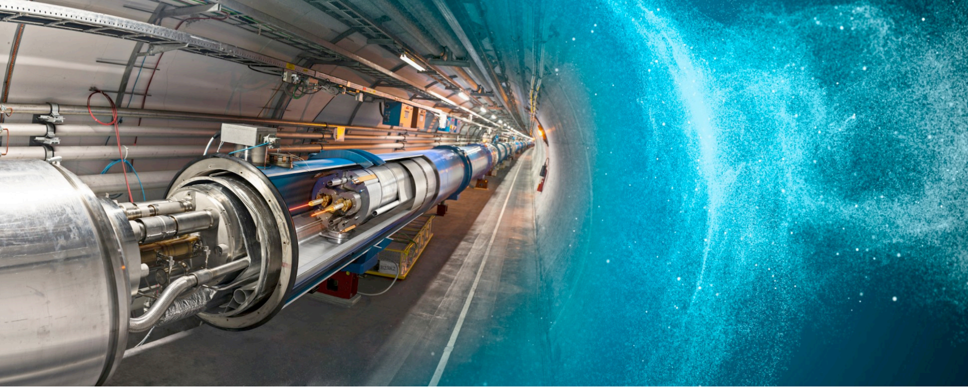


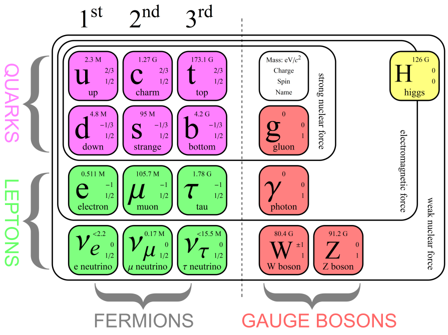
Electroweakly produced new physics with CMS: new intensity frontier at the LHC

Lesya Shchutska
ETH Zürich
CMS Collaboration

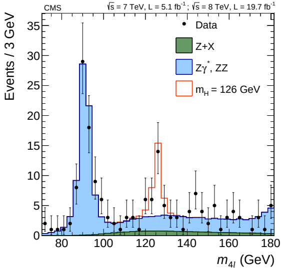
FNAL, Wine&Cheese Seminar
November 10, 2017

Triumph of the Standard Model (of particle physics)

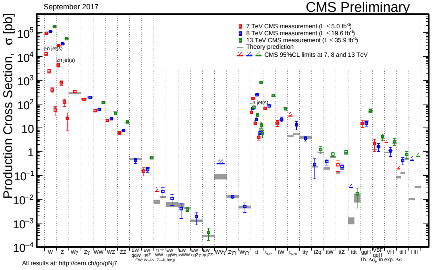
Turning **50** this year:



Proudly celebrating 5 years of completeness:



And not yielding the floor:

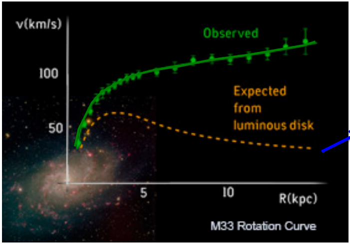


New physics in front of us: the SM is incomplete

Known facts of the physics beyond the SM:

- the nature of the dark matter
- matter-antimatter asymmetry of the universe
- neutrino masses and oscillations

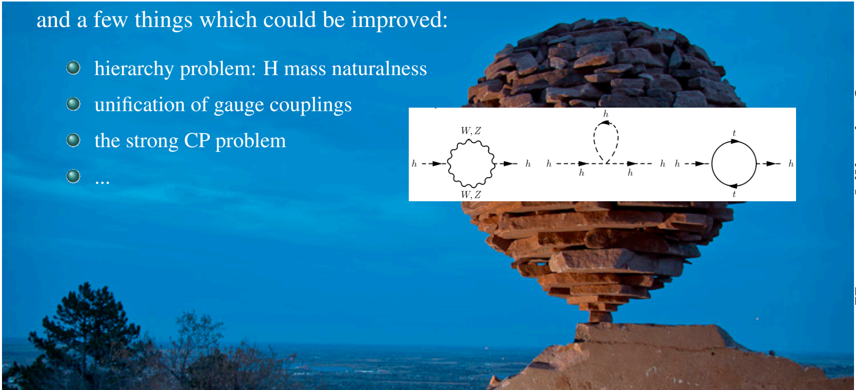
dark matter nature?



$$v^2 \propto \frac{M}{r}$$

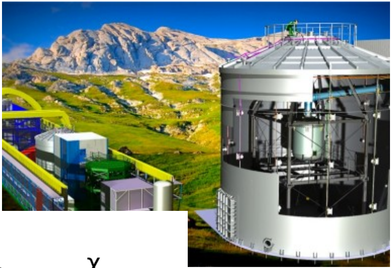
and a few things which could be improved:

- hierarchy problem: H mass naturalness
- unification of gauge couplings
- the strong CP problem
- ...



H mass stabilization?

In quest for the unknown: dark matter

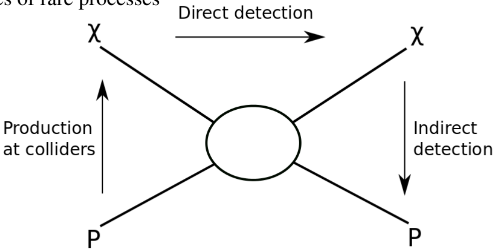


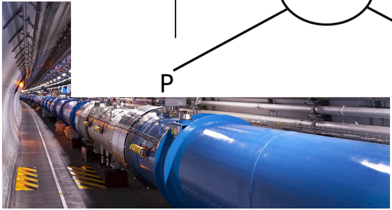
Exploit DM abundance in the universe:

- DM scattering experiments
- look for DM annihilation or decay products

Try to produce and detect it at colliders:

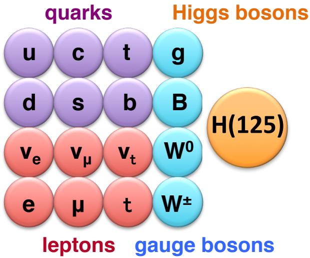
- look for signs of new particles
- measure rates of rare processes



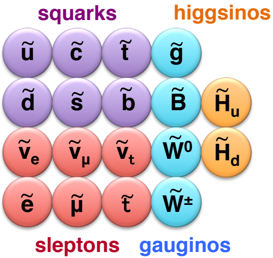


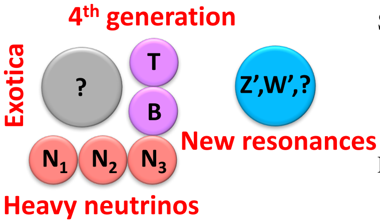
Flavors of new physics searches at the LHC

