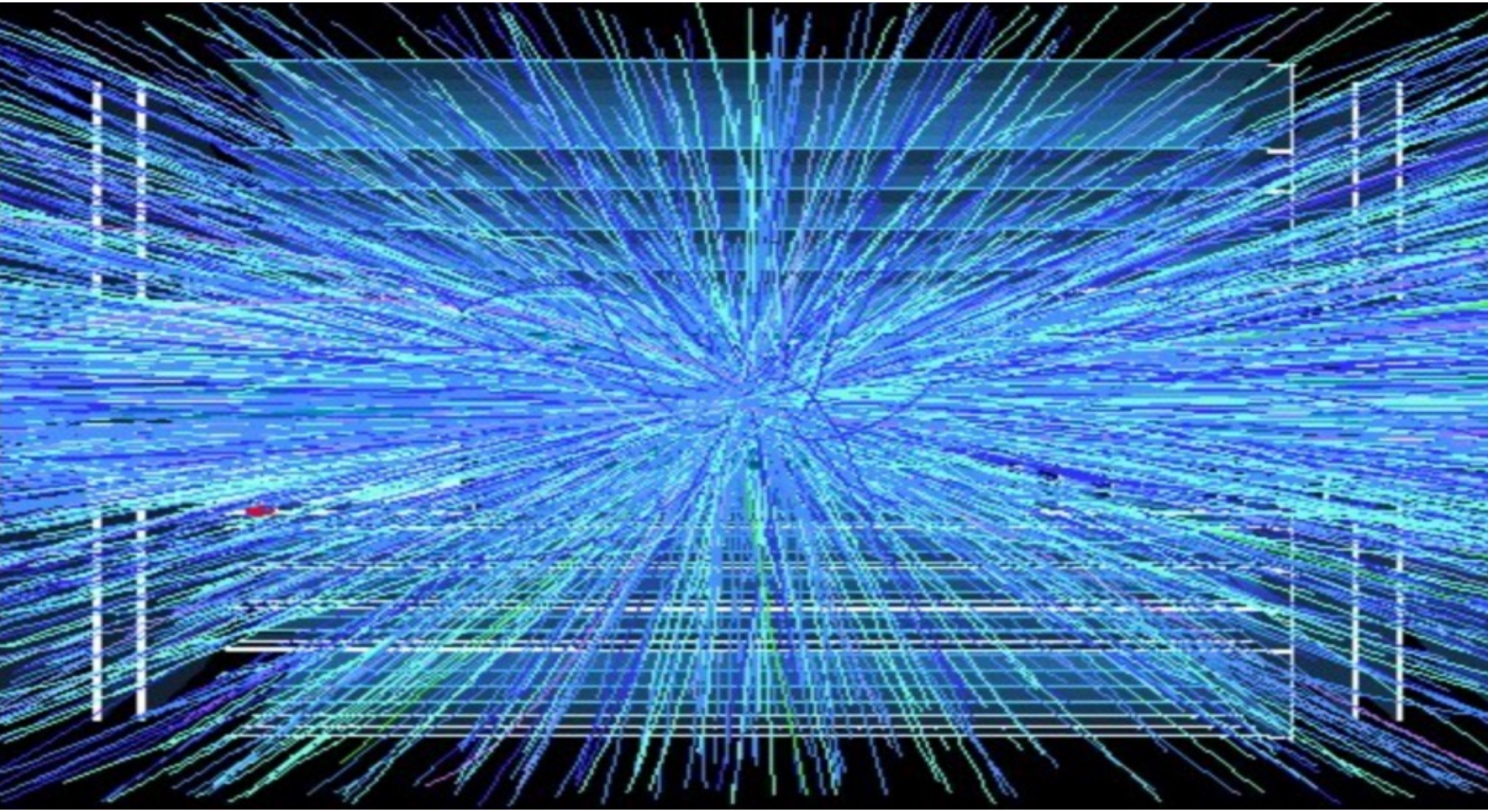
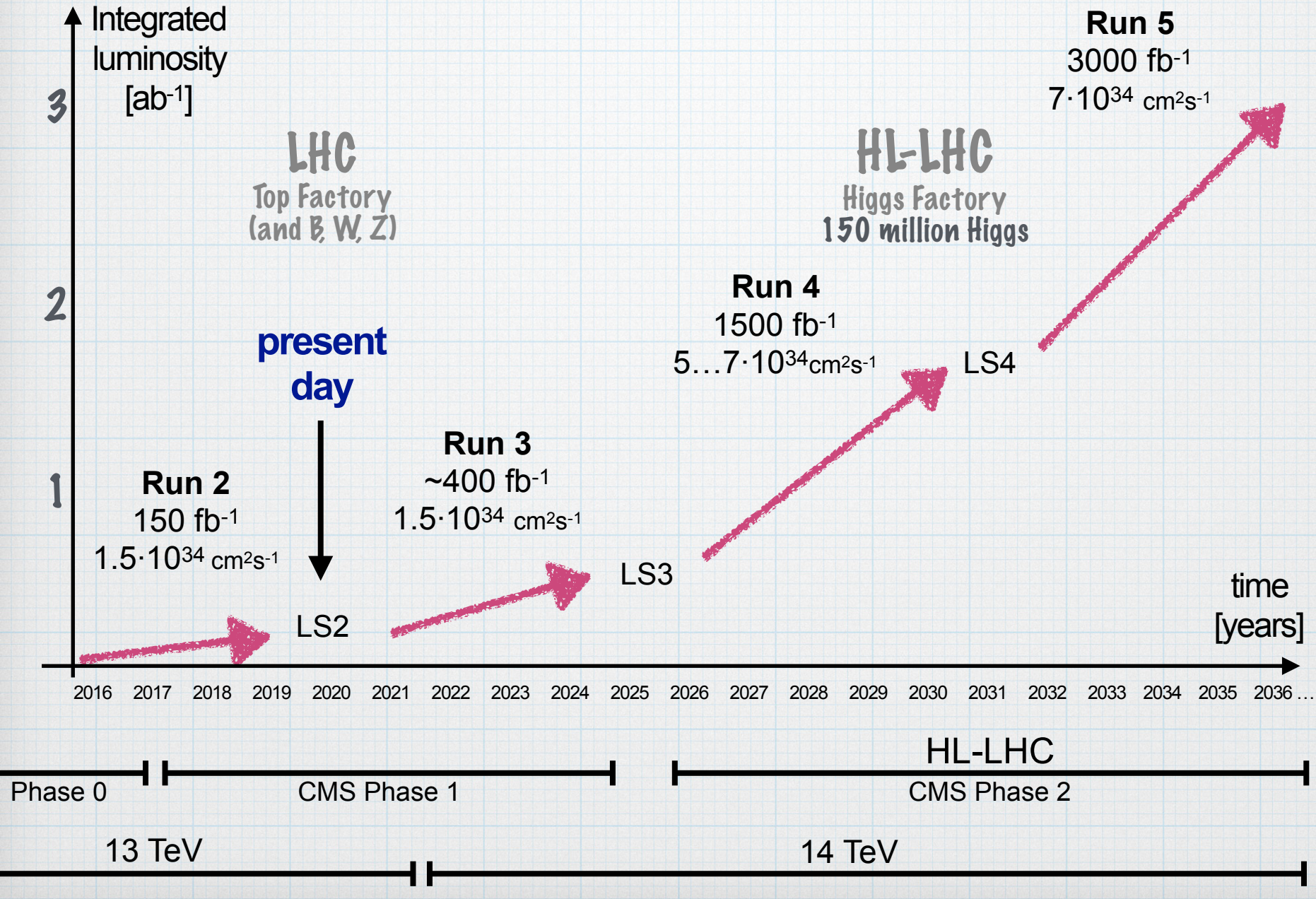
Physics with LHC Run-3 and HL-LHC



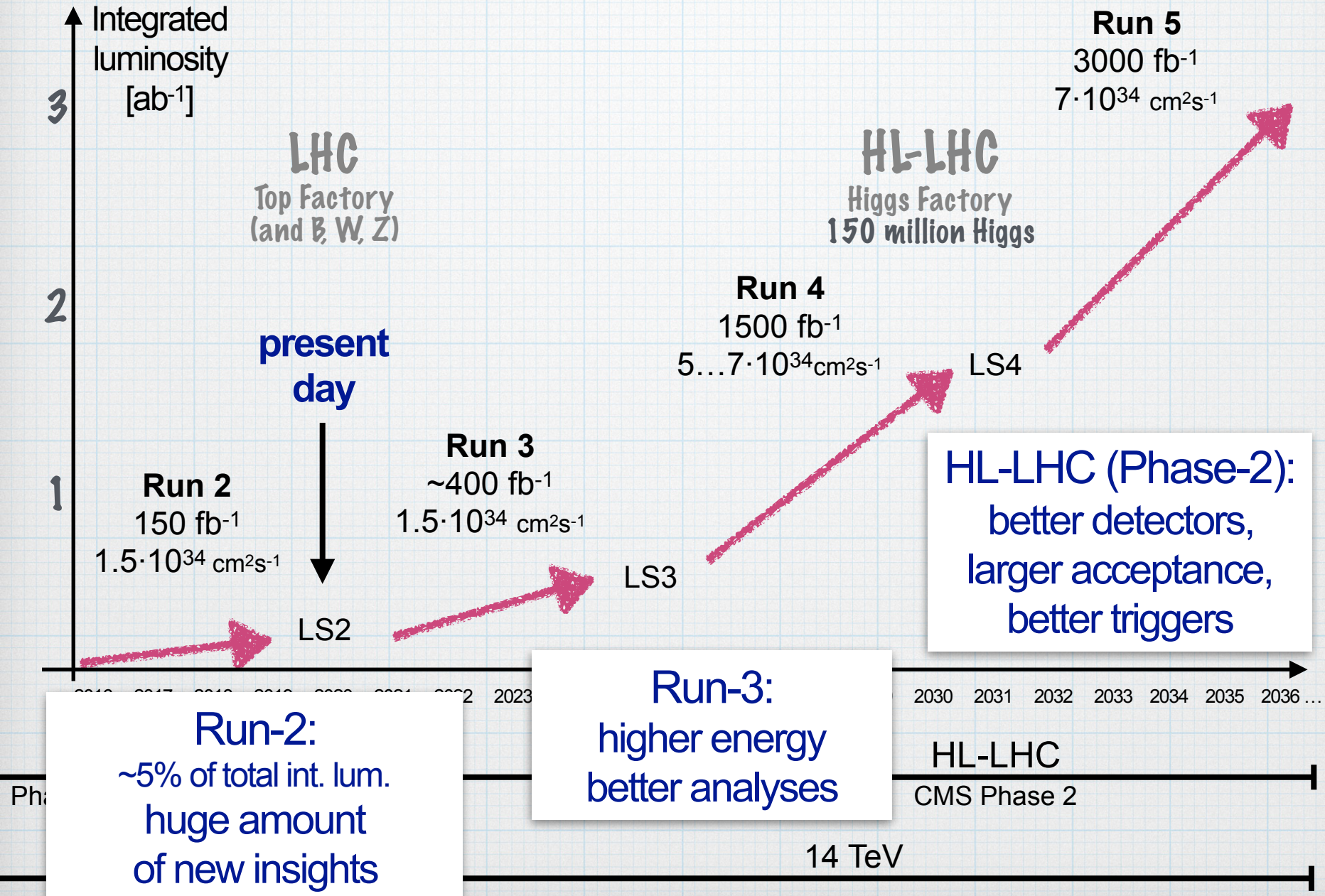
Andreas B. Meyer

D-CMS Workshop 2019 at KIT
13 September 2019

The Present and the Future



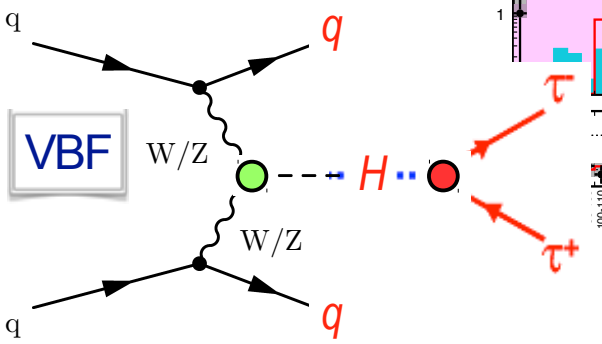
The Present and the Future



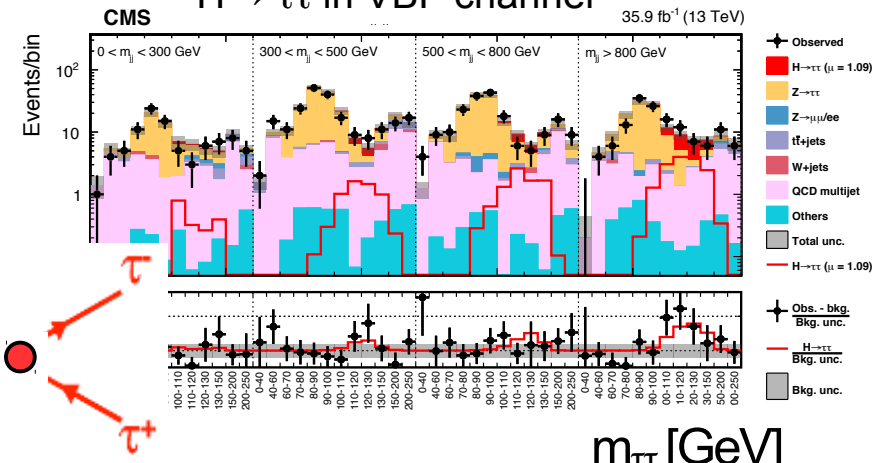
LHC Run-2 Observations

Higgs - τ

Summer 2017



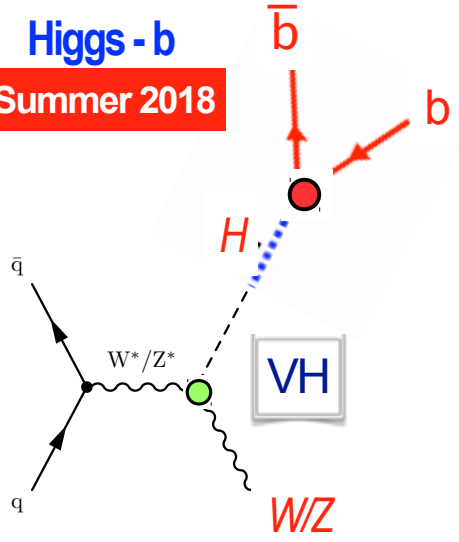
H→ ττ in VBF channel



$m_{\tau\tau}$ [GeV]

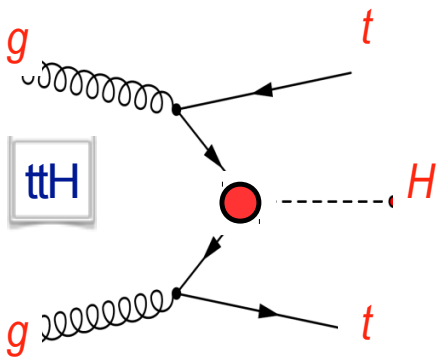
Higgs - b

Summer 2018

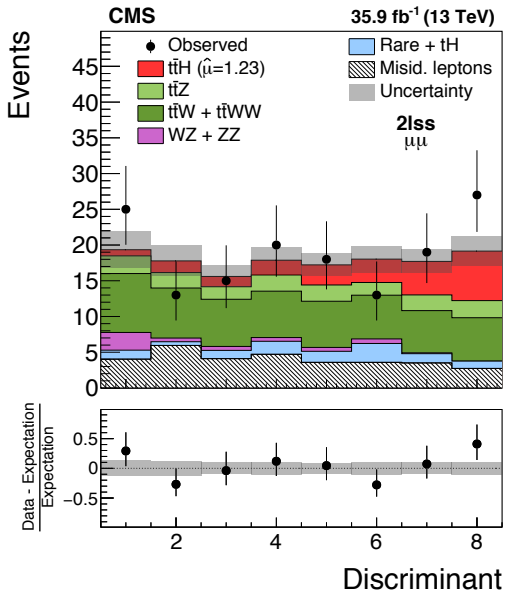


Higgs - top

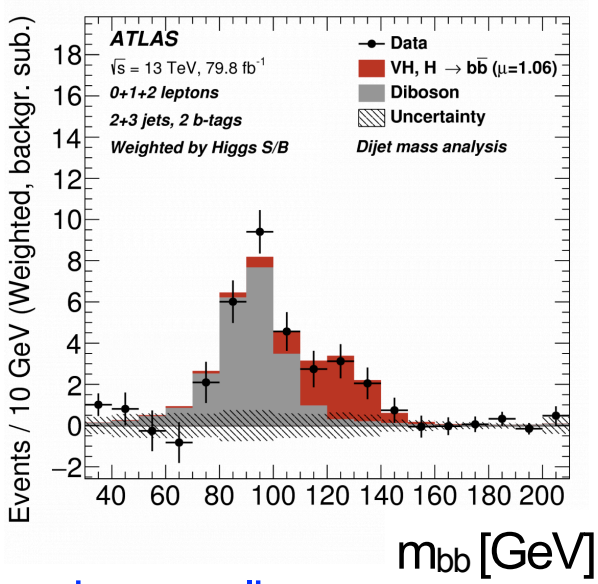
Spring 2018



ttH (μ±μ± category)



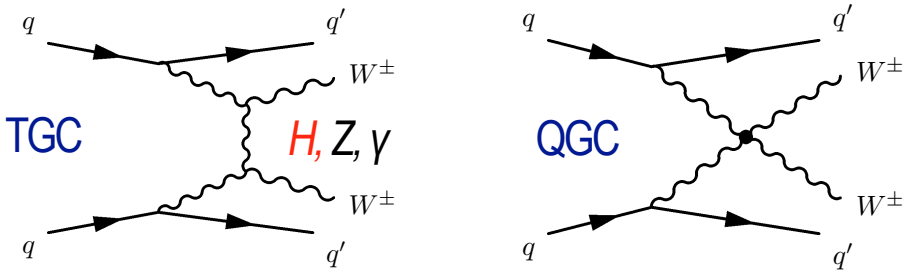
H→ bb in VH channel

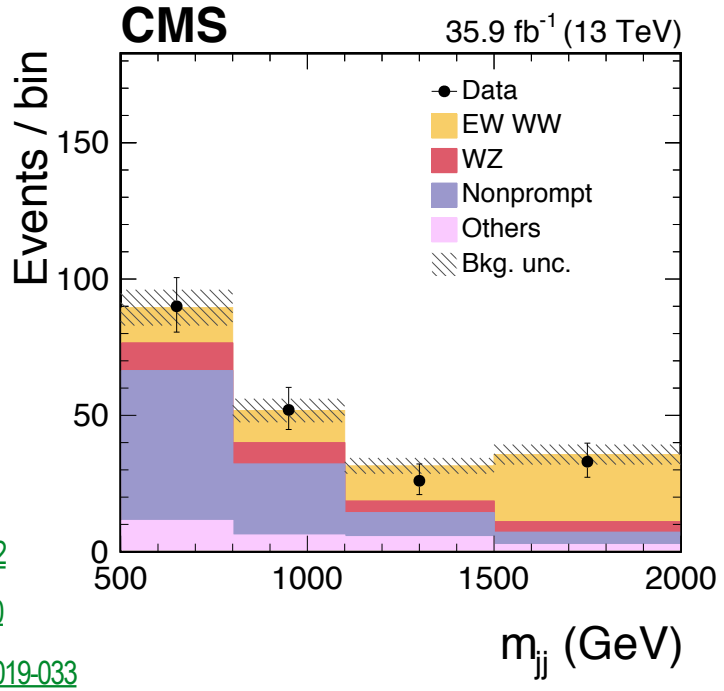


First direct observations of Higgs-fermion couplings

LHC Run-2 Observations

- Electroweak Vector Boson Scattering (VBS)

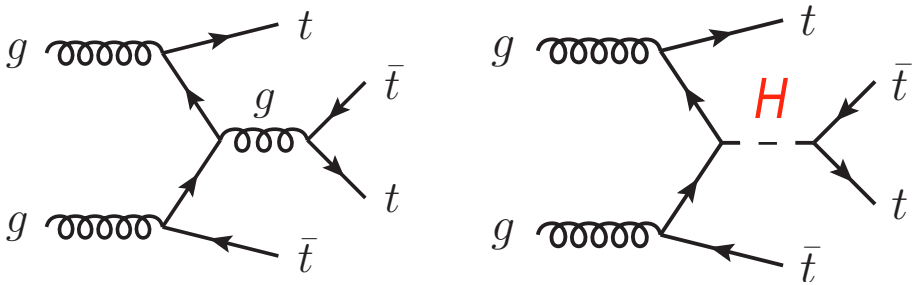


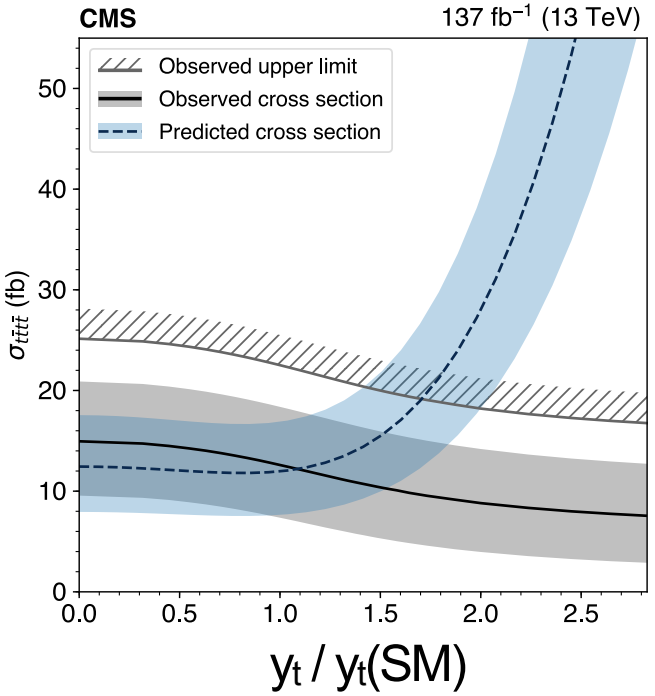


Summer '17	$W^{\pm}W^{\pm} \rightarrow 2\ell^{\pm}2\nu$ (CMS)	5.5(5.7) σ	arXiv:1709.05822
Winter '18	$WZ \rightarrow 3\ell\nu$ (ATLAS)	5.3(3.2) σ	arXiv:1812.09740
Summer '19	$ZZ \rightarrow 4\ell$ or $2\ell^{\pm}2\nu$ (ATLAS)	5.5(4.6) σ	ATLAS-CONF-2019-033

- 4-top production

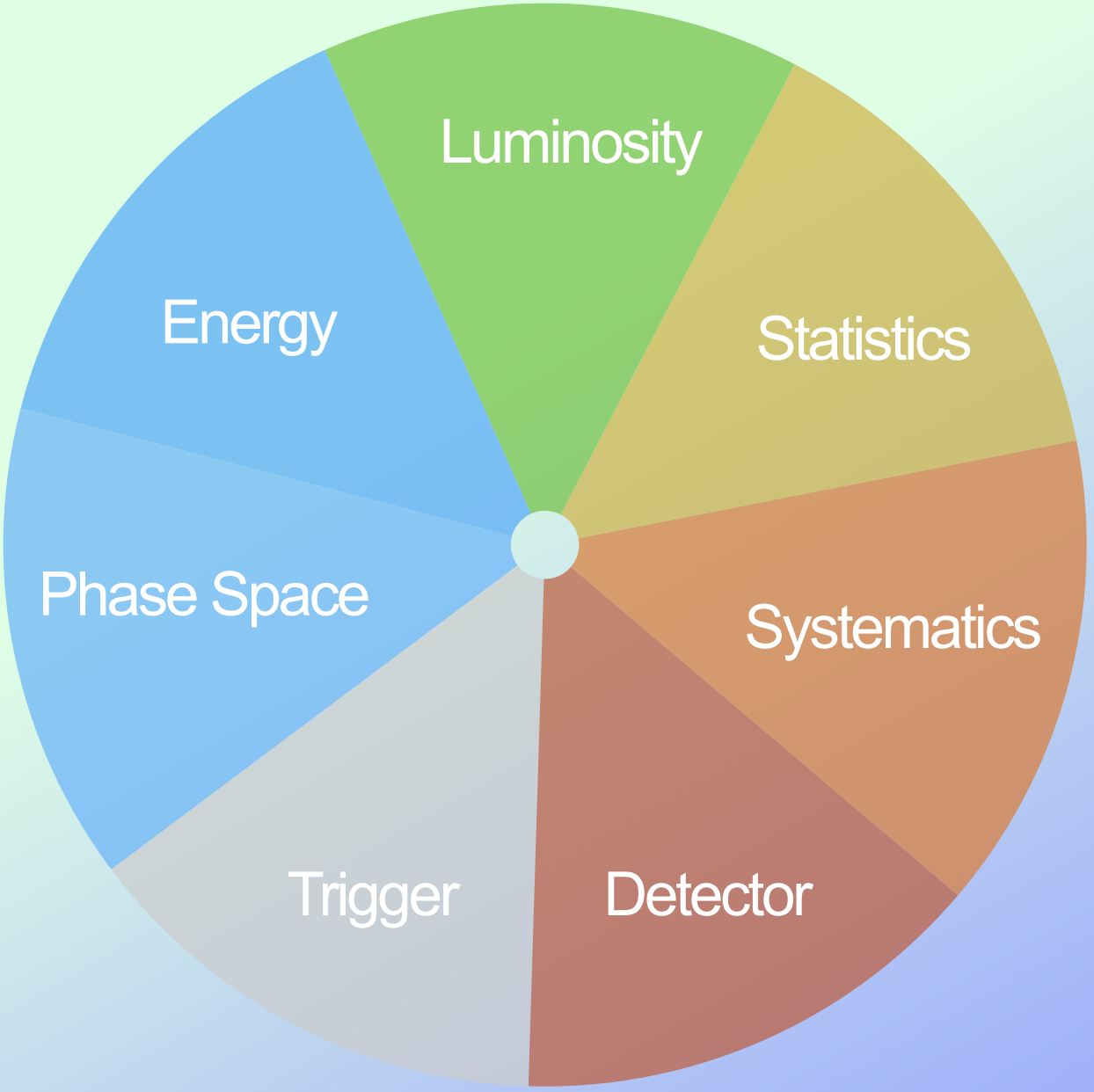
Summer '19	tttt → Multileptons	2.6(2.7) σ	arXiv:1908.06463



