Discovery Physics at the Energy Frontier

Where we stand and where we're headed with LHC Run II and beyond

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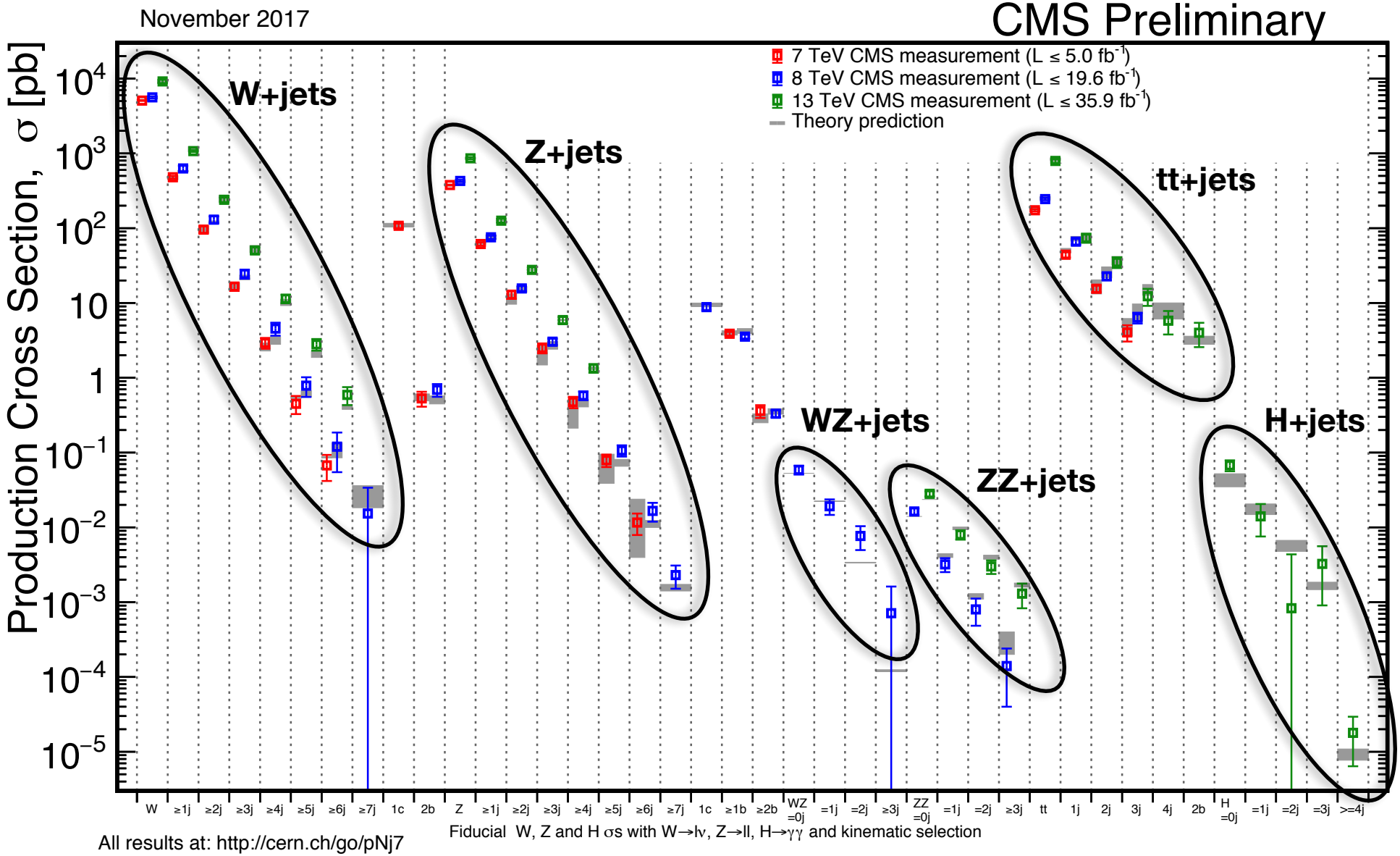
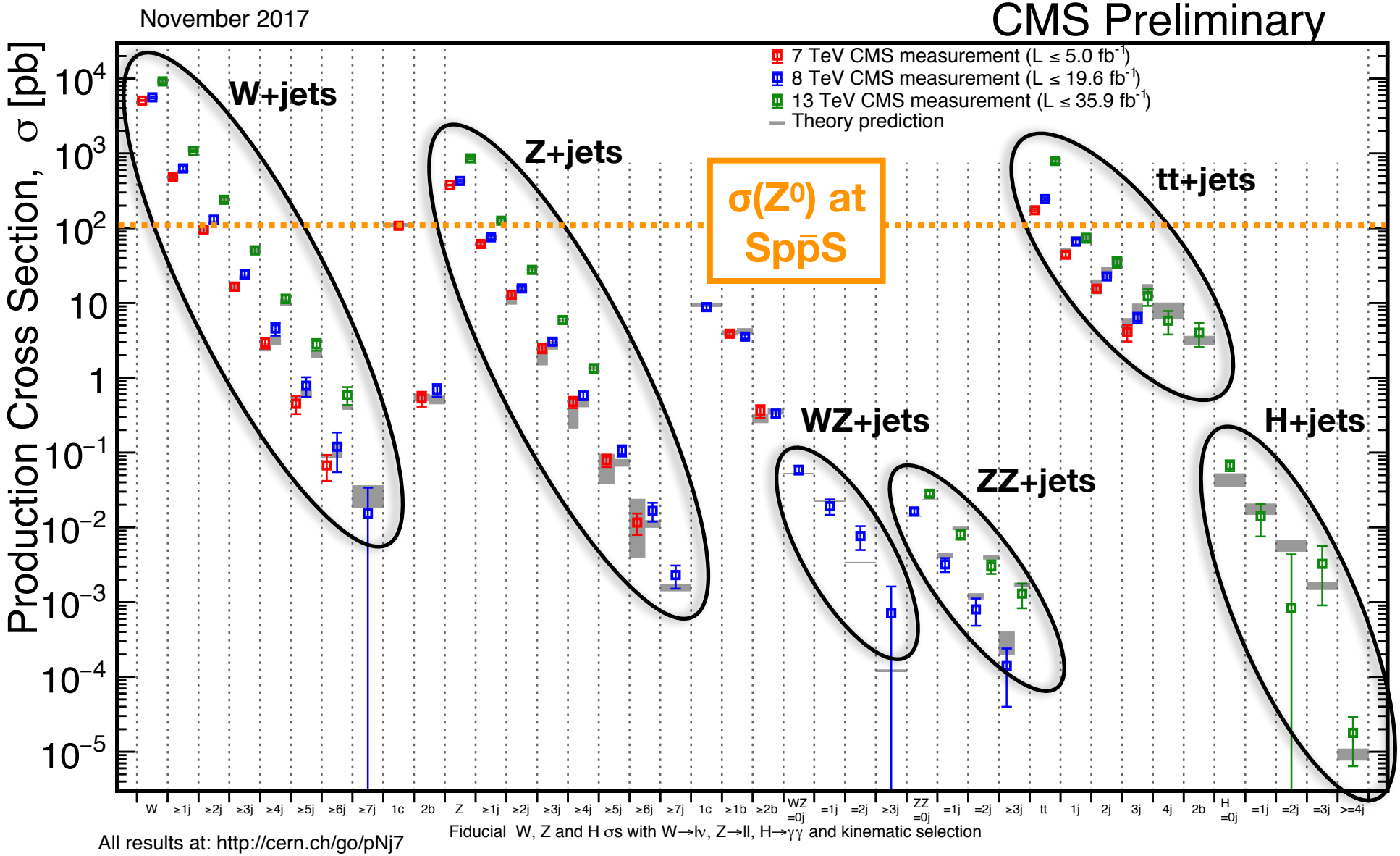
27.11.17

The Success of the Standard Model



The Success of the Standard Model



All results at: http://cern.ch/go/pNj7

So Why Do We Need More?