Standard model



Supersymmetry





Searches for new particle production:

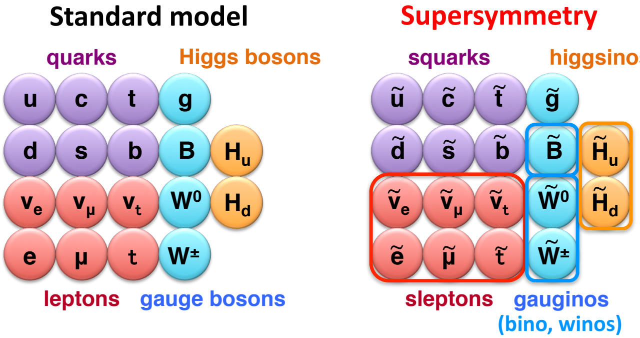
- resonant (heavy resonance-like)
- non-resonant (SUSY-like)
- long-lived signatures (charged or neutral)

Exploration of Higgs boson:

- invisible decays
- lepton-flavor violating decays

Zooming in into the electroweak sector

The superpartners of the SM EWK bosons (bino, 3 winos, 4 higgsinos) mix to form **mass eigenstates**:



$\tilde{\chi}_1^0$

$\tilde{\chi}_2^0$ $\tilde{\chi}_1^\pm$

$\tilde{\chi}_3^0$ $\tilde{\chi}_2^\pm$

$\tilde{\chi}_4^0$ **charginos**

neutralinos

If R-parity is conserved:

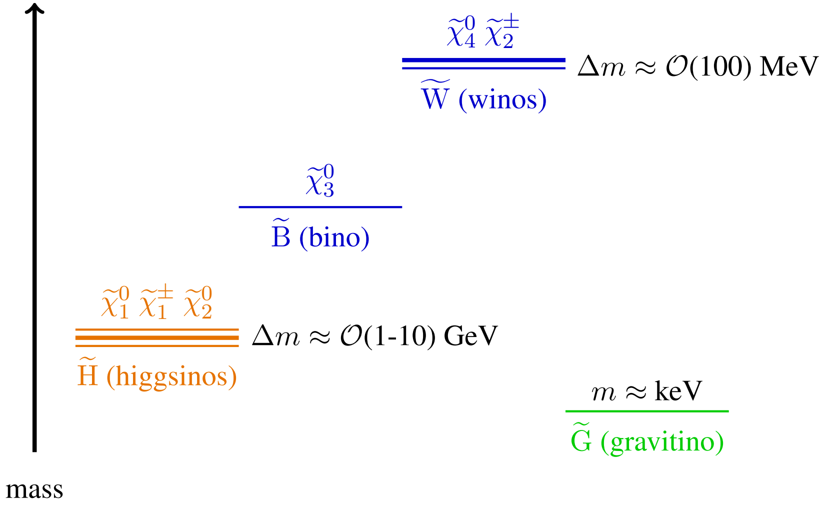
Lightest SUSY Particle (LSP) is stable and sparticles are produced in pairs.

Neutralino LSP can be **a dark matter candidate**:

the searches based on large $E_{\mathrm{T}}^{\mathrm{miss}}$ in final states

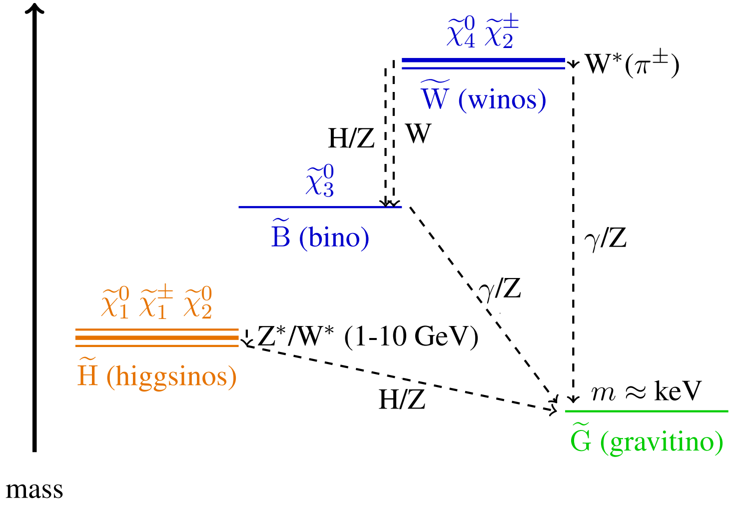
Possible spectra of EWK superpartners

Any bino/wino/higgsino mass hierarchy is allowed:



Possible decays of EWK superpartners

Any bino/wino/higgsino mass hierarchy is allowed...



arXiv:0908.3399

Favored mass range

Any bino/wino/higgsino mass hierarchy is allowed

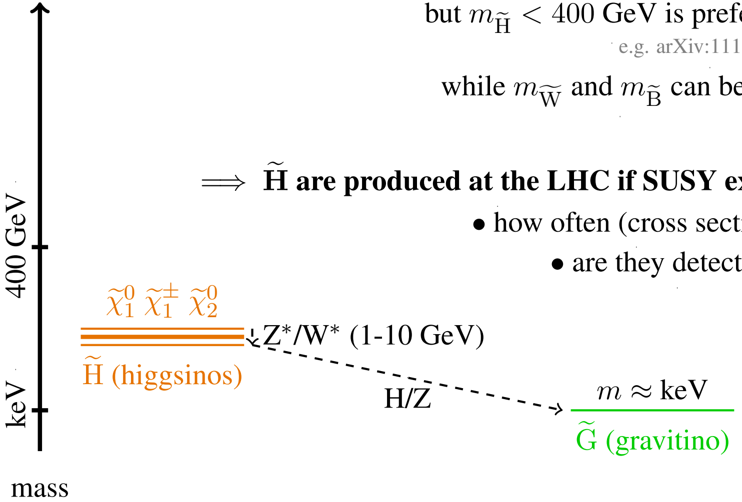
but $m_{\widetilde{\mathrm{H}}} < 400$ GeV is preferred

e.g. arXiv:1110.6926

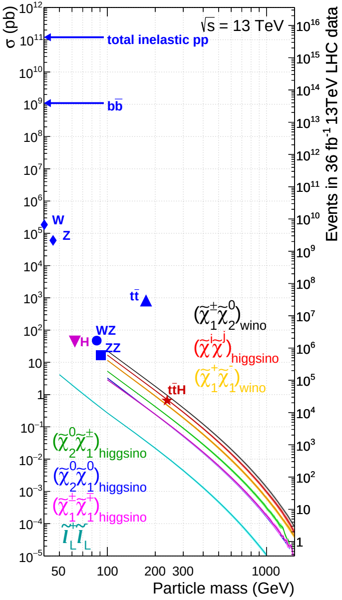
while $m_{\widetilde{\mathrm{W}}}$ and $m_{\widetilde{\mathrm{B}}}$ can be **any**

$\Longrightarrow$ **$\widetilde{\mathrm{H}}$ are produced at the LHC if SUSY exists!**

- how often (cross section)?
- are they detectable?



