PROSPECTS FOR PHYSICS @ HL-LHC

Personal highlights, with focus on the Higgs boson physics

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on behalf of ATLAS and CMS Collaborations
HC2018, Tokyo, 26-30 November 2018

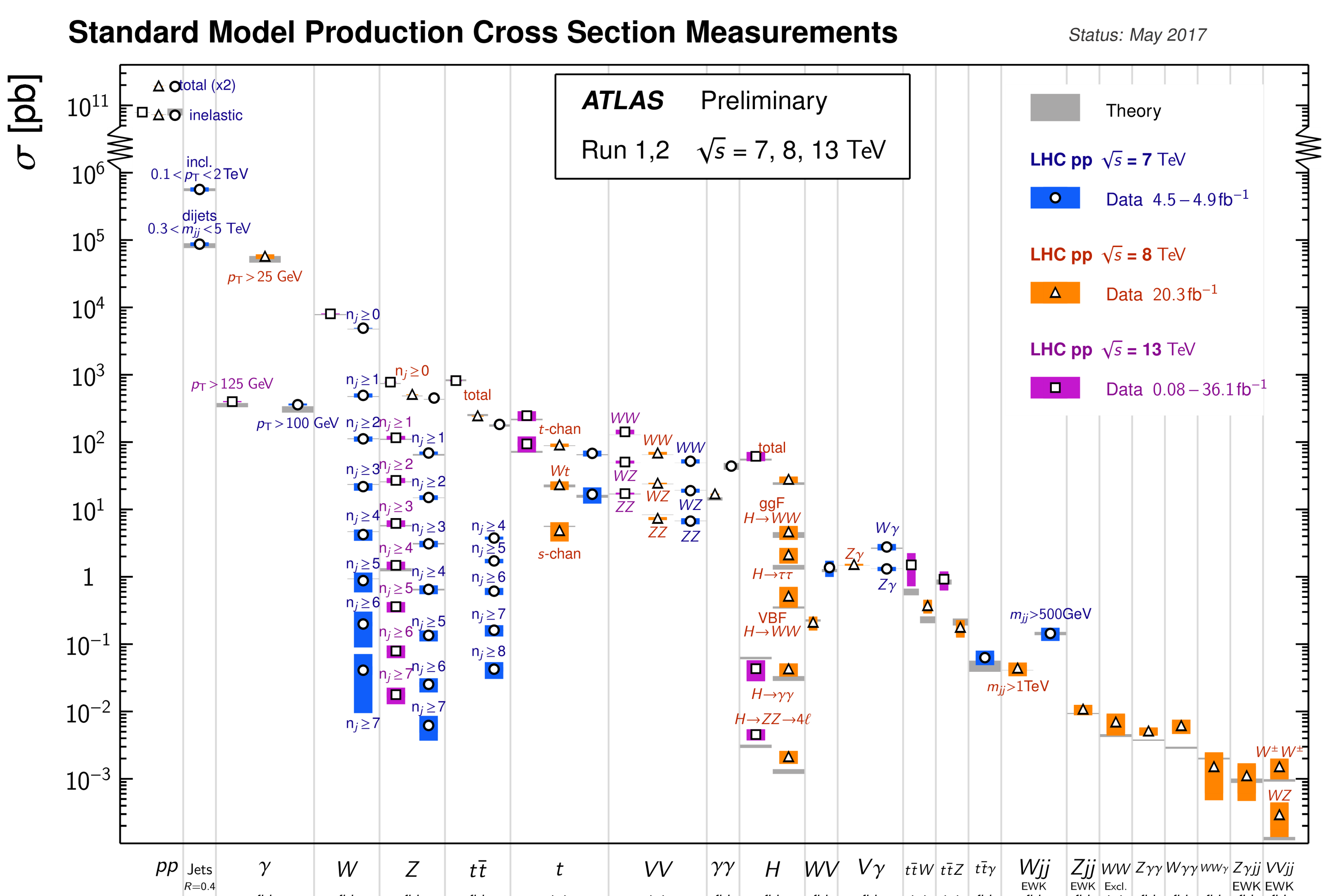
Preface

Excellence of LHC and its experiments @ Run 2: Enabled quick start after Run I and rich physics program @ 13 TeV

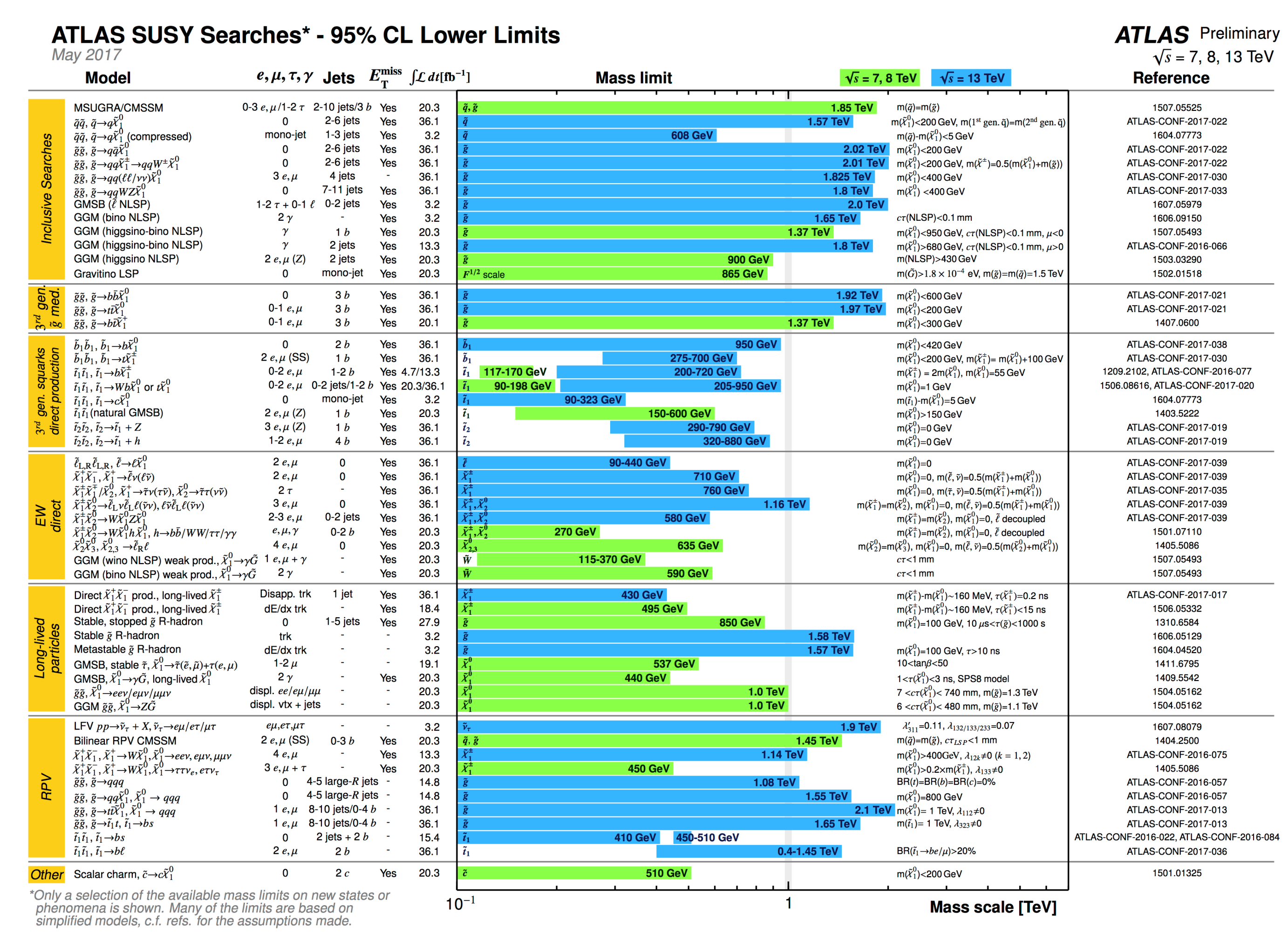
- **LHC**: more effective bunch collision schemes, increased machine availability (x2).
- **Experiments**: improved performance at high pile-up (and operation efficiency).

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

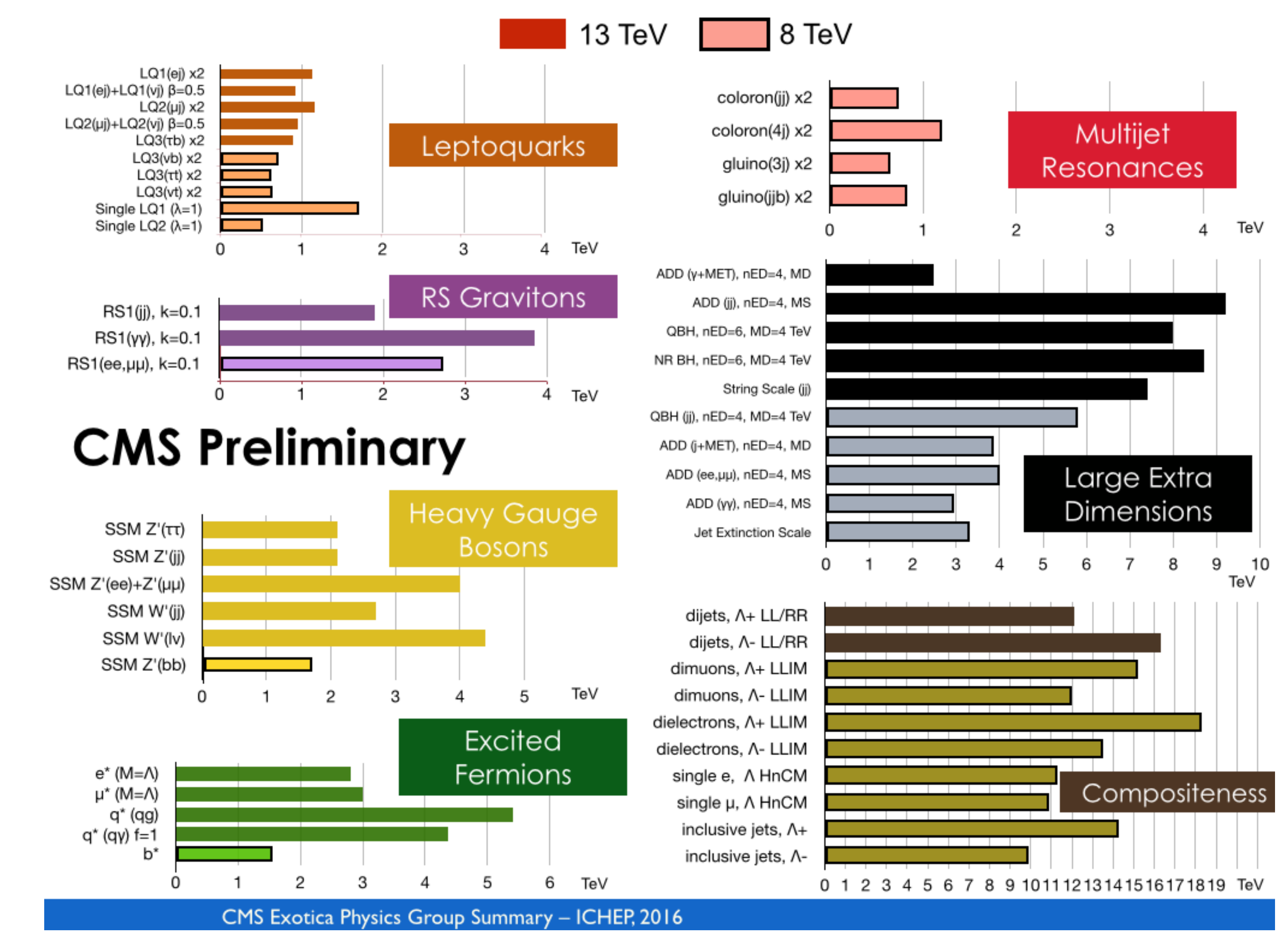
SM measurements



SUSY searches



Exotic searches



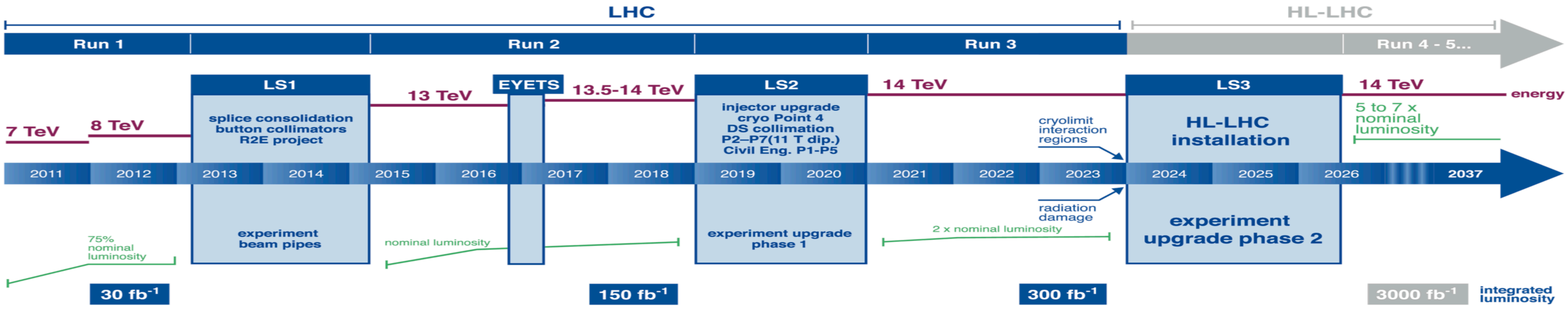
➡ No deviation from SM

➡ No indications for new physics phenomena

Need the LHC upgrade to fully exploit its potential and push the limits even further

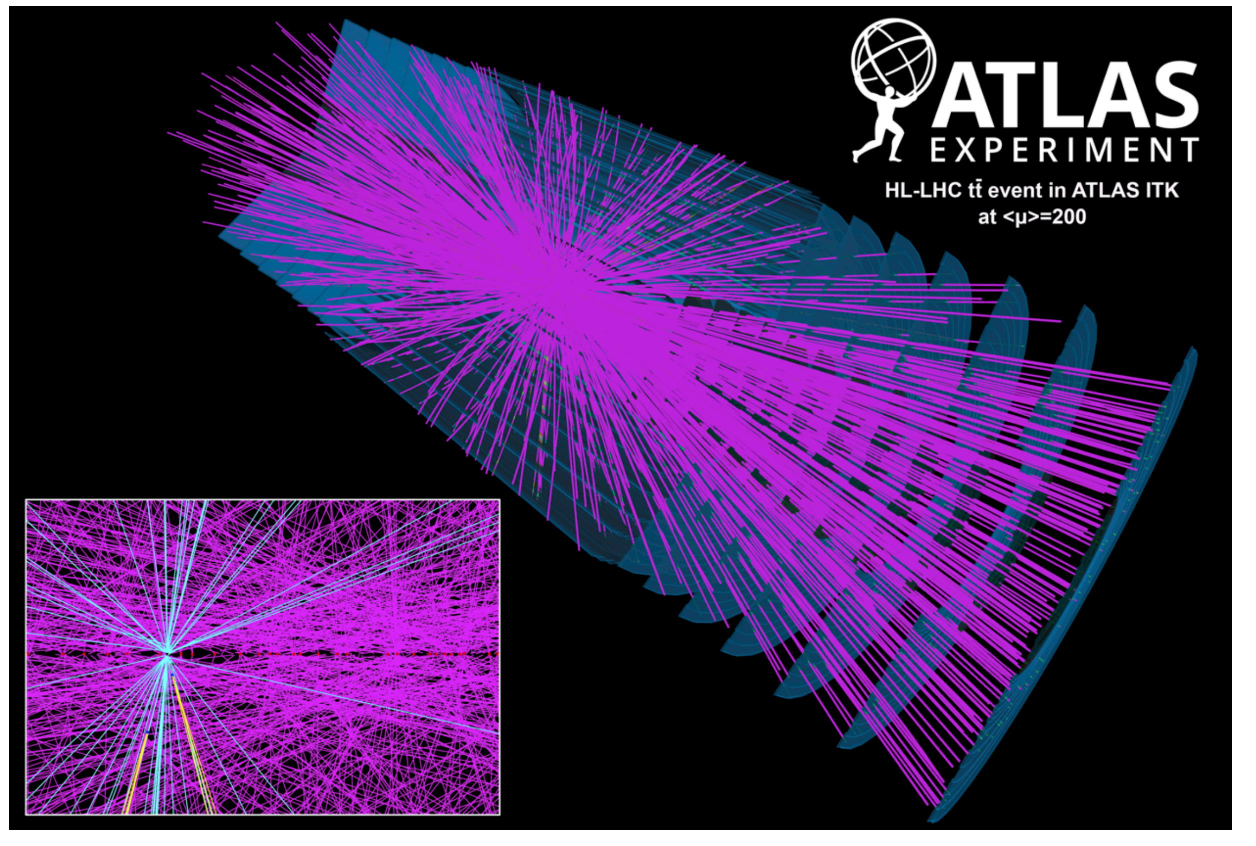
Towards the future: High-Luminosity LHC

From the early discovery machine … to the Higgs factory and its full discovery potential



HL-LHC goal: detailed topography of (the known) particle physics landscape:

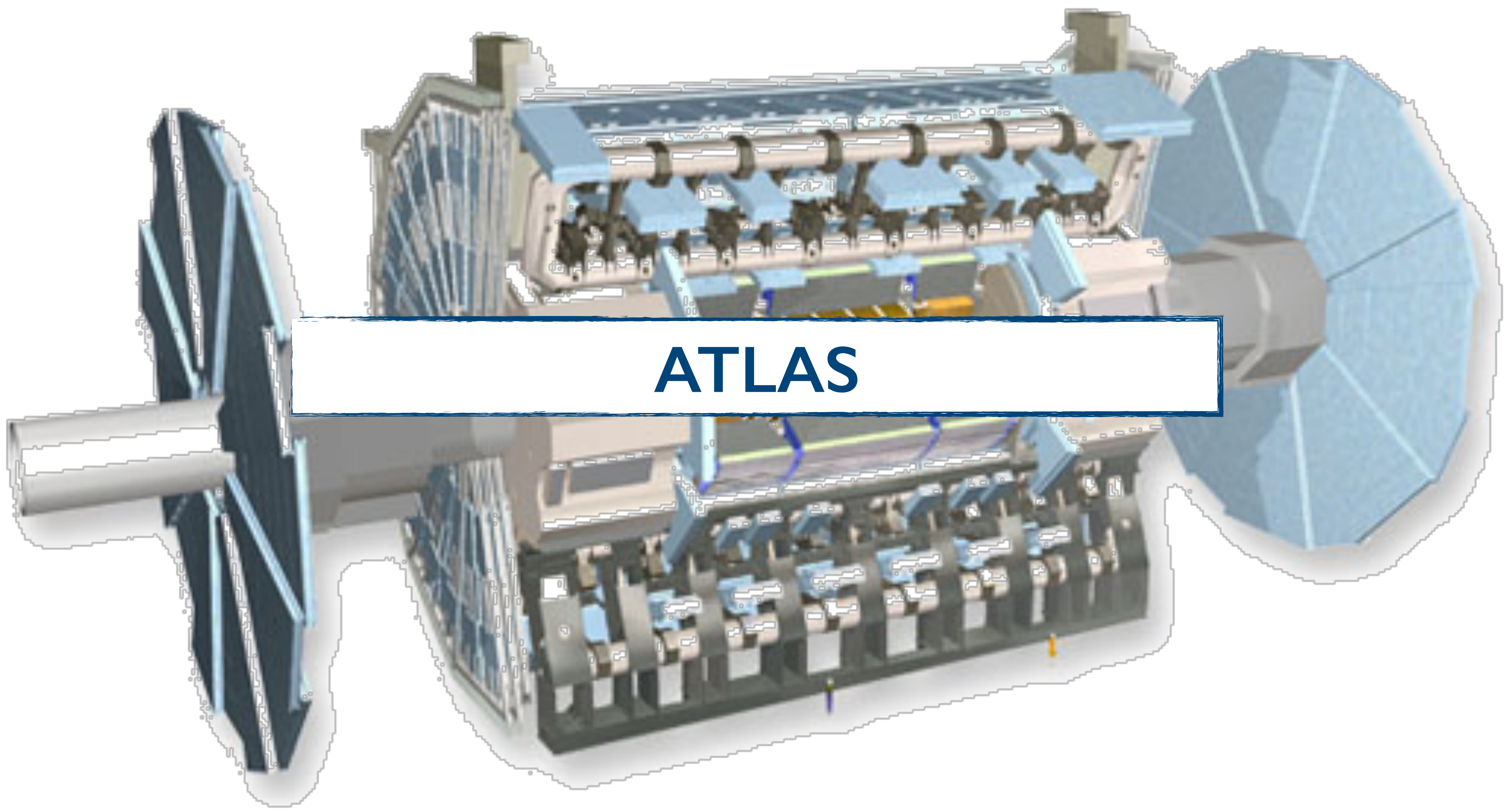
- Deeper understanding of the Higgs boson (couplings, potential).
- Precision measurements in QCD, EWK, Higgs (ultimate goal O(1%)).
- Probing new physics phenomena (directly & via precision measurements).

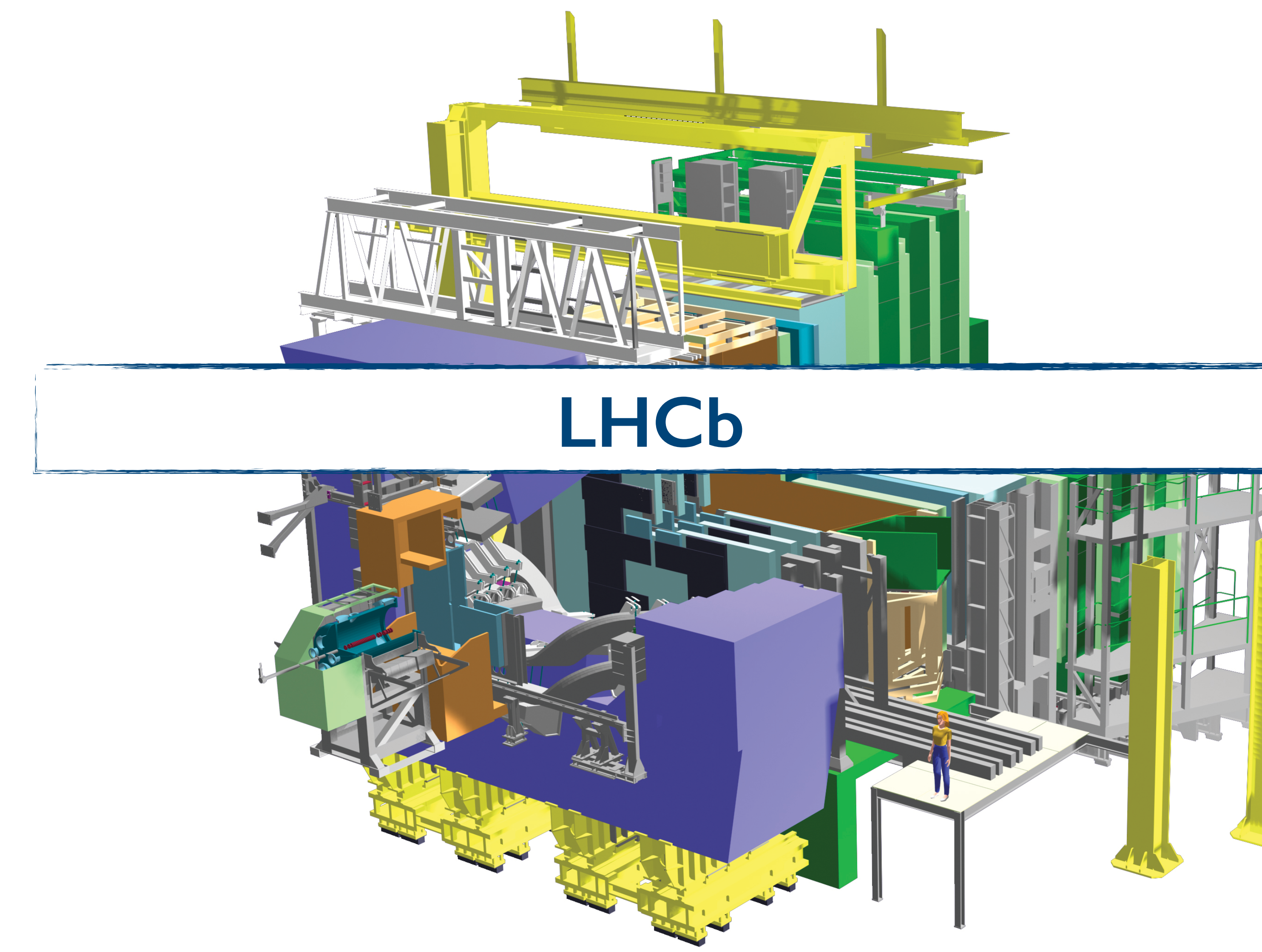


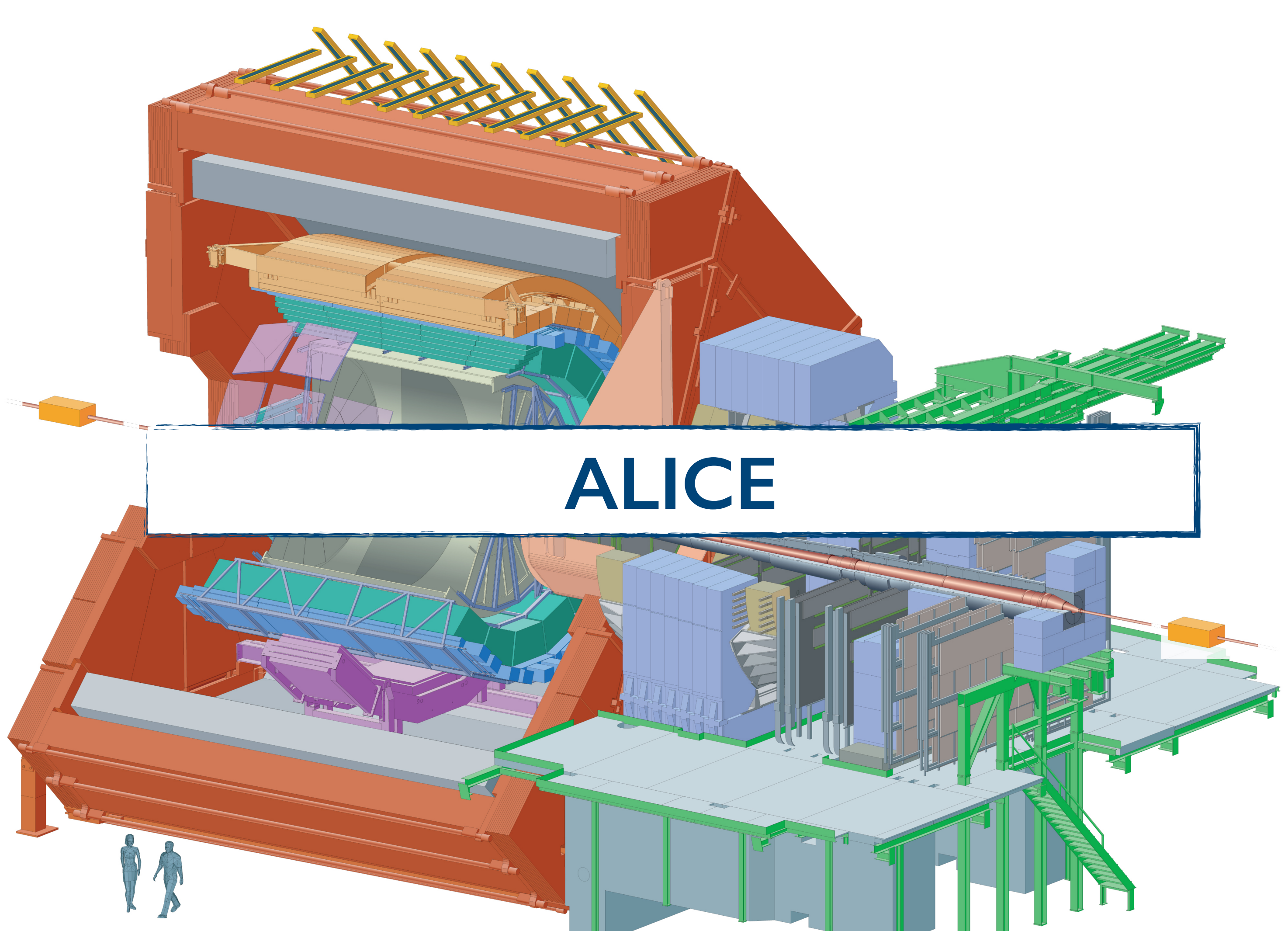
Challenges for the experiments:

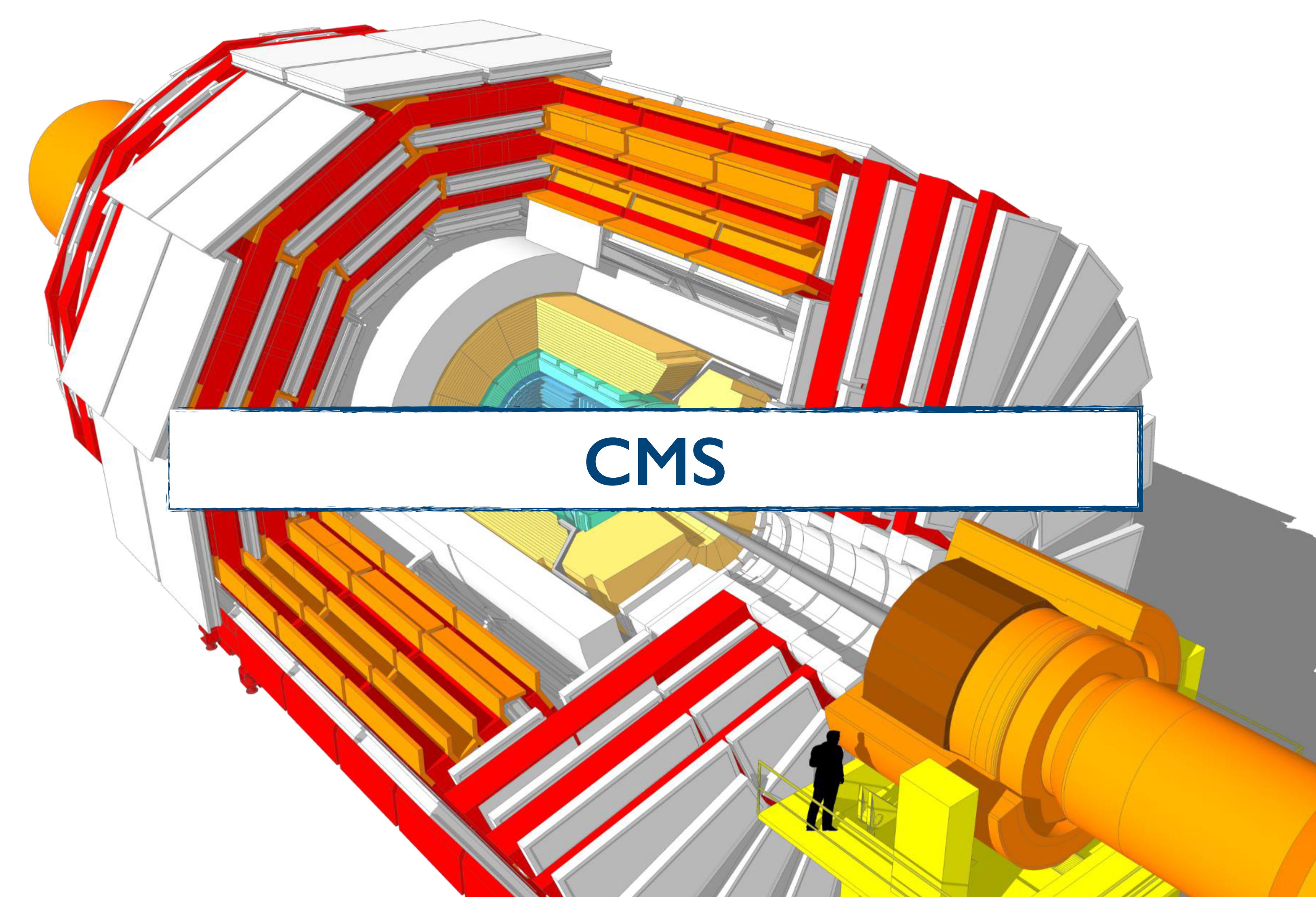
- Major experiment upgrades needed to improve radiation hardness, replace detectors at end-of-life or extend coverage,
- Provide handles to mitigate pileup and maintain/improve trigger acceptance.

Upgraded detectors @ HL-LHC



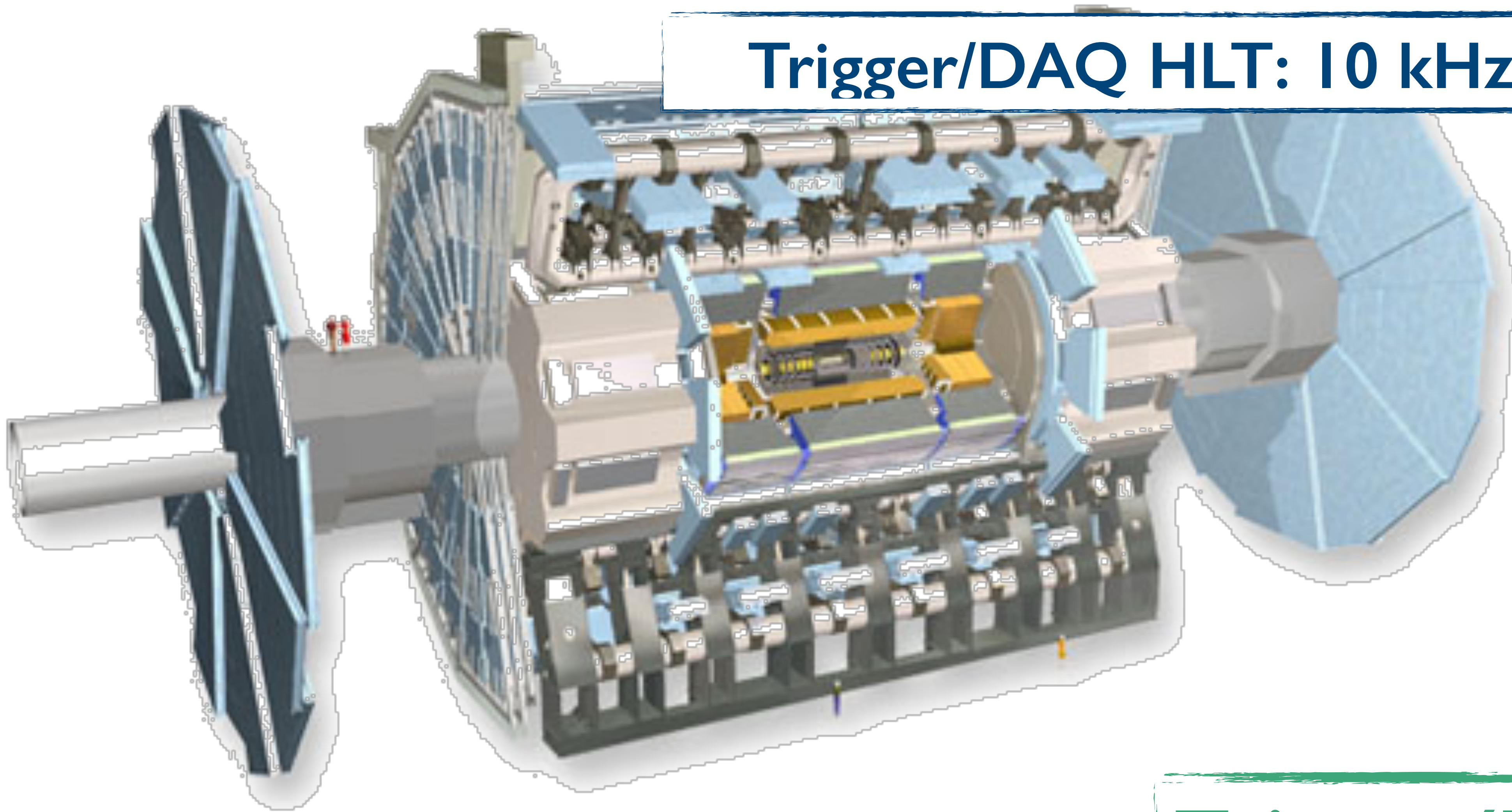




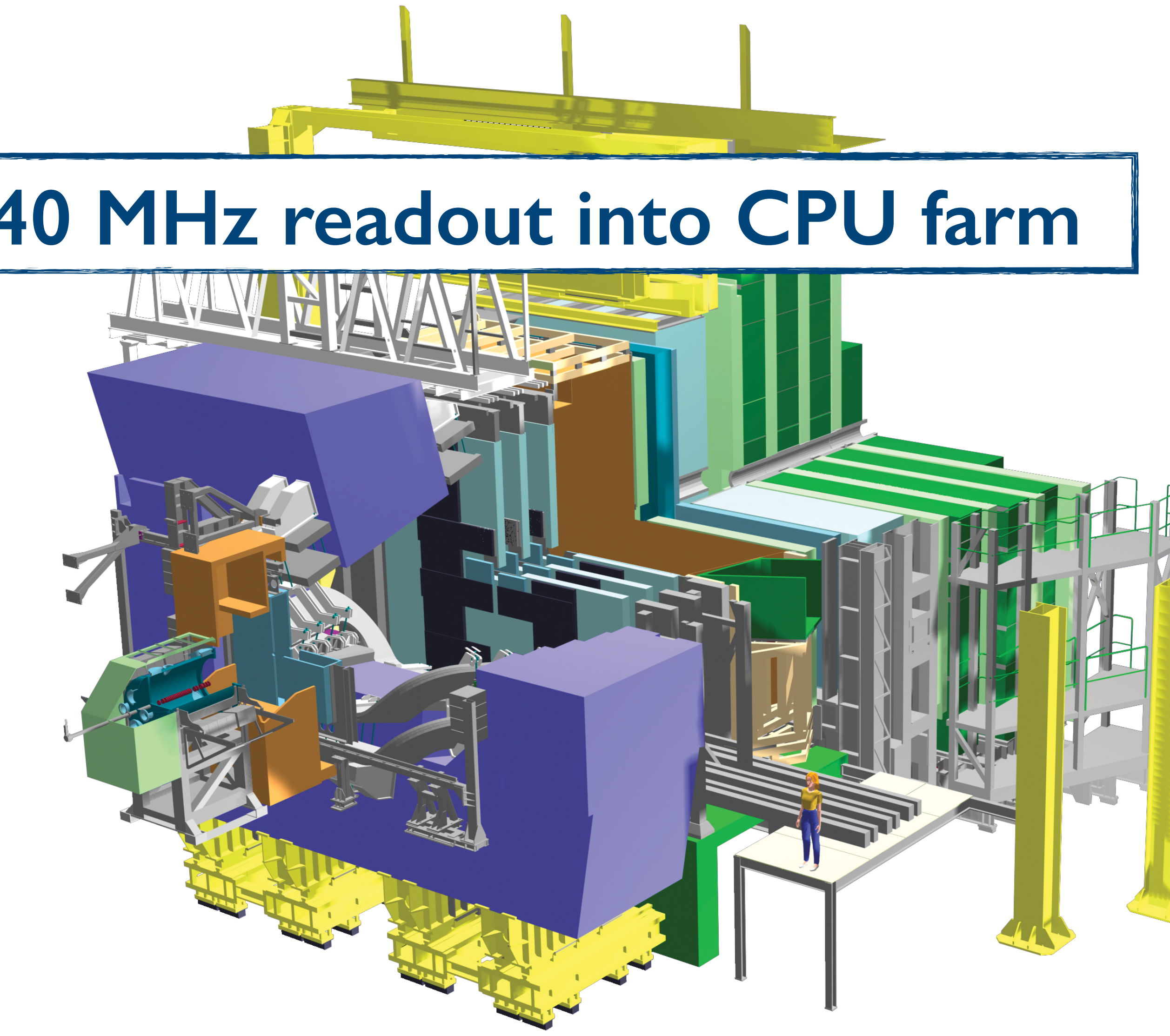


Upgraded detectors @ HL-LHC

Trigger/DAQ HLT: 10 kHz

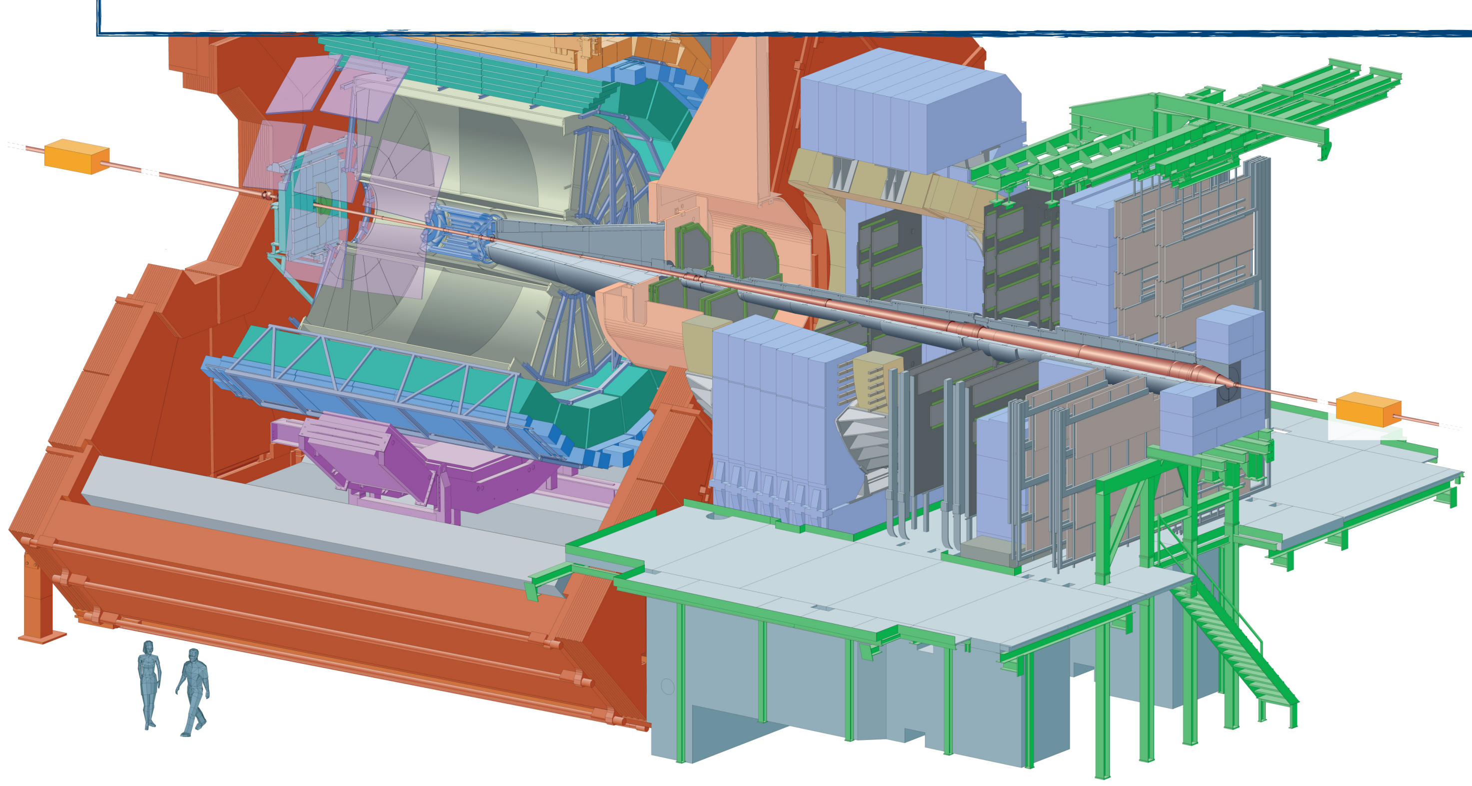


Full 40 MHz readout into CPU farm

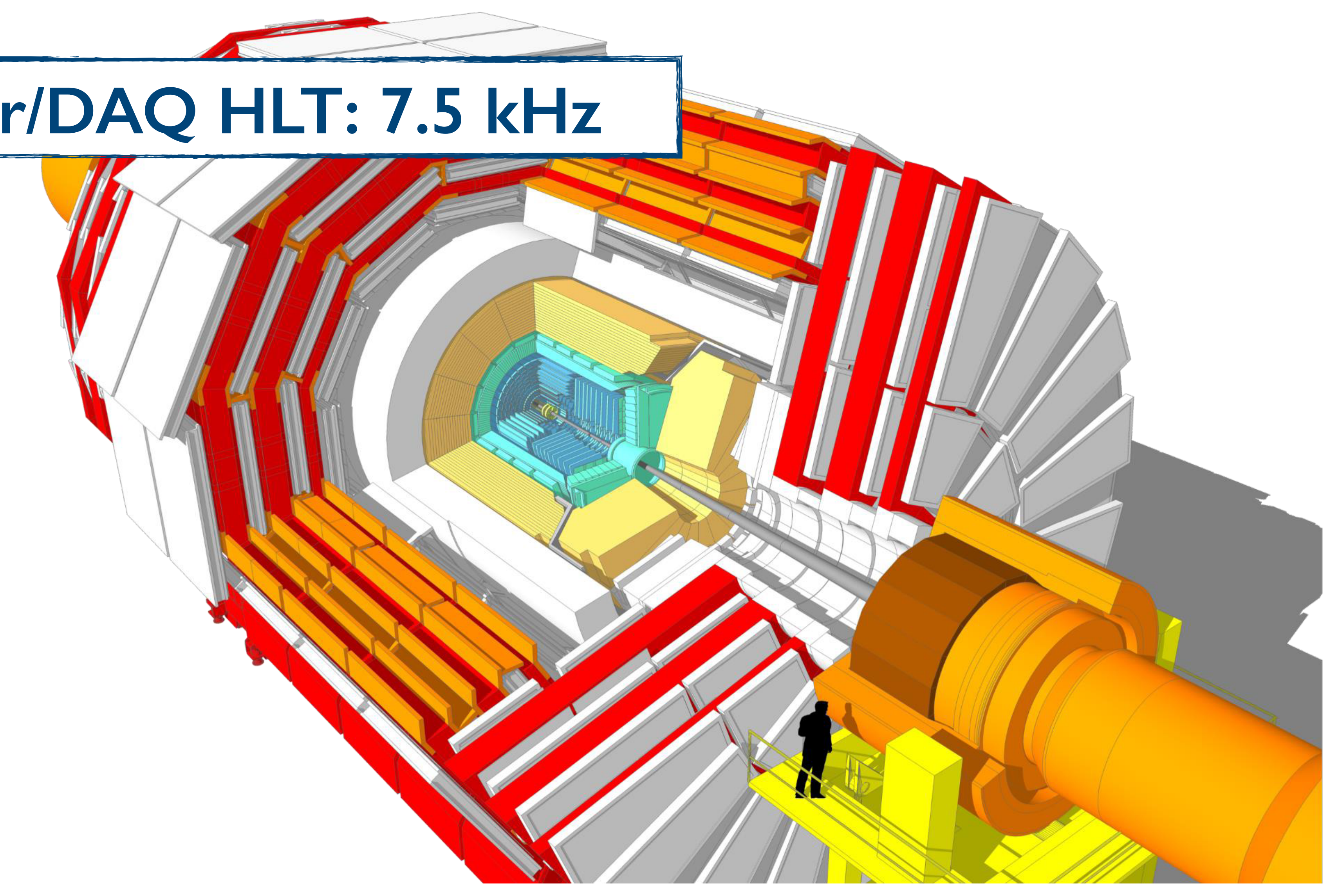


Trigger/DAQ upgrades

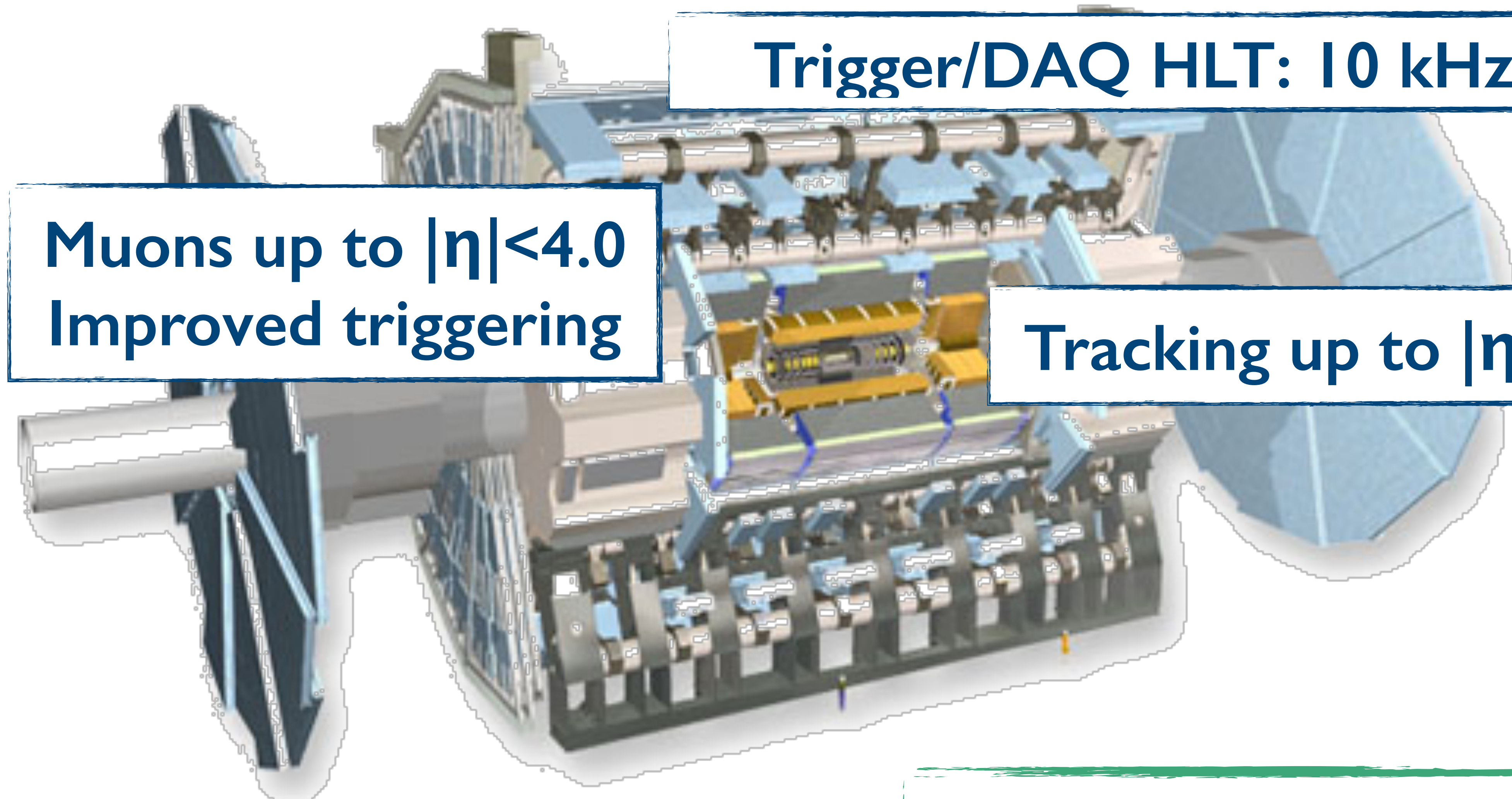
Major upgrade during LS2:
Forward Interaction Trigger, Inner Tracking System, Muon Forward Tracker

