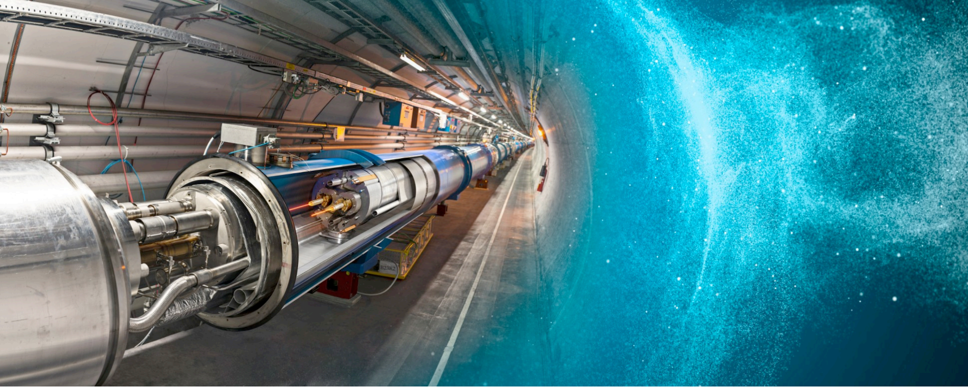
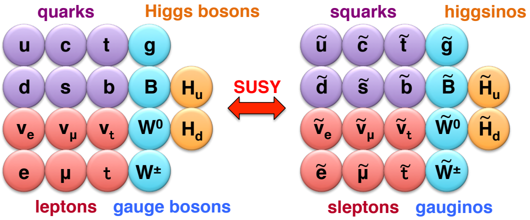


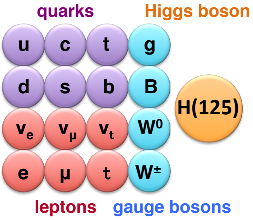
Review: The way forward for SUSY searches at the LHC and beyond

Lesya Shchutska
ETH Zürich
On behalf of ATLAS and CMS Collaborations

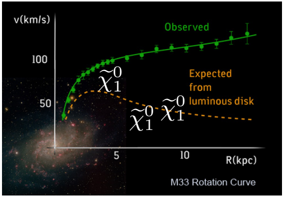
Moriond EWK, March 20, 2017

SUSY: expectation and reality

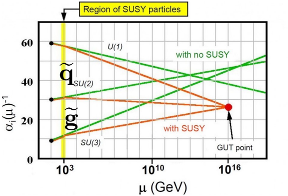


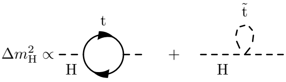


dark matter nature

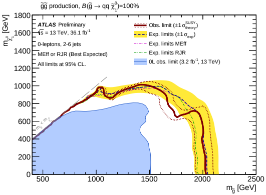


GUT





H boson mass stabilization



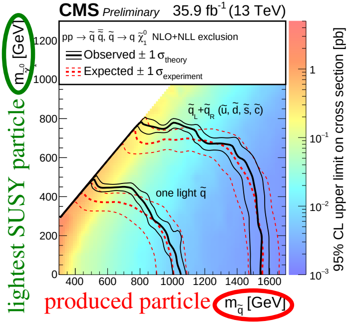
$$m(\widetilde{\mathrm{g}}^*) > 2.0\ \mathrm{TeV?}$$

$$m(\widetilde{\mathrm{t}}^*) > 1.1\ \mathrm{TeV?}$$

$$m(\widetilde{\chi}^*) > 0.5\ \mathrm{TeV?}$$

* *if exists at all...*

Setting the scene: how to interpret the limit plots



lightest SUSY particle

produced particle

UL on production cross section:

- ATLAS: numbers in the plot
- CMS: color map

Many assumptions enter mass exclusion lines shown before:

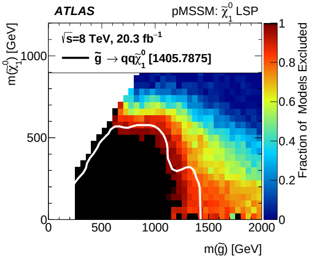
- always present - **simplified model spectrum (SMS)**: usually 2-particle spectrum with 100% BF to a considered final state
  - long chain decays ignored: can be important, lead to soft particles and low $E_T^{\text{miss}} \implies$ fall out of the acceptance of many searches
- assumptions on nature of produced particles, e.g.:
  - mass-degenerate squarks (8-fold cross section boost!)
  - type of produced EWK gauginos ($\sigma_{\text{wino}} > \sigma_{\text{higgsino}}$)
- assumptions enhancing BF to an analysis final state, e.g.:
  - decays via sleptons rather than W or Z: 100% BF to leptons
- always assume prompt decays of SUSY particles:
  - lifetime can be important in the diagonal (“compressed”) regions
  - in RPV models with small couplings
  - for wino (N)LSP (highly mass degenerate)

The question is: *does it make sense and are the limits general enough to draw any conclusions?*

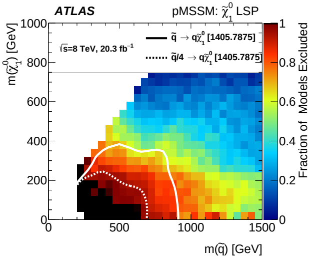
CMS-PAS-SUS-16-036

Guidance from full models: pMSSM (I)

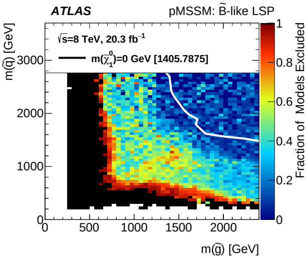
Falling back to a full 19-parameter pMSSM (8 TeV) shows how the assumptions hold:
color - fraction of excluded points (black = 100%); white line - corresponding SMS mass limit



gluinos mostly as in SMS



squarks: 2-fold degeneracy applies more often than 8-fold



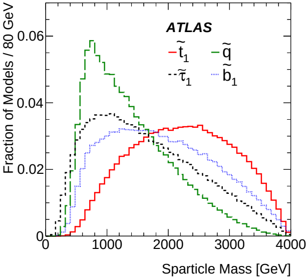
gluinos with bino-like LSP limits much weaker than in SMS: $\tilde{g}$ are very close in mass with LSP, "compressed" scenario

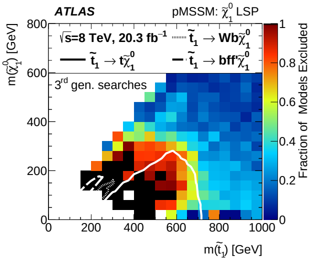
Strong sector mostly follows SMS apart from a special case of bino-like LSP

arXiv:1508.06608

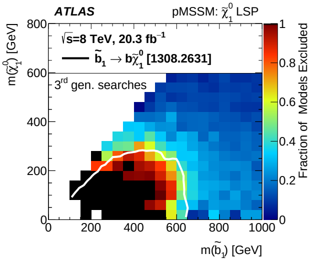
Guidance from full models: pMSSM (II)

3$^{\mathrm{rd}}$ generation squarks: sampled high $\tilde{\mathrm{t}}$ masses to reach 125 GeV for the lightest MSSM h (*ironically, $\tilde{t}$ needs to give large enough quantum corrections to h*)





stops: weaker than SMS because of competing decays e.g. $\tilde{t} \rightarrow b\chi^+$



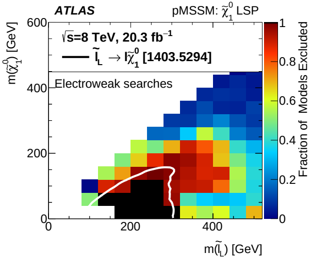
sbottoms similar to SMS

Findings correspond to the knowledge from SMS but space for exploration is limited

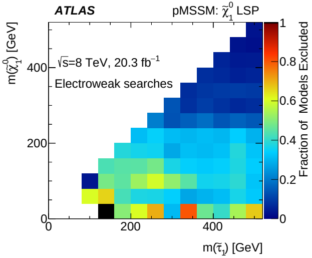
arXiv:1508.06608

Guidance from full models: pMSSM (III)