Production cross section

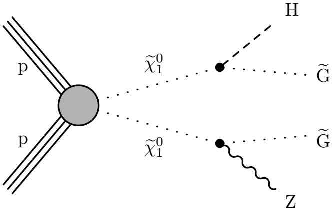


- cross sections are lower than those of the SM processes still to be discovered
- decay chains are complex:
  - involve Higgs bosons
  - or very soft objects (leptons and tracks)
  - can have low E_T^{miss}
- lead to nontrivial search strategies:
  - **Case 1:** assume existence of light $\widetilde{G}$ (GMSB)
  - **Case 2:** assume that higgsino $\tilde{\chi}_1^0$ is the LSP

GMSB-like case: Assumptions

- cross sections are calculated in the **mass degenerate** limit:

$$pp\rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0 + \tilde{\chi}_2^0\tilde{\chi}_1^\pm + \tilde{\chi}_1^\pm\tilde{\chi}_1^0 + \tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 + \text{low-}p_T \text{ SM}$$



- heavier states decay to $\tilde{\chi}_1^0$ which decays to $\tilde{G}$ via Higgs or Z bosons
- Δm between higgsino $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0$ are such that:
  - they have **short lifetimes**
  - decays produce SM particles **softer than 5-10 GeV** lepton/track vetoes
  - soft-SM decays preferred over **direct decays** to $\tilde{G}$

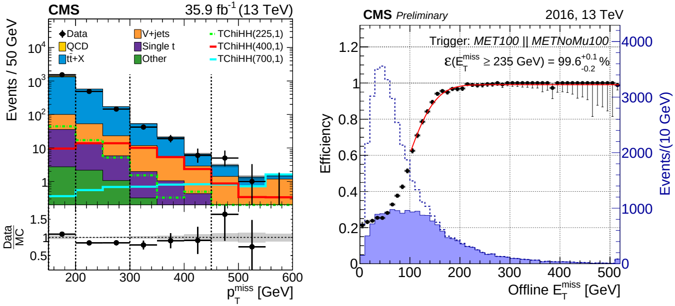
GMSB-like case: Searches

- several possible decay chains require looking at various topologies
- sensitivity of each search depends on SUSY mass spectrum and decay modes

Search	Signal topology			Reference
	ZZ	ZH	HH	
HH(4b)			✓	arXiv:1709.04896
H($\gamma\gamma$)		✓	✓	arXiv:1709.00384
$\geq 3\ell$ (incl. τ_{h})	✓	✓	✓	arXiv:1709.05406
Z(2ℓ)	✓	✓		arXiv:1709.08908
combination	✓	✓	✓	CMS-PAS-SUS-17-004

HH(4b) challenges

- not an easy task: 4 b jets and moderate E_T^{miss} (especially for low $m_{\tilde{\chi}}$)
- maximize the sensitivity by going beyond the standard approach:
  - to get access to low masses use the turn-on region of the E_T^{miss} trigger

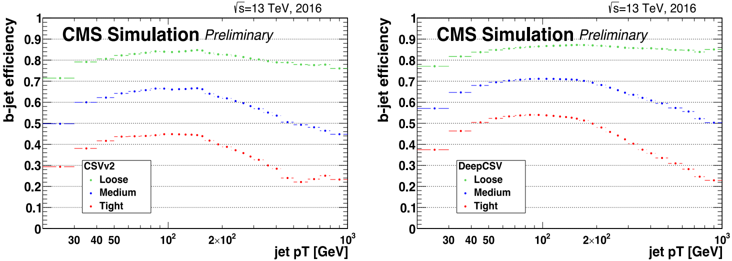


Offline selection: $E_T^{miss} > 150$ GeV

  - employ deep neural networks for b jet identification: **DeepCSV** (CMS-DP-2017-005)

Advanced b-tagging technique: DeepCSV

The same inputs as a standard CMS b-tagger (CSVv2), include information on more tracks, and combine with a **deep neural network** (**DeepCSV**):



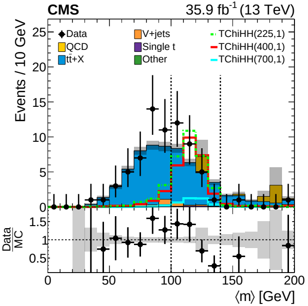
- significant improvement in b tagging efficiency:
  - +3% for loose WP (∼10% mistag)
  - +8% for medium WP (∼1% mistag)
  - +20% for tight WP (∼0.1% mistag)
- example impact on the 4b analysis bin (2T, 1M, 1L b jets):
  - bkg increases by ∼45%, signal increases by ∼30%
  - **improvement of sensitivity with the small background**

CMS-DP-2017-005

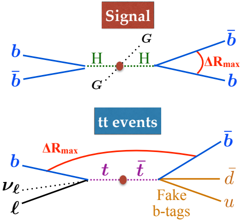
HH(4b): Elegant kinematic selection

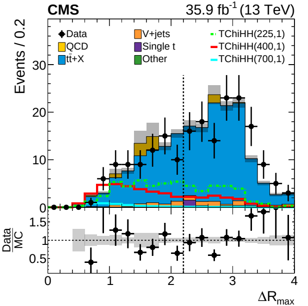
Di-Higgs reconstruction:

- use 4 most b-like jets for H_1H_2 pairings
- $\Delta m = \min_{i=1}^{3} |m_{H_1} - m_{H_2}| < 40$ GeV
- $100 \text{ GeV} < \langle m \rangle = \dfrac{m_{H_1} + m_{H_2}}{2} \leq 140 \text{ GeV}$
- use unbiased shape of $\langle m \rangle$ in non-b tagged events to obtain SM background