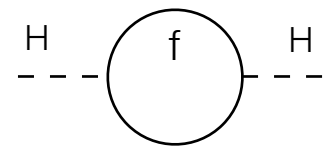
SM can't explain Dark Matter

Higgs mass 'unnaturally' fine-tuned

$$(m_H)^2 = (m_{H,0})^2 + (\Delta m_H)^2$$

$= 125$ GeV

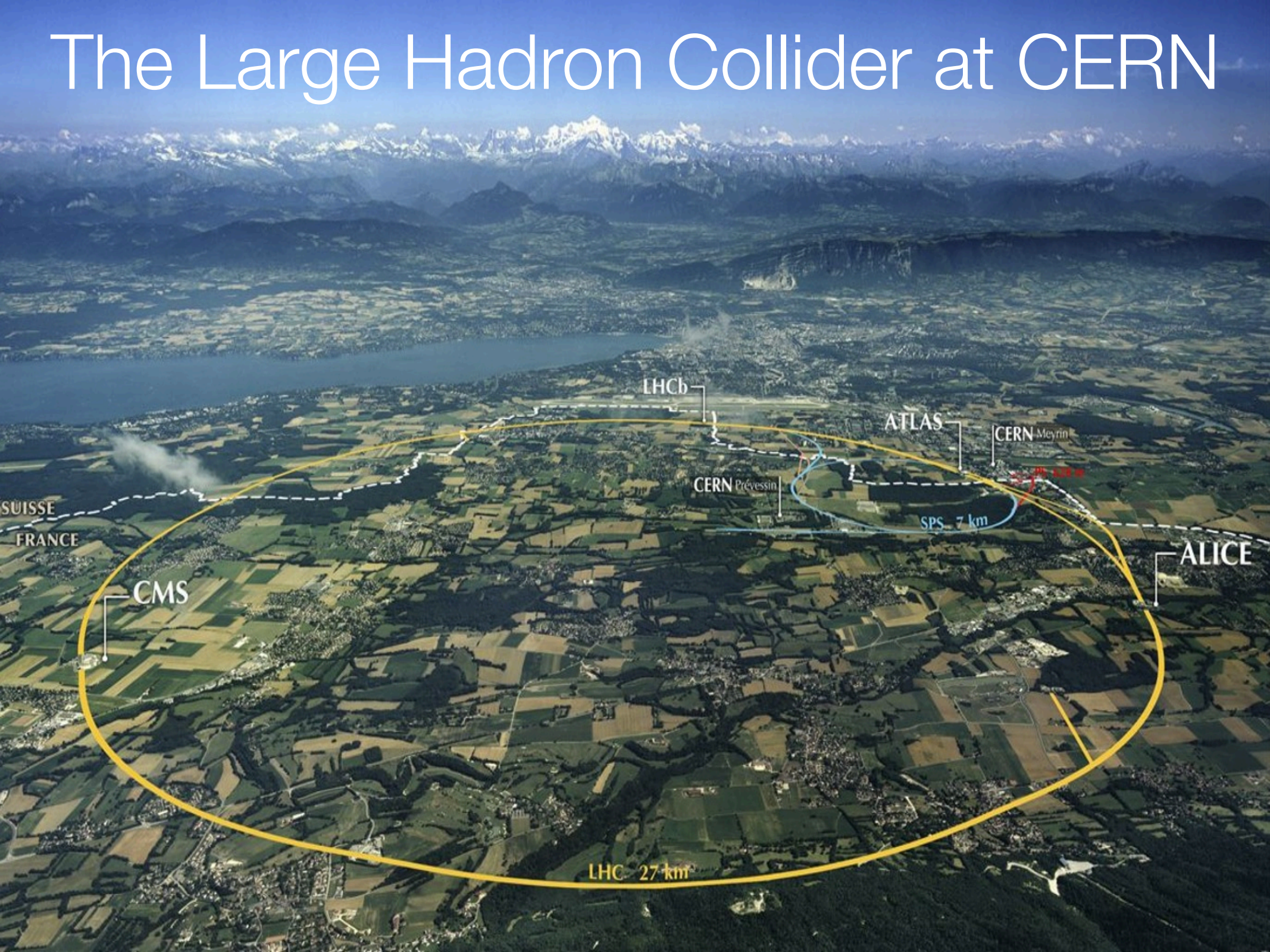
$$\propto \sum_f -g_f \Lambda_{UV}$$



…and Λ_{UV} can be as large as Λ_{Planck}

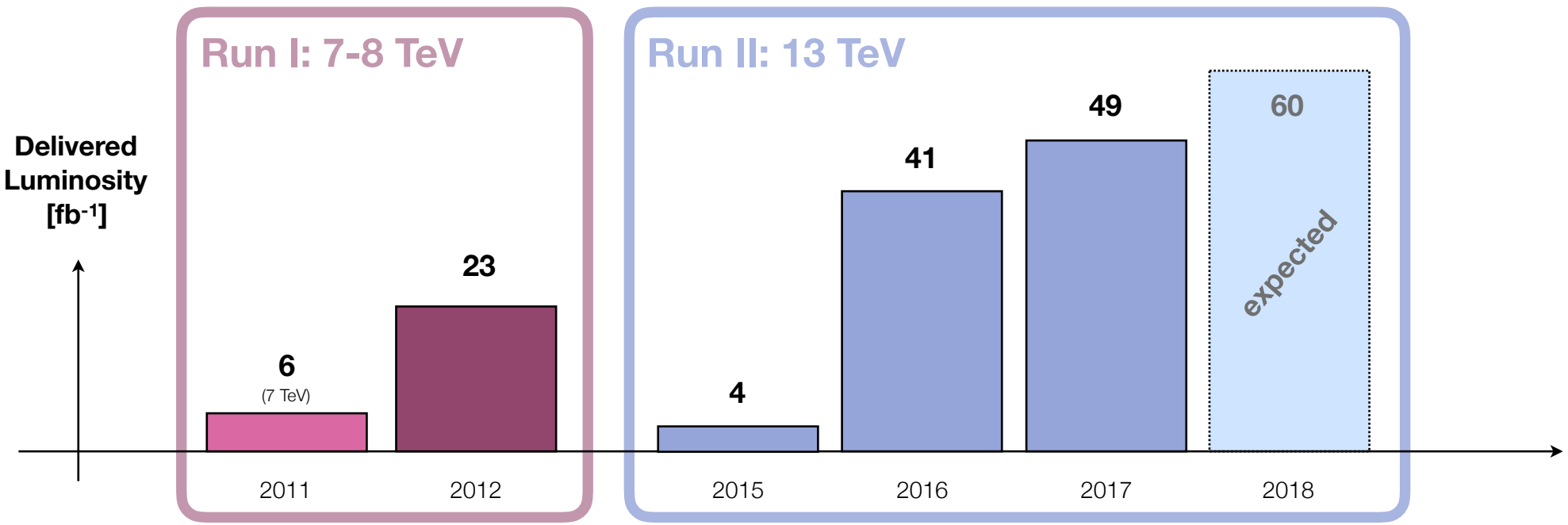
- Two **deep** problems of Standard Model: dark matter and fine-tuning
  - One from **experimental** data, one purely **theoretical**
  - One at **super-galactic** scale, one at **particle** scale

The Large Hadron Collider at CERN



LHC: The Particle Physics Energy Frontier

- 7, 8 and 13 TeV of proton-proton collisions: highest-energy collider **ever**
  - **Unprecedented** luminosity for a hadron collider: up to 2×10^{34} $cm^{-2}s^{-1}$
  - Plan to deliver **~150 fb^{-1}** of 13 TeV collisions by end of 2018



A Plethora of Opportunities for Searches

- LHC: a unique playground to search for new physics

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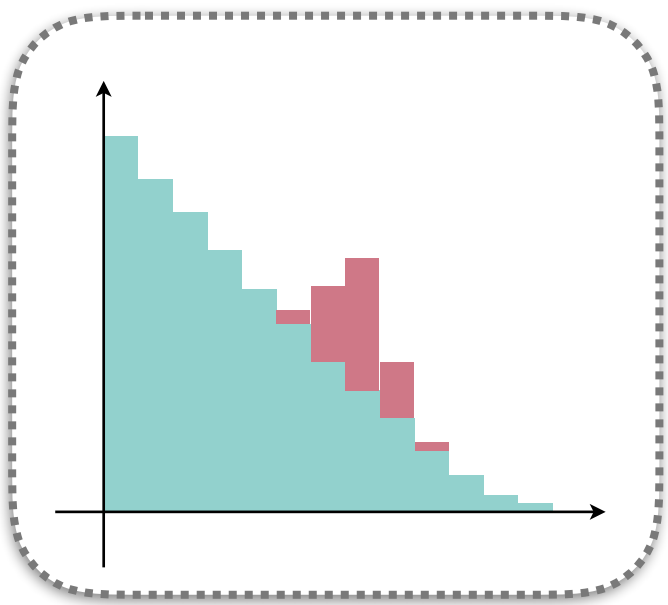
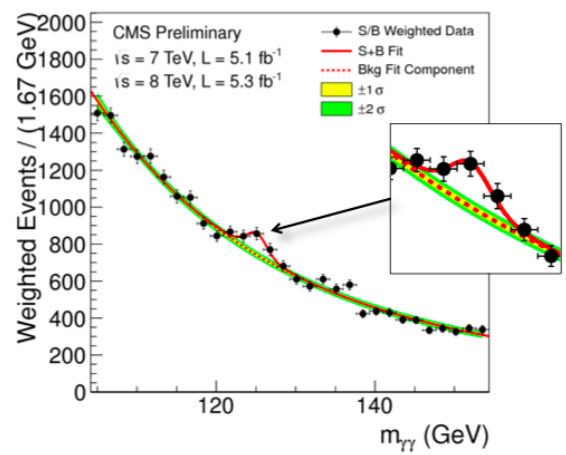
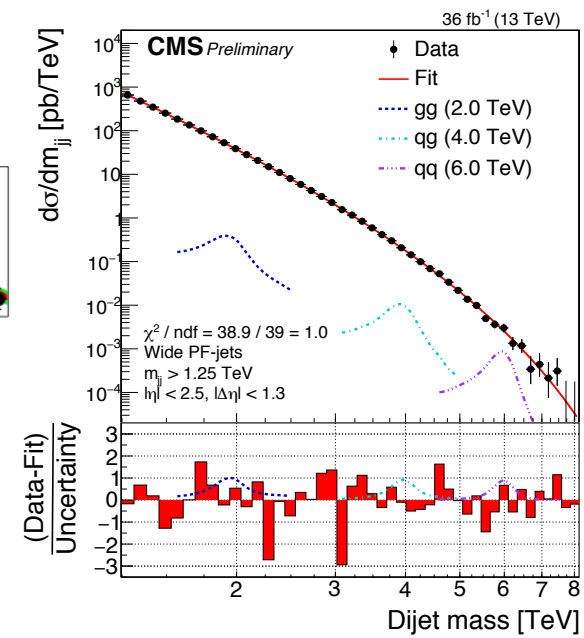
1. Direct searches for resonances



Higgs discovery



Dijet Resonances



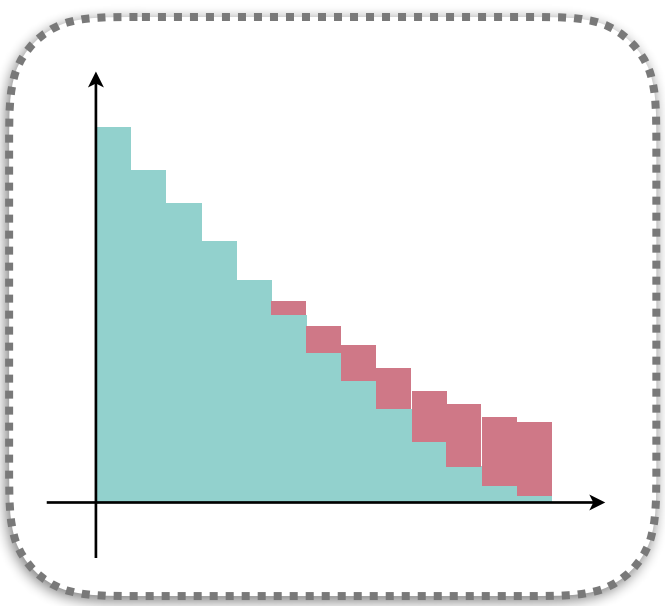
- **Localized** excess
- **Striking** signature
- Access to **high-mass** resonances

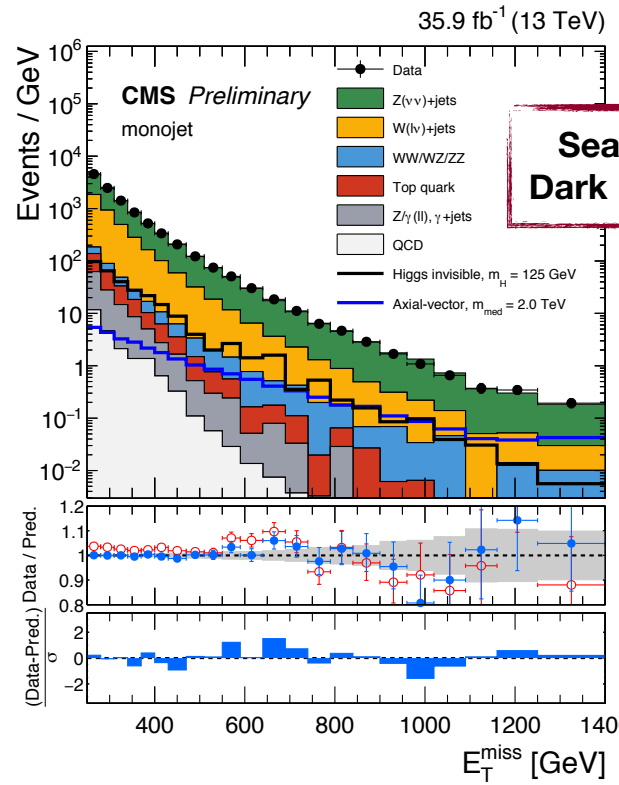
A Plethora of Opportunities for Searches

- LHC: a unique playground to search for new physics

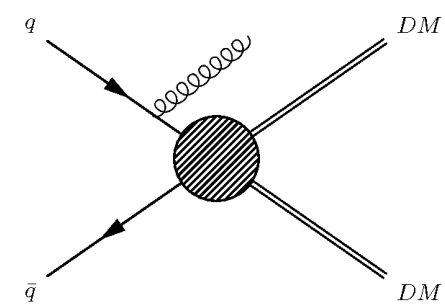
1. Direct searches for resonances

2. Searches for broad excesses





Search for Dark Matter…



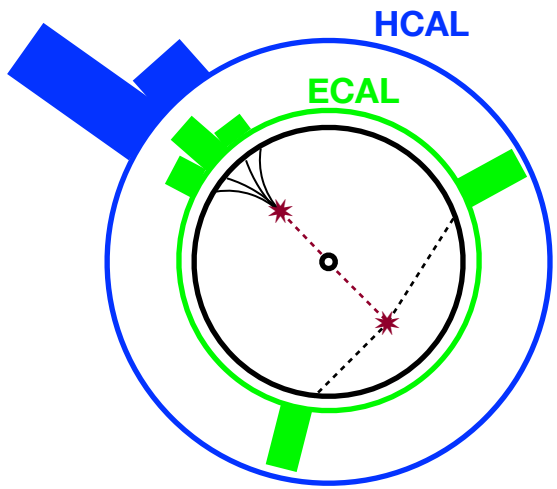
… or Supersymmetry

- Excesses in the **tails**
- Background estimation **crucial**

A Plethora of Opportunities for Searches

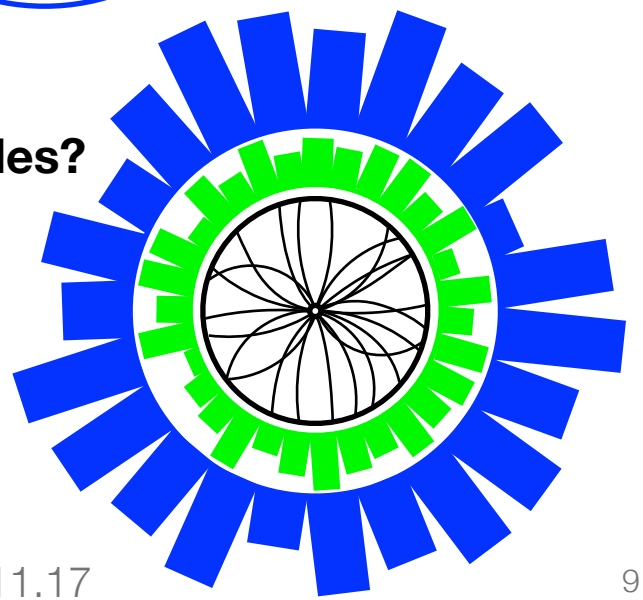
- LHC: a unique playground to search for new physics

1. Direct searches for resonances
2. Searches for broad excesses
3. Exotic signatures



Displaced signatures?

