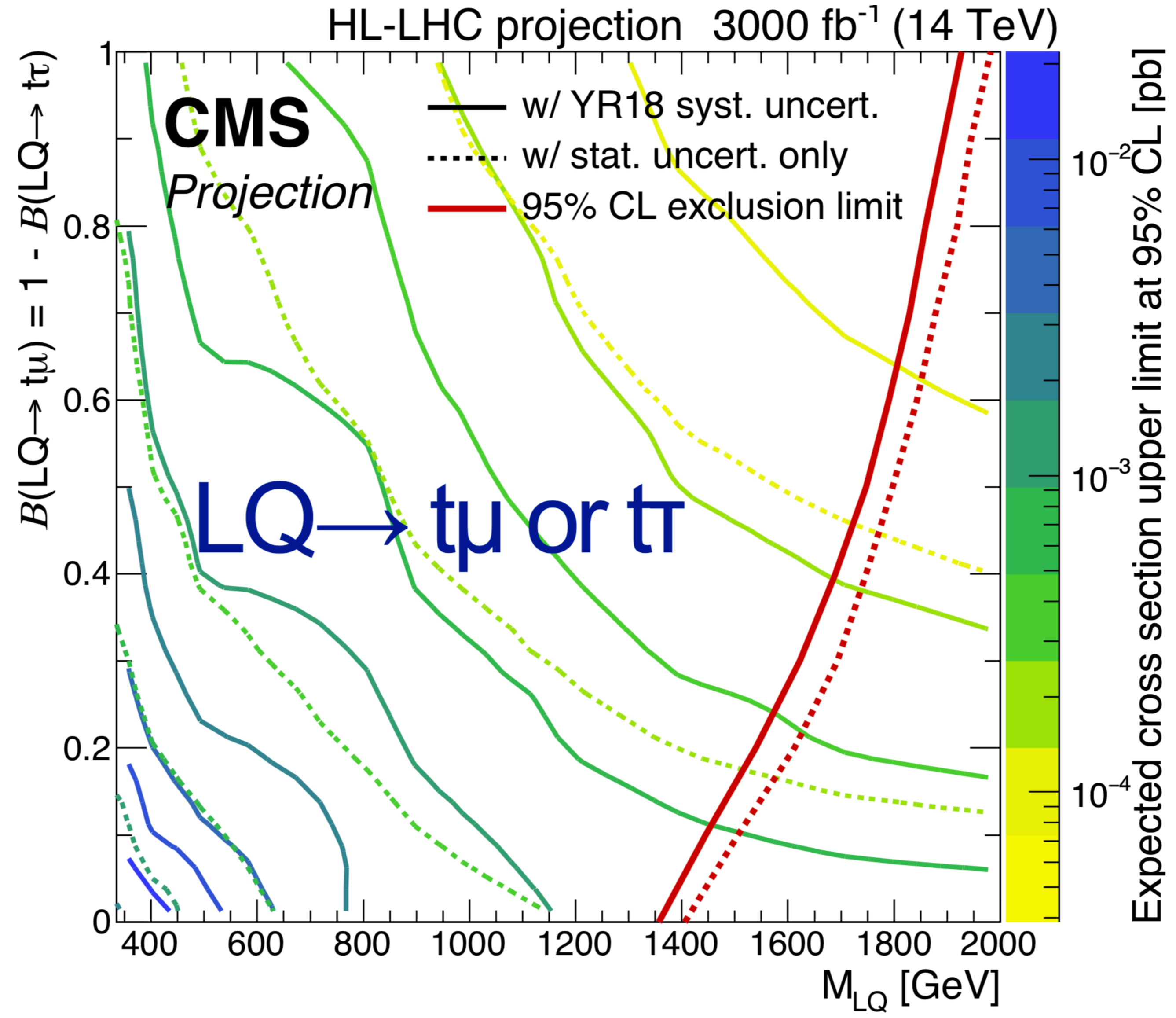
- **R(K*) & b → s $\ell^+\ell^-$**
  - Minimally flavour violating Z' ruled out (res. searches)
- **R(D) / R(D*) & b → c τ ν**
  - Good fits for W' vector, scalar, or vector LQ

Light LQ3 could explain R(D) and R(K*) ?

Flavour anomalies & LHCb



Flavour anomalies & Lepto-Quarks



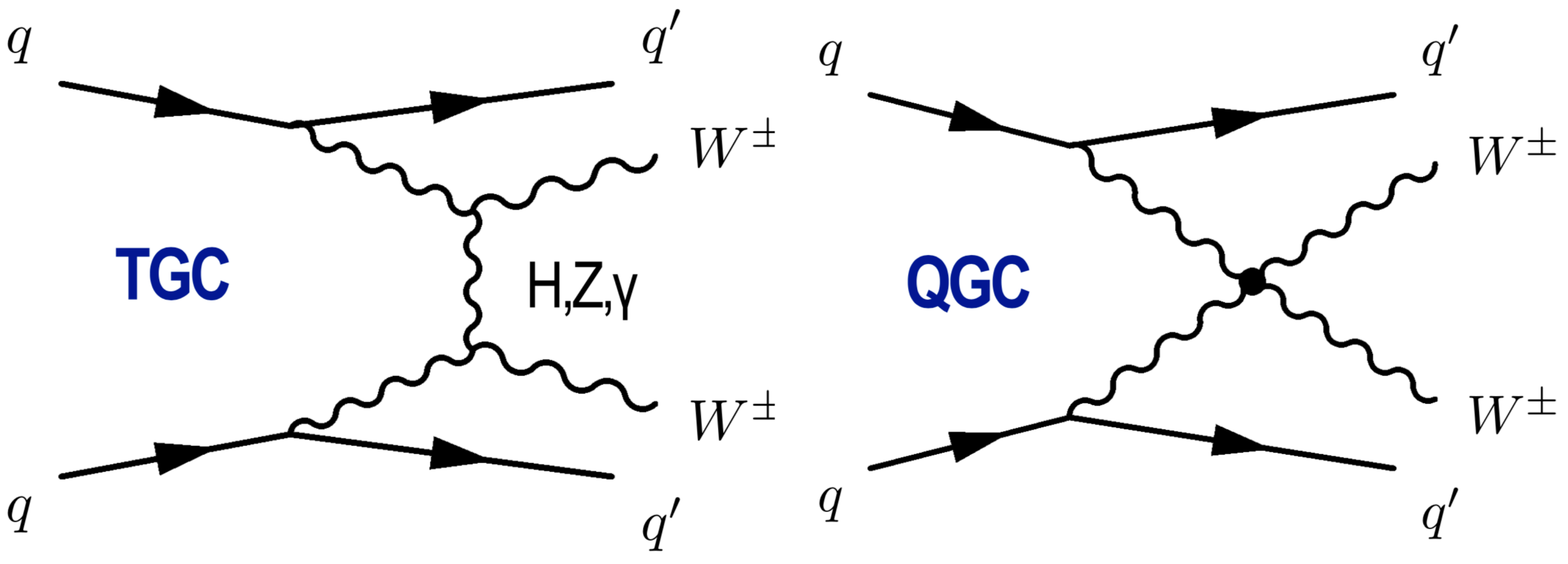
Vector boson scattering

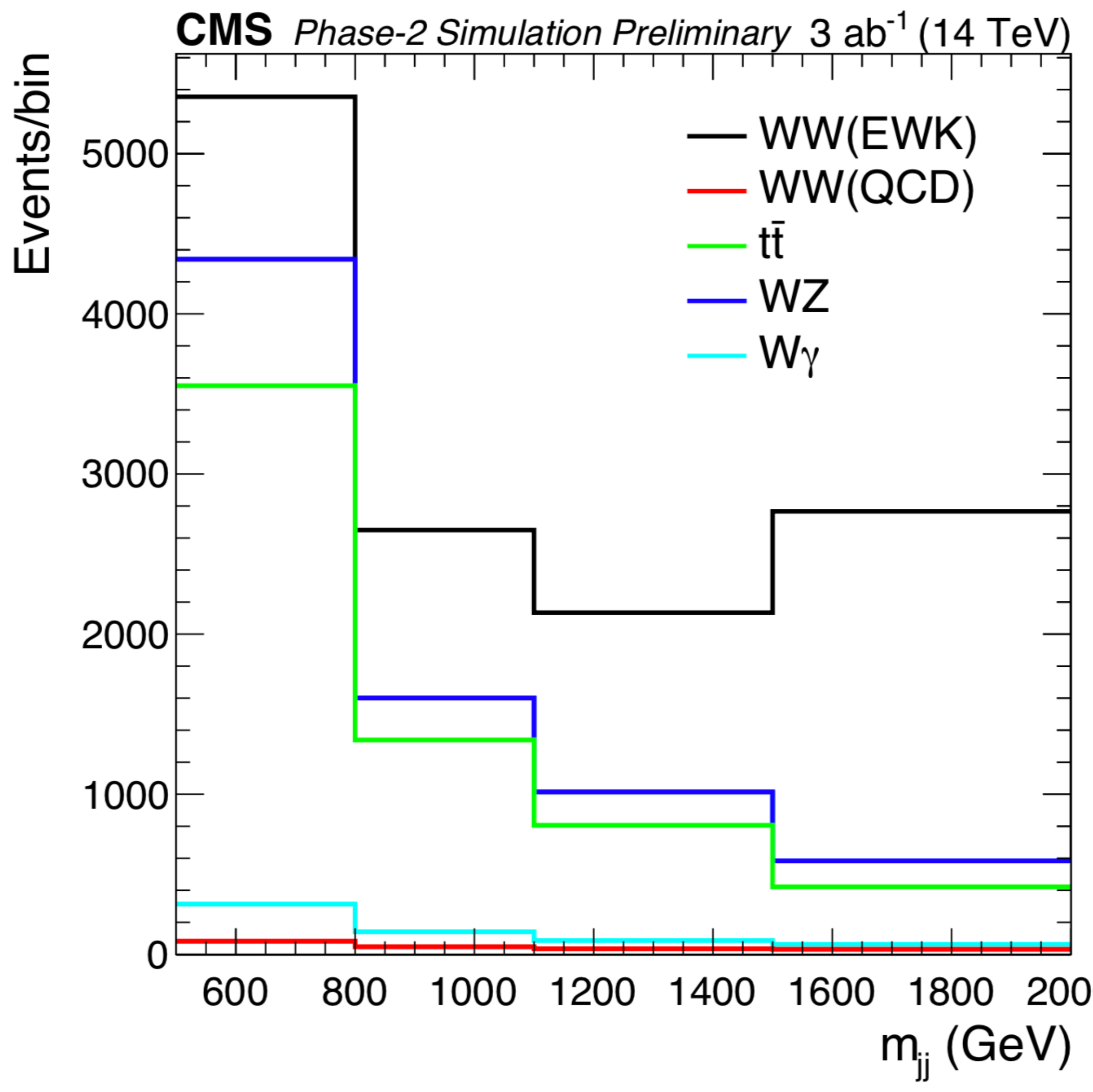
CMS-FTR-18-005
ATL-PHYS-PUB-2018-023
ATL-PHYS-PUB-2018-029

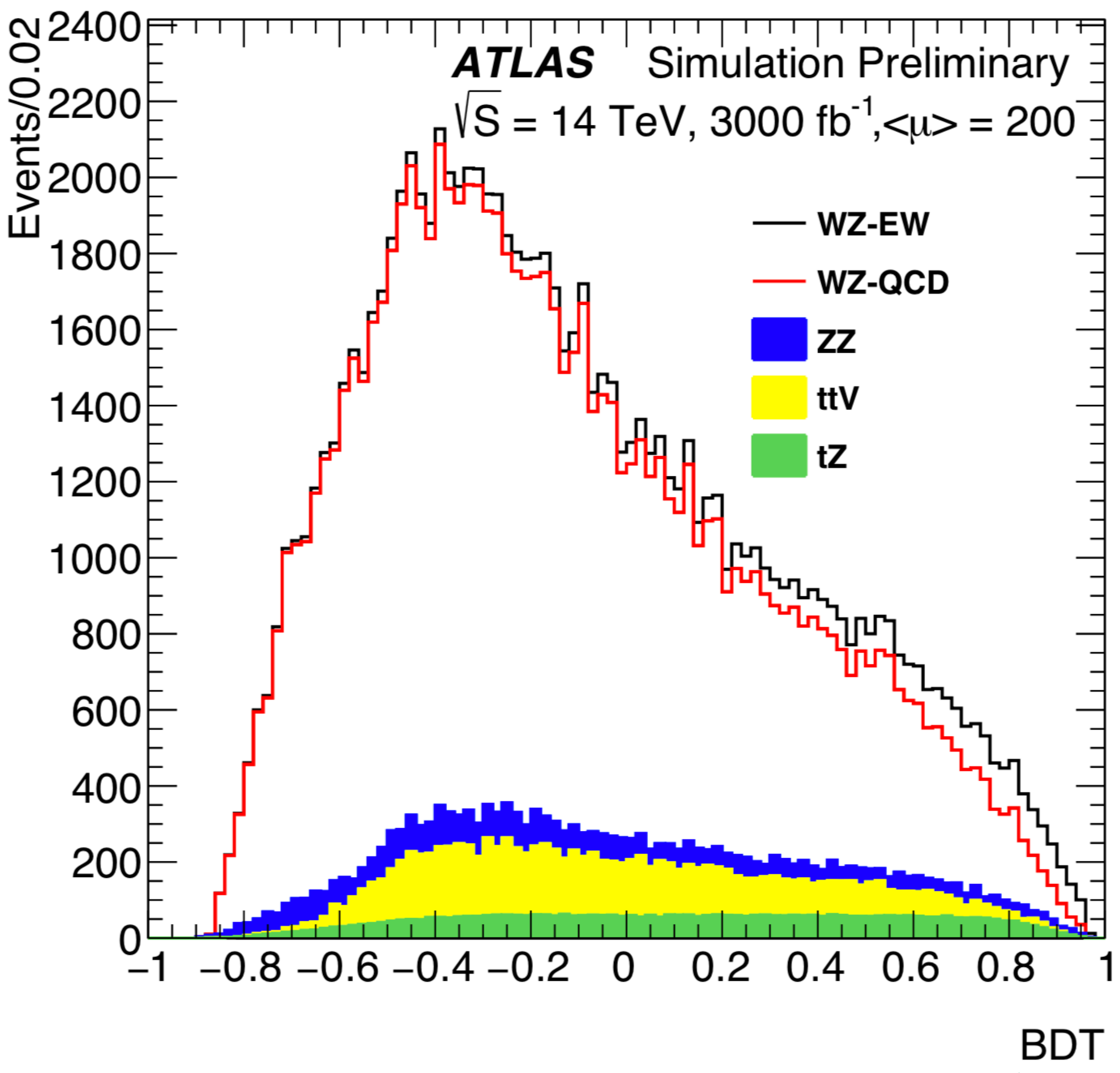
Vector boson scattering @ HL-LHC:

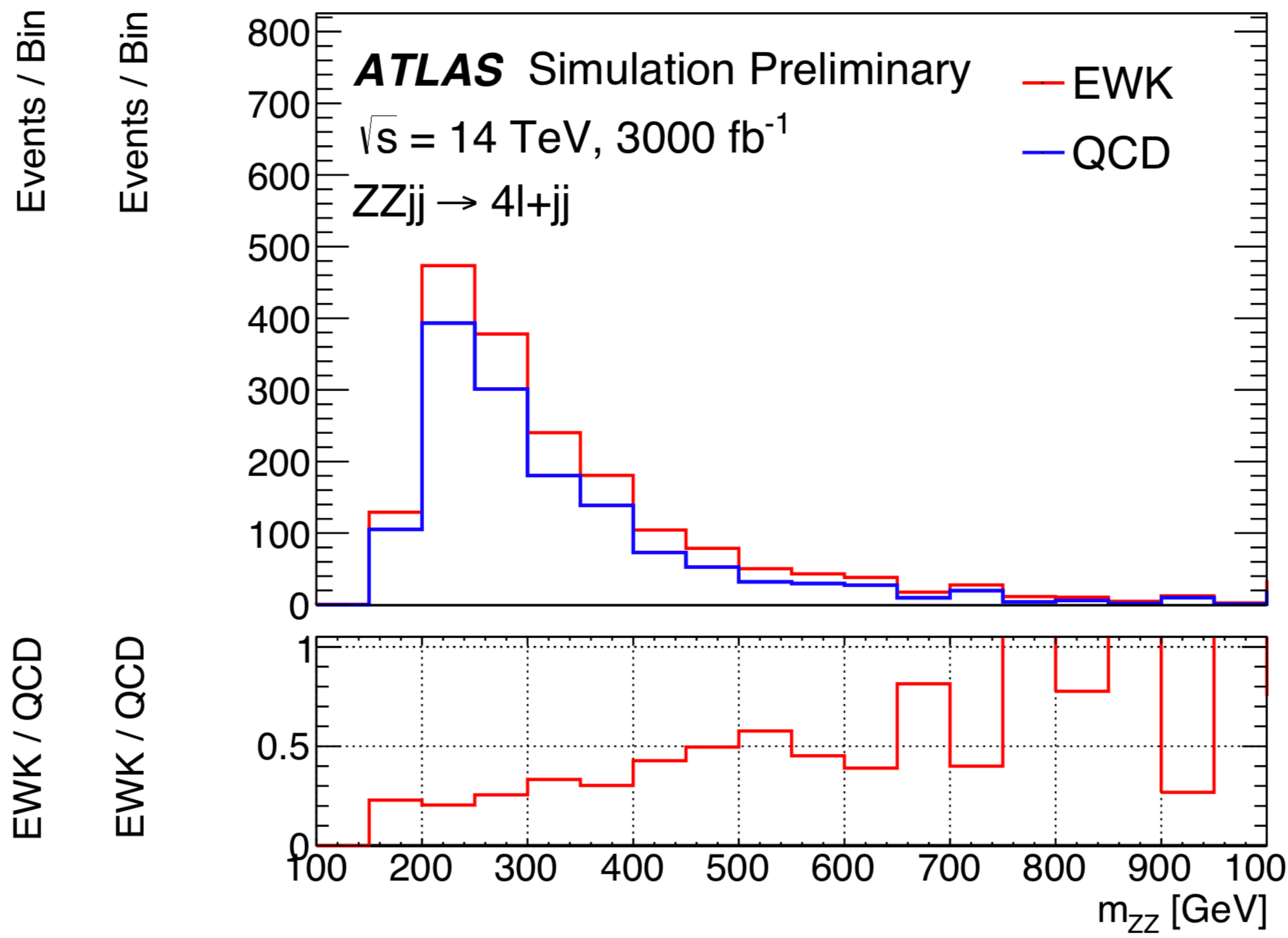
- Precision test of triple & quartic gauge couplings (TGC, QGC)
  - Electroweak WW and WZ scattering observed in Run-2
- Unitarization of $V_L V_L \rightarrow V_L V_L$ cross section at TeV scale:
  - Scalar Higgs and/or new physics to cancel divergence
- Direct test of EW-symmetry breaking mechanism

