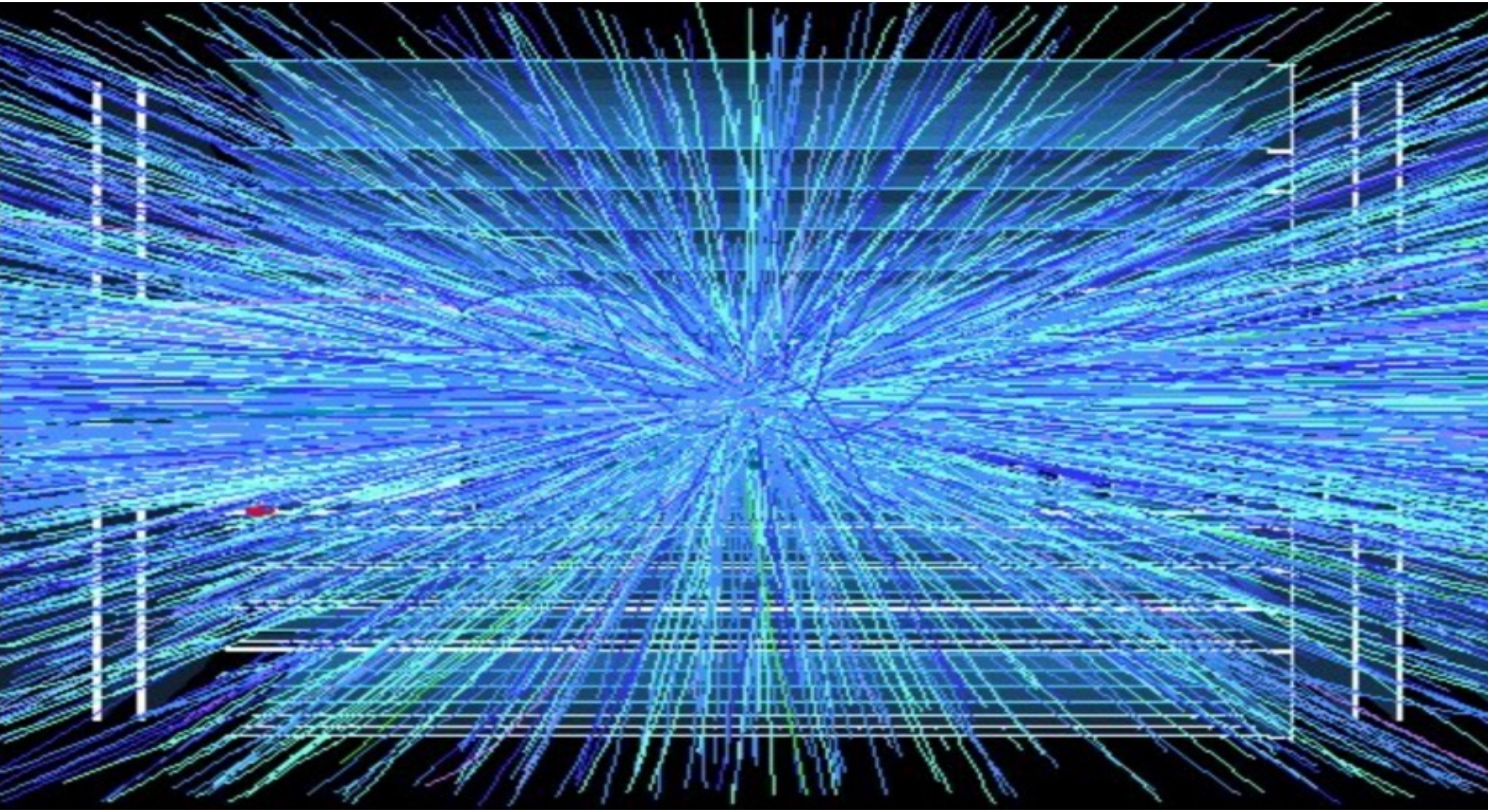
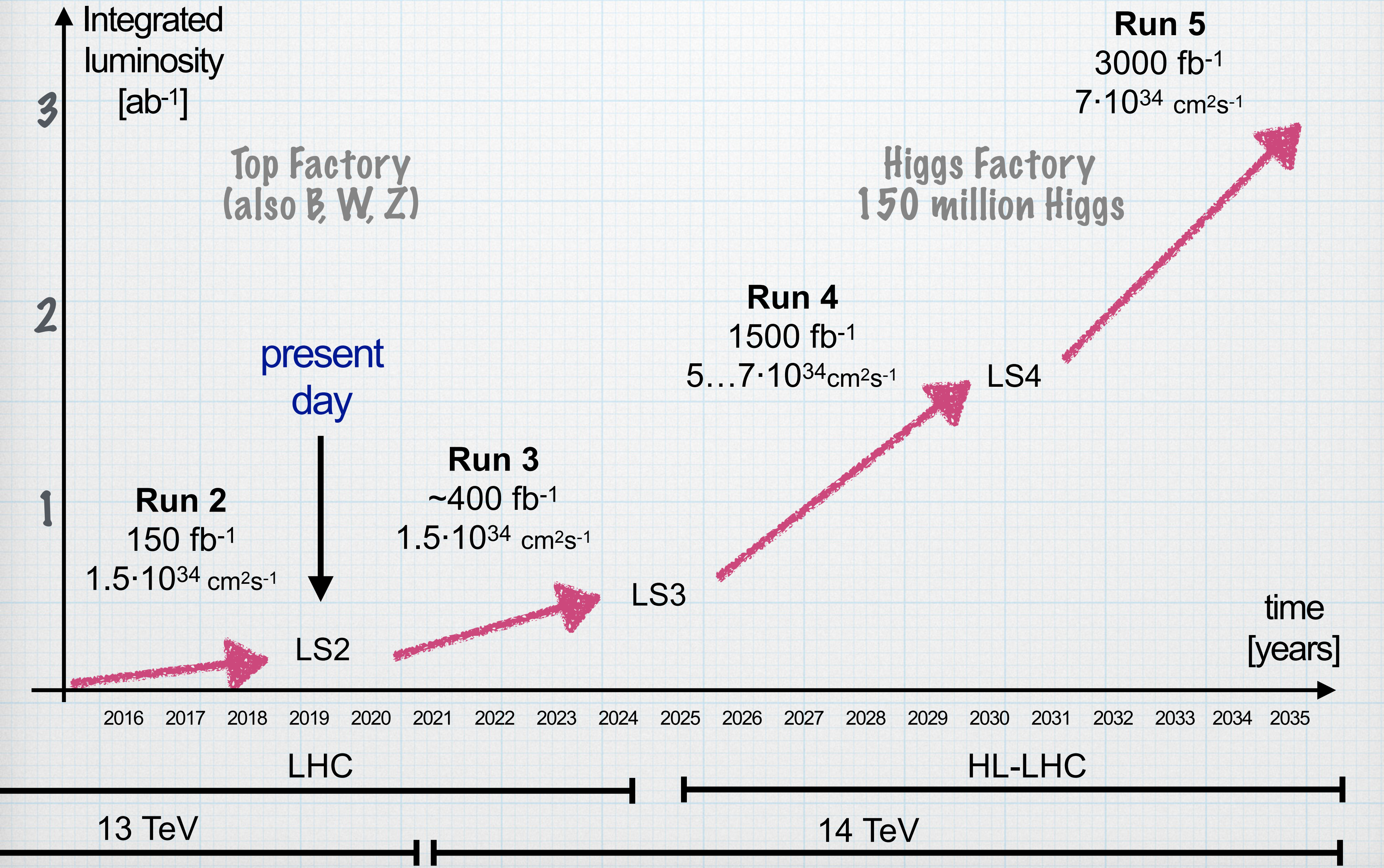
Physics at the High-Luminosity LHC



Andreas B. Meyer

LFC19
9 September 2019

The Past, the Present and the Future



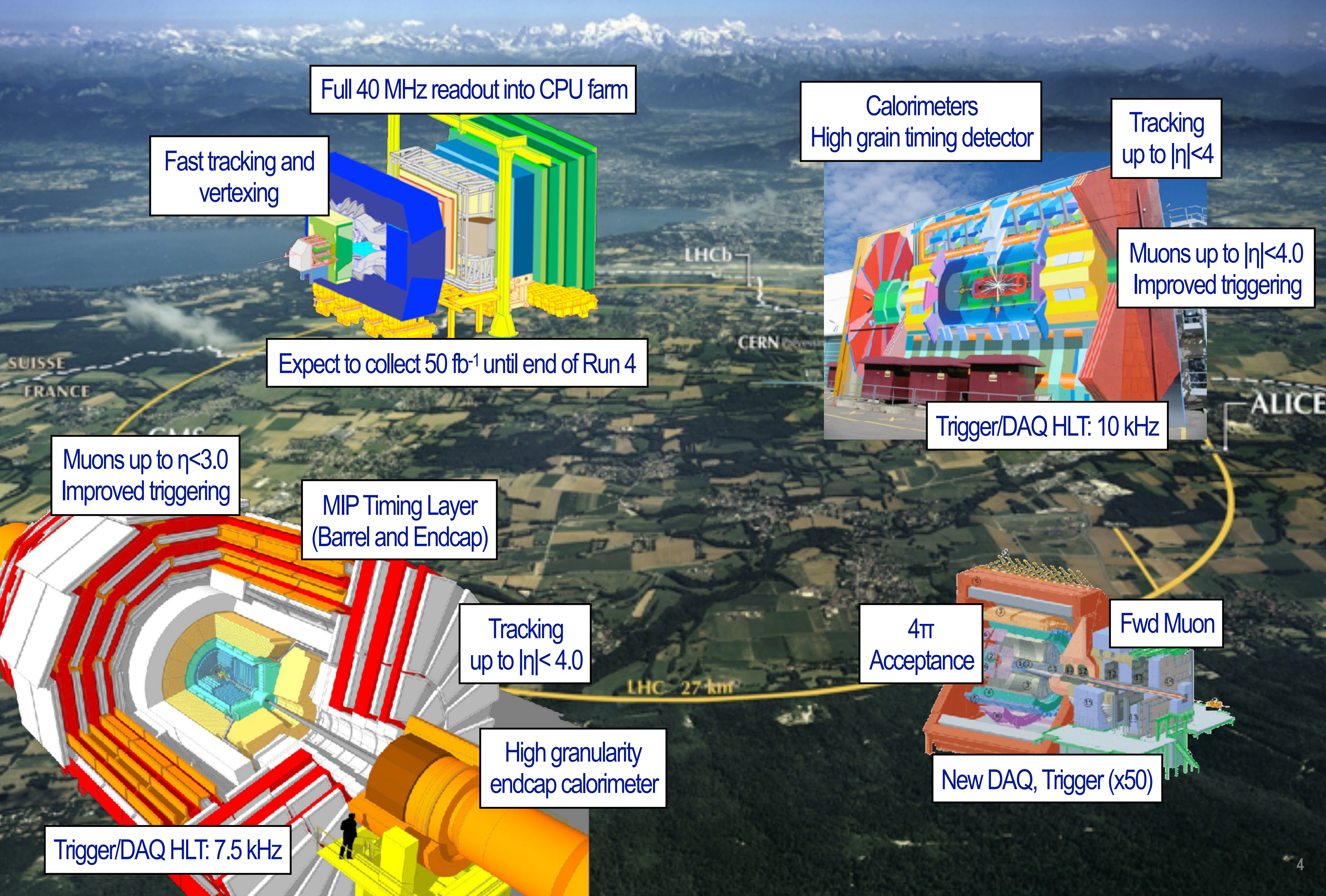
The High-Luminosity LHC

2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034

	LHC		High-Luminosity LHC			
	LS2	Run 3	LS3	Run 4	LS4	Run 5
ATLAS and CMS		2×10^{34} 300 fb^{-1}	Detector Upgrade	$5\text{-}7 \times 10^{34}$ ~1000 fb^{-1}		$5\text{-}7 \times 10^{34}$ 3000 fb^{-1}
LHCb	Detector Upgrade	2×10^{33} 20 fb^{-1}		2×10^{33} 50 fb^{-1}	Detector Upgrade II	2×10^{34} 300 fb^{-1}

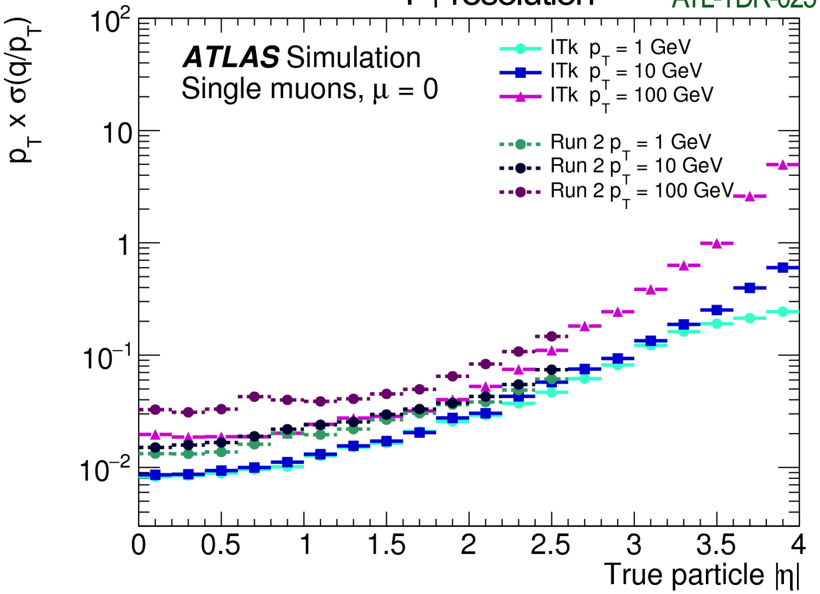
- 20 times more integrated luminosity than Run-2
- Better detectors, larger acceptance, better triggers
- Improved theory and analysis methods