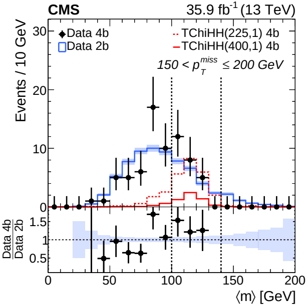


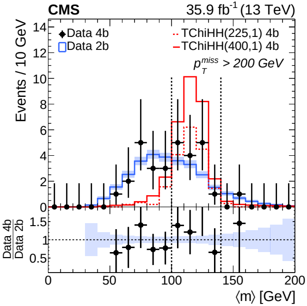
ΔR between b jets forming a H candidate:



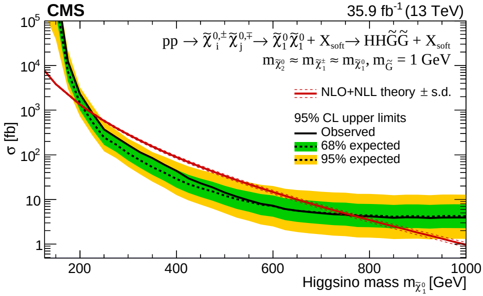


HH(4b): Results





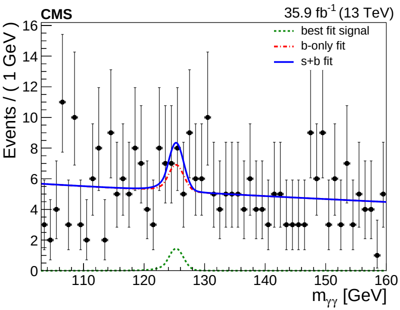
Higgsino masses are excluded for 230-770 GeV.

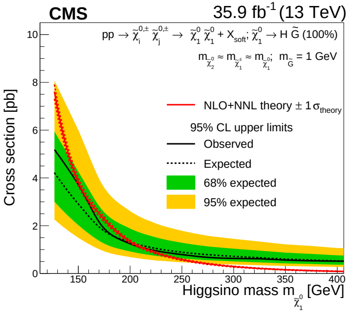


Higgsinos with H($\gamma\gamma$)

Use a Higgs boson discovery technique to find new physics:

- fit falling $m(\gamma\gamma)$ spectrum to “measure” H$\to \gamma\gamma$ rate in various kinematic selections
- compare with the SM Higgs boson production expectation
- provide complementary sensitivity in the low-mass region: exclude higgsinos below 205 GeV.





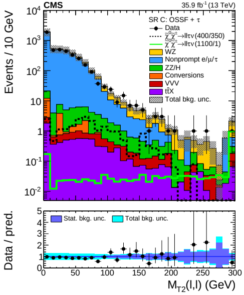
Higgsinos with multileptons

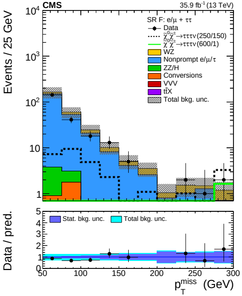
inclusive search with 2 e/μ of the same charge, or ≥ 3 leptons (with $\leq 2\tau_{\mathrm{h}}$)

- low-background search: recovers sensitivity to low-$E_{\mathrm{T}}^{\mathrm{miss}}$ cases (low $m_{\tilde{\chi}}$)
- keep in mind that $\mathcal{B}(\mathrm{H} \to 1\ell) = 9.3\%$ and $\mathcal{B}(\mathrm{H} \to 2\ell) = 9.1\%$
  - multileptons are about as frequent in H decays as in Z decays!
- challenges:
  - separate **prompt** (e.g. from W$\to \ell\nu$) and **nonprompt** (e.g. from b$\to$X$\ell\nu$) leptons

    $\Longrightarrow$ *develop new tools*
  - differentiate SM (e.g. WZ$\to 3\ell\nu$) and new physics multileptons:

    $\Longrightarrow$ *categorize by lepton flavor and use kinematical variables*

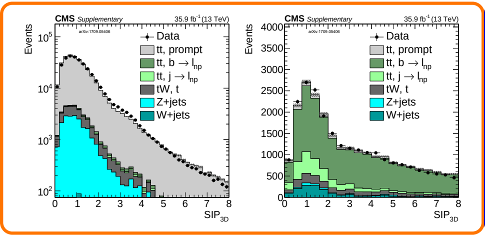


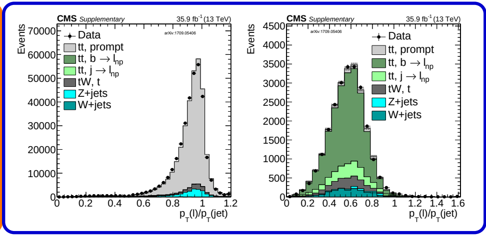


Multileptons: lepton identification

Develop and employ advanced lepton identification techniques:

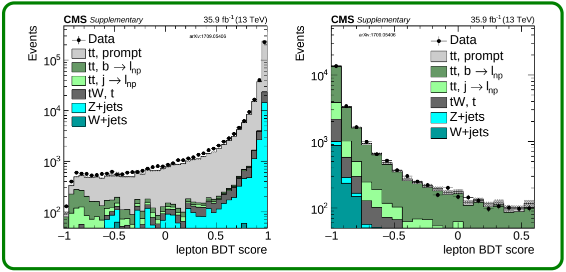
- improvement per lepton **triples** in the total signal efficiency
- use information on a lepton and its "surroundings":
  - pointing variables: impact parameter, **its significance**
  - isolation: energy in a cone around the lepton
  - jet clustered with a lepton: how **jet-like** or b-jet like it is



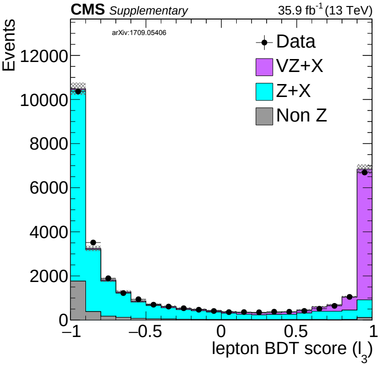


- put it all together into a BDT:
  - take into account relative prompt/nonprompt abundance along p_T spectrum

Multileptons: BDT performance

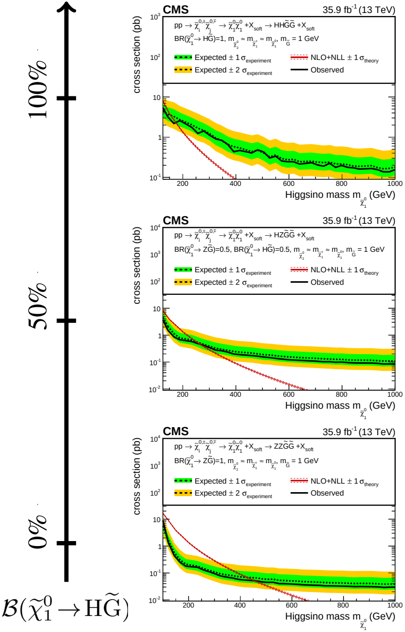


- ⟸ BDT score for **prompt** and **nonprompt** leptons from b decays (in $t\bar{t}$)
- ⇓ BDT score for **prompt** and **nonprompt** leptons from light flavor (in Z+jets)

