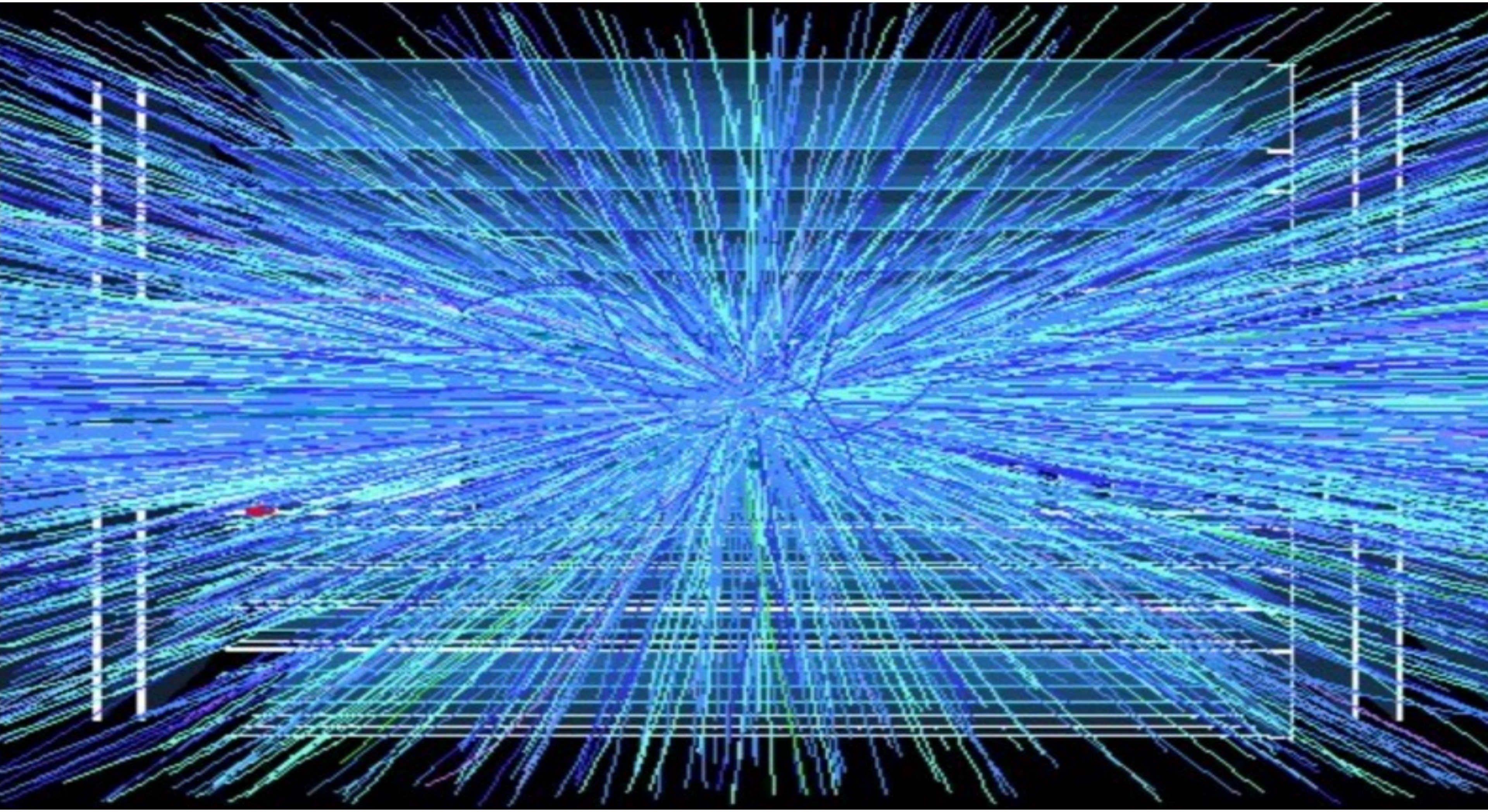
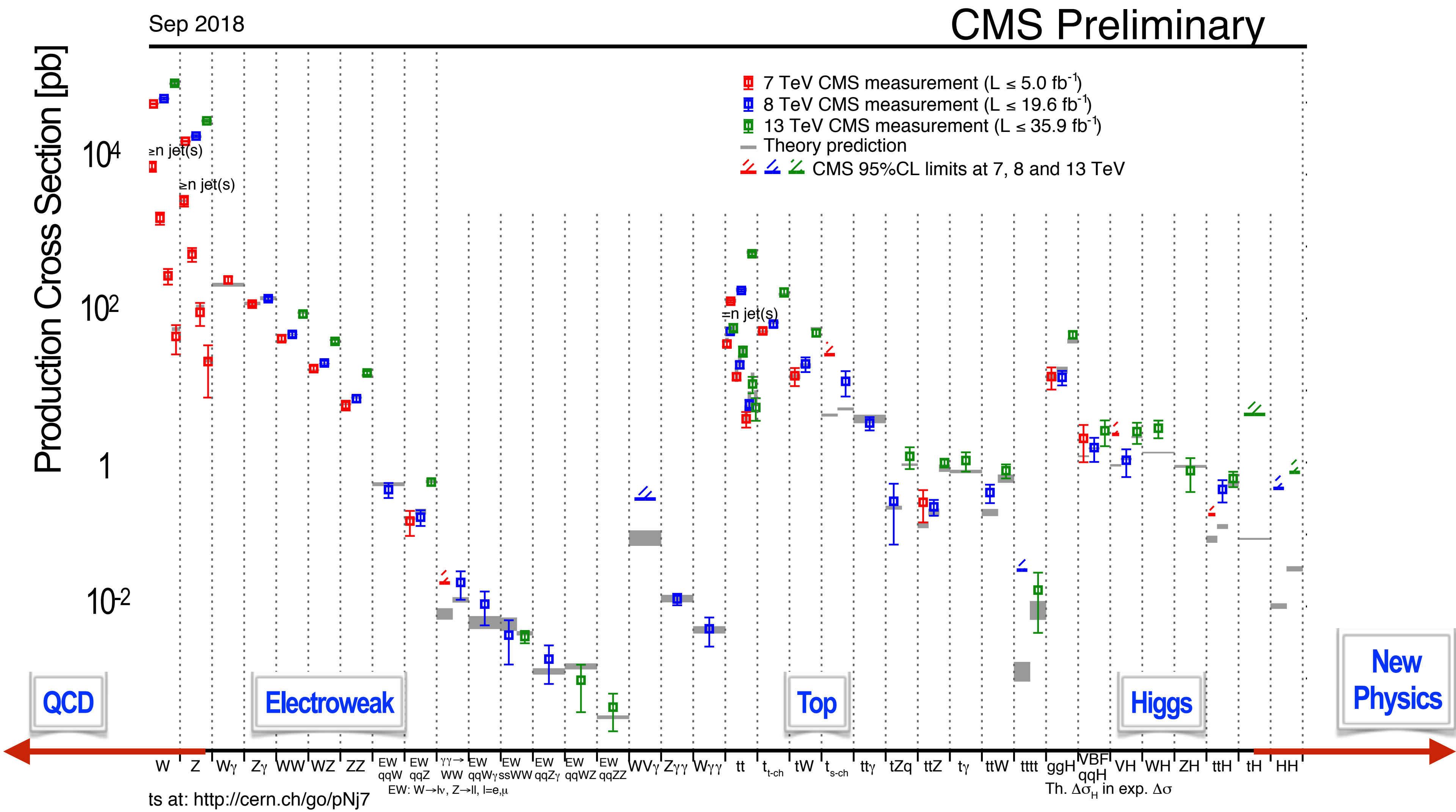
Physics at the HL-LHC



Andreas B. Meyer

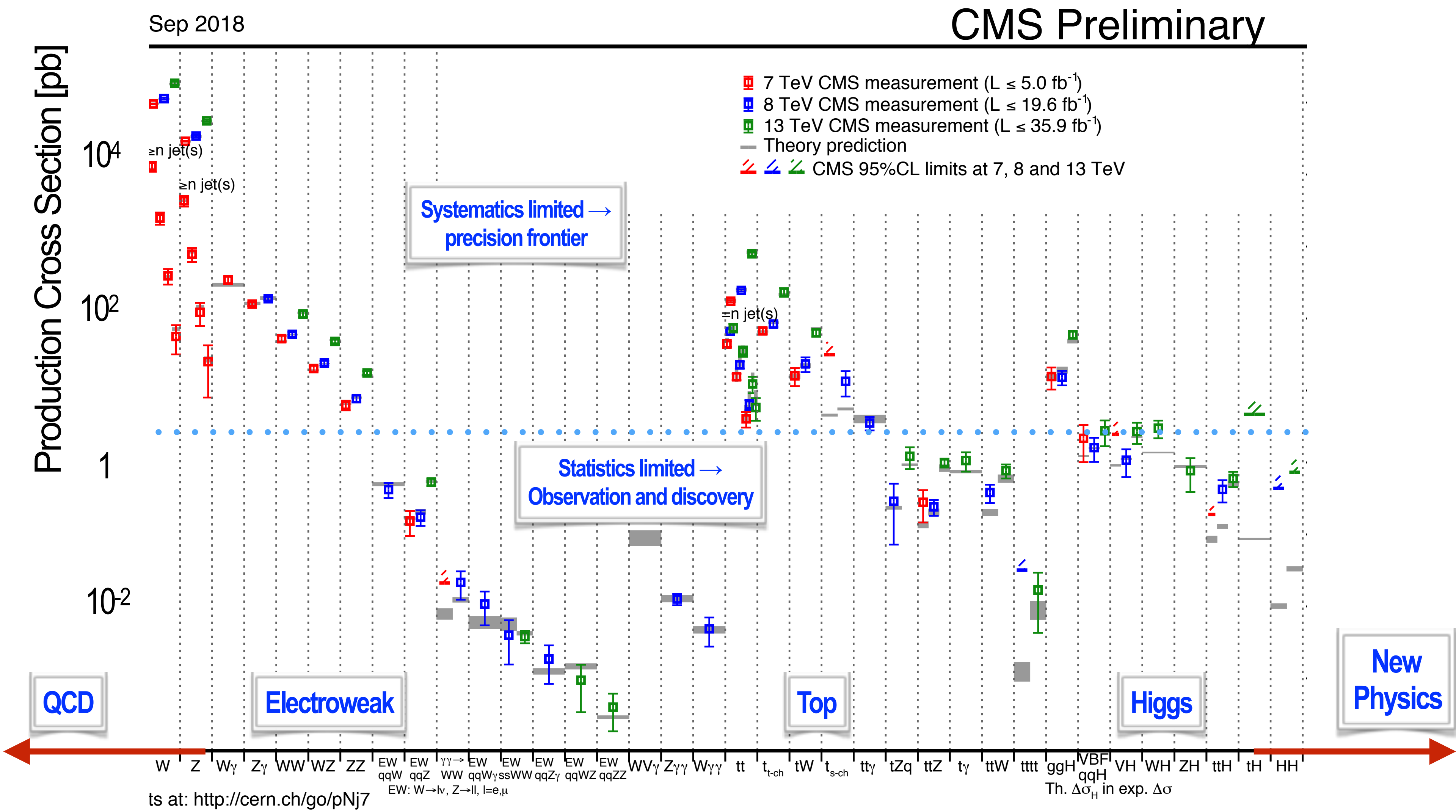
Terascale & Tuesday Seminar
27 November 2018

LHC Run-2



Sep 2018
CMS Preliminary
Production Cross Section [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 35.9 fb-1)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
QCD
Electroweak
Top
Higgs
New Physics
W Z Wγ Zγ WW WZ ZZ EW qqW EW qqZ γγ→WW EW qqWγ EW ssWW EW qqZγ EW qqWZ EW qqZZ WVγ Zγγ Wγγ tt t-ch tW ts-ch ttγ tZq ttZ tγ ttW tttt ggH VBF qqH VH WH ZH ttH tH HH
EW: W→lν, Z→ll, l=e,μ
Th. ΔσH in exp. Δσ
ts at: http://cern.ch/go/pNj7

LHC Run-2

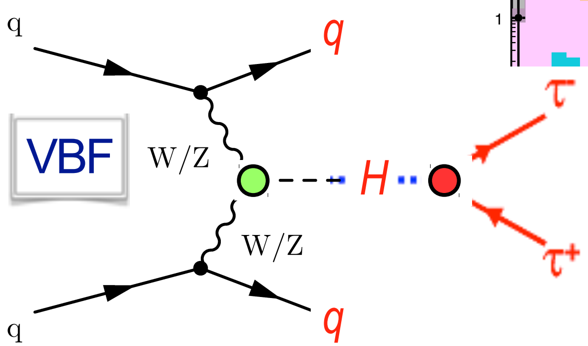


Huge Physics Reach

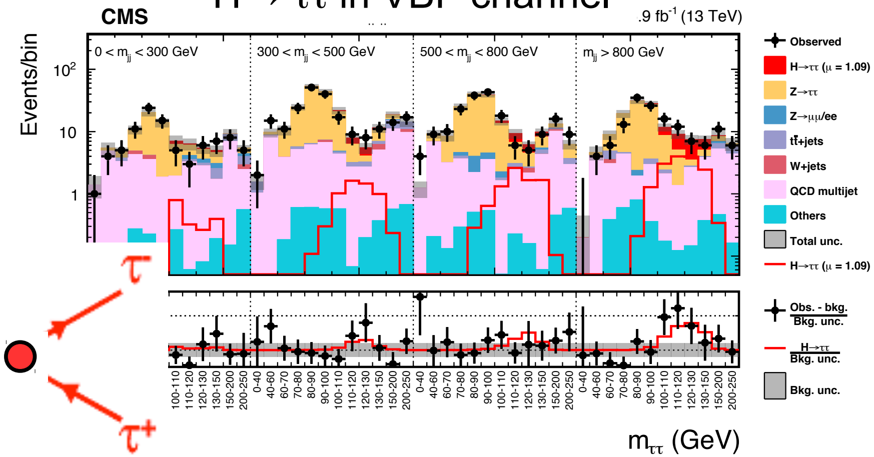
LHC Run-2 Highlight 17/18

Higgs - τ

Summer 2017

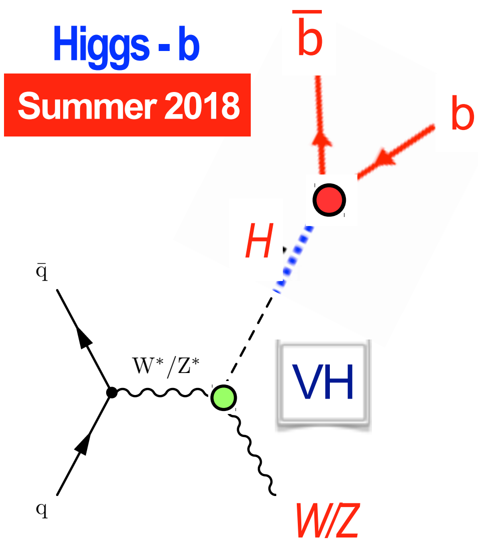


H→ ττ in VBF channel



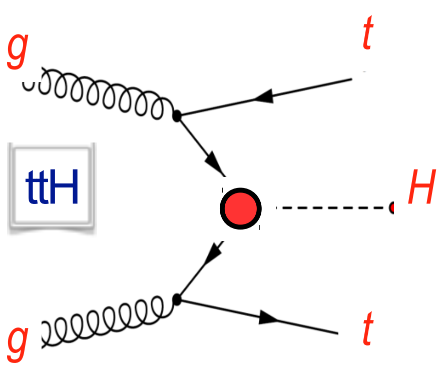
Higgs - b

Summer 2018

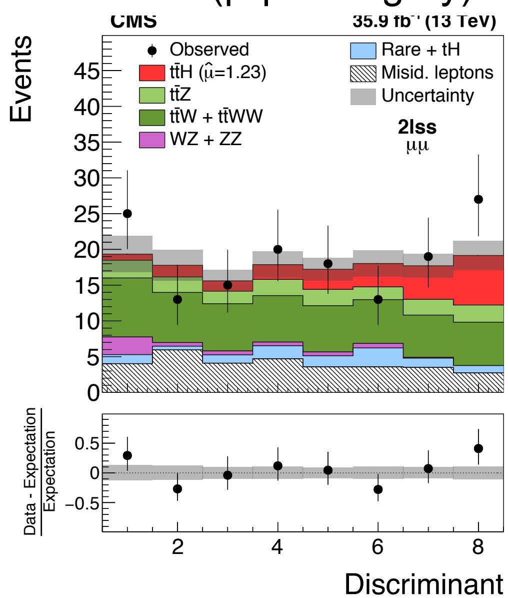


Higgs - top

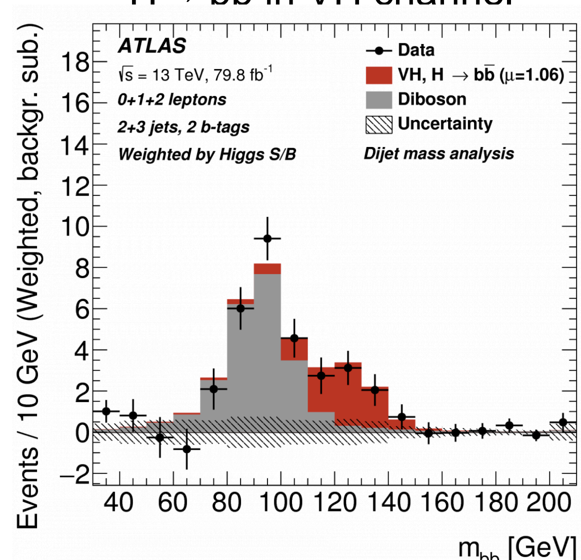
Spring 2018



ttH (μ±μ± category)

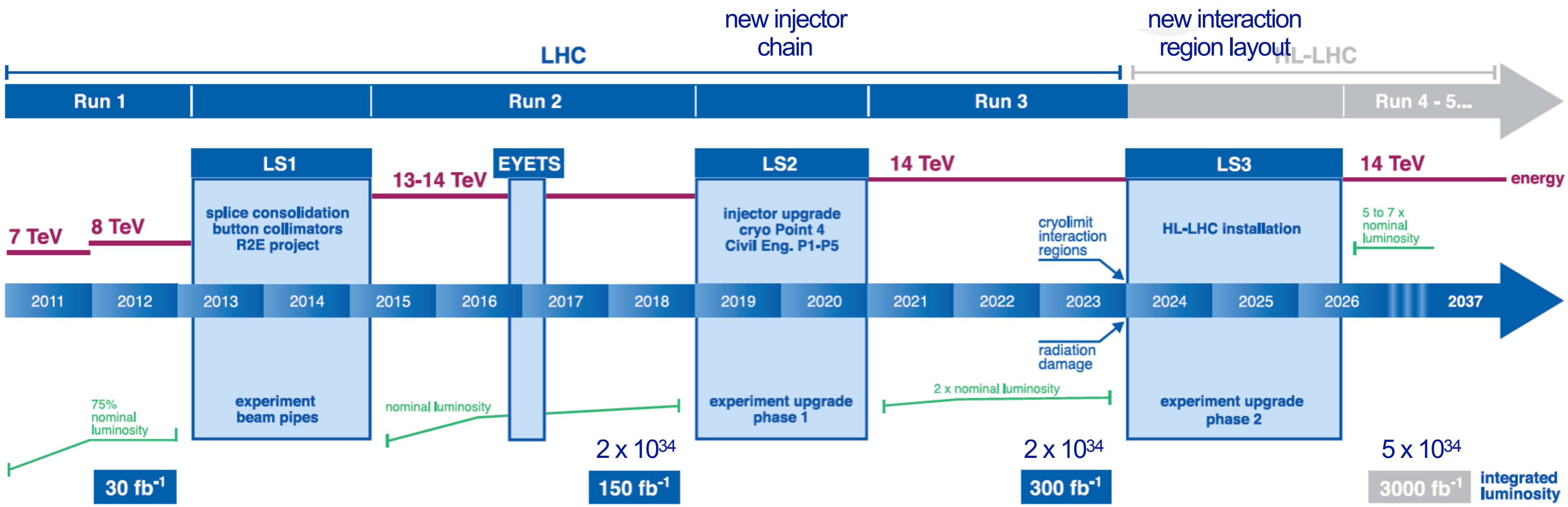


H→ bb in VH channel



Direct observation of Higgs-fermion couplings

The High-Luminosity LHC



Full exploitation of the LHC at the highest luminosity

- x 10 integrated luminosity (x 100 w.r.t 2016)
- Better detectors with larger acceptance, better triggers
- Improved analysis and theory