Detector Upgrades

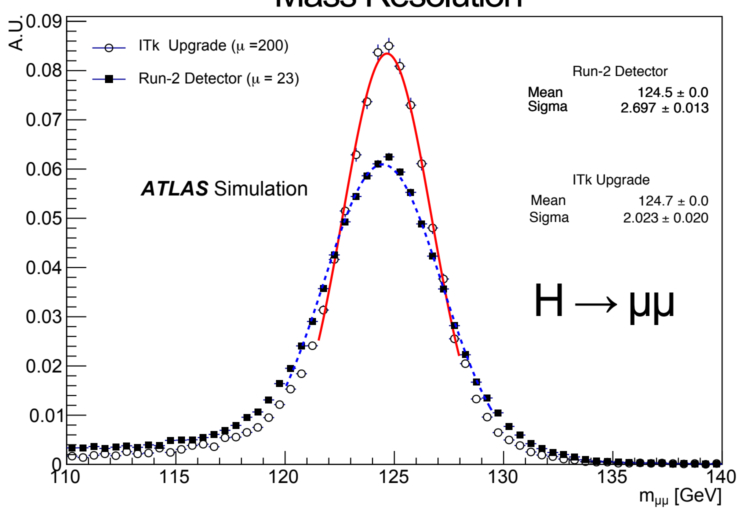


Detector Performance

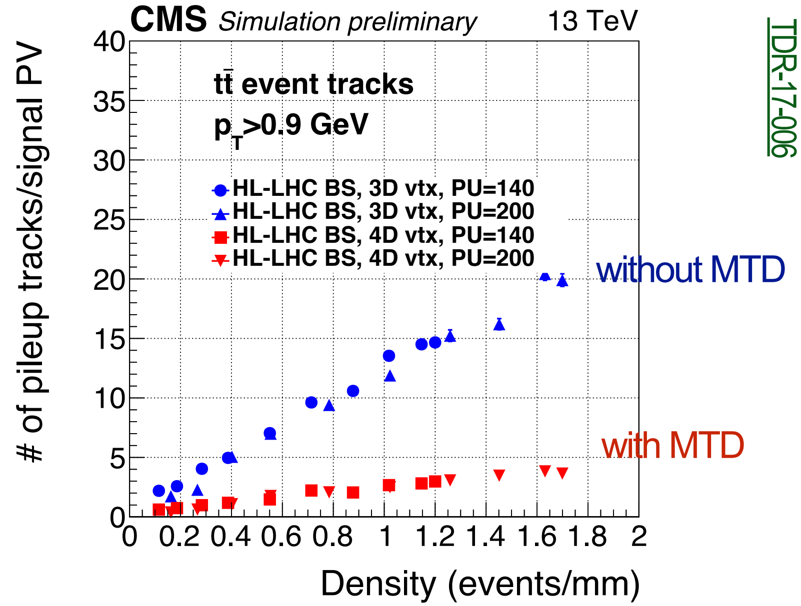
P_T resolution ATL-TDR-025



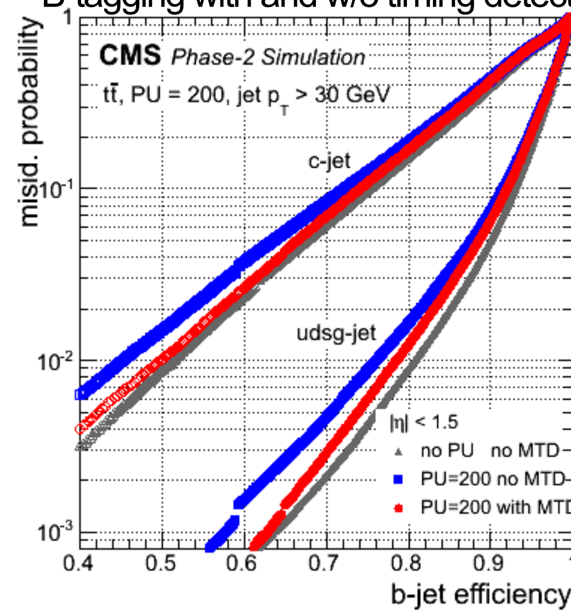
Mass Resolution



"4D-tracking" using MIP Timing Detector



B-tagging with and w/o timing detector

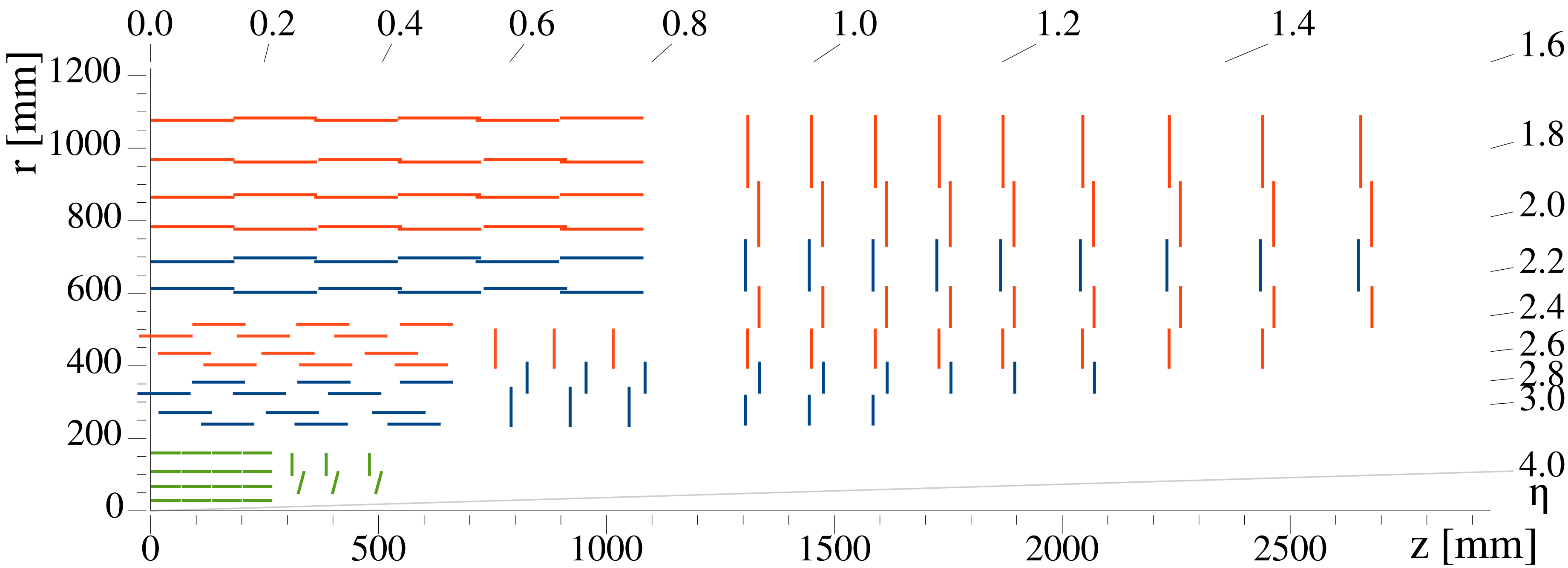


Generally similar or better performance under harsher conditions

Detector Acceptance

Example

CMS Run-2

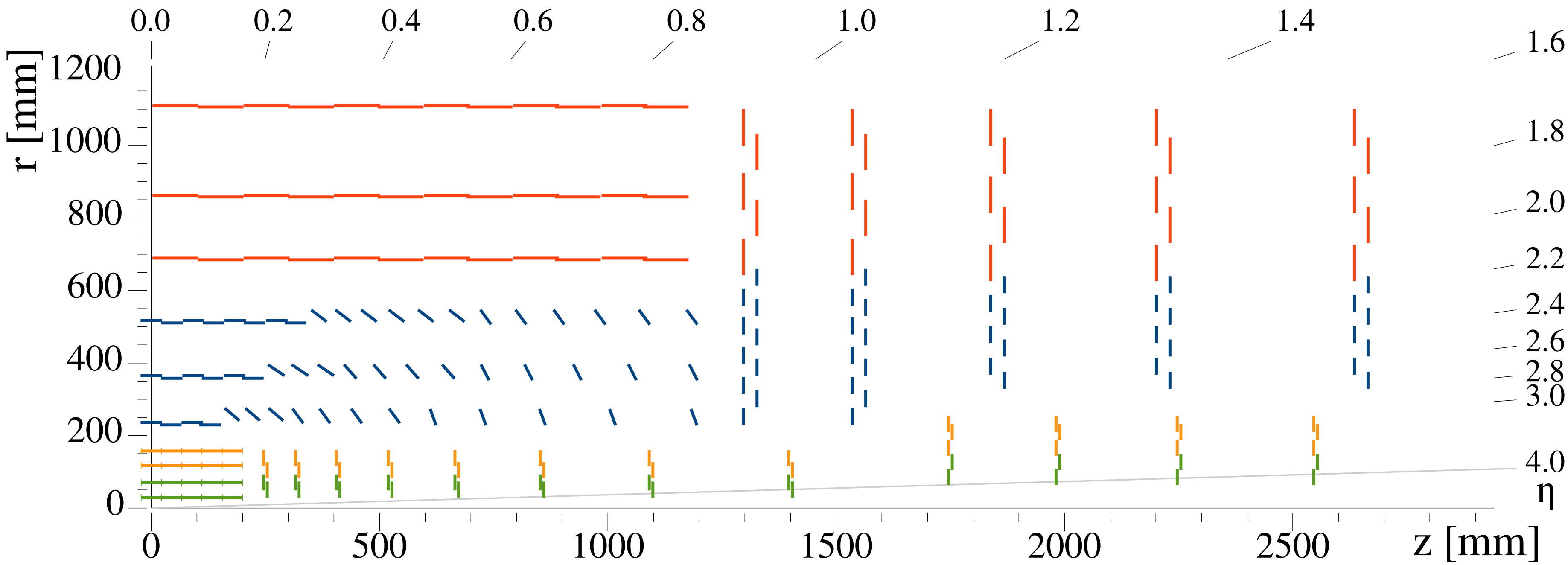


Acceptance: |η| < 2.5

Detector Acceptance

Example

CMS HL-LHC



Acceptance: |η| < 4.0

… and less detector material and better resolution

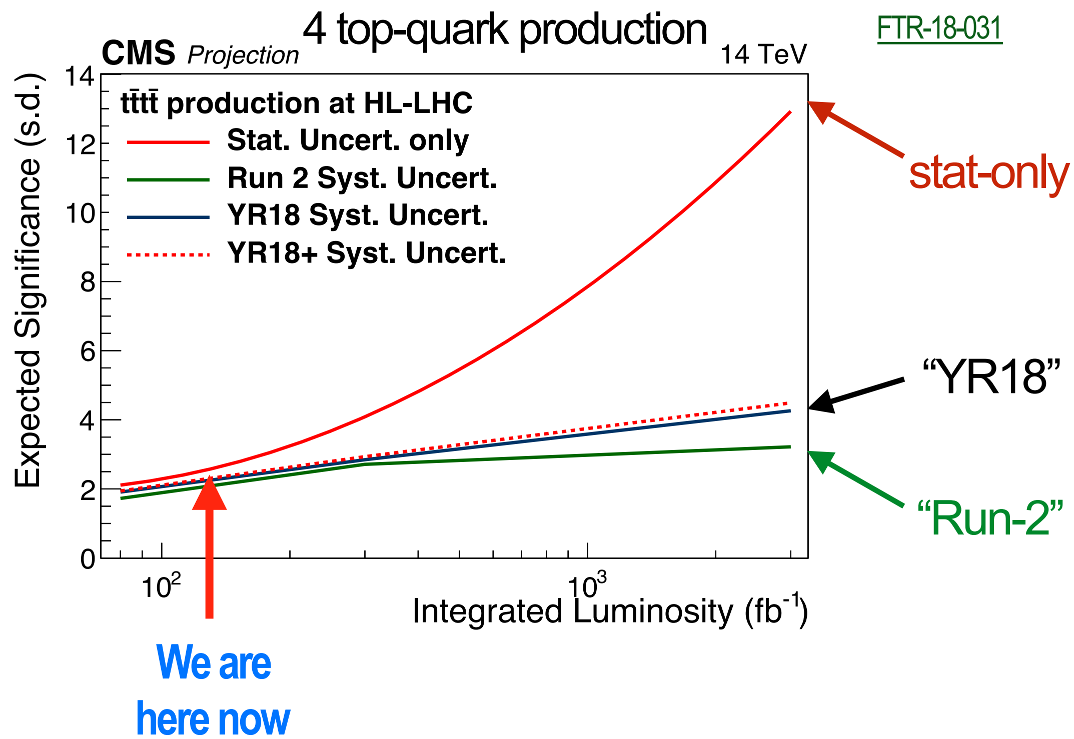
HL-LHC Projected Uncertainties

- Systematic uncertainties will be limiting factor for more and more measurements

- HL/E-LHC working group:
  Aim to make realistic projections based on Run-2 analyses
  → CERN Yellow Report (backup)

- Convention "YR18":
  - Statistics scale as $1/\sqrt{L}$
  - No uncertainty due to MC statistics
  - Theory reduced by factor 2
  - Exp. systematics scale as $1/\sqrt{L}$ → until "floor"
  - "Floor" values for all physics objects estimated and agreed
  - Keeping "Run-2" and "stat-only" for comparison

FTR-18-031



Realistic estimate of uncertainties

Expecting to exceed expectations

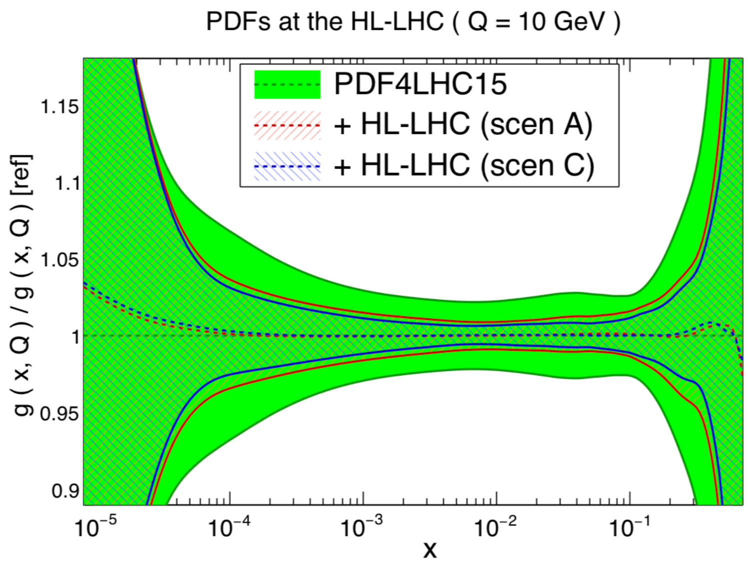
Standard Model

Precision Measurements

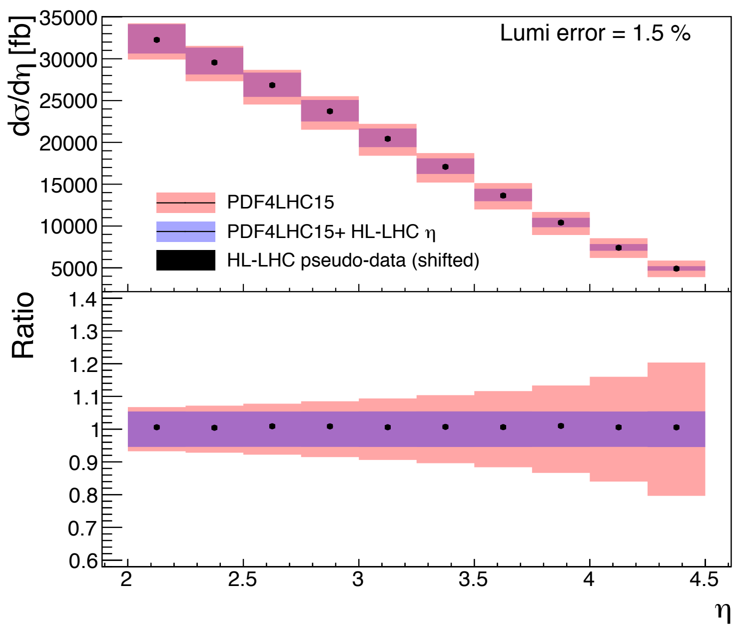
Ultimate Precision PDF

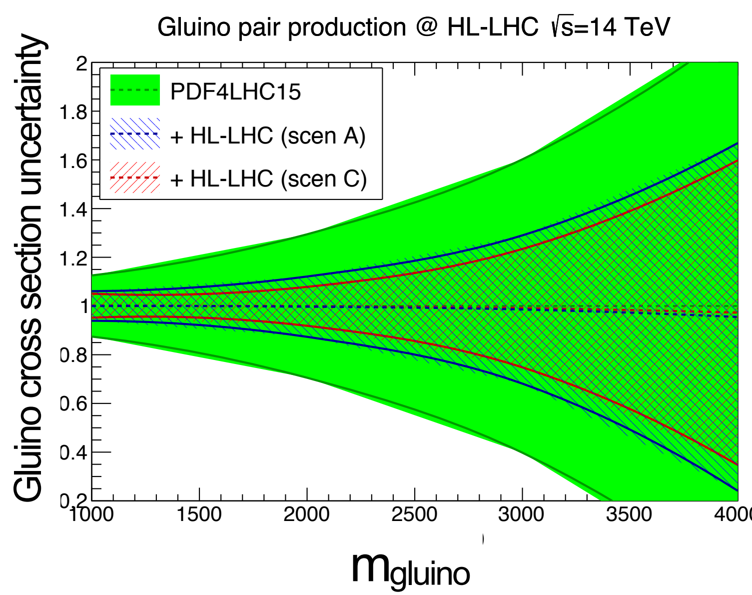
arXiv:1810.03639

- Parton density distributions based on differential cross sections at ultimate precision
- Projection using pseudo-data
  Z(pt), high-mass DY, top quark pair,
  W+charm, direct photon and inclusive jets



Example: W+charm (ATLAS, CMS, LHCb)





Factor 2–5 expected improvement

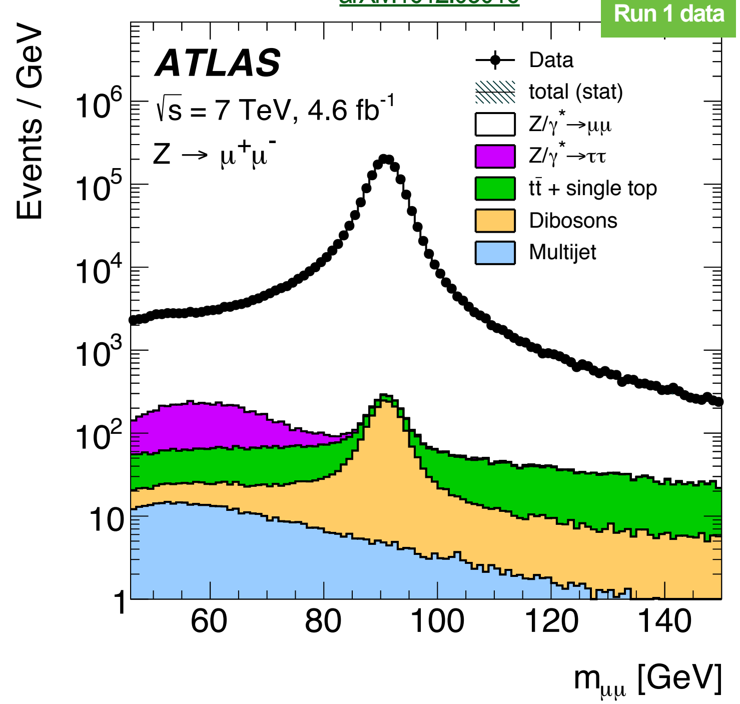
Ultimate Precision Cross Sections

- Run-1 example: $\sigma_{fid}(Z/\gamma^* \to \ell\ell) = 502.2 \pm 0.3\ (stat) \pm 1.7\ (syst) \pm 9.0\ (lumi)$ pb

- Systematic uncertainties
  - Lepton ID: 0.3%
  - Lepton isolation: 0.15%
  - Signal modelling: 0.2%
  - Integrated luminosity: ~2%

Luminosity is single largest uncertainty

arXiv:1612.03016



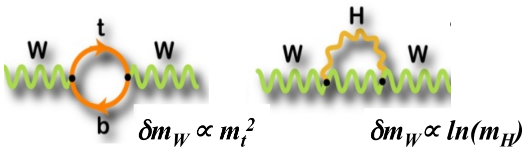
- HL-LHC
  - Improved luminosity detectors (being designed)
  - Further refined Van-der-Meer analysis
  - Additional low-PU runs for cross section measurements (no uncertainty due to low-to-high PU extrapolation)

- Once measured at (sub-)percent level, Z-boson rate measurement can help luminosity measurement → planning for proof of concept in Run-3

arXiv:1806.02184

Target luminosity uncertainty YR2018: 1%

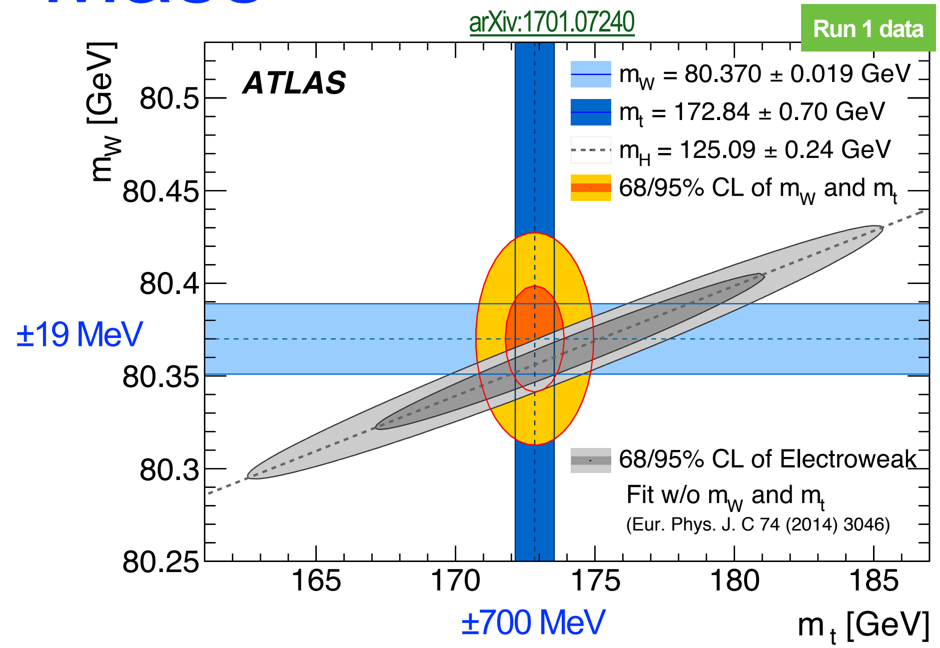
Ultimate Precision W Mass

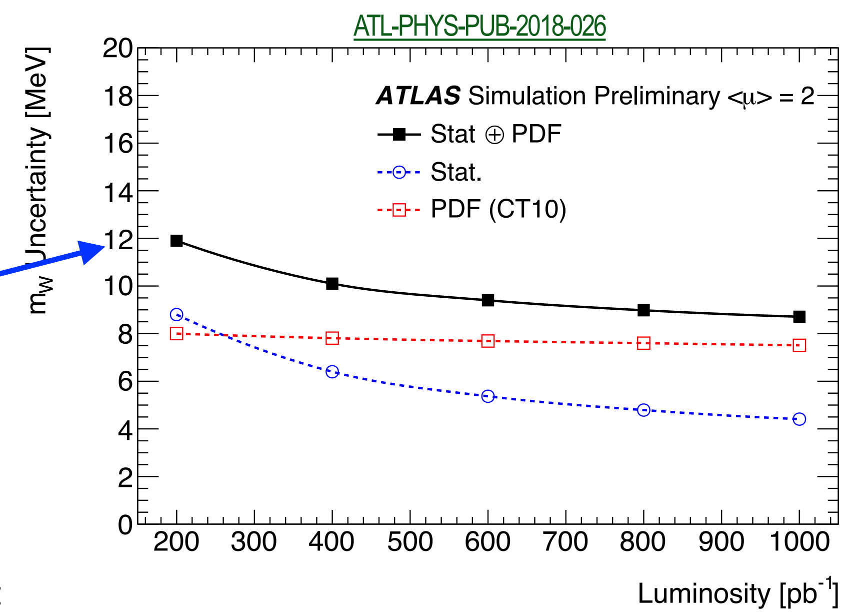


- m_{top}, m_W and m_H connected via loop corrections → constrain and test SM

- Current dominant uncertainty: PDF
- Extended η-range: measurements in central and forward regions are anti-correlated.
-
- Low PU: high-resolution missing energy

- Low-PU run (μ~2) at HL-LHC:
  - 200 pb^{-1}, |η|<2.4: 2x10^6 evts. 16 MeV
  - 200 pb^{-1}, |η|<4: 12 MeV
  - 1 fb^{-1}, |η|<4: 9 MeV
  - **+ ultimate PDF: 5 MeV**

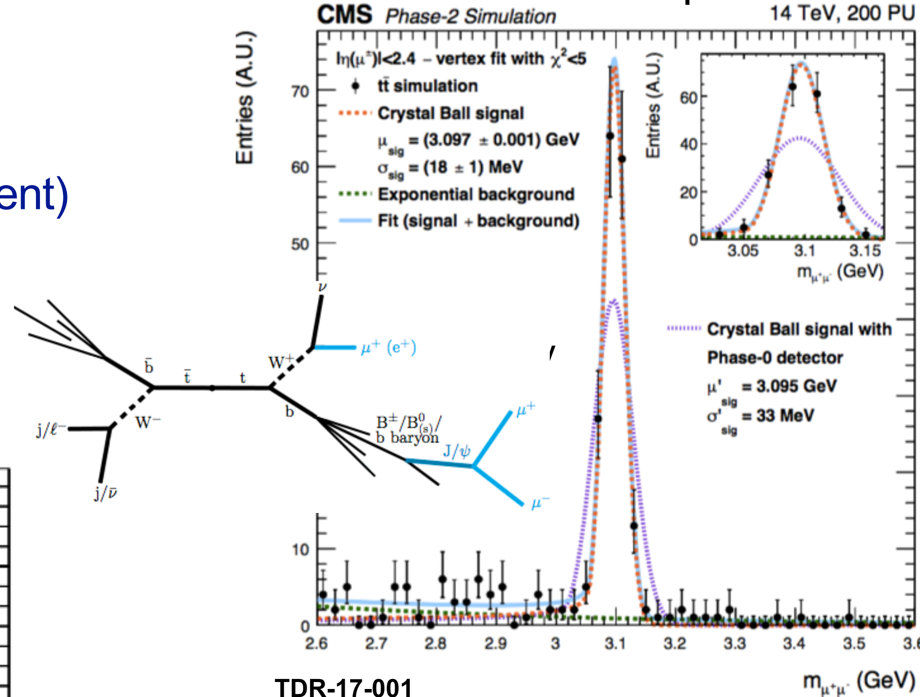




Ultimate Precision Top Mass

- More statistics → samples and calibration
- Better systematics (both theory and experiment)
- Combination of different methods arXiv:1807.06617

