Prospects for LHC Run 3 and HL-LHC

Experimental overview

Monica D'Onofrio, University of Liverpool

Warning!

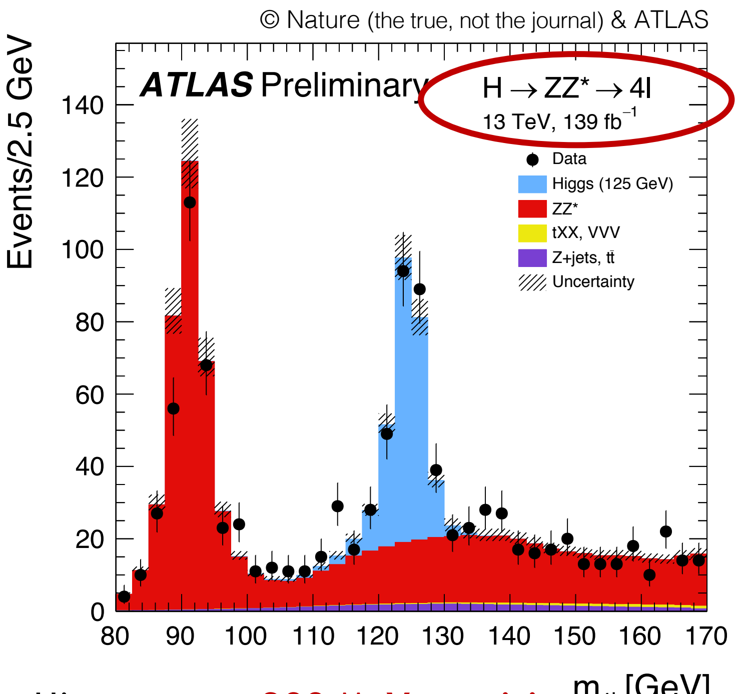
Only a small subset of interesting results and prospects are shown in this talk, focusing on ATLAS and CMS

UK HEP Forum 2019

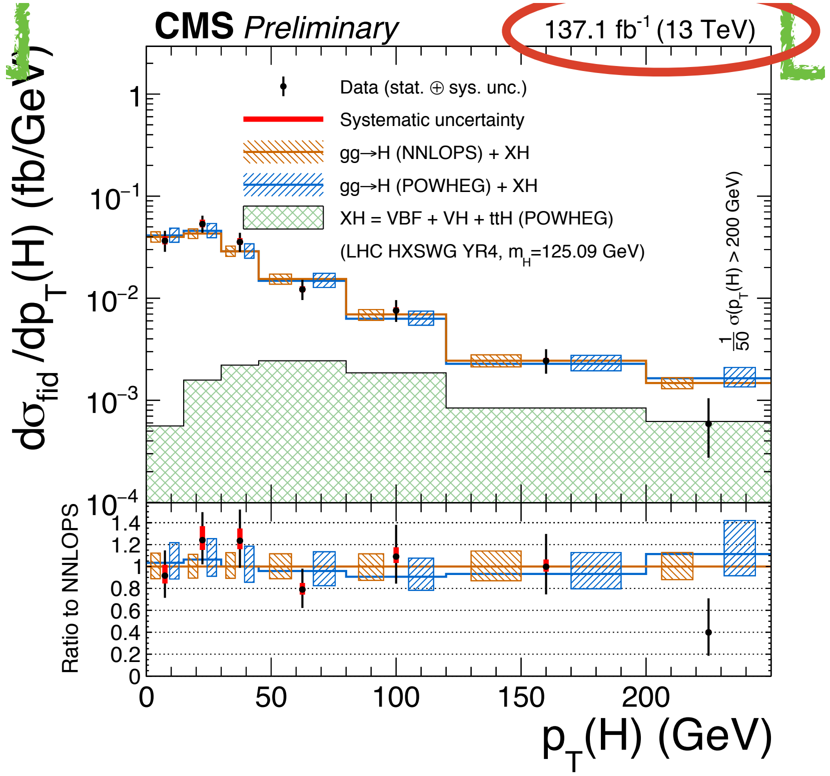
The Cosener's House, Oxford, UK, 24/9/2019

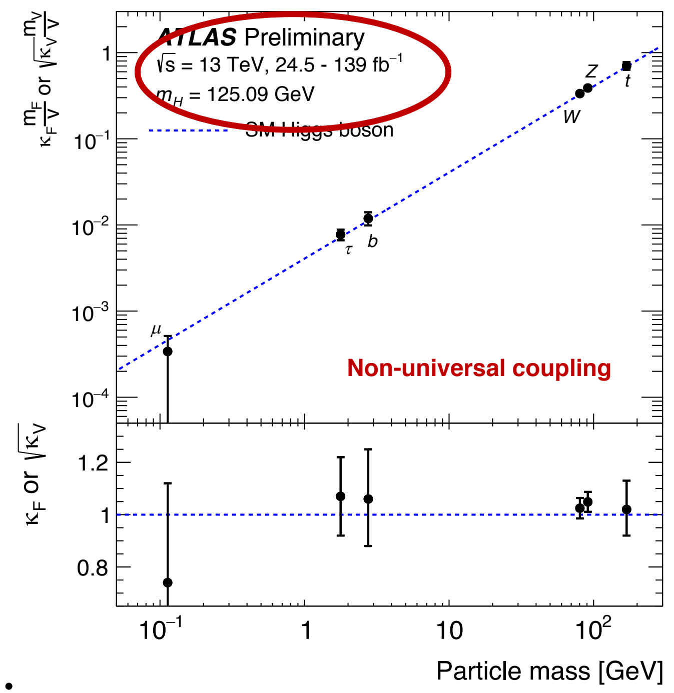
The Run 2 legacy

- LHC data collected during Run-2 (~140 fb^{-1} / exp.) are being analysed now
- Fantastic results have been already achieved, and more are in the pipeline:
  - Broad and diverse research programme → data-driven times – experiments take the lead!
  - **Precise Higgs mass, cross-section and coupling measurements**



Higgs mass: **~200 MeV precision**
dominated by statistical uncertainty





Also:
→ **Width: $0.08 < \Gamma_H < 9.16$ MeV** (CMS)
(SM: 4.1 MeV)

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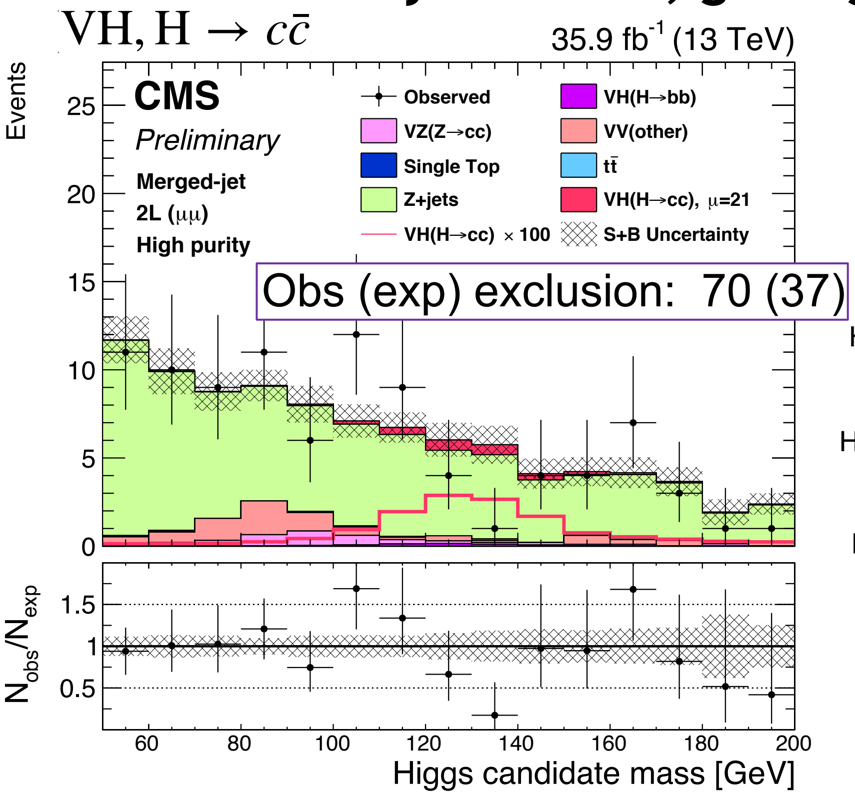
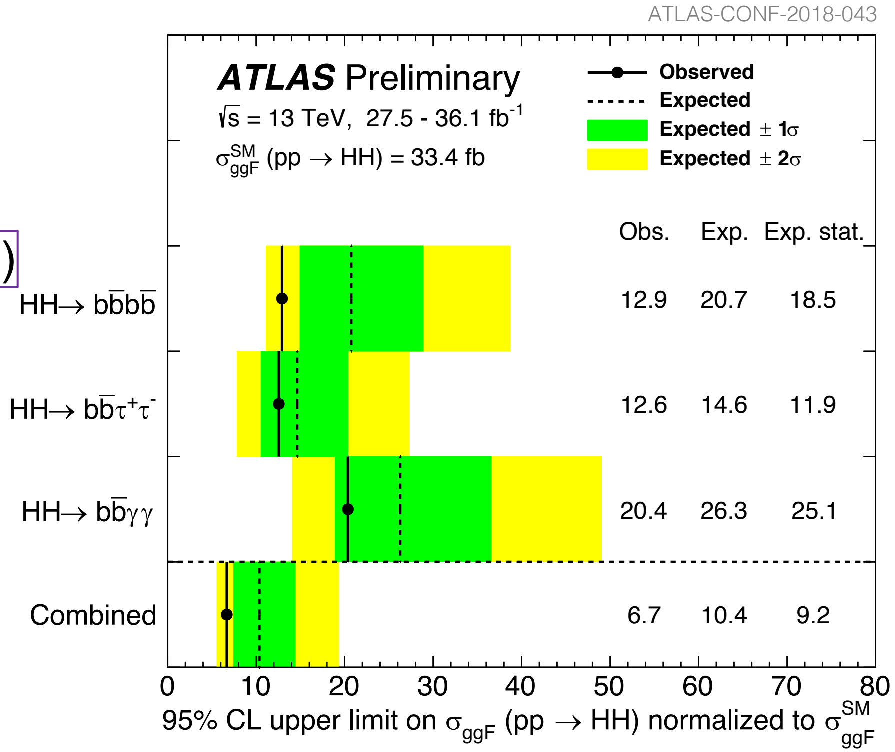
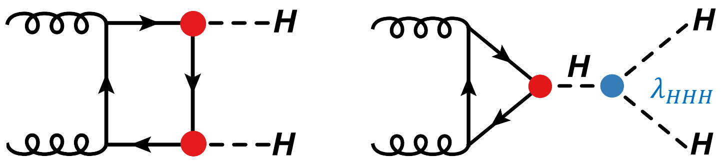
  - **rare decay searches, getting closer to di-Higgs production**







$\lambda_{HHH} = \frac{m_H^2}{2v^2} \sim 0.13$

Combined fit yields 95% CL allowed range

$$-5.0 < \frac{\lambda_{HHH}(\text{obs})}{\lambda_{HHH}(\text{SM})} < 12.1$$

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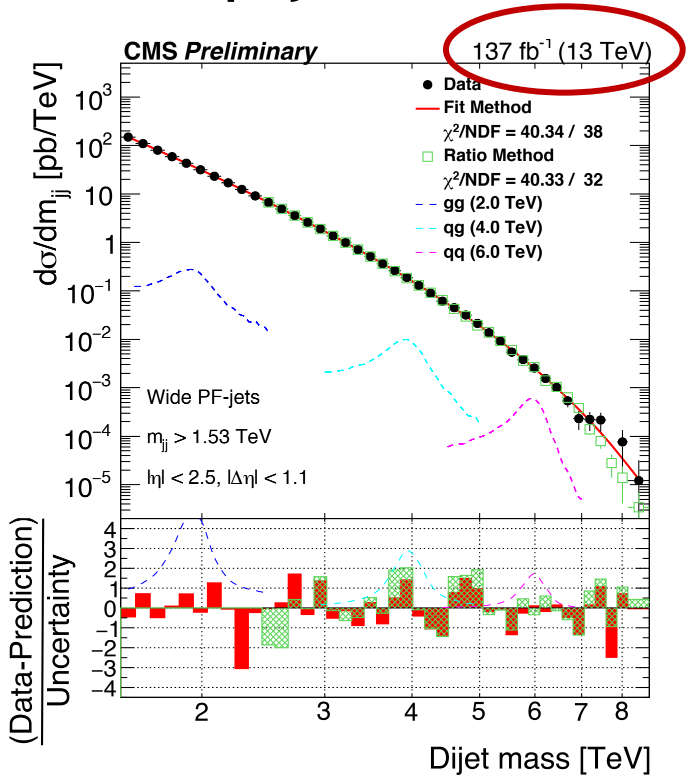
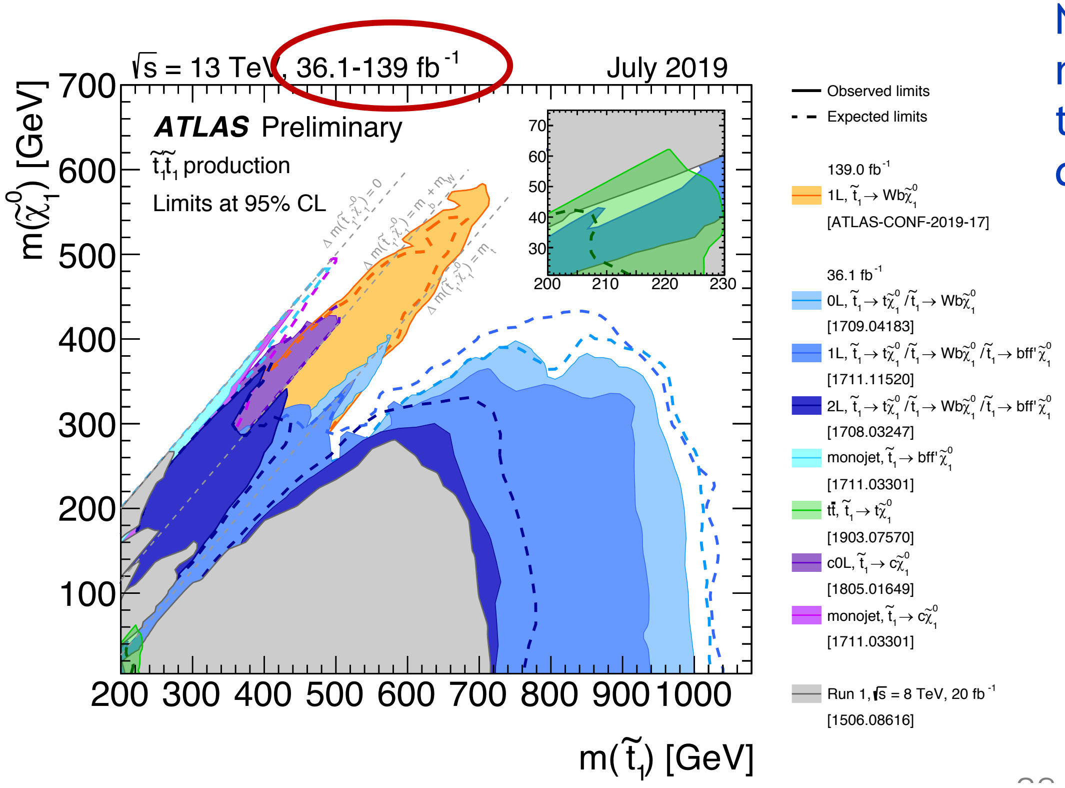
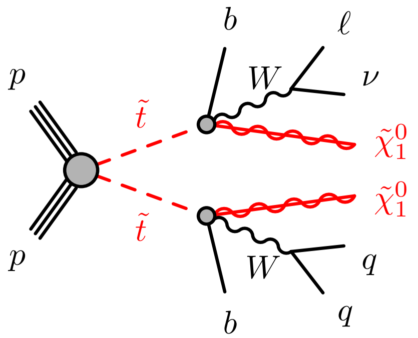
  - **New physics searches continue to improve their sensitivity and probe new signatures**





New searches address "difficult" regions with diverse techniques that push the capabilities of the detectors

Soft-leptons for top squarks



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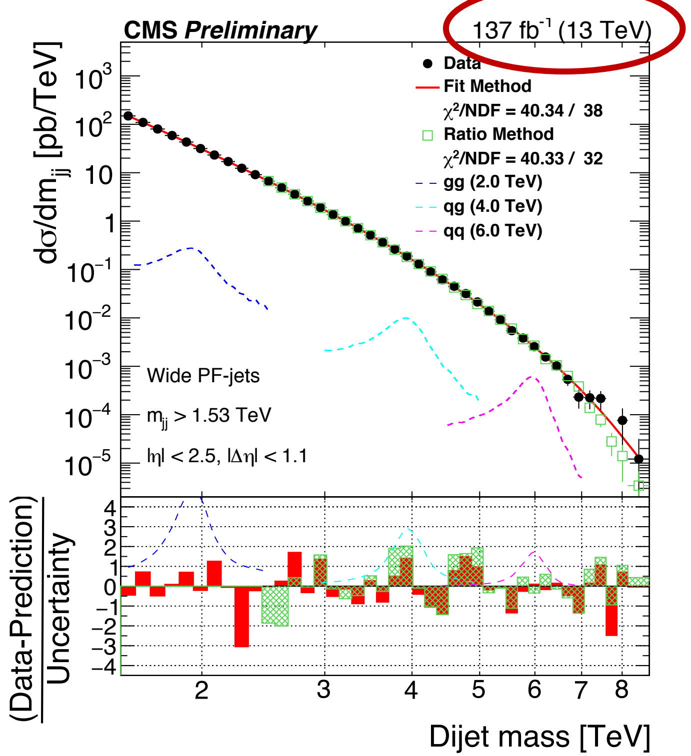
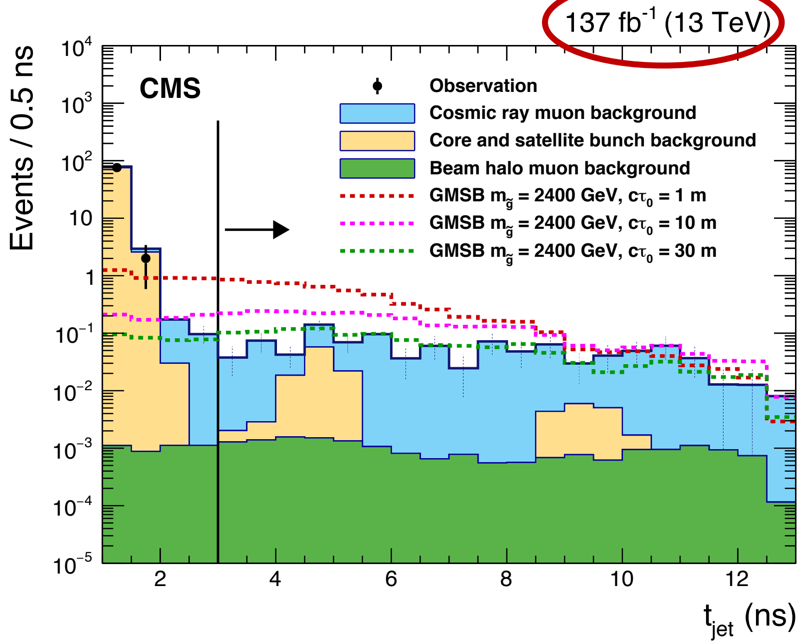
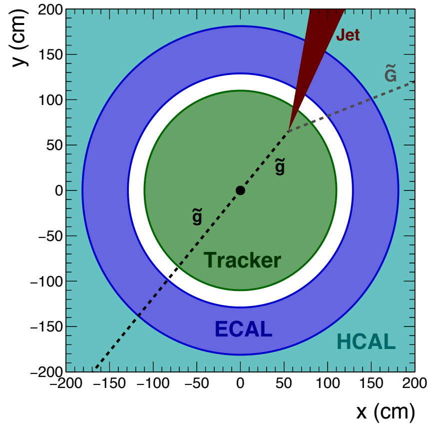




main backgrounds from cosmics & satellite bunches

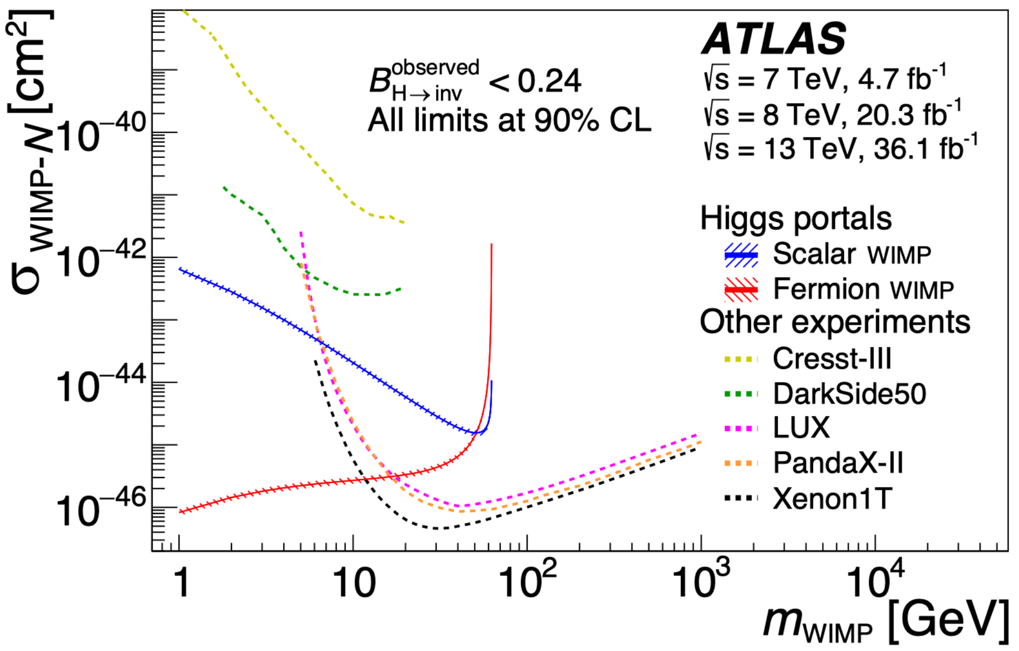
New searches address "difficult" regions with diverse techniques that push the capabilities of the detectors

Delayed jets for Long-Lived gluinos

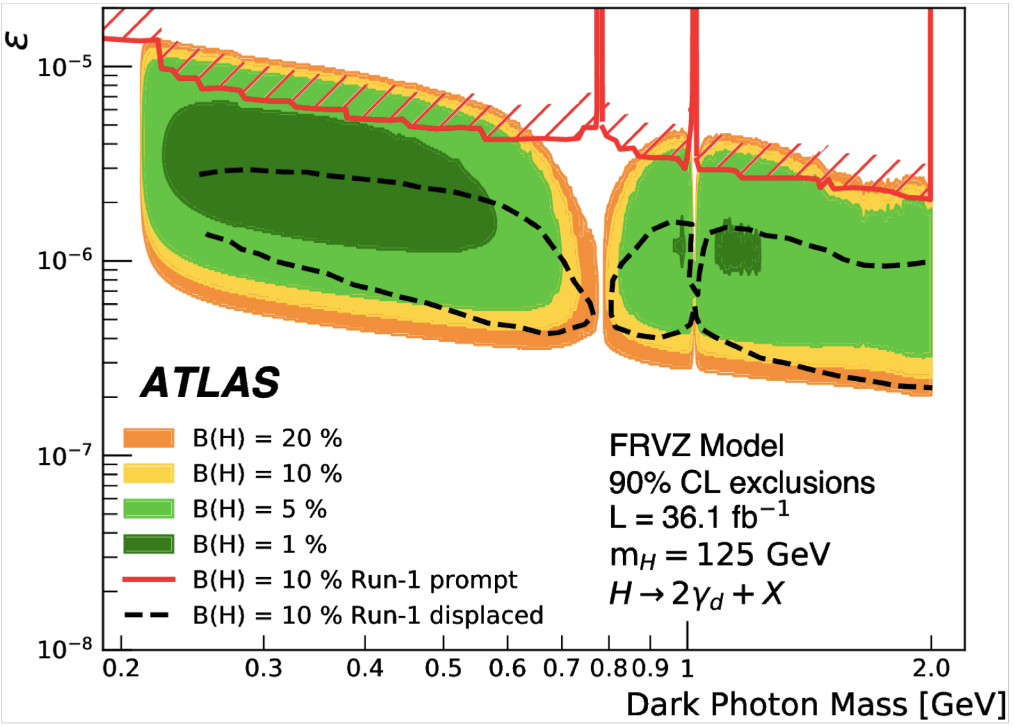


The Run 2 legacy

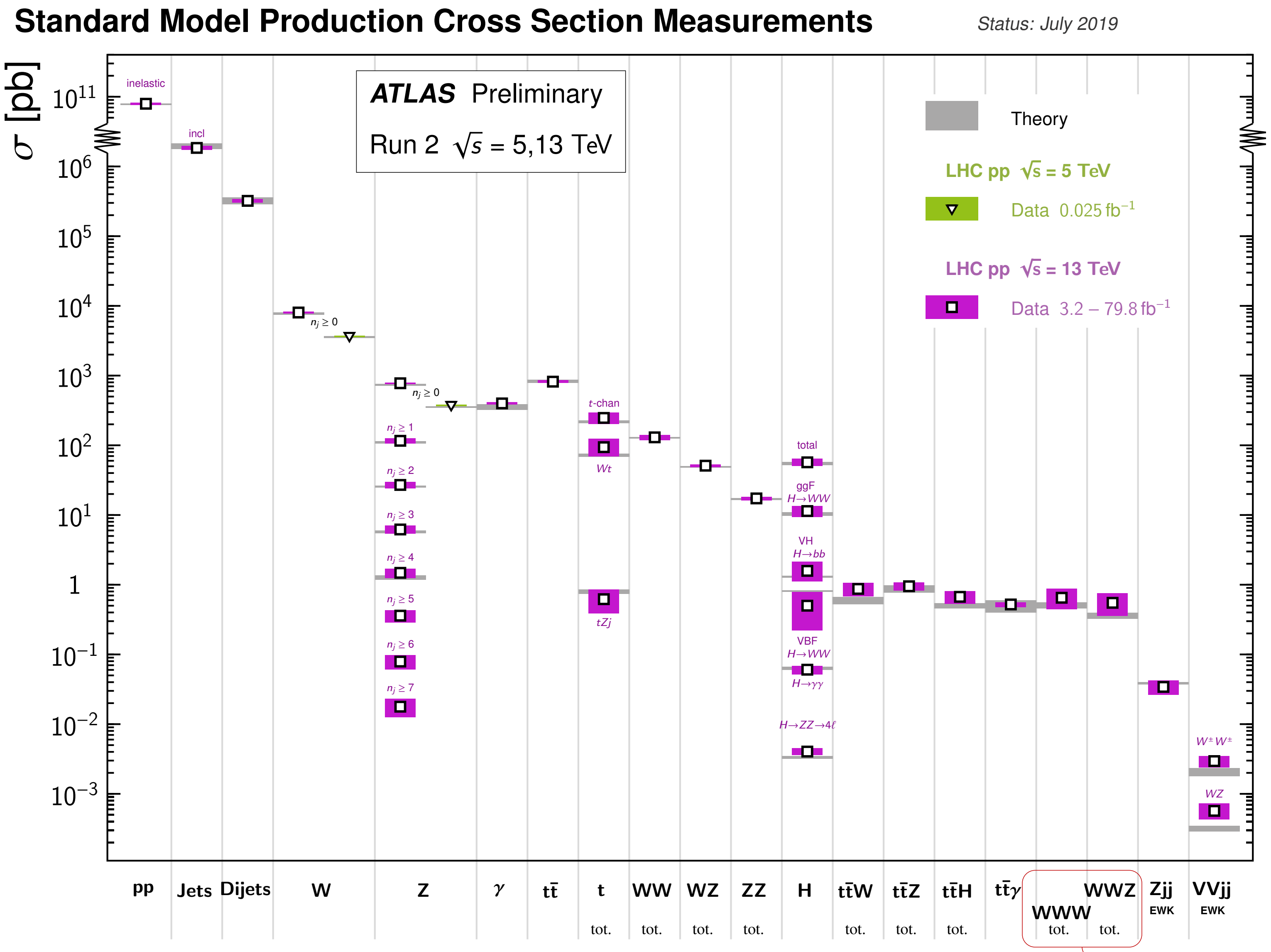
- LHC data collected during Run-2 (~140 fb^{-1} / exp.) are being analysed now
- Fantastic results have been already achieved, and more are in the pipeline:
  - Broad and diverse research programme → data-driven times – experiments take the lead
  - **Synergies with other experiments being exploited: i.e. Dark Matter and Dark Sectors**



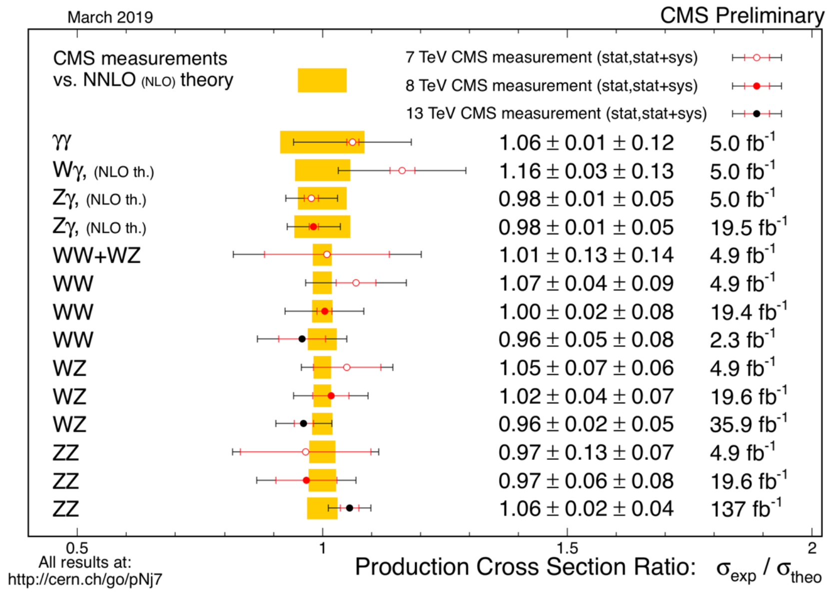
Constraints on spin-independent
WIMP-nucleon scattering cross section



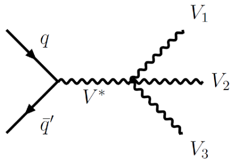
Thoroughly investigating the SM…



Probing over 14 orders of magnitude in cross section, as well as regions of phase space also useful for searches beyond SM



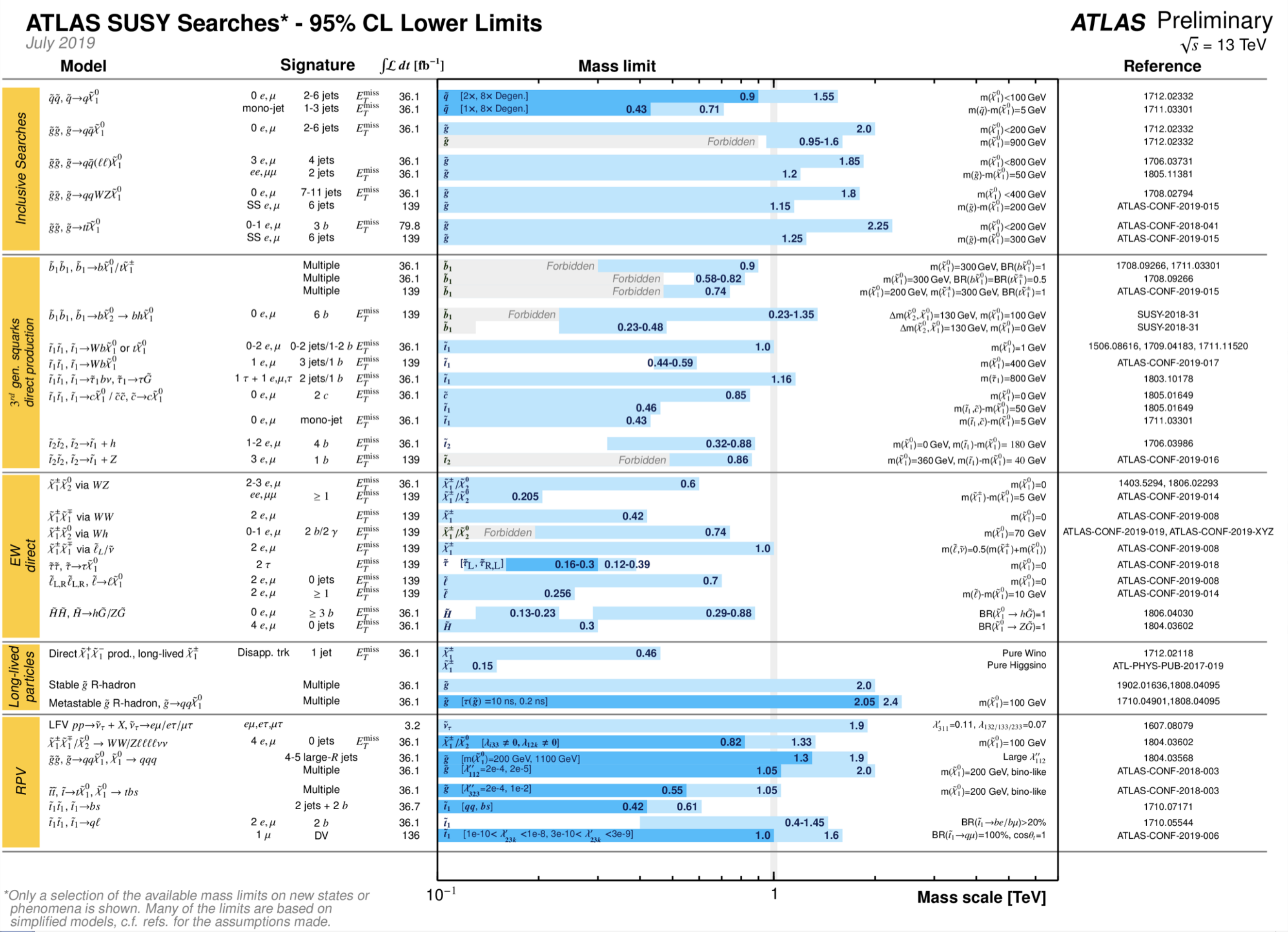
> 4σ Evidence for weak triboson production by ATLAS using 2015–2017 data