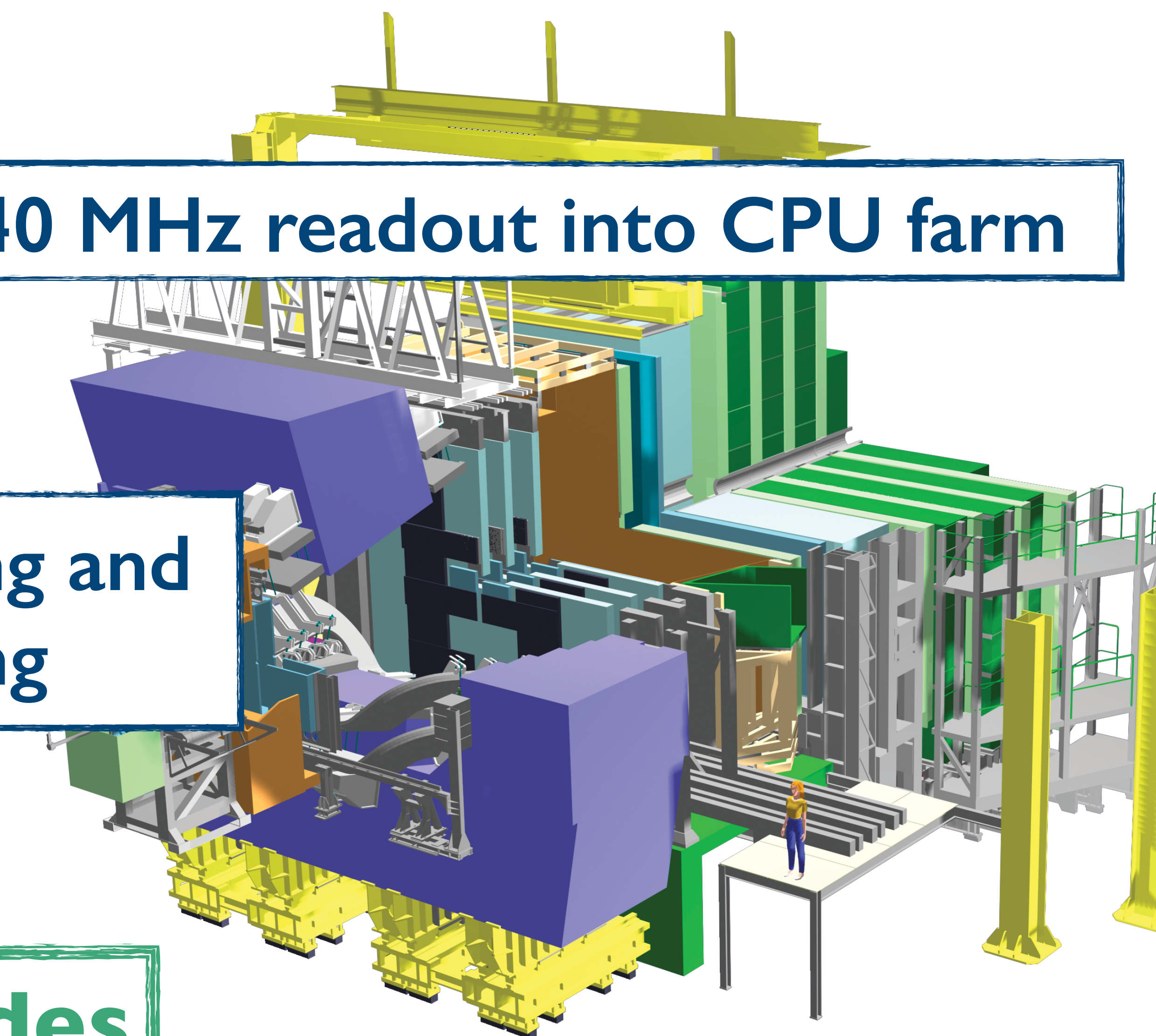


Trigger/DAQ HLT: 7.5 kHz

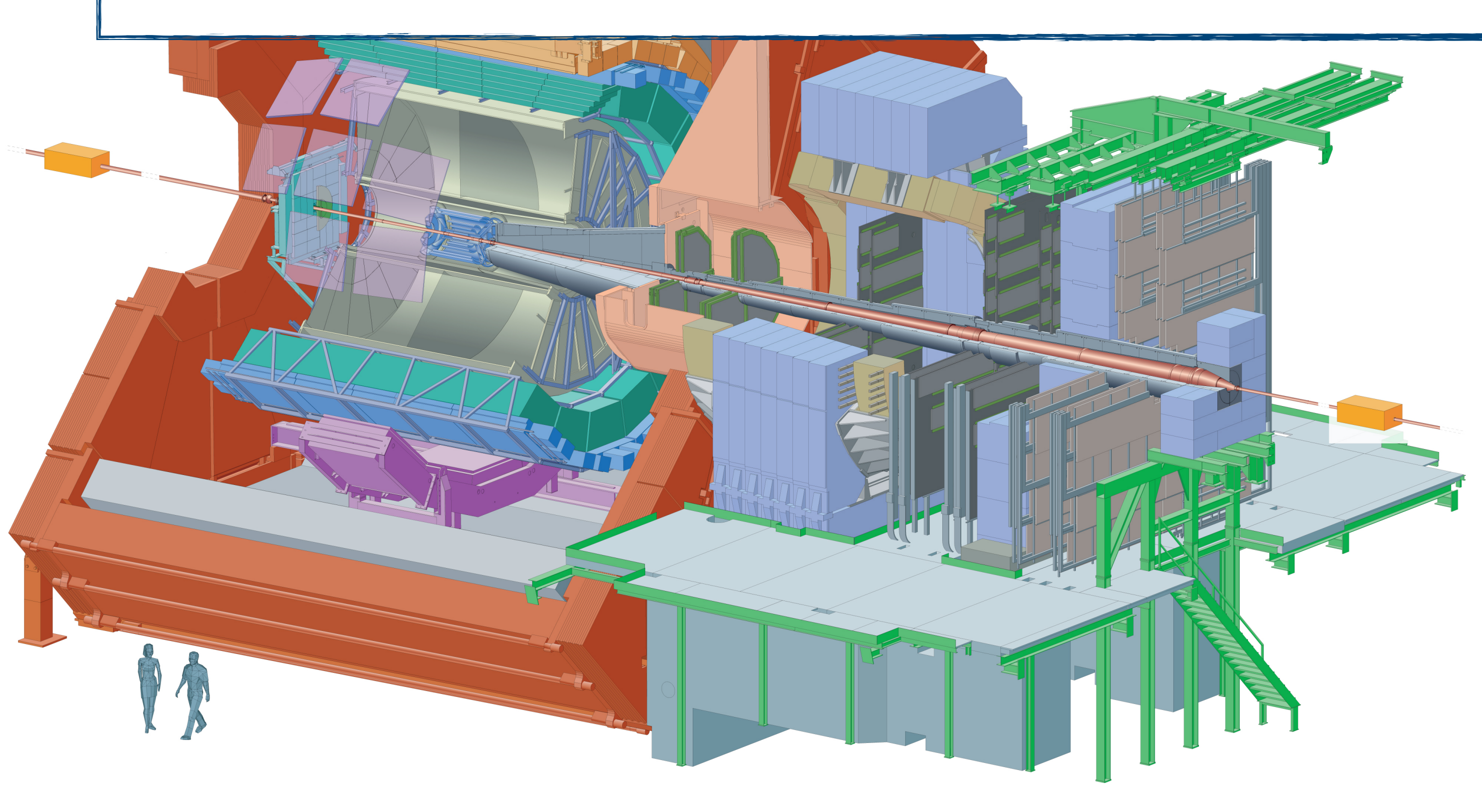


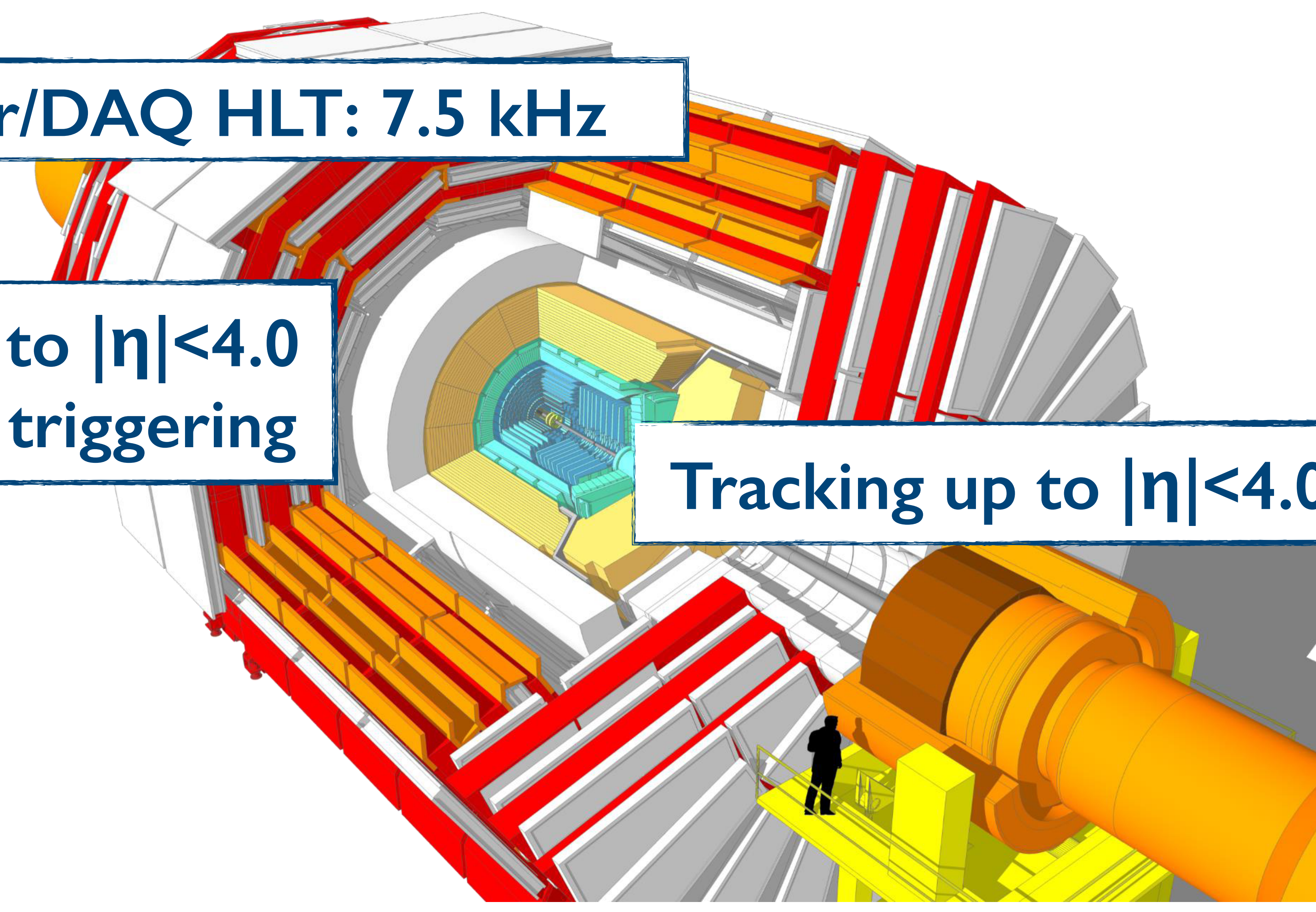
Upgraded detectors @ HL-LHC





Tracking/Muons/coverage upgrades





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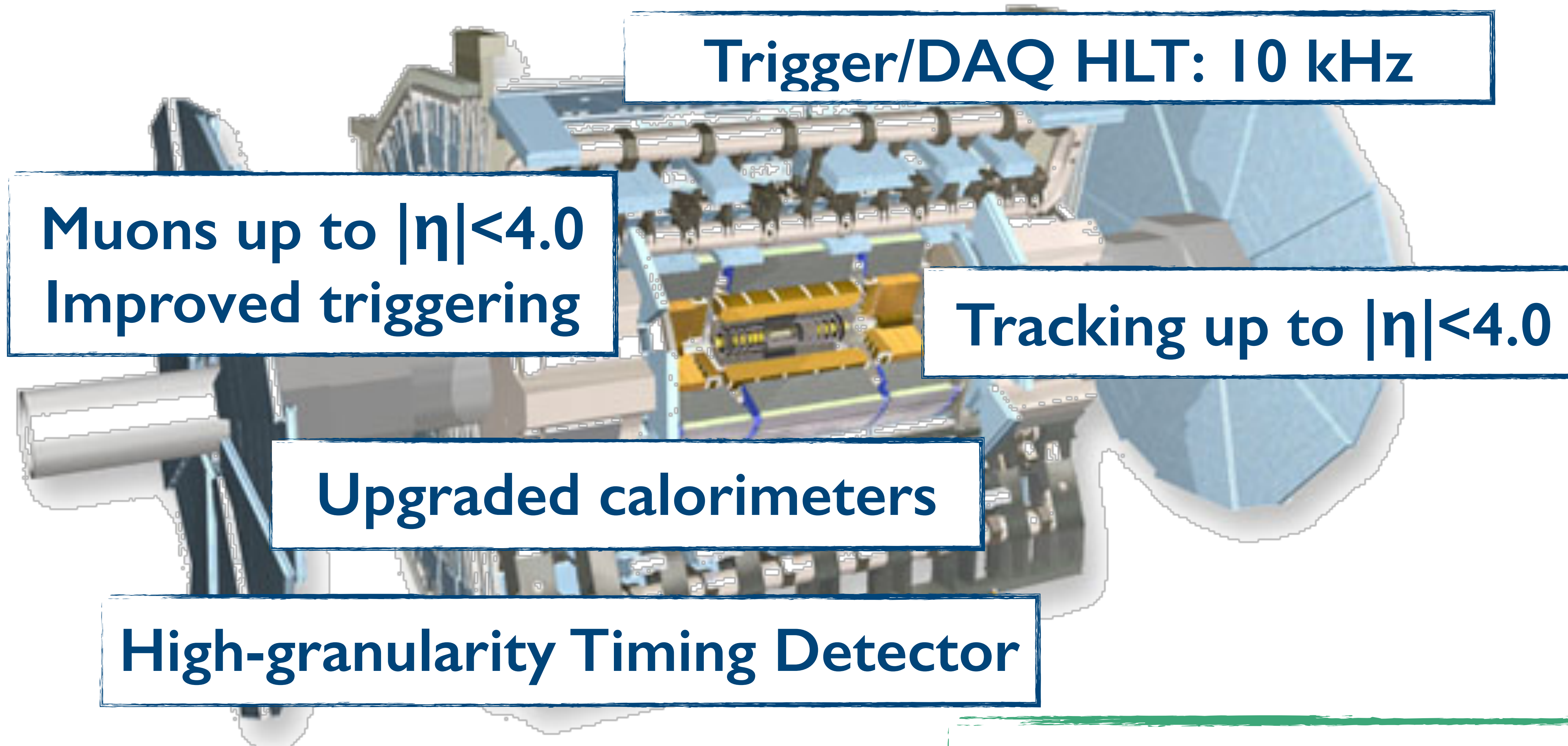


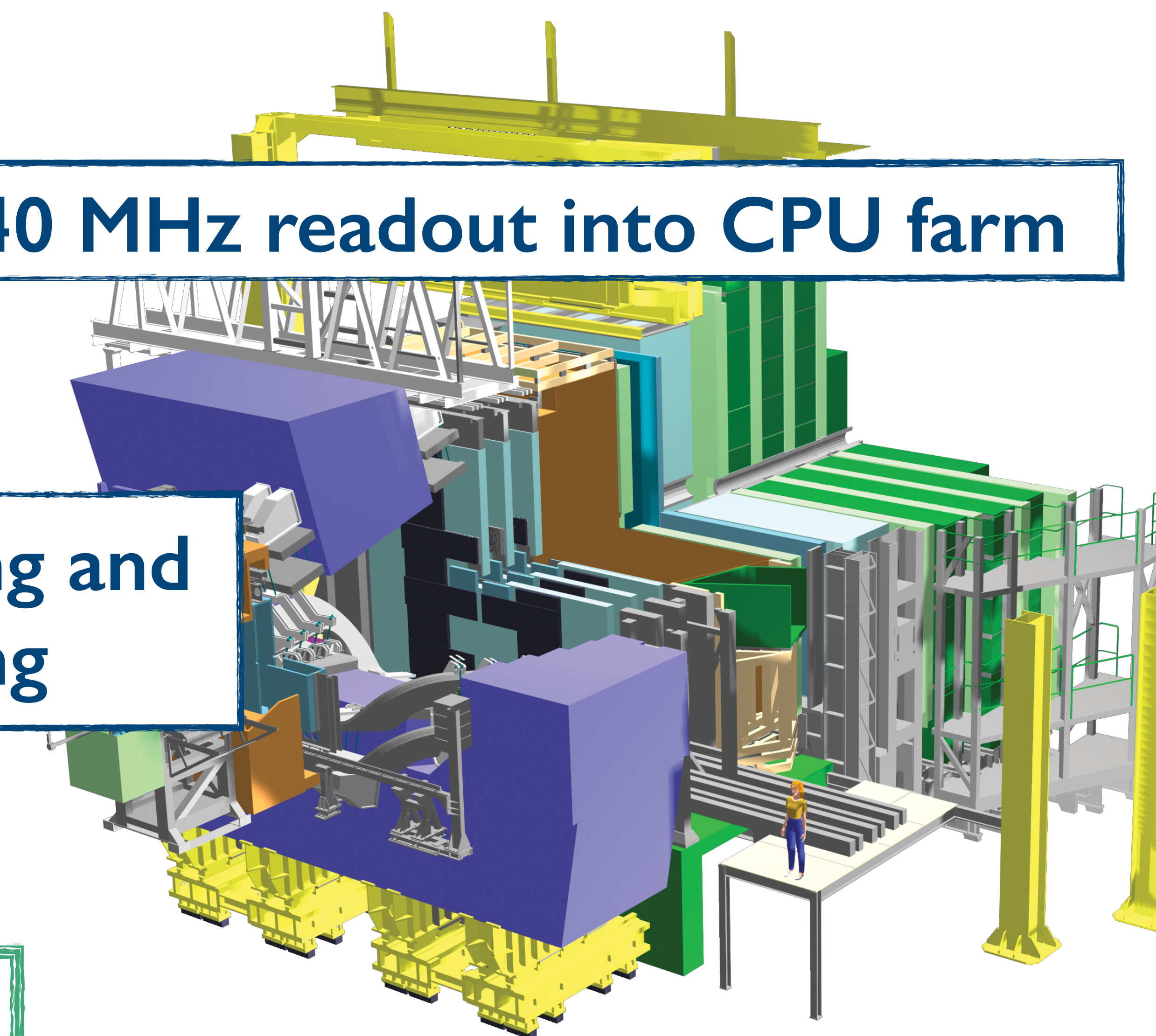
Trigger/DAQ HLT: 10 kHz

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

Calorimeters/timing upgrades

Major upgrade during LS2:
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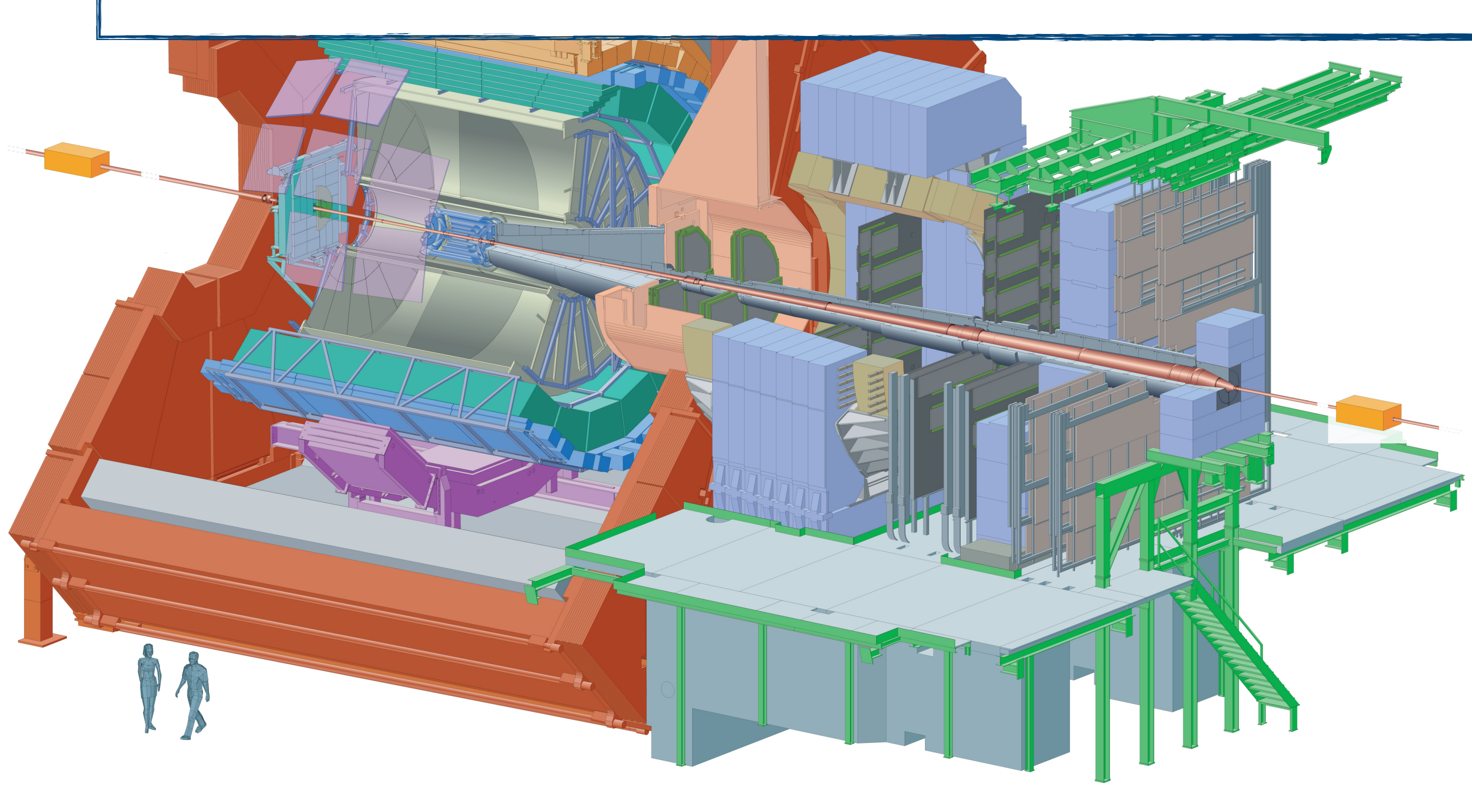
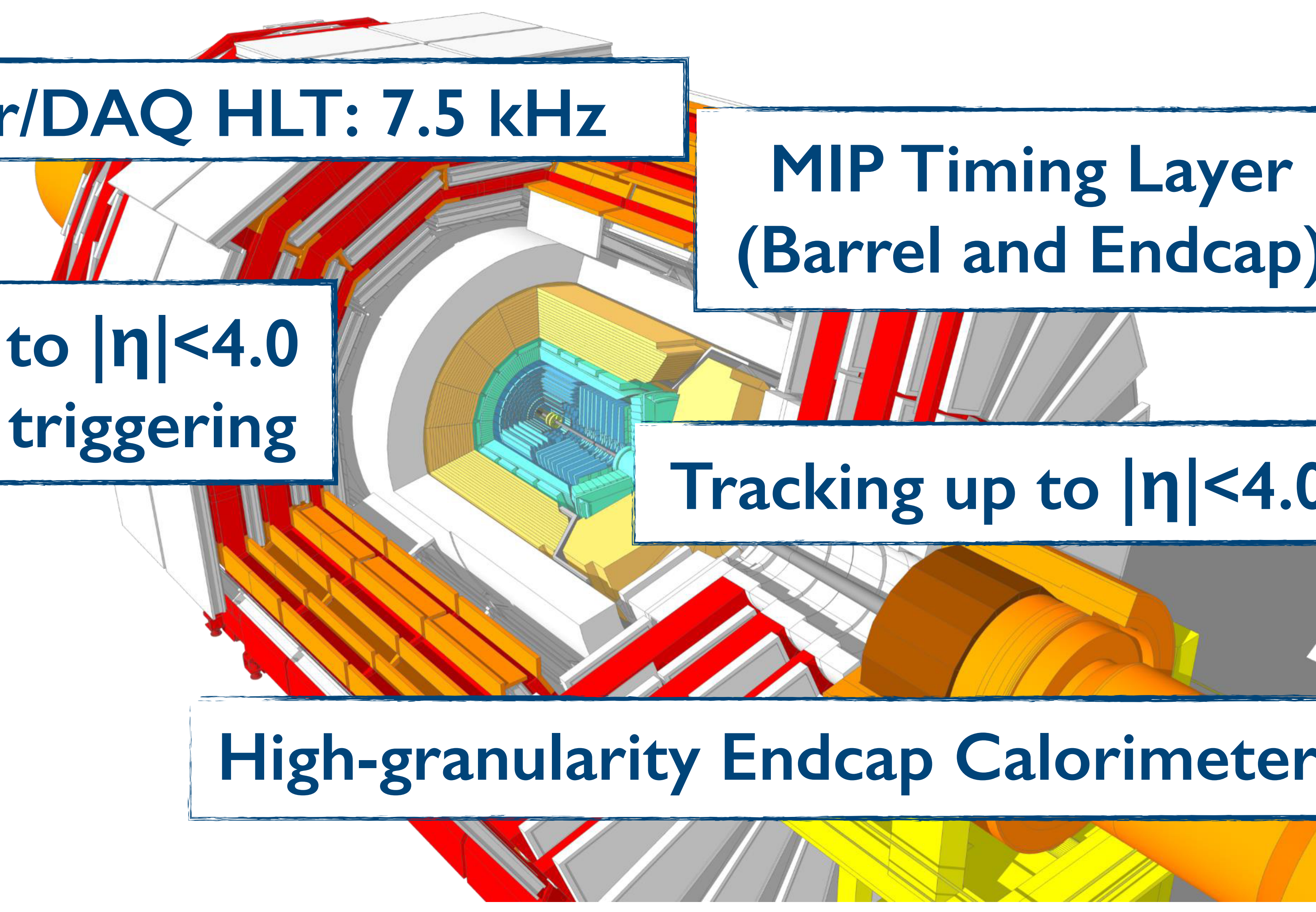




Trigger/DAQ HLT: 7.5 kHz

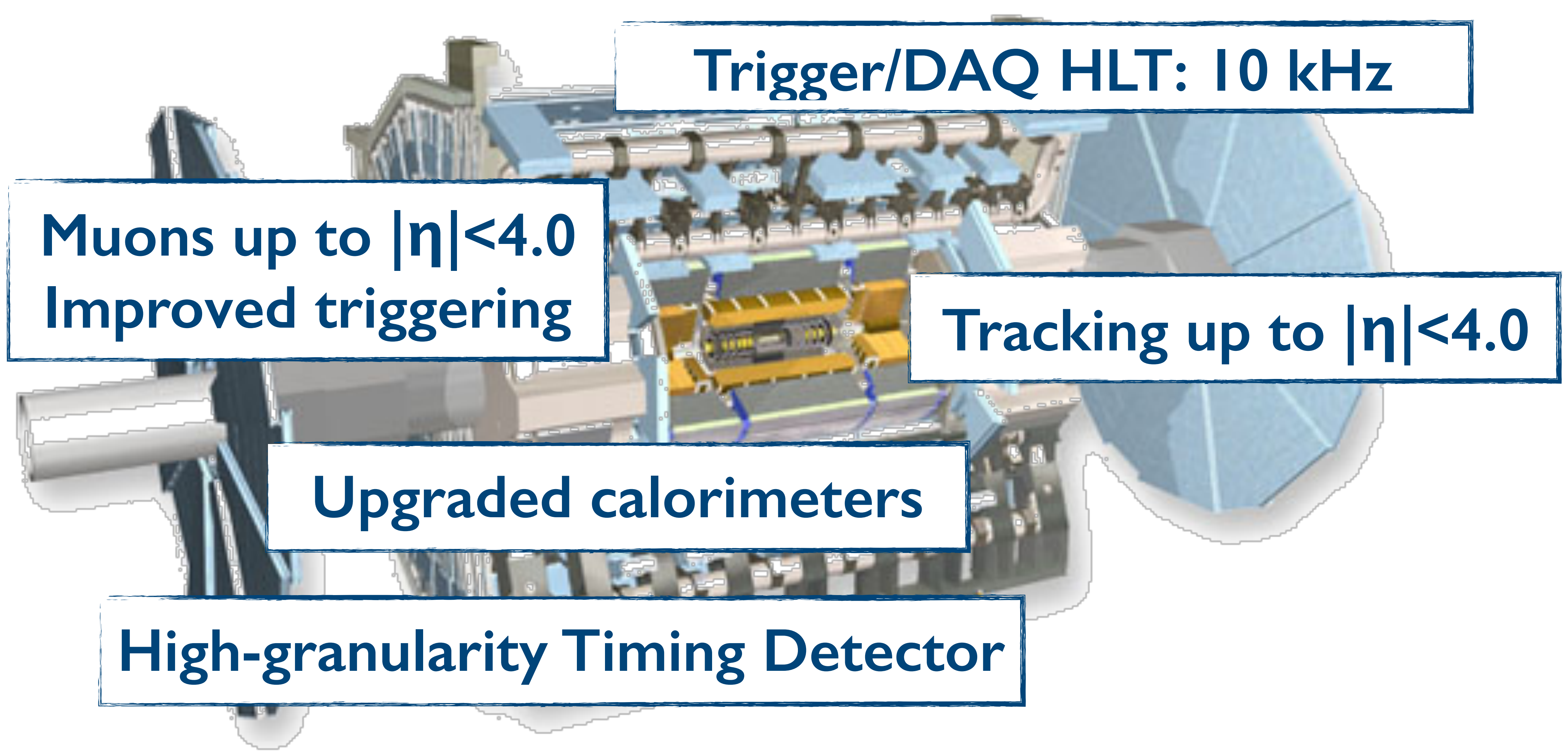
MIP Timing Layer (Barrel and Endcap)

