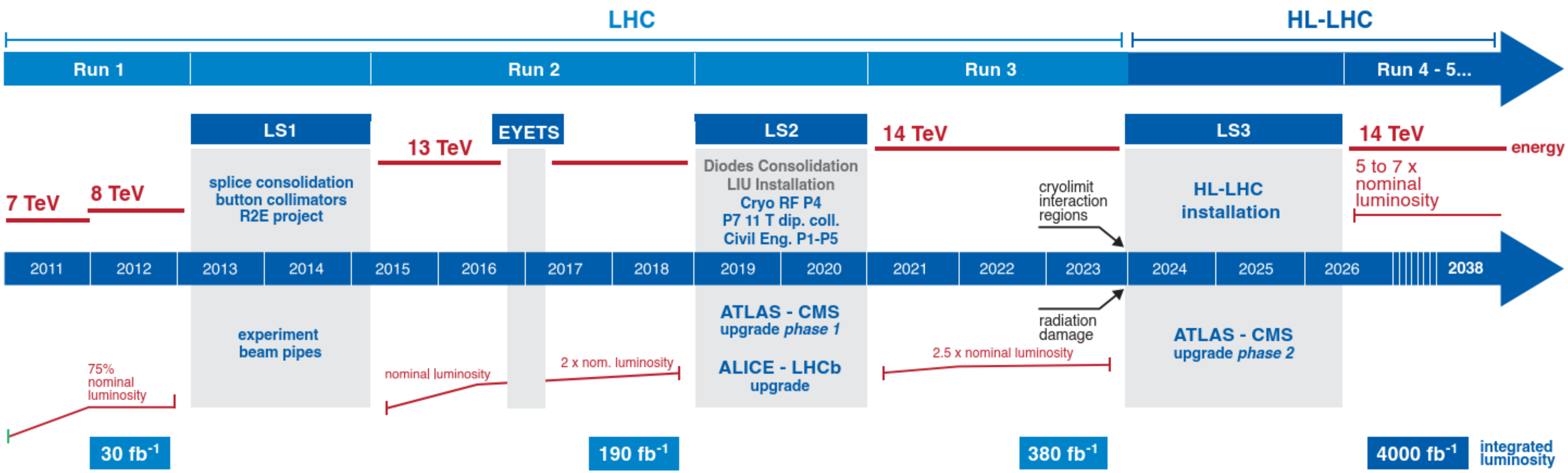
HL-LHC and HE-LHC Highlights

- Summary of HL(HE)-LHC Yellow Report
  - Work carried out by experimentalists and theorists
  - Goals
    - Update and extend on existing projections
    - Highlight new opportunities for BSM discoveries in view of recent theory developments and data results
    - Explore possible new directions and/or extensions of the approved HL-LHC programme, i.e. in flavour sector, search for elusive BSM phenomena, study of QCD matter at high density
  - More than 1000 pages split up in 5 volumes
    - SM+Top, Higgs, SUSY+exotics, Flavour, Heavy Ions
    - HL-LHC summary, HE-LHC summary
    - ATLAS and CMS Pub notes
  - Input to the update of European strategy for PP
    - Next meeting in Granada in May
    - Approval by CERN council in May 2020
- Can only show some select examples in the following…

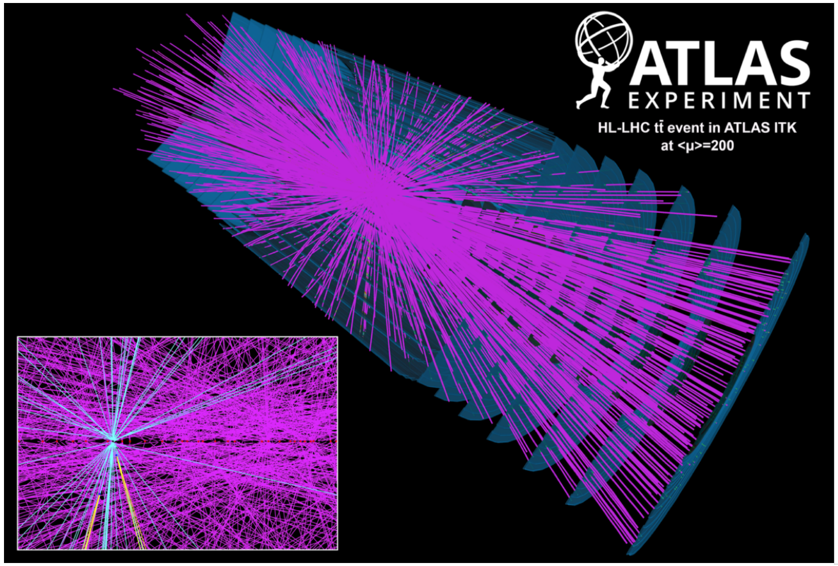
HL-LHC Timeline, Energy & Integrated Luminosity



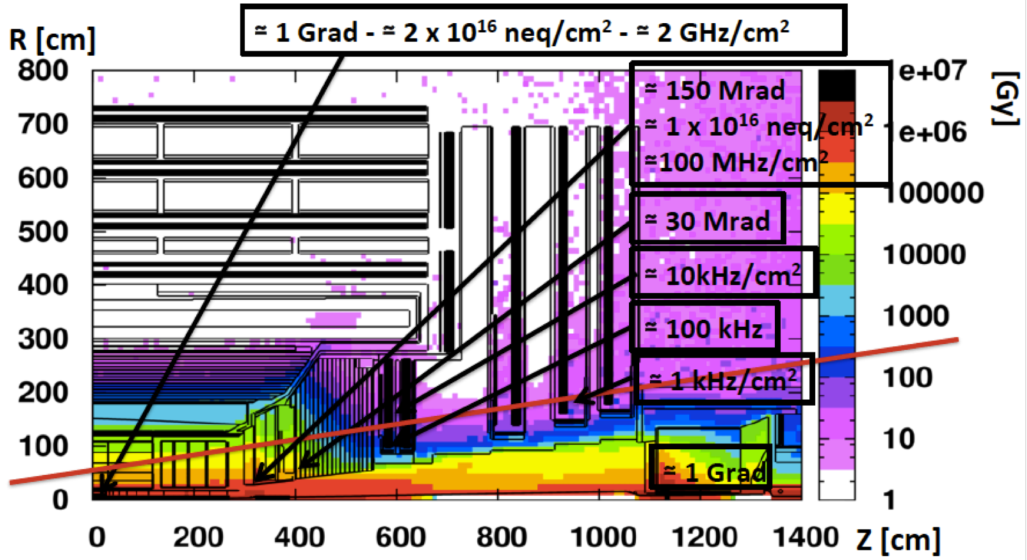
- ATLAS + CMS
  - $\sqrt{s}$ = 14 TeV, L= 5-7.5 $\times$ 10^{34} $cm^{-2}s^{-1}$, 3-4 ab^{-1}, pileup <μ>=140 - 200
    - For YR we only assumed 3000 fb^{-1}
- LHCb
  - $\sqrt{s}$ = 14 TeV, L= 2 $\times$ 10^{34} $cm^{-2}s^{-1}$, 300 fb^{-1}, <μ> = 50
- Heavy Ion programme
  - Pb-Pb: 13 nb^{-1} (7$\times$Run-2)
  - p-Pb: 1.2 pb^{-1} ATLAS/CMS, 0.6 pb^{-1} ALICE/LHCb
  - also colliding other ions e.g. Ar-Ar, O-O, p-O)

HL-LHC Challenges for experiments

Very high pileup

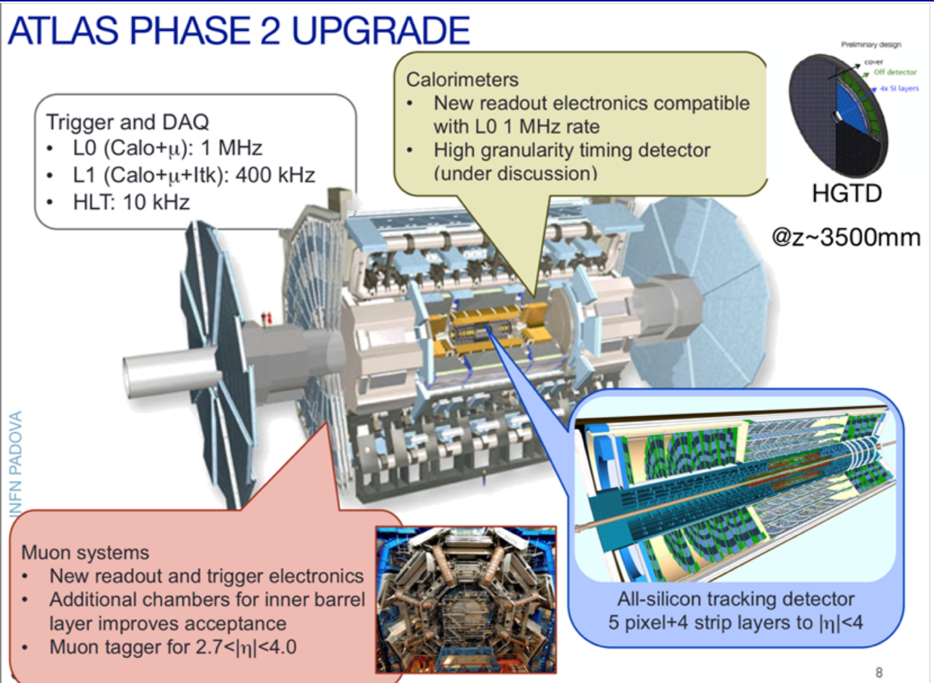


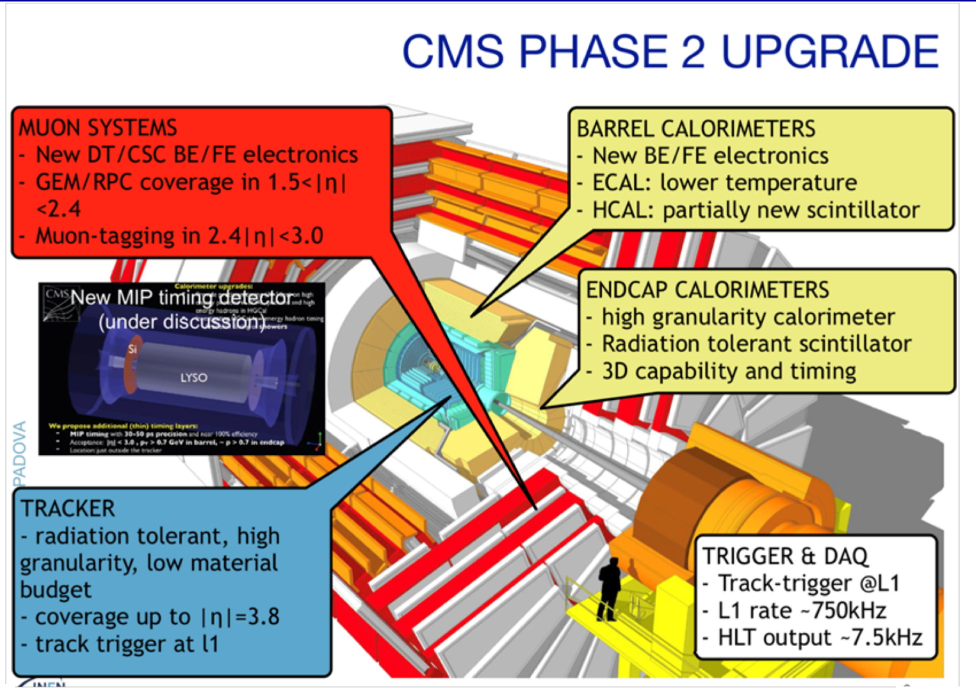
Intense radiation



- Major experiment upgrades needed to
  - Improve radiation hardness and replace detectors at end-of-life
  - Provide handles for mitigating pileup (high granularity, fast timing)
  - Allow higher event rates to maintain/improve trigger acceptance
- Maintain or improve over current performance

Detector upgrades



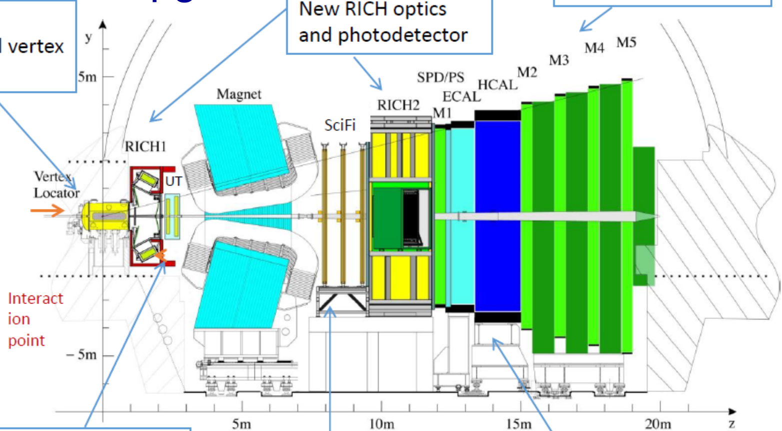


LHCb LS2 Upgrade

VELO
New pixel vertex detector

RICh detectors
New RICH optics and photodetector

MUON system
New electronics



UT
New silicon Upstream Tracker

SciFi
New SCIntillator Fiber tracker

CALORIMETERS
New electronics

ALICE LS2 Upgrade

New Inner Tracking System (ITS)
-CMOS pixel, MAPS technology
-Improved resolution, less material, faster readout

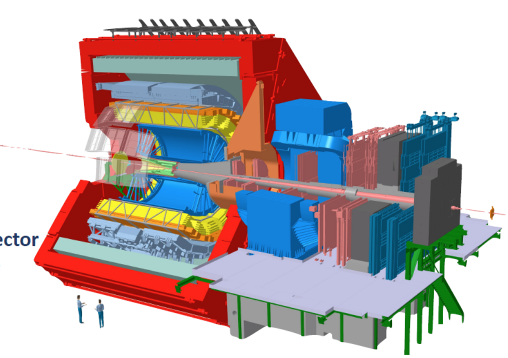
New Muon Forward Tracker (MFT)
-CMOS Pixels, MAPS technology
-Vertex tracker at forward rapidity