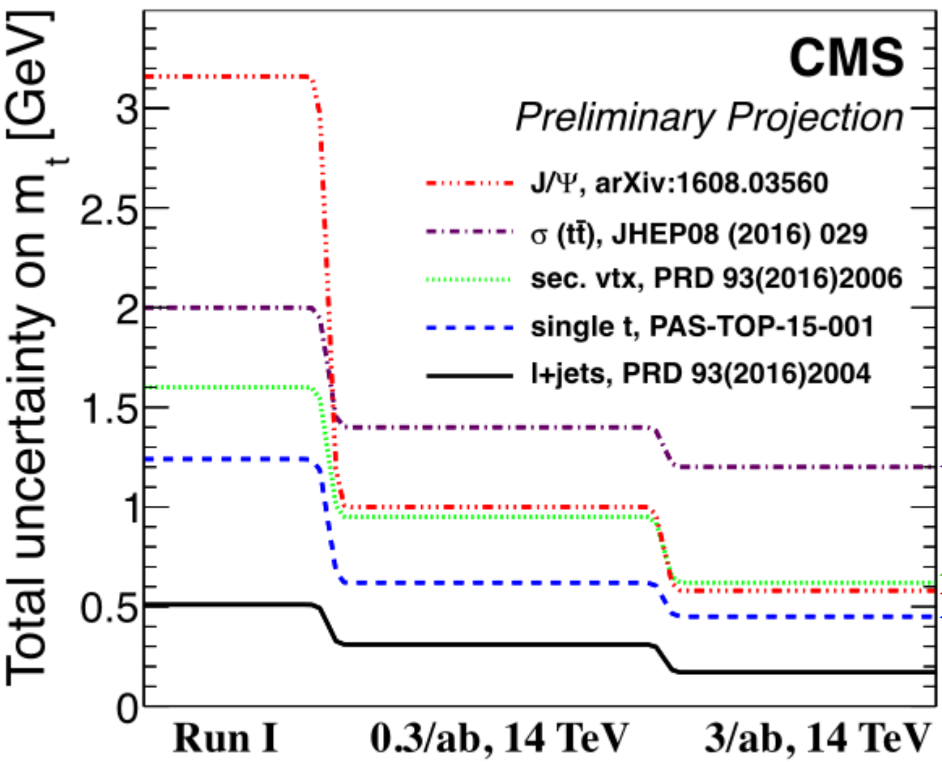
$t \rightarrow bW \rightarrow J/\psi\, X \ell \nu$



TDR-17-001

J/ψ: $\delta m_{top} \sim 0.5$ GeV

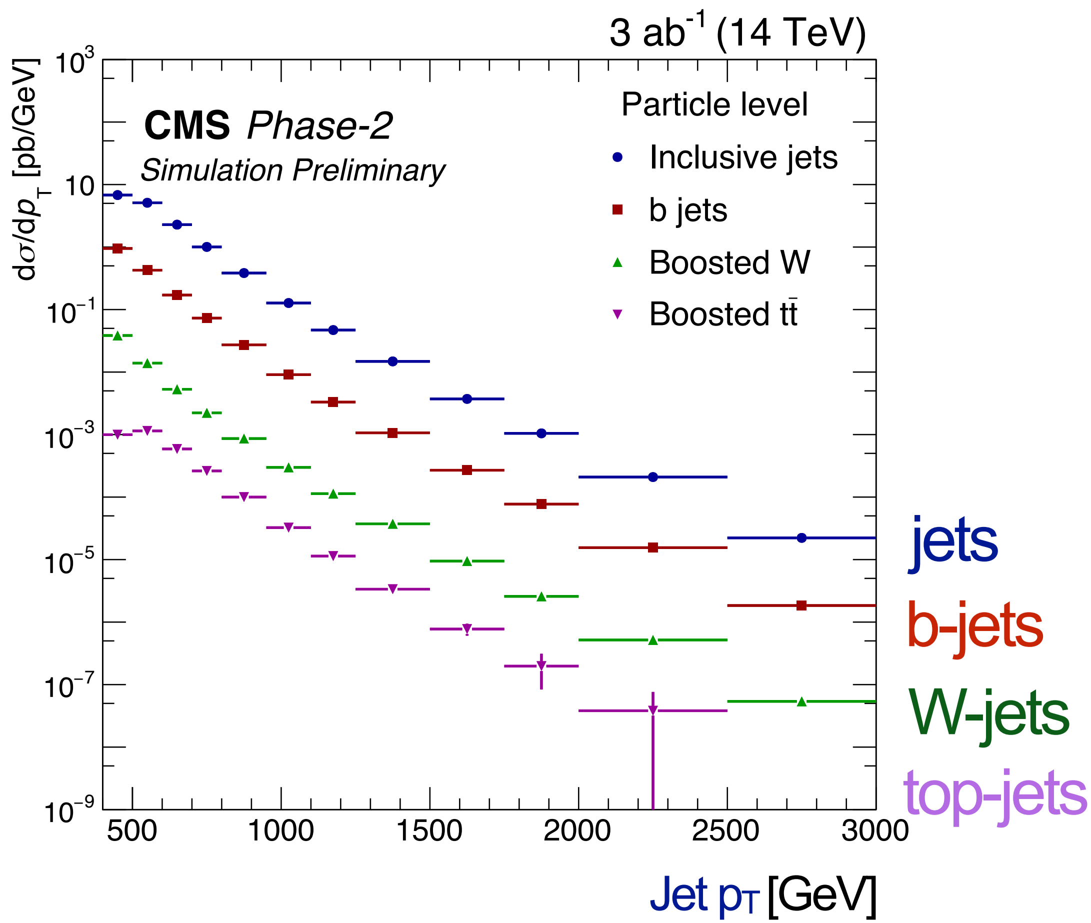
CMS-PAS-FTR-16-006

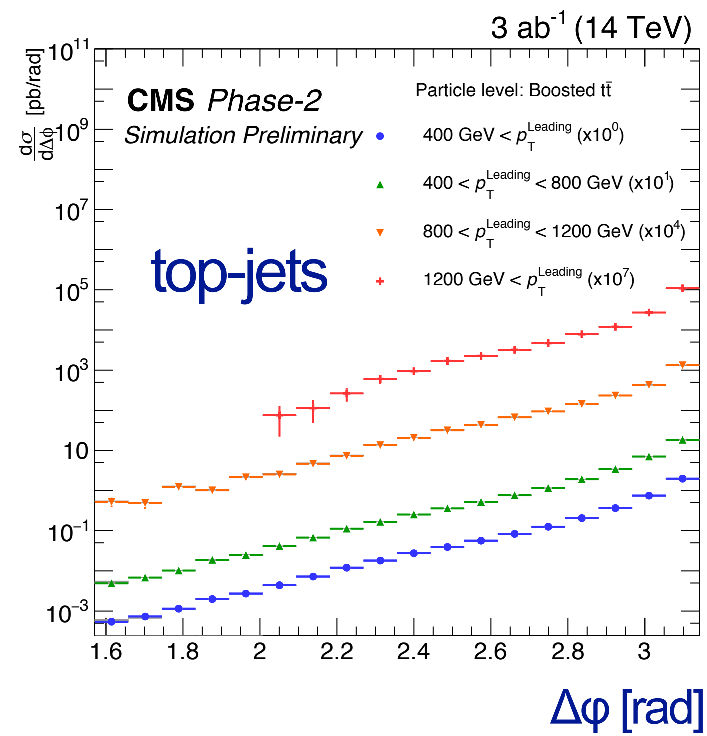


m_{pole} from $\sigma(tt)$ (already better now)
2ndary vertex
J/ψ
single top
ℓ+jets

Jet Cross Sections

CMS-PAS-FTR-18-032



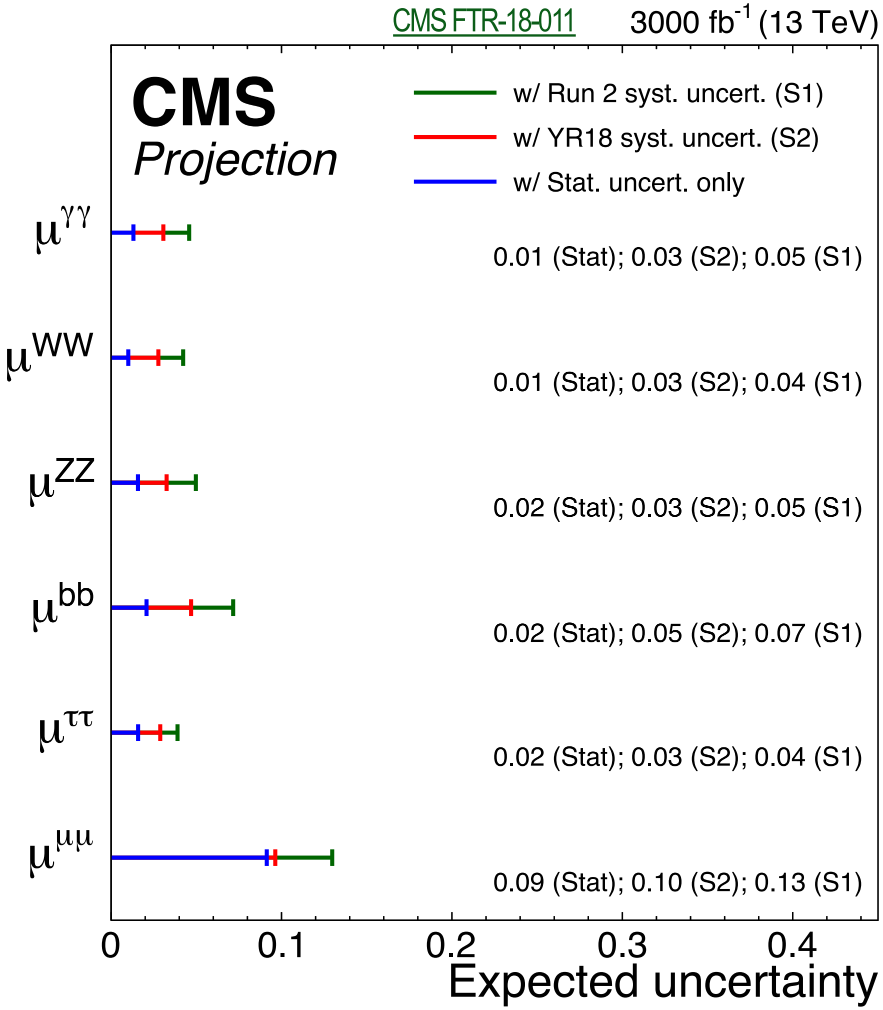


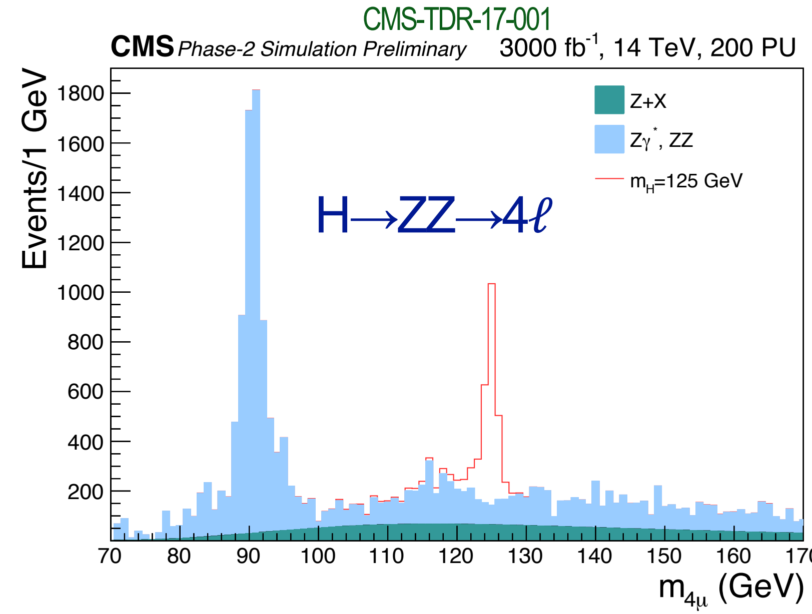
- Differential jet cross sections - expect O(10) inclusive di-jet events above 4 TeV
- Angular correlations of jets in different regimes (pt vs mass and color)

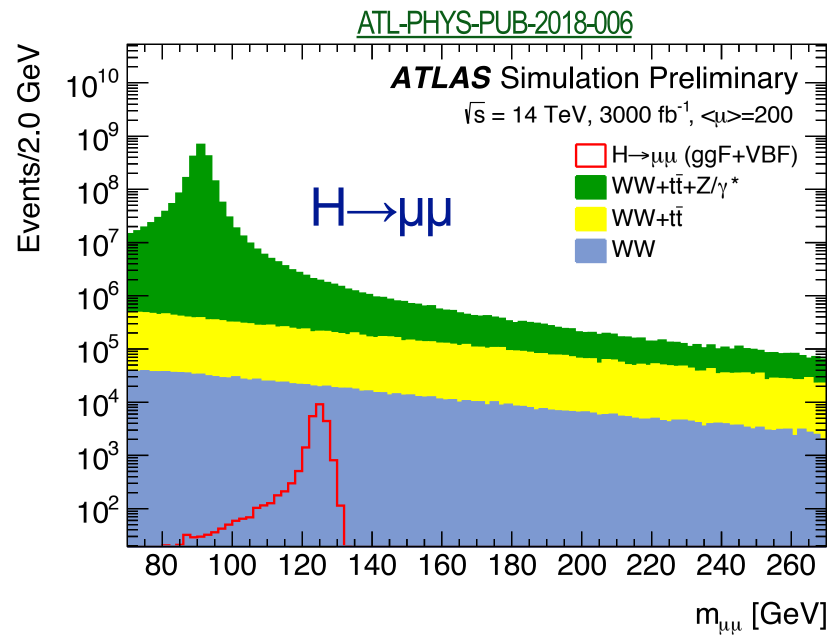
Higgs

Precise Properties and Couplings for H(125)
Searches in the Higgs Sector

Higgs Measurements



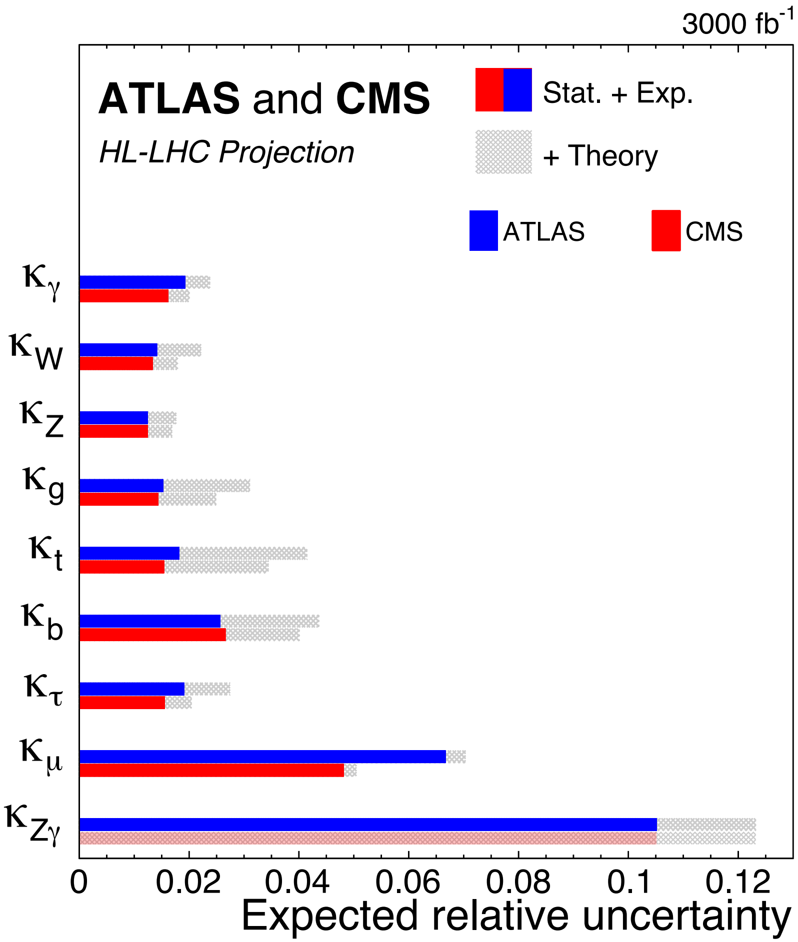


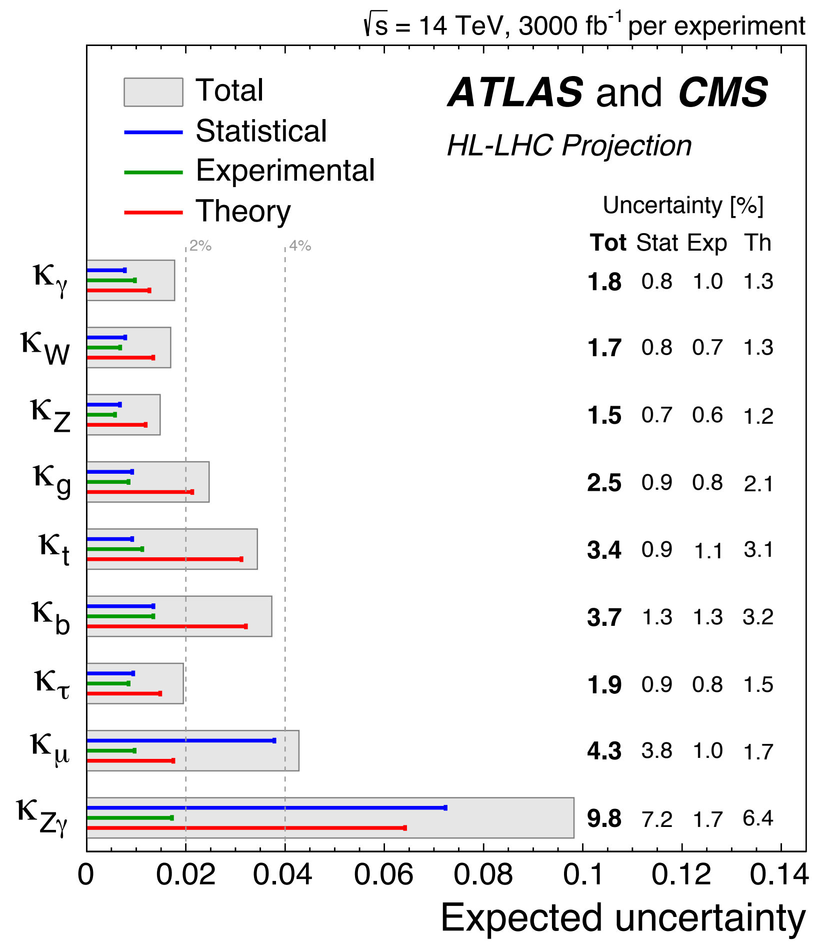


Signal strength uncertainties: most channels ~3%, bb ~5%, μμ ~10%

Higgs Combination

CMS FTR-18-011 ATL-PHYS-PUB-2018-054

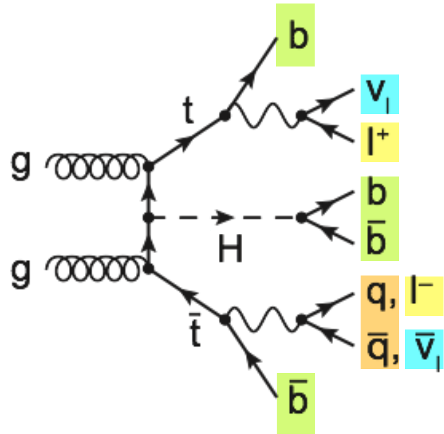




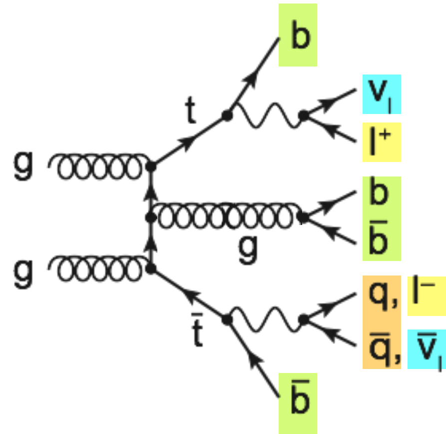
Uncertainties dominated by theory uncertainty estimates (!)

