Physics Prospects for the HL-LHC and HE-LHC

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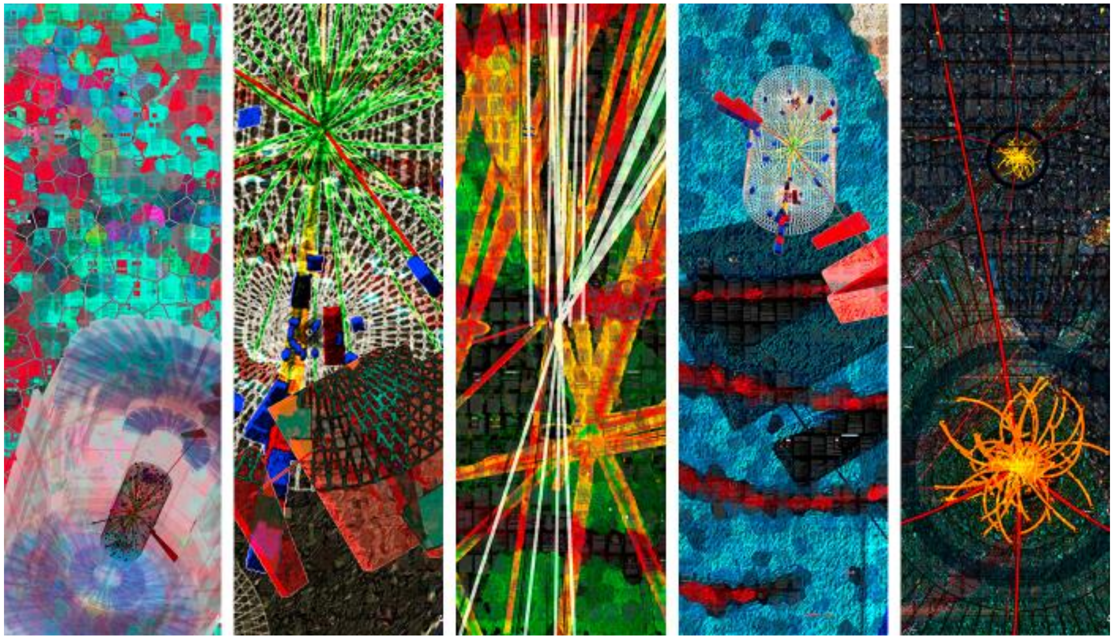
ICFA Seminar
November 2017



Why explore the TeV scale?

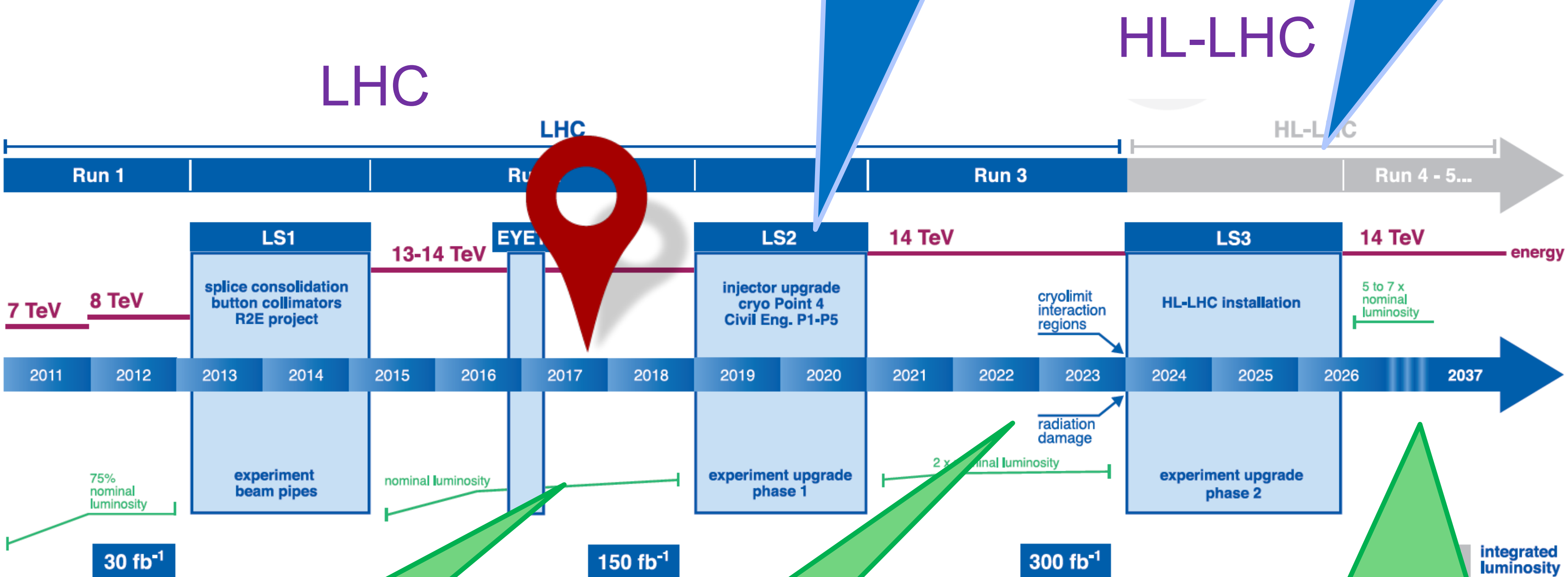
- Standard Model works beautifully
  - currently no direct evidence of new physics at the LHC
- Key questions remain unanswered
  - What gives rise to the matter-antimatter asymmetry in the universe?
  - What is dark matter made of? What is dark energy?
  - Why is gravity so weak? ➔ hierarchy problem
    - Small Higgs mass requires spectacular cancellations if SM is valid to Planck scale
    - Strong motivation for new physics at the TeV scale (➔ new particles, interactions, dimensions)
- The answers may lie at the TeV scale…

- HL-LHC will deliver 3/ab (x50 today's data sample) @ 14 TeV
  - Study the Higgs boson in detail
    - BSM physics could manifest itself in deviations from SM predictions
  - Measure rare SM processes
    - BSM could have a large effect
  - Search for new particles/phenomena at the TeV scale
    - Could provide solution to the hierarchy problem (e.g. top quark partners)
    - Can dark matter be produced at the LHC?
- HE-LHC would double the collision energy to 27 TeV
  - Higher mass reach for new physics – deeper exploration of TeV scale
- Investigate properties of new particles which are observed along the way!

HL-LHC plan

upgrade of injector chain to deliver brighter bunches

new interaction region layout and crab cavity



Run 2:
Design $\mathcal{L} = 10^{34}/\mathrm{cm}^2/\mathrm{s}$

Run 3:
$\mathcal{L} = 2\times10^{34}/\mathrm{cm}^2/\mathrm{s}$
for 300/fb

HL-LHC: Peak $\mathcal{L} = 2\times10^{35}/\mathrm{cm}^2/\mathrm{s}$
level luminosity to
Nominal scenario: $\mathcal{L} = 5\times10^{34}/\mathrm{cm}^2/\mathrm{s}$
for 3000/fb; Pile-up <μ> = 140
Ultimate Scenario: $\mathcal{L} = 7.5\times10^{34}/\mathrm{cm}^2/\mathrm{s}$
for 4000/fb; Pile-up <μ> = 200
$\Rightarrow$25% increase in integrated lum.

HE-LHC

- Center of mass energy: 27 TeV pp collision
  - [~ 14 TeV x 16 T/8.33T]
  - "This "Energy Doubler" option with high-field magnets constitutes an adiabatic approach to pp-collisions at higher energy."*[1]
  - Target luminosity ≥ 4 x HL-LHC
  - Integrated Luminosity: >10 ab^{-1} over 20 years
- Pile up of up to ~800 at 25 ns bunch spacing
  - (~400 at 12.5 ns or with luminosity leveling)
  - excellent prospects for lepton-hadron & heavy-ion collisions

- HE-LHC main challenges
  - Technical schedule defined by the magnet program
- Earliest technically possible start of physics: 2040
  - This would require HL-LHC stop at LS5 (in 2034)

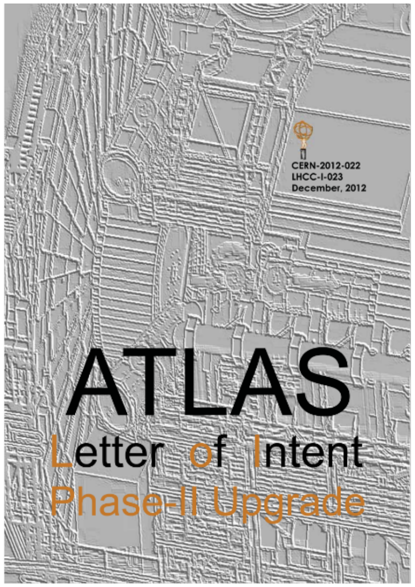
- [1] For details see presentations at the HL/HE-LHC kick-off workshop at CERN: https://indico.cern.ch/event/647676/.

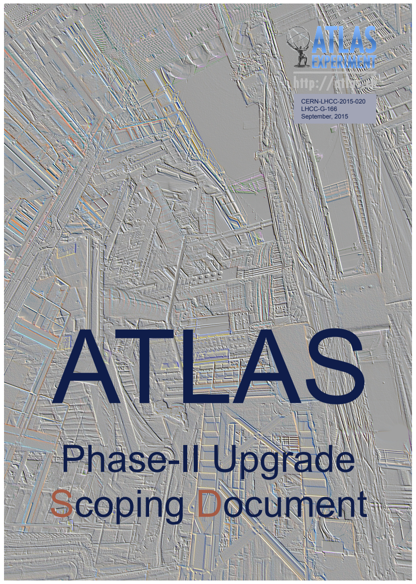
ATLAS & CMS DETECTOR UPGRADES

To achieve the physics reach

ATLAS and CMS Documents

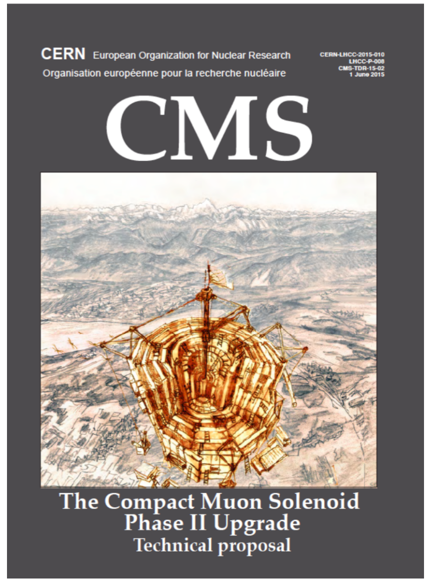
- ATLAS letter of intent and scope document

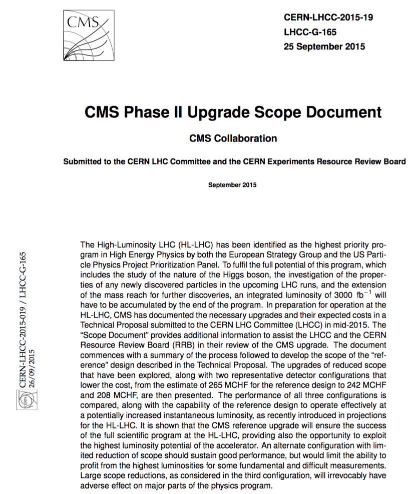




CERN-LHCC-2012-022
https://cds.cern.ch/record/1502664
CERN-LHCC-2015-020
https://cds.cern.ch/record/2055248

- CMS technical proposal and scope document





CERN-LHCC-2015-19
LHCC-G-165
25 September 2015

CMS Phase II Upgrade Scope Document

CMS Collaboration

Submitted to the CERN LHC Committee and the CERN Experiments Resource Review Board

September 2015

CERN-LHCC-2015-019 / LHCC-G-165
26/09/2015

The High-Luminosity LHC (HL-LHC) has been identified as the highest priority program in High Energy Physics by both the European Strategy Group and the US Particle Physics Project Prioritization Panel. To fulfil the full potential of this program, which includes the study of the nature of the Higgs boson, the investigation of the properties of any newly discovered particles in the upcoming LHC runs, and the extension of the mass reach for further discoveries, an integrated luminosity of 3000 fb^{-1} will have to be accumulated by the end of the program. In preparation for operation at the HL-LHC, CMS has documented the necessary upgrades and their expected costs in a Technical Proposal submitted to the CERN LHC Committee (LHCC) in mid-2015. The "Scope Document" provides additional information to assist the LHCC and the CERN Resource Review Board (RRB) in their review of the CMS upgrade. The document commences with a summary of the process followed to develop the scope of the "reference" design described in the Technical Proposal. The upgrades of reduced scope that have been explored, along with two representative detector configurations that lower the cost, from the estimate of 265 MCHF for the reference design to 242 MCHF and 208 MCHF, are then presented. The performance of all three configurations is compared, along with the capability of the reference design to operate effectively at a potentially increased instantaneous luminosity, as recently introduced in projections for the HL-LHC. It is shown that the CMS reference upgrade will ensure the success of the full scientific program at the HL-LHC, providing also the opportunity to exploit the highest luminosity potential of the accelerator. An alternate configuration with limited reduction of scope should sustain good performance, but would limit the ability to profit from the highest luminosities for some fundamental and difficult measurements. Large scope reductions, as considered in the third configuration, will irrevocably have adverse effect on major parts of the physics program.

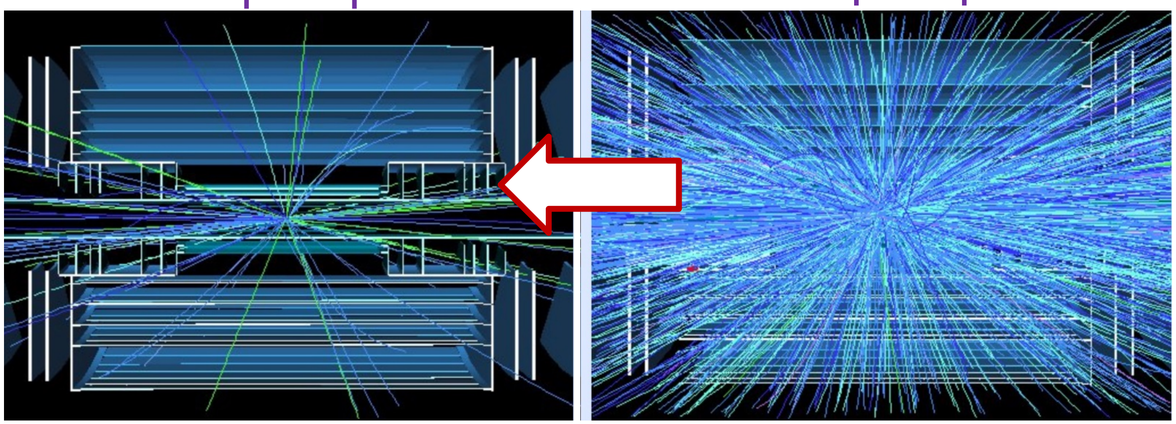
CERN-LHCC-2015-010
https://cds.cern.ch/record/2020886
CERN-LHCC-2015-019
https://cds.cern.ch/record/2055167

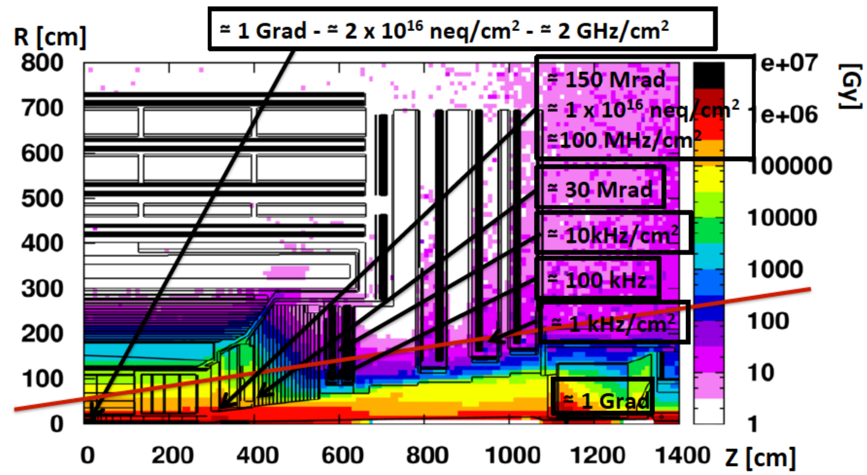
Technical Design reports for sub detector systems are being prepared & under review

Swarms of Particles and High Radiation!