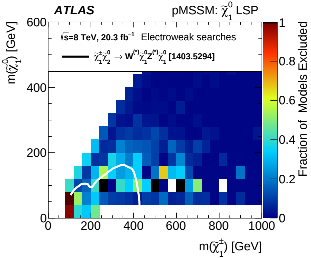
Electroweak sector: the lowest production cross sections - the hardest to constrain



sleptons mostly as in SMS:
lose sensitivity in the diagonal



staus: no sensitivity

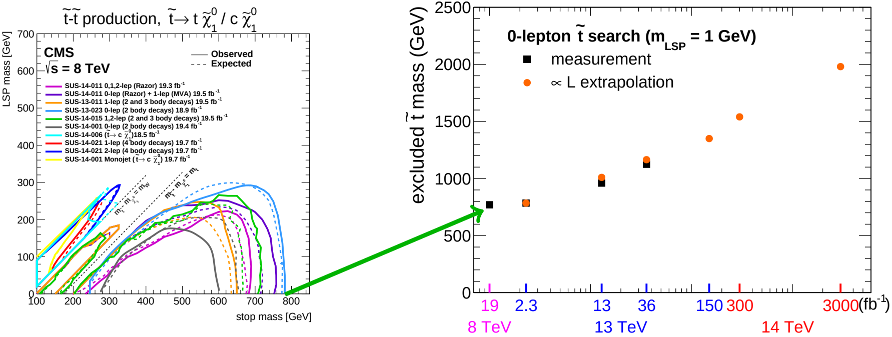


charginos:
diagonal - long-lived searches;
“bulk” is weaker constrained
due to cross-sections assumptions

Electroweak sector has the most to gain from the increase in the dataset!

arXiv:1508.06608

Prediction power of the common sense: $\tilde{t}$ example

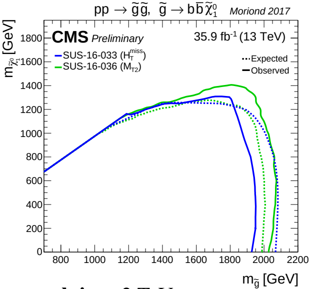


extrapolation with ≈ 0 background in the **highest mass** excluded point works very well

Assuming that the detector performance does not degrade with time/conditions!

(that is where the hard work in all projection studies enters)

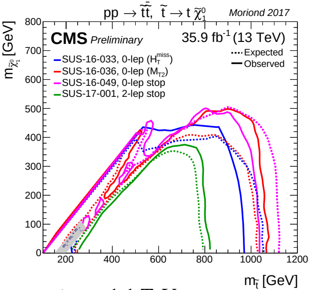
Places to hunt for?



gluinos 2 TeV now

2.5 TeV @ 300/fb

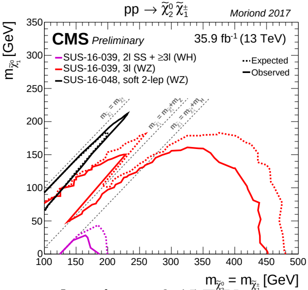
3 TeV @ 3000/fb



stops: 1.1 TeV now

1.5 TeV @ 300/fb

2 TeV @ 3000/fb



charginos: 0.45 TeV now

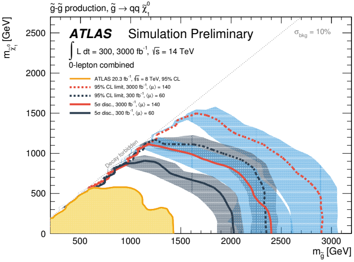
0.75 TeV @ 300/fb

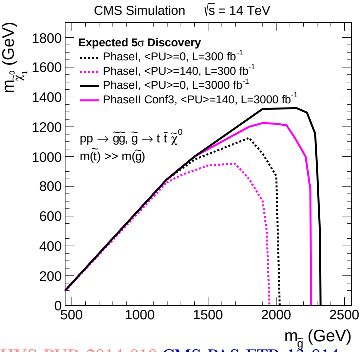
1.2 TeV @ 3000/fb

But this works only for some of the “high-Δm” cases. Assumptions do not hold if:

- **gluinos**: in very “compressed” with the LSP scenario
- **stops**: $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \lesssim 175$ GeV: soft decay products, similarity to SM $t\bar{t}$ production
- **charginos, neutralinos**:
  - “high-Δm”: current limits and projections are done with too optimistic cross sections
  - $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \lesssim 100$ GeV: new dedicated search appeared to target this region