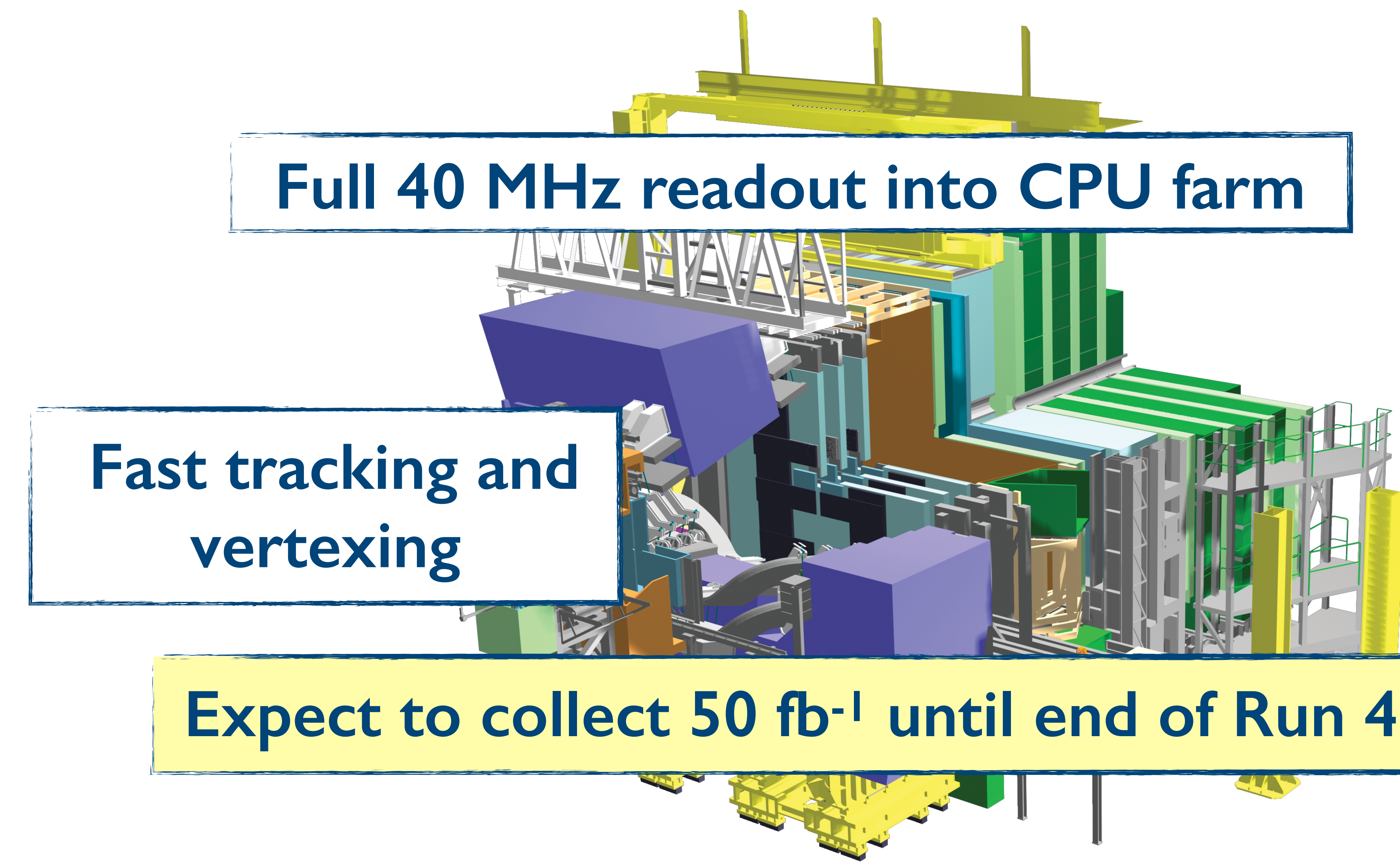
Muons up to |η|<4.0
Improved triggering

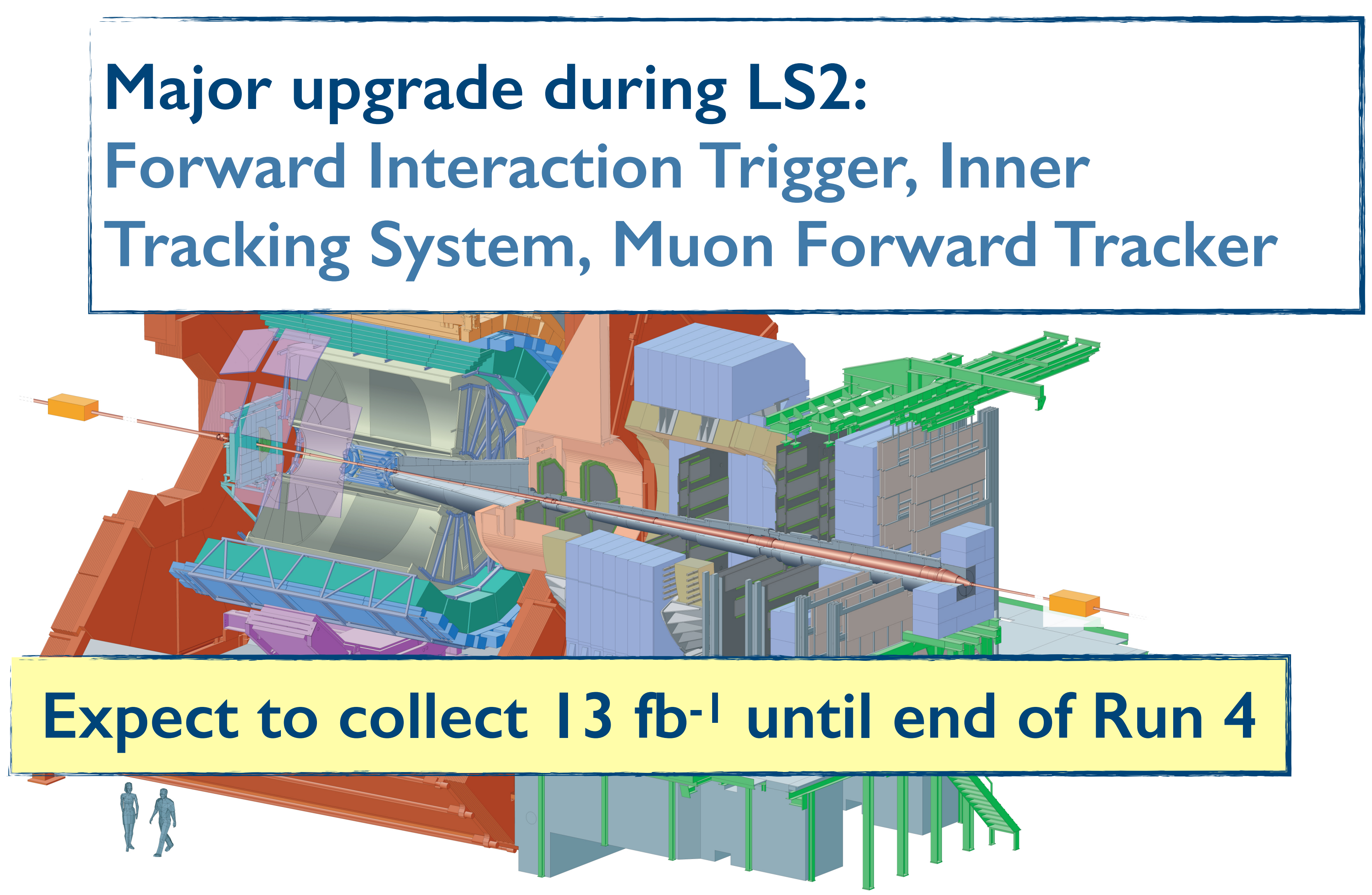
Tracking up to |η|<4.0

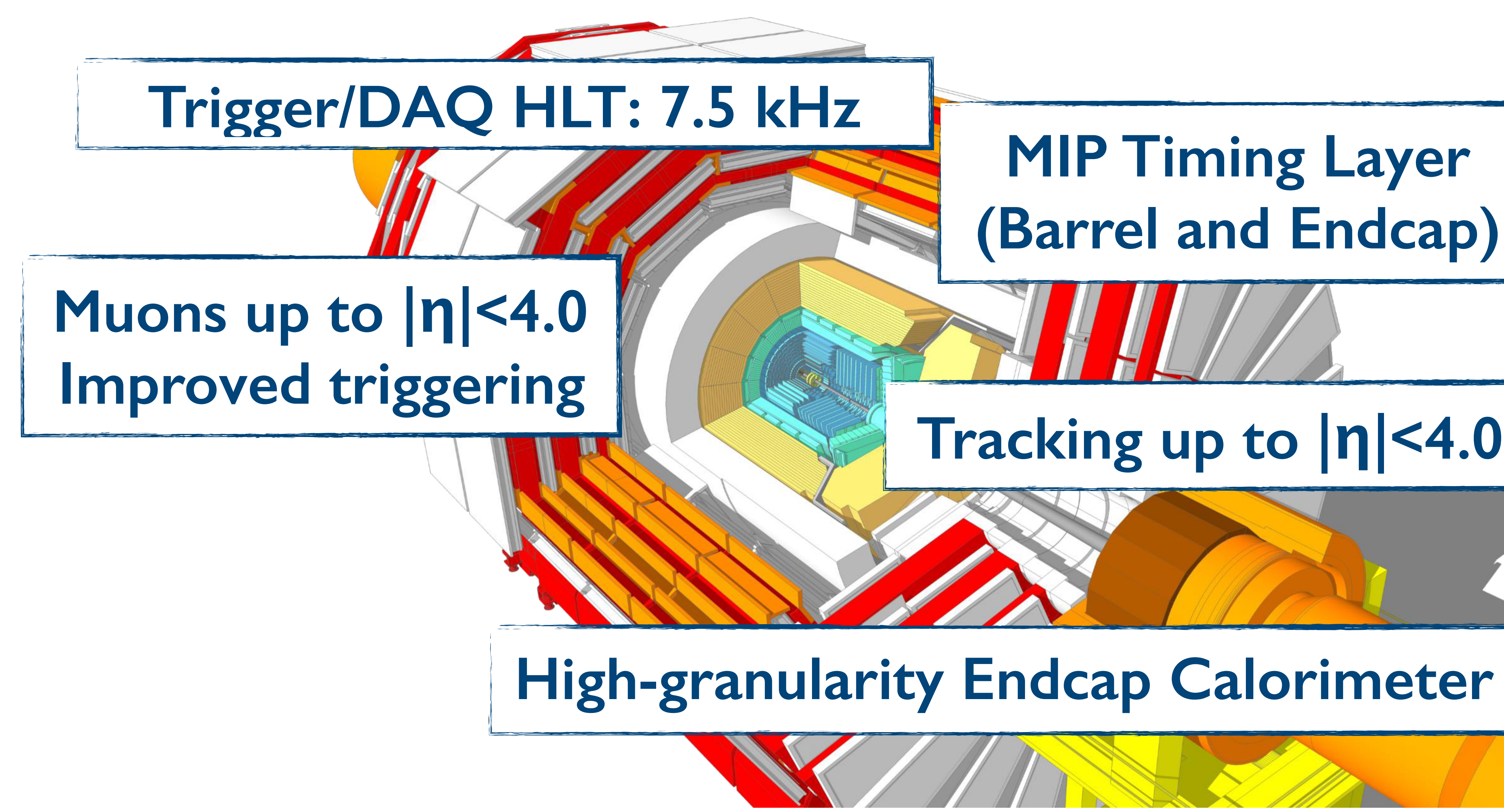
High-granularity Endcap Calorimeter

Upgraded detectors @ HL-LHC









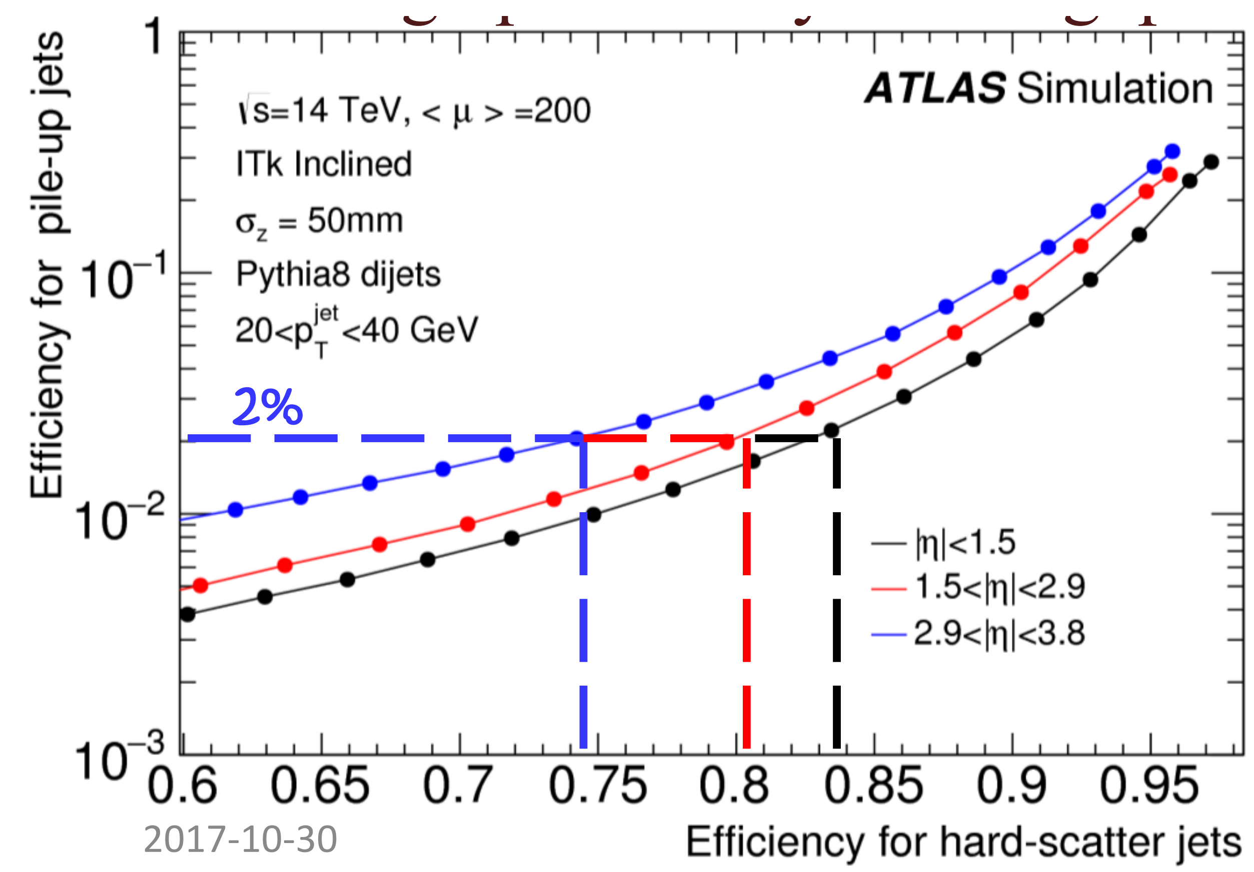
Experiments' TDRs

Detectors performance @ HL-LHC

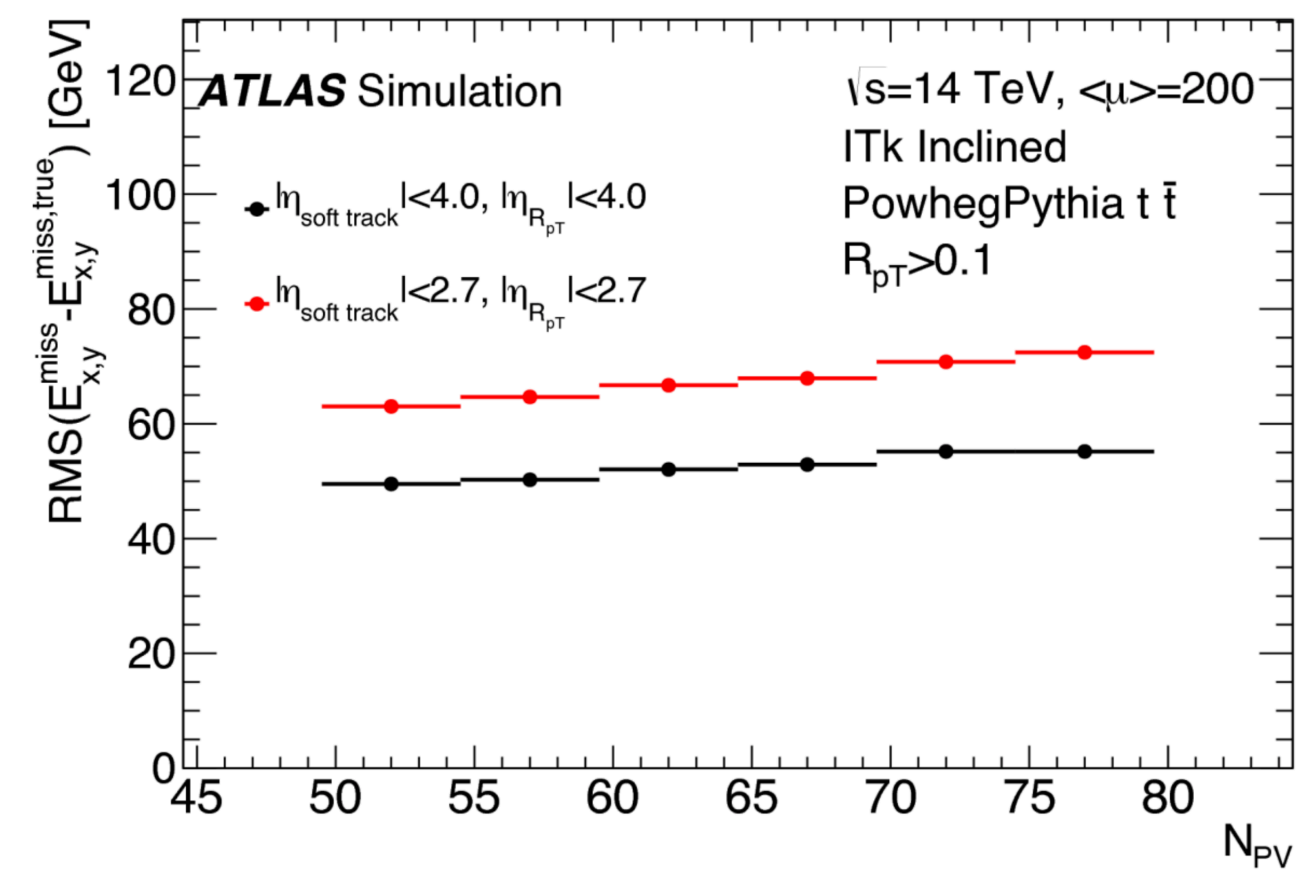
Detector performance after Phase-2 upgrades:

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

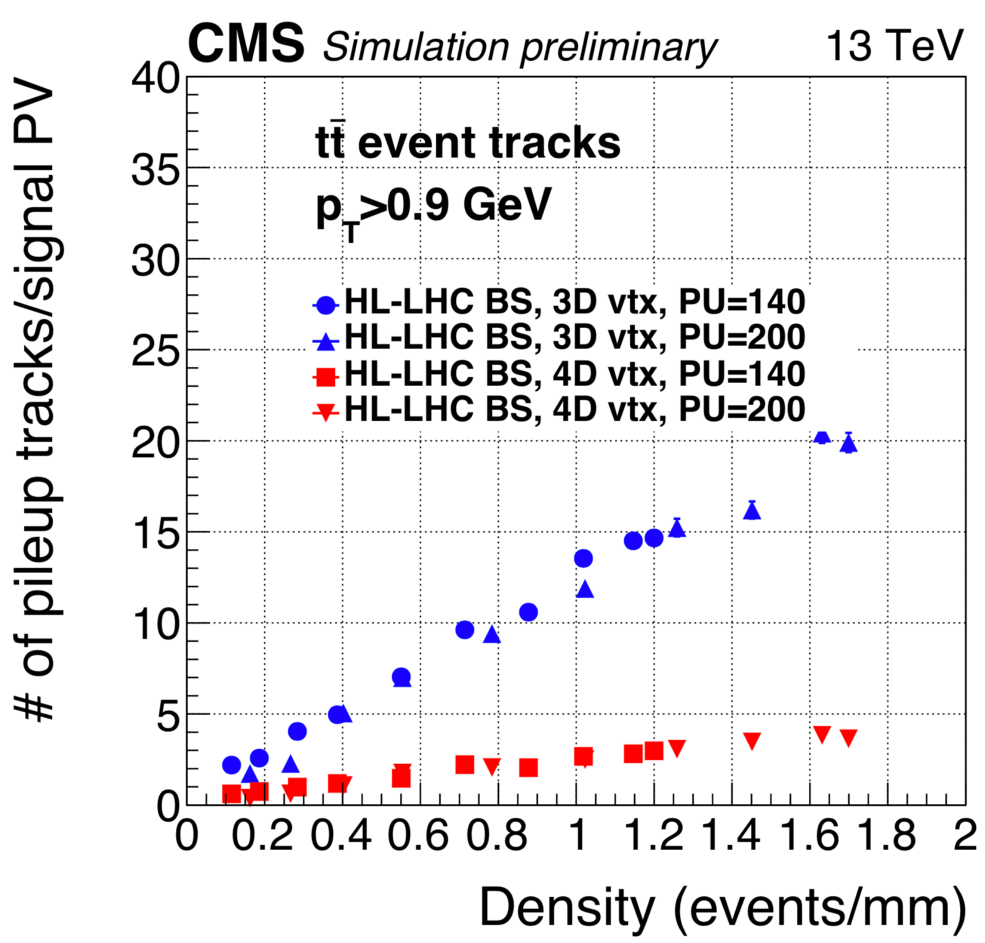
Jets



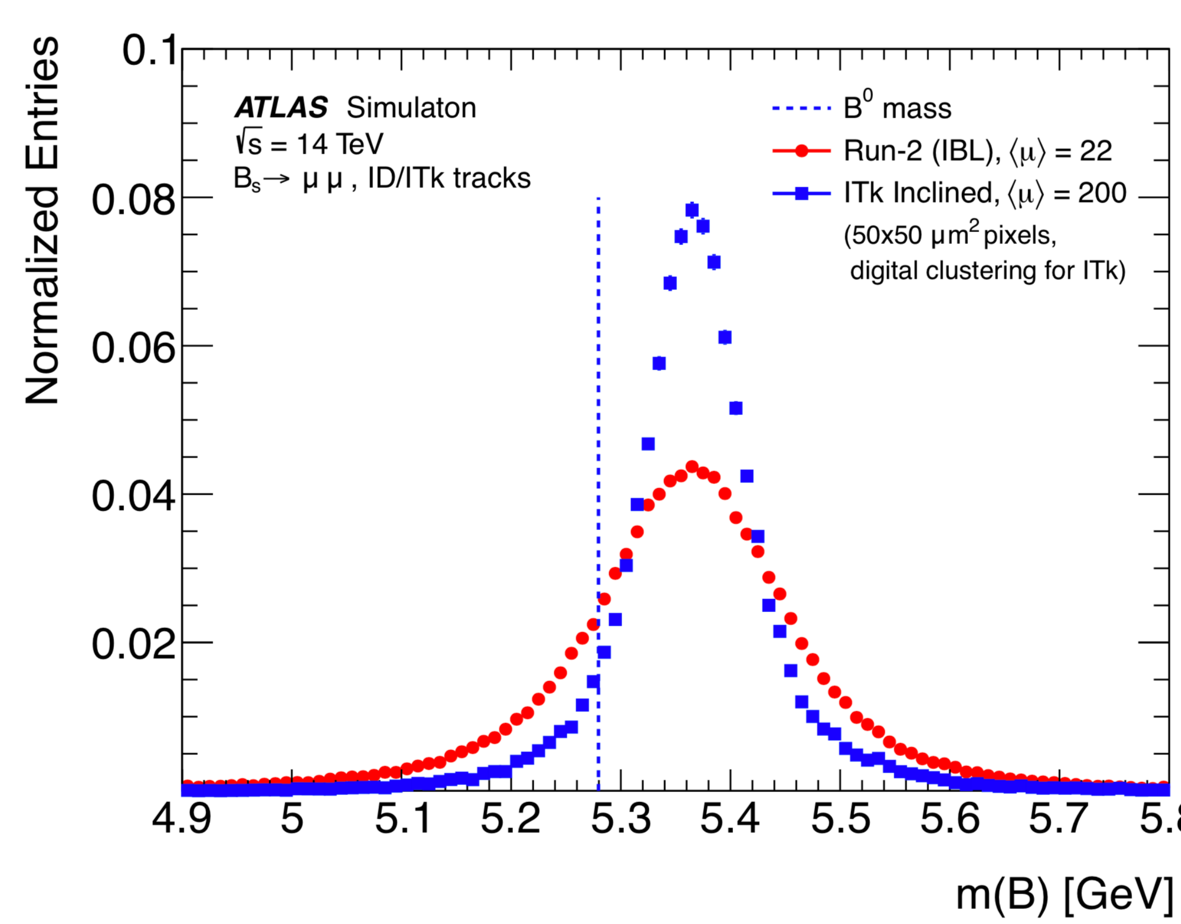
MET resolution



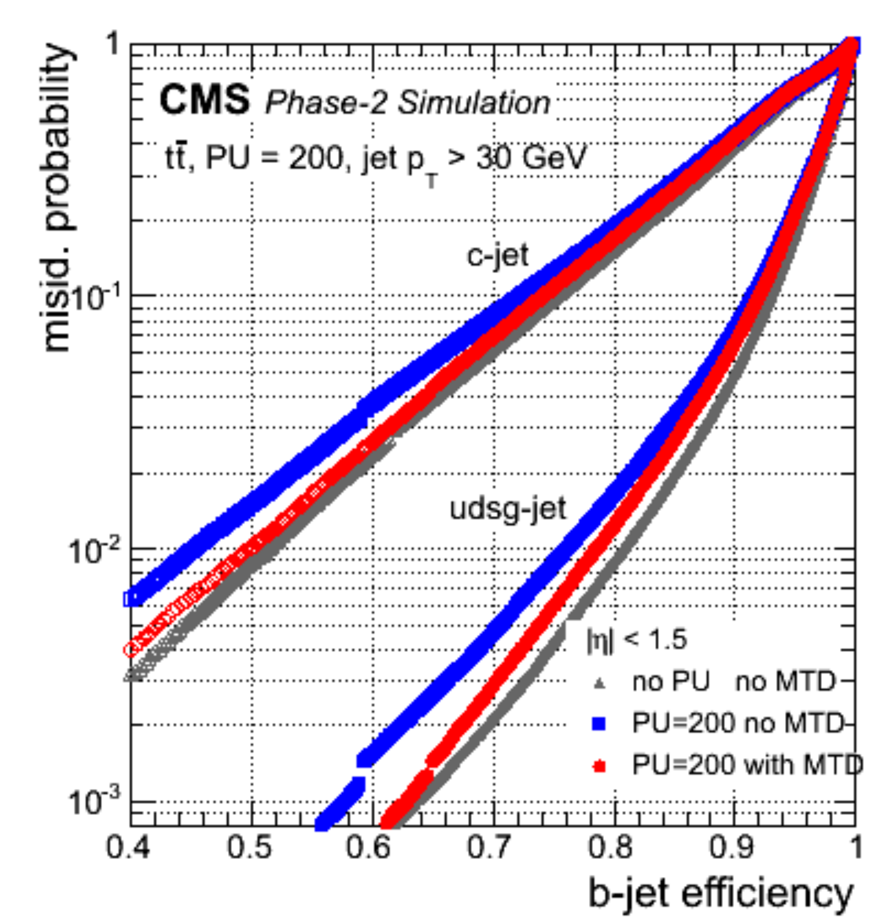
Pile-up suppression



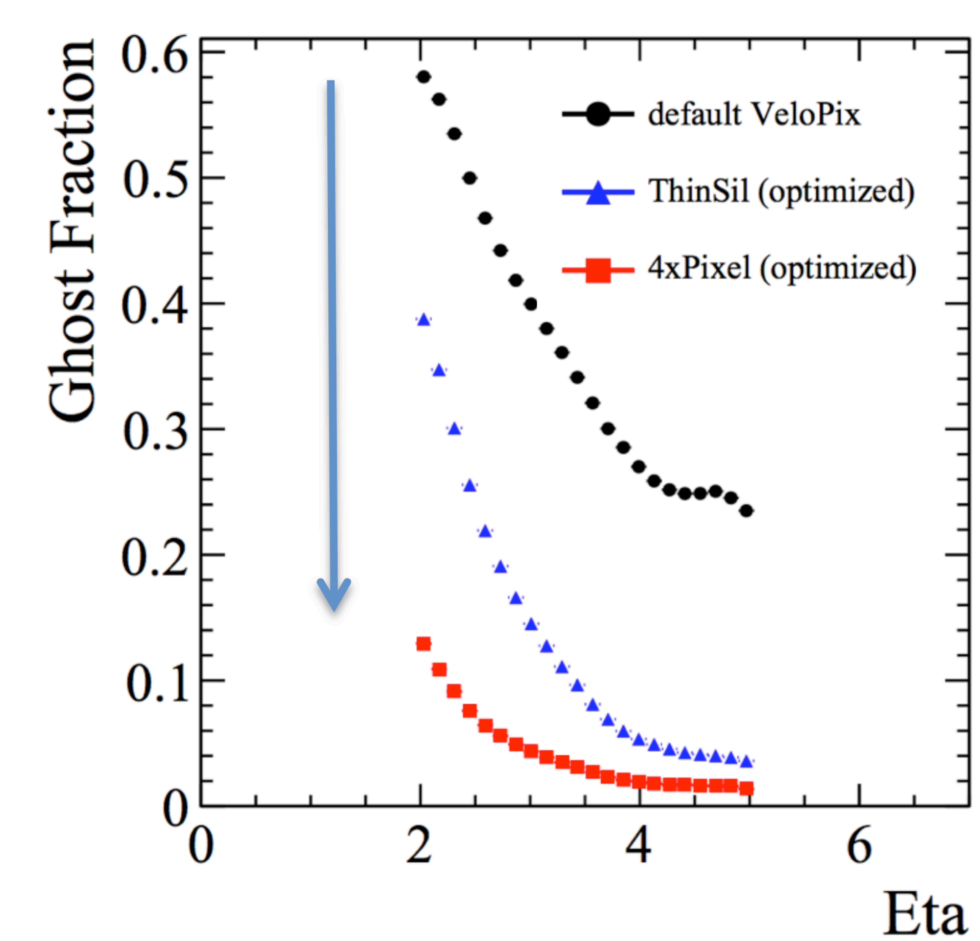
Mass resolution



B-tagging



LHCb Vertex Locator



Workshop on Physics at HL-LHC and Perspectives for HE-LHC

- HE/HL-LHC effort : goals, organisation, timeline
- Extrapolation methodology and uncertainties assumptions

HE/HL-LHC studies

Extensive studies & updated projections, organised in form of WGs:

- Review, extend and further refine our understanding of the **physics potential of the HL-LHC**
- Opportunity for a more systematic study of physics at the **HE-LHC** (pp collisions @27 TeV)
- Stimulate new ideas for measurements and observables

WG 1	WG 2	WG 3	WG 4	WG 5
QCD, EWK, TOP	Higgs & EWSB	BSM	Flavour	Heavy Ion

Reports and timeline:

- **Yellow Report:** Summary of public studies from theorists and experiments.
- **Executive Summaries:** Input for CERN Council for discussion on EU Strategy for Particle Physics.
- **Effort/report timeline:**

More info: http://lpcc.web.cern.ch/hlhe-lhc-physics-workshop

Nov 2017	June 2018	Oct 2018	Nov 2018	Dec 2018
Kick-off	Plenary	Plenary	First YR draft	Publication

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In this talk: Present selected topics on physics prospects @HL-LHC

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.

Ultimate precision for PDFs @ HL-LHC

arXiv:1810.03639

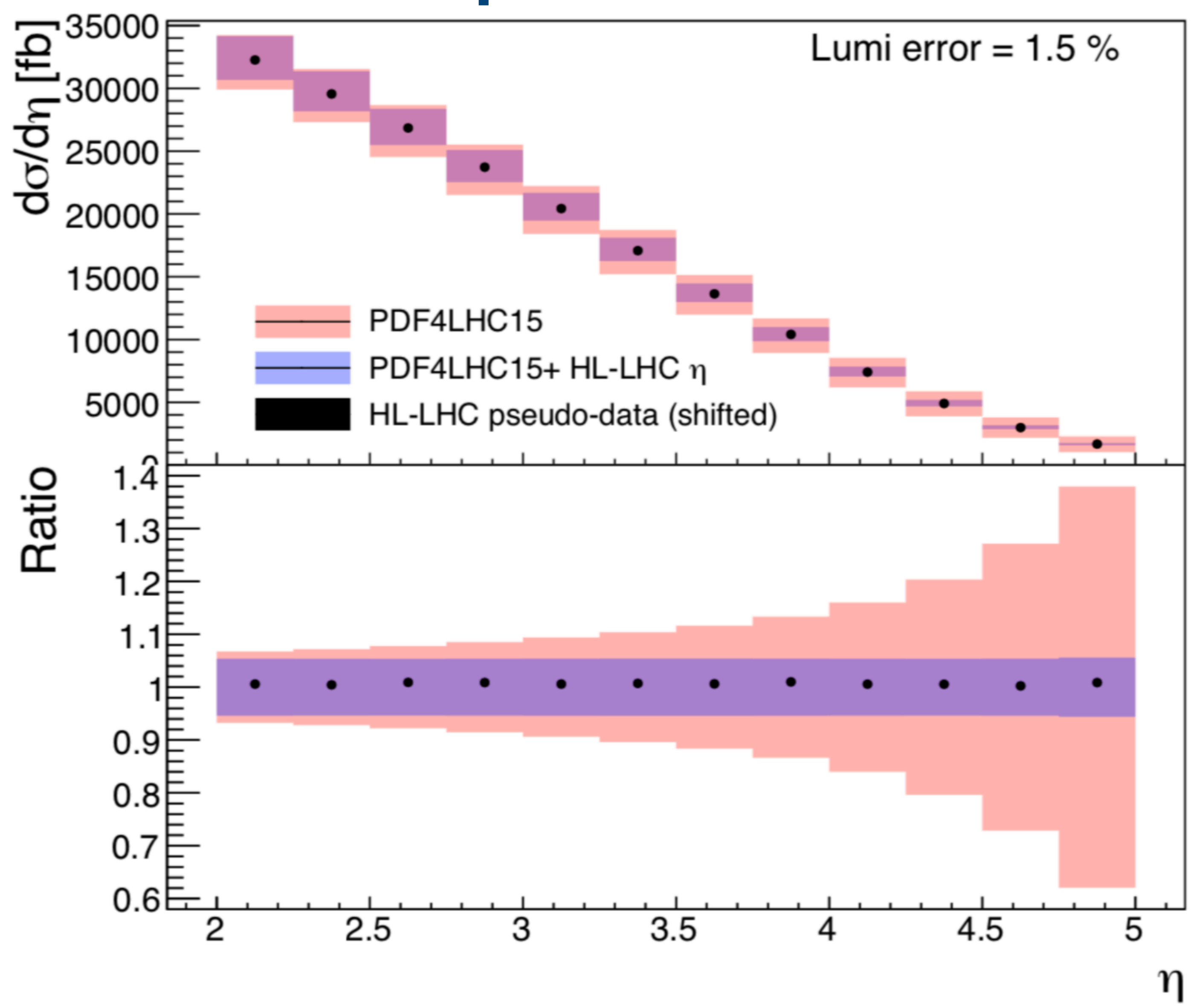
Knowledge of PDFs required to extract:

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

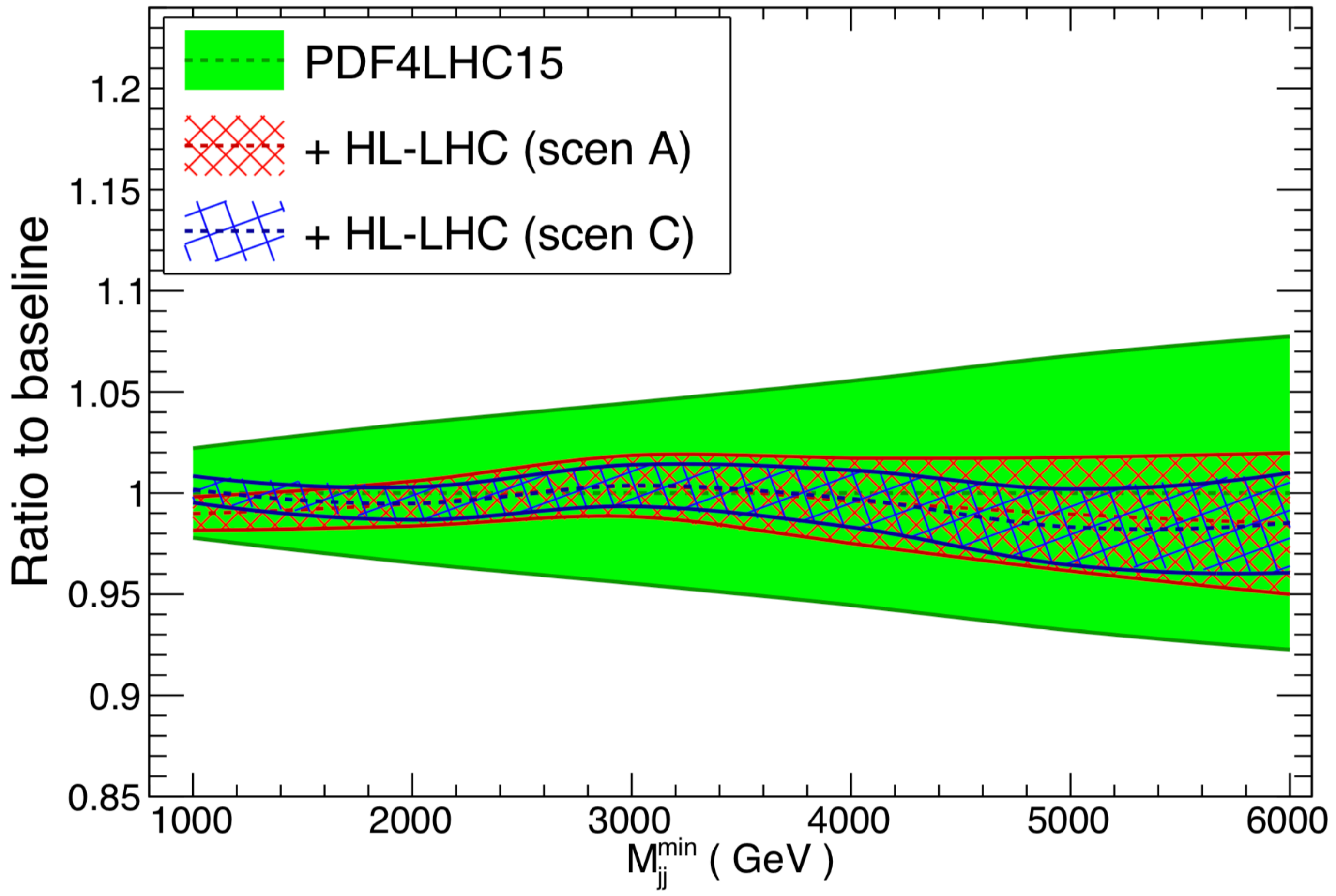
Estimate of PDFs constraints:

- 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

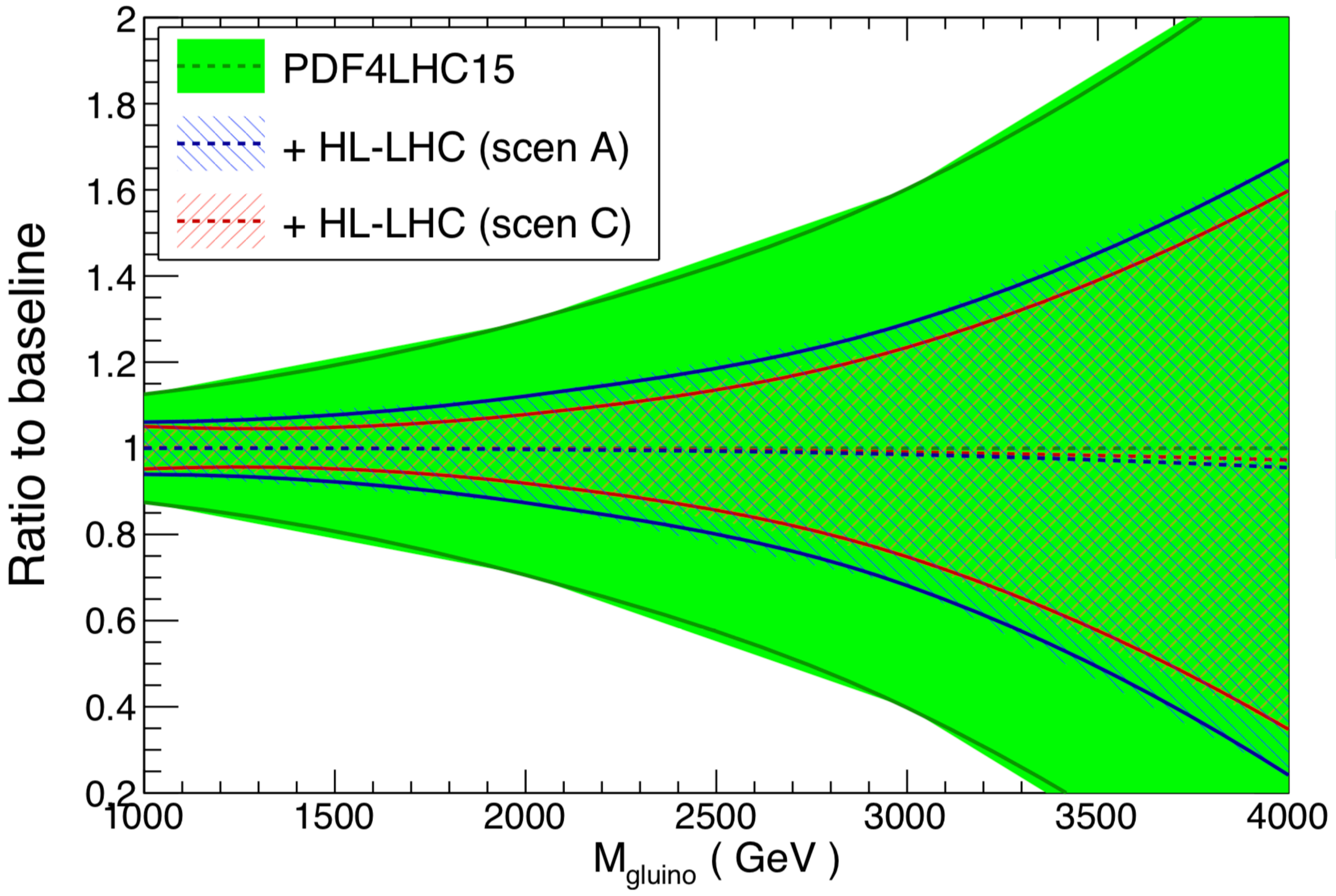
Example W+c data



Di-jet production



Gluino pair production



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

Physics Prospects @HL-LHC

EWK phenomena, QCD & Flavour physics

- Precision of $\sin^2\theta_{eff}$, m_W and m_{top} measurements
- Production of EWK gauge bosons (VBS, etc.)
- QCD at large Q^2, CKM unitarity, B-physics anomalies
- High-density QCD with heavy-ion/proton beams

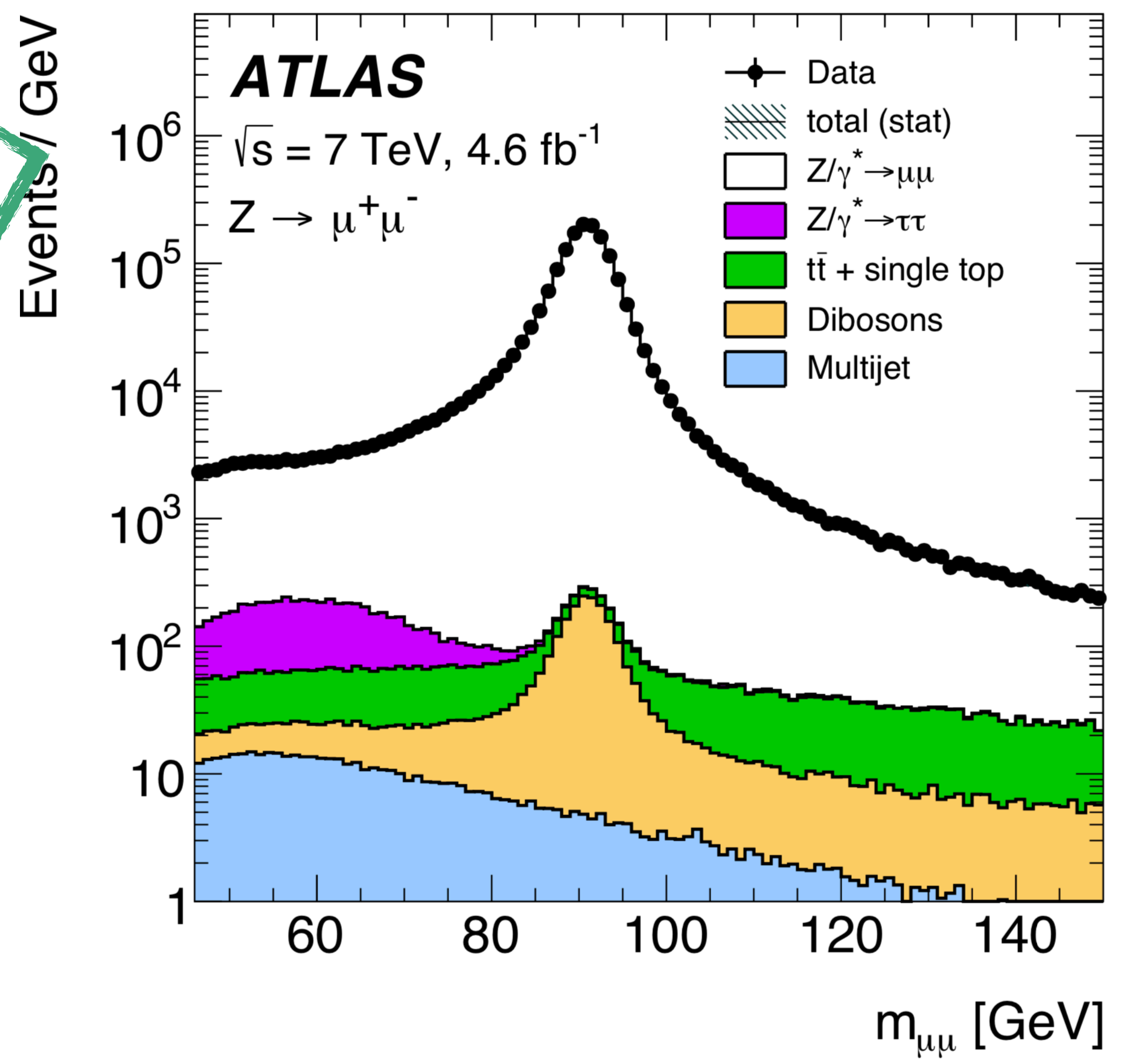
Precision cross sections, EWK mixing $\sin^2\theta_W$

arXiv:1612.03016
arXiv:1806.02184

Ultimate precision for cross sections:

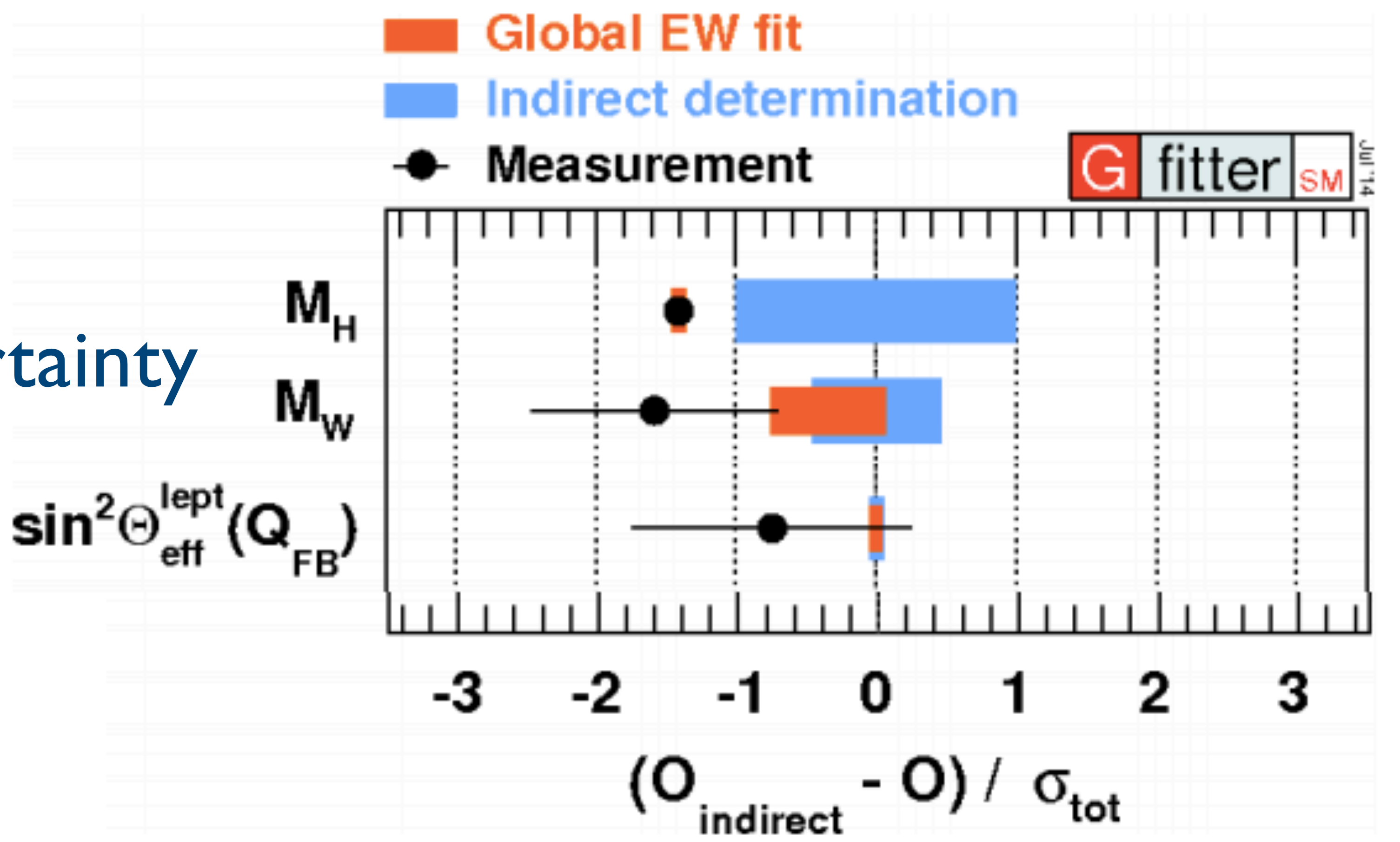
- @LHC: $\sigma(Z \rightarrow \mu\mu) = 502.2 \pm 0.3$ (stat) ± 1.7 (syst) ± 9.0 (lumi)
  - single dominant uncertainty : luminosity ~2%
- Measurement @HL-LHC:
  - Improved lumi. detectors, refined VdM scans, use of low-PU runs
- Once measured at (sub-)percent level,
  use Z cross section to help luminosity 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 uncertainty
  - Strong benefit from tracker/muon system coverage
  - Complementary ATLAS (electron) and
    CMS (muon) measurements
- Study effect of improved PDFs



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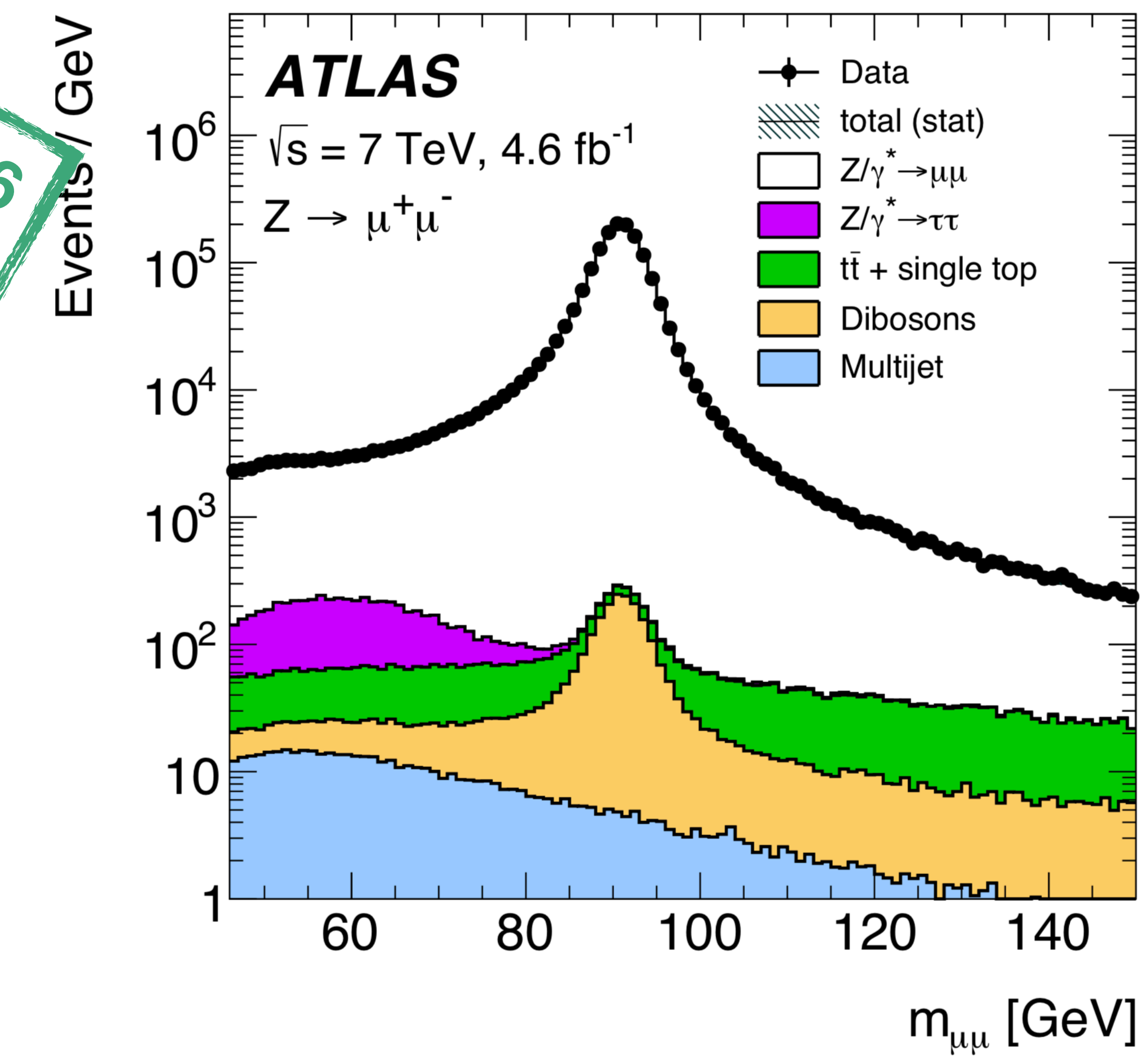
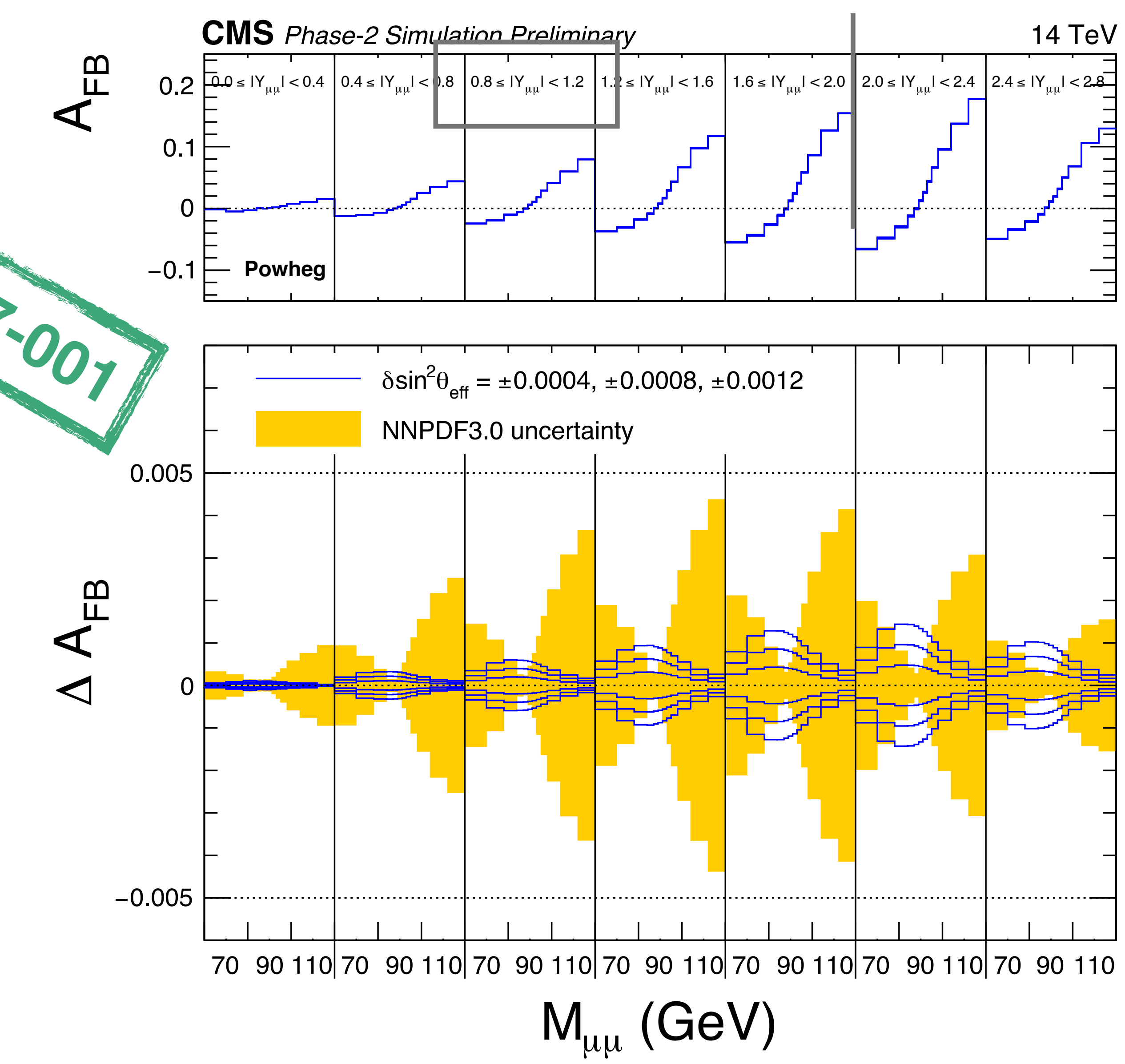