New TPC Readout Chambers (ROCs)
-Gas Electron Multiplier (GEM) technology
-New electronics (SAMPA), continuous readout

New Fast Interaction Trigger (FIT) Detector
-Centrality, event plane, luminosity, interaction time

Readout upgrade
-TOF, TRD, MUON, ZDC, Calorimeters

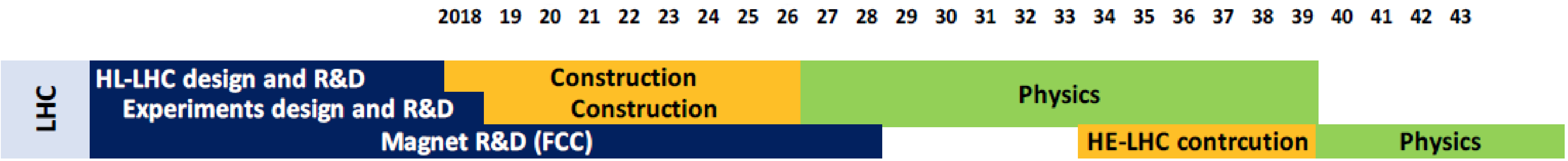
Integrated Online-Offline system (O²)
-Record Minimum-Bias Pb-Pb data at 50 kHz



HL-LHC detector upgrades

- ATLAS and CMS
  - New Tracker with granularity increase by $\simeq 5$ (pixels and strips), reduced material by $\simeq 50\%$, extension to $\eta \simeq 4$
  - CMS High Granularity End-cap Calorimeter - based on CALICE concept
  - Precision timing detectors
  - New trigger strategy with track reconstruction in hardware trigger level
    - ATLAS L0 at 1 MHz possible upgrade to 4 MHz with regional tracker readout and L1-Level
    - CMS 40 MHz Outer Tracker $p_T \geq 2$ GeV
- LHCb
  - Full software trigger running at 40 MHz!
  - New pixel detector (in LS2)
- ALICE
  - 50 kHz full online reconstruction with FPGAs & GPUs (reduce 1 TB/s to 90 GB/s for storage)
  - New pixel tracker

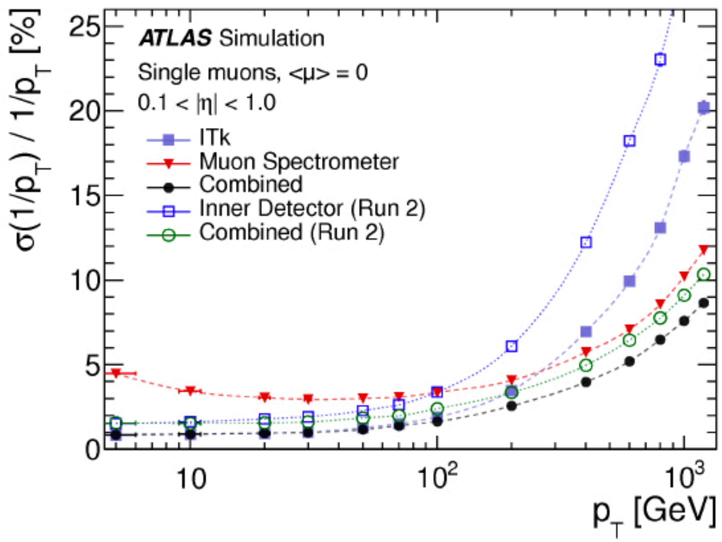
HE-LHC

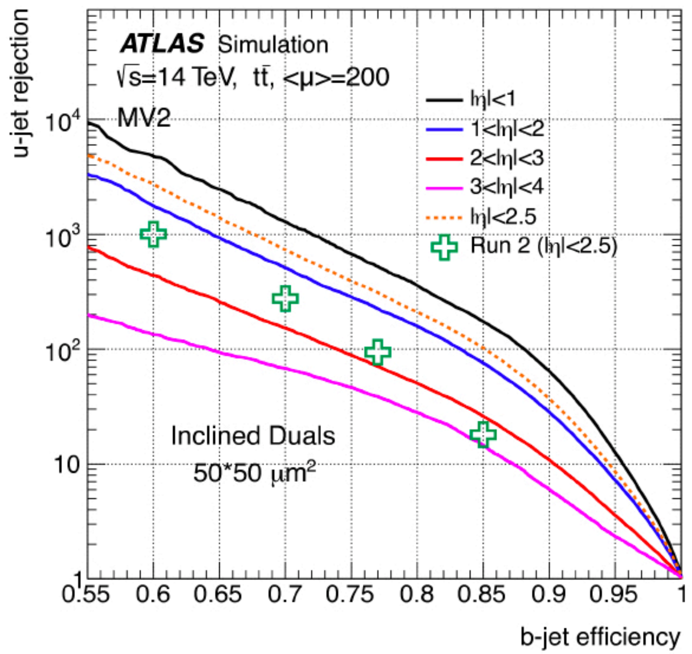


- Potential HL-LHC successor
  - Reuse existing LHC tunnel
  - Use of ~16 T magnets in LHC (designed for FCC)
  - Strong physics case if new physics from LHC/HL-LHC
- $\simeq$ 10 years running at $\sqrt{s}$ = 27 TeV collecting 15 ab^{-1}
  - L> 2.5×10^{35} $cm^{-2}s^{-1}$, $<\mu>$ = 850
- New detectors needed for this upgrade, currently 2 experiments envisaged

Analyses techniques

- Three main approaches for HL-LHC
  - Full simulation
  - Analysis with parameterised detector performance
    - ATLAS: smearing of generated particle energy and p_T, identification eff., mis-tag rates etc plus overlay of pileup jets
    - CMS: DELPHES with up-to-date detector performance
    - Analysis guided by present analysis. Limited optimisation for HL-LHC environment
  - Projections using Run-2 signal/bkd samples scaled to 14 TeV





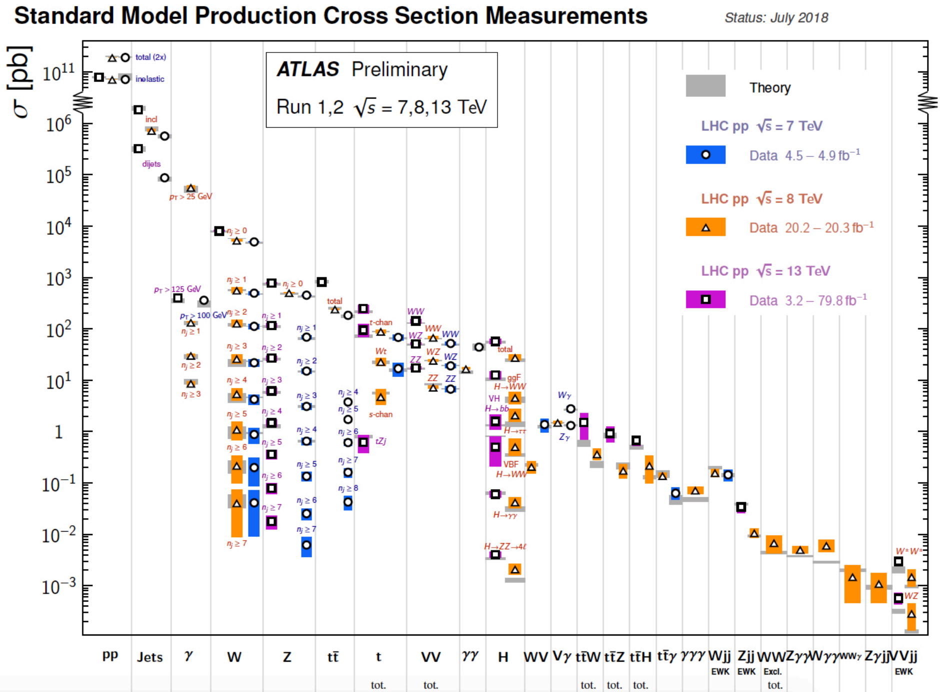
Analyses techniques and systematics

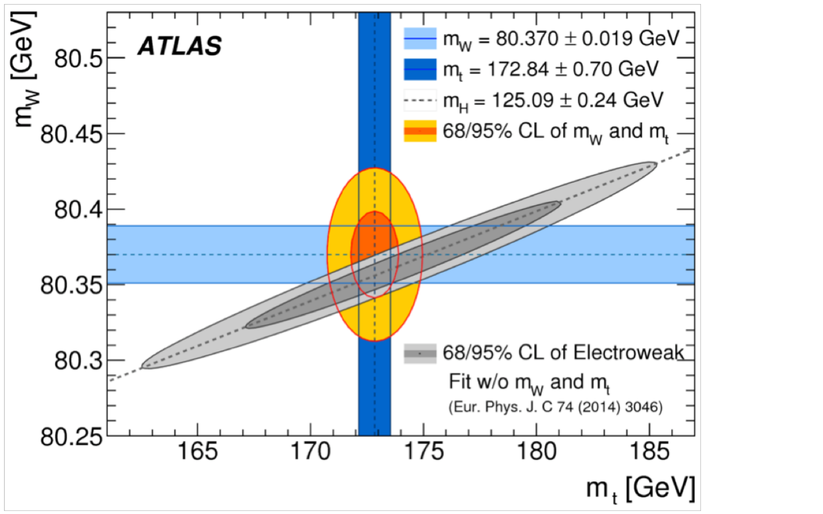
- HE-LHC techniques
  - Assume detector performances as for HL-LHC or
  - Use special DELPHES option (similar performances as at HL-LHC) or
  - Projections from HL-LHC results by scaling cross sections / lumi
- Systematics
  - Agreement between experimentalists and theorists involved in YR
  - General "rule of thumb":
    - Most theoretical uncertainties scaled down by a factor ½
    - Experimental uncertainties scaled down by $\sqrt{L}$ until they reach a defined lower limit.
    - Modelling uncertainties to be halved
    - Uncertainties due to the finite number of simulated events are neglected

Standard Model

Standard Model

- So far SM works incredibly well…
- Precision measurements of SM remains major topic at HL-LHC
  - Advances in theory as well as increase in statistics will further improve the precision of SM measurements
  - Each deviation could be hint of new physics!



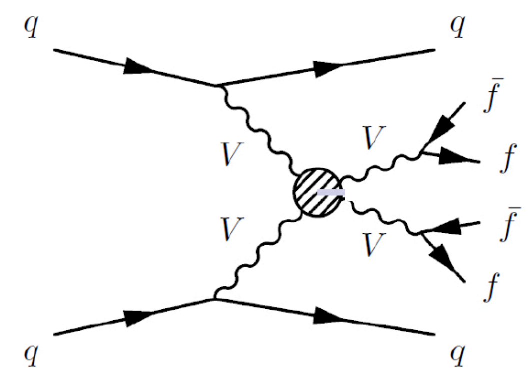


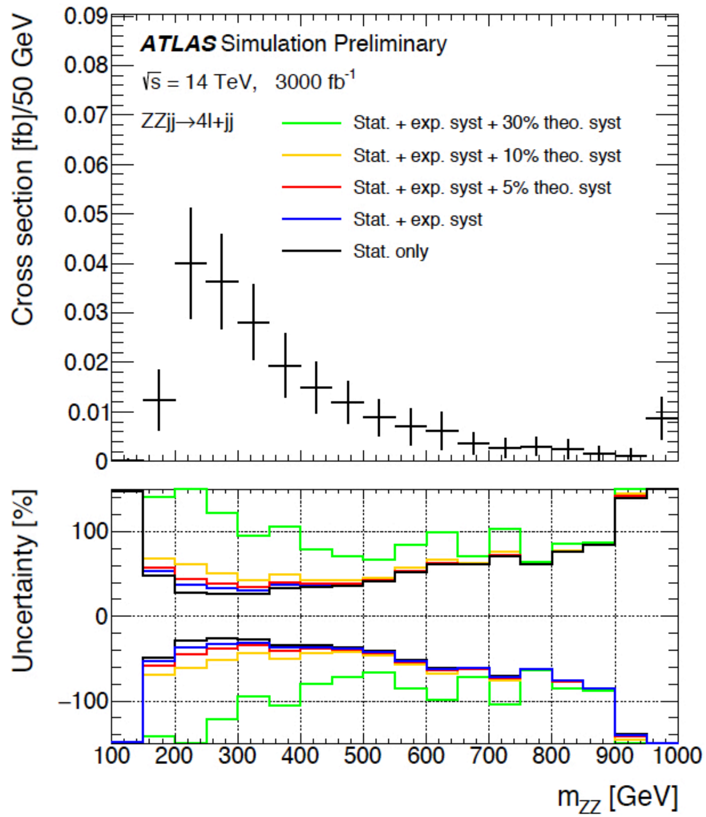
Vector boson scattering

- Crucial for probing EW symmetry breaking within SM
  - Currently
    - 1st observation for WW and WZ
  - 5σ observation for all processes, very good precision at HL-LHC

Process Final state	$W^{\pm}W^{\pm}$ $\ell^{\pm}\ell^{\pm}$jj	WZ 3ℓjj	WV ℓjjjj	ZZ 4ℓjj
Precision	6%	6%	6.5%	10–40%
Significance	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$

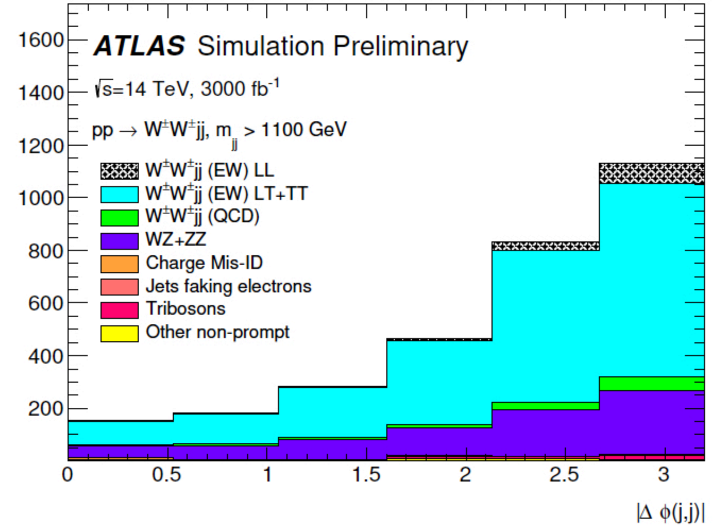
- Differential cross sections measurement feasible for ZZjj
  - Look at final state with 4 leptons from Z with 2 jets in forward/backward region
  - Experimental and modelling uncertainties dominate