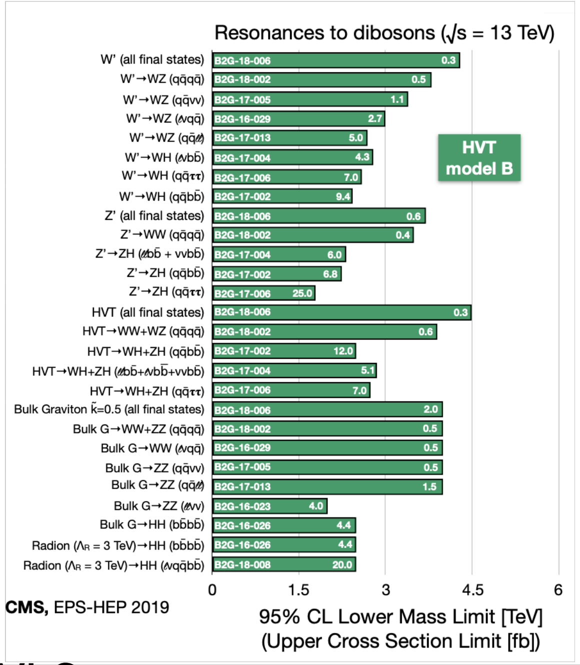


arXiv:1903.10415

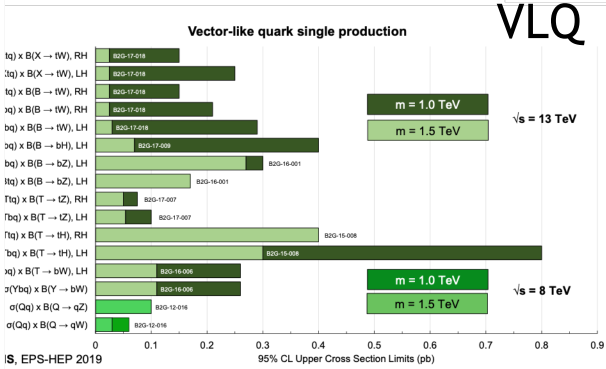
..and searching everywhere

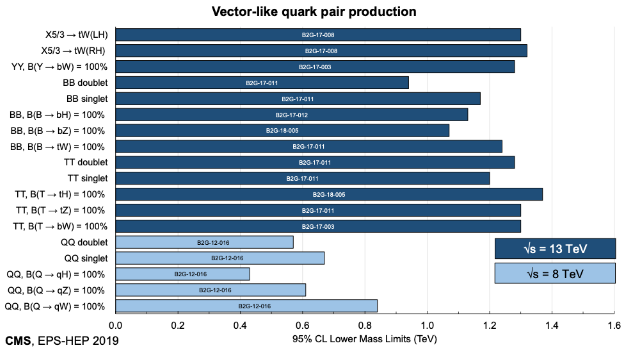
Model-dependent searches as well as theory-agnostic and signature-based ones

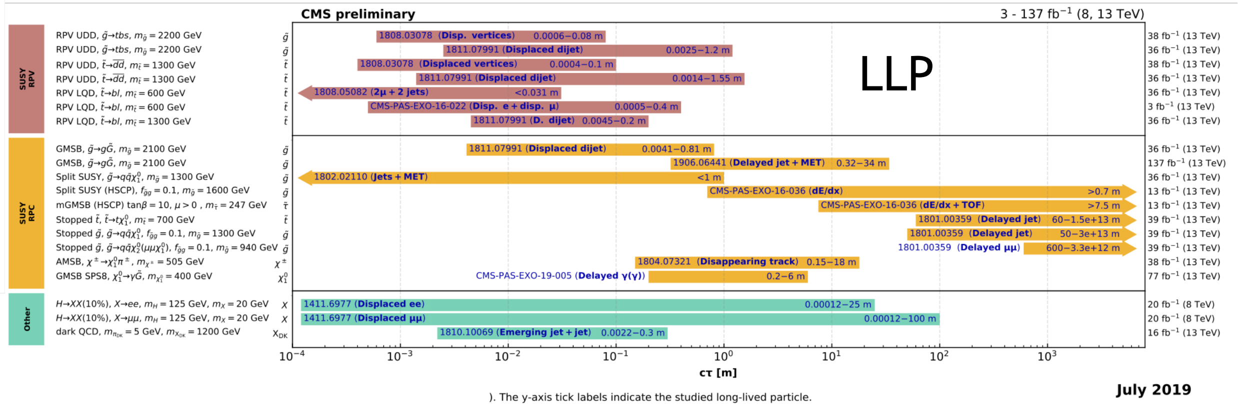




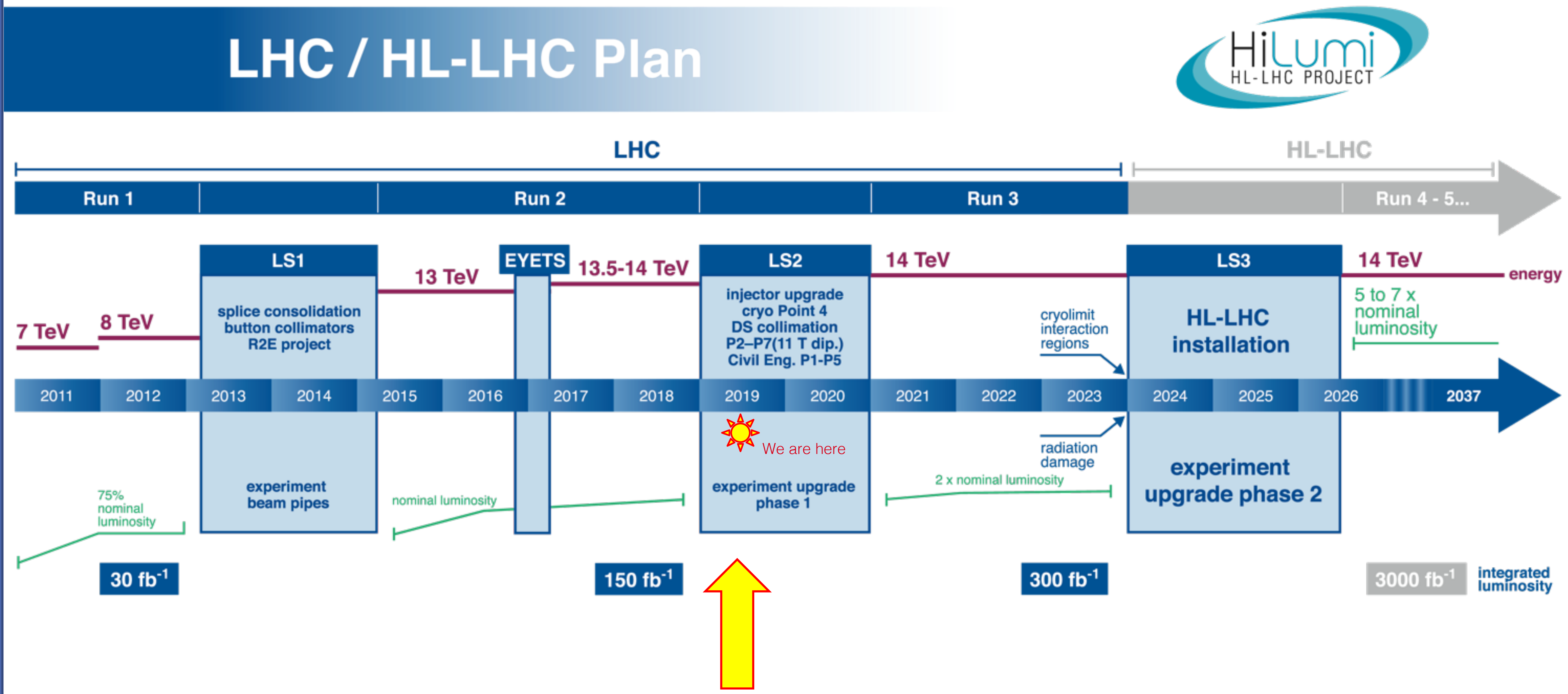
VLQ







A long and bright future: the road for the HL-LHC

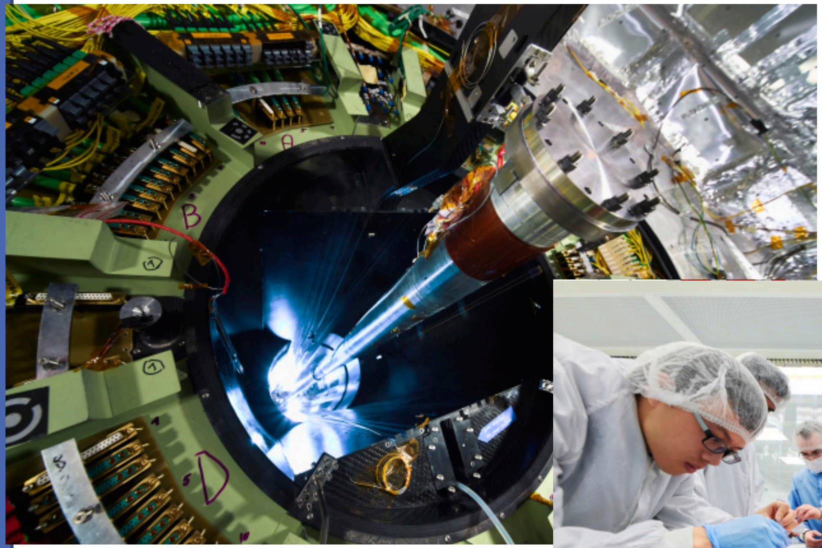


Short-term future: Run 3

➨ First round of upgrades for ATLAS and CMS detectors being finalized

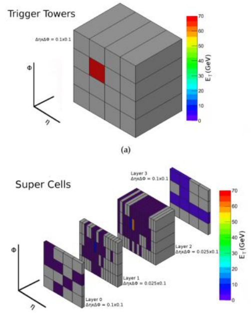
Phase-1 upgrades of CMS

- Calorimeter (HCAL barrel): installation of new readout system
- **Tracker (Pixel detector):** replacement of layer 1 and DCDC converters



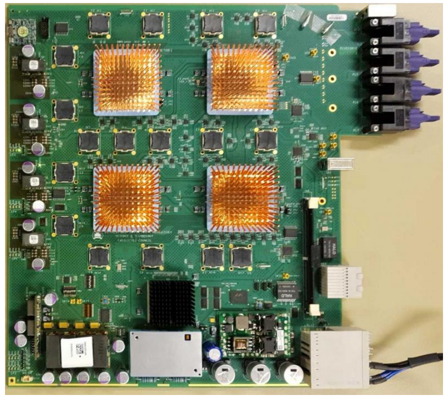
Phase-1 upgrades of ATLAS

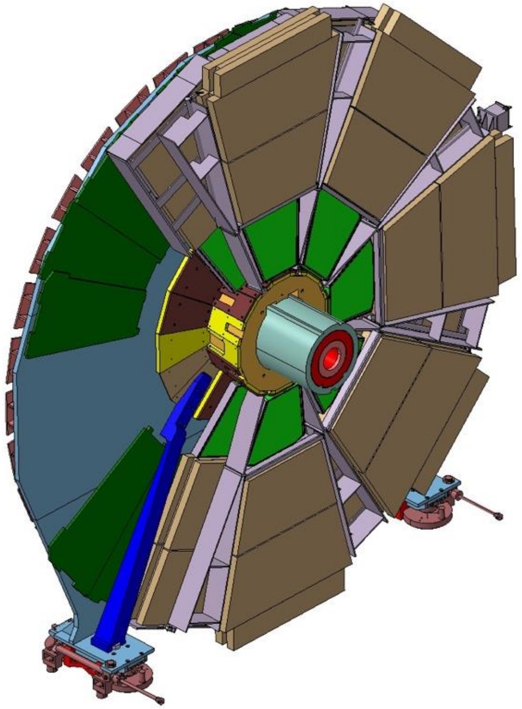
- **Trigger DAQ upgrade:** L1 Calo, L1 Muon, High Level Trigger, readout
- **New Small Muon Wheels**
- Forward detector system



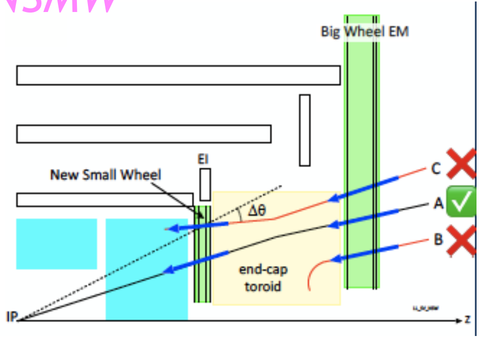
TDAQ

eFEX in September 2019





NSMW



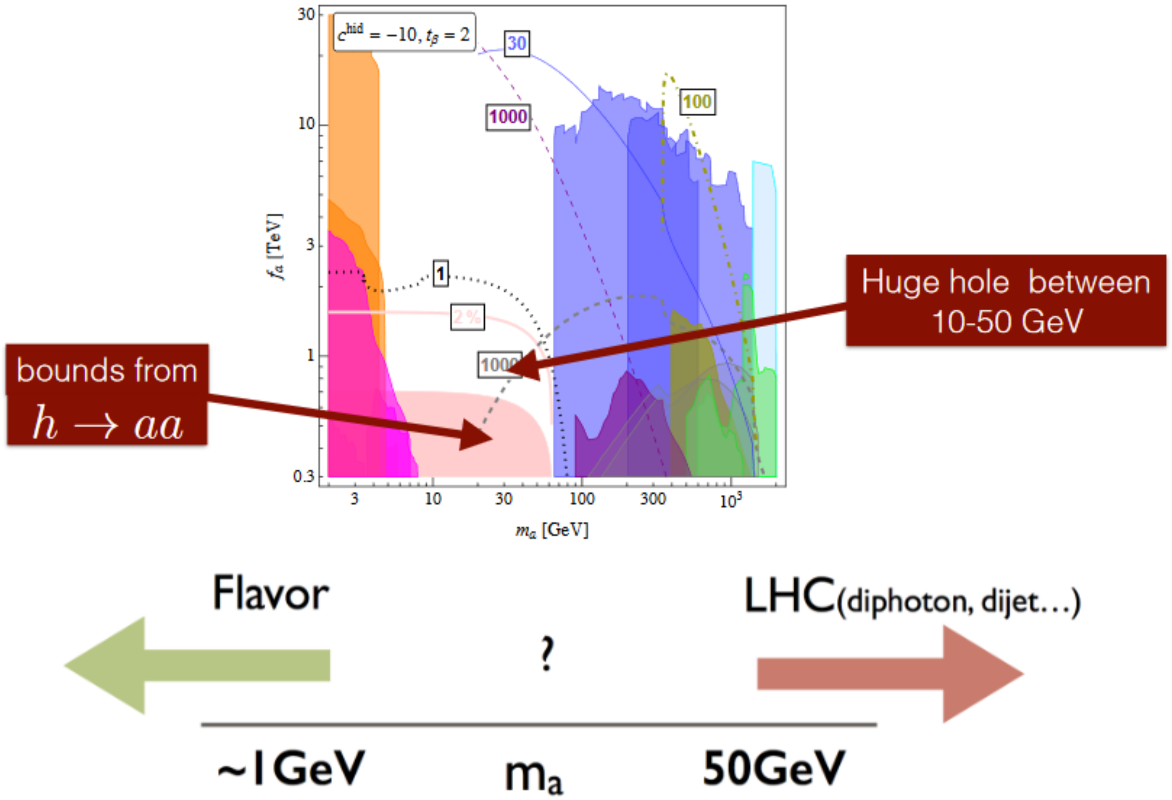
Short-term future: Run 3

- Run 3 provides the opportunity to implement novel trigger and new analysis methods and approaches (e.g. machine learning)
  - Unprecedented accuracy and search reach.
- A couple of examples

Axion-like scalar particles

Additional scalar particles below the higgs mass
Looking at h → $\gamma\gamma$ with m($\gamma\gamma$) < 65 GeV

Major limitation in trigger, plans to lower thresholds and improve triggers at L1



https://arxiv.org/abs/1710.01743

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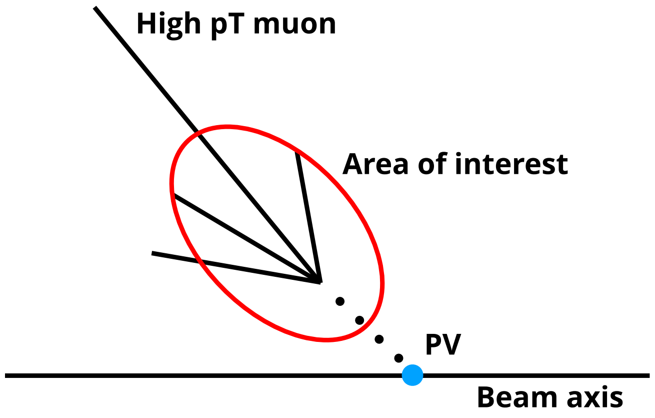


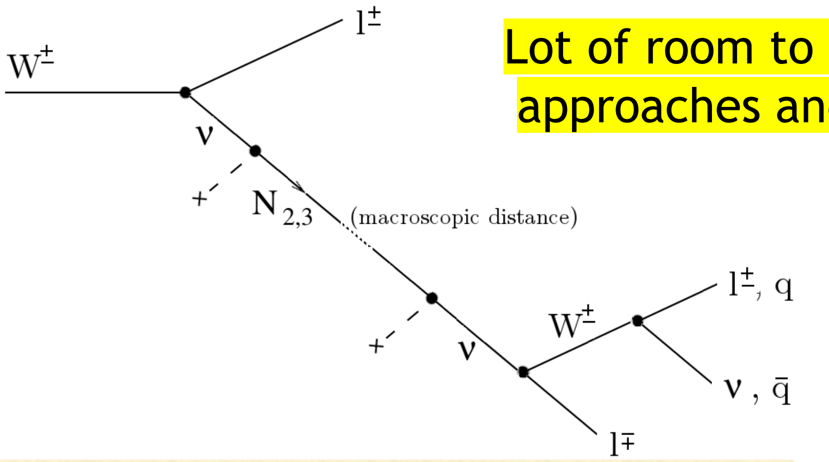
Displaced vertex at Trigger level

New particles might be long-lived (from SUSY to heavy Majorana neutrinos… a wide area not yet fully covered)

Use L1 object to identify the Primary Vertex and area of interest

OR

Improve selection at trigger level associating displaced leptons or tracks to standard object

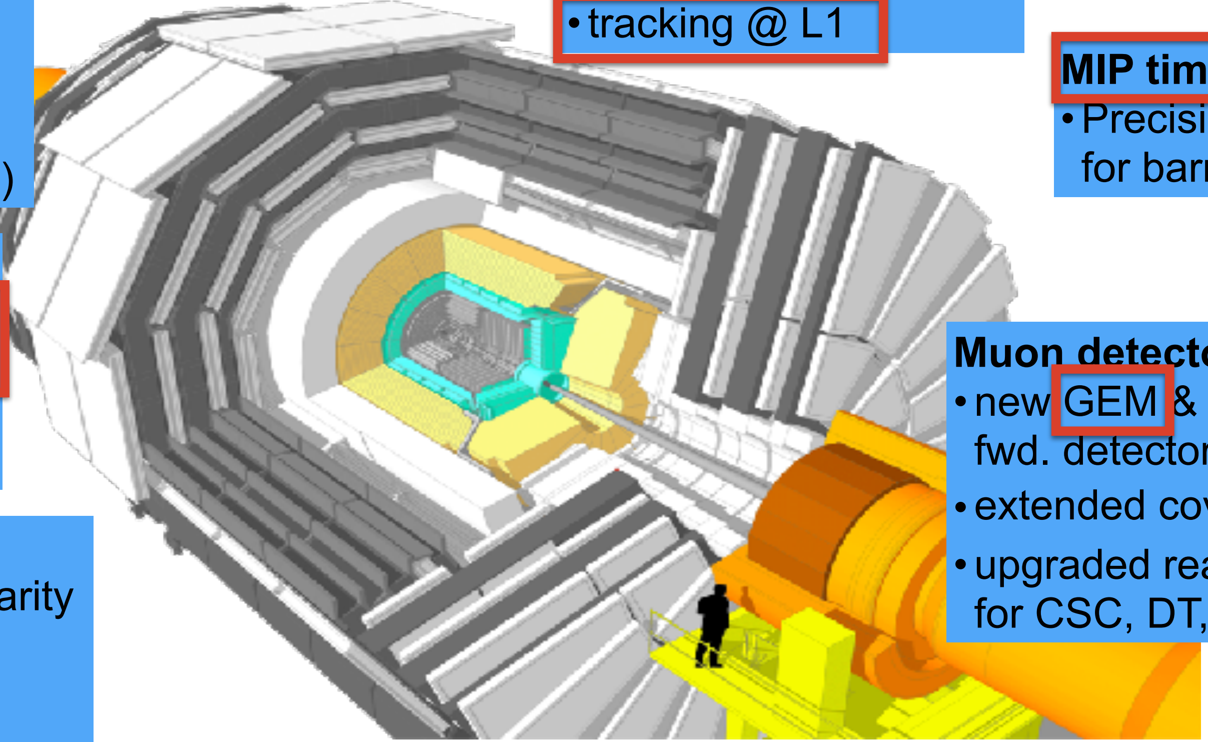


Lot of room to try new approaches and ideas

Medium-long term: Run 4, better known as HL-LHC

- Major upgrades for ATLAS and CMS detectors expected and in track

Phase-2 upgrades of CMS



Tracker
- increased granularity & extension to c=3.8
- tracking @ L1

Trigger
- incl. tracker at 40MHz
- increase max. rate to 750kHz (L1) /7.5kHz (HLT)

MIP timing detector
- Precision timing for barrel & endcaps

Calorimeter endcaps
- Si-based high-granularity calorimeter
- 3D shower measurement + timing

Muon detectors
- new GEM & RPC fwd. detectors
- extended coverage to $|\eta|=3$
- upgraded readout for CSC, DT, RPC

Barrel calorimeters
- ECAL crystal-granularity readout @ 40MHz
- new ECAL&HCAL backend boards

Taken from
W. Adam: Highlights from the CMS experiment

Many new & Innovative elements!

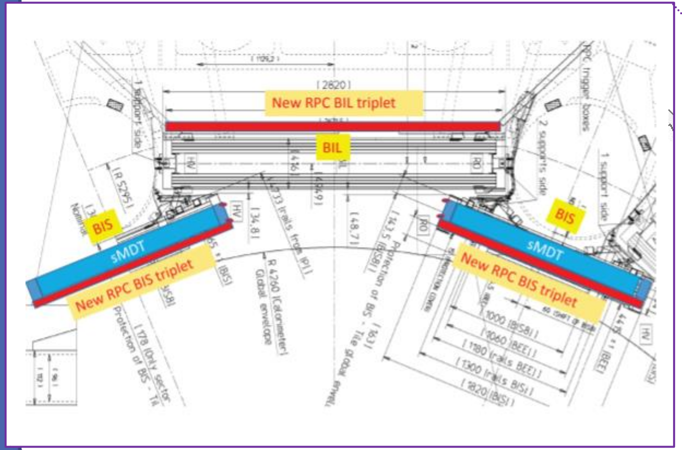
Phase-2 upgrade starts now!

Medium-long term: Run 4, better known as HL-LHC

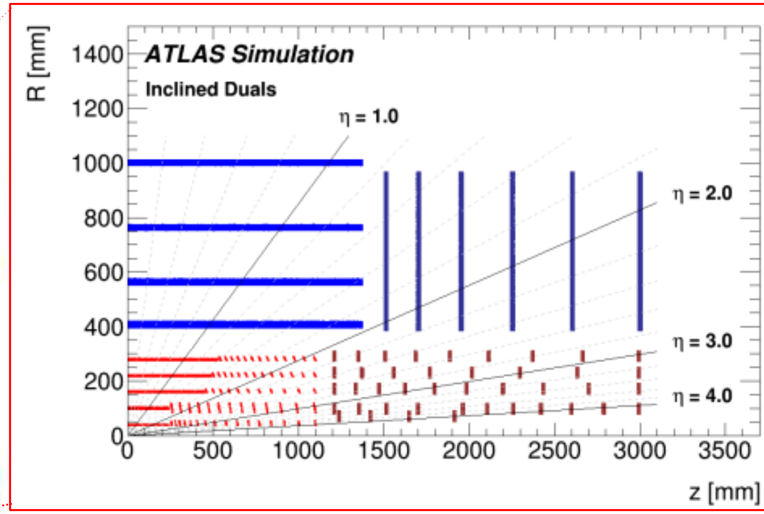
➨ Major upgrades for ATLAS and CMS detectors expected and in track

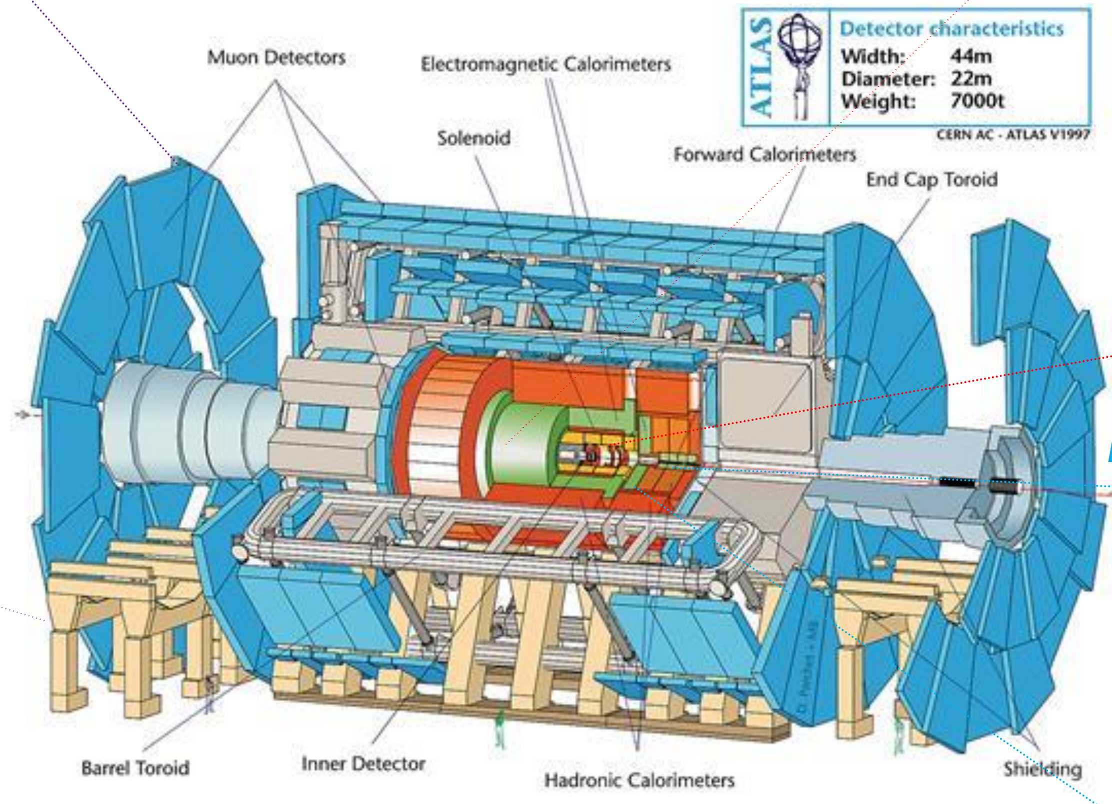
Phase-2 upgrades of ATLAS

Upgraded Muon system

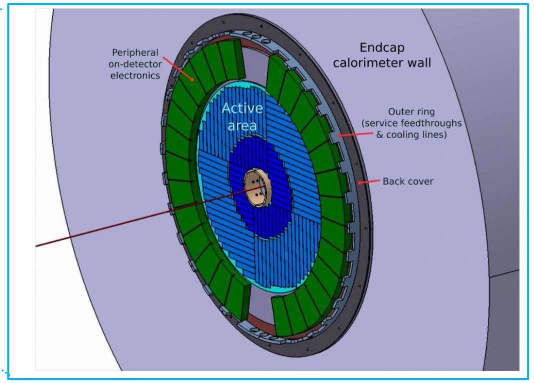


New Inner Tracking detector (ITK)
Strips and pixels





High Granularity Timing detector



TDAQ Upgrade and more

The HL-LHC potential

- The physics potential of the HL-LHC and a possible HE upgrade has been studied in detail for the European Strategy. *Open symposium in Granada – May 2019*

- Prospects were presented in all areas:
  - **5 Working Groups (SM, Higgs, BSM, Flavour, Heavy Ion):** ATLAS, CMS, LHCb, ALICE exp. and theorists worked to enrich and consolidate the HL physics program: precision, exploration potential and breadth
  - Prospects for a 27 TeV HE-LHC are also studied
  - Five dedicated reports and two executive summaries for HL and HE have been released in December ''18 and updated in February '19 → over 1000 pages of documents!
  - See also: HLHELHCWorkshop

The physics potential of HL-LHC

Editors:
Workshop steering group: A. Dainese, M.L. Mangano, A.B. Meyer, A. Nisati, G.P. Salam, M. Vesterinen
WG1 conveners: P. Azzi, S. Farry, P. Nason, A. Tricoli, and D. Zeppenfeld
WG2 conveners: M. Cepeda, S. Gori, P. Ilten, M. Kado, and F. Riva,
WG3 conveners: X. Cid-Vidal, M. D'Onofrio, P. J. Fox, R. Torre, and K. Ulmer
WG4 conveners: A. Cerri, V.V. Gligorov, S. Malvezzi, J. Martin Camalich, and J. Zupan
WG5 conveners: Z. Citron, J. F. Grosse-Oetringhaus, J. M. Jowett, Y.-J. Lee, U. Wiedemann, M. Winn
Contributing authors: see Addendum

ABSTRACT

This document presents the executive summary of the findings of the Workshop on "The physics of HL-LHC, and perspectives on HE-LHC", which has run for over a year since its kick-off meeting on 30 October – 1 November 2017. We discuss here the HL-LHC physics programme. As approved today, this covers *(a)* pp collisions at 14 TeV with an integrated luminosity of 3 ab^{-1} each for ATLAS and CMS, and 50 fb^{-1} for LHCb, and *(b)* Pb–Pb and p–Pb collisions with integrated luminosities of 13 nb^{-1} and 50 nb^{-1}, respectively. In view of possible further upgrades of LHCb and of the ions programme, the WG reports assume 300 fb^{-1} of luminosity delivered to an Upgrade II of LHCb, 1.2 pb^{-1} of integrated luminosity for p–Pb collisions, and the addition of collisions with other nuclear species. A separate submission covers the HE-LHC results.
The activity has been carried out by five working groups (WGs): "Standard Model" (WG1), "Higgs" (WG2), "Beyond the Standard Model" (WG3), "Flavour" (WG4) and "QCD matter at high density" (WG5). Their reports, extending this executive summary with more results and details, are available on the CERN Document Server [1–5], and will appear on arXiv. The WG results include both phenomenological studies and detailed simulations of the anticipated performance of the LHC detectors under HL-LHC conditions. These latter studies implement the knowledge acquired during the preparation of the technical design reports for the upgraded detectors, and reflect the experience gained by the experiments during the first two runs of the LHC. The documents describing in full detail the HL-LHC studies performed by the experiments can be found in Ref. [6] (available in early 2019) and in Ref. [7].
Three goals have been set for the Workshop: (i) to update and extend the projections for the precision and reach of the HL-LHC measurements, and for their interpretation; (ii) to highlight new opportunities for discovery of phenomena beyond the Standard Model (BSM), in view of the latest theoretical developments and of recent data; (iii) to explore possible new directions and/or extensions of the approved HL-LHC programme, particularly in the area of flavour, in the search for elusive BSM phenomena, and in the study of QCD matter at high density. In addition to enriching and consolidating the physics plans for HL-LHC, and highlighting the significant advances that the full HL-LHC programme will bring relative to today's landscape, this contribution to the European Strategy for Particle Physics Update process is intended to help put in perspective the physics potential of future projects beyond HL-LHC.