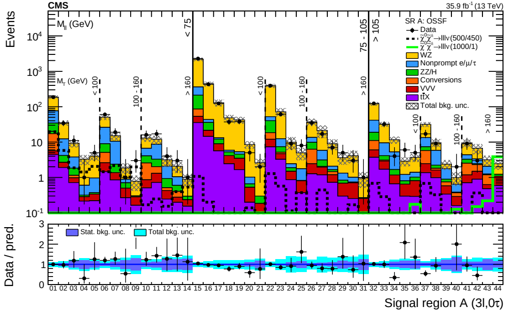


- choose operating BDT value to retain the same signal efficiency
- reach factor 2 of background rejection
- gain in the sensitivity is equivalent to up to **+40% in dataset size**!
- important for rare processes search

Multileptons: results



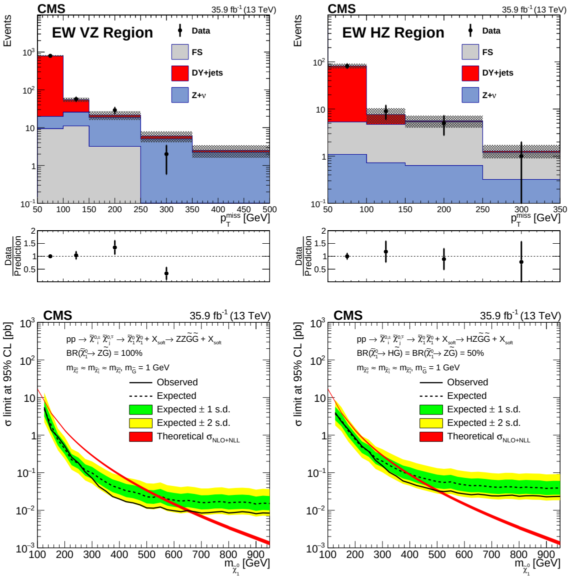
One category: 3 e/μ with an opposite charge same flavor pair



- to take into account all possible HH decay modes use almost all search categories for the interpretation
- the strongest exclusion for the 100% decays to Z boson
- sensitivity weakens with growing decay rate to Higgs boson

Higgsinos with dileptons

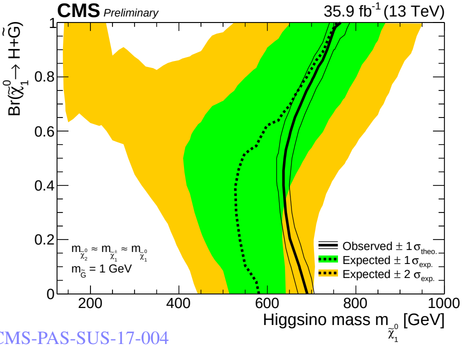
Z($\ell\ell$) + Z/H(dijet): important for larger $m_{\tilde{\chi}}$ (larger $E_{\mathrm{T}}^{\mathrm{miss}}$)

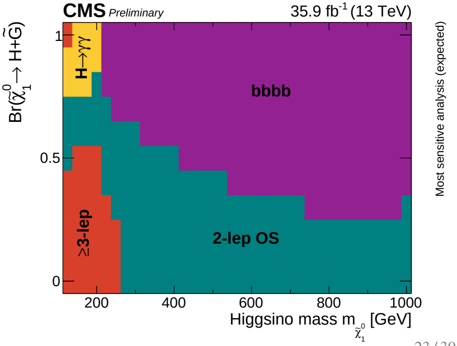


- select V(jj)Z($\ell\ell$) or H($b\bar{b}$)Z($\ell\ell$) candidates
- use eμ events in data to estimate **flavor-symmetric (FS)** background
- derive **DY+jets** from fit with the γ+jets $E_{\mathrm{T}}^{\mathrm{miss}}$ templates
- scale **Z+ν** processes in multilepton control regions in data (WZ, ZZ)
- exclude higgsinos below:
  - 650 GeV for 100% decays to Z
  - 500 GeV for 50% decays to Z

Full picture: Combination

- an interplay of various final states due to complexity of the final states with intermediate Higgs bosons!
- close to the confident exclusion of higgsinos below 400 GeV in GMSB scenarios
- **still remember about assumption limitations:**
  - visible intermediate decay products, larger lifetime, or direct decays of heavier higgsinos to $\widetilde{G}$ would impact the sensitivity



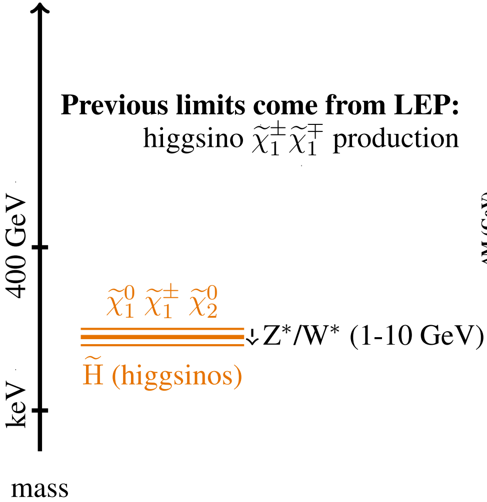


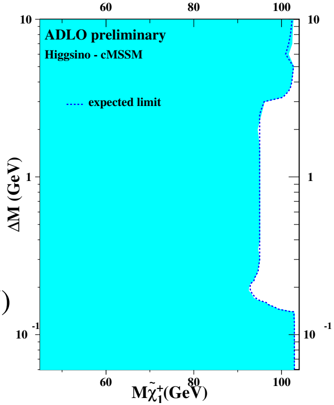
CMS-PAS-SUS-17-004

Case 2: Higgsino-only spectrum

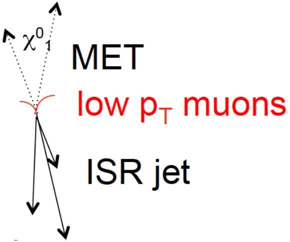
Higgsino LSP is stable:

Previous limits come from LEP:
higgsino $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production