Black holes?



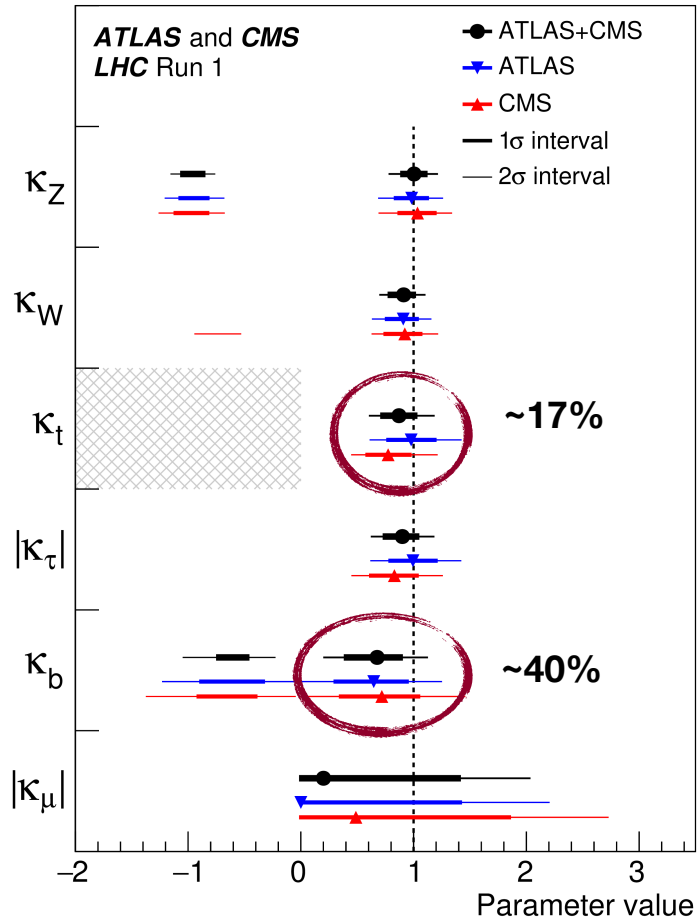
- New physics might have **unconventional** signatures
- Need to be ready: **specialized** searches
- Detector needs to be understood **well**

A Plethora of Opportunities for Searches

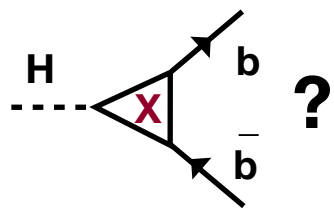
- LHC: a unique playground to search for new physics

1. Direct searches for resonances
2. Searches for broad excesses
3. Exotic signatures
4. Indirect searches

m_H measured with 0.2% precision



- New physics could be **hiding** in the loops
- In Standard Model m_H determines **all** Higgs properties
- **Precision** measurement of couplings: is Higgs exotic?



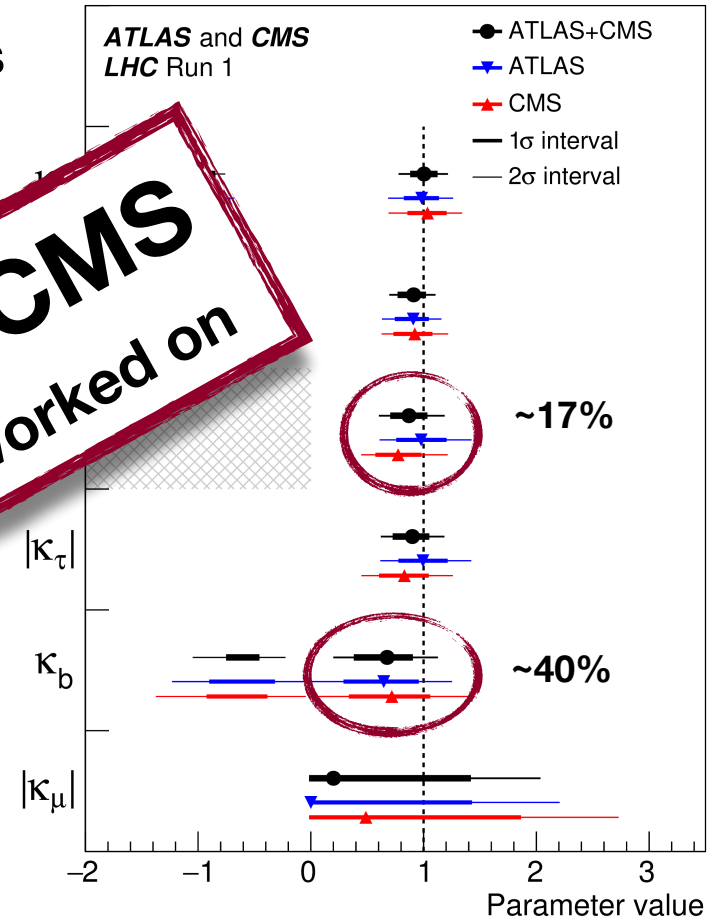
A Plethora of Opportunities for Searches

- LHC: a unique playground to search for new physics

1. Direct searches for resonances
2. Searches for broad excesses
3. Exotic signatures
4. Indirect s… …ured … % precision

A Lot of Searches at CMS

Will focus on ones I personally worked on



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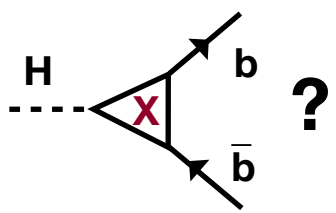
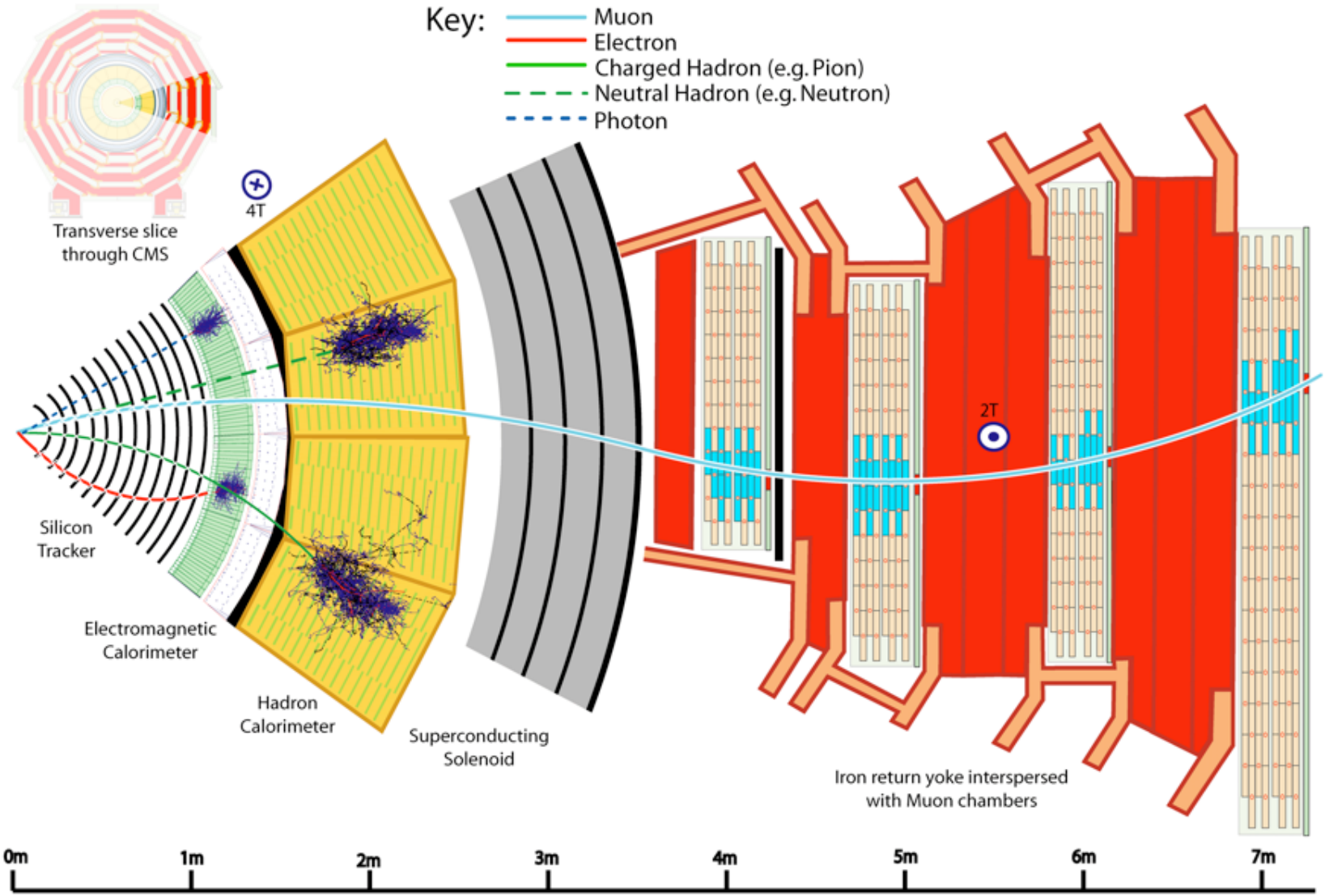
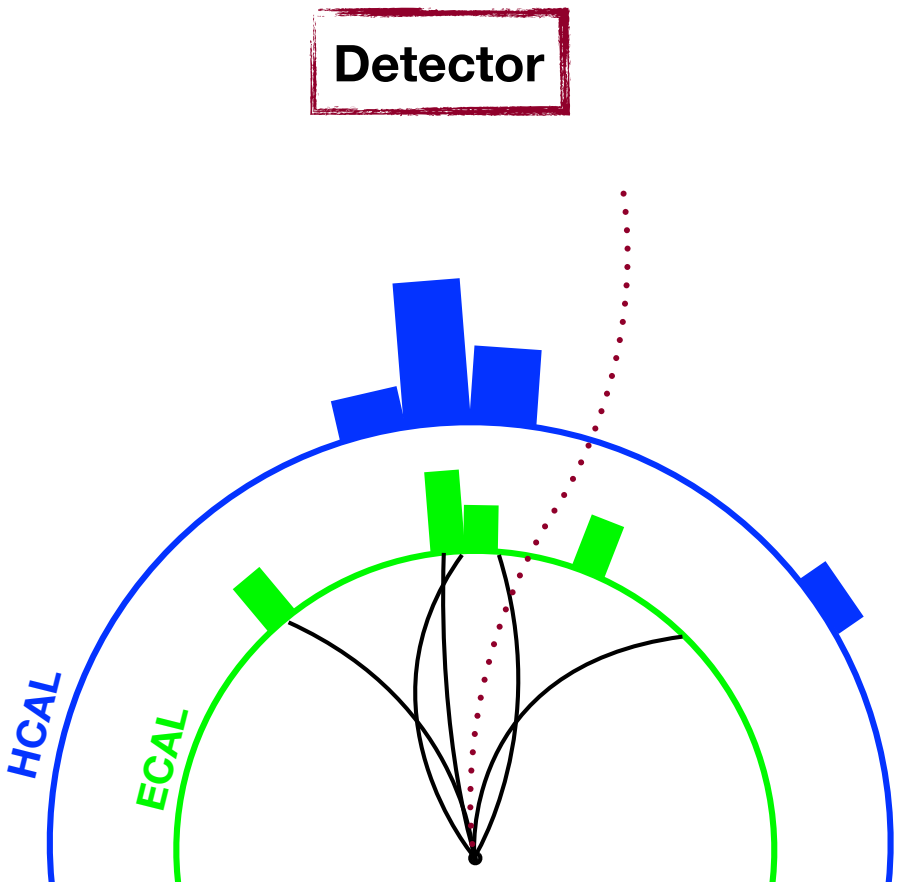
- In Standard Mode… m_H determines all Higgs properties
- **Precision** measurement of couplings: is Higgs exotic?