Vector boson scattering









$\delta\sigma_{EWK}$(WW): ~3%

$\delta\sigma_{EWK}$(WZ): 5-10%

$\delta\sigma_{EWK}$(ZZ): ~10%

CMS-FTR-18-005
ATL-PHYS-PUB-2018-023

Vector boson scattering

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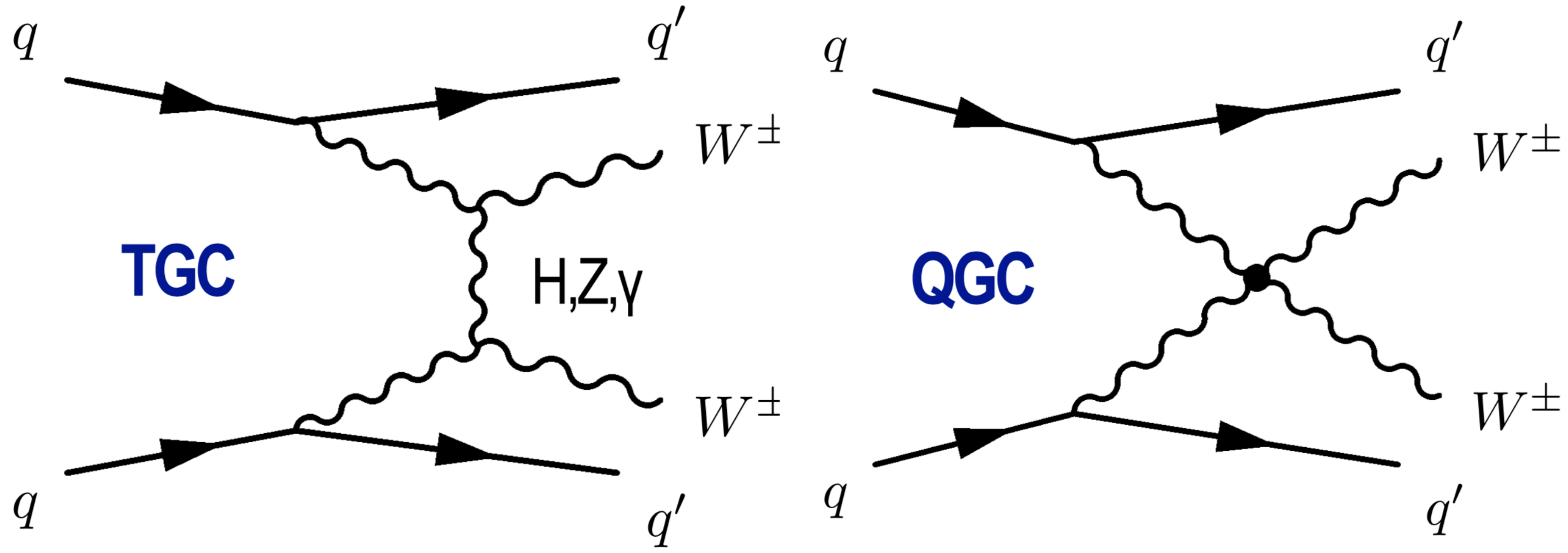
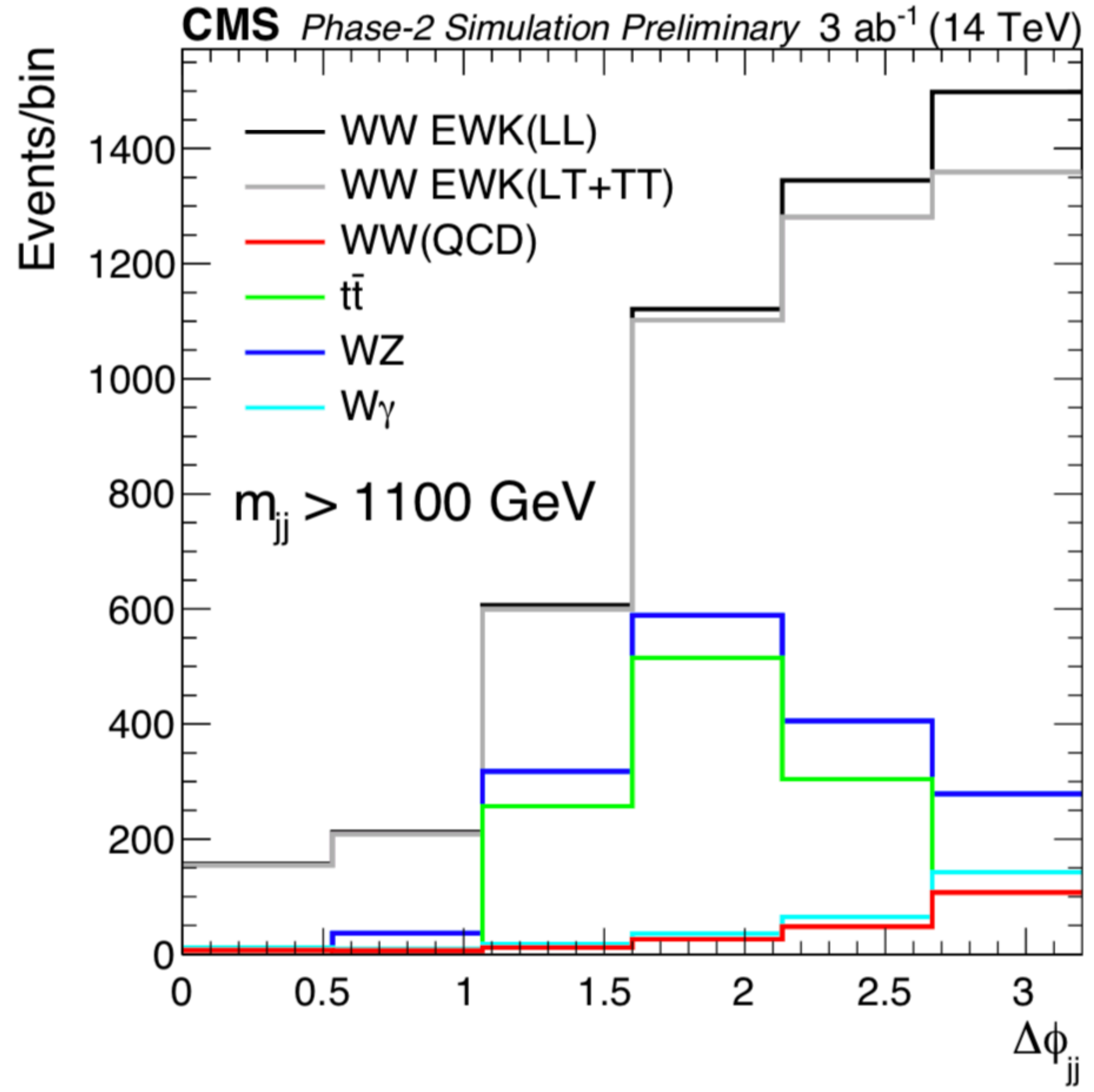
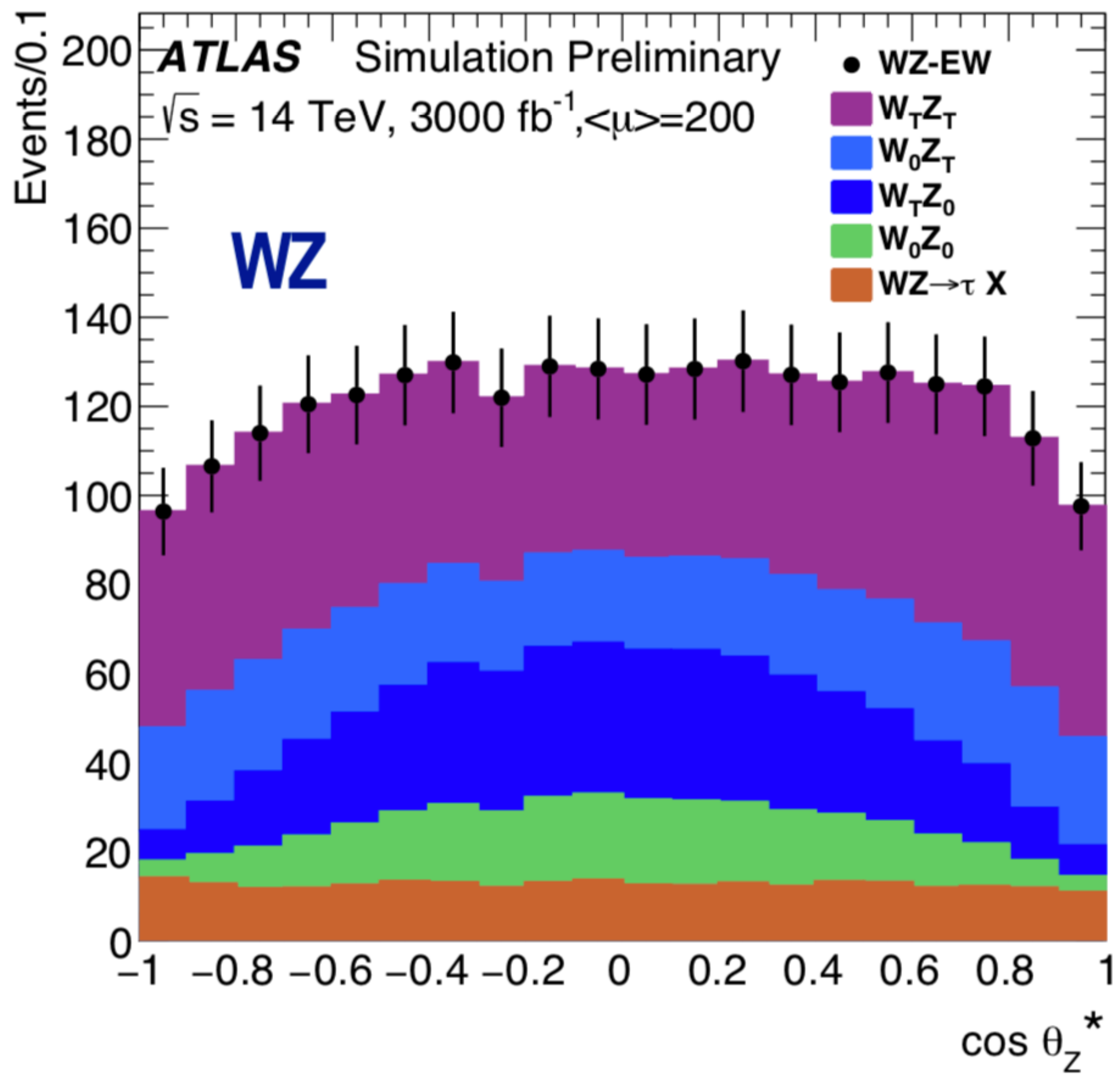






$V_LV_L \to V_LV_L$ discovery significance up to 3σ combining channel and experiments!

$gg \to H$ @ HE/HL-LHC

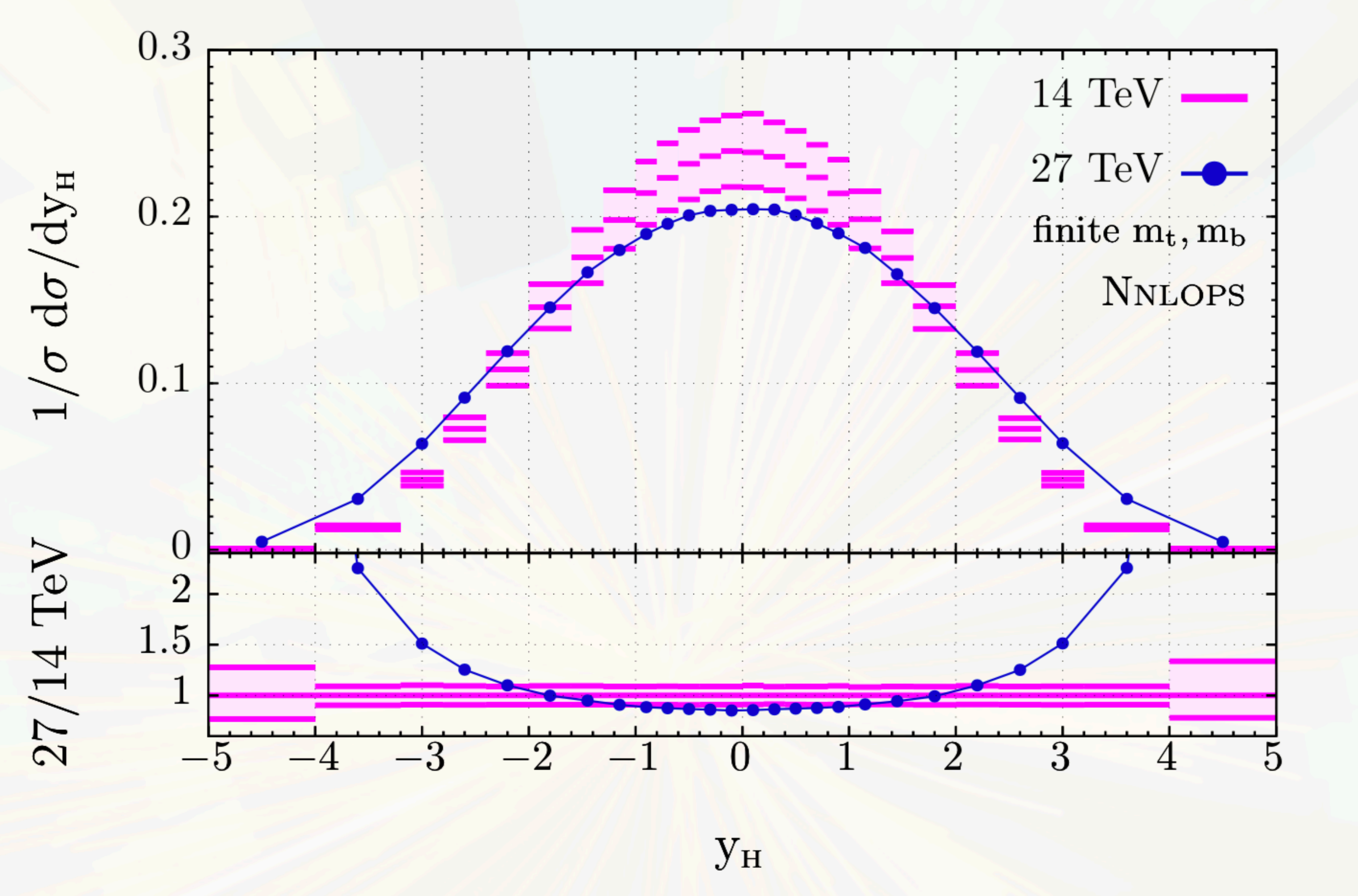
Inclusive NNLO estimates for $gg \to H$:

- Huge sample of H decays expected at HE/HL-LHC

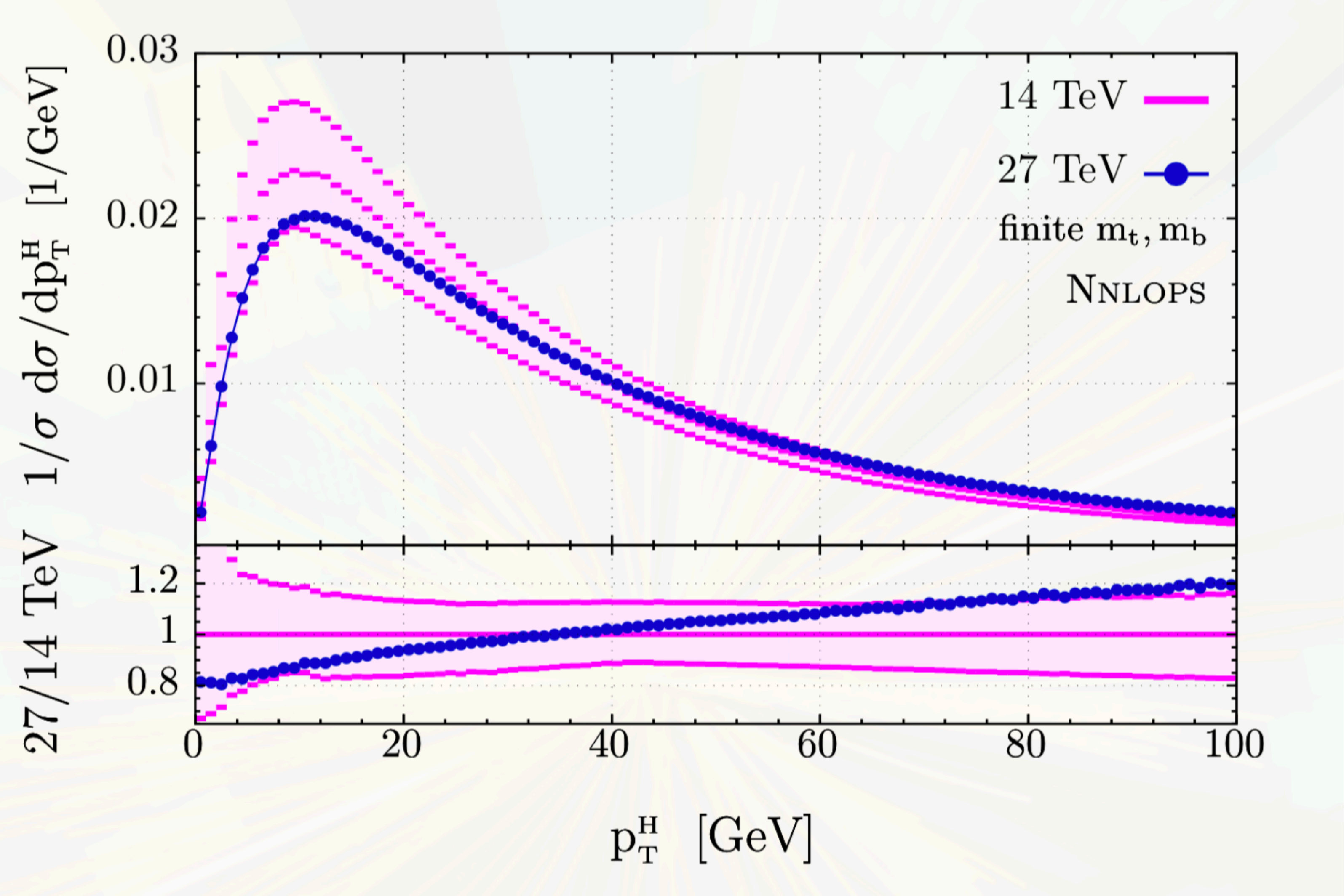
14 TeV with 3 ab^{-1} : $\sigma_{\text{tot}} = 49.6\,^{54.1}_{45.2}$ pb → 149 million $gg \to H$ events

27 TeV with 15 ab^{-1} : $\sigma_{\text{tot}} = 133\,^{145.6}_{122.2}$ pb → 2.00 billion $gg \to H$ events

rapidity(H)



p_T(H)



NNLO estimates for differential effects:

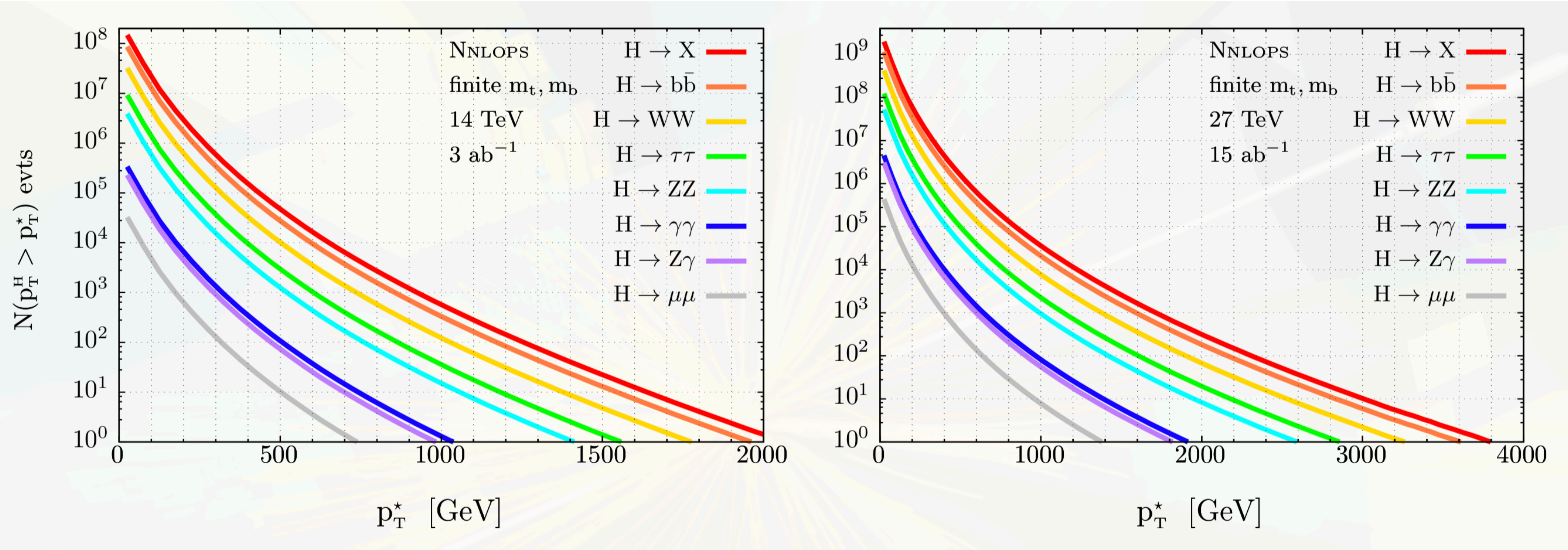
- Rapidity distn shape significantly broadened from 14 TeV → 27 TeV
- Markedly hardened & broadened pT spectrum already in [0,100] GeV

gg → H @ HE/HL-LHC

Inclusive NNLO estimates for gg → H:

- Huge sample of H decays expected at HE/HL-LHC

event yield for $p_T(H) > p^*_T$



NNLO estimates for differential effects:

- Factor ~1.8 increased reach in pT for a given event yield, N<105, for 14 → 27 TeV
- No Higgs after 2 TeV with 3 ab-1 @14 TeV, or 3.8 TeV with 15 ab-1@27 TeV

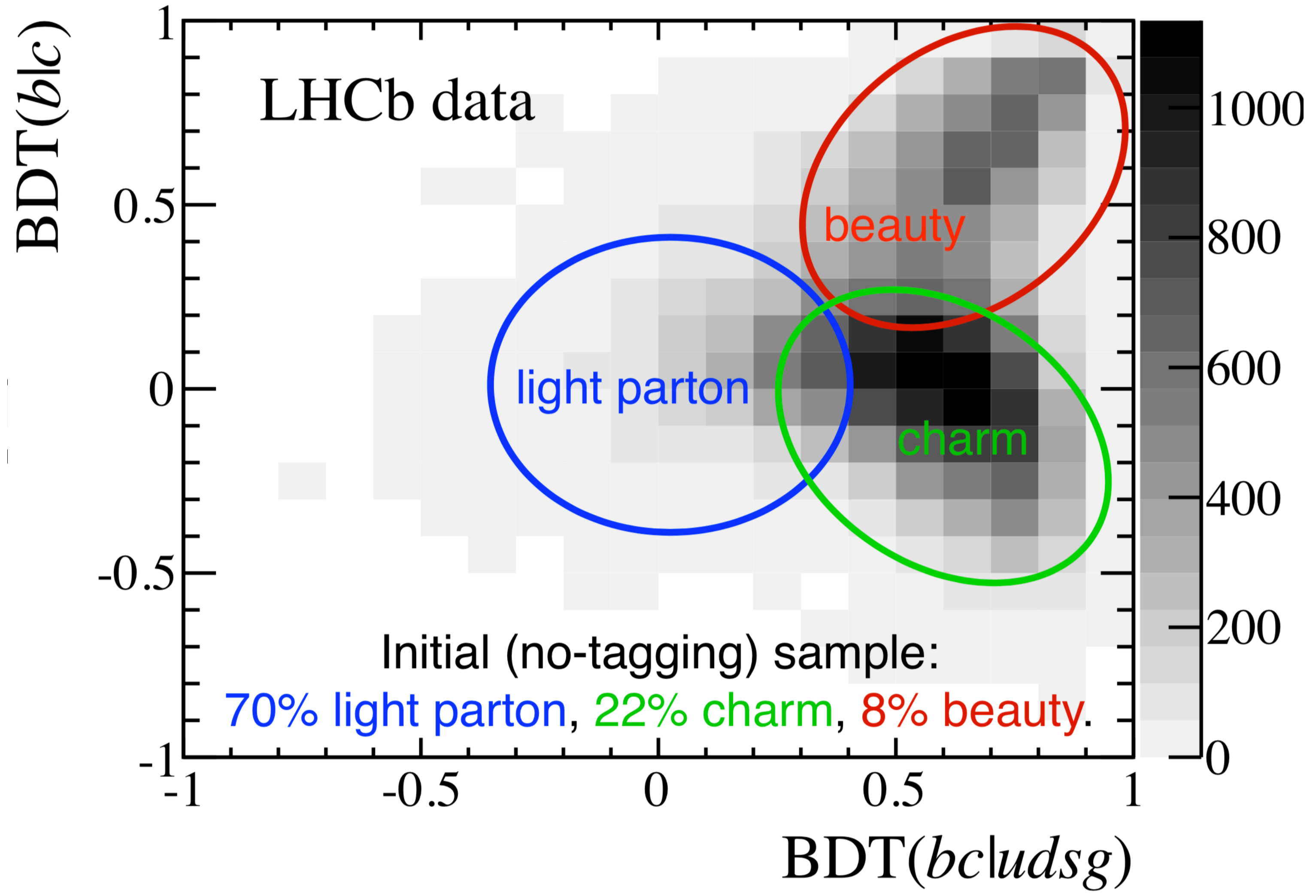
Higgs boson coupling to 2nd generation

ATL-PHYS-PUB-2018-016

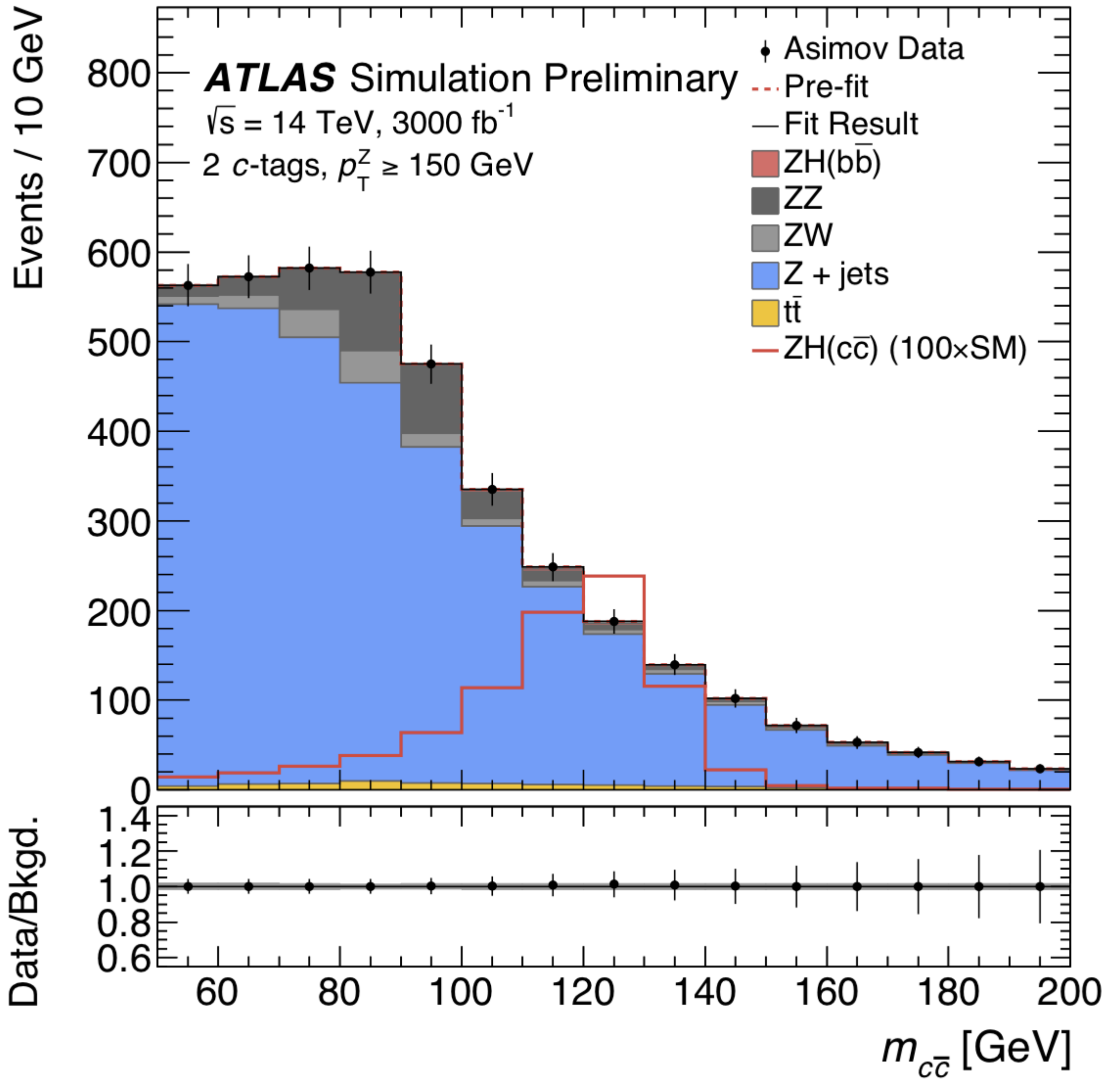
Establishing coupling to charm is one of the key tasks:

- **LHCb:** Leading the effort - already at 300 fb^{-1} expect limits < 7x SM.
  Ongoing development of multi-class flavour separation algorithms for further improvements.
- **ATLAS:** At 3000 fb^{-1} expect limits < 6.3x SM.