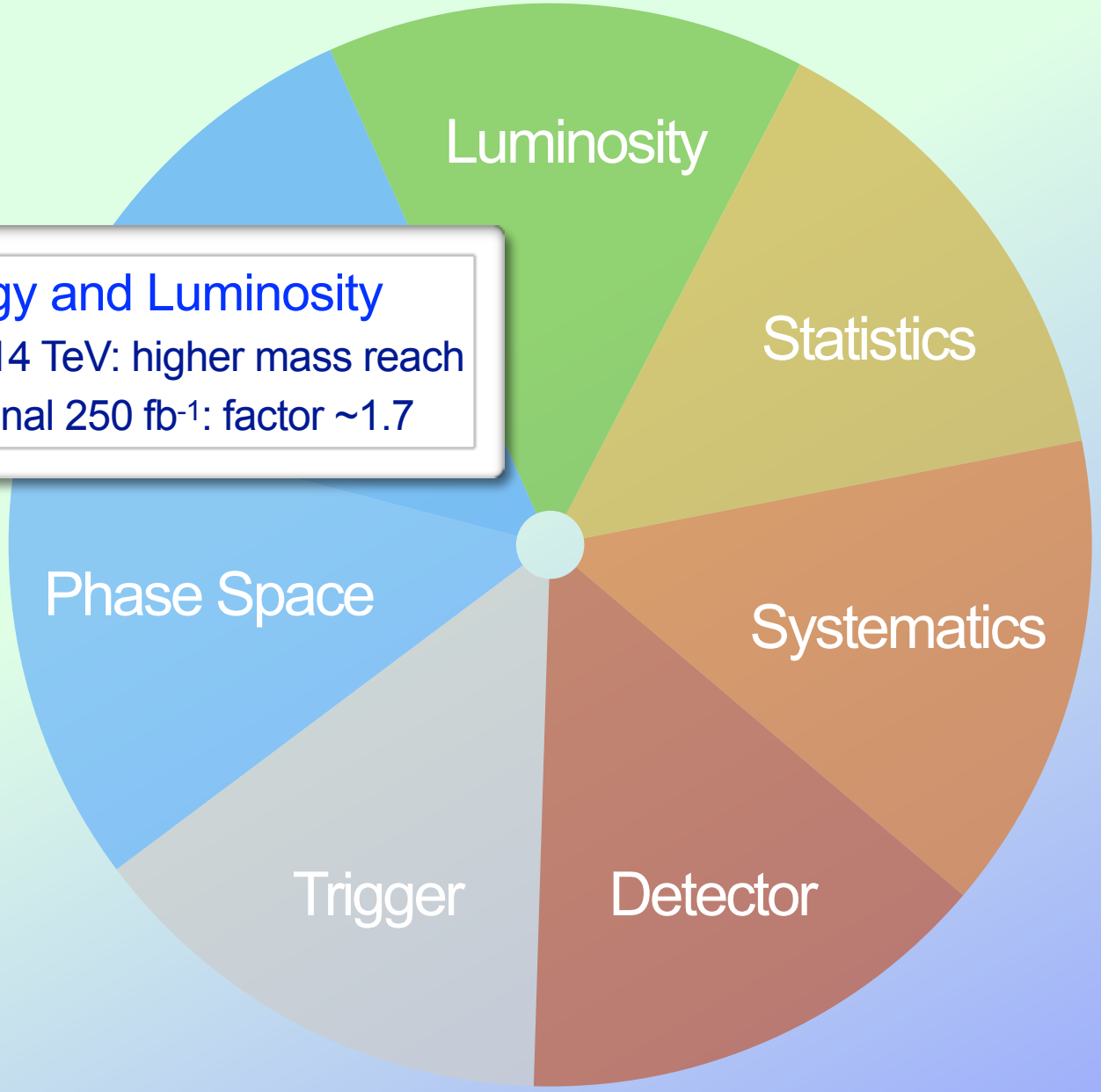


Starting to also scrutinize the virtual Higgs boson

Opportunities in Run-3



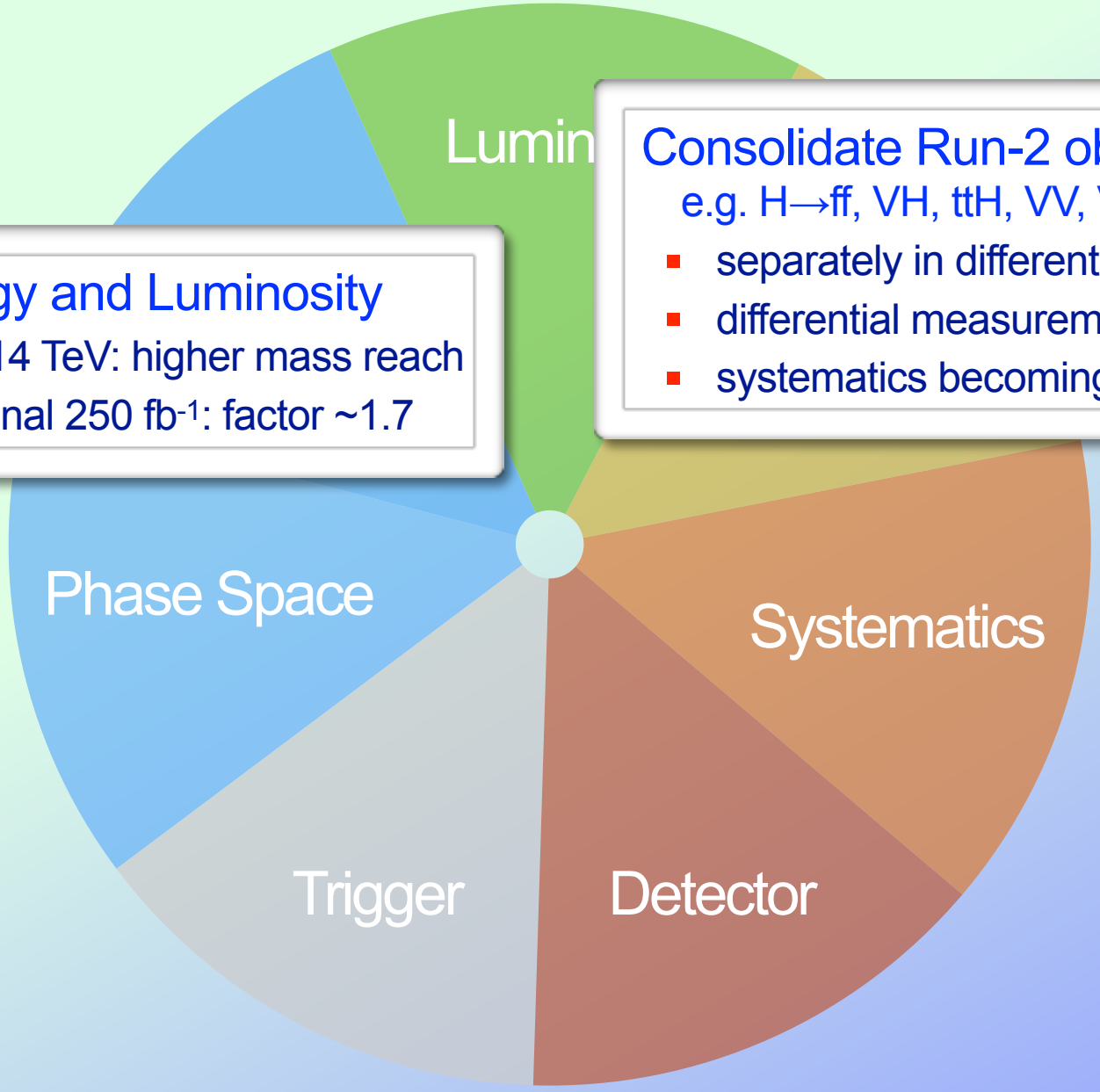
Opportunities in Run-3



Energy and Luminosity

- 13 → 14 TeV: higher mass reach
- Additional 250 fb^{-1}: factor ~1.7

Opportunities in Run-3



Energy and Luminosity

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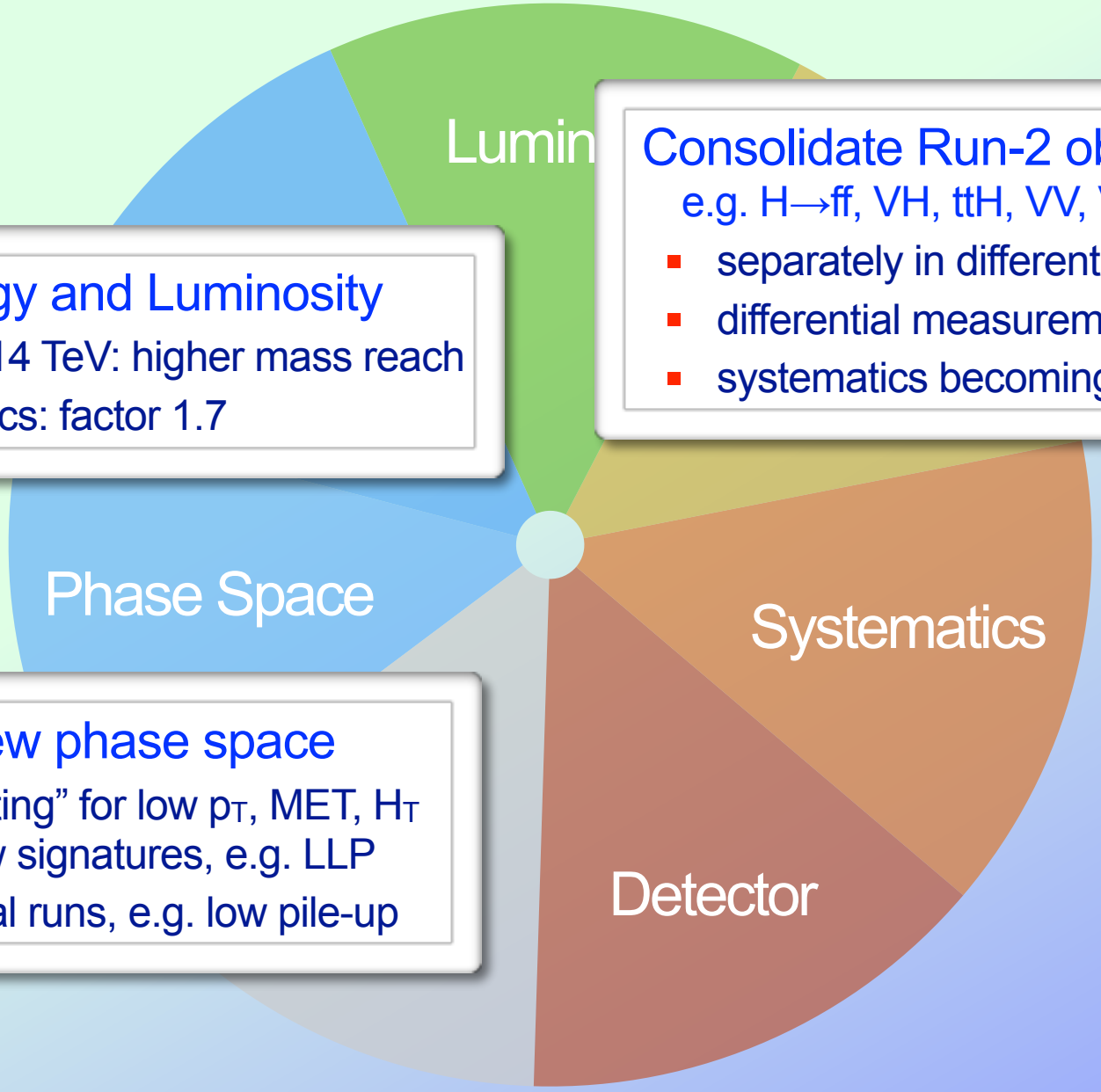
Consolidate Run-2 observations

e.g. H→ff, VH, ttH, VV, VBS, tttt, …

- separately in different channels
- differential measurements
- systematics becoming relevant

Opportunities in Run-3



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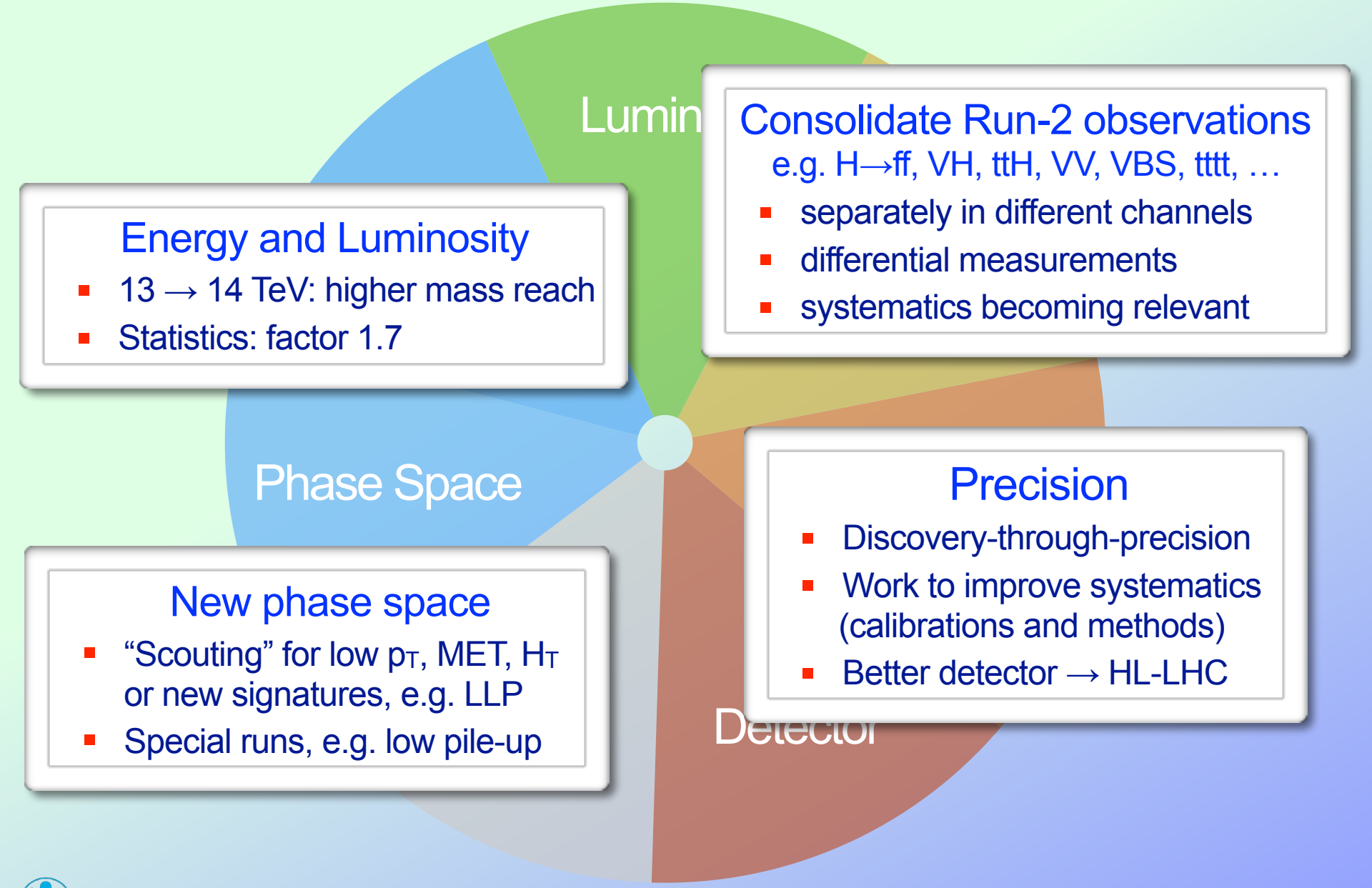
New phase space

- “Scouting” for low p_T, MET, H_T or new signatures, e.g. LLP
- Special runs, e.g. low pile-up

Opportunities in Run-3



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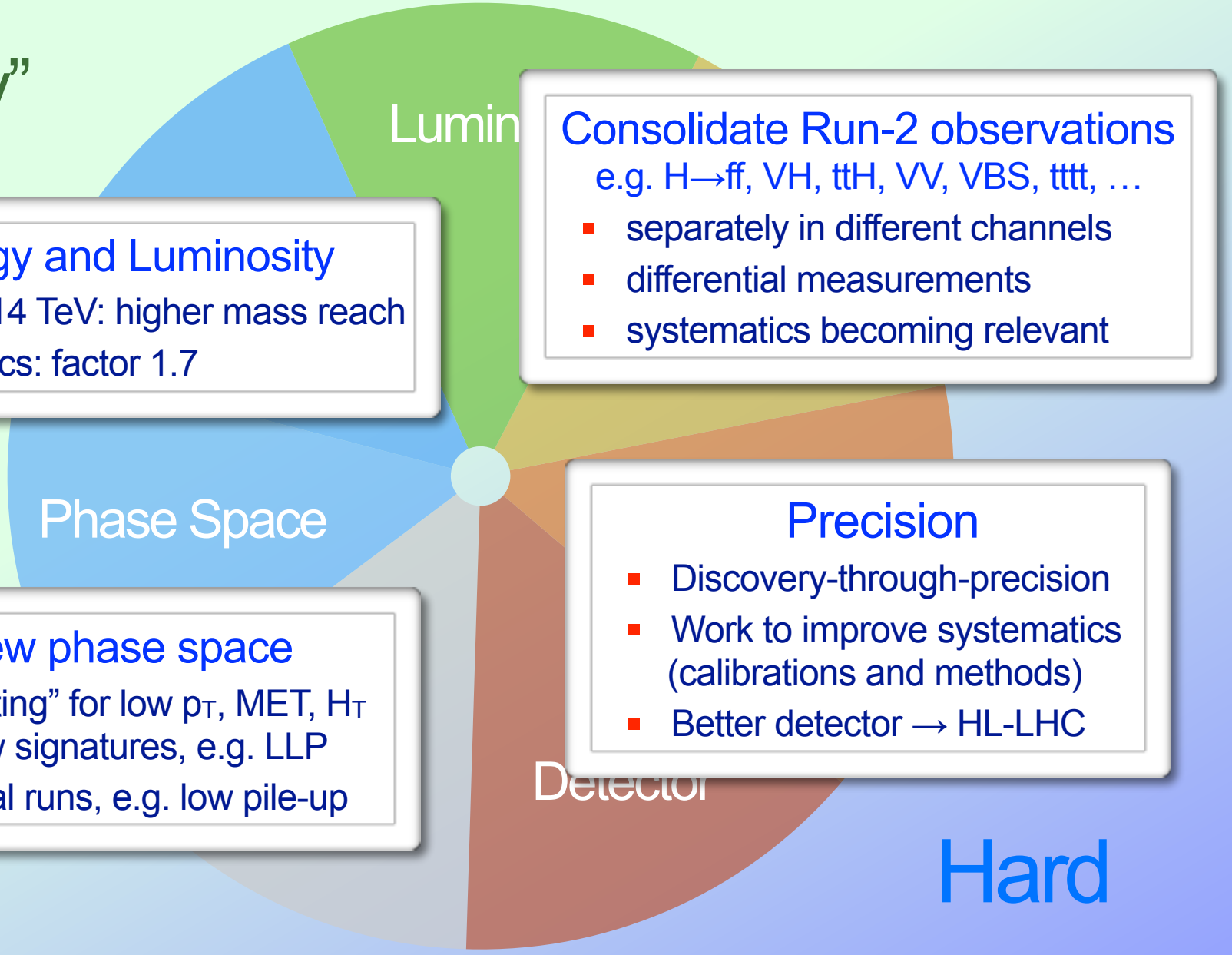
Precision

- Discovery-through-precision
- Work to improve systematics (calibrations and methods)
- Better detector → HL-LHC

Opportunities in Run-3

"Easy"



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- 13 → 14 TeV: higher mass reach
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e.g. H→ff, VH, ttH, VV, VBS, tttt, …

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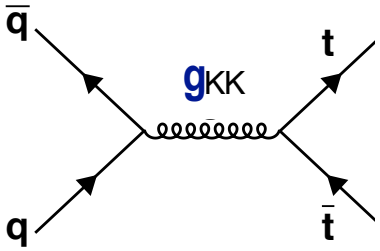
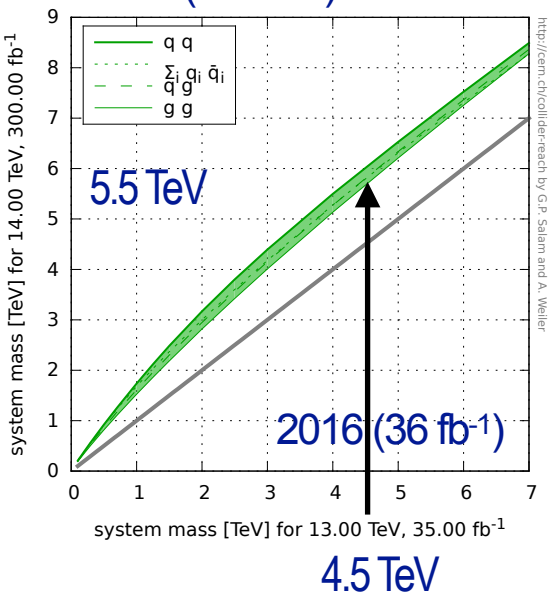
Precision

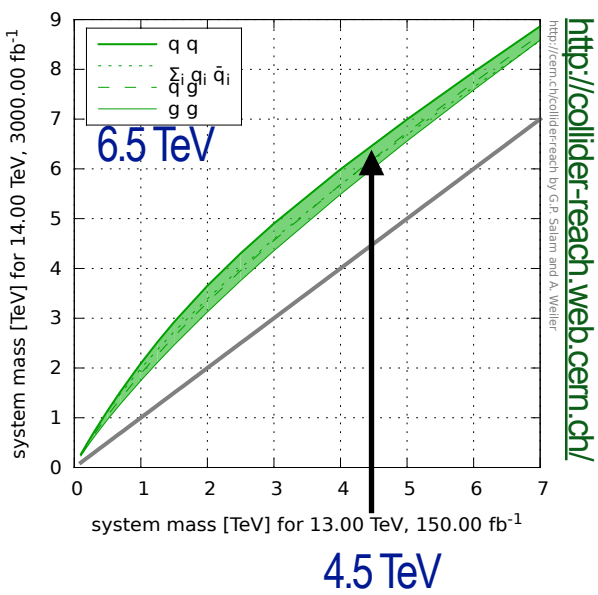
- Discovery-through-precision
- Work to improve systematics (calibrations and methods)
- Better detector → HL-LHC

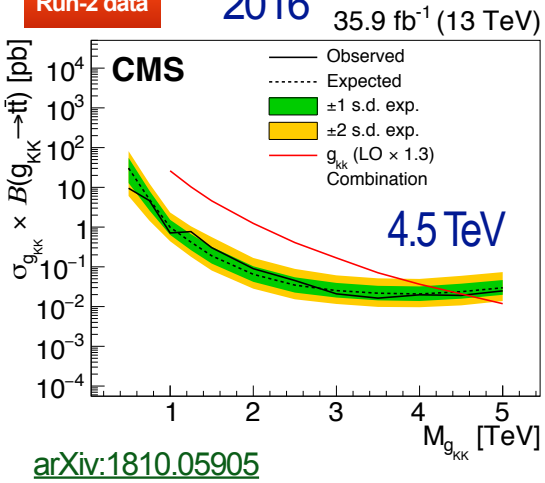
Run-3 High-Mass Reach

- 14 TeV: higher masses
- Example: Randall-Sundrum-Gluon RSG → tt

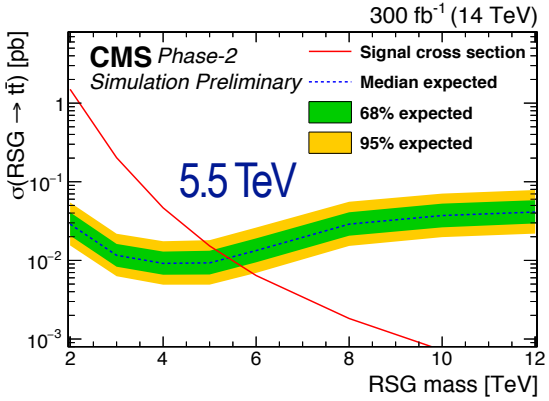




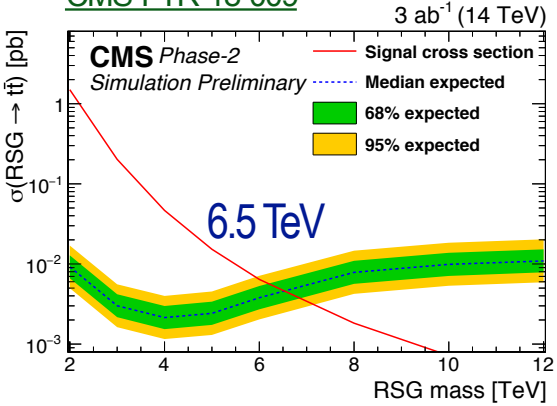




arXiv:1810.05905



CMS-FTR-18-009



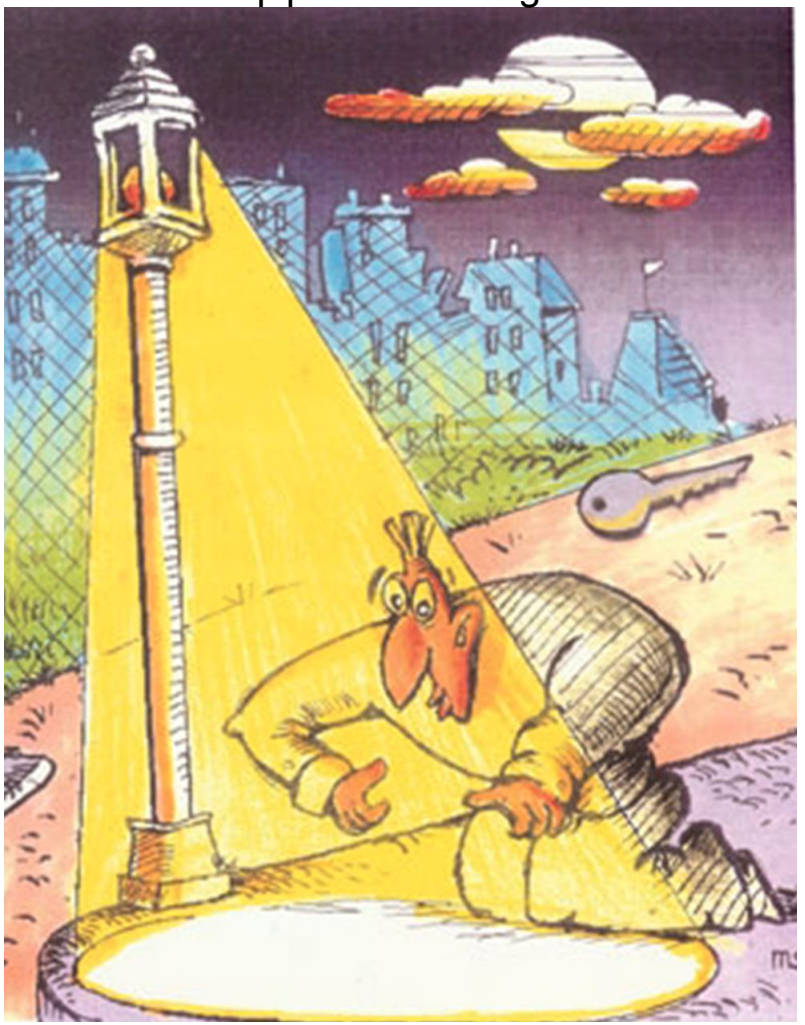
Run-3: expect ~1 GeV w.r.t. 2016

Data “Scouting”

- Also known as **trigger-level analysis**
  - HLT-reconstructed events with reduced event-content
    - size ~ 1.5 kB/evt
    - rate ~ 5 kHz established
  - No raw data stored
  - No prompt reconstruction

- In contrast: data “**parking**”
  - Store full raw data for later reconstruction
  - 2018: 12 billion B-candidate events, currently being reconstructed

Lamp posts to flood lights !