References

1. P. Azzi, S. Farry, P. Nason, A. Tricoli, and D. Zeppenfeld, (conveners), et al, *Standard Model Physics at the HL-LHC and HE-LHC* , CERN-LPCC-2018-03, CERN, Geneva, 2018. https://cds.cern.ch/record/2650160.
2. M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, CERN, Geneva, 2018. https://cds.cern.ch/record/2650162.
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The physics potential of HE-LHC

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WG5 conveners: Z. Citron, J. F. Grosse-Oetringhaus, J. M. Jowett, Y.-J. Lee, U. Wiedemann, M. Winn
Contributing authors: see Addendum

ABSTRACT

This document summarizes the physics potential of the High-Energy LHC (HE-LHC), under consideration as a possible future project at CERN. The HE-LHC is a 27 TeV pp collider, to be installed in the LHC tunnel, relying on the 16 T magnet technology being developed for the 100 TeV Future Circular Collider (FCC-hh). The HE-LHC is designed to deliver 10-15 ab^{-1} of integrated luminosity to two general purpose detectors, during 20 years of operation. As for the LHC, the facility could host a dedicated interaction point focused on flavour physics, delivering 3 ab^{-1} of integrated luminosity to an upgraded LHCb detector, and would continue the programme of heavy ion collisions. The results presented here were obtained in the context of the Workshop on "The physics of HL-LHC, and perspectives on HE-LHC", which ran for over a year after its kick-off meeting on 30 October – 1 November 2017. These studies complemented those focused on the engineering and technological aspects of the project, performed in the context of the FCC conceptual design report (CDR) for the HE-LHC, and documented elsewhere [1].
The activity has been carried out by five working groups (WGs): "Standard Model" (WG1), "Higgs" (WG2), "Beyond the Standard Model" (WG3), "Flavour" (WG4) and "QCD matter at high density" (WG5). The reports from the WGs, extending this executive summary with much more detail and many more results, are available on the CERN Document Server [2–6], and will appear on arXiv. The documents describing in full detail the HL-LHC and HE-LHC studies performed by the ATLAS and CMS Collaborations can be found in Ref. [7] (available in early 2019).

References

1. M. Benedikt, J. Gutleber, and F. Zimmermann, (editors), *Future Circular Collider Study. Volume 4: The High Energy LHC (HE-LHC) Conceptual Design Report*, CERN-ACC-2018-0059, CERN, Geneva, Dec, 2018. Submitted to Eur. Phys. J. ST. http://cern.ch/go/S9Gq.
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4. X. Cid-Vidal, M. D'Onofrio, P. J. Fox, R. Torre, and K. Ulmer, (conveners), et al, *Beyond the Standard Model Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-05, CERN, Geneva, 2018. https://cds.cern.ch/record/2650173.
5. A. Cerri, V. V. Gligorov, S. Malvezzi, J. Martin Camalich, and J. Zupan, (conveners), et al, *Flavour Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-06, CERN, Geneva, 2018. https://cds.cern.ch/record/2650175.
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WG5 conveners: Z. Citron, J. F. Grosse-Oetringhaus, J. M. Jowett, Y.-J. Lee, U. Wiedemann, M. Winn

Analyses strategies

- Different approaches have been used by experiments and in theoretical prospects
  - **Extrapolations** of existing results using simple scale factors on individual processes
  - **Fast-simulations**, e.g. using DELPHES (CMS, theorists) and common HL-LHC cards
  - **Parametric-simulations**, using particle-level definitions for the main objects and taking into account the pile-up conditions, effects of an upgraded detector taken into account by applying smearing functions.
  - **Systematic uncertainties** are based on existing data analyses and estimated using common guidelines for projecting the expected improvements foreseen thanks to large dataset and upgraded detectors
    - intrinsic statistical uncertainty is reduced by a factor $1/\sqrt{L}$
    - Theoretical uncertainties are halved or divided by 4; PDF reduced up to 20-50%
    - Detector-related uncertainties (JES, JER, b-tagging, $e/\gamma/\mu/\tau$ ID) are ~ halved

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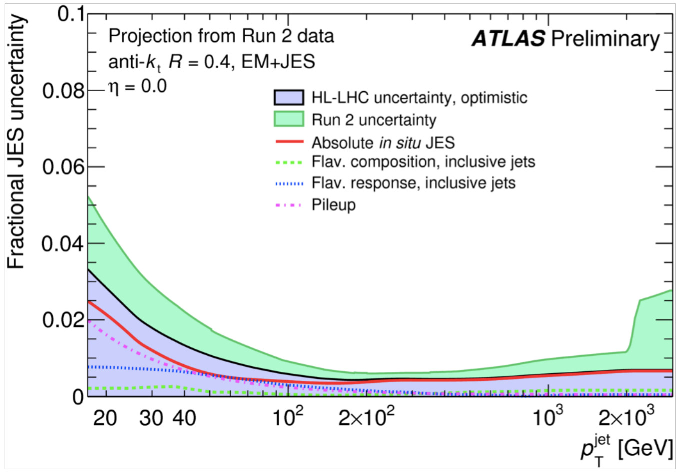
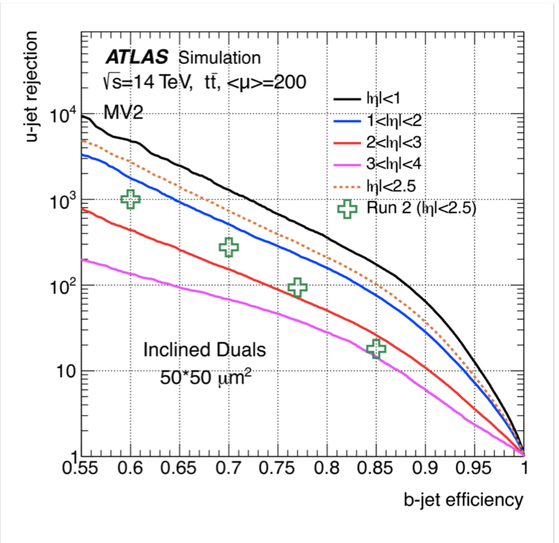
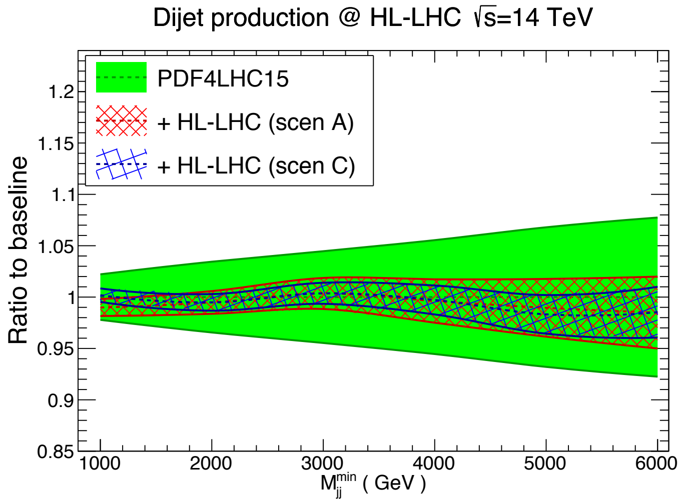






Higgs physics

Question	κ_V	κ_3	κ_g	κ_γ	λ_{hhh}	σ_{hZ}	$\mathrm{BR}_{\mathrm{inv}}$	$\mathrm{BR}_{\mathrm{und}}$	κ_ℓ	μ_{4f}	$\mathrm{BR}_{\tau\mu}$	Γ_h
Is h Alone?	+	+			+	+				+		+
Is h elementary?	+	+	+	+		+						
Why $m_h^2 \ll m_{\mathrm{Pl}}^2$?	+	+					+	+		+		+
1st order EWPT?			+	+	+	+				+		
CPV?		+(CP)										
Light singlets?							+	+	+	+		+
Flavor puzzles?		+							+		+	

B. Heinemann (Granada'19)

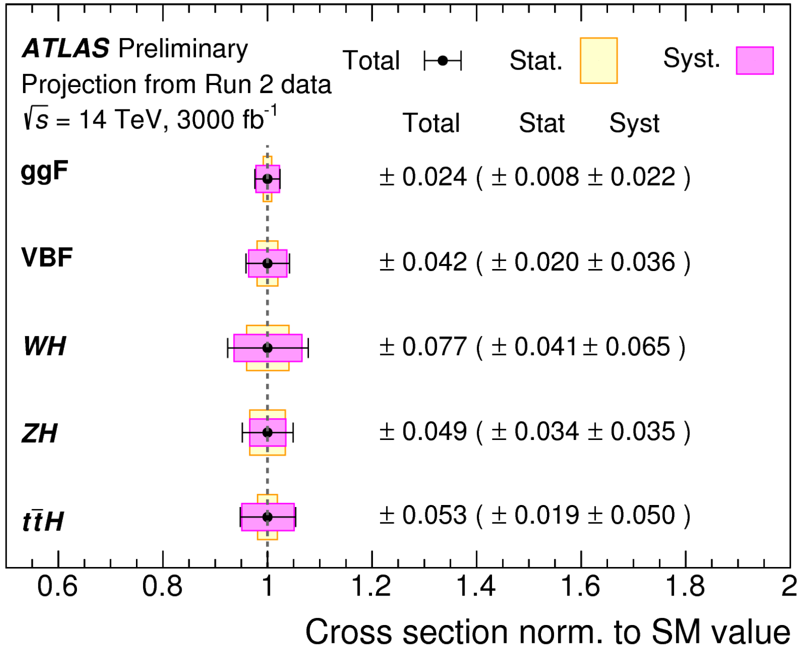
Many problems of particle physics today relate to Higgs observables

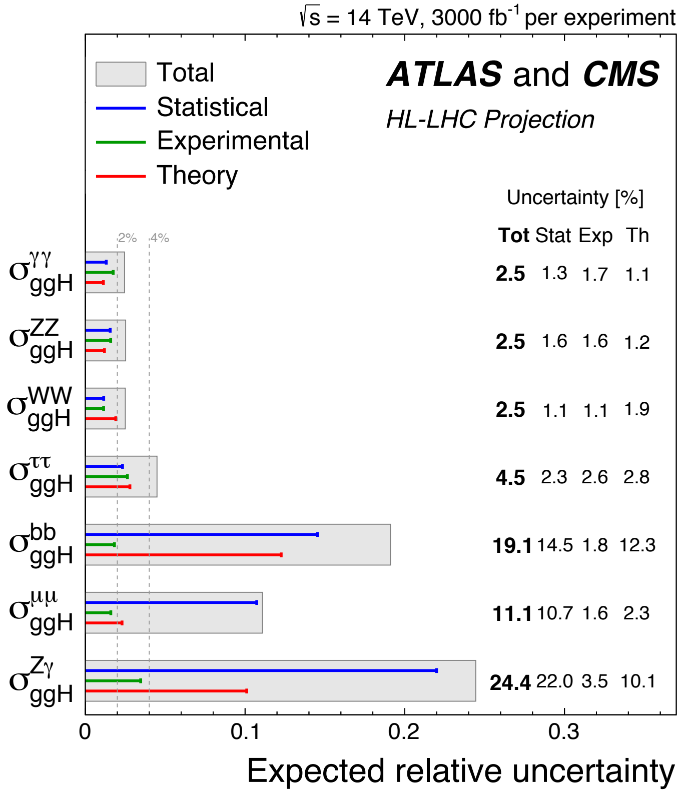
Higgs physics: properties

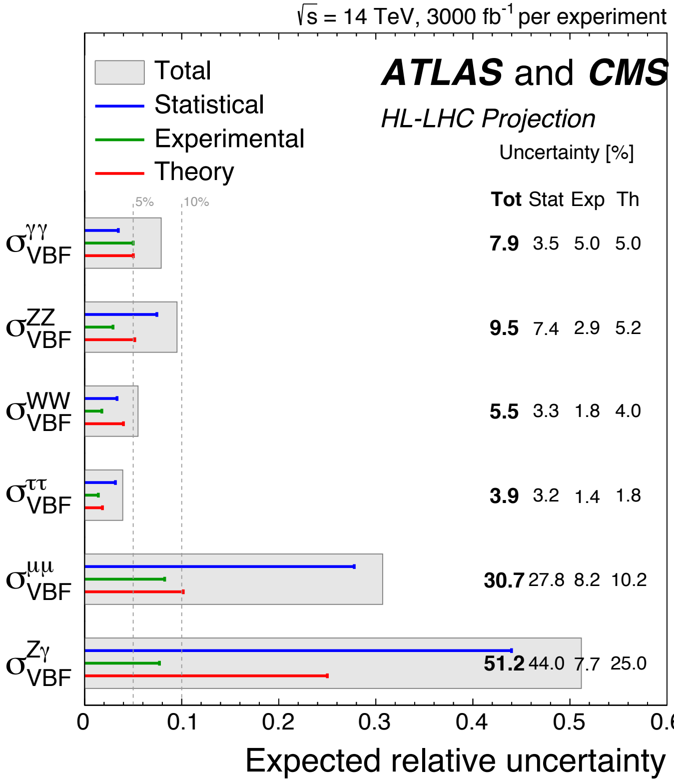
- The exploration of the Higgs sector includes precision measurements, as well as searches for rare production and decay processes:
  - All production modes/decays including rare ones such as **h → $\mu^+\mu^-$ and h → Zγ will be observable** at HL
  - Rate measurements show that **percent level precision can be reached for most couplings**
  - With minimal assumptions, the **total width Γ_H will be constrained with a 5%** precision and an upper limit on the **Higgs invisible BR of 2.5%** will be reached.

arXiV:1902.00134

(e.g.) ATL-PHYS-PUB-2018-054







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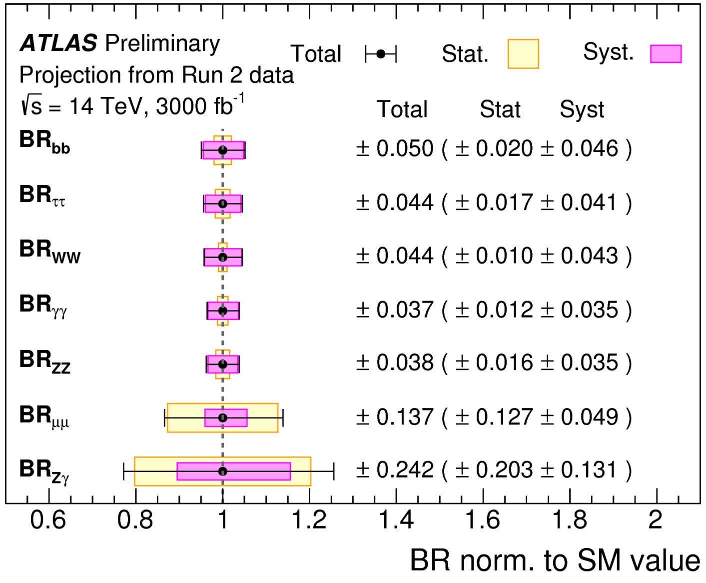
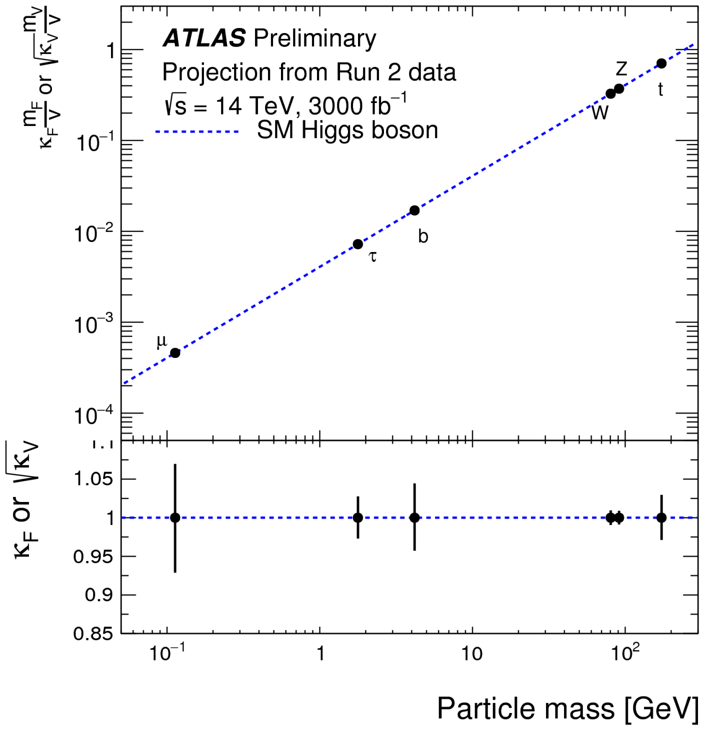
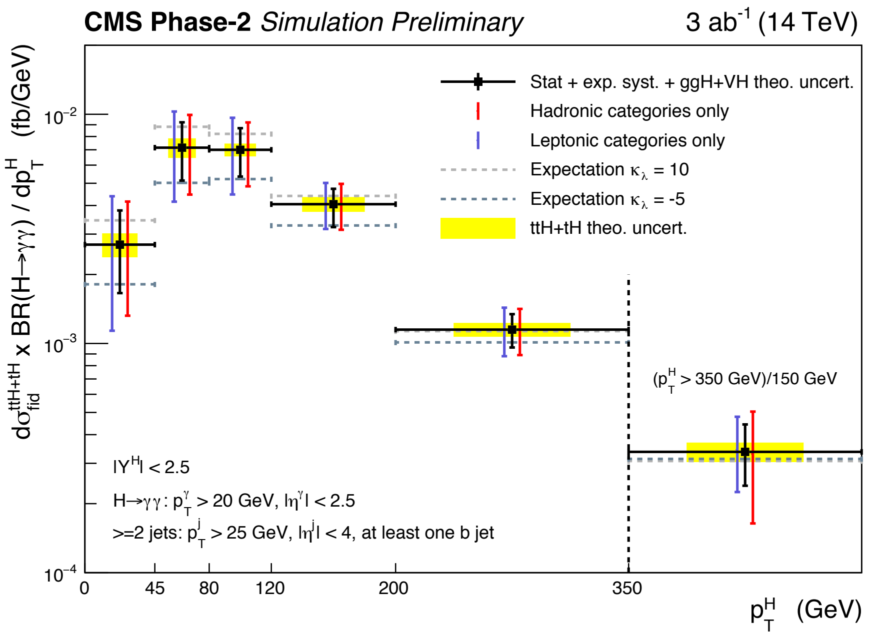




also differential cross sections!

expected p_{H_T} differential ttH + tH σ, h→$\gamma\gamma$



Higgs physics: properties

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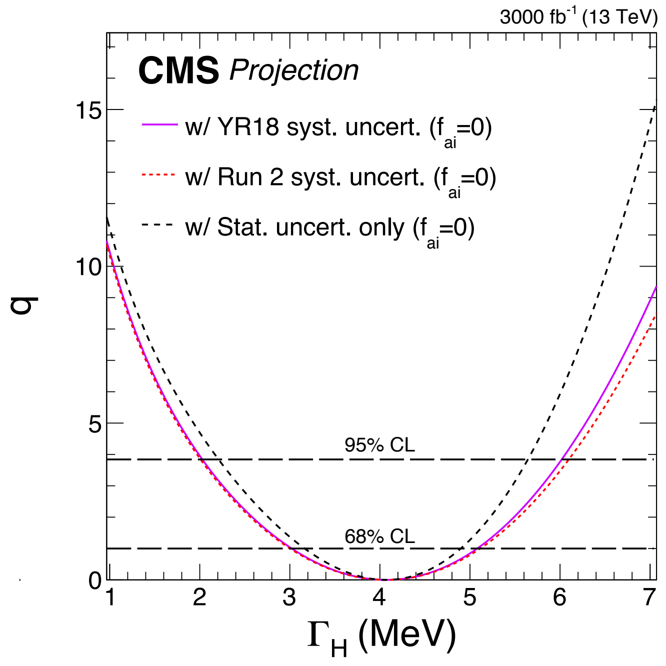
SM prediction of $\Gamma_H \sim 4$ MeV
Off-shell methods used by ATLAS and CMS (H→4l, ggF, VBF and VH productions)

Combination of the results:

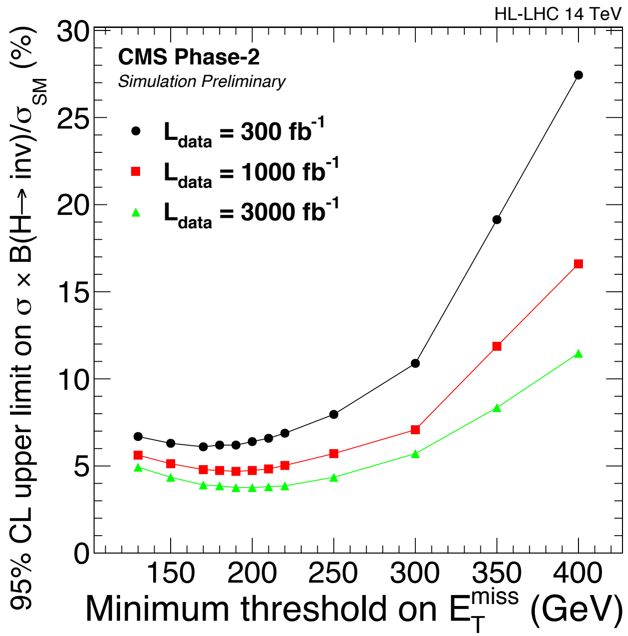
$$\Gamma_H = 4.1^{+0.7}_{-0.8}\ \mathrm{MeV}$$



(mass unc. foreseen to be reduced to 10-20 MeV)

Higgs invisible in VBF, M_{jj}>2500 GeV

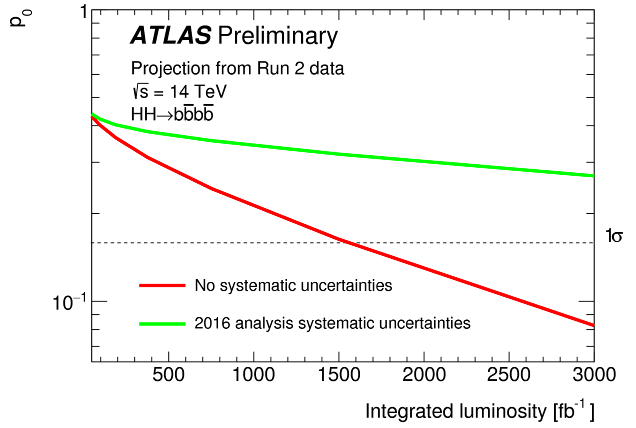
ATLAS+CMS, VBF and VH

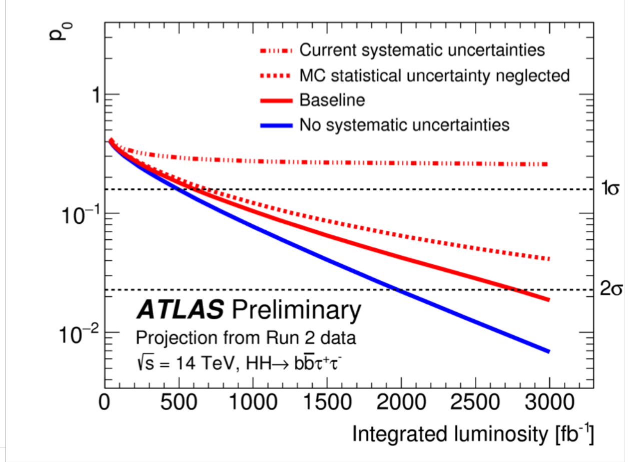


$$\left(\mu_{\mathrm{VBF},VH} \cdot \mathrm{BR}_{\mathrm{inv}}\right)^{\mathrm{HL\text{-}LHC}} \leq 2.5\%$$

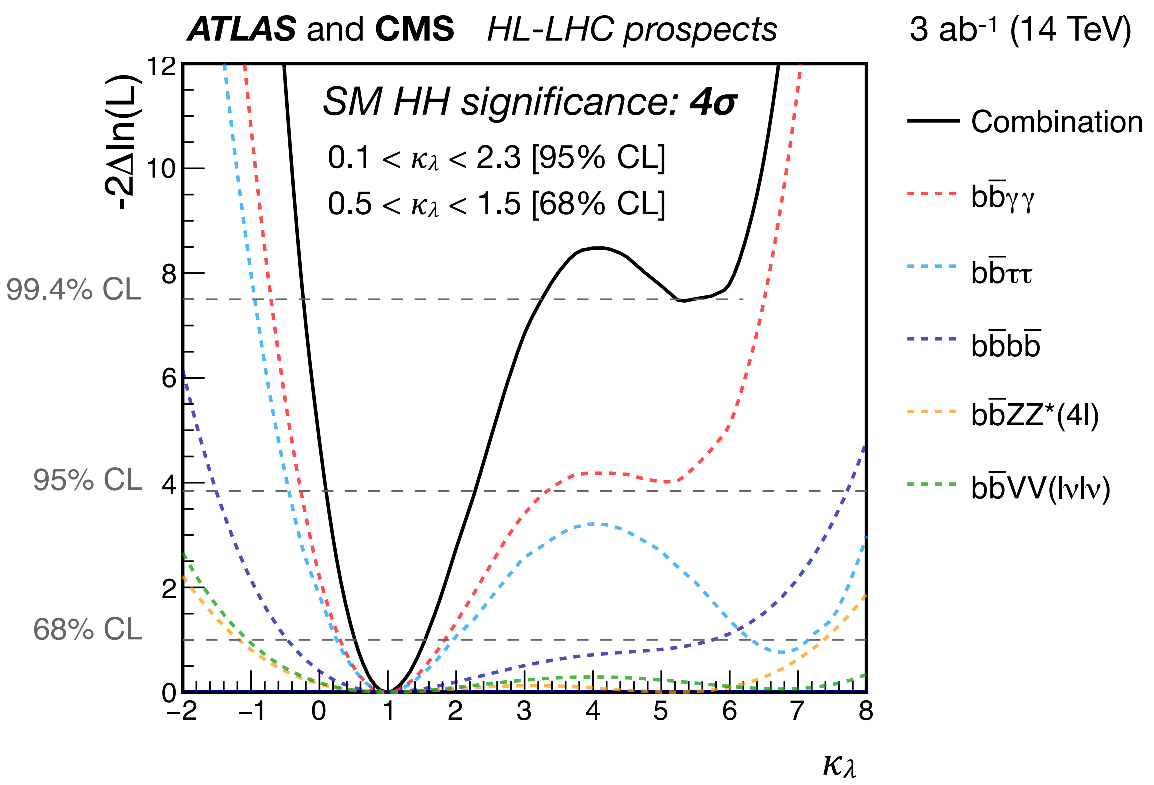
Higgs physics: di-higgs

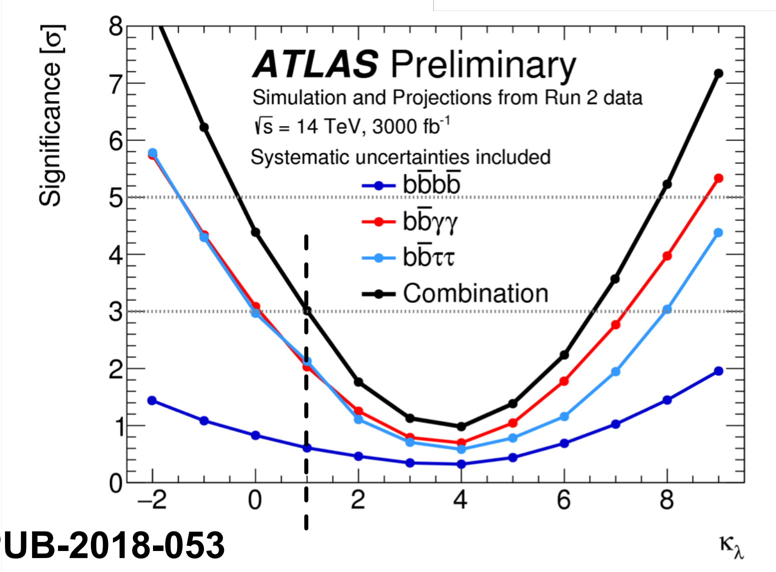
- ggF HH→ 4b / bbττ / bbγγ with detailed analysis of systematic uncertainties impact
- Assuming SM Higgs self-coupling λ: **observation sensitivity of 3 s.d. per exp., 4 s.d. combined**





likelihood profile as a function of κ_λ





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The secondary minimum can be excluded at 99.4% CL, with a constraint on the Higgs self-coupling of $0.5 < \kappa_\lambda < 1.5$ at the 68% CL.