CMS-FTR-17-001



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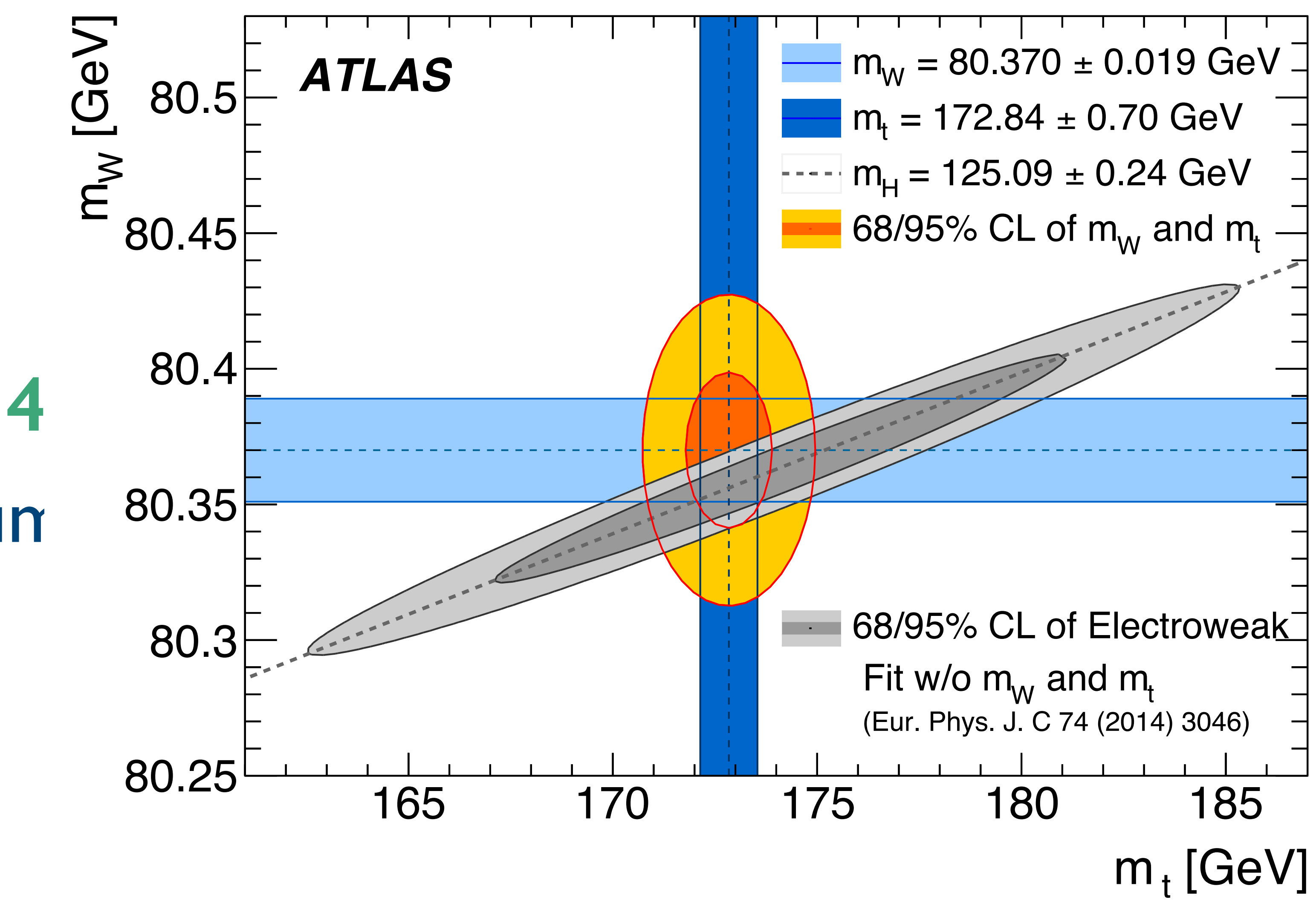
Ultimate precision for W mass

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 momentum
  - low-pile-up runs are a necessity

Latest m_W result @LHC

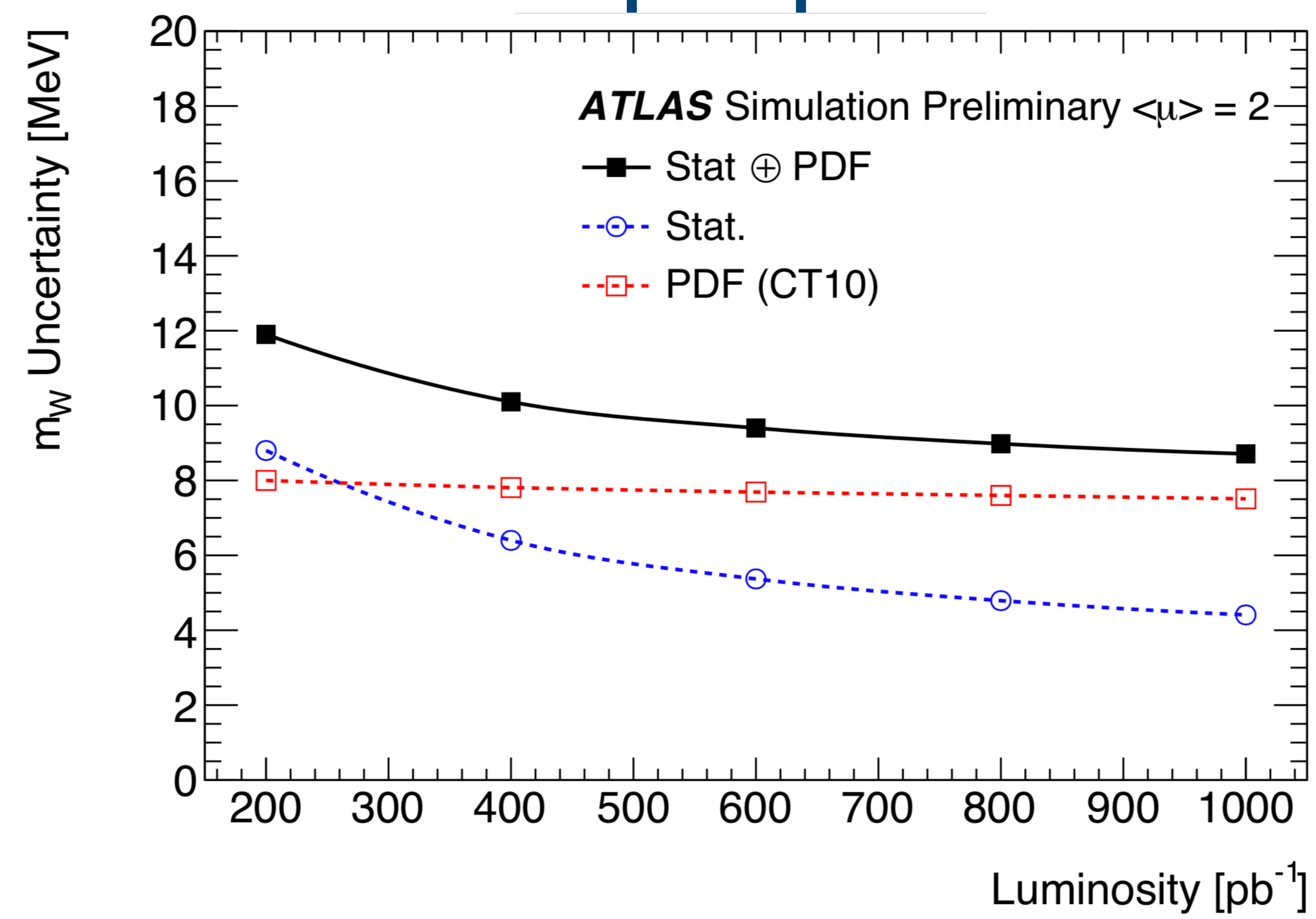


Precision @HL-LHC:

- 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

Gluino pair production



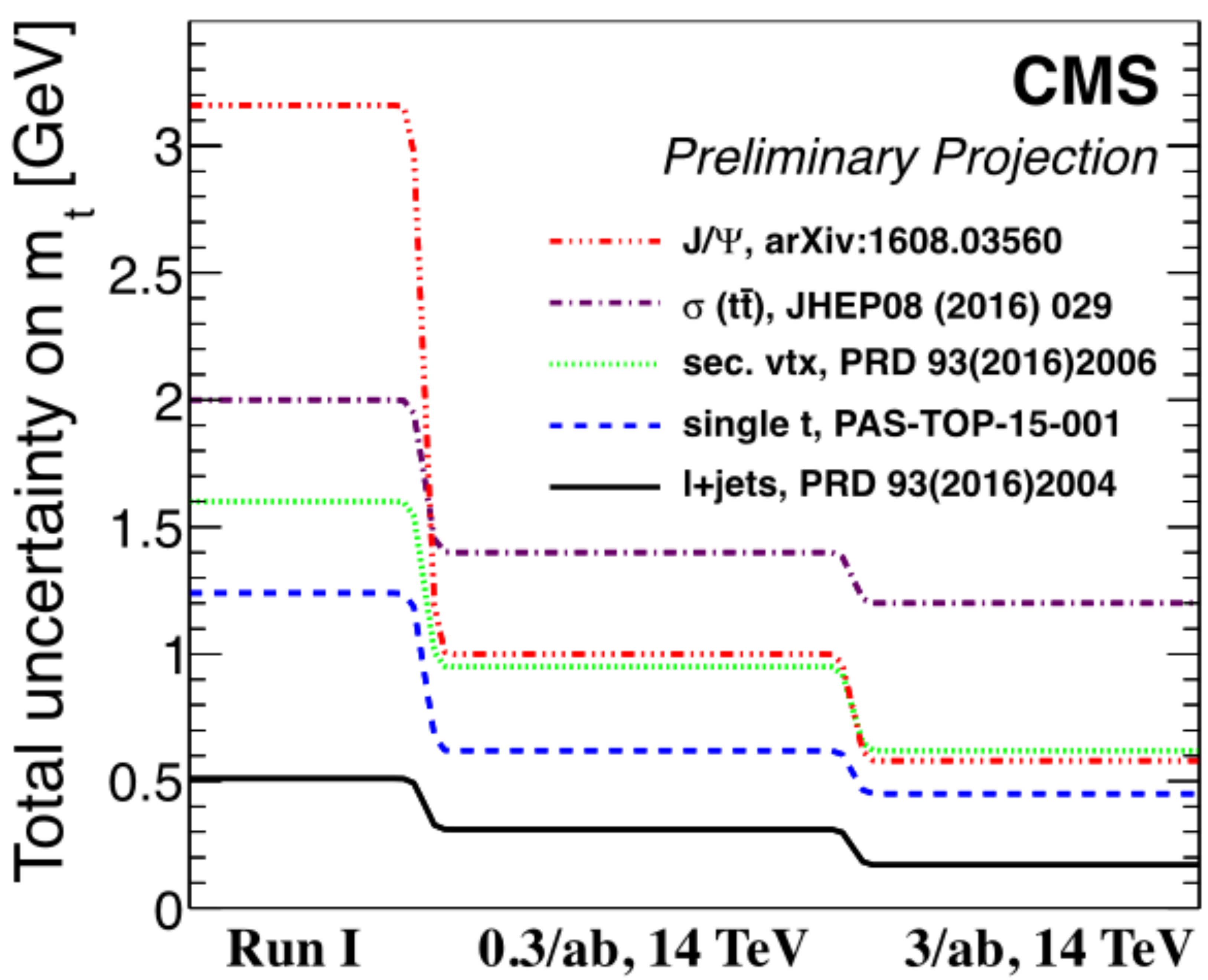
Ultimate precision for top mass

CMS FTR-18-005

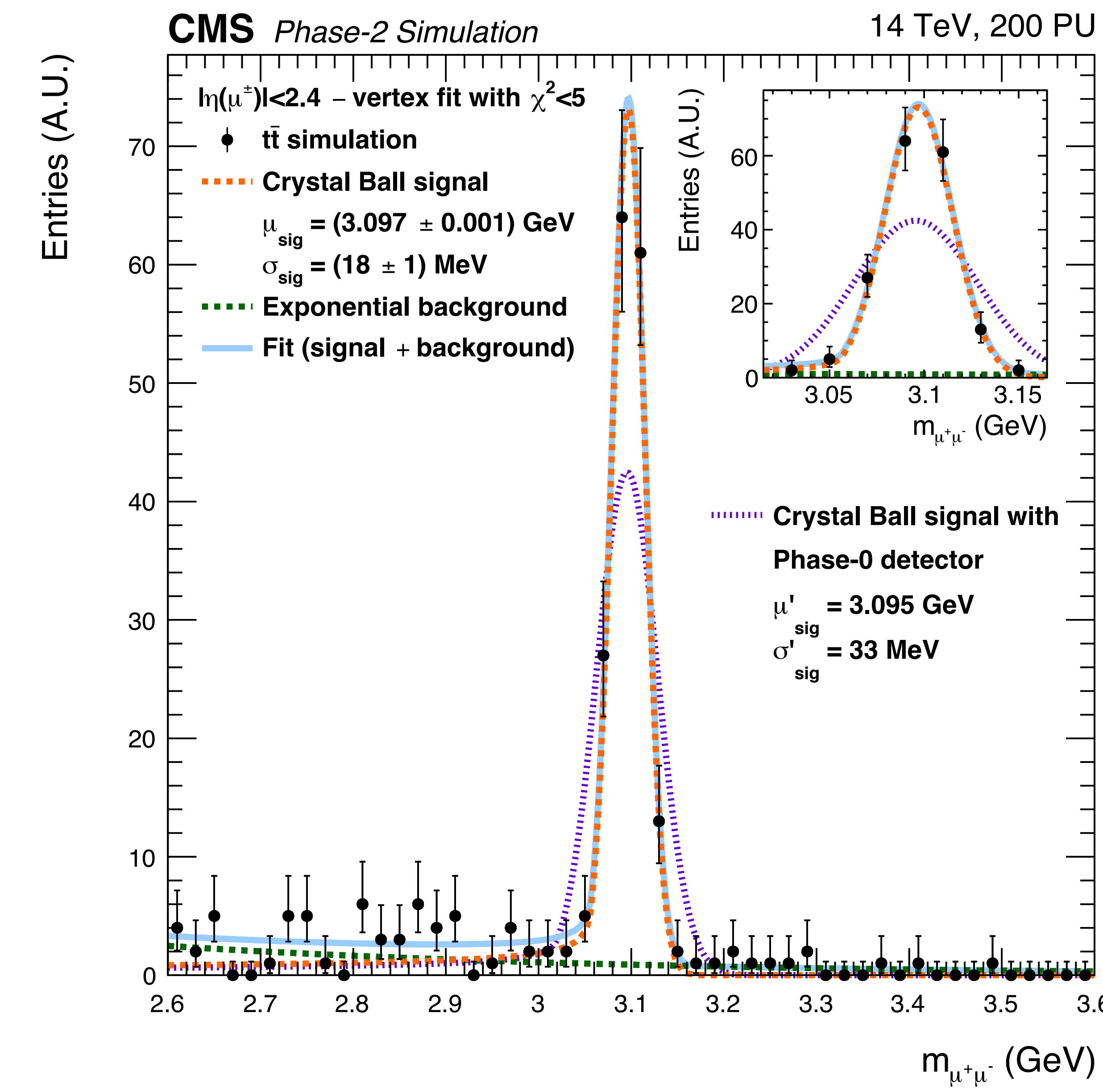
Top mass measurement @HL-LHC:

- 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" ($t \to bW \to J/\psi l \nu X$)



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 $\Delta m_{TOP} < \pm 0.2$ GeV

Anomalies in "Flavour" Physics

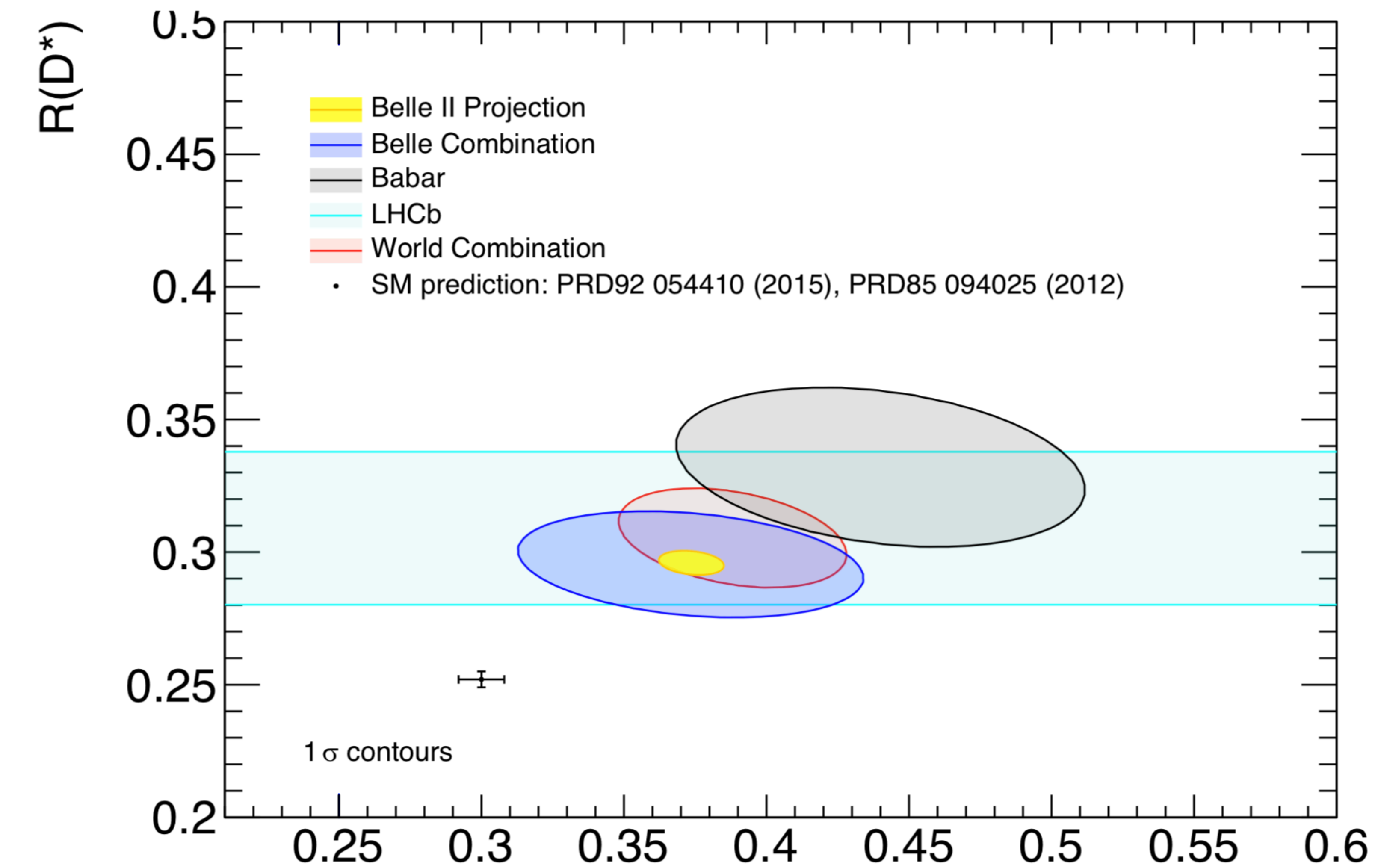
Flavour anomalies - low-q^2 :

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

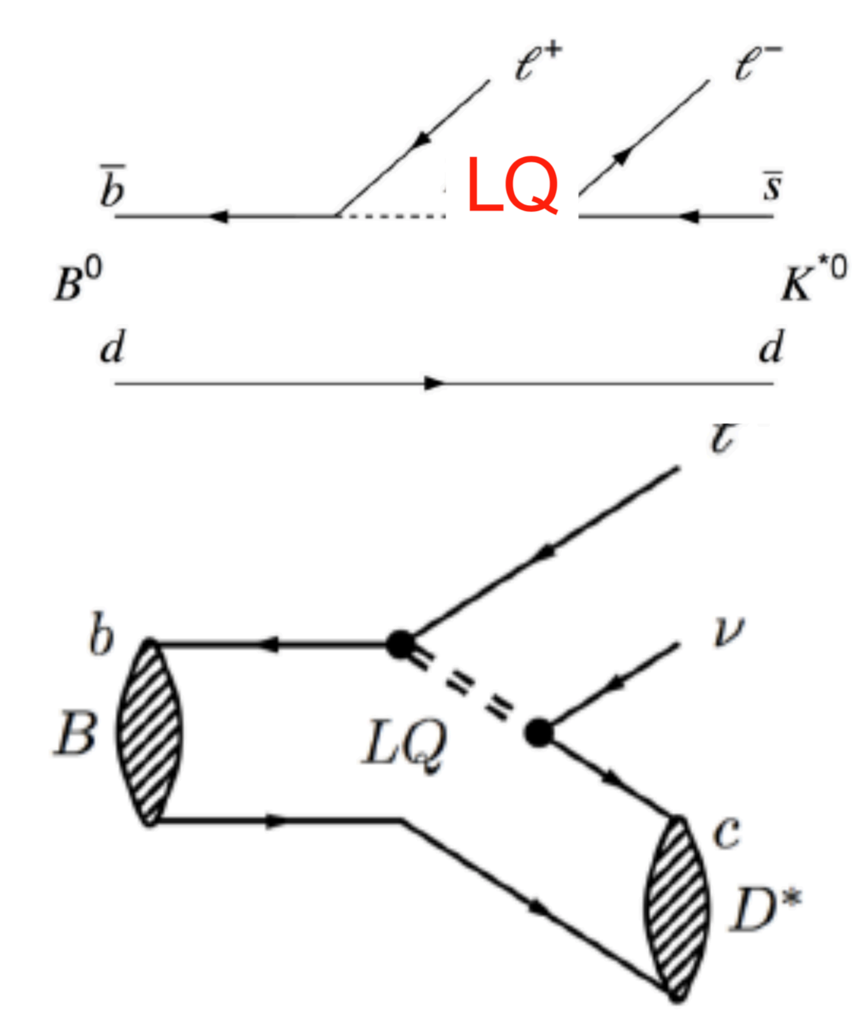
Flavour anomalies - high-q^2 :

- **R(K*) & $b \rightarrow s\ \ell^+\ell^-$**
  - Minimally flavour violating Z' ruled out (res. searches)
- **R(D) / R(D*) & $b \rightarrow c\ \tau\ \nu$**
  - 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 **$B \to D^{(*)} \ell^+ \ell^-$**
  - incompatibility with SM (by LHCb, Belle, BaBar)

➡ LHCb able to measure in several channels

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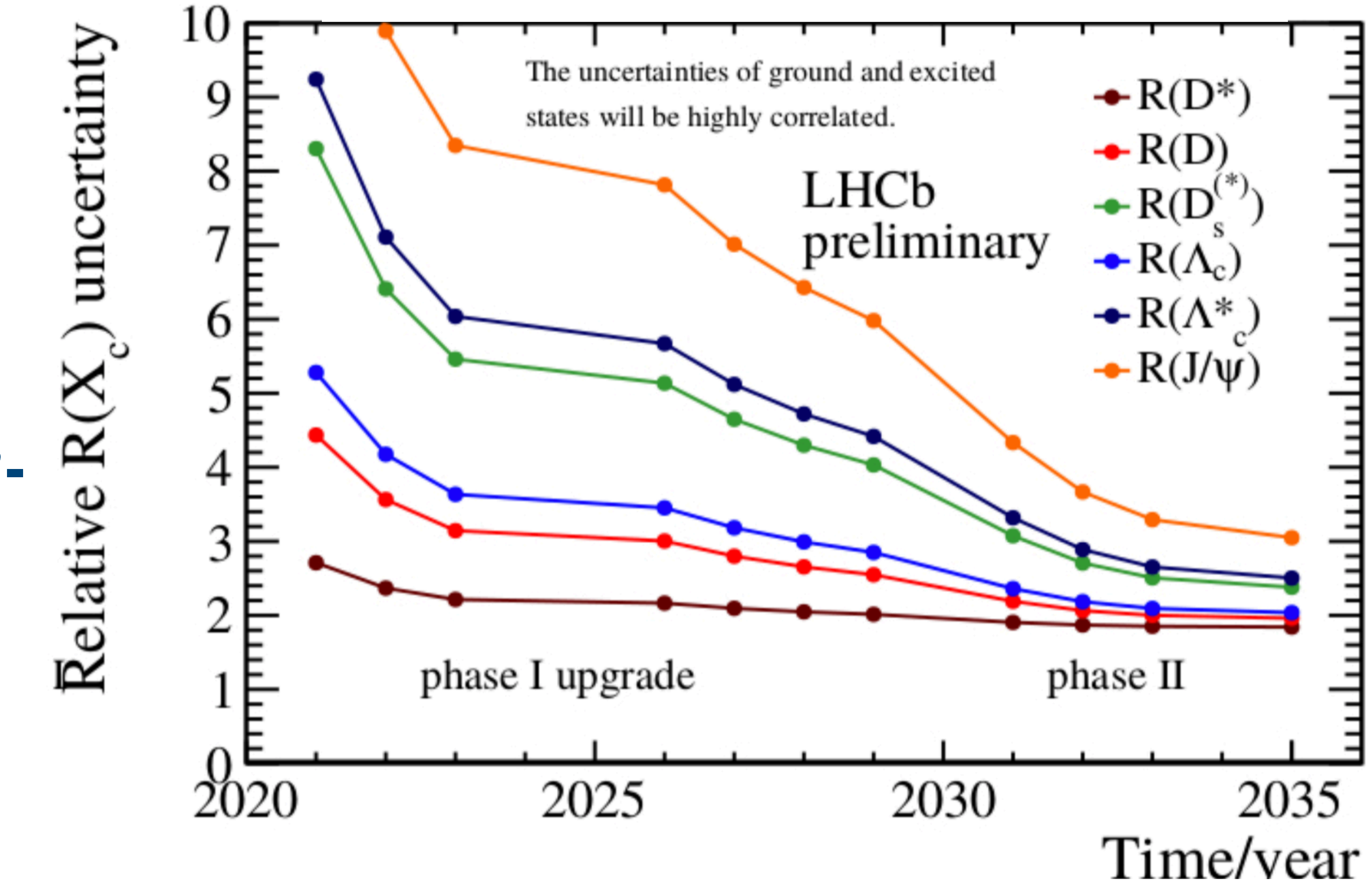
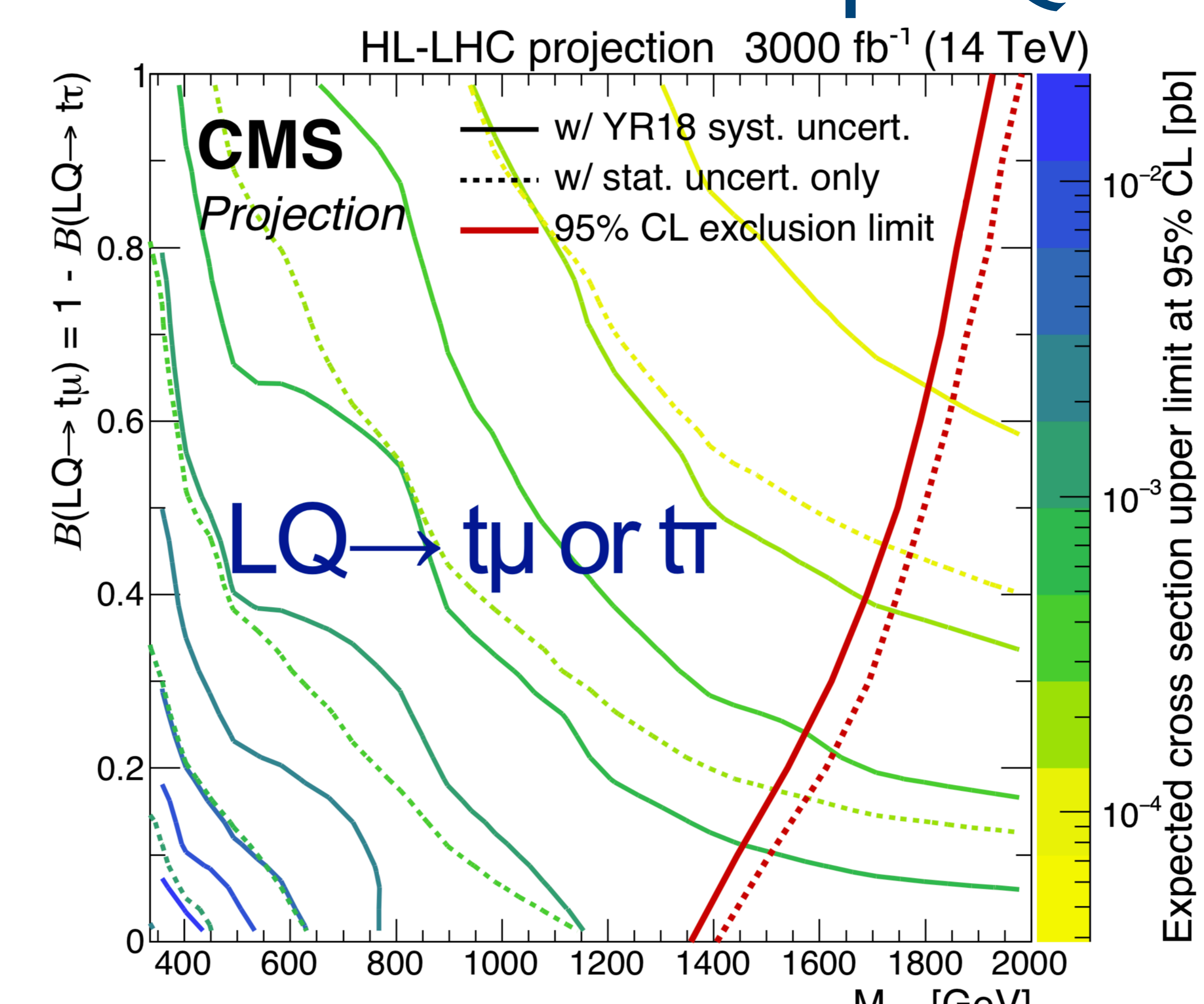
  - Minimally flavour violating Z' ruled out (res. searches)
- **R(D) / R(D*) & b → c τ ν**
  - Good fits for W' vector, scalar, or vector LQ

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

Flavour anomalies & LHCb



Flavour anomalies & Lepto-Quarks



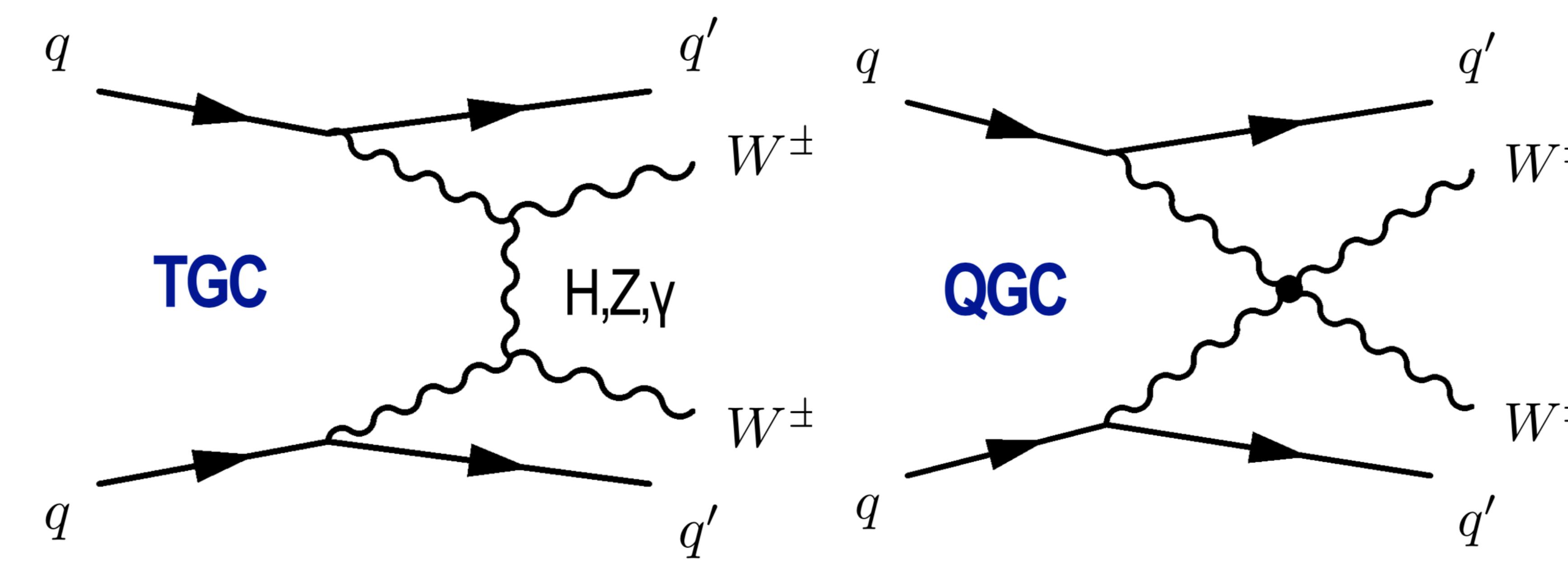
Vector boson scattering

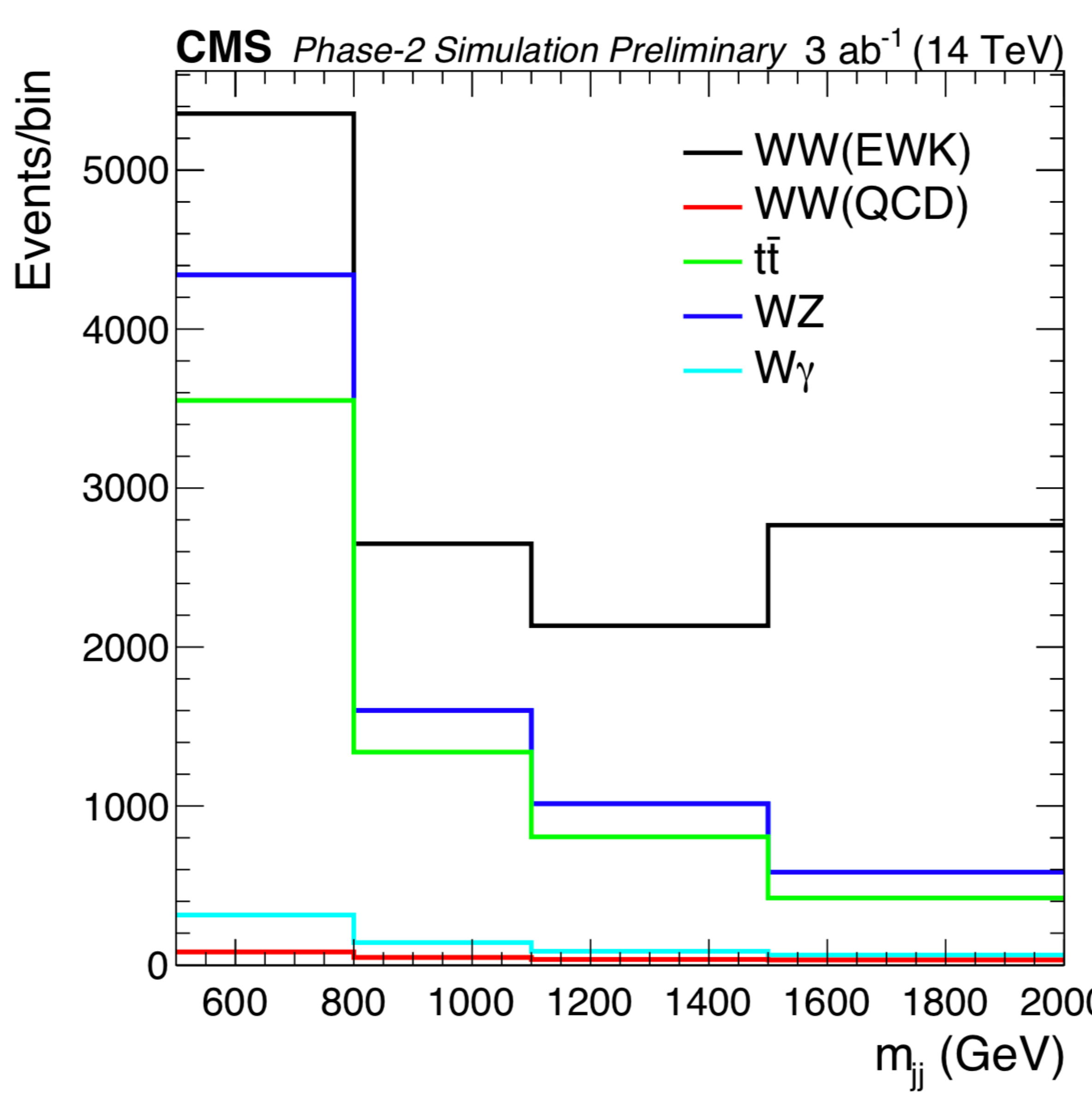
CMS-FTR-18-005
ATL-PHYS-PUB-2018-023
ATL-PHYS-PUB-2018-029

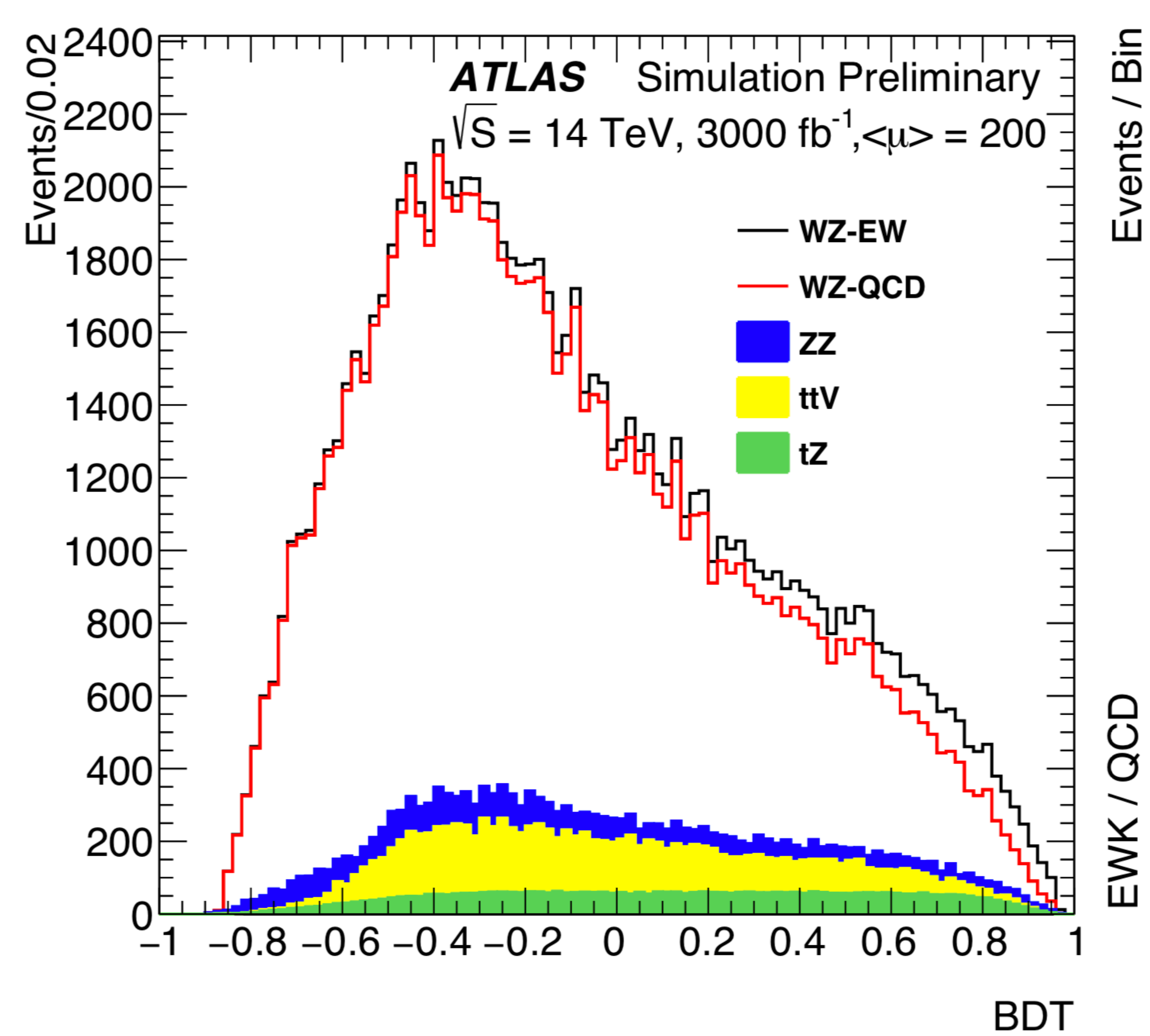
Vector boson scattering @ HL-LHC:

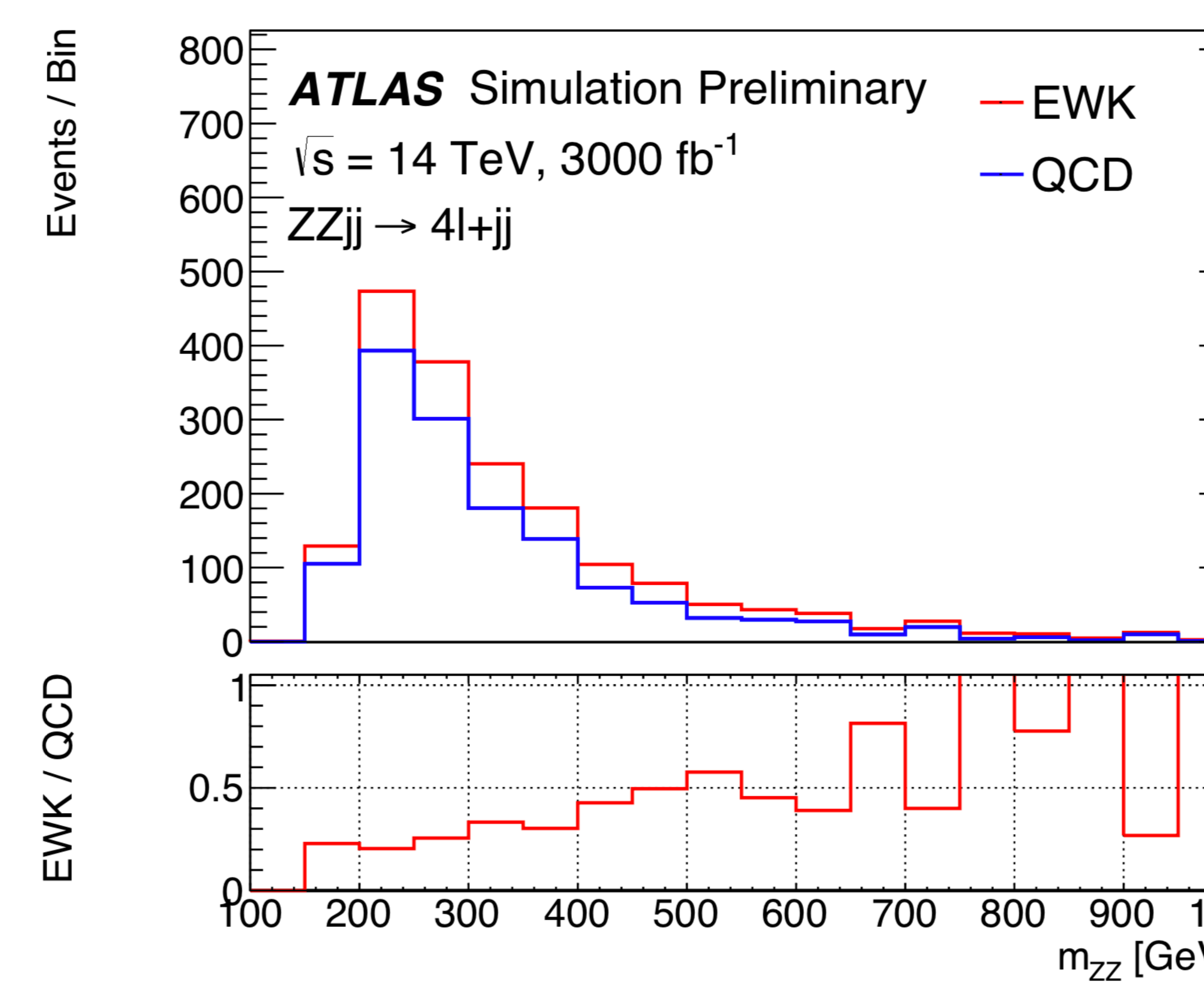
- Precision test of triple & quartic gauge couplings (TGC, QGC)
  - Electroweak WW and WZ scattering observed in Run-2
- Unitarization of $V_L V_L \rightarrow V_L V_L$ cross section at TeV scale:
  - Scalar Higgs and/or new physics to cancel divergence
- Direct test of EW-symmetry breaking mechanism

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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- Precision test of triple & quartic gauge couplings (TGC, QGC)
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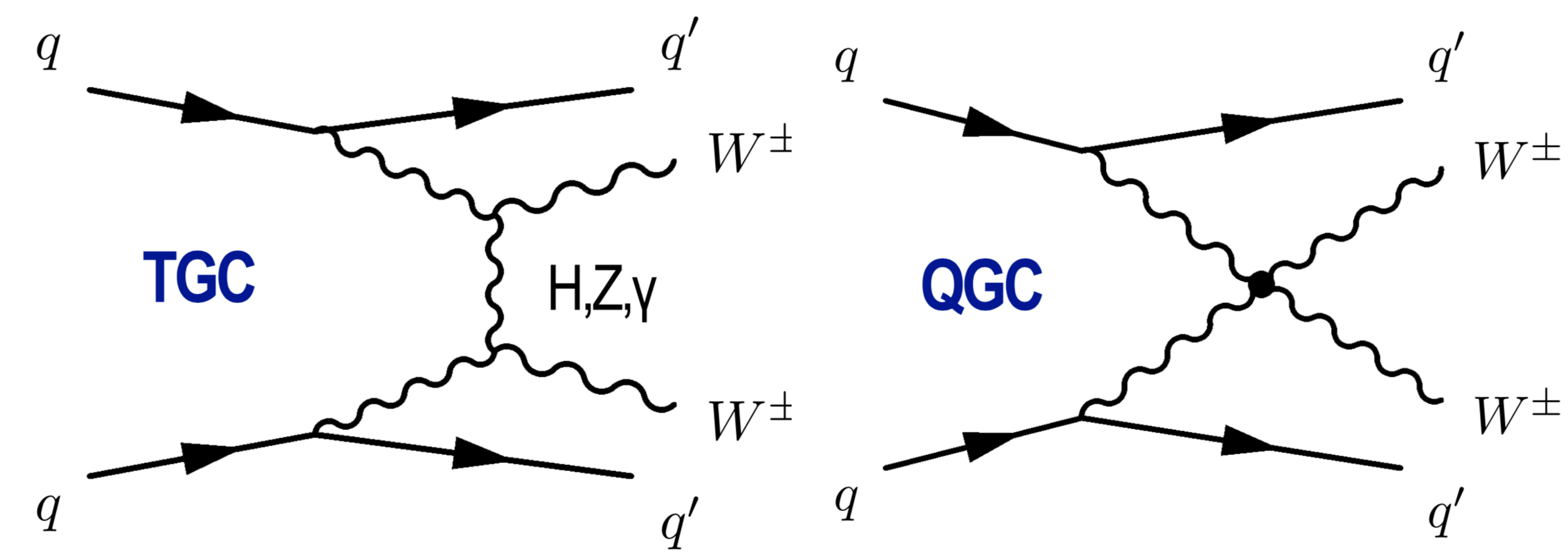
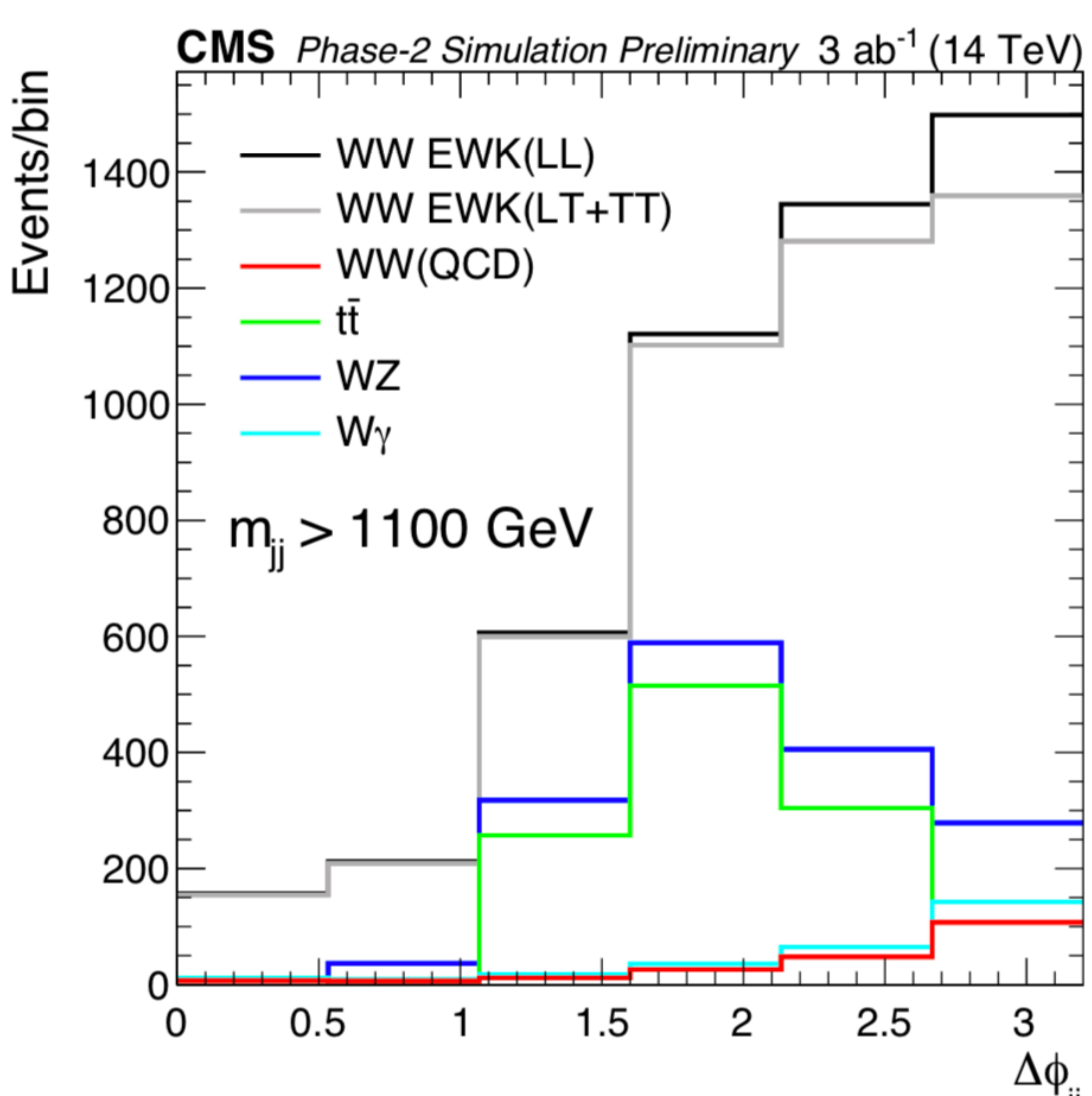
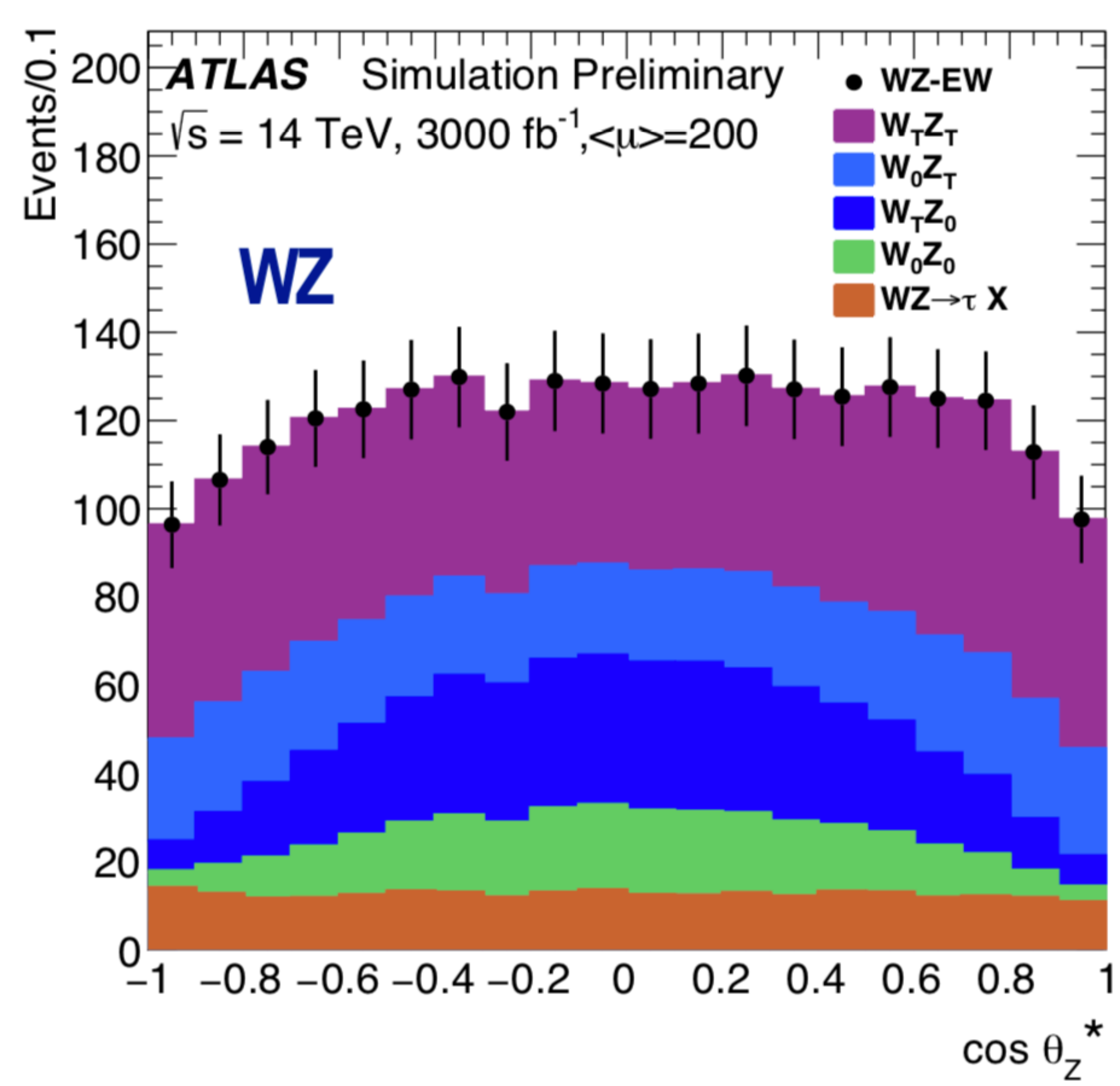






$V_L V_L \rightarrow V_L V_L$ discovery significance up to 3σ combining channel and experiments!

Physics Prospects @HL-LHC

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

Characterisation of the Higgs boson

- Couplings, production & differential XS measurements
- Higgs potential and trilinear self-coupling
- Probe for anomalous interactions & rare/exotic decays

Higgs boson couplings

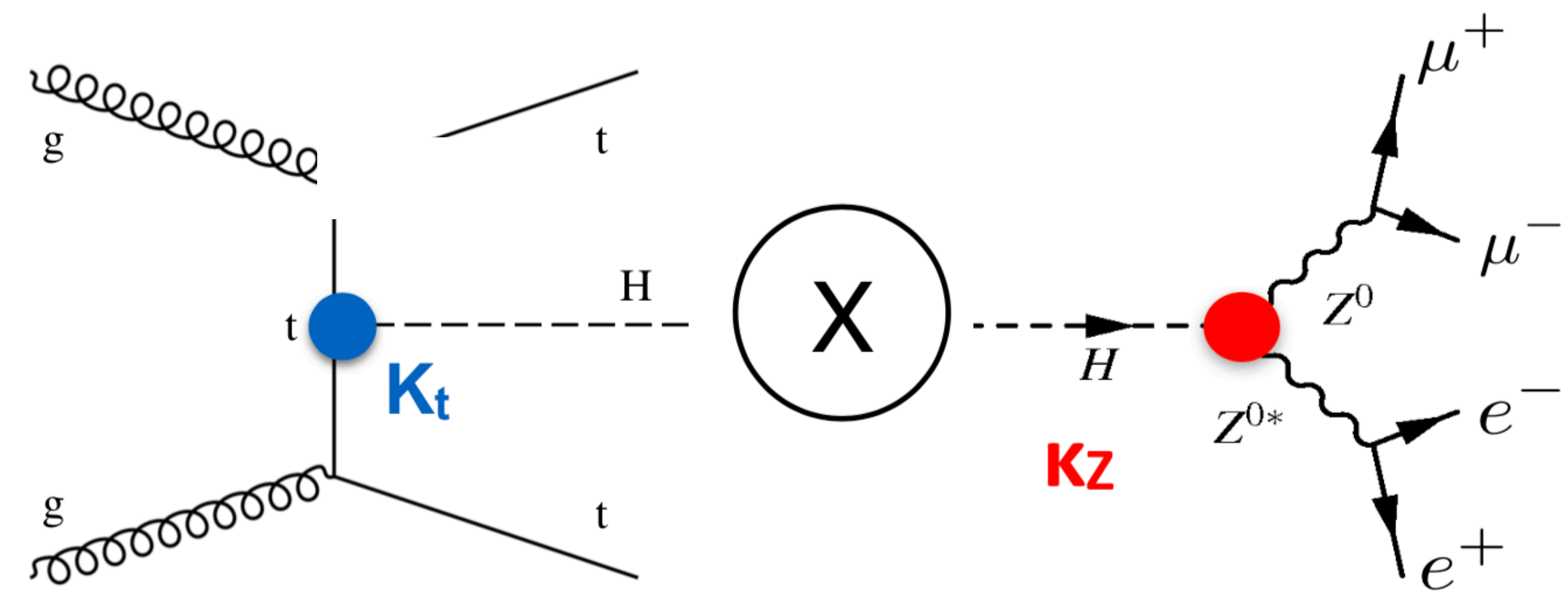
HL-LHC as a "Higgs Factory":

- Expected: ~170M Higgs bosons,
  ~120k of HH pairs
- Enables a **rich Higgs physics program**, including couplings precision measurements.

Higgs boson couplings @ HL-LHC:

- ATLAS and CMS measure a range of processes with different production and decay modes
- Projections based on LHC Run-2 results (36-80 fb^{-1})
- Consider model(s) with the most important physics message: κ_t, κ_b, κ_τ, κ_μ, κ_W, κ_Z, (+ κ_g, κ_γ)

κ-framework : coupling modifiers



$$\sigma_{SM}(ttH) \cdot B_{SM}(H \to ZZ) \cdot \frac{\kappa_t^2 \kappa_Z^2}{\kappa_H^2}$$

see Andrew's and Stefan's talks for details

Channels used by ATLAS and/or CMS

channel used by ATLAS and/or CMS	ggF	VBF	VH	ttH
$H \to ZZ \to 4l$	✓	✓	✓	✓
$H \to \gamma\gamma$	✓	✓	✓	✓
$H \to WW$	✓	✓	✓	✓
$H \to bb$	✓		✓	✓
$H \to \tau\tau$	✓	✓		✓
$H \to \mu\mu$	✓	✓		
$H \to Z\gamma$	✓	✓	✓	

BSM effects on Higgs coupling (1-10%)

arXiv:1310.8361 $M_{NP} \sim$ 1TeV

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

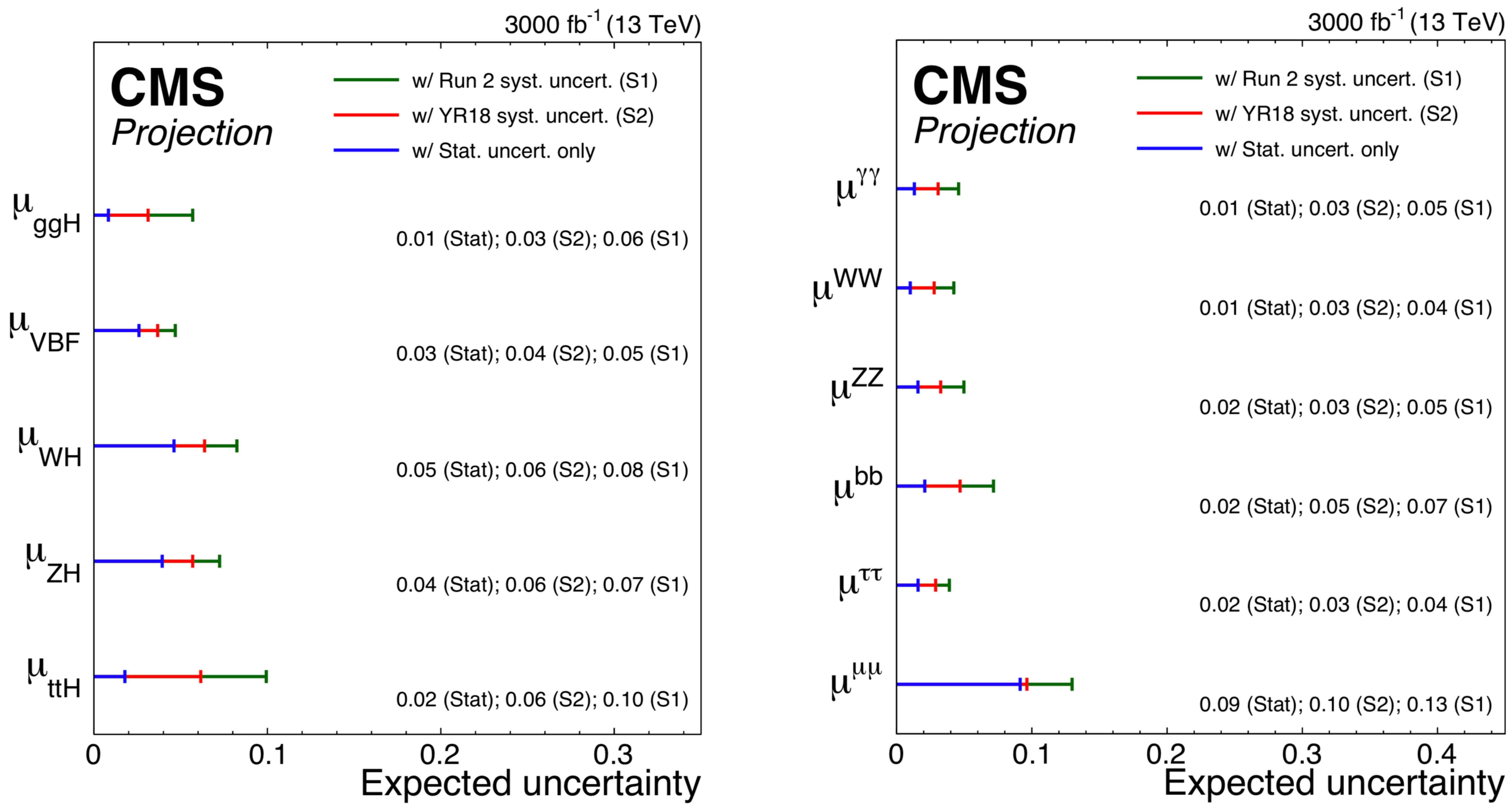
Higgs boson couplings measurements

ATLAS studies coming soon.

CMS-FTR-18-011

Sensitivity estimated using combined HIG measurements @13 TeV:

- Consider signal strengths per-production and per-decay mode



achievable precision @3000fb^{-1} : 3-6% (for μμ decay 10%)

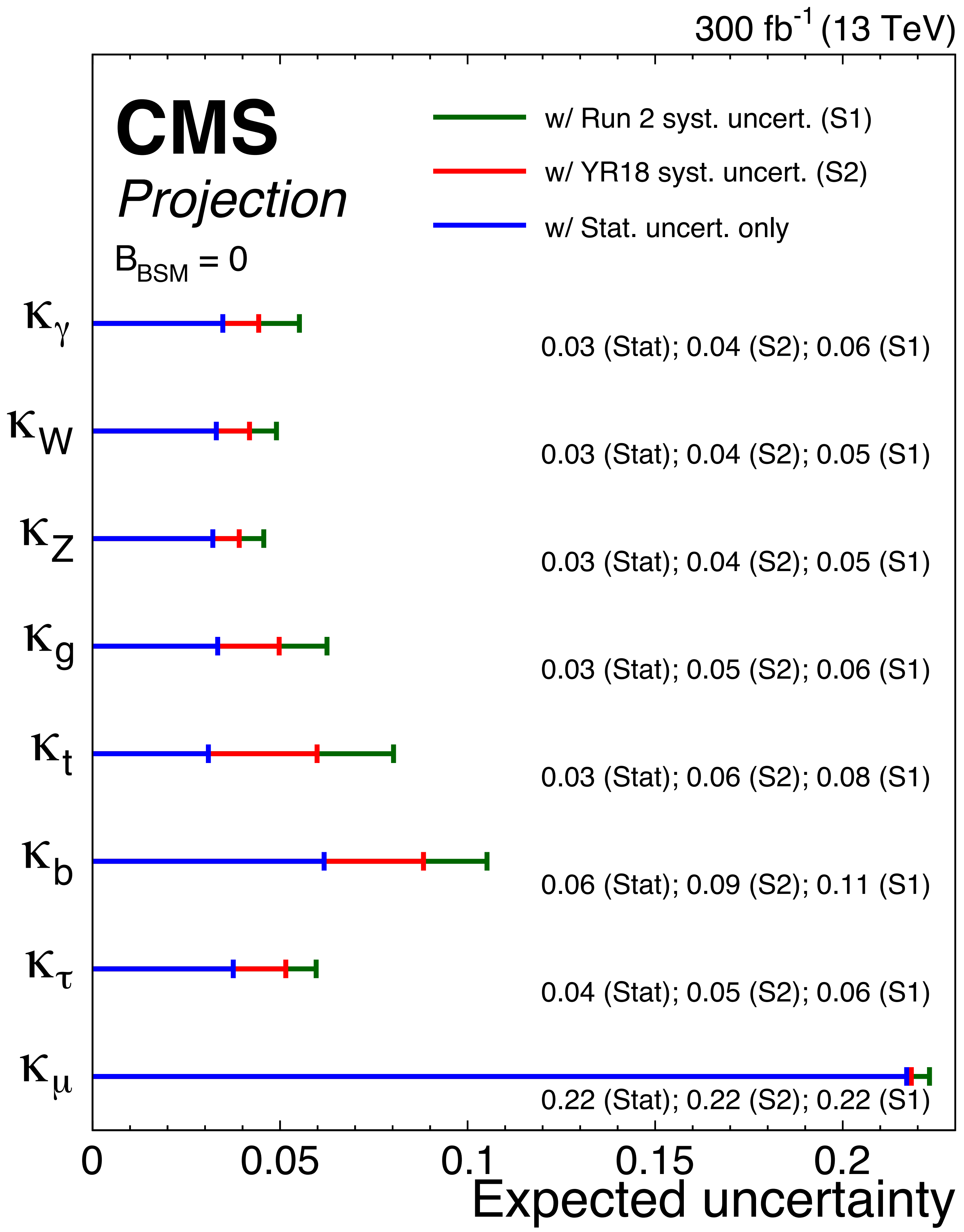
Higgs boson couplings measurements

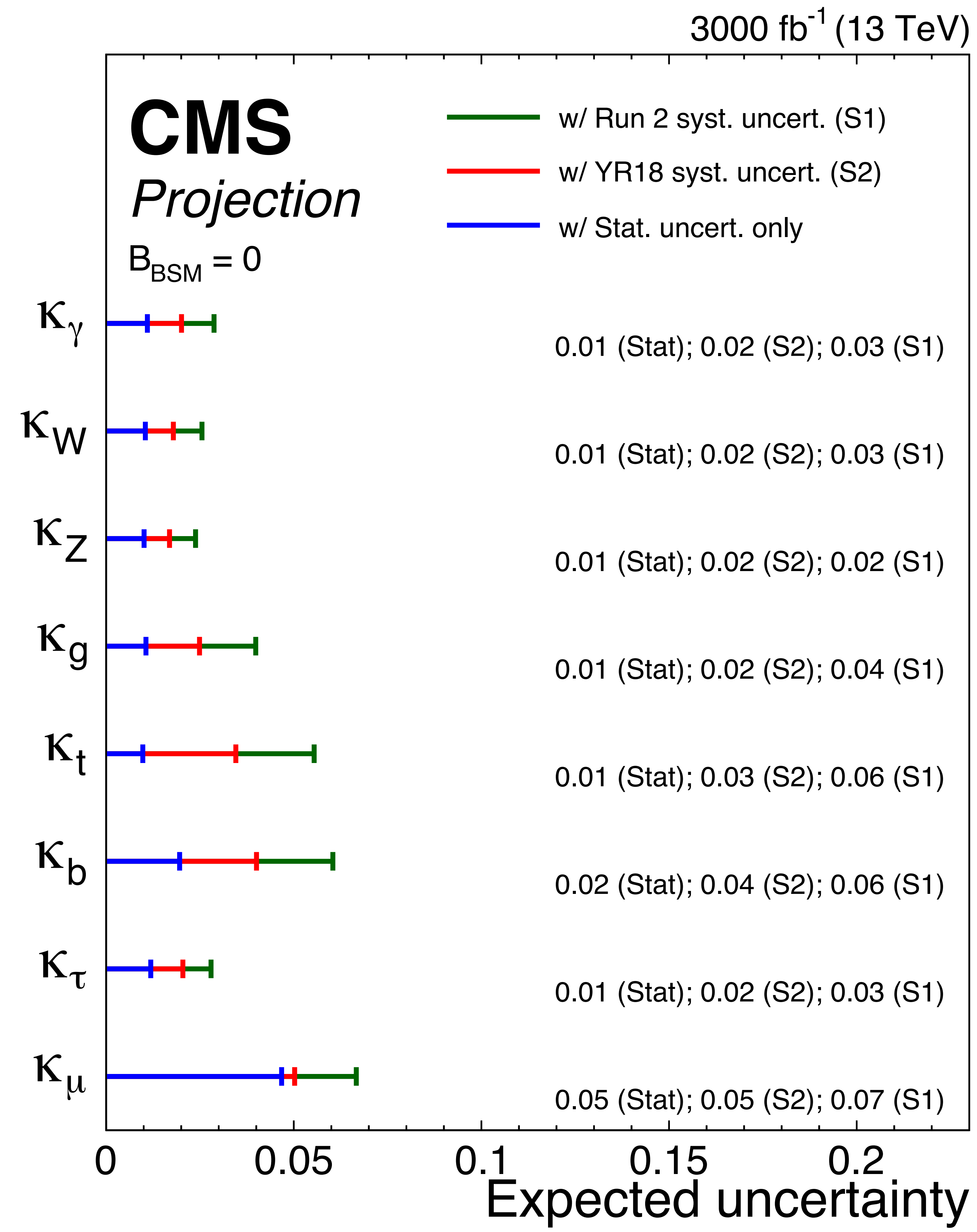
ATLAS studies coming soon...

CMS-FTR-18-011

Sensitivity estimated using combined HIG coupling "modifiers" @13 TeV:

- Consider model(s) with the most important physics message: **κ_t, κ_b, κ_τ, κ_μ, κ_W, κ_Z,** (+ **κ_g, κ_γ**)





total uncertainties 2-5% @3000fb^{-1} for B_{BSM}=0

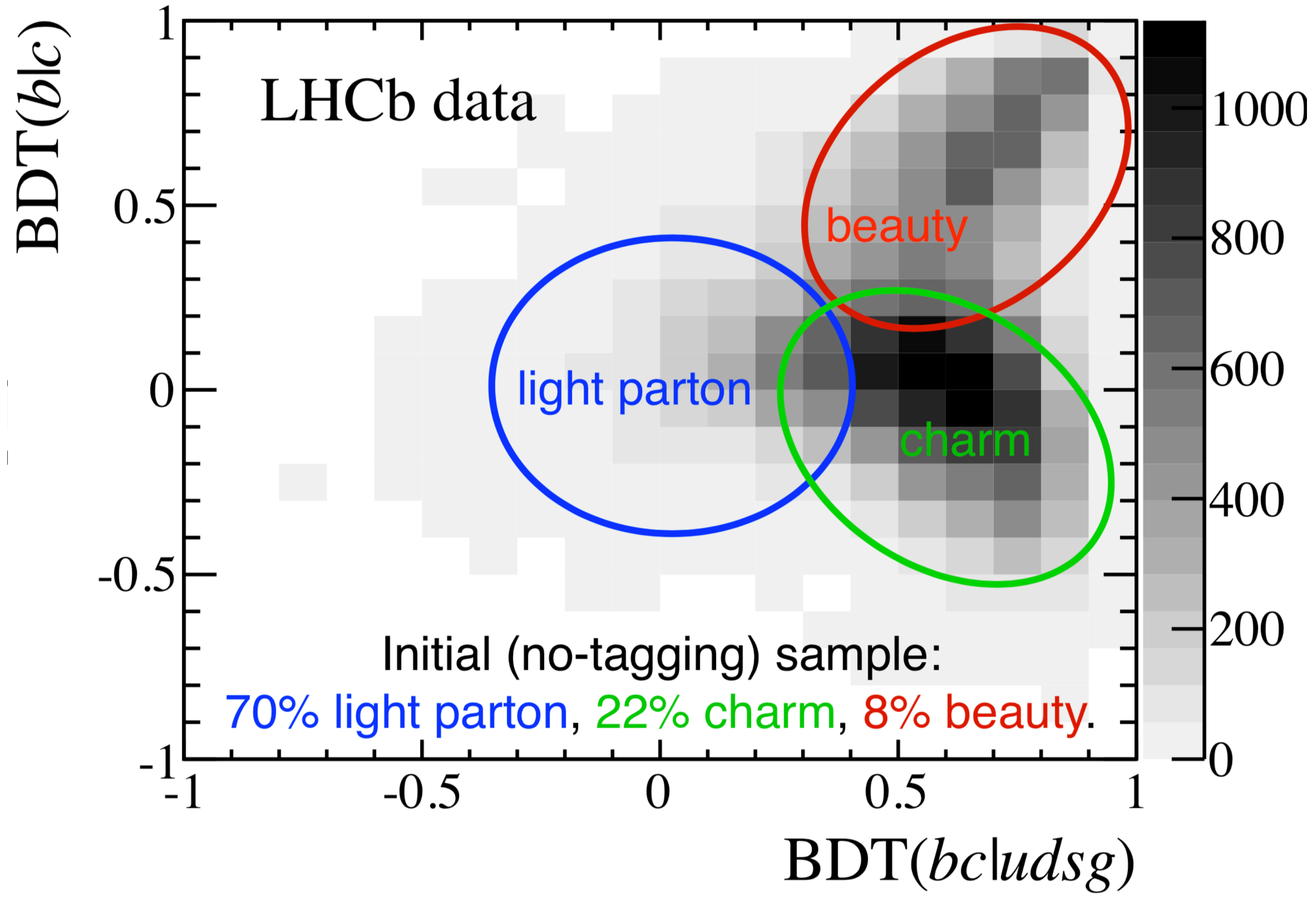
Higgs boson coupling to 2nd generation

ATL-PHYS-PUB-2018-016

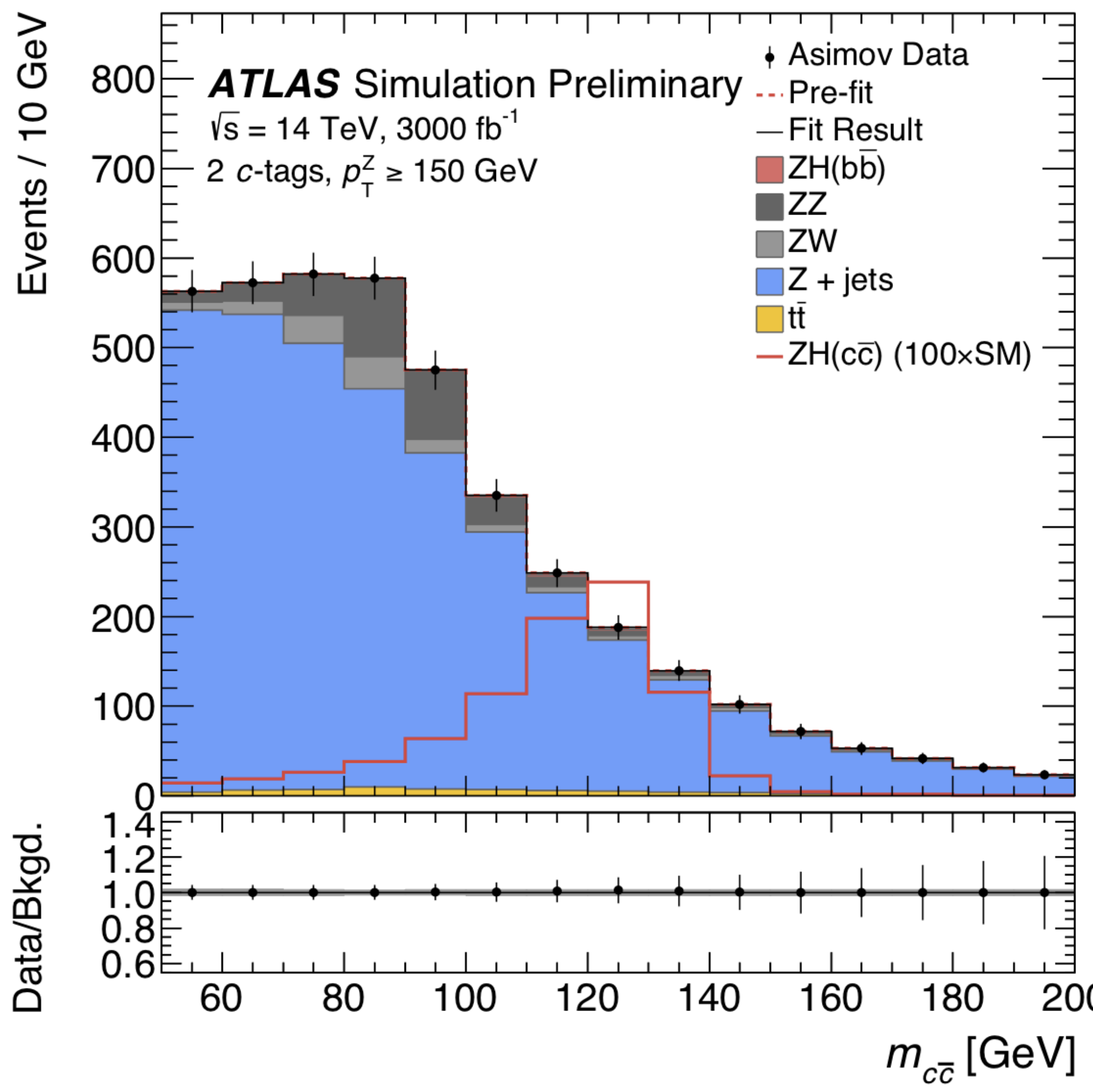
Establishing coupling to charm is one of the key tasks:

- **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.

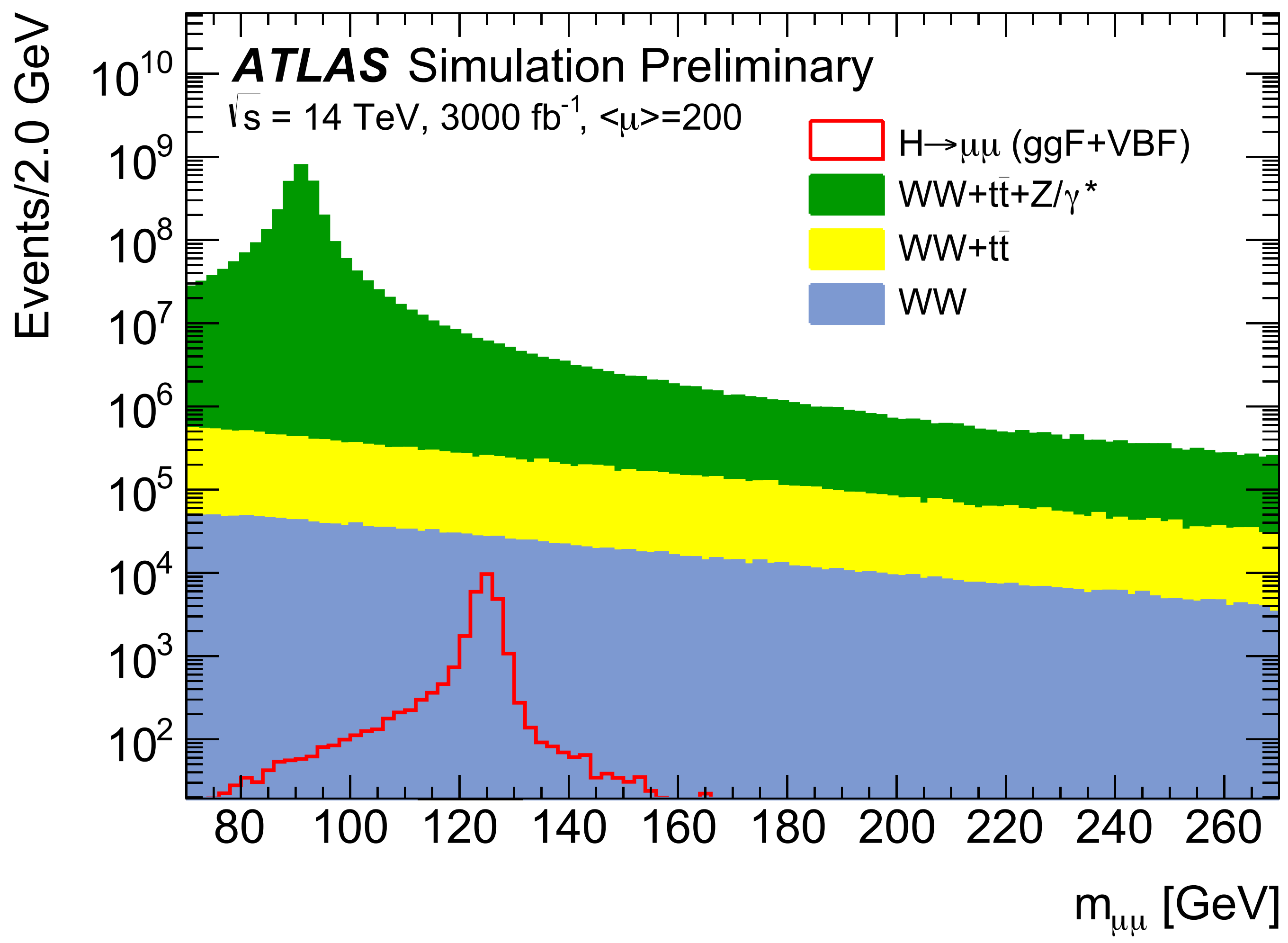
LHCb : BDT flavour separation



ATLAS : ZH→ℓℓcc



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%.

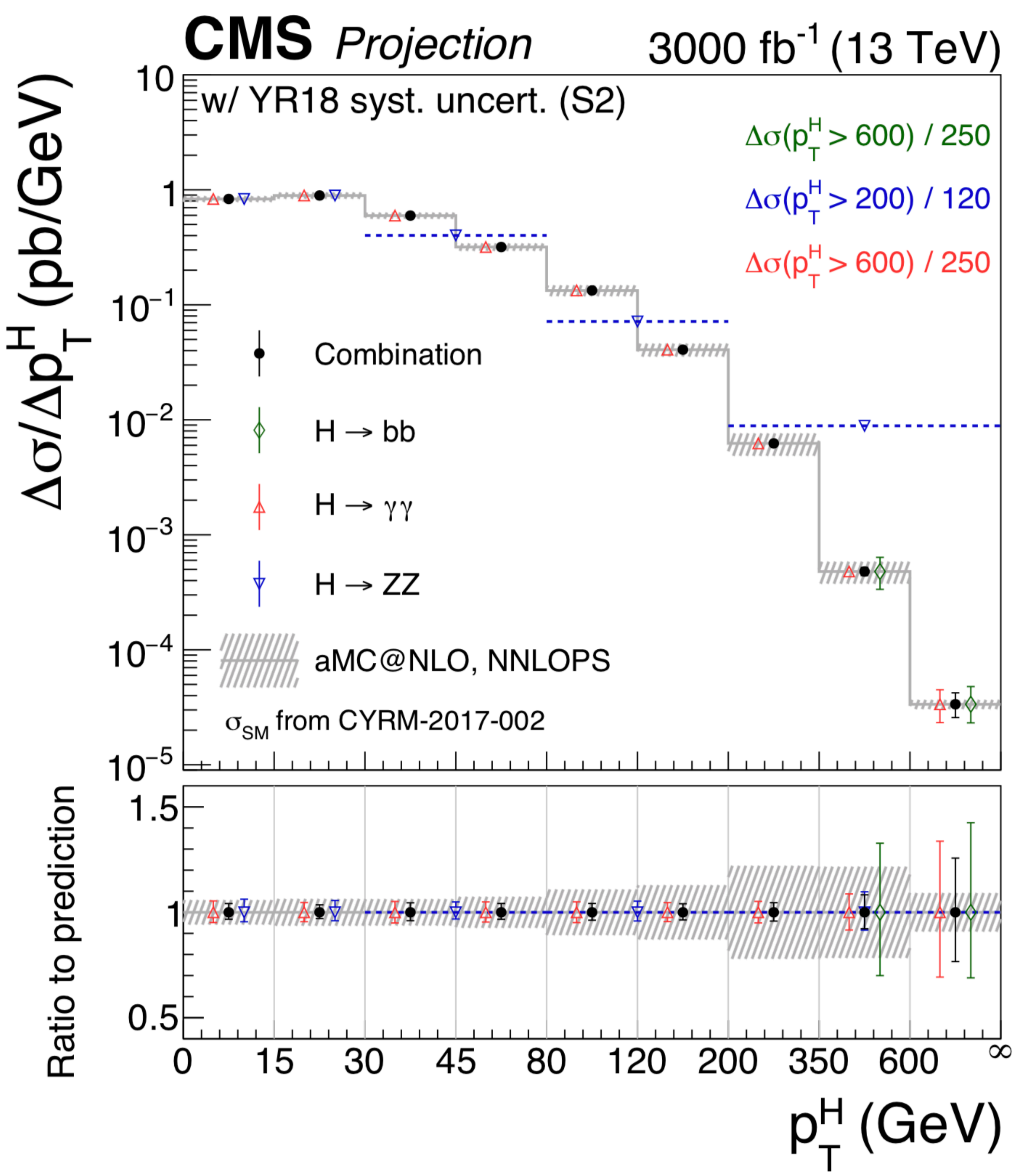
CMS-FTR-18-011

Differential XS and limits on k_b, k_c, k_t, c_g

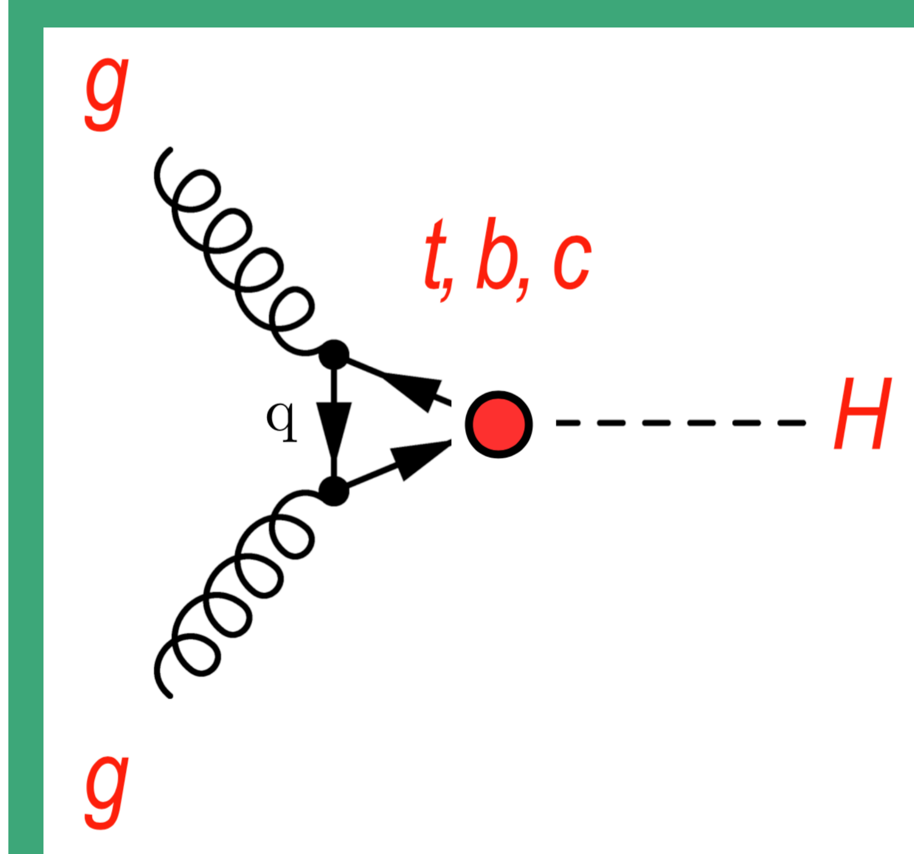
Projections of the combination of fiducial differential XS @13 TeV (36.6 fb^{-1}):

- Sensitivity to modelling of hard quark and gluon radiation, BSM effects in the loops, etc.
- Sensitivity from the shape important with higher lumi.