Increase kinematic reach substantially

Data “Scouting”

CMS-PAS-EXO-19-018

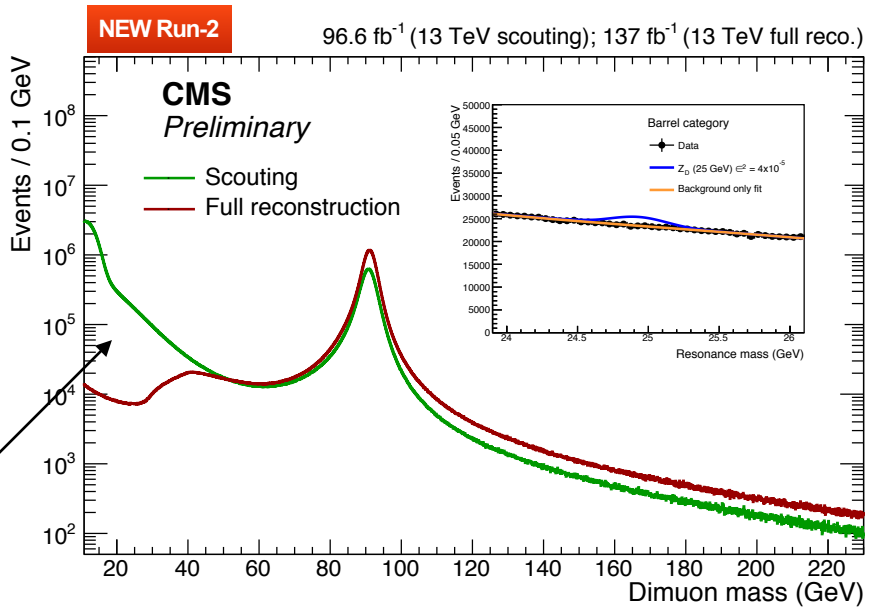
- Also known as **trigger-level analysis**
  - HLT-reconstructed events with reduced event-content
    - size ~ 1.5 kB/evt
    - rate ~ 5 kHz established
  - No raw data stored
  - No prompt reconstruction

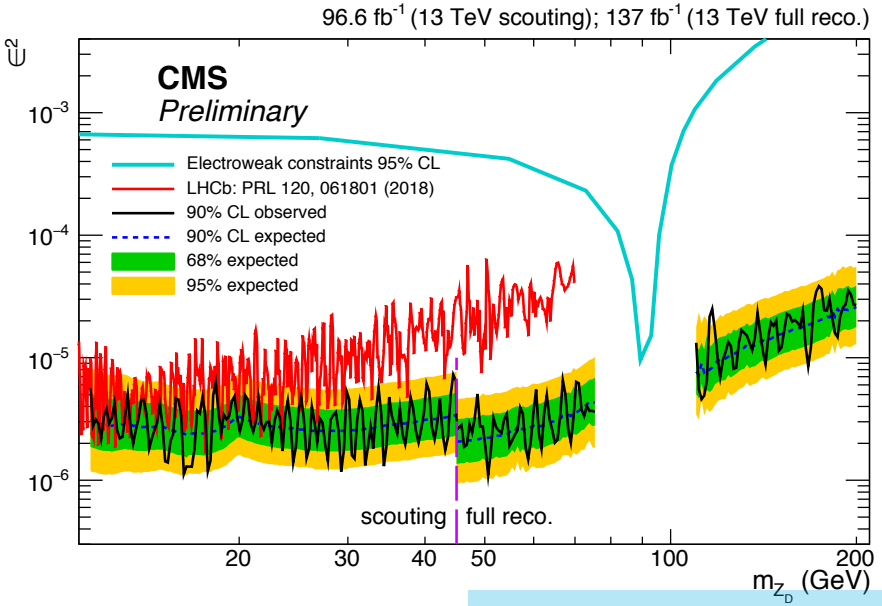
- Run 2 results:
  - Search for Dark Photons in μμ events
  - Dijet and tri-jet resonance searches

arXiv:1810.10092 arXiv:1806.00843

- Run-3 and HL-LHC: more “scouting” e.g. for low p_T and long-lived particles in discussion / preparation

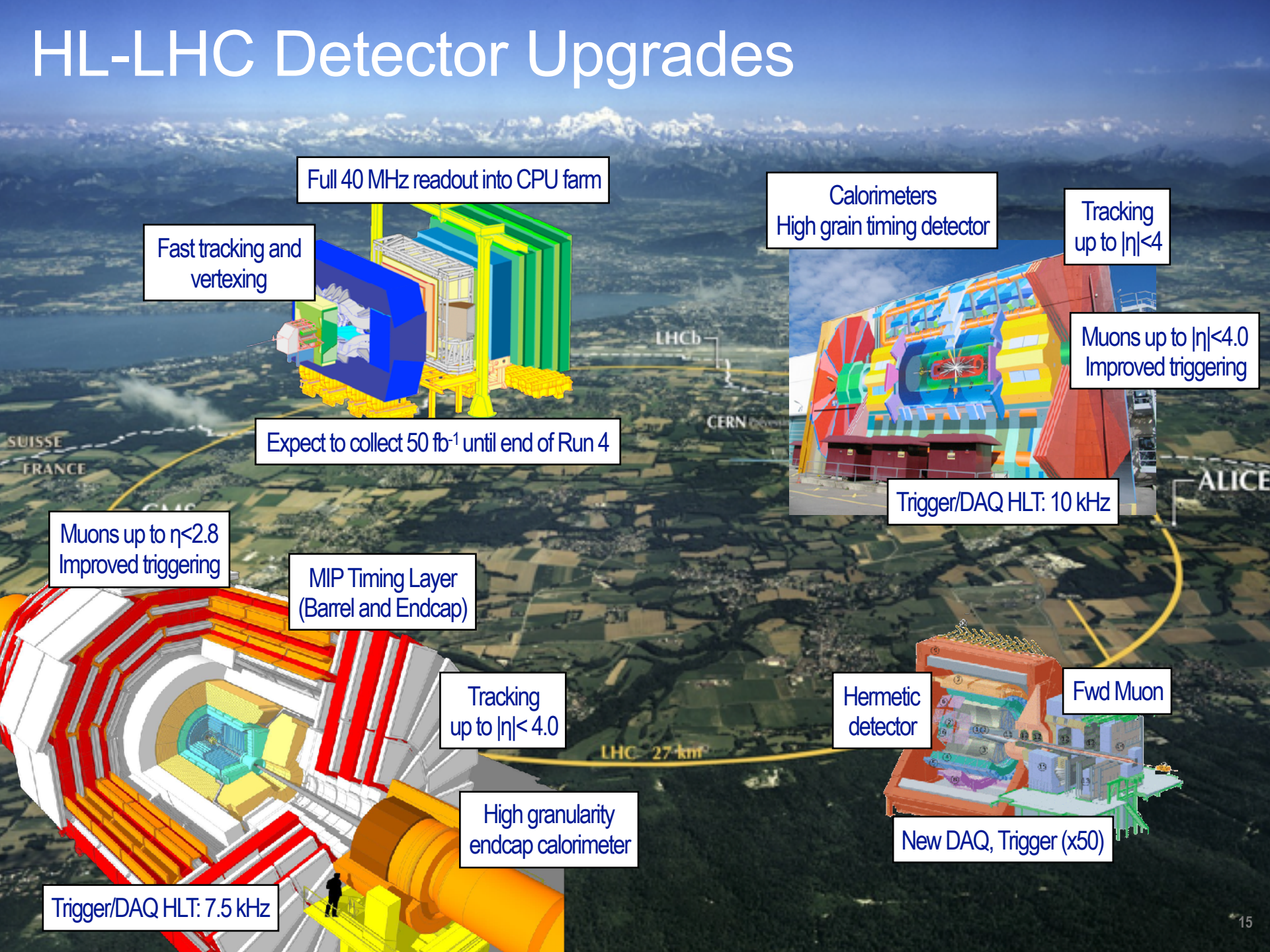
Increase kinematic reach substantially





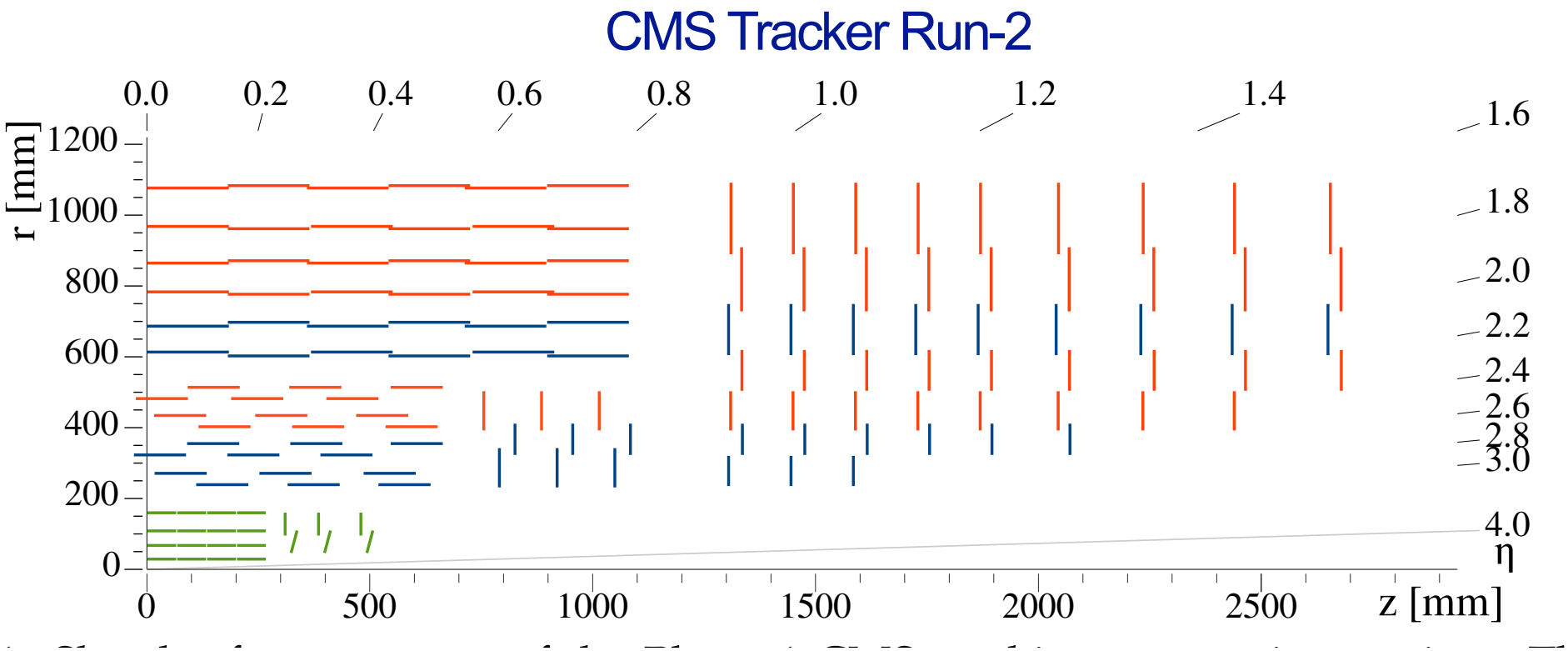
talk by Swagata Mukherjee

HL-LHC Detector Upgrades



HL-LHC

much improved detectors and higher luminosity

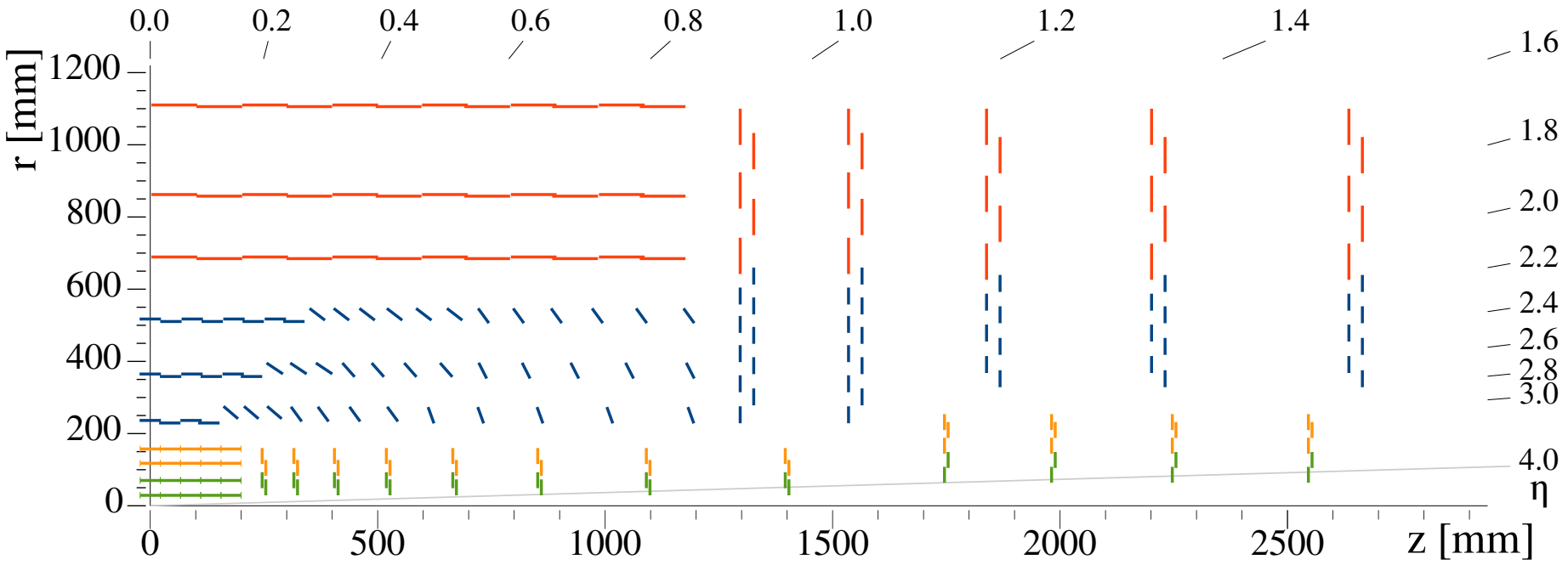


Acceptance: $|\eta| < 2.5$

HL-LHC

much improved detectors and higher luminosity

CMS Tracker HL-LHC

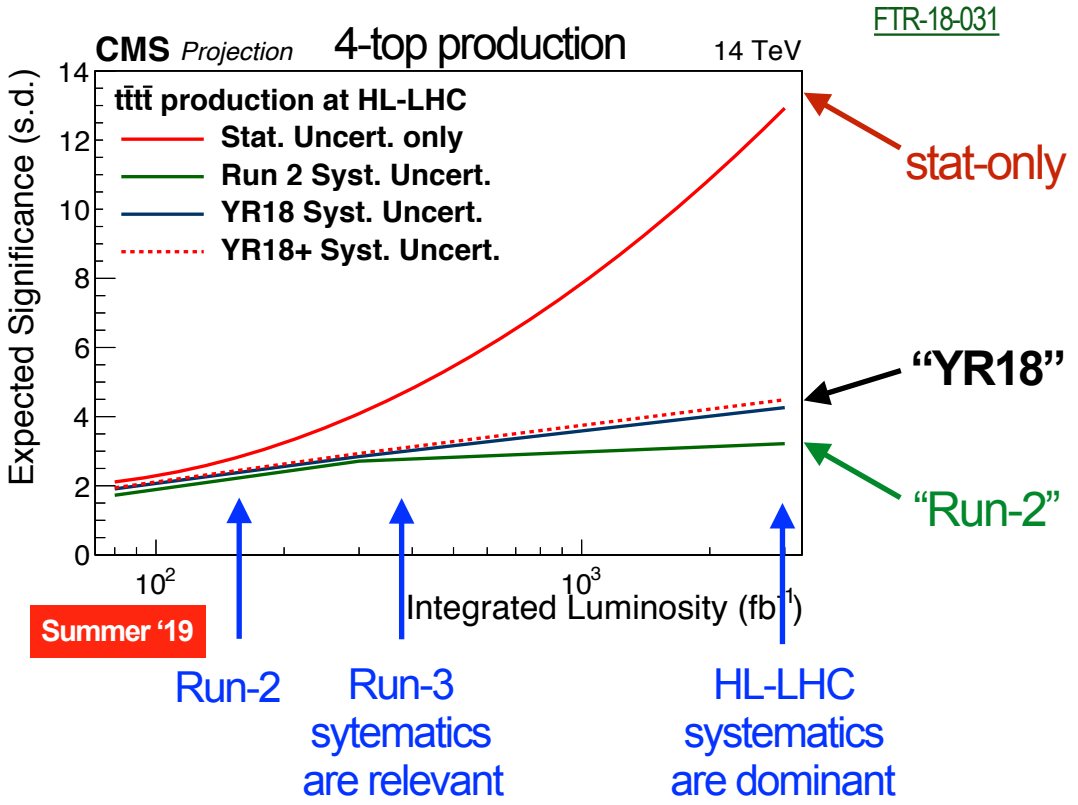


Acceptance: |η| < 4.0

… and less detector material and better resolution

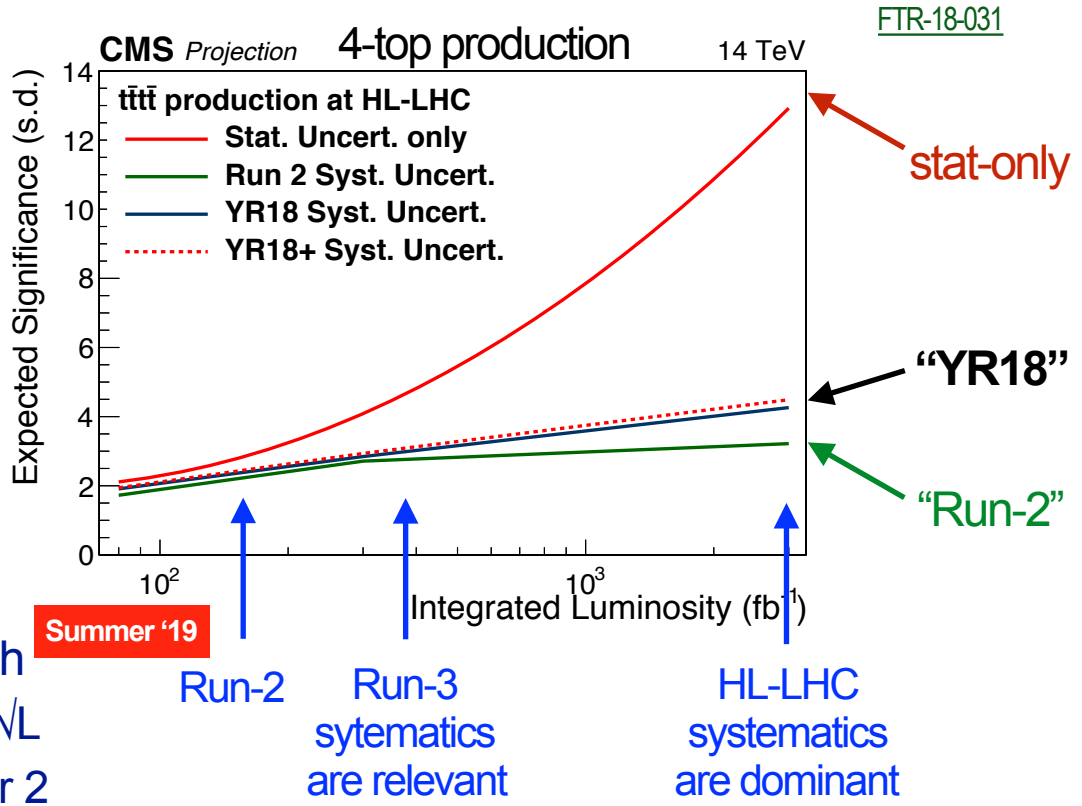
HL-LHC Projected Uncertainties

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



HL-LHC Projected Uncertainties

- Systematic uncertainties will be limiting factor for more and more measurements
- Realistic projections for HL-LHC, based on Run-2 analyses
- ATLAS and CMS common approach
  - Statistical uncertainties scale as $1/\sqrt{L}$
  - Theory: assume reduction by factor 2
  - MC statistics assumed to give zero uncertainty
  - Experimental systematics scale as $1/\sqrt{L} \rightarrow$ until "floor"



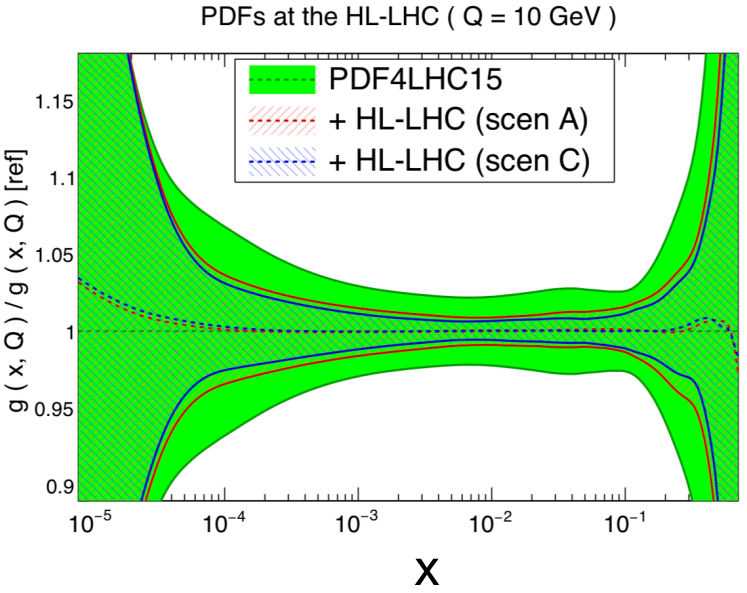
"YR18": agreed-upon common ATLAS and CMS "floor"-values for all physics objects

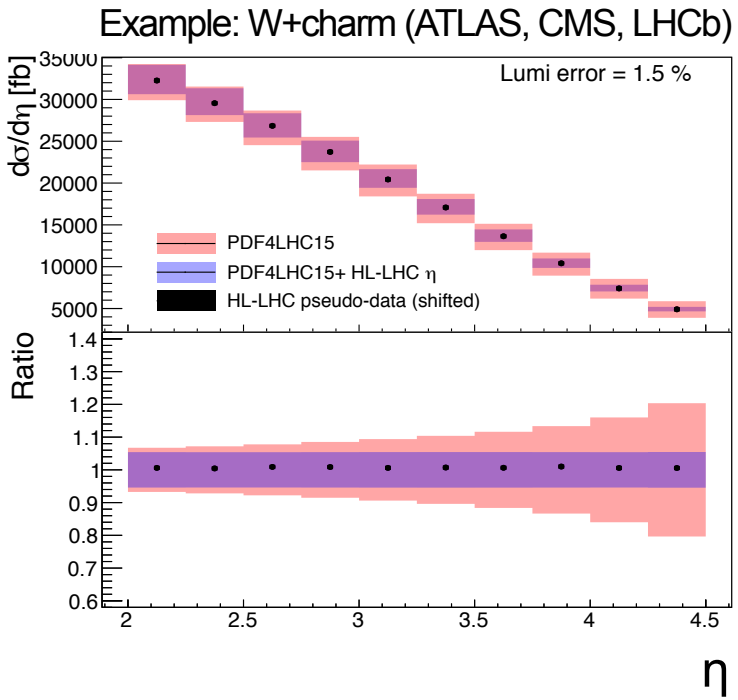
Future work: improve floor beyond current expectations

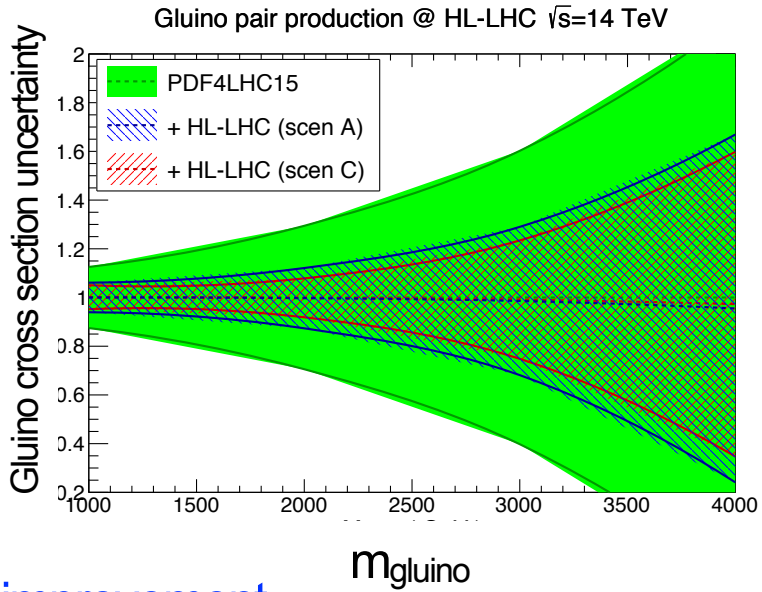
Ultimate Precision PDF

arXiv:1810.03639

- Parton density distributions based on differential cross sections at ultimate precision
- Projection using differential pseudo-data (DY, ttbar, W+c, direct γ, and incl. jets)