Higgs physics: portals to NP

HL-LHC will enhance the sensitivity to BSM physics. For example:

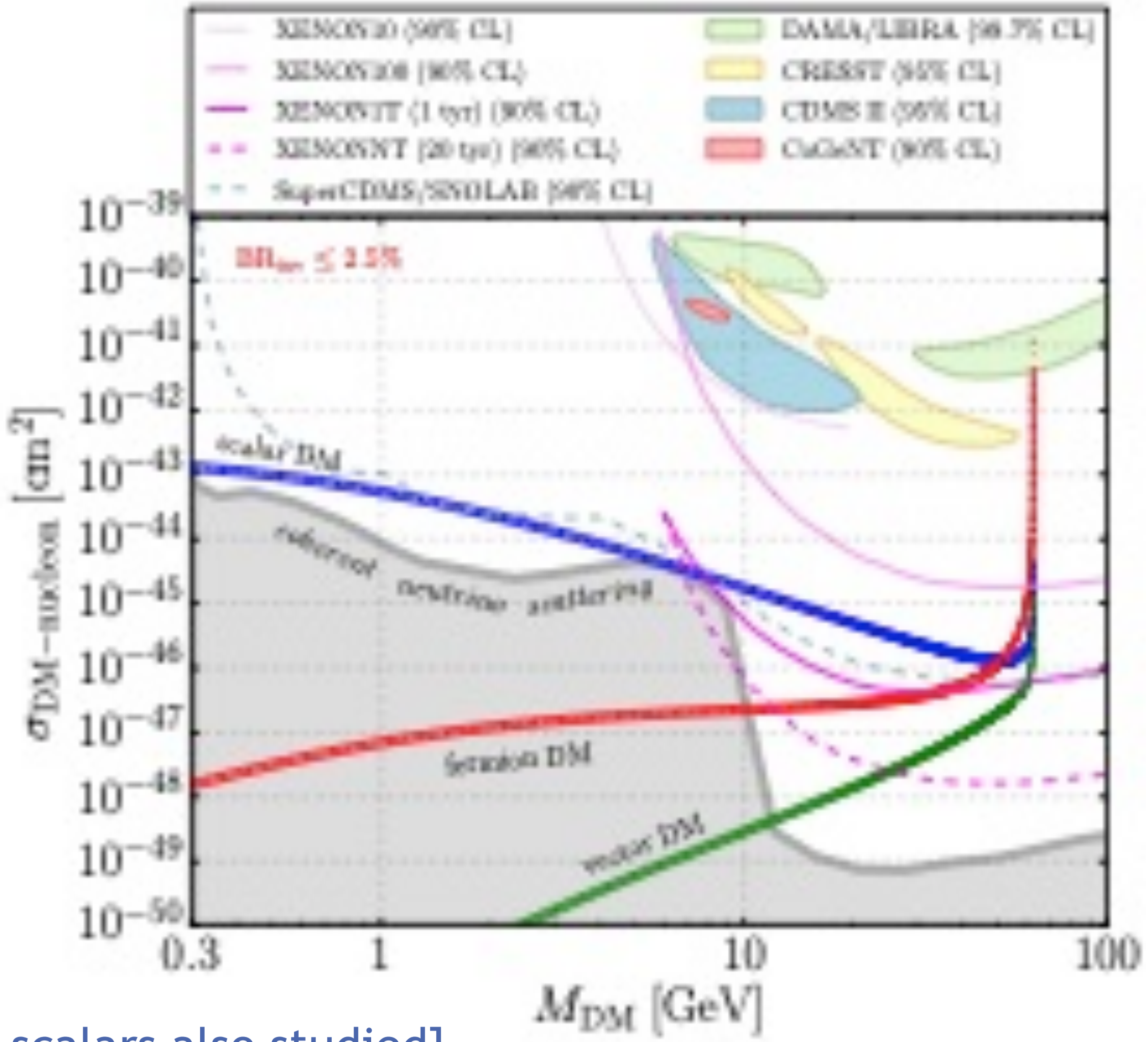
Minimal Higgs - Dark Matter portal models

$$\mathcal{L} \supset -\tfrac{1}{4}\lambda_{hSS} H^\dagger H S^2 \qquad \text{(scalar DM)} \quad \text{or}$$
$$\mathcal{L} \supset +\tfrac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu \qquad \text{(vector DM)} \quad \text{or}$$
$$\mathcal{L} \supset -\tfrac{1}{4}\frac{\lambda_{h\chi\chi}}{\Lambda} H^\dagger H \bar{\chi}\chi \qquad \text{(fermion DM)},$$

Scalar or Vector quartic interaction of the SM Higgs doublet field H with the DM field

If $M_{\rm DM} < M_H/2 \simeq 62.5\text{GeV}$

→ Higgs invisible constraints can be translated in terms of upper limits on λ → related to $\sigma_{\text{DM-nucleon}}$



[constraints on other models e.g. with additional heavy scalars also studied]

SM measurements and top physics

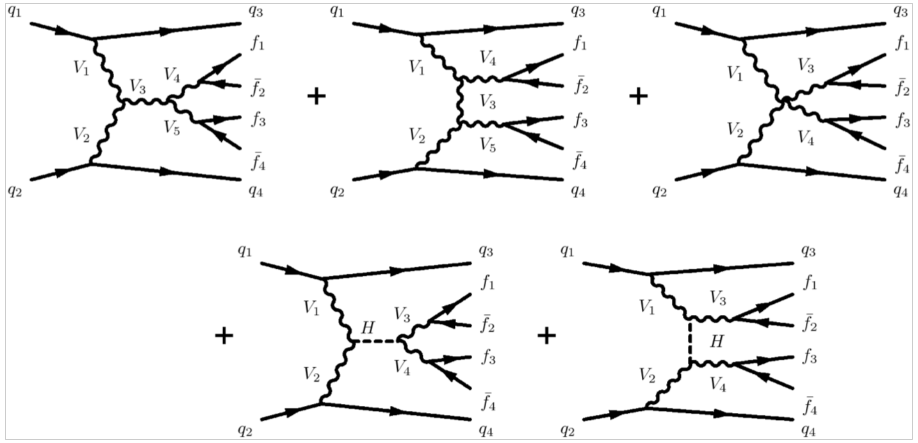
HL-LHC will be critical to reduce systematics or bypass their limitations with new analyses, lead to measurements of unanticipated precision and give access to rare phenomena

Some examples in the following

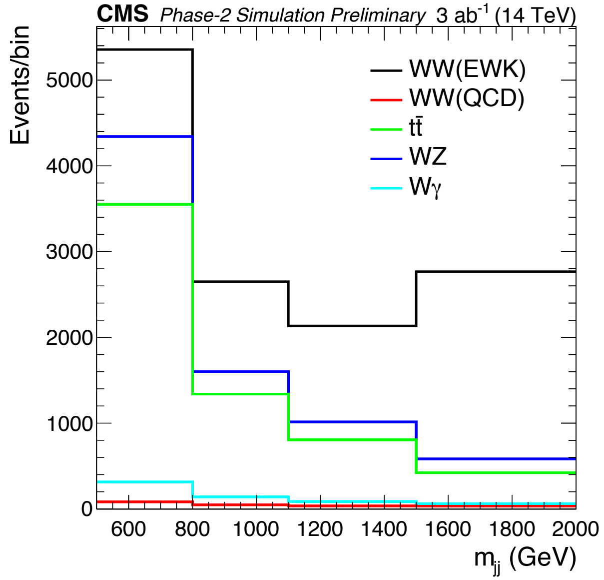
Multi-boson production @ HL-LHC

1902.04070

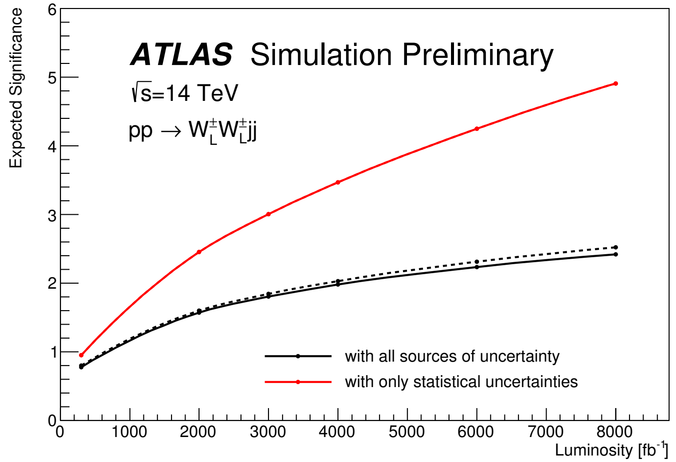
- Prospects for **same-sign WW**
  - Also > 3 s.d. evidence for $W_L W_L$ production



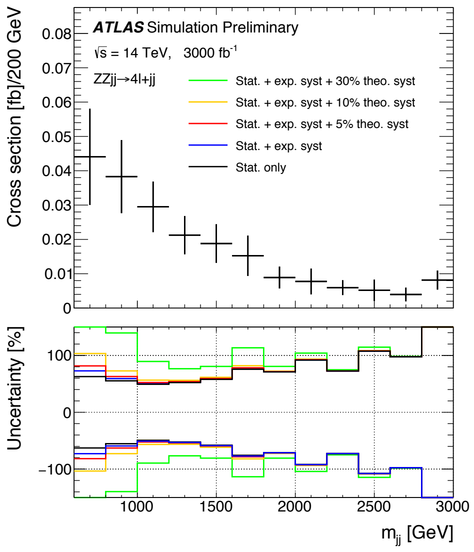
same-sign WW

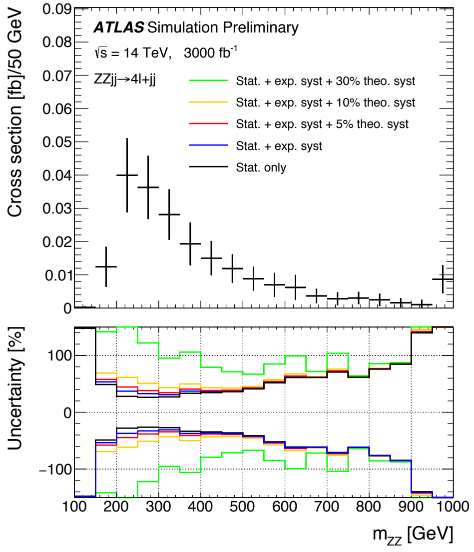


$W_L W_L$



- Excellent prospects for **multiboson** productions
  - Interesting differential cross section measurements
  - Results can be used to constrain anomalous couplings





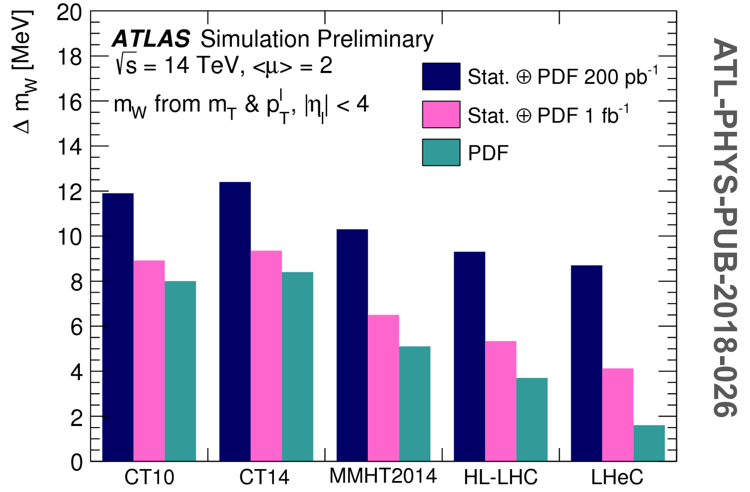
Process	$W^{\pm}W^{\pm}$	WZ	WV	ZZ	WWW	WWZ	WZZ
Final state	$\ell^{\pm}\ell^{\pm}jj$	$3\ell jj$	$\ell jjjj$	$4\ell jj$	$3\ell 3\nu$	$4\ell 2\nu$	$5\ell\nu$
Precision	6%	6%	6.5%	10–40%	11%	27%	36%
Significance	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	3.0σ	3.0σ

W and top mass precision measurements

- **W mass** precision measurement uses dedicated dataset at low <mu>
  → exploit the extended leptonic coverage

Measurement parameters		Uncertainty in m_W [MeV]		
$\sqrt{s}$ [TeV]	η_ℓ range	Scenario 1	Scenario 2	Scenario 3
14	$\lvert\eta_\ell\rvert < 2.4$	11.1 (9.9 ⊕ 5.0)	11.5 (10.0 ⊕ 5.8)	11.5 (10.0 ⊕ 5.7)
14	$\lvert\eta_\ell\rvert < 4$	9.1 (8.5 ⊕ 3.2)	9.3 (8.6 ⊕ 3.7)	9.2 (8.6 ⊕ 3.2)

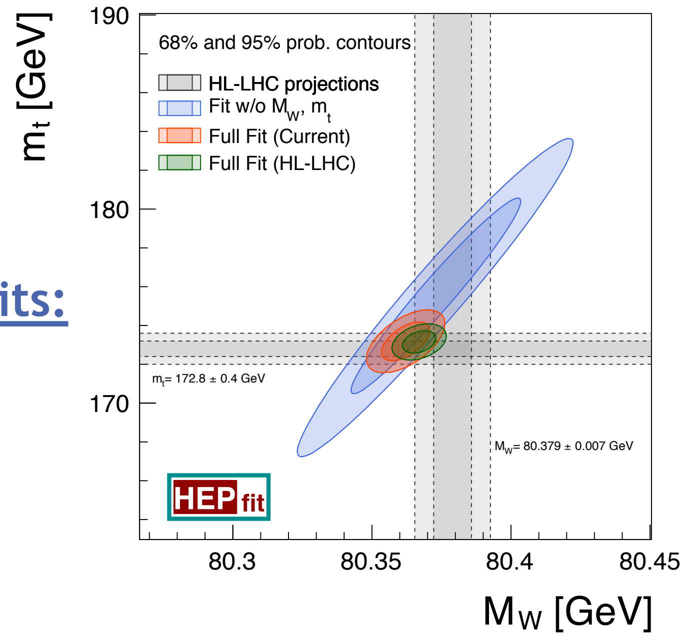
Δm_W = ±6 MeV (with reduced PDF unc from HL LHC)
Δm_W = ±2 MeV (with improved PDF from LHeC)



- Precision better than $5 \cdot 10^{-5}$ for **$\sin^2\theta_{eff}$**
- **Top mass** precision measurement
  - Several methods compared

Method:	$t\bar{t}$ lepton+jets	t-channel single top	$m_{SV\ell}$	J/ψ	$\sigma_{t\bar{t}}$
Δm_{top} (GeV):	0.17	0.45	0.62	0.50	1.2

EW fits:

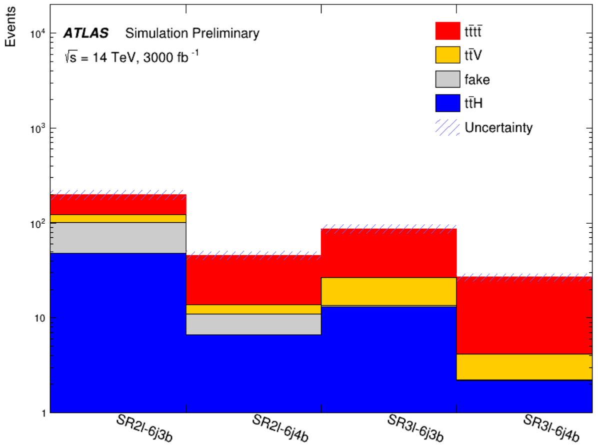


Progress on Δm_t will be driven by future theoretical developments

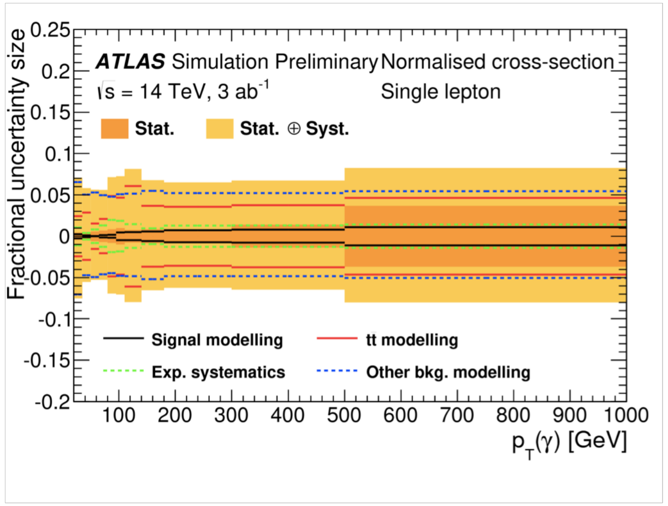
Rare top processes and FCNC

- Prospects for measurements of **rare top processes**

(1) tttt (4 tops): also a probe for new physics



(2) ttγ: fiduciál differential cross section measurements



5-10% uncertainties

Process	HL-LHC
$t\bar{t}$	3×10^{9}
$t\bar{t}$ ($p_T^{top} > 2$ TeV)	3×10^{2}
t-channel	8×10^{8}
Wt	2×10^{8}
s-channel	3×10^{7}
tqZ	3×10^{6}
$t\bar{t}$W	2×10^{6}
$t\bar{t}$Z	3×10^{6}
$t\bar{t}$H	2×10^{6}
tH	3×10^{5}
$t\bar{t}t\bar{t}$	5×10^{4}

- **Flavor changing neutral currents** are forbidden at tree level, and strongly suppressed by GIM mechanism – SM predicts O(10^{-12} – 10^{-16}), BSM extensions allow significant enhancements
- Anomalous couplings:
  - **top-g/γ/Z/H**

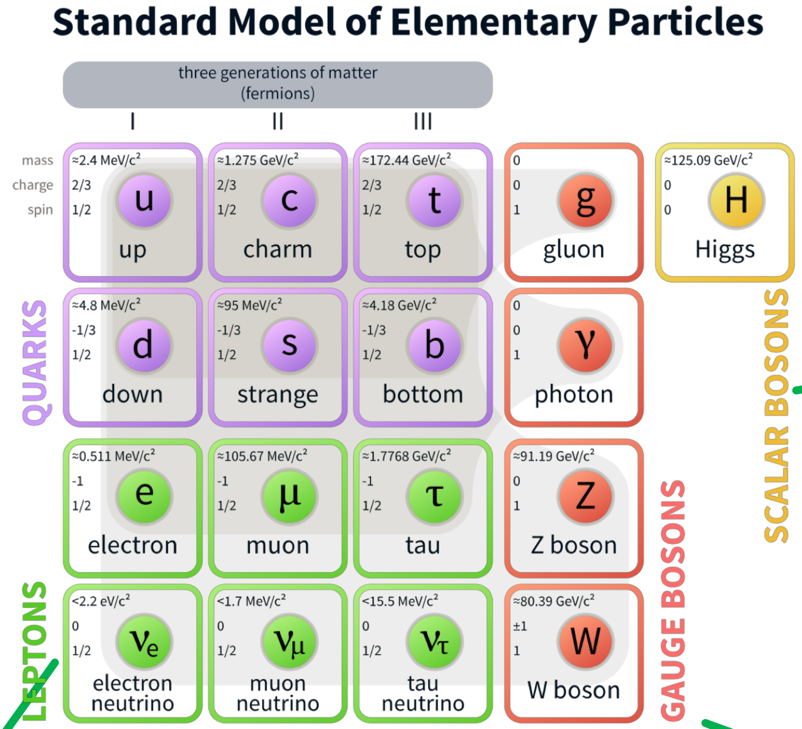
$t\to gu$	$t\to gc$	$t\to qZ$	$t\to\gamma u$	$t\to\gamma c$	$t\to Hq$
3.8×10^{-6}	3.2×10^{-5}	$2.4-5.8\times10^{-5}$	8.6×10^{-6}	7.4×10^{-5}	10^{-4}

Beyond Standard Model

- **What's the origin of Dark matter / energy ?**
- **What's the origin of baryon asymmetry in the universe?**
- **What's the origin of neutrino masses?**
- **What's the origin of EW symmetry breaking?**
- **What's the origin of the flavour structure of the SM?**
- **What's the solution to the hierarchy problem?**
- **..**

Everything is a BSM search in the end ....

Searching for new physics: what



Non minimal Higgs sector

- Exotics / Rare / Invisible decays
- Higgs as portal to DM
- Extended: Two-Higgs-Doublet-Models, MSSM, NMSSM and more
- Charged Scalars
- Composite Higgs

"Exotics": referred to a large variety of theories and models

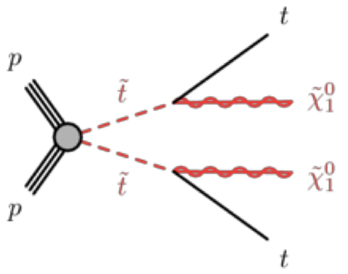
- Heavy vector bosons, vector-like quarks, excited quarks, non-SUSY Dark-Matter models, lepto-quarks, dark/hidden sectors and more
- **The unknown!**

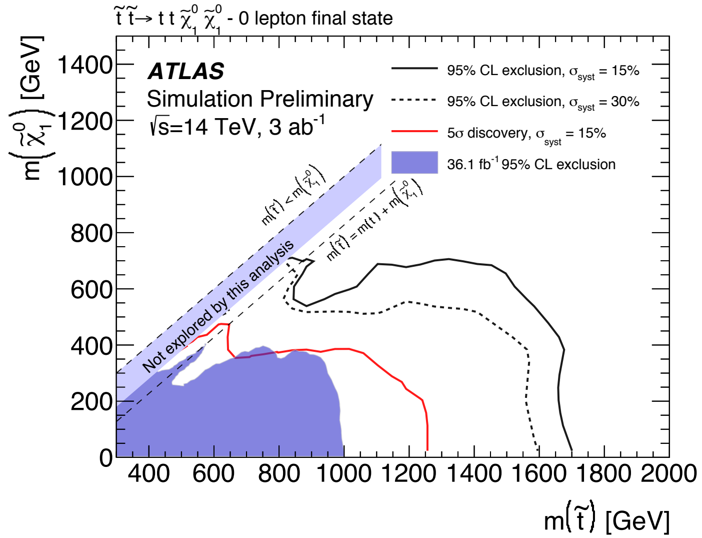
SUSY, SUSY-inspired

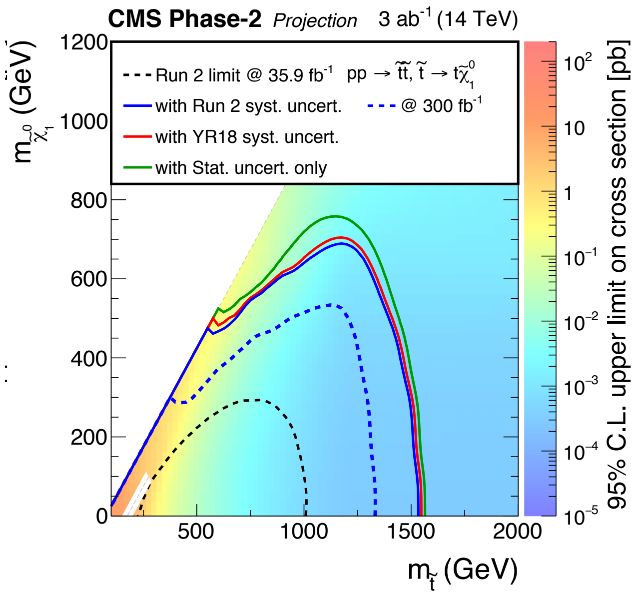
- many variants and kind (MSSM, NMSSM, R-parity conservation or violation..)
- mostly heavy super-partners, prompt or long-lived, several Higgs bosons

SUSY: strong production

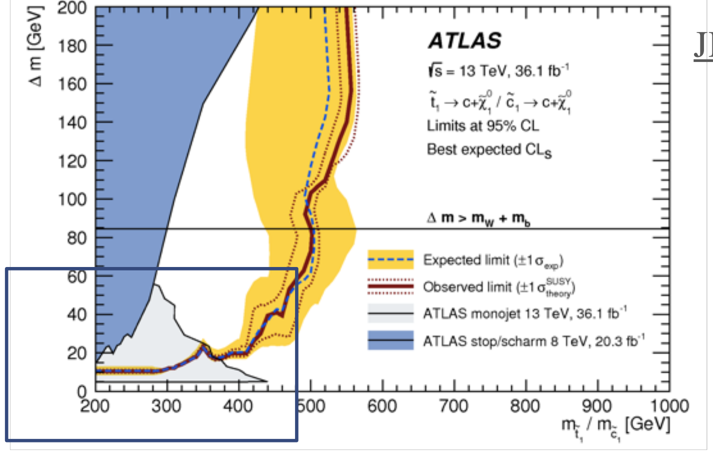
- **Top squarks** might have a prominent role for regularization of the higgs mass
  - Analyses for large and medium ΔM (stop, neutralino)







- Compressed scenarios, small $\Delta M = m_{stop} - m_{LSP}$:



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Good potential from analyses:
(1) monojet (ΔM ~ 2 – 10 GeV)
(2) soft leptons

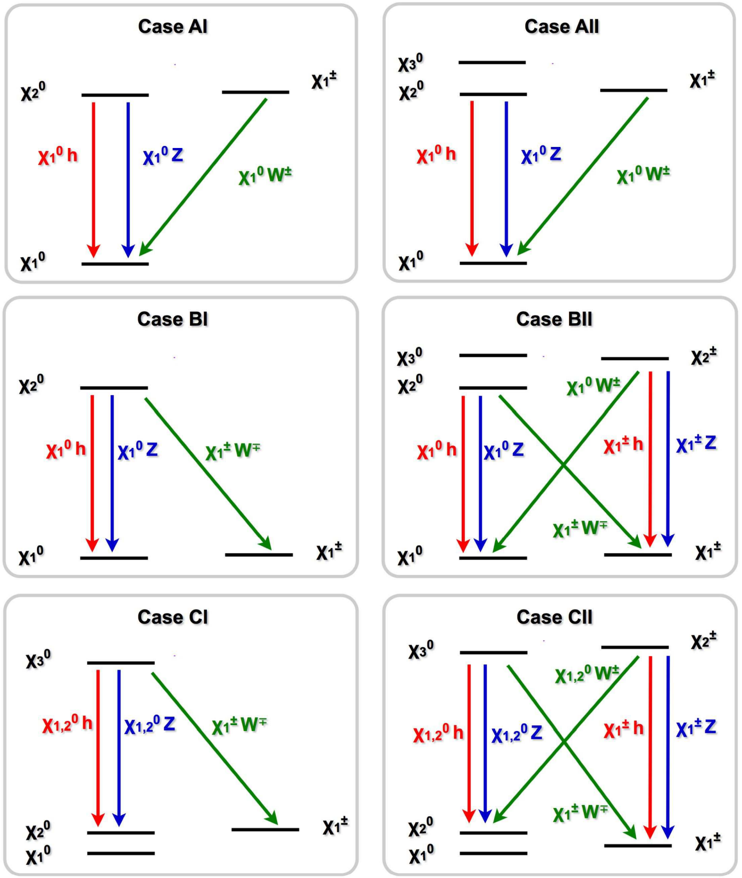
Projections with ColliderReachTool:
HL-LHC → 0.95 TeV;
[confirmed by theorists' studies]

→ Might be conservative: e.g. recoil-jet pt thresholds can be adjusted

In addition: Gluino masses will also be constrained up to >3 TeV (20-50% increase depending on model assumptions)

SUSY EWK production: Phenomenology

- Mass and hierarchy of the four neutralinos and the two charginos, as well as their production cross sections and decay modes, depend on the M_1, M_2, μ (bino, wino, higgsino) values and hierarchy
  - EWK phenomenology broadly driven by the LSP and Next-LSP nature
  - Examples of classifications (cf: arXiV: 1309.5966)



- **Scenario A:** $M_1 < M_2, |\mu|$

  Bino LSP

- **Scenario B:** $M_2 < M_1, |\mu|$

  Wino LSP

- **Scenario C:** $|\mu| < M_1, M_2$

  Higgsino LSP

Used as benchmarks:

- Bino LSP, wino-bino cross sections
  (1) Mass($\chi^{\pm}_1$) = Mass (χ^0_2)
  (2) $\chi^+_1\chi^-_1$ and $\chi^{\pm}_1\chi^0_2$ processes

$$\sigma_W(\chi^{\pm}_1\chi^0_2) \sim 2\,\sigma_W(\chi^+_1\chi^-_1)$$

- Higgsino-LSP, higgsino-like cross sections
  (1) Small mass splitting $\chi^0_1, \chi^{\pm}_1, \chi^0_2$
  (2) Consider triplets for cross sections
  (3) Role of high-multiplicity neutralinos and charginos also relevant

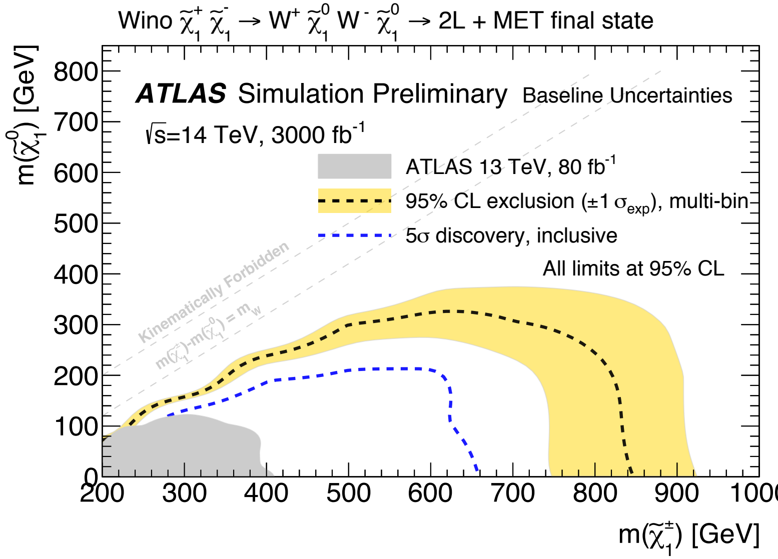
$$\sigma_H(\chi^{\pm}_1\chi^0_2 + \chi^+_1\chi^-_1 + \chi^{\pm}_1\chi^0_1) < 0.7\,\sigma_W(\chi^{\pm}_1\chi^0_2)$$

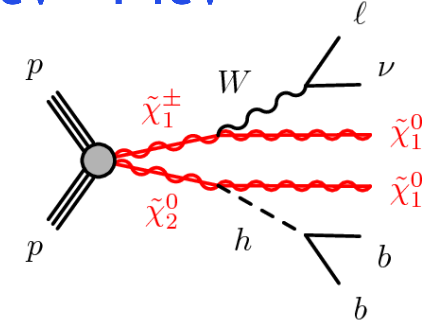
[depending on masses!]

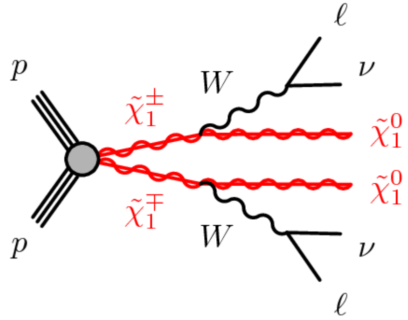
Charginos and neutralinos

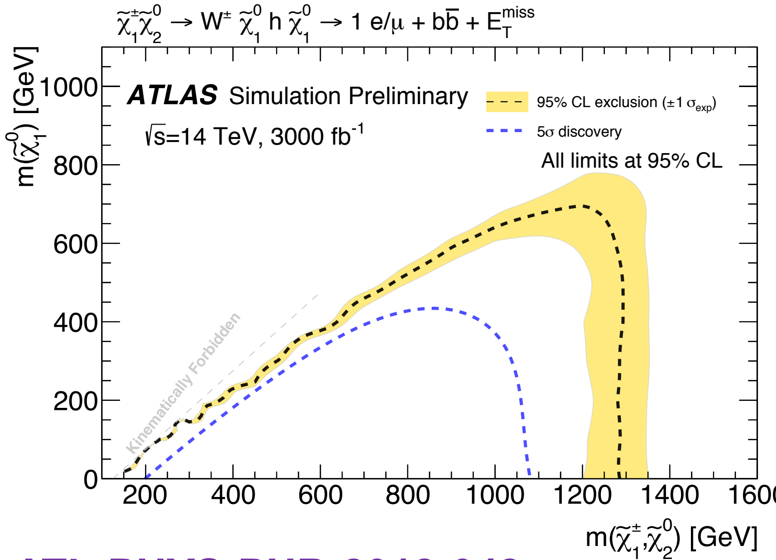
➨ The sensitivity to EW states will extend considerably at the HL-LHC

Wino-like cross section: Reach above 800 GeV - 1 TeV









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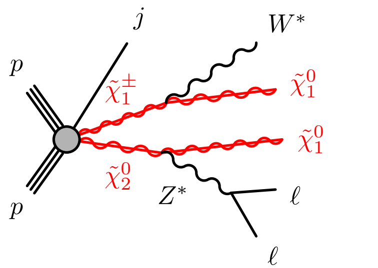
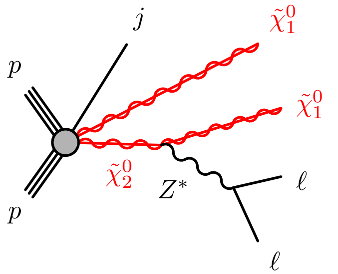
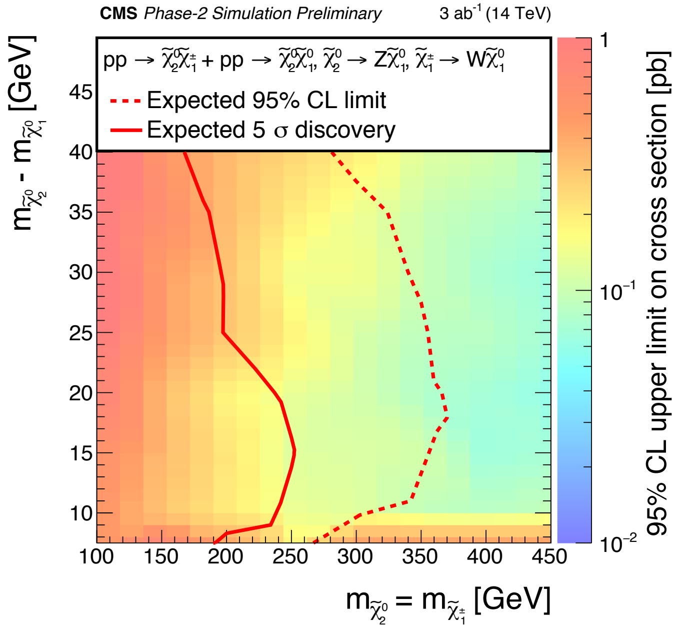
Higgsino-like compressed scenarios: challenging but not impossible

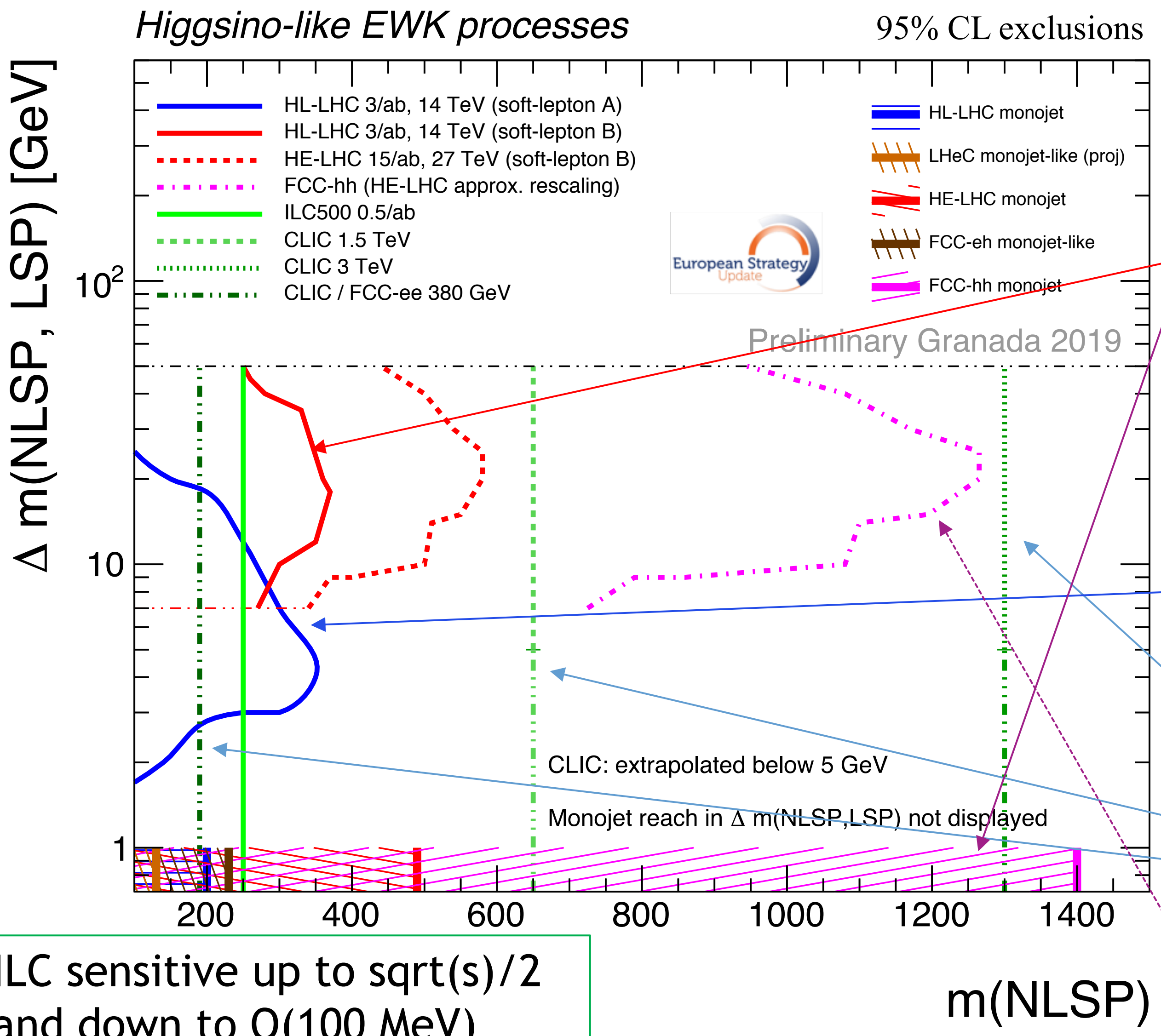






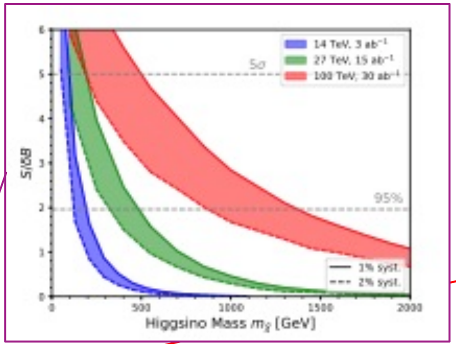
Complementarities!