The High-Luminosity LHC

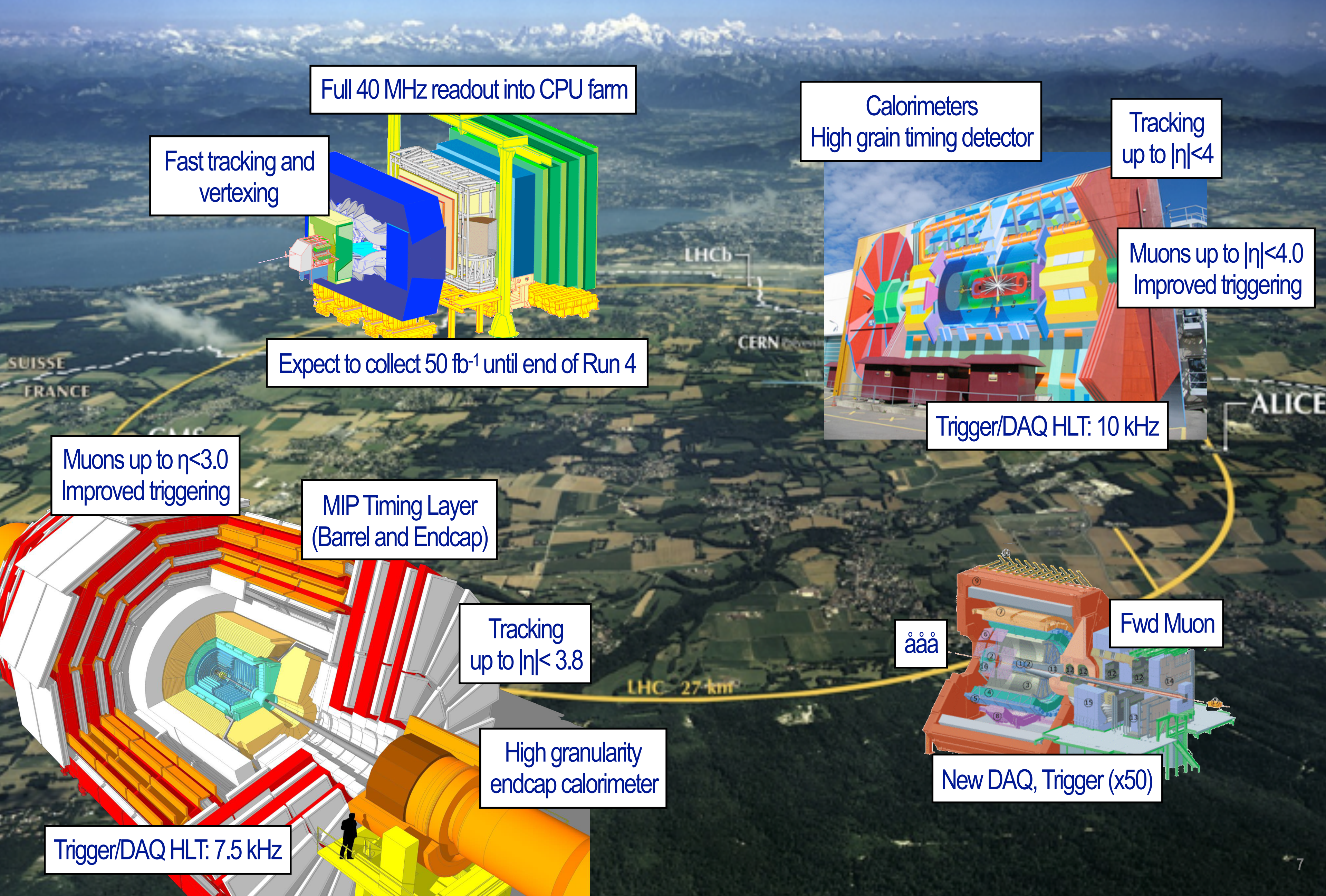
2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034

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

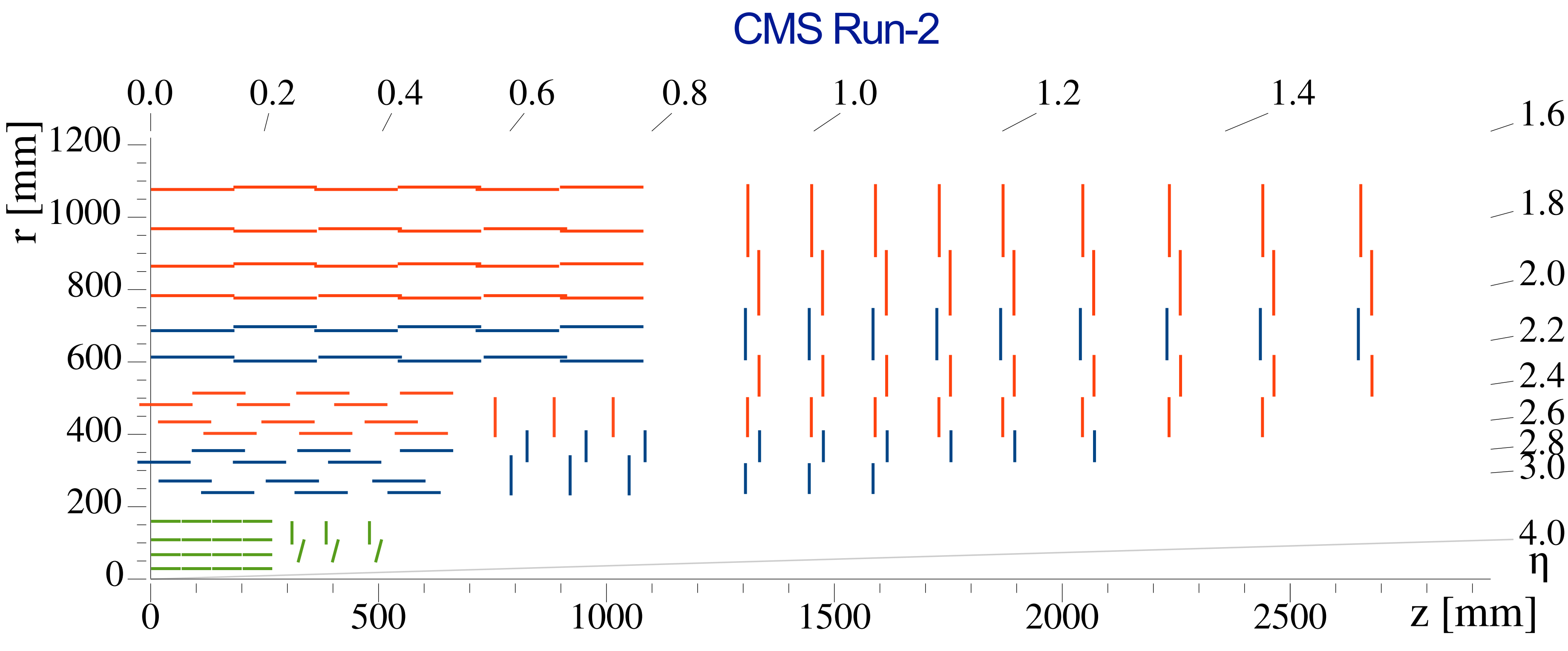
Full exploitation of the LHC at the highest luminosity

- x 10 integrated luminosity (x 100 w.r.t 2016)
- Better detectors with larger acceptance, better triggers
- Improved analysis and theory

Detector Upgrades

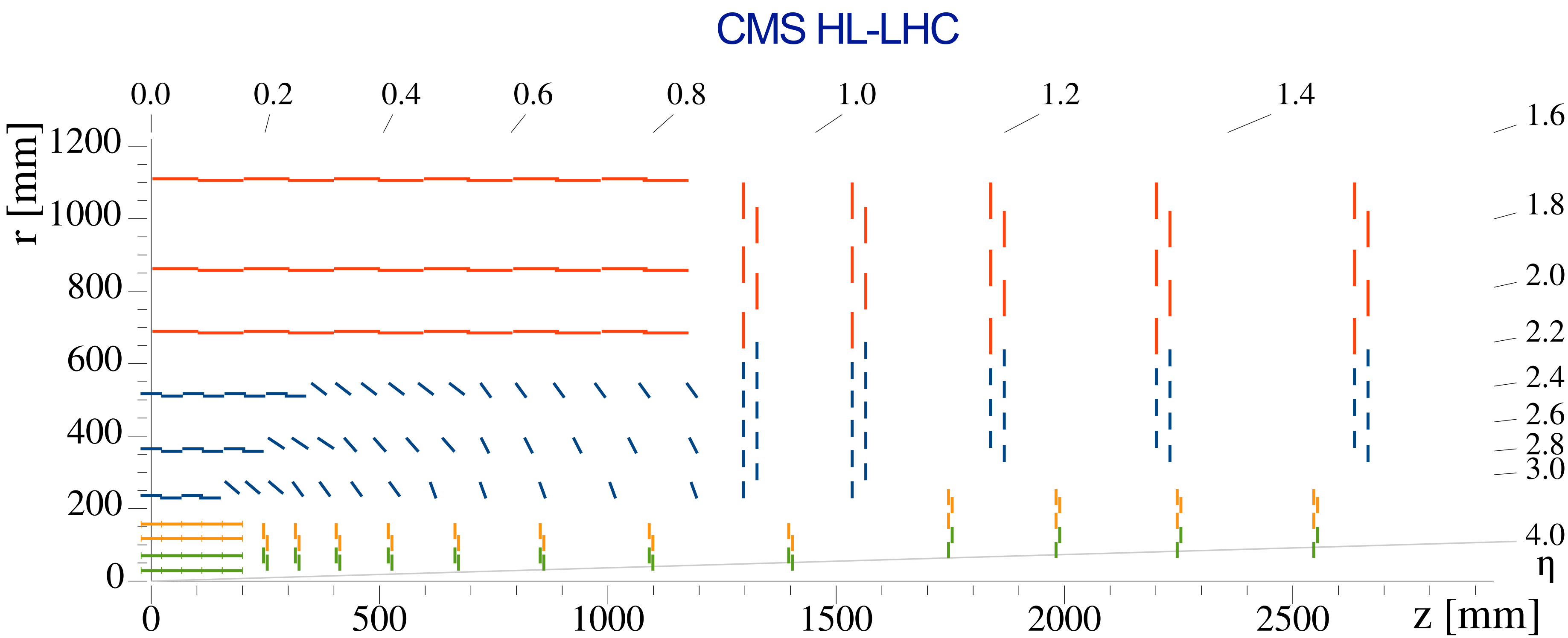


Example: Inner Track Detectors



Acceptance: |η| < 2.5

Example: Inner Track Detectors

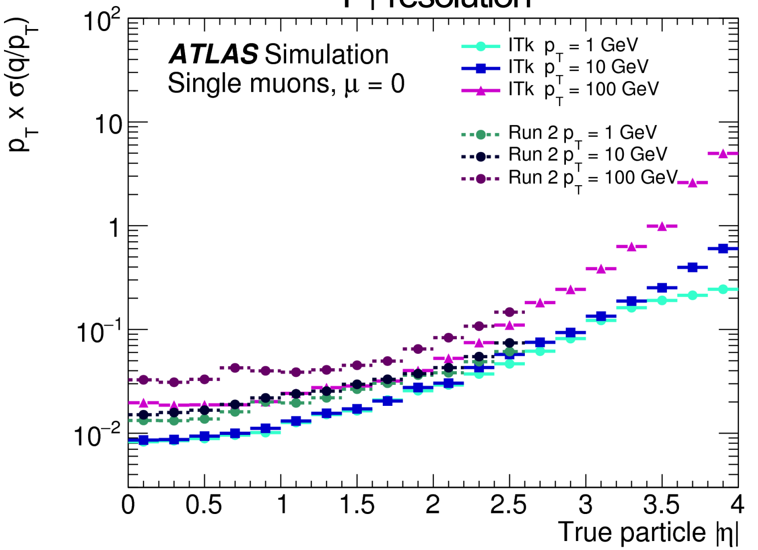


Much larger acceptance: |η| < 4
less detector material and better resolution

Detector Performance

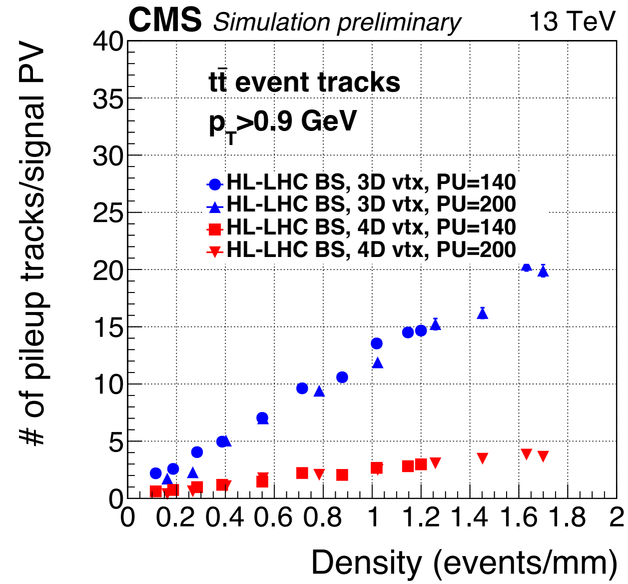
P_T resolution

ATL-TDR-025

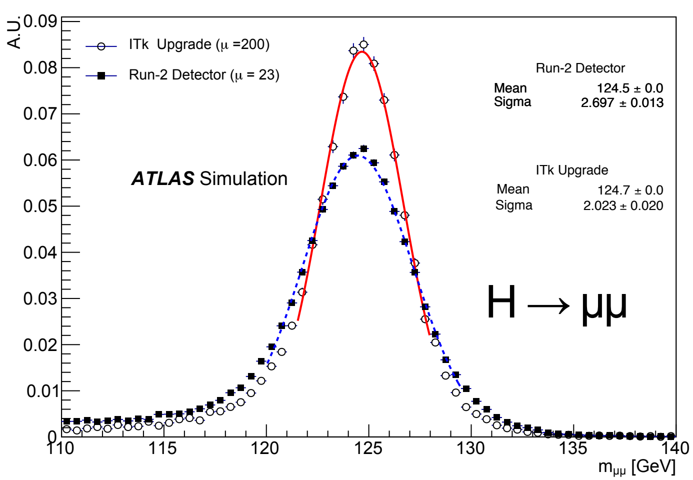


Suppression of PU-tracks using timing detector

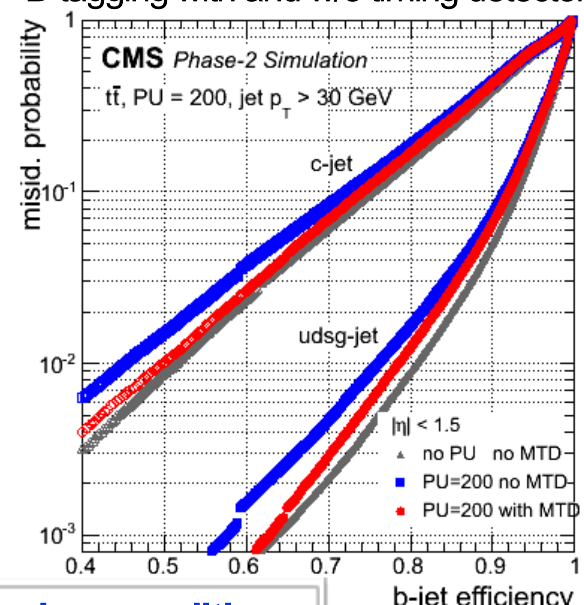
CMS-TDR-17-006



Mass Resolution



B-tagging with and w/o timing detector



Generally similar or better performance under harsher conditions

HL-LHC Physics

- **Standard Model**
  - Ultimate precision measurements and constraints
- **Higgs**
  - Precise determination of H(125) properties
  - Search for new phenomena in the Higgs sector
- **Direct Searches**
  - Supersymmetry
  - Long-lived particles
  - Dark Matter
  - Heavy Resonances
- **Flavour**
  - CKM metrology and QCD spectroscopy
  - Rare decays → flavour anomalies ?
- **Heavy Ions**
  - Precision study of material properties of QCD media
  - Study HI-like behaviour in small systems (pp and pA)

3 billion top / exp.

Higgs factory:
150 million H and 120 k HH

Novel approaches, better detectors: stringent tests of BSM scenarios

Low-P_T/high-P_T complementarity
No-lose theorem ?

Precise differential measurements

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
- Discuss new ideas and reassess prospects, in light of increased precision and new methods
- Begin a study of physics at the HE-LHC, a possible pp collider with energy of ~27 TeV
- Working Group Report, "YR2018", is imminent
- Two 10-page executive summaries (one on HL-LHC and one on HE-LHC) to be submitted to the European Strategy in December 2018

October 2017
Kick-off meeting

June 2018
Plenary meeting

December 2018
Submission of reports

1 March 2019
Jamboree

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

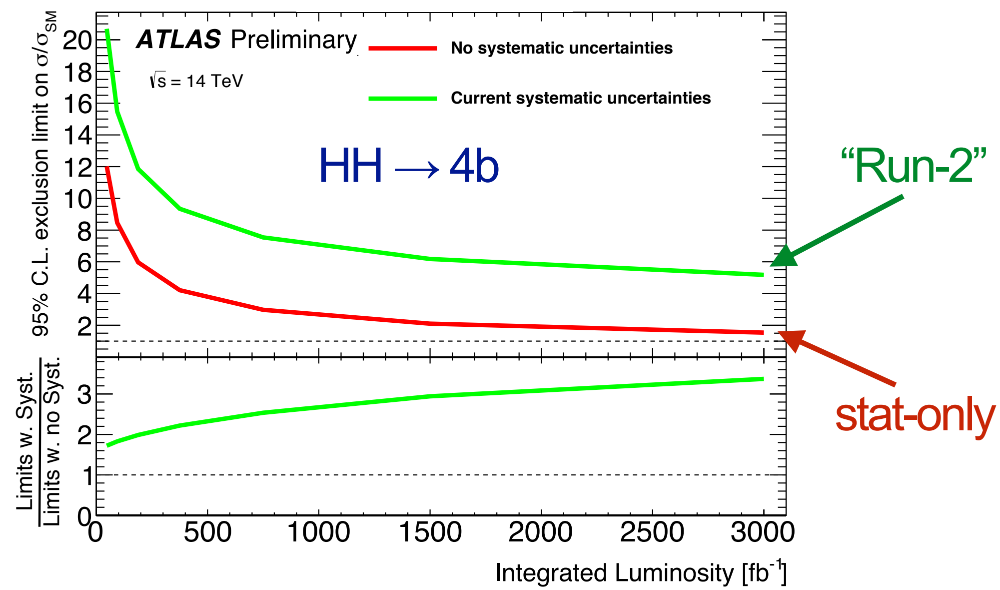
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FTR/index.html

HL-LHC Projected Uncertainties

- Effort to make realistic projections,
  → assumptions affect conclusions

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

ATL-PHYS-PUB-2016-024

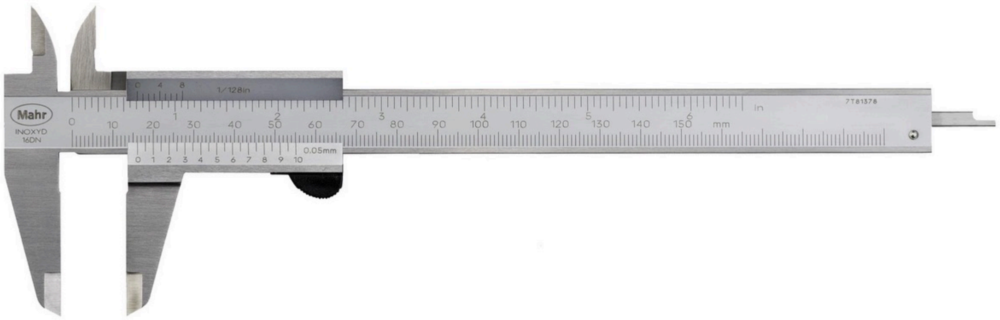


- ATLAS and CMS common approach
  - Statistical uncertainties scale as 1/√L
  - Theory: assume reduction by factor 2
  - Experimental systematics scale as 1/√L → until "floor"