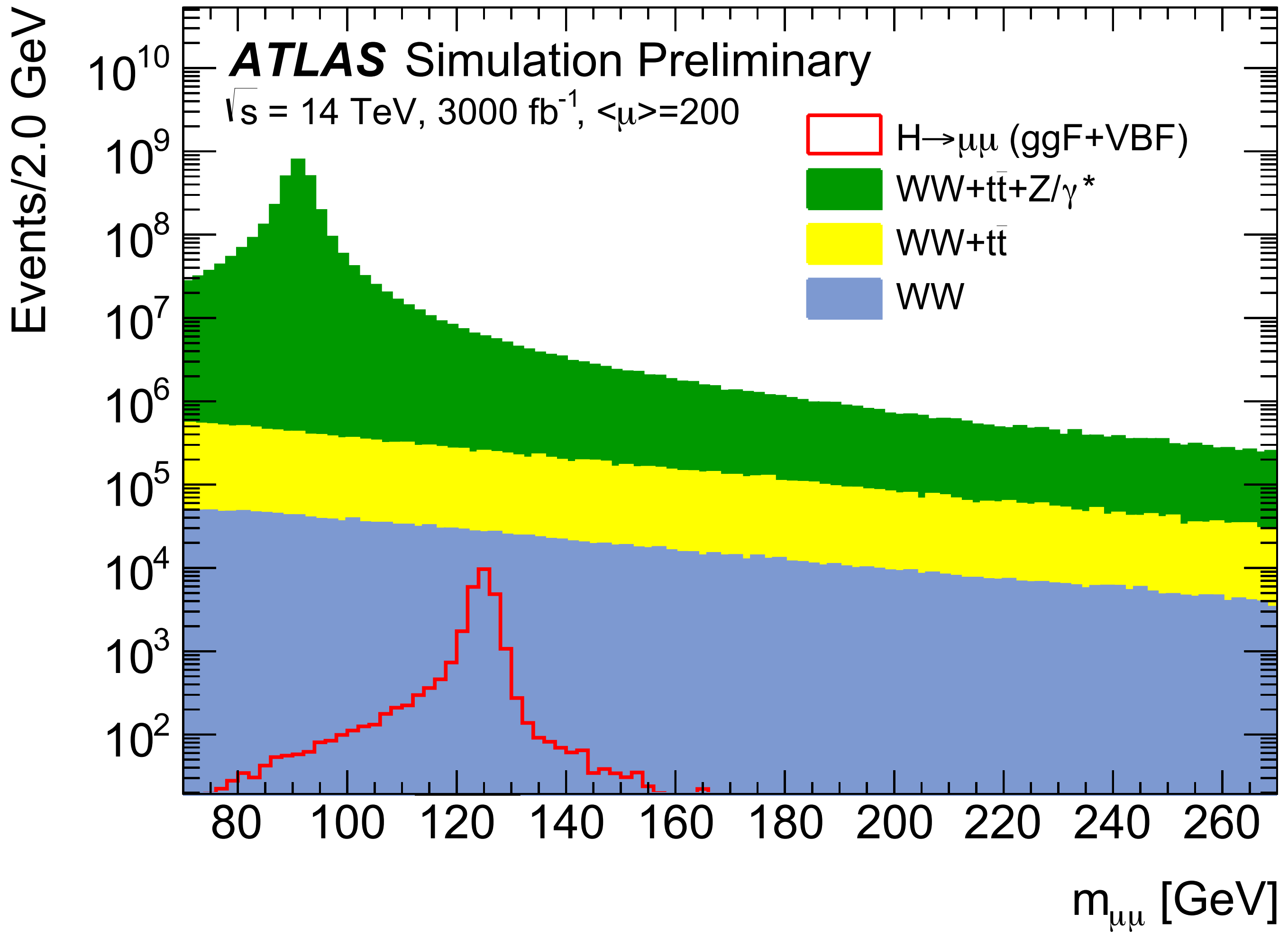
LHCb : BDT flavour separation



ATLAS : ZH→$\ell\ell cc$



ATLAS : H→μμ



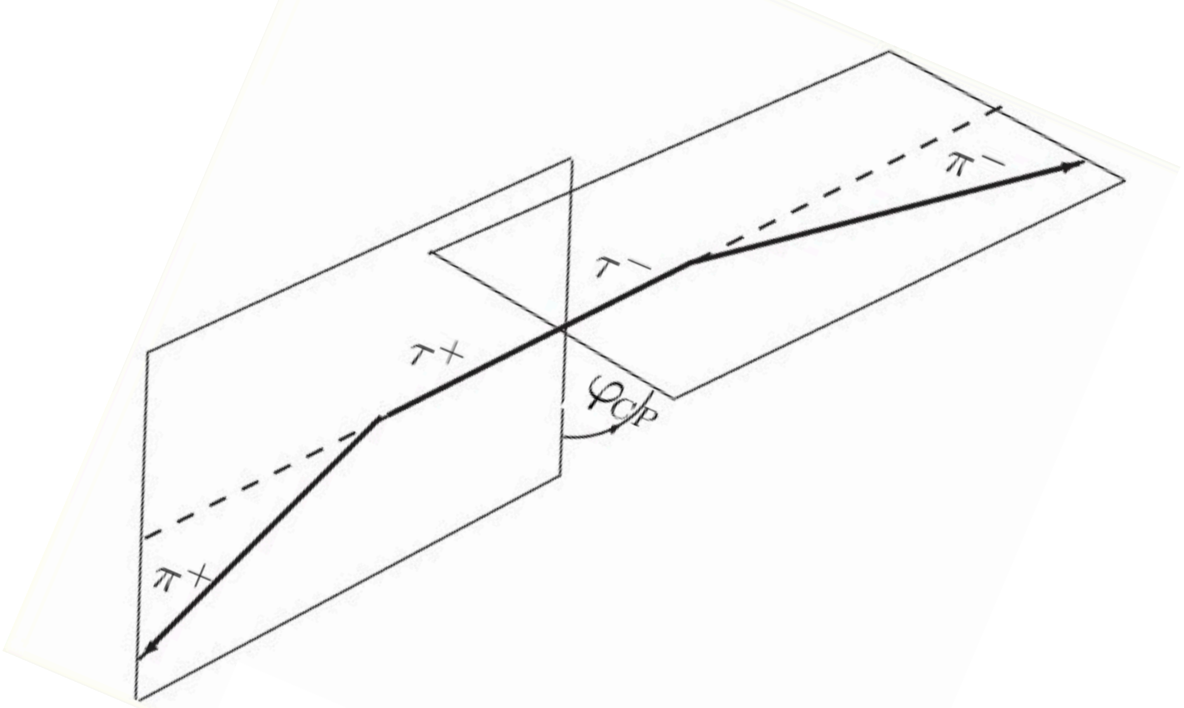
Establishing coupling to muons is another key tasks:

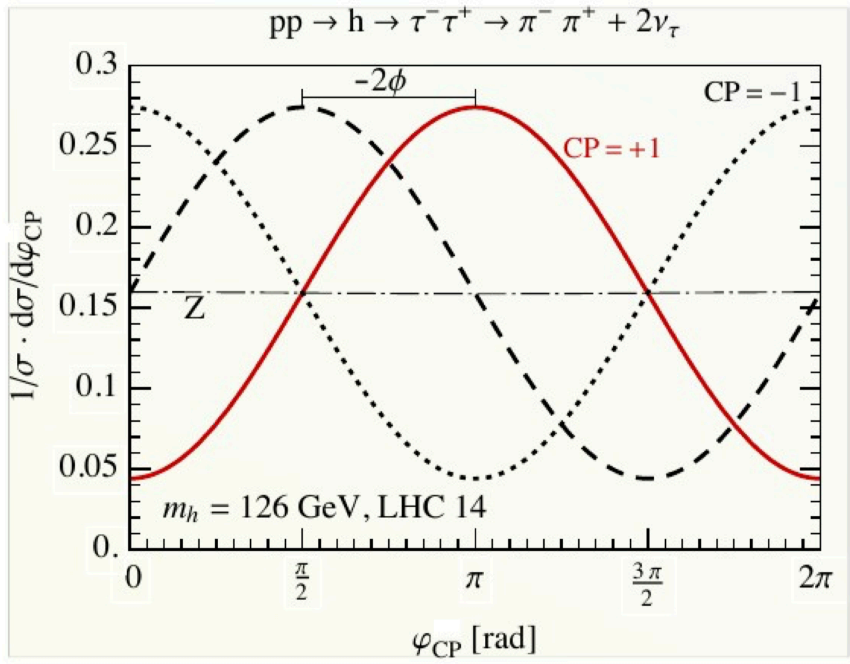
- **@HL-LHC:** New analyses techniques exploiting the improved resolution of upgraded detectors.
  Expected uncertainty on coupling about 5%.

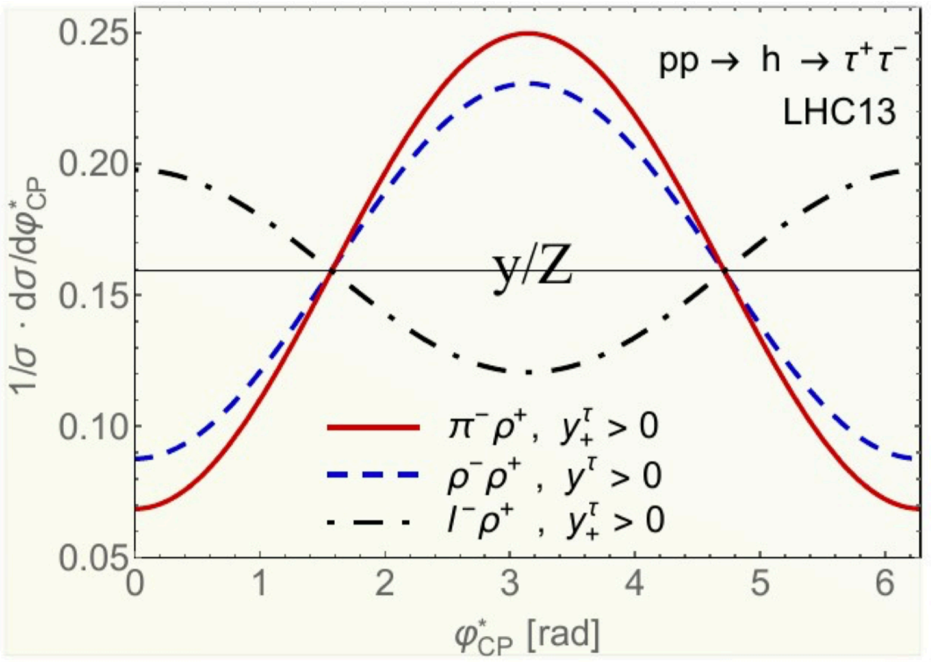
Anomalous Hff interactions

Decays H → ττ offer possibility to probe anomalous Hff interactions (CP-odd):

- Sensitivity from the angle between tau decay planes **Φ_{CP}**
- Consider several decay modes (lπ, lρ, ππ, πρ, ρρ, etc.). Apply conventional CMS H → ττ selection



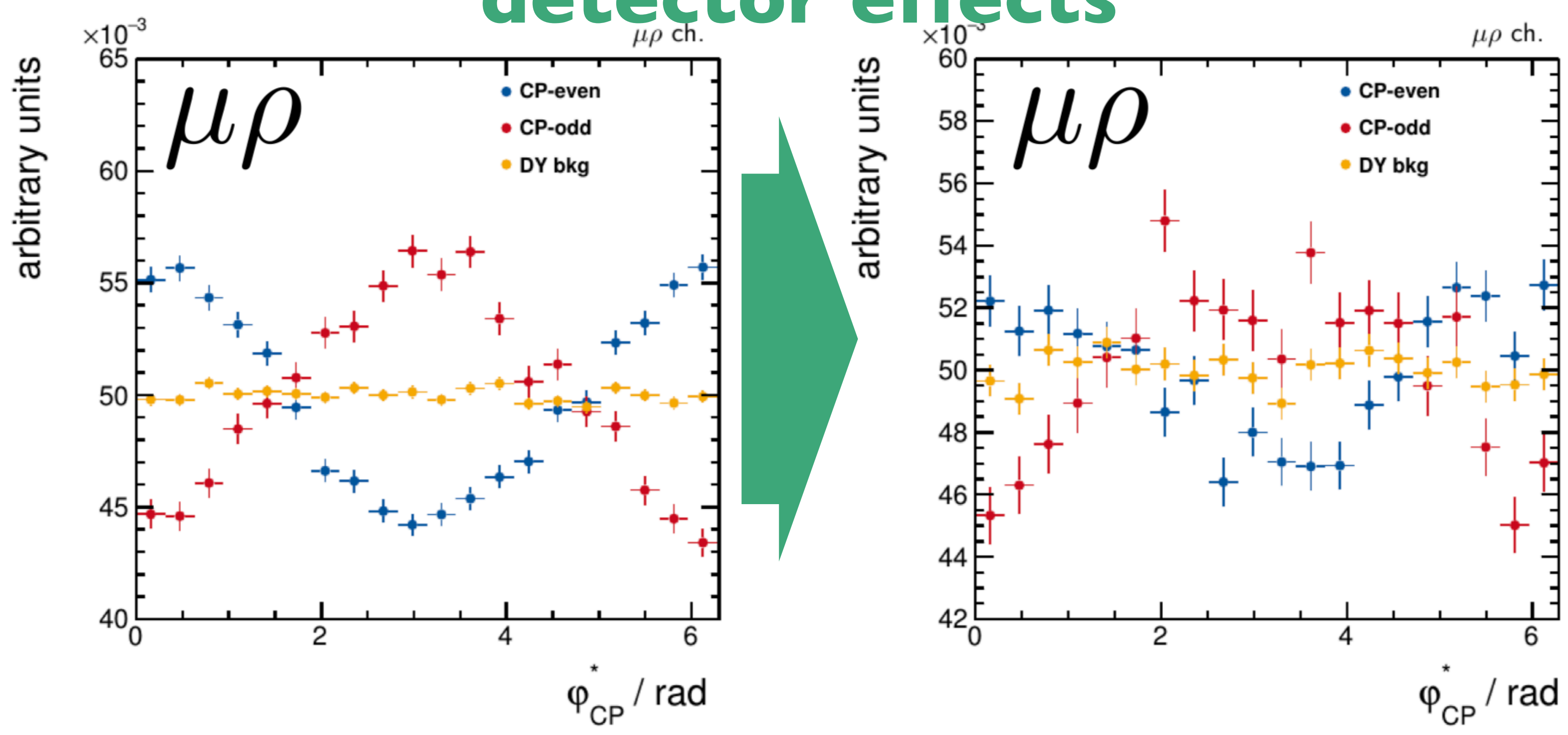




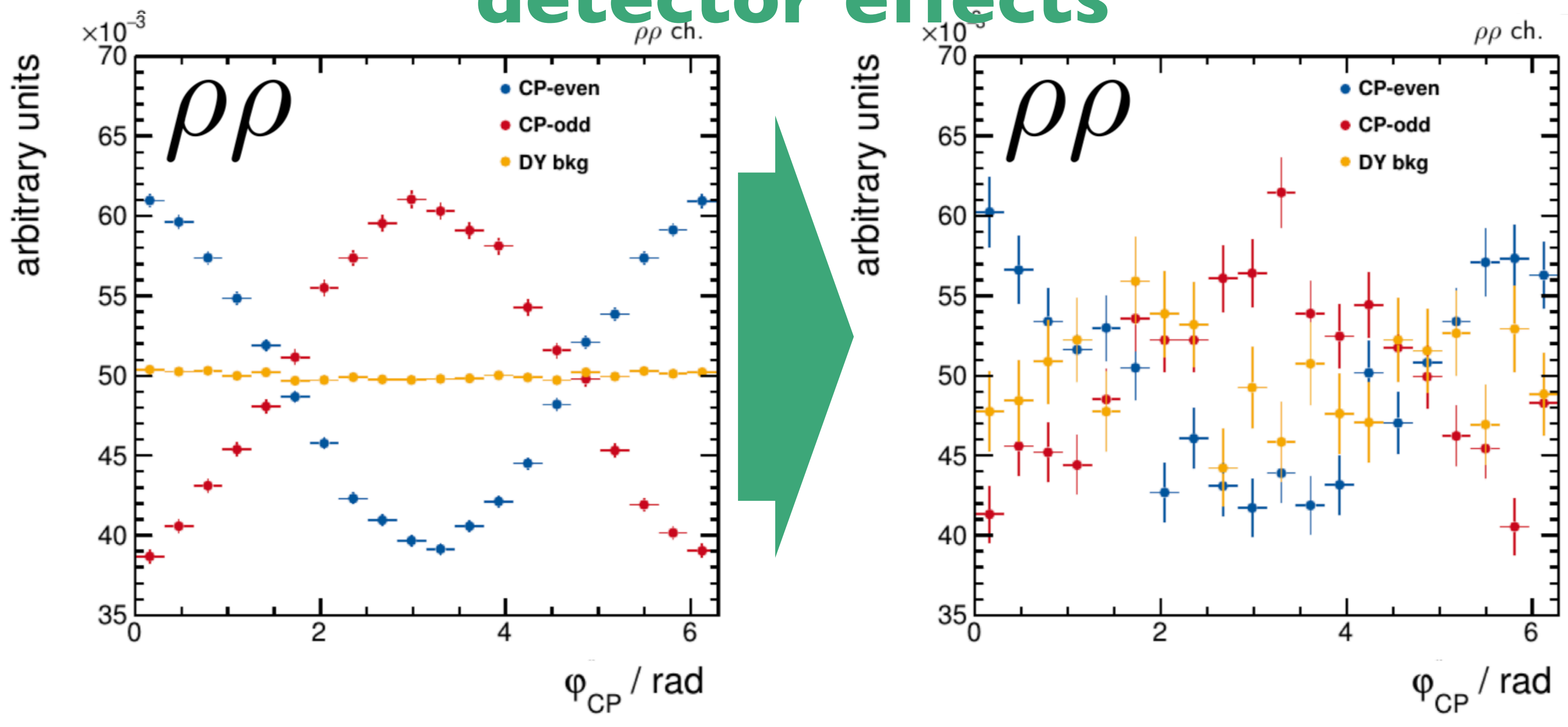
Limiting factors in the measurement and to-do list:

- Detector effects (PCA resolution) and large statistical uncertainty in dominant Z → ττ background
- Need to perform study with Phase-2 upgrade, and to obtain realistic estimate of sensitivity

detector effects



detector effects

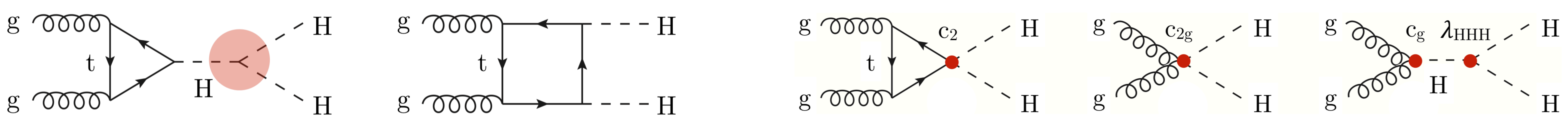


CMS-FTR-18-019

HH production and self-coupling

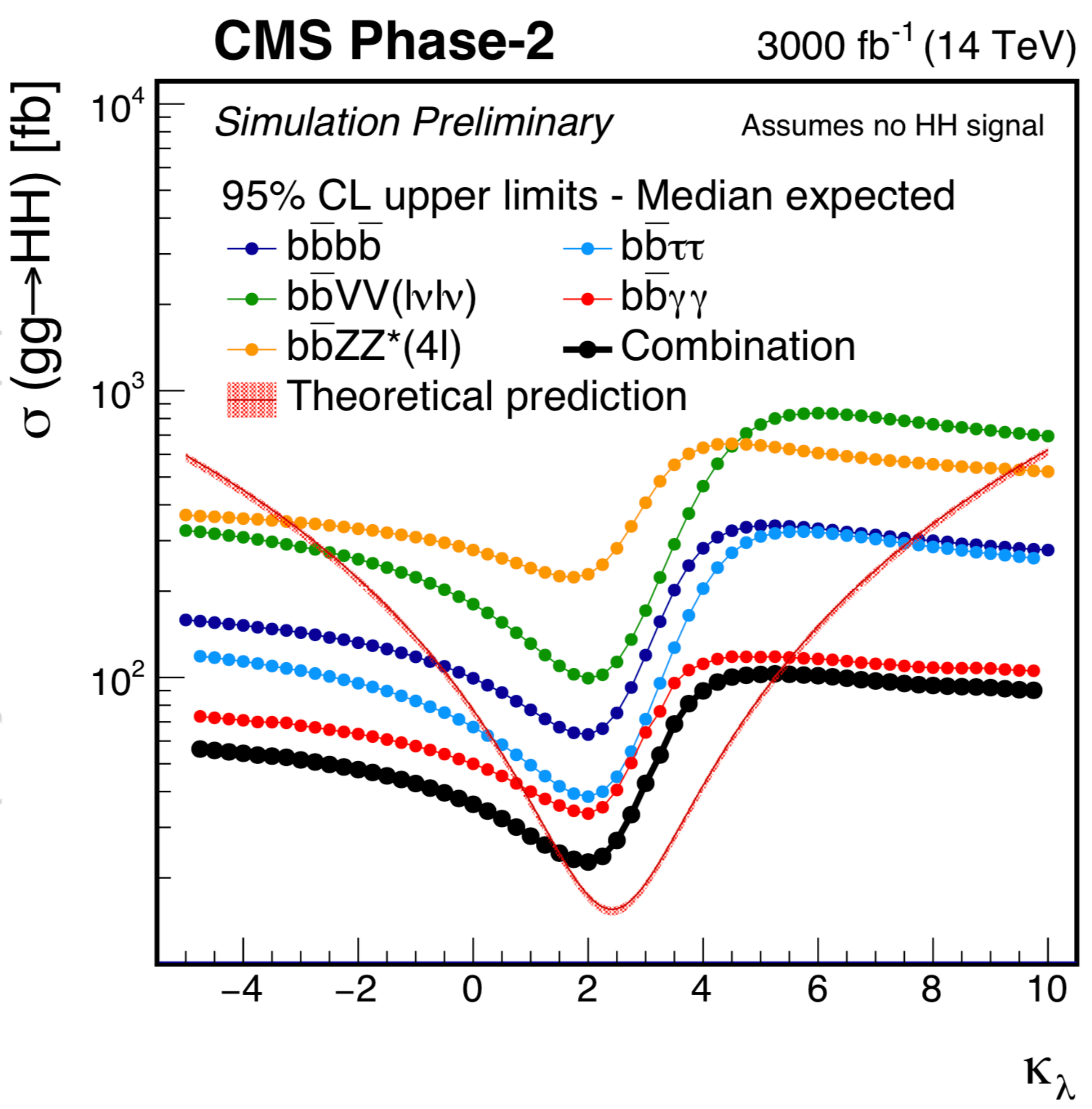
Probing HIG boson trilinear coupling λ_{HHH} important @HL-LHC

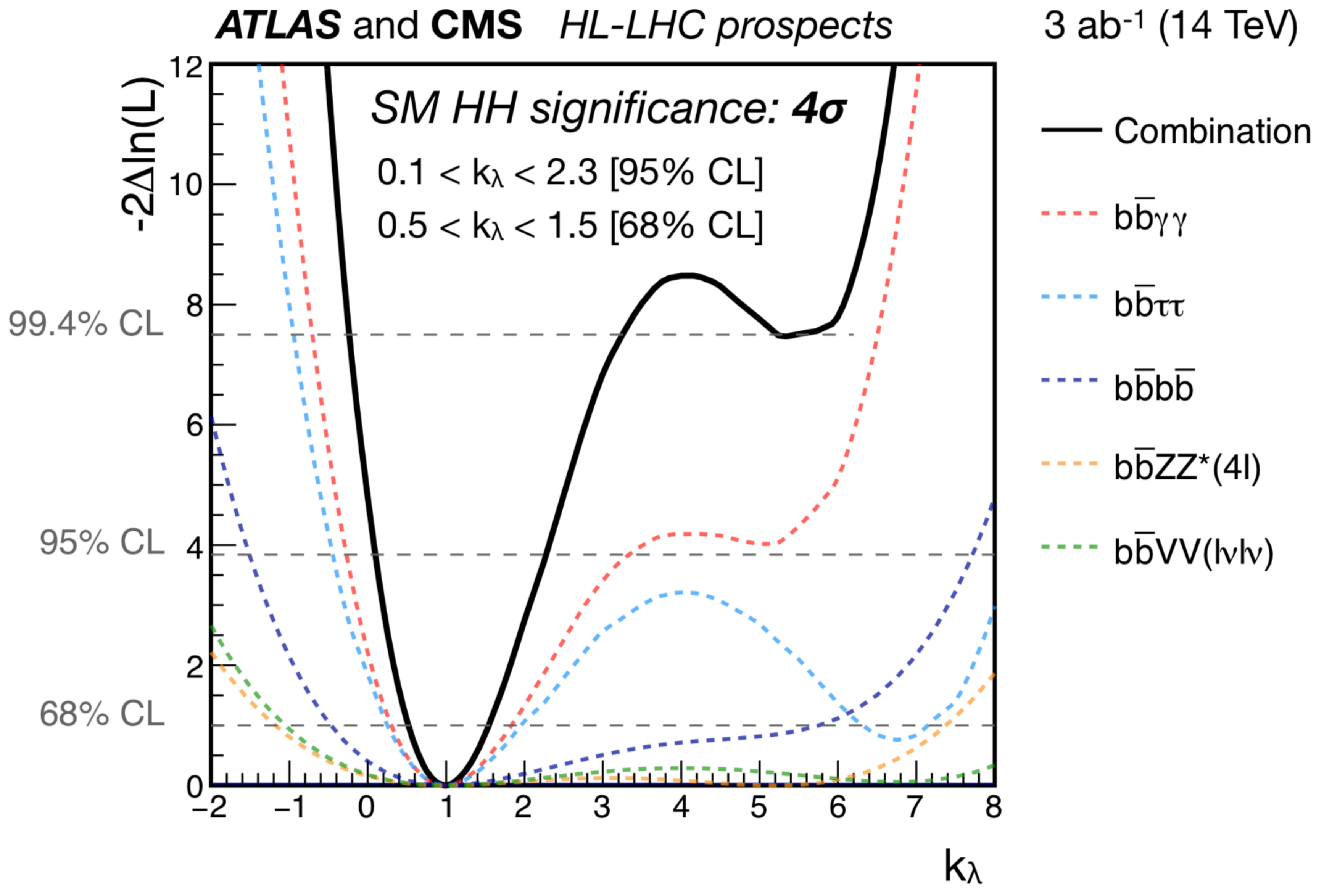
- Information on the shape of the scalar Higgs potential, and potential anomalous effects



ATLAS and CMS performing extensive sensitivity studies in individual channels:

- Analyses in **bbbb, bbVV, bb$\tau\tau$, bb$\gamma\gamma$** (expertise from LHC Run-2 + further optimisation/developments)
- Performed combination of all channels, and also **ATLAS+CMS combination**





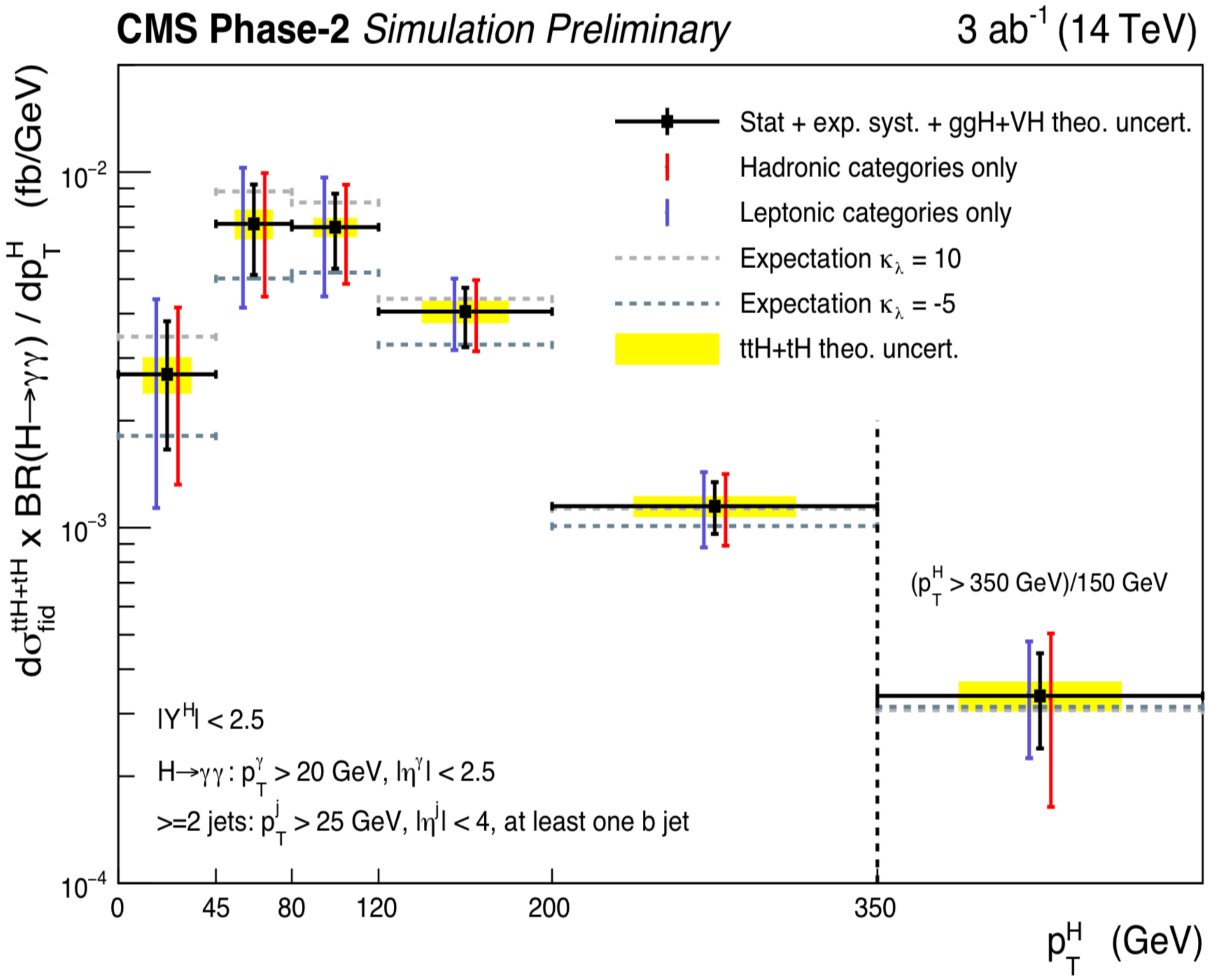
Differential XS and limits on self-coupling

CMS-FTR-18-020

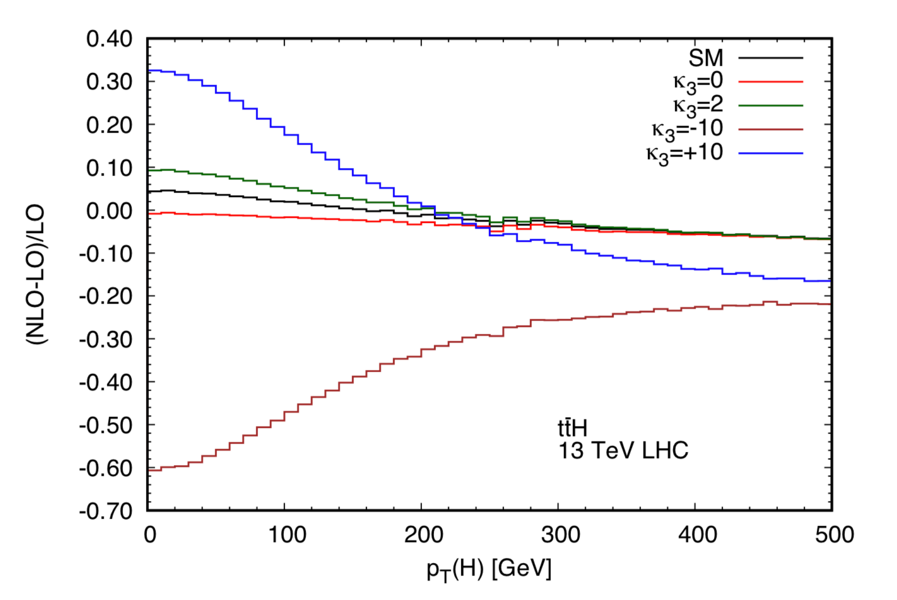
Performed first studies of differential XS for exclusive production (@HL-LHC):

- Sensitivity of differential distributions to loop-corrections involving self-coupling.

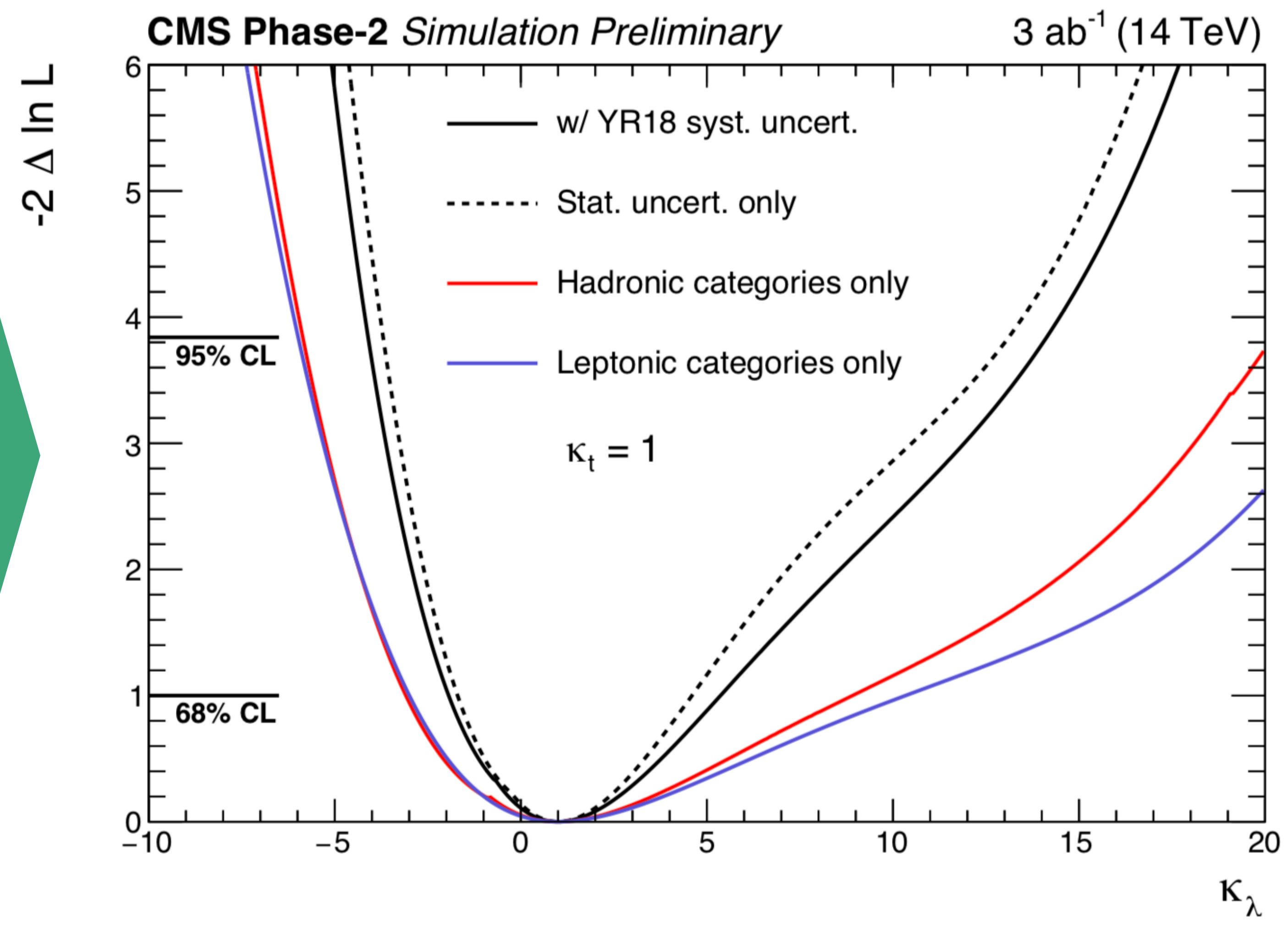
Differential $p_T(H)$ in ttH(H→γγ)



$p_T(H)$ parametrised in terms of kλ



Expected 1D limits for kλ



Constraints on effective kλ coupling :