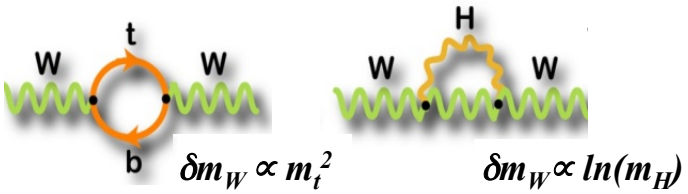






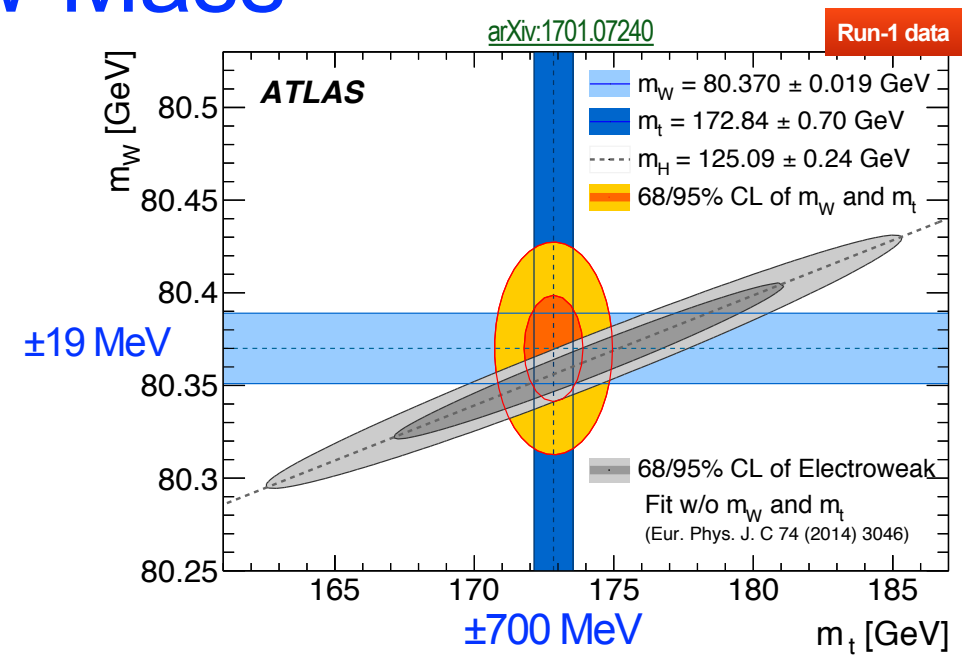
Expect factor 2–5 improvement

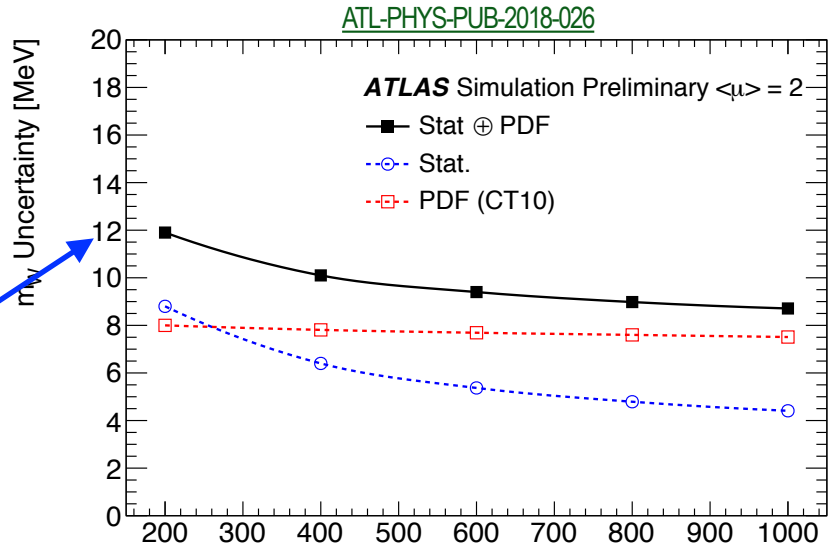
Ultimate Precision W Mass



$\delta m_W \propto m_t^2$ $\quad$ $\delta m_W \propto \ln(m_H)$

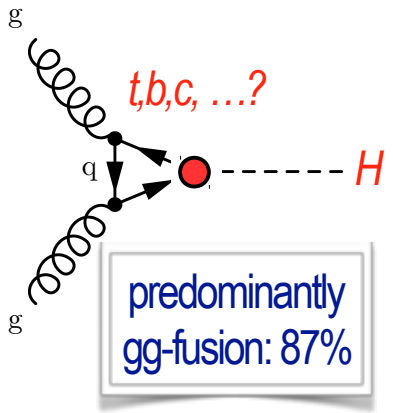
- m_{top}, m_W and m_H connected via loop corrections → constrain and test SM (discovery-through-precision)
- Current dominant uncertainty: PDF
- Extended η-range: central and forward regions are anti-correlated.
- Low PU: high-resolution MET
- Low-PU run (μ~2) at HL-LHC:
  - 200 pb^{-1}, $|\eta|<2.4$: 2x10^6 evts. 16 MeV
  - 200 pb^{-1}, $|\eta|<4$: 12 MeV
  - 1 fb^{-1}, $|\eta|<4$: 9 MeV
  - **+ ultimate PDF: 5 MeV**

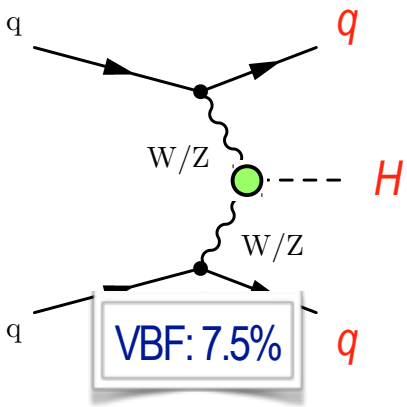


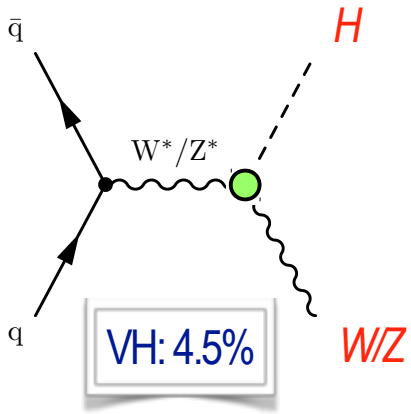


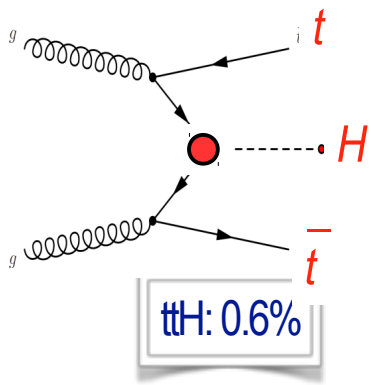
Higgs Production and Decay

Production:

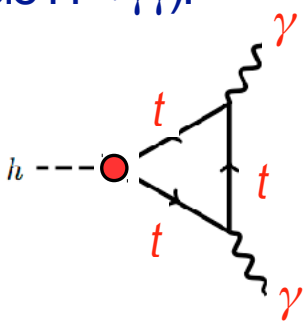


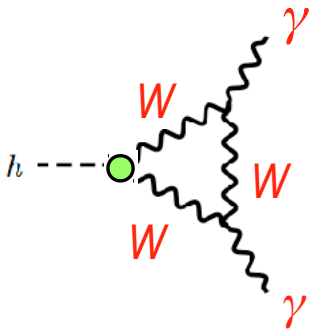






Decay (Example H→γγ):

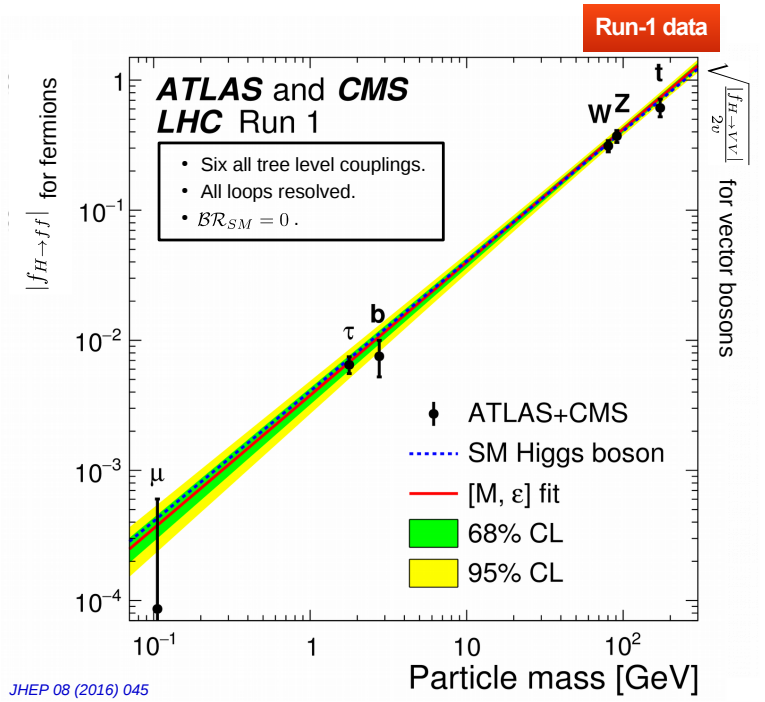




Kappa-framework:

$$\mu_i^f = \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \kappa_f^2}{\sum_j \kappa_j^2}$$

κ-factors quantify H-couplings w.r.t SM expectation

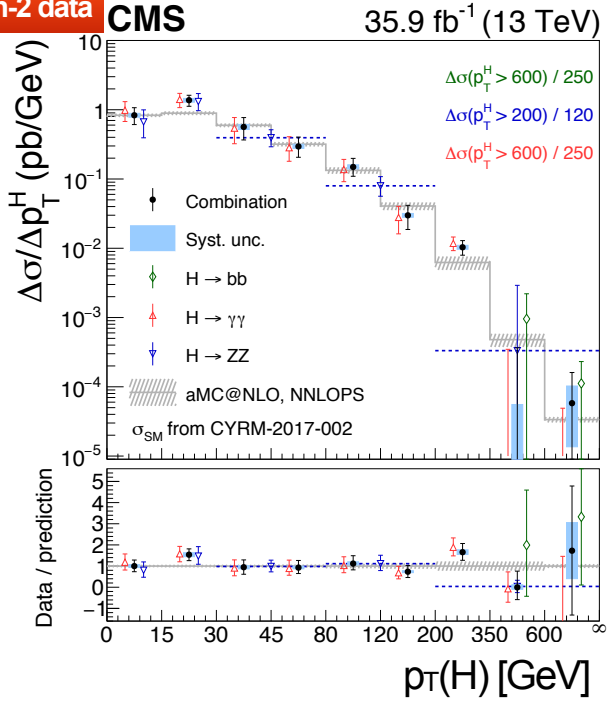


JHEP 08 (2016) 045

Higgs at Run-2 and Run-3

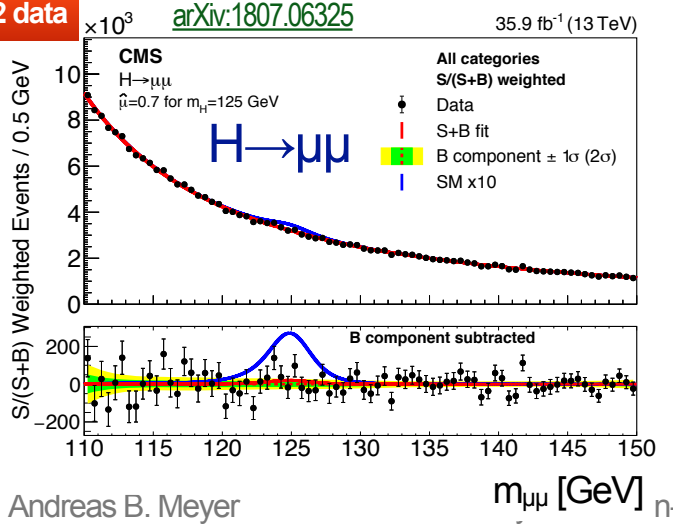
Run-2 data

arXiv:1812.06504

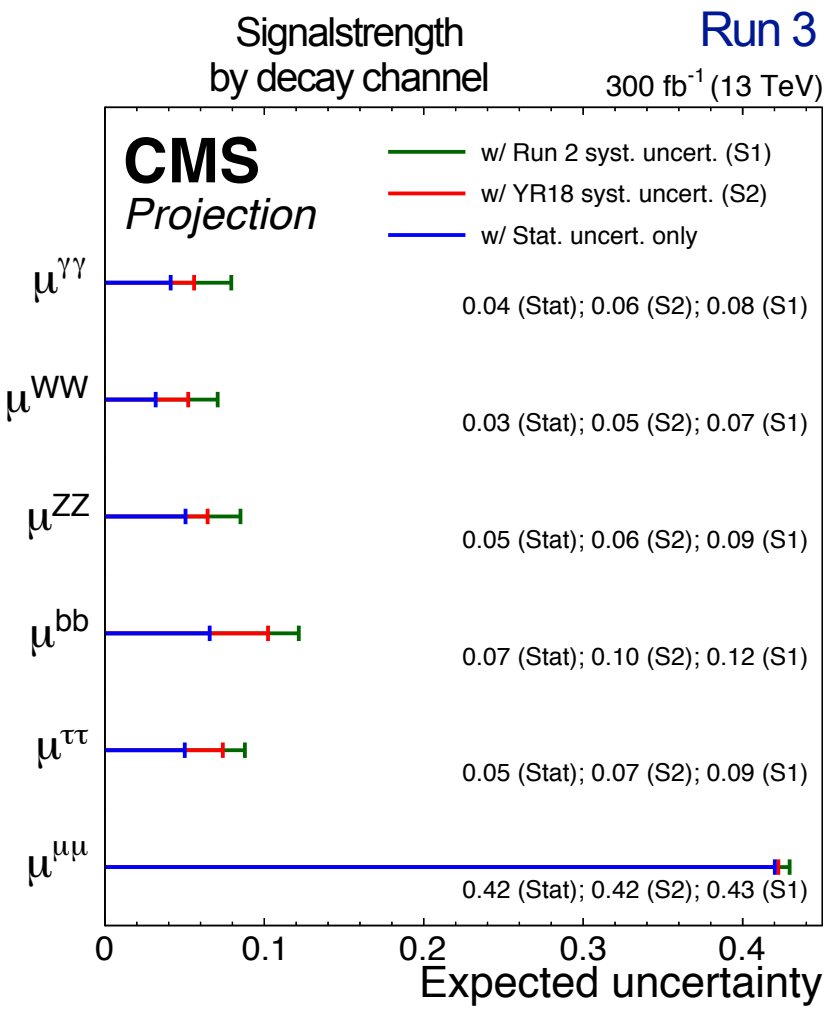


Run-2 data

arXiv:1807.06325



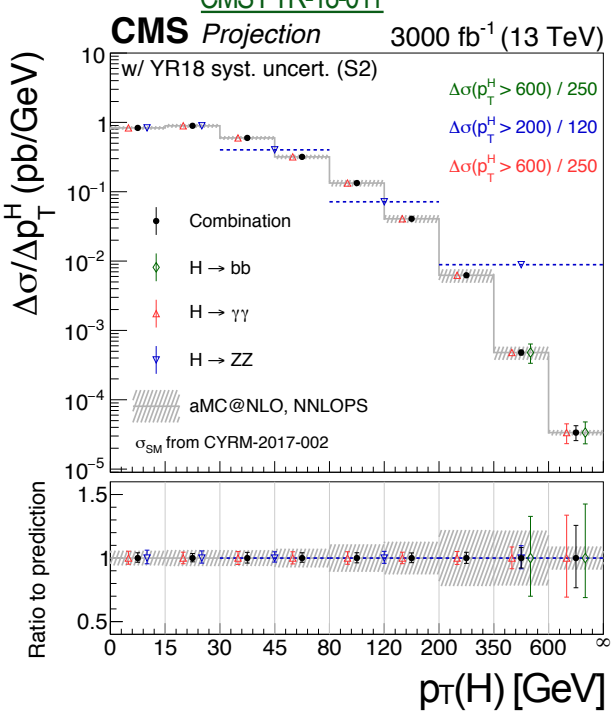
CMS FTR-18-011



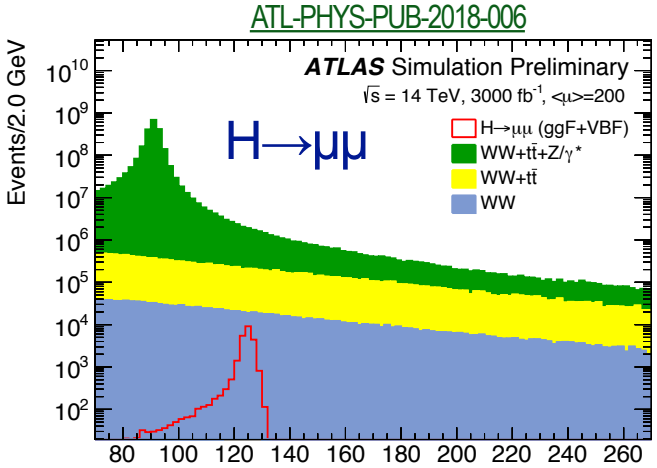
Uncertainty: 5% - 10% (μμ ~40%)

Higgs at the HL-LHC

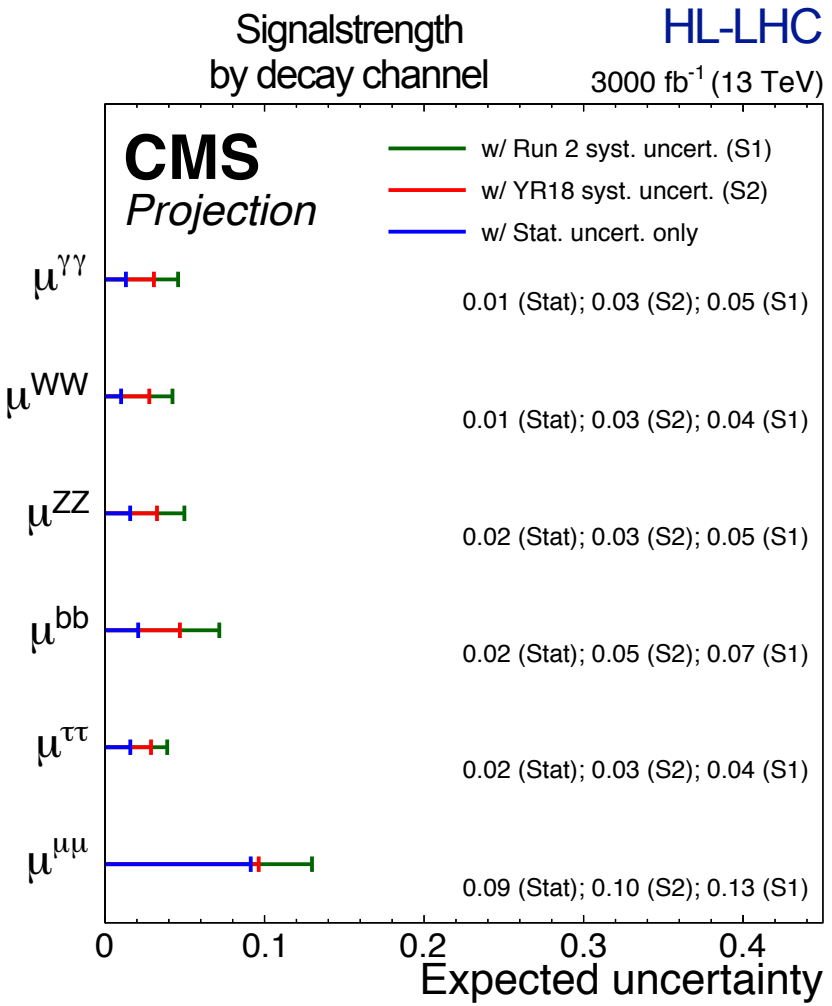
CMS FTR-18-011



ATL-PHYS-PUB-2018-006

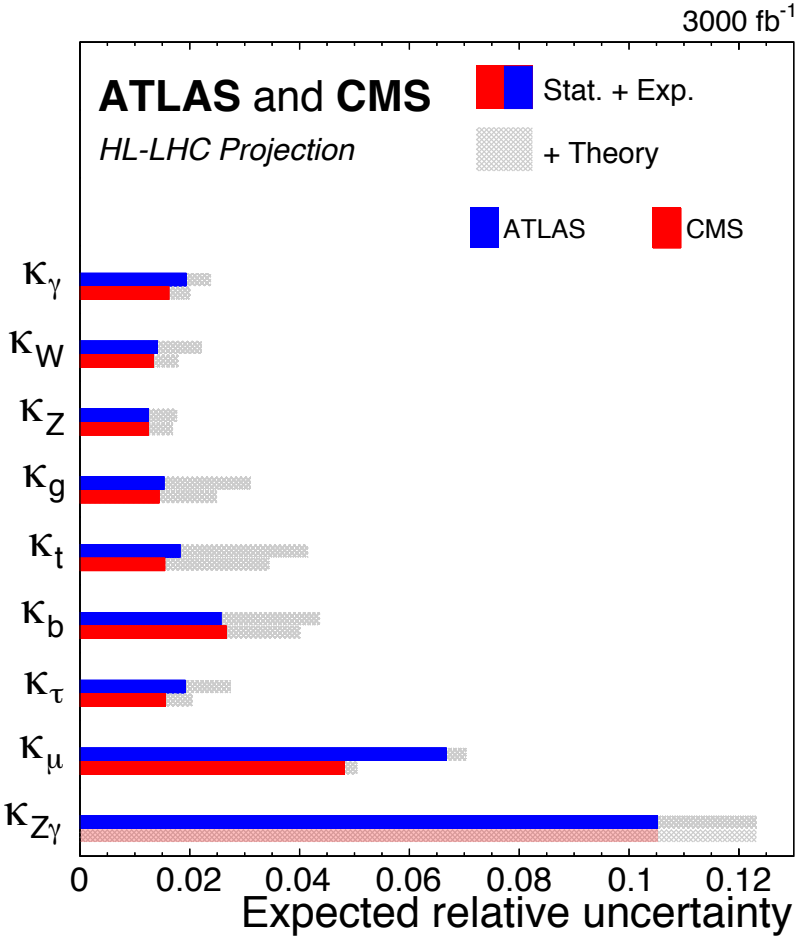


CMS FTR-18-011

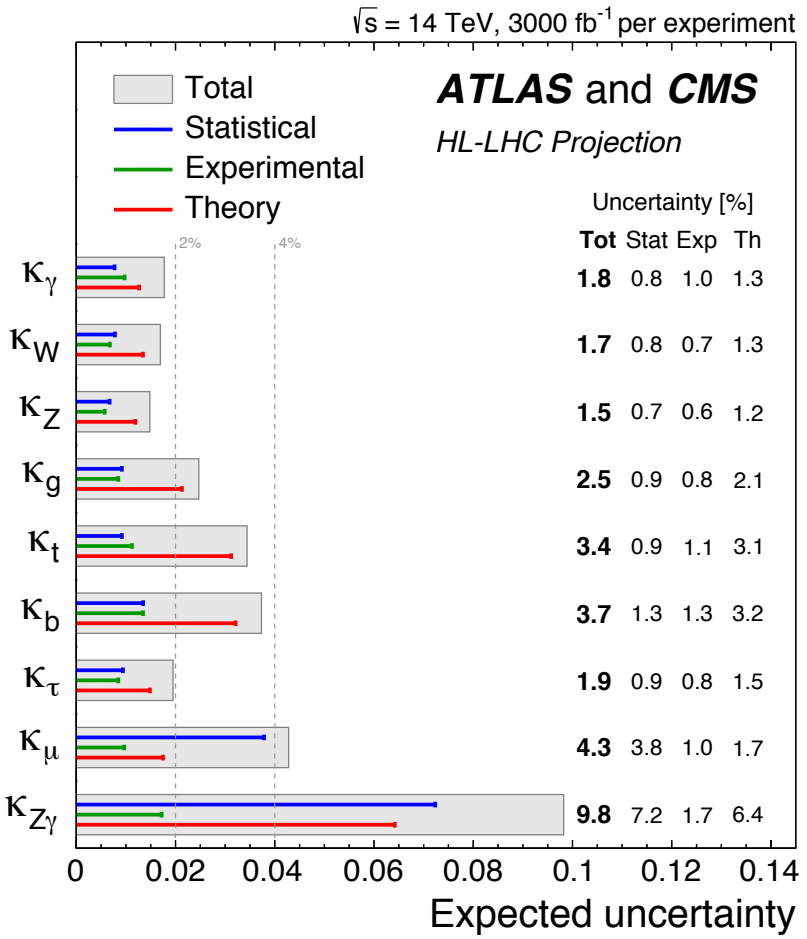


Uncertainty: 3% - 5% (μμ ~10%)