MD Granada '19

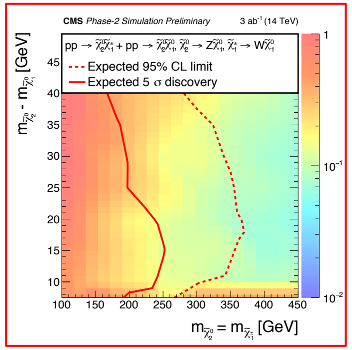


ILC sensitive up to sqrt(s)/2 and down to O(100 MeV)

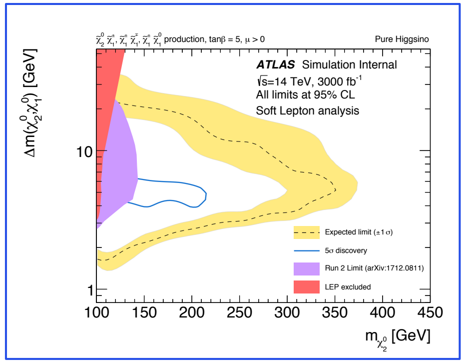
Monojets (HL/HE/FCC-hh/LHeC/FCC-eh)



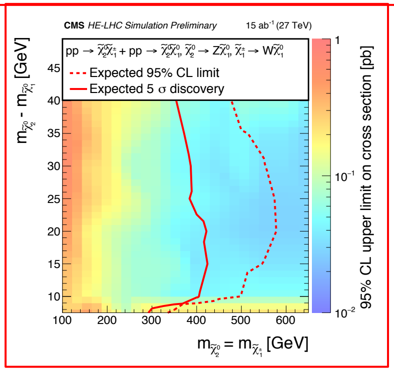
HL-LHC soft lepton analysis CMS

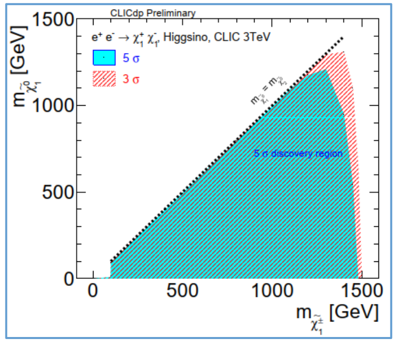


HL-LHC soft lepton analysis ATLAS



HE-LHC soft lepton analysis





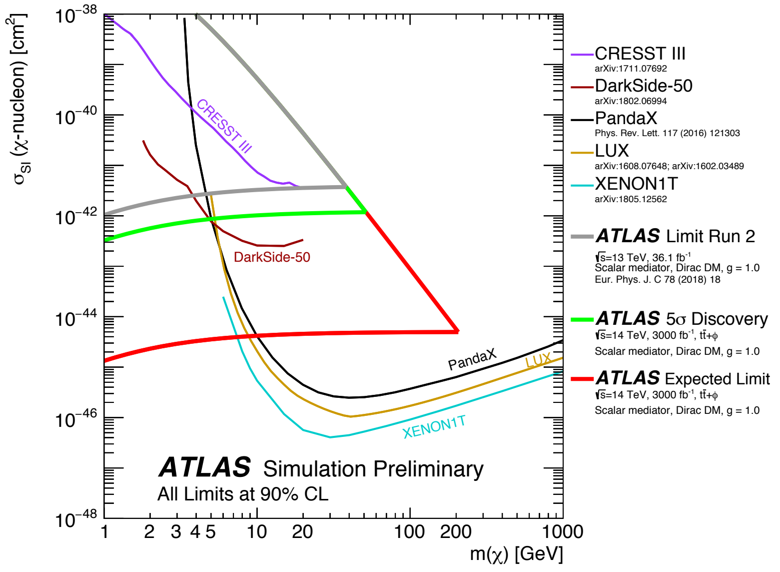
CLIC 3 TeV, results rescaled also for CLIC1.5, CLIC380, FCC-ee **(tbc)**

Indicative partonic rescaling of HE for FCC-hh soft-lepton

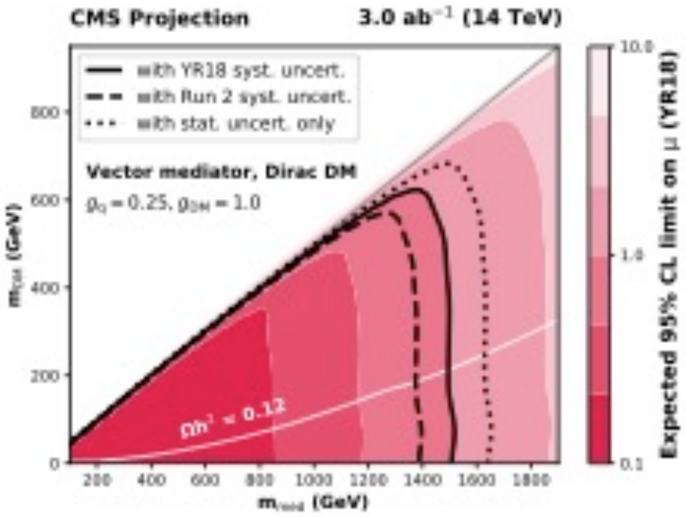
Direct searches for new physics: Dark Matter

- Several searches for **DM candidates**, SUSY-like and beyond
- Mono-X searches reach sensitivity 2-8 times better than Run 2
- Good complementarity ATLAS – CMS, with various scenarios covered
  - Monojet, MET+HF, monotop, monophoton and VBF prospects (ATLAS)
  - Mono-Z - CMS
    - Also complementary with 4-top 2HDM-a model studies

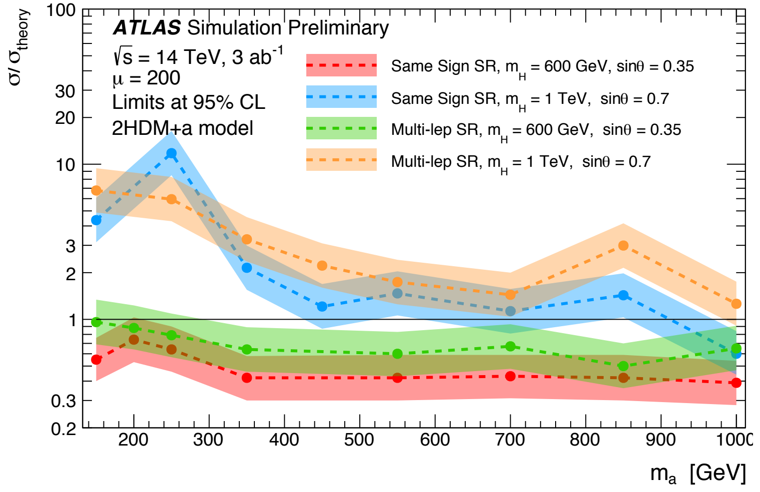
DM + top/bottom quarks

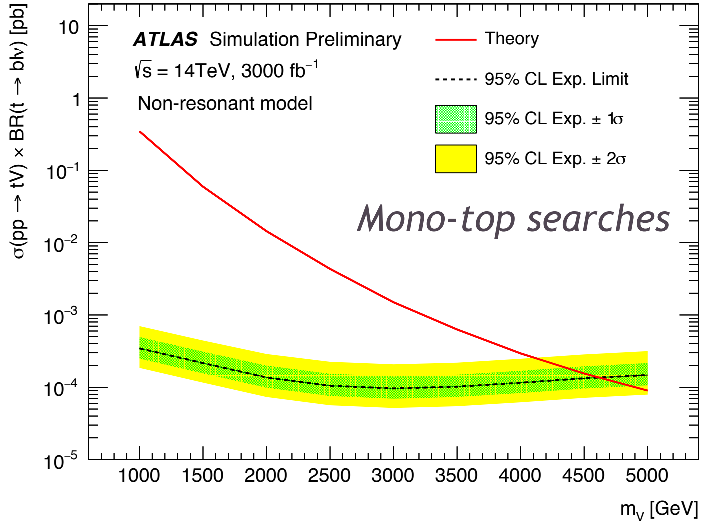


Mono-Z searches



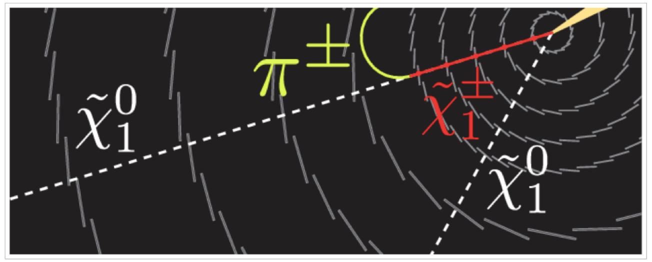
4top searches

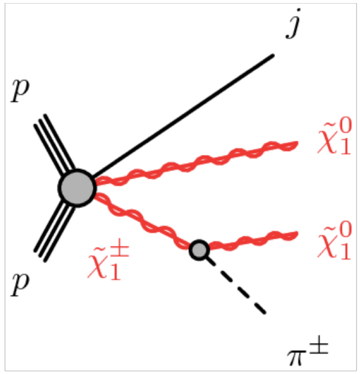


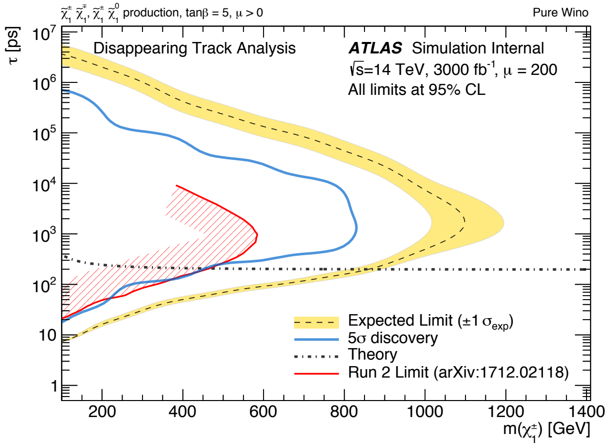


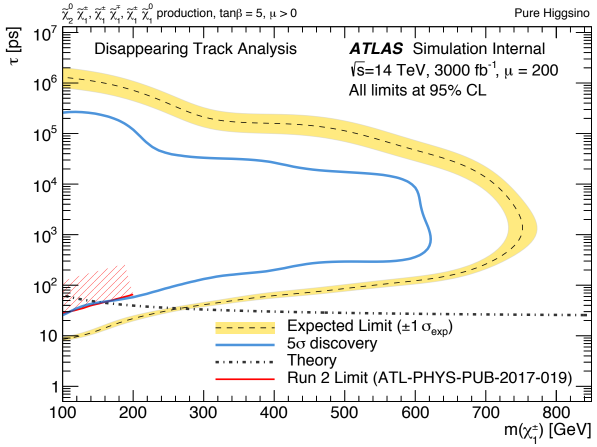
Non-prompt signatures and DM

- Disappearing track analyses are quite relevant for DM WIMPs searches

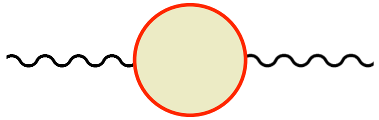


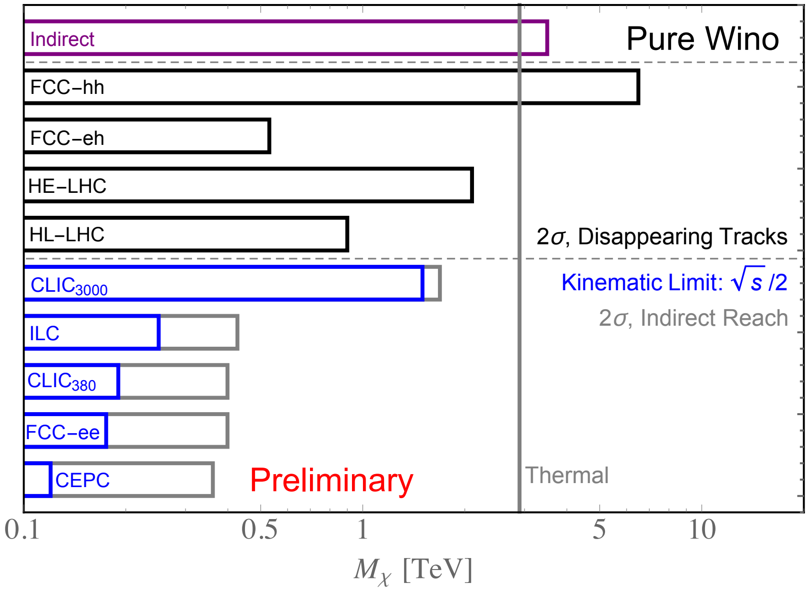


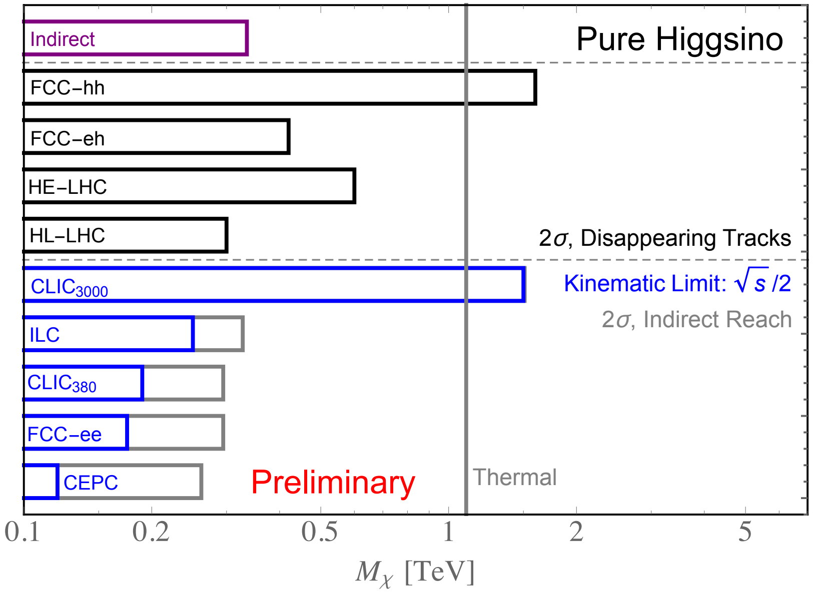




EWKinos in loop change prop
(W, Y parameters)







M. McCullough Granada '19

Long-lived particles

- Various feebly interacting particle cases studied for HL-LHC
- Examples: displaced muons, lepton-jets – e.g. targeting dark photons

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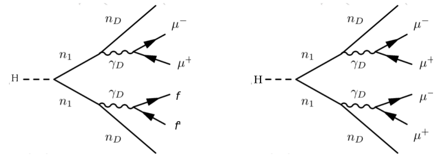
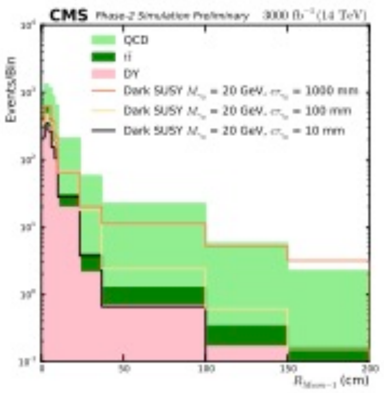
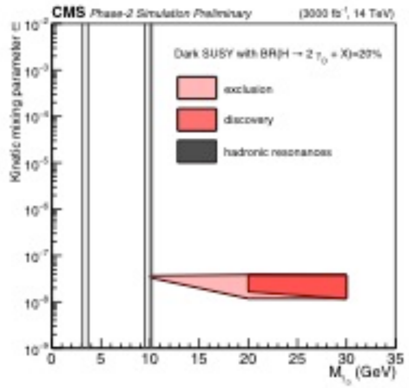
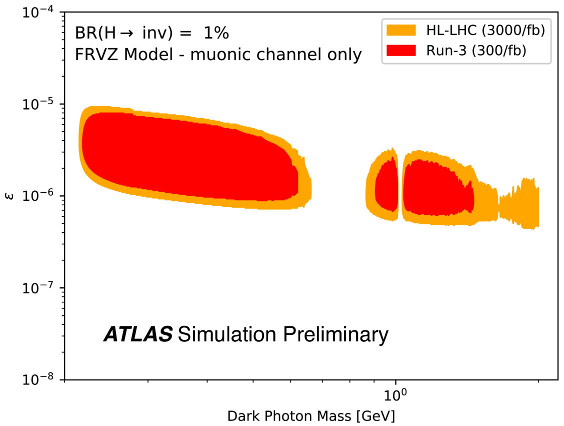
Lepton-jets

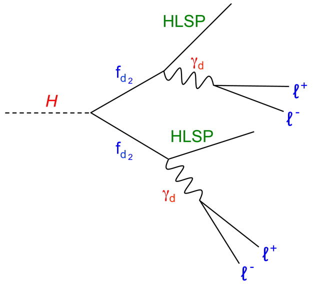


CMS displaced-muon

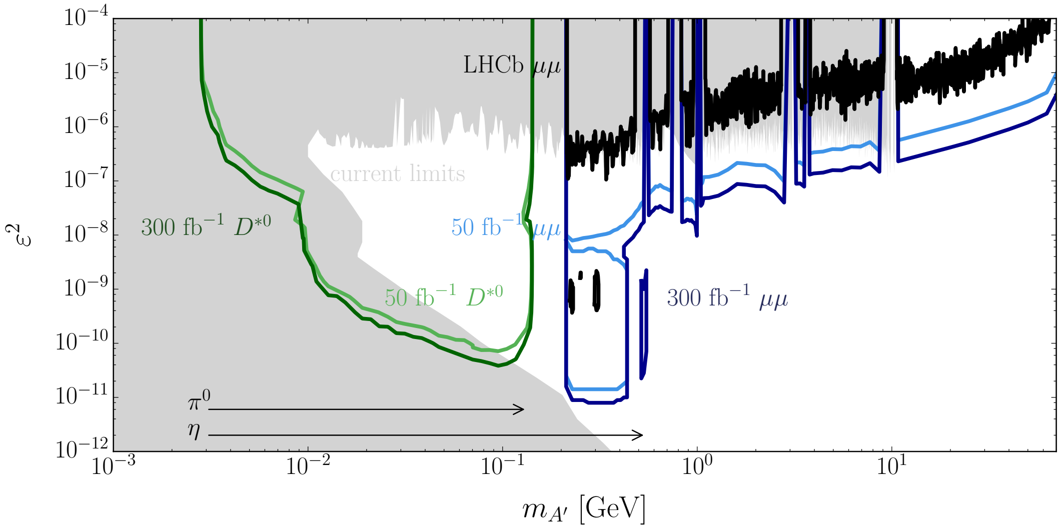




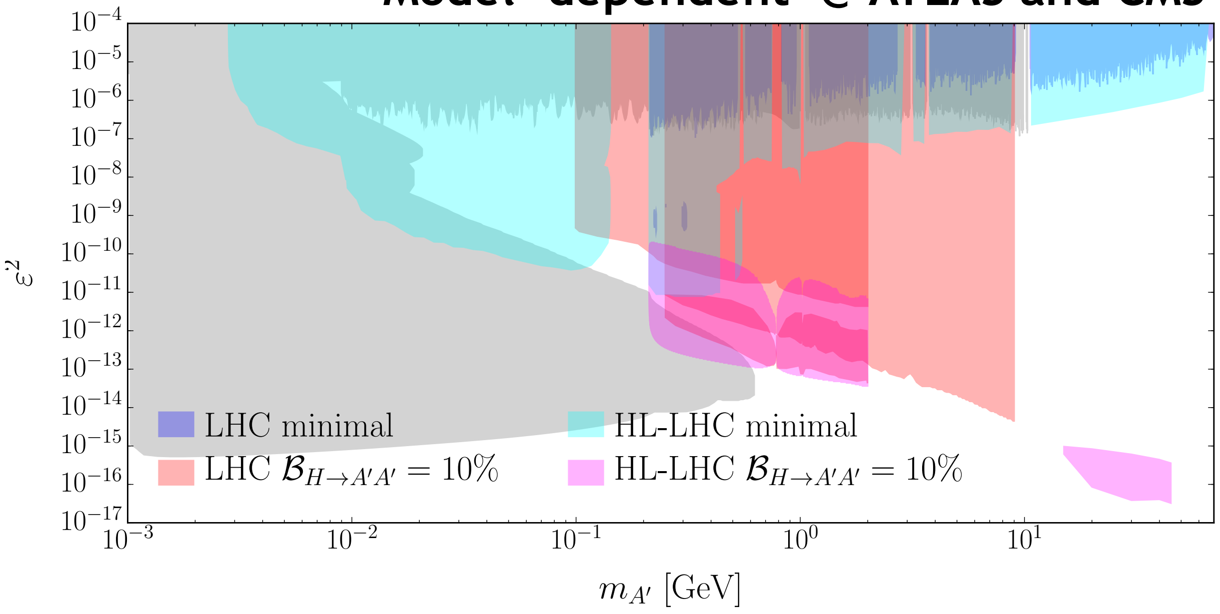




Model 'independent' results from LHCb



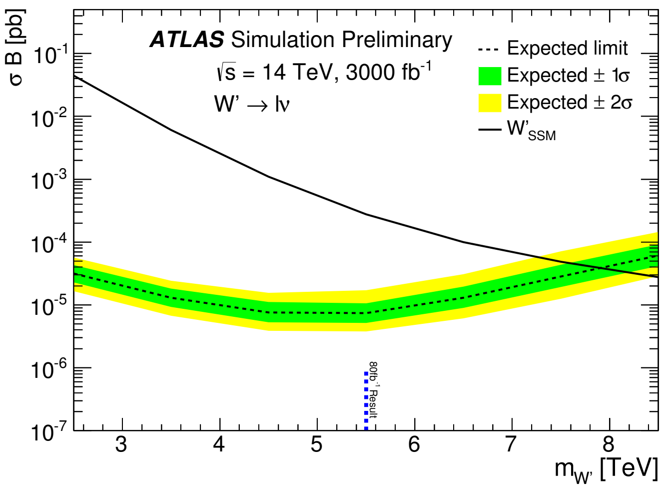
Model 'dependent' @ ATLAS and CMS



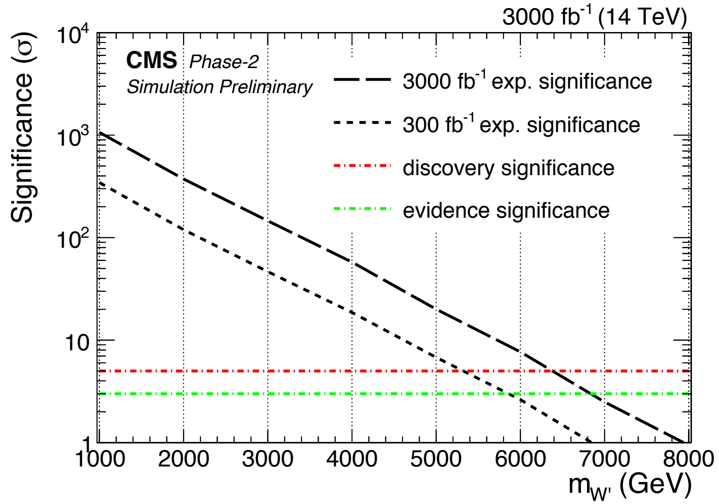
Direct searches for new physics: Resonances

- Searches for Z' and W' have been performed in a variety of final states

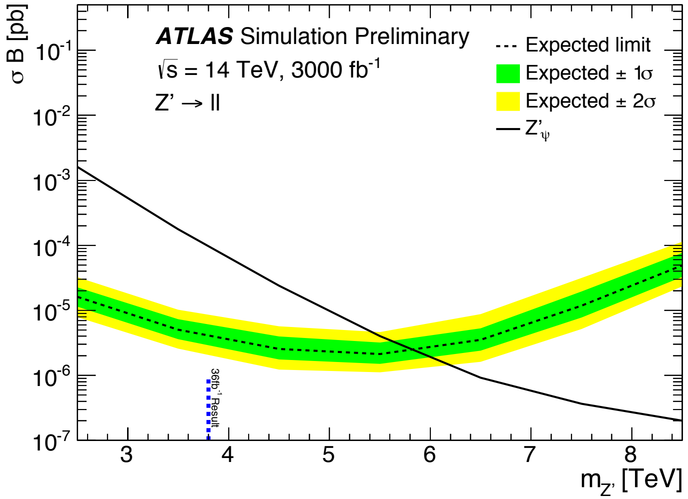
W' mass reach improves by more than 2 TeV w.r.t. the Run 2, by **more than 1TeV w.r.t. 300 fb^{-1}**



Decay	Exclusion [TeV]	Discovery [TeV]
$W'_{\mathrm{SSM}} \to e\nu$	7.6	7.5
$W'_{\mathrm{SSM}} \to \mu\nu$	7.3	7.1
$W'_{\mathrm{SSM}} \to \ell\nu$	7.9	7.7



For Z'_{SSM} and Z'_{ψ} in dilepton final states, exclusion (discovery) is up to masses of **6.5TeV (6.4TeV) and 5.8 TeV (5.7 TeV)**



good complementarity and agreement for top-like final states

Indirect constraints from interference effects modifying DY also very powerful (see back-up)

Flavor physics: a wide program relevant for NP

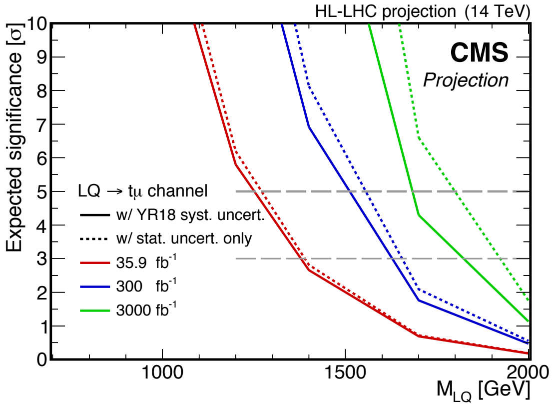
- There is a wide program of studies with progressive improvements which provides also a window for NP
  - **“High pT” flavor physics**
  - CKM unitarity and related observables
  - Charm-quark probes for NP
  - Strange-quark probes for NP
  - Tau leptons and LFV
  - Hadron spectroscopy
  - Bottom probes and B-anomalies

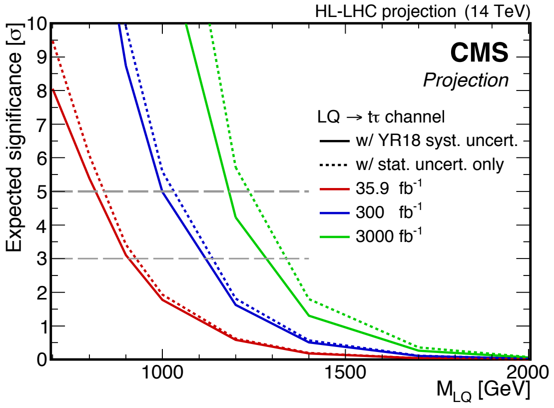
[more in Heavy Flavour talk]

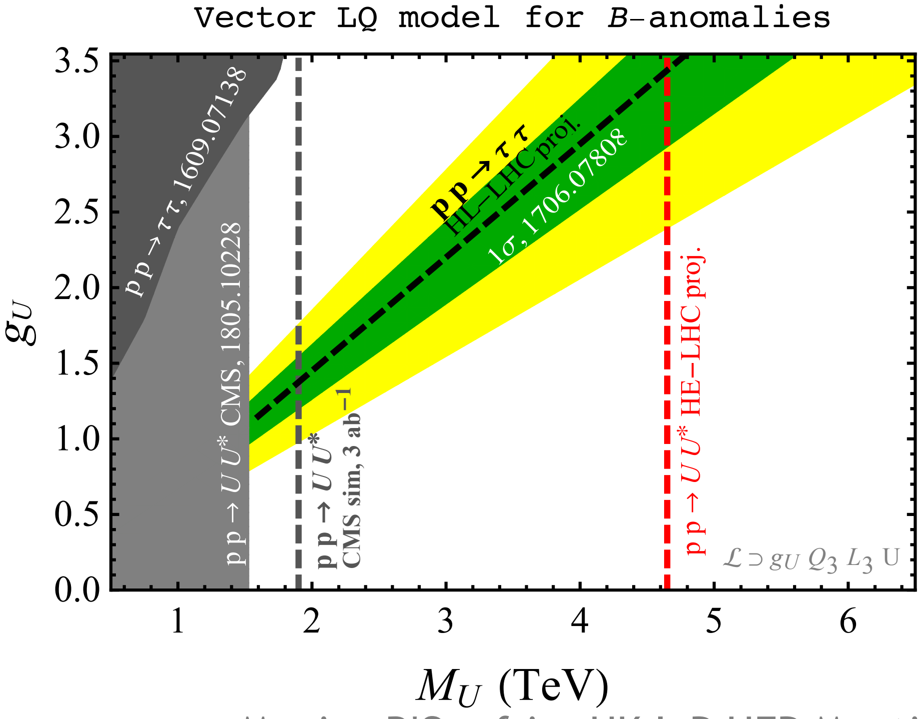
Observable	Current LHCb	LHCb 2025	Upgrade II
EW Penguins			
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [5]	0.025	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [6]	0.031	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	0.02, 0.02, 0.05
CKM tests			
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [7]	4°	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [8]	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [9]	0.011	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [10]	14 mrad	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [11]	35 mrad	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [12]	39 mrad	11 mrad
a_{sl}^s	33×10^{-4} [13]	10×10^{-4}	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [14]	3%	1%
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$			
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [15]	34%	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [15]	8%	2%
$S_{\mu\mu}$	–	–	0.2
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**			
$R(D^*)$	0.026 [16, 17]	0.0072	0.002
$R(J/\psi)$	0.24 [18]	0.071	0.02
Charm			
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [19]	1.7×10^{-4}	3.0×10^{-5}
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [20]	4.3×10^{-5}	1.0×10^{-5}
$x\sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [21]	3.2×10^{-4}	8.0×10^{-5}
$x\sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K3\pi)$ 8.0×10^{-6}

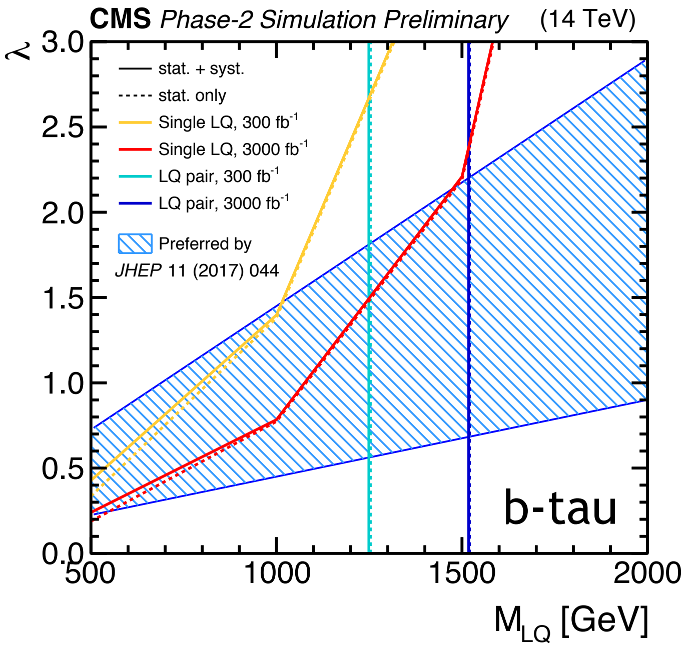
High-pT flavour-related studies

- High p_T searches for possible motivation of flavour anomalies:
  - Test of Z’ and lepto-quark models which could explain them
- Searches for LQ:
  - b+tau projections
  - top+tau/mu projections
  - Results can be interpreted in terms of scalar/vector LQ