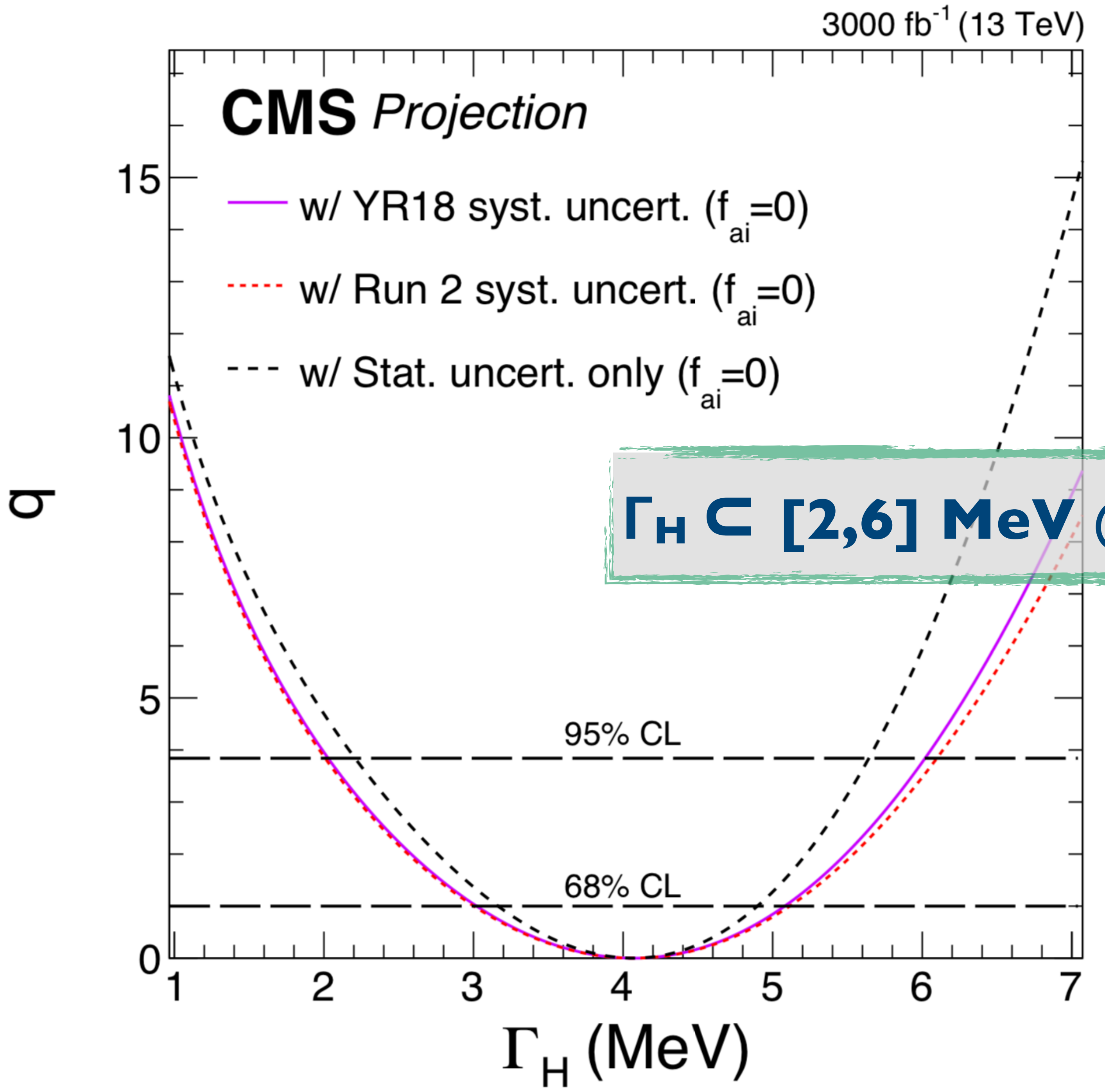
- Need to study all production modes and decays channels to fully exploit the potential.
- Important complementarity with direct probes of HH production.

CMS-FTR-18-011
ATL-PHYS-PUB-2013-013

Higgs boson width

Indirect constraints from off-shell

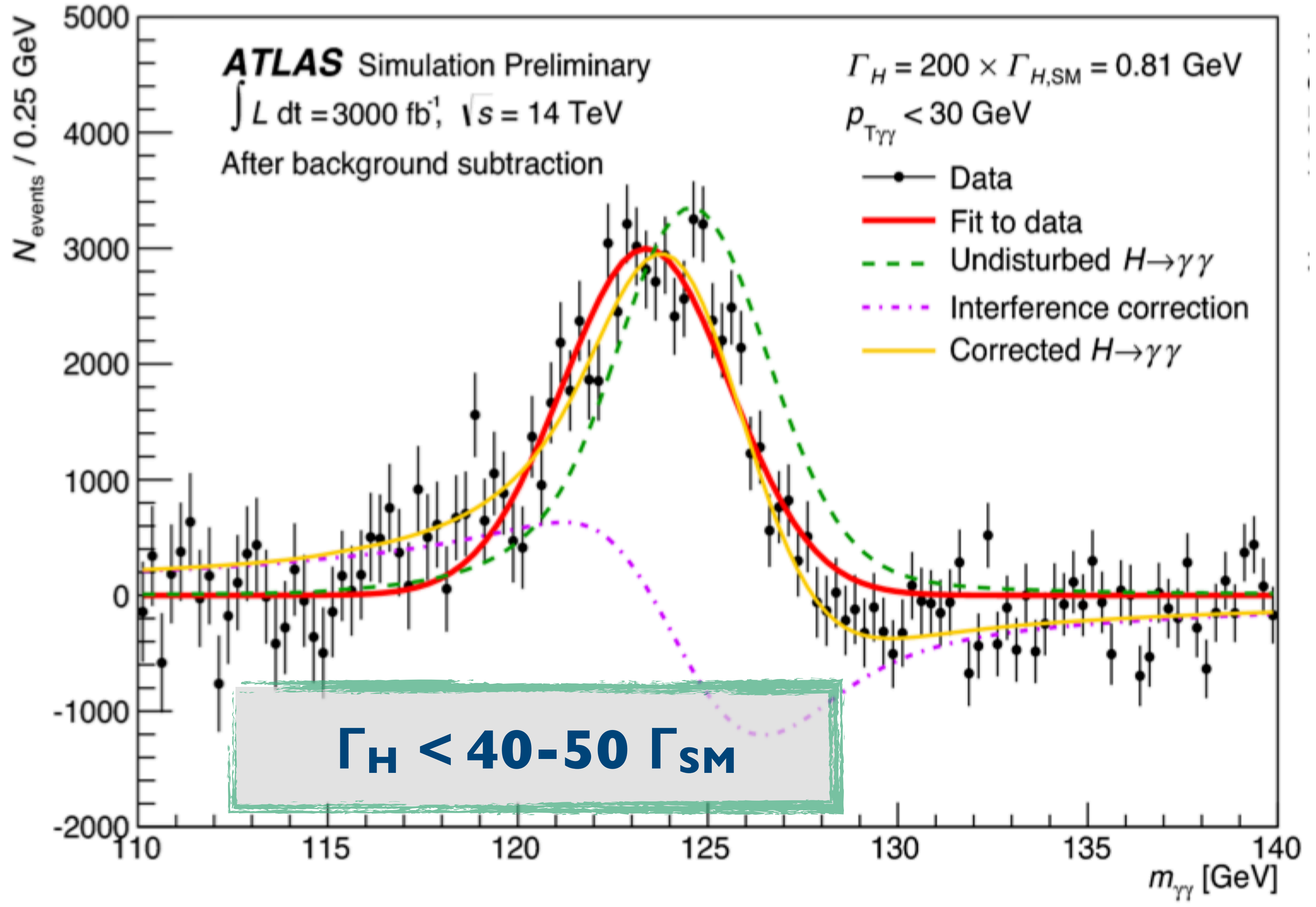
- gg → VV, gg → H* → VV



$\Gamma_H \subset [2,6]$ MeV @ 95%CL

Direct constraints from interference

- gg → γγ, gg → H → γγ



$\Gamma_H < 40\text{-}50\ \Gamma_{SM}$

Some points to be understood/answered/addressed:

- Direct constraints: suffer from limited experimental sensitivity.
- Indirect constraints: need better understanding of dominant TH uncertainties.

Anomalous HVV interactions

CMS-FTR-18-011

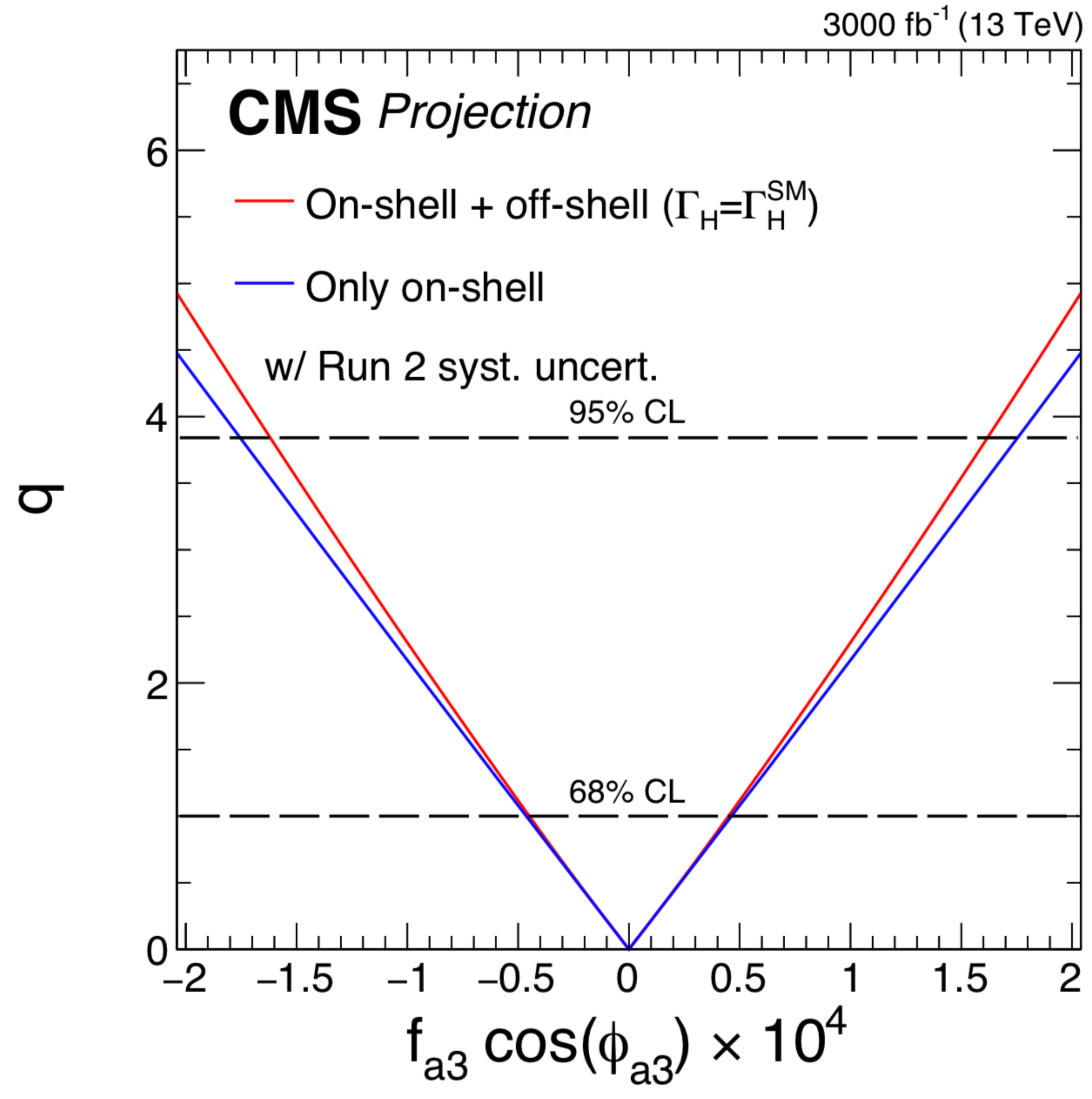
Performance to be estimated using the H→ 4ℓ analysis @13 TeV.

- Parameterisation of decay amplitude:

$$A = \frac{1}{v}\left[\overset{\text{SM}}{a_1^{VV}} + \overset{\text{leading momentum expansion}}{\frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2}}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \overset{\text{higher order cp-even}}{a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}} + \overset{\text{cp-odd}}{a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}$$

Powerful constraints on anomalous couplings:

- Exploiting information from:
  - H decay (on-shell)
  - H on-shell production
  - H off-shell production:
- Sensitivity driven by on-shell production-level info. Some model dependance from assumption on HWW/HZZ relation.



Parameter	Information from	95% CL interval
f_{a3}	decay	$\pm 120 \cdot 10^{-4}$
f_{a3}	decay & production	$\pm 1.8 \cdot 10^{-4}$
f_{a3}	decay & production & off-shell	$\pm 1.6 \cdot 10^{-4}$

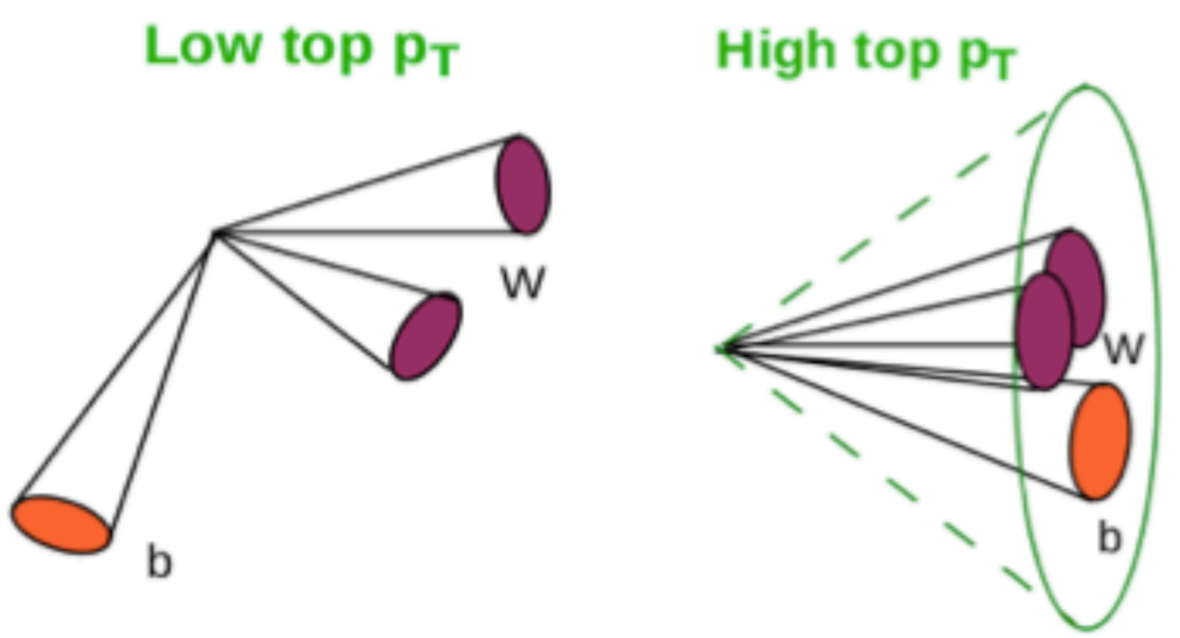
Constraints on fractional CP-odd presence $<1.6 \cdot 10^{-4}$

New resonances @ HL-LHC

CMS-FTR-18-003
ATL-PHYS-PUB-2018-022

Performance estimated using Z' and W' searches @ 13 TeV (HVT or RS model)

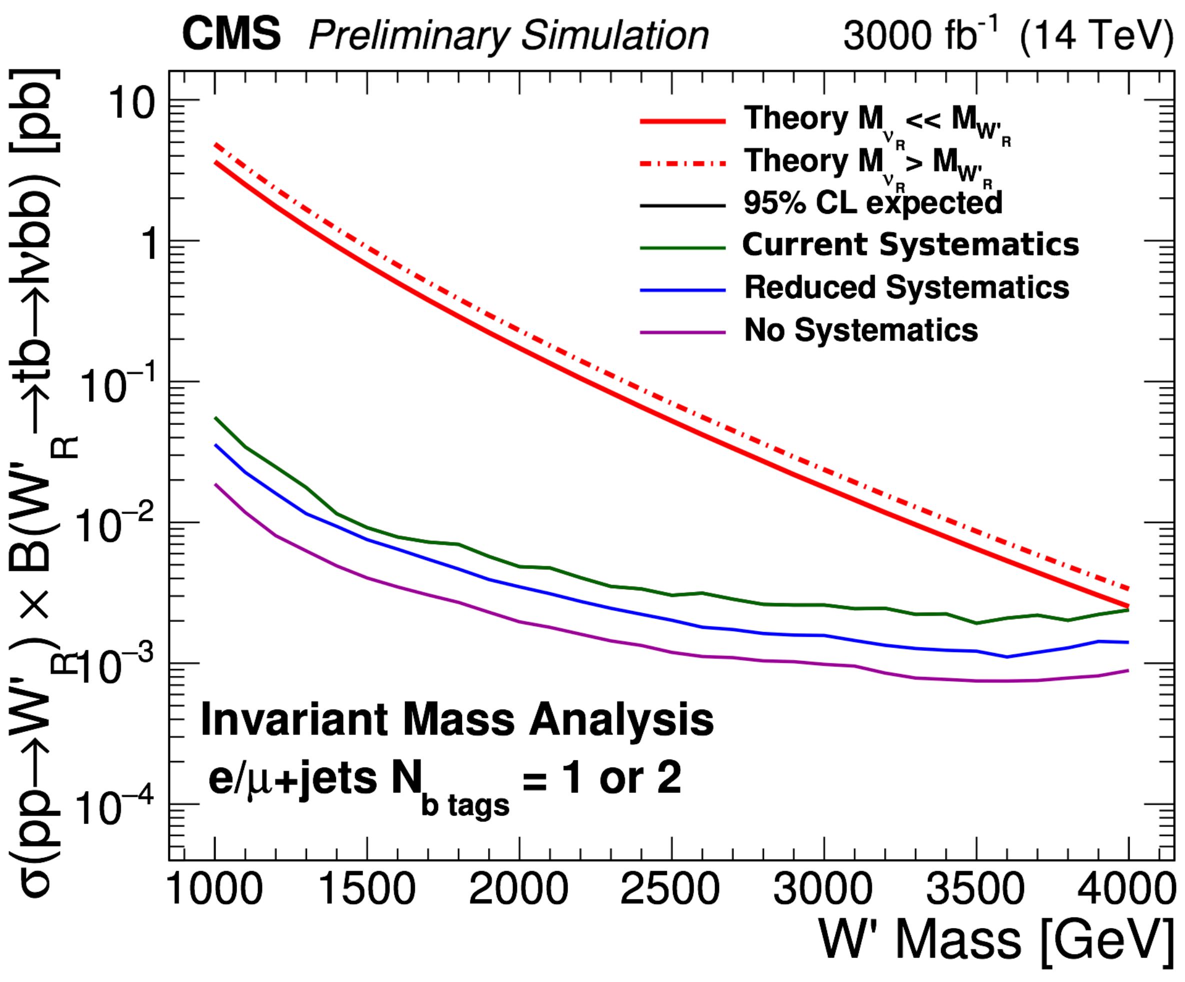
- **W' → tb → bbℓν :** high-p_T lepton, significant E_{Tmiss}, two b-jets
- **Z' → tt → ℓνb qq'b / qq'b qq'b :** Exploit boosted topologies



Search for resonance decaying to HH (WED or KK model)

- Exploit boosted H->bb final states (narrow width approximation).