Higgs Combination



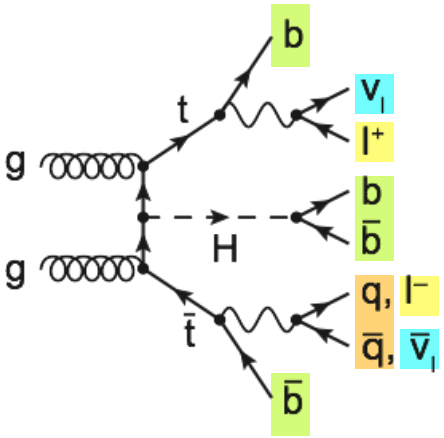
arXiv:1902.00134



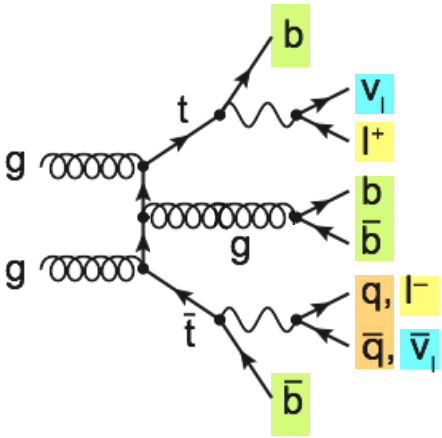
ATLAS and CMS very consistent

Experimental uncertainties: 1-1.5% (μ ~4%)

ttH → bb

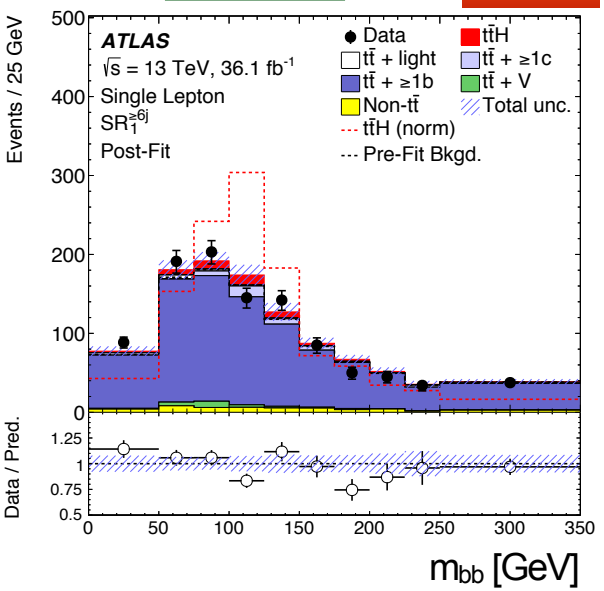


ttH signal



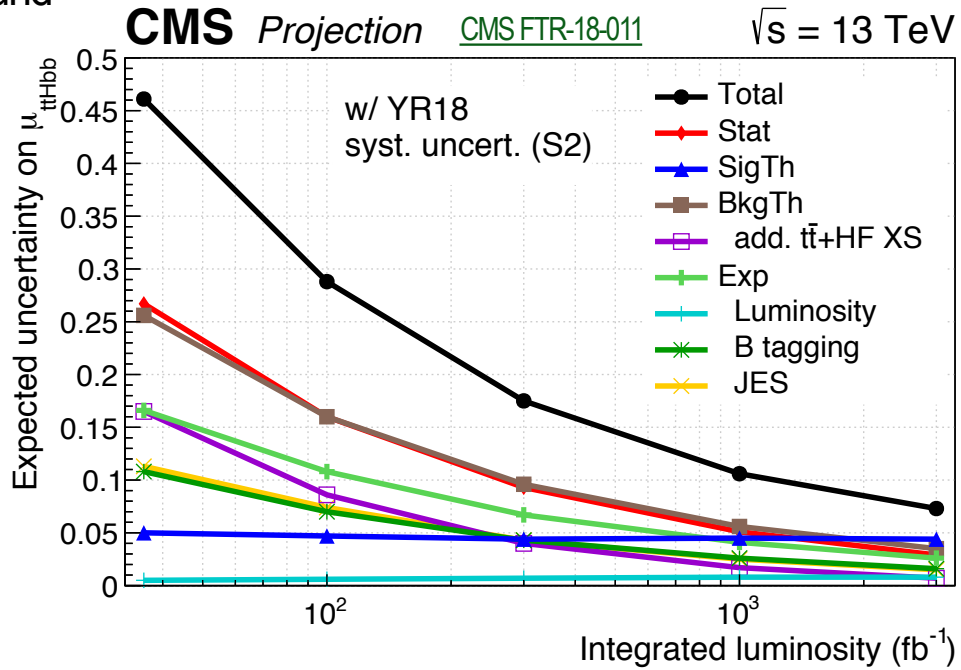
tt+HF background

CMS-PAS-HIG-18-030 arXiv:1712.08895 Run-2 data



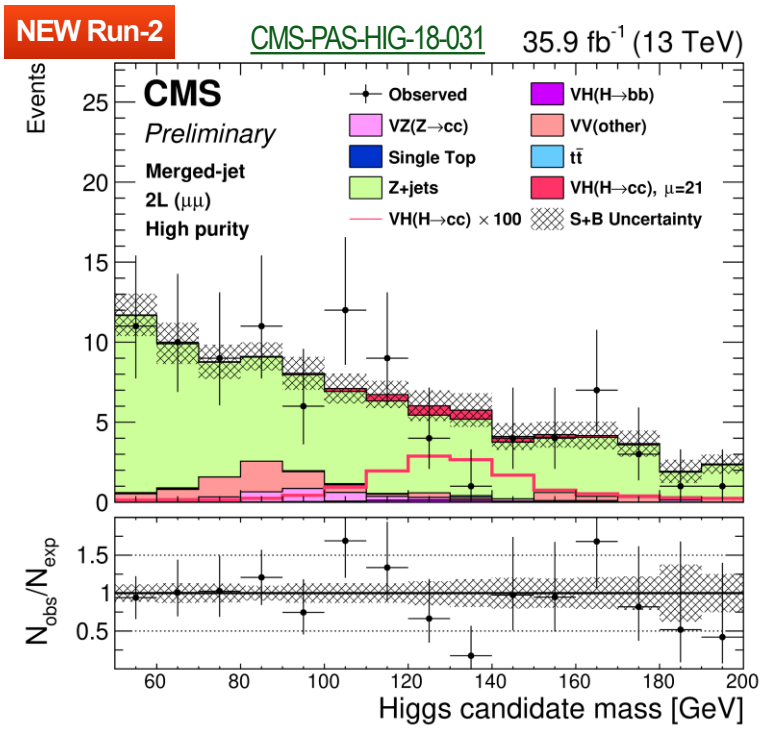
- CMS: for 3 ab^{-1} expect δμ ~ 7%
- dominant uncertainty on μ: signal theory

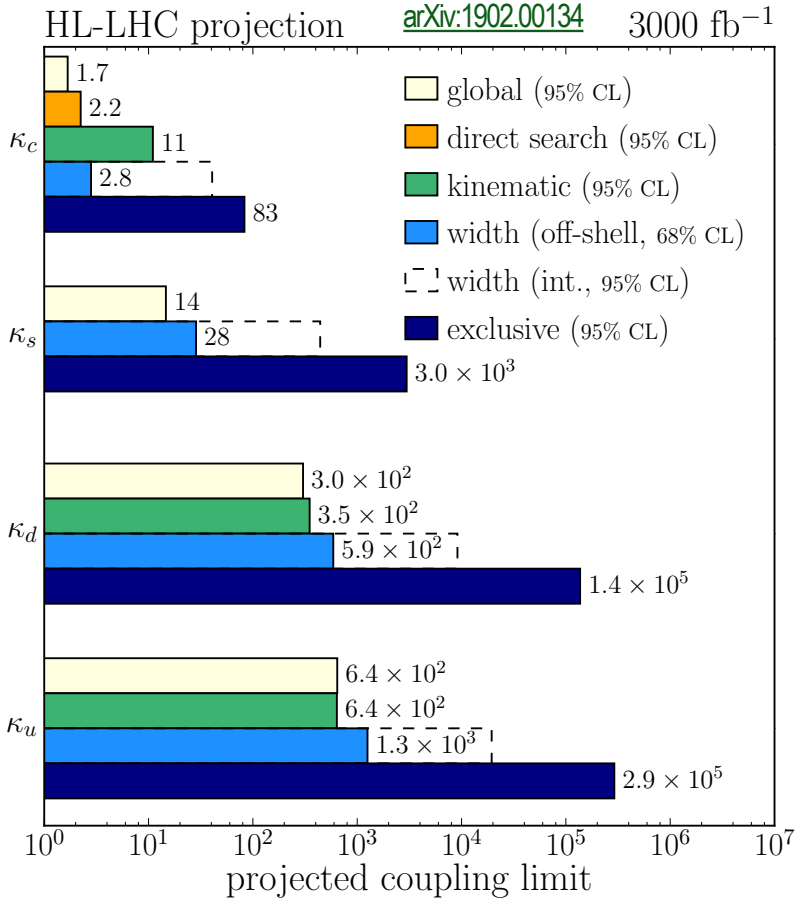
Non-resonant tt+HF background constrained from data



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 (previous slide)
  - total width (off/on-sh & interf. in pp→4ℓ and $\gamma\gamma$)
  - exclusive decays (e.g. H → J/$\psi\gamma$)



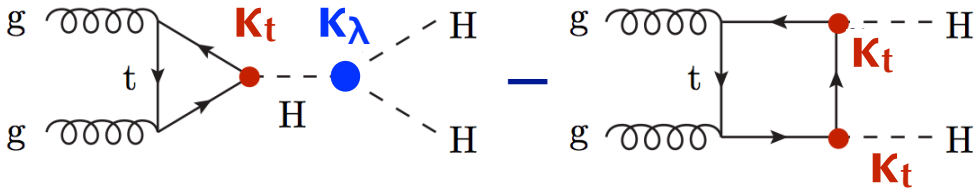


- Direct search: VH→cc
  - ATLAS (36fb^{-1}): μ < 110 x SM @ 95CL — arXiv:1802.04329
  - CMS (36fb^{-1}): μ < 70 x SM @ 95CL — CMS-PAS-HIG-18-031
  - ATLAS (3000fb^{-1}): μ < 6.3 x SM @ 95CL — arXiv:1902.00134
  - LHCb (Run-5: 300 fb^{-1}): μ < 5-10 x SM — LHCb-CONF-2016-006

With further improvements,
Higgs-charm could be in reach

talk by Luca Mastrolorenzo

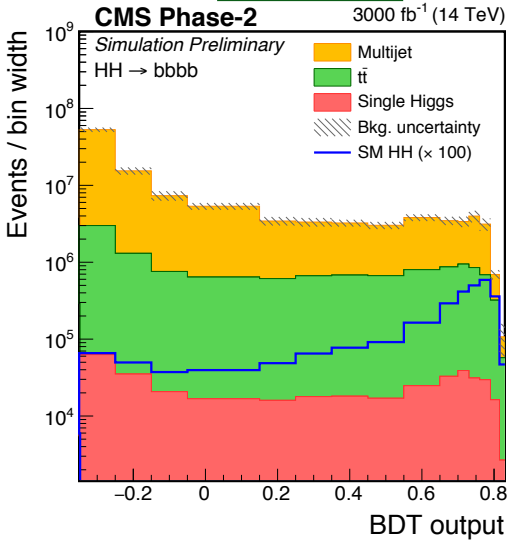
HH



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

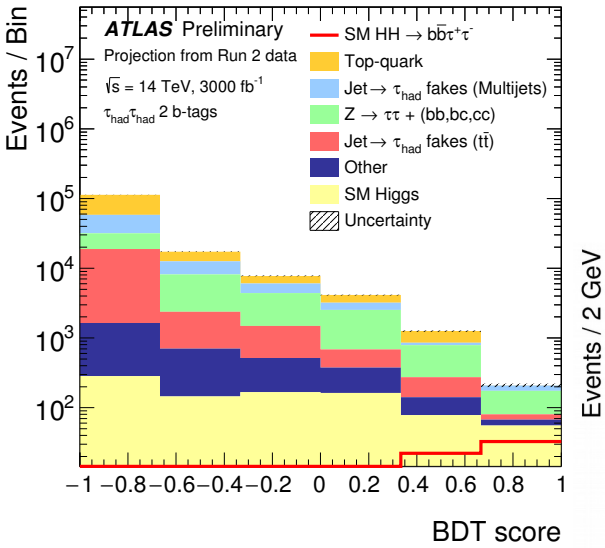
HH→bbbb

CMS-FTR-18-019



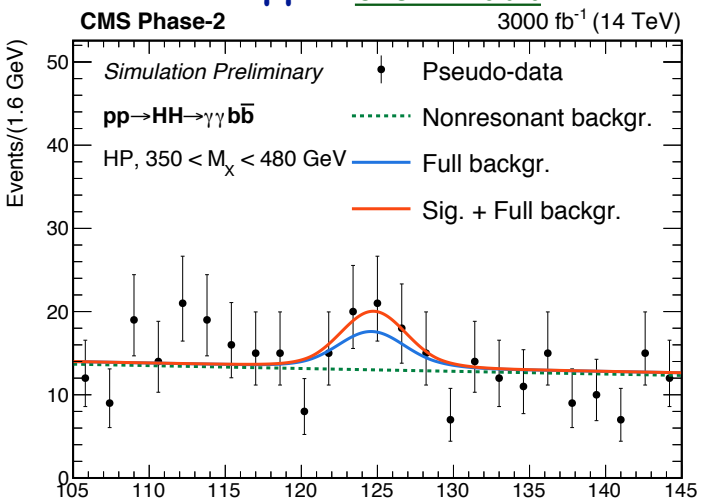
HH→bbττ

ATL-PHYS-PUB-2018-053



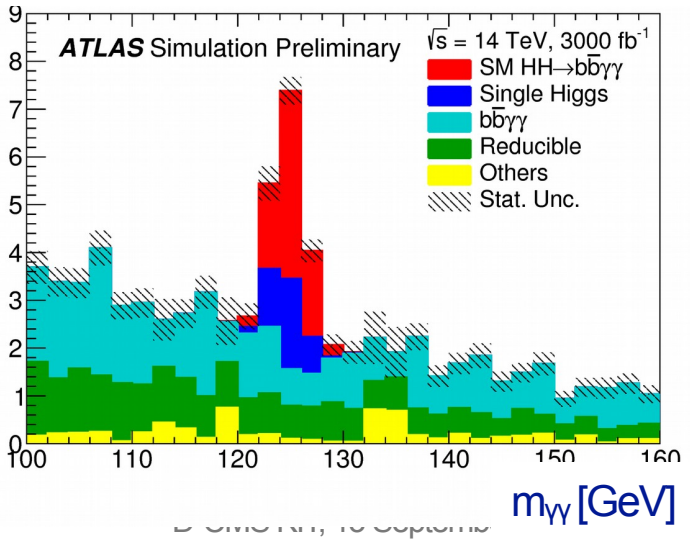
HH→bbγγ

CMS-FTR-18-019



HH→bbγγ

ATL-PHYS-PUB-2018-053

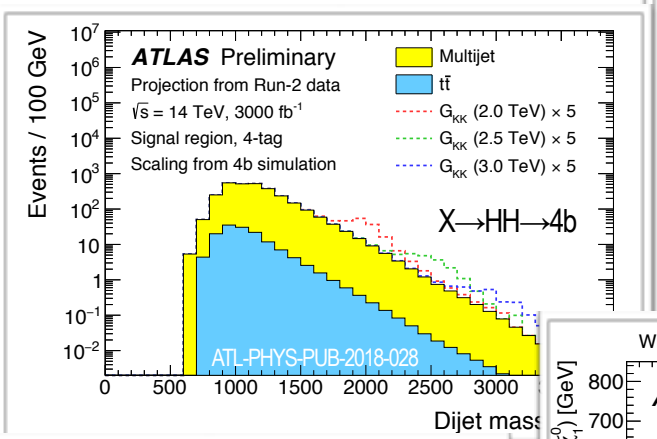


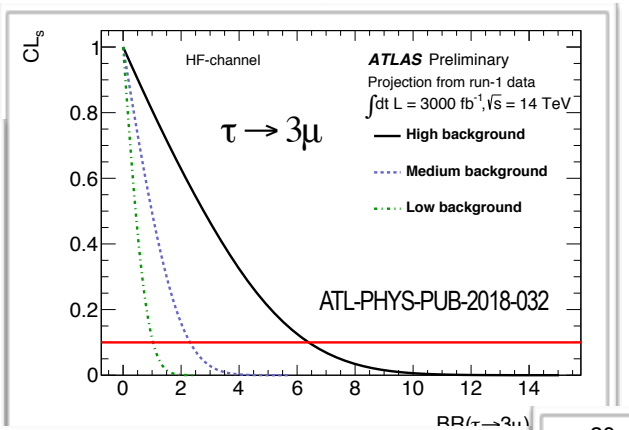
CMS and ATLAS combined

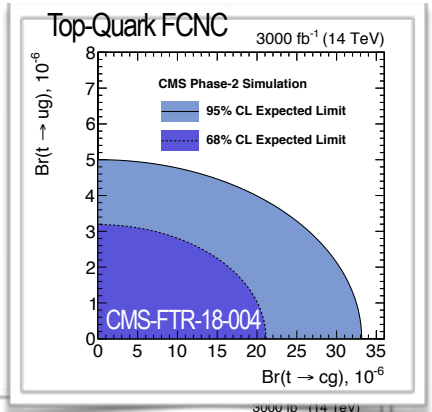
Signal-strength significance: 4σ

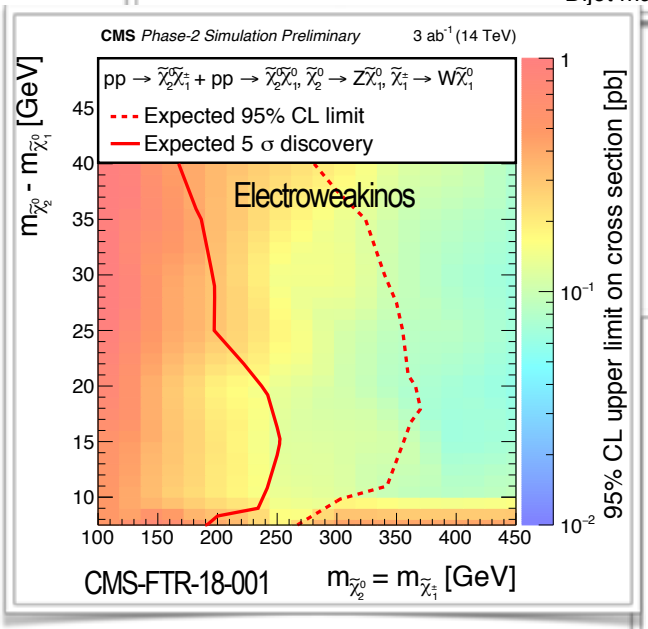
$0.1 < \kappa_\lambda < 2.3$ (at 95% CL)

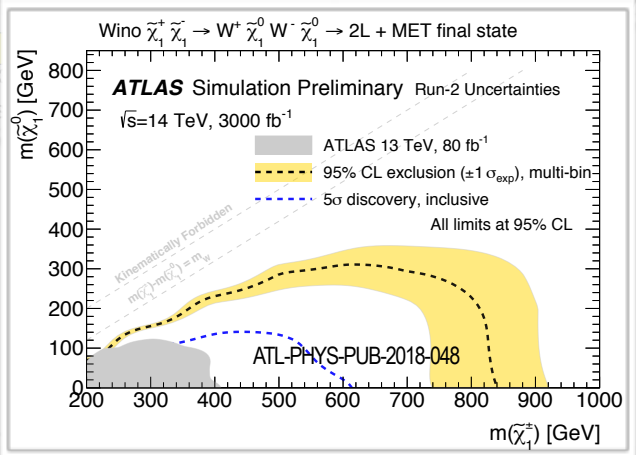
Direct Searches

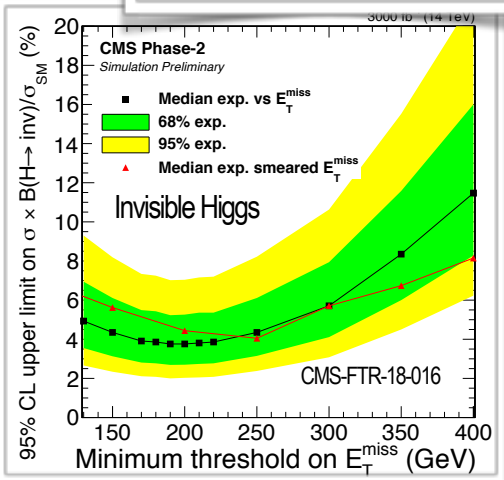


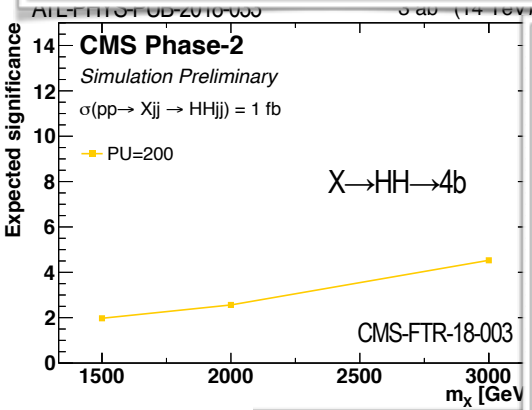


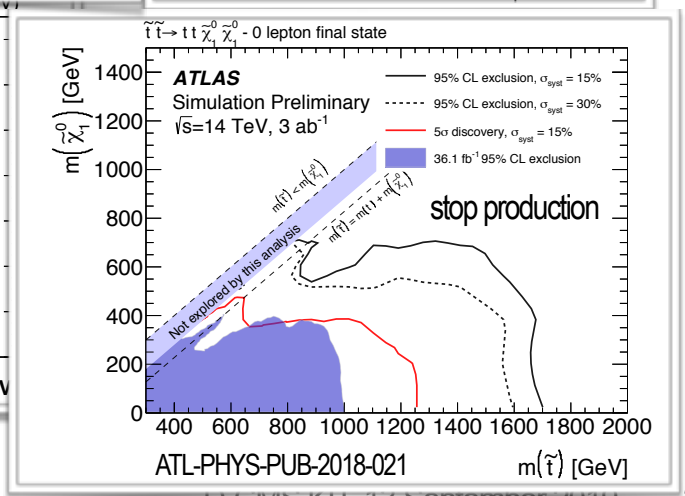






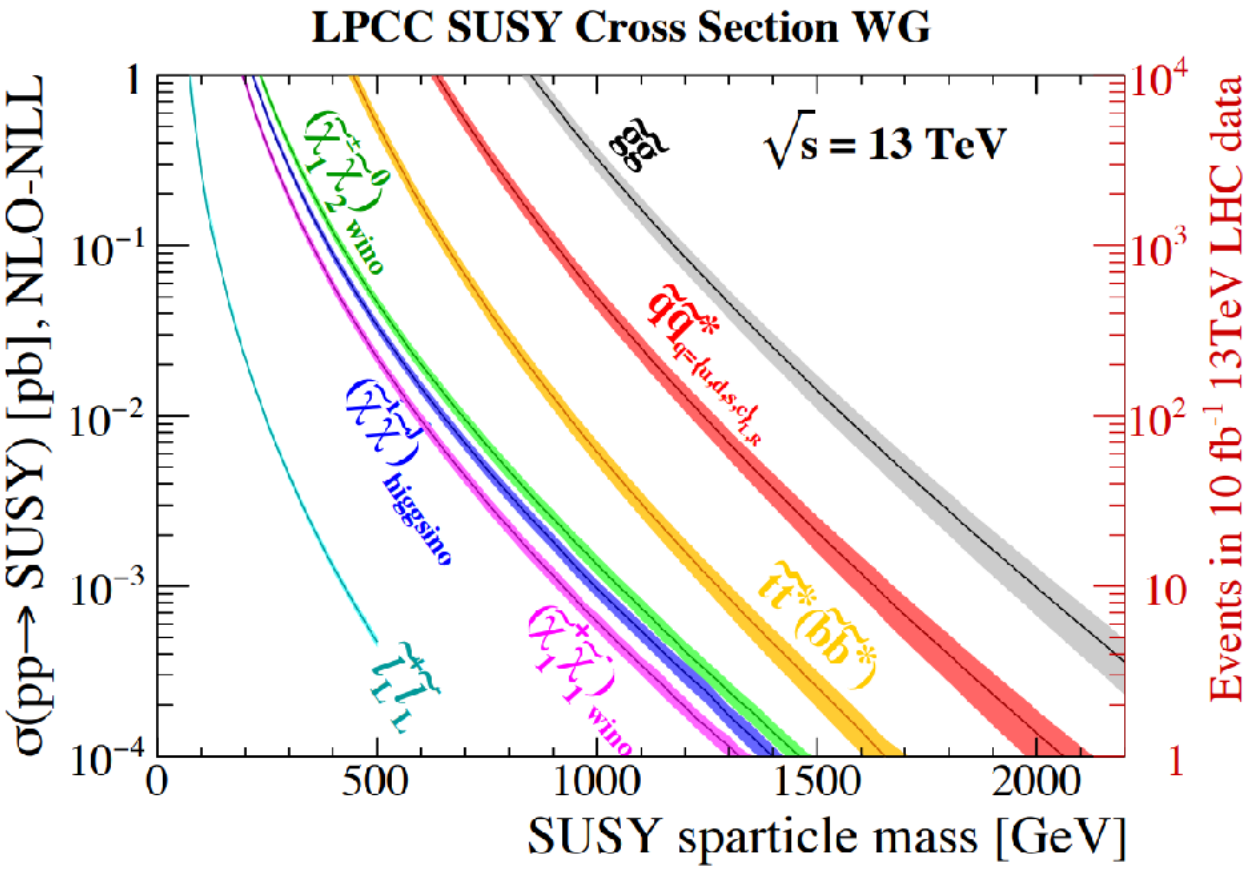




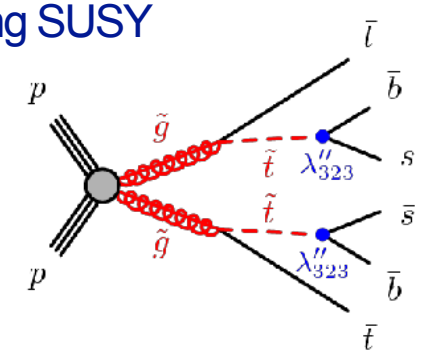


Subset of the BSM projections by ATLAS and CMS

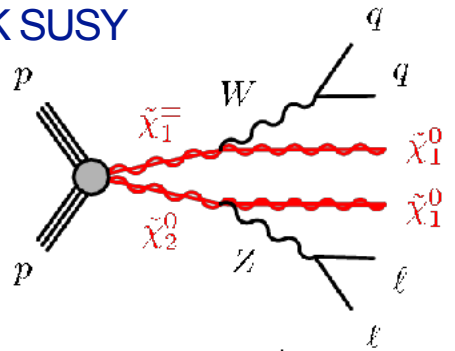
Supersymmetry

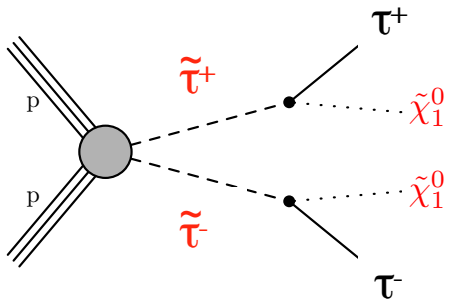


Strong SUSY



EWK SUSY

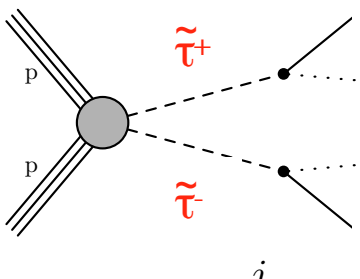


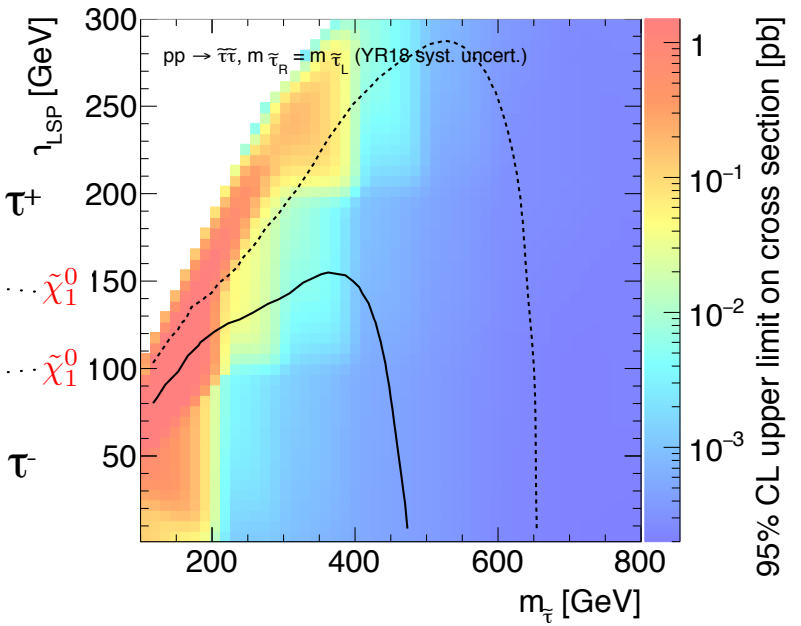


- Strong SUSY: many scenarios already excluded up to ~1 TeV
- Electroweak SUSY (σ < 0.1 pb at m = 500 GeV): could still be light