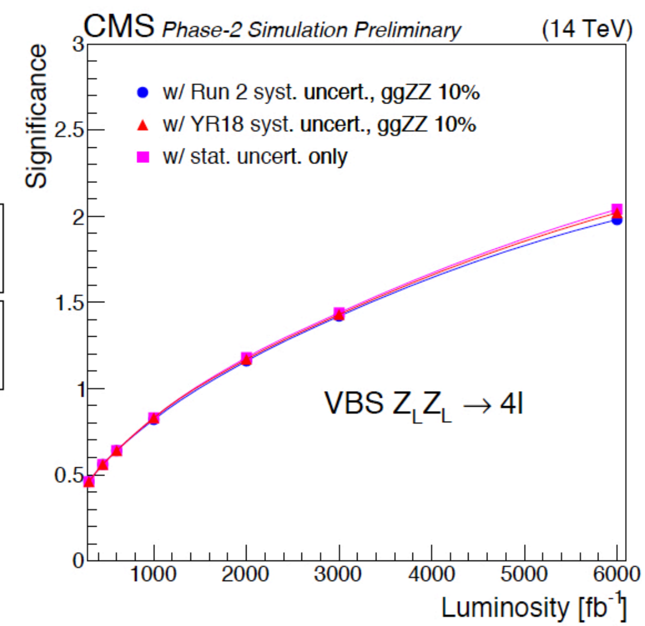


Vector boson scattering

- Measurement of longitudinal polarisation
  - In SM, Higgs unitarises longitudinal VV scattering amplitude completely ⇒ inside in nature of EWSB mechanism
  - Use $\Delta\phi_{jj}$ between 2 leading jets to separate out LL component
- Expect >3σ and 1.4σ evidence for W_LW_Ljj and Z_LZ_Ljj production ATLAS/CMS combined
- HE-LHC needed for observation

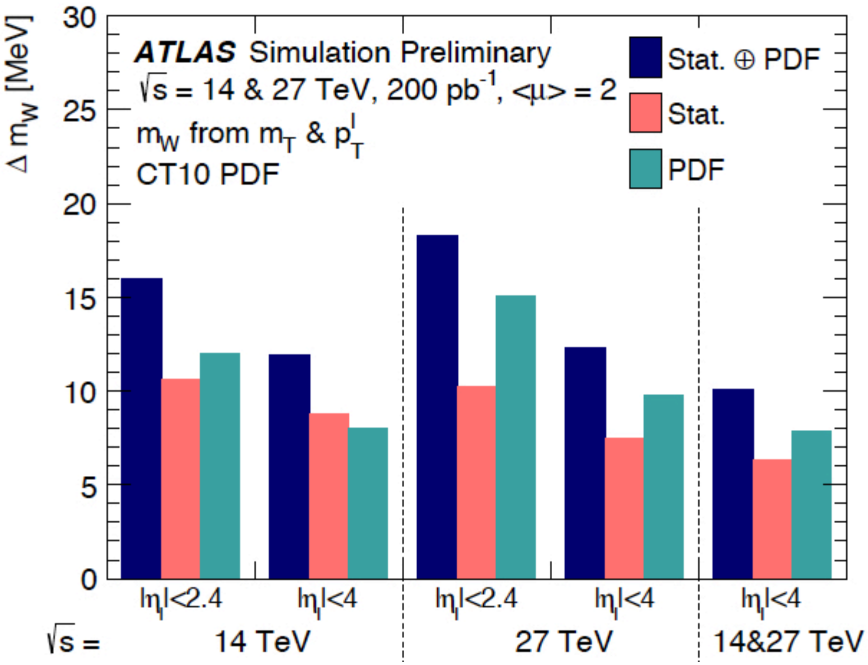


	significance		precision (%)	
	w/ syst. uncert.	w/o syst. uncert.	w/ syst. uncert.	w/o syst. uncert.)
HL-LHC	1.4σ	1.4σ	75%	75%
HE-LHC	5.2σ	5.7σ	20%	19%



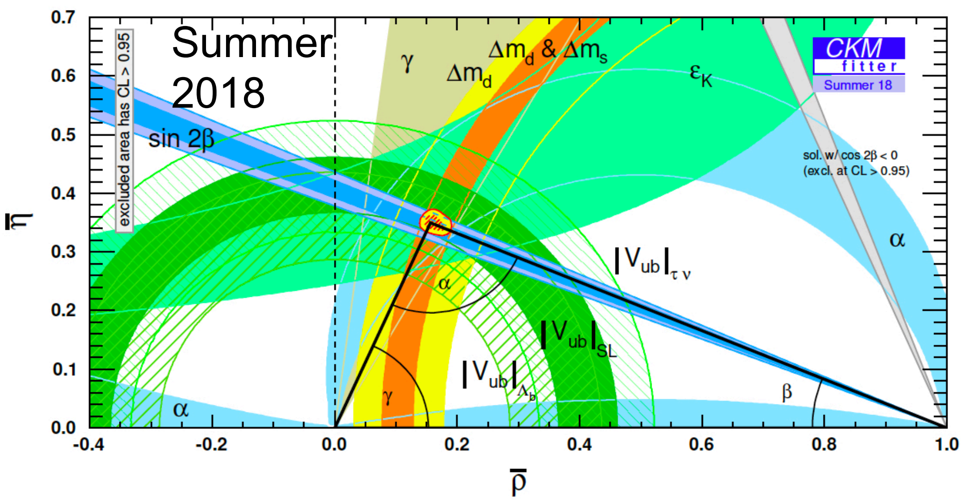
W mass measurement

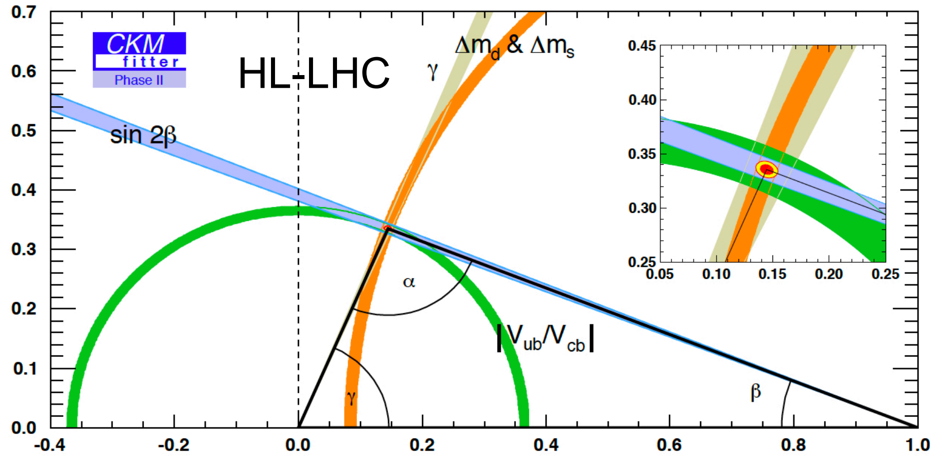
- Special low pileup runs of large interest for W mass measurement both at HL-LHC and HE-LHC
  - Assume 200 pb^{-1} of data taken with $\langle\mu\rangle \sim 2$ in 5-10 weeks
- Measurement using $W \rightarrow \ell\nu$ decays profits from tracker coverage up to $|\eta|$=4.0
- Accuracy of W mass (ATLAS) assuming current PDF uncertainties
  - Currently ATLAS: 19 MeV
  - ~12 MeV at HL-LHC
  - ~12 MeV at HE-LHC
  - ~10 MeV combined
- PDF uncert. to be improved HL (HE) LHC
  - Increase in ID acceptance
  - Increase in energy at HE-LHC



CKM Unitarity

- Projected constraints from LHCb measurements and lattice QCD calculations alone





LHCb measurements on V_{ub} and V_{cb} from semileptonic decays, γ from $B^{\pm}\rightarrow DK^{\pm}$, $B^{\pm}\rightarrow DK^{*\pm}$, $B^0\rightarrow DK^{*0}$, $B^0_{(s)}\rightarrow K^0_s h^+h^-$, $B^0_{(s)}\rightarrow h^+h^-h^0$, $B^+\rightarrow h^+h^+h^-$, … Δm_d, Δm_s from semileptonic decays of D^- or D^{*-} mesons, $B^0_s\rightarrow D^-_s\pi^-$, …, α from $B\rightarrow\pi\pi$, $B\rightarrow\rho\rho$, $B\rightarrow\rho\pi$, …

	Summer 18	Current	Phase I	Phase II
A	0.0129	0.0120	0.0058	0.0057
λ	0.0002	0.0007	0.0004	0.0004
$\bar{\rho}$	0.0085	0.0085	0.0027	0.0018
$\bar{\eta}$	0.0083	0.0087	0.0024	0.0015
$\lvert V_{ub}\rvert$	0.000076	0.000096	0.000027	0.000023
$\lvert V_{cb}\rvert$	0.00073	0.00070	0.00026	0.00025
$\lvert V_{td}\rvert$	0.00017	0.00014	0.00006	0.00006
$\lvert V_{ts}\rvert$	0.00068	0.00054	0.00026	0.00025
$\sin 2\beta$	0.012	0.015	0.004	0.003
α (°)	1.4	1.4	0.4	0.3
γ (°)	1.3	1.3	0.4	0.3
β_s (rad)	0.00042	0.00042	0.00012	0.00010

Charm mixing and CPV

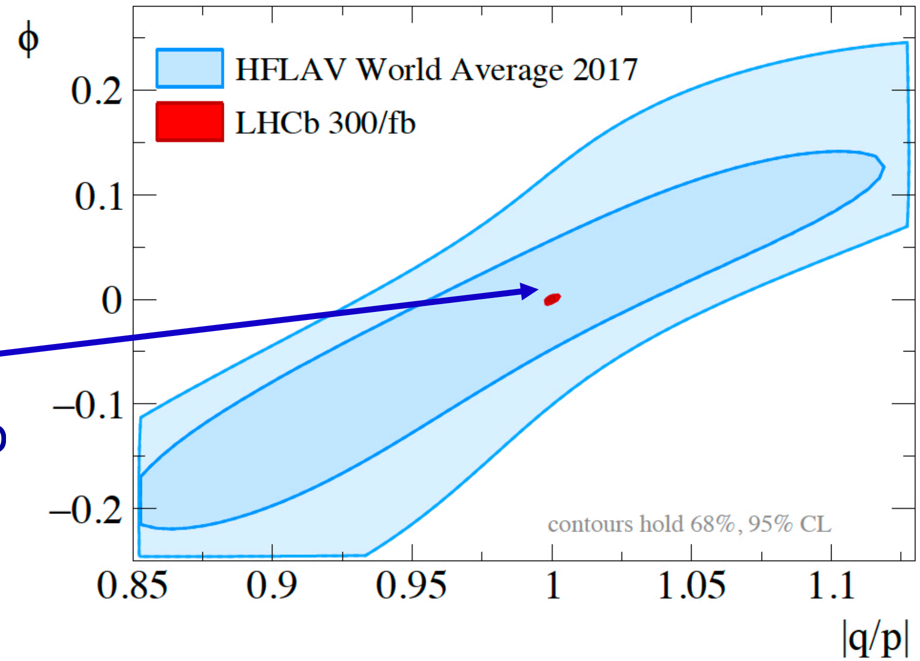
- Billions of reconstructed charm signals
- Indirect CP violation asymmetry A≈x sin(ϕ) in charm

	$D^0 \to K^\pm \pi^\mp$	$D^0 \to K^\mp \pi^\pm \pi^+ \pi^-$	$D^0 \to K_S \pi^+ \pi^-$	A_Γ
Current: LHCb	$\pm 80.0 \times 10^{-5}$	$\pm 96.0 \times 10^{-6}$	$\pm 14.0 \times 10^{-5}$	$\pm 13.0 \times 10^{-5}$
2025: Belle II	$\pm 46.0 \times 10^{-5}$		$\pm 12.0 \times 10^{-5}$	$\pm 35.0 \times 10^{-5}$
2025: LHCb	$\pm 32.0 \times 10^{-5}$	$\pm 40.0 \times 10^{-6}$	$\pm 6.2 \times 10^{-5}$	$\pm 4.3 \times 10^{-5}$
HL-LHC	$\pm 8.0 \times 10^{-5}$	$\pm 8.0 \times 10^{-6}$	$\pm 1.4 \times 10^{-5}$	$\pm 1.0 \times 10^{-5}$

$$A_\Gamma \equiv \frac{\hat{\Gamma}(D^0 \to h^+h^-) - \hat{\Gamma}(\overline{D}^0 \to h^+h^-)}{\hat{\Gamma}(D^0 \to h^+h^-) + \hat{\Gamma}(\overline{D}^0 \to h^+h^-)}$$

- Improvement of factor 4-5 w.r.t. LHC

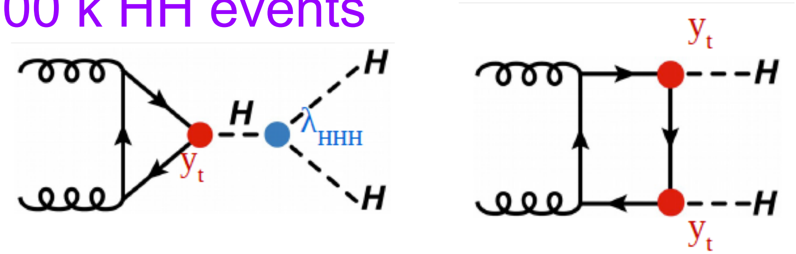
Impressive power to characterise new physics contributions to CP violation!