  - "Floor" values for all physics objects estimated and agreed
  - Keeping "Run-2" and "stat-only" for comparison

Expect to exceed expectations

Standard Model

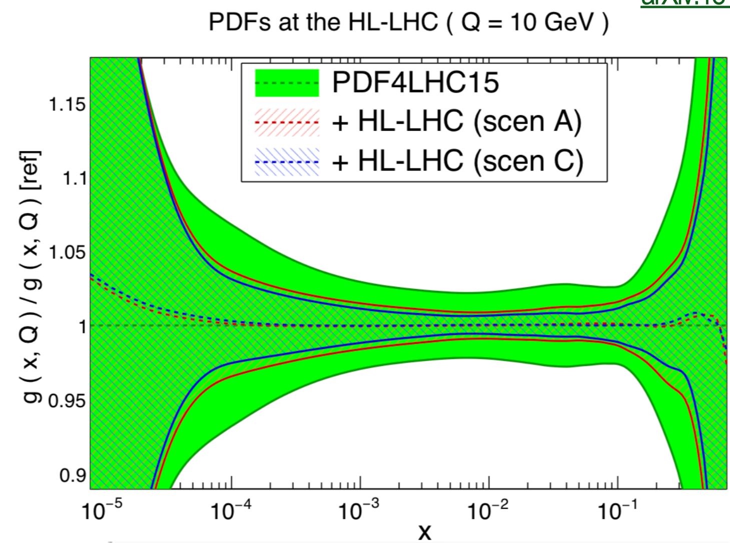


Ultimate Precision Measurements

Ultimate Precision PDF

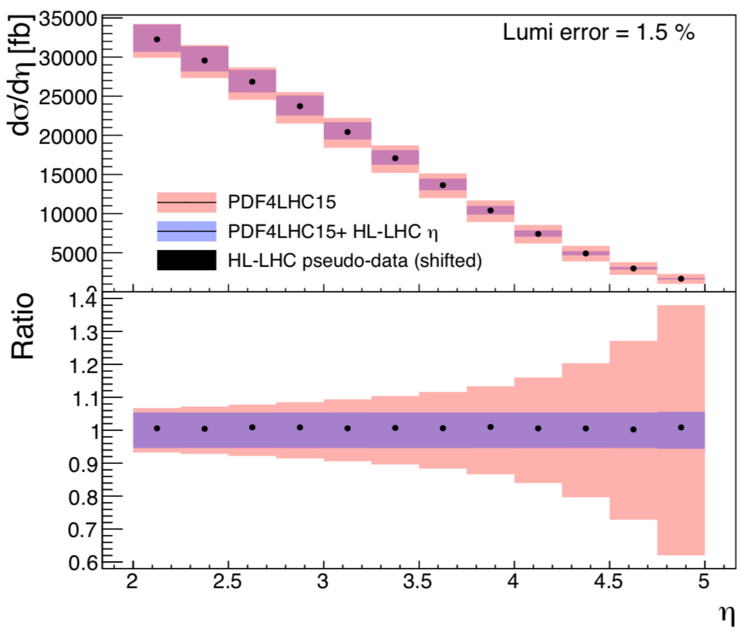
arXiv:1810.03639

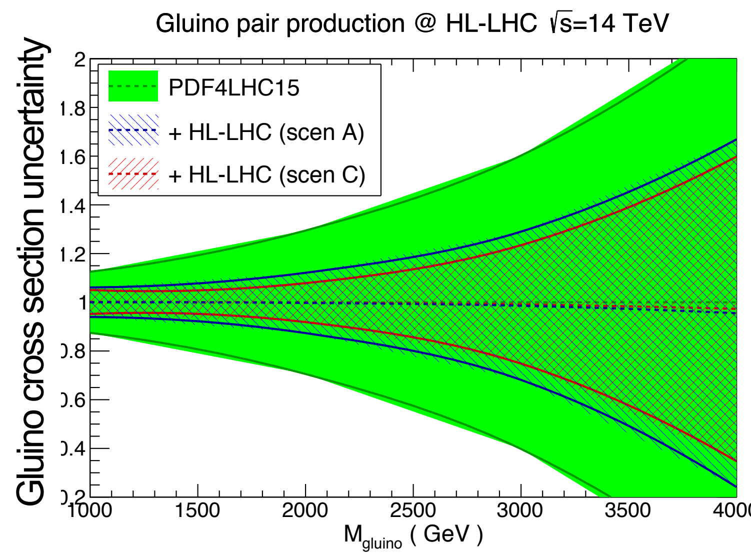
- Parton density distributions based on ultimate precision differential cross sections
- Projection using pseudo-data of Z(pt), high-mass DY, top quark pair, W+charm, direct photon, inclusive jets



Factor 2–5 expected improvement

Example W+charm





Strong impact on high mass searches

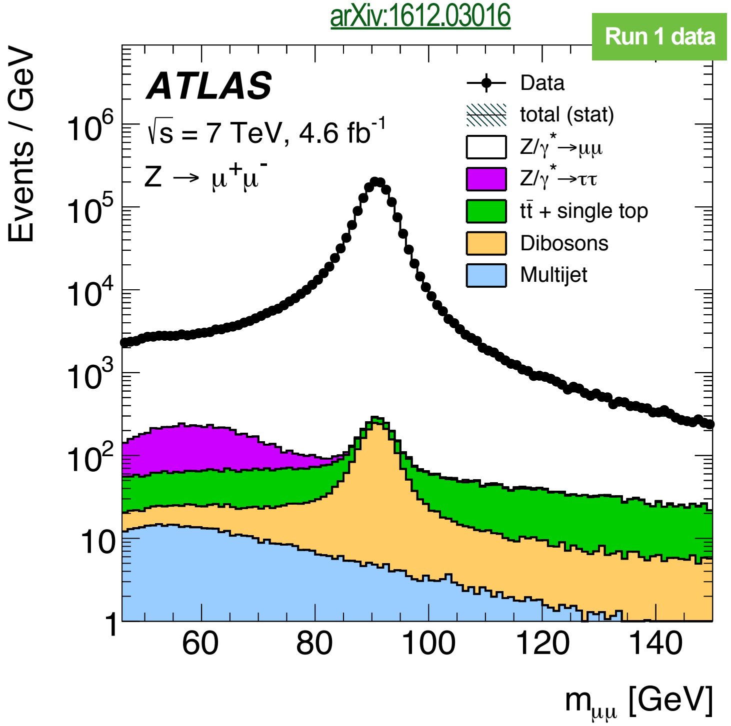
Ultimate Precision Cross Sections

- Run-2 example: $\sigma_{fid}(Z/\gamma^* \rightarrow \ell\ell)$ = 502.2 ± 0.3 (stat) ± 1.7 (syst) ± 9.0 (lumi) pb

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

Luminosity is single dominant uncertainty

arXiv:1612.03016



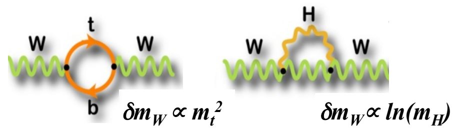
- HL-LHC
  - Improved luminosity detectors (being designed)
  - Further refined Van-der-Meer analysis
  - Additional low-PU runs for cross section measurements (no uncertainty due to low-to-high PU extrapolation)

- Once measured at (sub-)percent level, Z production rate can help luminosity measurement → test and prove in Run-3

arXiv:1806.02184

Target luminosity uncertainty YR2018: 1%

Ultimate Precision W Mass

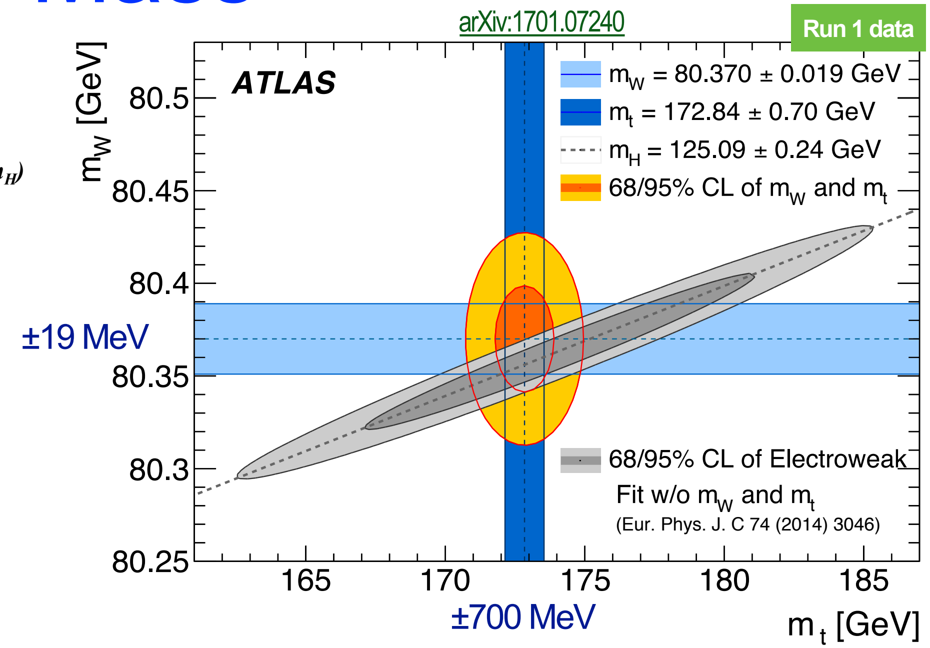


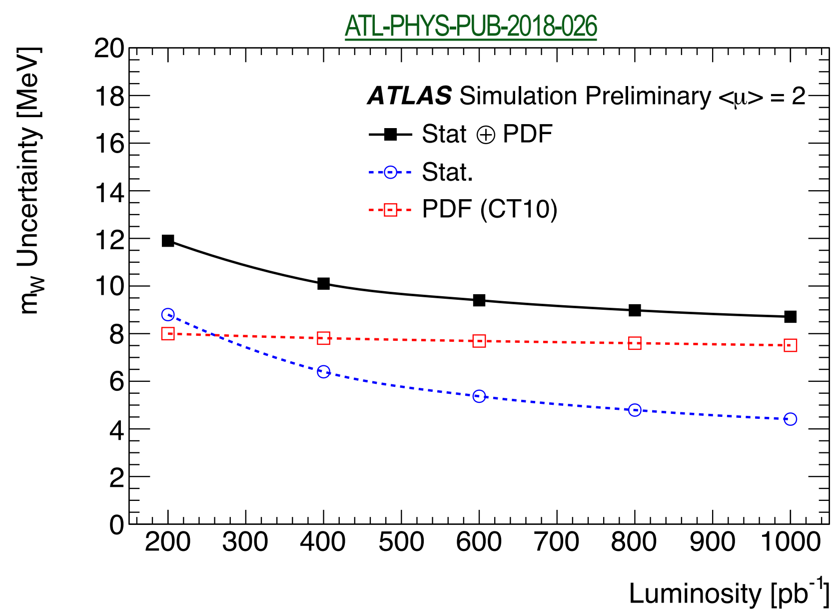
- m_{top}, m_W and m_H connected via loop corrections → constrain and test SM

- Current dominant uncertainty: PDF

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

- 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**

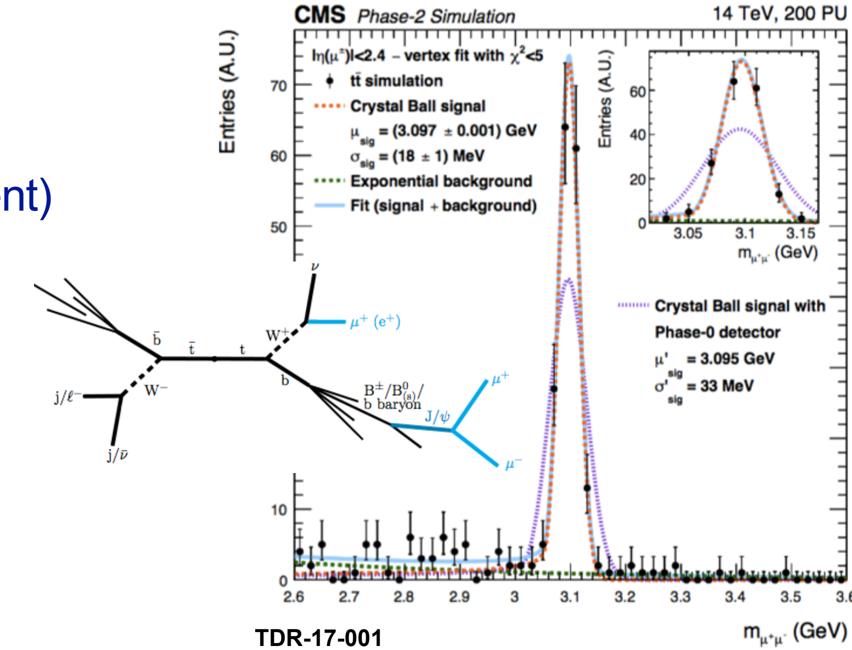




Ultimate Precision Top Mass

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

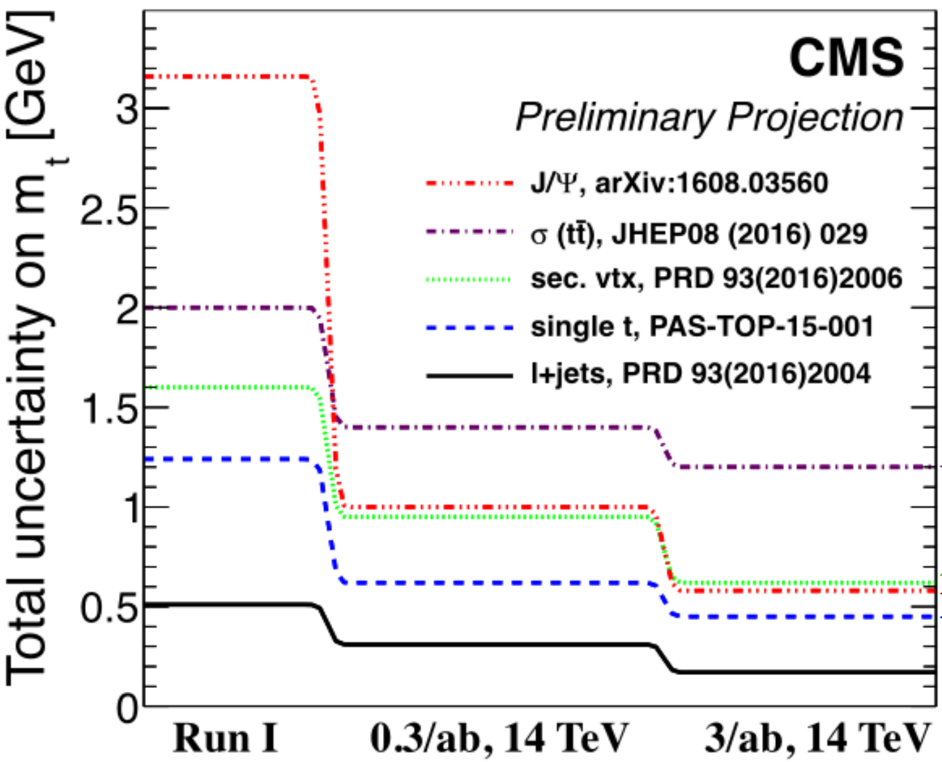
$t \to bW \to J/\psi\, X \ell \nu$



TDR-17-001

J/ψ: δm_{top} ~ 0.5 GeV

CMS-PAS-FTR-16-006



m_{pole} from σ(tt)
2ndary vertex
J/ψ
single top
ℓ+jets

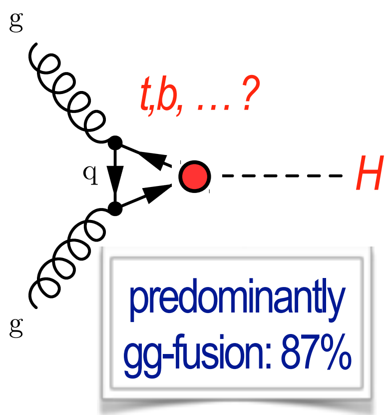
better already now

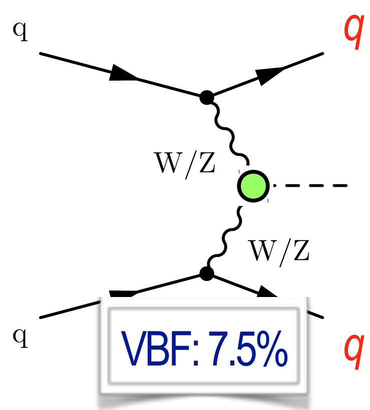
CMS-TOP-18-004

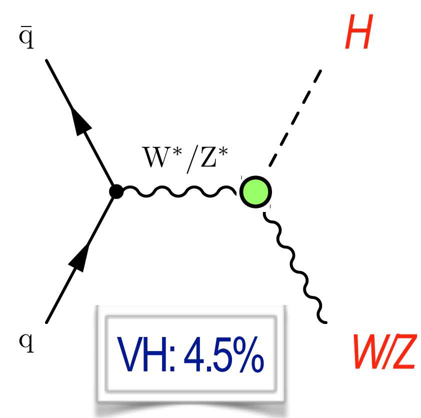
Higgs

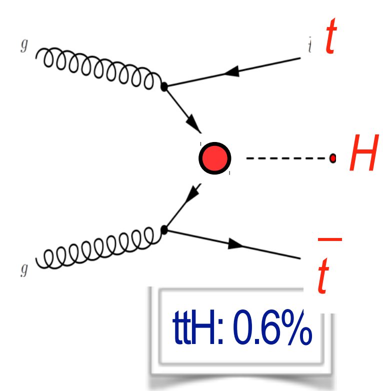
Precise Properties and Couplings for H(125)
Searches in the Higgs Sector