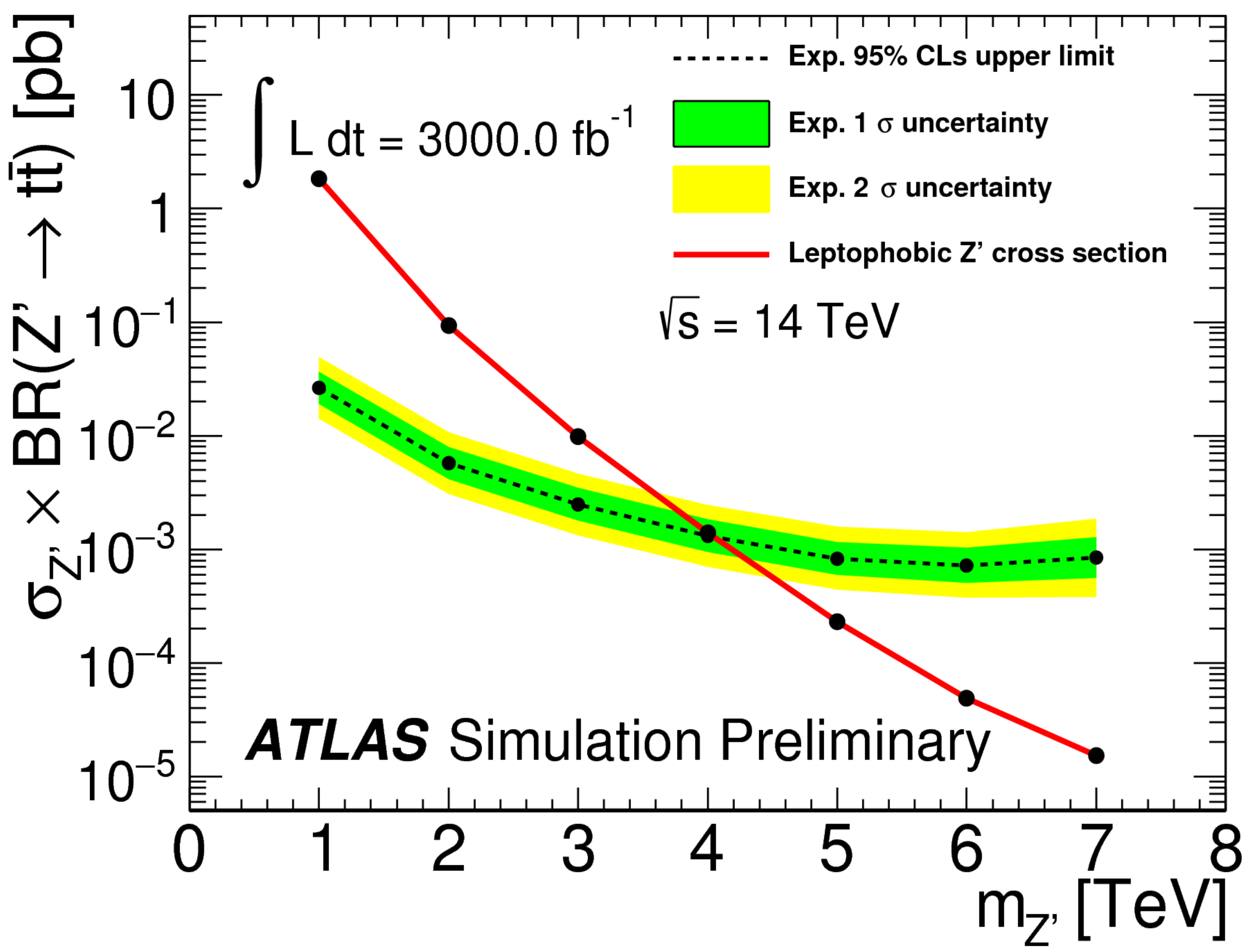
W' → tb → bbℓν



Exclusion: m(W') > 4 TeV

current limits about 2.7 TeV

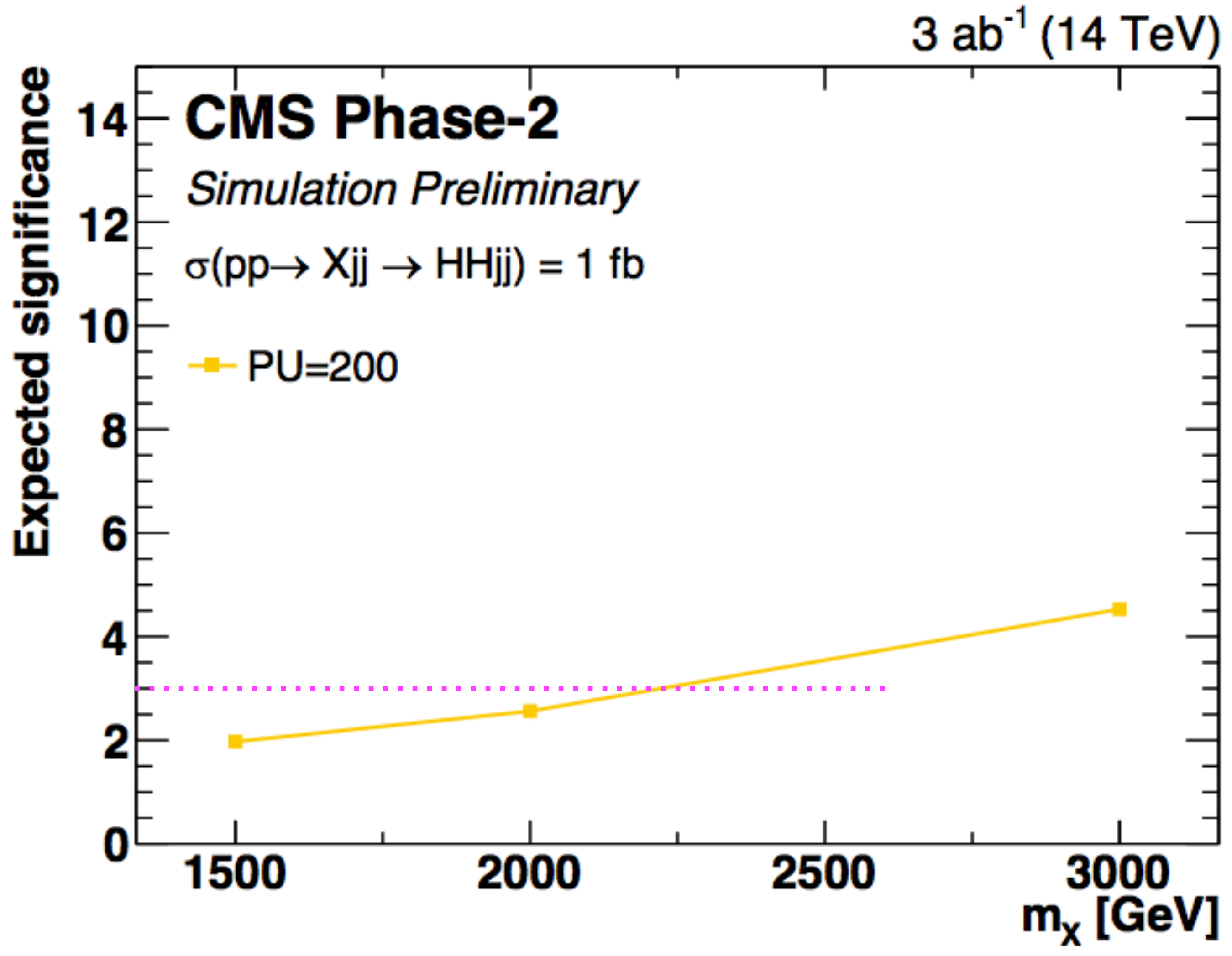
Z' → tt (hadronic)



Exclusion: m(Z') > 4 TeV

current limits about 2 TeV

X → HH → bbbb (boosted)

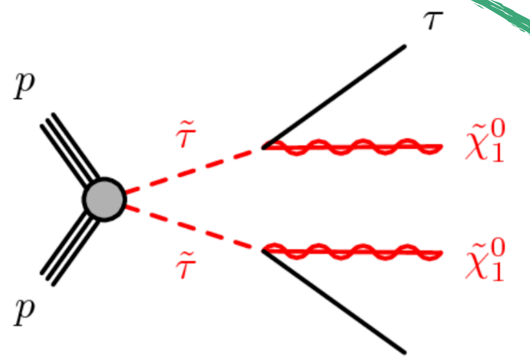


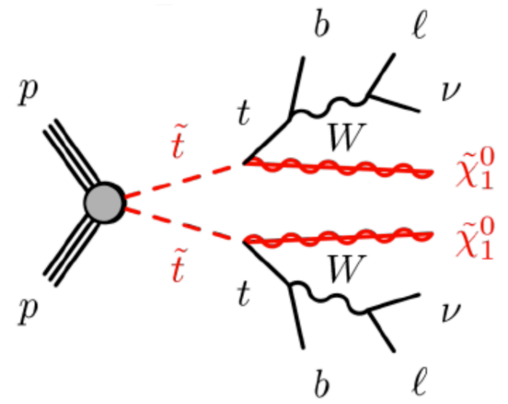
Evidence: m(X) < 2.2 TeV

for narrow width, 1fb cross section

CMS FTR-18-010
ATL-PHYS-PUB-2018-021

SUSY searches @ HL-LHC

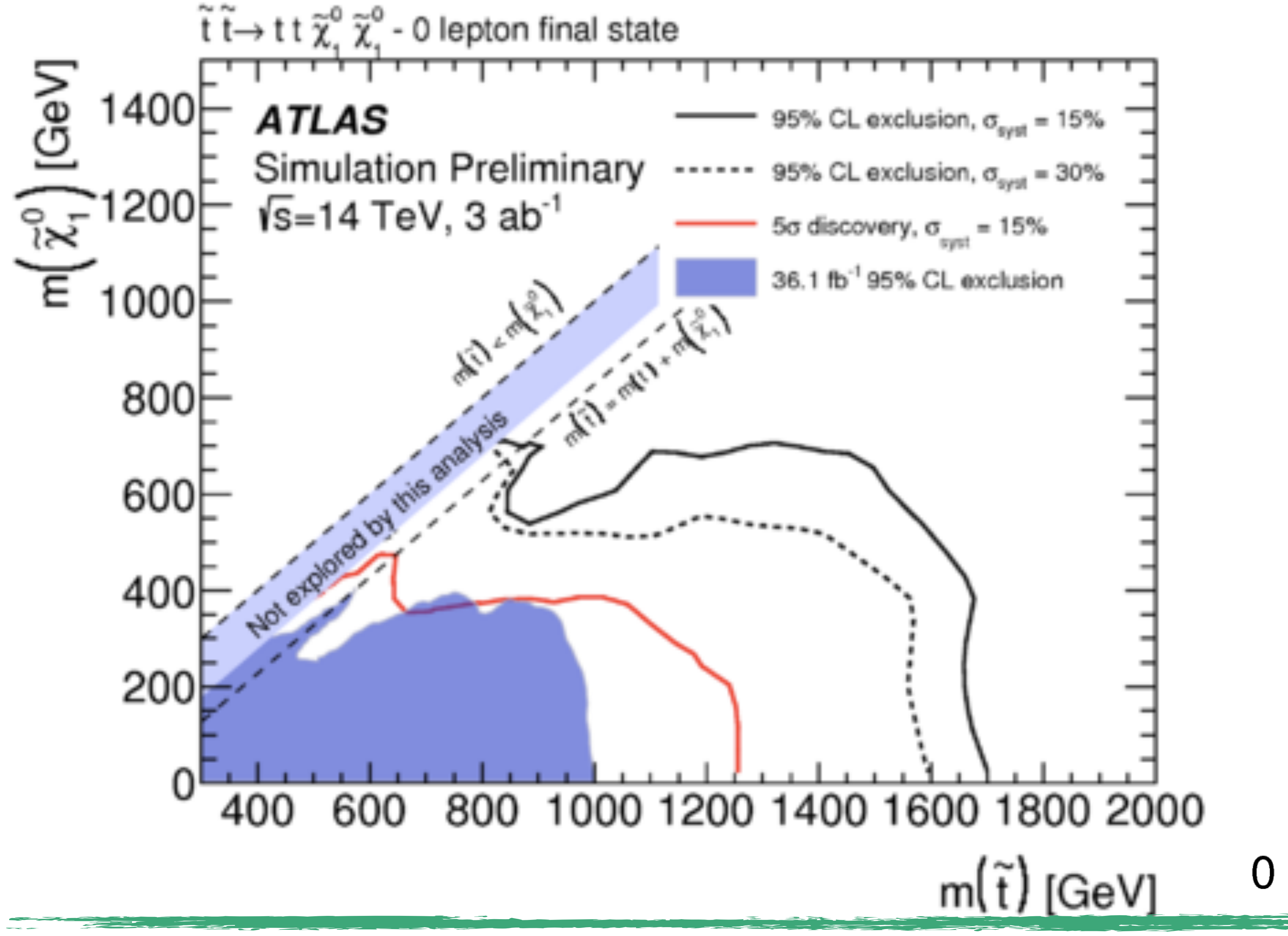




Performance estimated using the (simplified) analyses

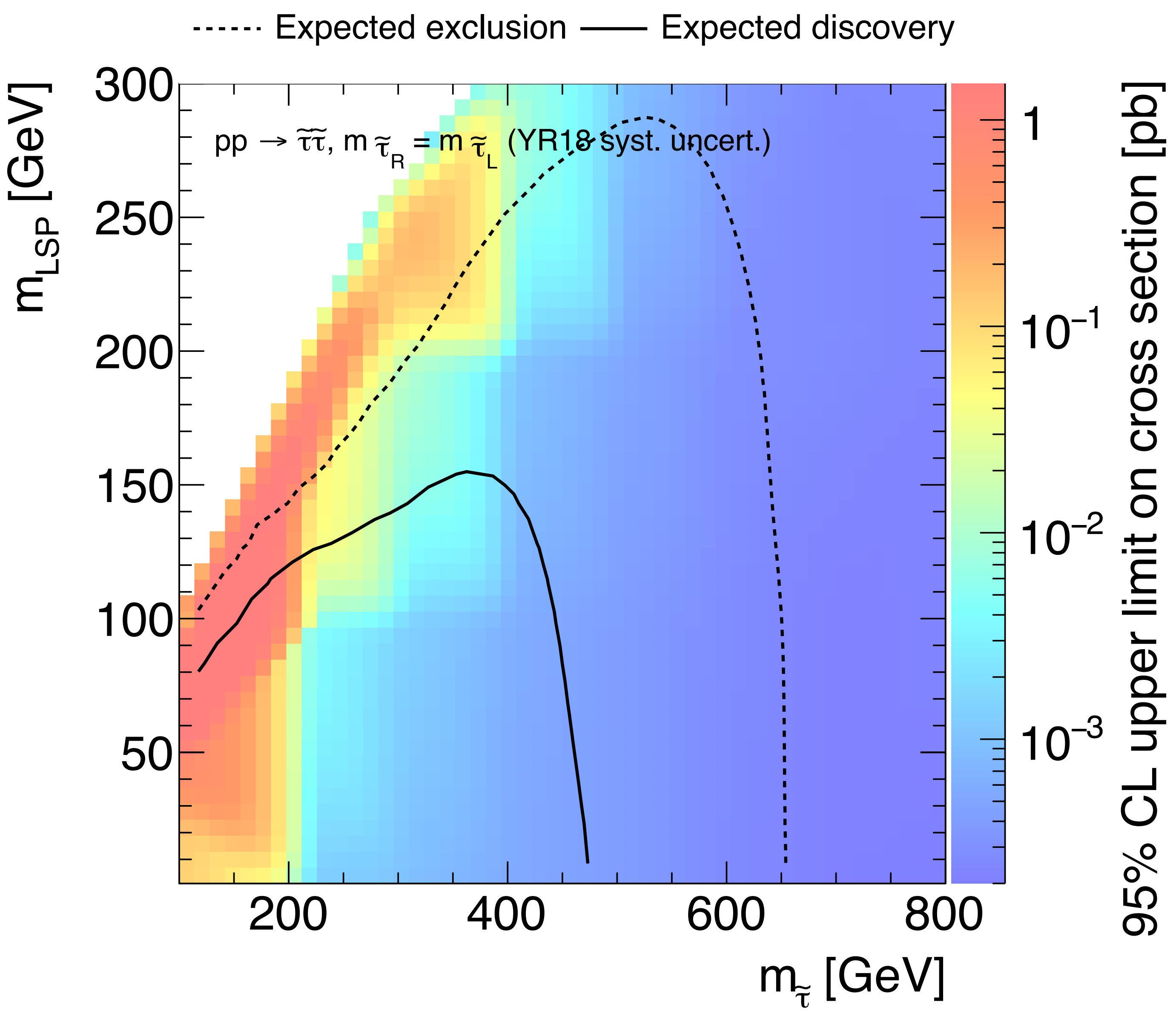
- **Direct stau pair production:** Simplified models, assume 100% BR of $\tau \rightarrow \tau\ \chi^0_1$
  - Main background: W+jets, ttbar
- **Direct stop pair production:** Compressed mass spectra
  - Low stop - neutralino mass difference, channel needs high luminosity