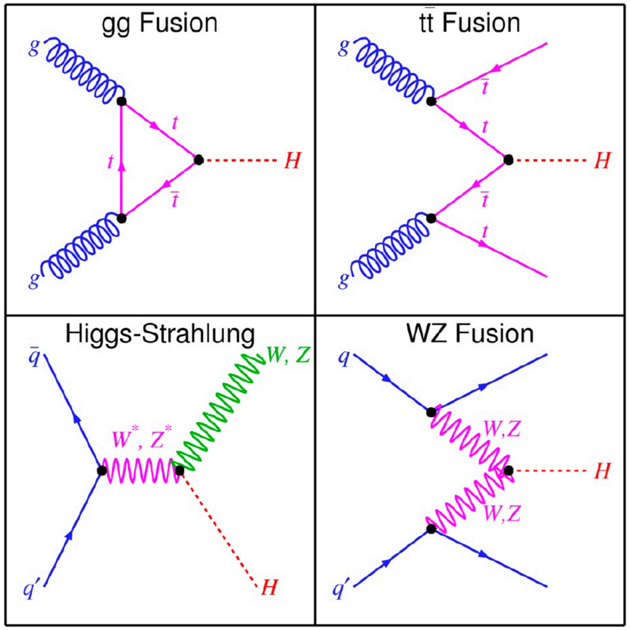


Higgs

Higgs

- HL-LHC is Higgs factory
  - Expect 170×10^6 Higgs bosons
  - Typically > 1×10^6 for each of the main production modes
  - ~100 k HH events





- Broad physics programme
  - Precision measurements (O(few %))
  - Exploration of Higgs potential (HH production)
  - Sensitivity to rare decays involving new physics
  - Extend BSM Higgs searches (extra scalars, BSM Higgs resonances, exotics decays…)

Higgs Boson Properties

- So far, Higgs boson properties in agreement with the SM expectation
- HL-LHC analysis
  - Projection of results from 2015-2017 ATLAS data and 2016 CMS data
  - Main production (gluon fusion, VBF, VH, ttH) and decay modes (γγ, ZZ, WW, bb, ττ, μμ, Zγ) considered

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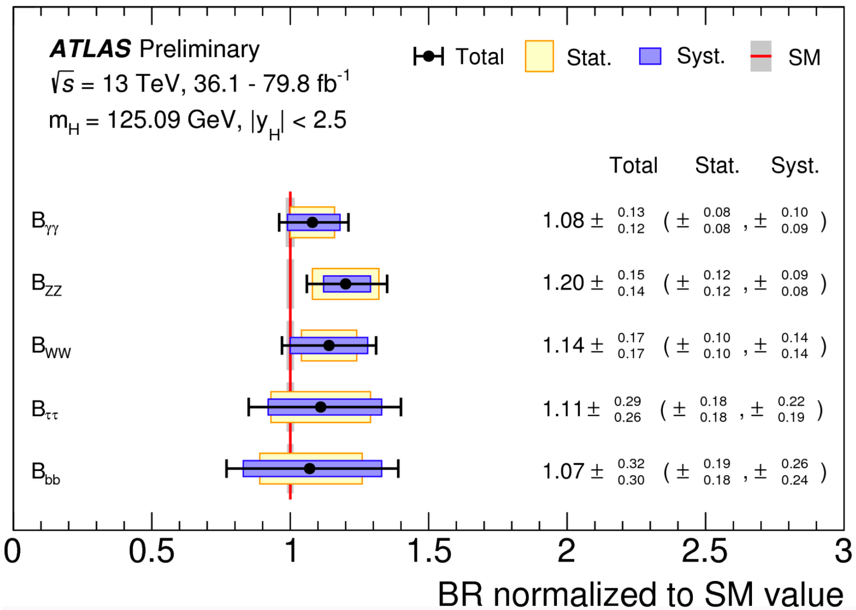

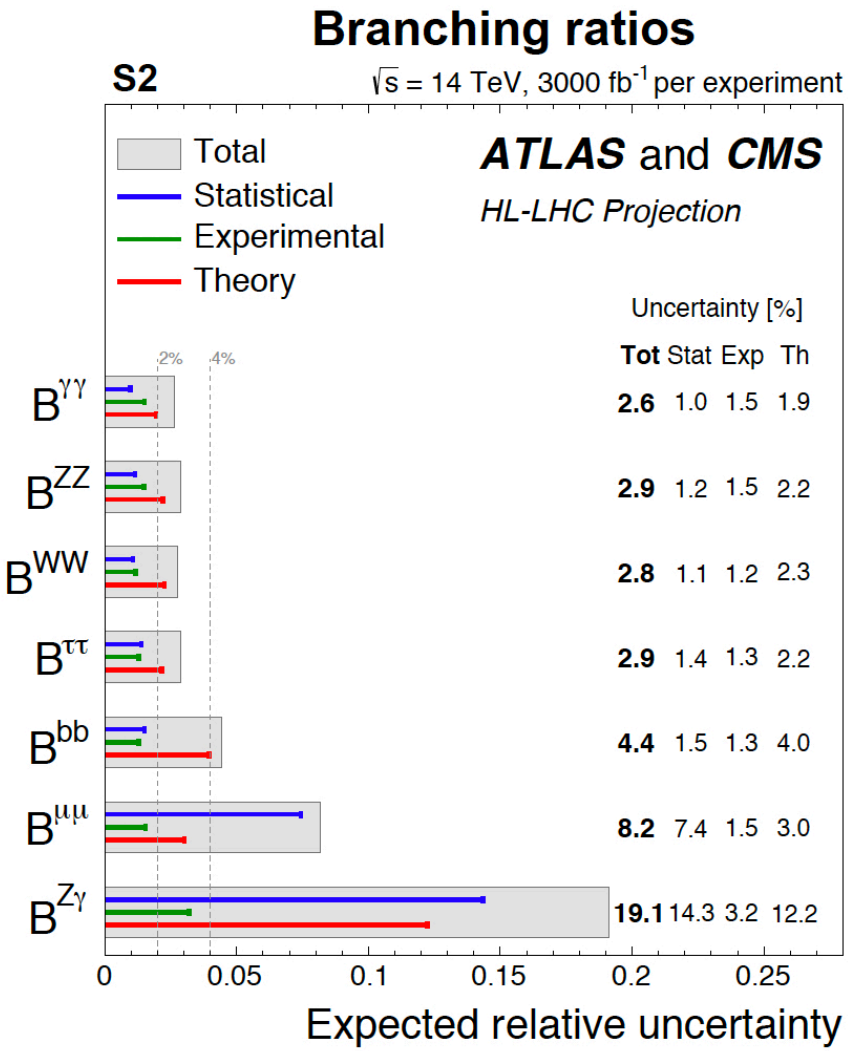

Higgs coupling measurements

- "κ framework": Consider coupling modifiers $\kappa_j^2 = \sigma_j/\sigma_j^{SM}$, or $\kappa_j^2 = \Gamma_j/\Gamma_j^{SM}$
  - Parametrises potential deviations from the SM predictions
- Uncertainties on the κ's 2-5%, apart from Zγ
  - Mostly limited by theoretical uncertainties

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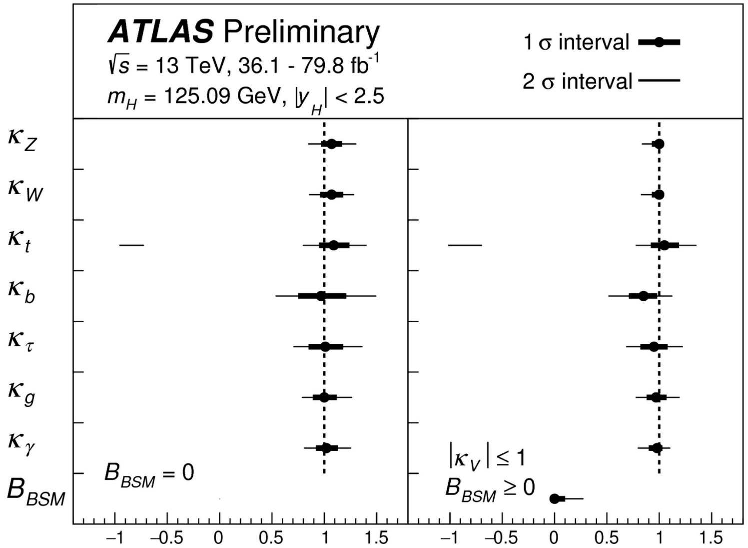
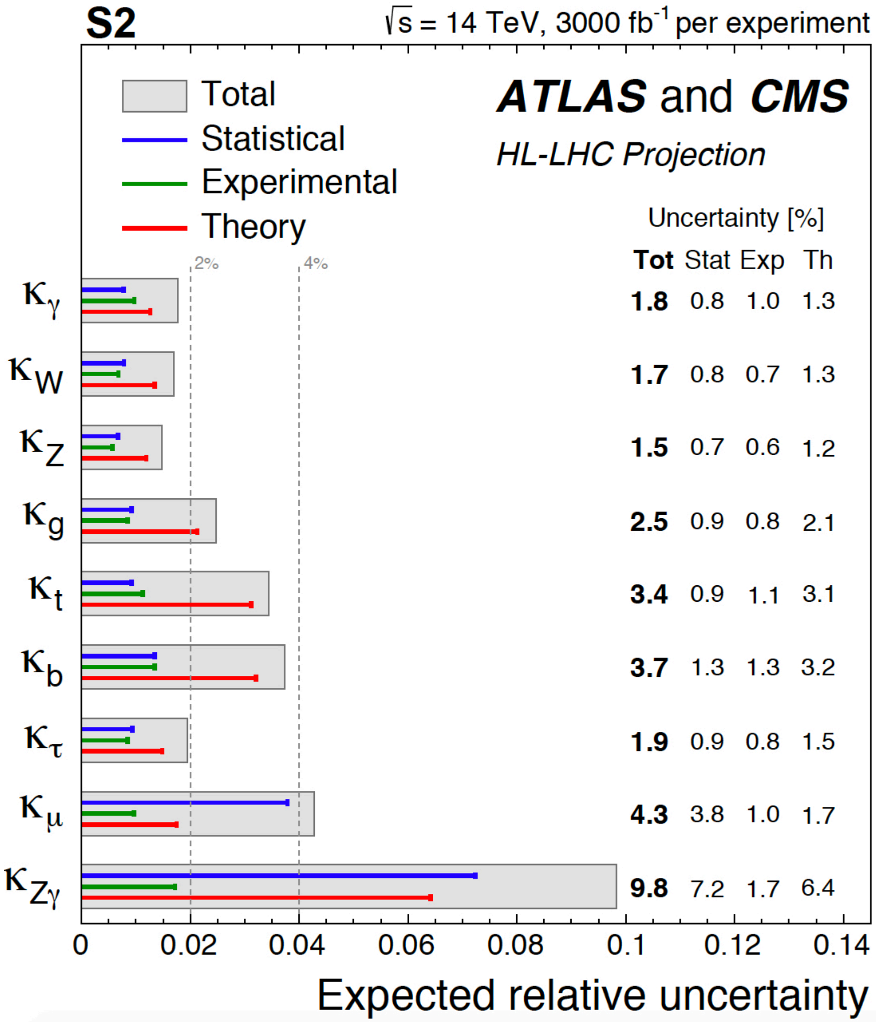
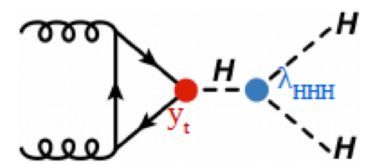
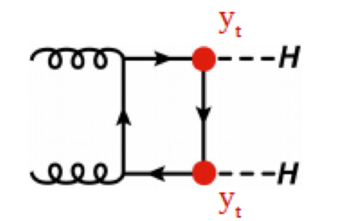




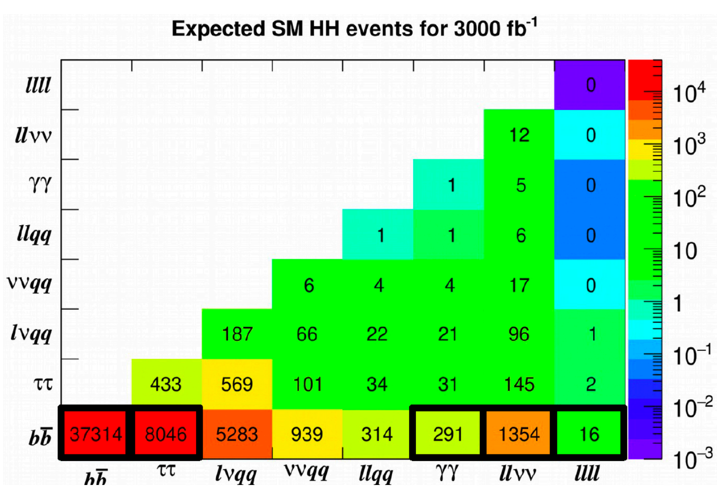
Di-Higgs production





- Rare process of the SM
  - $\sigma(gg \to HH) \approx 0.1\% \times \sigma(gg \to H)$
- BSM contributions can modify the Higgs boson coupling parameters and modify the HH cross section:
  - Define $\kappa_\lambda = c_{hhh} = \lambda_{HHH} / \lambda_{HHH}^{SM}$
- Either extrapolations from Run-2 analyses, or dedicated studies with smeared/parametric detector response