- High luminosity ➔ 200 soft pp interactions per crossing
  - Increased combinatorial complexity, rate of fake tracks, spurious energy in calorimeters, increased data volume to be read out in each event
- Detector elements and electronics are exposed to high radiation dose
  - Requires new tracker, endcap calorimeters, forward muons, replacing readout systems

25 pileup 200 pileup

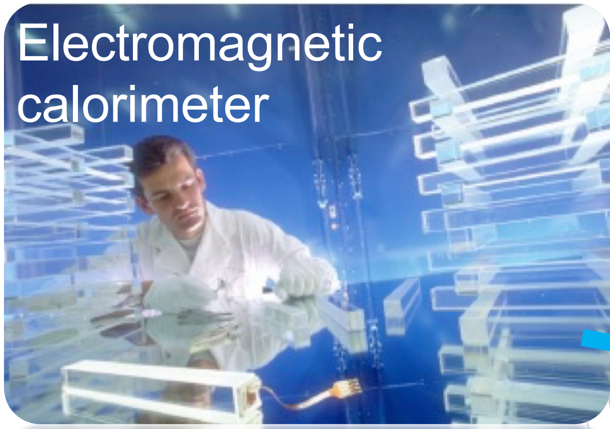


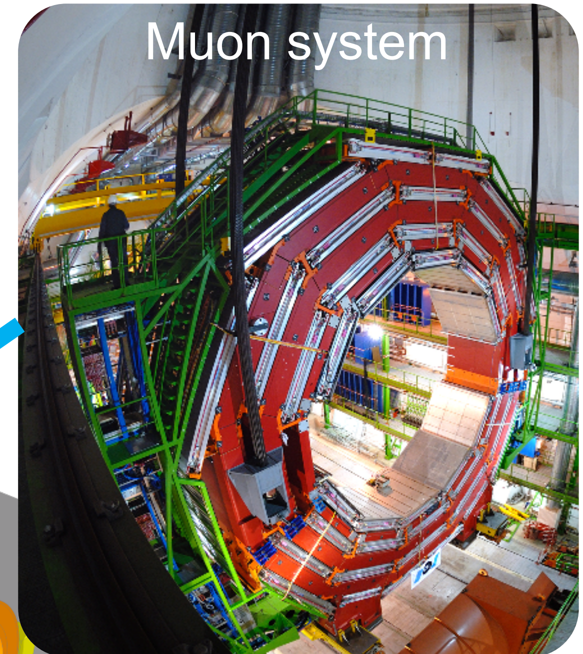


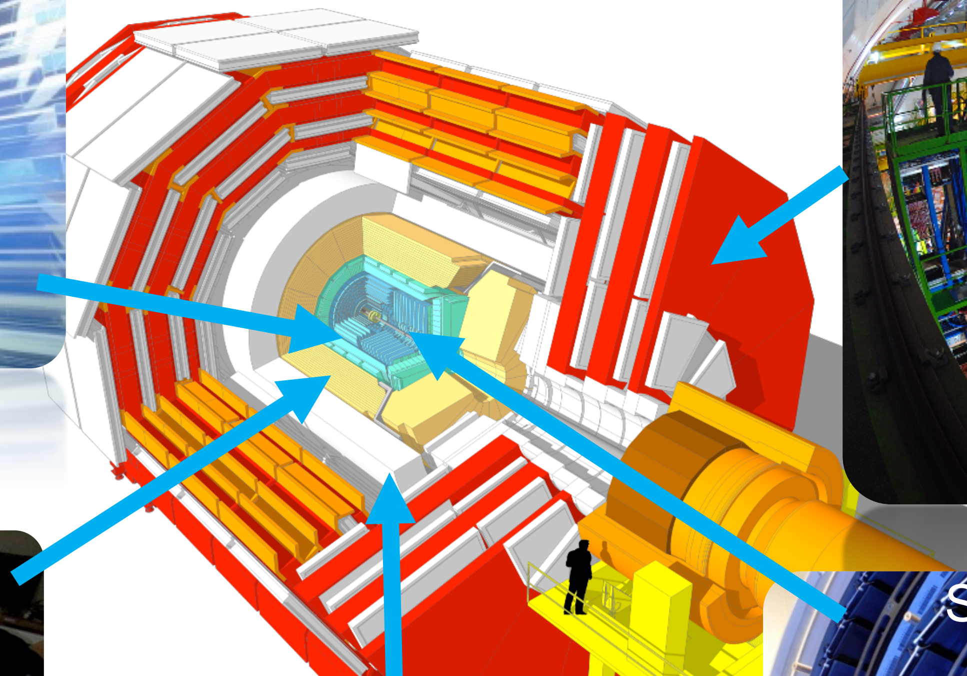
Roughly reaching limits of current techniques in several systems

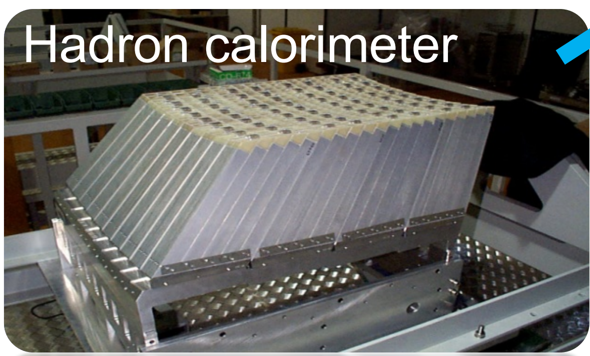
- Goal of ATLAS and CMS detector upgrades
  - make HL-LHC events look like LHC events (~25 additional interactions)
  - For precision measurements and observations of very rare processes, we need to at least maintain current performance for all physics objects. Requires excellence in every corner
  - associating particles with primary hard scatter collision with high efficiency
  - Increased spatial granularity to resolve signals from individual particles
  - Precise timing measurements to provide an additional dimension for discrimination

CMS


Electromagnetic calorimeter


Muon system



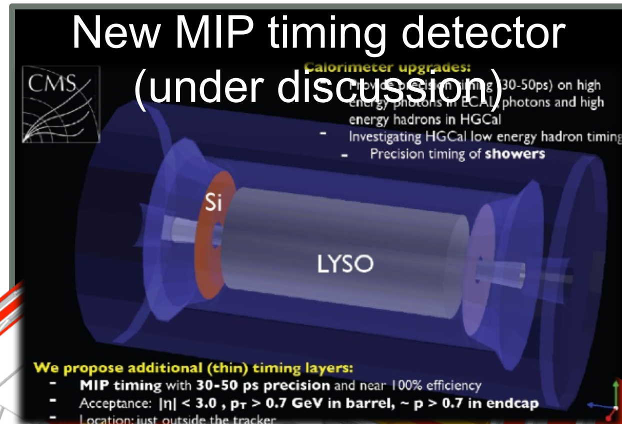

Hadron calorimeter


3.8 T solenoid

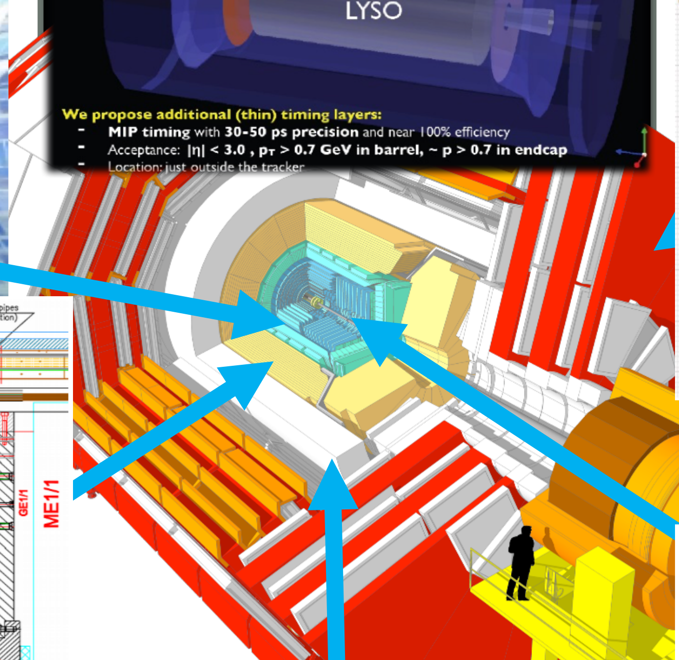

Silicon tracker

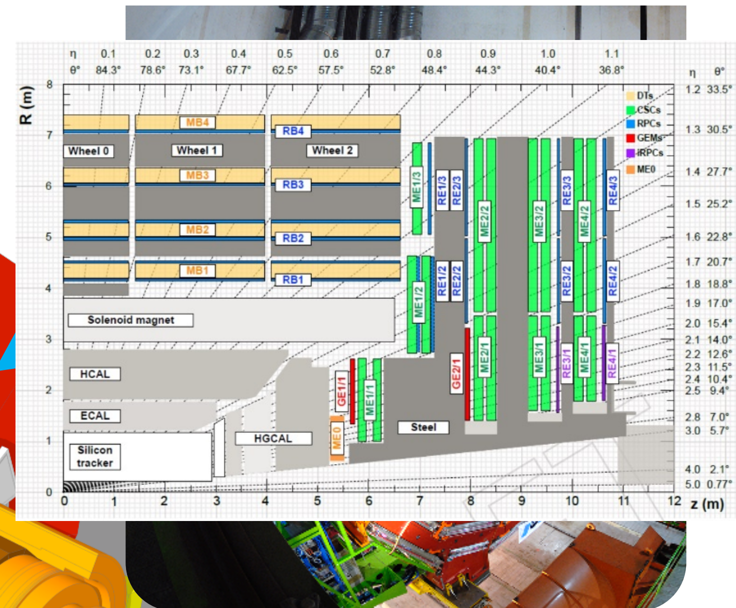
CMS upgrade

Improved barrel calorimeter readout and trigger

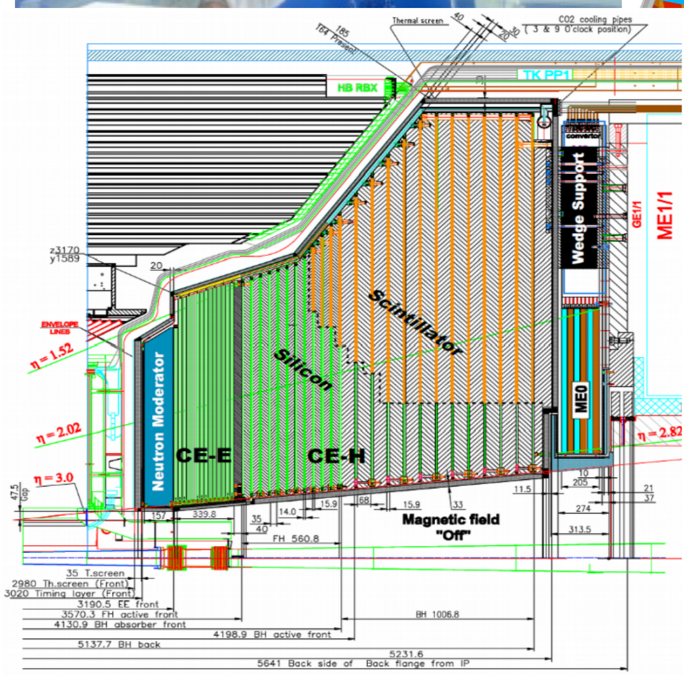


New MIP timing detector (under discussion)



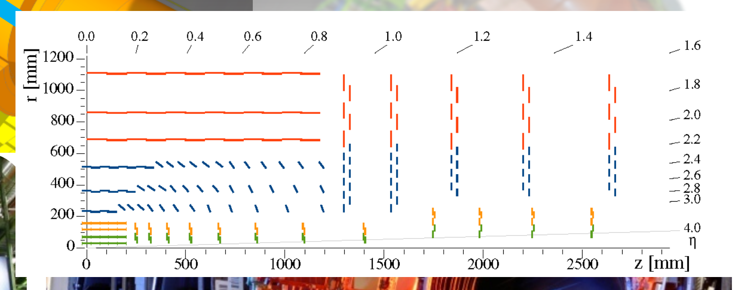


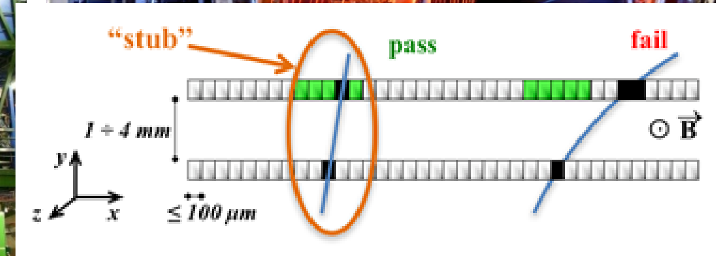
Additional chambers and η-coverage for muon system



New high granularity silicon endcap calorimeter

3.8 T solenoid



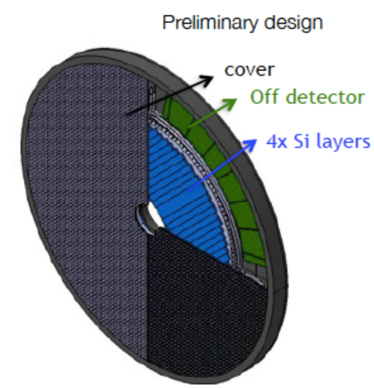


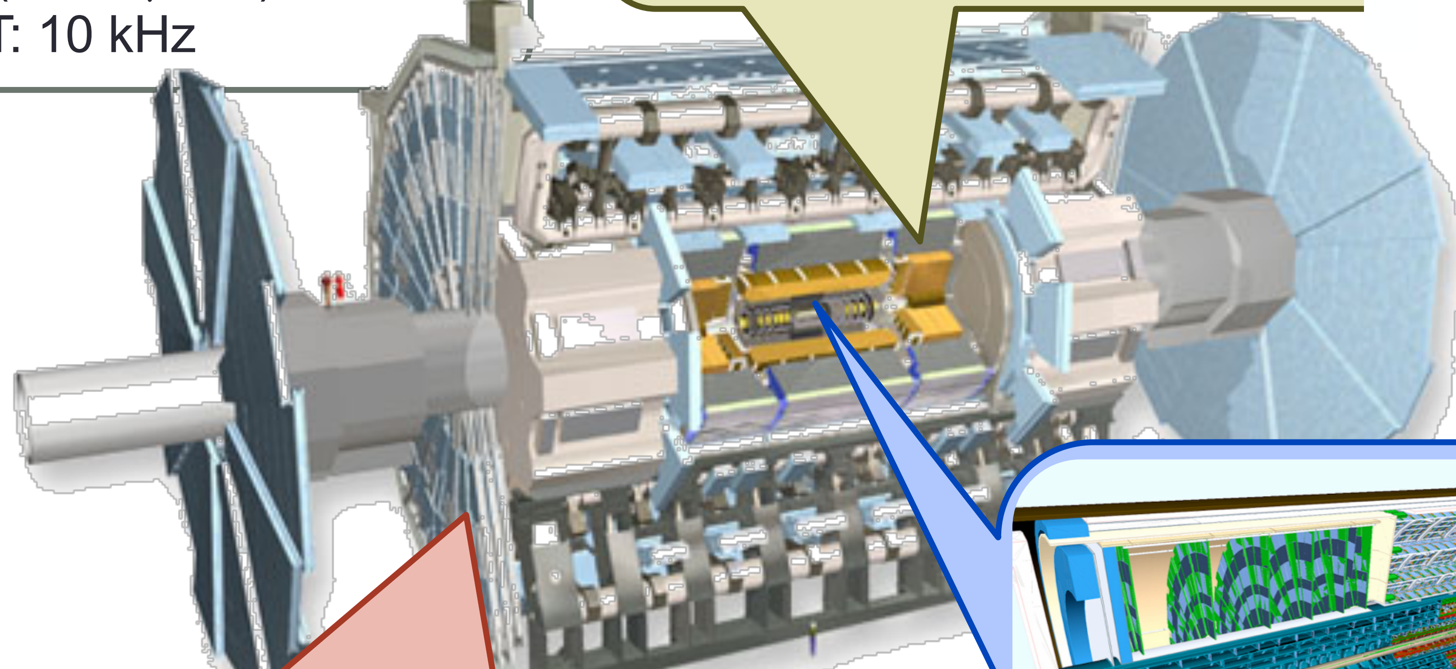
Level 1 track trigger and extended η-coverage for silicon tracker

ATLAS upgrade

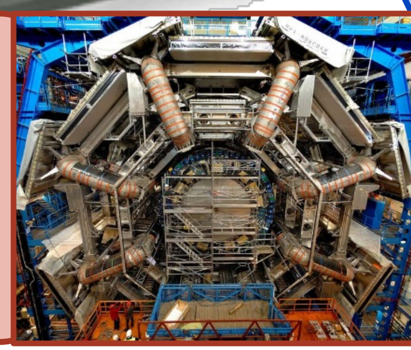
Trigger and DAQ
- L0 (Calo+μ): 1 MHz
- L1 (Calo+μ+Itk): 400 kHz
- HLT: 10 kHz

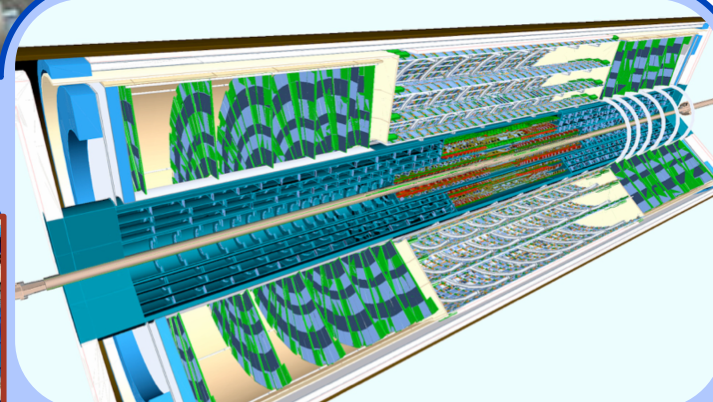
Calorimeters
- New readout electronics compatible with L0 1 MHz rate
- High granularity timing detector (under discussion)