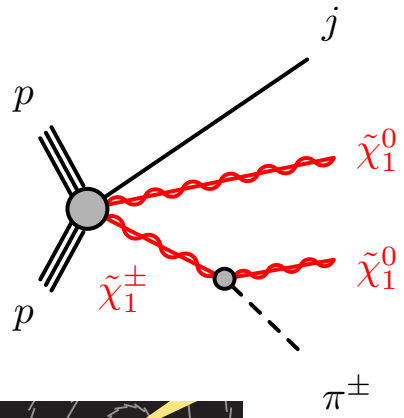
Electroweak SUSY

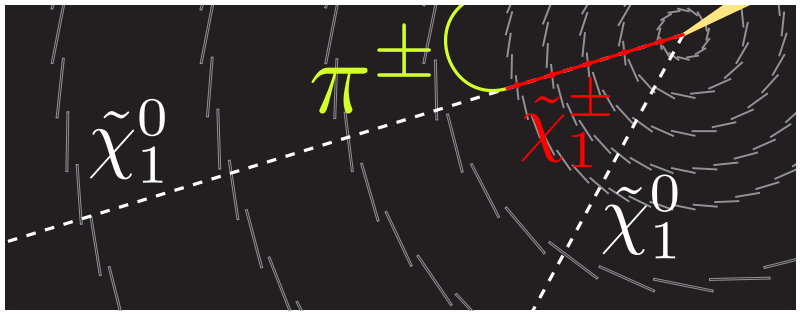
- Stau pairs:
  - Final state: $\tau_h\tau_h$ or $\ell\tau_h$ + MET
  - Run-2: No stringent limits yet
    CMS-SUS-18-006
  - HL-LHC excl. limit: 650 GeV

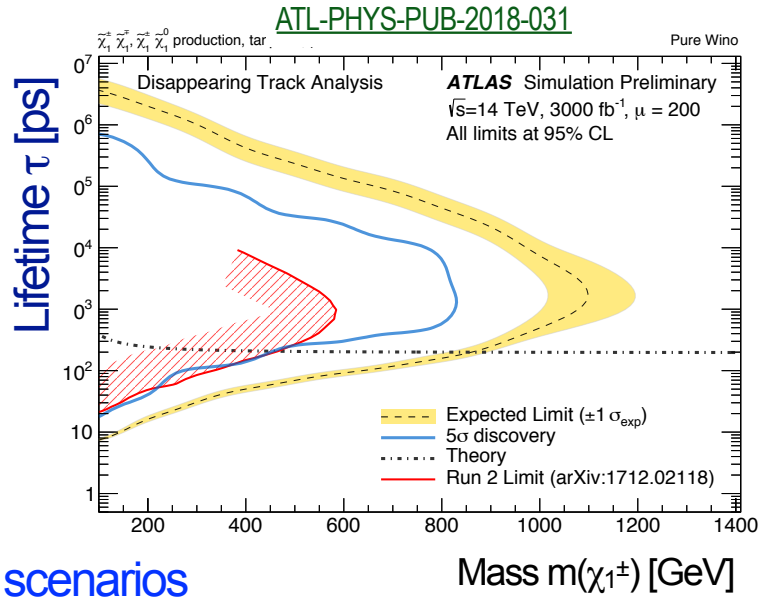




- Electroweakinos:
  - Degenerate mass scenarios
    → compressed spectra
    and/or long lifetimes
  - Use ISR jet for triggering
  - Detect disappearing track



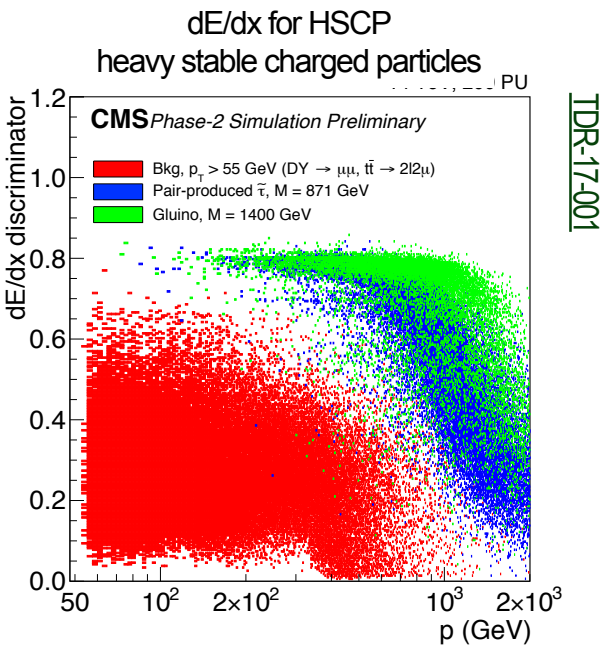


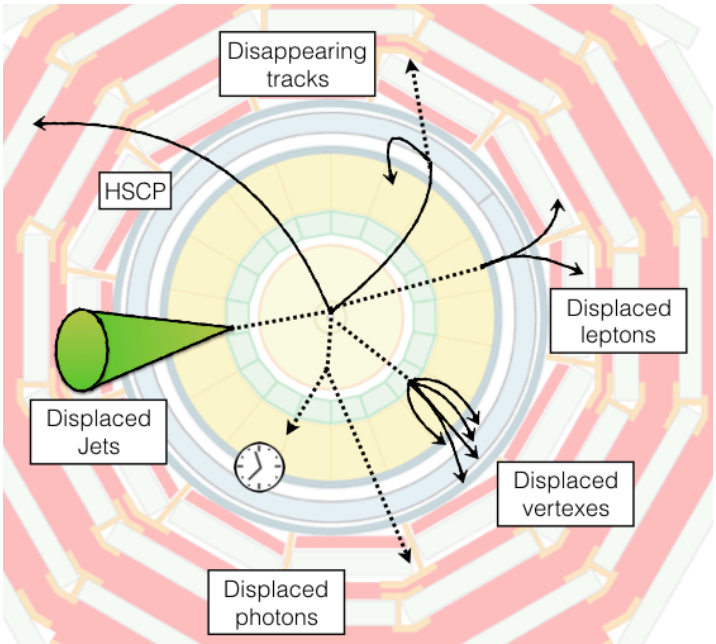


Sensitivity to new scenarios

Long-Lived Particles

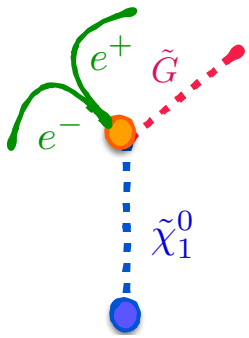
- Various scenarios: mass degeneracy, small couplings, heavy mediators
- Many standard model particles are long-lived !
- Detect LLP signatures through novel approaches, triggers (e.g. scouting) and creative analysis



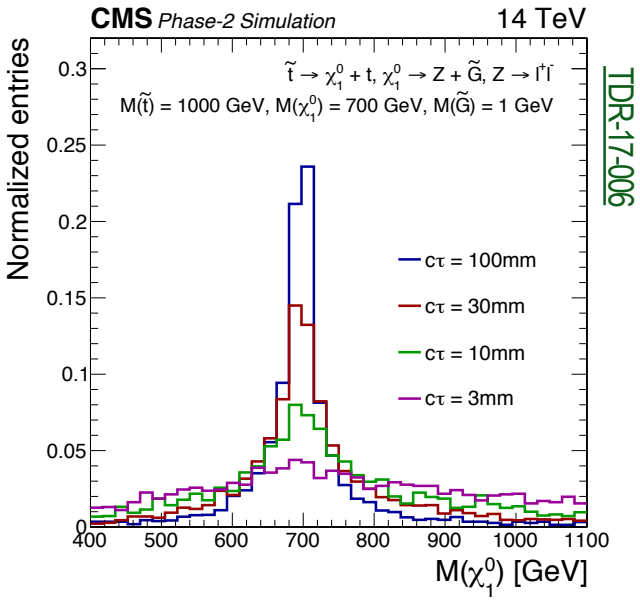


Example: Neutralino decay into Gluino and Z

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



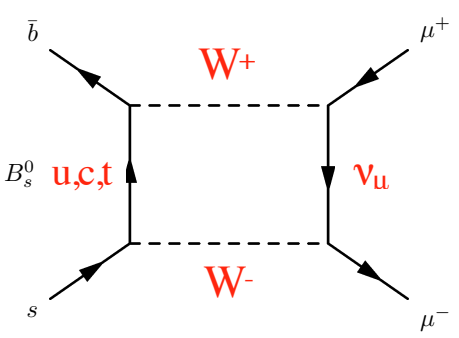
Use MIP timing detector information to reconstruct neutralino mass



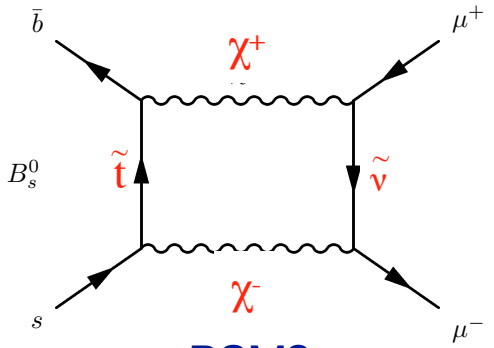
Significant benefits from improved detectors

Flavour Physics

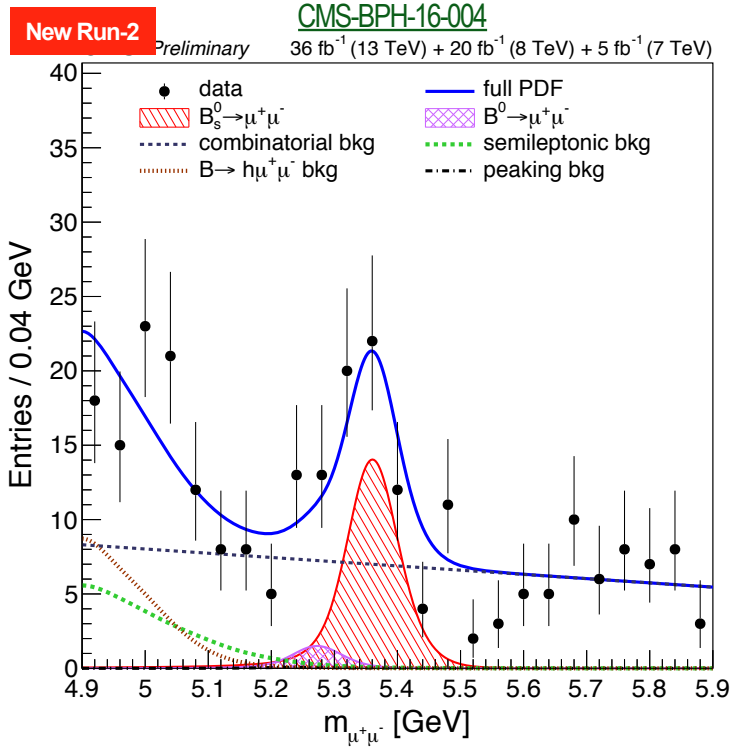
- First observation of $B^0_s \to \mu\mu$ in a single experiment

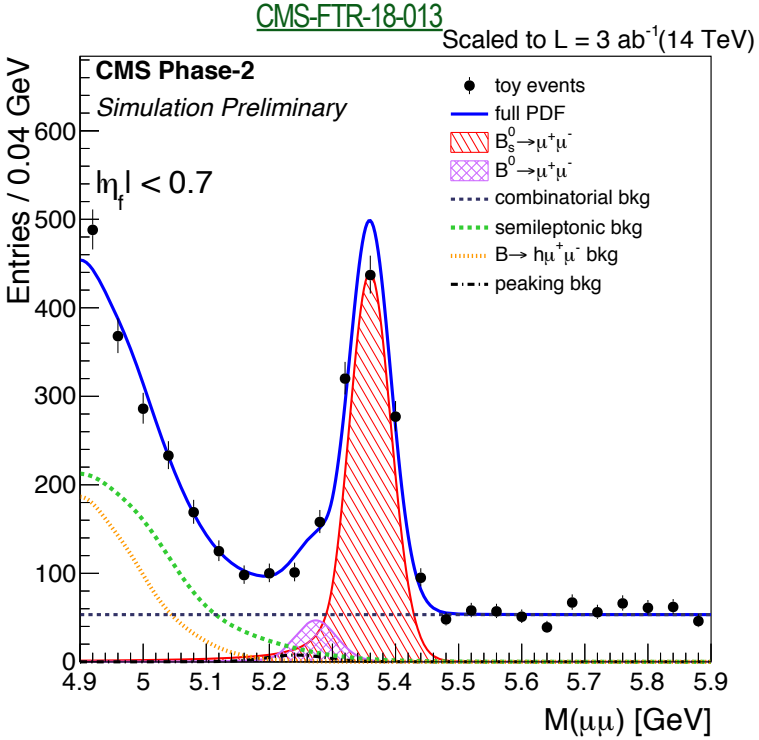


SM



BSM?



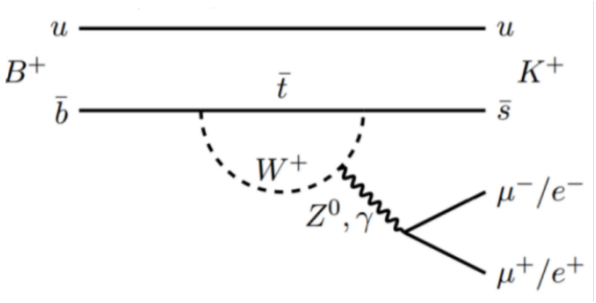


HL-LHC: expect to also measure $B^0_d \to \mu\mu$

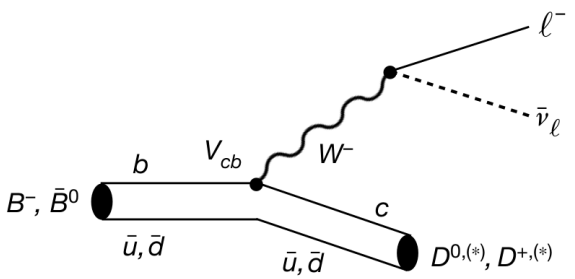
… and much more with future L1 track trigger, with parking and "scouting"

Flavour Anomalies

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

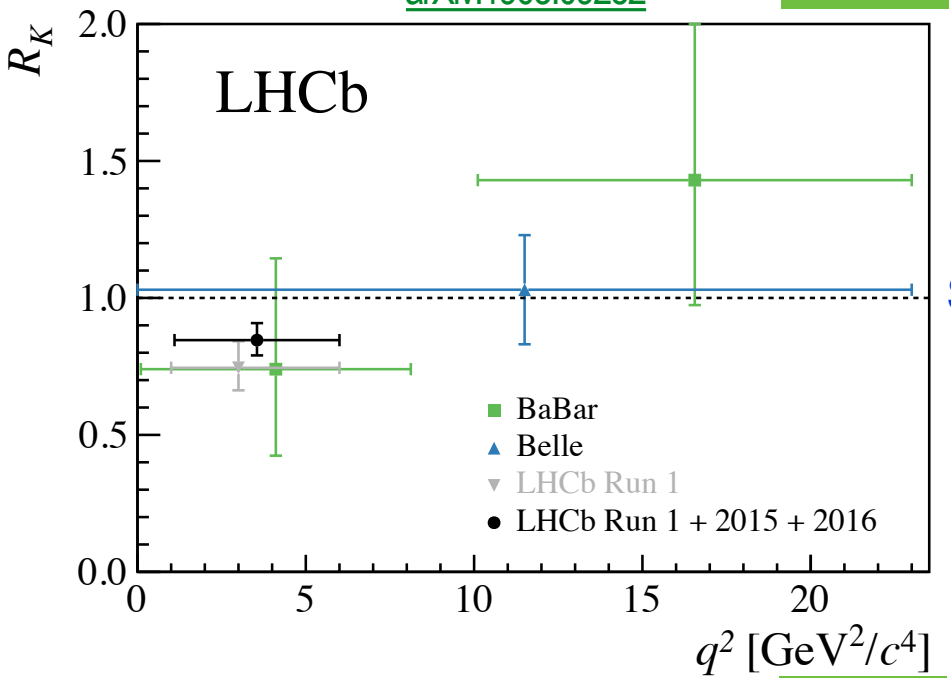


$$R^{\tau/\ell}_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$



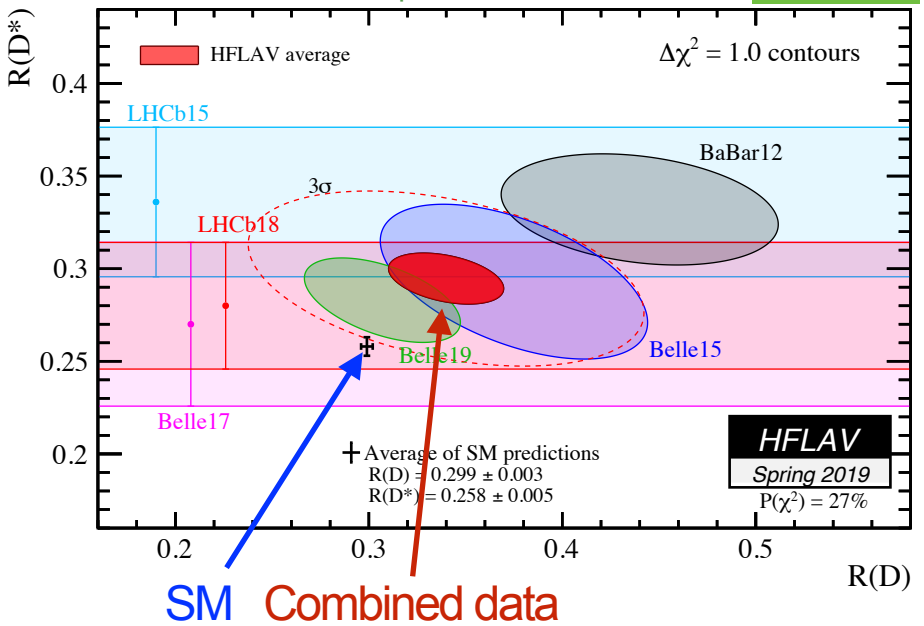
arXiv:1903.09252

B factory data



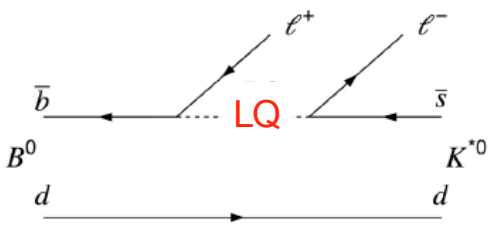
https://hflav.web.cern.ch/

B factory data



Flavour Anomalies

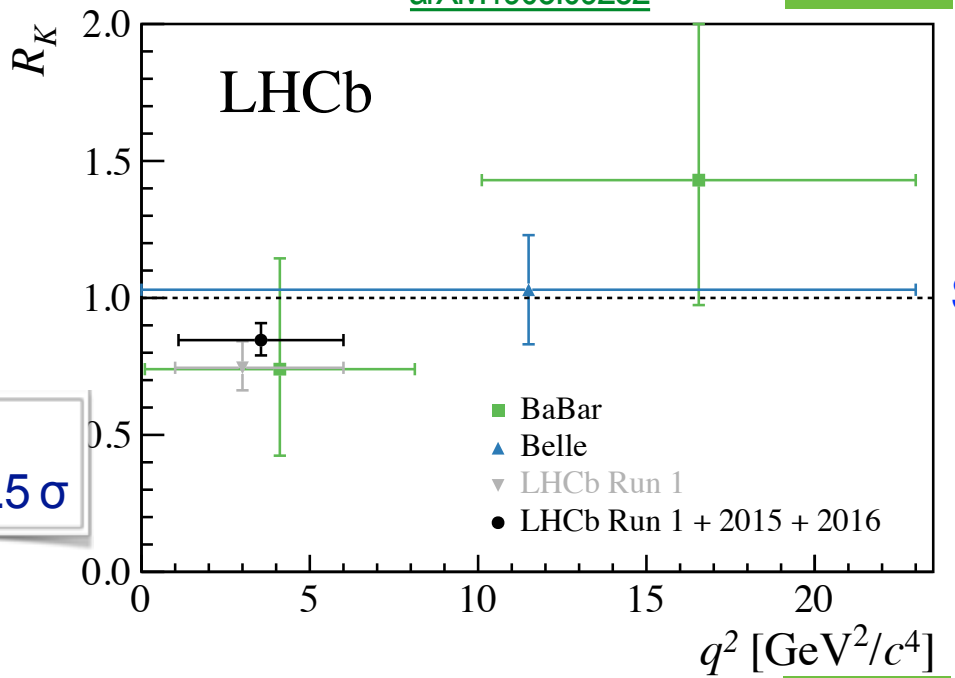
$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$



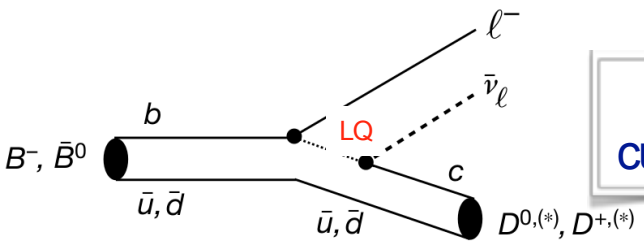
tension currently 2.5 σ

arXiv:1903.09252

B factory data



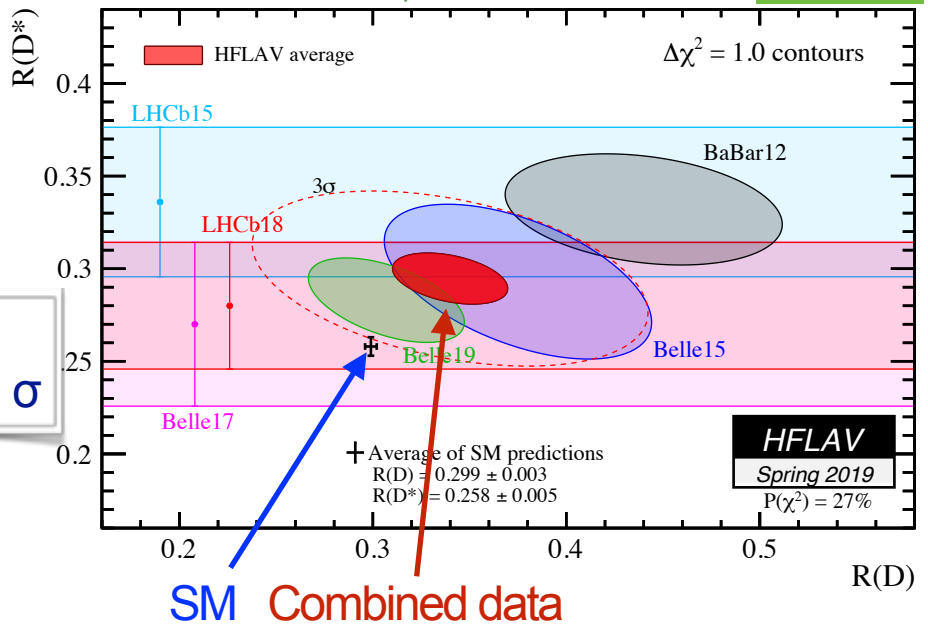
$$R^{\tau/\ell}_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$



tension currently 3.1 σ

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

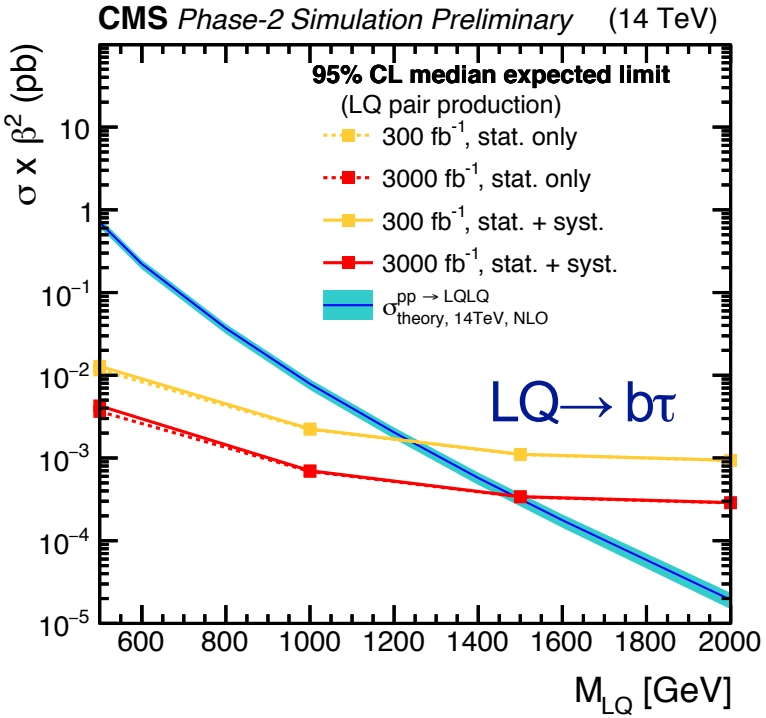
B factory data



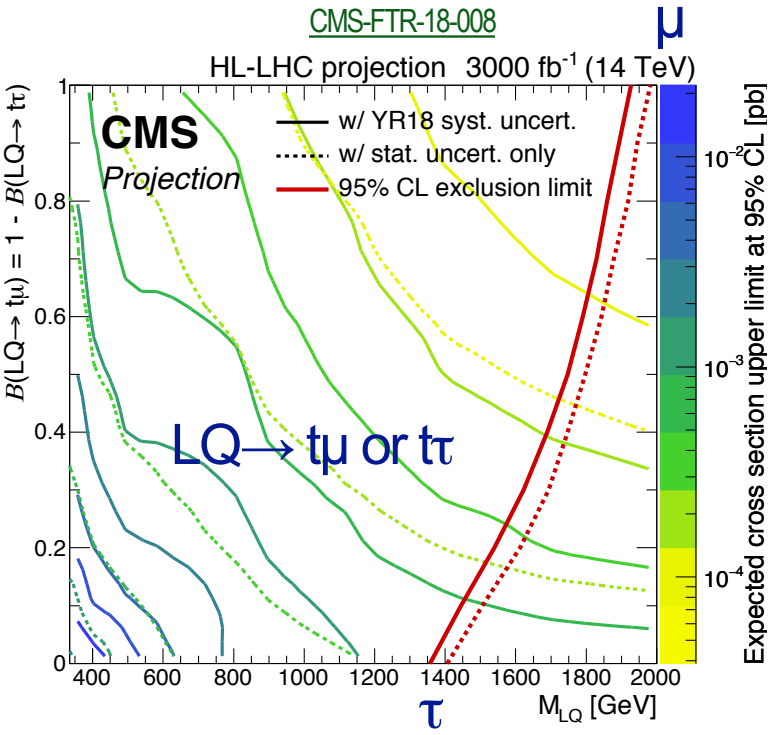
LQ could explain R(D*) and R(K*)

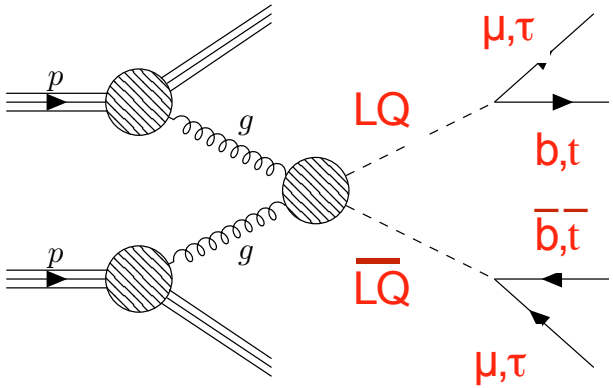
Flavour Anomalies: High p_T

CMS-FTR-18-028



CMS-FTR-18-008





If a LQ exists at the TeV scale,
we might be able to see it directly

Could this be a
no-lose theorem ?