Higgs Production and Decay



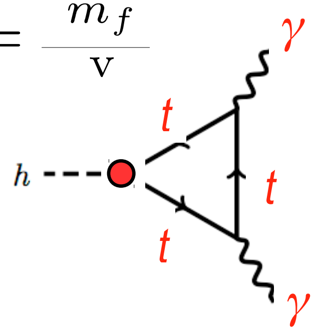




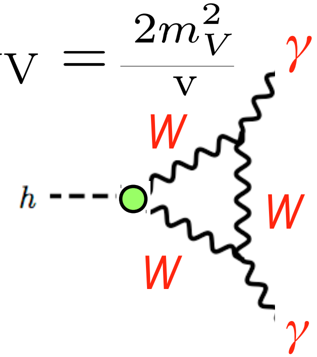


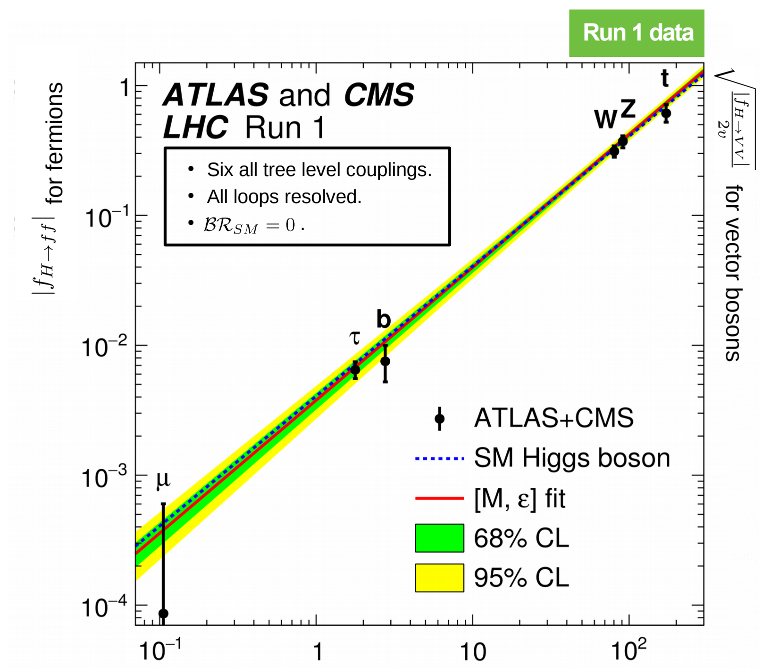
- "κ-model": Fit of scale-factors κ to the data assuming SM processes

$$\kappa_{\mathrm{Hff}} = \frac{m_f}{v}$$



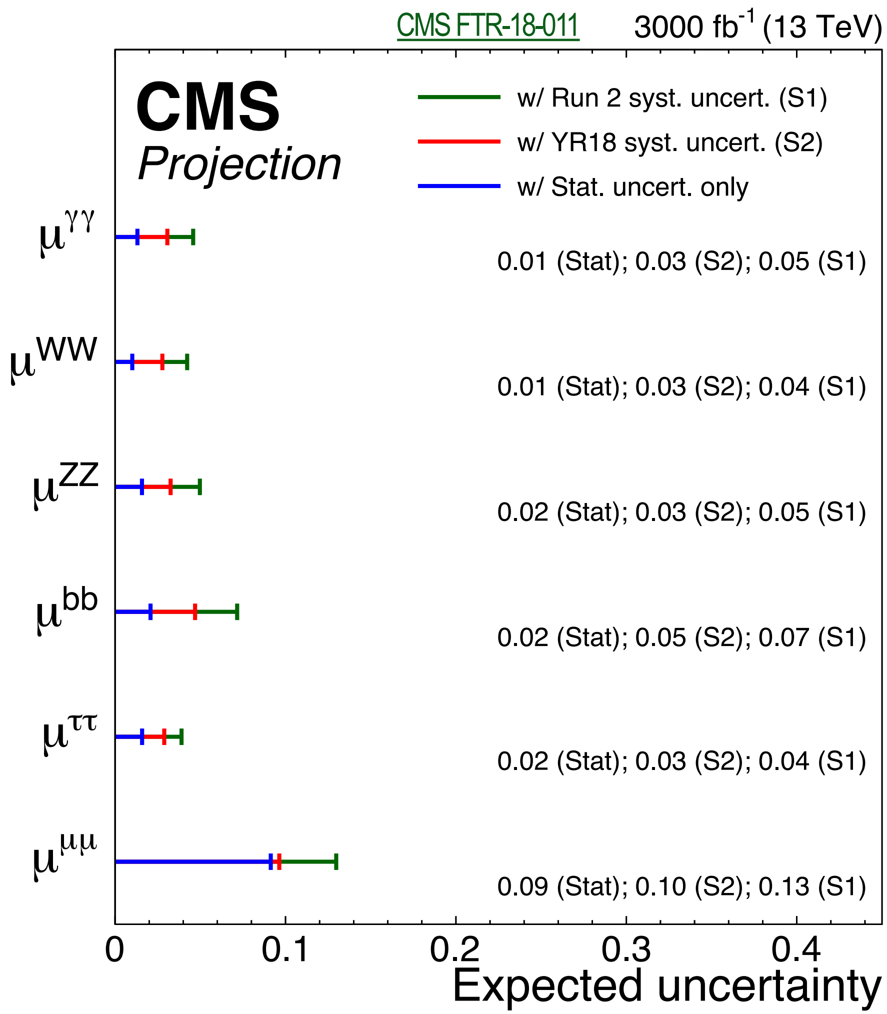
$$\kappa_{\mathrm{HVV}} = \frac{2m_V^2}{v}$$

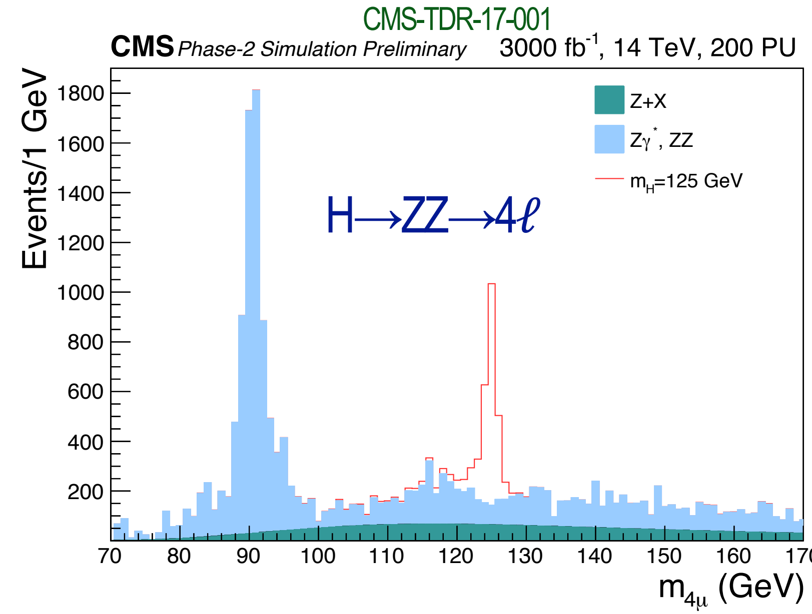


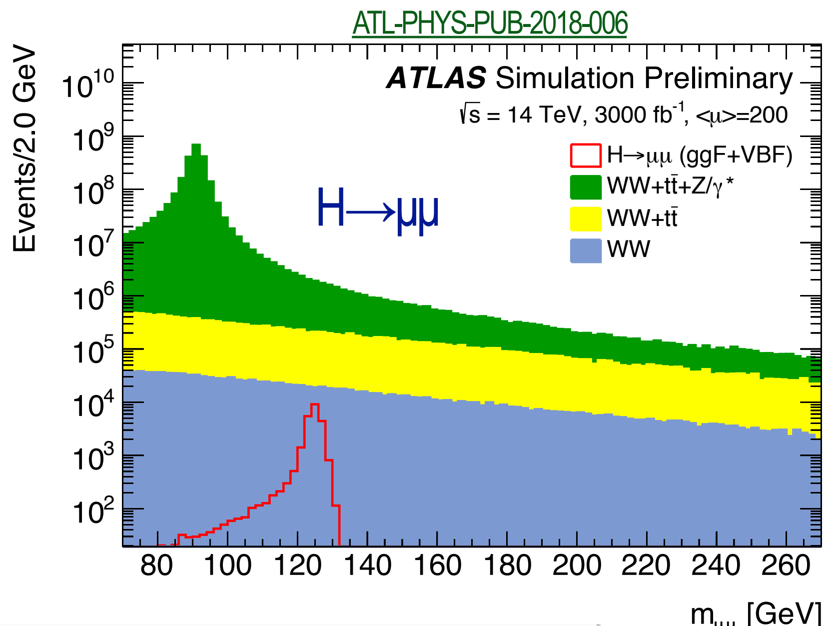


JHEP 08 (2016) 045

Higgs Measurements



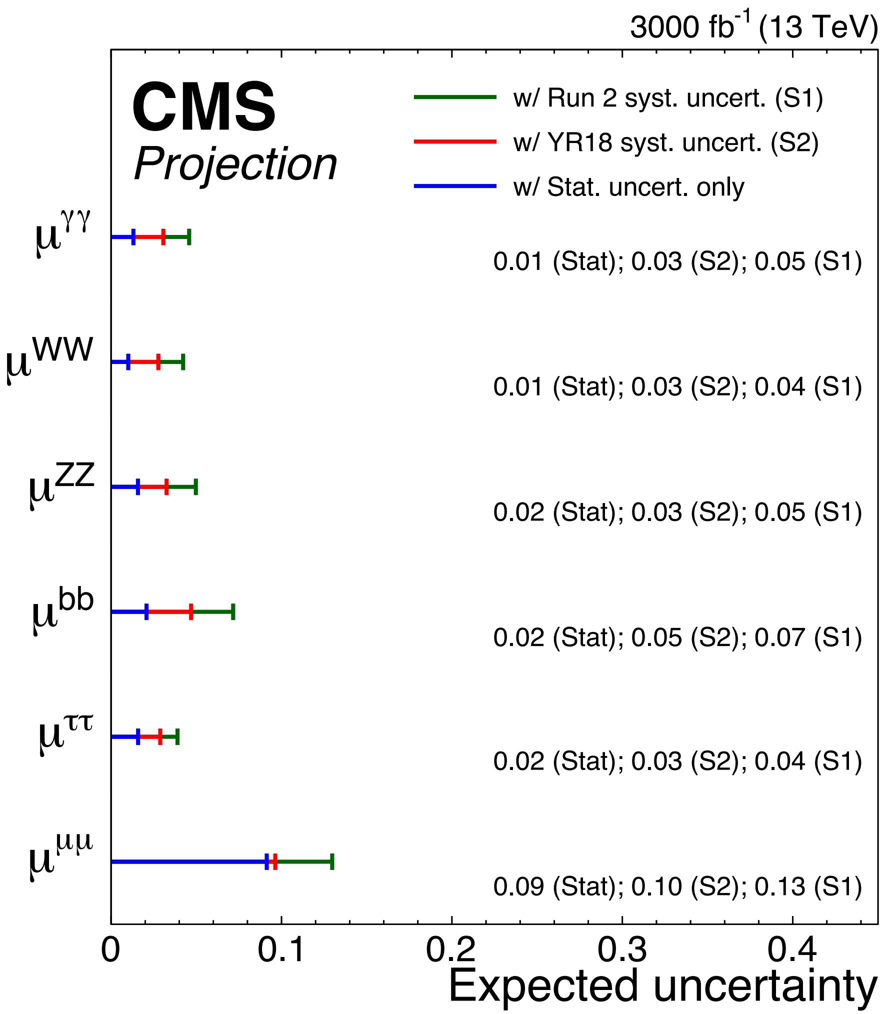


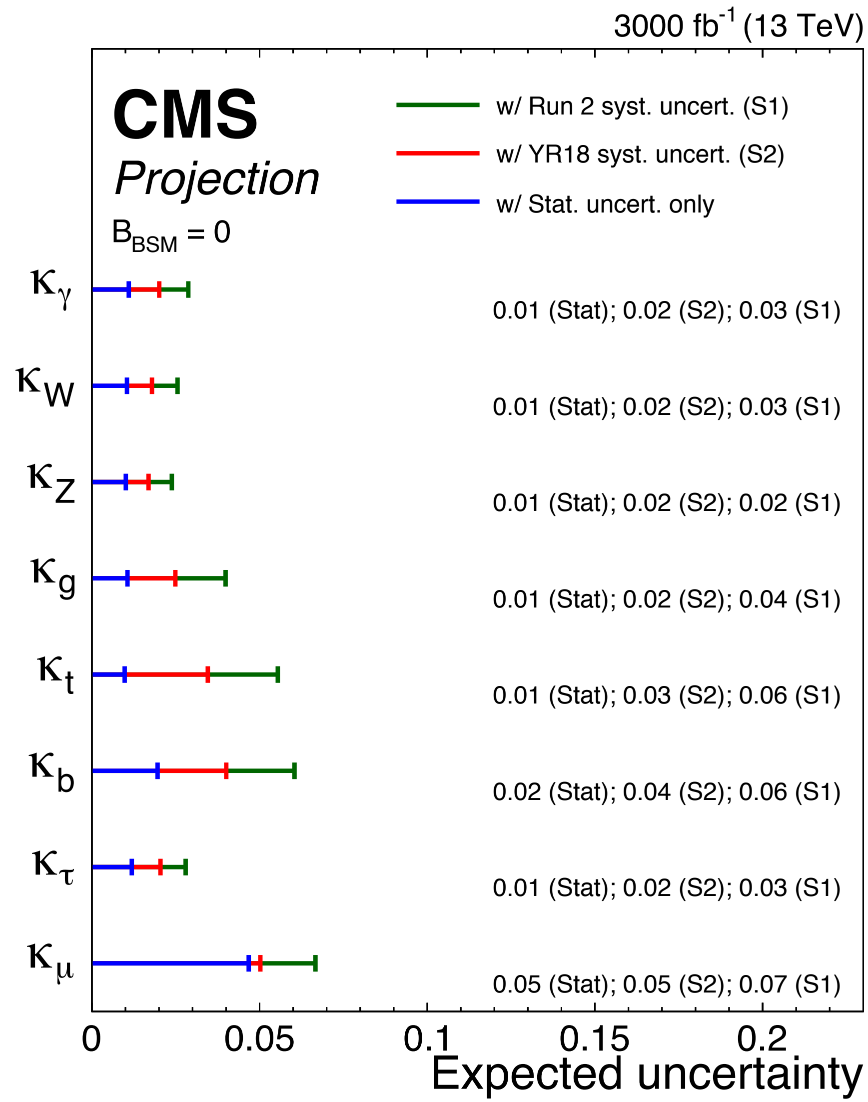


Signal strength uncertainties: most channels ~3%, bb ~5%, μμ ~10%

Higgs Couplings

CMS FTR-18-011

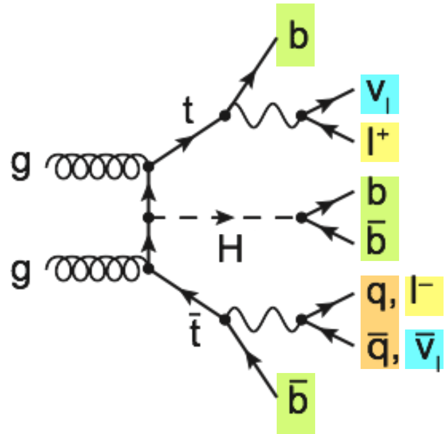




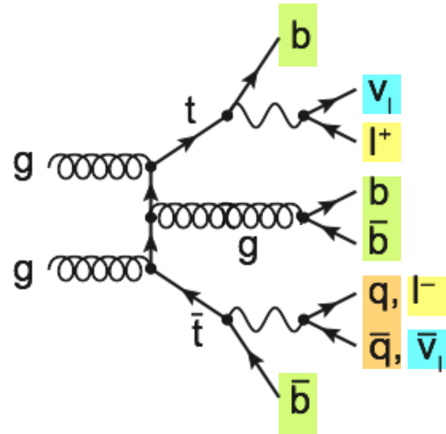
Combination of ATLAS and CMS underway

κ: 2-4%, κ_μ ~5%

ttH → bb

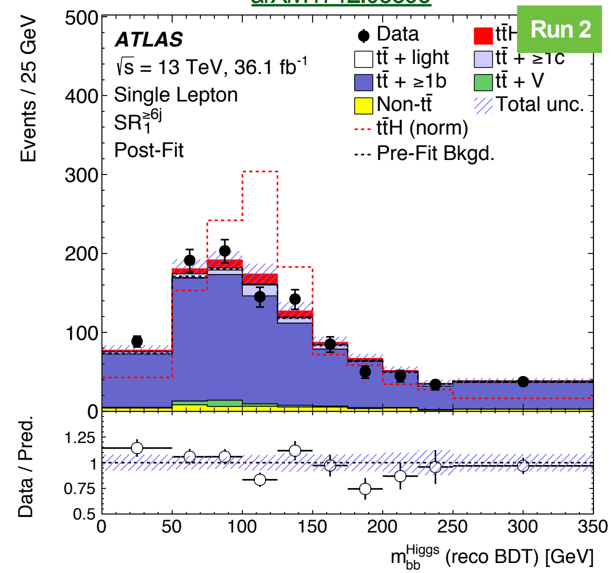


ttH signal



tt+HF background

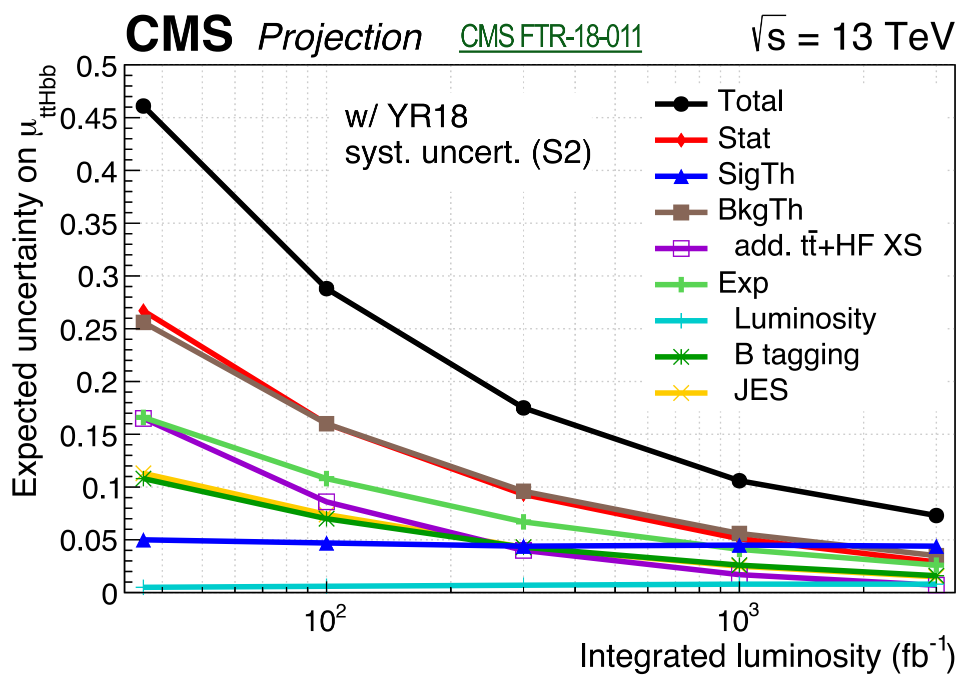
arXiv:1712.08895



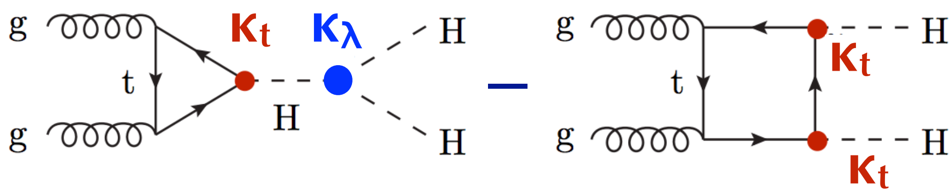
- For 3ab⁻¹ CMS expects δμ ~ 7%
  - tt+HF background constrained by data
  - dominant uncertainty: signal theory

- For ATLAS/CMS combination:
  CMS tt+HF uncertainty set to 10%
  no significant impact on κ-results