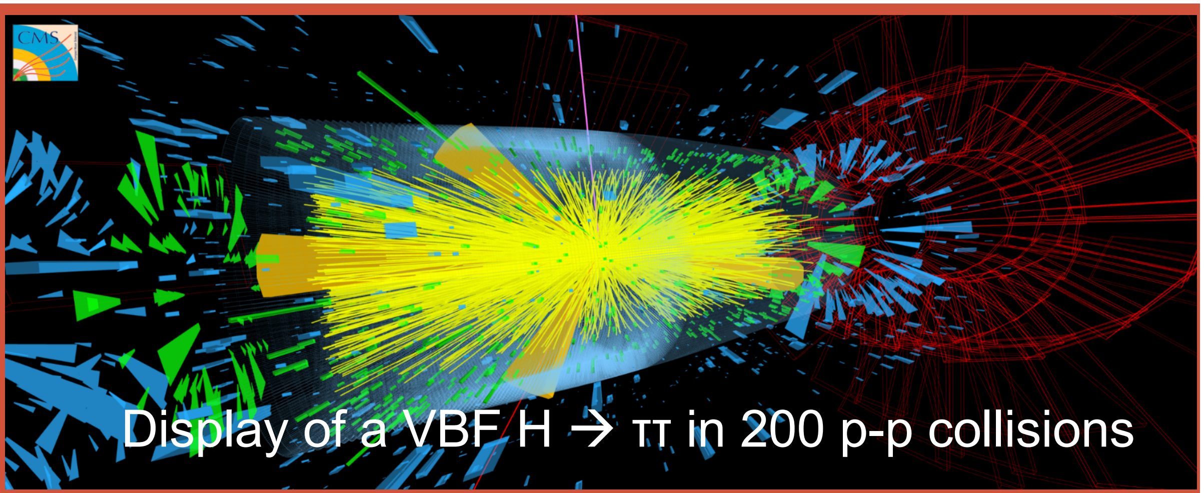


Muon systems
- New readout and trigger electronics
- Additional chambers for inner barrel layer improves acceptance
- Muon tagger for 2.7<|η|<4.0

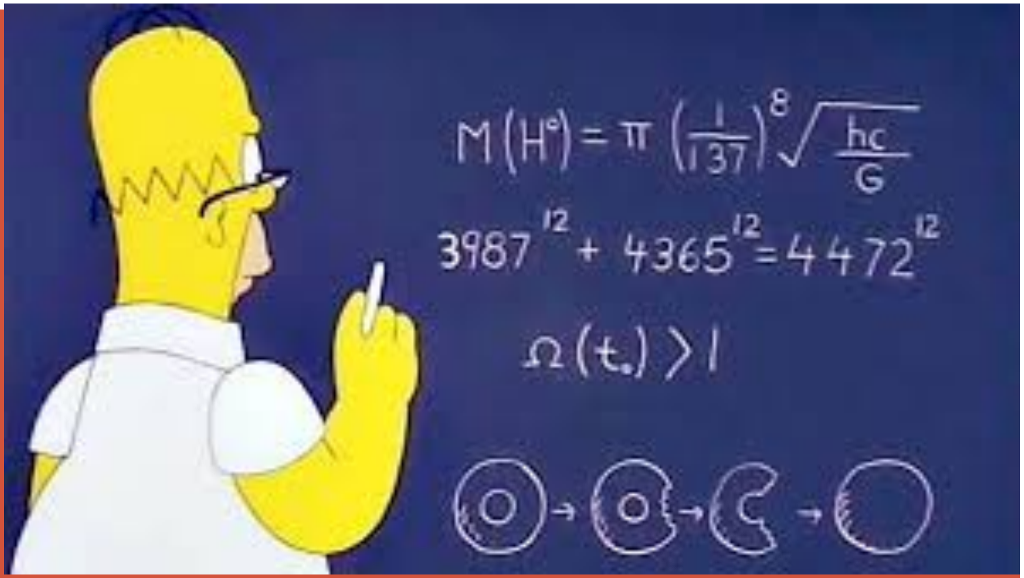




All-silicon tracking detector
5 pixel+4 strip layers to |η|<4



PHYSICS REACH

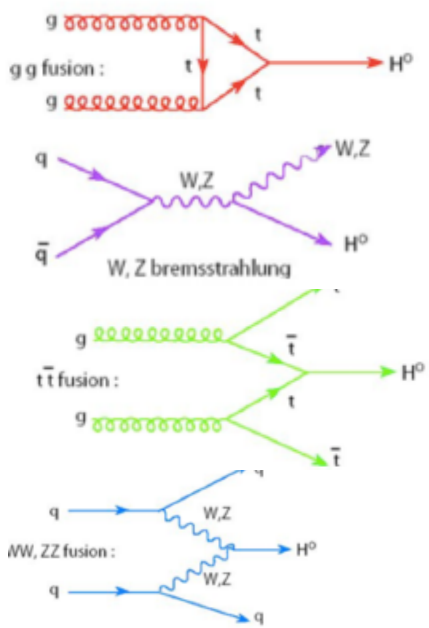


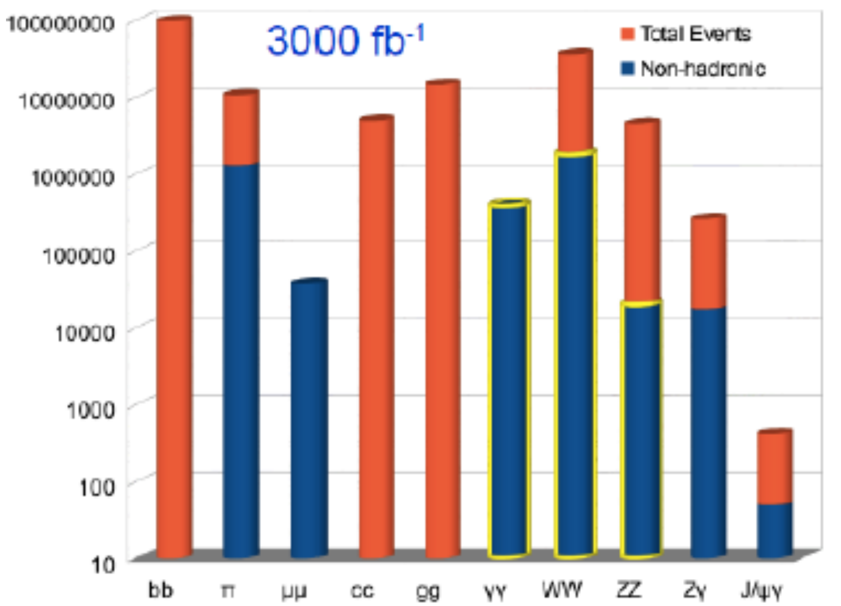
THE HIGGS SECTOR

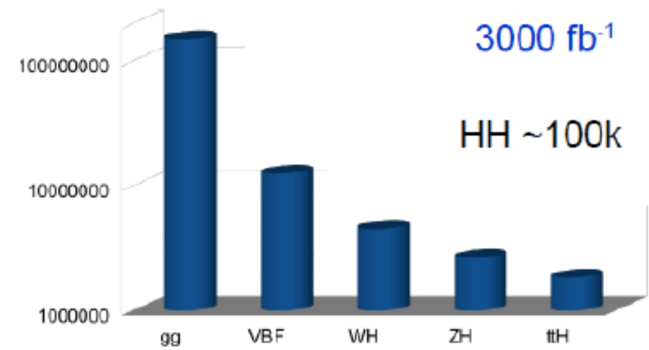
- A major component of HL-LHC physics program.

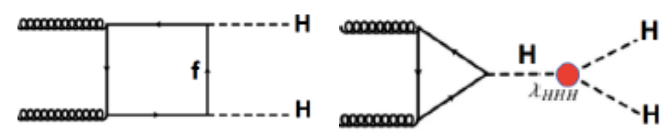
HL-LHC as a Higgs Factory

- At HL-LHC, we expect to produce ~170M Higgs Bosons including ~120k of pair produced events
- Over 1Million for each of the main production mechanisms, spread over many decay modes



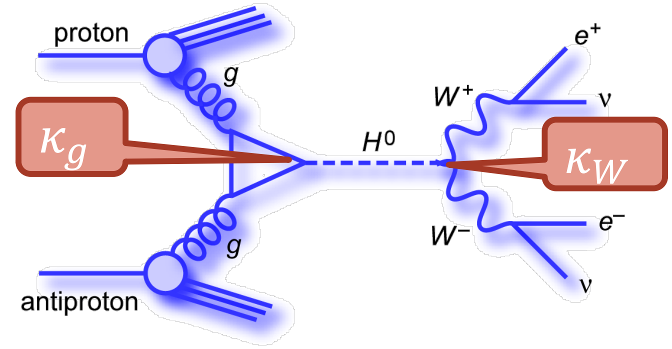




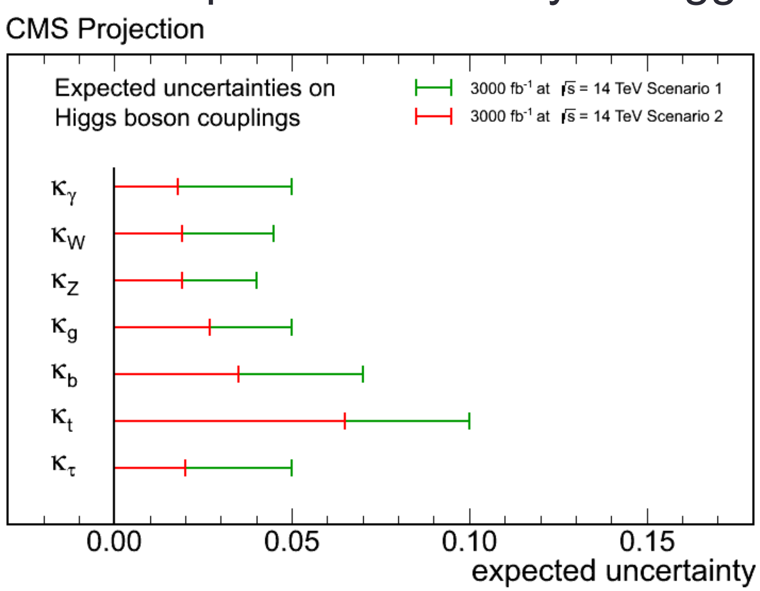


- Enables a broad program:
  - Precision O(1-10%) measurements of coupling across broad kinematics
    - can reveal new particles in loops or non-fundamental nature of Higgs
  - Exploration of Higgs potential (**hh** production)
  - Sensitivity to rare decays involving new physics
  - **BSM Higgs searches** (extra scalars, BSM Higgs resonances, exotic decays…)

Higgs Coupling

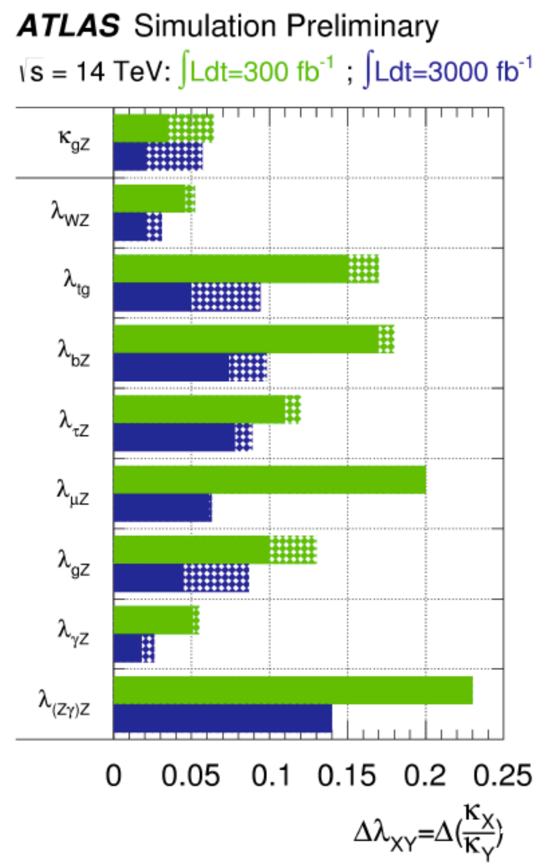


- Coupling measurements:
- Rate of a given process depends on several couplings
- Example gg→h→WW: $\sigma B \propto \frac{\kappa_g^2 \kappa_W^2}{\kappa_H^2}$
  - The κ's multiply the SM couplings. κ_g is a function of κ_t and κ_b.
  - κ_H multiplies the Higgs width and depends on all couplings
- Currently κ's are typically measured to ≈20%.
- Expected deviations from SM predictions by various models (Singlet mixing, 2HDM, Decoupling MSSM, Composite, Top Partner..) predicted to be between 1-10%.
- Comprehensive study of Higgs couplings at the HL-LHC



Projections at 3-10%-level with 3000 fb^{-1}.
HL-LHC will improve measurement precision by a factor 2-3!

Reduced theoretical uncertainties needed (improvement since 2014)

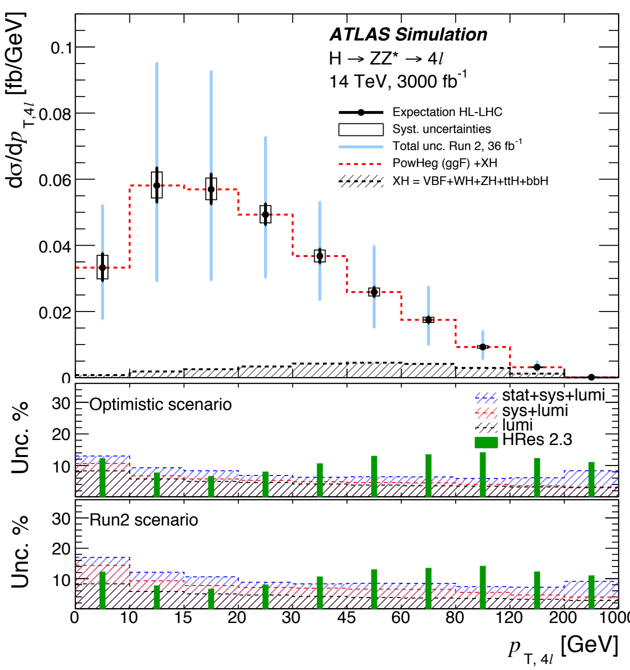


Higgs Production & Couplings ($h \rightarrow ZZ$)

Differential Cross Section $p_T(h)$

- probes perturbative QCD calculations
- information on (new) particles contribution to the gluon fusion loop
- Sensitive to κ_b/κ_c (low p_T) κ_t/BSM (high p_T)

- @high p_T dominated by stat. unc ≈4-9%
- For 300 fb^{-1} stat. uncertainty: 10-29%!



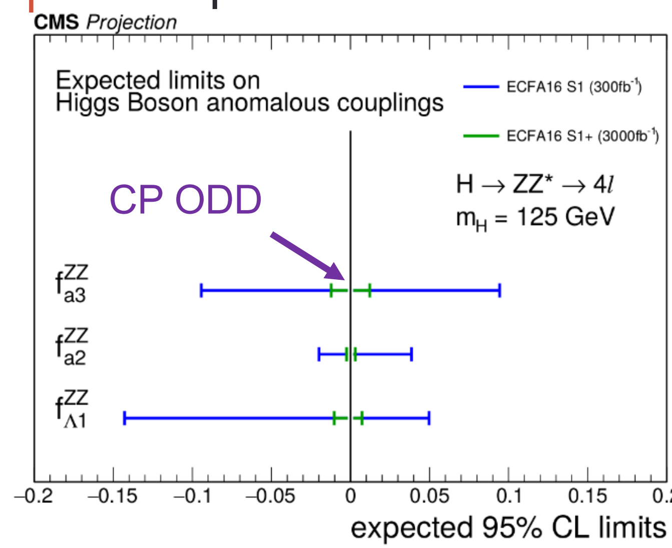
Anomalous couplings

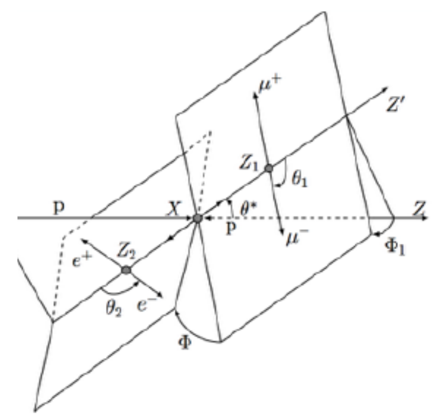
$$A(H \rightarrow ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^\star \epsilon_2^\star + a_2 f_{\mu\nu}^{\star(1)} f^{\star(2),\mu\nu} + a_3 f_{\mu\nu}^{\star(1)} \tilde{f}^{\star(2),\mu\nu}\right)$$

SM tree processes | loop CP-even contributions | CP-odd contributions (BSM)

- H ZZ 4l : reconstruct the full angular decay structure $f_{ai} = \frac{|a_i|^2\sigma_i}{\sum_j |a_j|^2\sigma_j},\ \phi_{ai} = \tan^{-1}(a_i/a_1)$

- Expect to constrain f < ~1%



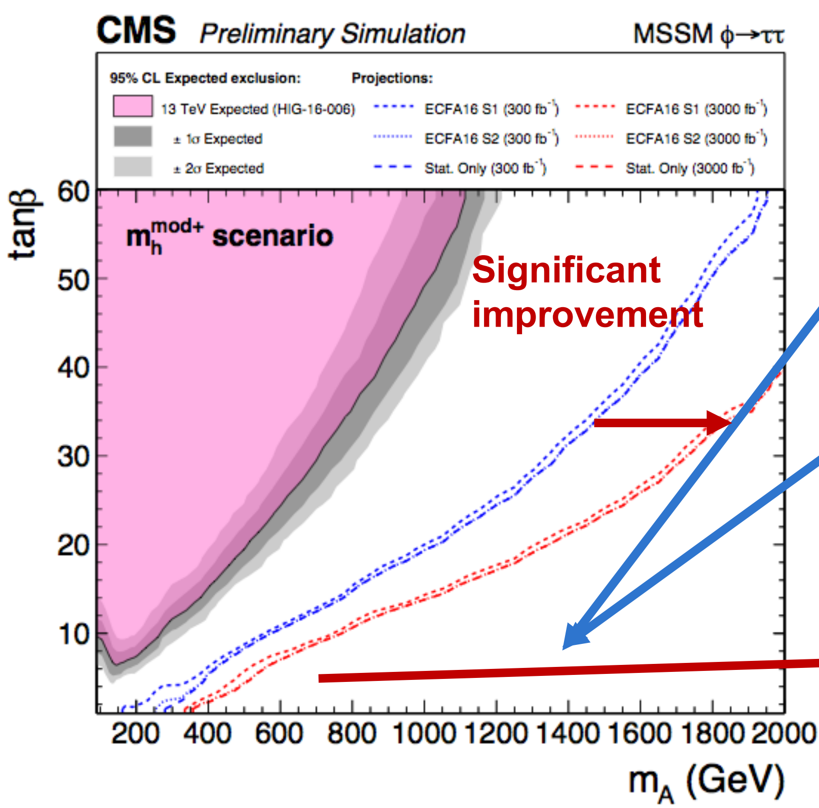


- Statistically dominated: huge increase in sensitivity going from 300 to 3000 fb^{-1}.