Summary

- **Run 3: additional 250 fb^{-1} at 14 TeV**
  - Gain from luminosity and energy increase ~1.7
  - Consolidate Run-2 observations of rare SM processes
  - Experimental improvements (trigger, analyses, systematics)

- **HL-LHC: 3000 fb^{-1} and superior detectors**
  - Standard model: discovery through precision
  - Higgs: H(125) properties at the percent level
  - Direct searches: discover new physics or close a few chapters
  - Flavour: high/low p_T complementarity
  - Heavy Ion (not shown): precise differential measurements

Exciting physics times ahead !

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 >1000 authors each submitted to the European Strategy Update Group
  - 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

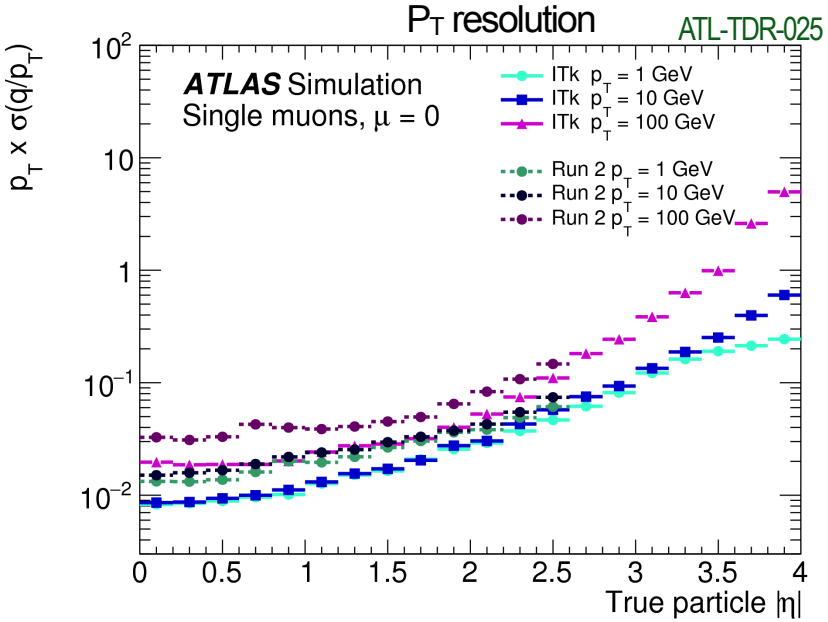
June 2018
Plenary meeting

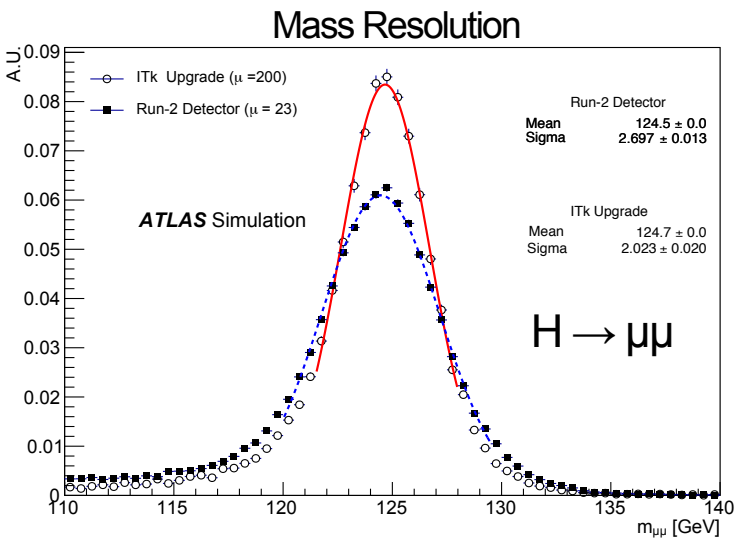
December 2018
Reports submitted to EPPSU

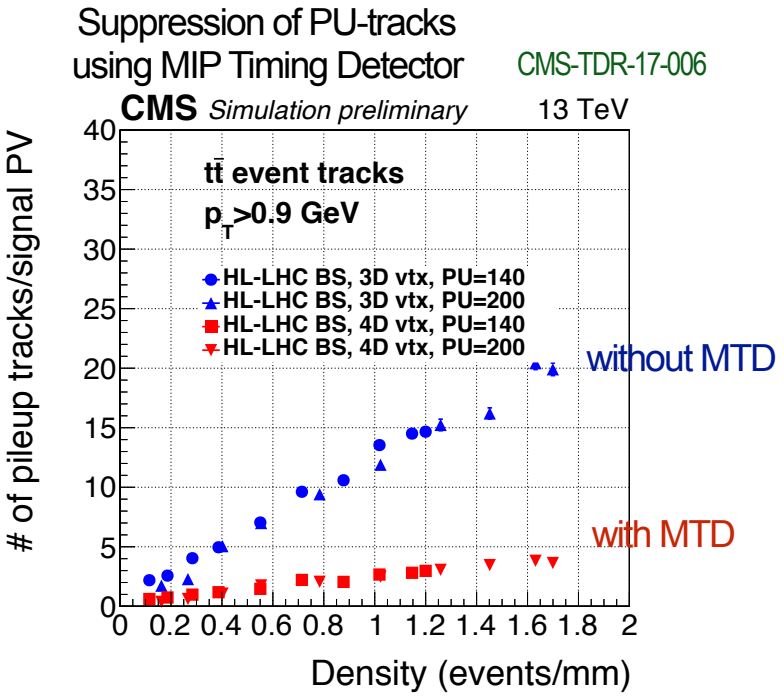
1 March 2019
Jamboree

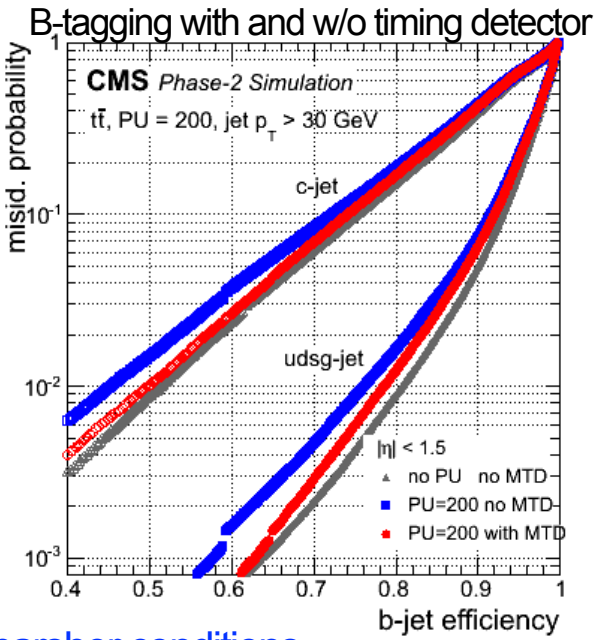
13-16 May 2019
Open EPPSU Meeting
Granada

Detector Performance









Generally similar or better performance under harsher conditions

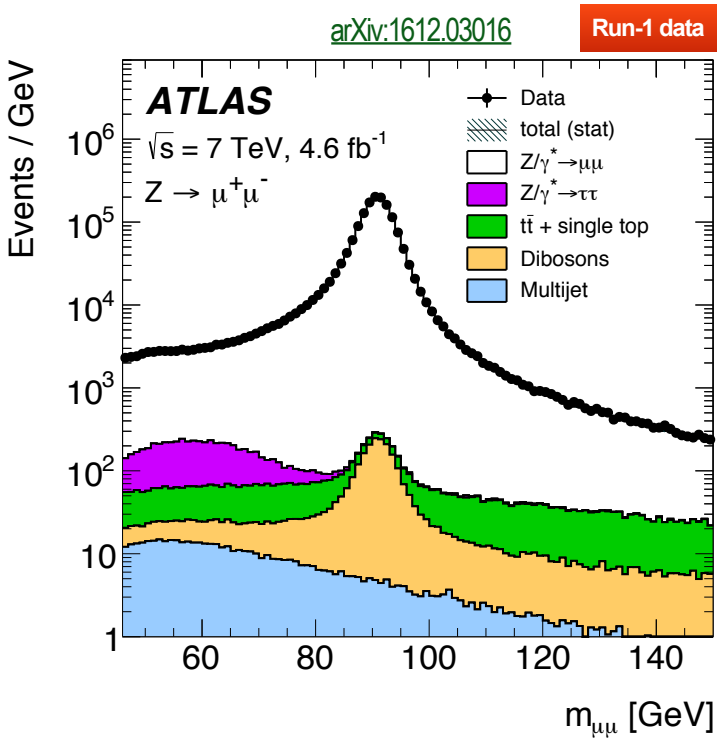
Ultimate Precision Cross Sections

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

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

Luminosity is single largest uncertainty

- 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 production rate can help luminosity measurement → planning for proof of concept in Run-3

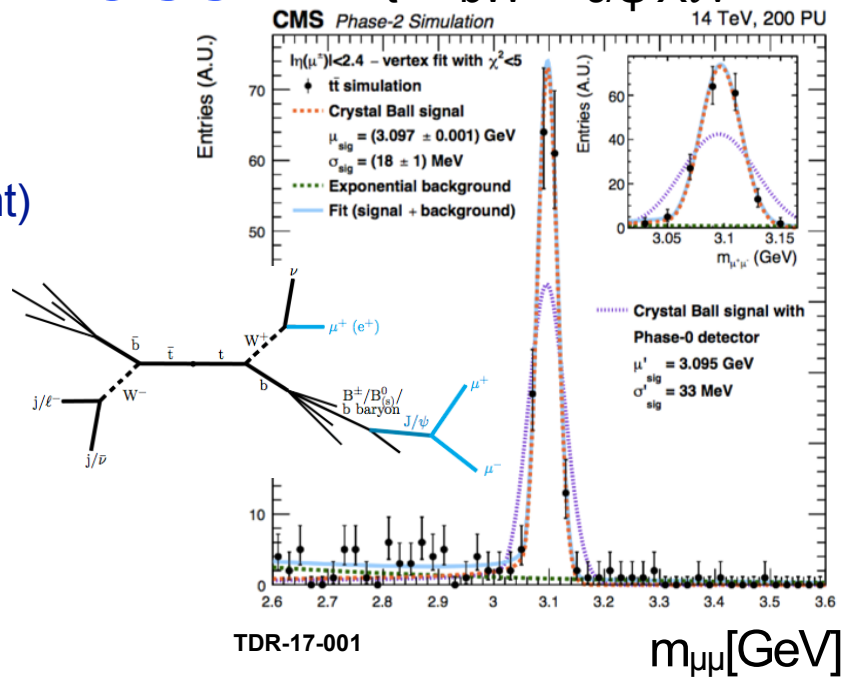
arXiv:1806.02184

Target luminosity uncertainty YR2018: 1%

Ultimate Precision Top Mass

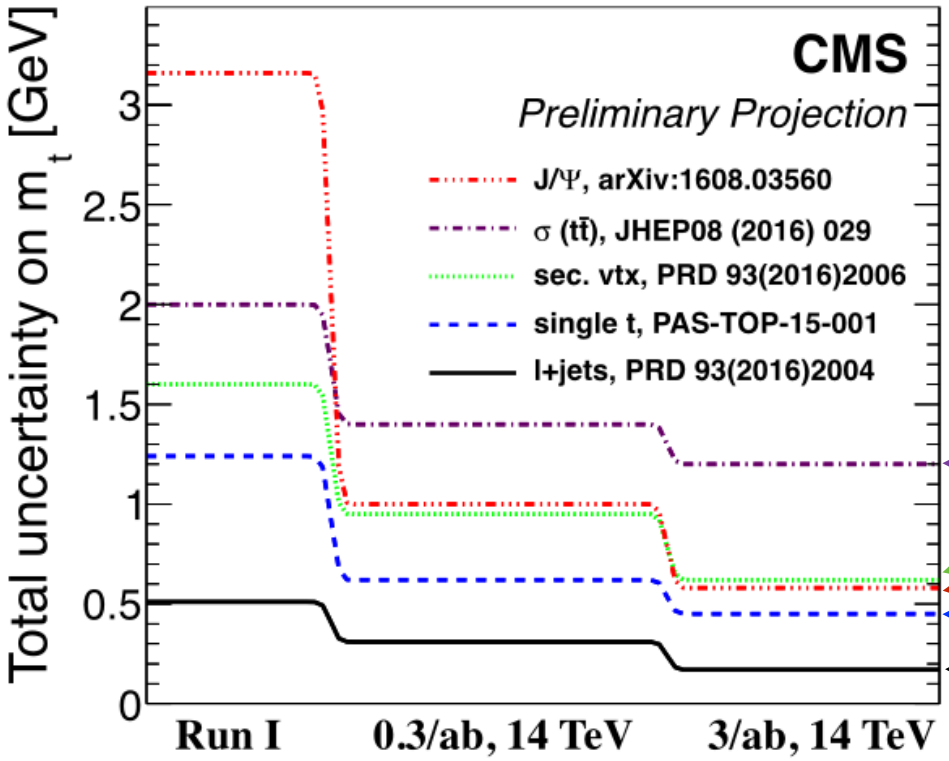
- More statistics → samples and calibration
- Better systematics (both theory and experiment)
- Combination of different methods arXiv:1807.06617

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



J/ψ: $\delta m_{top} \sim 0.5$ GeV

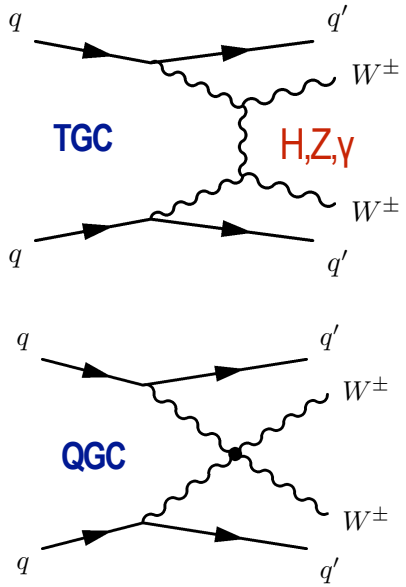
CMS-PAS-FTR-16-006



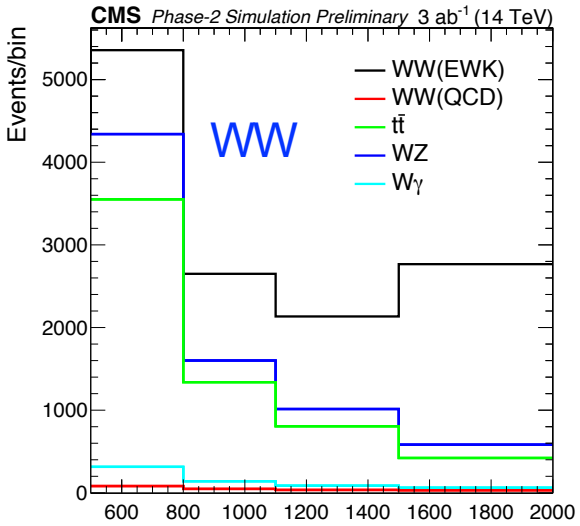
m_{pole} from σ(tt)
2ndary vertex
J/ψ
single top
ℓ+jets

(m_{pole} better alreadynow) arXiv:1904.05237

Vector Boson Scattering

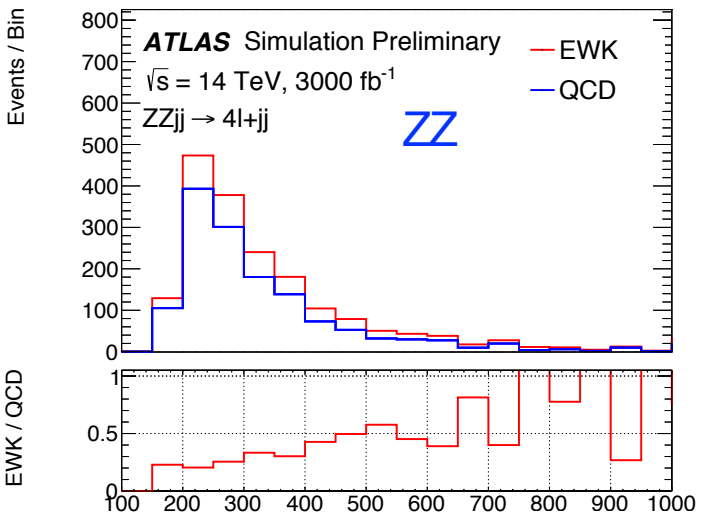


CMS-FTR-18-005



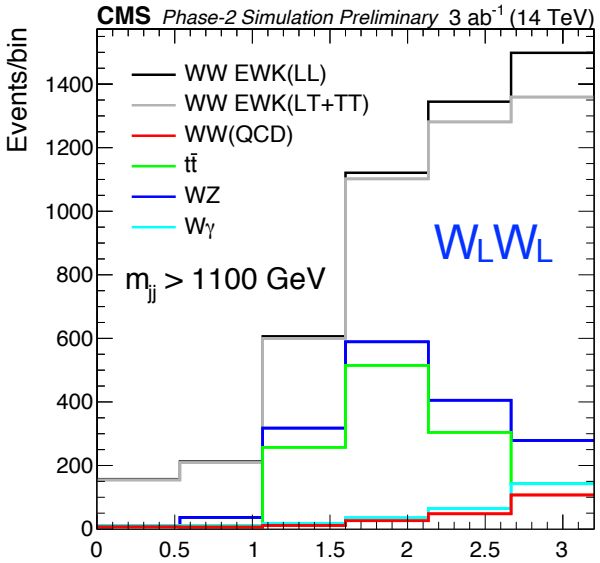
δσ ~ 5%

ATL-PHYS-PUB-2018-029



δσ ~10%

CMS-FTR-18-005



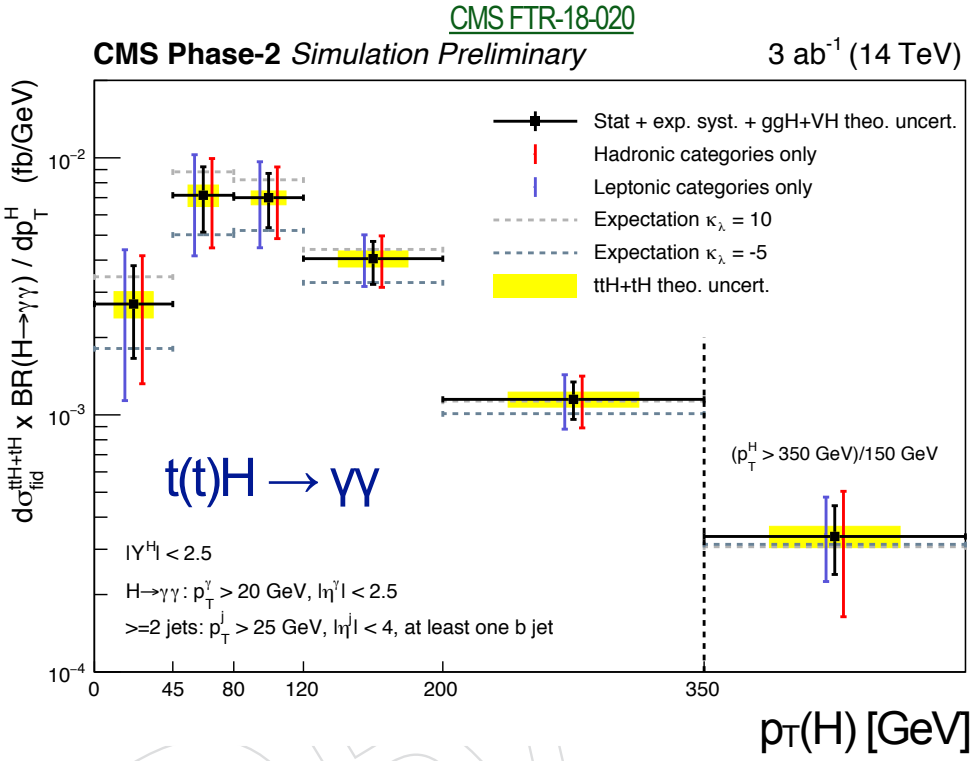
10-page summary HL-LHC: Table 1

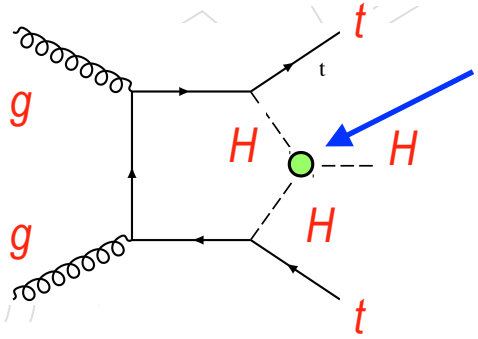
Process	$W^{\pm}W^{\pm}$	WZ	WV	ZZ	WWW	WWZ	WZZ
Final state	$\ell^{\pm}\ell^{\pm}$jj	3ℓjj	ℓjjjj	4ℓjj	$3\ell3\nu$	$4\ell2\nu$	$5\ell\nu$
Precision	6%	6%	6.5%	10–40%	11%	27%	36%
Significance	$>5\sigma$	$>5\sigma$	$>5\sigma$	$>5\sigma$	$>5\sigma$	3.0σ	3.0σ

- Longitudinal VBS, $V_LV_L \rightarrow V_LV_L$ cross section:
  - unitarized by scalar Higgs and/or new physics
  - in SM few percent of total EWK VBS

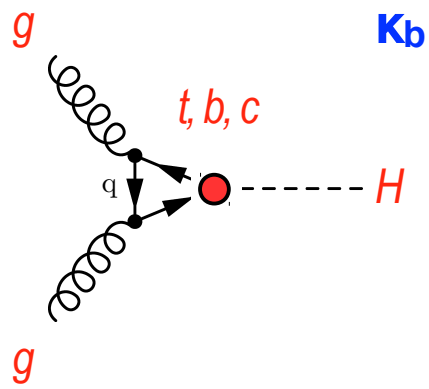
V_LV_L discovery significance ~3σ / experiment

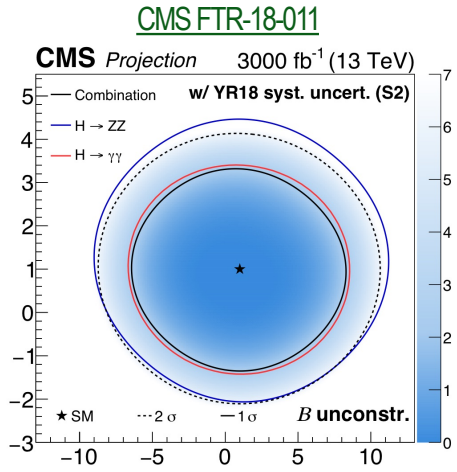
Differential Higgs Measurements





$\kappa_\lambda = [-4.1, 14.1]$ @ 95%CL

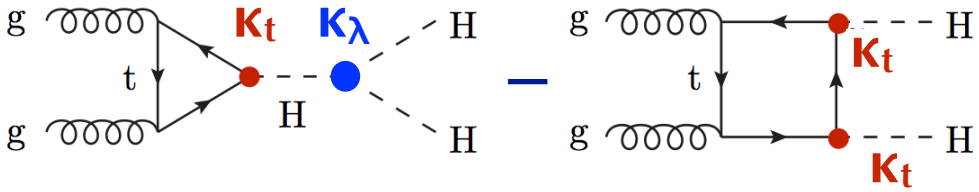




- p_T(Higgs) distribution:
  - t(t)H: sensitive to self-coupling κ_λ
  - ggH: sensitive to interference between quark loops → κ_b and κ_c