Experimental uncertainties: ~1% (μ ~4%)

ttH → bb

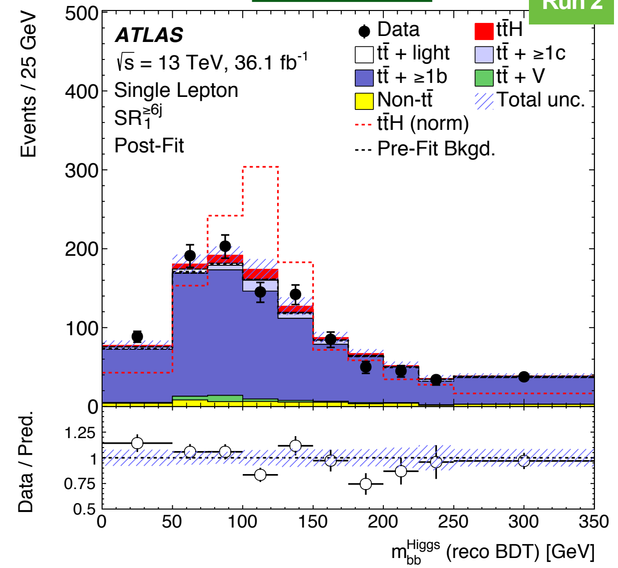


ttH signal



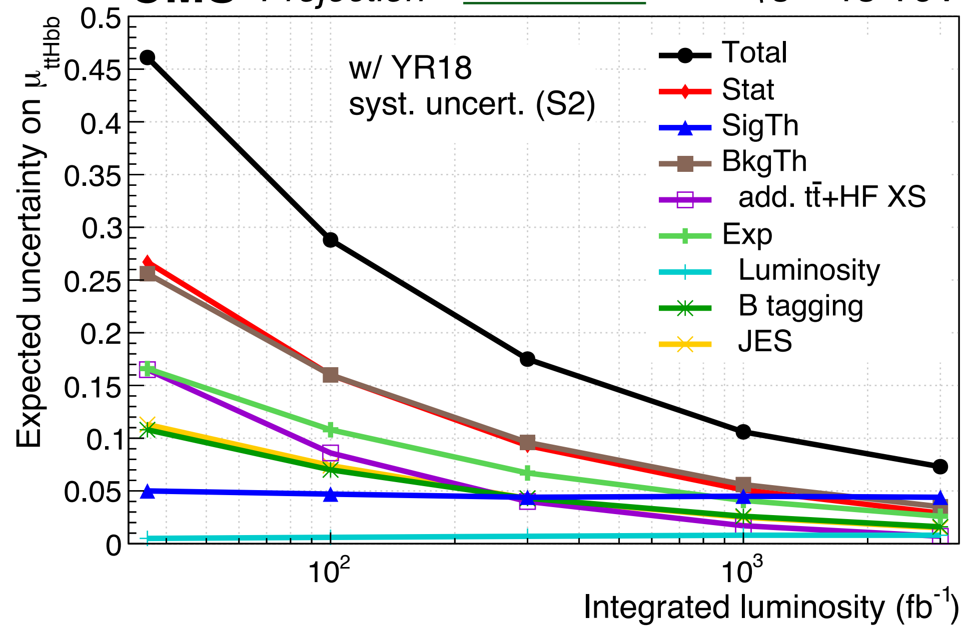
tt+HF background

arXiv:1712.08895



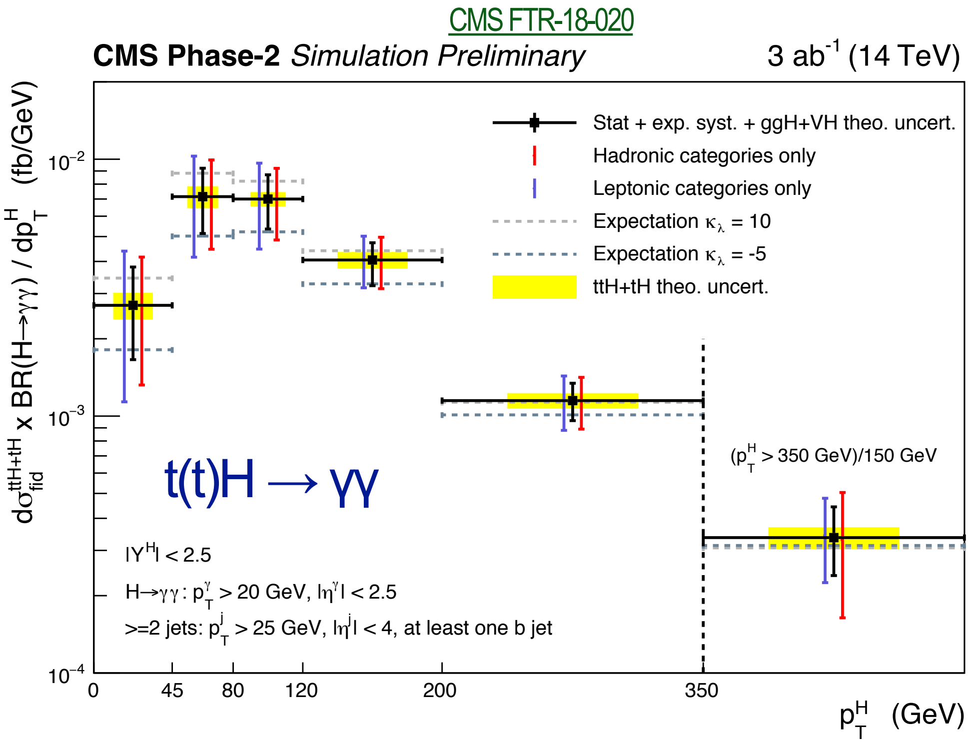
- For 3 ab^{-1} CMS expects δμ ~ 7%
  - tt+HF background constrained by data
  - dominant uncertainty on μ: signal theory
- For ATLAS/CMS combination
  CMS tt+HF uncertainty "floored" at 10%:
  no significant impact on κ-results

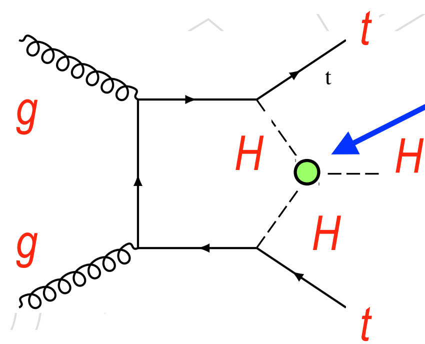
CMS FTR-18-011



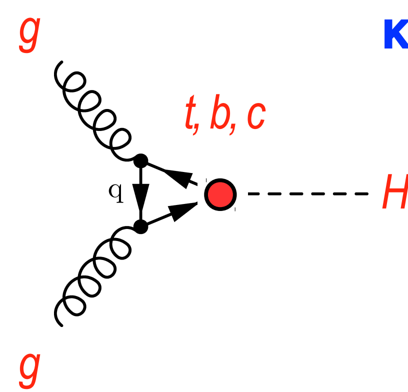
Statistics helps constrain systematics

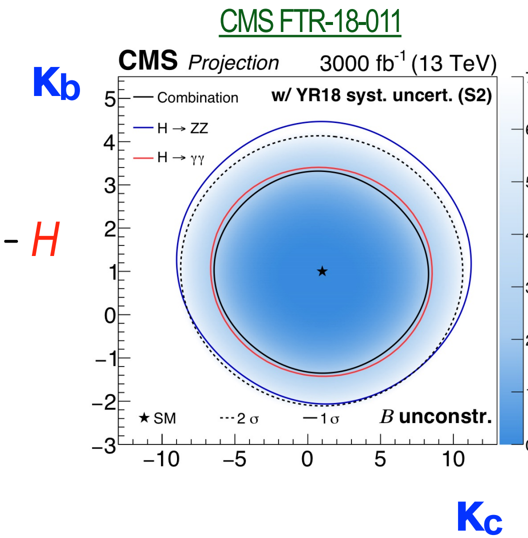
Differential Higgs Measurements





κ_λ = [-4.1,14.1] @ 95%CL



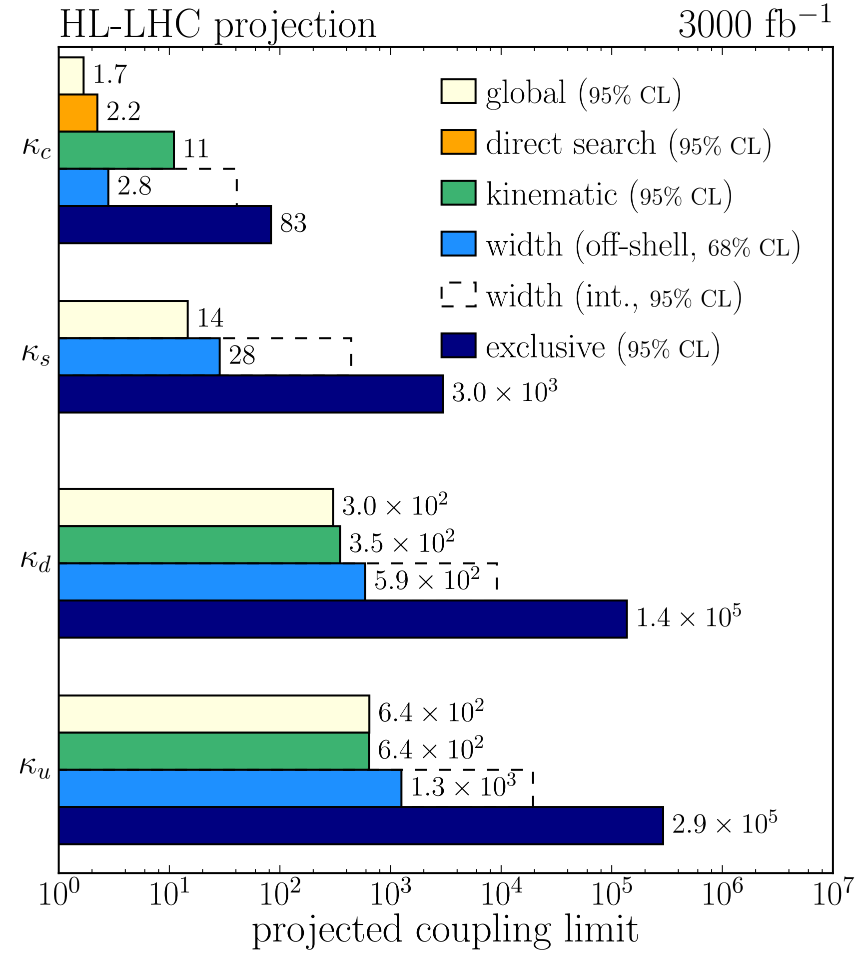


- p_T(Higgs) distribution:
  - t(t)H: sensitive to self-coupling κ_λ
  - ggH: sensitive to interference between quark loops → κ_b and κ_c

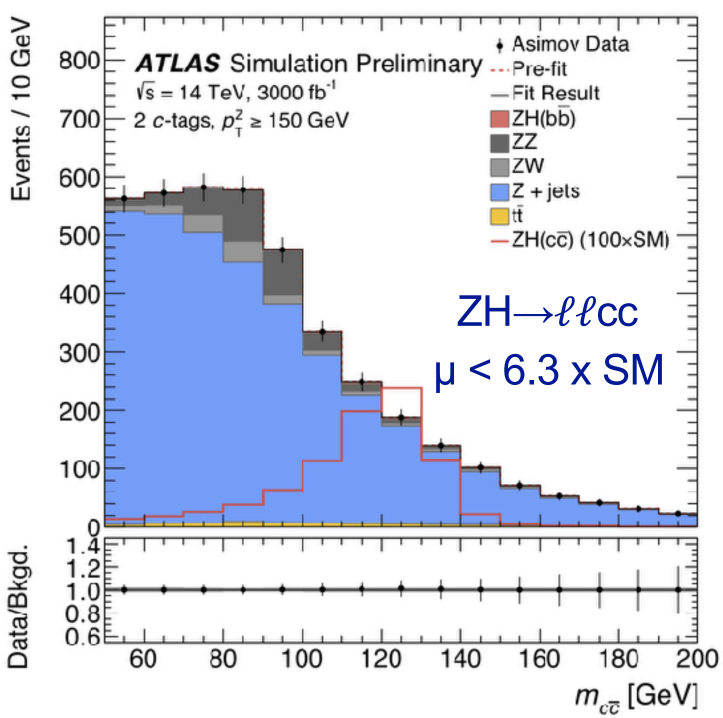
With 3000 fb^{-1} constrain κ_c and κ_λ to a few times SM

Higgs and Charm

- Limits on $\kappa_{c,s,d,u}$ for 2 x 3000 fb^{-1}
  - global fit to production cross section (κ-fit)
  - direct search for a cc final state (VH→cc)
  - differential cross-sections (e.g. previous page)
  - total width (off/on-sh & interf. in pp→4ℓ and γγ)
  - exclusive decays (e.g. H → J/ψγ)



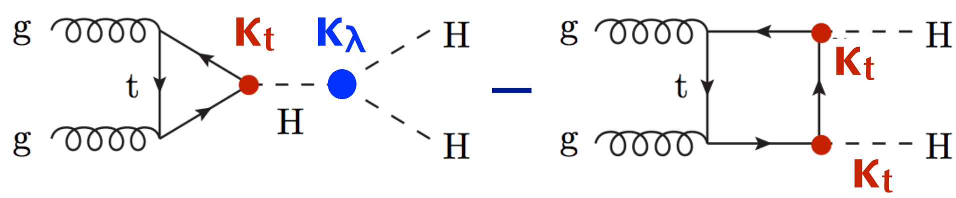
ATL-PHYS-PUB-2018-016



- ZH → ℓℓcc arXiv:1802.04329
  - ATLAS Run-2 / HL-LHC: μ < (110) 6.3 x SM @ 95CL
  - CMS Run-2: μ < 70 x SM @ 95CL
- VH(→cc): LHCb-CONF-2016-006
  - LHCb (Run-1) 300 fb^{-1}: μ < (7900) 5-10 x SM

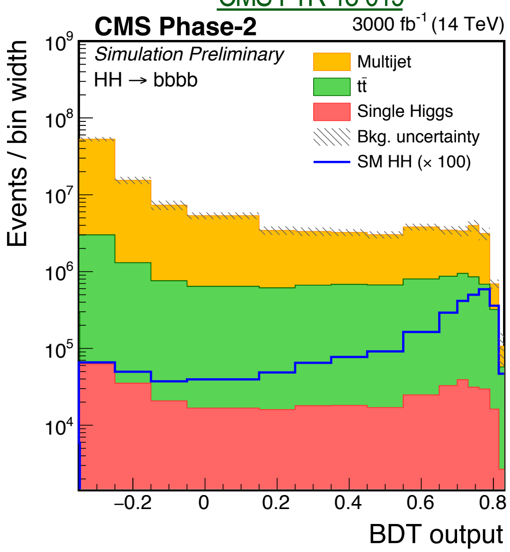
With further improvements, Higgs-charm could be in reach

HH

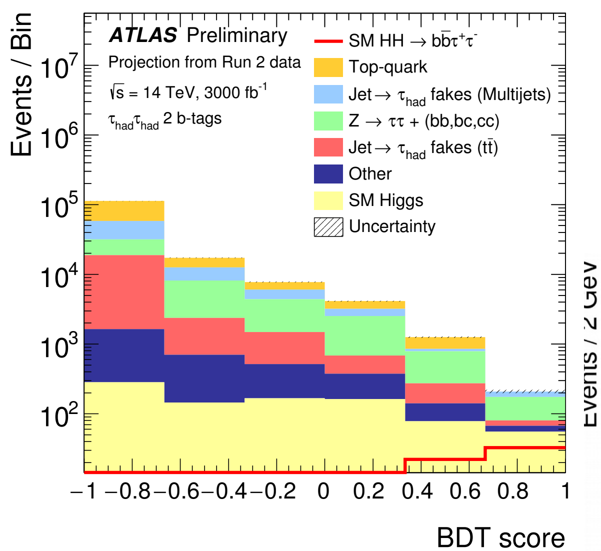


- Ultimate goal: observation of trilinear coupling
- 120k HH events expected
- Best sensitivity (BR vs. bg): bbττ and bbγγ
- Also analysed bbVV (ℓℓνν) and bbZZ (4ℓ)

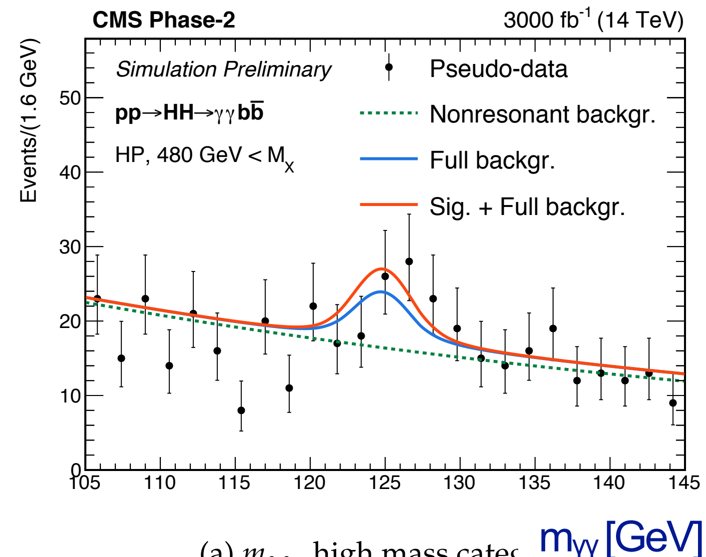
HH→bbbb
CMS-FTR-18-019



HH→bbττ
ATL-PHYS-PUB-2018-053

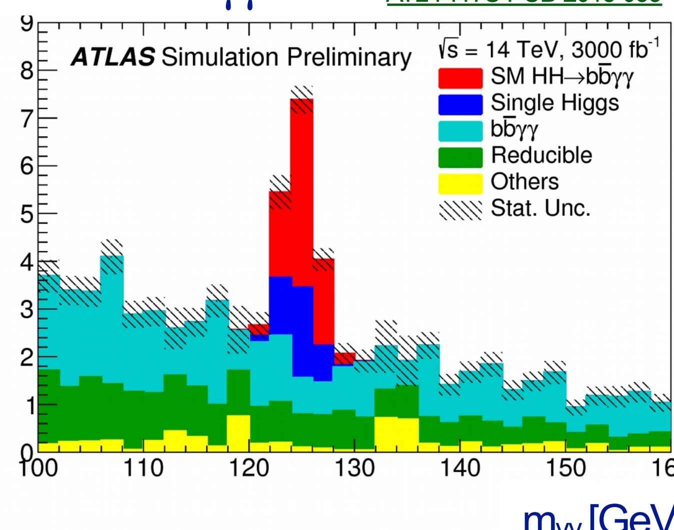


HH→bbγγ
CMS-FTR-18-019



(a) $m_{\gamma\gamma}$, high mass categ

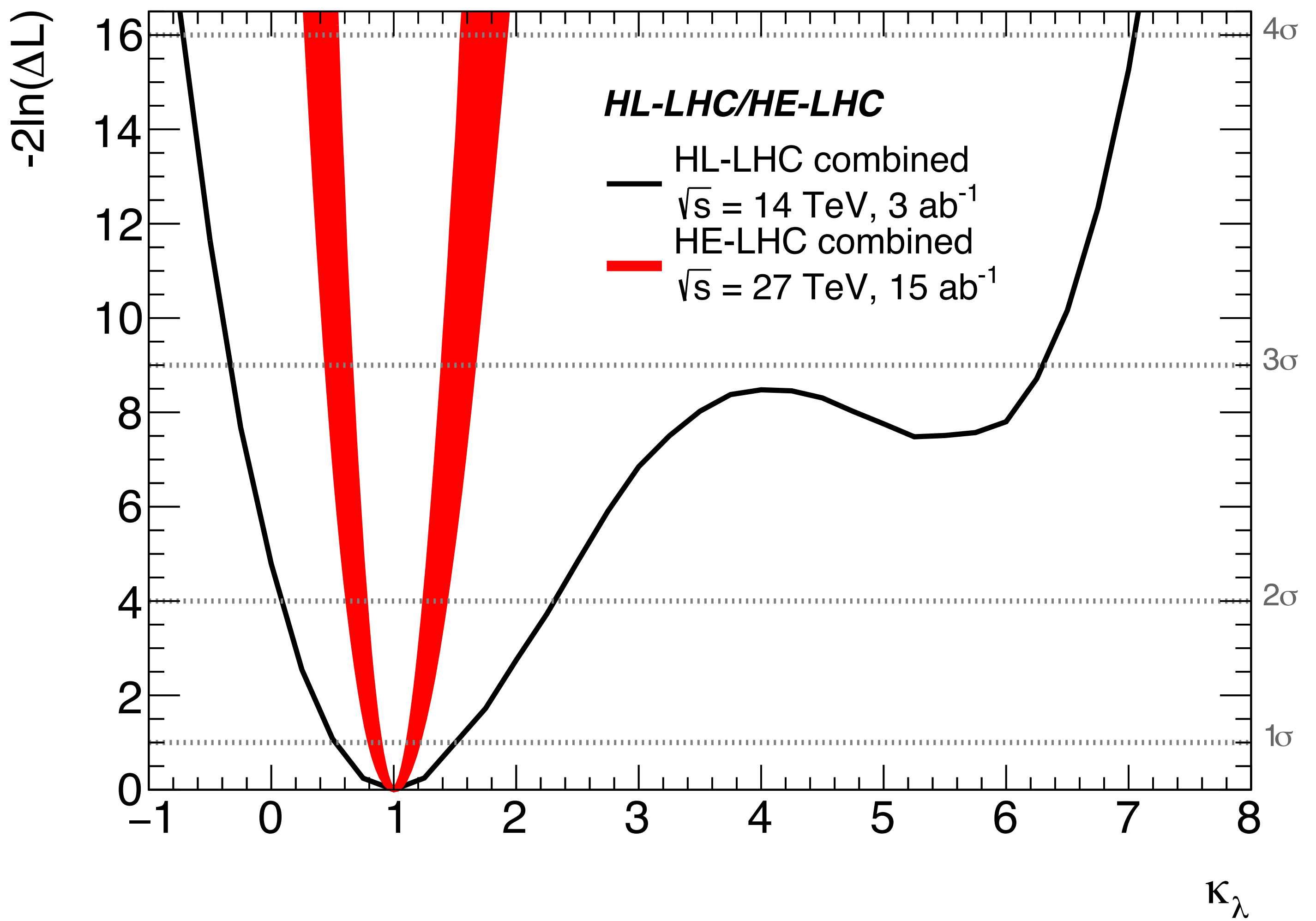
HH→bbγγ
ATL-PHYS-PUB-2018-053



ATLAS and CMS combination:
signal strength: 4σ (stat. + syst.)
$0.1 < \kappa_\lambda < 2.3$ (at 95% CL)