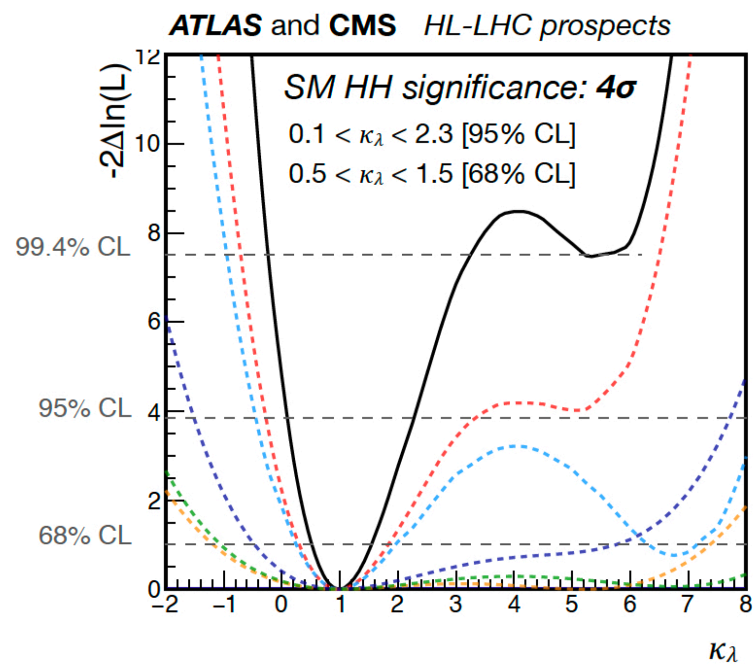
	ATLAS	CMS	
bbbb	extrapolation	parametric	Largest BR ☺ Large multijet and tt bkg ☹
bbττ	extrapolation	parametric	Sizeable BR ☺ Relatively small bkg ☺
bbγγ	smearing	parametric	Small BR ☹ Good diphoton resolution ☺ Relatively small bkg ☺
bbVV (→ lνlν)		parametric	Large BR ☺ Large bkg ☹
bbZZ (→ 4l)		parametric	Very small BR ☹ Very small bkg ☺



Di-Higgs production

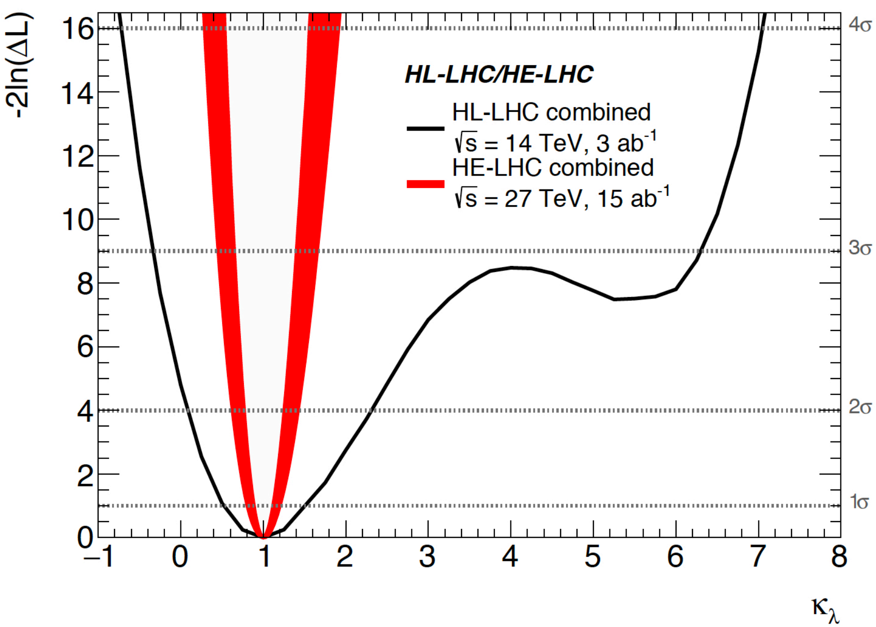
- Expected significance (SM) with/without systematics at HL-LHC
  - 4σ expected with ATLAS+CMS!
- Measurement of κ_λ
  - For 68% CI: 50%
  - 2nd minimum excluded at 99.4% CL due to m_{HH} shape information
    - 2nd minimum from increase in cross section vs coupling strength

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



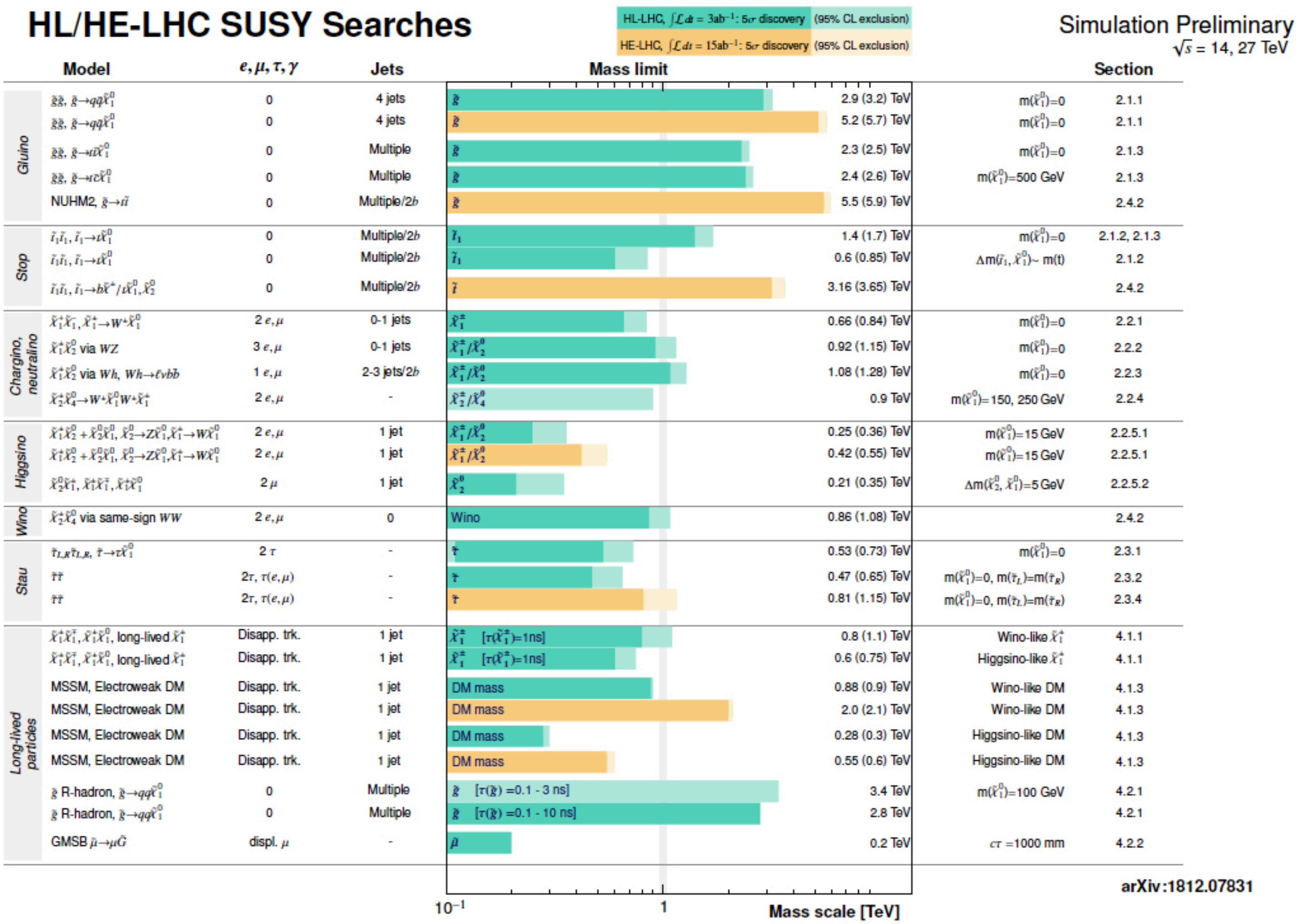
HE-LHC prospects

- Extrapolation of ATLAS HL-LHC results to HE-LHC
  - Scale cross-section to 27 TeV ($\times$4) and luminosity to 15 ab^{-1} ($\times$5)
- No systematic uncertainties
  - $bb\tau\tau$ channel: significance: 10.7σ, precision on κ_λ: 20%
  - $bb\gamma\gamma$ channel: significance: 7.1σ, precision on κ_λ: 40%
    - Pessimistic as analysis not optimised for measurement of κ_λ
    - Phenomenology study: 15% precision on κ_λ
- κ_λ could be measured with a 68% CI of 10 to 20% without uncertainties



Beyond Standard Model Searches

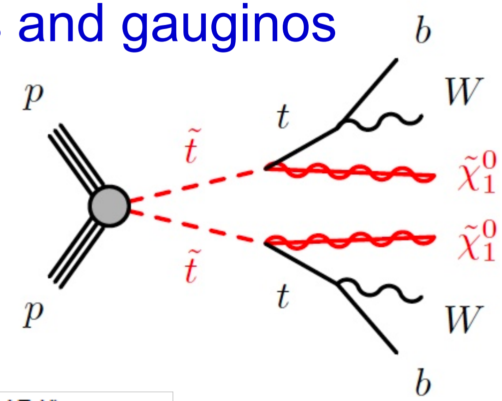
YR Supersymmetry summary

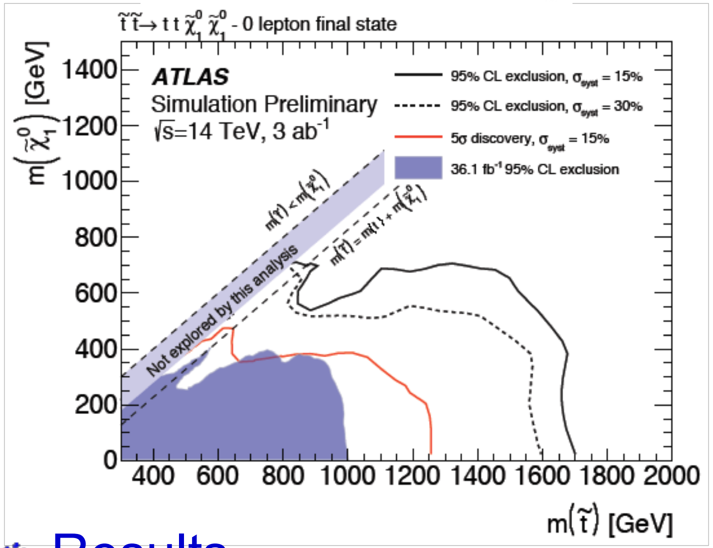


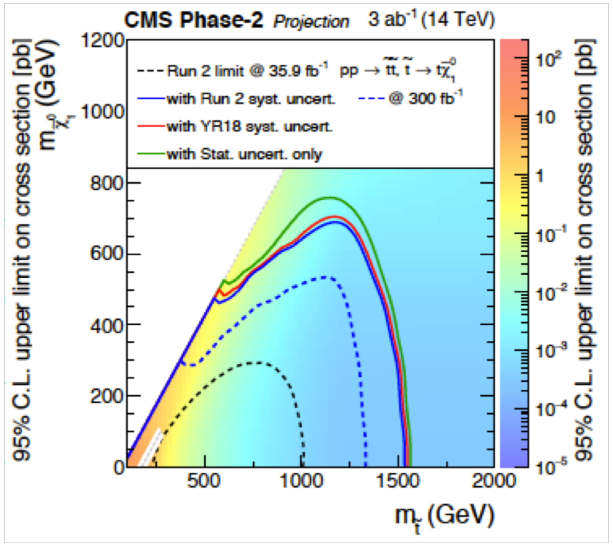
- In most of these scenarios HL-LHC will increase present mass reach by 20-50% compared to current results

3rd generation: stop-pair production

- Squarks from 1st and 2nd generations and gluinos may be heavy, naturalness requires not too heavy 3rd gen. squarks and gauginos
- Final state with ≥4 jets, large MET, no leptons
  - Exploit potential presence of boosted top's & W's
- Optimised selections for ATLAS analysis
  - $\Delta m\left(\tilde{t},\tilde{\chi}_1^0\right) \gg m_{\text{top}}$ and $\Delta m\left(\tilde{t},\tilde{\chi}_1^0\right) \sim m_{\text{top}}$

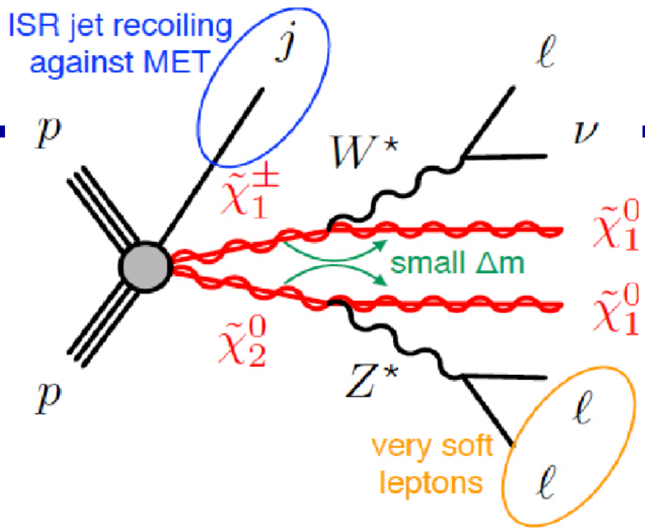




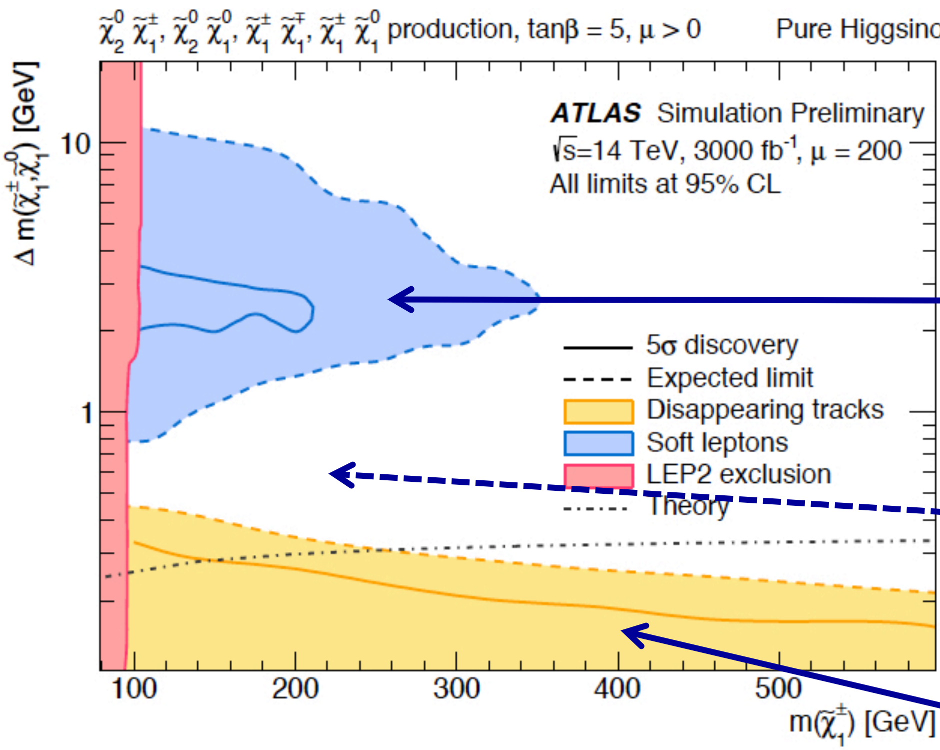


- Results
  - Top squarks discovery (exclusion) up to masses of 1.4 (1.7) TeV
  - In small Δm region, discovery (exclusion) reach is 650 (850) GeV