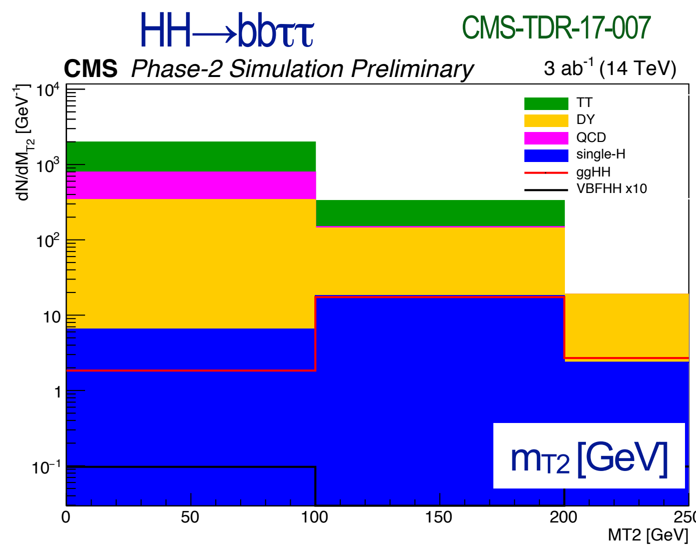
CMS FTR-18-011

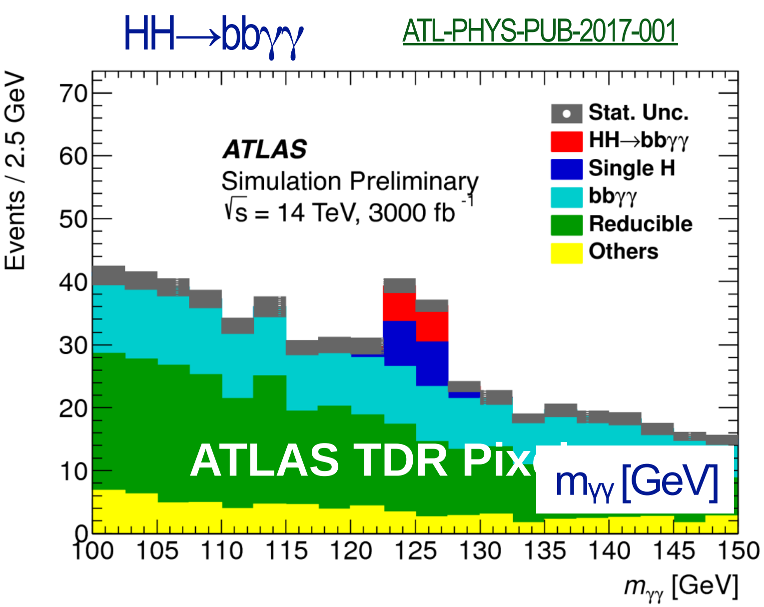


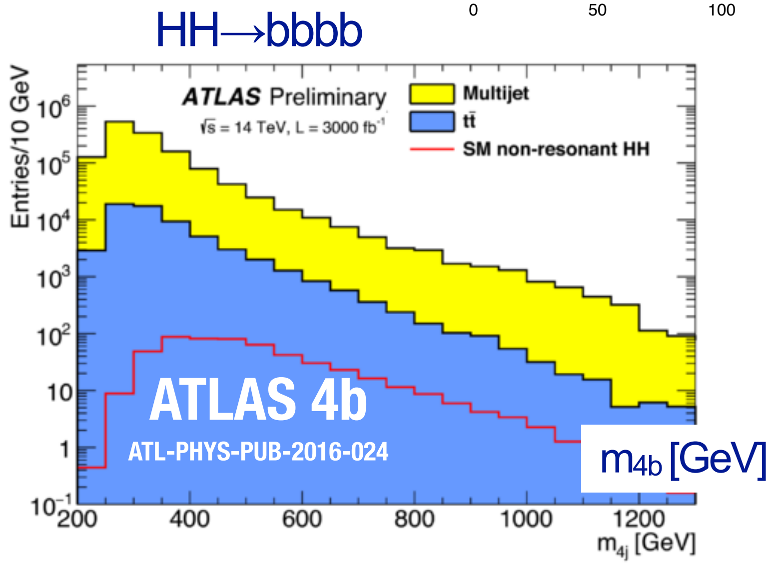
HH



- HL-LHC ultimate goal: observation of trilinear coupling
- 120k HH events expected
- High backgrounds (bbbb, bbττ) or small BR (bbγγ)
- Additional constraints on κλ, e.g. from differential measurements of single Higgs

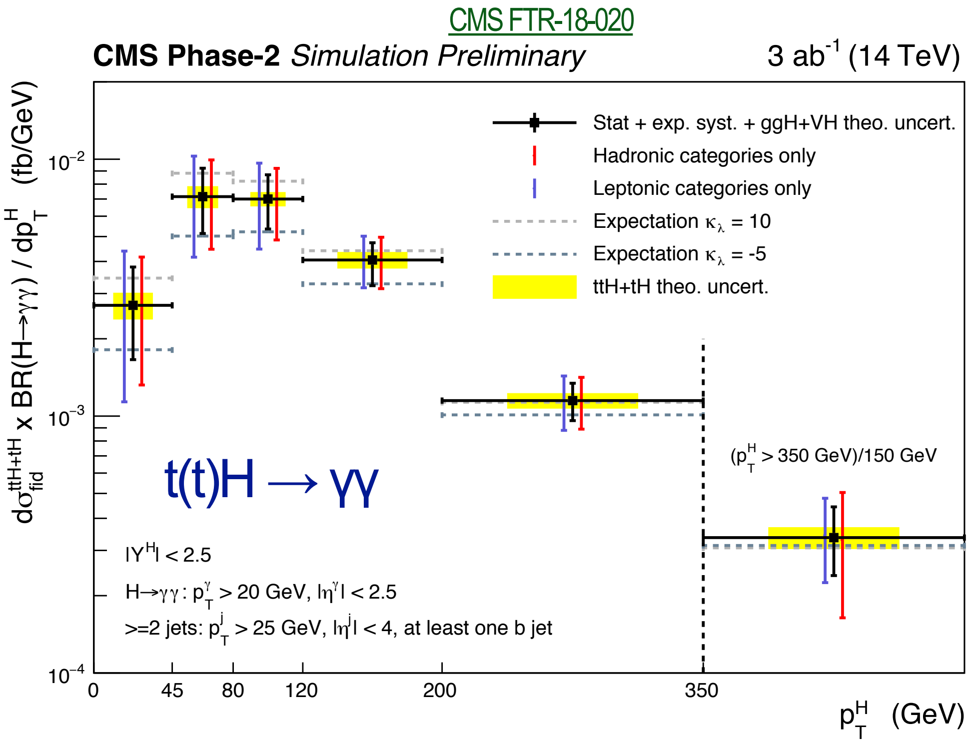


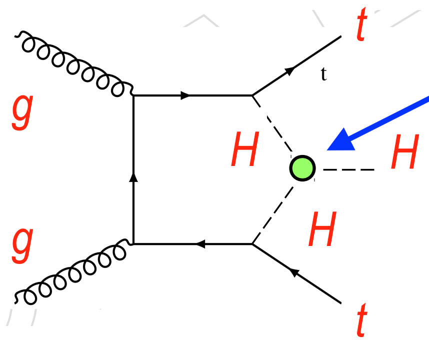




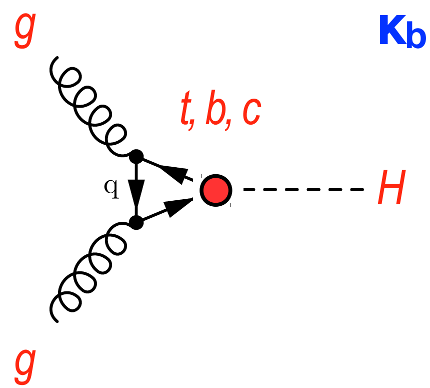
Being updated for YR2018: expect 2-3σ significance per experiment

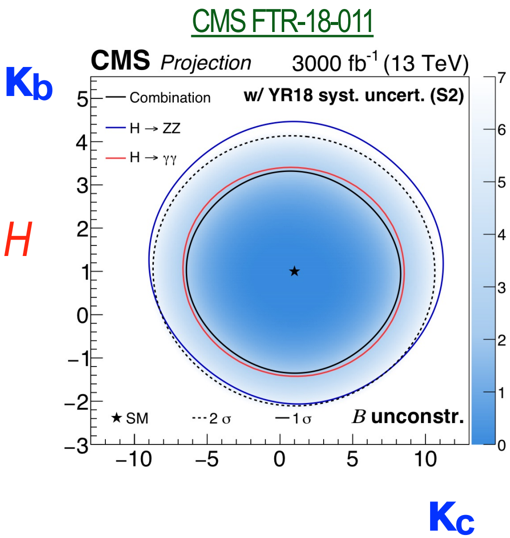
Differential Higgs Measurements





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

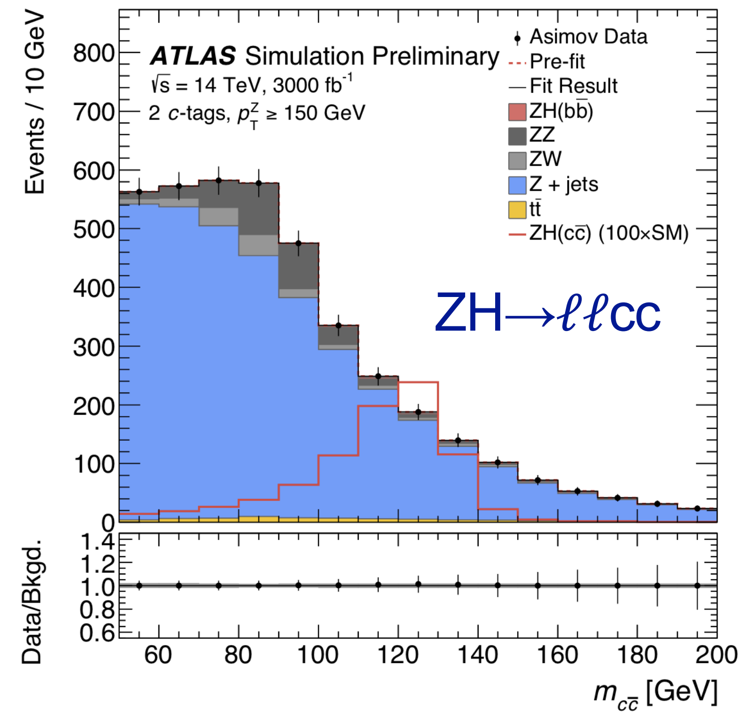
With 3000 fb^{-1} constrain κ_c and κ_λ to a few times SM

Higgs and Charm

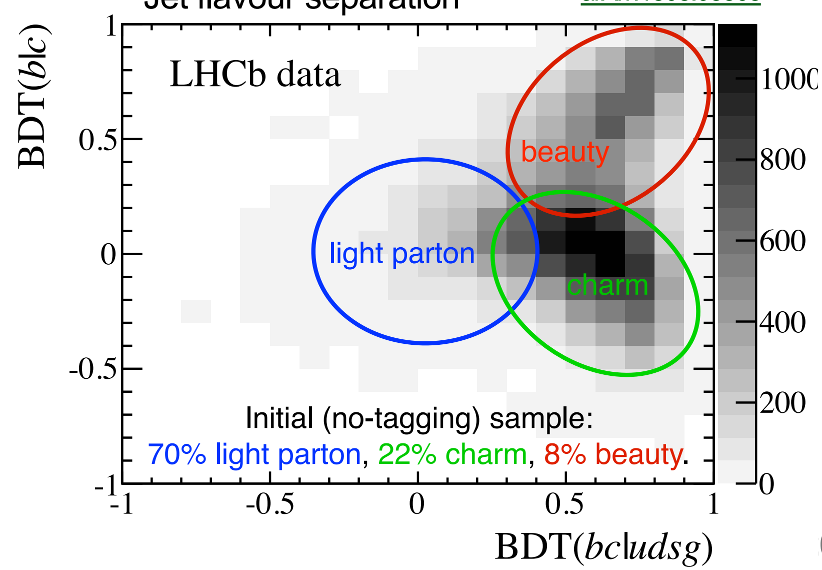
- BR(H → cc): ~3%
- ATLAS: ZH →ℓℓcc
  - Run-2: μ < 110 x SM @ 95CL arXiv:1802.04329
  - HL-LHC: μ < 6.3 x SM @ 95CL
- LHCb:
  - H → cc (Run-1): μ < 7900 x SM LHCb-CONF-2016-006
  - For 300 fb^{-1} expect better than 7 x SM
- Refined multi-class flavour separation algorithms promise further improvements

Good prospects also for H→cc

ATL-PHYS-PUB-2018-016



Jet flavour separation arXiv:1808.08865

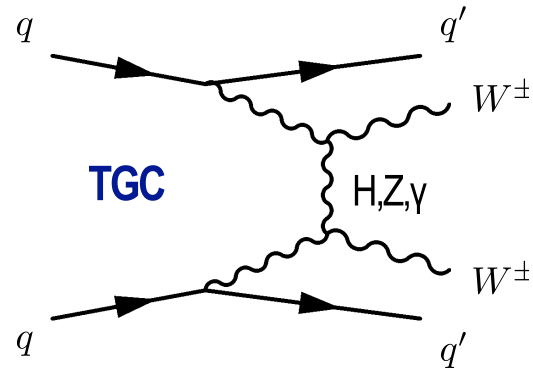


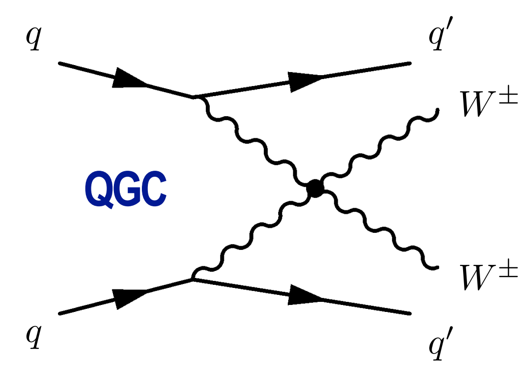
Vector Boson Scattering

- Triple and quartic gauge couplings
- Electroweak WW and WZ scattering observed in Run-2

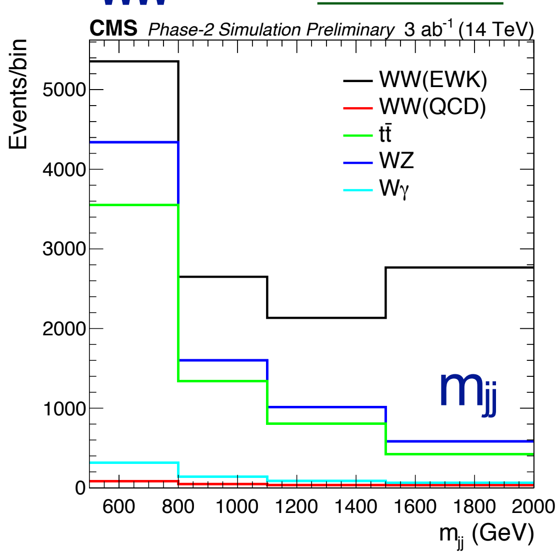
ATLAS-CONF-2018-033 arXiv:1709.05822

- WW, WZ, ZZ studied for YR2018



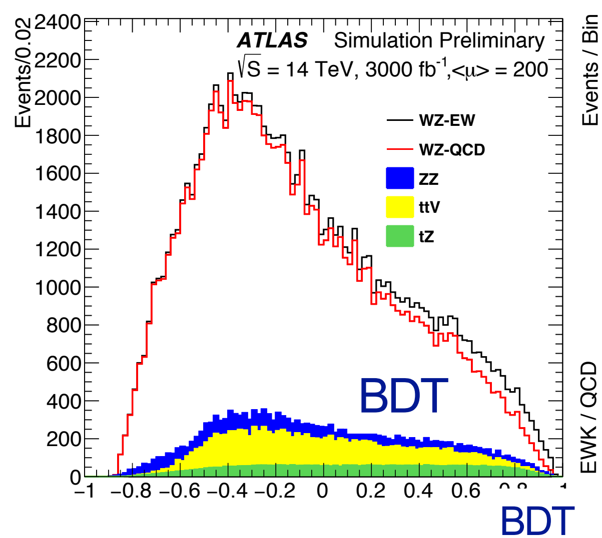


WW CMS-FTR-18-005



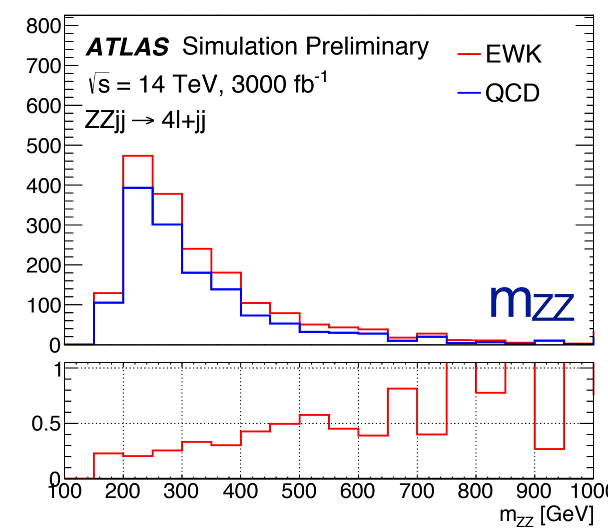
δσ ~ 3% and < 10% in Run 3

WZ ATL-PHYS-PUB-2018-023



δσ 5 - 10%

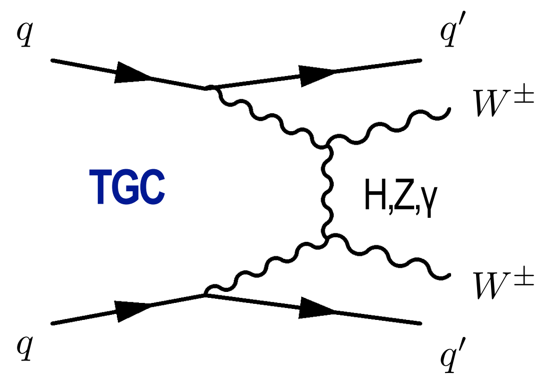
ZZ ATL-PHYS-PUB-2018-029



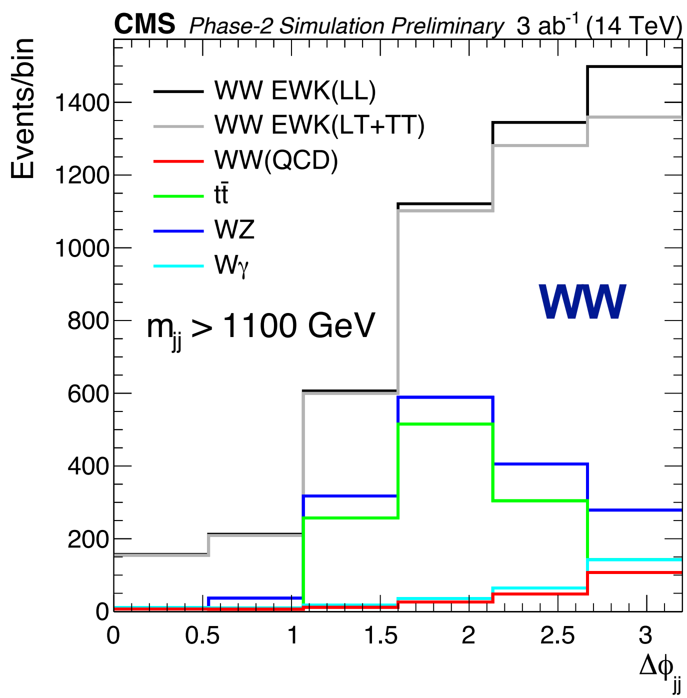
δσ ~10%

Longitudinal Vector Boson Scattering

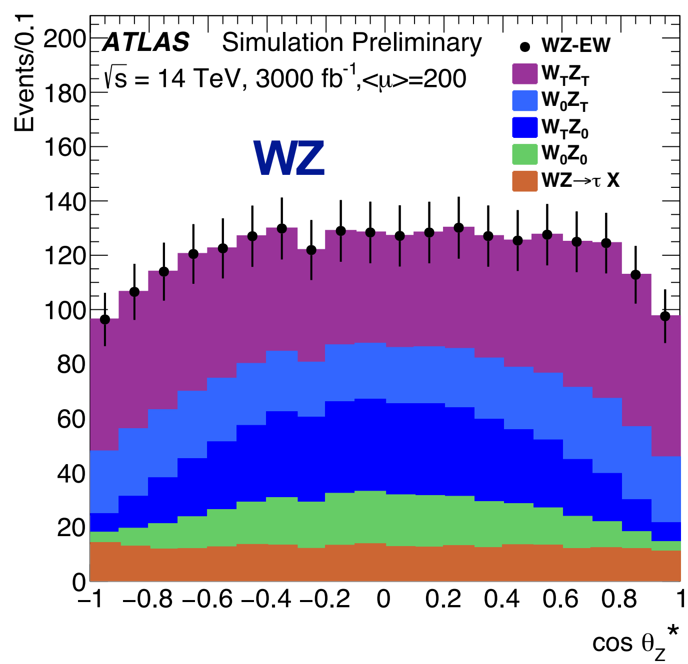
- Unitarization of $V_L V_L \rightarrow V_L V_L$ cross section at TeV scale: Scalar Higgs and/or new physics to cancel divergence
- Direct test of EW-symmetry breaking mechanism
- HL-LHC improved forward detectors and acceptance