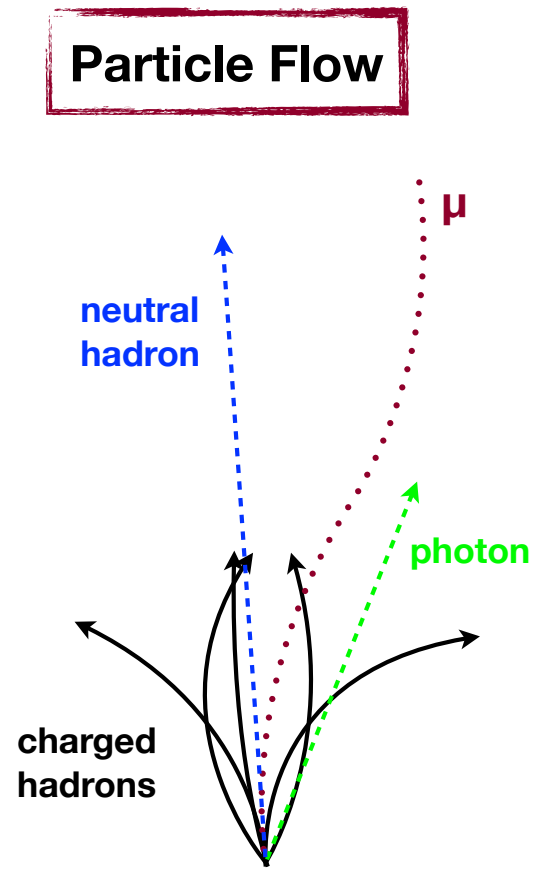


The Compact Muon Solenoid



Particle Flow Event Reconstruction at CMS

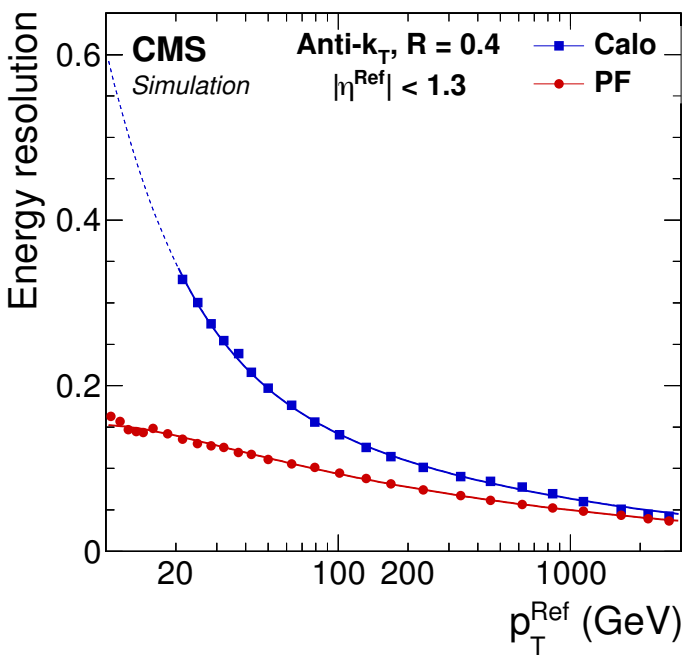




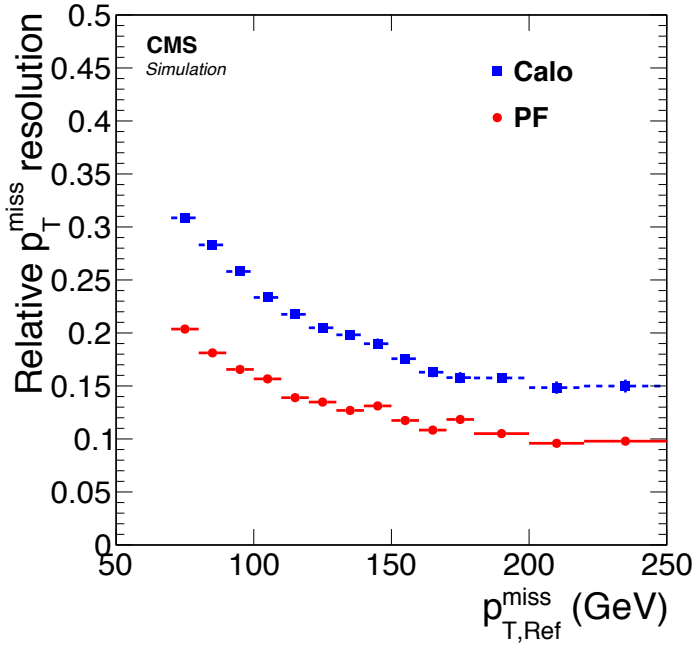
Jets = clustered particles (anti-k_T, R=0.4), **ME_T = vectorial sum of all particles p_T**

Particle Flow: Best Jet/ME_T Resolution

Jet Resolution

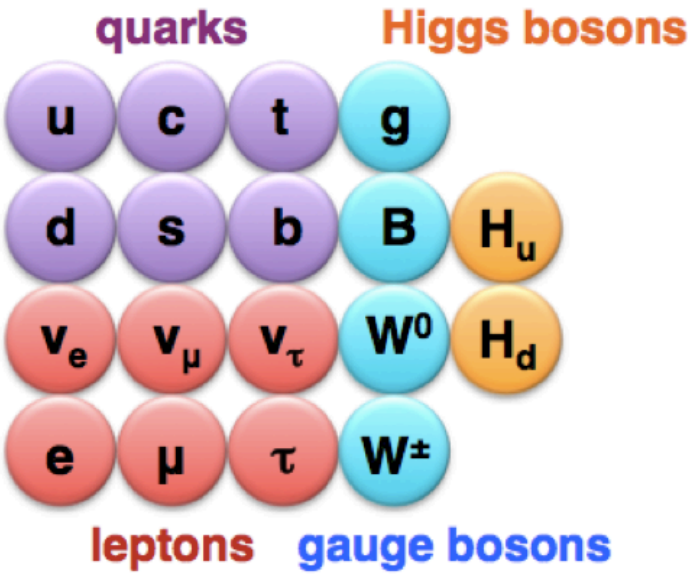


ME_T Resolution

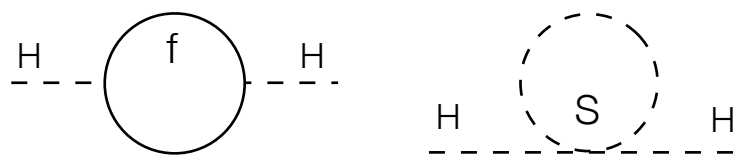


- **Significantly better** than traditional calorimeter-based algorithms
  - **Crucial** for ME_T-based searches

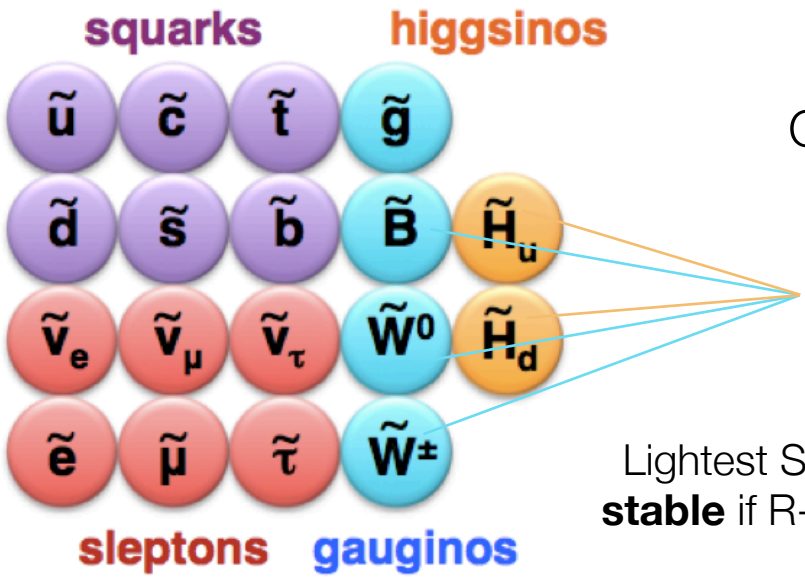
Supersymmetry: A Possible Solution



For every fermion add a **scalar** with same mass/couplings



Cancels Δm_H at leading order: **solves** fine-tuning



Gauginos and higgsinos mix:

$\chi_1^\pm$, $\chi_2^\pm$ — **four charginos**

χ_1^0, χ_2^0, χ_3^0, χ_4^0 — **four neutralinos**

Lightest Susy Particle (LSP): **stable** if R-Parity is conserved

Dark Matter candidate

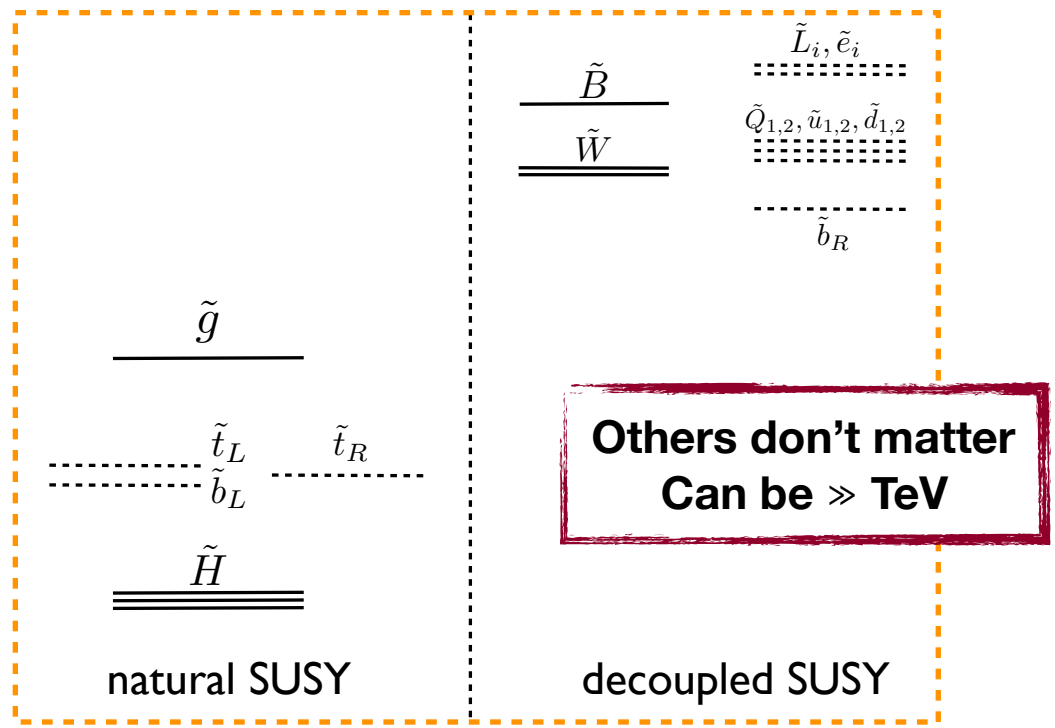
SUSY ‘Naturalness’ as a Guideline

- Can’t fix naturalness with unnaturalness → SUSY should be **natural**

- **Higgsino mass**
  - Can’t be ≫ v = 246 GeV
    (Should be < 350 GeV)