(Boosted) Higgsino searches

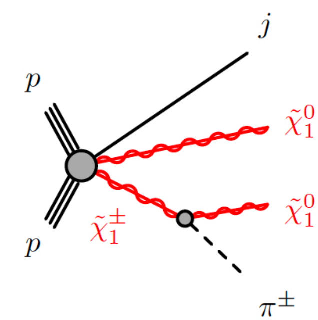


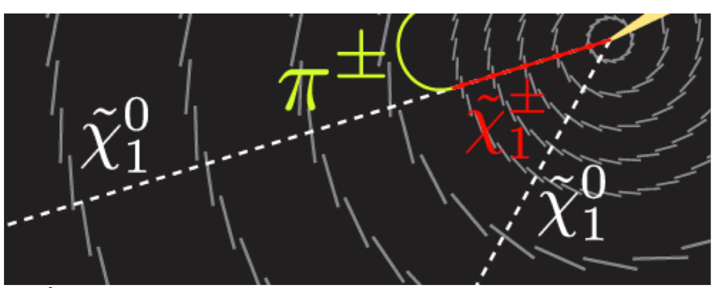
- Higgsino mass << bino & wino mass
  - $\tilde{\chi}^0_1$, $\tilde{\chi}^{\pm}_1$, $\tilde{\chi}^0_2$ ~ mass degenerate



Exploit ISR jet + MET + soft muons (p_T > 3 GeV)

Gap needs to be filled
- mono-photon from FSR? VBF?

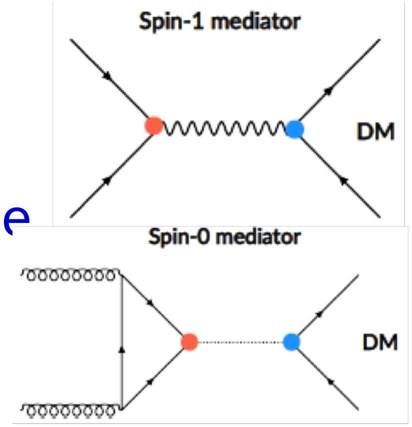


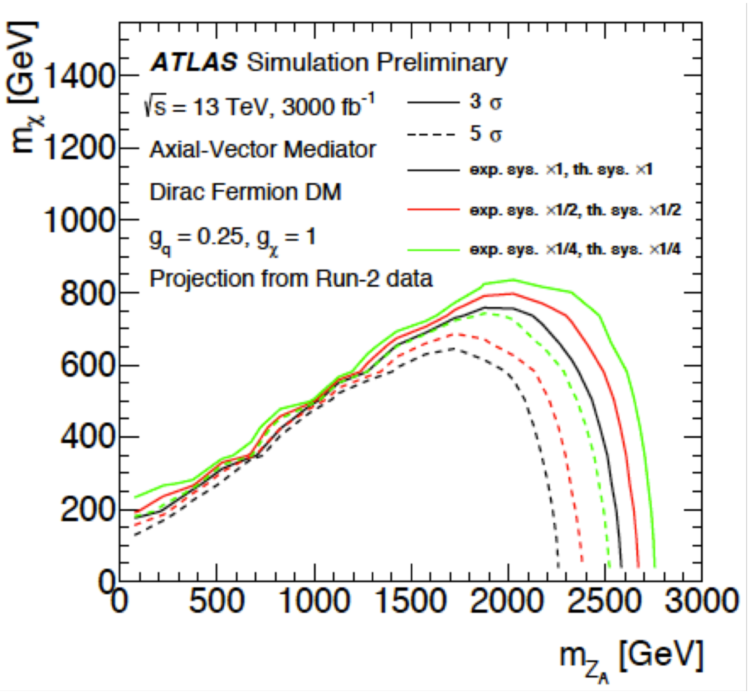


Disappearing track (long-lived charginos)
- Chargino decays before exiting tracker into a very soft π and $\tilde{\chi}^0_1$
- Special track reconstruction needed

Dark Matter searches

- Foreseen by full theories as SUSY but also searched with 'simplified models'
  - Simplified models have few free parameters, m_{med}, m_{DM}, med-quark and med-DM coupling
- Strategy: search for associated production with SM particle
  - Jet, photon, Z, single/double top, bottom, Higgs
- Flagship DM analysis: search for high-p_T jet + large MET

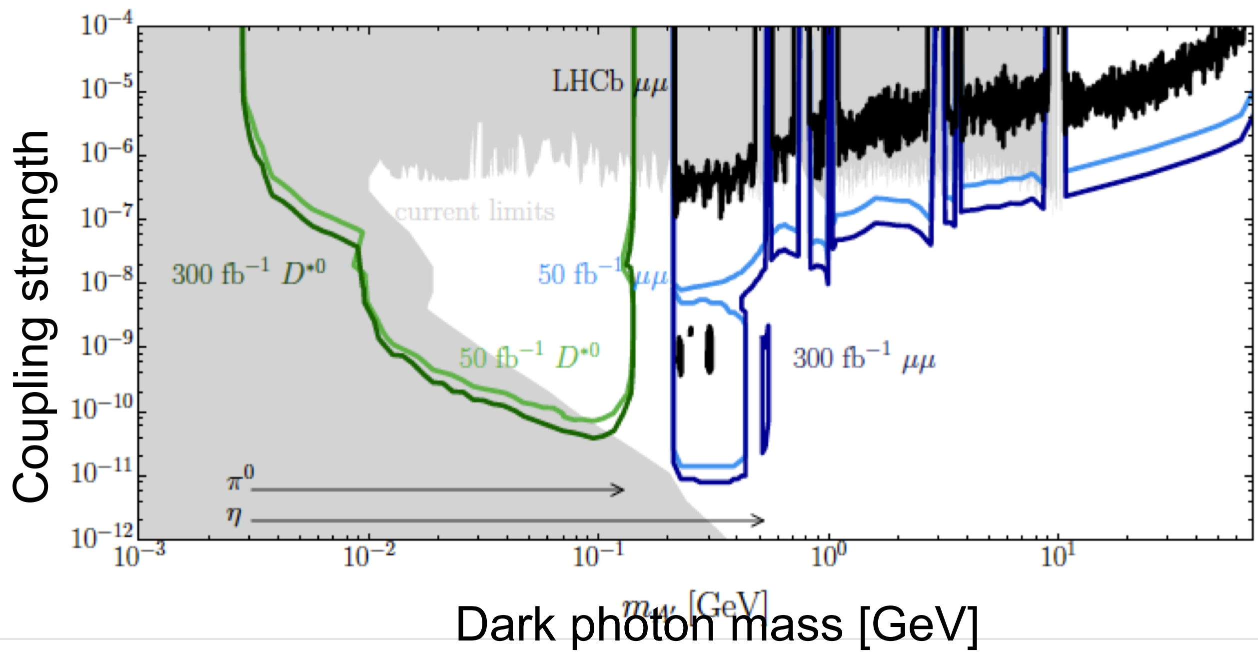




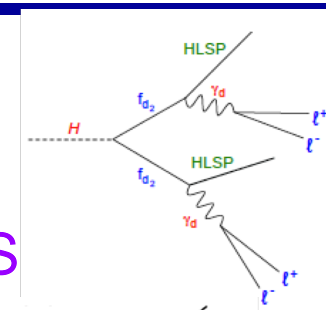
- Results
  - Discovery (exclusion) of $m(Z_A)$ up to 2.25 (2.65) TeV
  - Main uncertainty from modelling of signal and background, + jet/MET scale and resolution

Search for dark photons

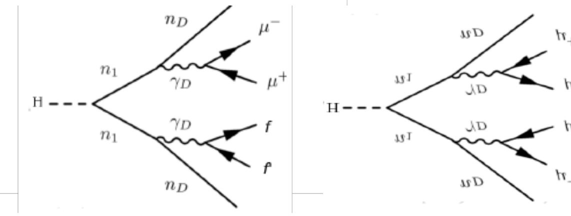
- Many BSM theories predict some sort of hidden sector, weakly coupled to visible sector
- E.g. dark sector which couples to SM via dark photon A' which mixes with the SM γ
- LHCb particularly well suited to probe new physics in low p_T region and has excellent capabilities to reconstruct b and c-hadrons
- Look for
  - $D^* \to D^0 A'$, $A' \to e^+e^-$
  - $A' \to \mu^+\mu^-$ (prompt and displaced)
  - Fully data-driven approach for 2nd study, A' rate inferred from SM prompt μμ spectrum



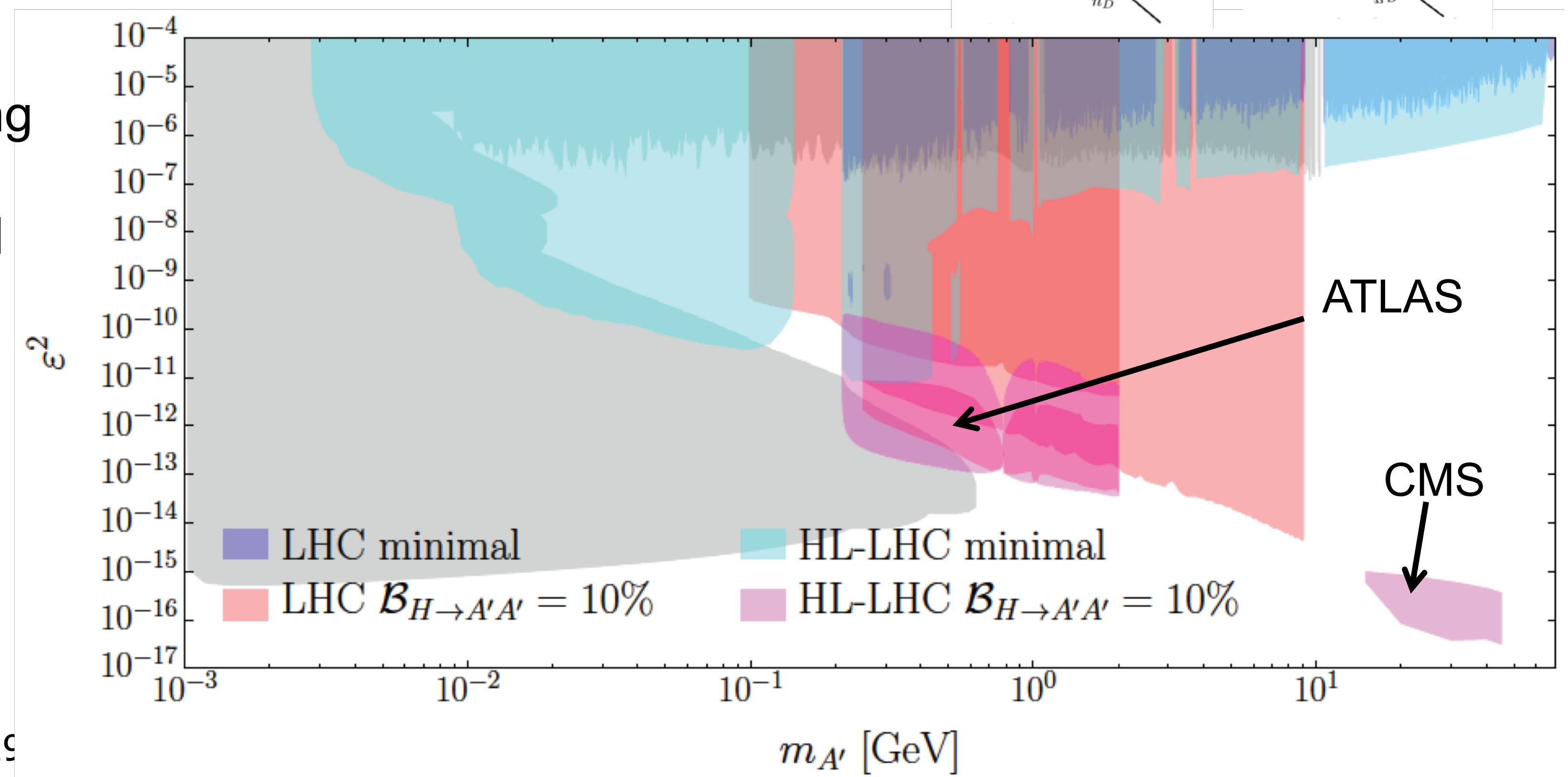
Search for dark photons



- Dark photons can be also produced through Higgs portal (assume H→A’A’ with BR = 10%)
  - Search for displaced collimated muon jets in ATLAS
- Also predicted in Dark Susy models
  - Search for 2 displaced muon in CMS