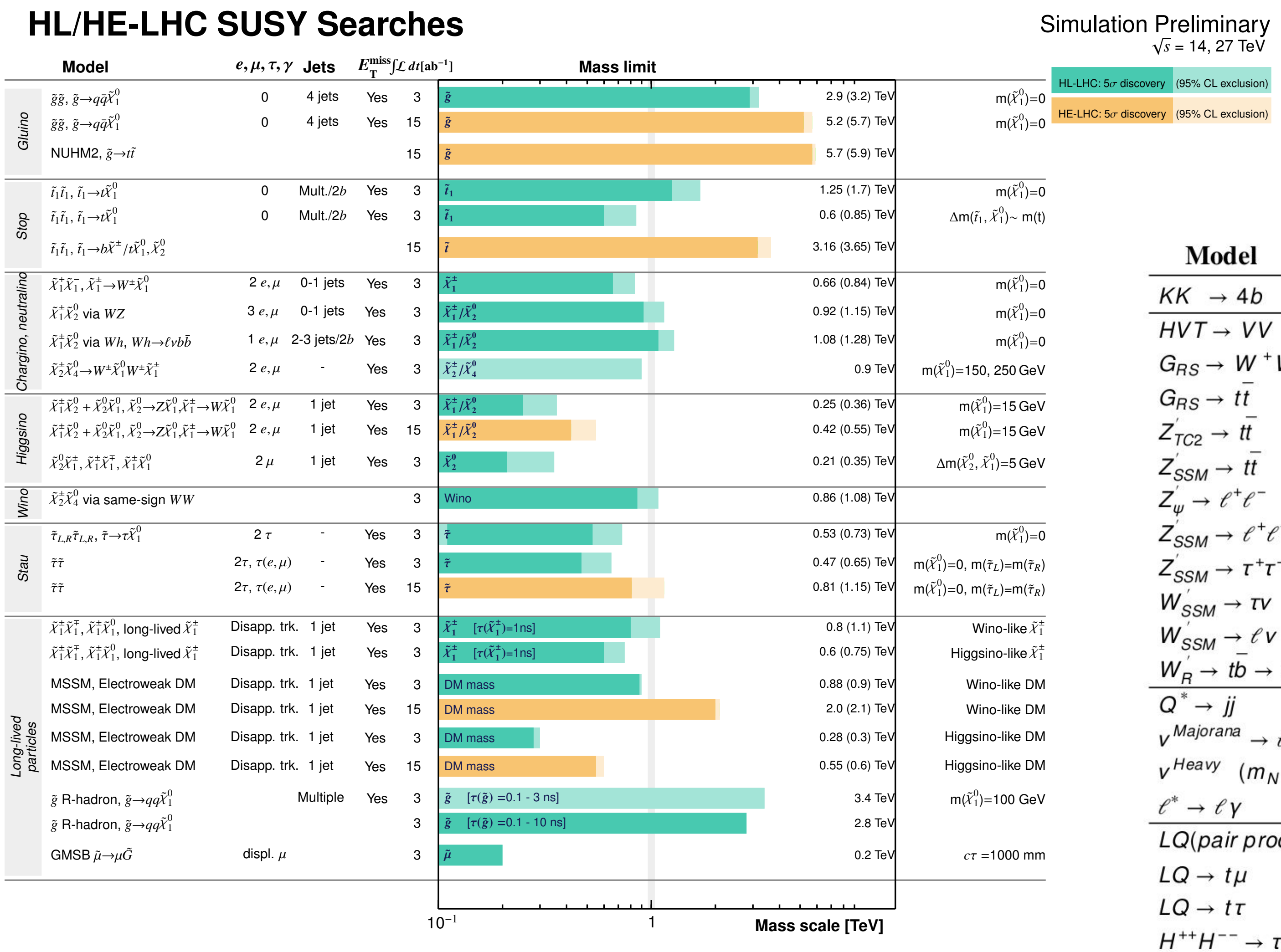


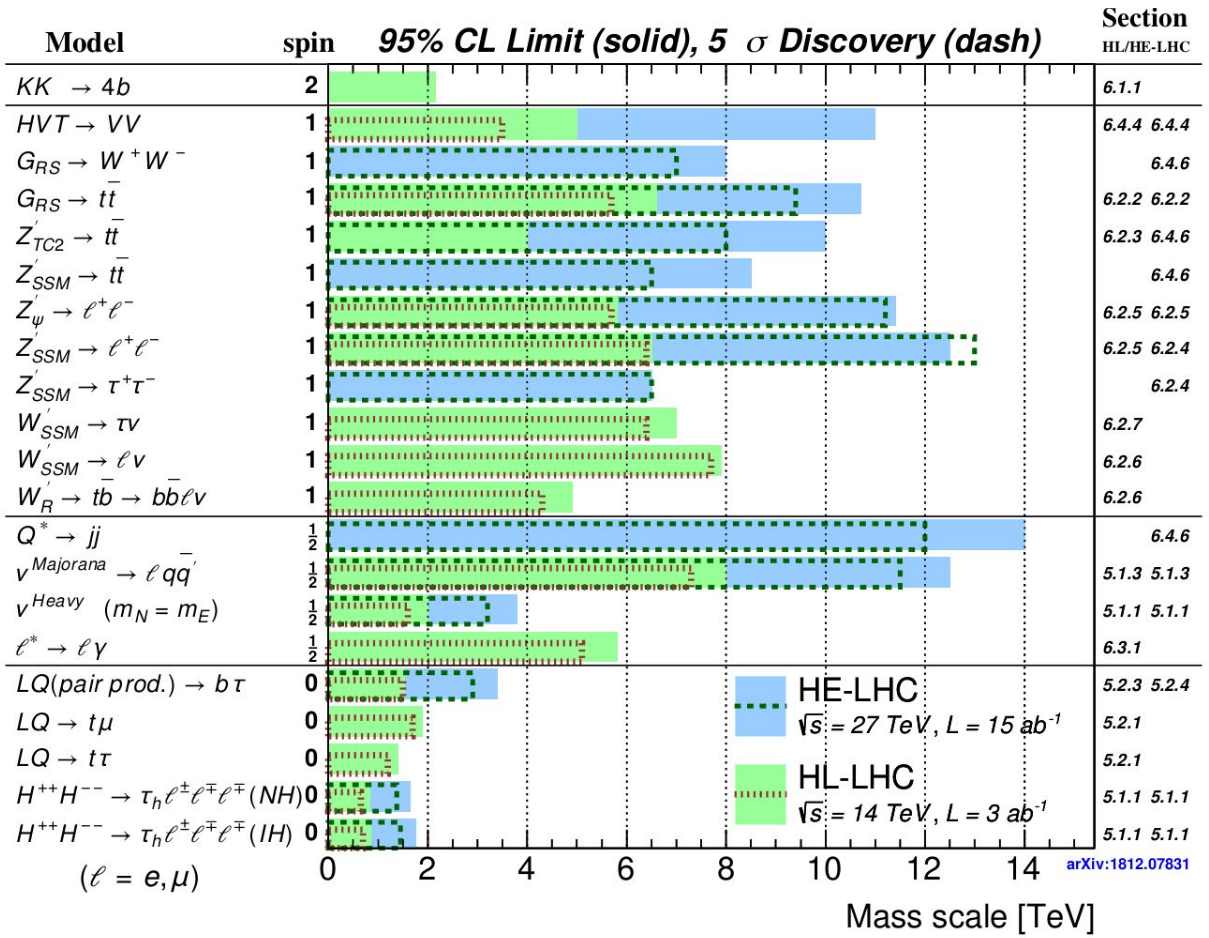




Room for improvements

BSM summary plots





Conclusions

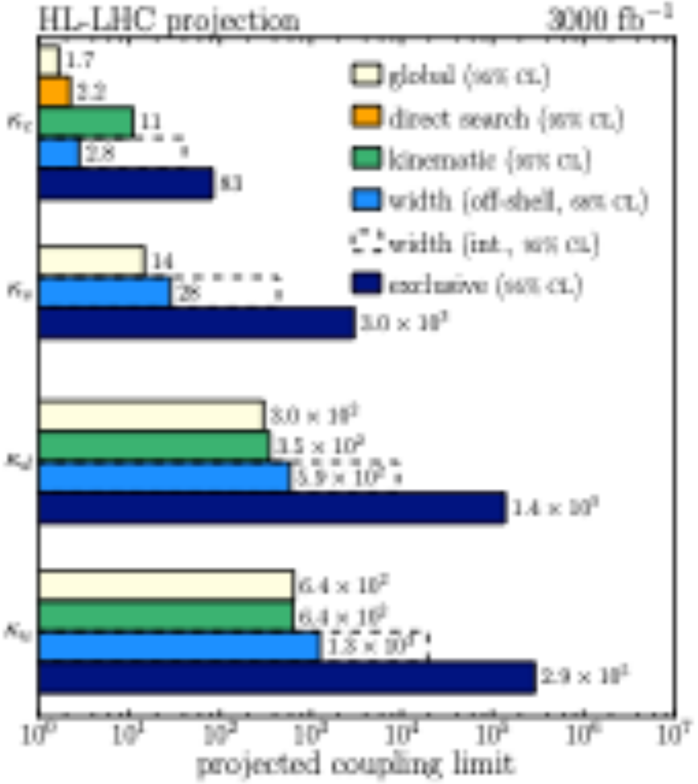
- Run 2 results are being released using the full data-set: very high precision SM measurements, access to rare processes, wide programme of searches, and much more to be investigated!
- The Run-3 and Run-4 (HL-LHC) upgrades are well on-track
- Preparation for HL-LHC in terms of physics programme has seen a big boost in the past ~2 years in view of the European Strategy. Five documents have been delivered on SM, Higgs, BSM, Flavor physics and Heavy Ions for a total of +1K pages plus two short summaries.
- Overall a very strong programme for the HL-LHC:
  - Impressive potential in the higgs sector for properties and BSM prospects [CMS-ATLAS combined]
  - Impressive expectations for di-higgs production using bb+X modes [CMS-ATLAS combined]
  - Possibilities to discover new particles, i.e. in the EWK SUSY sector, and/or at high mass
  - Precision SM measurements that allow reduction of uncertainties and provide indirect probe to searches for NP
  - interesting studies possible in the context of Heavy Ion and forward physics (some in back-up)
- Now, let's build the new detectors (while waiting to see what comes next…)

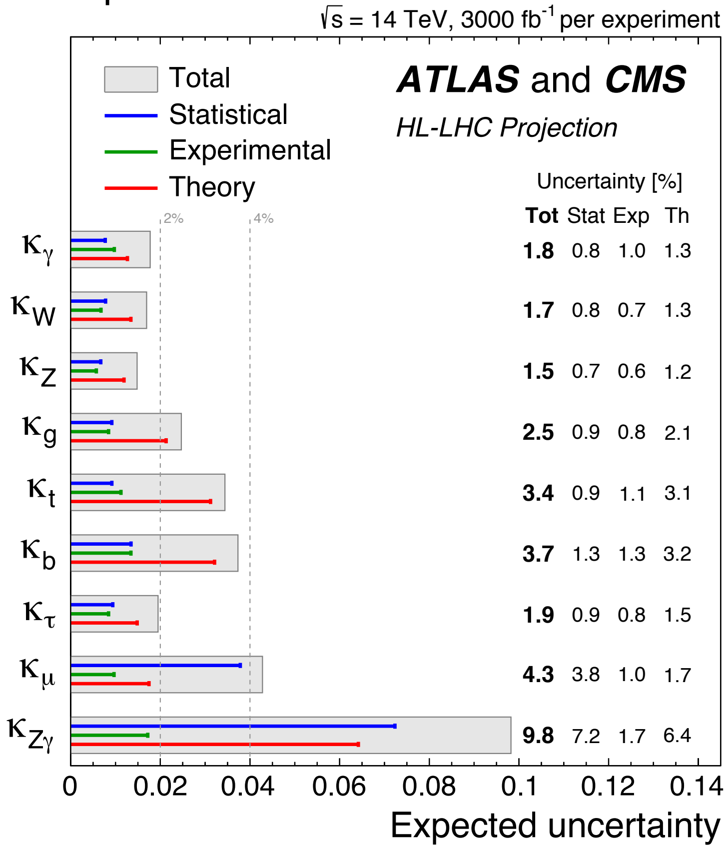
Back up

Higgs physics: properties

- The exploration of the Higgs sector includes precision measurements, as well as searches for rare production and decay processes:
  - All production modes/decays including rare ones such as **h → $\mu^+\mu^-$ and h → Zγ will be observable** at HL
  - Rate measurements show that **percent level precision can be reached for most couplings**
  - With minimal assumptions, the **total width Γ_H will be constrained with a 5%** precision and an upper limit on the **Higgs invisible BR of 2.5%** will be reached.

κ_i : coupling strength modified parameters

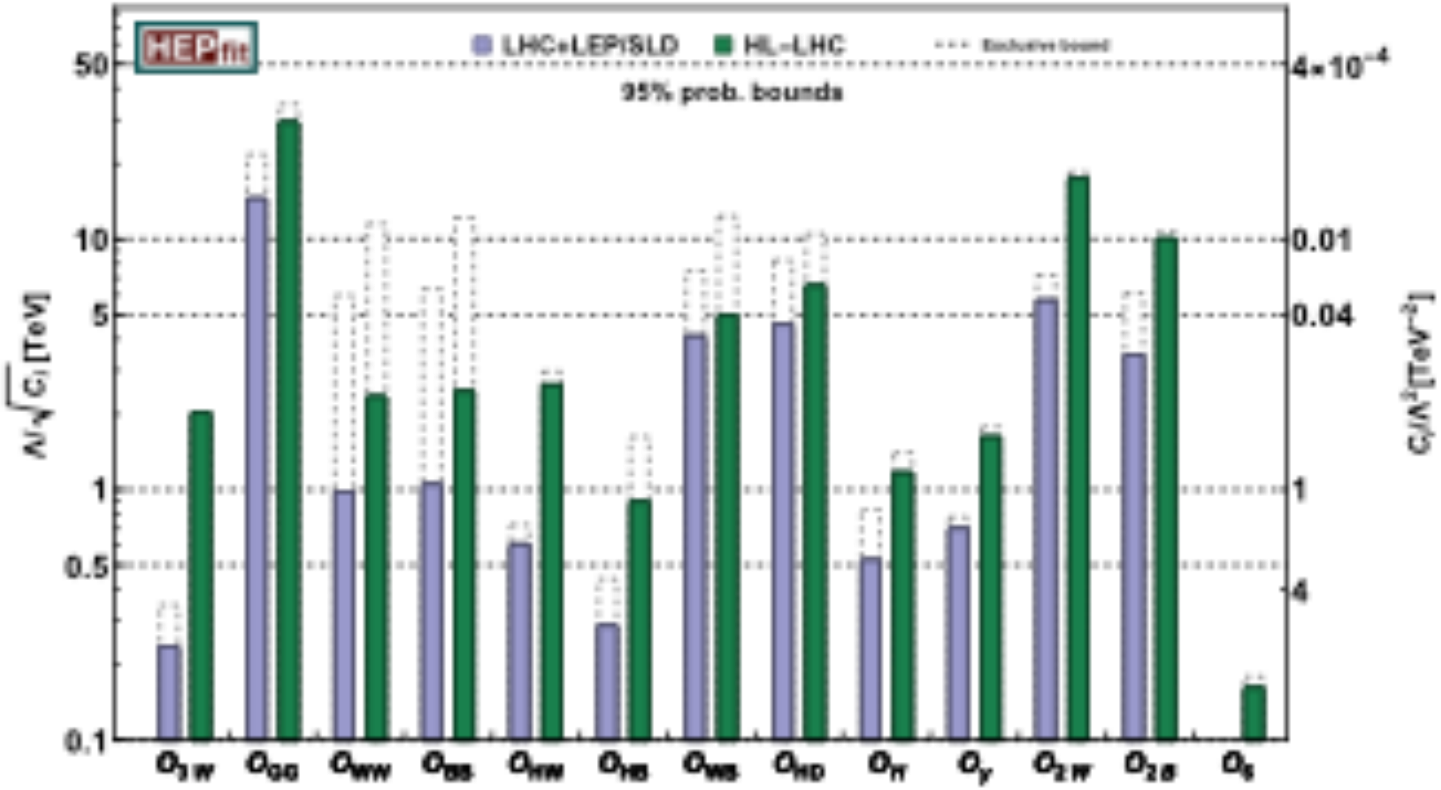




Higgs physics: Effective Field Theory

Global fit to observables in Higgs physics, diboson and DY

- The EFT framework, where the SM Lagrangian is supplemented with dimension-6 operators, allows to systematically parametrise BSM effects
- E.g.. Constraints translate into a sensitivity to the **Higgs compositeness scale f > 1.6 TeV**, corresponding to a new physics mass scale of **20 TeV** for an underlying strongly coupled theory

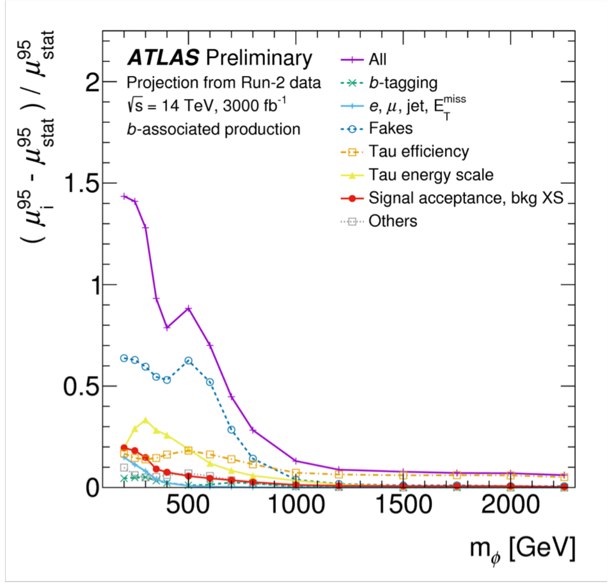


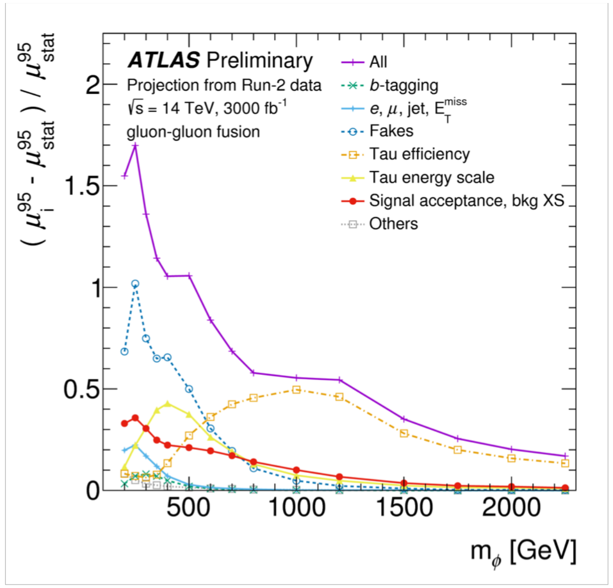
Higgs physics: BSM

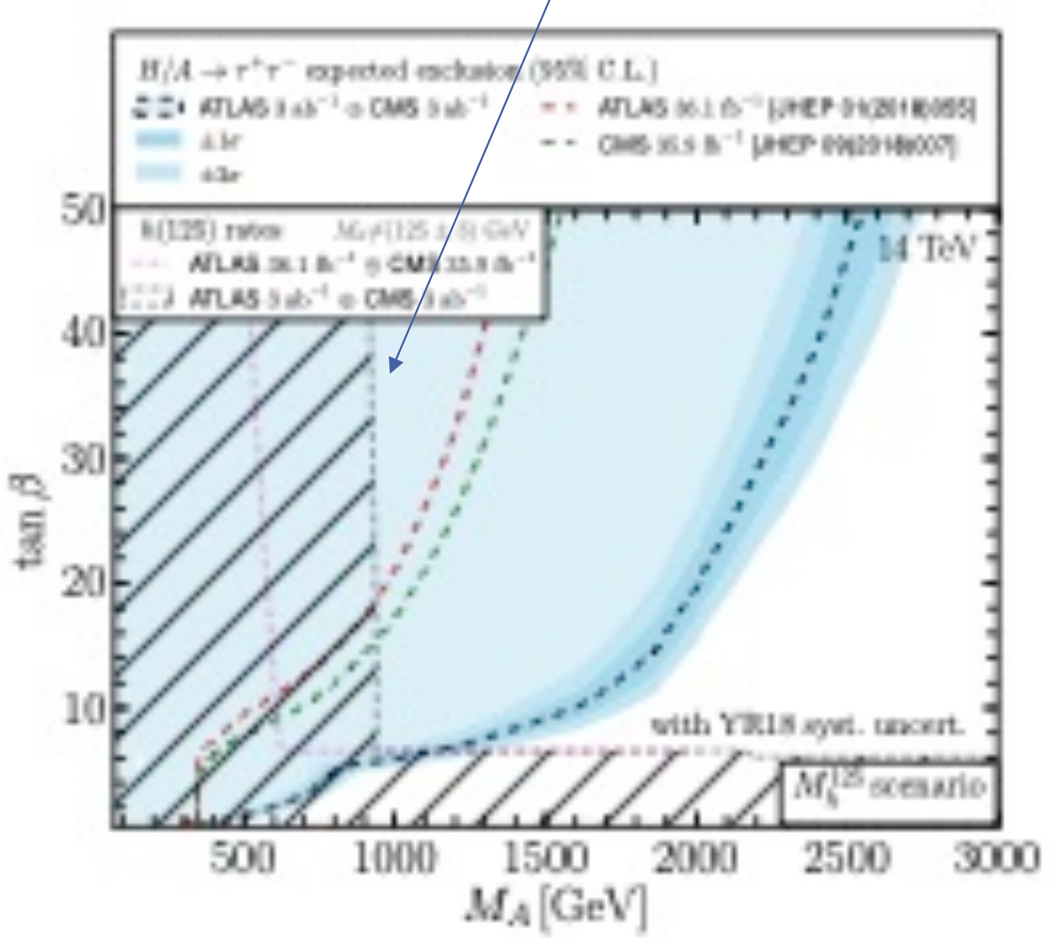
HL-LHC will enhance the sensitivity to BSM physics. For example:

Expected bound coming from Higgs precision coupling measurements

H/A → ττ (in ggF and b-associated production)







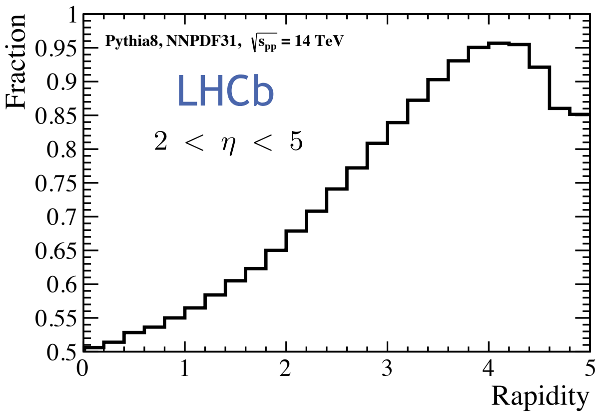
τ_{had} **and** τ_{lep}

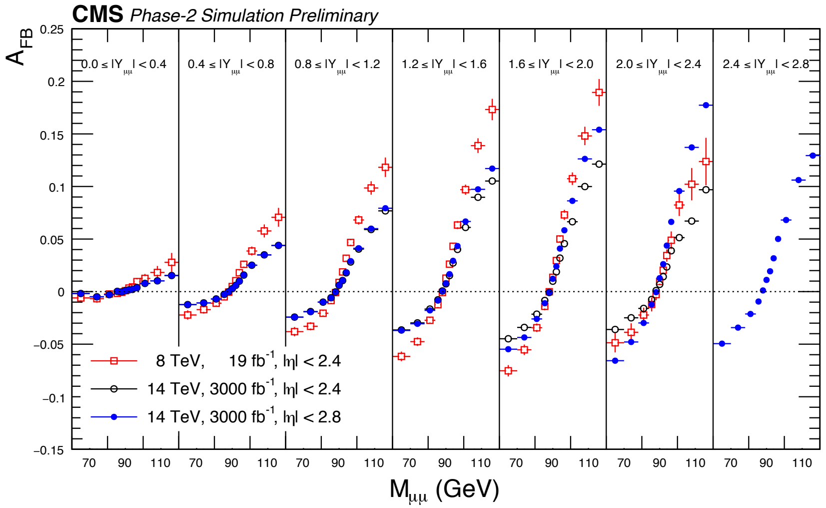
tau ID efficiency and careful assessment of systematics are fundamental

access to new Higgs bosons as heavy as 2.5 TeV for tan β > 50

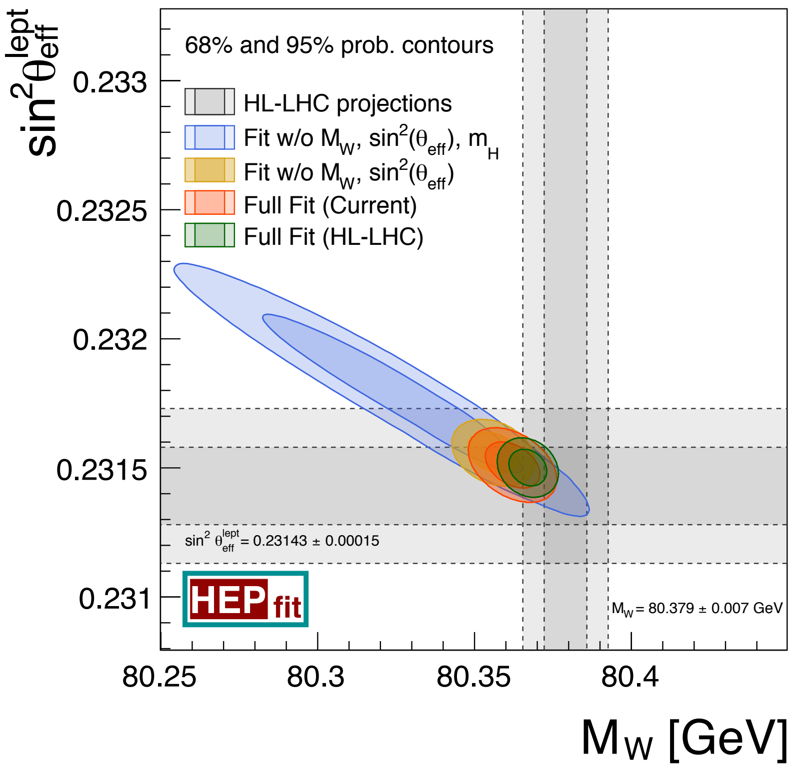
Weak mixing angle

- Prospects for the measurement of the effective weak mixing angle using the forward-backward asymmetry, A_{FB}, in Drell-Yan di-lepton events. LHCb data used for high rapidity coverage





EW global fits

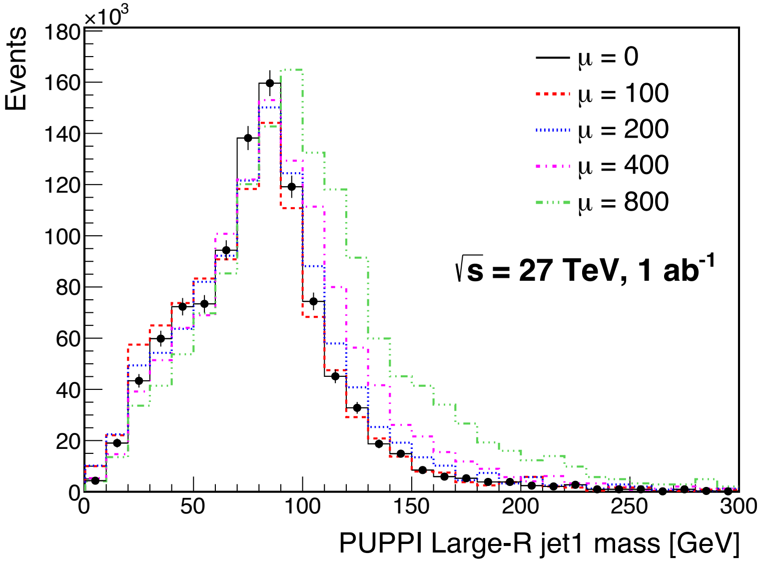


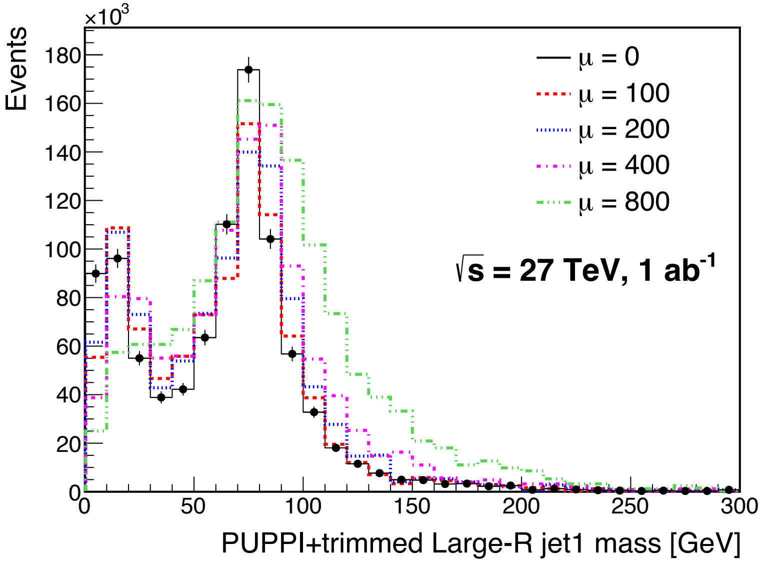
	ATLAS $\sqrt{s} = 8$ TeV	ATLAS $\sqrt{s} = 14$ TeV	ATLAS $\sqrt{s} = 14$ TeV
$\mathcal{L}$ [fb^{-1}]	20	3000	3000
PDF set	MMHT14	CT14	PDF4LHC15$_{HL-LHC}$
$\sin^2\theta^{lept}_{eff}$ [$\times 10^{-5}$]	23140	23153	23153
Stat.	$\pm$ 21	$\pm$ 4	$\pm$ 4
PDFs	$\pm$ 24	$\pm$ 16	$\pm$ 13
Experimental Syst.	$\pm$ 9	$\pm$ 8	$\pm$ 6
Other Syst.	$\pm$ 13	-	-
Total	$\pm$ 36	$\pm$ 18	$\pm$ 15

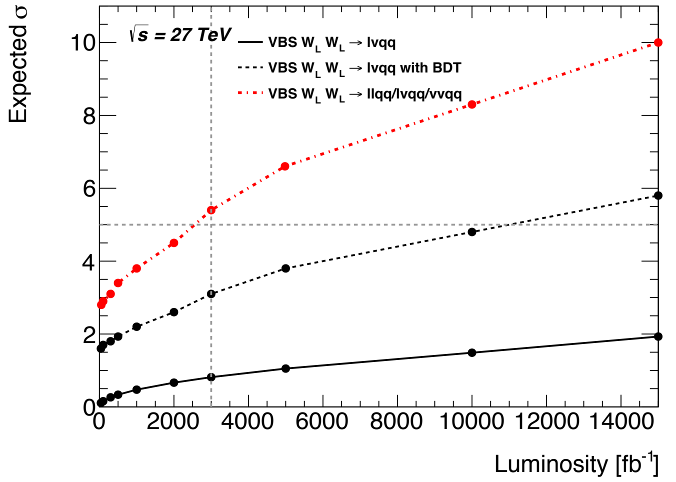
- Precision better than $5 \cdot 10^{-5}$ for $\sin^2\theta_{eff}$ → **$1 \cdot 10^{-5}$ if PDF unc. are improved with LHeC**

WW/WZ at HE-LHC

- HE-LHC will certainly improve high-p_T measurements
- However, the experimental environment is expected to be challenging at the HE-LHC
  - assess the performance of pile-up mitigation technique at the HE-LHC in order to have a reliable estimate of the search sensitivity [reminder, pile-up @ HE is ~ 800!]