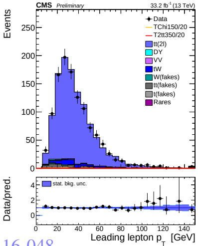
Soft leptons

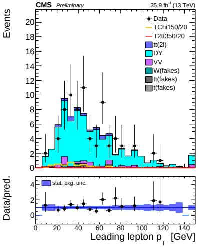


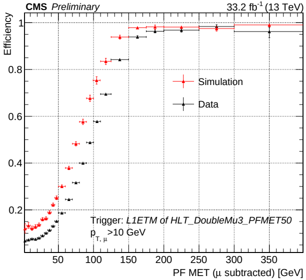
- **Final state:** compressed spectra $\implies$ decay products (and LSP!) produced at rest $\implies$ no visible $E_{\mathrm{T}}^{\mathrm{miss}}$
- **Solution:** boost all system to kick LSP (visible $E_{\mathrm{T}}^{\mathrm{miss}}$) and decay products (harder objects) $\implies$ ISR jet + $\mathrm{Z}^* \to \ell\ell$
- **Downside:** hit on already low production cross section

To maximize signal acceptance:

- introduce new trigger with low-p_{T} muons and $E_{\mathrm{T}}^{\mathrm{miss}}$: offline select $E_{\mathrm{T}}^{\mathrm{miss}} > 125$ GeV
- commission low-p_{T} leptons: down to 5 GeV

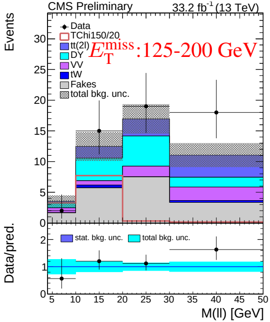


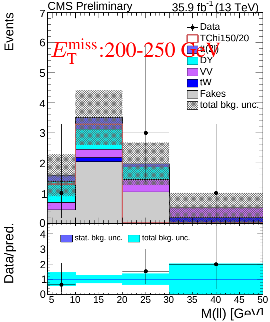


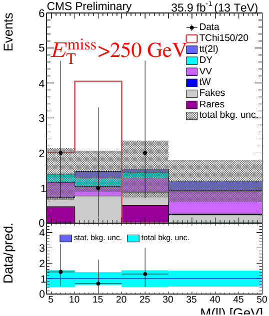


CMS-PAS-SUS-16-048

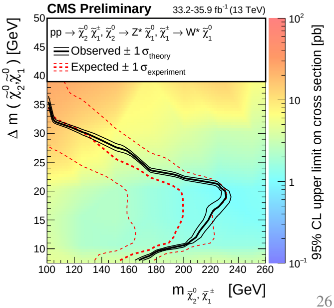
Results for wino $\tilde{\chi}^0_2\tilde{\chi}^\pm_1$





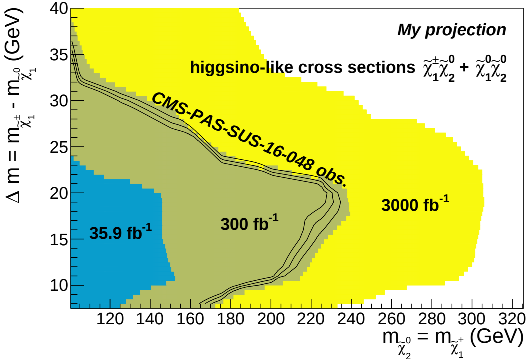


- interpretation is available for wino-like $\tilde{\chi}^0_2\tilde{\chi}^\pm_1$
- production cross sections are larger by a factor of 3
- for higgsinos mass limit is weaker



Higgsinos: "Recast" and projections

Wino limit rescaled for higgsino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 + \tilde{\chi}_1^0\tilde{\chi}_2^0$:



- reach up to ~ 150 GeV
- for the first time surpass LEP in higgsinos!
- CMS higgsino result is in preparation
- **projection**: scale the sensitivity as $\sqrt{\mathcal{L}}$
- *pessimistic:* no analysis improvement
- *optimistic:* can support trigger

With HL-LHC can approach to "excluding" SUSY as a theory

meaning covering large territory for $m_{\tilde{H}} \lesssim 400$ GeV...

- time to think about covering the gaps: low $\Delta m \lesssim 7$ GeV
- e.g. monojet analysis for very compressed case?

CMS-PAS-SUS-16-048

Beam energy rise:

5 fb^{-1} @ 7 TeV (2011)

25 fb^{-1} @ 8 TeV (2012)

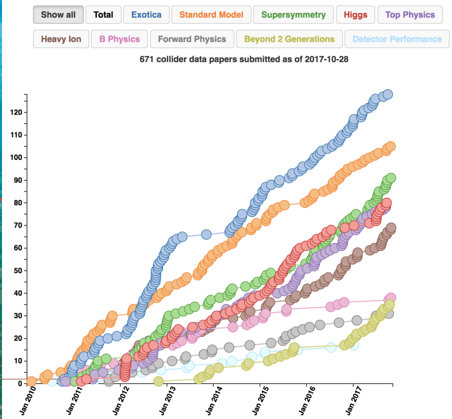
3 fb^{-1} @ 13 TeV (2015)

Huge luminosity jump:

36 fb^{-1} @ 13 TeV (2016)

44+ fb^{-1} @ 13 TeV (2017)

Next: intellectual rise?



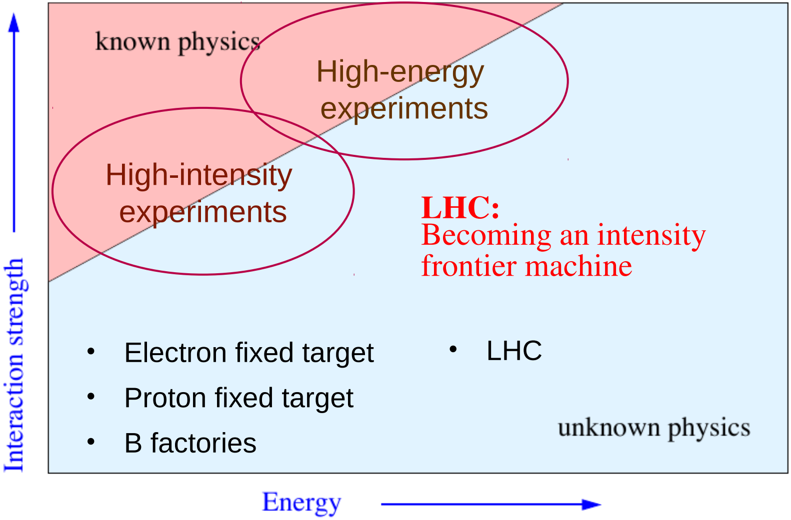
A general purpose detector

Higgs boson discovery (2012)