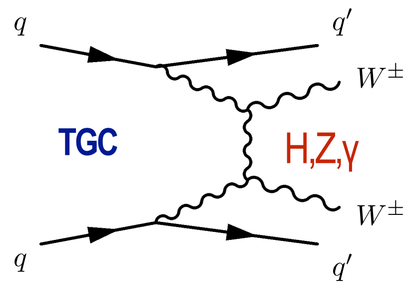
Higgs Self-Coupling: HL-LHC and HE-LHC

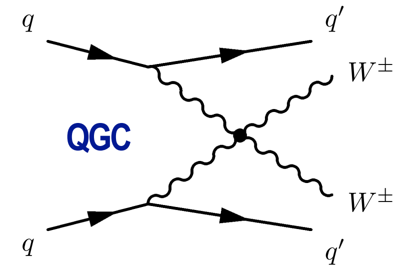
arXiv:1902.00134



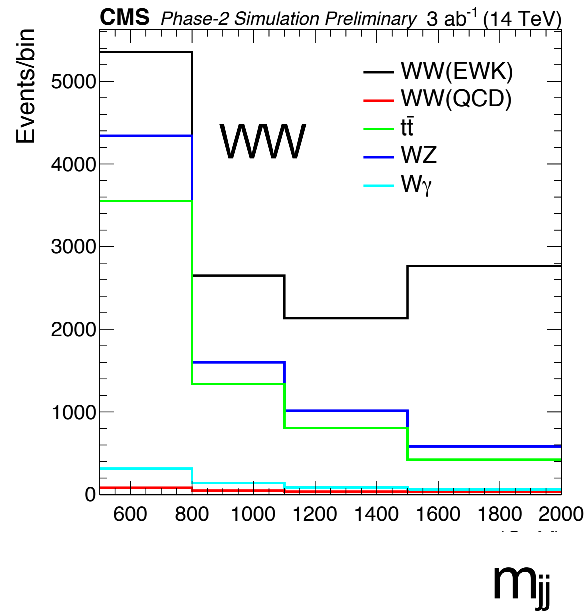
HE-LHC (15 ab^{-1} at 27 TeV) will be able to pin κ_λ down fully (~15%)

Vector Boson Scattering

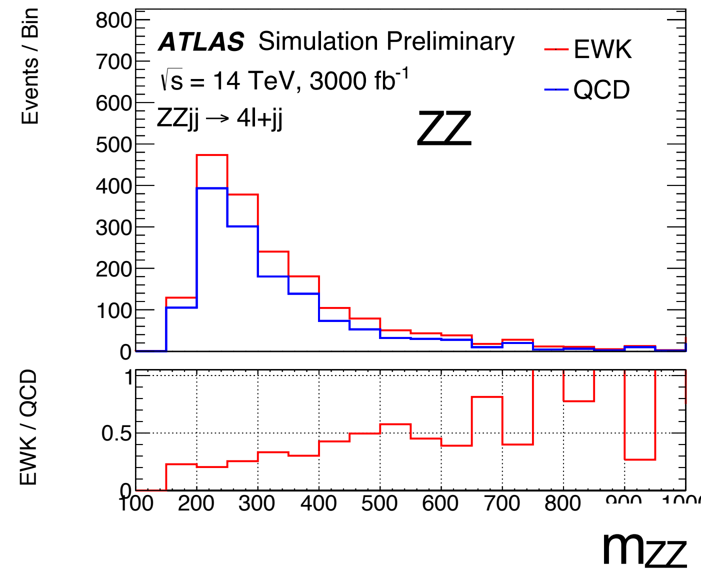




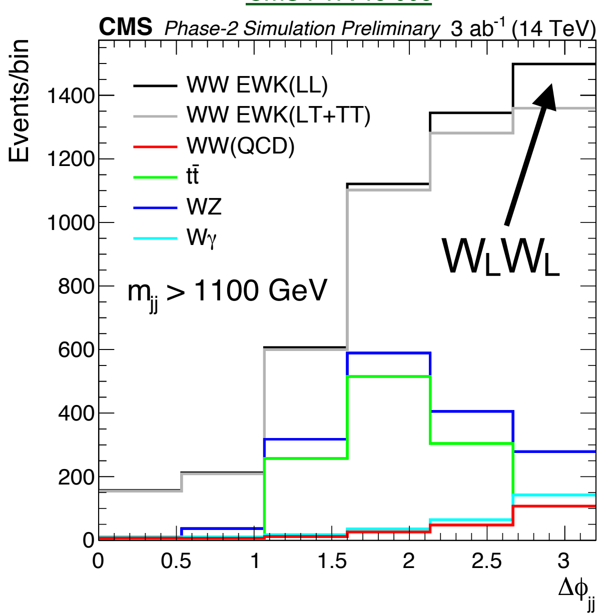
CMS-FTR-18-005



ATL-PHYS-PUB-2018-029



CMS-FTR-18-005



VBS(WW): $\delta\sigma \sim 5\%$

VBS(ZZ): $\delta\sigma \sim 10\%$

10-page summary HL-LHC: Table 1

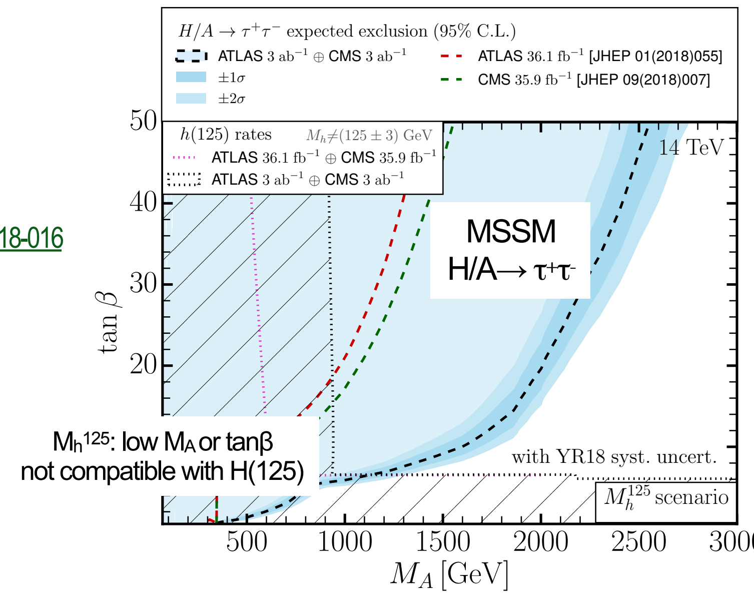
Process	$W^\pm W^\pm$	WZ	WV	ZZ	WWW	WWZ	WZZ
Final state	$\ell^\pm\ell^\pm$jj	3ℓjj	ℓjjjj	4ℓjj	$3\ell 3\nu$	$4\ell 2\nu$	$5\ell\nu$
Precision	6%	6%	6.5%	10–40%	11%	27%	36%
Significance	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	3.0σ	3.0σ

$V_L V_L$ discovery significance: $\sim 3\sigma$ / experiment

BSM Higgs

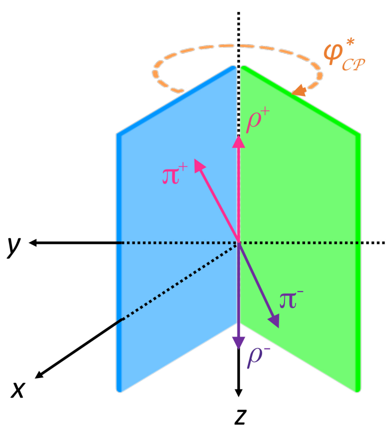
CMS-FTR-18-017

- From kappa fit (for κ_V<1): B_{BSM} < 2.5%
- Direct h→invisible: B_{inv} < 2.5% ATL-PHYS-PUB-2013-014 CMS-FTR-18-016
- MSSM Higgs: H/A →ττ: M_A limit increased to ~2 TeV



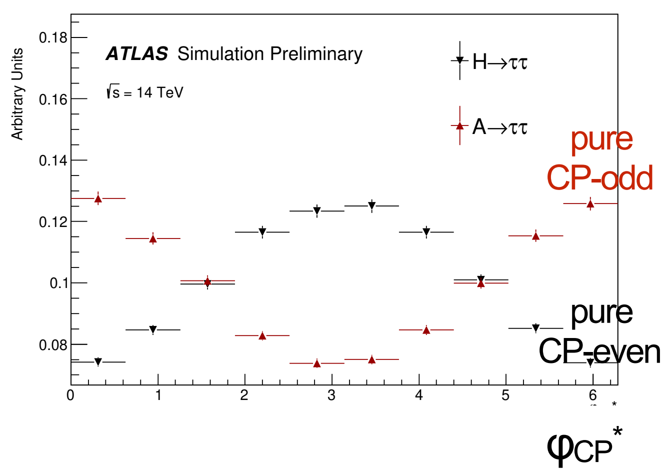
- CP-odd Hff couplings from ττ spin correlations (limits so far only for HVV)
  - H → ττ with $\tau^\pm \to \rho^\pm \nu_\tau \to \pi^\pm \pi^0 \nu_\tau$
  - φ^*_{CP} = angle between the two τ decay planes
  - Sensitivity strongly depends on π^0 resolution and τ-ID

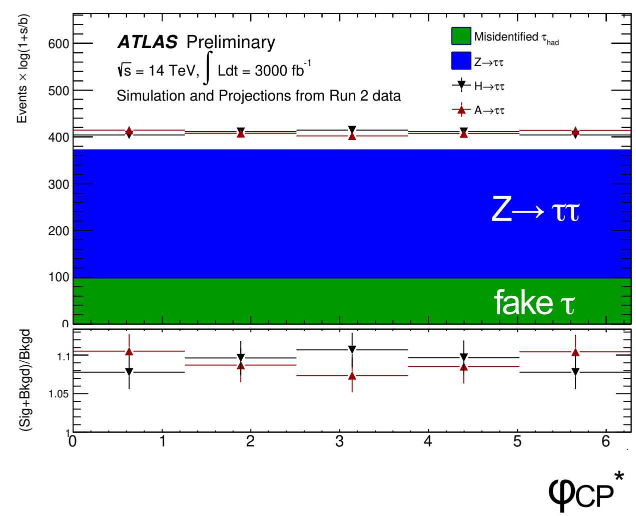
ATL-PHYS-PUB-2019-008



(a) φ^*_{CP} illustration

Frame: Σ p(vis. dec. products) = 0



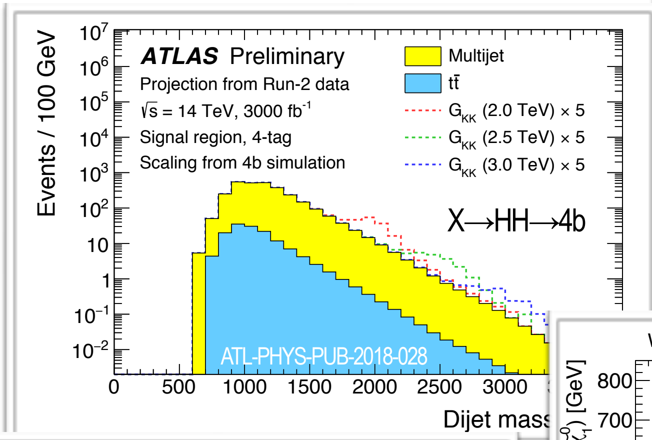


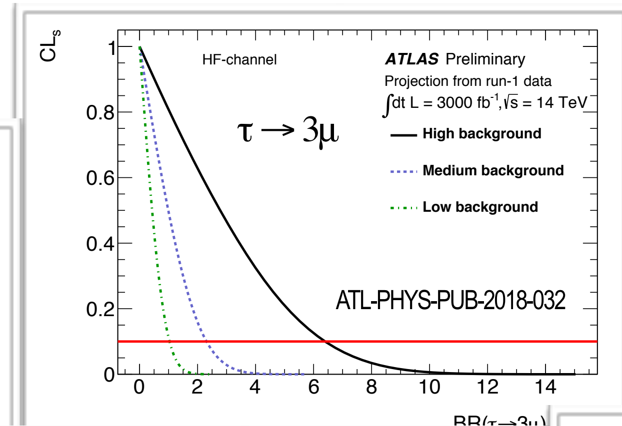
Possible exclusion of CP-odd H-τ coupling with this analysis alone: ~2σ

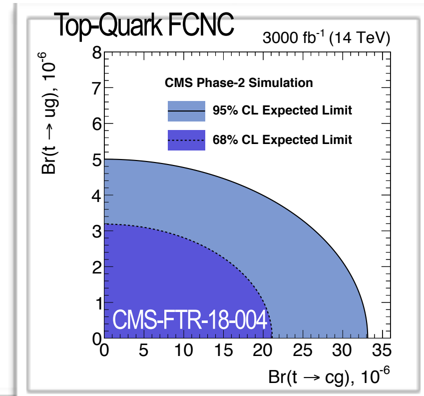
Direct Searches

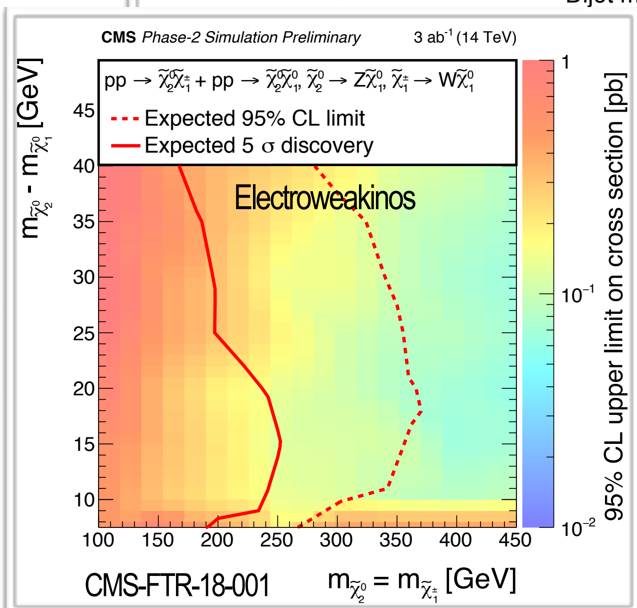
Heavy Resonances, Supersymmetry, Long-Lived Particles, Dark Matter

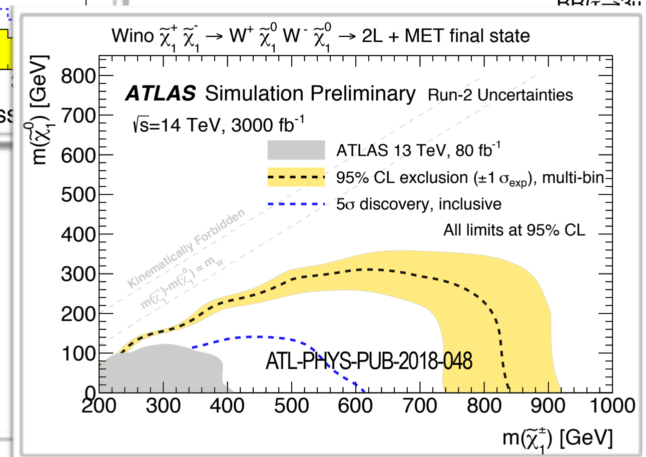
Direct Searches

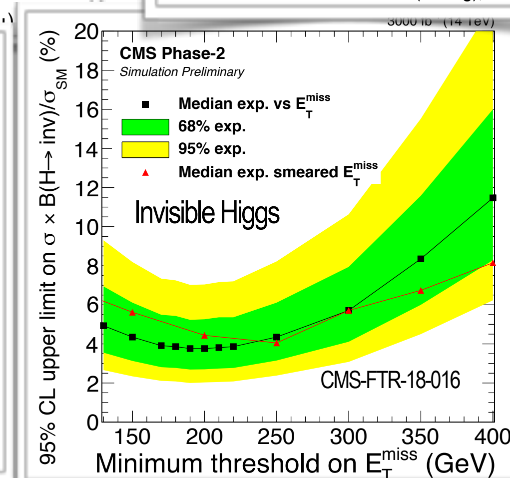


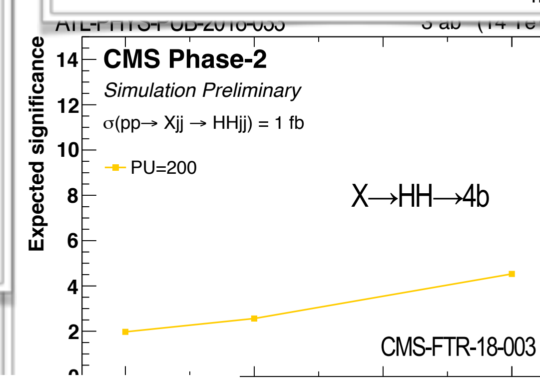


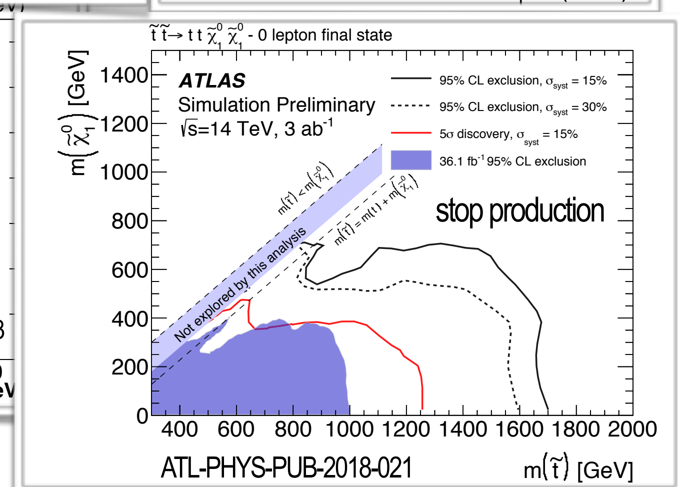










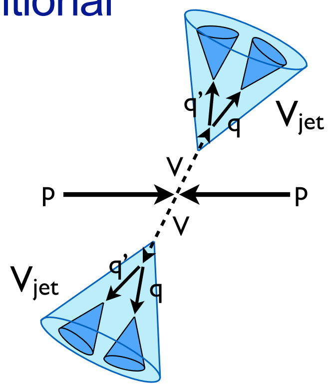


Subset of BSM projections by ATLAS and CMS for the HL-LHC Yellow Report

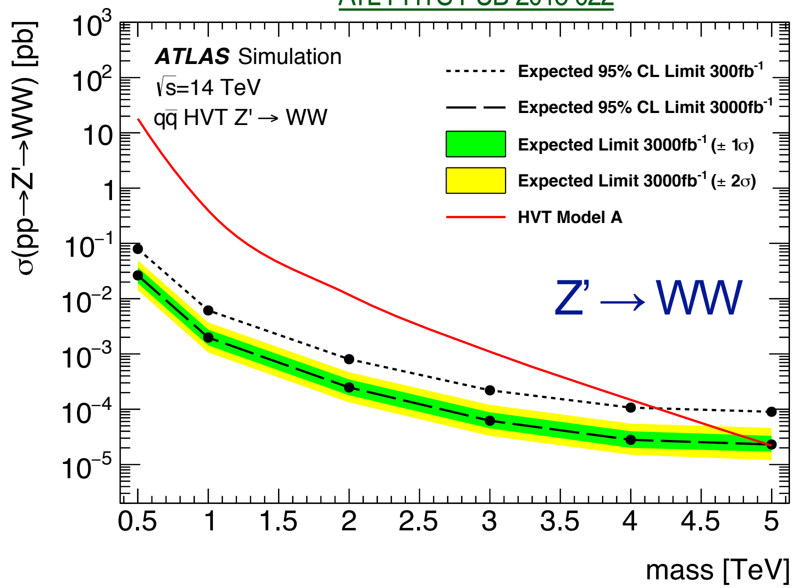
Heavy Resonances

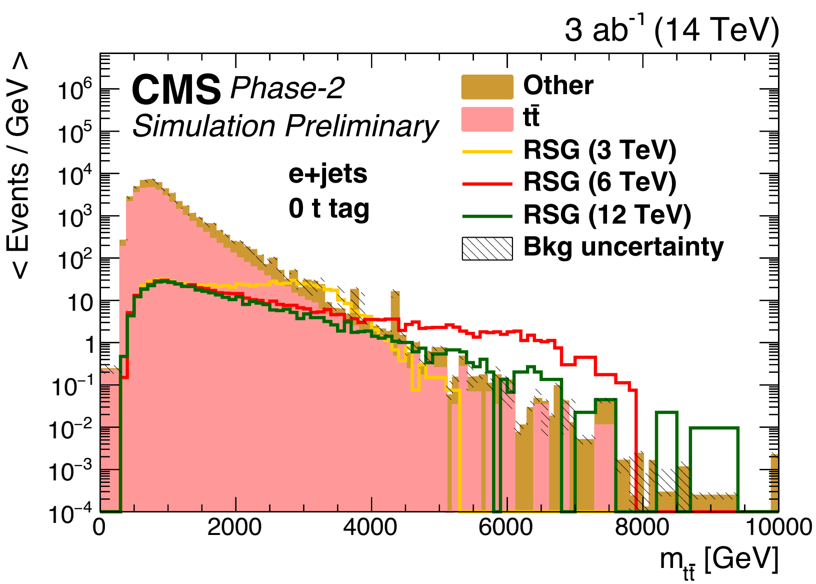
- Heavy Vector Triplet (HVT) model: composite Higgs and three additional vector bosons Z' and W'± Z' and W'± → WW, WZ or ZZ