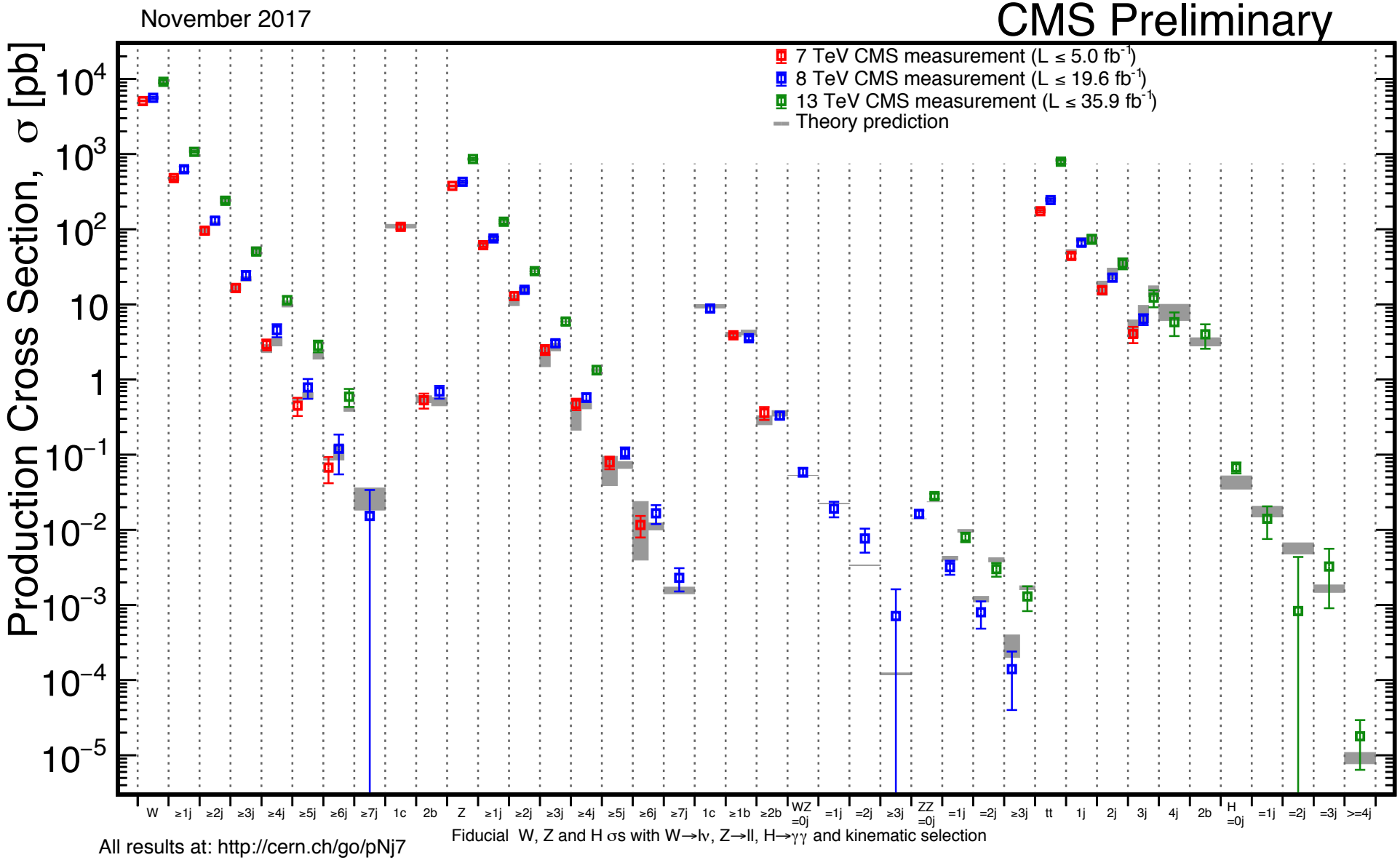
- **Stop mass:** first-order Δm_H
  - Can’t be ≫ m_H
    (Should be < 700 GeV)

- **Gluino mass:** first-order Δm_t
  → second-order Δm_H
  - Should be < 1.5 TeV



Papucci, Ruderman, Weiler. arxiv: 1110.6926

We Have the Reach to Probe Natural SUSY



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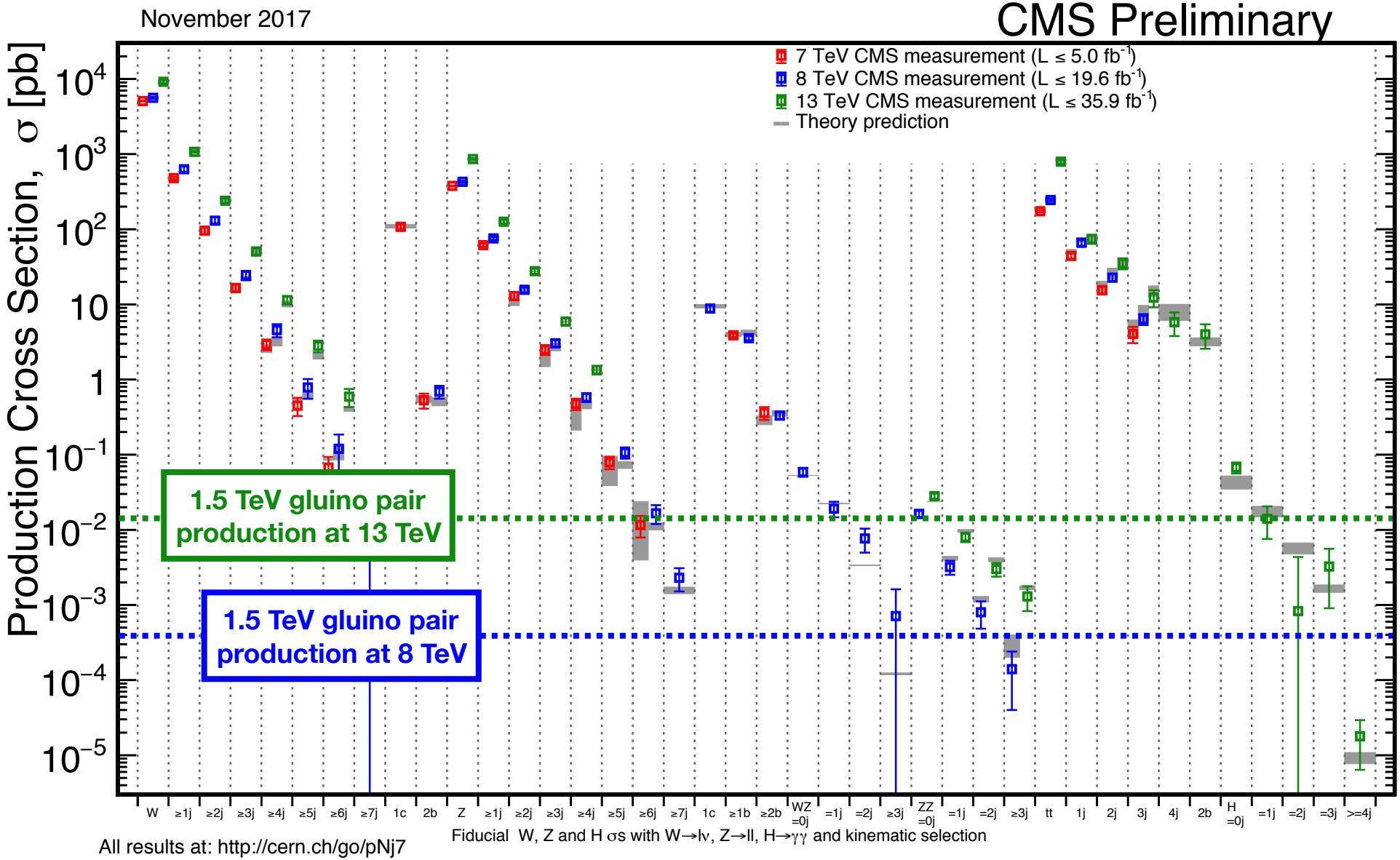

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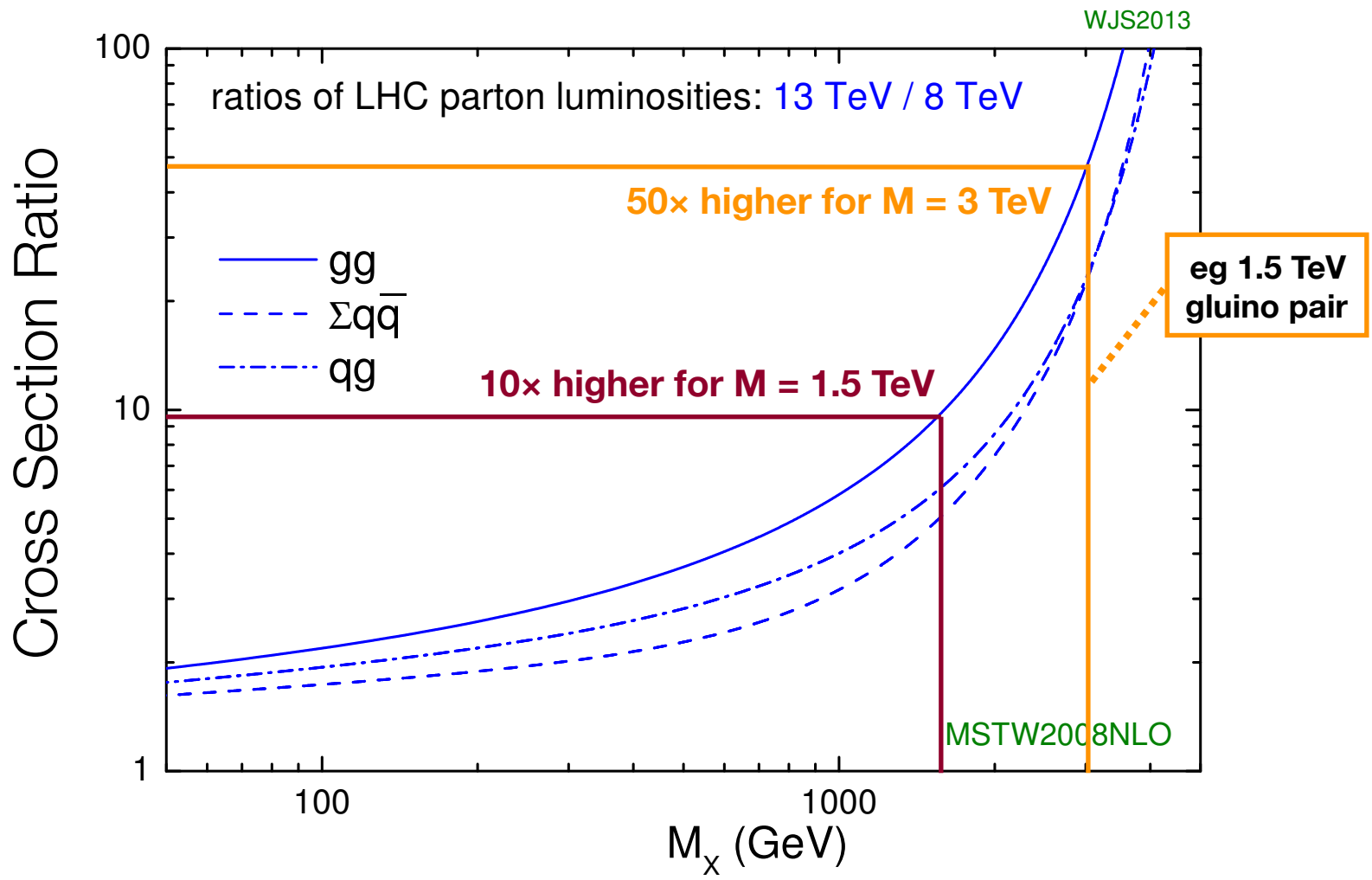
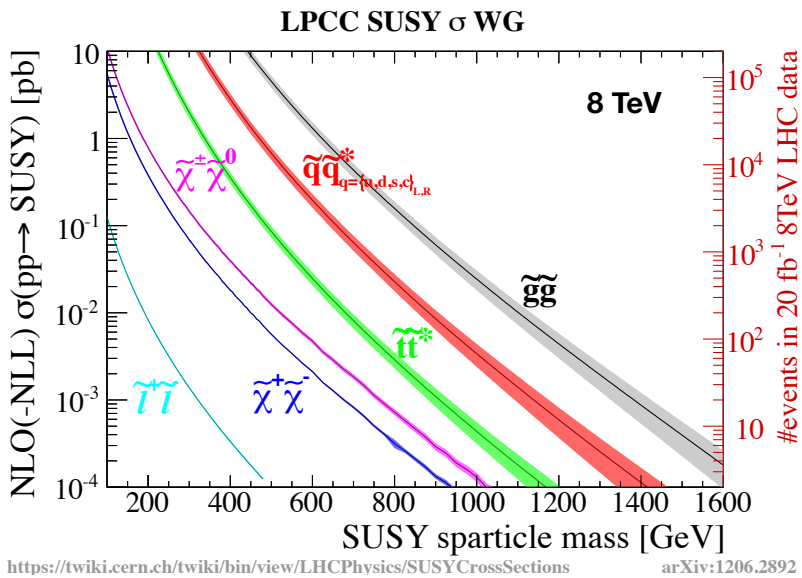
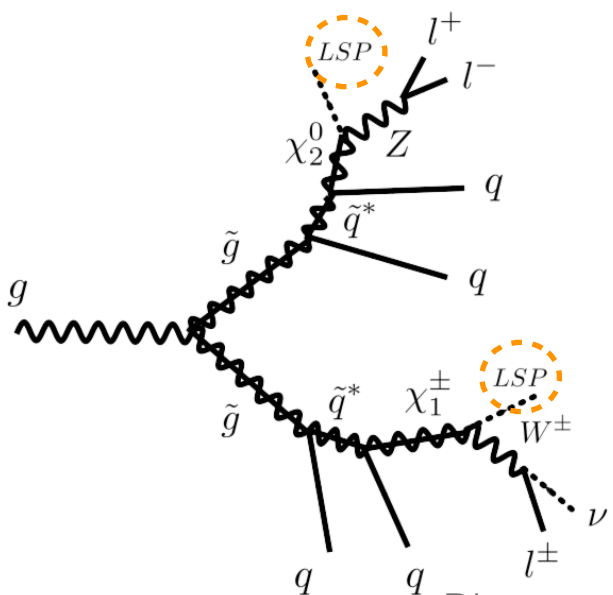
8→13 TeV is a Game Changer