BSM Processes

- MSSM $\Phi \rightarrow \tau\ \tau$
  - One of the most sensitive channels to constrain extended Higgs sectors
  - MSSM parameter space can be constrained to a heavy Higgs boson with masses up to 2 TeV.

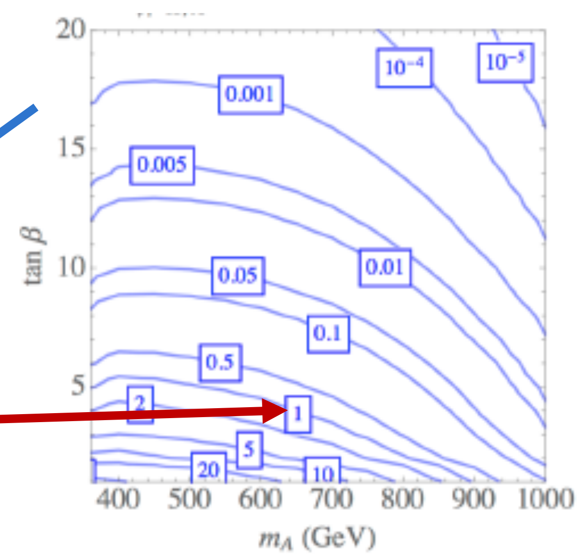
CMS-PAS-HIG-16-006



What about the low tanβ vs M_A region?

Consider tau-phobic signatures
A possible scenario is ttH production
Signatures: 4top or 2b+2top

$$\sigma(pp \rightarrow ttH, H \rightarrow tt)\ [fb]$$



statistics limited!
~ 30 events now
Will benefit from HL-LHC, HE-LHC

Gori et al, 1602.02782

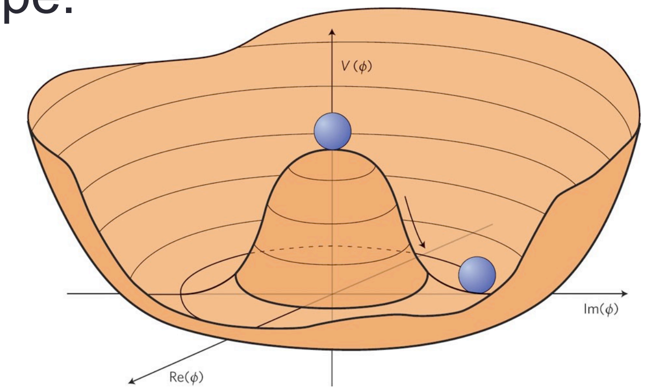
Higgs Pair Production and Self Coupling

- Shape of the Higgs potential postulated but not taken from first principles.
- Indirectly constrained within SM assuming quartic shape.
- Higgs potential after spontaneous symmetry breaking

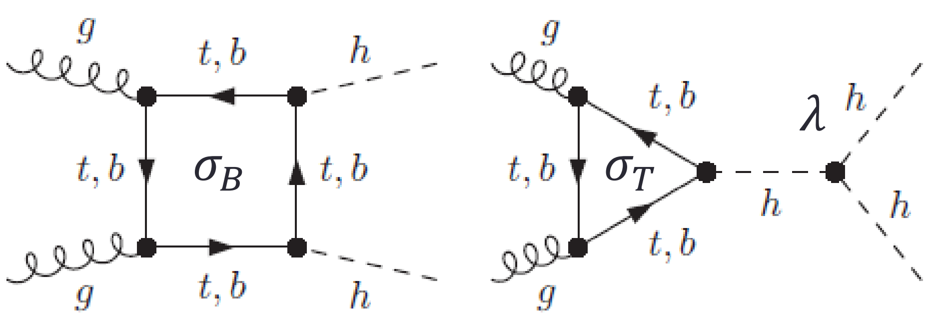
$$V = \frac{1}{2} m_h^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

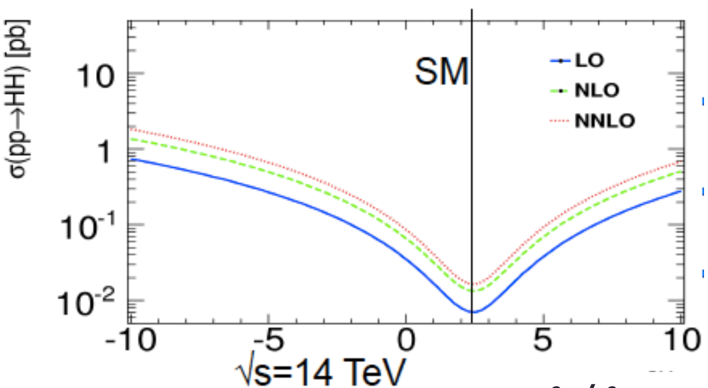
with $m_h^2 = 2\lambda v^2$ and $v^2 = \frac{1}{\sqrt{2} G_F}$

$\frac{\delta\lambda}{\lambda} = 2\frac{\delta m}{m} \approx 0.4\%.$ (indirect constraint)



- Thus in the SM, the Higgs potential is completely determined by m_h and G_F
- Direct constraint possible with Higgs pair production



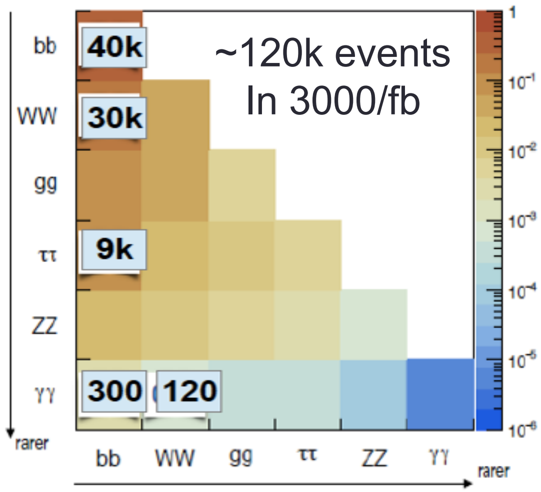


$\kappa_\lambda = \lambda / \lambda_{SM}$

- Destructive interference ➔ $\sigma_{hh} \approx \frac{\sigma_T + \sigma_B}{2.5}$ ➔ $\sigma_{hh} = 39.5$ fb @14 TeV
- Models with extended Higgs sector modify σ by typically 20%
- Higgs resonances can also modify the Higgs pair production rate

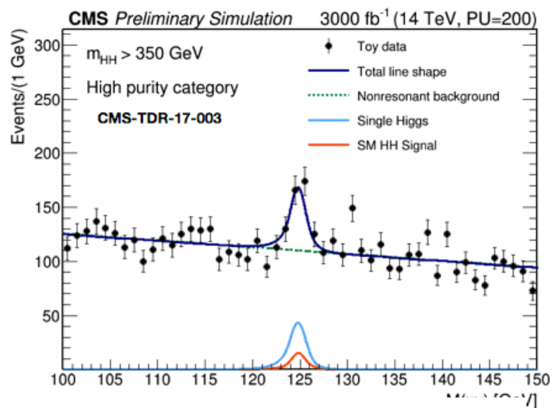
Higgs Pair Production at HL-LHC

Expected number of events



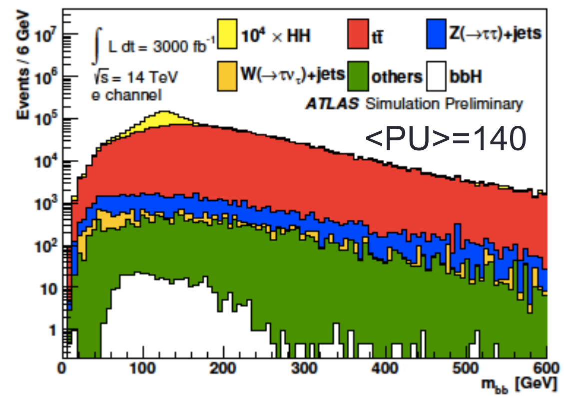
Promising final states

$HH \rightarrow bb\gamma\gamma$



$m_{\gamma\gamma}\ (GeV)$

$HH \rightarrow bb\tau\tau$



$m_{bb}\ (GeV)$

HH physics is a benchmark channel for HL-LHC program

- Run II results are reaching 15 times SM, with loose constraint on κ_λ between -9 and 15.
- Exp. significance per experiment ≈1-2 σ (HL-LHC)
- The possibility of "evidence" of HH can be reached combining all channels in CMS and ATLAS.

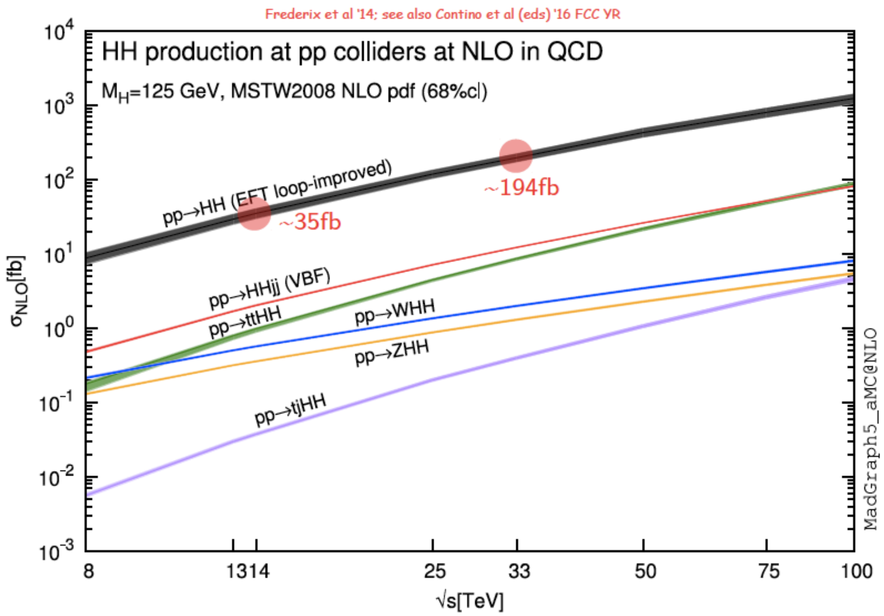
- Improvement foreseen driven by :
  - Detector optimization, analysis algorithms
  - Theory : Impact of NLO correction on differential distributions ?

Expected significance
95% CL intervals

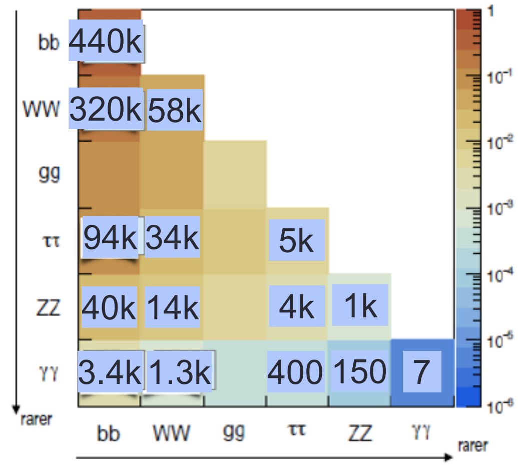
Final state	ATLAS	CMS
HH→bbγγ	1.05 σ $-0.8 < \kappa_\lambda < 7.7$	1.43 σ
HH→bbττ	0.6 σ $-4.0 < \kappa_\lambda < 12$	0.39 σ
HH→bbbb	$-3.5 < \kappa_\lambda < 11$	0.39 σ
HH→bbVV		0.45 σ
ttHH, HH→bbbb	0.35 σ	

Higgs pair production at HE-LHC

- HH cross section @ 27 TeV = 128 fb (±11%)



Expected number of events @ 27 TeV and 10/ab



➔ event yields increase by factor 10

- Projections for λ from hh production: $\delta\kappa_\lambda$. ($\kappa_\lambda = \lambda / \lambda_{SM}$)

$\delta\kappa_\lambda$ bound / scenario	68%	95%
HL: h incl, hh incl	[0, 2.5] U [4.9, 7.4]	[−0.8, 8.5]
HL: h incl, hh diff	[-1.1, 1.3]	[−1.7, 6.5]
HE: h incl, hh incl	[-0.3, 0.3] U [5.0, 6.0]	[-0.5, 0.7] U [4.5, 6.7]
HL + HE	[-0.3, 0.3]	[-0.5, 0.6] U [4.8, 6.0]
FCC 100 TeV 30/ab h incl, hh diff	[−0.03, 0.03]	[−0.06, 0.06]

Work is just starting

S. Di Vita HE/HL-LHC workshop, Nov 2017

EXPLORING THE TEV SCALE

LHC is a discovery machine.

BSM searches at HL-LHC not a linear extrapolation from present →widen the scope, e.g.:

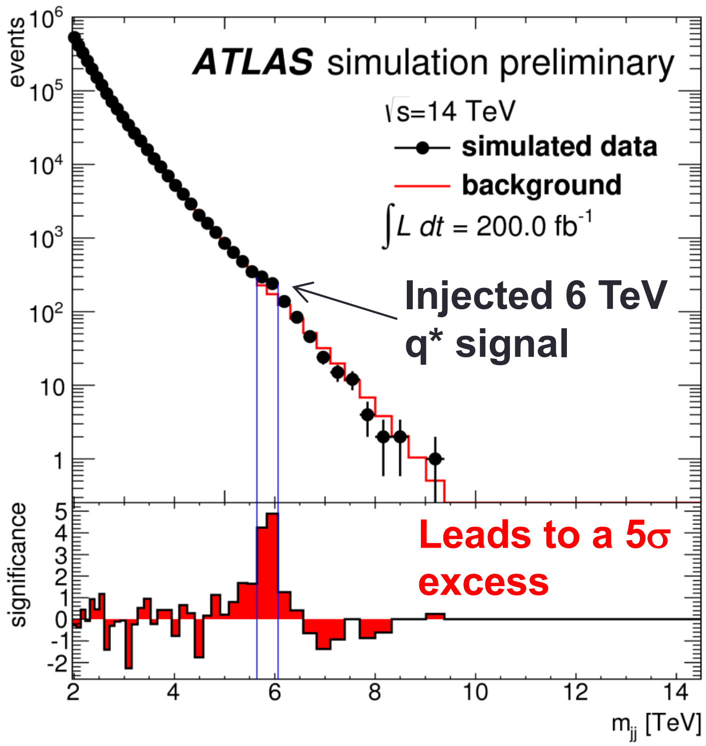
- Rare processes, weaker couplings
- More model-independent not to miss anything

How to prepare for physics?