Combined differential $p_T(H)$



$p_T(H)$ parametrised in terms of k_b, k_c



Constraints on effective k_b, k_c, k_t, c_g couplings :

- Competitiveness with direct probes of Higgs couplings (in particular κ_c)

Differential XS and limits on k_b, k_c, k_t, c_g

CMS-FTR-18-011

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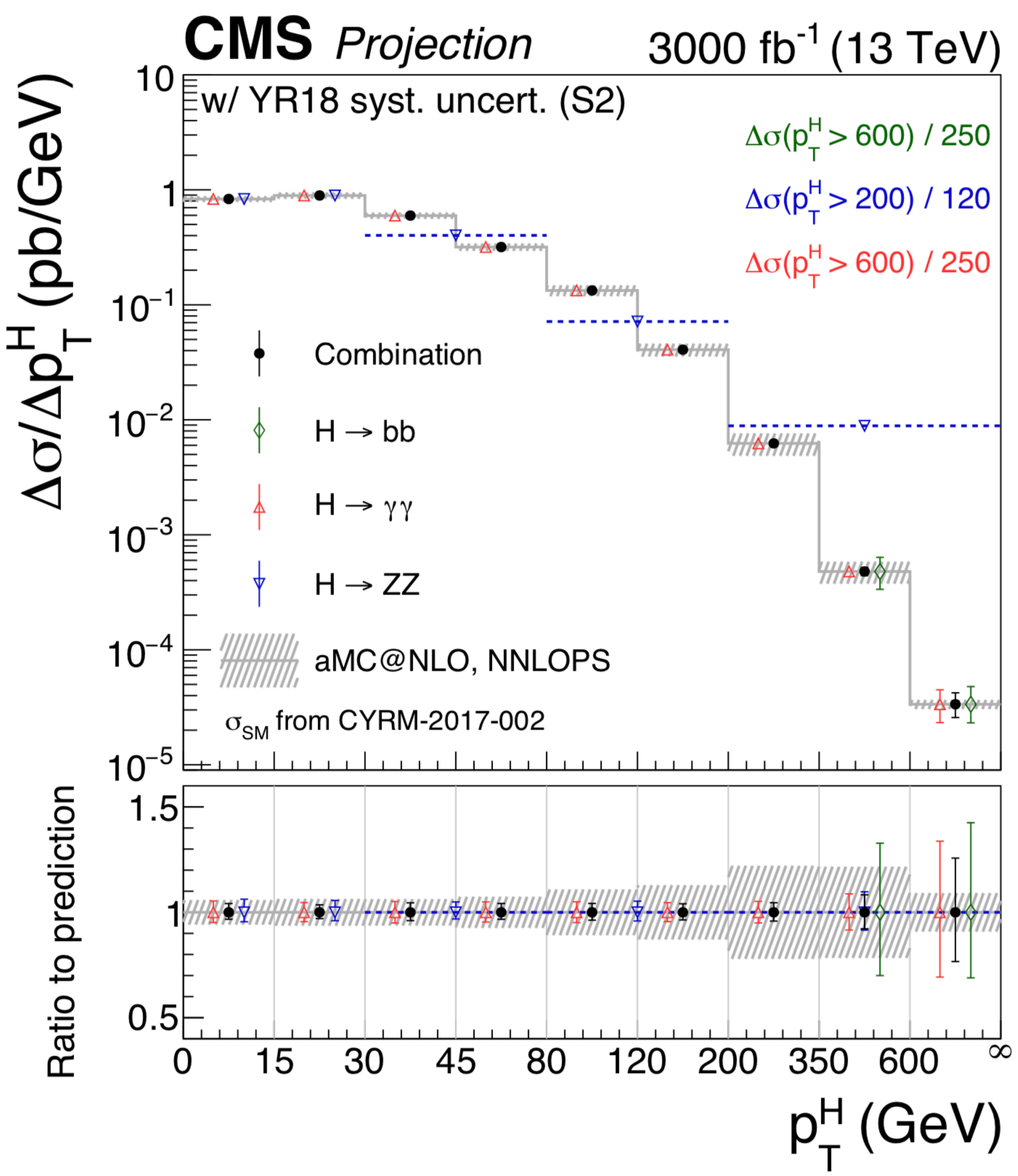

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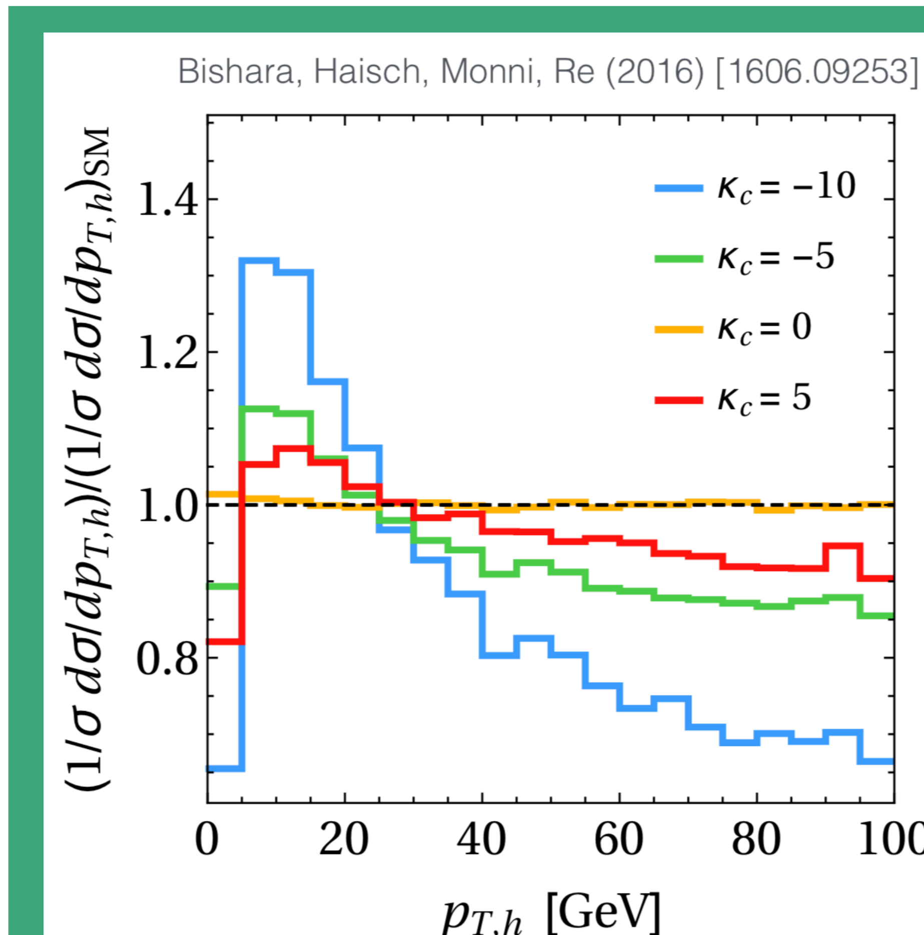
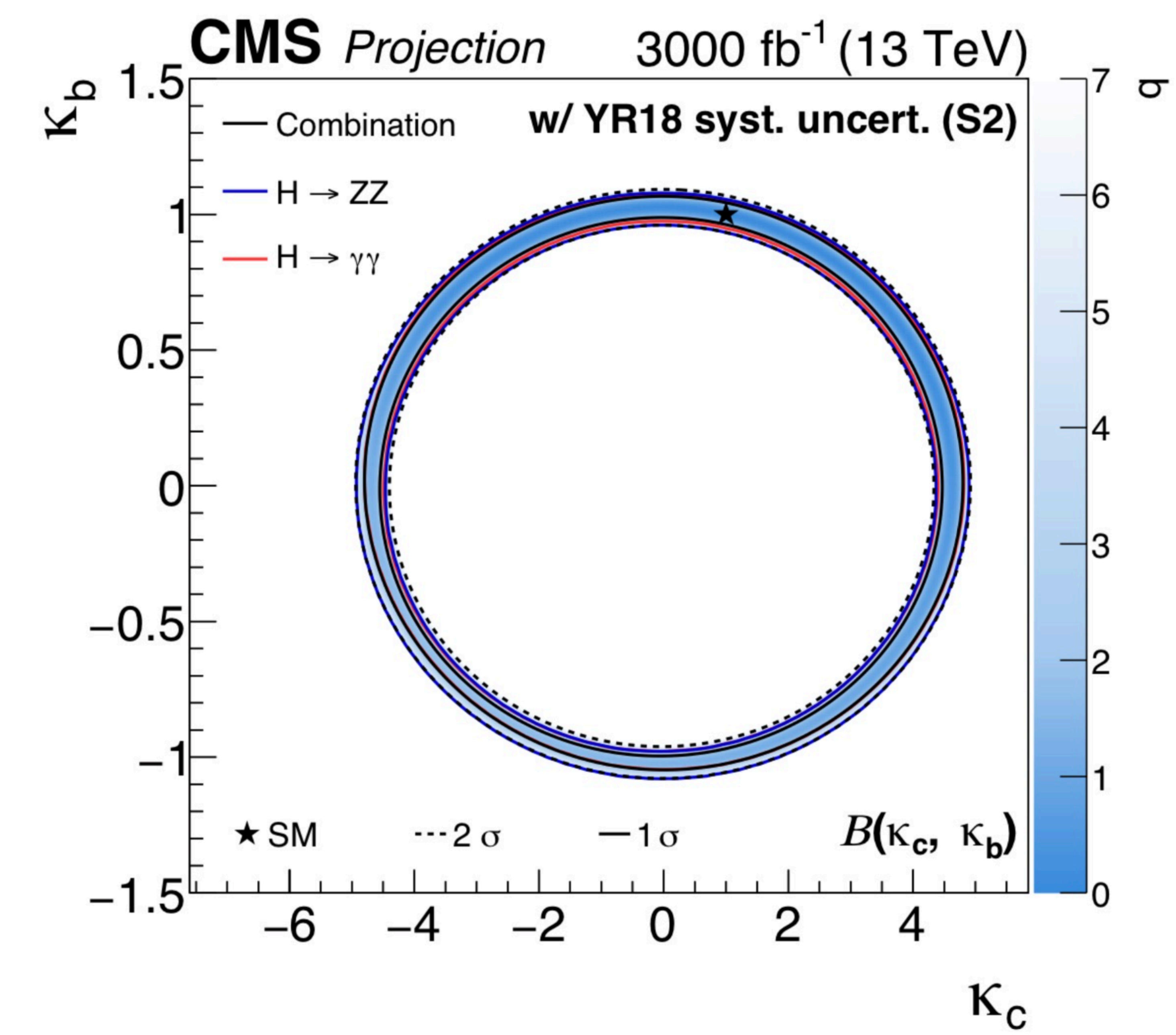


Expected 2D limits in (k_b, k_c) plane



Constraints on effective k_b, k_c, k_t, c_g couplings :

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Differential XS and limits on k_b, k_c, k_t, c_g

CMS-FTR-18-011

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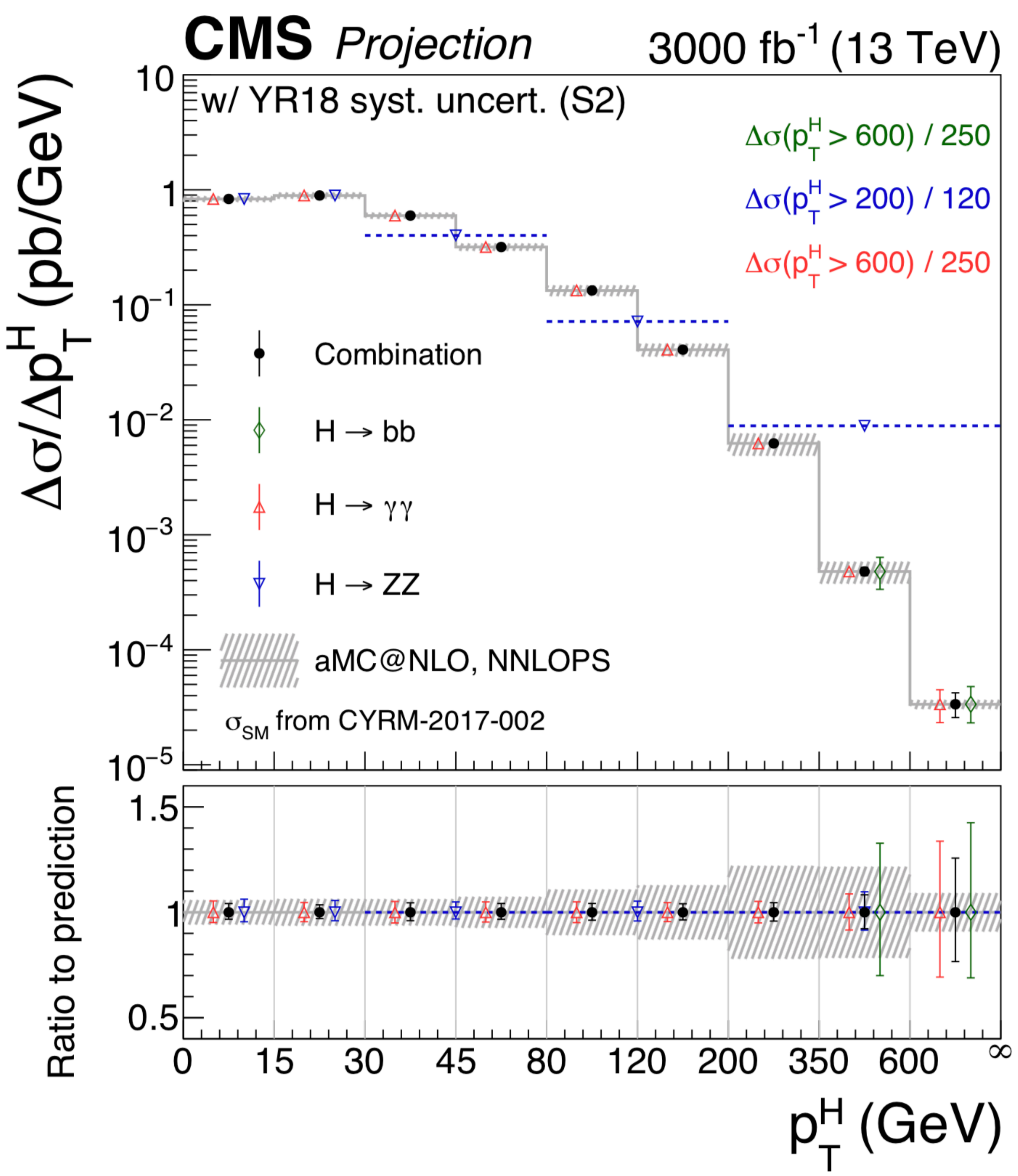
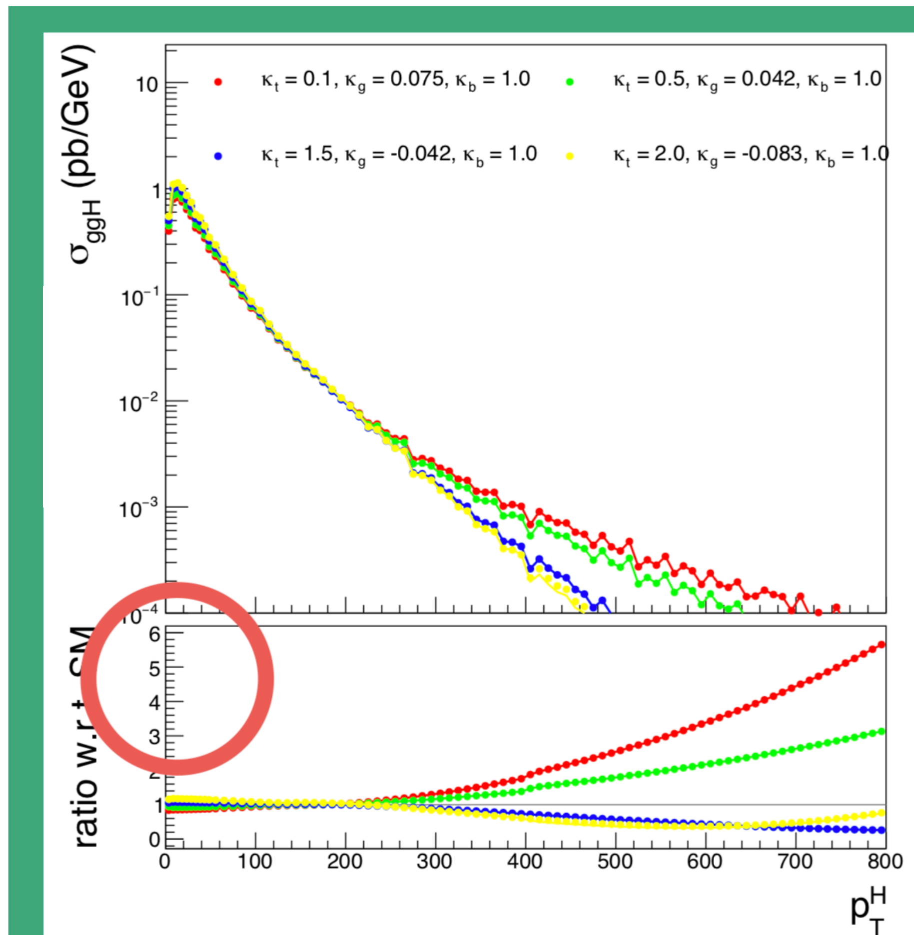
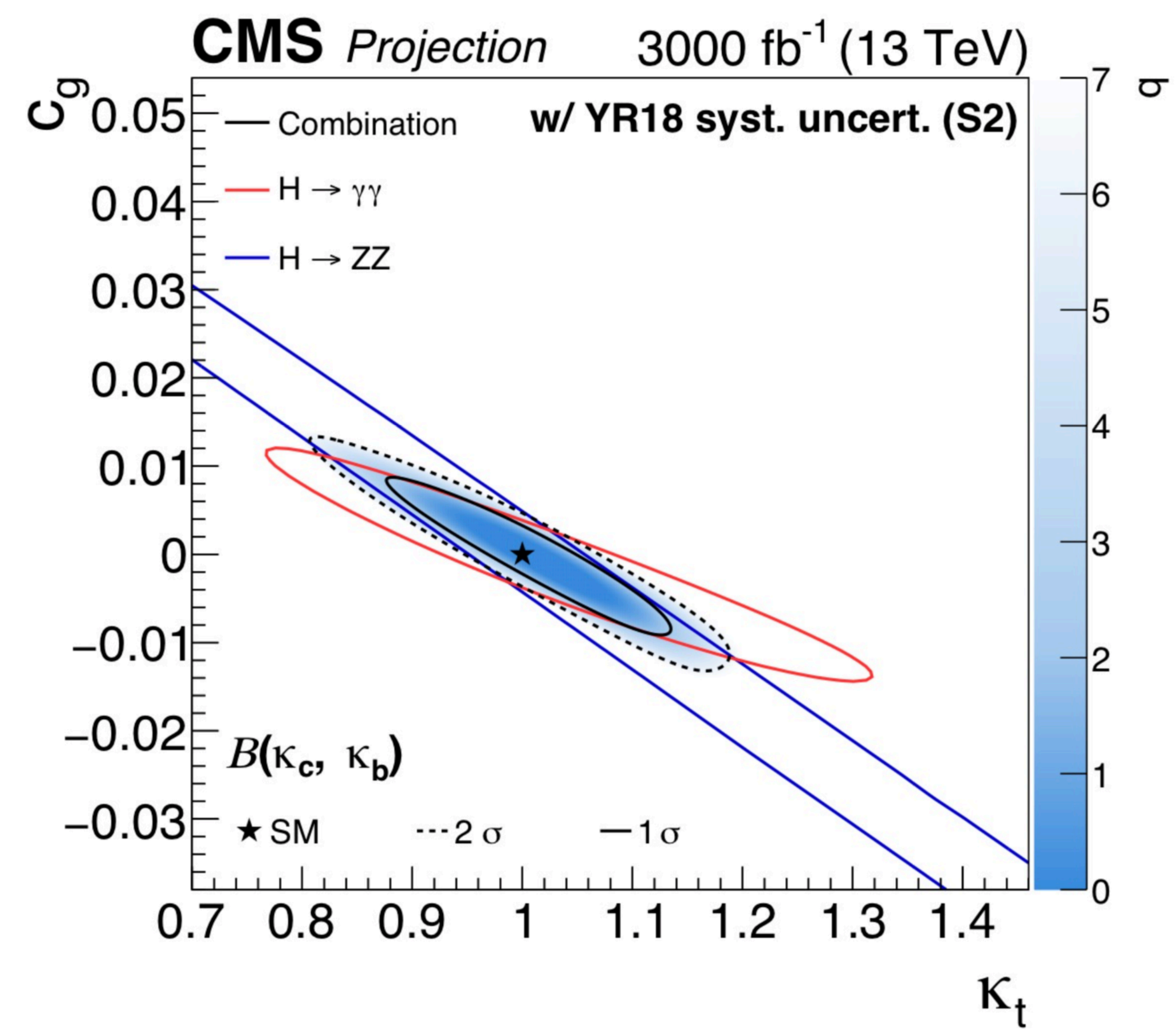


$p_T(H)$ parametrised in terms of c_g, k_t



Need better theory description of high-p_T tails

Expected 2D limits in (c_g, k_t) plane



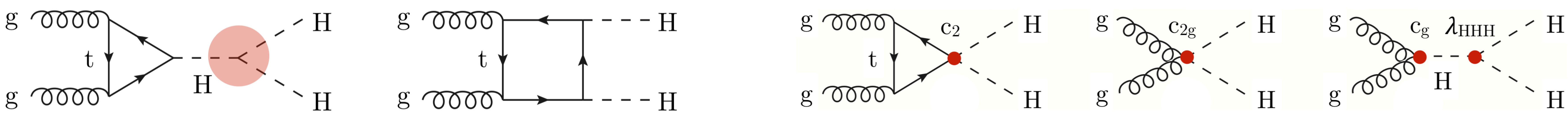
Constraints on effective k_b, k_c, k_t, c_g couplings :

- Competitiveness with direct probes of Higgs couplings (in particular κ_c)

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)
- Performing combination of all channels, and also **ATLAS+CMS combination** (to be public soon)

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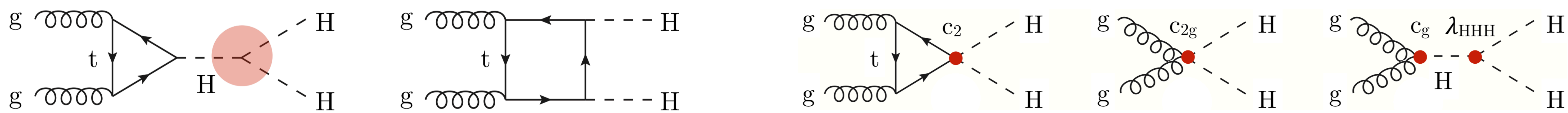

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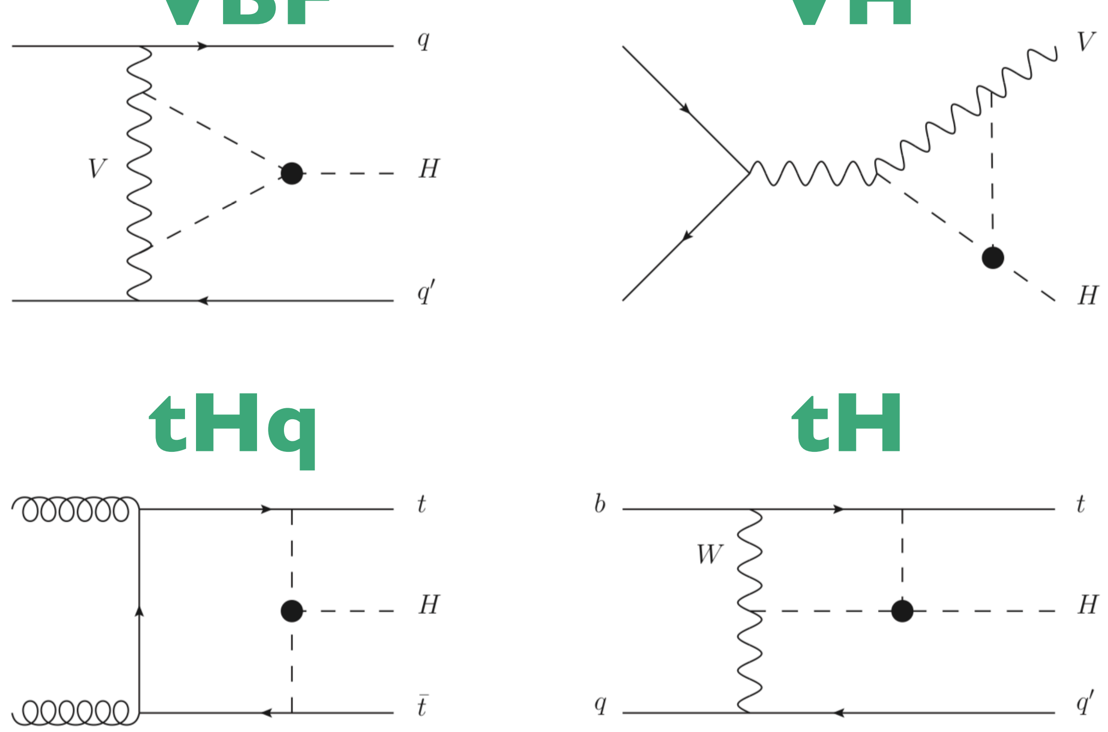
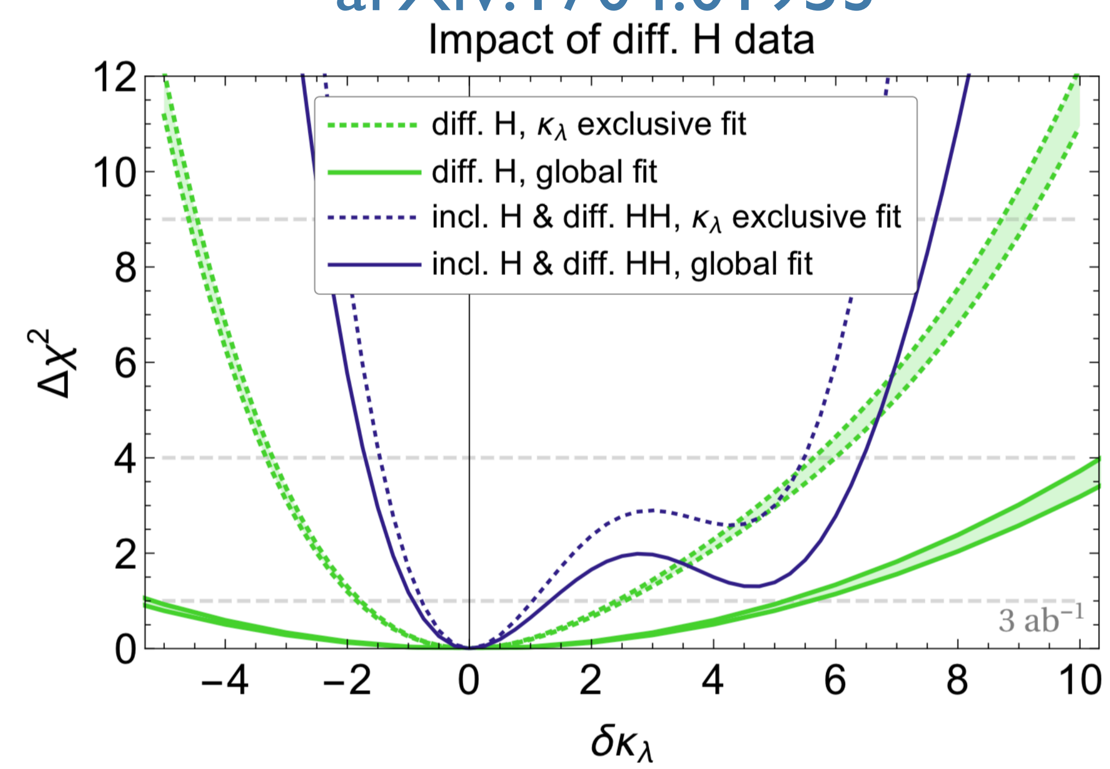
VBF **VH**

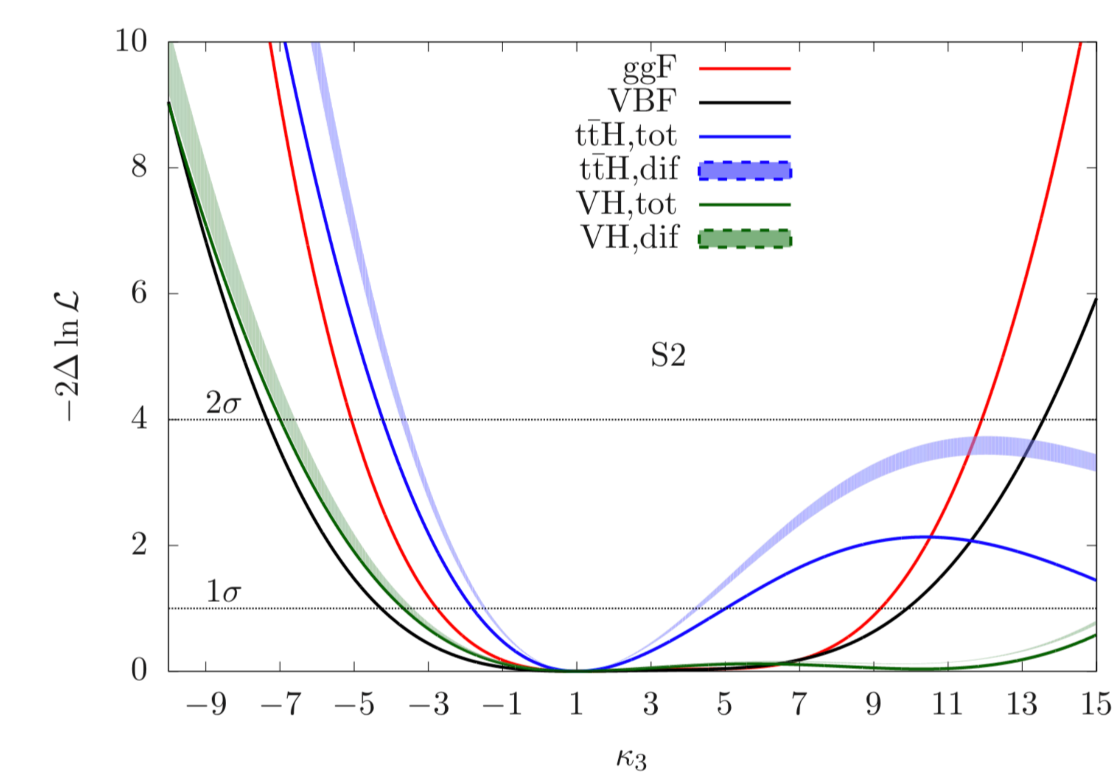
tHq **tH**



arXiv:1704.01953



arXiv:1709.08649



- Important possibility to **constrain λ_{HHH} from single Higgs precision measurements**
  - HH differential information further improves the measurement

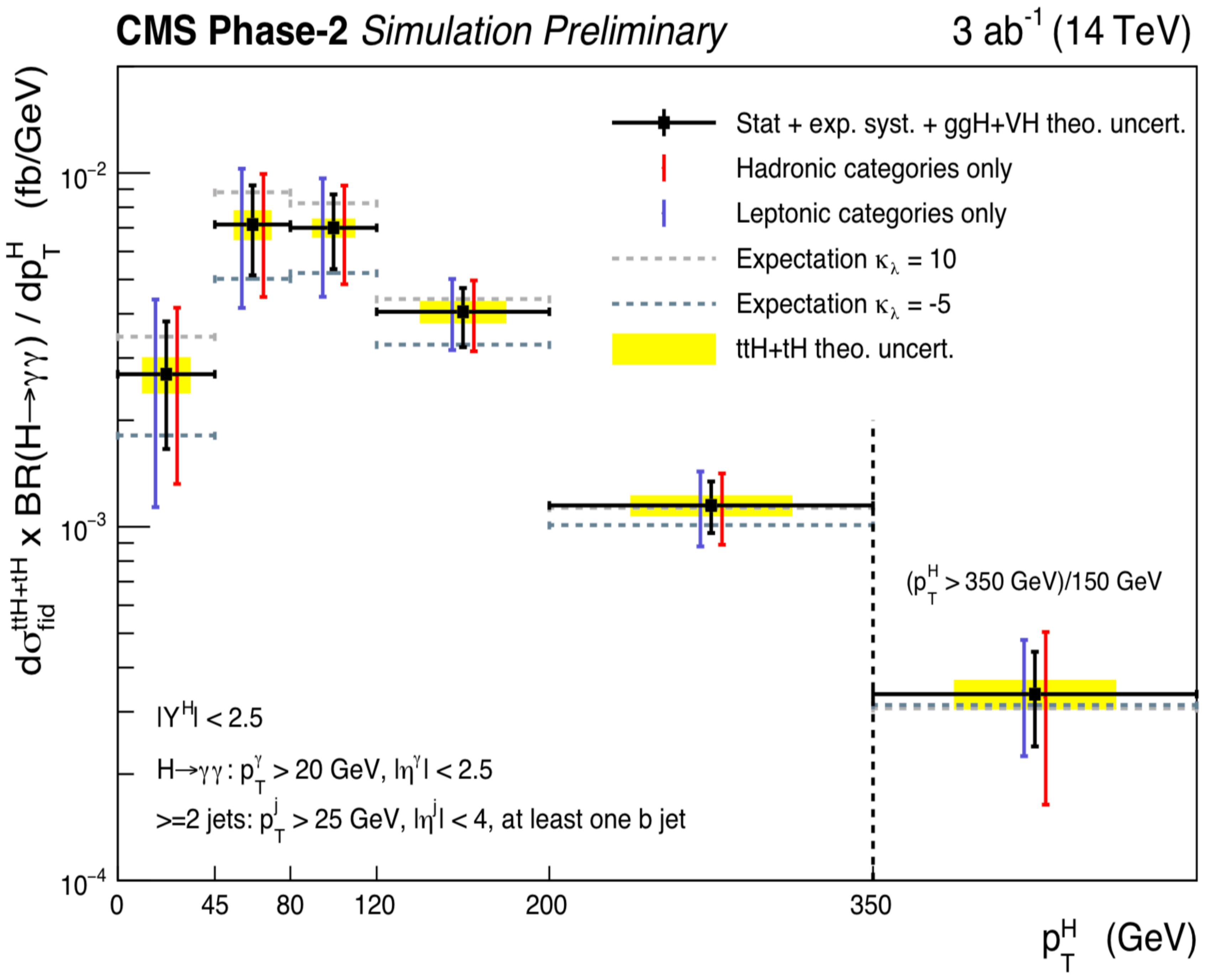
Differential XS and limits on self-coupling

CMS-FTR-18-020

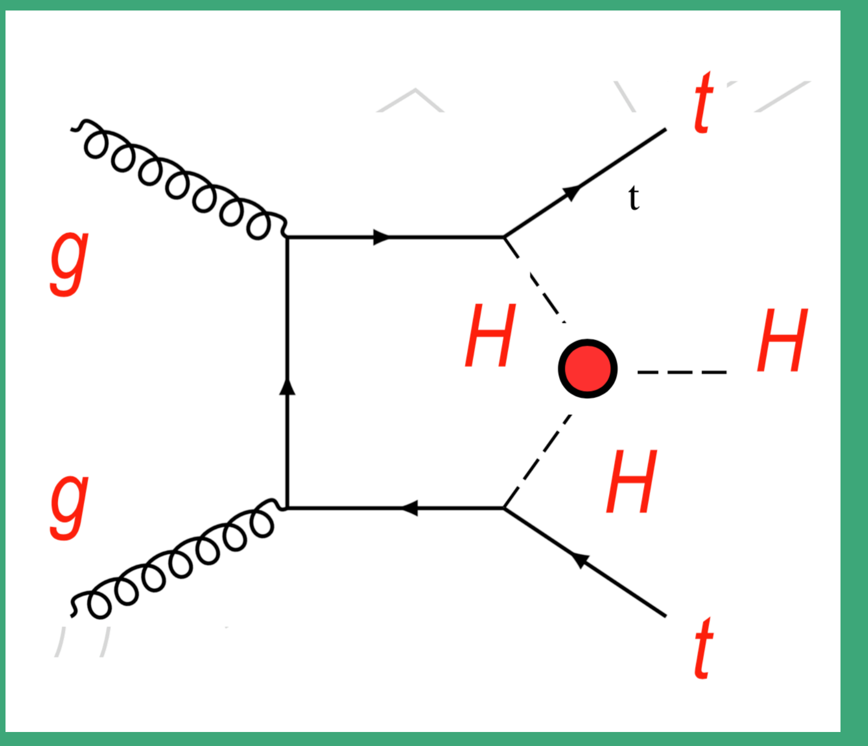
Performed first studies of differential XS for exclusive production (@HL-LHC):

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

Differential $p_T(H)$ in ttH($H\to\gamma\gamma$)



$p_T(H)$ parametrised in terms of k_λ



Constraints on effective k_λ coupling :

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

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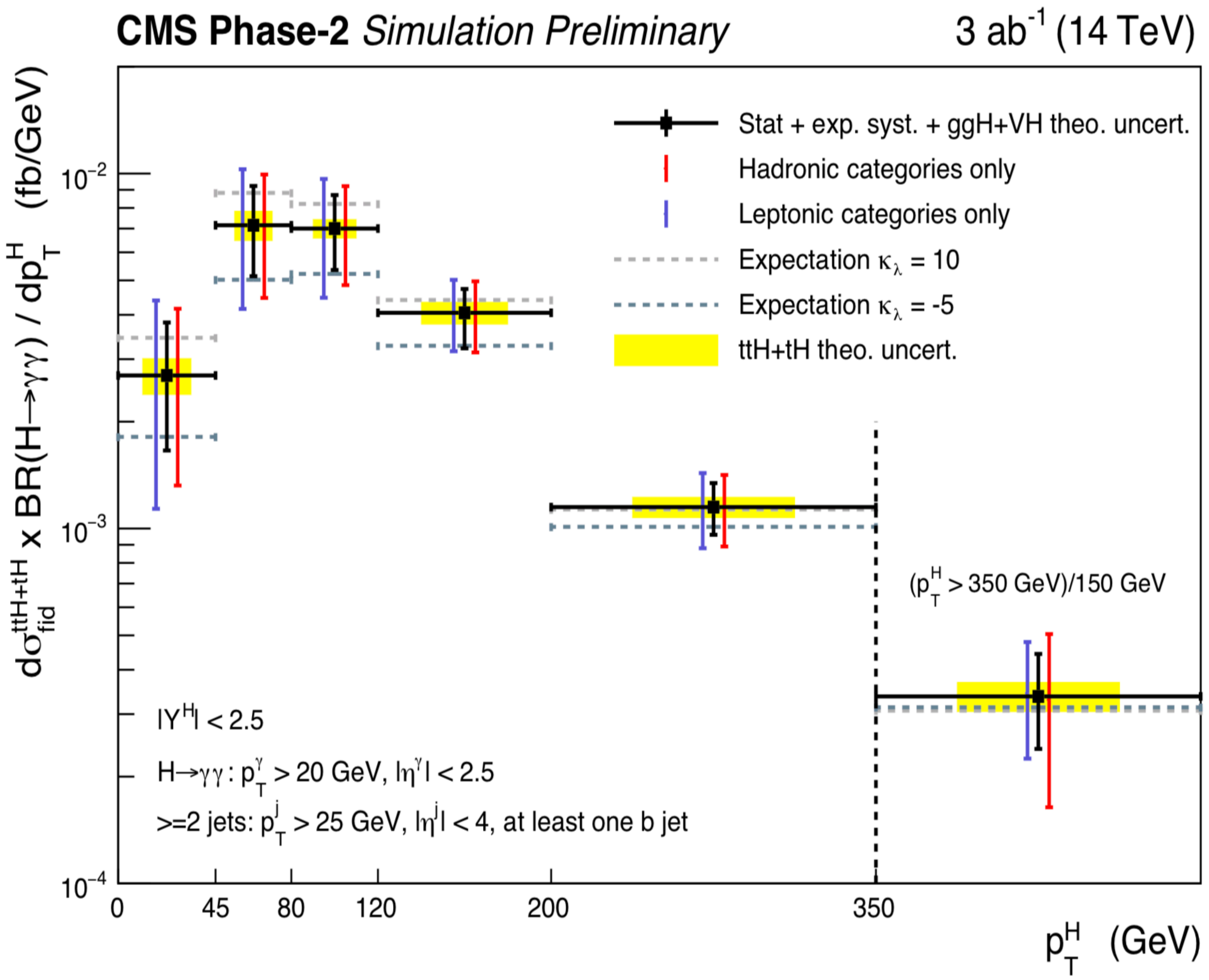

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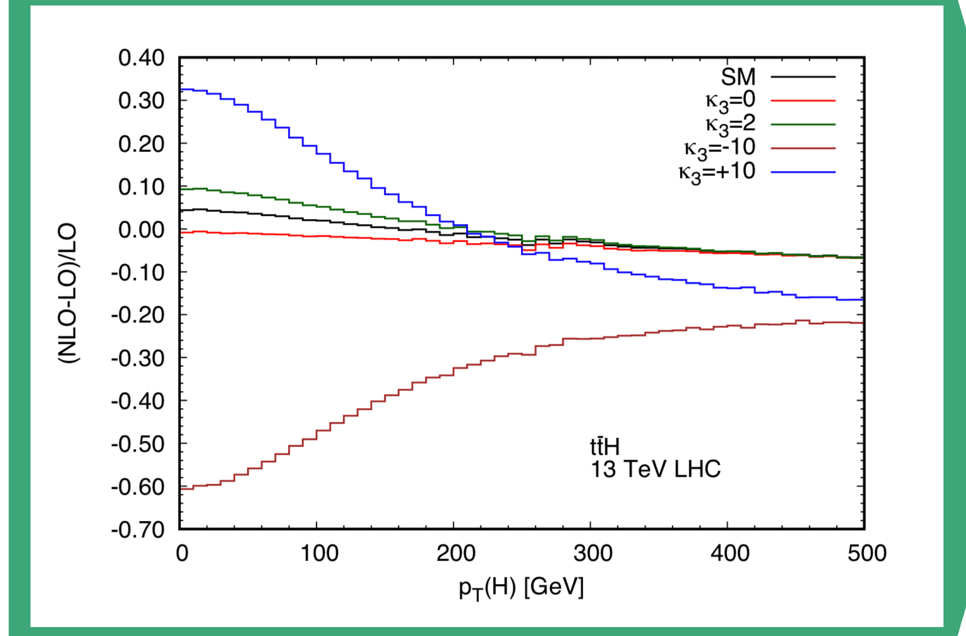
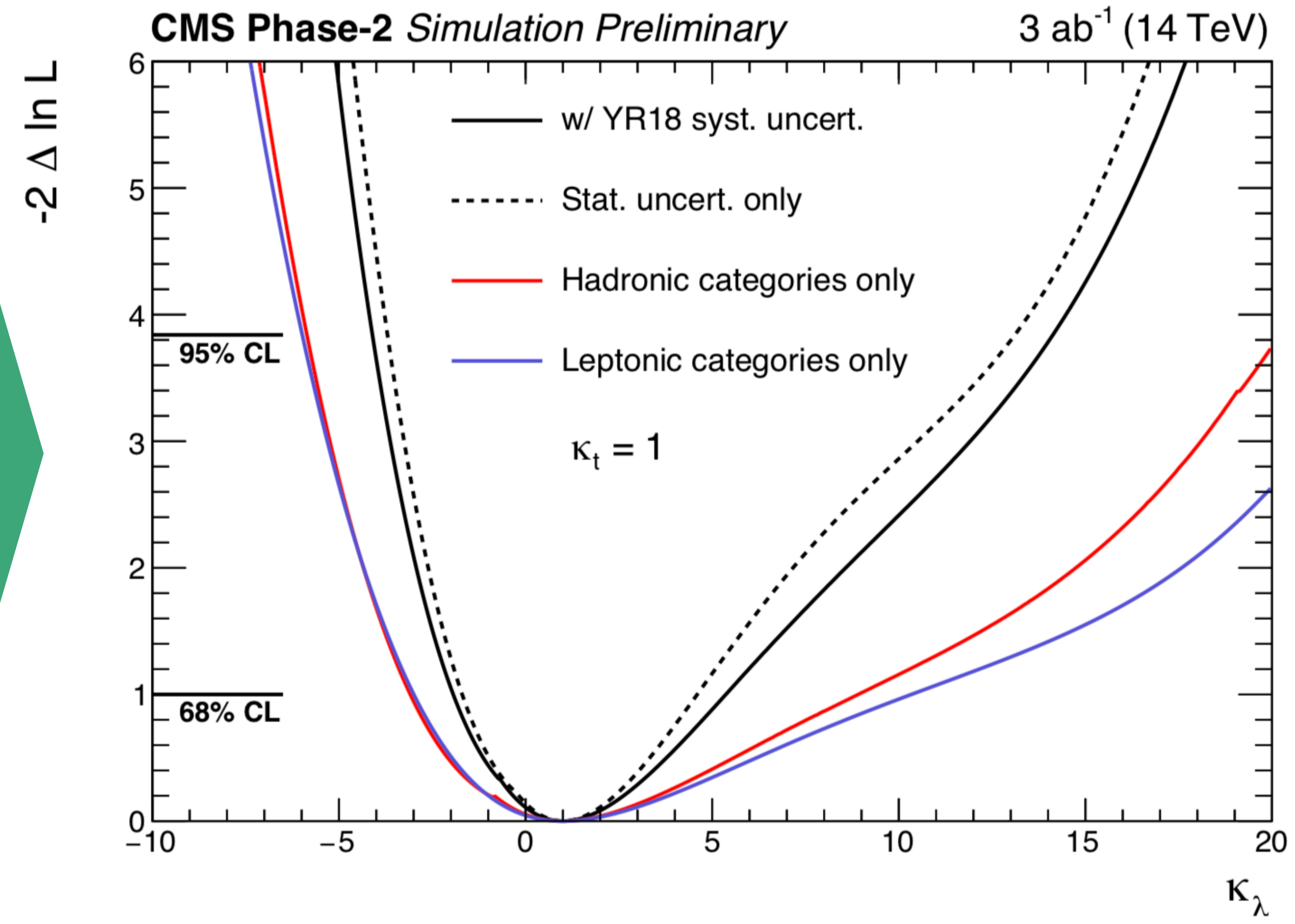


Expected 1D limits for k_λ



Constraints on effective k_λ coupling :

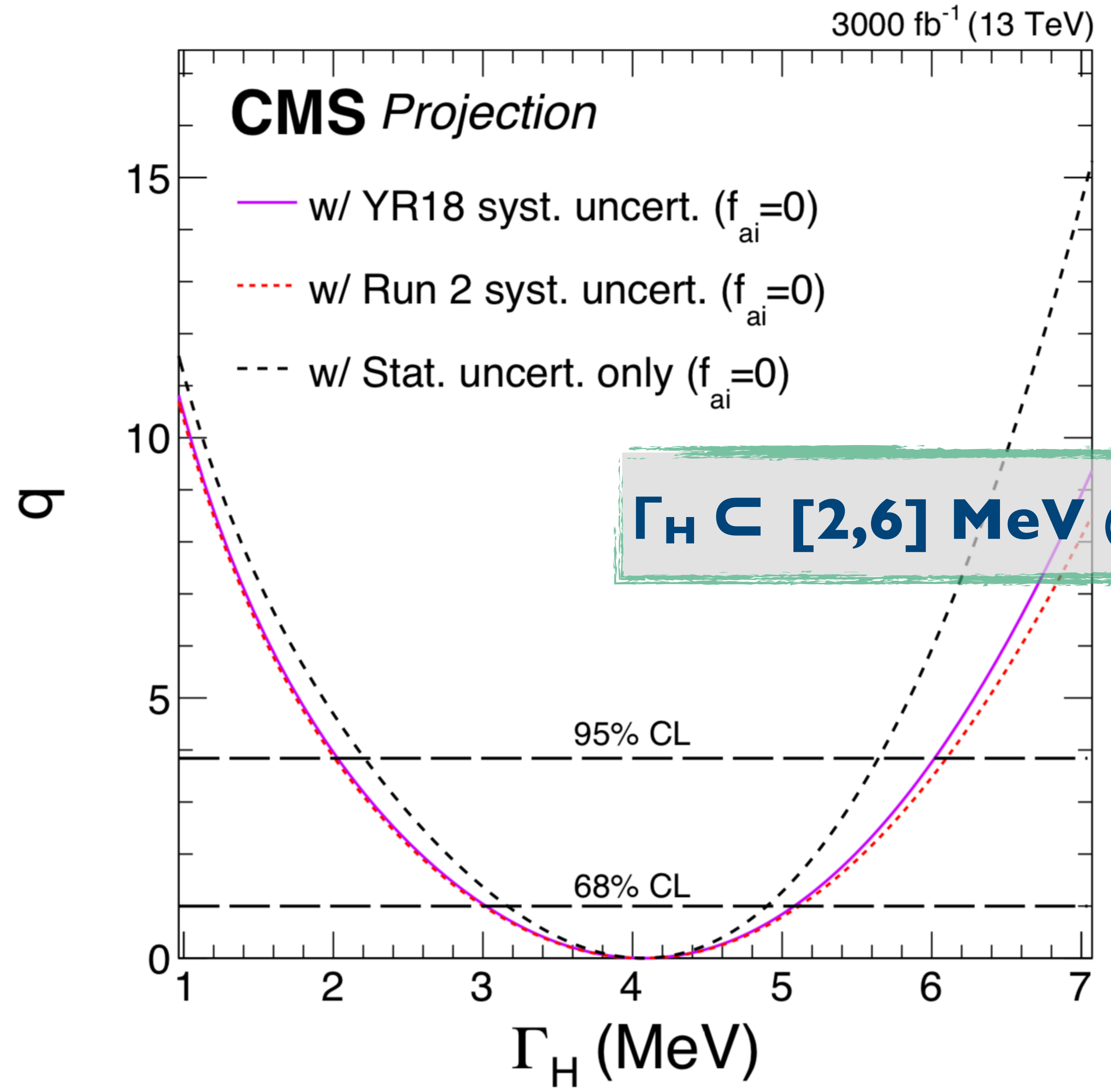
- Need to study all production modes and decays channels to fully exploit the potential.
- Important complementarity with direct probes of HH production.