Gluinos: official projections

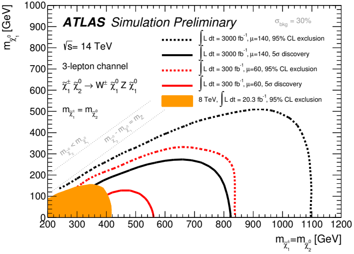


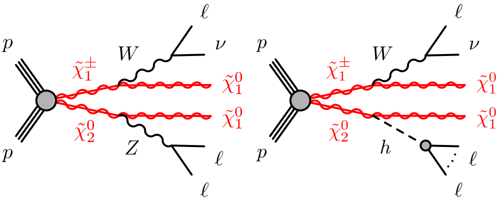


ATL-PHYS-PUB-2014-010 CMS-PAS-FTR-13-014

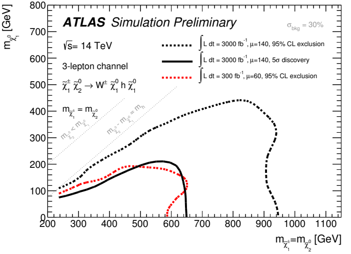
- for the massless LSP simple calculation checks out
- for more complicated compressed case: gluinos can be excluded up to about 1.7 TeV after HL-LHC
  - with a small window remaining between 1.2 and 1.8 TeV
  - 300/fb 5σ discovery case is practically excluded
- sensitivity at the diagonal comes from the ISR-tagging
  - reduced signal acceptance $\implies$ weaker sensitivity

Charginos and neutralinos: official projections





- fuller picture includes decays to both WZ and WH:
  - sensitivity is in between the shown curves
- projections do not include sensitive in high masses $W(\ell\nu)H(b\bar{b}) + E_T^{miss}$ search
  - expect improvement from this
- to recall that when generalizing the main limitations come from:
  - the lower realistic production cross section
  - compressed higgsino or wino cases which are not included in projections!



ATL-PHYS-PUB-2014-010 CMS-PAS-FTR-13-014

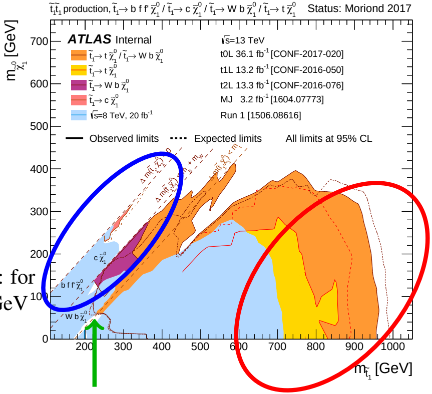
Current toolbox: not fully employed in projections

“low Δm”

$\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ or $\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0$:

- $\tilde{t}_1$ could be long-lived
- ISR-tagging
- charm-tagging
- very soft leptons: down to 3.5 GeV
- secondary vertex tagging: for b-quarks with $p_T < 20$ GeV

often systematics-limited!



SM-like $\tilde{t}_1$ production:

- kinematics very similar to $t\bar{t}$
- probed by $t\bar{t}$ cross section and polarizaton measurements
- ISR-tagging for higher LSP mass

“high Δm”

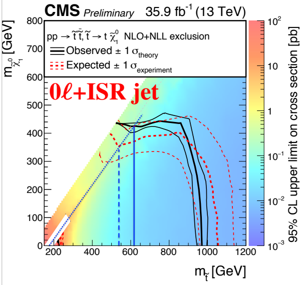
low-SM background:

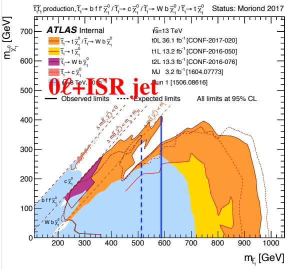
- limited by cross section
- employ merged t and V reconstruction

The same “low Δm” and “high Δm” tools are used for other sparticle searches

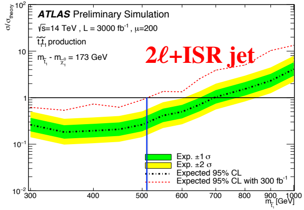
Difficult corners of the phase-space: stops

- always large SM backgrounds: with no change in analysis strategy bound by $\sqrt{\mathcal{L}}$
- in reality: the progress is driven by the **(r)evolution of ideas** rather than dataset growth
- e.g. compare the current reach of 0ℓ searches for $\tilde{t}_1$ in the regime $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = m_t$