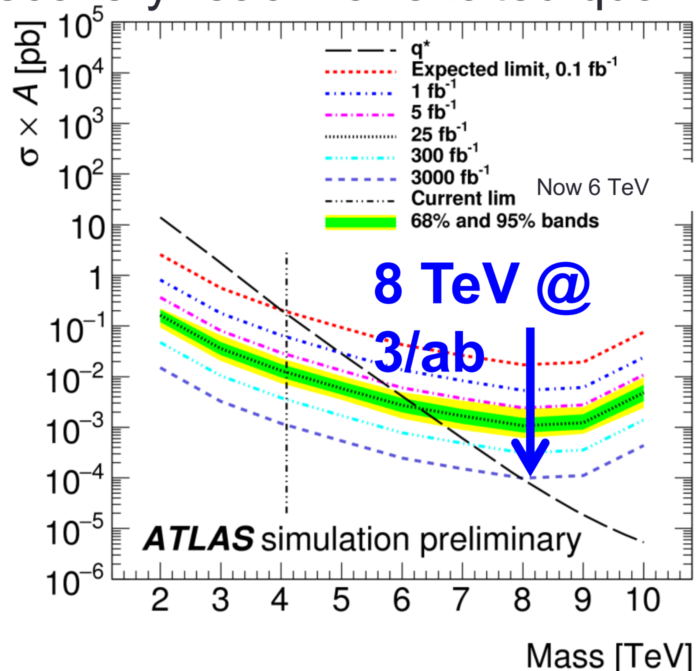
- Continue benchmark analyses . Develop new analysis strategies

Search for New Particles: bump hunting

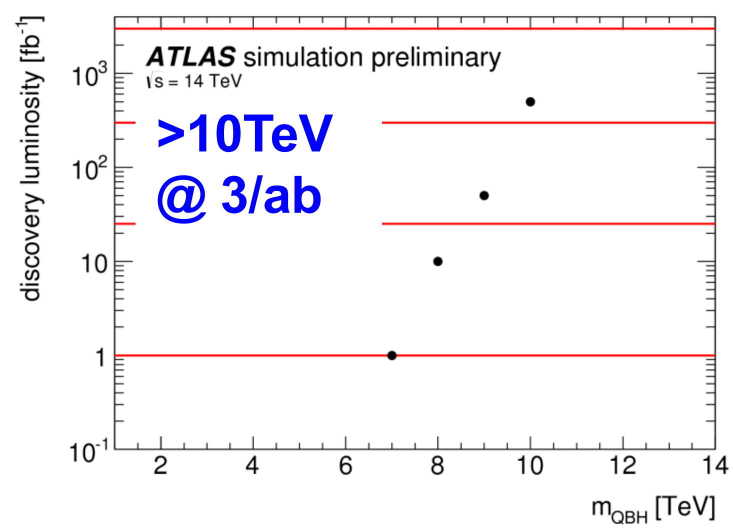
- Plethora of new physics models predicting resonances decaying to 2 jets: quantum black holes, excited quarks, Z'/W' bosons, W* bosons
- **Look for:**
  - **bumps in mjj**
  - deviations from flat distribution in $\chi=\exp|y_1-y_2|$
- Powerful search technique for new physics, model-independent as long as a sharp resonance.
- Greatly profit from increase in energy (HE-LHC)
-

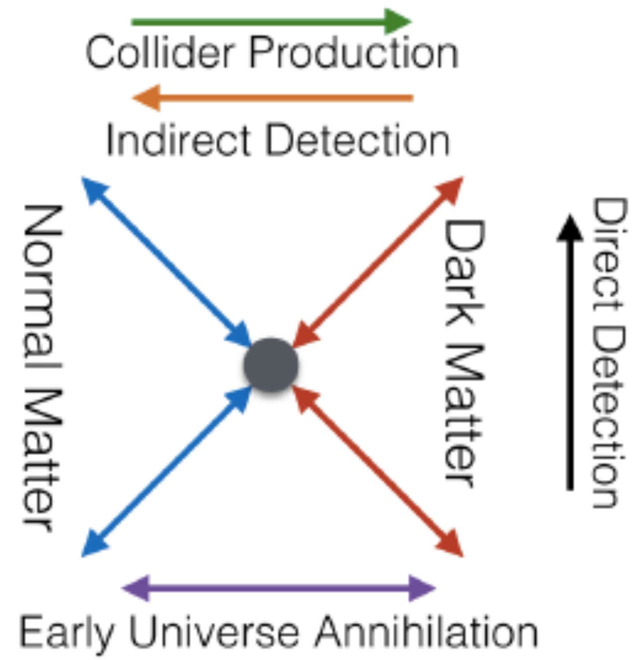


Discovery reach for excited quarks q*



Discovery reach quantum black holes



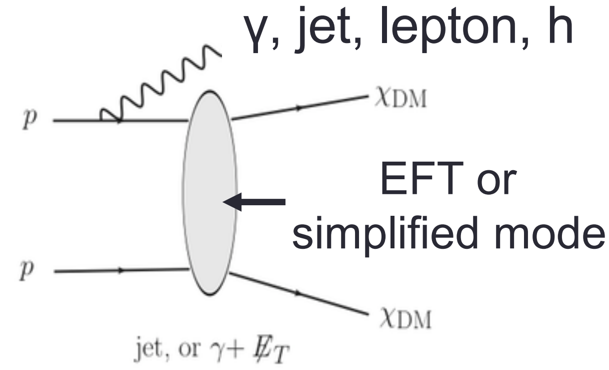


DARK MATTER:

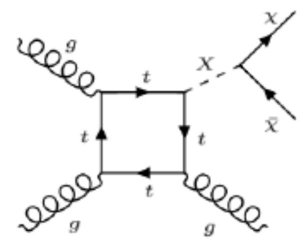
Next discovery?

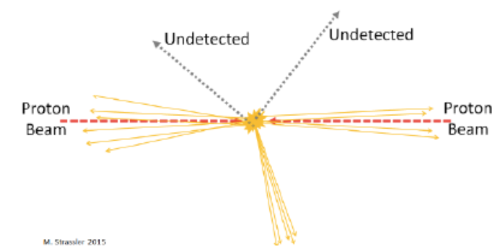
- Guess: DM is a thermal relic of the early universe
- Weak-scale interactions with the SM
- LHC searches complement direct detection experiments.
- Complication: translation between annihilaton and experimental cross section very model dependent.
- In recent years significant theoretical and experimental developments, e.g. EFT→simplified models.

Dark Matter Searches:

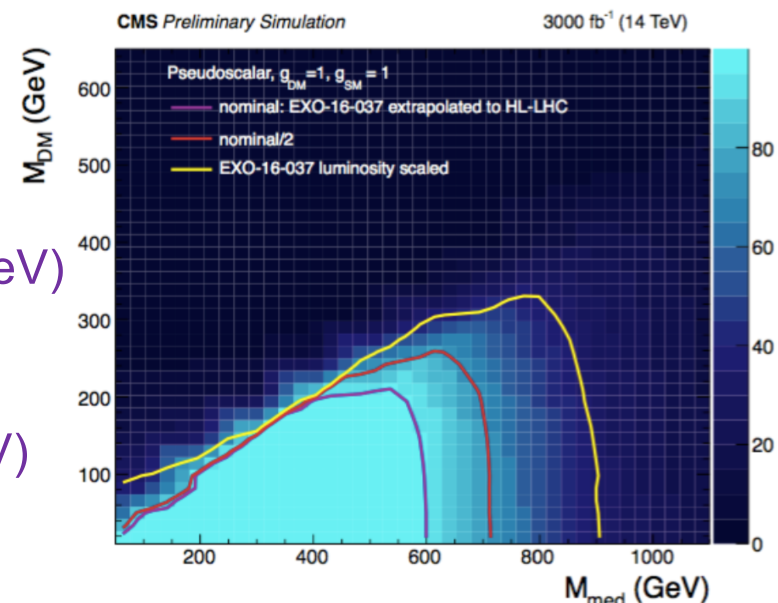


- Searches based on Simplified Models
  - Dirac WIMP mediators
    - scalar, pseudoscalar, vector/axial-vector
  - With distinct kinematic distributions
  - Aids in design of generic searches
    - Missing ET+ X (jets, g, Z, leptons, dileptons, ..)





- Search for Dark Matter in Missing E_T+jets
  - Suppressed in direct detection.
  - LHC provides complementary sensitivity.
  - Benchmark among many DM collider searches.
- Interpretation in simplified models with 4 parameters (**M_{med}, m_{DM}**, g_{SM}, g_{DM})



- Axial vector mediator :
  - Exclusion possible up to 3 TeV. (current reach ~2TeV)
- Pseudoscalar Mediator:
  - Spin-0 mediator, pseudoscalar gSM = 1, gDM = 1
  - Exclusion possible up to 900 GeV (current ~0.4 TeV)
  - Reach in mediator mass influenced by systematics.

HE-LHC: WIMP search using Missing ET+jets

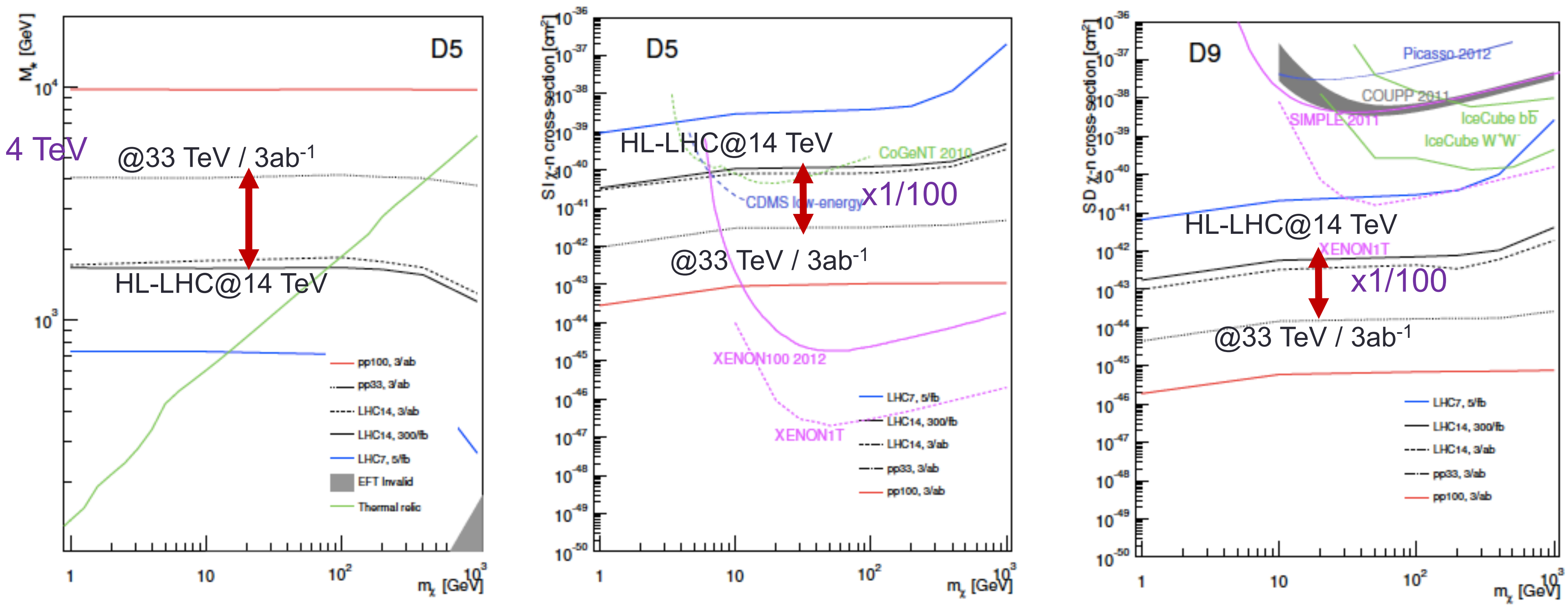
- Significant gains with the HE-LHC:
  - Models tested (circa 2013) – somewhere collider exclusion dominates, others where direct detection dominates.

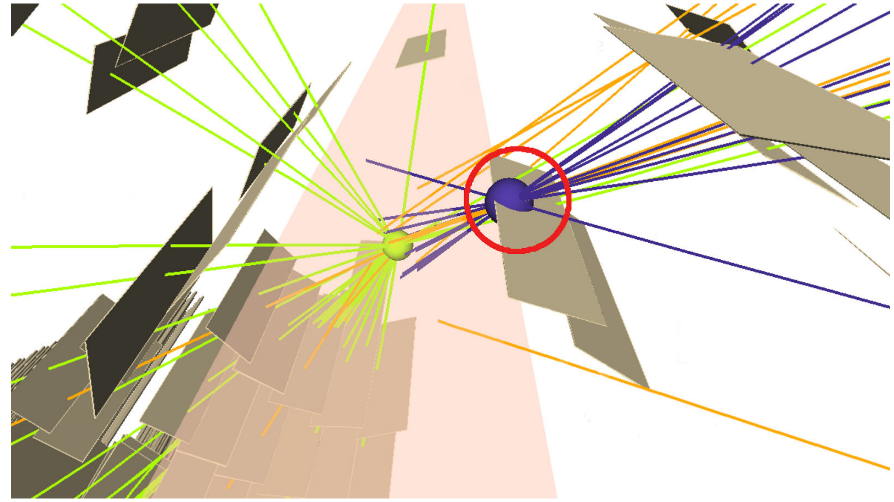
- Sensitivity to WIMP pair production via effective operators and light mediators

arXiv:1307.5327

Spin independent

Spin dependent





LONG-LIVED PARTICLES (LLP)

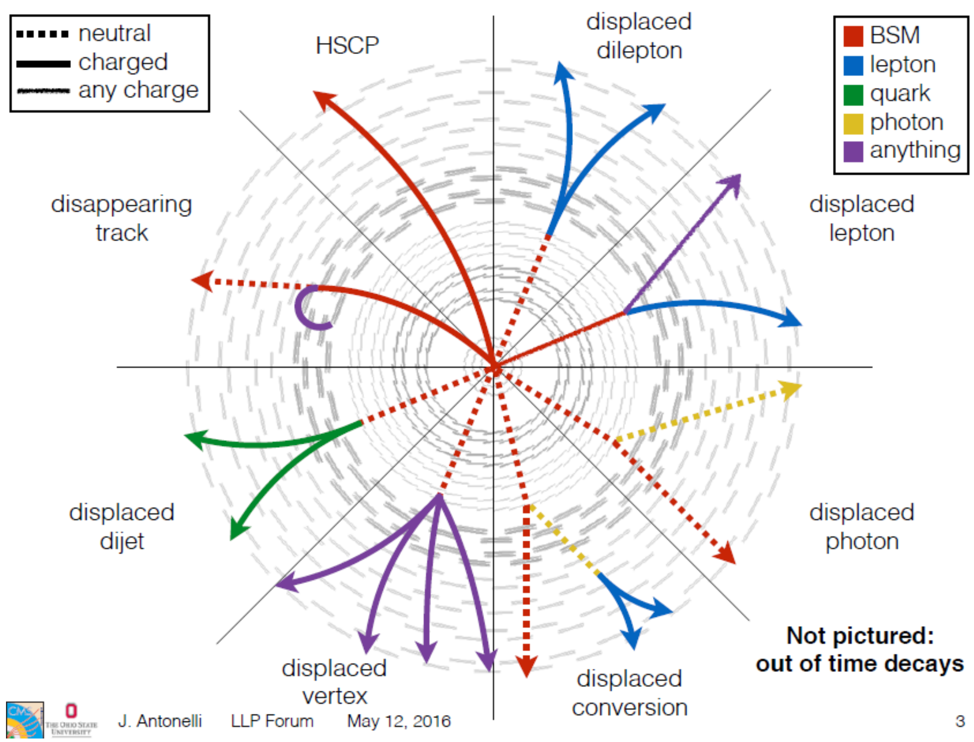
and Special Signatures

The secret lives of long-lived particles

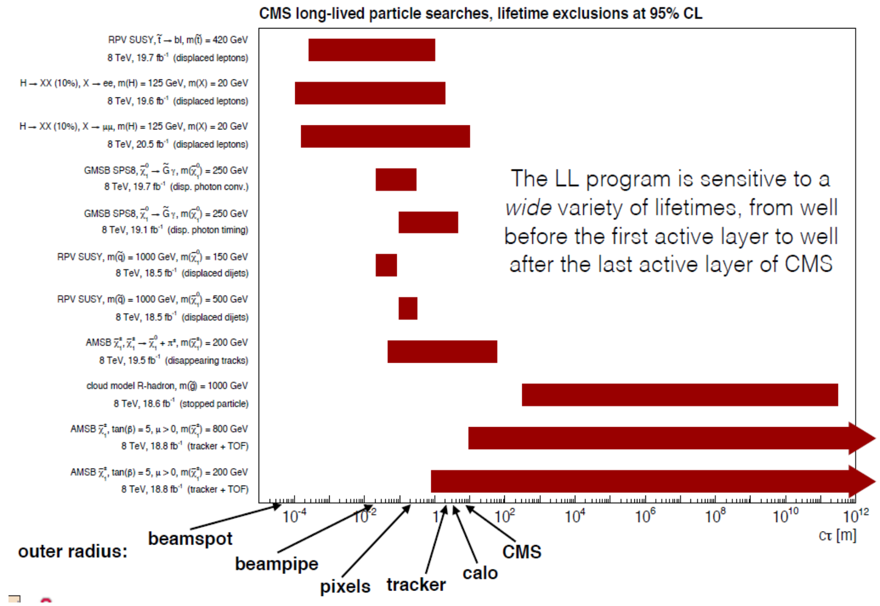
09/16/16 | By Sarah Charley

A theoretical species of particle might answer nearly every question about our cosmos—if scientists can find it.