Supersymmetry at a Hadron Collider

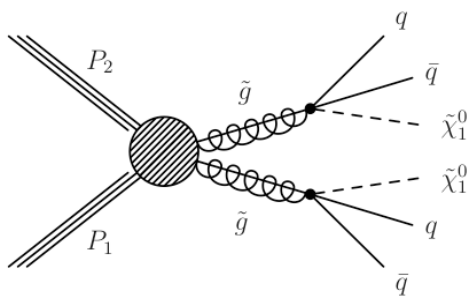




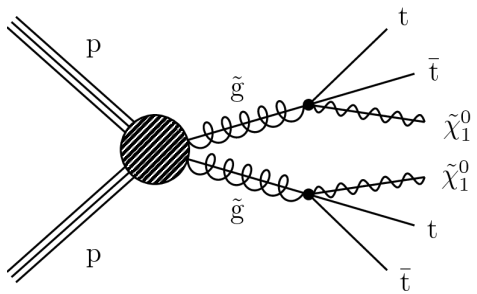
- Gluino and squark production
  - **Largest** σ at a hadron collider
  - Colored: decay mostly to **quarks**
- If R-parity conserved:
  - Sparticles produced in **pairs**
  - LSP stable and **undected** → ME_T
- So look for events with:
  - High **ME_T**
  - Lots of **hadronic activity**

Searching for SUSY in All-Hadronic Events

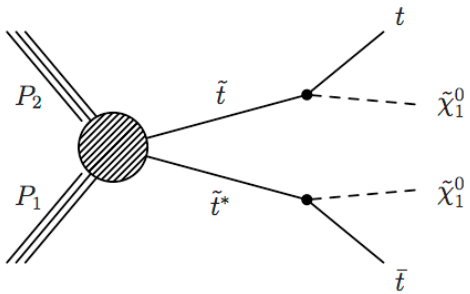
Different models, different final states



4 jets + ME_T

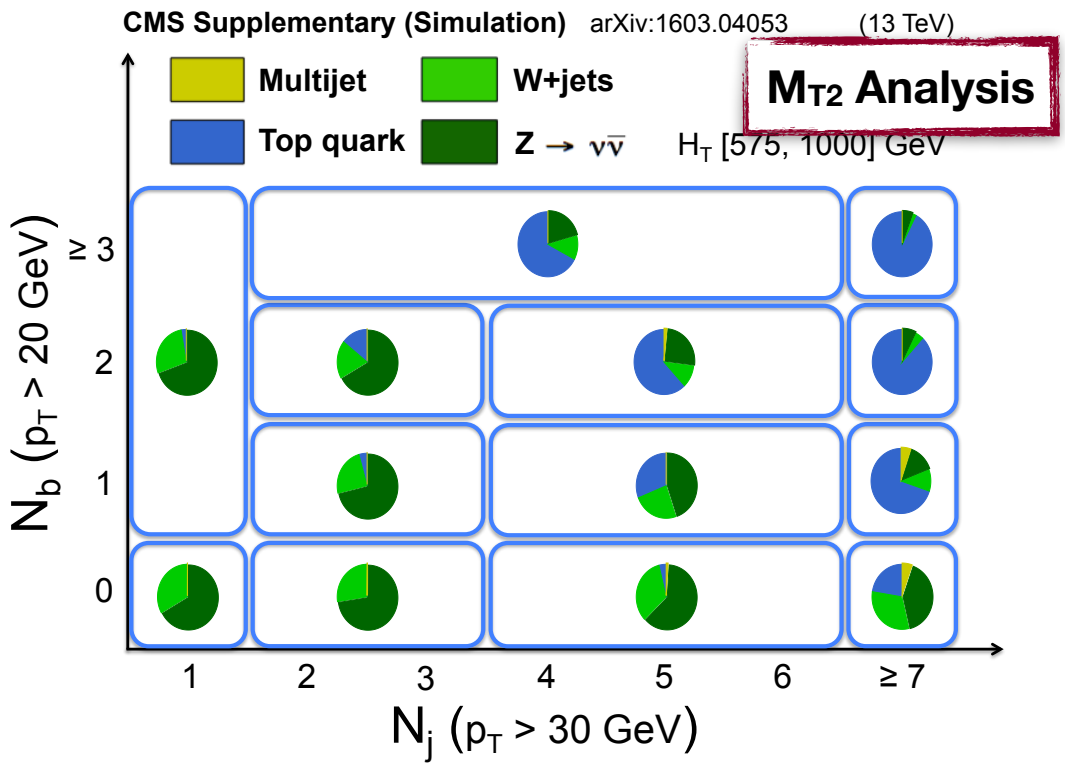


≤12 jets + ME_T (4 b-jets)

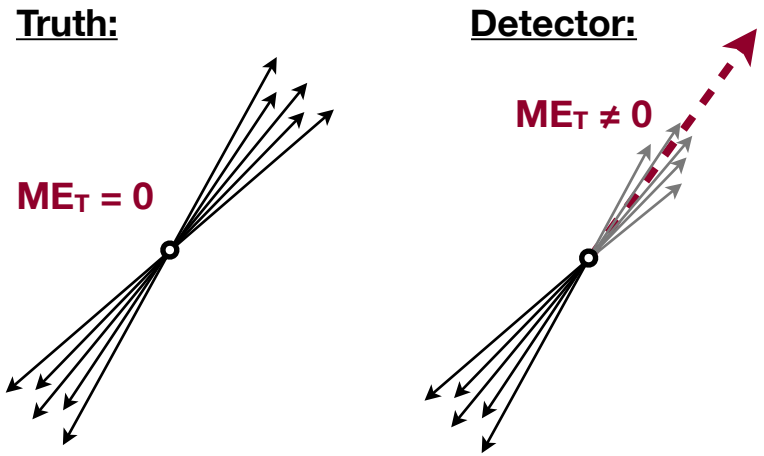


≤6 jets + ME_T (2 b-jets)

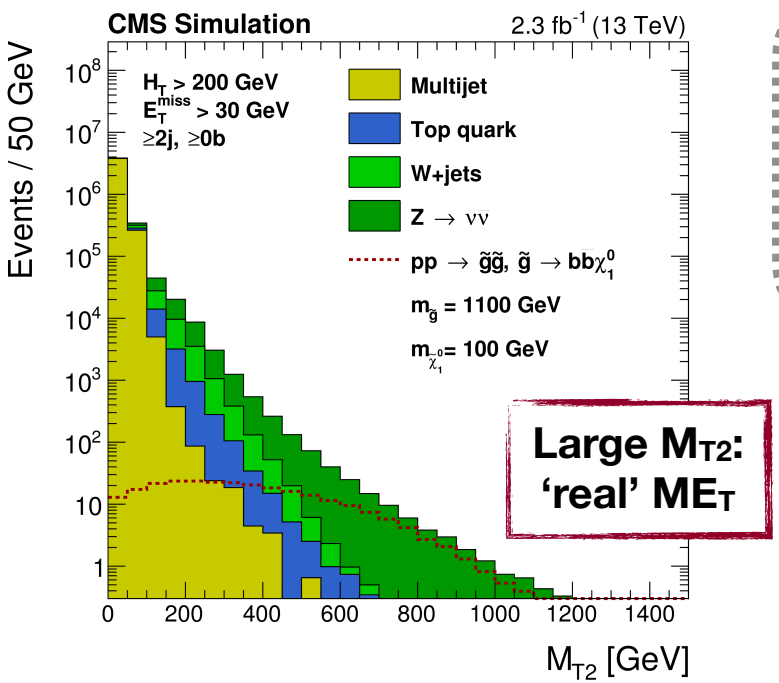
- Want to be sensitive to **most** of them
  - **Categorize** on jet multiplicity and visible energy scale



What We Need is a QCD Killer



- **Main** background: QCD multijet
  - **Intrumental** ME_T
- M_{T2} is a ME_T-like variable
  - **Less** sensitive to detector effects



For di-jet events:

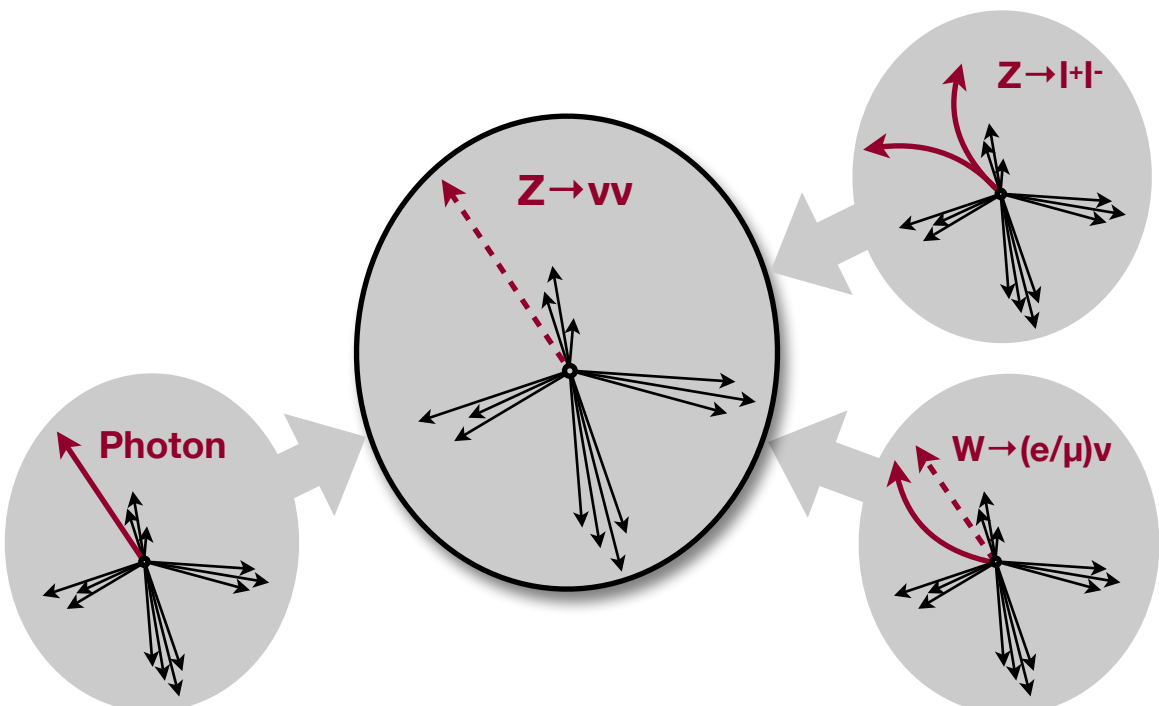
$$(M_{T2})^2 \simeq 2\, p_T^{vis(1)} p_T^{vis(2)} (1 + \cos\Delta\phi_{12}) \xrightarrow{\Delta\phi_{12}\to\pi} 0$$