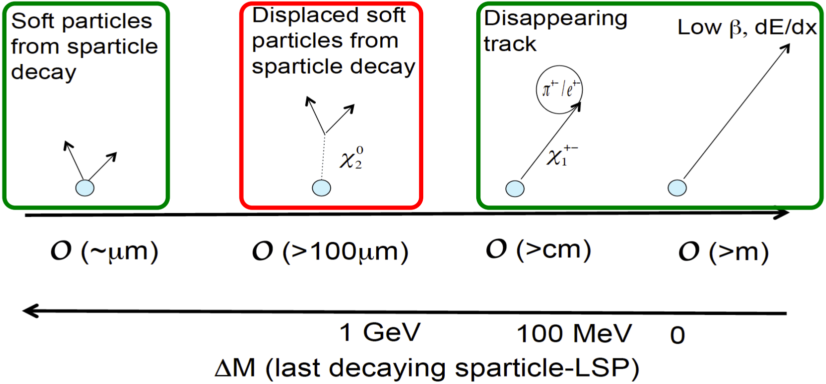
Wide physics programme

What's next?

- no large energy jump is foreseen in the near future
- need to be more creative: what have we accidentally missed in a (SUSY) rush?



High volumes of data: access to rare final states



Need to check various signatures to cover all the grounds:

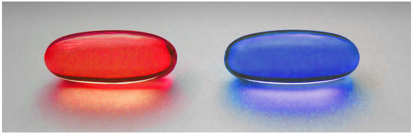
- some of the listed searches **exist**, e.g. disappearing track analysis
- some are still to be **developed**, e.g. displaced soft particles + E_T^{miss}
- all results are still to be put together to have a complete picture

Are we looking everywhere?

- most SUSY searches are designed to be sensitive to deviation from the SM expectation in a broad phase-space
- in specific cases of extremely low cross sections the optimization is more targeted

To be open to any possibility - cannot stay too specific in new physics searches

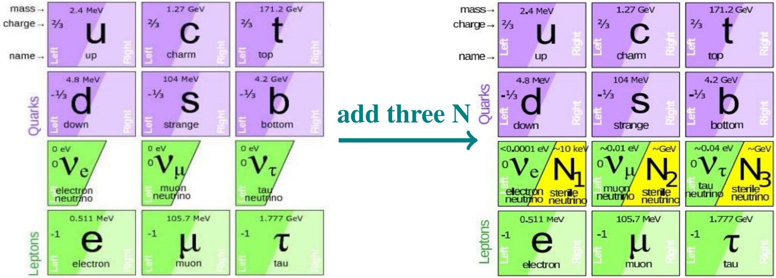
Choose which price to pay: sensitivity vs. generality



- can check performance of a general SUSY search on a non-SUSY model as an example

ν Minimal Standard Model (νMSM)

Appealing minimal extension of the SM which solves a range of questions:

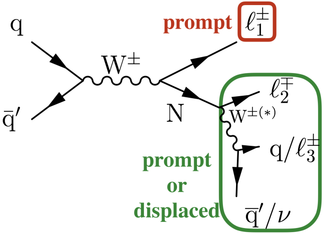


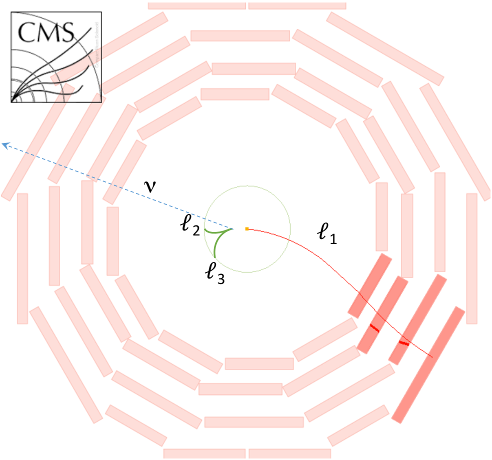
1. **neutrino masses**
   - via seesaw mechanism
2. **matter-antimatter asymmetry**
   - degenerate N_2 and N_3 (mass from ~ 1 to $\sim 10^2$ GeV) could lead to dramatic increase of CP violation
3. lightest N_1 (a few keV) is a perfect **dark matter candidate**
   - observable decay mode $N_1 \to \nu\gamma$
   - search for mono-line in galactic photon spectrum, $E_\gamma = M_N/2$

Heavier N_2 and N_3 can be searched for at the LHC

Shaposhnikov and Asaka

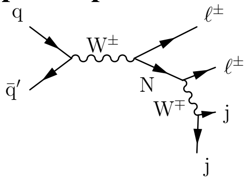
Heavy neutrinos at the LHC



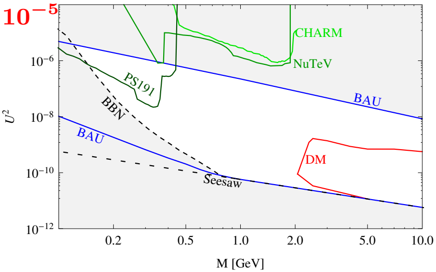


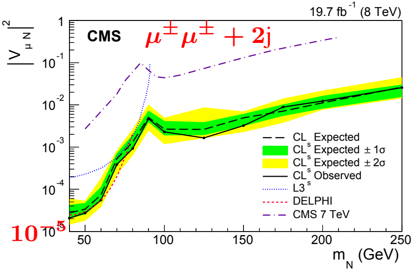
- **N production**: in decays of W bosons
- **N decays**: $N \to W\ell$ or $N \to Z\nu$ or $N \to H\nu$
- **N lifetime**: from very small (**prompt** decays) to macroscopic distances from production vertex (**displaced** decays) as $\tau \propto |V_{\ell N}|^{-2} m^{-5}$

Interesting phase space



- so far dedicated searches were done in prompt same-sign dileptons for high mass
- probed phase-space is far beyond the range of the preferred phase-space derived from BAU



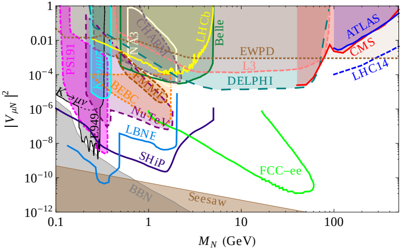


- from cosmology to create needed BAU:
  - $M_N < M_W$ [hep-ph/0505013]
  - or $M_N \sim$ TeV [hep-ph/0506107]