Higgs boson width

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

Indirect constraints from off-shell

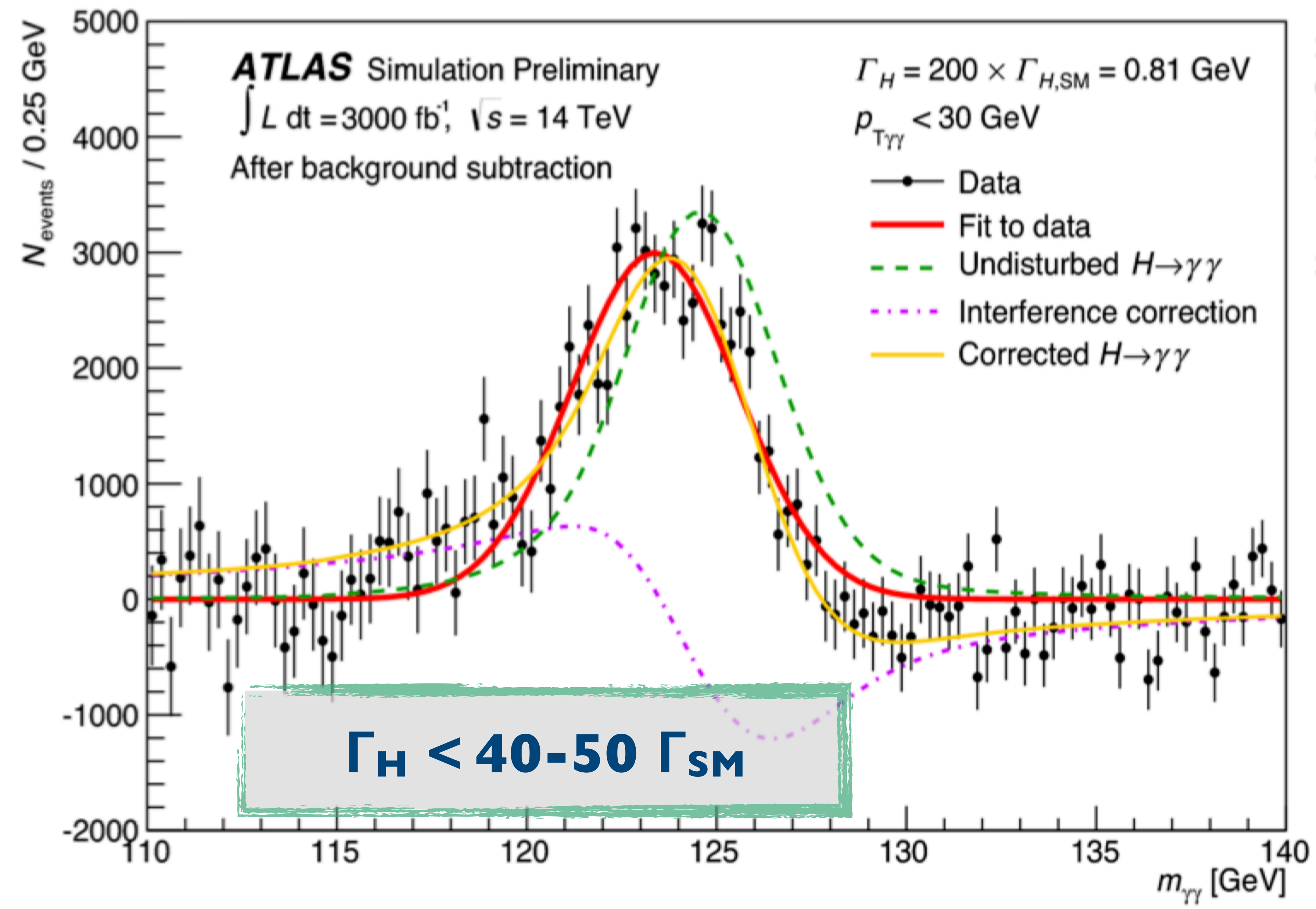
- gg → VV, gg → H* → VV



$\Gamma_H \subset$ [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.

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

Anomalous HVV interactions

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

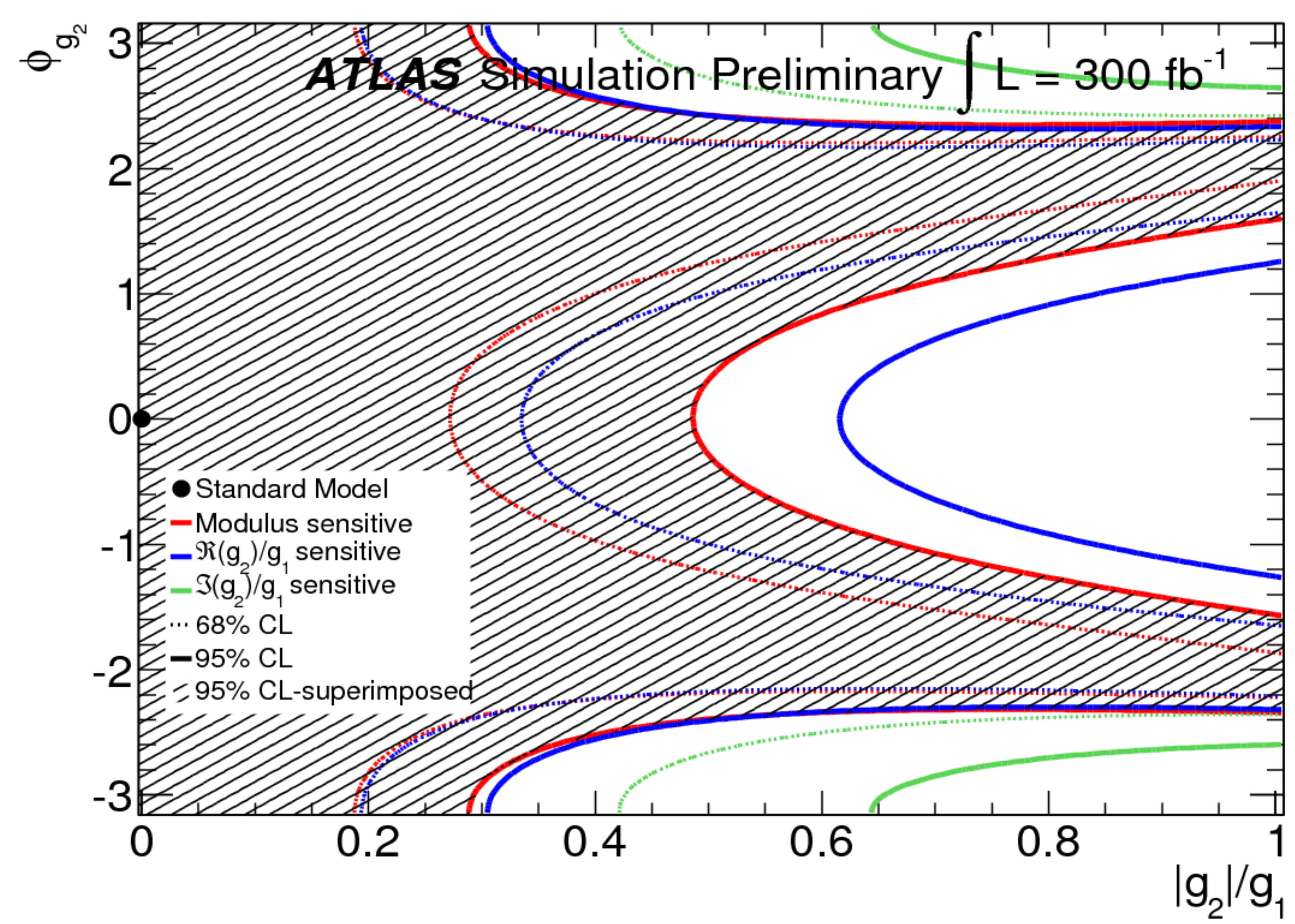
- Parameterisation of decay amplitude:

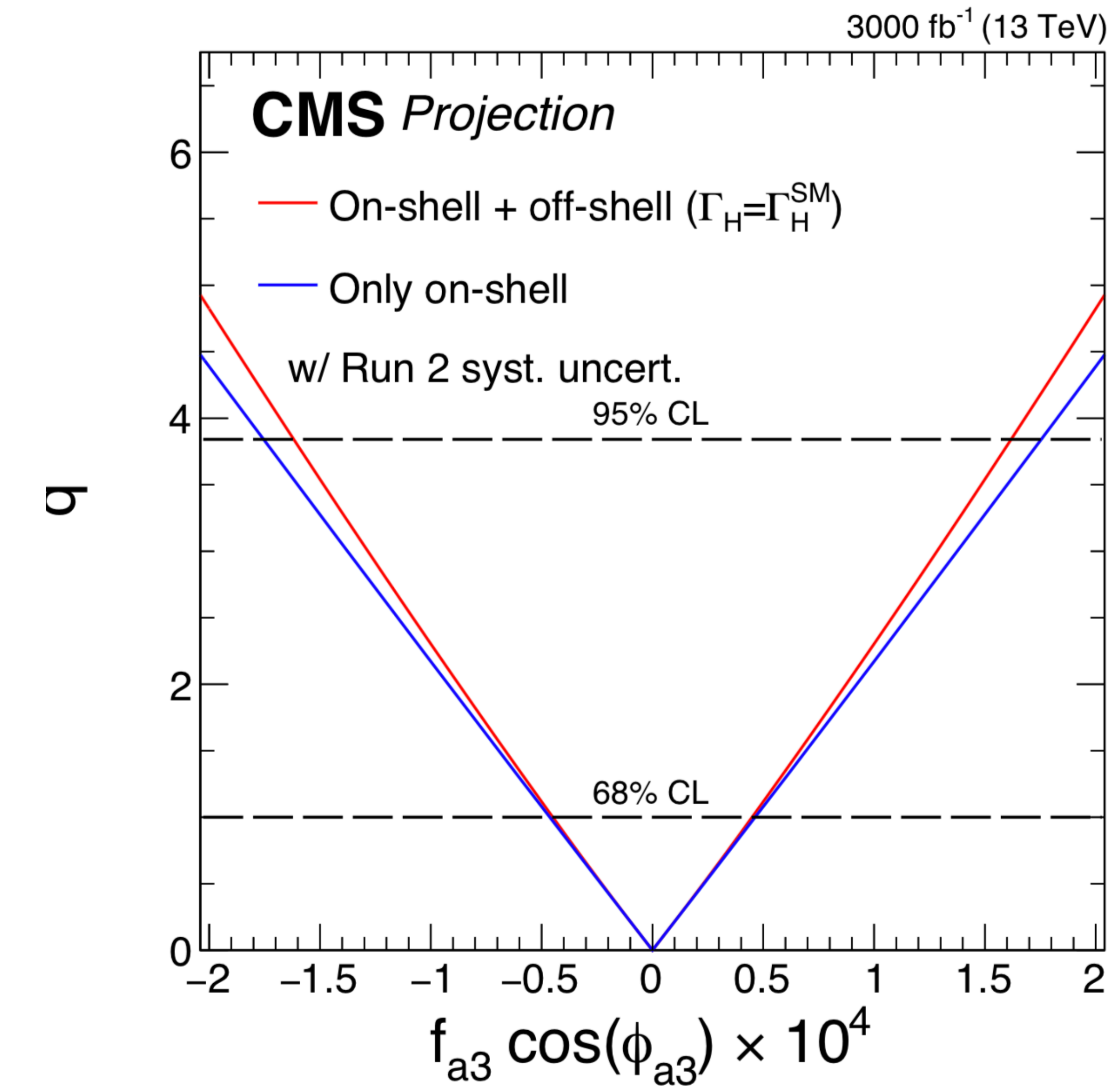
SM | leading momentum expansion | higher order cp-even | cp-odd

$$A = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

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	$\pm120 \cdot 10^{-4}$
f_{a3}	decay & production	$\pm1.8 \cdot 10^{-4}$
f_{a3}	decay & production & off-shell	$\pm1.6 \cdot 10^{-4}$

Constraints on fractional CP-odd presence <1.6· 10^{-4}

Physics Prospects @HL-LHC

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

Prospects for physics phenomena beyond SM

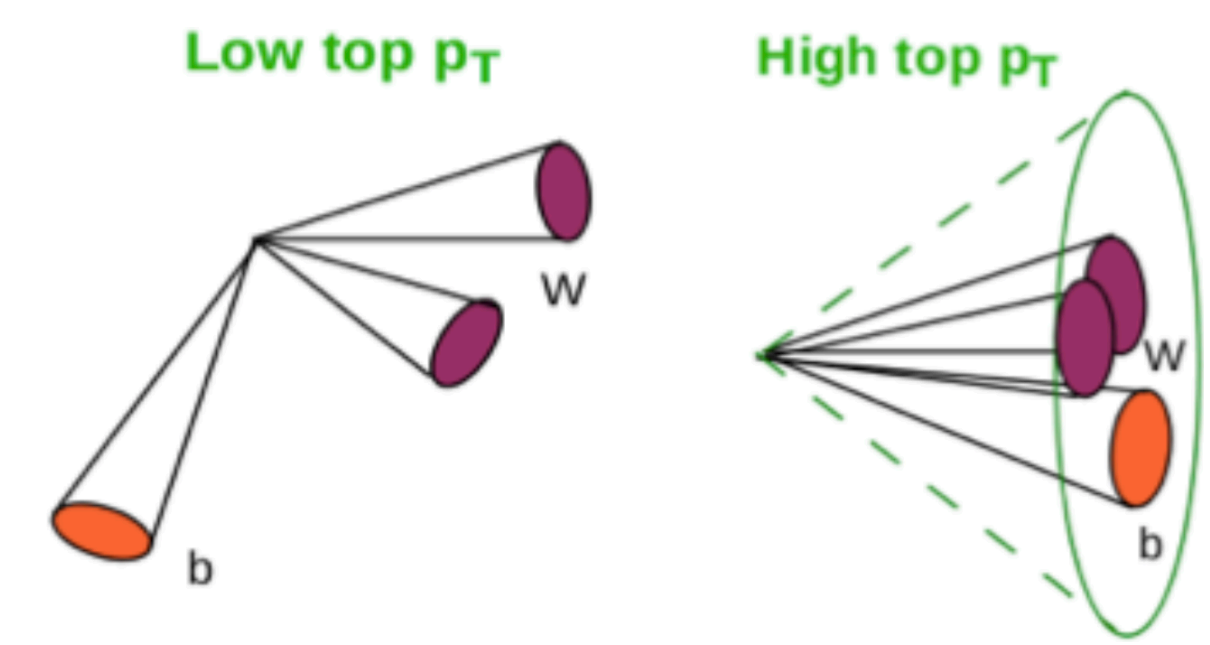
- Search for heavy resonances
- Search for SUSY signatures
- Exploring the "dark sector"

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)

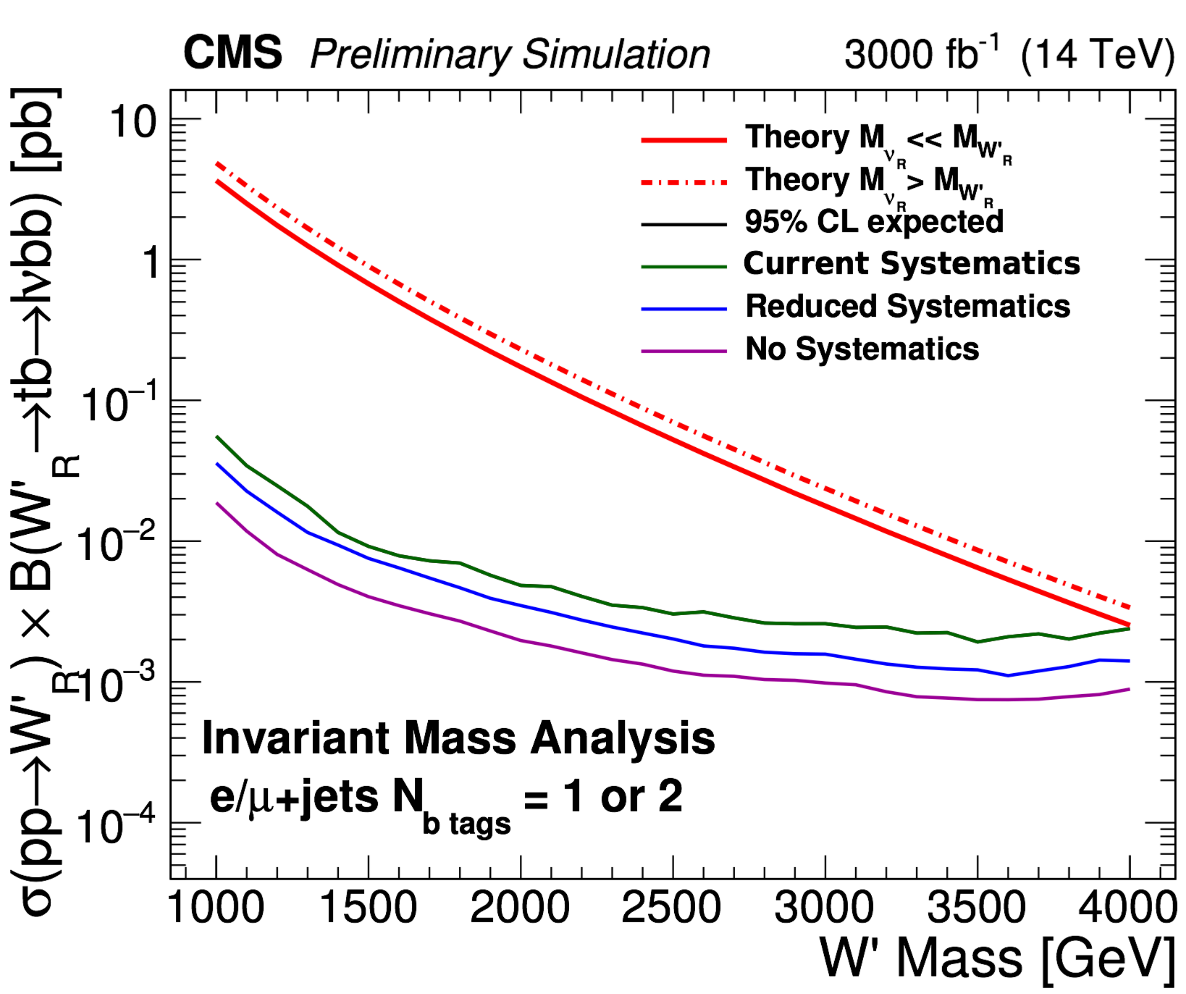
- **W' → tb → bbℓν :** high-p_T lepton, significant E_{Tmiss}, two b-jets
- **Z' → tt → ℓνb qq'b / qq'b qq'b :** Exploit boosted topologies



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

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

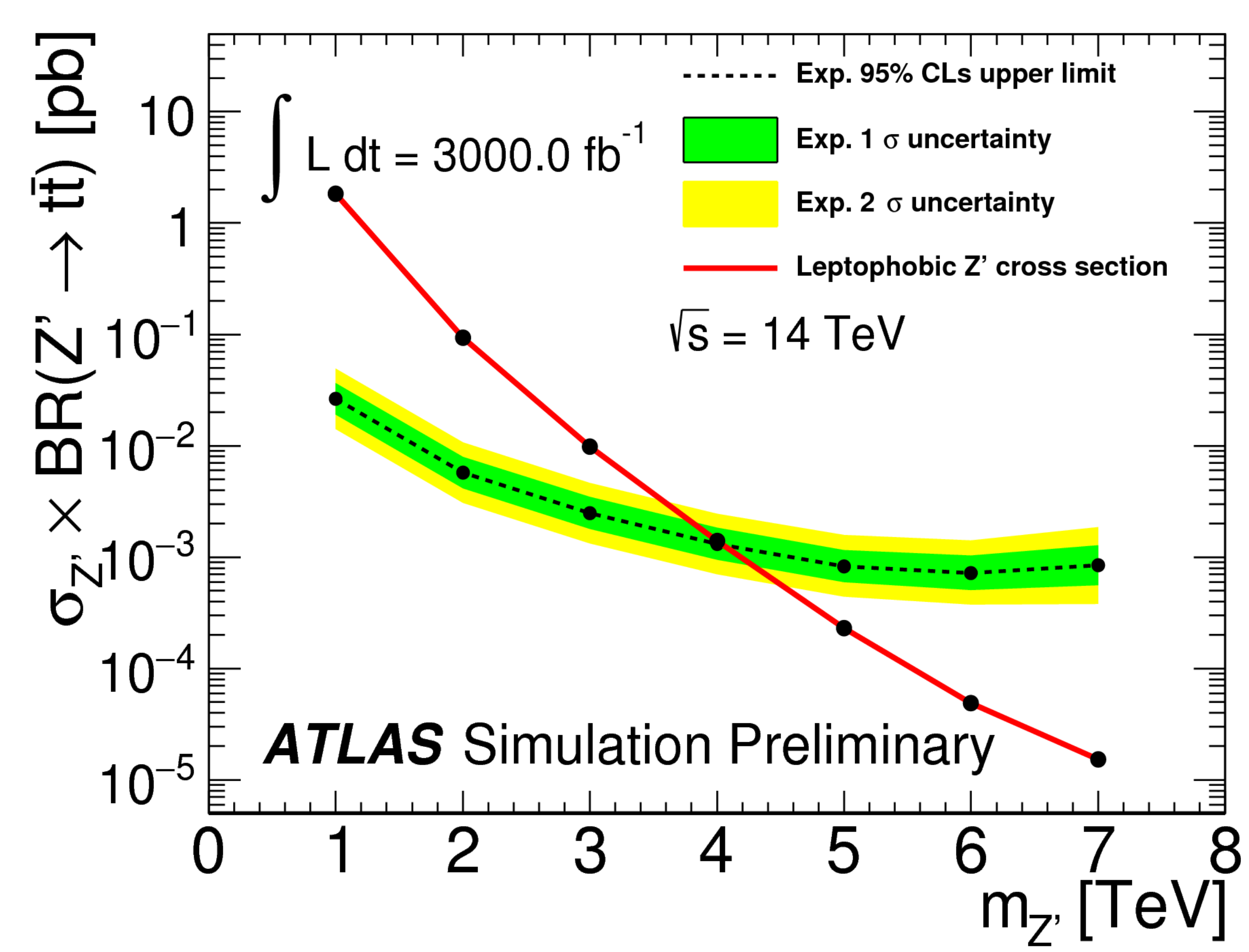
W' → tb → bbℓν



Exclusion: m(W') > 4 TeV

current limits about 2.7 TeV

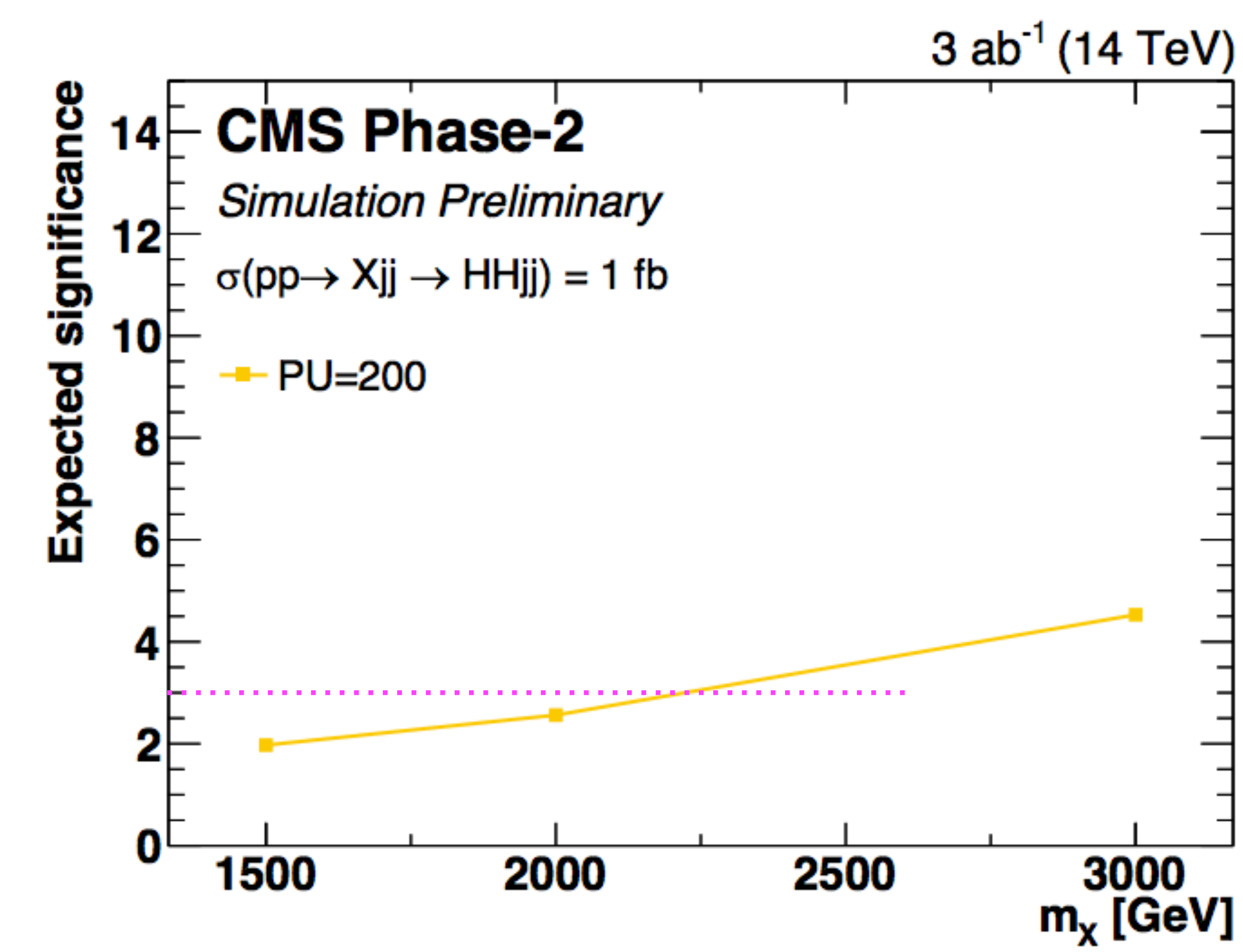
Z' → tt (hadronic)



Exclusion: m(Z') > 4 TeV

current limits about 2 TeV

X → HH → bbbb (boosted)



Evidence: m(X) < 2.2 TeV

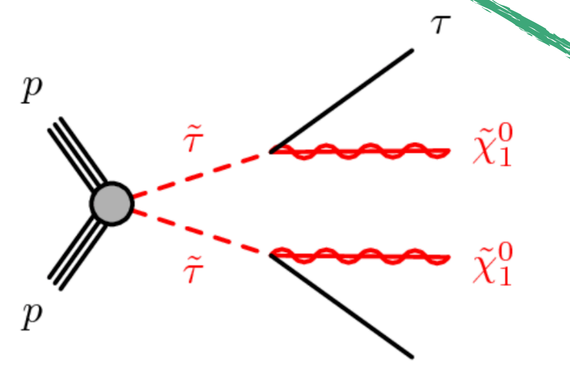
for narrow width, 1fb cross section

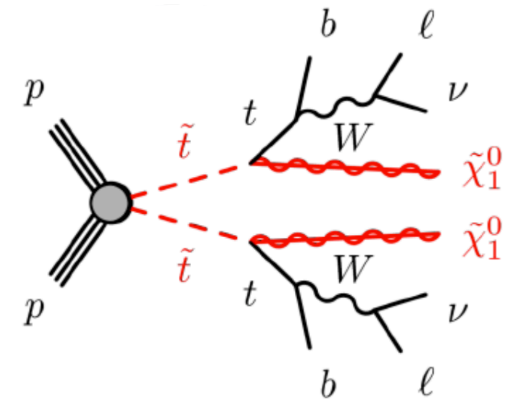
SUSY searches @ HL-LHC

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

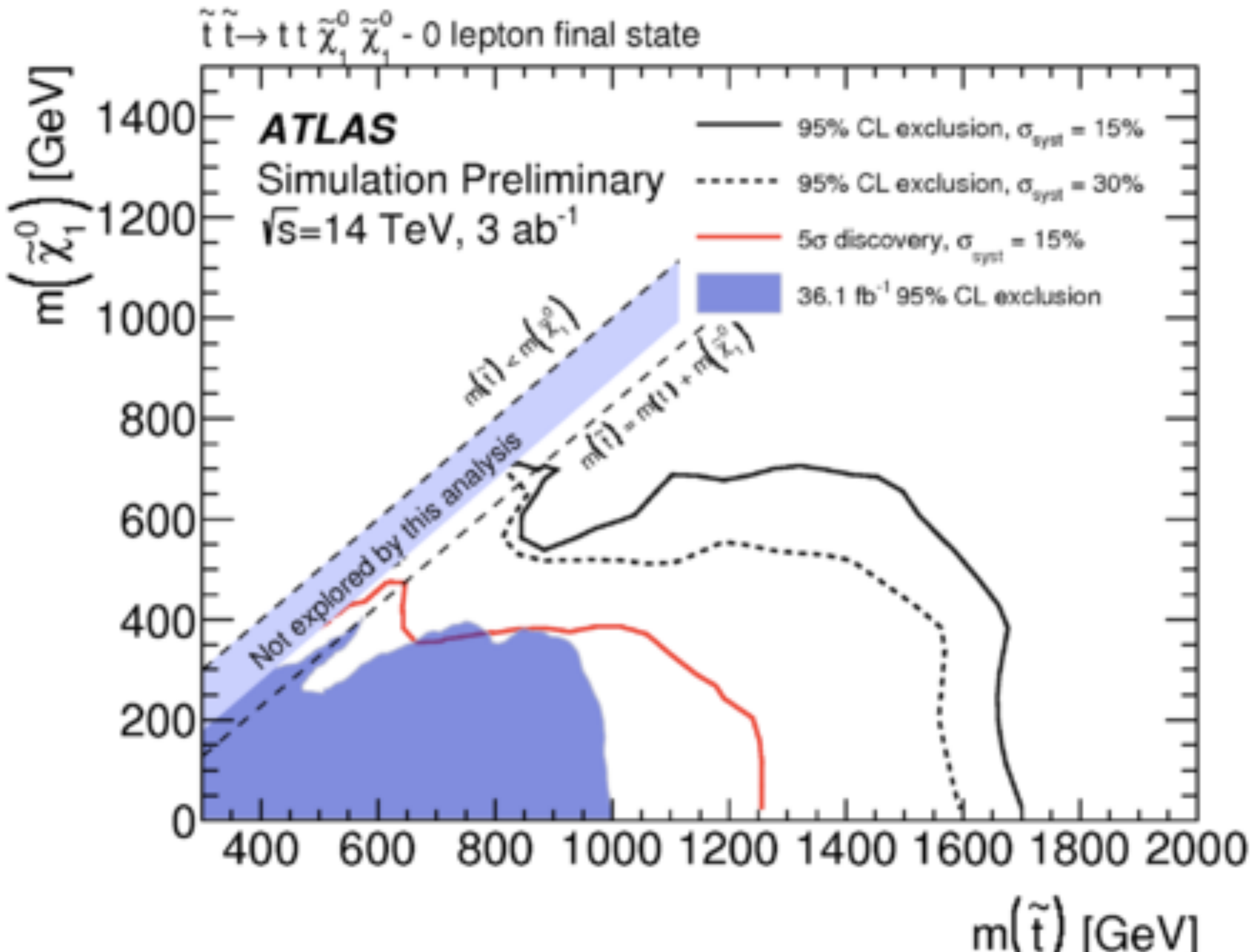
Performance estimated using the (simplified) analyses

- **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



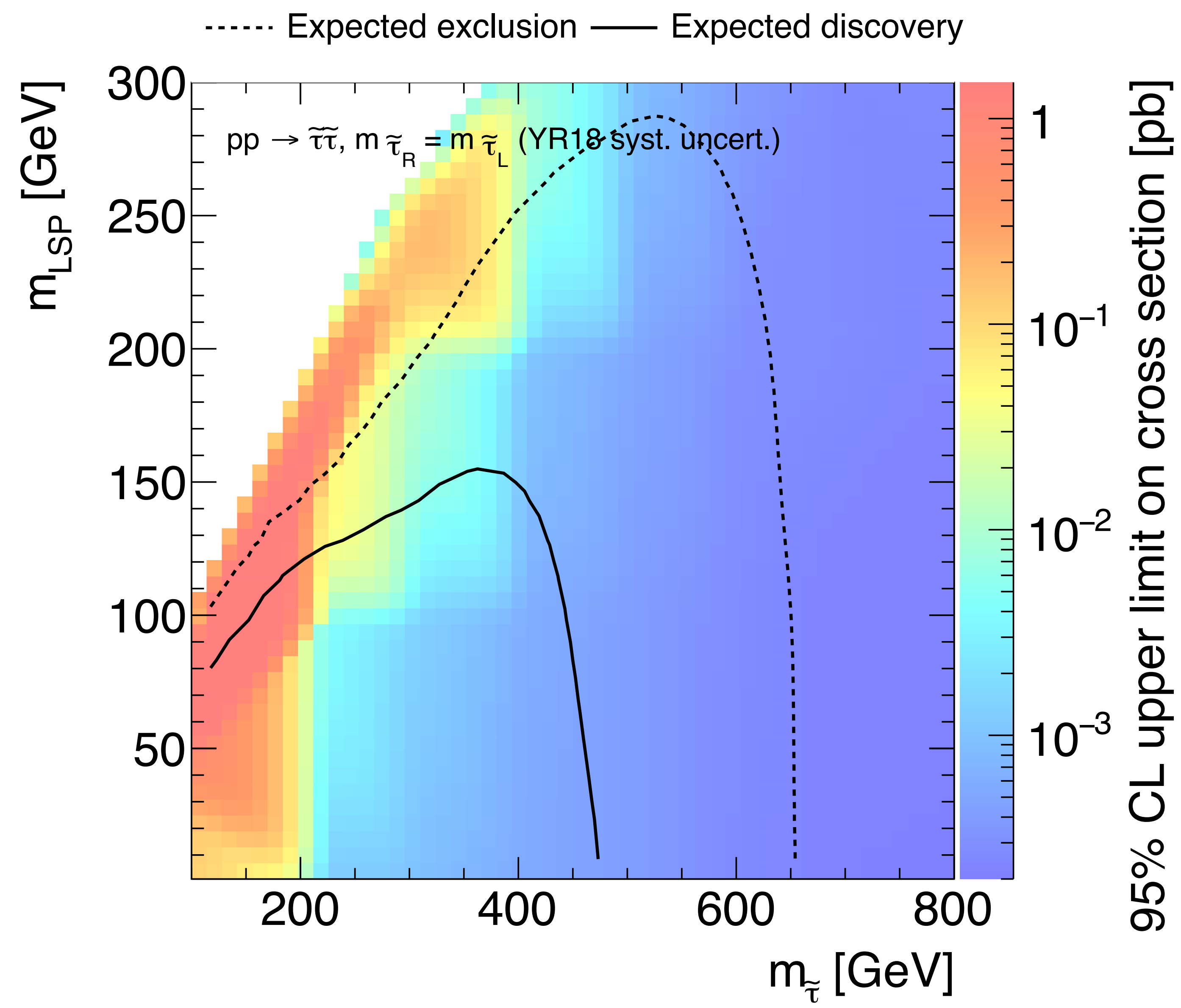


Direct stop pair production:



0

Direct stau pair production:



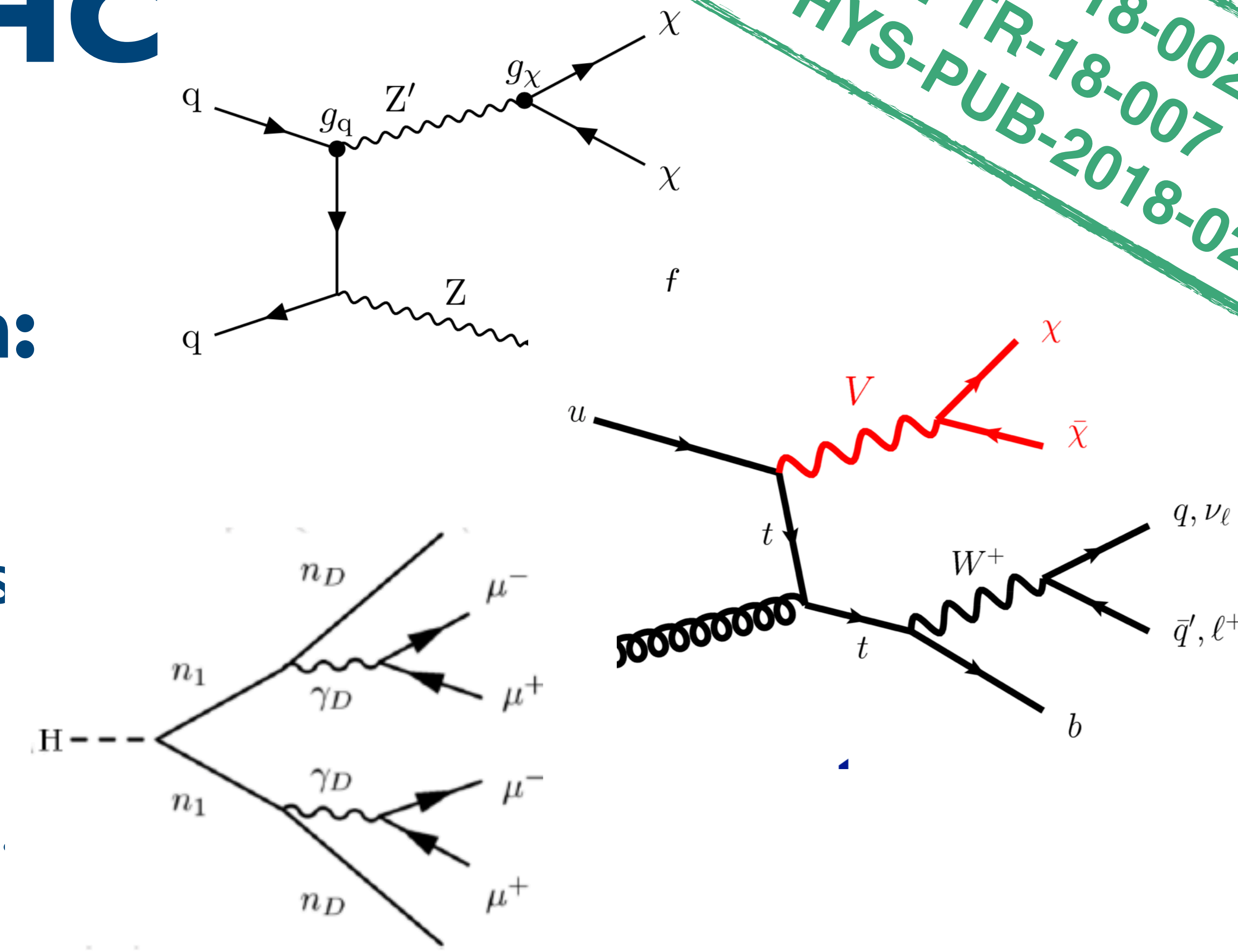
Discovery reach m(stop) < 1.25 TeV

Discovery reach m(stau) < 470 GeV

current exclusion limits about 110 GeV

Dark sector @ HL-LHC

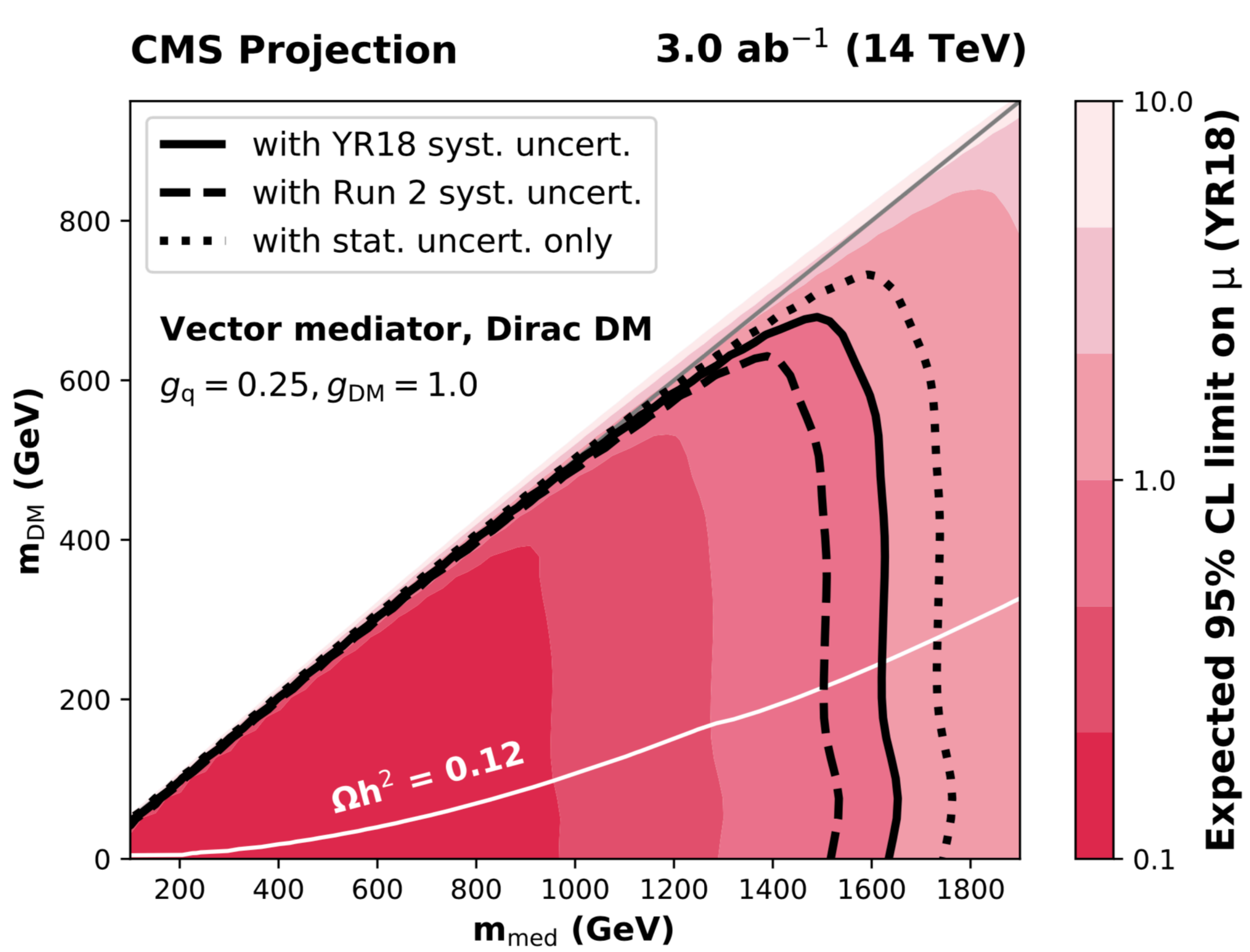
CMS FTR-18-002
CMS FTR-18-007
ATL-PHYS-PUB-2018-024