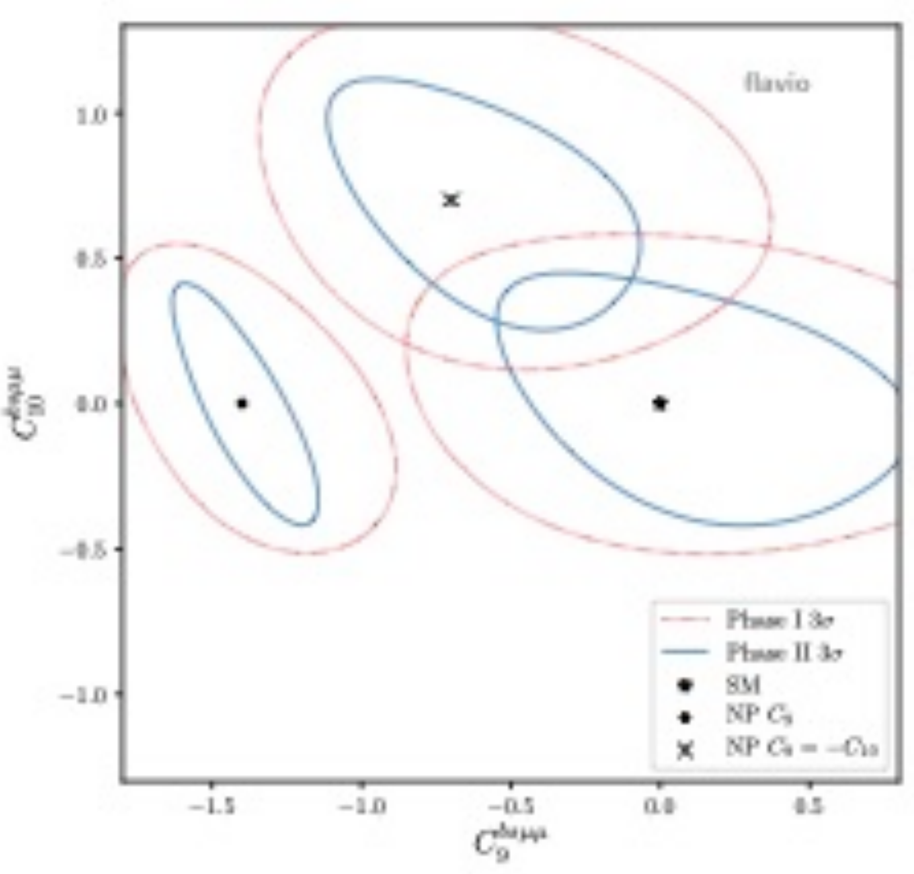




Possibility of using reliable techniques to identify W/Z boson improve the expected significance for VBS W_LW_L analyses

A way to quantify this: global fits

- global significance of the tensions can be defined in a specific framework of NP
  - Sensitivity to Wilson-Coefficient C_9 and C_{10}
  - illustrating scenarios with modifications of just C_9 (vector current) and of both $C_9 = -C_{10}$ (pure left-handed current).
  - Use $B_S \rightarrow \mu\mu$ and the angular observables from the decay $B_0 \rightarrow K*_0\mu^+\mu^-$ in the low-q^2 region (e.g. P'_5).



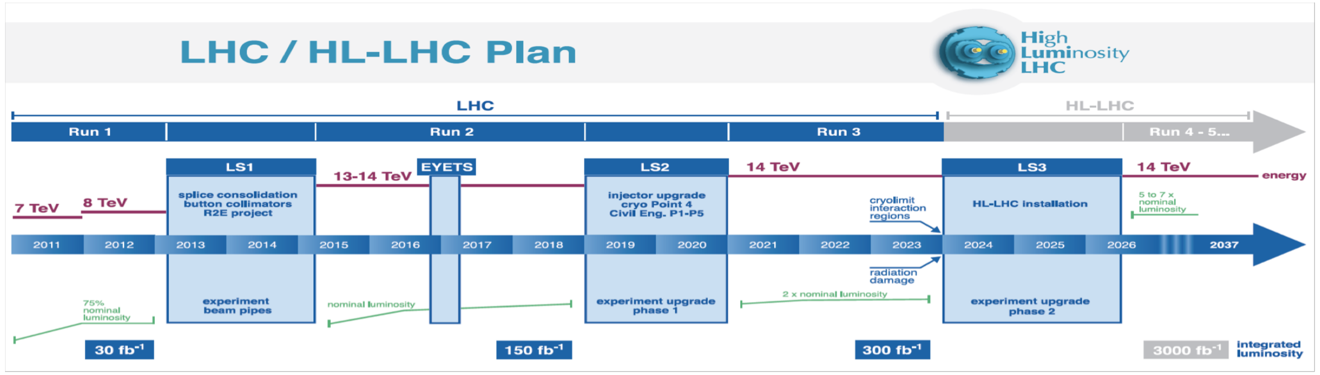
Reach for generic new physics at tree-level is found to exceed 100 TeV

Foreword

Common assumptions:

- **HL-LHC:** 3/ab @ 14 TeV c.o.m. with <μ>=200
  - **For LHCb:** luminosity of 50/fb and 300/fb assumed for Phase1b and 2 upgrades
- **HE-LHC:** 15/ab @ 27 TeV c.o.m. (<μ>=800)

NOTE: results for BSM searches and SM measurements often refer to a **single experiment**
BUT: Statistical combinations in case of **Higgs** studies



Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] [e^-/e^+]	N(Det.)	$\mathscr{L}_{inst}$ [10^{34}] cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]
HL-LHC	pp	14 TeV	-	2	5	6.0	12
HE-LHC	pp	27 TeV	-	2	16	15.0	20
FCC-hh	pp	100 TeV	-	2	30	30.0	25
FCC-ee	ee	M_Z	0/0	2	100/200	150	4
		$2M_W$	0/0	2	25	10	1-2
		240 GeV	0/0	2	7	5	3
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5
							(+1)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5
		350 GeV	±80/±30	1	1.6	0.2	1
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5
							(+1)
CEPC	ee	M_Z	0/0	2	17/32	16	2
		$2M_W$	0/0	2	10	2.6	1
		240 GeV	0/0	2	3	5.6	7
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8
		1.5 TeV	±80/0	1	3.7	2.5	7
		3.0 TeV	±80/0	1	6.0	5.0	8
							(+4)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25

(arXiv:1905.03764)

HE-LHC: 10/ab per experiment in 20 years

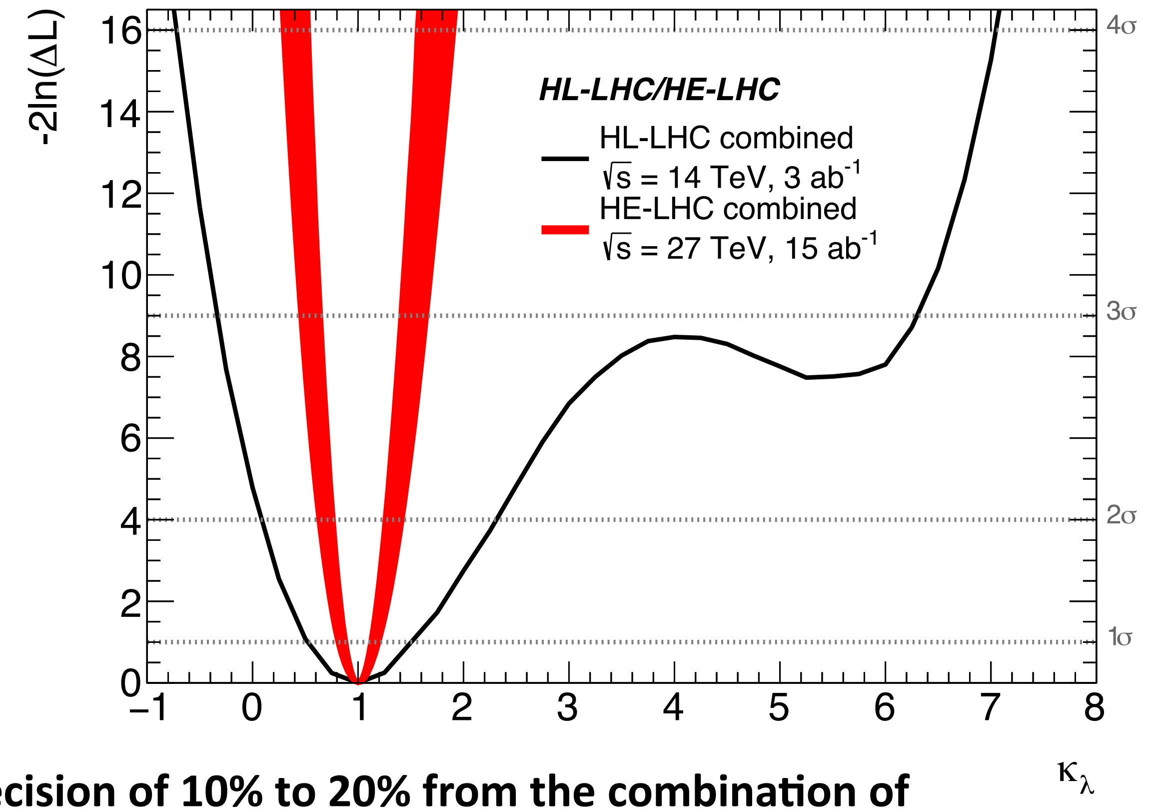
Prospects for High-Energy

- Higgs samples will typically increase by a factor between 10 and 25
  - Potential reduction in the statistical uncertainties by factors of 3 to 5
- Biggest improvements arise for the channels favoured by the higher energy, such as ttH and HH.

	$gg \to H$	VBF	WH	ZH	$t\bar{t}H$	HH
N_{27}	2.2×10^9	1.8×10^8	5.4×10^7	3.7×10^7	4×10^7	2.1×10^6
N_{27}/N_{14}	13	14	12	13	23	19

Coupling	S2	S2′
k_γ	1.6	1.2
k_W	1.5	1.0
k_Z	1.3	0.8
k_g	2.2	1.3
k_t	3.2	1.9
k_b	3.5	2.1
k_τ	1.7	1.1
k_μ	2.2	1.7
$k_{Z\gamma}$	6.9	4.1

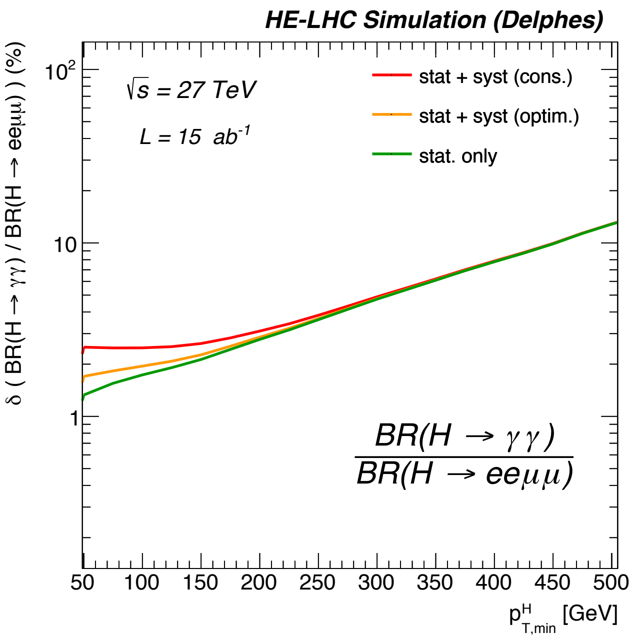
Projected sensitivities with different assumptions on systematics

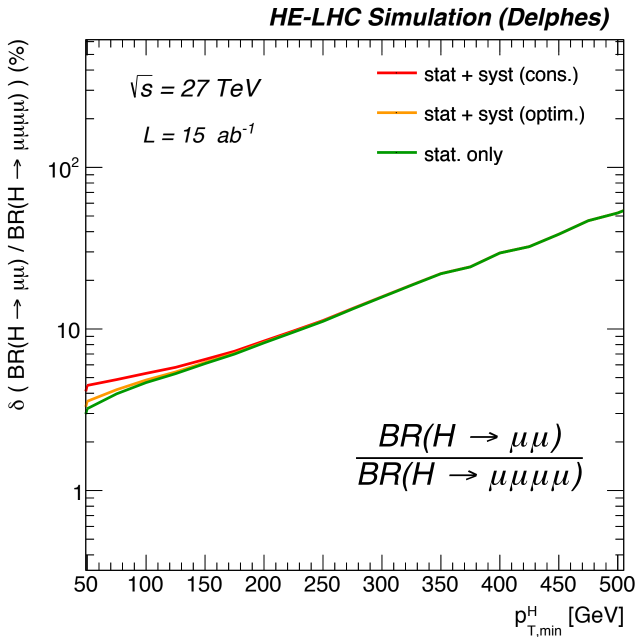


precision of 10% to 20% from the combination of $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ channels alone.

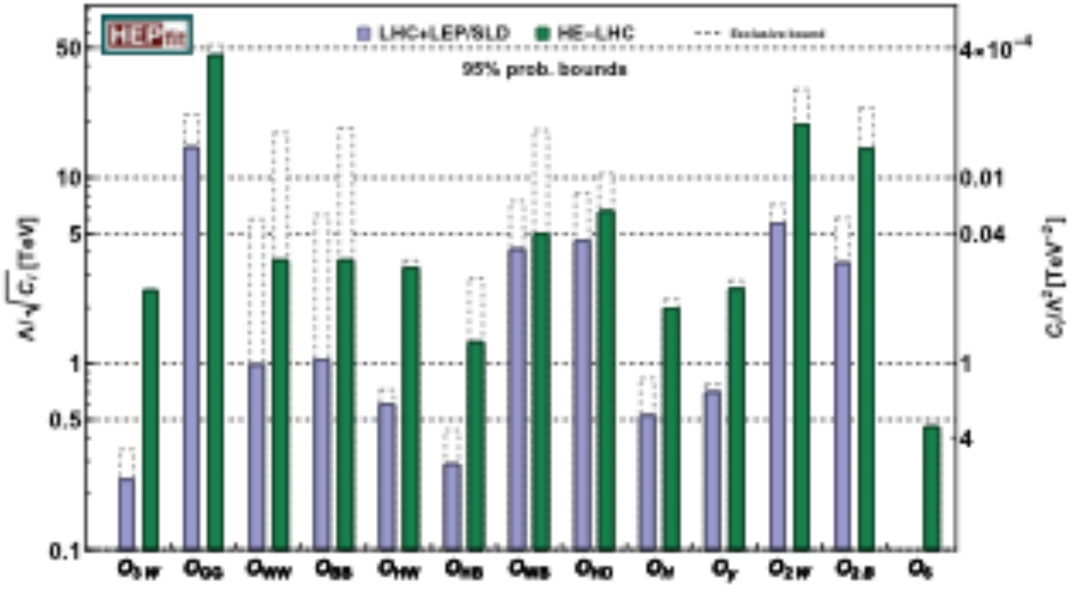
Prospects for High-Energy (2)

- For Higgs boson transverse momenta between 50 and 500 GeV, a precision in the range of 2-4% is achievable for the ratios BR(H→μμ)/BR(H→γγ) and BR(H→ 4l)/BR(H→γγ), and therefore of order 1-2% for the ratios of the relevant Higgs couplings.





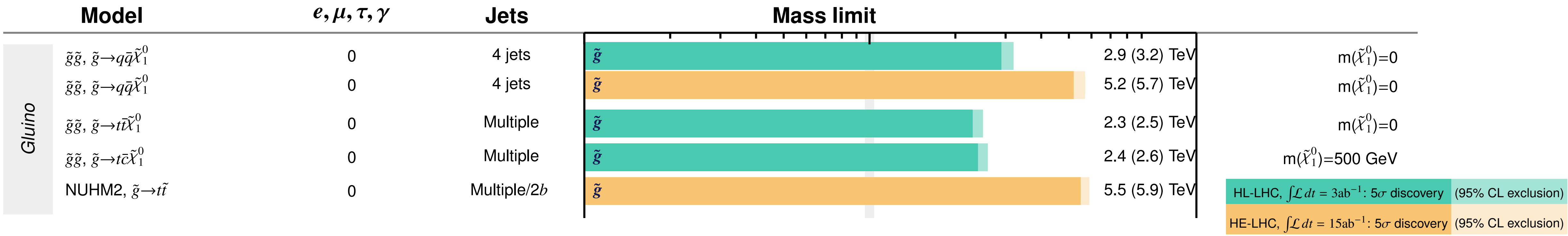
constraints on the EFT operators



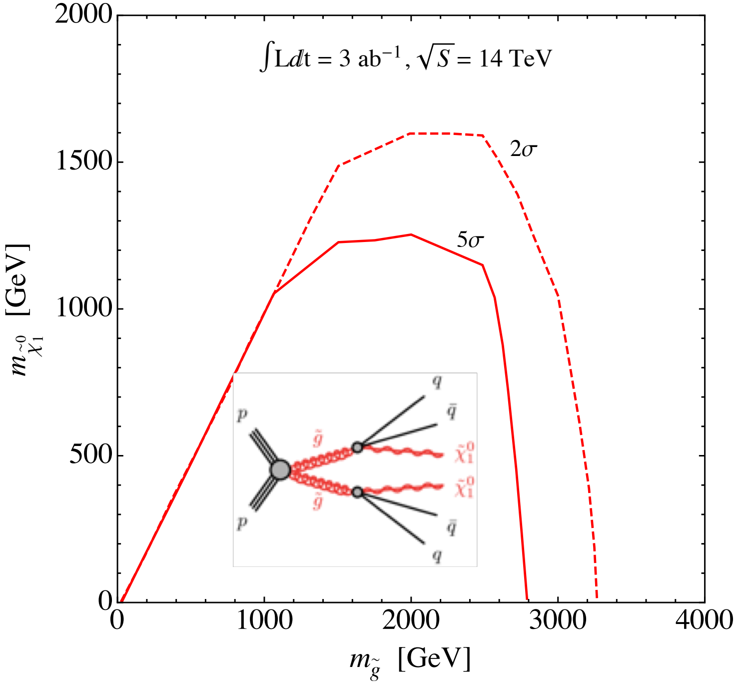
- Potential for discovery of deviations will grow considerably, allowing to test energy scales ~ 25 TeV
- Other highlights: longitudinal scattering, exotics Higgs decays, heavier additional higgses

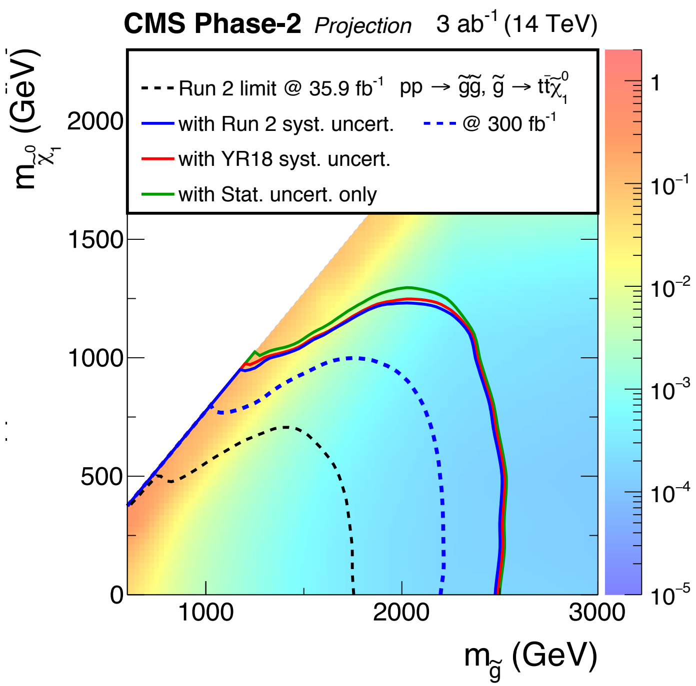
SUSY: strong production (1)

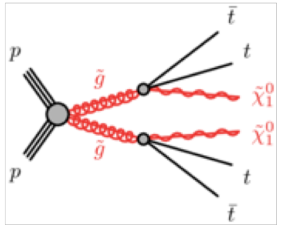
https://arxiv.org/pdf/1812.07831.pdf



- At the **HL-LHC,** exclusion 3.2 TeV (qqχ^0), 2.5 TeV (ttχ^0), 2.6 TeV (tcχ^0)
  - Valid for low χ^0 mass; reach deteriorates when increasing mass of the lightest SUSY particle, χ^0





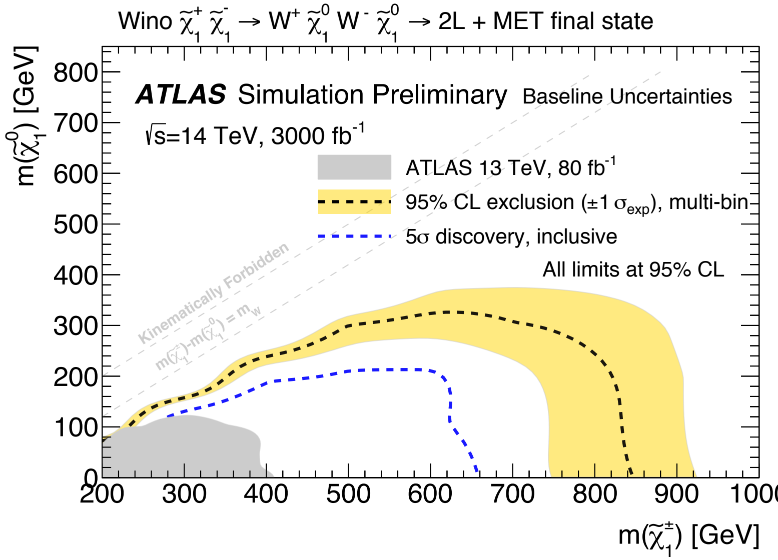


Searches: **Jets(+b/lepton)+E_T^{Miss}**

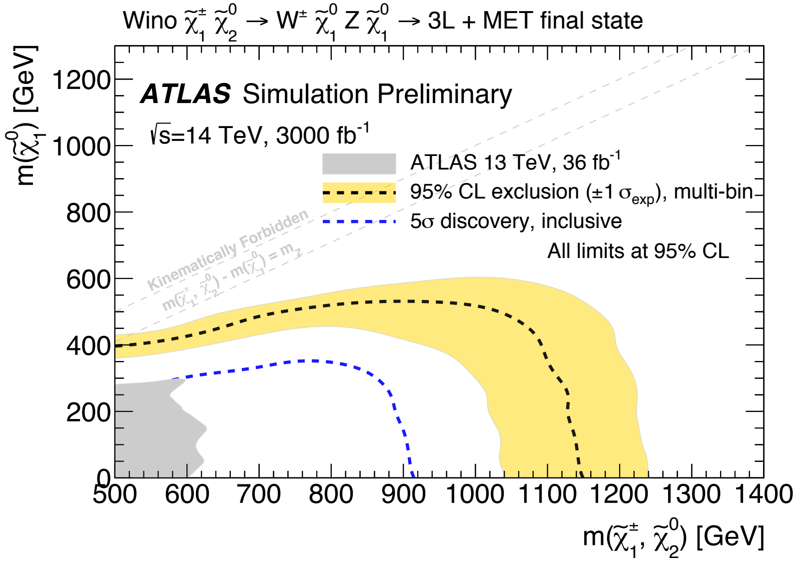
Discovery potential: **~500 GeV _lower_ than exclusion**

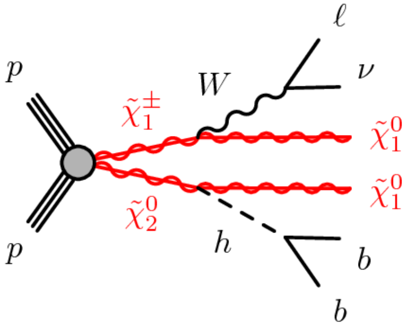
Charginos and neutralinos (wino-cross sections)

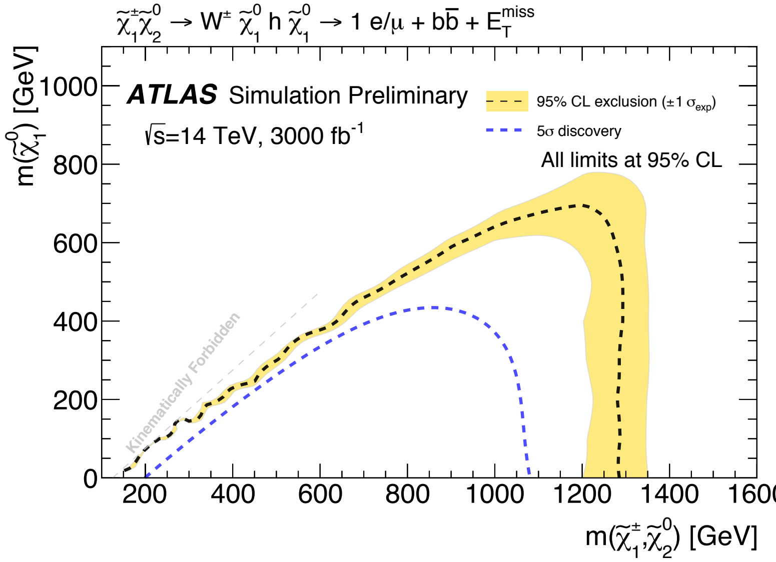
- For SUSY, the kinematic reach is reflected foremost in the sensitivity to EW states

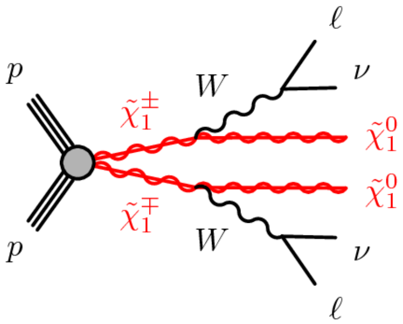


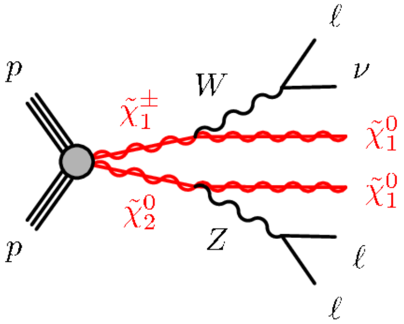
Reach above 800 GeV - 1 TeV







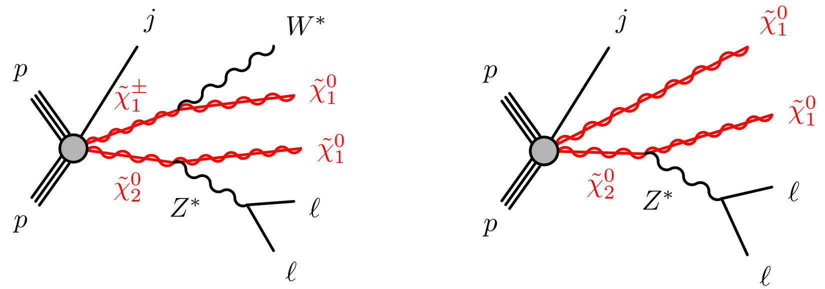


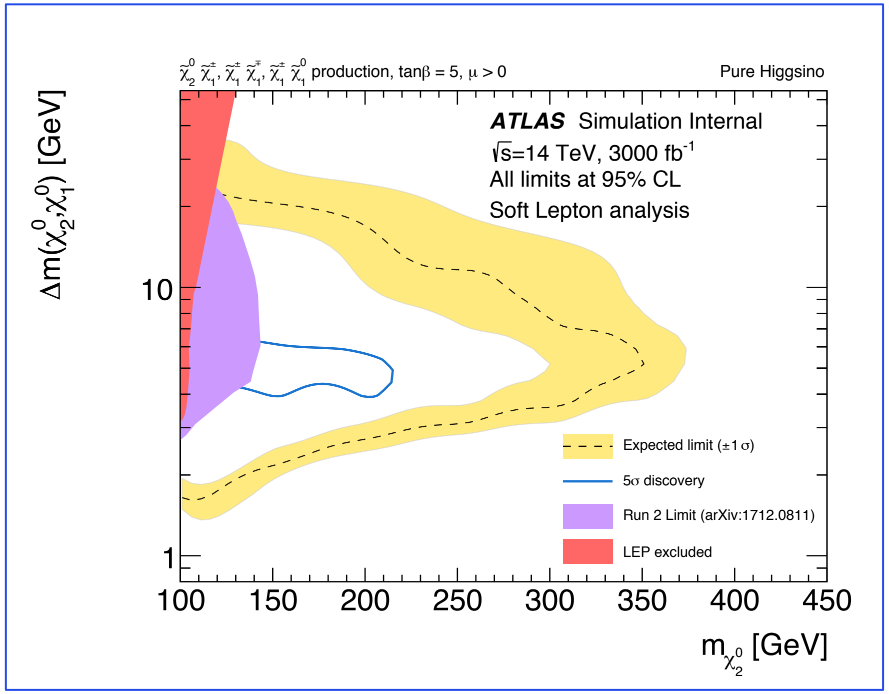


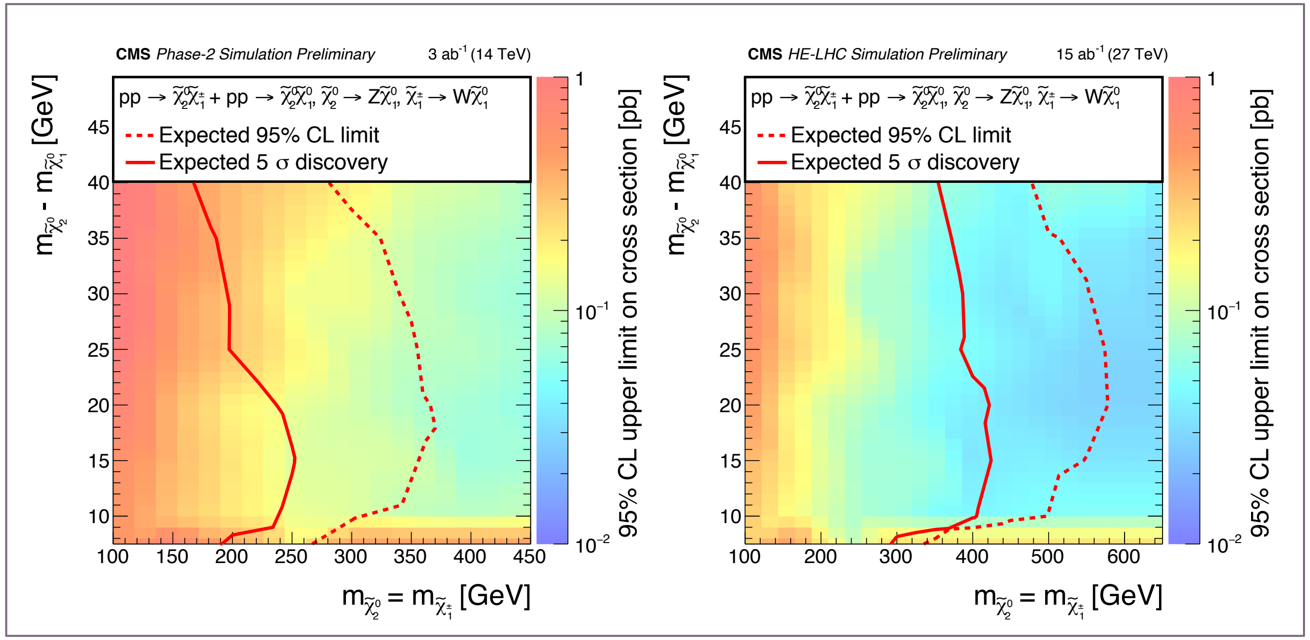
ATL-PHYS-PUB-2018-048

Charginos and neutralinos (higgsino-like)

- charginos and neutralinos scenarios in case of compressed scenarios – challenging but not impossible



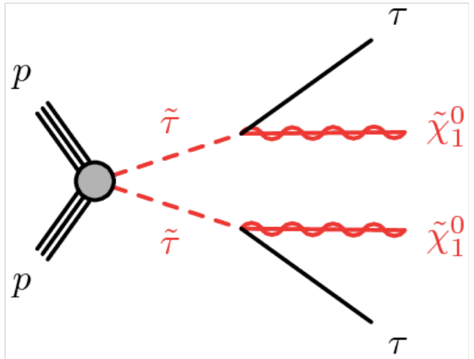




Discovery potential up to ~ 200 GeV

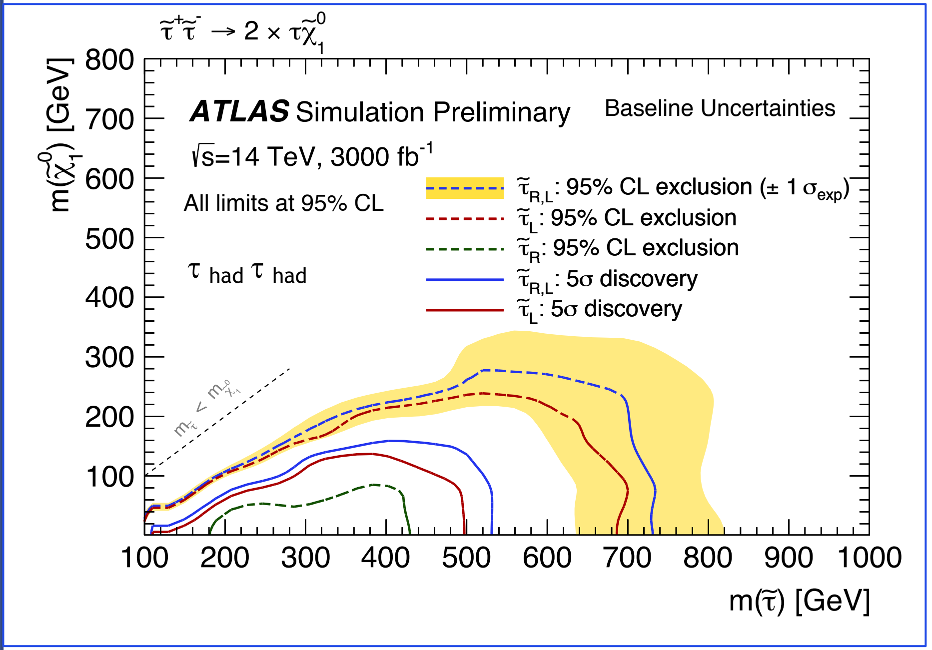
Stau reach

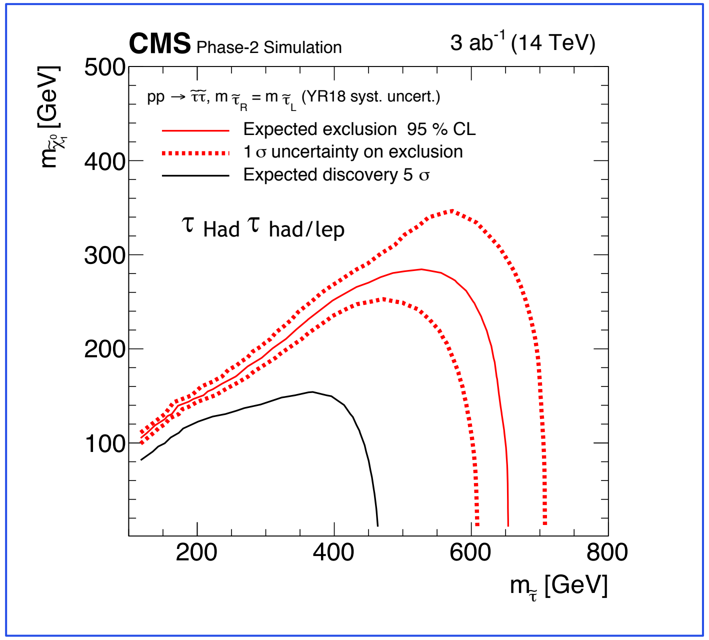
τ_1 is the lightest of two states, mixing of LH and RH component of τ
Cross section depends on that → τ_R very challenging!