- Randall-Sundrum-Gluon: RSG → tt

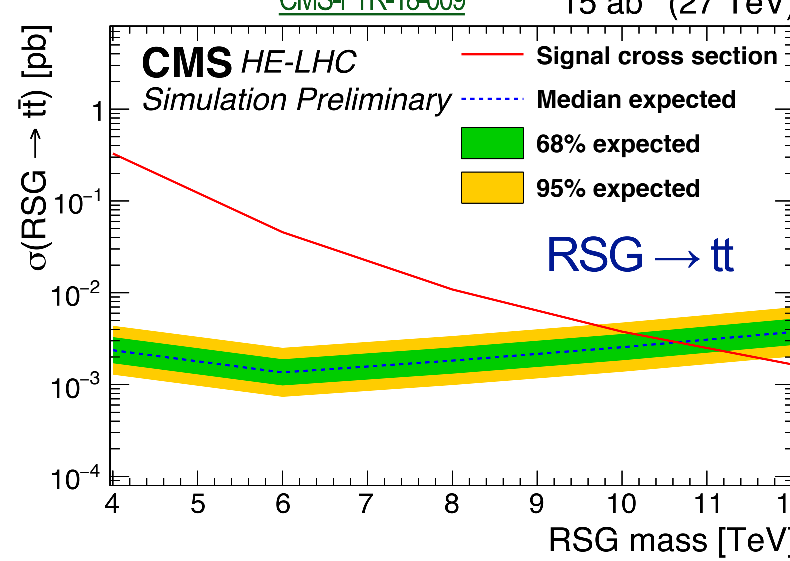


ATL-PHYS-PUB-2018-022



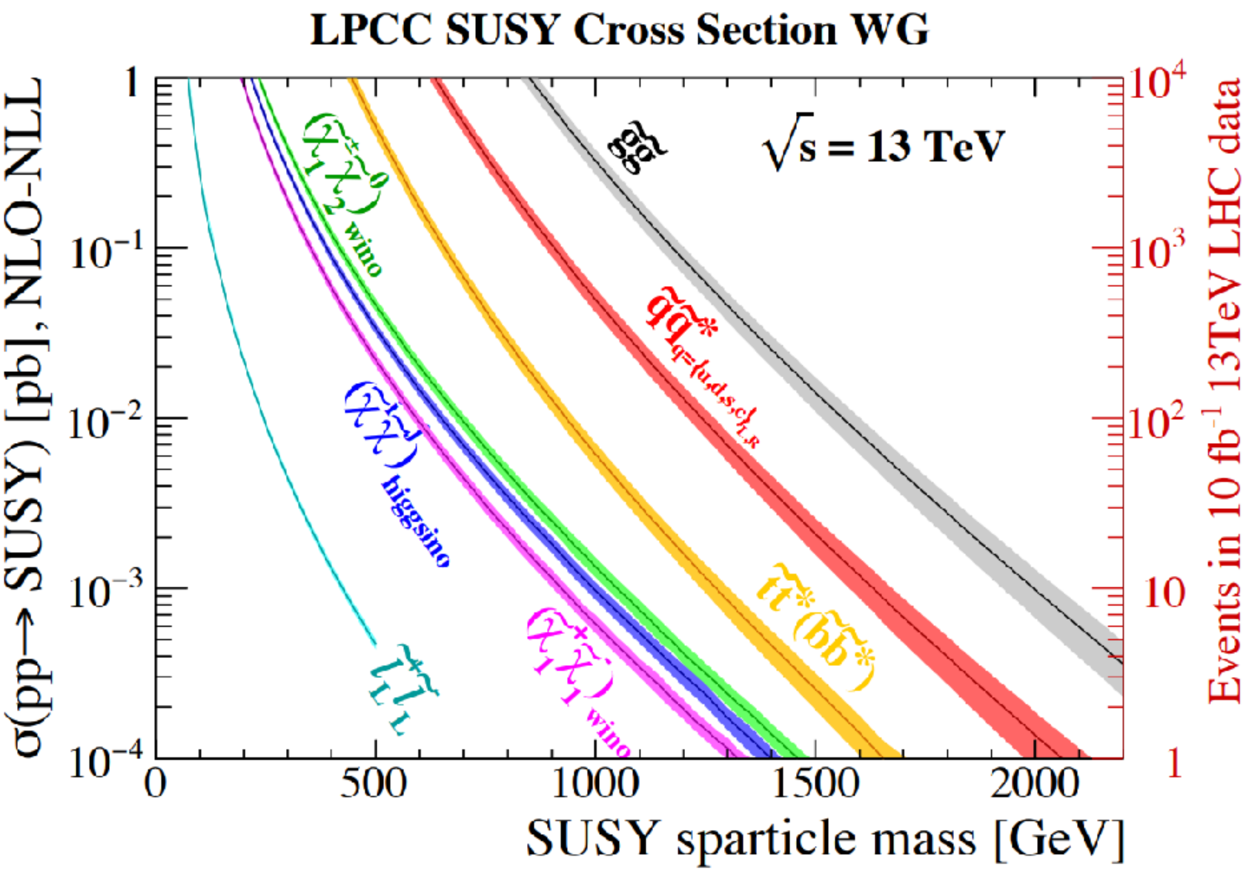


CMS-FTR-18-009

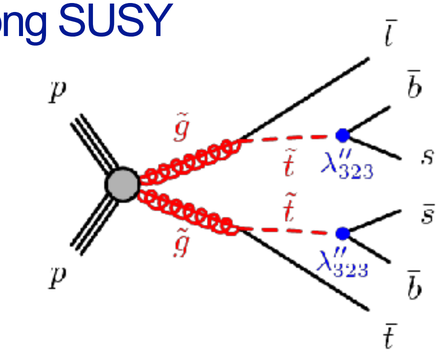


Mass reach: exclusion up to 5-6 TeV at HL-LHC — 10-11 TeV at HE-LHC

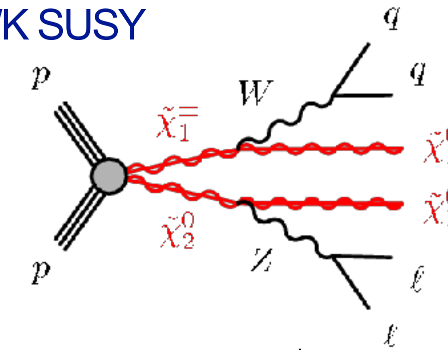
Supersymmetry

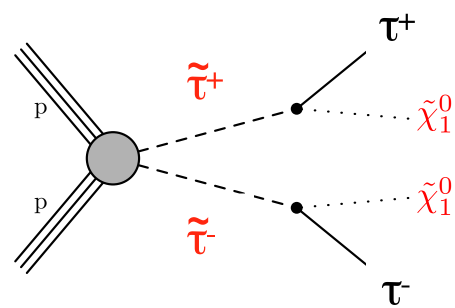


Strong SUSY



EWK SUSY



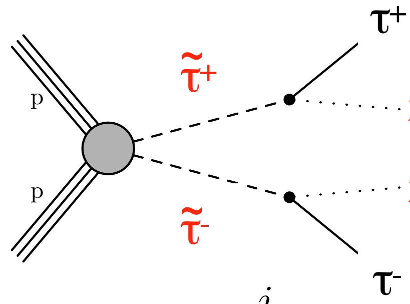


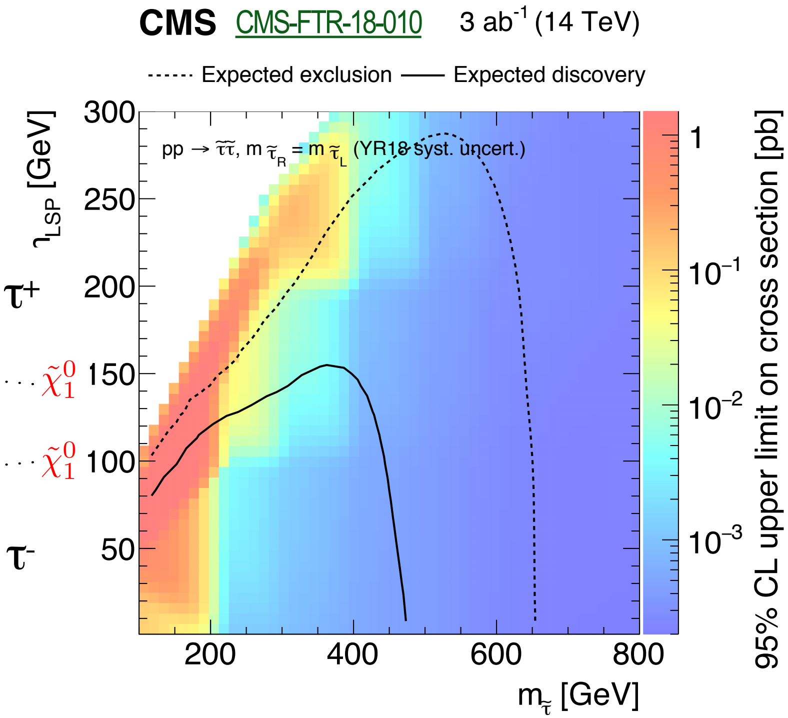
- Strong SUSY (σ≥1 pb at m = 500 GeV): many scenarios already excluded up to 1 TeV
- Electroweak SUSY (σ < 0.1 pb at m = 500 GeV): could still be light

Electroweak SUSY

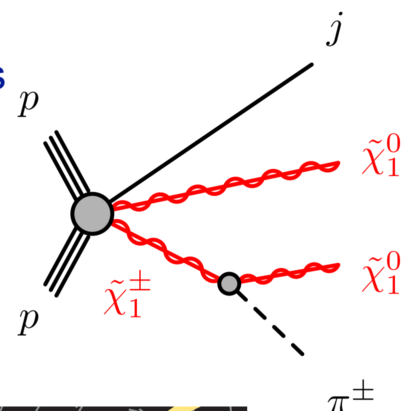
- Stau pairs:
  - Final state: $\tau_h\tau_h$ or $\ell\tau_h$ + MET
  - Run-2: No stringent limits yet

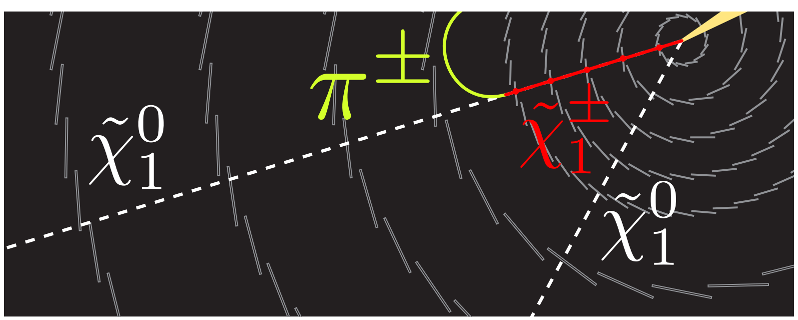
    CMS-SUS-18-006
  - HL-LHC excl. limit: 650 GeV

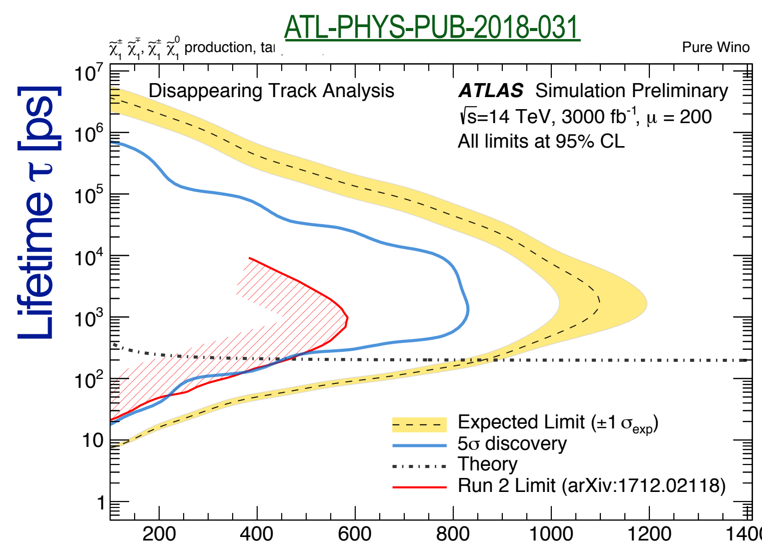




- Electroweakinos:
  - Degenerate mass scenarios → compressed spectra and/or long lifetimes
  - Use ISR jet for triggering
  - Detect disappearing track







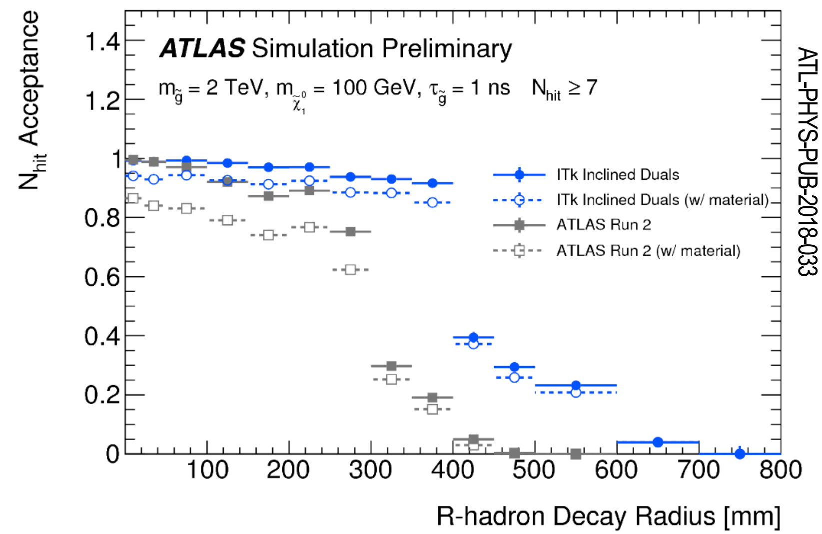
Mass $m(\chi_1^\pm)$ [GeV]

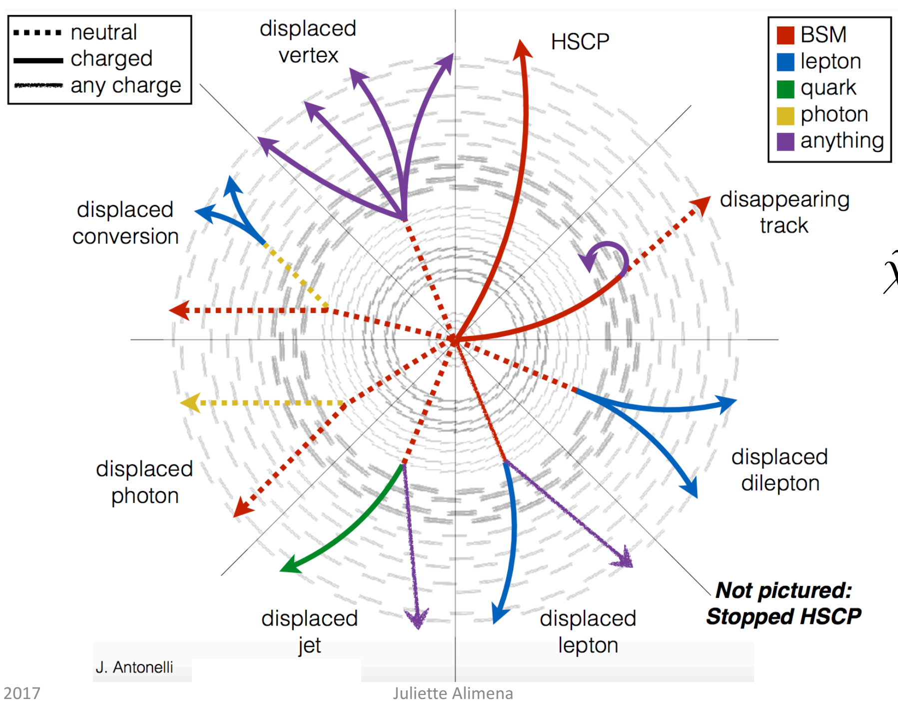
Sensitivity to new scenarios

Long-Lived Particles

- Many standard model particles are long-lived !
- Various scenarios: mass degeneracy, small couplings, heavy mediators
- Detect LLP signatures
  → novel approaches

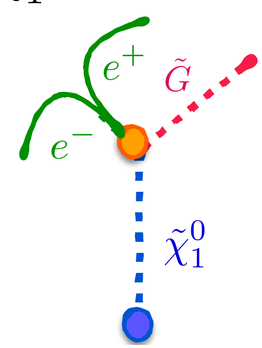
track efficiency as fct of vertex radius