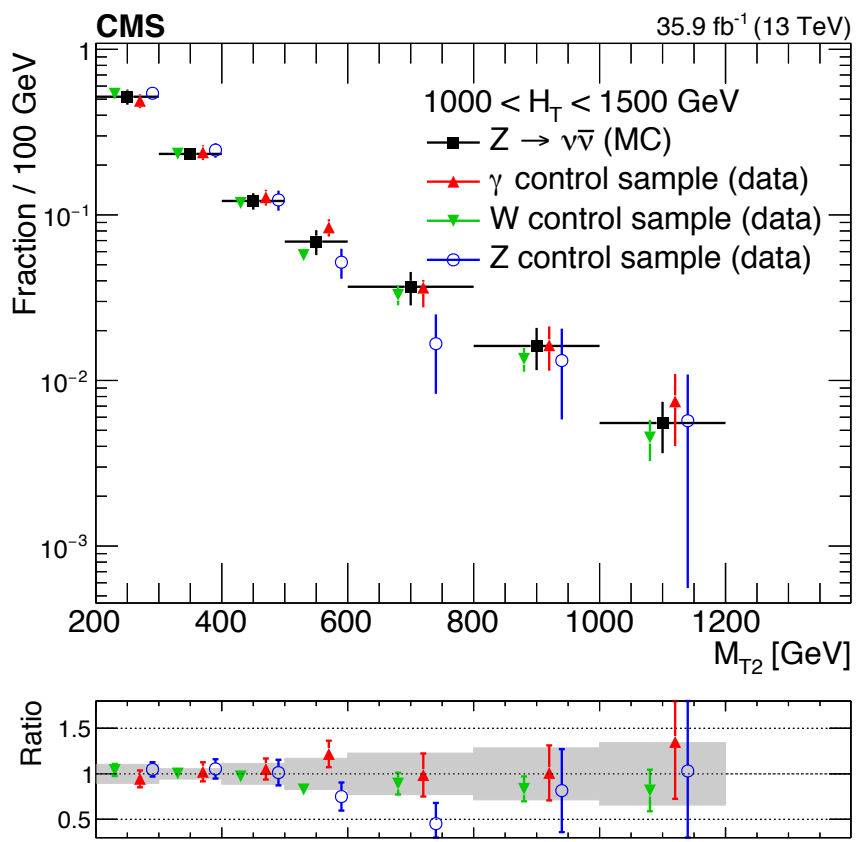
$$(E_T^{miss})^2 = (p_T^{vis(1)} - p_T^{vis(2)})^2 + 2\, p_T^{vis(1)} p_T^{vis(2)} (1 + \cos\Delta\phi_{12})$$

- Signal: excess in the **tails**
  - Need to know **well** shape of backgrounds

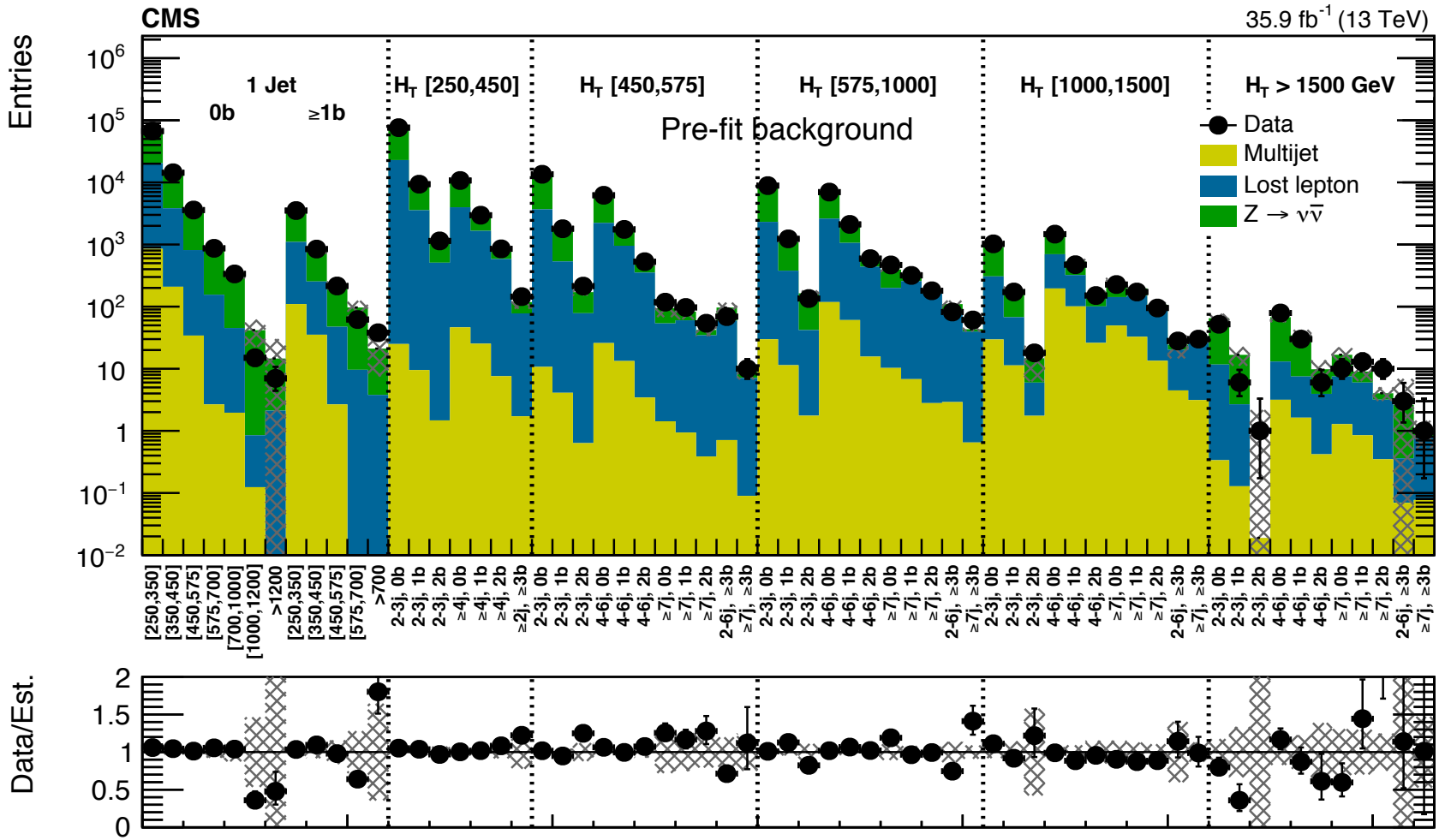
Background Estimation is a Serious Matter

- Need robust and precise estimations for rare processes, out to the **tails**
  - Almost a **precision measurement** of Standard Model processes
- **Dominant** background: (Z→νν)+jets
  - Estimated w/ **three** data control samples

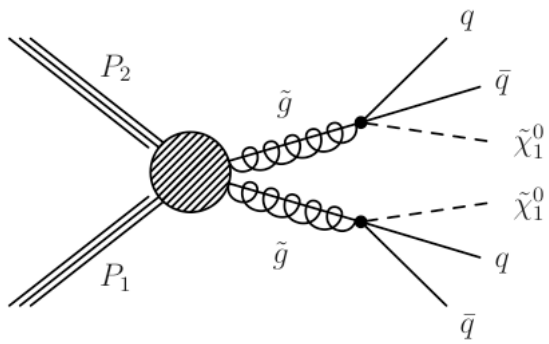


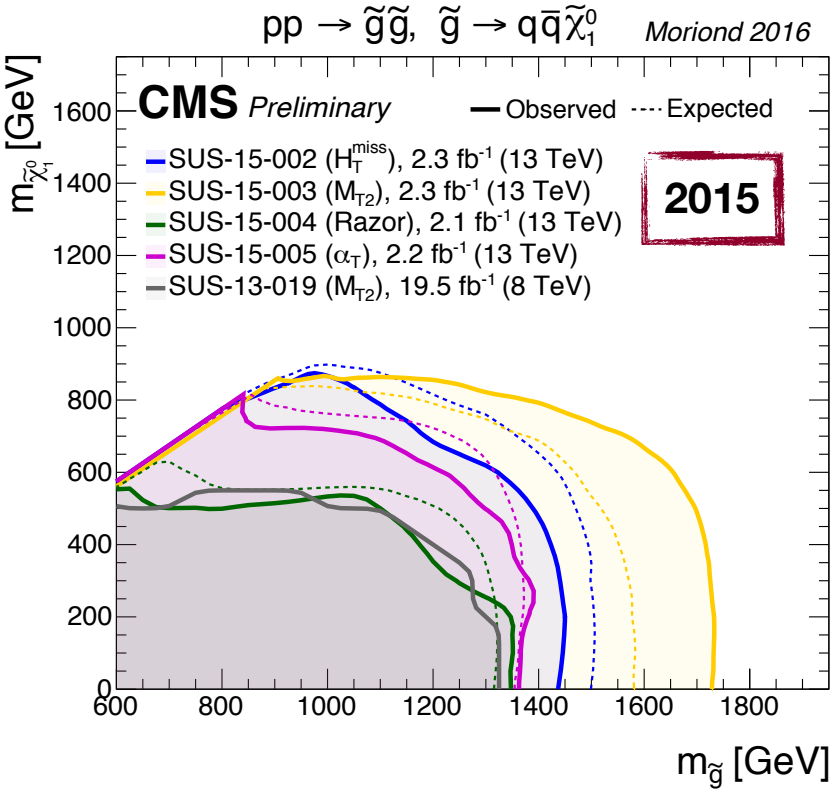


We Are Looking Everywhere



Cornering Natural SUSY with LHC Run II



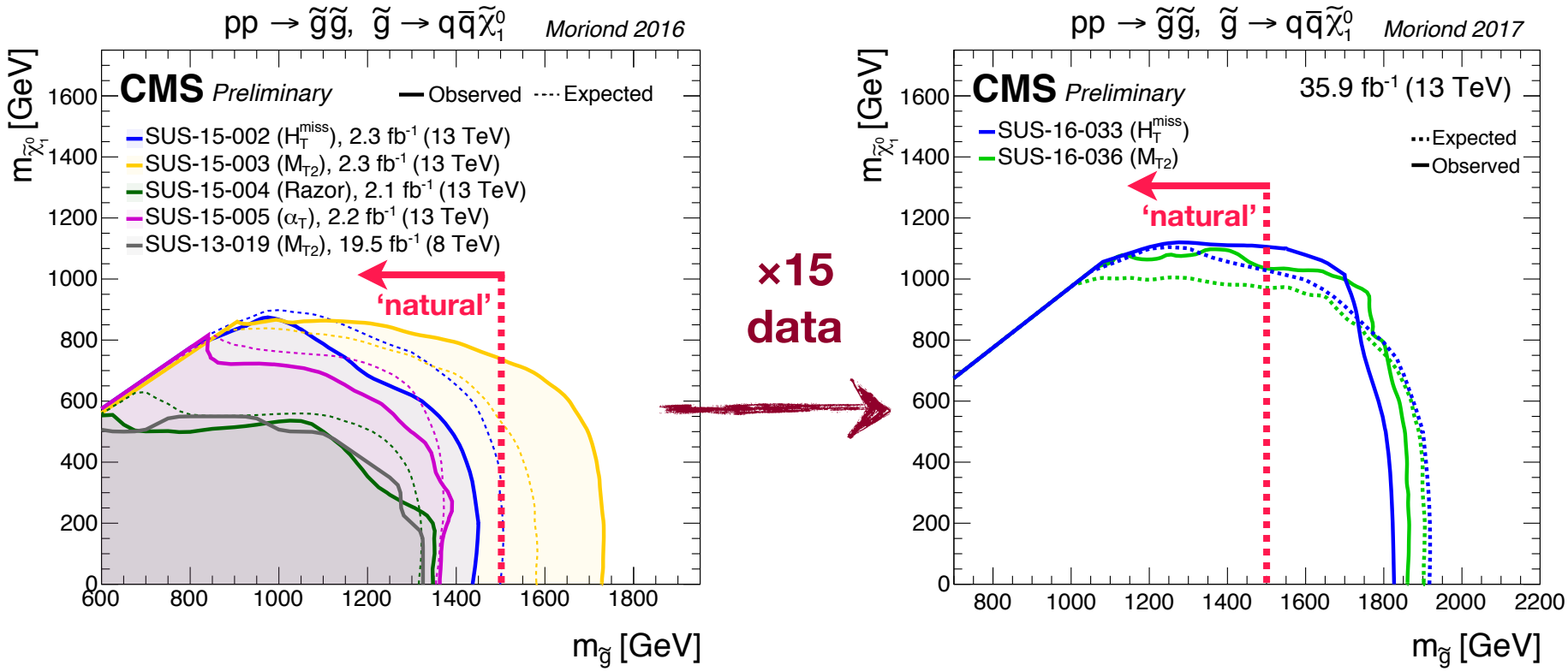


- If LSP is **light**:
  - High ME_T → **best** analysis performance
- If LSP is **heavy**:
  - As m(LSP) → m(gluino): LSP at rest
  - Not much ME_T → **worse** performance
- Only 2.3 fb^{-1} of 13 TeV data already ‘retired’ Run I results on 20 fb^{-1}