Long Lived Particles (LLP)



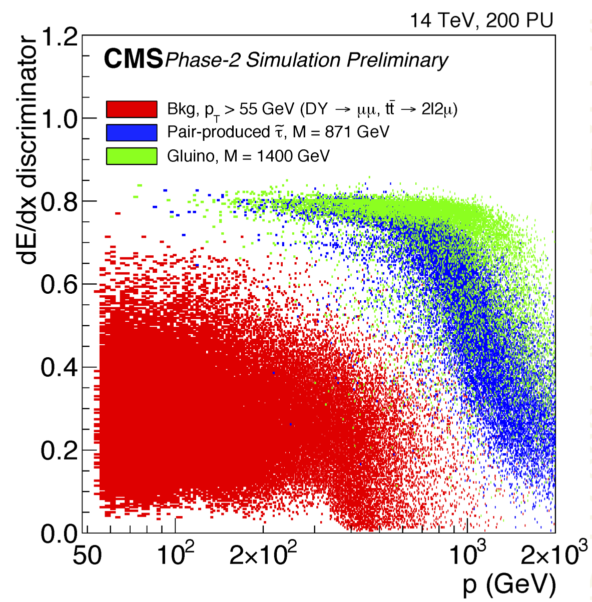
Target complementary lifetimes and ranges. Variety of dedicated techniques to cover whole range of lifetimes (cτ)

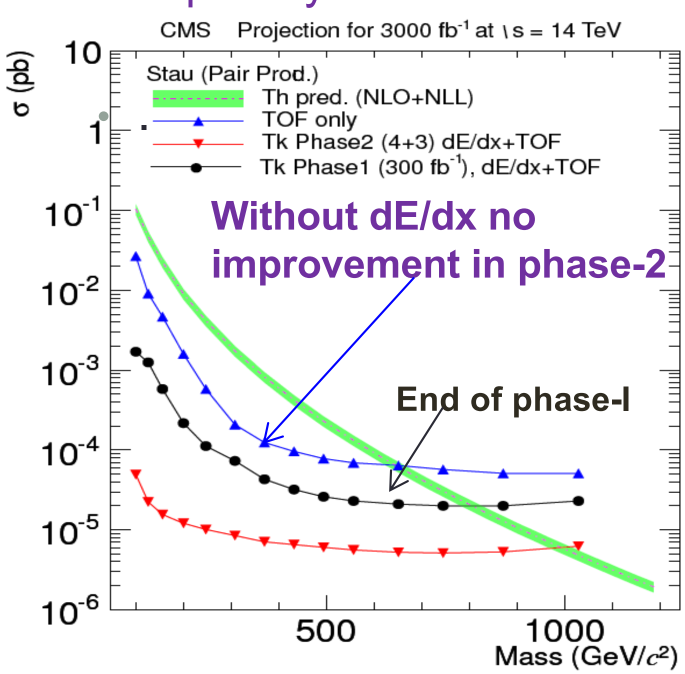


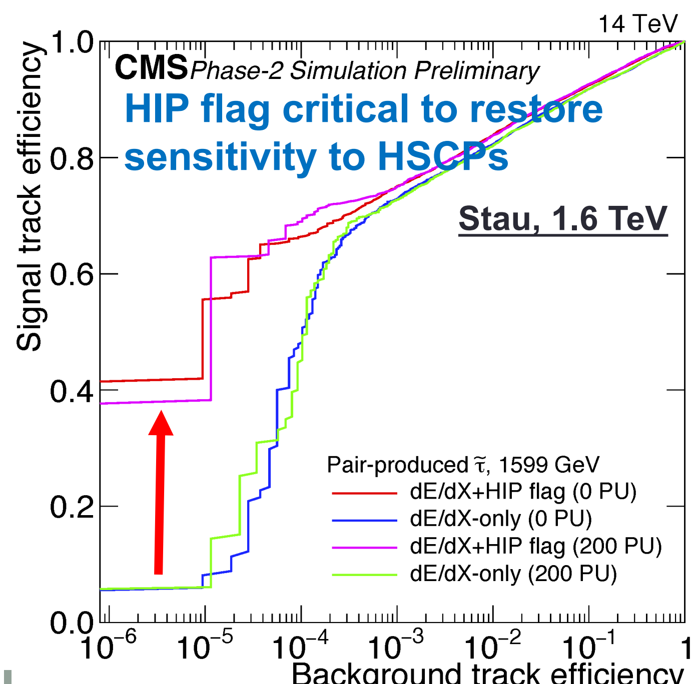
- Particles decaying non-promptly are a new focus at the LHC, for present and future
- Long-lived neutral particle (X) decays after some cτ to displaced leptons or jets.
- Signature driven searches, with great discovery potential, Issues and opportunities with LLP signatures:
  - Need dedicated tools for non-standard objects, custom trigger/reconstruction/simulation
  - Potential gains from high luminosity, track-trigger, fast timing, better directionality.

Heavy Stable Charged Particles

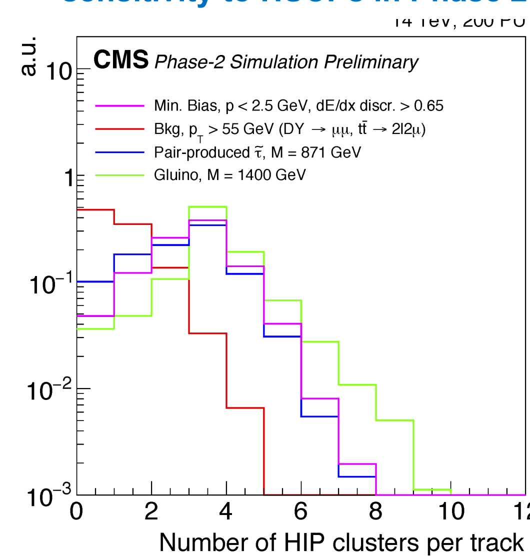
- HSCPs: New, heavy particles could propagate through the detector before decaying
- Needs HL-LHC for sensitivity because of small xsec.
- Detection technique
  - Could look like heavy, highly-ionizing, slow-moving muons
  - dE/dx discriminator shows large separation between signal and background
  - Physics studied demonstrated the need to keep dE/dx capability in the tracker







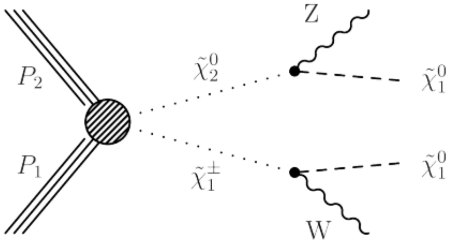
HIP flag is critical to restore tracker sensitivity to HSCPs in Phase 2

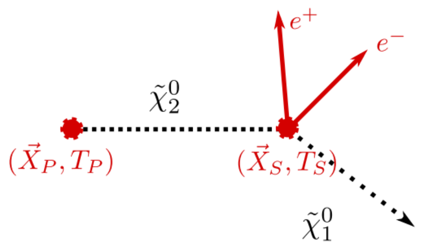


Long-Lived Neutralinos

- Long-lived neutralinos in GMSB **with small mass difference**

$M(\tilde{\chi}^{\pm}) = M(\tilde{\chi}_2^0)$ = 400 GeV,
$M(\tilde{\chi}_1^0)$ = 390 GeV



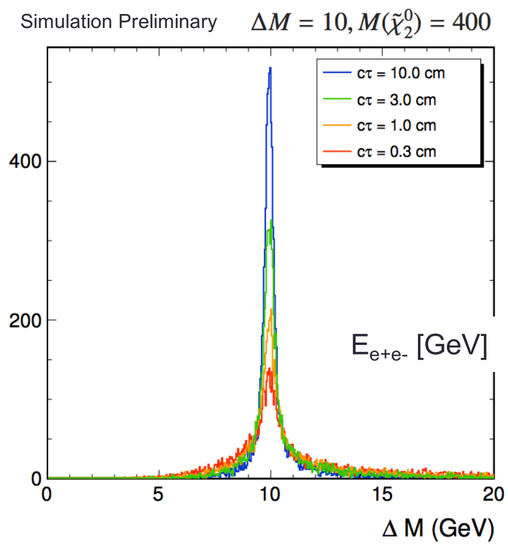


- Use MIP timing detector for precision measurement time of flight
- **assign times to vertices and charged particles**
- **With the timing information, can reconstruct LLP time-of-flight and mass**

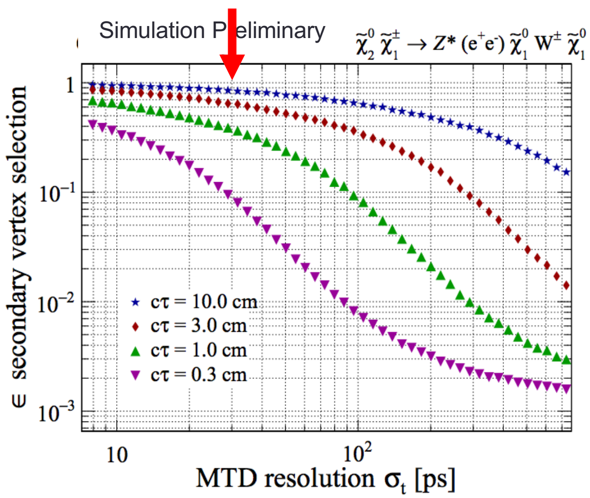
Reconstructed E_{e+e-}

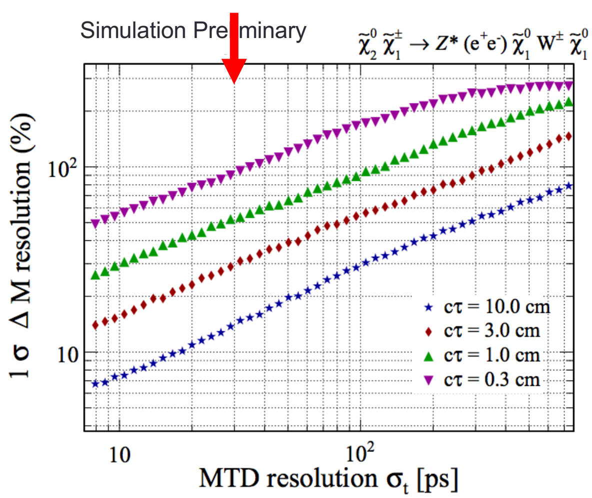
$$E = \Delta M = M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)$$

Assume 30 ps timing resolution of MTD



Select events with a displaced secondary vertex with 3σ significance in both space and time:



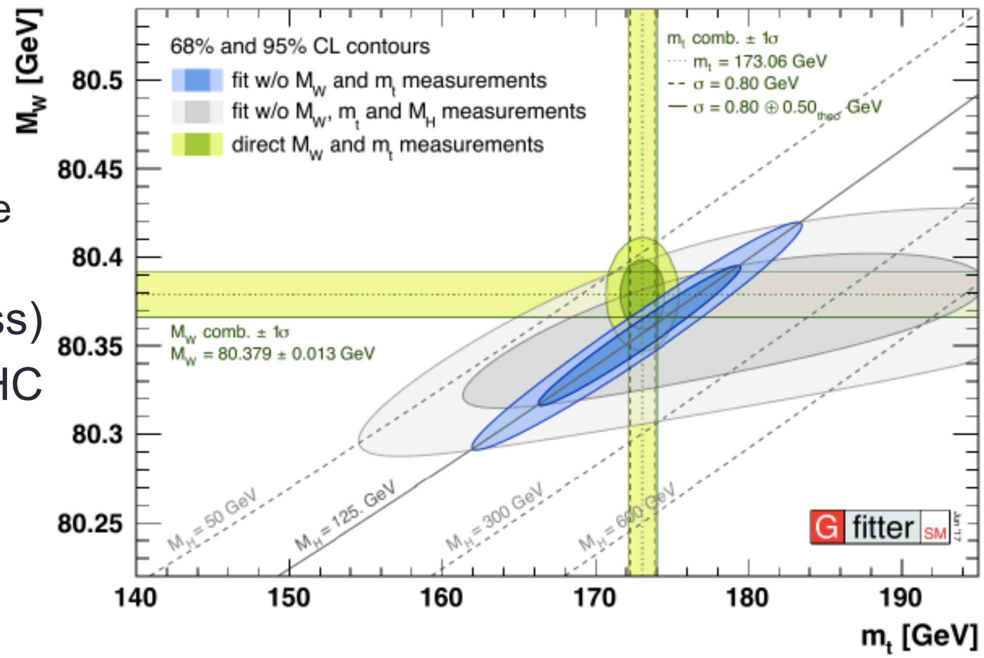


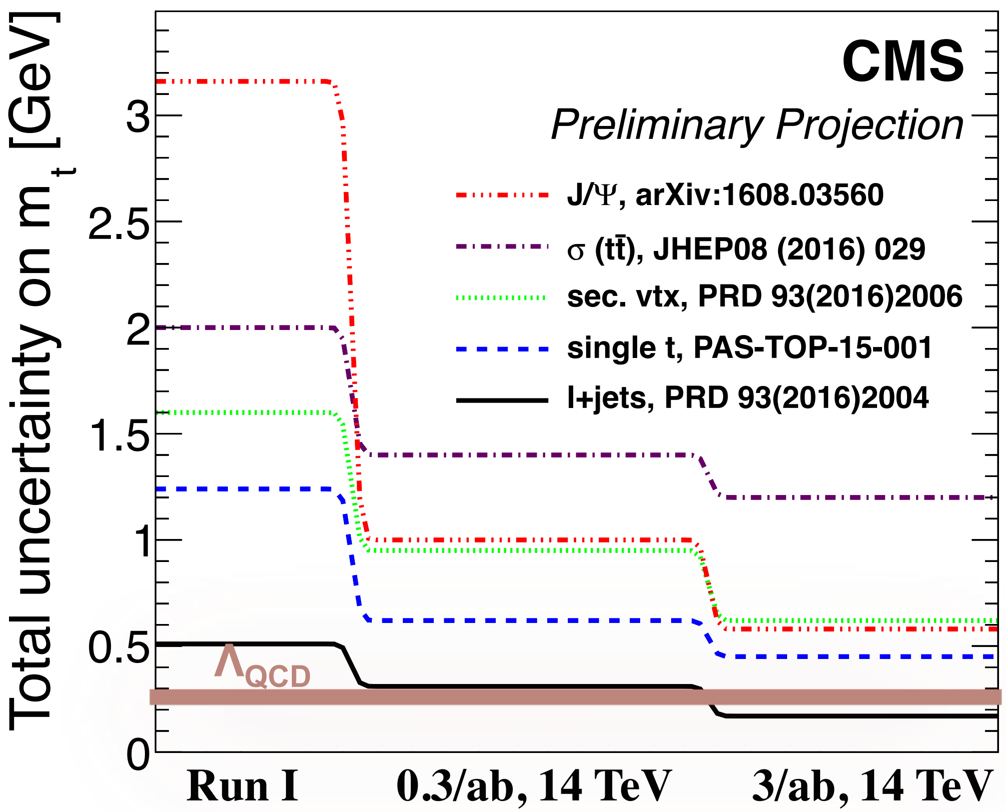
STANDARD MODEL MEASUREMENTS

- SM processes e.g. production of γ, W, Z, or top quarks + jets always appear as irreducible or reducible background
- Have their own intrinsic interest, e.g.
  - tests of the unitarity-cancellation mechanism in the SM; top-quark mass
- **SM measurement can also be a portal to new physics:**

Precision Physics: Top Quark Mass

- Large data samples allow exploration of complementary approaches
- top mass unc: ~0.5GeV → ~ 0.17 GeV
  - theoretical uncertainty due to the conversion to the MSbar mass 0.25 GeV?
- Higgs mass unc 0.25 GeV → 0.10 GeV ?(guess)
- W mass unc 0.013 GeV → ? unclear for HL-LHC



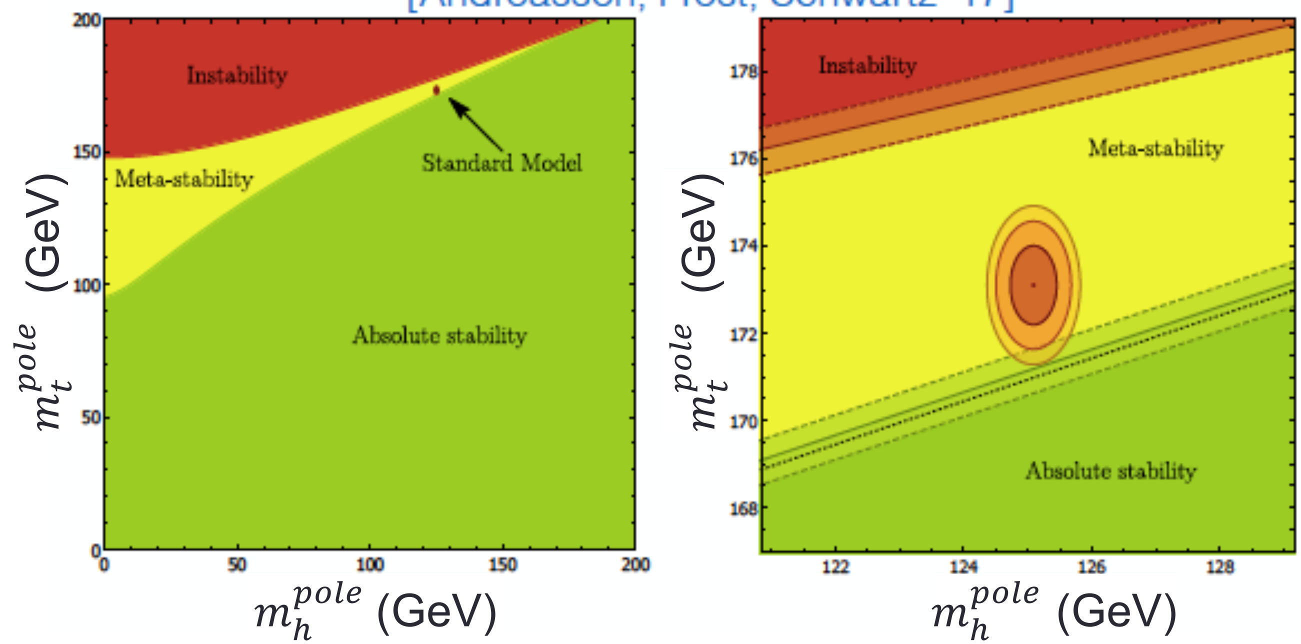


- From $t\bar{t}$ cross-section
  - Limited by theory uncertainty and luminosity measurement
- J/ψ and secondary vertex
  - Statistically dominated
- Single top
- Standard $t\bar{t} \rightarrow \ell$+jets measurement
  - Expect $\Delta m_{top}/m_{top}$ ~ 0.17 GeV

Precision Physics: Top Quark Mass

[Andreassen, Frost, Schwartz '17]

Fate of the vacuum



- Need better precision for top mass to resolve the vacuum stability
  - HL-LHC top mass uncertainty ~0.5 GeV → ~ 0.17 GeV
  - theoretical uncertainty due to the conversion to the MSbar mass 0.25 GeV
  - Currently PDG quotes 3 masses for the top quark:
    - Direct measurements 173.1 ± 0.6 GeV
    - From cross section 160^{+5}_{-4} GeV
    - Pole mass from cross section 173.5 ± 1.1 GeV
- With increasing precision interpretation is the big issue!!!