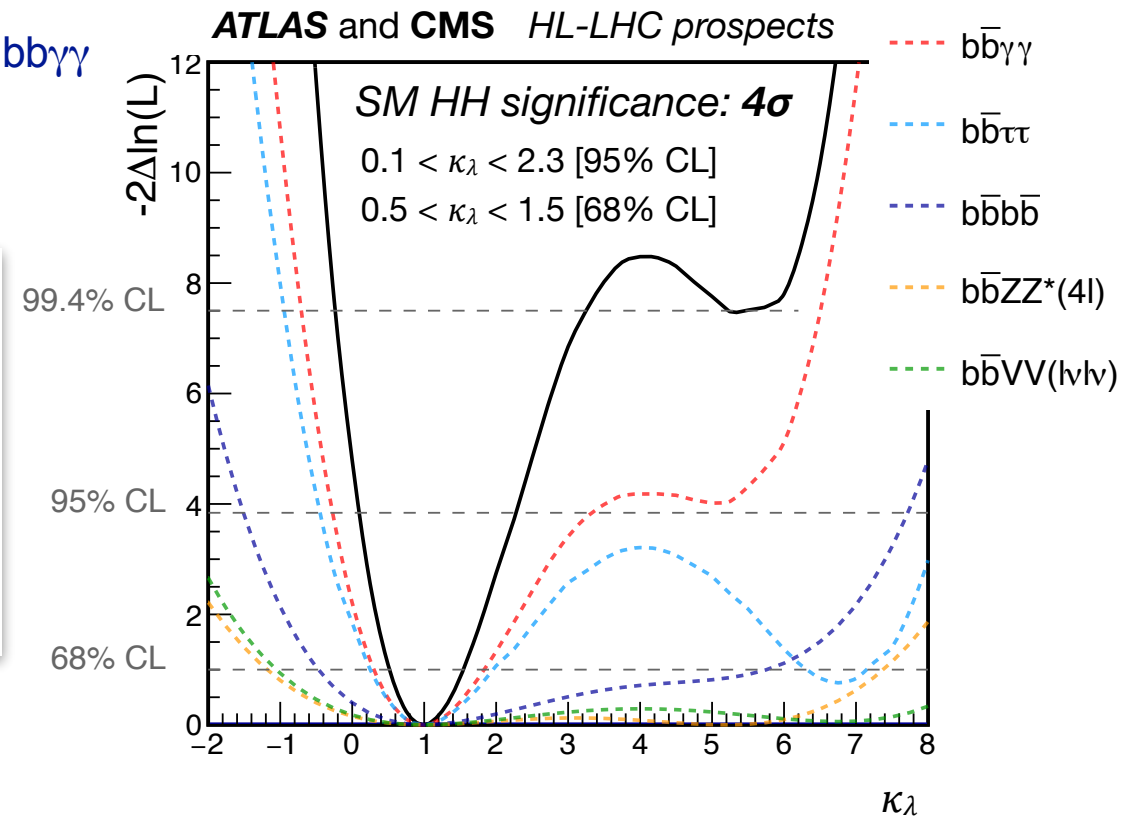
With 3000 fb^{-1} constrain κ_c and κ_λ to a few times SM

HH



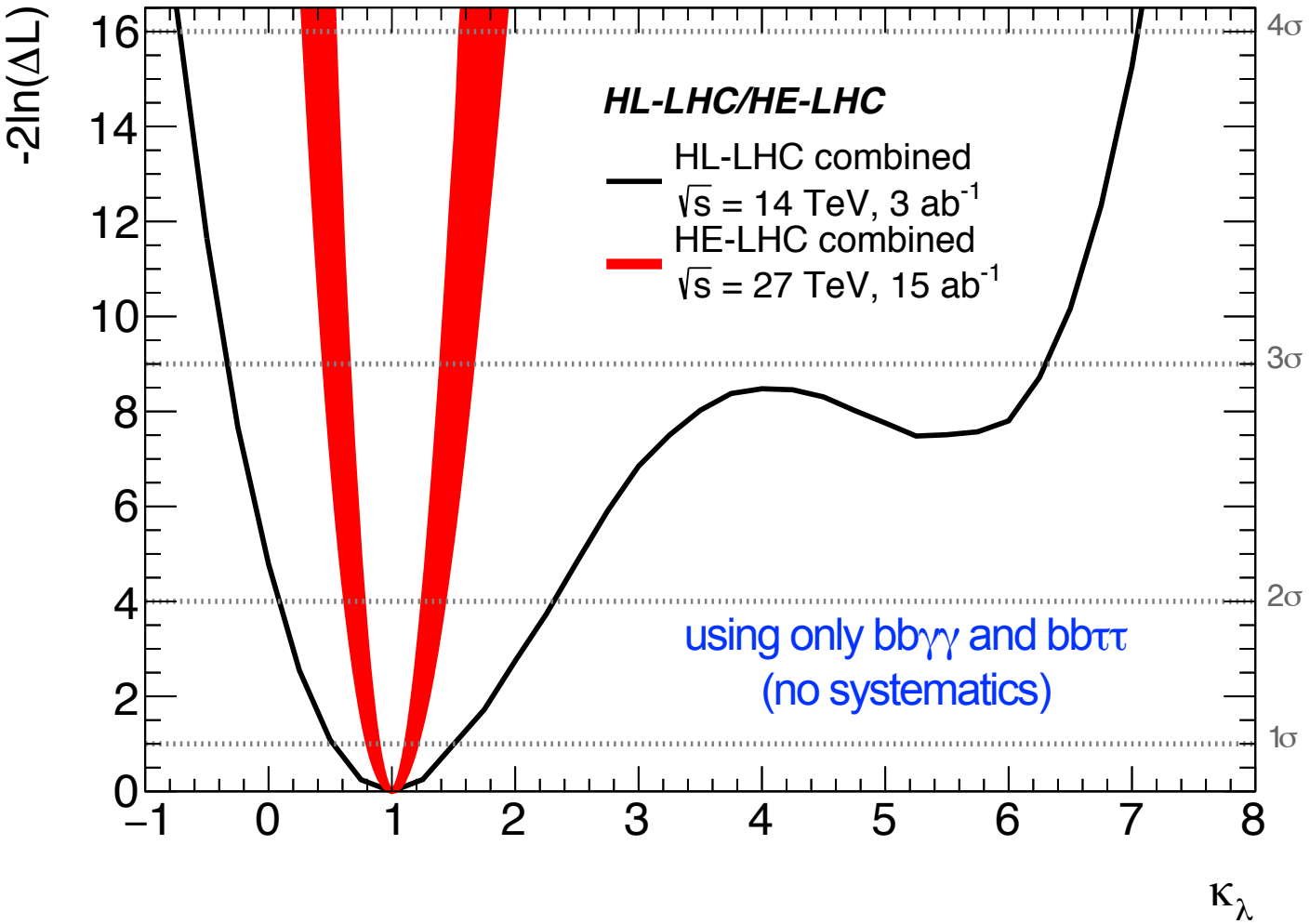
- Ultimate goal: observation of trilinear coupling
- 120k HH events expected
- Best sensitivity (BR vs. bg): bbττ and bbγγ

	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.)

Higgs Self-Coupling: HE-LHC combination



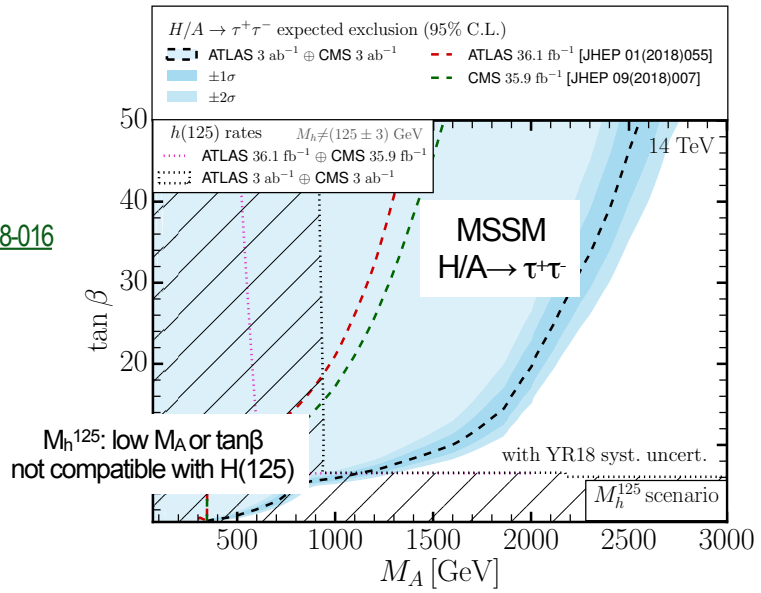
HE-LHC (15 ab^{-1} at 27 TeV) will be able to pin κ_λ down fully (~15%)

BSM Higgs

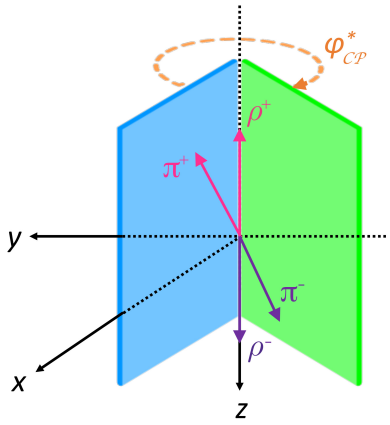
- From kappa fit (for κ_V<1): B_{BSM} < 2.5%
- Direct h→invisible: B_{inv} < 2.5% ATL-PHYS-PUB-2013-014 CMS-FTR-18-016
- MSSM Higgs: H/A →ττ: M_A limit increased to ~2 TeV

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

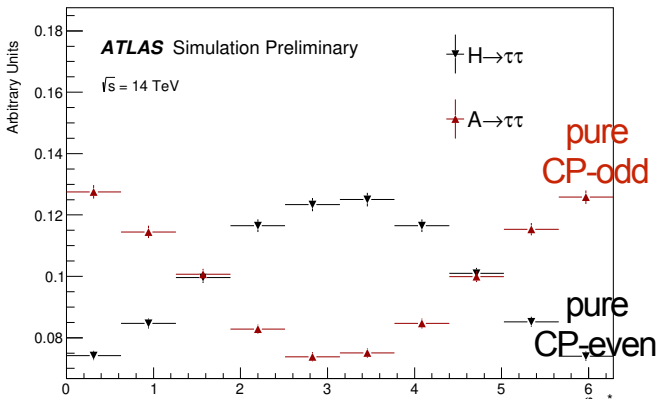
CMS-FTR-18-017

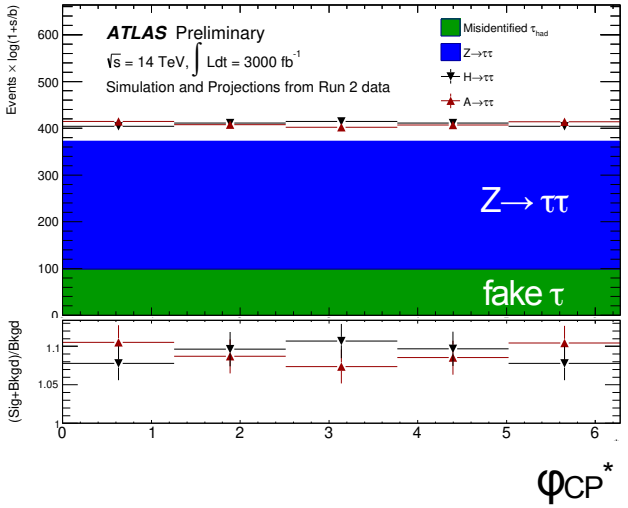


ATL-PHYS-PUB-2019-008



(a) φ^*_{CP} illustration





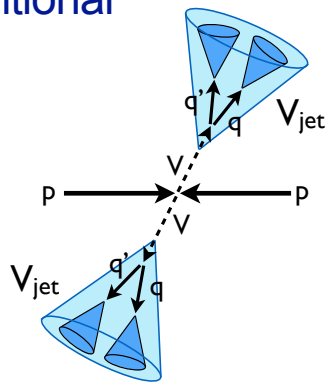
Frame: Σ p(vis. dec. products) = 0

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

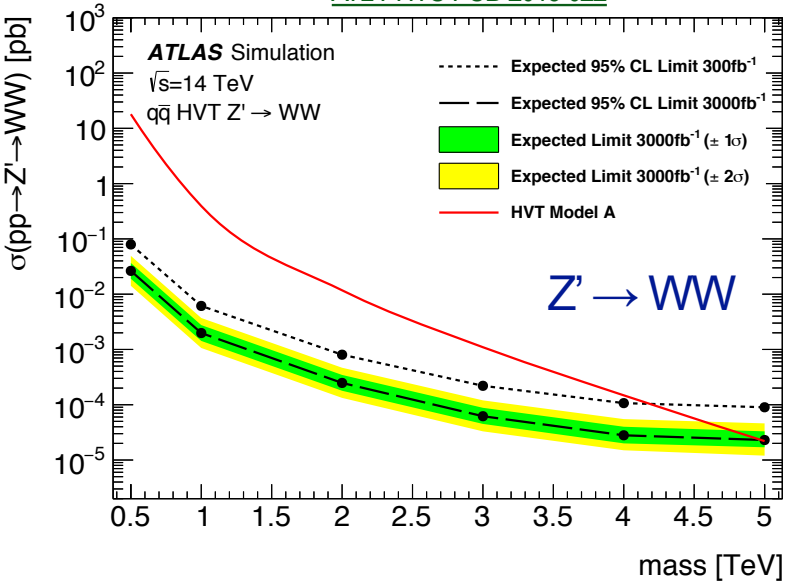
Heavy Resonances

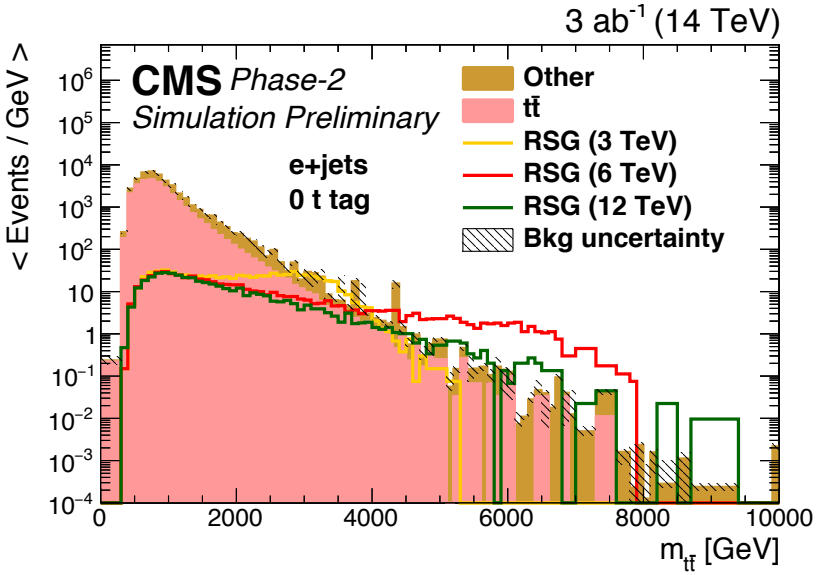
- Heavy Vector Triplet (HVT) model: composite Higgs and three additional vector bosons Z' and W'±
  Z' and W'± → WW, WZ or ZZ

- Randall-Sundrum-Gluon: RSG → tt

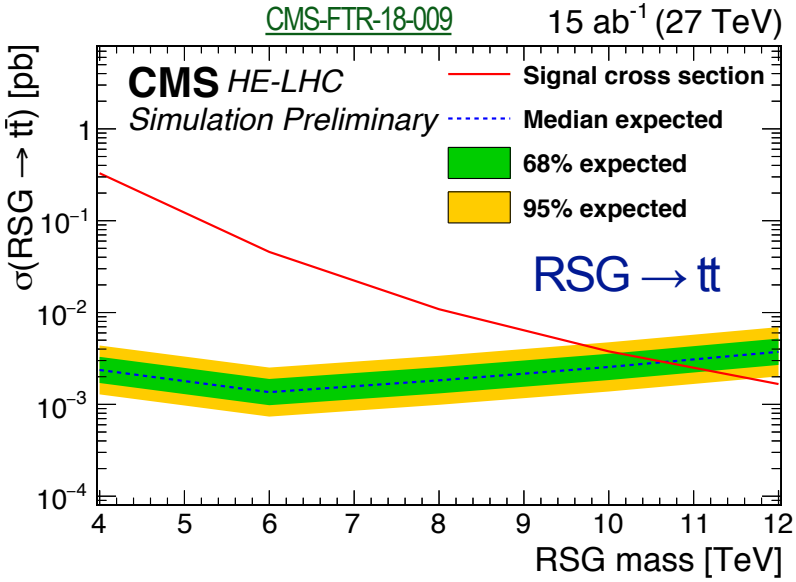


ATL-PHYS-PUB-2018-022





CMS-FTR-18-009

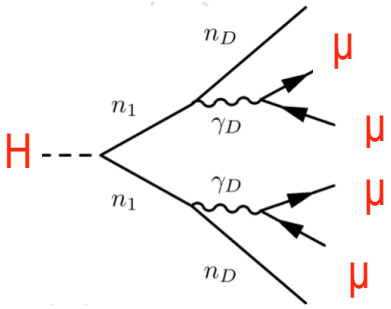


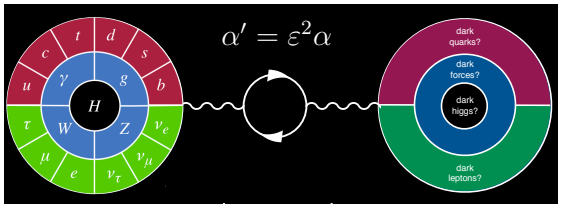
Mass reach: exclusion up to 5-6 TeV at HL-LHC — 10-11 TeV at HE-LHC

Dark Sector

Displaced muons from long-lived dark photons

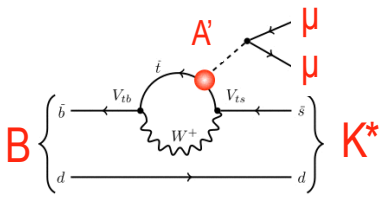
H→4μ + X



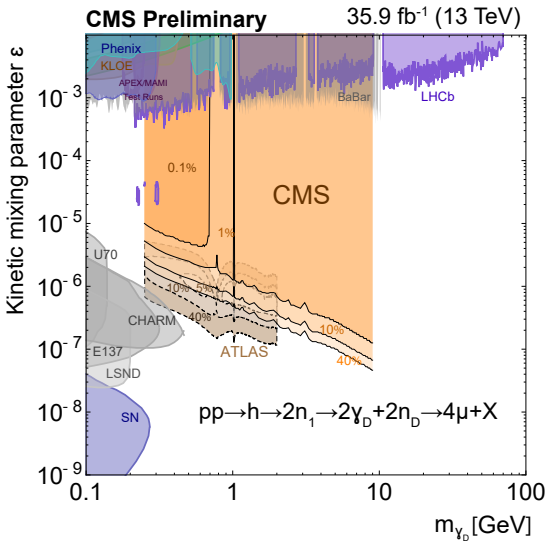


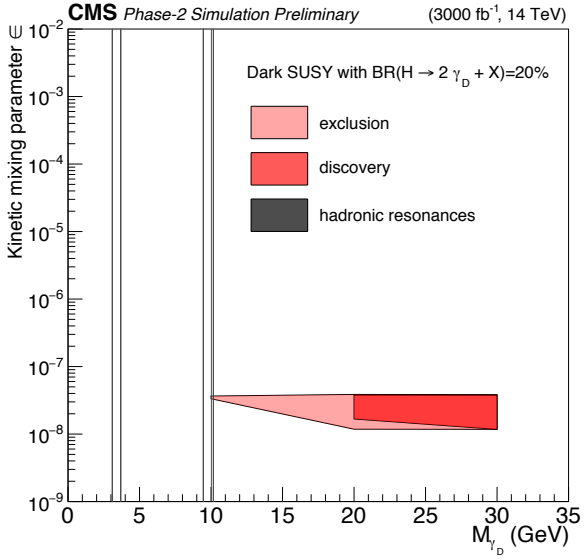
Dark photons in B decays

A'→μμ (or ee)



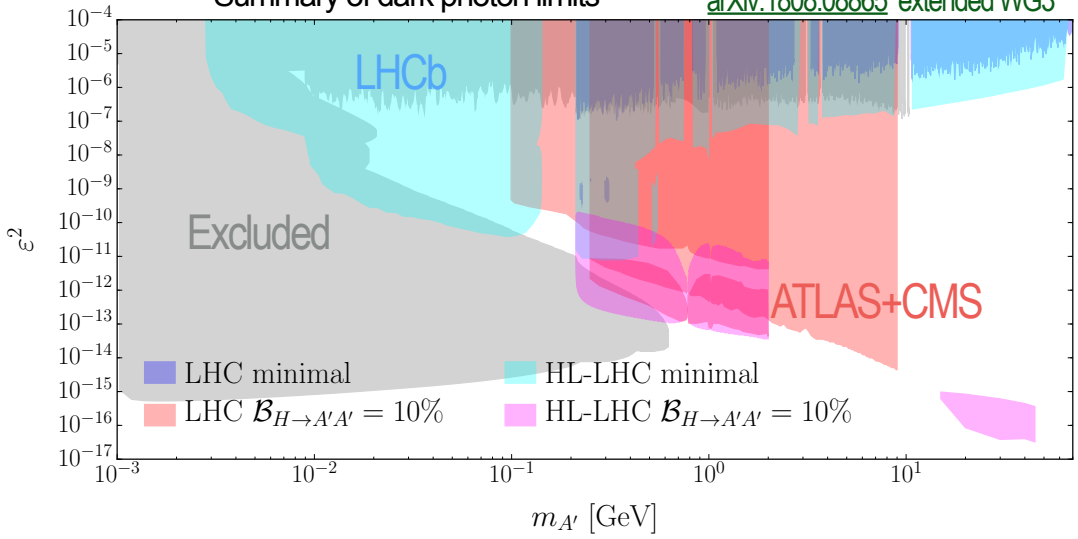
CMS-FTR-18-002





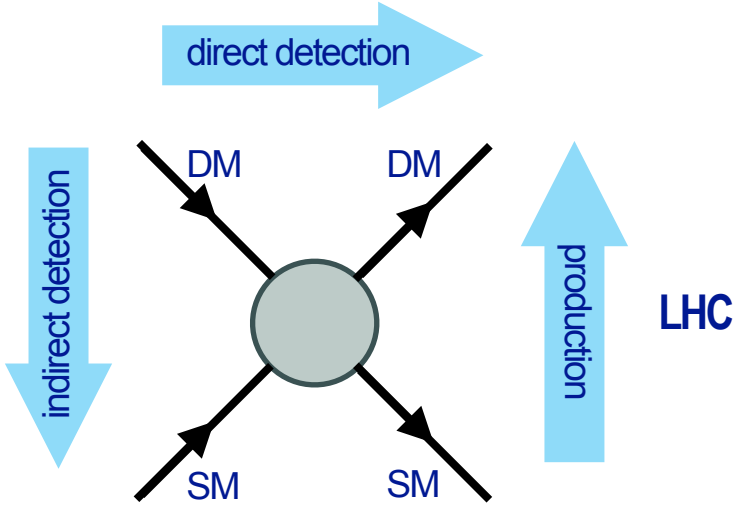
Summary of dark photon limits

arXiv:1808.08865 extended WG3

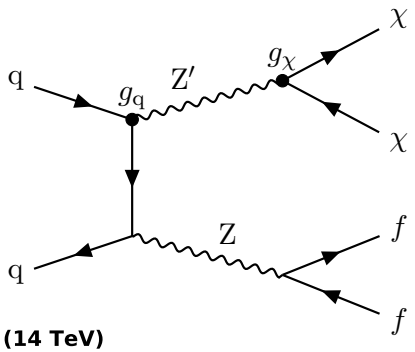


Dark Matter …

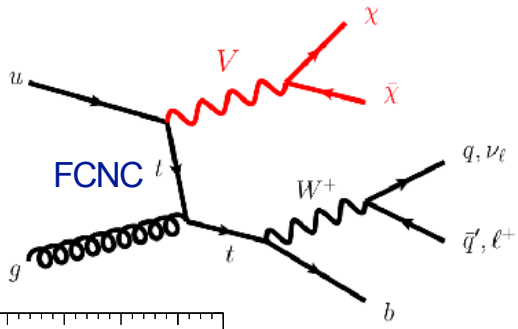
- … is known to exist:
  → uncover its elementary nature at the LHC (?)
- Simplified models for comparison with direct detection experiments



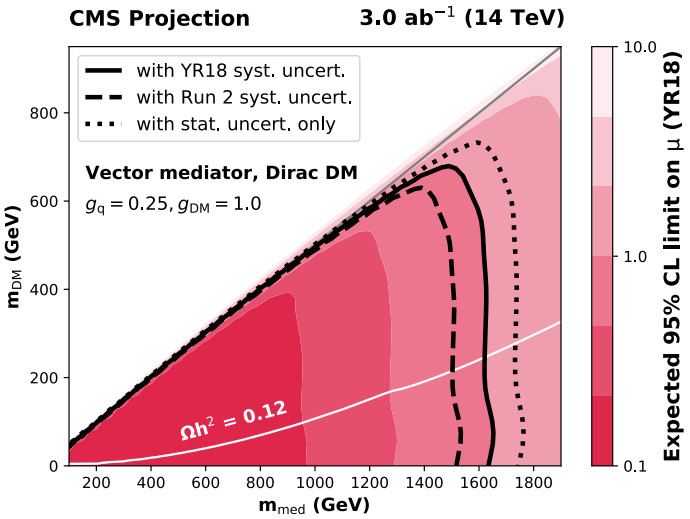
mono-Z:



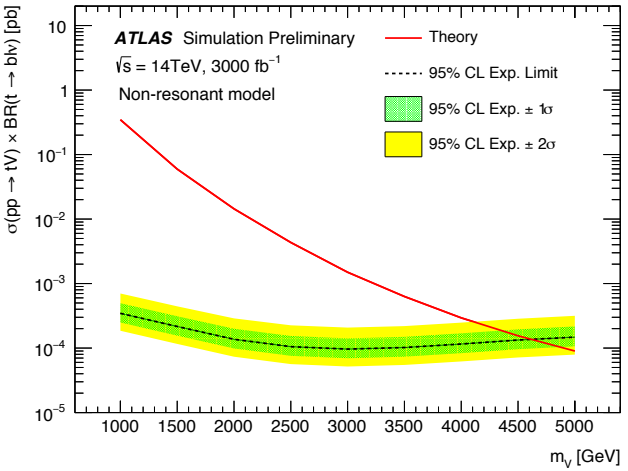
mono-top:



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)