Direct stop pair production:



Discovery reach m(stop) < 1.25 TeV

Direct stau pair production:

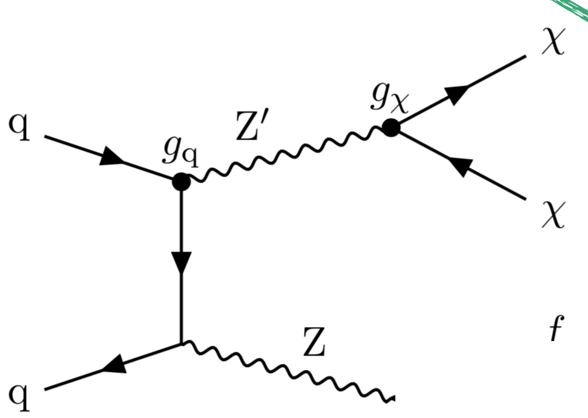


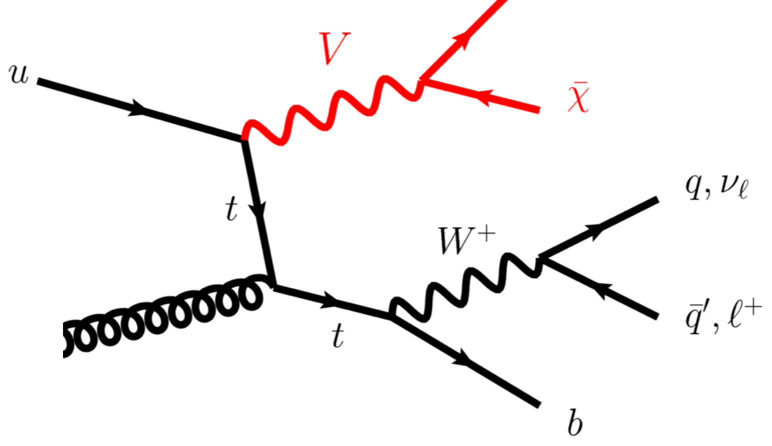
Discovery reach m(stau) < 470 GeV

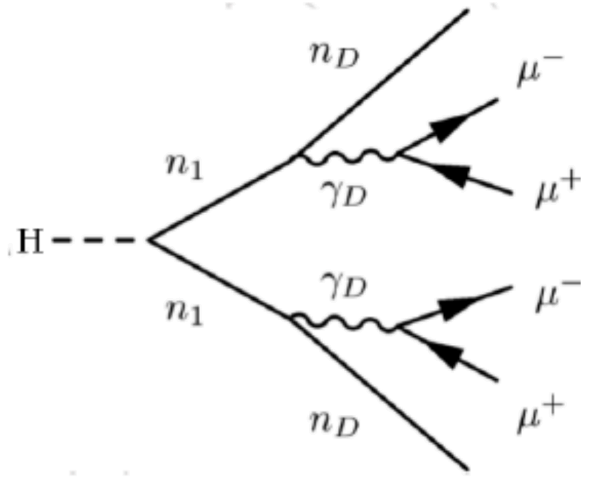
current exclusion limits about 110 GeV

Dark sector @ HL-LHC

CMS FTR-18-002
CMS FTR-18-007
ATL-PHYS-PUB-2018-024



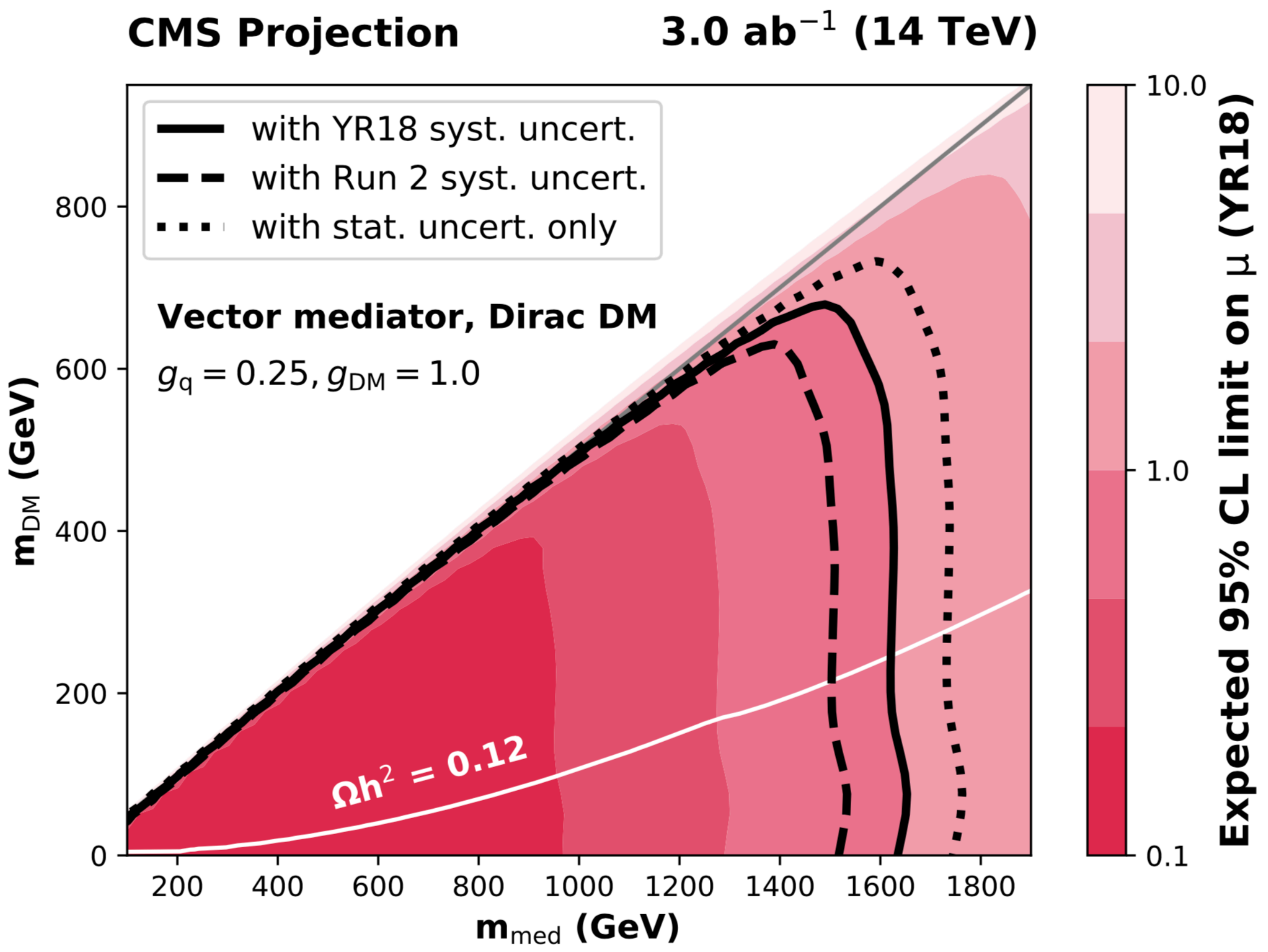




Simplified models for comparisons with direct detection:

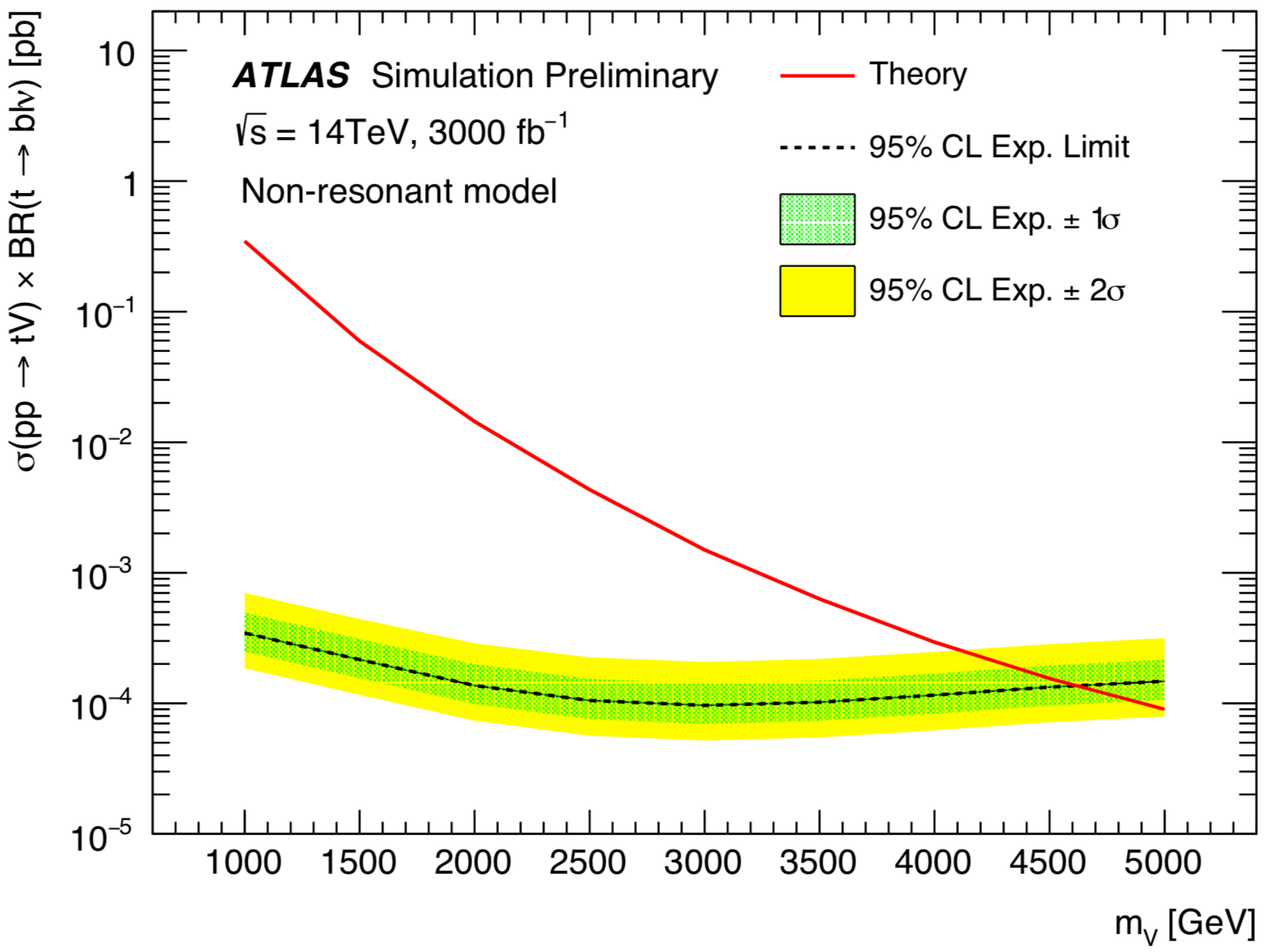
- **mono-Z :** Z accompanied by a mediator decaying to DM particles
- **mono-top :** Top accompanied by a mediator decaying to DM particles
- **dark photon :** It can couple to SM particles via kinetic mixing.
  (possible long-lived signatures for small kinetic mixing).

Mono Z search



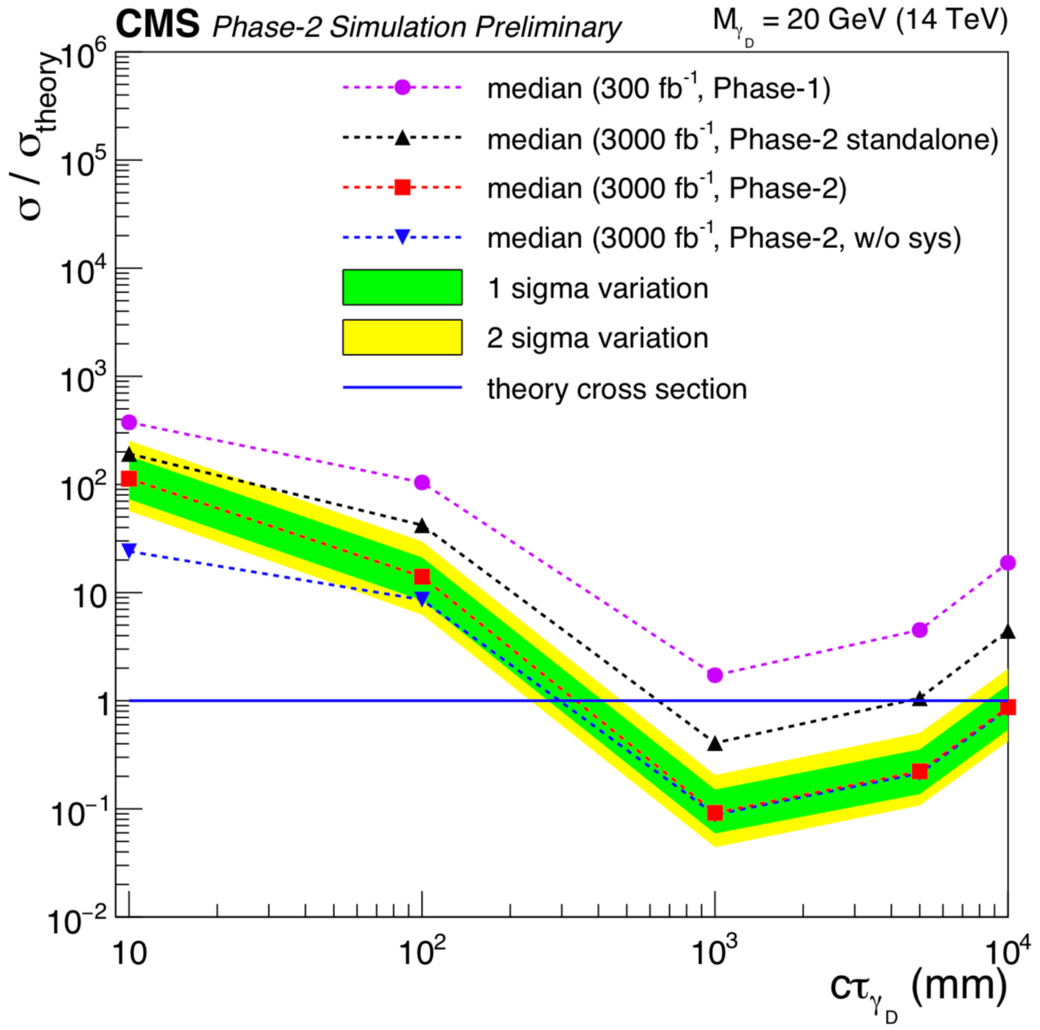
Exclusion: m(med) > 1.6 TeV

Mono top search



Exclusion: m(V') > 4.6 TeV

Dark photon search



Excl.: 10 < m(γ_D) < 30 GeV
depending on kin. mixing.