Summary

- The HL-LHC program is a high-value flagship program of the HEP scientific community.

- HL-LHC will reach unprecedented running conditions, very challenging for the detectors but offering exciting physics perspectives
- Main challenge is mitigation of large number of pileup interactions
  - Trigger – more bandwidth, new capabilities
  - Increased detector granularity and acceptance in η
  - Timing measurements will add an additional dimension to pileup rejection
- Baselines for the upgraded detectors have been defined

- Compelling program of precision measurements in Higgs sector, testing further the SM and constraining BSM
- Continued exploration of the TeV scale via heavy new particle searches
- Various Physics prospects are under study with simulations that are continuously optimized.

- HE-LHC – needed for discoveries; increased sensitivity to larger masses
  - Work on compiling the physics prospects is beginning (in the context of European Strategy document)
- We look forward to an exciting physics program at LHC for the next 20+ years

References

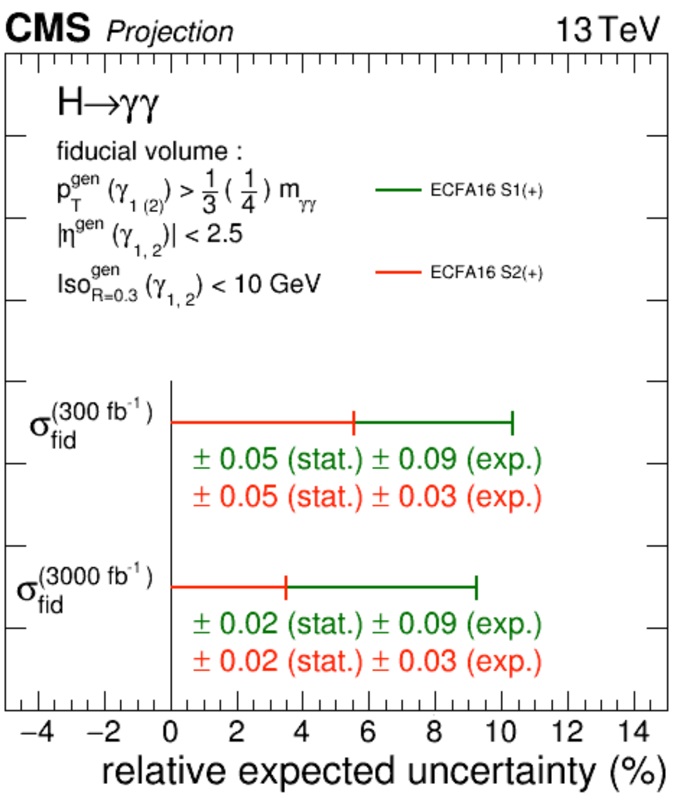
- CMS Collaboration, "Technical Proposal for the Phase-II Upgrade of the Compact Muon Solenoid", Technical Report CERN-LHCC-2015-010, LHCC-P-008, 2015.
- CMS scope document LHCC-G-165, 2015.
- Documents on ATLAS and CMS Public Results pages
- For details see presentations at the HL/HE-LHC kick-off workshop at CERN: https://indico.cern.ch/event/647676/.
- Higgs Working Group Report of the Snowmass 2013 Community Planning Study, arXiv:1310.8361 [hep-ex]
- Slides of previous talks by colleagues
  - Some of which I have shamelessly borrowed from (many thanks).

Higgs Cross Section Projections

Fiducial Cross Section (h→γγ)

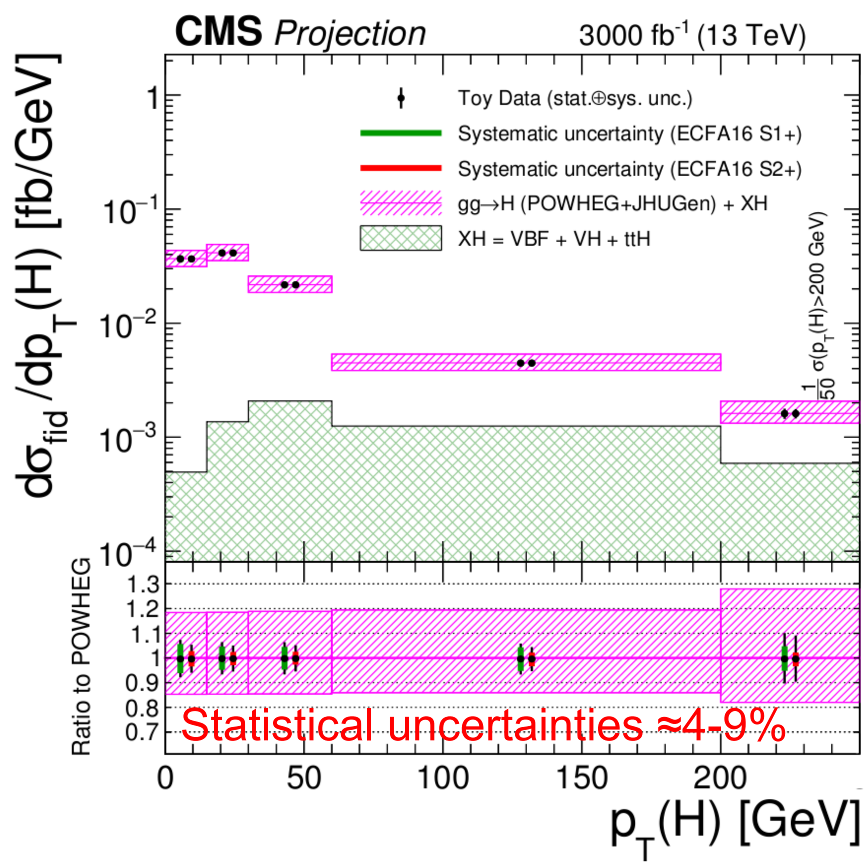
- Statistically limited
- Independent of theoretical uncertainty
- Further improvement expected in mass resolution and uncertainty from timing

  O(30 ps) for photons & charged particles

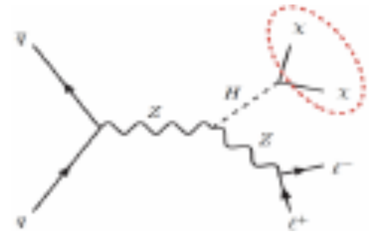


Differential p_T(h) Cross Section (h→ZZ)

- More detailed comparison with SM predictions
- Sensitive to kb/kc (low pT) kt/BSM (high)
- At high pT, dominated by statistical uncertainty even @ 3000 fb-1

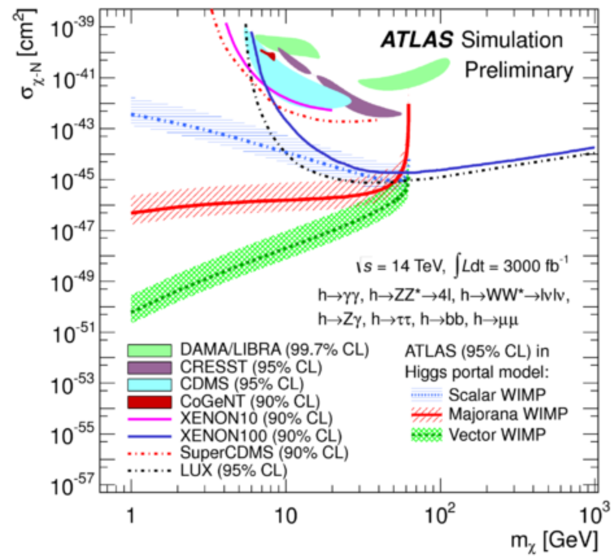


Dark Matter Searches:

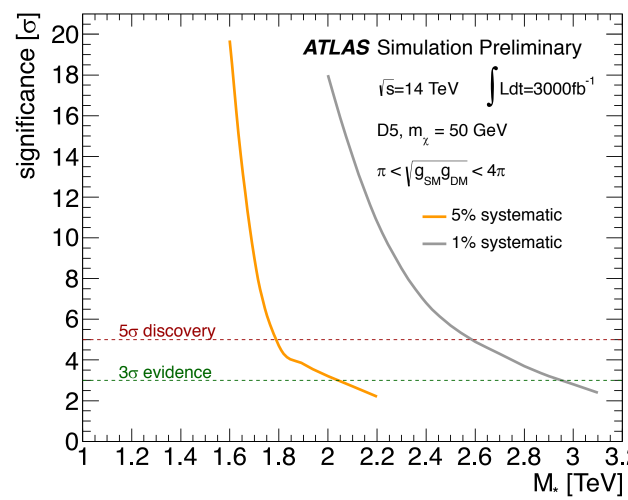


ATL-PHYS-PUB-2014-017

- Higgs Portal to Dark Matter:
- Recast from
  - Searches for Higgs coupling measurements
  - Direct search in Higgs decays to invisible (ZH→ll+invisible)
    - Fit parameters: κ_g, κ_γ, $\kappa_{Z\gamma}$, BR_{inv}
    - BRinv<0.13(0.09 w/o the. unc.)
      - Run2: BRinv< 67% (39%) obs.(exp)
- Excellent sensitivity for low-mass DM particles



- WIMP Dark Matter in Effective Field Theory
  - mediator mass, M_{med},is much heavier that the typical scale of the interaction Q_{tr}.
  - In EFT, the suppression scale $M^* = M_{med} / \sqrt{(g_{SM} g_{DM})}$
  - 5σ discovery reach: 1.8 (2.6) TeV for 5%(1%) uncertainty
    - Reach very sensitive to the uncertainties
  - Outstanding issues:
    - Understand impact of EWK corrections.
    - Reach 1% uncertainties.
  - Understand correlations between theoretical uncertainties.

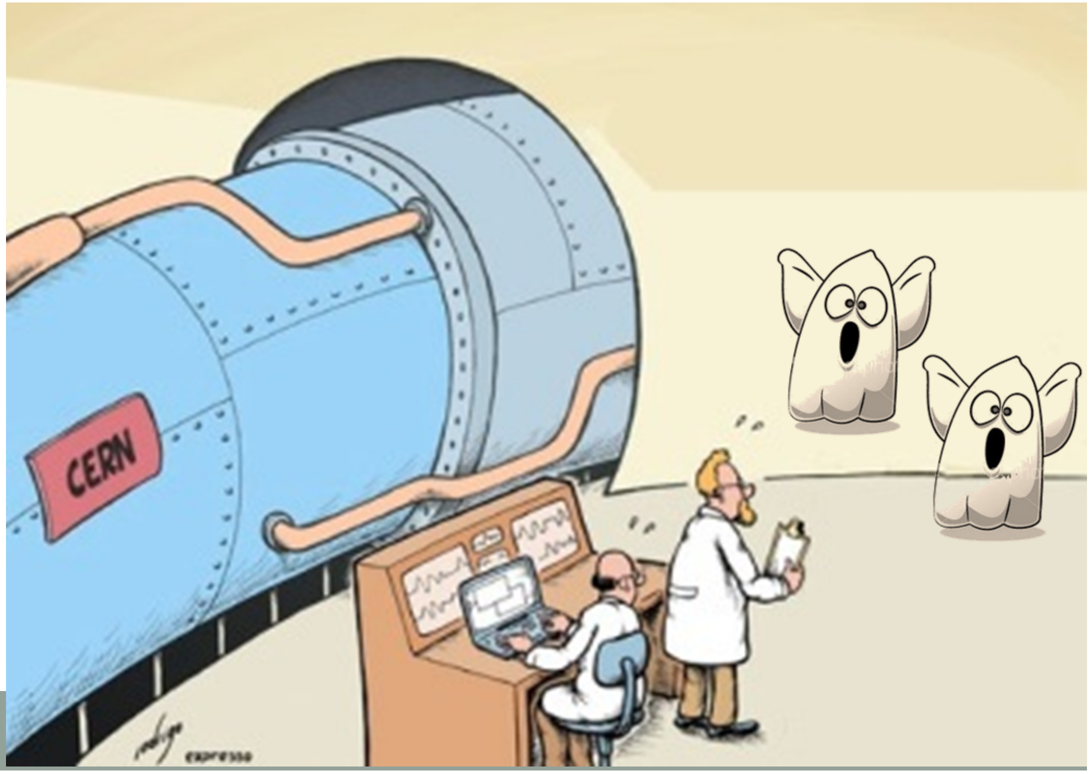


ATLAS-COM-PHYS-2014-549

SUPER-SYMMETRY

Focus for HL LHC:

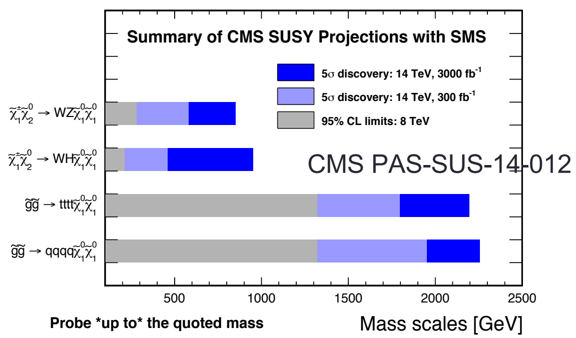
- Study properties, if new particle(s) discovered
- Turn to processes with low cross sections and compressed mass spectra (e.g. EWK SUSY, 3rd generation squarks..)
- Special signatures

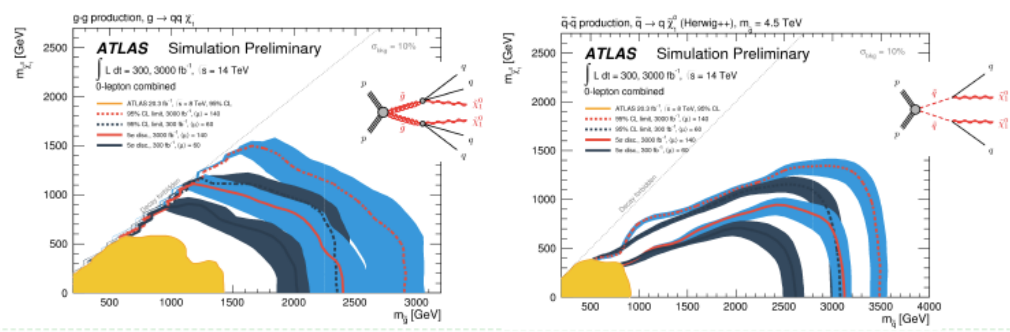


SUSY Particle reach at HL-LHC

- Two strategies employed to cover the vast phase space:
- Projections of individual analyses for simplified models
- Interplay of several analyses for full models
  - If there is SUSY, it will be seen across multiple signatures
  - A broad program ensures 2-3σ evidence in several places can be as interesting as 5σ in one analysis!
- HL-LHC Can extend reach to higher masses: gain several hundred GeV in squark and gluino masses and even more for charginos and neutralinos

ATLAS-PHYS-PUB-2014-010

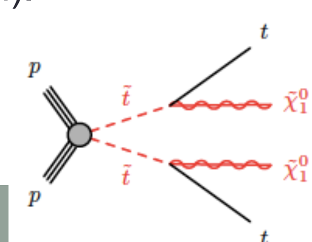


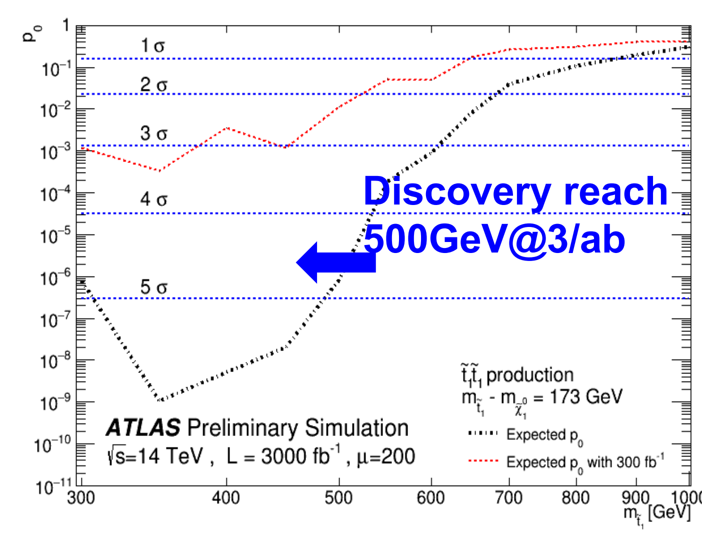


- Continue to study challenging scenarios:
- Third generation squarks:

$$(m_{\tilde t_1}, m_{\tilde\chi_1^0}) \cong m_t$$

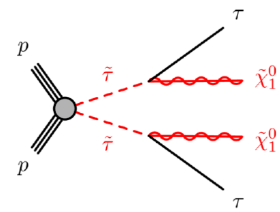
  - Direct stop Pair Production with Compressed Mass Spectra
  - Scenario with low stop-neutralino mass difference
  - Project sensitivity of 2-lepton channel (needs luminosity)
  - **key to study stop properties** (e.g. spin).
  - Signature: 2 leptons + 2 b-jets + MET
  - .