CMS-FTR-18-005



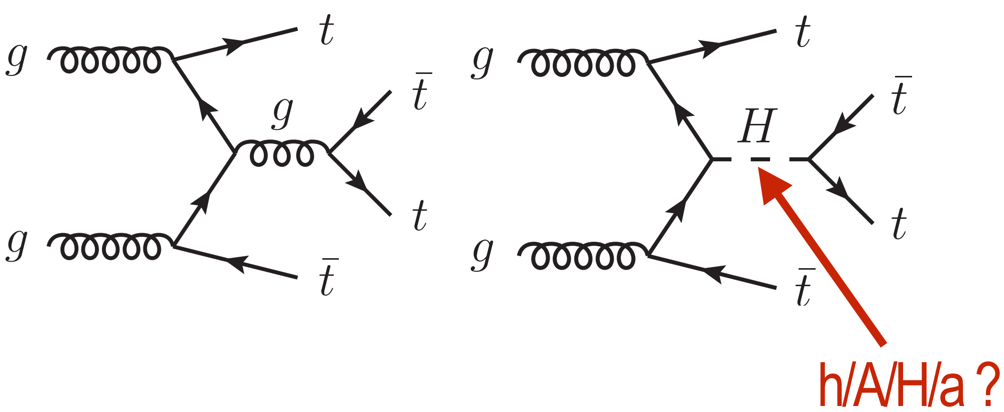
ATL-PHYS-PUB-2018-023

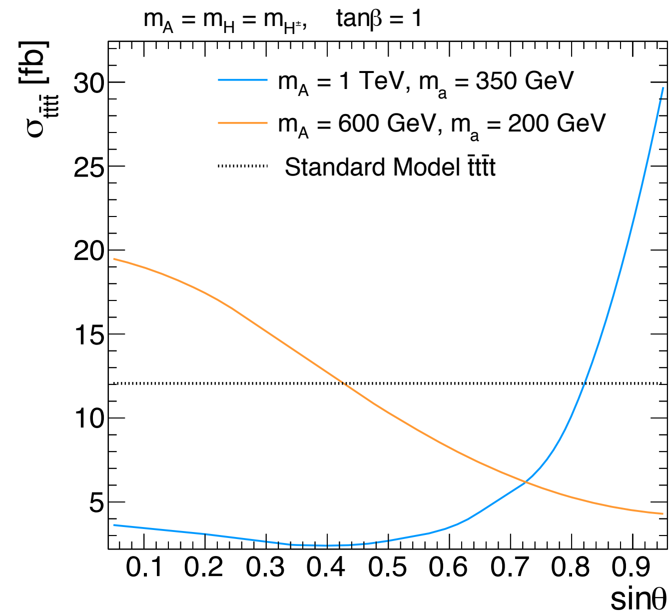


Expect $V_L V_L$ - scattering discovery significance: ~ 3σ per experiment

tttt Production

ATL-PHYS-PUB-2018-027

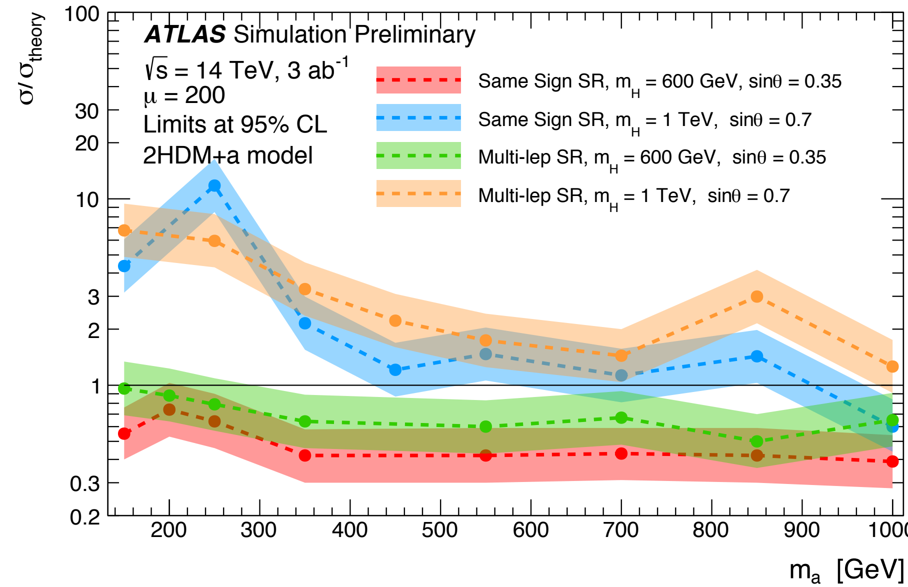




- SM cross section: σ_{tttt} = 12 fb
- Off-shell Higgs-induced contribution

- Evidence expected during Run-3
- Measurement of ~10-20% during HL-LHC

- 4-top highly relevant in many BSM scenarios
- 2HDM+*a*: phenomenology depending on m_H, m_A, m_a, and A-*a* mixing angle *θ*



BSM Searches in the Higgs Sector

- CP even established, but CP odd admixture not excluded
  - HVV in production and decay
  - Hff in decay:
    - require fermion with observable polarisation: $H \to \tau\tau$
    - No projections available yet

CP odd

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

SM

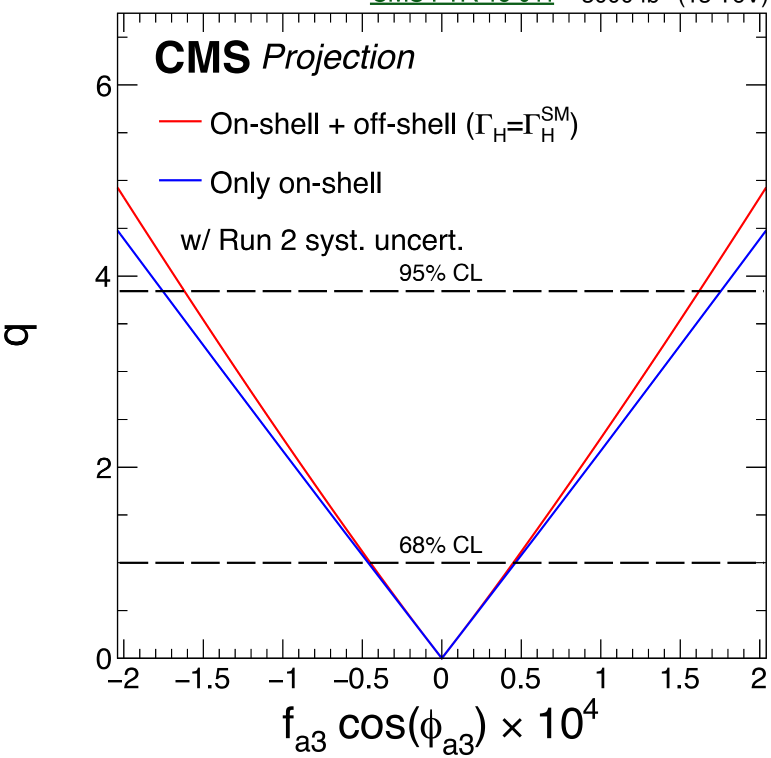
$$f_{ai} = |a_i|^2 \sigma_i \Big/ \sum |a_j|^2 \sigma_j \qquad \phi_{ai} = \arg\left(a_i / a_1\right)$$

- Invisible Higgs decays: CMS-FTR-18-016
  unseen SM (e.g. neutrino) or BSM (e.g. DM)
  B_{inv} < 4% (20%) HL-LHC (Run2) @95 CL

- Exotic decays: CMS-FTR-18-011
  H→BSM or forbidden SM decays (for $\kappa_V \leq 1$)
  B_{BSM} < 6% (34%) HL-LHC (Run2) @95 CL

- Rare SM decays: e.g. H→J/psi γ ATL-PHYS-PUB-2015-043
  B(H→J/\psiγ) < 44 x 10^{-6} @ 95 CL (20 x SM)

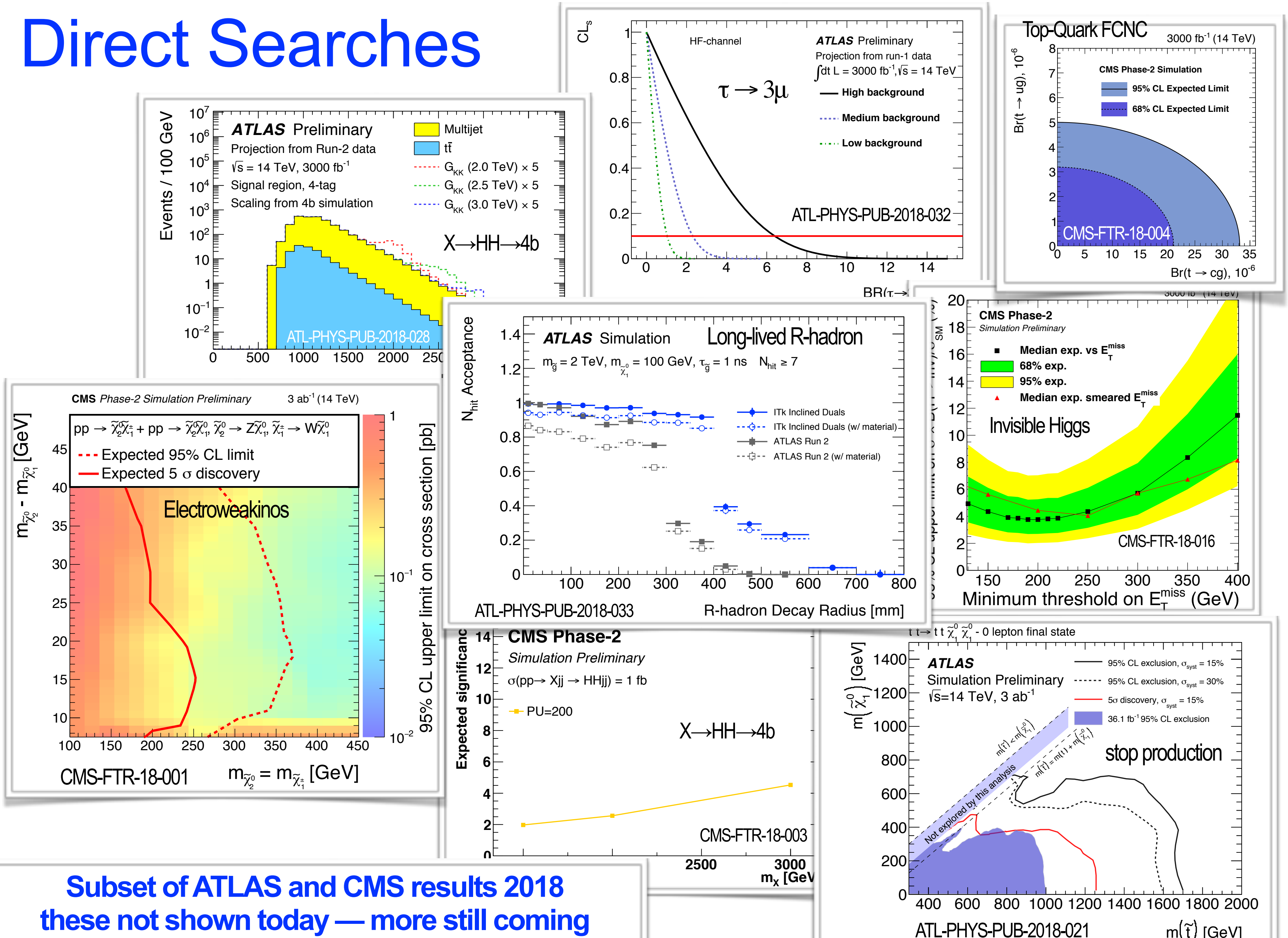
CMS-FTR-18-011



Direct Searches

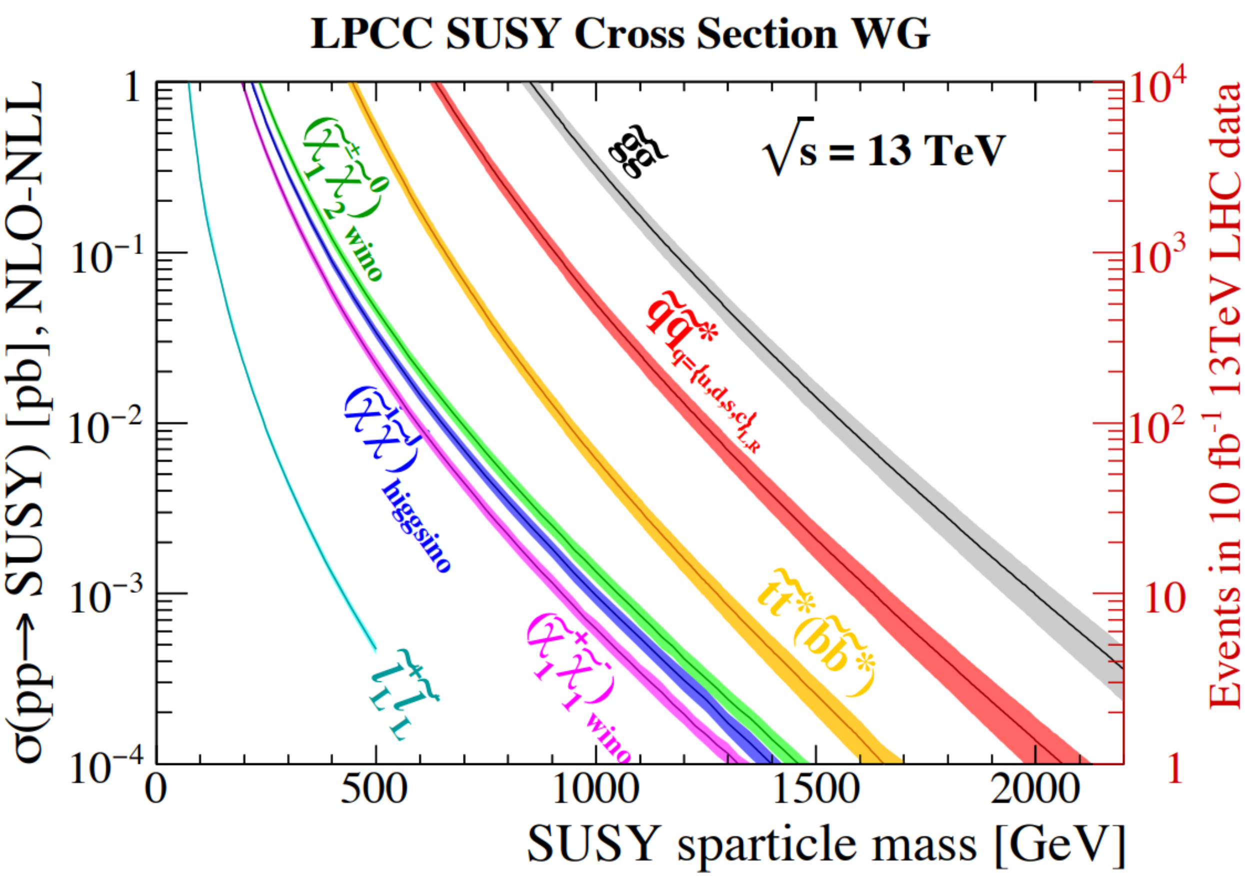
Supersymmetry, Long-Lived Particles, Dark Matter, Heavy Resonances

Direct Searches

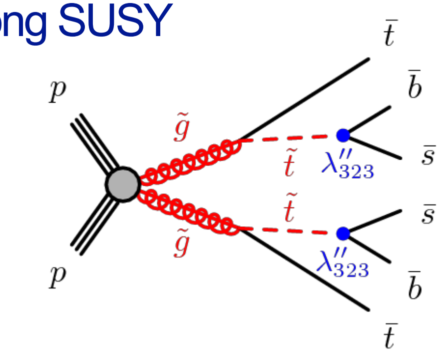


Subset of ATLAS and CMS results 2018
these not shown today — more still coming

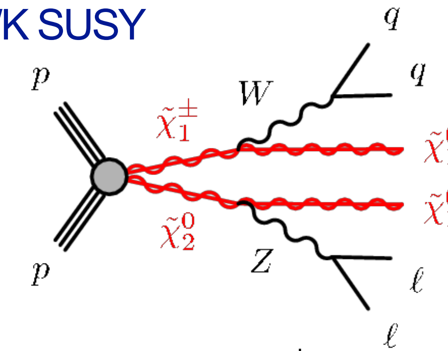
Supersymmetry

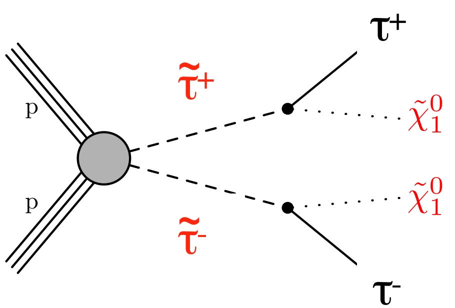


Strong SUSY



EWK SUSY

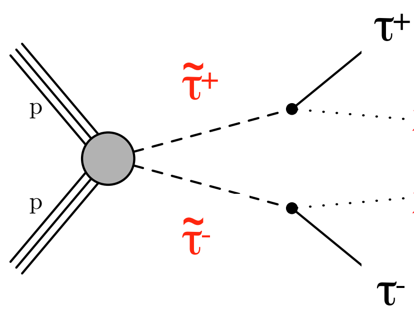


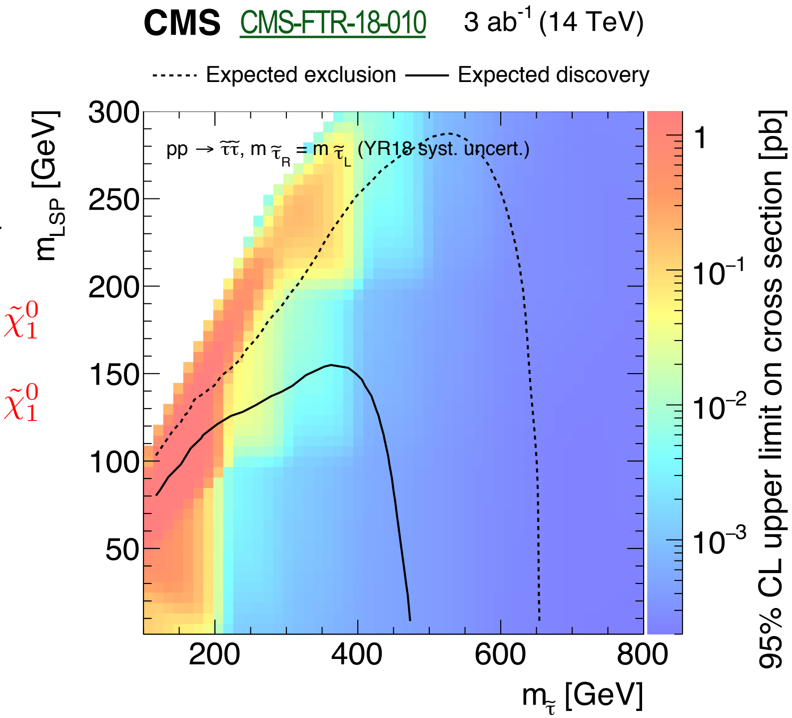


- Strong SUSY (σ≳1 pb at m = 500 GeV): many scenarios up to 1 TeV already excluded
- Electroweak SUSY (σ < 0.1 pb at m = 500 GeV): could still be light