Projection to 300(0)/fb@14 TeV



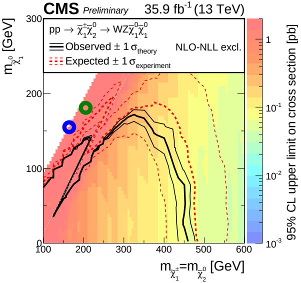
- with 36/fb @13 TeV the sensitivity has surpassed the projection to 300/fb @ 14 TeV!
  - the projection uses **only 2ℓ final state** - cleanest final state and lowest branching fraction decay mode
  - *projections take into account changed conditions: in this case PU increased from 30 to 200*

CMS-PAS-SUS-16-033 ATL-PHYS-PUB-2016-022

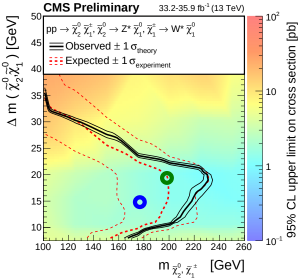
New ideas $\Longrightarrow$ Exponential improvement ($\tilde{\chi}_1^\pm \tilde{\chi}_2^0$)

- traditional analysis excludes signal strength of **12× for (200, 180)** and **27× for (175, 160)**
- even if scale with $\mathcal{L}$(optimistic!) $\Longrightarrow$ need > 300/fb of data to probe this value!
- new analysis is sensitive there already **now**

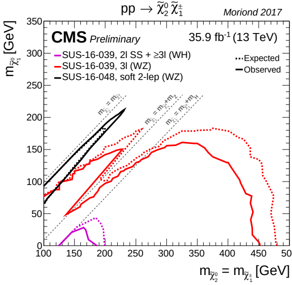
traditional 3ℓ search



soft 2ℓOS+ISR search



complementarity



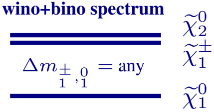
Bonuses of the new analysis:

- use very soft leptons to access low mass splittings: down to $p_T = 3.5$ GeV (b-physics level)
- no penalty with BF(W→ $\ell\nu$)

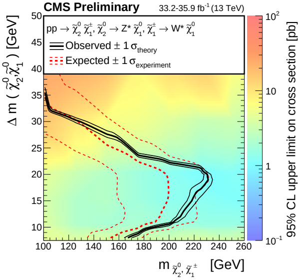
CMS-PAS-SUS-16-039 CMS-PAS-SUS-16-048

A higgsino projection for the future

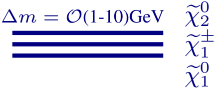
wino+bino spectrum

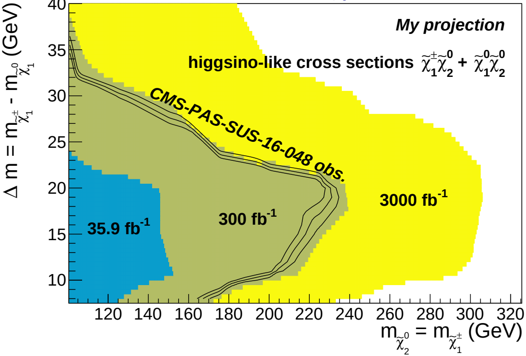


line with wino-like cross sections



higgsino spectrum

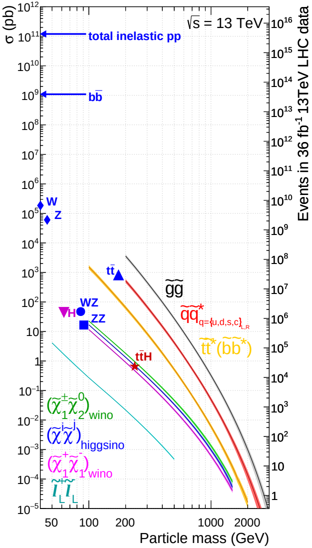




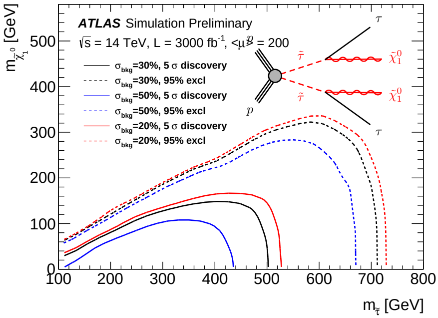
- whole new sensitivity to an unprobed before at the LHC SUSY scenario is opened!
- **new result** $\Longrightarrow$ no official projections to HL-LHC (*yet*)
- $\sqrt{\mathcal{L}}$ scaling leads to 230 GeV @ $\Delta m = 7.5$ GeV with 3000/fb