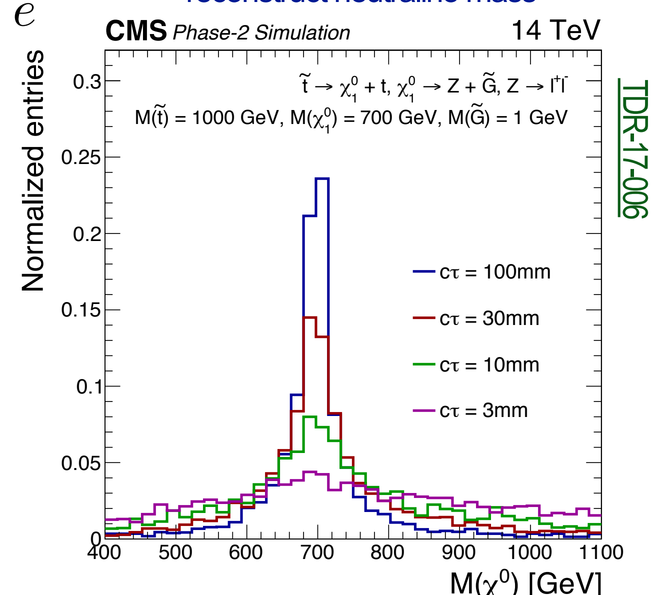


Example:

$$\tilde{\chi}_1^0 \rightarrow \tilde{G} + e^+e^-$$



Use MIP timing detector information to reconstruct neutralino mass

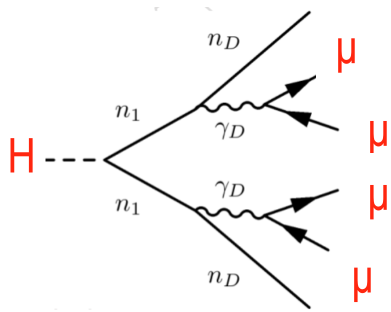


Significant benefits from improved detector

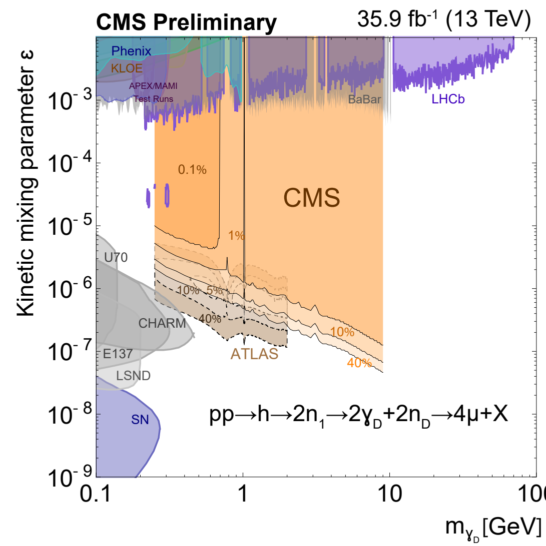
Dark Sector

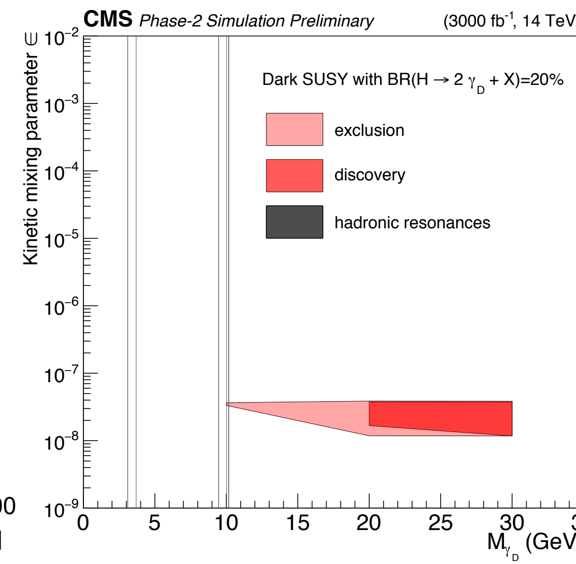
Displaced muons from long-lived dark photons

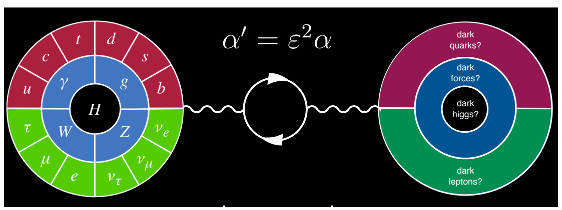
H→4μ + X



CMS-FTR-18-002

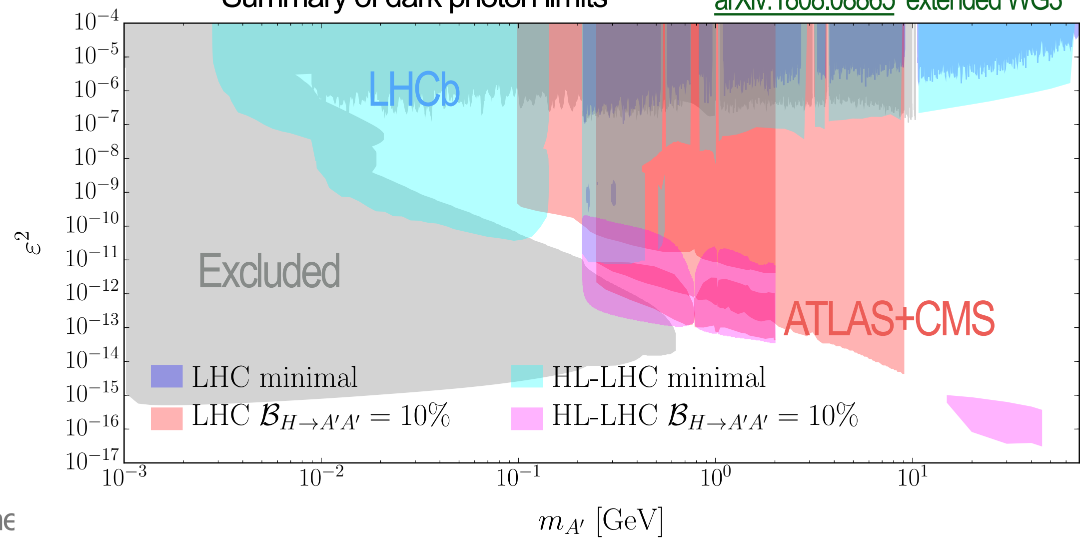




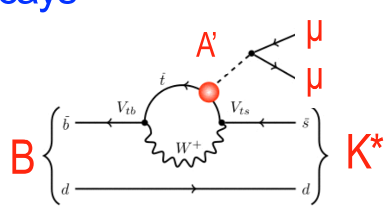


Dark photons in B decays

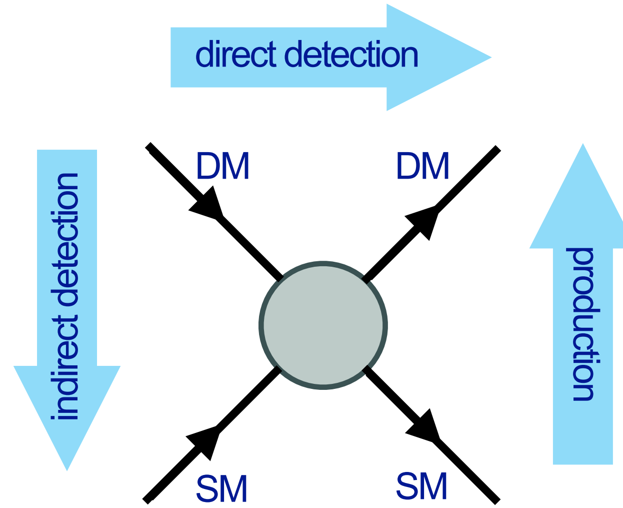
arXiv:1808.08865 extended WG3



A'→μμ (or ee)



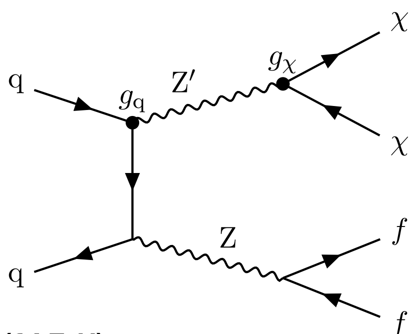
Dark Matter …



LHC

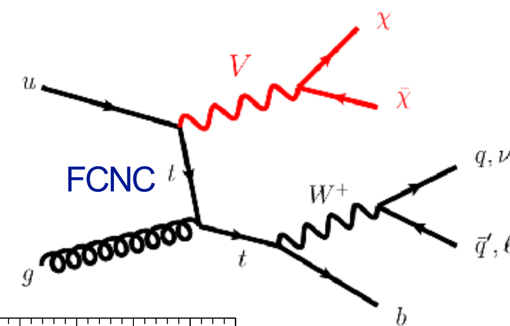
- … is known to exist:
  → uncover its elementary nature at the LHC (?)
- Simplified models for comparison with direct detection experiments

mono-Z:

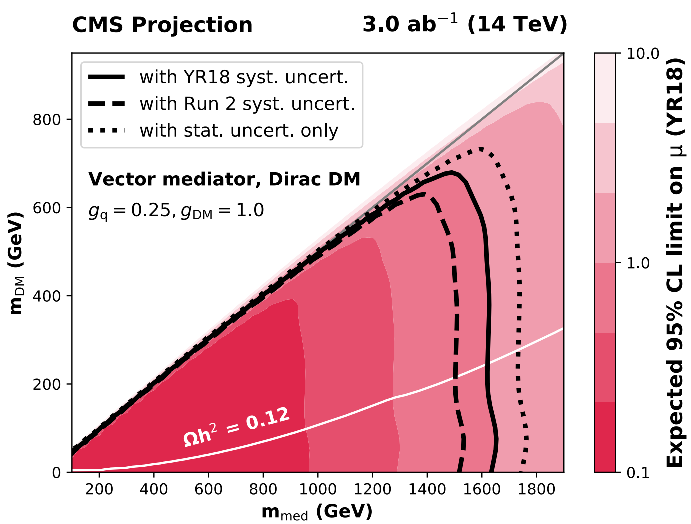


mono-top:

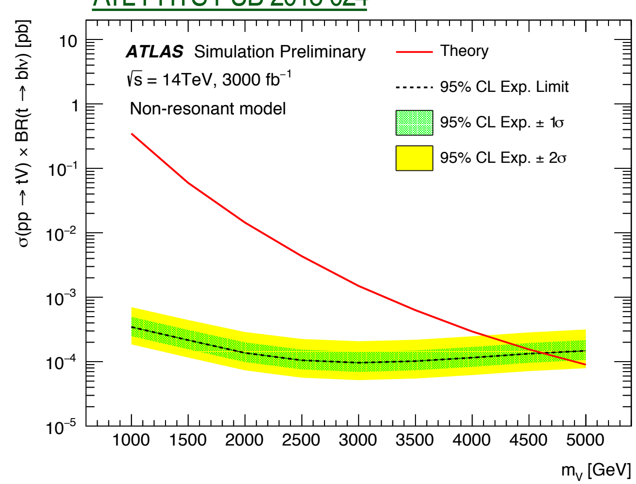
FCNC



CMS-FTR-18-007



ATL-PHYS-PUB-2018-024



Limit on m_V ~4.5 TeV (for m_{DM} = 1GeV, a=0.5 and g=1)

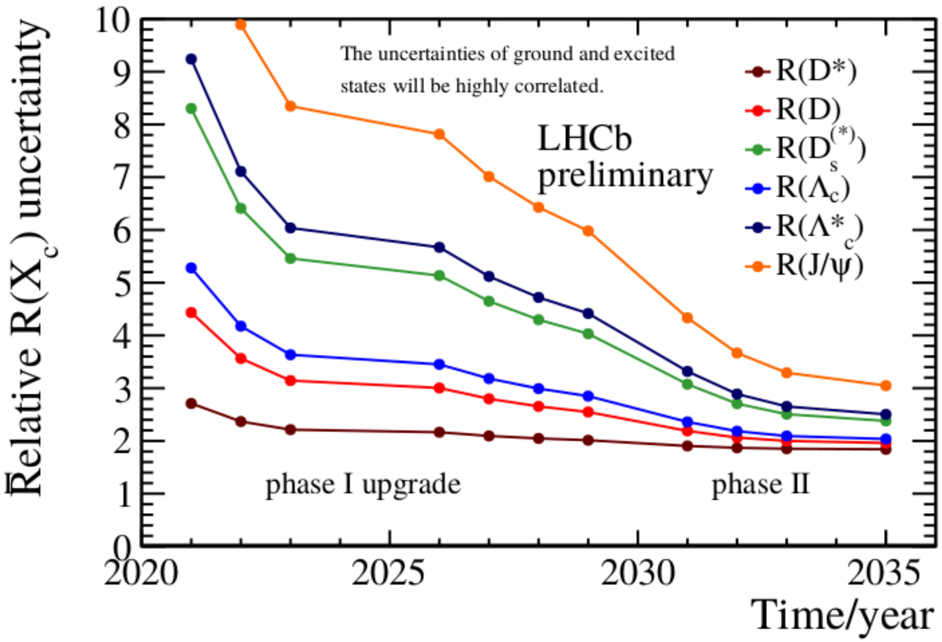
Flavour

Low p_T / High p_T Complementarity

Flavour Anomalies: Low p_T

- Tension in current measurements
  - R(K*), $b \to s\mu\mu$: 2-3σ below expectation
  - R(D*), $b \to c\tau\nu$: 3-4σ above expectation
  - P_5' from $B \to K^*\mu\mu$: LHCb also in tension

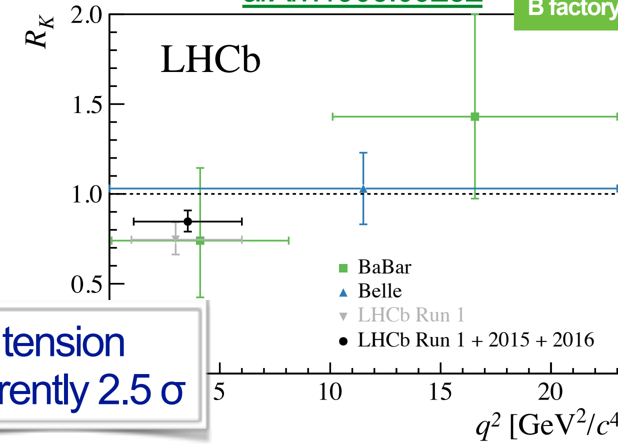
- LHCb will measure several more channels, also with B_S, Λ_b and B_c



$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$

arXiv:1903.09252

B factory data

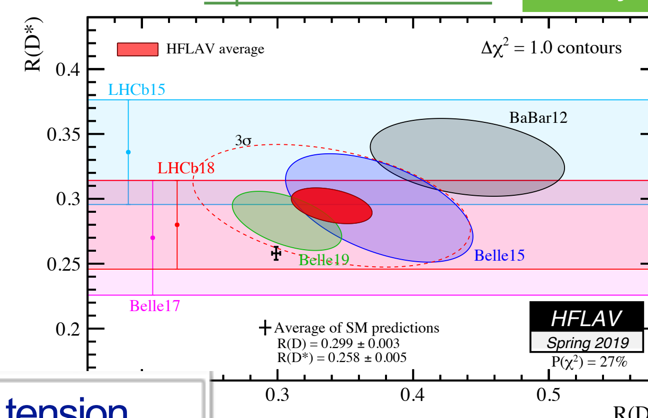


tension currently 2.5 σ

$$R^{\tau/\ell}_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$

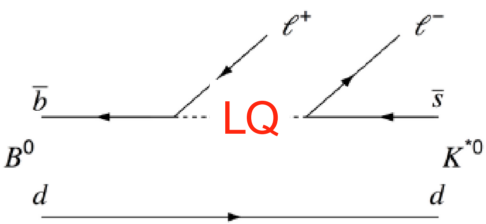
https://hflav.web.cern.ch/

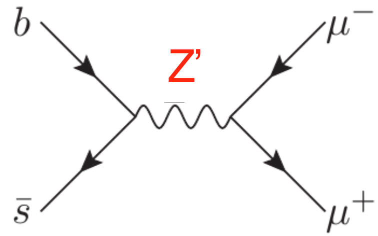
B factory data



tension currently 3.1 σ

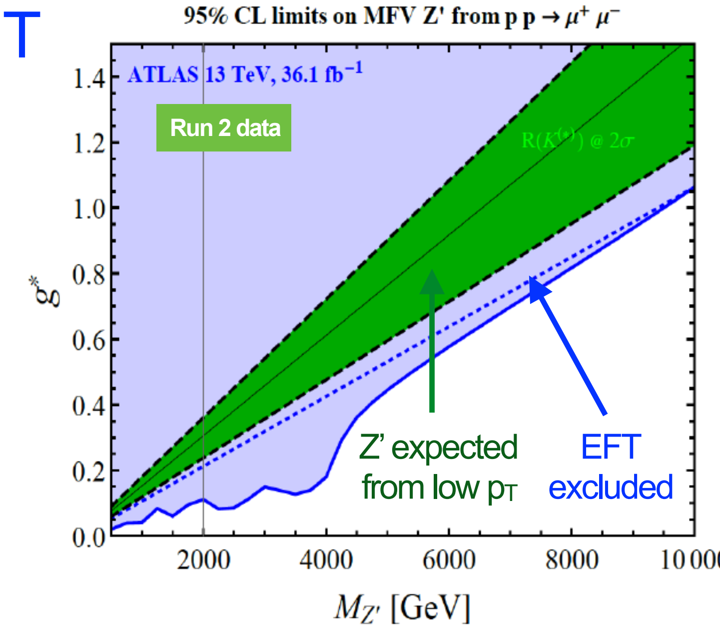
Flavour Anomalies: High p_T

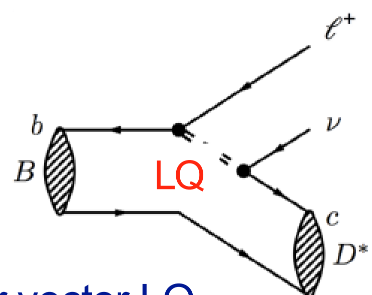




- R(K*) b → sℓℓ
  - Theoretically very clean
  - Could be explained by LQ or flavour violating Z'
  - However, Z'→ μμ already excluded (EFT)

arXiv:1704.09015

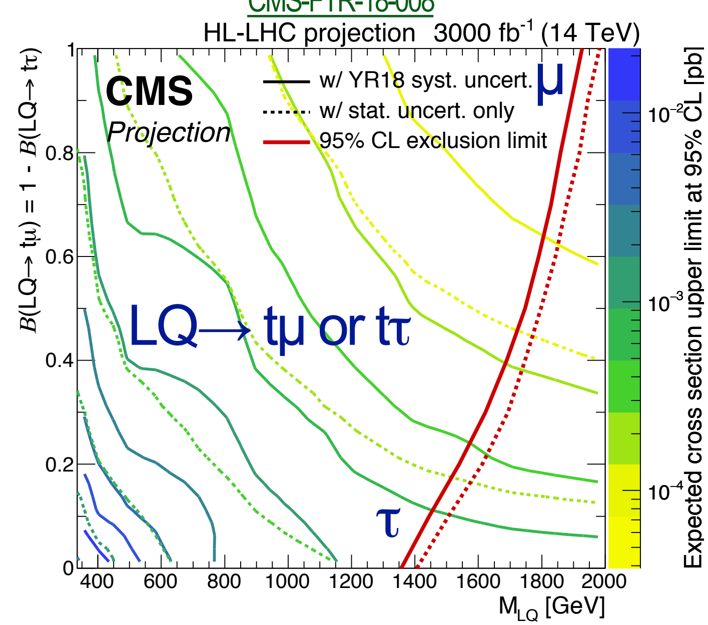




- R(D) and R(D*): b→ cℓν
  - Good fits for W' vector, scalar or vector LQ
  - Full range of LQ searches,
    Exclude LQ→tℓ up to M_{LQ} ~ 2 TeV

LQ could explain R(D*) and R(K*)
Could this be a no-lose theorem ?