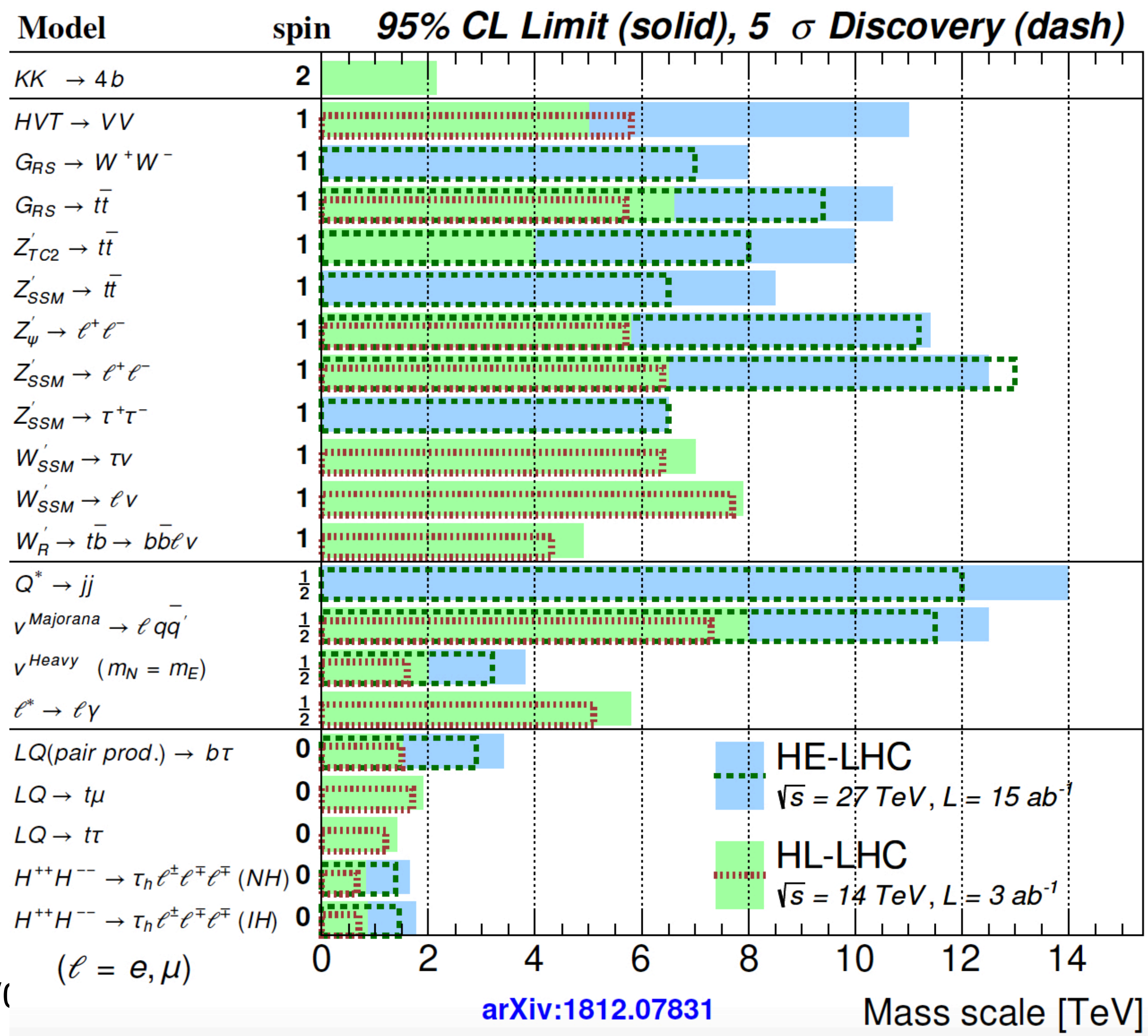


Assuming BR(H→ A’A’)=0.1



YR Exotics summary

- Many BSM scenarios studied in Yellow Report

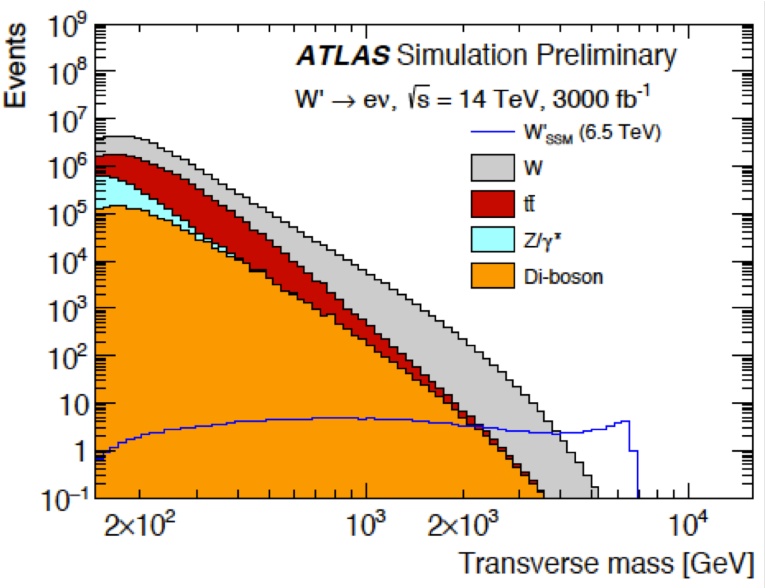


W'→lν resonance searches

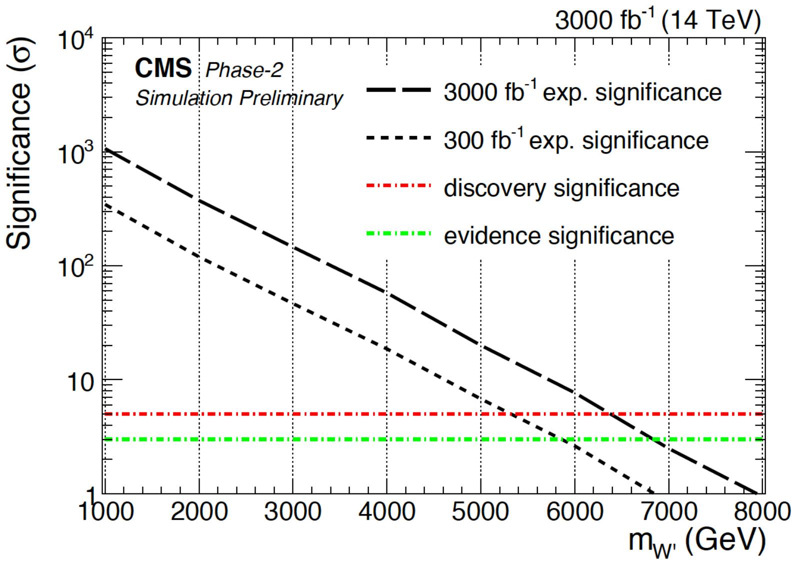
- W'→lν, l=e,μ search (ATLAS)
  - Assume W' predicted by SSM

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

  - Current exclusion up to 5.6 TeV



- W'→τν search (CMS)
  - Discovery up to m(W')=6.4 TeV
  - Exclusion up to m(W')=7 TeV

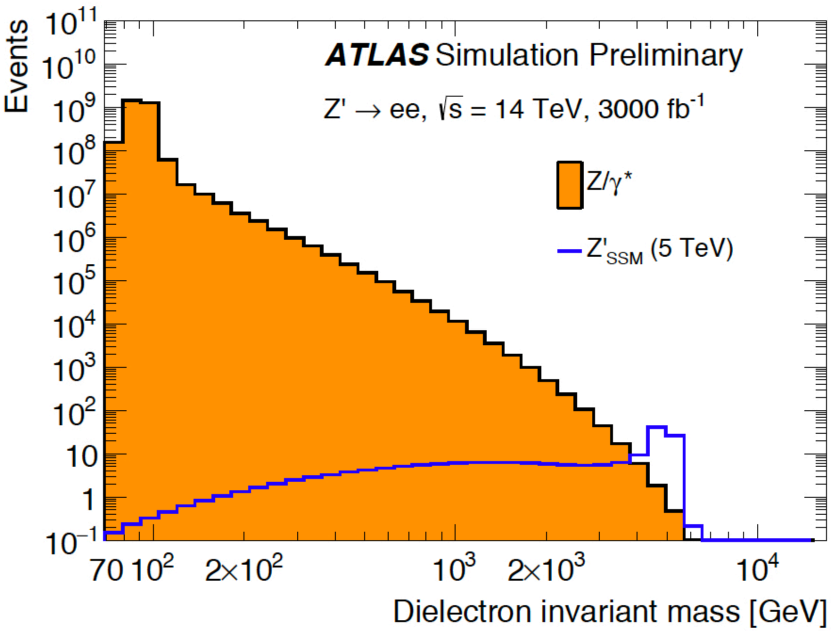


Z'→ll resonance searches

- Z'→ll, l=e,μ search (ATLAS)
  - Current exclusions (139 fb^{-1})

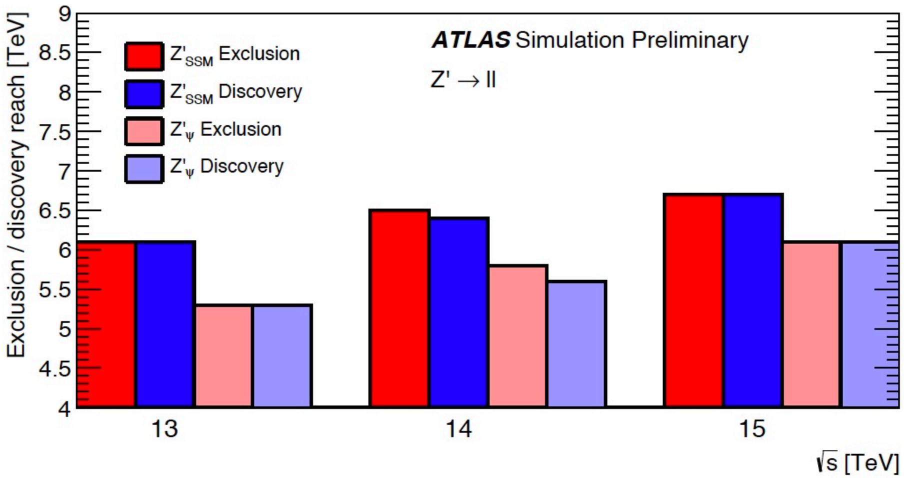
ATLAS-CONF-2019-001

Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.3	4.3	4.0	3.8	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.1	4.8	4.7
Z'_{SSM}	4.9	4.9	4.5	4.4	5.1	5.0



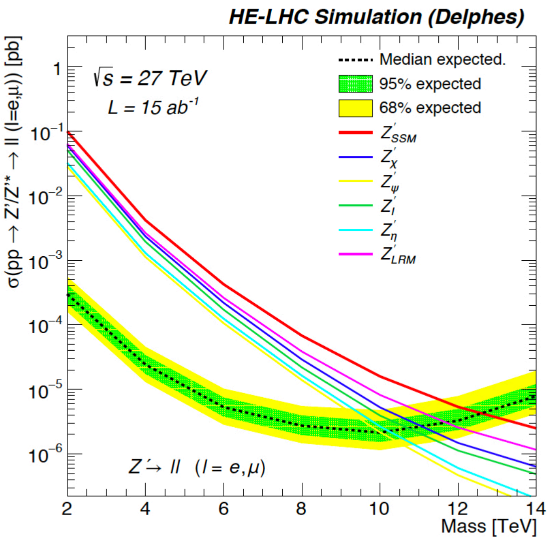
  - Consider Z'$_{SSM}$ & Z'$_\psi$ for HI-LHC

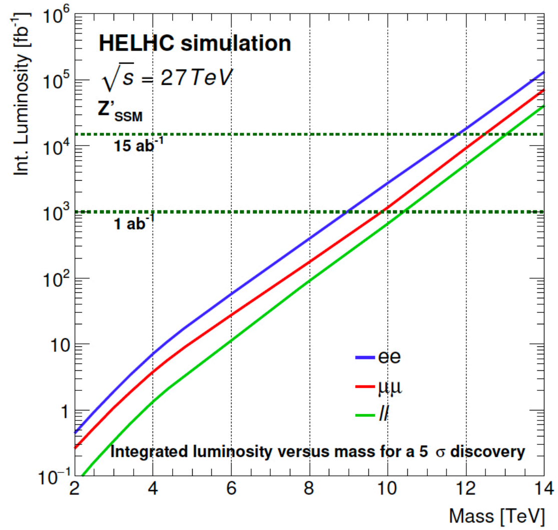
Decay	$\sqrt{s} = 14$ TeV Exclusion	Discovery
$Z'_{\mathrm{SSM}} \to ee$	6.4 TeV	6.3 TeV
$Z'_{\mathrm{SSM}} \to \mu\mu$	5.8 TeV	5.7 TeV
$Z'_{\mathrm{SSM}} \to \ell\ell$	6.5 TeV	6.4 TeV
$Z'_\psi \to ee$	5.7 TeV	5.6 TeV
$Z'_\psi \to \mu\mu$	5.2 TeV	5.0 TeV
$Z'_\psi \to \ell\ell$	5.8 TeV	5.7 TeV