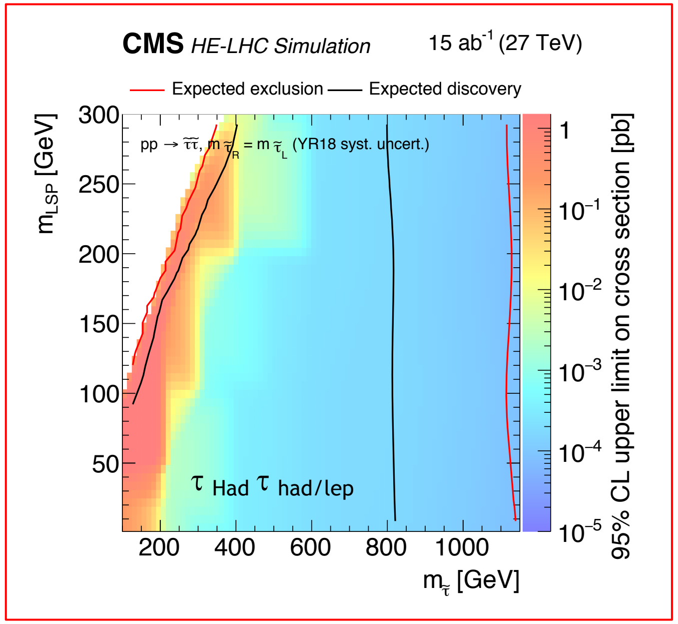


HL discovery up to 550 GeV ($\tilde{\tau}_R=\tilde{\tau}_L$)
For HE: ~ 800 GeV

Compressed regions can be addressed with ISR+$\tau\tau$







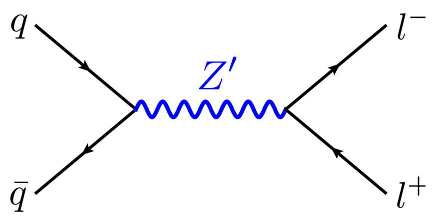
Direct vs indirect constraints

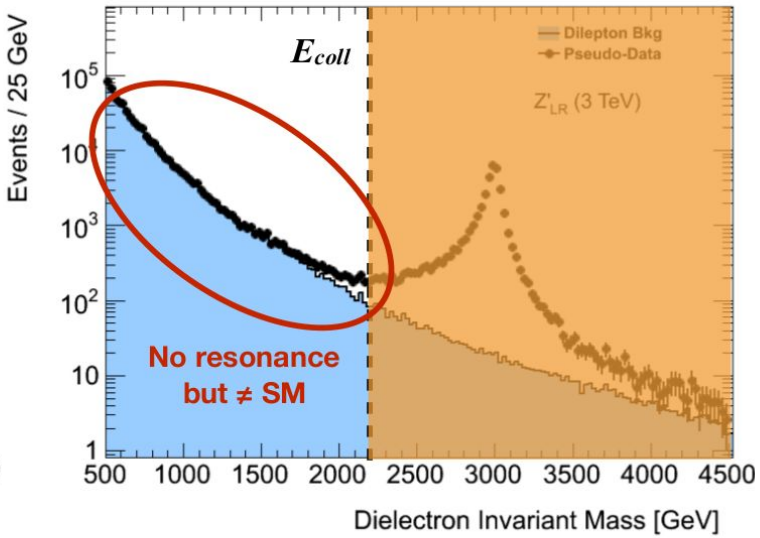
J. De Blas

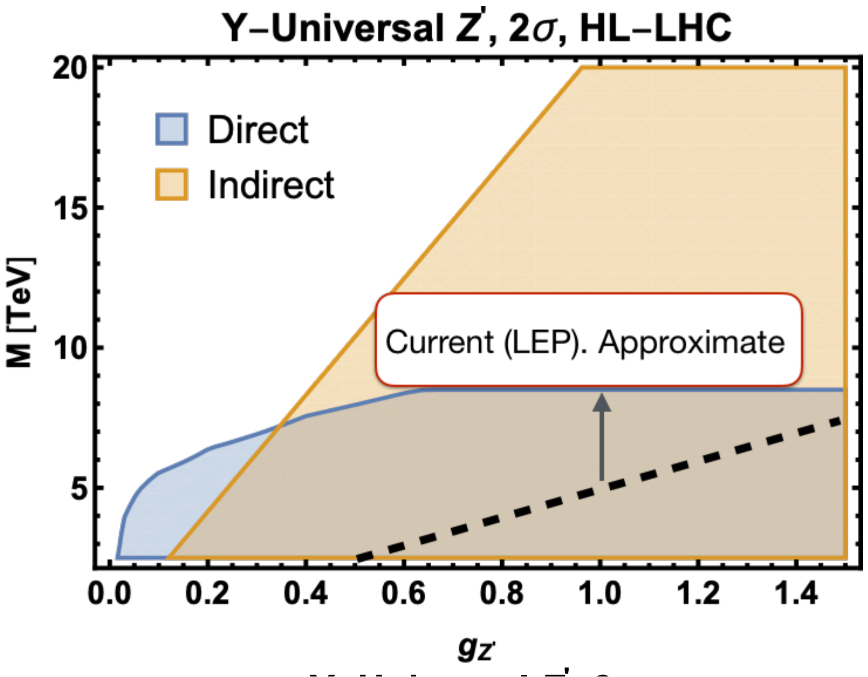
- If mZ'>>5 TeV, main contributions from interference effects modifying DY
- Complementarities hadron / lepton colliders
- Hadron colliders relevant for $g_{Z'} > g_{SM}$

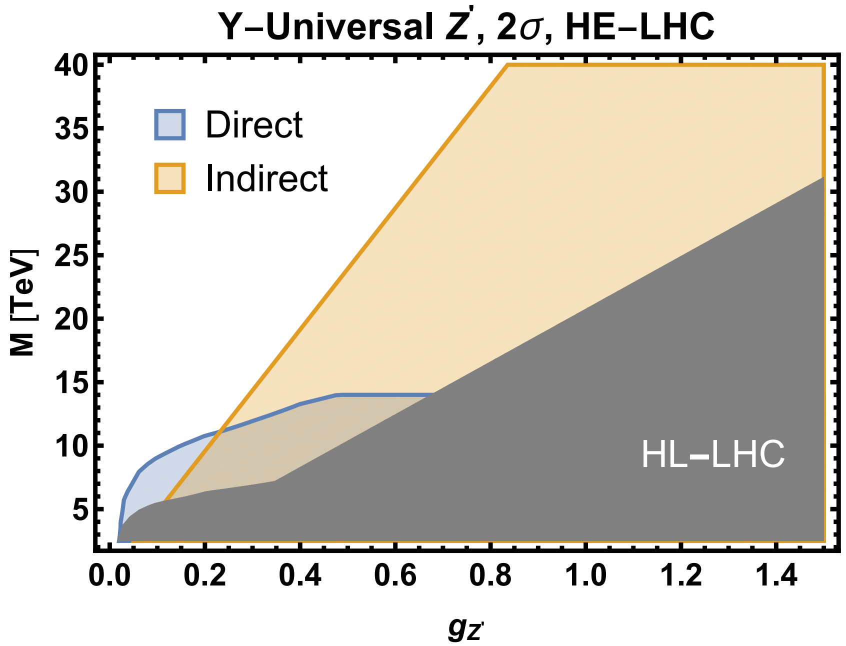
couplings: [mass/coupling] ≫ 0.5√s

(lepton colliders; sensitive to [mass/coupling] ≫ √s)







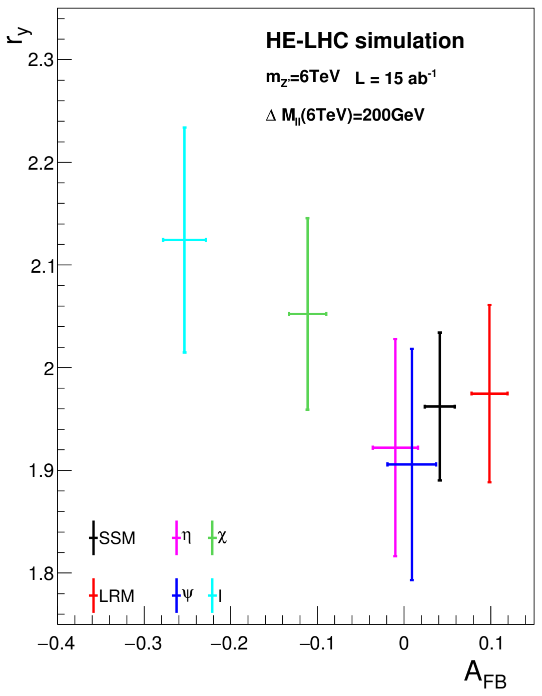


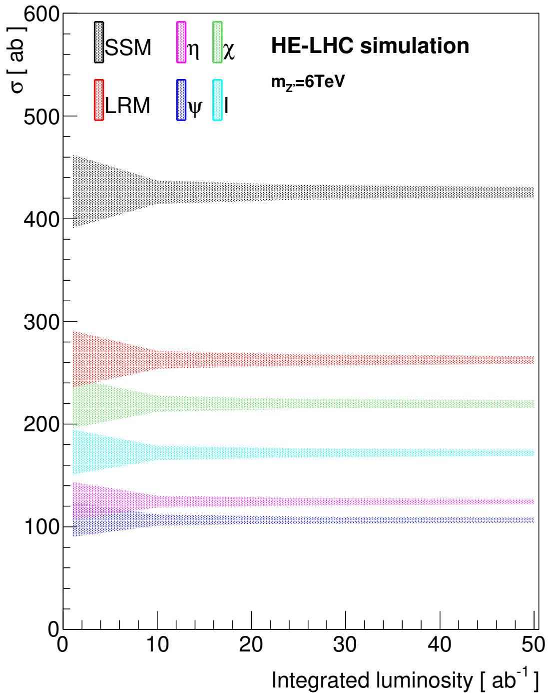
A. Wulzer
Granada '19

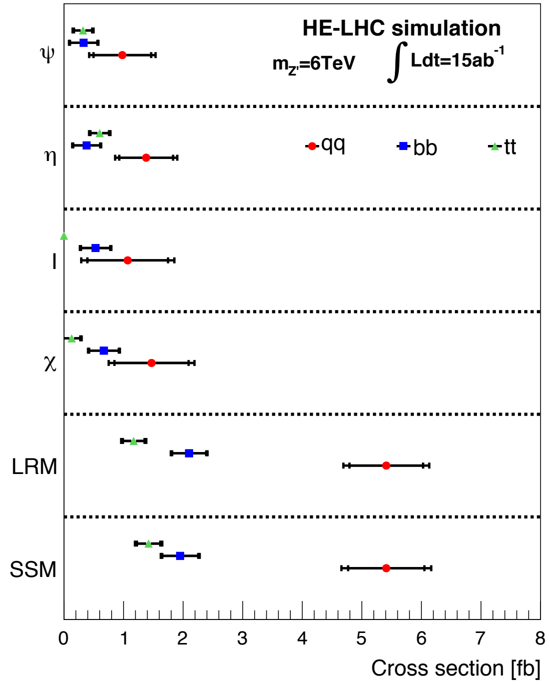
Characterizing a discovery @ HE-LHC

- IF a Z' resonance of 6 TeV is seen at HL-LHC, it can be "characterized" at HE-LHC via cross sections, AFB and central/forward ratios

$$A_{FB} = A_C = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)}, \qquad r_y = \frac{\sigma(|y_{Z'}| < y_1)}{\sigma(y_1 < |y_{Z'}| < y_2)}, \quad y_1 = 0.5 \text{ and } y_2 = 2.5$$





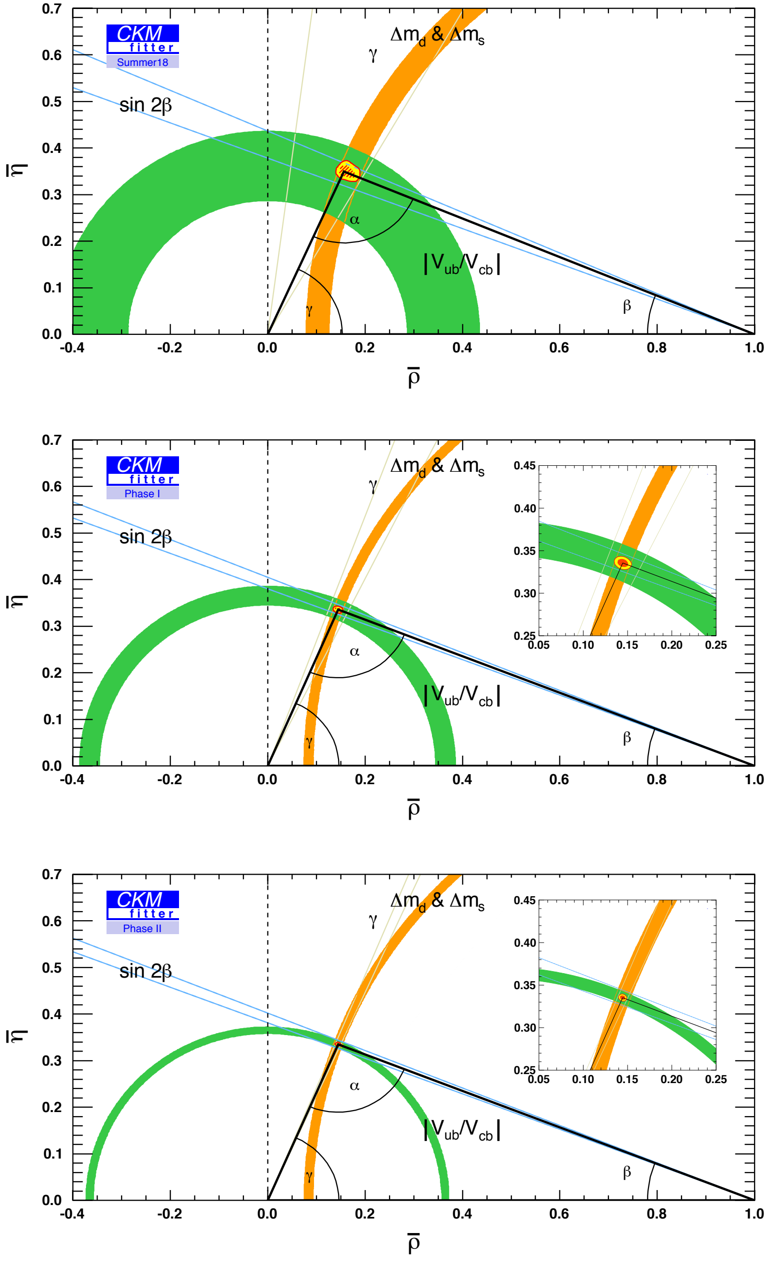


CKM unitarity triangle

- Improved knowledge of parameters
- The evolving constraints in the $\bar{\rho}$ – $\bar{\eta}$ plane from LHCb inputs and lattice-QCD calculations are shown standalone.

	Current.	LHCb 2025	LHCb p.2
CKM tests			
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [7]	4°	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [8]	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [9]	0.011	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [10]	14 mrad	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [11]	35 mrad	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [12]	39 mrad	11 mrad
$a_{\rm sl}^s$	33×10^{-4} [13]	10×10^{-4}	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [14]	3%	1%

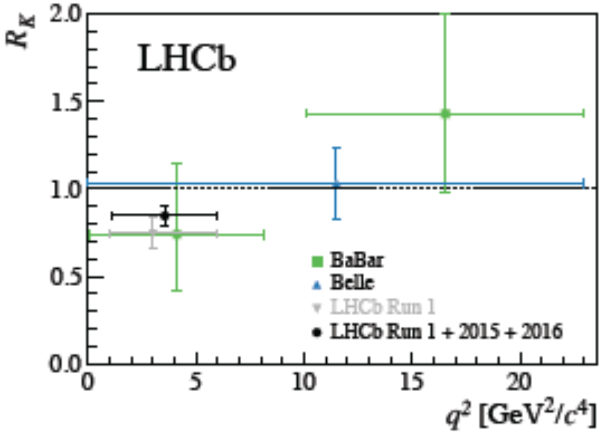
ρ–η plane



prospects for *B*-anomalies

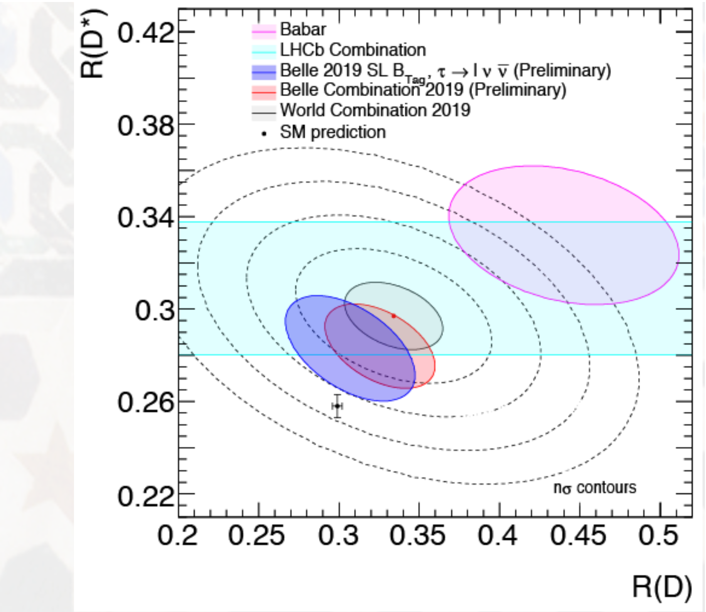
- Good prospects for confirming or discarding anomalies

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{=} 1.0$$



Moriond EW 2019

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)} \quad (\ell = e, \mu)$$



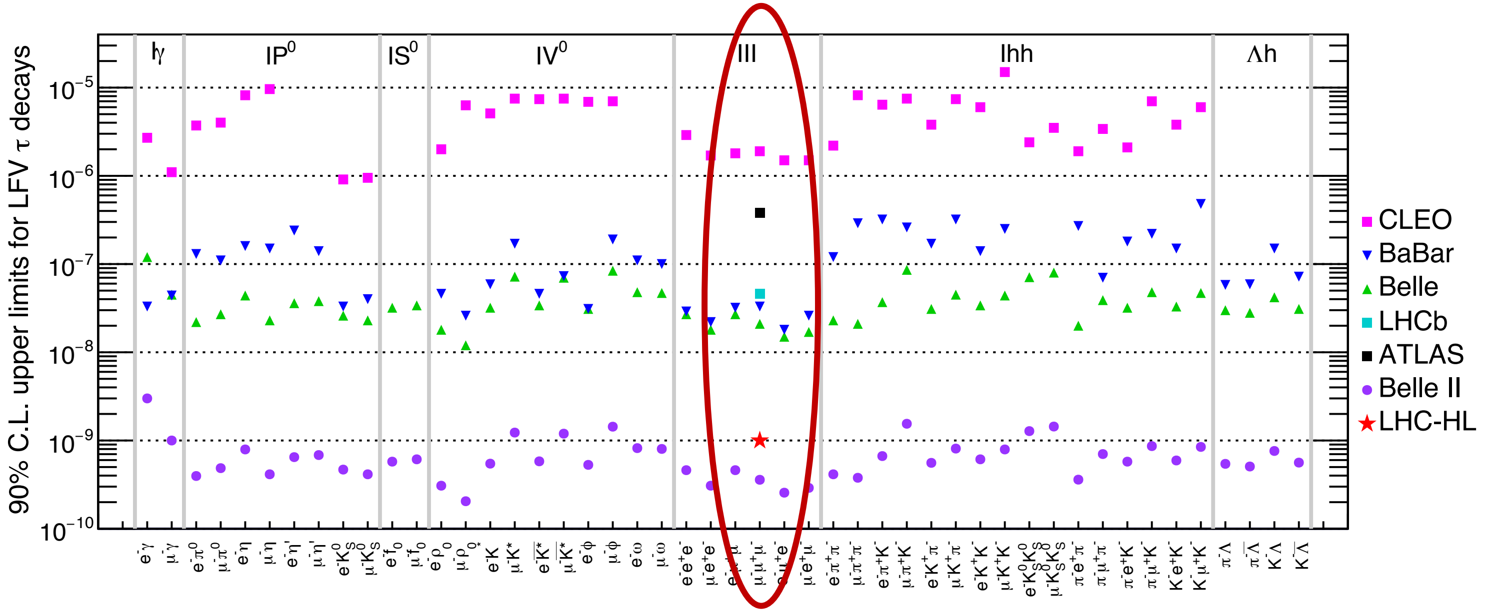
- Large improvements predicted

$b \to c\ell^-\bar{\nu}_l$ **LUV studies**			
$R(D^*)$	0.026 [16, 17]	0.0072	0.002
$R(J/\psi)$	0.24 [18]	0.071	0.02

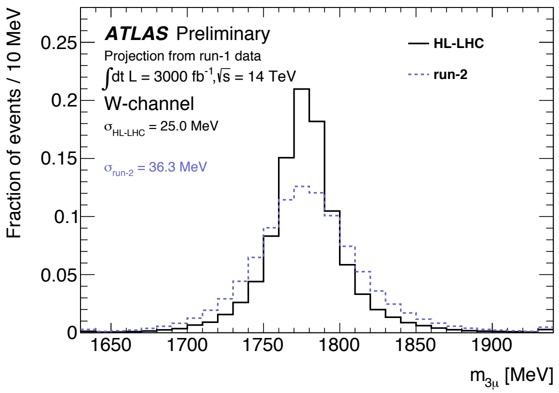
Observable	Current LHCb	LHCb 2025	Upgrade II
EW Penguins			
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [5]	0.025	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [6]	0.031	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	0.02, 0.02, 0.05

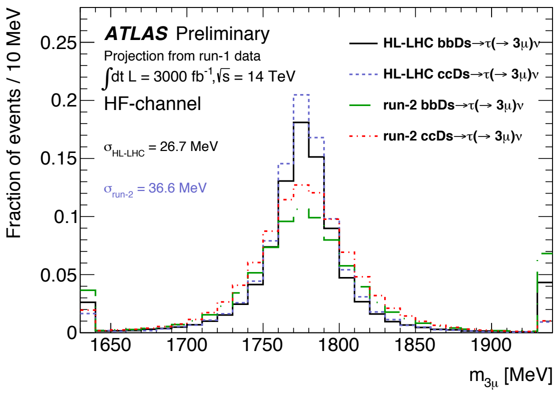
Lepton Flavour Violation in τ decays

- Bounds on Tau Lepton Flavour Data from the existing experiments are compiled by HFLAV



Good synergy ATLAS/CMS/LHCb for $\tau \to 3\mu$





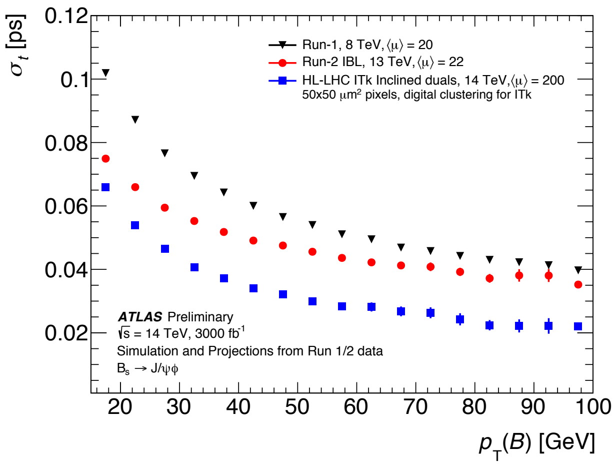
$BR(\tau \to 3\mu)$ (90% CL limit)	Ref.	Comments
3.8×10^{-7}	ATLAS [429]	Actual limit (Run 1)
4.6×10^{-8}	LHCb [428]	Actual limit (Run 1)
3.3×10^{-8}	BaBar [417]	Actual limit
2.1×10^{-8}	Belle [423]	Actual limit
3.7×10^{-9}	CMS HF-channel at HL-LHC	Expected limit (3000 fb^{-1})
6×10^{-9}	ATLAS W-channel at HL-LHC	Expected limit (3000 fb^{-1})
2.3×10^{-9}	ATLAS HF-channel at HL-LHC	Expected limit (3000 fb^{-1})
$\mathcal{O}(10^{-9})$	LHCb at HL-LHC	Expected limit (300 fb^{-1})
3.3×10^{-10}	Belle-II [196]	Expected limit (50 ab^{-1})

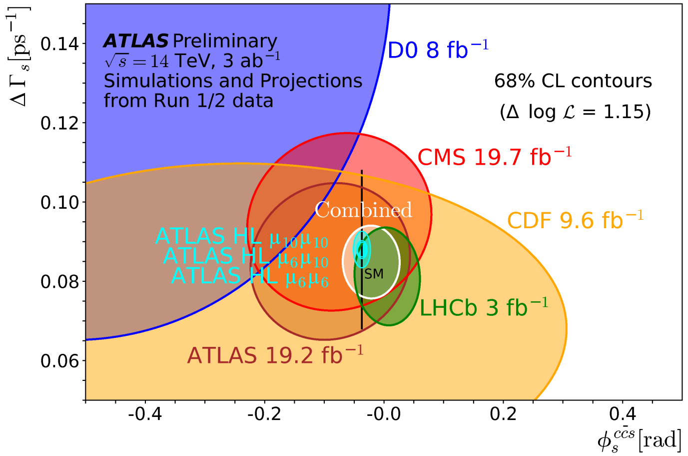
Flavour physics @ ATLAS and CMS

- Interesting and competitive studies can be performed at HL-LHC ATLAS and CMS also in B/C sectors thanks to the enhanced B-physics capabilities of the upgrades. E.g.:
  - Measurements of the CP-violating phase ϕ_s, potentially sensitive to BSM, in $B_s^0 \to J/\psi\ \phi$ **channel**

Exploit improvements on the proper decay time resolution thanks to ITk → by 20% (40%) wrt Run 2 (Run 1)

Results strongly depend on the trigger thresholds

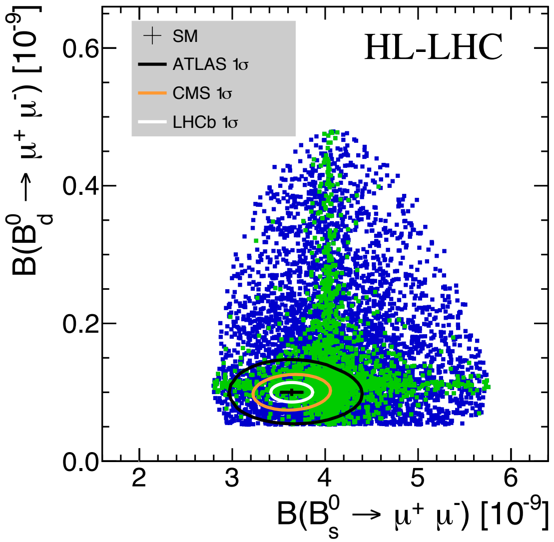




- Prospects for measuring the BR of the very rare decays $B^0_s \to \mu^+\mu^-$ **and** $B^0 \to \mu^+\mu^-$

Fundamental probe for BSM and/or LFV:
→ HL-LHC will provide increased mass resolution and large statistics
→ Statistics can be improved but depends on triggers

	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$		$\mathcal{B}(B^0 \to \mu^+\mu^-)$	
	stat $[10^{-10}]$	stat + syst $[10^{-10}]$	stat $[10^{-10}]$	stat + syst $[10^{-10}]$
Run 2	7.0	8.3	1.42	1.43
HL-LHC: Conservative	3.2	5.5	0.53	0.54
HL-LHC: Intermediate	1.9	4.7	0.30	0.31
HL-LHC: High-yield	1.8	4.6	0.27	0.28

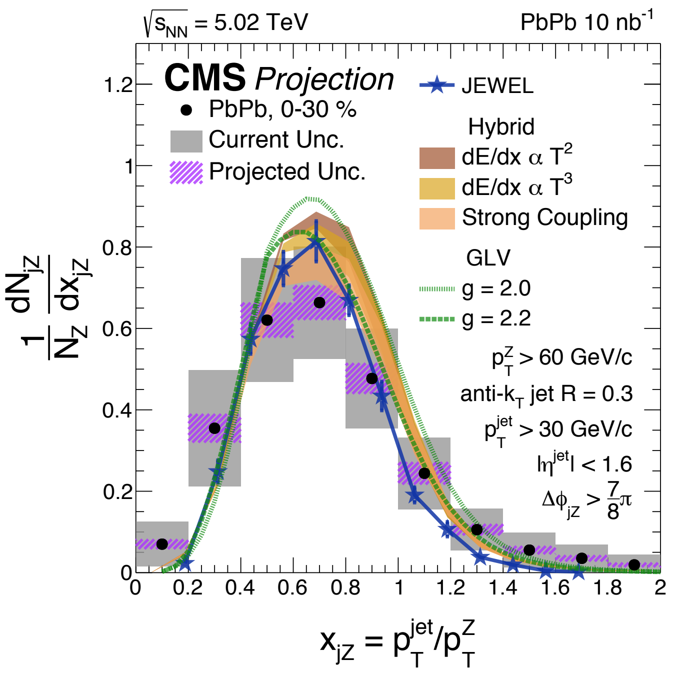


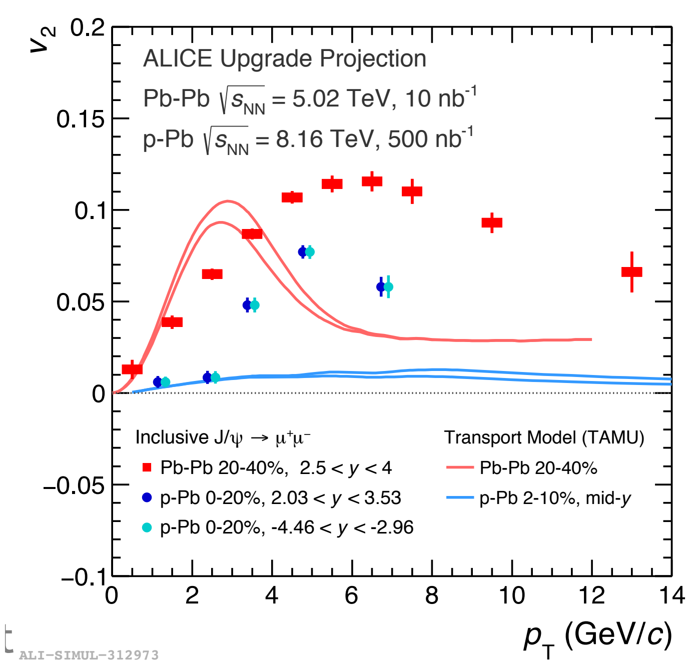
Heavy Ion Physics

Heavy Ion physics

- Very detailed research programme
  - The integrated luminosity target of 13 nb^{-1} by the end of Run 4 (= a seven-fold increase wrt Run 2)
  - high-density QCD and the Quark-Gluon Plasma (QGP)
  - Goals:
    1. Characterizing the macroscopic long-wavelength properties of the QGP with unprecedented precision.
    2. Accessing the microscopic parton dynamics underlying QGP properties.
    3. Developing a unified picture of QCD particle production from small (pp) to larger (pA and AA) systems.
    4. Probing nuclear PDFs in a broad (x, Q^2) range, searching for the possible onset of parton saturation.

Z–jet momentum imbalance in Pb–Pb





J/ψ elliptic flow in p–Pb and Pb–Pb (ALICE)

ALICE dominates but interesting results from ATLAS and CMS as well

Heavy Ion physics (2)

- Very detailed research programme
  - The integrated luminosity target of 13 nb−1 by the end of Run 4 (= a seven-fold increase wrt Run 2)
  - high-density QCD and the Quark-Gluon Plasma (QGP)
  - Also, searches for new physics!

Just one example: **ATL-PHYS-PUB-2018-018**

Measurements of Photon-Induced Processes in Ultra-Peripheral Collisions of Heavy Ions

Photon-photon interactions in lead-lead collisions
Good potential for axion-like particle searches