CMS-PAS-SUS-16-048

Staus with the HL-LHC



- the main battle is against
  - the production cross section
  - τ_h reconstruction efficiency
  - high W+jets SM background
- currently no sensitivity shown
- at HL-LHC could discover $\tilde{\tau}$ with masses up to 0.5 TeV



ATL-PHYS-PUB-2016-021

Discovery scenarios

“Natural Models”

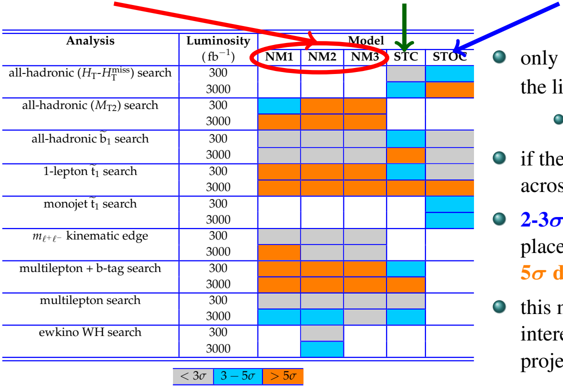
- light $\tilde{g}(\sim 1.7$ TeV), $\tilde{t}/\tilde{b}$ (1 TeV)
- NM1: light $\tilde{\ell}$
- 1,2: bino $\tilde{\chi}_1^0$; 3: higgsino $\tilde{\chi}_1^0$

“$\tilde{\tau}$ coannihiliation”

- heavy $\tilde{g}$ (3 TeV)
- light $\tilde{t}/\tilde{b}$ (1 TeV)
- $\tilde{\tau}$-NLSP, +10 GeV

“$\tilde{t}$ coannihiliation”

- light $\tilde{t}$-NLSP (0.4 TeV)
- $\tilde{t} \rightarrow c\tilde{\chi}_1^0$
- 2.1 TeV $\tilde{g} \rightarrow t\bar{c}\tilde{\chi}_1^0$



Analysis	Luminosity (fb^{-1})	Model				
		NM1	NM2	NM3	STC	STOC
all-hadronic (H_T-H_T^{miss}) search	300				▨	🟦
	3000				🟦	🟧
all-hadronic (M_{T2}) search	300	🟦	🟧	🟧		
	3000	🟧	🟧	🟧		
all-hadronic $\tilde{b}_1$ search	300	▨	▨	▨	🟦	▨
	3000	▨	▨	▨	🟧	▨
1-lepton $\tilde{t}_1$ search	300	🟧	🟧	🟧	🟦	▨
	3000	🟧	🟧	🟧	🟧	🟧
monojet $\tilde{t}_1$ search	300					🟦
	3000					🟦
$m_{\ell^+\ell^-}$ kinematic edge	300	▨	▨	▨		
	3000	🟧	▨	▨		
multilepton + b-tag search	300	🟧	🟧	🟧	🟦	
	3000	🟧	🟧	🟧	🟧	
multilepton search	300	▨	▨	▨	▨	
	3000	🟦	🟦	▨	🟦	
ewkino WH search	300		▨			
	3000		🟦			

▨ $< 3\sigma$ 🟦 $3-5\sigma$ 🟧 $> 5\sigma$

- only benchmark analyses are in the list
  - *we have many more*
- if there is SUSY: it is visible across multitude of signatures
- **2-3σ evidence** in multiple places could be as good as **5σ discovery** in one channel
- this makes 95%CL curves as interesting as 5σ ones in projections

Could seem tight for the discovery at the (HL-)LHC
but there is plenty of phase-space for strong hints!