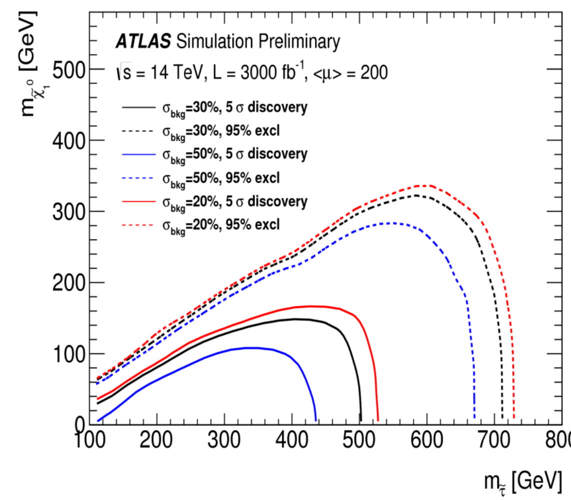




SUSY Particle reach at HL-LHC

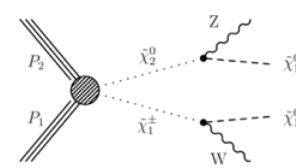
- Direct Production of stau Pairs
  - Assume 100% BR to SM tau and LSP.

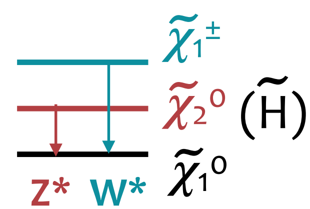




Signature: 2 tau jets (hadronically decaying tau) and large MET (from $\tilde{\chi}_1^0$)

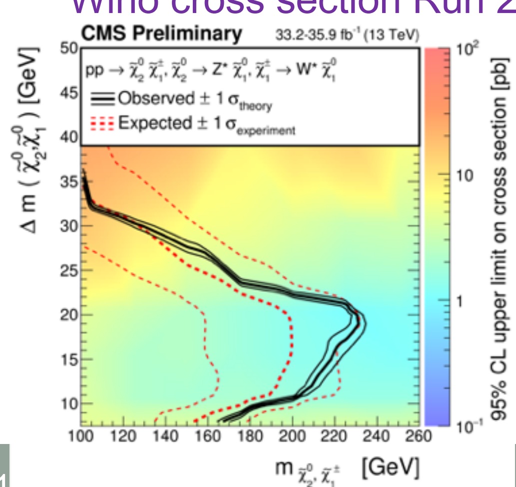
- Discovery reach : 430-520 GeV @ 3/ab (depending on bkg)



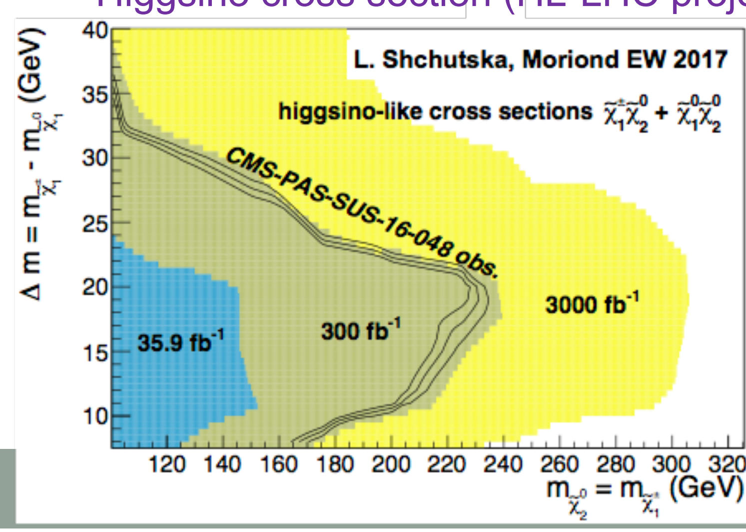


- Electroweak SUSY:
- Compressed EWK-inos
  - Require ISR jet, and focus on soft lepton from off-shell Z decay
  - Bin in Missing ET and opposite-sign dilepton mass

Wino cross section Run 2



Higgsino cross section (HL-LHC projection)



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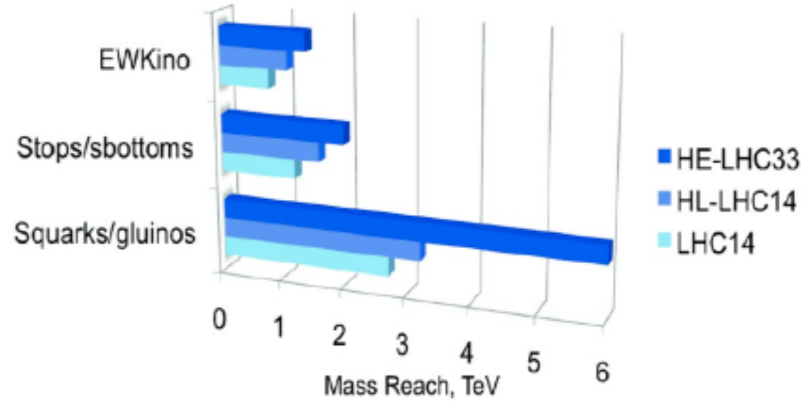
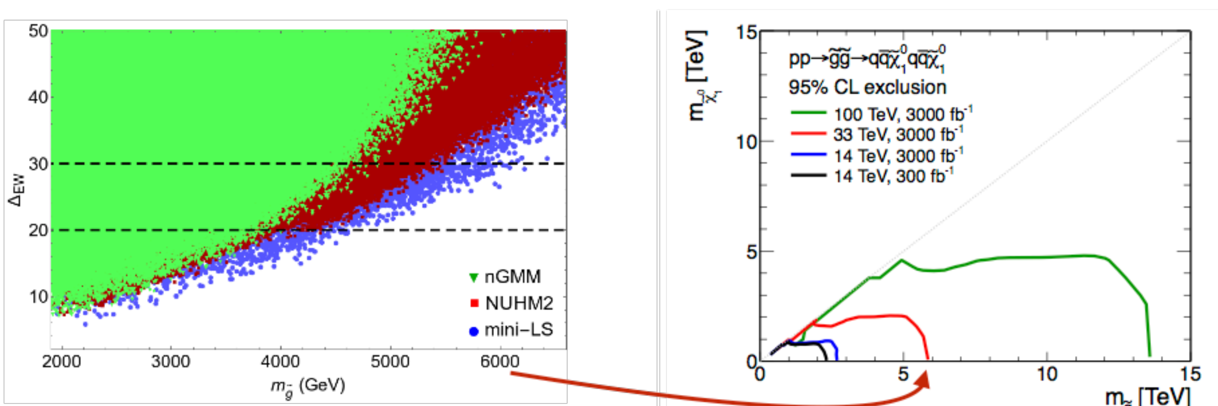
SUSY Particle reach at HE-LHC

- LHC at 14 TeV and HE-LHC at 33 TeV expand the reach for SUSY particles to much higher masses.As expected, the gain of HL-LHC is modest in this case.

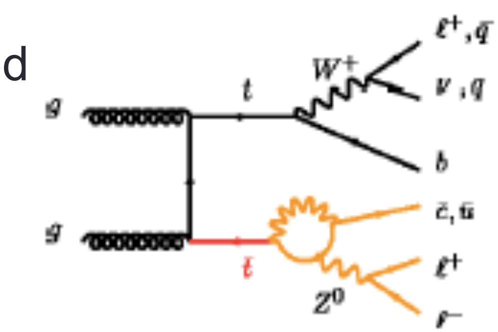


- A scenario for HE-LHC:
- models with light Higgsinos, can still achieve naturalness without requiring Winos with mass < 1 TeV
- In all cases they have gluinos with mass < 6 TeV
- Out of reach for HL-LHC (~2.5 TeV), but perfect for a 33 TeV HE-LHC



FCNC in top decays

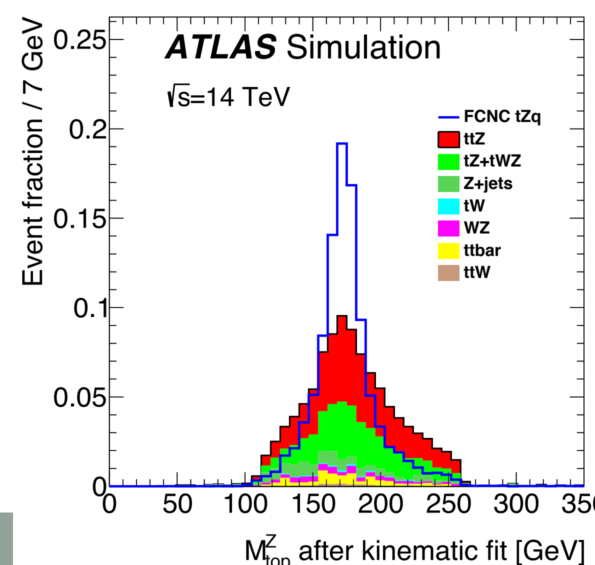
- BR ($t \to Wb$) ~100% in SM
- Flavor changing neutral current(FCNC) decay is highly suppressed
  - BR ($t \to Zq$) ~ 10^{-14} (SM)
  - BR ($t \to cH$) ~ $3x10^{-17}$ (SM)
- BSM models may give rise to FCNC at the level of BR<10^{-4}
- Any measurable BR is a compelling indication for new physics
- Higher luminosity will definitely help to reach BSM scenarios



	SM	2HDM	MSSM
BF($t\to cg$)	$5\cdot 10^{-12}$	$10^{-8}-10^{-4}$	$10^{-7}-10^{-6}$
BF($t\to cZ$)	$1\cdot 10^{-14}$	$10^{-10}-10^{-6}$	$10^{-7}-10^{-6}$
BF($t\to c\gamma$)	$5\cdot 10^{-14}$	$10^{-9}-10^{-7}$	$10^{-9}-10^{-8}$
BF($t\to cH$)	$3\cdot 10^{-15}$	$10^{-5}-10^{-3}$	$10^{-9}-10^{-5}$

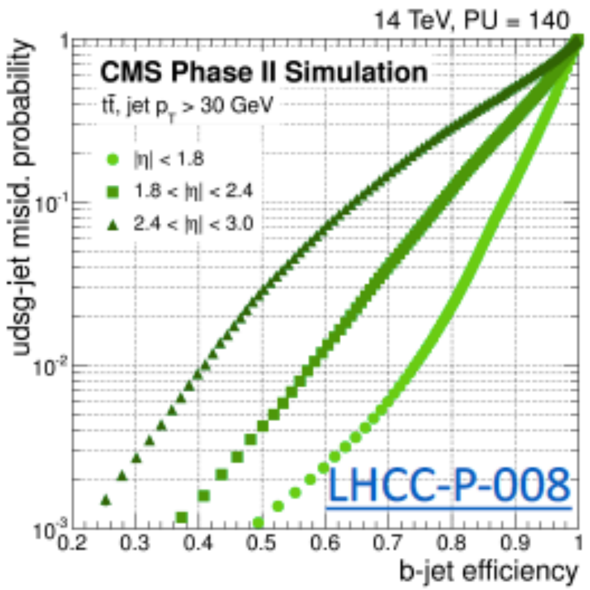
- Search in single top production and top-pair decays
  - $c\gamma\gamma$, multileptons, 2 or 3 b-jets with 3, 4, 5, or ≥6 jets

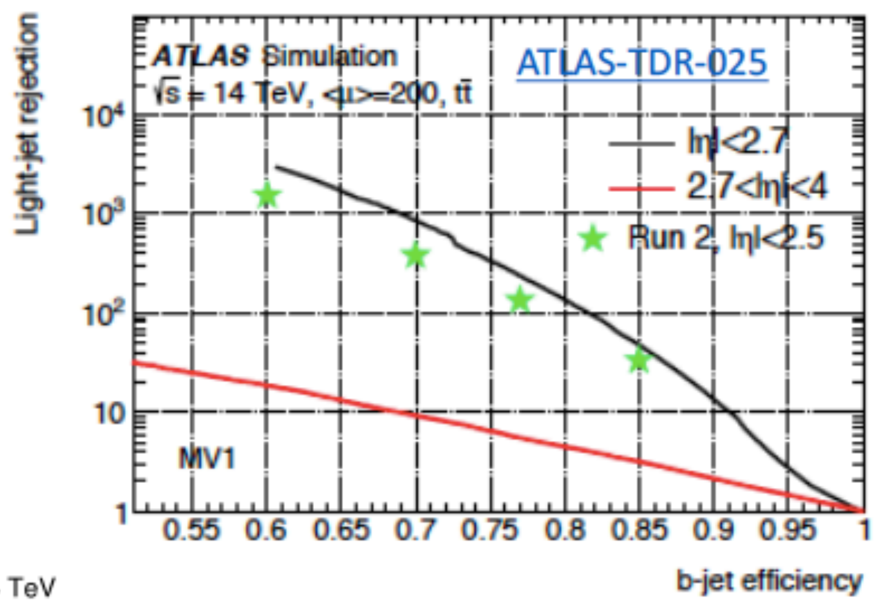
- Projected sensitivity
- ATLAS:
- $t \to Zu/c$: ~ 2.4-5.8 x 10^{-5} (FCNC modelling)
  - Run 1: 5x 10^{-4} →Sensitivity increase by factor 2 to 6
- $t \to Hu/c$: ~ 0.55-1.2 x 10^{-4}. (flavor of q)
  - Run 1: 45x10^{-4} → Sensitivity increase by factor >20
- CMS:
- $t \to c\gamma$: ~4.6x10^{-5} (Run1: 1.7x10^{-3})
- $t \to u\gamma$: ~3.4x10^{-4}. (Run 1: 1.3 x10^{-4})
  - Sensitivity increase by factor 3 to 10



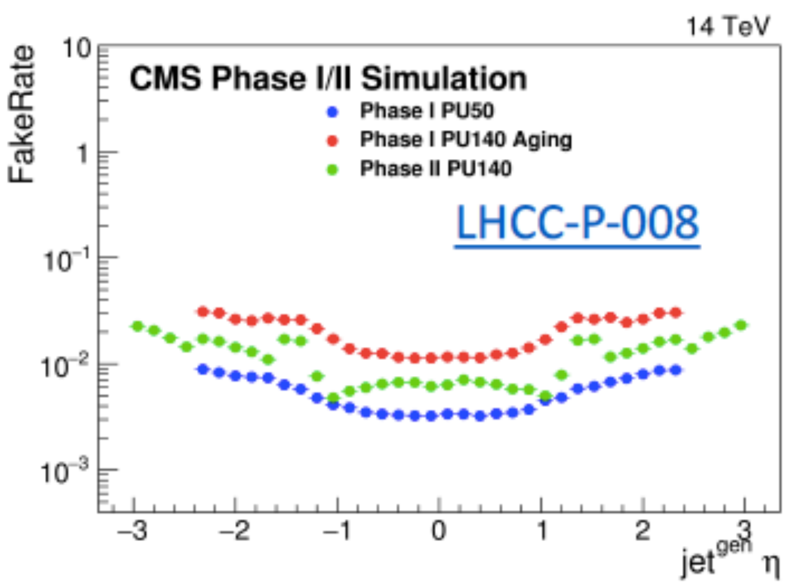
Detector performance

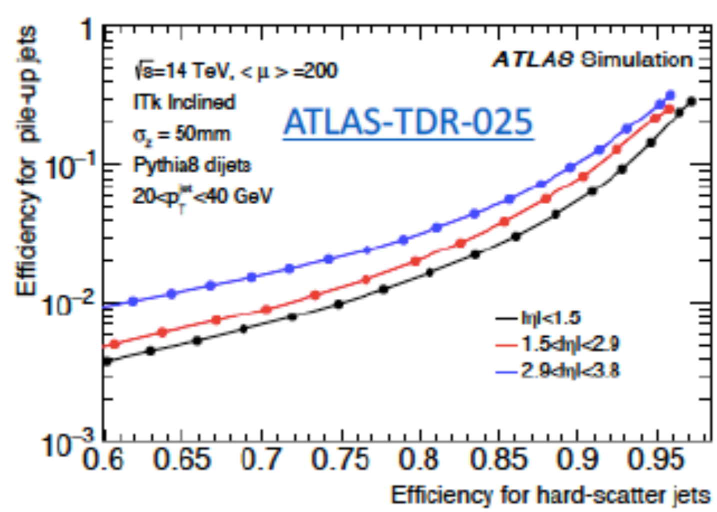
- Maintain performance close to Run 2





Light-jet rejection better with the upgraded detectors





Extended tracker to $|\eta| < 4$
Achieve good pile-up jet and fake tau rejection