Simplified models for comparisons with direct detection:

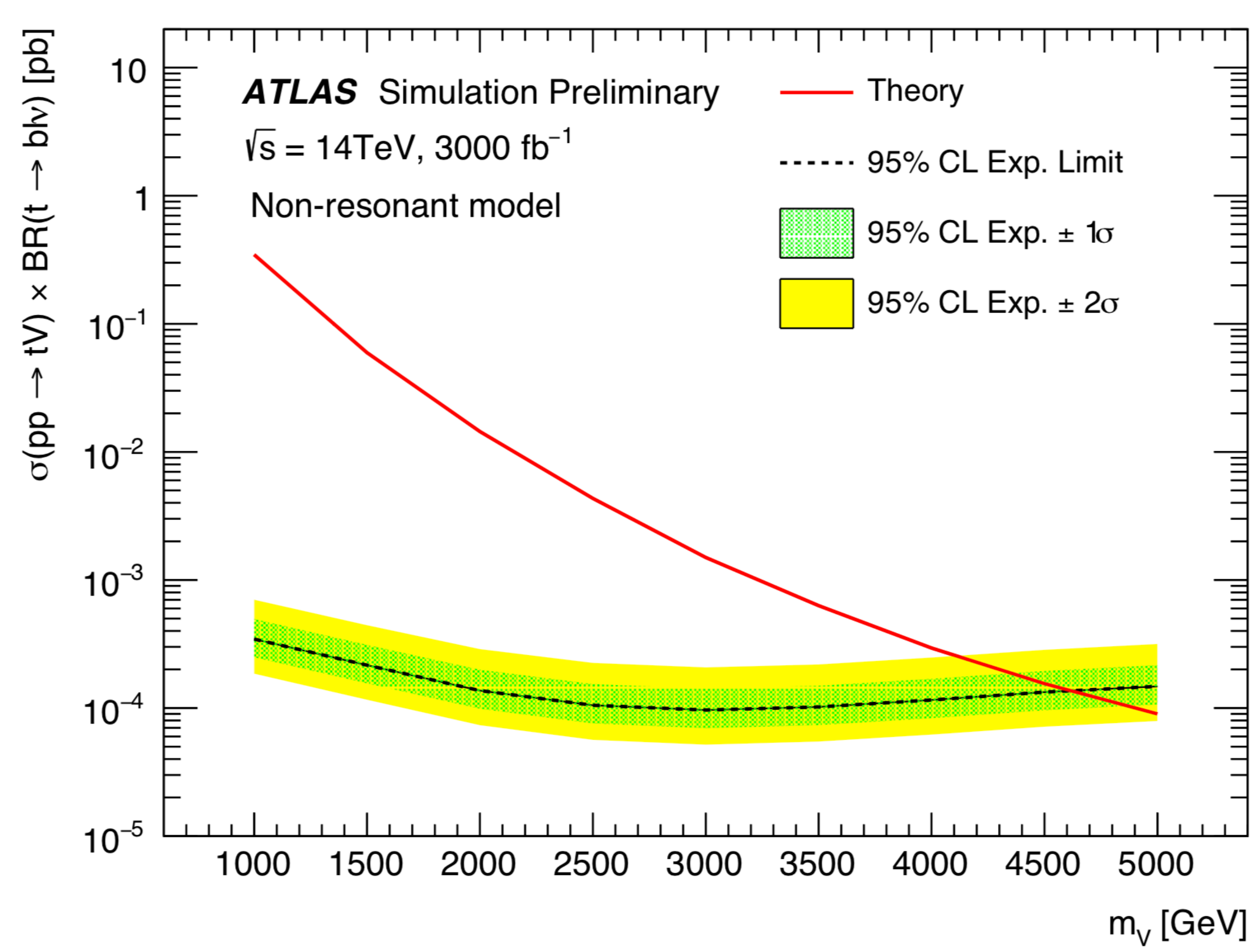
- **mono-Z :** Z accompanied by a mediator decaying to DM particles
- **mono-top :** Top accompanied by a mediator decaying to DM particles
- **dark photon :** It can couple to SM particles via kinetic mixing. (possible long-lived signatures for small kinetic mixing).

Mono Z search



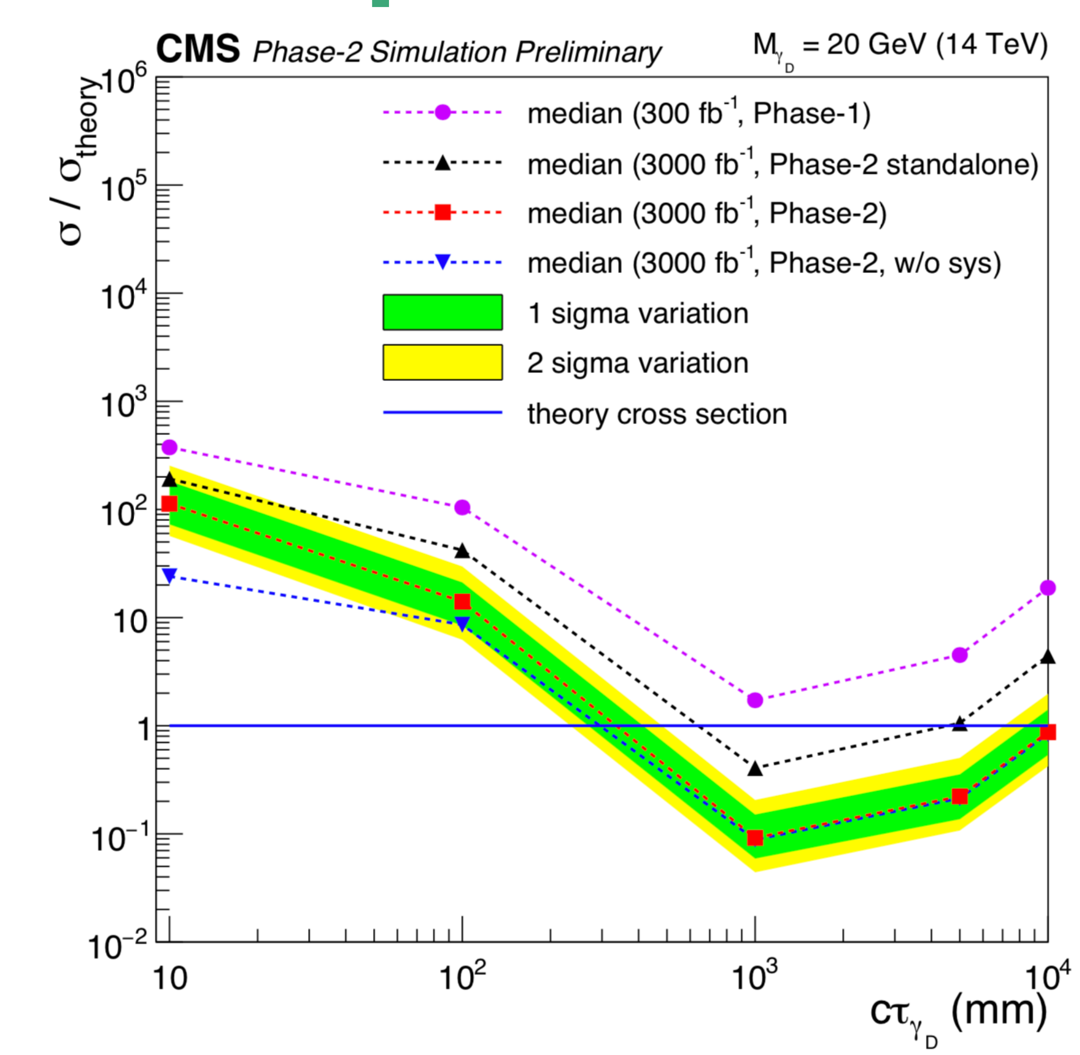
Exclusion: m(med) > 1.6 TeV

Mono top search



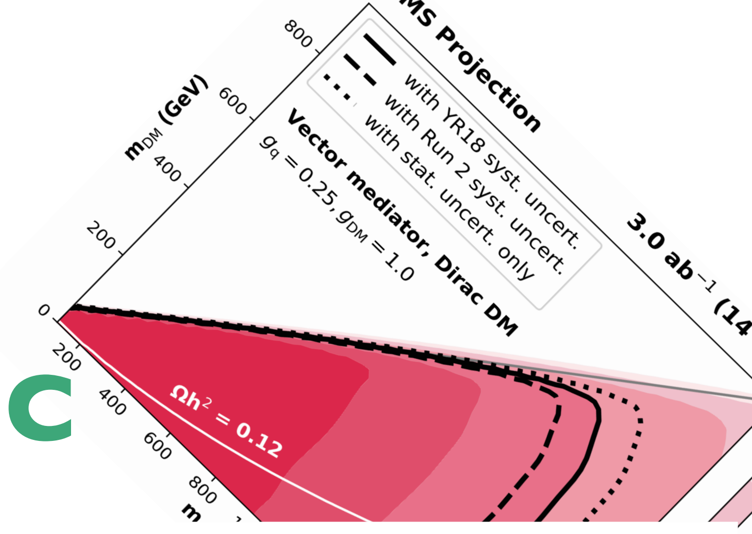
Exclusion: m(V') > 4.6 TeV

Dark photon search



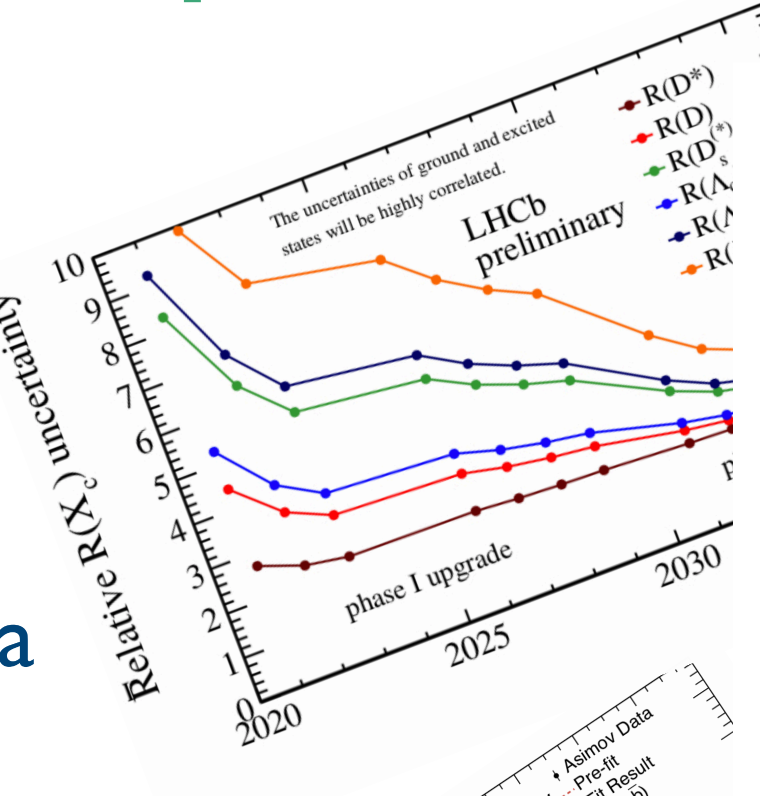
Excl.: 10 < m(γ_D) < 30 GeV
depending on kin. mixing.

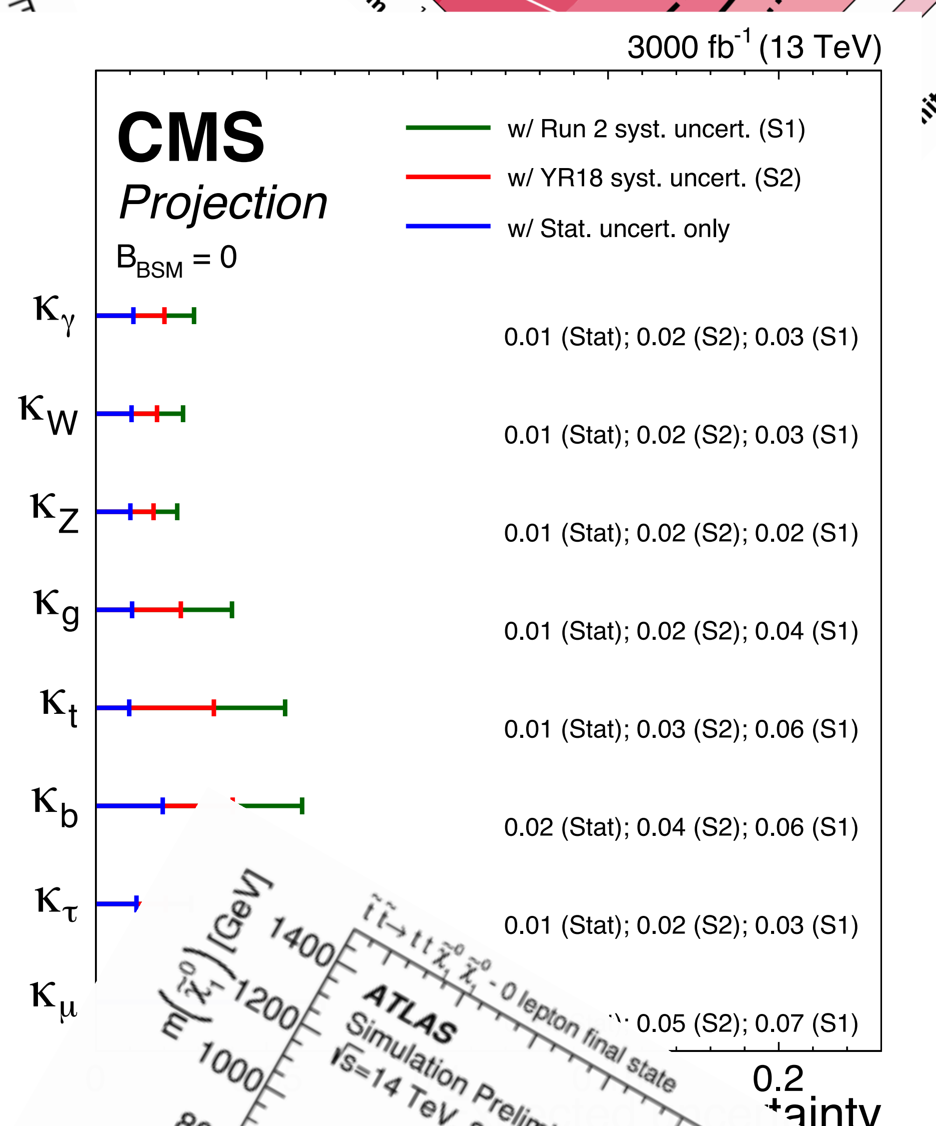
Summary



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

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

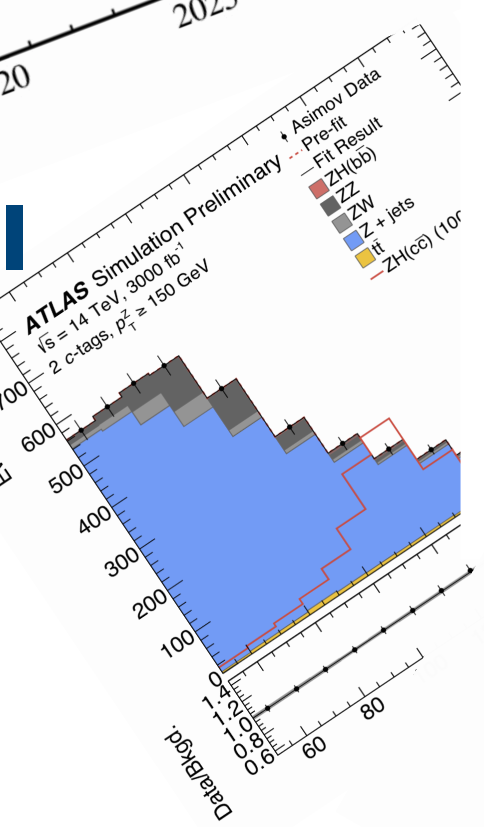




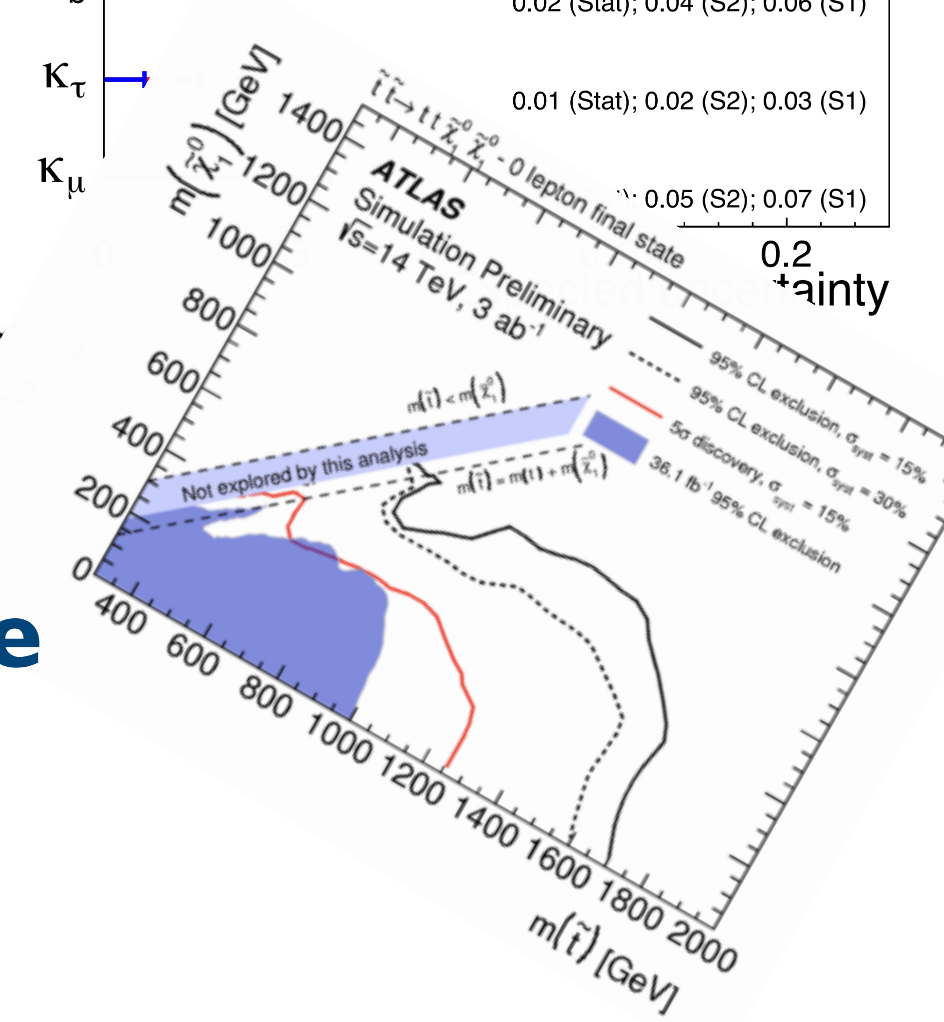
Near-term future measurements @ 13 TeV might provides us with some hints…

- Higgs boson might offer **a portal to the new physics** phenomena

High-Luminosity 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 the future of particles physics and to our understanding of the Nature

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

Physics prospects at HL-LHC

Additional material

ATLAS and CMS Upgrade Documents

ATLAS

Letter of Intent CERN-LHCC-2012-022
https://cds.cern.ch/record/1502664
Scope Document CERN-LHCC-2015-020
https://cds.cern.ch/record/2055248
Itk Strip TDR
http://cdsweb.cern.ch/record/2257755
Muons TDR
http://cdsweb.cern.ch/record/2285580
Liquid Argon Calorimeter TDR
http://cdsweb.cern.ch/record/2285582
Tile Calorimeter TDR
http://cdsweb.cern.ch/record/2285583
Itk Pixel TDR
https://cds.cern.ch/record/2285585/
TDAQ TDR
https://cds.cern.ch/record/2285584/

PHYSICS STUDIES
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

CMS

Technical Proposal: CERN-LHCC-2015-010
https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019
https://cds.cern.ch/record/2055167
Tracker TDR
https://cds.cern.ch/record/2272264
Barrel Calorimeter TDR
https://cds.cern.ch/record/2283187
Muon TDR
http://cds.cern.ch/record/2283189

PHYSICS STUDIES
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FTR/index.html

Future upgrade(s) of the LHC

- Basic physics parameters for HL-LHC and HE-LHC

HL-LHC (I)

talk by L. Rossi

Goal of High Luminosity LHC (HL-LHC) as fixed in November 2010

From FP7 HiLumi LHC Design Study application

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} $cm^{-2}s^{-1}$ with levelling**, allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.
This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

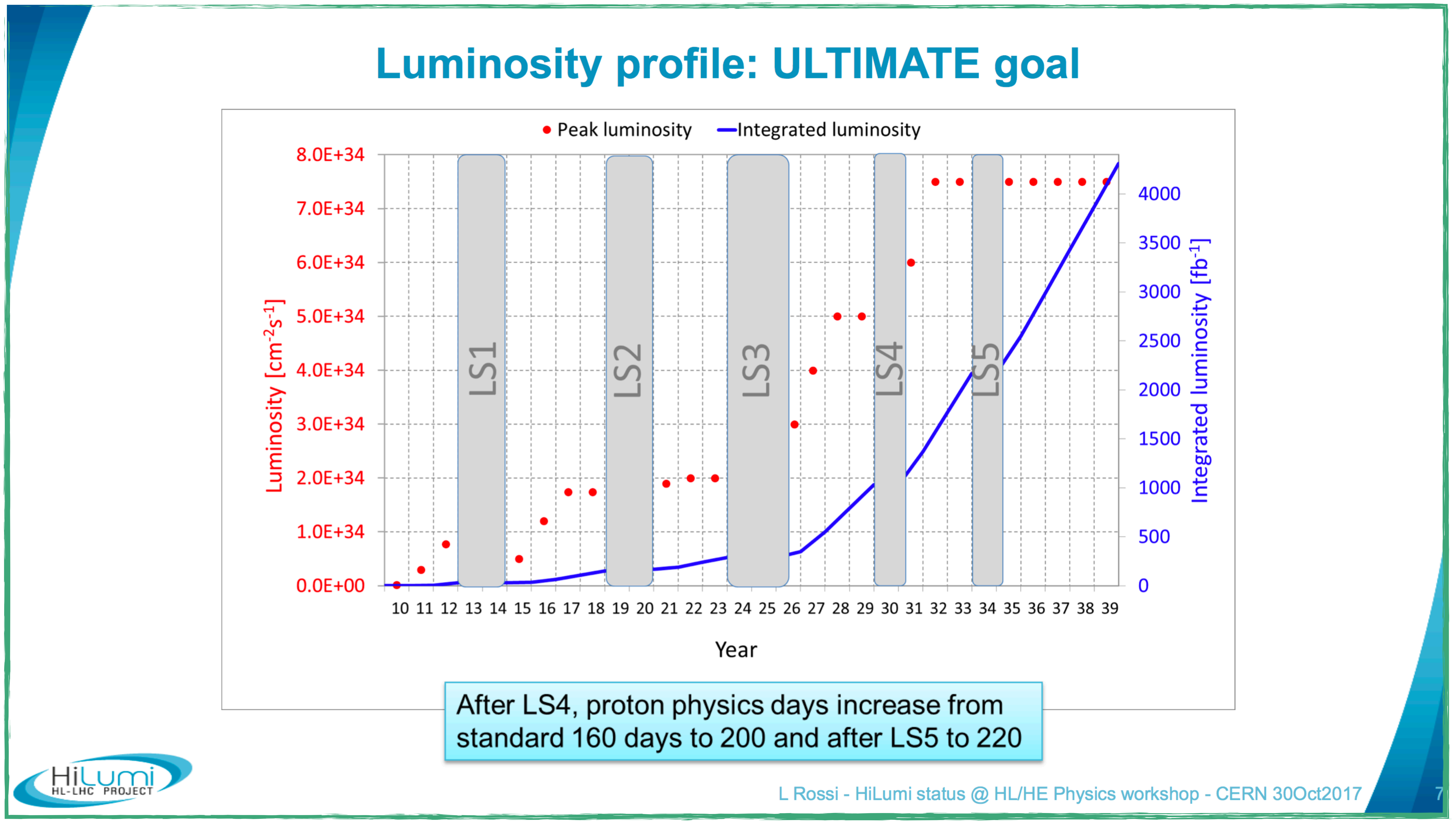
Ultimate performance established 2015-2016. With same hardware and same beam parameters, by using **engineering margins:**
$L_{peak\ ult} \cong 7.5\ 10^{34}$ $cm^{-2}s^{-1}$ and **Ultimate Integrated $L_{int\ ult}$ ~ 4000 fb^{-1}**
LHC should not be the limit, would Physics require more than nominal

HiLumi HL-LHC PROJECT

L Rossi - HiLumi status @ HL/HE Physics workshop - CERN 30Oct2017 2

HL-LHC (2)

talk by L. Rossi



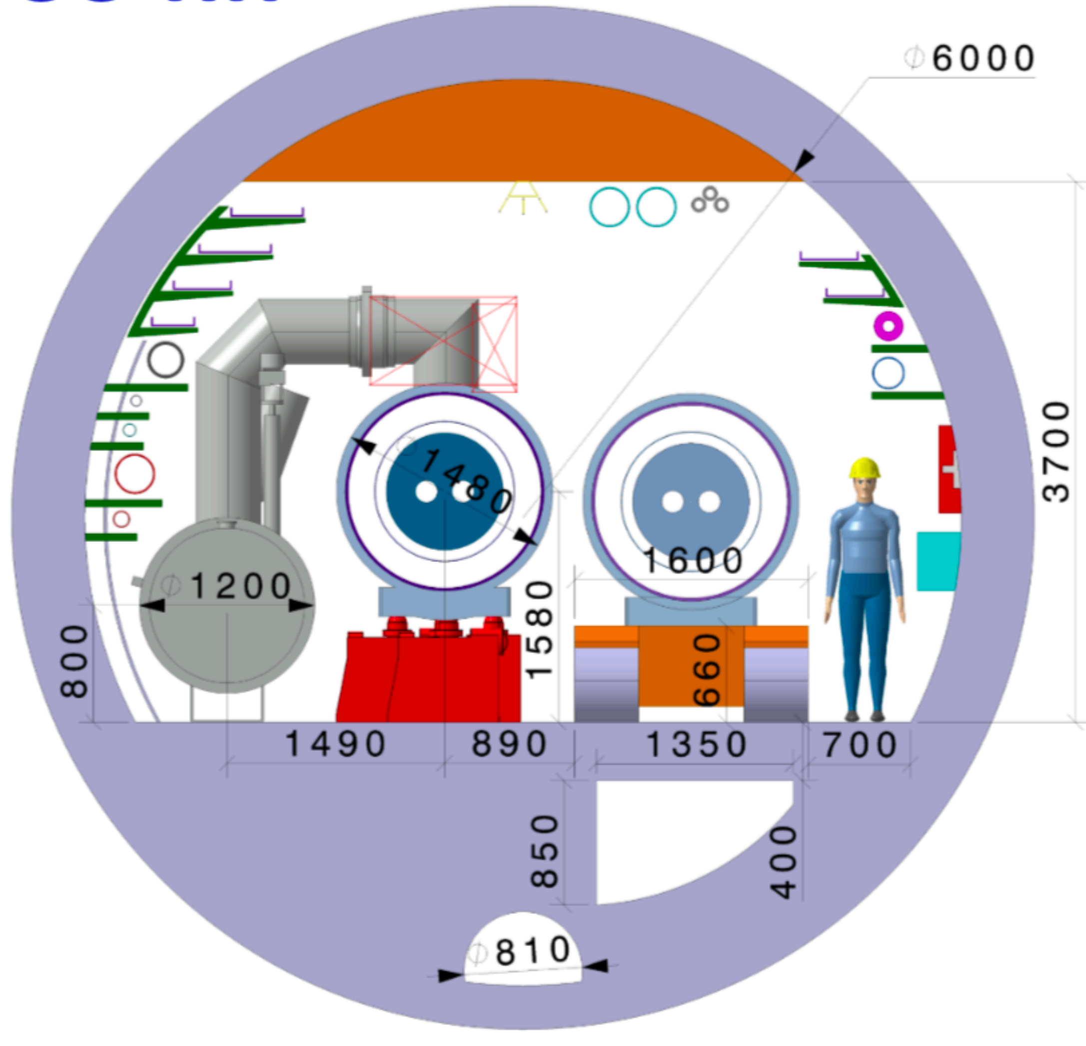
- Development and testing progress as planned after redefinition of baseline design in 2016

HE-LHC

HE-LHC design/idea:

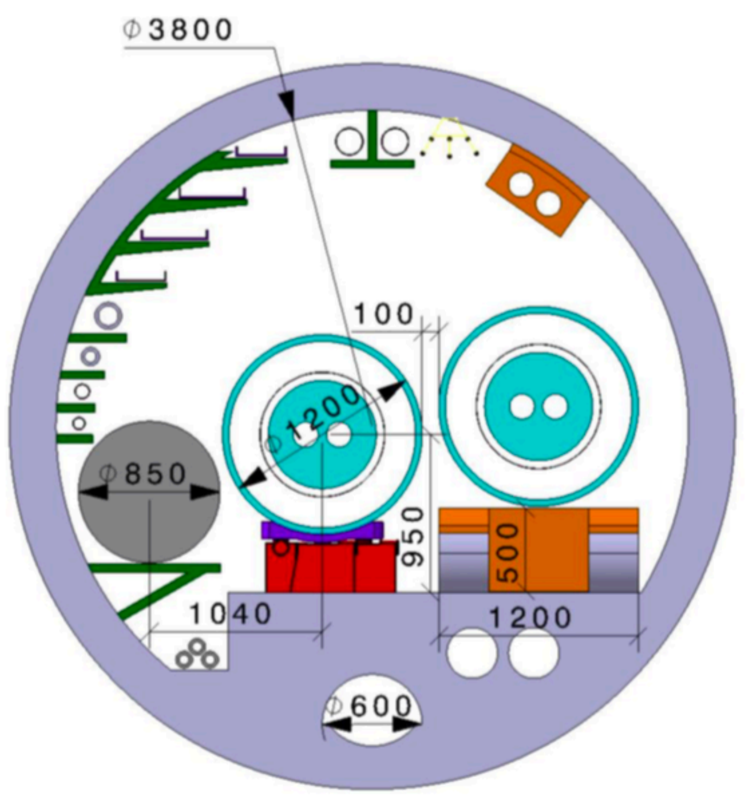
- **Working hypothesis:** Upgrade LHC energy without major CE modifications on tunnel and caverns
  - Similar geometry and layout as LHC machine and experiments
  - Maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm
- **Strategy:** Develop a single 16 T magnet, compatible with both HE-LHC and FCC-hh requirements
  - Assume similar detector technology requirements in terms of resolution and radiation hardness.

FCC-hh



HE-LHC

V. Mertens et al.



HL-LHC physics parameters:

- pp collisions @ **27 TeV**
- **>10 ab^{-1}** over 20 years
- pile up of up to 800
  (for 25 ns bunch spacing)

from talk by M. Benedikt

HE/HL-LHC parameters

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.12	1.12	0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.20	0.55
normalized emittance [μm]	2.2 (0.4)		2.5 (0.5)	2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	25	5	1
events/bunch crossing	170	1000 (200)	~800 (160)	135	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

Other aspects of Higgs boson physics

- Higgs bosons production @HE/HL-LHC
- Other precision HIG measurements

gg → H @ HE/HL-LHC

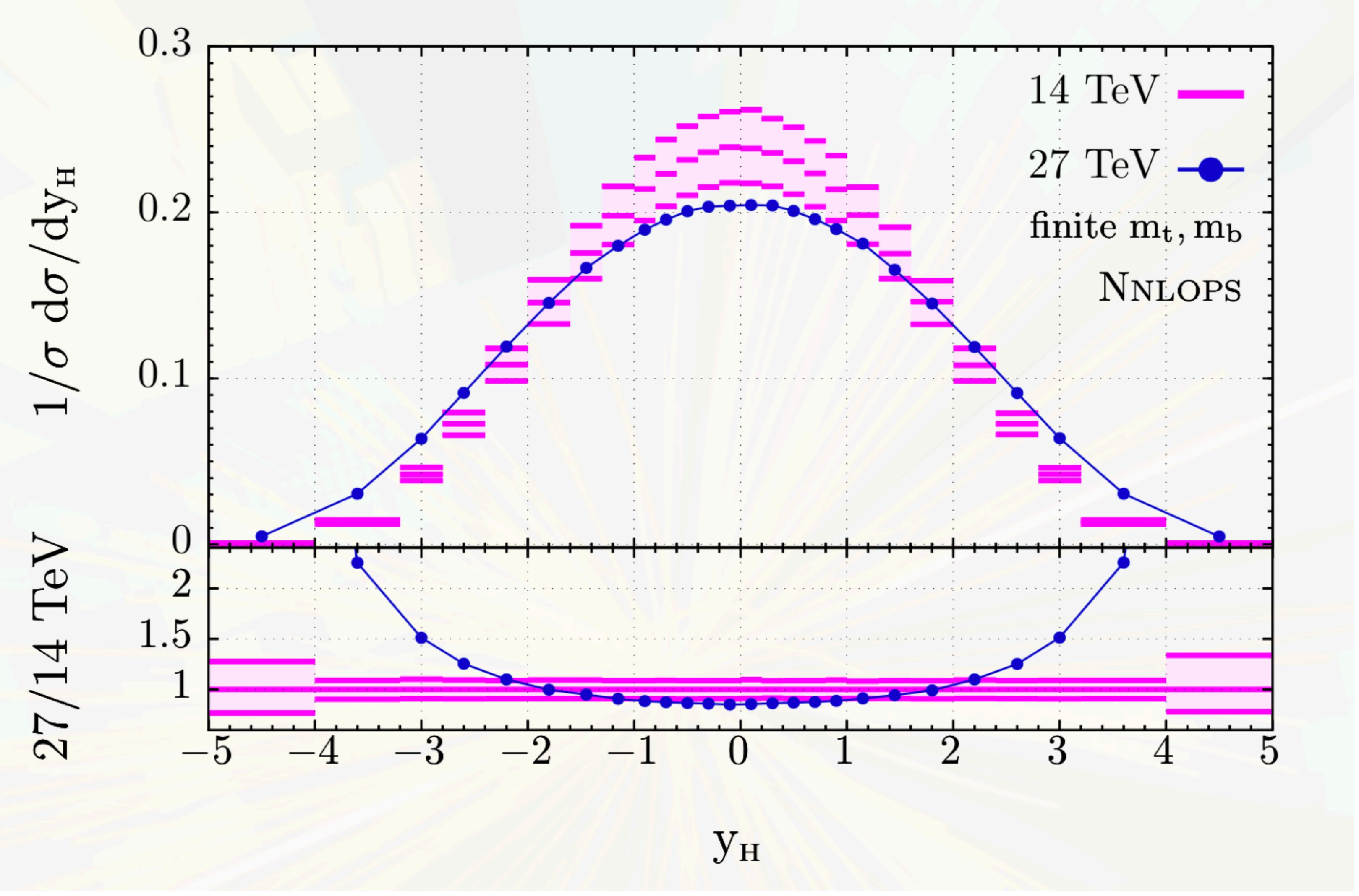
Inclusive NNLO estimates for gg → H:

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

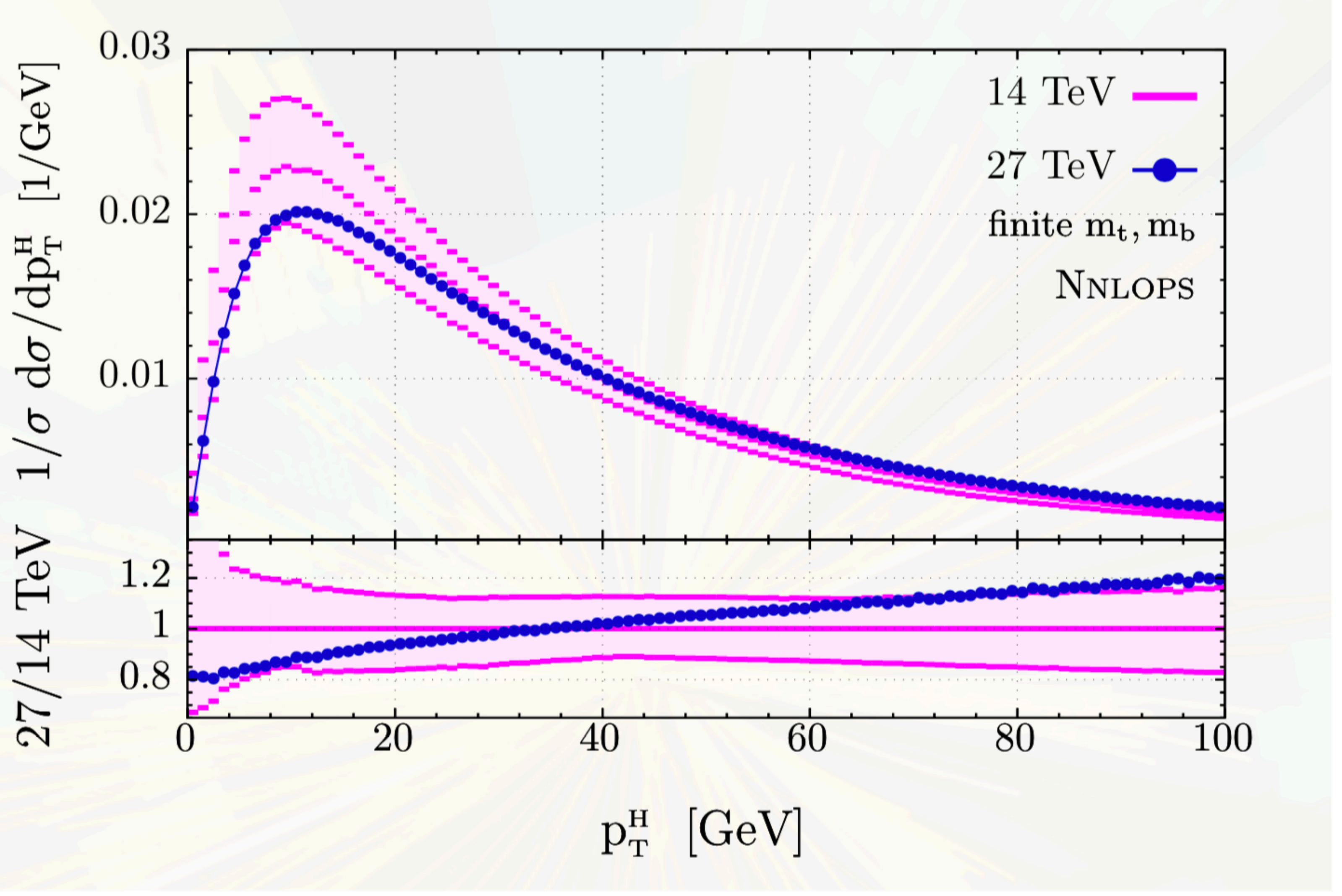
14 TeV with 3 ab^{-1} : $\sigma_{tot} = 49.6^{54.1}_{45.2}$ pb → 149 million gg → H events

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

rapidity(H)



p_T(H)



NNLO estimates for differential effects:

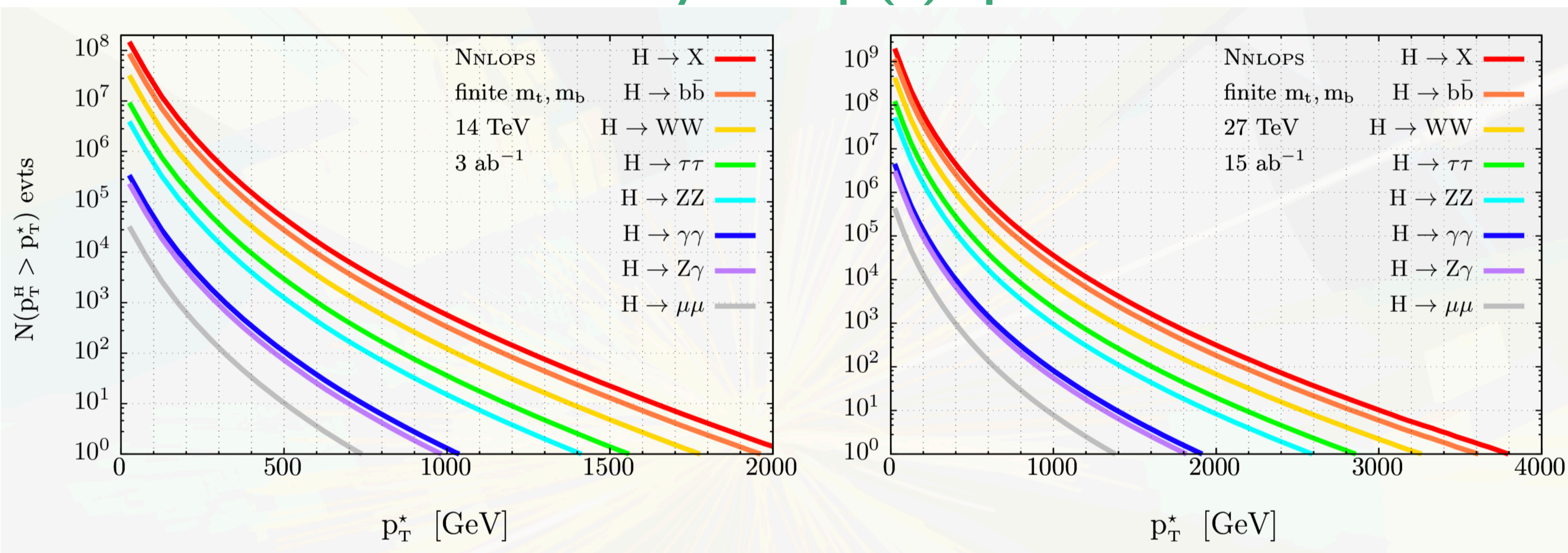
- Rapidity distn shape significantly broadened from 14 TeV → 27 TeV
- Markedly hardened & broadened pT spectrum already in [0,100] GeV

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