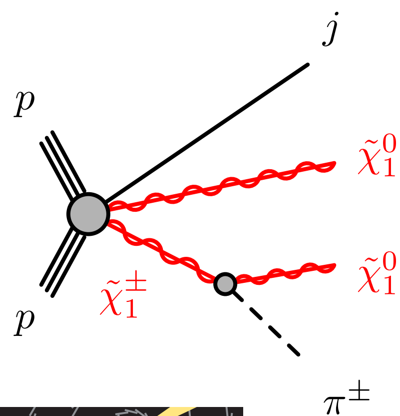
Electroweak SUSY

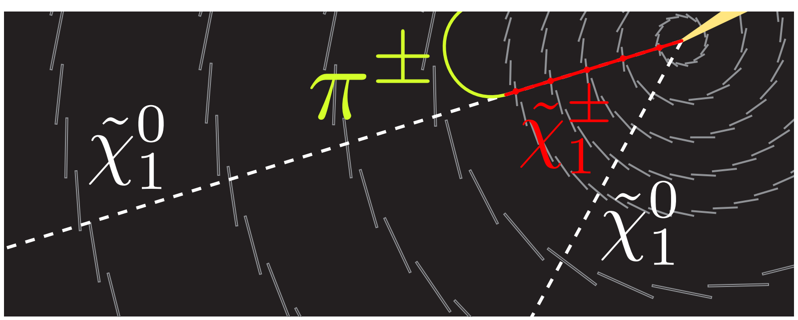
- Stau pairs:
  - Final state: $\tau_h\tau_h$ or $\ell\tau_h$ + MET
  - 2016 data: no sensitivity
  - HL-LHC excl. limit: 650 GeV

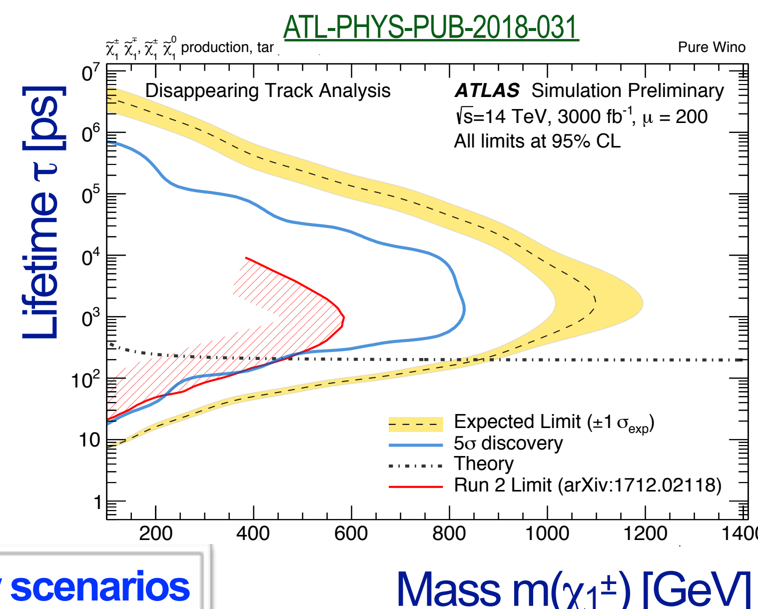




- Electroweakinos:
  - degenerate mass scenarios → compressed spectra and/or long lifetimes
  - Use ISR jet for triggering
  - Disappearing tracks



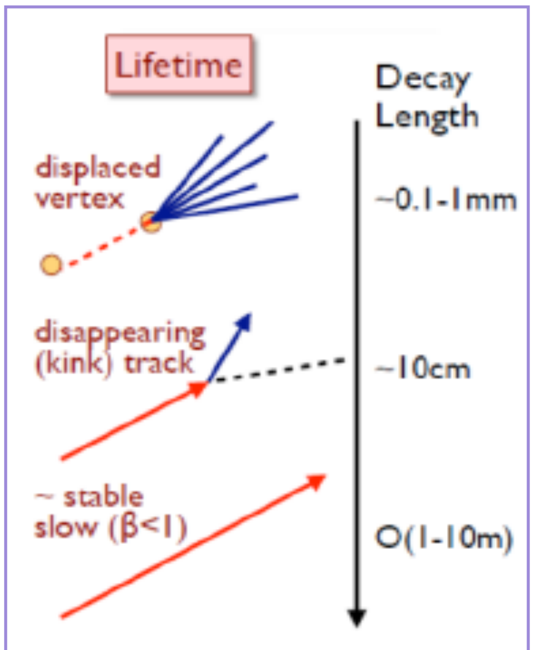


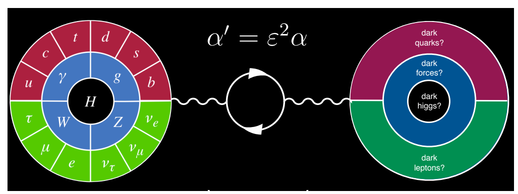


Sensitivity to new scenarios

Long-Lived Particles

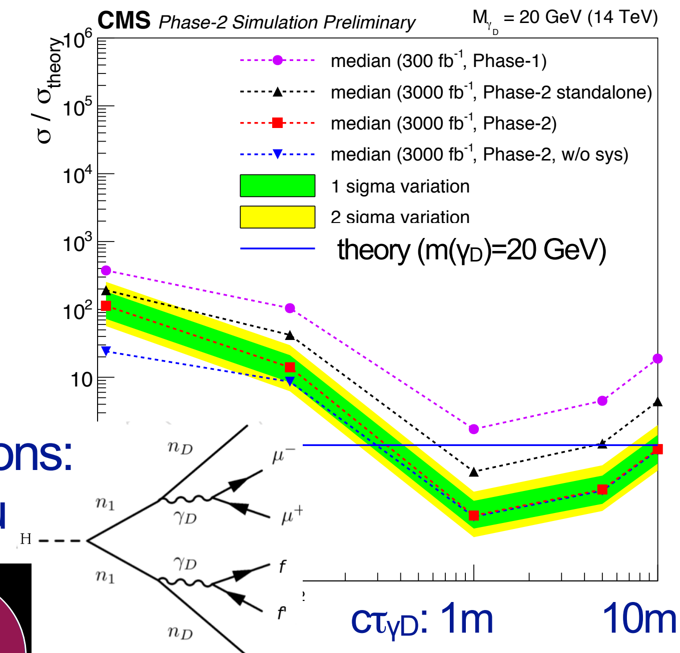
- Various scenarios: mass degeneracy, small couplings, heavy mediators,
- Direct detection or collateral event features → creative use of experiments
- Dedicated LHC experiments Codex-b, Mathusla, MilliQan, Faser





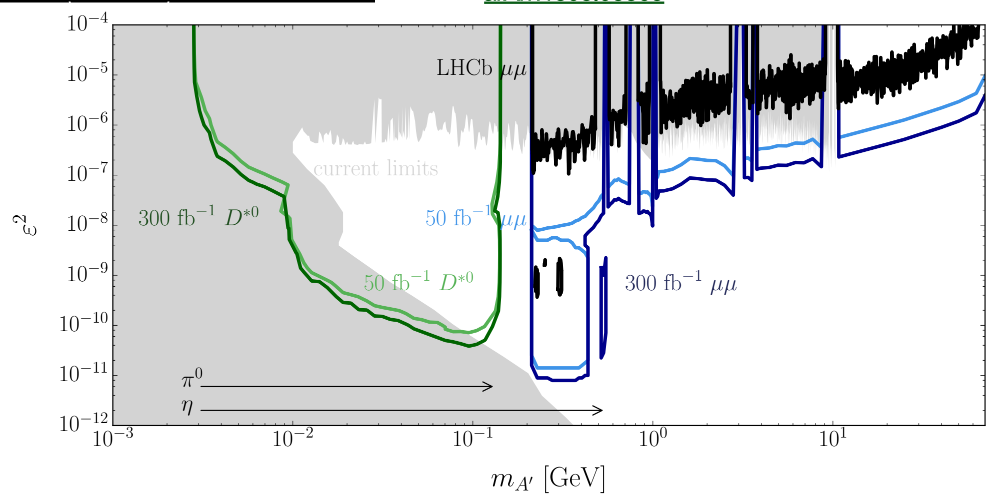
Dark photons: $\gamma_D \to \mu\mu$

CMS-FTR-18-002



$c\tau_{\gamma D}$: 1m 10m

arXiv:1808.08865

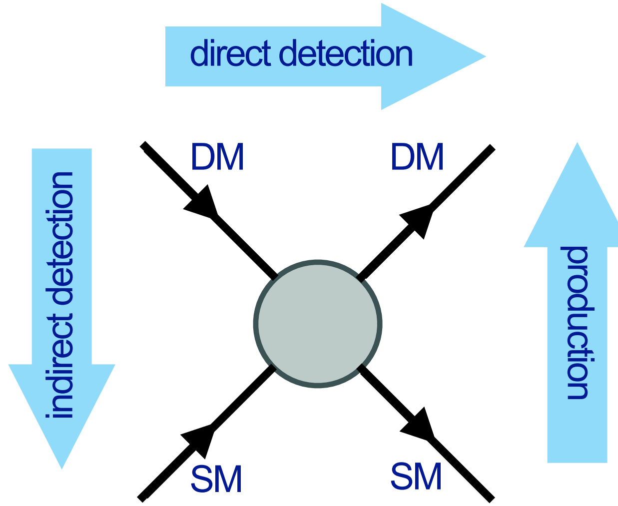


Significant benefits from improved detectors

Dark Matter …

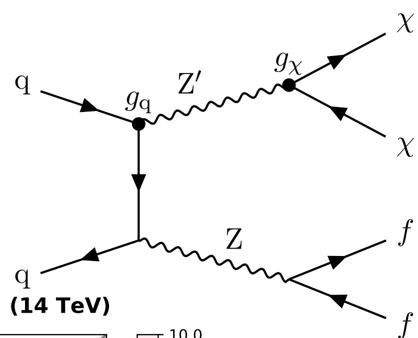
- … is known to exist:
  → reveal its elementary nature at the LHC ?

- Simplified models for comparison
  with direct detection experiments

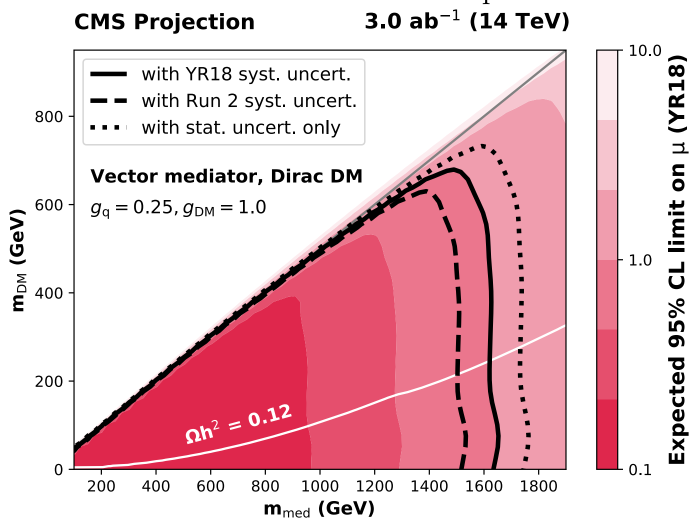


LHC

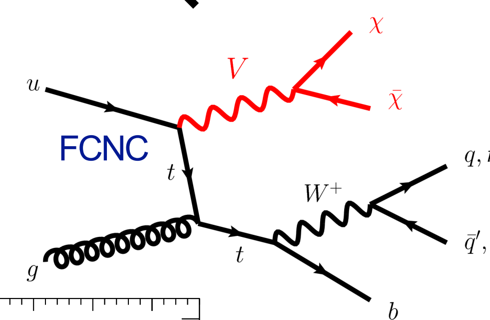
mono-Z



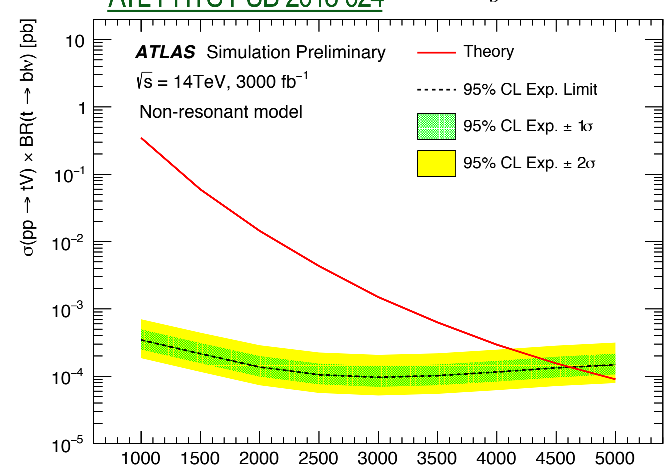
CMS-FTR-18-007



mono-top:



ATL-PHYS-PUB-2018-024

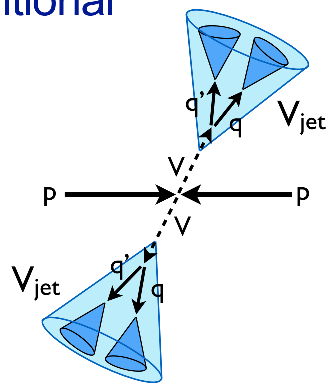


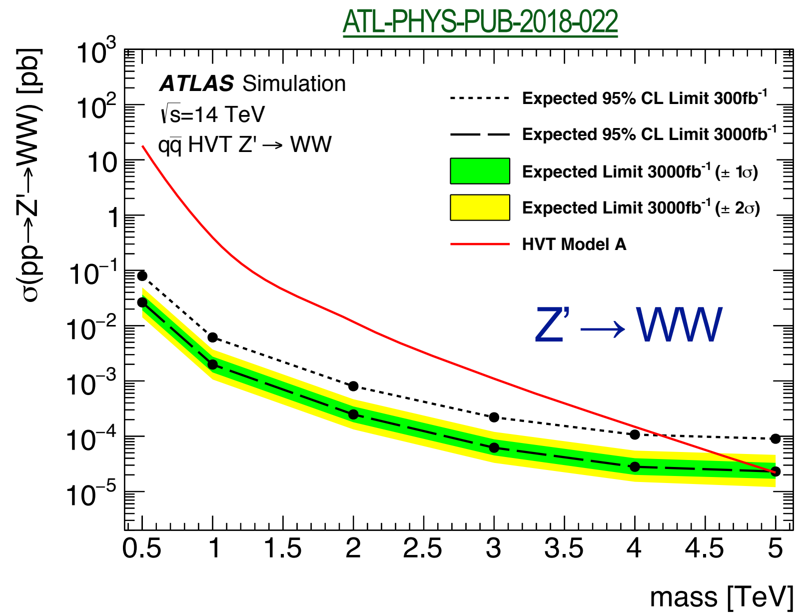
Limit on m_V ~4.5 TeV (for m_{DM} = 1 GeV)

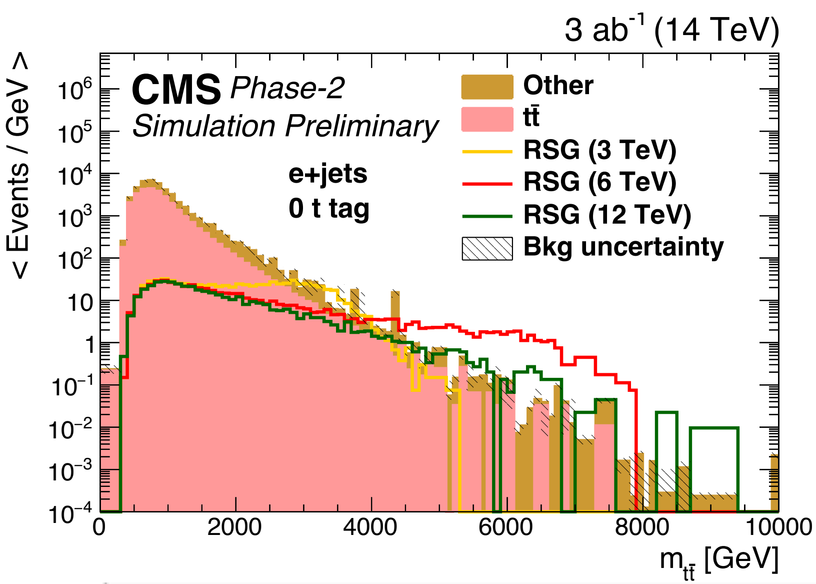
Heavy Resonances

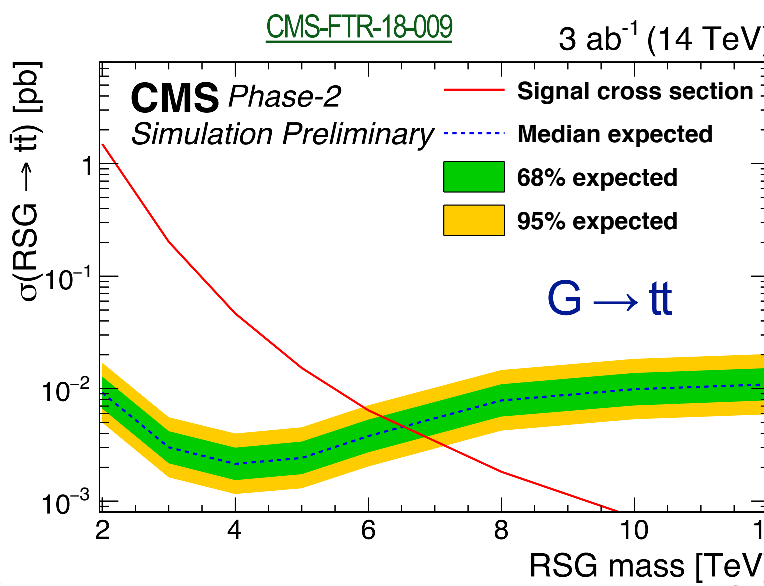
- Heavy Vector Triplet (HVT) model: composite Higgs and three additional vector bosons Z' and W'$^{\pm}$
  Z' and W'$^{\pm}$ → WW, WZ or ZZ

- Randall-Sundrum-Gluino:
  RSG → tt



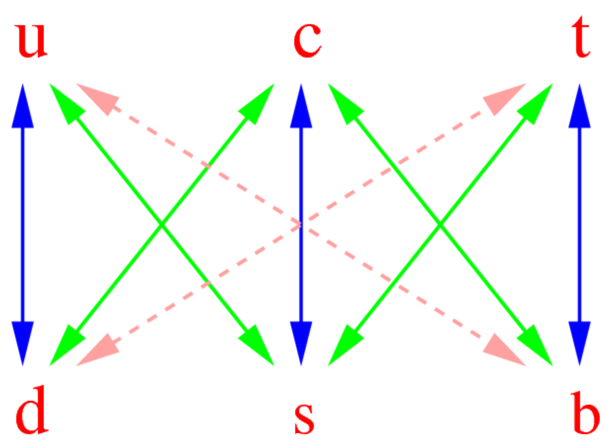






Mass reach: exclusion up to 5-6 TeV at HL-LHC — (~10-11 TeV for HE-LHC)