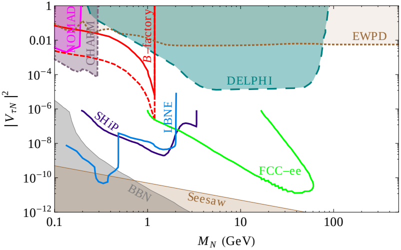
Expanding interesting phase space

- these dedicated searches just start to probe regions not excluded by the electroweak precision data (EWPD)
  - plot: filled areas - excluded; contours - projected experiments

coupling to muons



coupling to taus

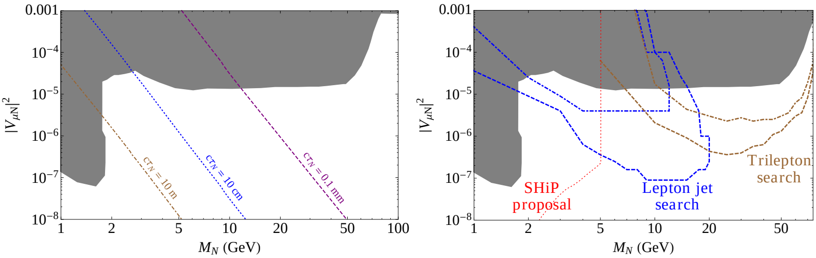


- but other new physics searches at the LHC are already sensitive to a region of m_{N} 5-100 GeV with very low couplings

arXiv:1502.06541

Phenomenological estimates

Reinterpretation of existing multilepton SUSY searches + guesstimates: arXiv:1504.02470:



1. **trileptons**: recasted CMS SUSY multilepton analysis
2. **lepton-jet**: 2 displaced leptons sensitivity (background estimated from another topology)

Reach reported for the 20 fb^{-1} @ 8 TeV and for 300 fb^{-1} @ 13 TeV

With the dedicated search and larger dataset could probe interesting phase-space already now!

arXiv:1504.02470

Conclusions

- with the available dataset sensitive to processes with very low rates
- we started cornering higgsinos and hence SUSY at the LHC!
- with HL-LHC can cover most of the “allowed” higgsino parameter space
- in the absence of SUSY, our searches are sensitive to other new physics scenarios:
  - including those which would **appear only in one signature**
  - and those which always **profit from larger dataset**
  - e.g. **dark matter particles with low couplings**, **sterile neutrinos with low mixing parameter**...

The LHC still gives an opportunity for a discovery!

We are on the right path:

Aim broad!

Seesaw mechanism

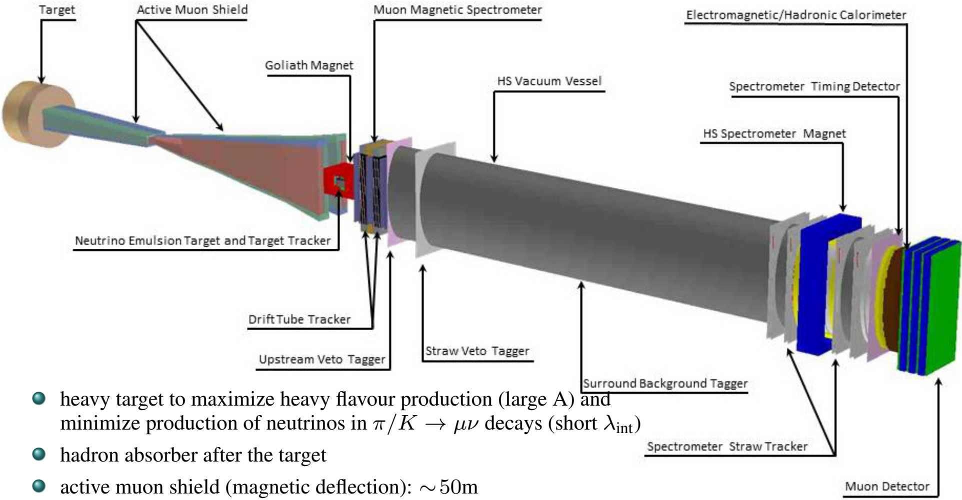
In a nutshell:

- since right neutrinos are truly neutral under all charges of SM:
  - no electric charge
  - no weak interaction
  - no strong interaction
- they have more flexibility than other fields (particles)
- allow two ways of adding neutrino mass:
  - $m_D \nu_L \bar{\nu}_R$ (Dirac) or $M_R \overline{\nu_R^c} \nu_R$ (Majorana)
- mass eigenstates ν and N are found from diagonalization of mass matrix:

$$\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \Longrightarrow m_\nu = \frac{m_D^2}{M_R}$$

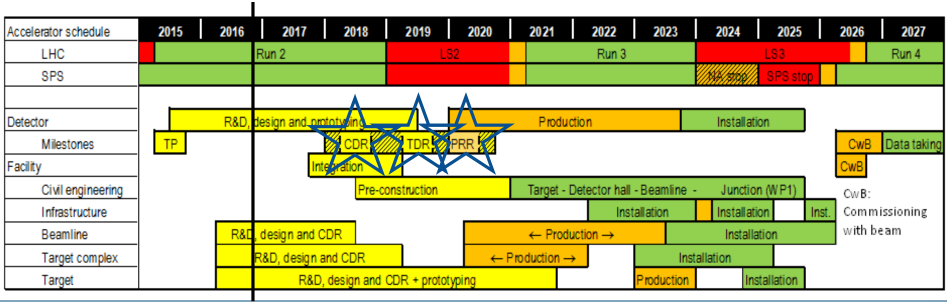
- **weak eigenstate** (what is produced): $\nu_L = \nu \cos\theta + N \sin\theta$
- **massive eigenstate** (what is flying): $\nu = \nu_L \cos\theta - N_R^c \sin\theta$
  - where $\theta \approx \frac{m_D}{M_R} \ll 1$

SHiP: new proposed experiment at the SPS



- heavy target to maximize heavy flavour production (large A) and minimize production of neutrinos in $\pi/K \to \mu\nu$ decays (short λ_{int})
- hadron absorber after the target
- active muon shield (magnetic deflection): $\sim$50m
- slow (and uniform) beam extraction $\sim$1s to reduce occupancy in the detector
- long decay volume: $\sim$50m
- spectrometer with usual detectors

SHiP schedule



- the schedule is designed to be compatible with the one of the accelerators
- currently is in active R&D and detector design optimization
- aim for CDR next year, and TDR a year later
- data-taking not earlier than 2026
    - *by then the LHC should deliver 300/fb to CMS and ATLAS*
    - *complementary sensitivity and a window for discovery!*