CMS-FTR-18-008



Summary

- **HL-LHC: superior detectors, refined analyses, advanced theory**
  - Recent detailed update and extension of HL-LHC projections
  - Yellow Report imminent (links to pre-prints in backup)

- **3000 fb^{-1} of extremely rich and exciting physics**
  - Standard model: ultimate precision and rare processes
  - Higgs: precise determination of the H(125) properties and searches
  - Direct searches: discover new physics or close a few chapters
  - Flavour: high/low p_T complementarity
  - Heavy Ion (not shown): precise differential measurements

Expecting to exceed expectations

Backup

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

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

- Review, extend and refine our understanding of the HL-LHC physics potential
- Begin a study of physics at the HE-LHC, a possible pp collider with energy of ~27 TeV
- Working Group Report, "YR2018" — >1000 authors
  - WG1: Standard Model — arXiv:1902.04070 — 220 pages, ~200 authors
  - WG2: Higgs — arXiv:1902.00134 — 364 pages, ~400 authors
  - WG3: BSM — arXiv:1812.07831 — 281 pages, ~300 authors
  - WG4: Flavour — arXiv:1812.07638 — 298 pages, ~300 authors
  - WG5: High-density QCD — arXiv:1812.06772 — 209 pages, ~200 authors
  - Addendum (ATLAS&CMS notes) arXiv:1902.10229 1377 pages, >5000 authors
- Two 10-page executive summaries submitted to the European Strategy Update Group — >1000 authors each
  - HL-LHC https://indico.cern.ch/event/765096/contributions/3295995/
  - HE-LHC https://indico.cern.ch/event/765096/contributions/3296016/

October 2017
Kick-off meeting

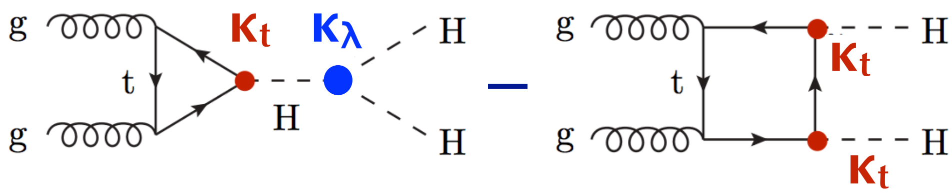
June 2018
Plenary meeting

December 2018
Reports submitted to EPPSU

1 March 2019
Jamboree

13-16 May 2019
Open EPPSU Meeting
Granada

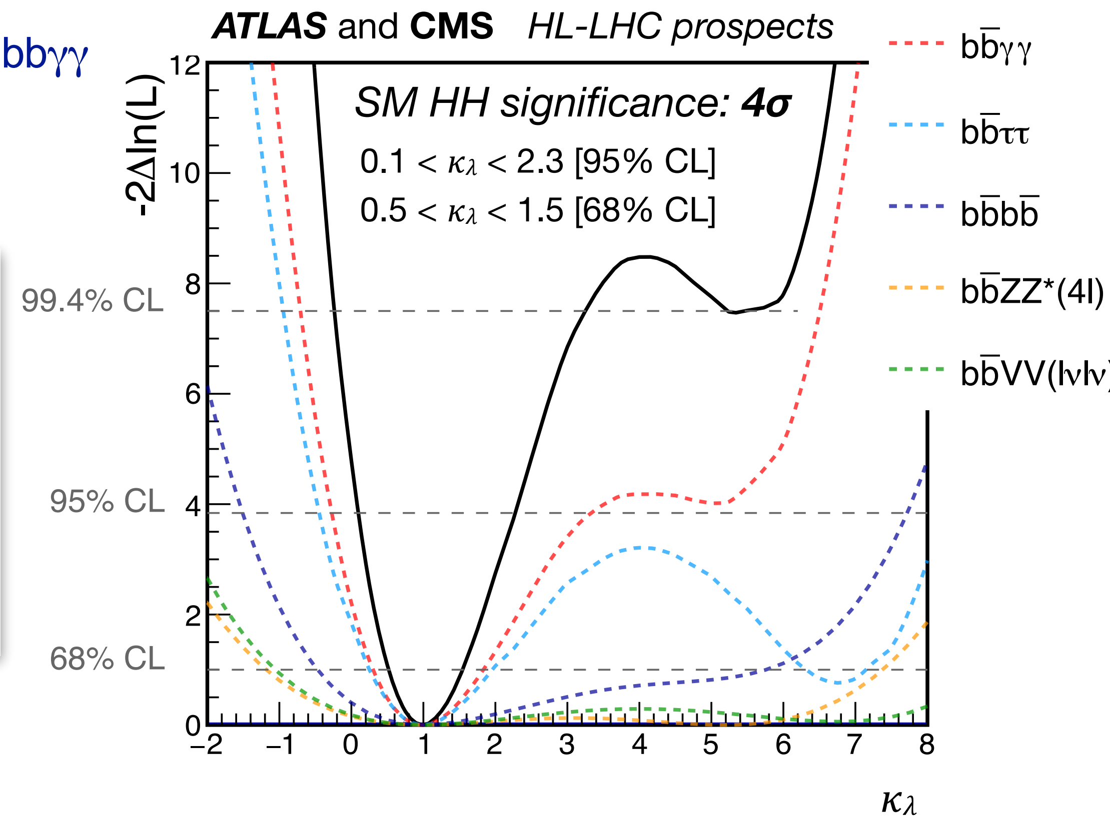
HH



arXiv:1902.00134

- Ultimate goal: observation of trilinear coupling
- 120k HH events expected
- Best sensitivity (BR vs. bg): bbττ and bbγγ

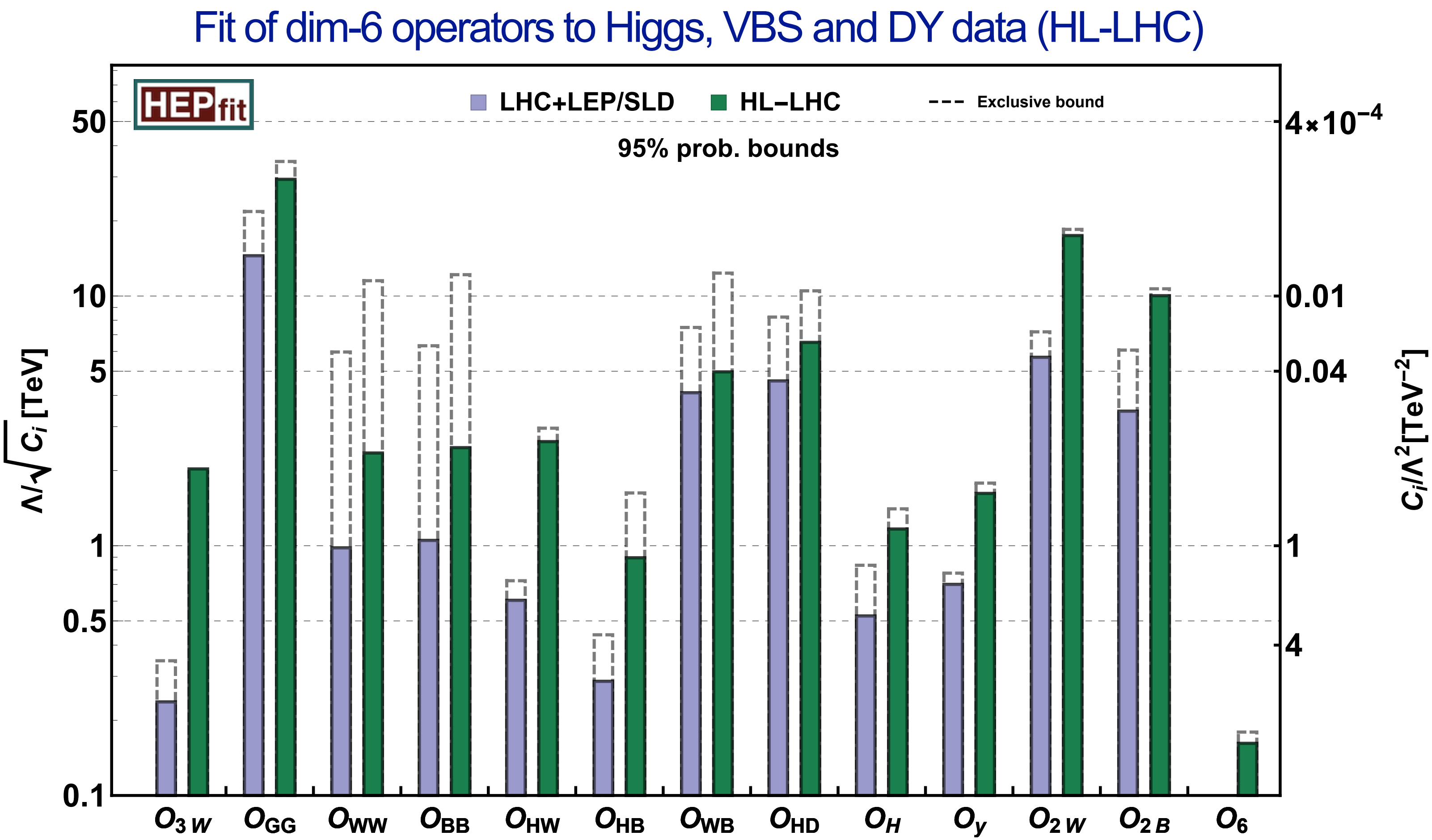
	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37
combined	3.0	2.6
	Combined	
	4.0	



Combined signal strength significance: 4σ (stat. + syst.)

Effective Field Theory (EFT)

arXiv:1902.00134

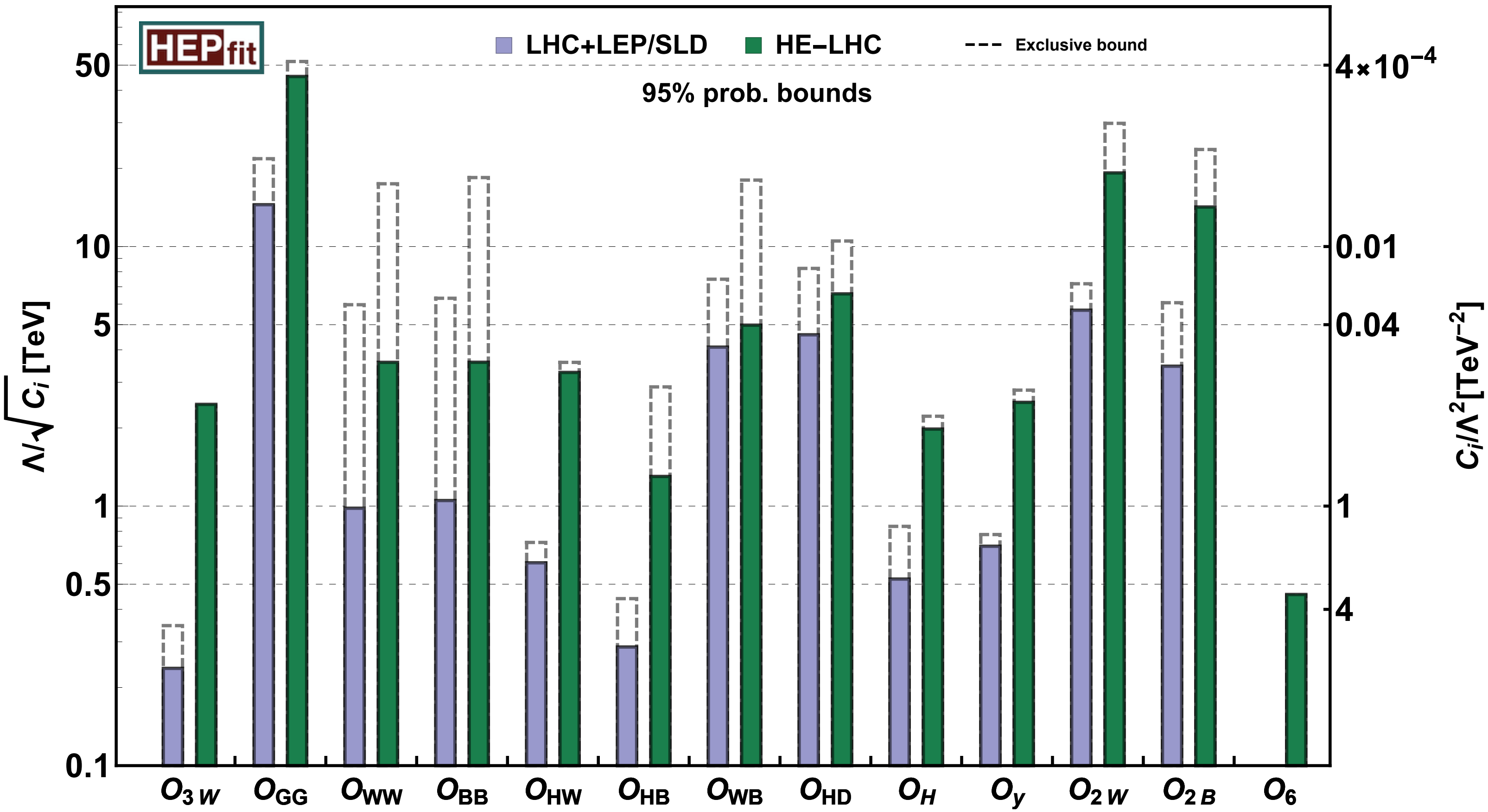


constrain several Wilson coefficients to the percent level (exclusive bound)

Effective Field Theory (EFT)

arXiv:1902.00134

Fit of dim-6 operators to Higgs, VBS and DY data (HE-LHC)



constrain several Wilson coefficients to the sub-percent level (exclusive bound) arXiv:1812.07831

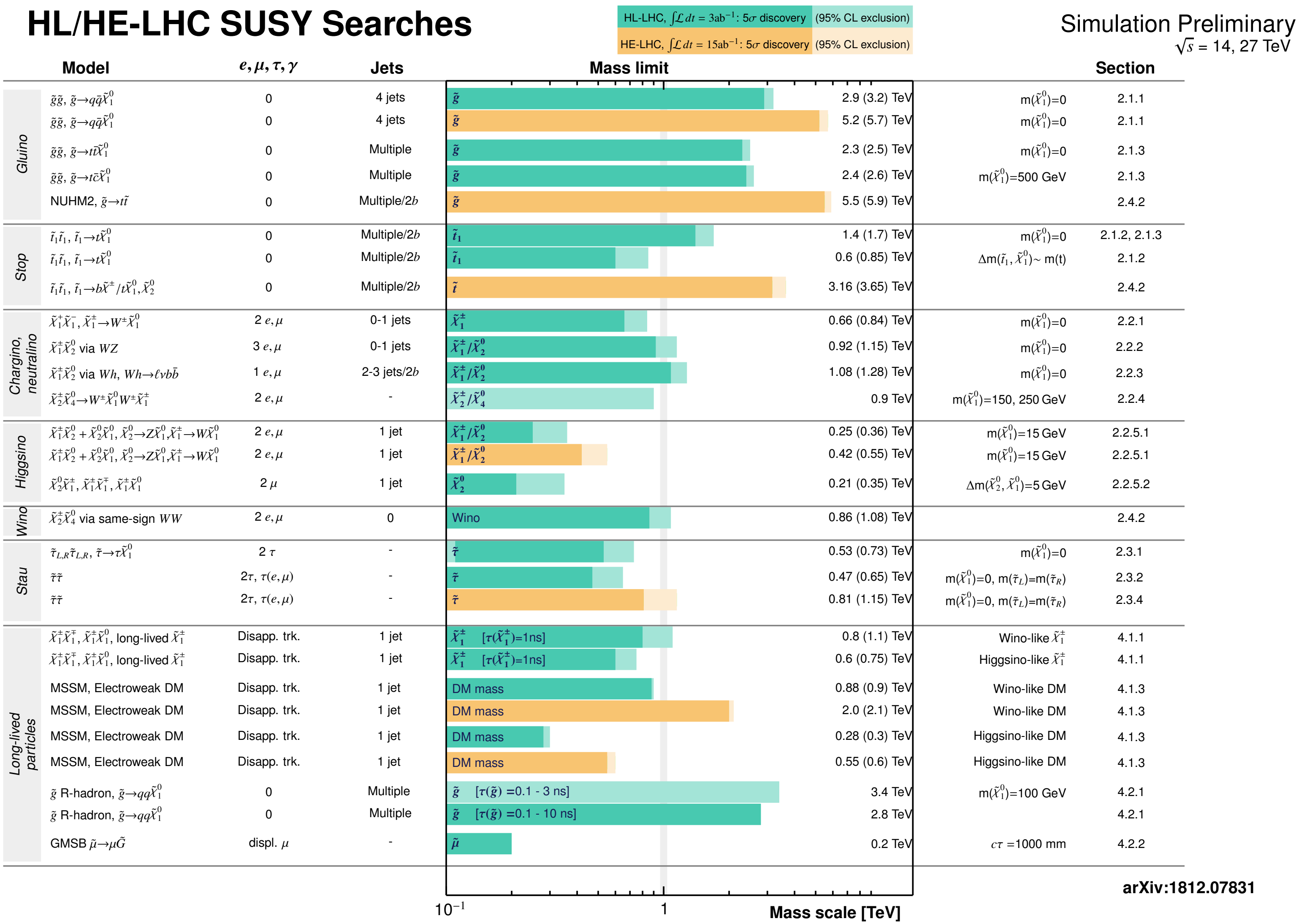
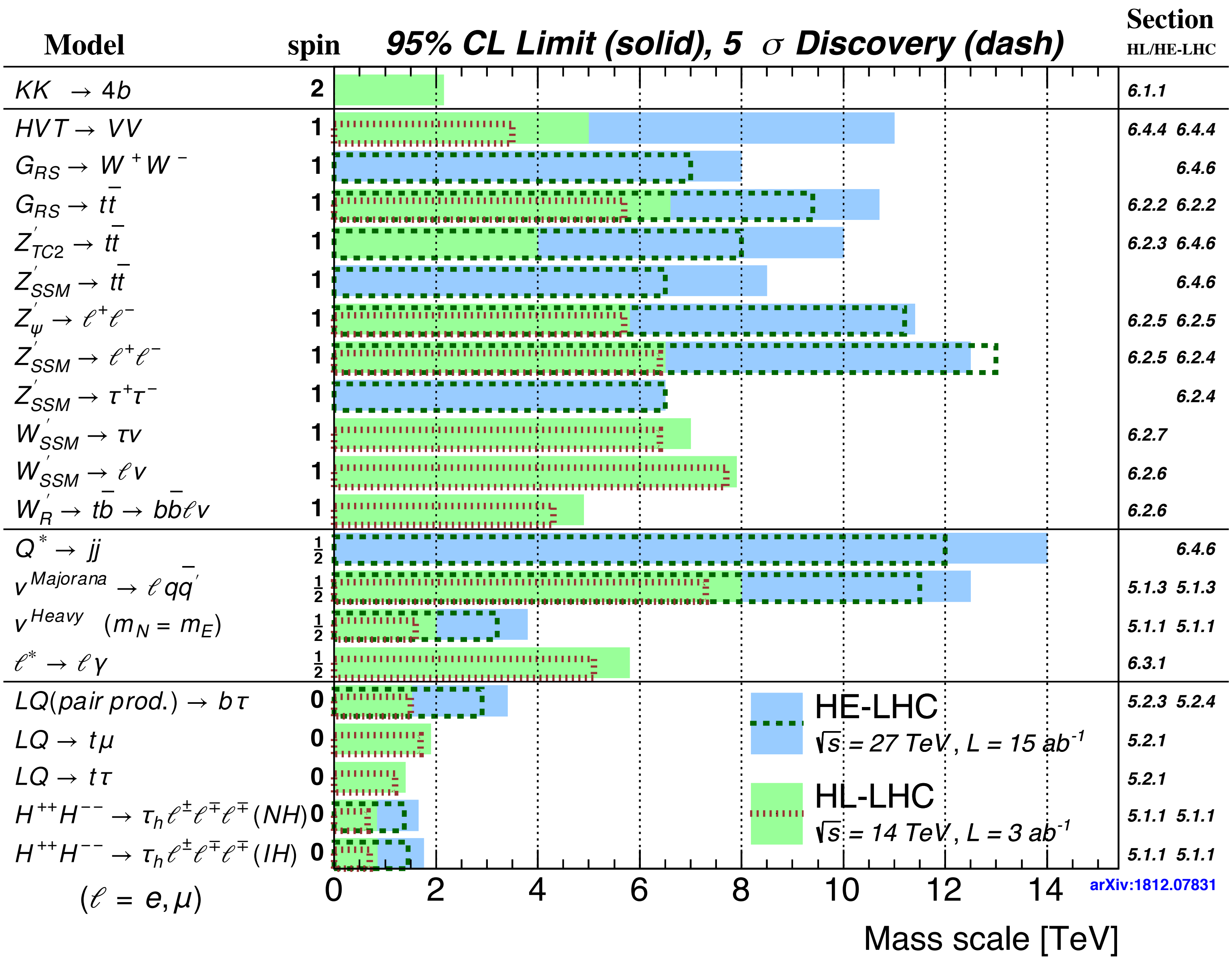


Fig. 7.1: A summary of the expected mass reach for 5σ discovery and 95% C.L. exclusion at the HL/HE-LHC, as presented in Section 2.


Model
spin
95% CL Limit (solid), 5 σ Discovery (dash)
Section
HL/HE-LHC
KK → 4b 2 6.1.1
HVT → VV 1 6.4.4 6.4.4
G_RS → W+W− 1 6.4.6
G_RS → tt̄ 1 6.2.2 6.2.2
Z′_TC2 → tt̄ 1 6.2.3 6.4.6
Z′_SSM → tt̄ 1 6.4.6
Z′_ψ → ℓ+ℓ− 1 6.2.5 6.2.5
Z′_SSM → ℓ+ℓ− 1 6.2.5 6.2.4
Z′_SSM → τ+τ− 1 6.2.4
W′_SSM → τν 1 6.2.7
W′_SSM → ℓν 1 6.2.6
W′_R → tb̄ → bb̄ℓν 1 6.2.6
Q* → jj 1/2 6.4.6
ν^Majorana → ℓqq̄′ 1/2 5.1.3 5.1.3
ν^Heavy (m_N = m_E) 1/2 5.1.1 5.1.1
ℓ* → ℓγ 1/2 6.3.1
LQ(pair prod.) → bτ 0 5.2.3 5.2.4
LQ → tμ 0 5.2.1
LQ → tτ 0 5.2.1
H++H−− → τ_hℓ±ℓ∓ℓ∓ (NH) 0 5.1.1 5.1.1
H++H−− → τ_hℓ±ℓ∓ℓ∓ (IH) 0 5.1.1 5.1.1
(ℓ = e, μ)
HE-LHC
√s = 27 TeV, L = 15 ab⁻¹
HL-LHC
√s = 14 TeV, L = 3 ab⁻¹
0 2 4 6 8 10 12 14
Mass scale [TeV]
arXiv:1812.07831