Z'→ll resonance searches

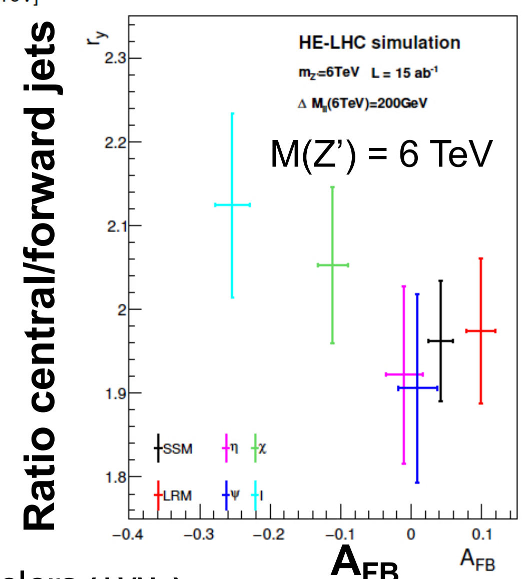
- HE-LHC projections for Z'→ll





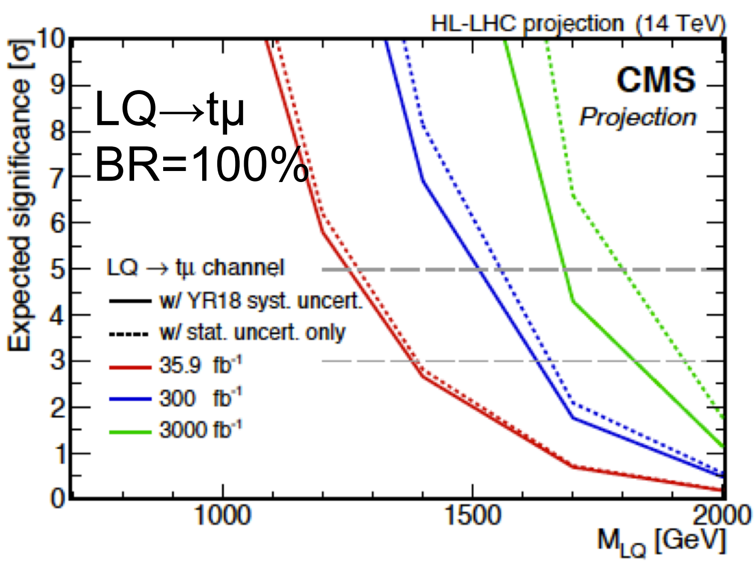
  - SSM Z' excluded/discovered up to ~12.5 TeV

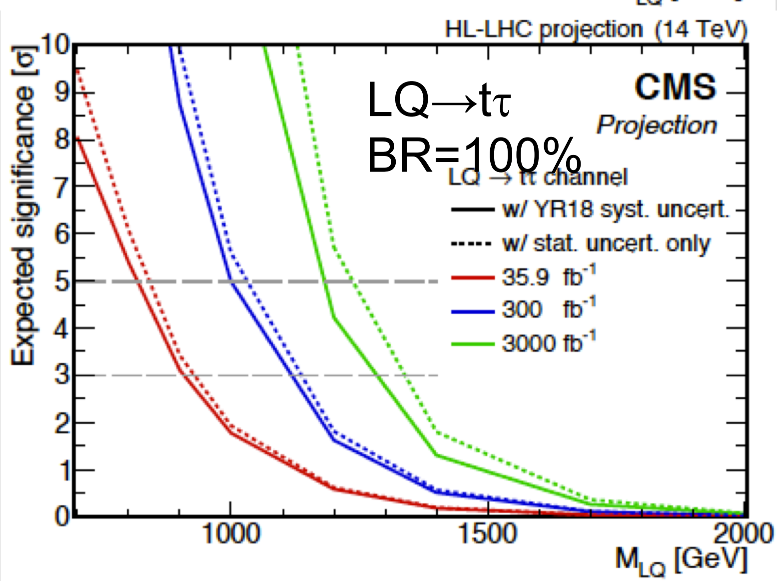
- And if we find Z' at HE-LHC?

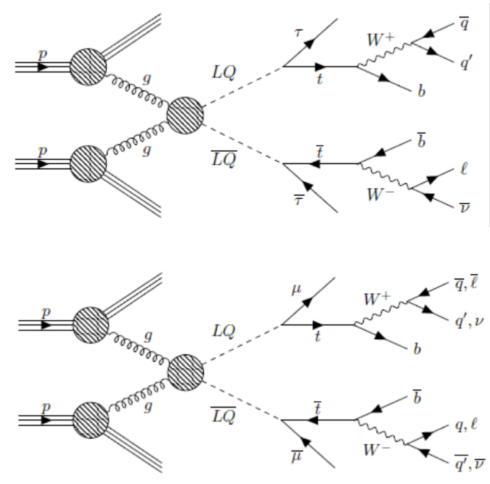


LQ→tτ or tμ search

- 3rd gen. LQ are favoured by models interpreting observed B-anomalies!

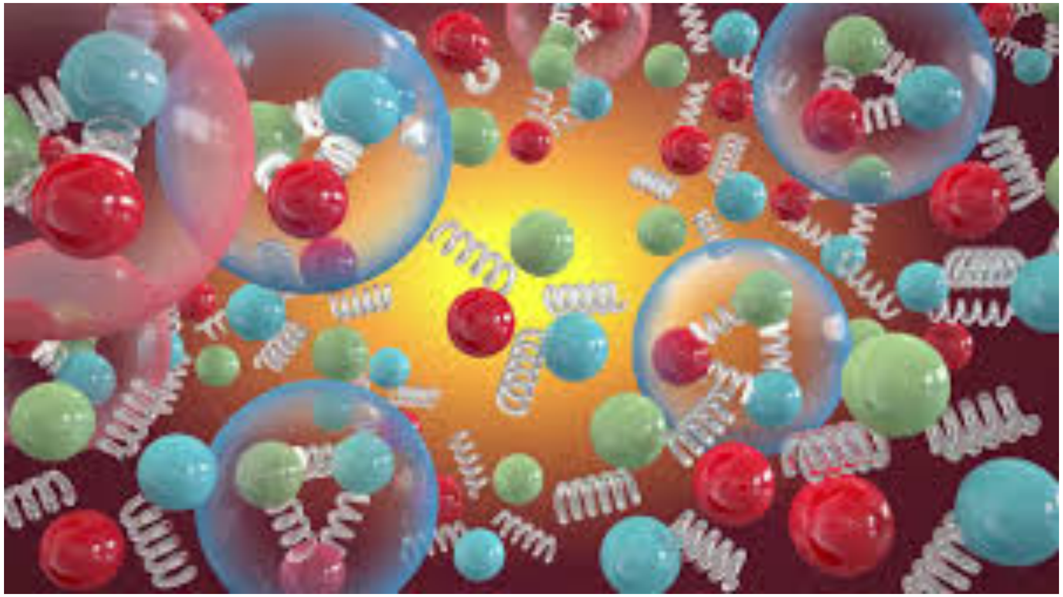






- Discovery reach M_{LQ}~1.7 TeV (tμ) and 1.2 TeV (tτ) assuming 100% BR for either channel
- Exclusion limits ~200 GeV higher
- Present limits: 1.4 TeV (tμ), 0.9 TeV (tτ)

Heavy Ions



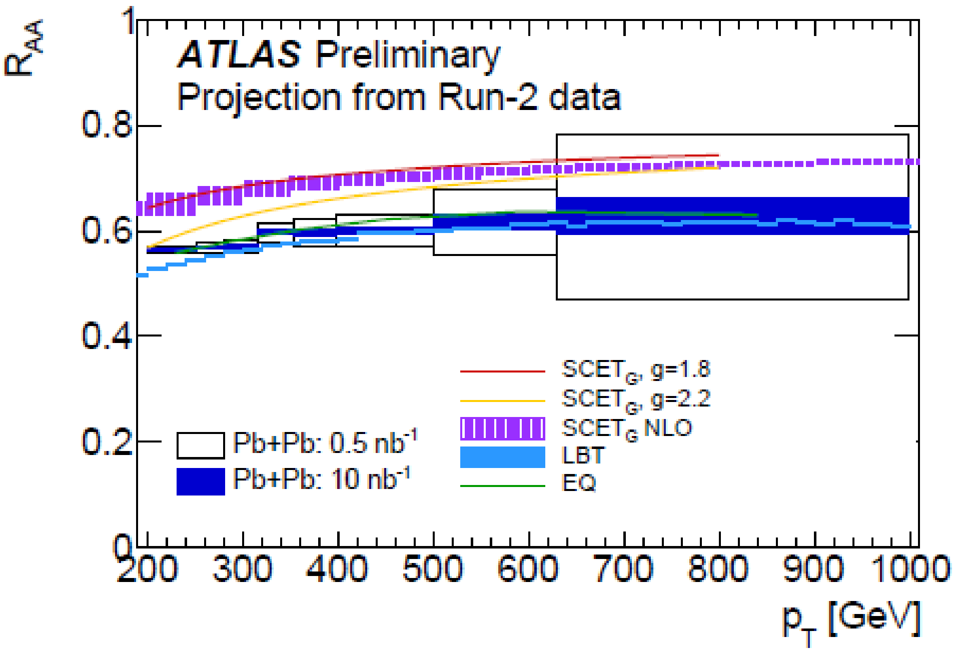
Heavy Ion Programme

- Macroscopic properties of the QGP
  - temperature will be, for the first time at the LHC, determined with an accuracy of about 20% by measuring thermal radiation
  - heavy-quark diffusion coefficient $2\pi T\ D_s$, which at a temperature T of 1–2 × the QCD critical temperature T_C will be constrained with a 2 × improved accuracy
- Microscopic structure and inner workings of the QGP
  - Multi-differential jet measurements
  - Measurements of the production of charmonium and bottomonium states with different binding energies give access to a well-defined set of length scales for the study of the QCD potential and its modification in a colour-deconfined medium via the characterization of the mechanisms of melting and regeneration
- QCD dynamics from small to larger systems.
- Nuclear parton densities and search for saturation
  - Pb/Pb and p/Pb also contains gamma/Pb collisions helps to measure PDFs in nuclei, probes low-x region

Jet Modification in HI Collisions

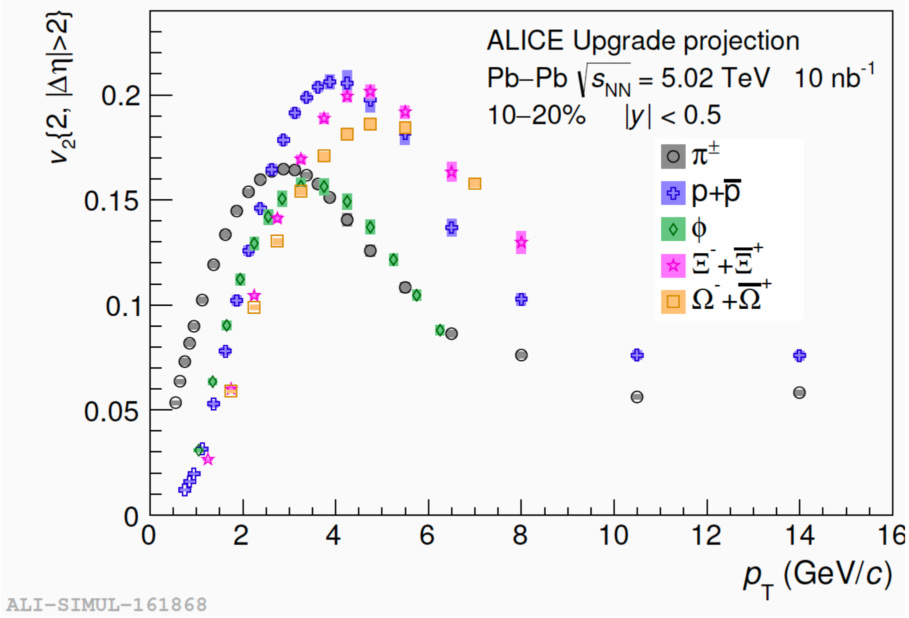
- Compare jet production in Pb-Pb with pp collisions
- Projections based on 10 nb^{-1} of Pb-Pb data
- Measure energy lost by parton shower due to interactions with (deconfined) QCD medium
  - Aka jet quenching
  - Nuclear modification factor

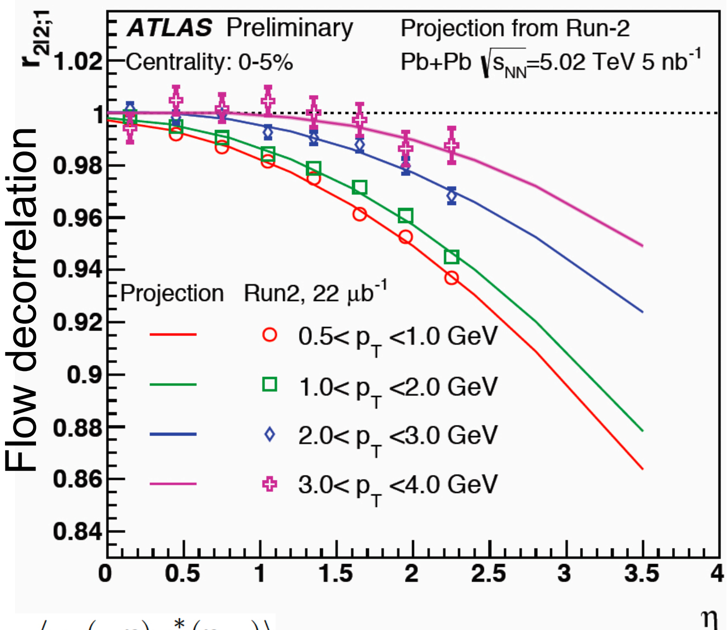
$$R_{AA} = \frac{\frac{1}{N_{evt}^{tot}} \frac{d^2 N_{jet}}{dp_T dy}\Big|_{cent}}{T_{AA} \frac{d^2 \sigma_{jet}}{dp_T dy}\Big|_{pp}}$$



Prospects of flow measurements

- Unprecedented high precision and differential measurements of flow harmonics and their event-by-event fluctuations
  - New constraints on the QGP initial density profile, formation time, properties and hadronisation





$$r_{n|n;1}(\eta) = \frac{\langle \mathbf{v}_n(-\eta)\mathbf{v}_n^*(\eta_{\rm ref})\rangle}{\langle \mathbf{v}_n(\eta)\mathbf{v}_n^*(\eta_{\rm ref})\rangle}$$

- Pseudorapidity dependence of flow measurement over a larger η range up to 4 for ATLAS/CMS at HL-LHC
  - New insights into longitudinal structure of the QGP (event-plane decorrelation)

Summary

- Enormous amount of physics analyses shown in Yellow report
  - Input to European strategy
- Results are mostly very conservative
  - Advances in analyses techniques and better optimisations will improve results
- But first, we'll have to upgrade the detectors for HI-LHC…