CMS-PAS-SUS-14-012

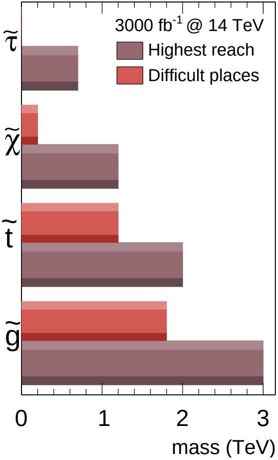
Conclusions and summary

After Run II successful restart:

- no quick and easy discovery after the energy jump $\Longrightarrow$ *we are forced to get creative!*

Lessons learned with the transition from Run I to Run II:

- long shutdown brought many new ideas and R&D in the discovery tools
- current results often surpassed projections to 300/fb with 3-year old knowledge
- the only certain limitation to a future discovery at the (HL-)LHC is cross section at high masses - unsurmountable barrier
- difficult corners can still bring surprises: monojet or VBF topologies start to become interesting!

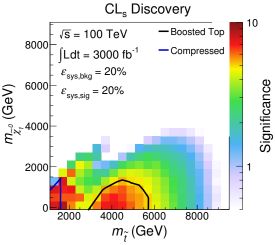


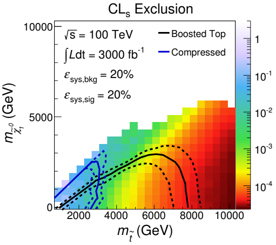
Disclaimer:

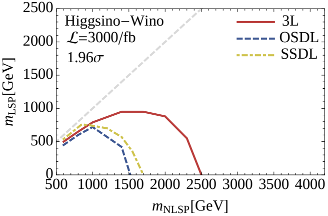
- long-lived scenarios and RPV corner could bring more handles - not covered here

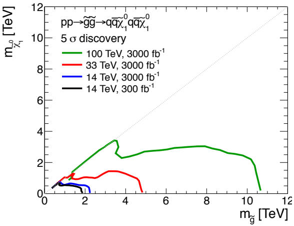
Beyond... the conclusions

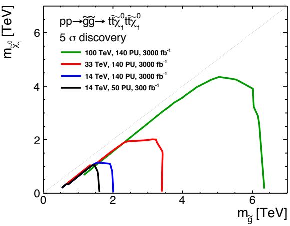
Going not only to 3000/fb but to **3000/fb @ 100 TeV pp FCC** opens a new world:

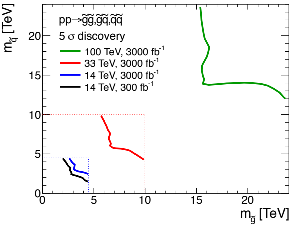






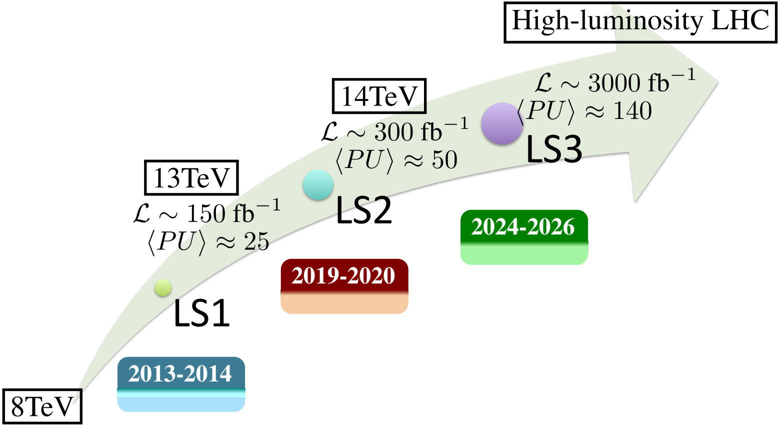






arXiv:1606.00947

(HL-)LHC timeline



High-luminosity LHC

14TeV

$\mathcal{L} \sim 300\ \mathrm{fb}^{-1}$

$\langle PU \rangle \approx 50$

13TeV

$\mathcal{L} \sim 150\ \mathrm{fb}^{-1}$

$\langle PU \rangle \approx 25$

$\mathcal{L} \sim 3000\ \mathrm{fb}^{-1}$

$\langle PU \rangle \approx 140$

LS3

LS2

LS1

2024-2026

2019-2020

2013-2014

8TeV