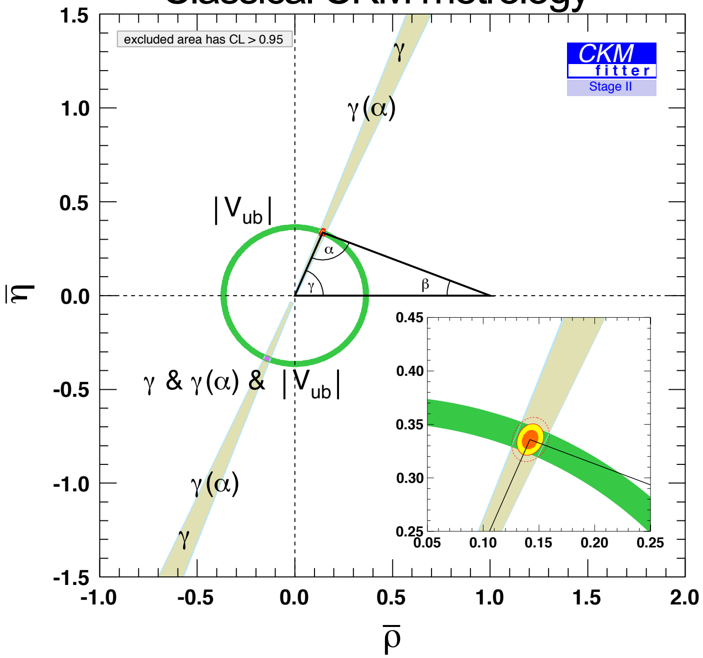
Flavour



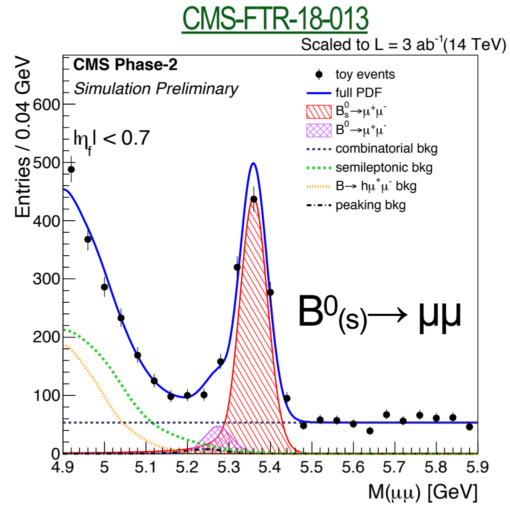
Low p_T / High p_T Complementarity

Flavour Physics

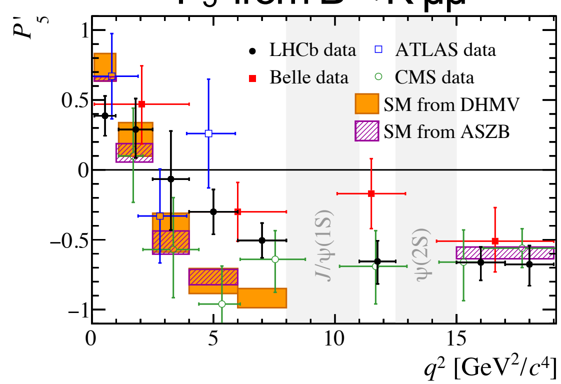
Classical CKM metrology



expectation using 50ab-1 Belle II and 50fb-1 LHCb data

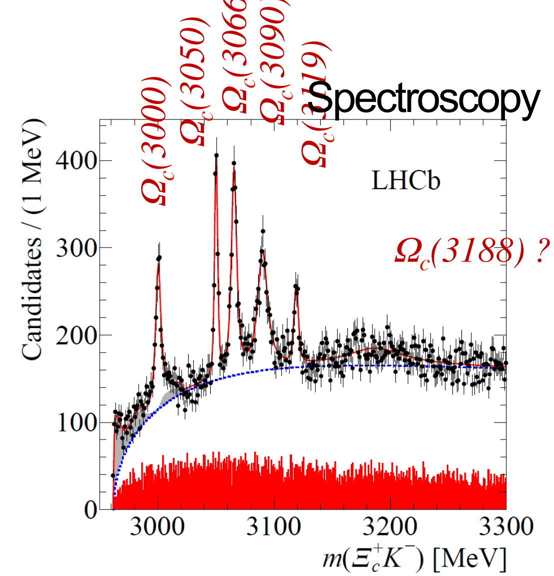


P5' from B→K*μμ

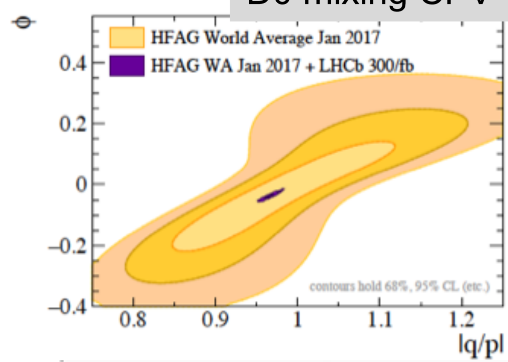


ATLAS and CMS can help in a few channels

Spectroscopy



D0 mixing CPV



In several areas LHCb (also Belle) are w/o cross check

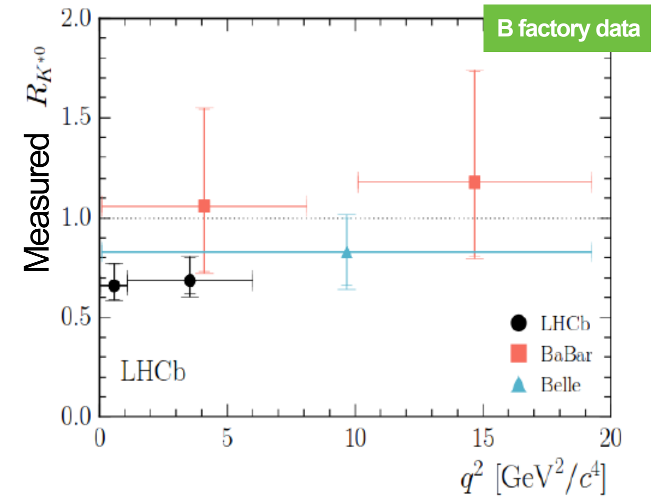
- New physics reach of flavour up to 100 TeV
- If/when SM is falsified, is there a chance to understand the new physics?

Flavour Anomalies: low p_T

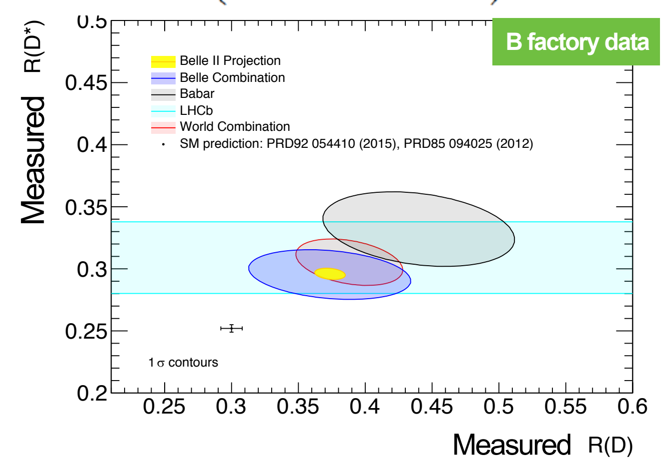
- Tension in current measurements
  - R(K*), b → sμμ: 2-3σ below expectation
  - R(D*), b → cτν: 3-4σ above expectation
  - P_5' from B→K*μμ: LHCb also in tension

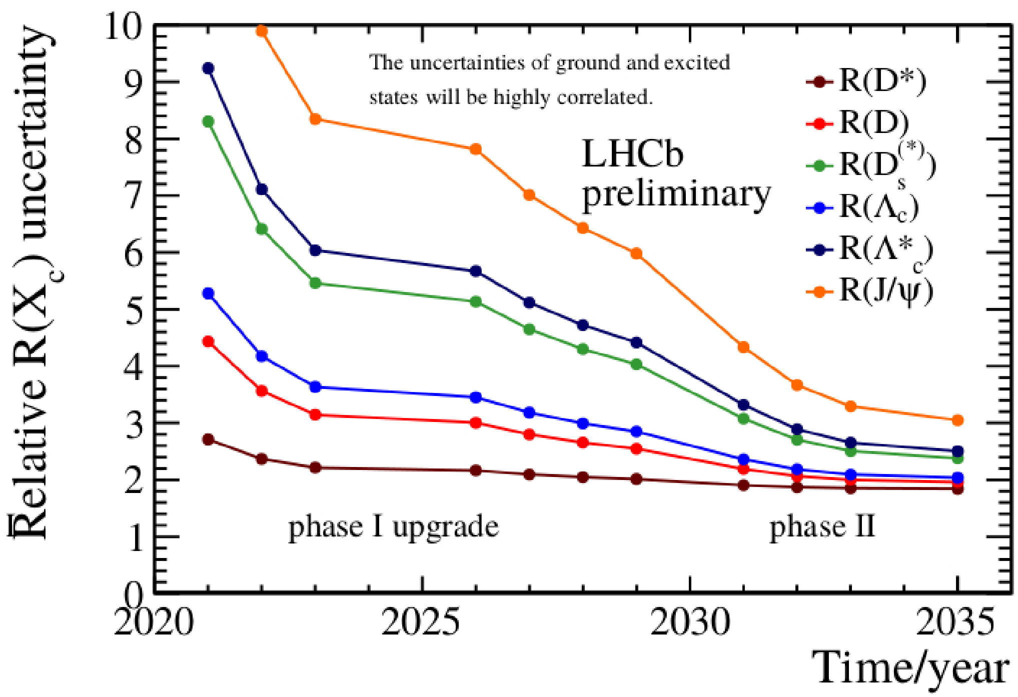
- LHCb will measure several more channels, also with B_S, Λ_b and B_c

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

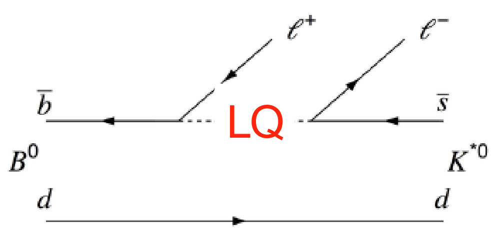


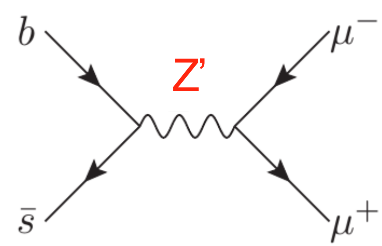
$$R^{\tau/\ell}_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$

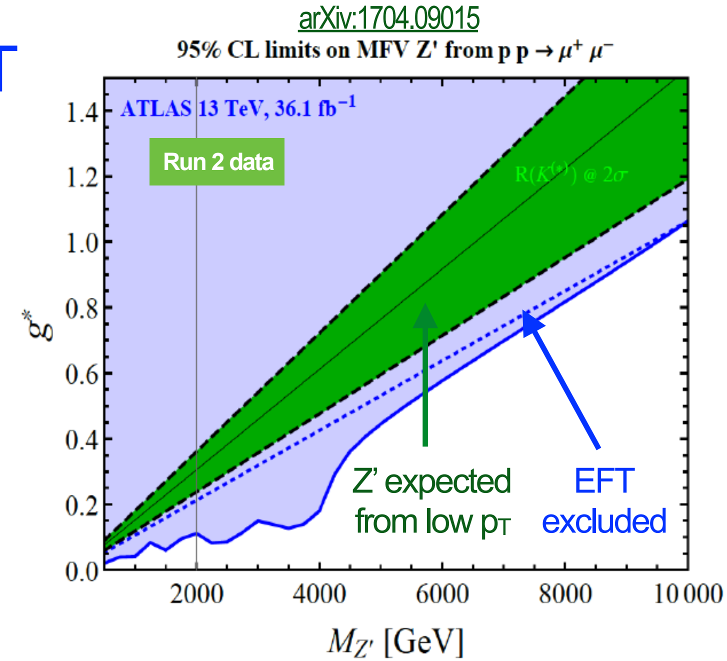




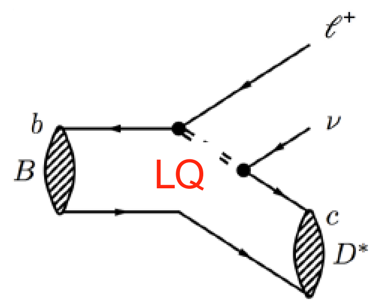
Flavour Anomalies: high p_T

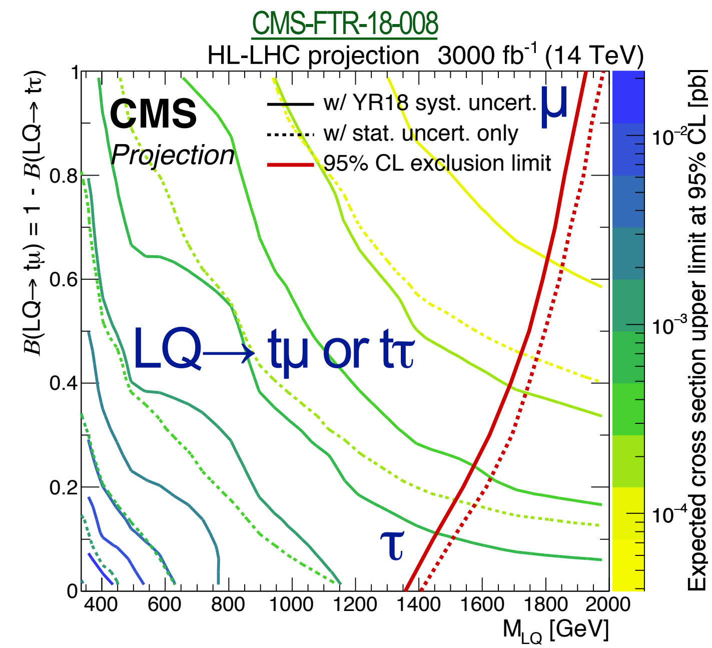






- R(K*) b → sℓℓ
  - Theoretically very clean
  - Could be explained by LQ or flavour violating Z'
  - Z'→ μμ already excluded

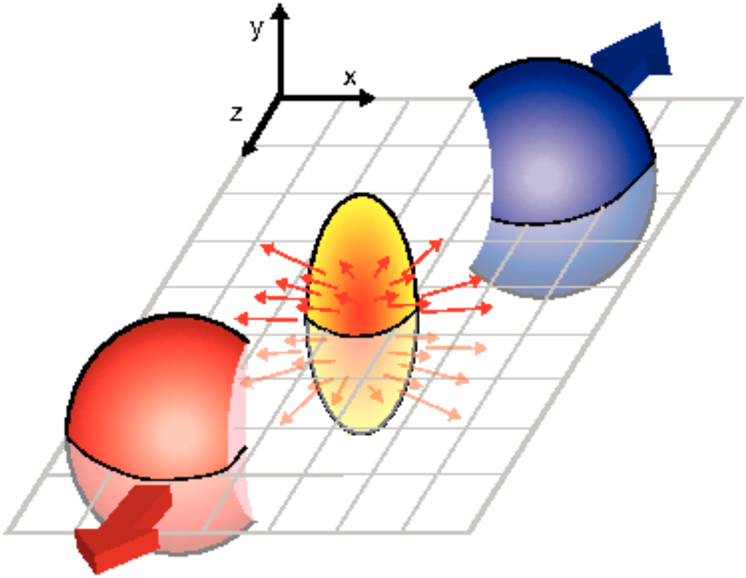




- R(D) and R(D*): b→ cℓν
  - Good fits for W' vector, scalar or vector LQ
  - Full range of LQ searches

LQ could explain R(D*) and R(K*)
No-lose theorem ?

Heavy Ion Physics



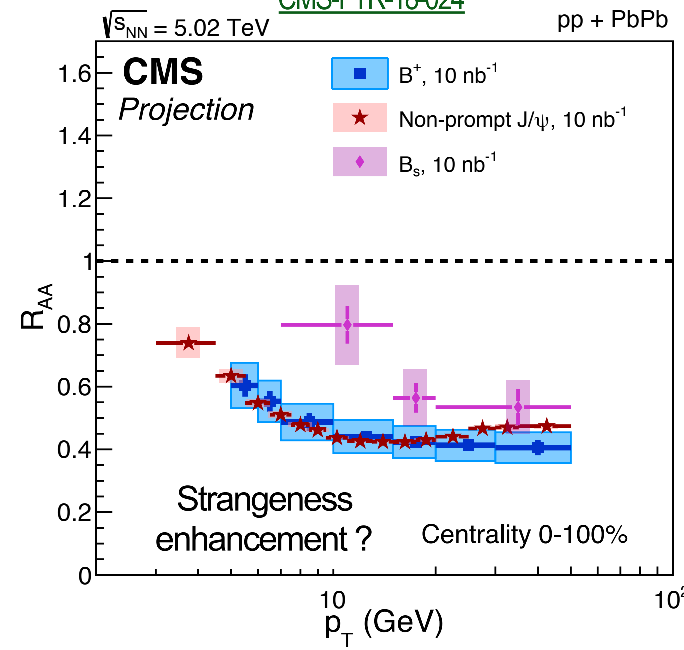
Precise Differential Measurements

Heavy Ion Physics

- Determine material properties of QCD media
- Study HI-like behaviour also in pp and pA
  (Flow behaviour, long-range correlations, nPDF)

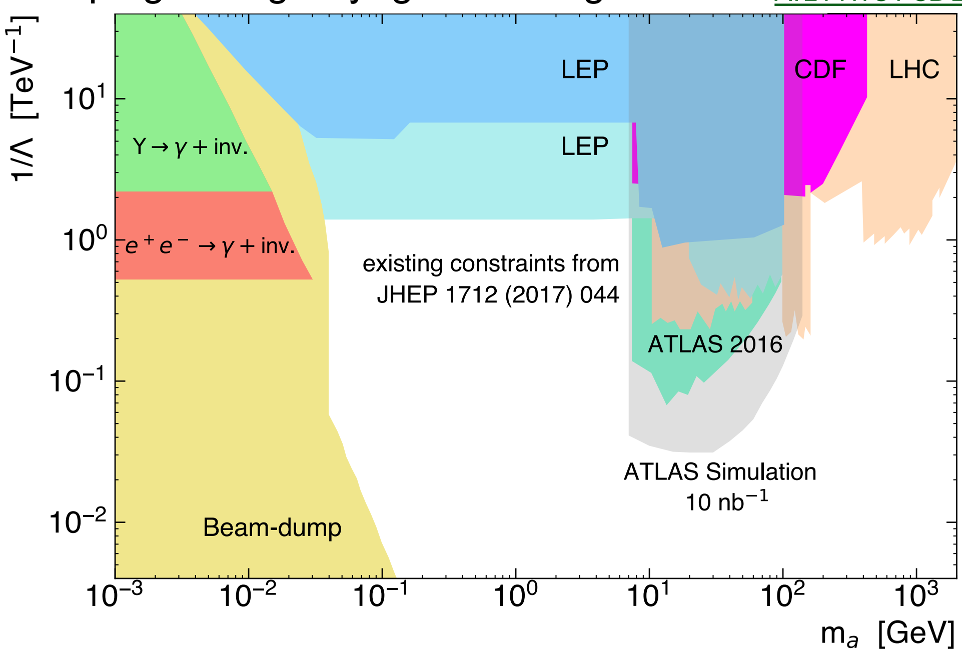
- Future HI running (Run-3 and Run-4):
  - Factor ~20 (100) more data for CMS, ATLAS (Alice)
  - Precise differential measurements

CMS-FTR-18-024

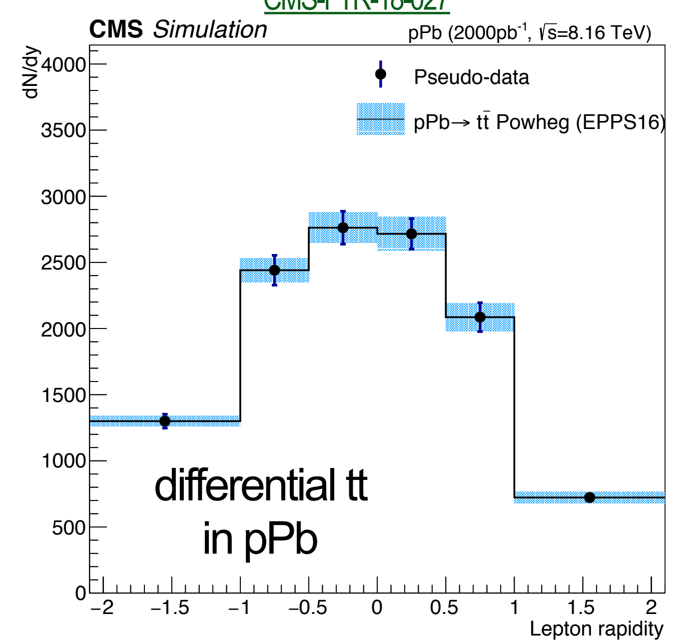


Exclusion limits on Axion-like particle (ALP) masses vs coupling from light-by-light scattering in UPC

ATL-PHYS-PUB-2018-018



CMS-FTR-18-027



Summary

- **HL-LHC: superior detectors, refined analyses, advanced theory**
  - Recent detailed update and extension of HL-LHC projections
- **3000 fb^{-1} of extremely rich and exciting physics**
  - Standard Model: Ultimate Precision
  - Higgs: Full factory mode
  - Direct searches: Discover new physics or close a few chapters
  - Flavour: High/low p_T complementarity
  - Heavy Ion: precise differential measurements

Expect to exceed expectations