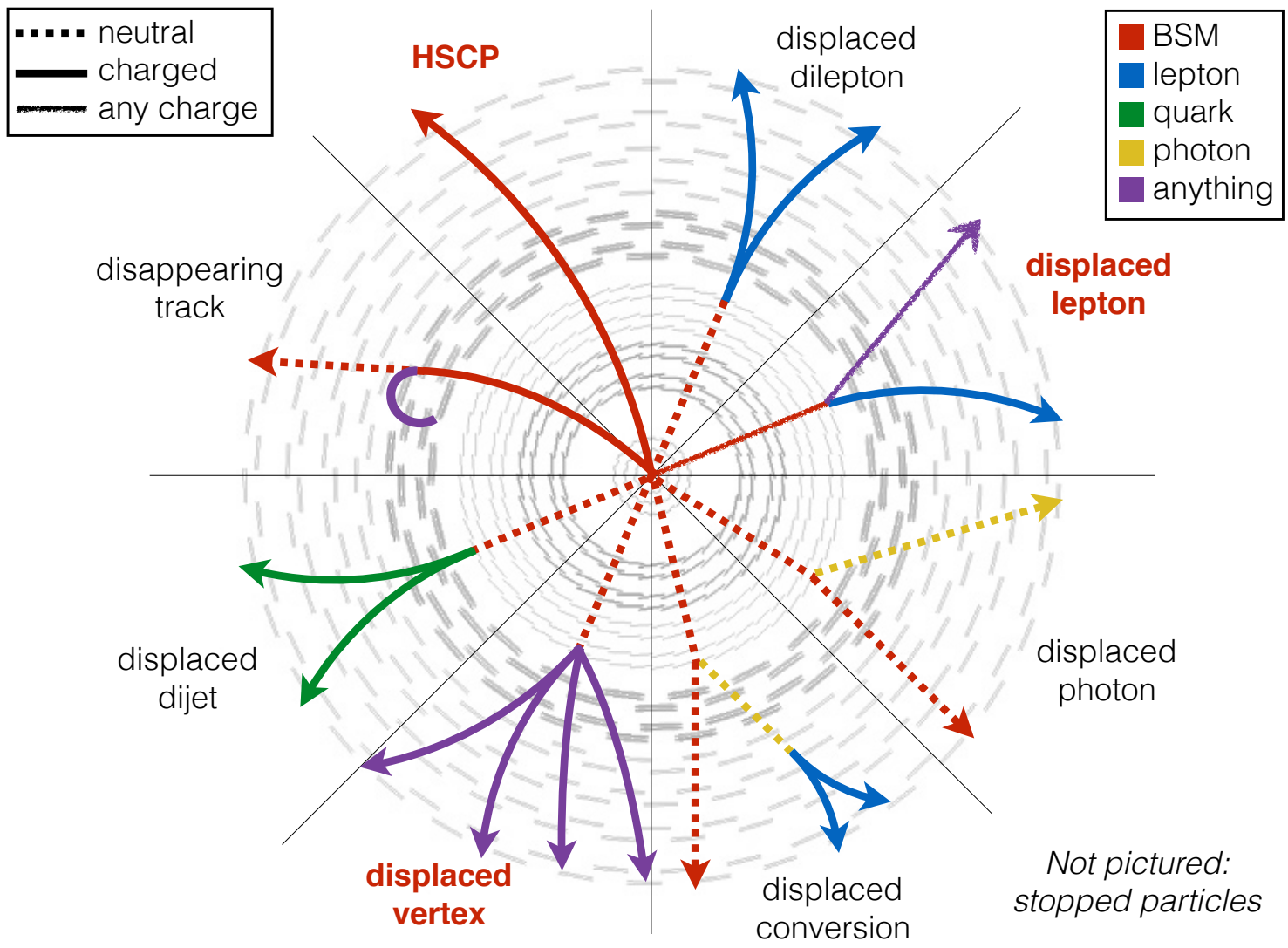
“compressed spectrum”

Is This the End of Natural SUSY?

- Increasing dataset from 2.3 to 36 fb^{-1} → another ~300 GeV improvement
  - Seems like already **not much space** left for natural SUSY

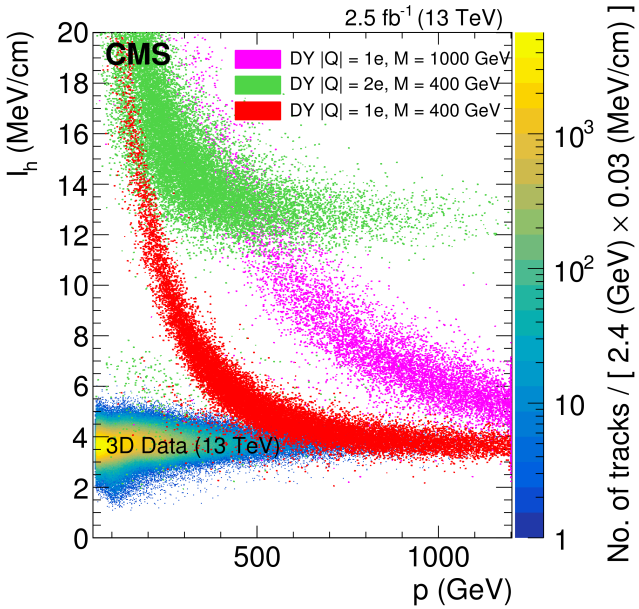


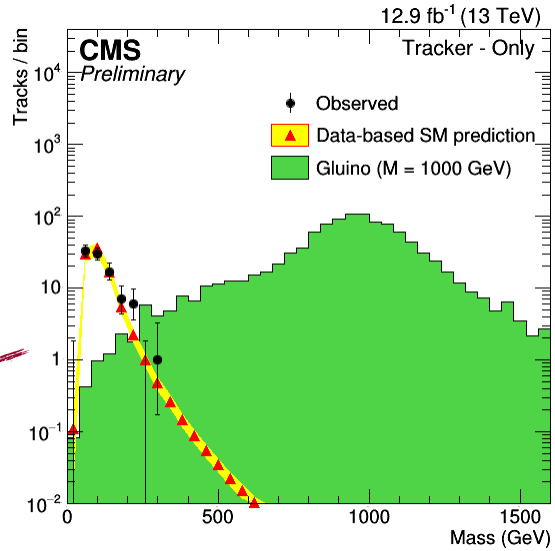
Going Exotic: Long Lifetimes

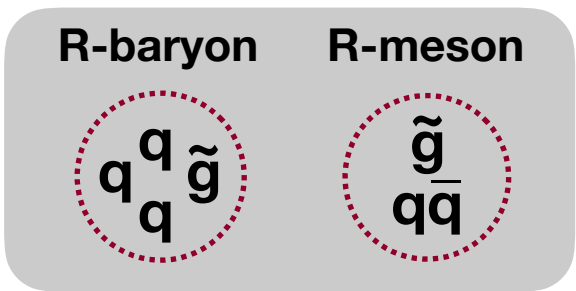


Split SUSY: Heavy Stable Charged Particles

- ‘Split’ SUSY: **very heavy** squarks (≫TeV), light gluinos
  - Main gluino decay $\tilde{g} \rightarrow \tilde{q}\chi_0$ heavily **suppressed**
  - Resulting in gluinos with **long lifetimes**
- Produced gluinos will **hadronize** into ‘R-hadrons’
  - **Slow** speed ($v < 0.9c$) already if $M > 400$ GeV
  - Selected with dE/dx in silicon tracker





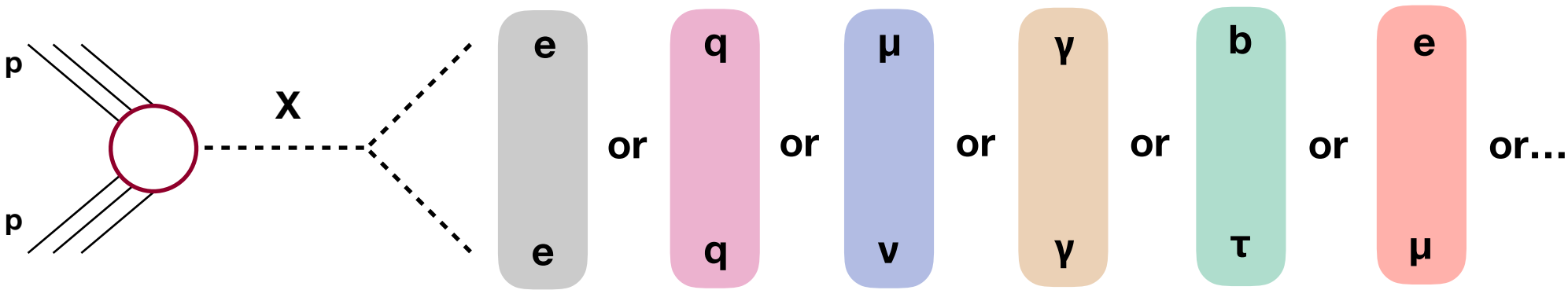


Mass reconstructed from:

$$\frac{dE}{dx} = K\frac{m^2}{p^2} + C$$

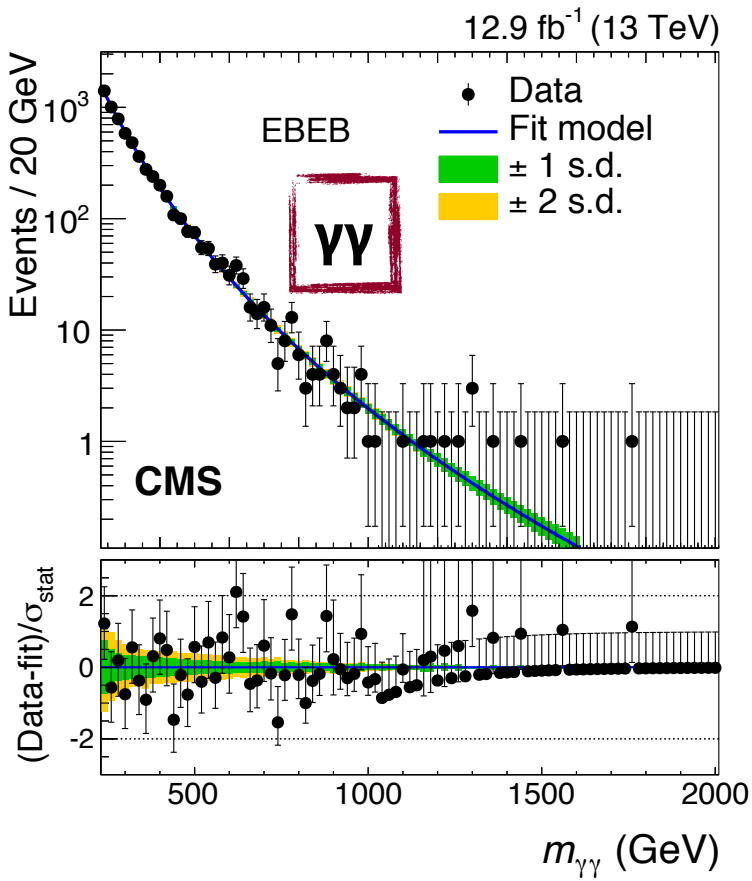
Thinking Outside of the SUSY Box

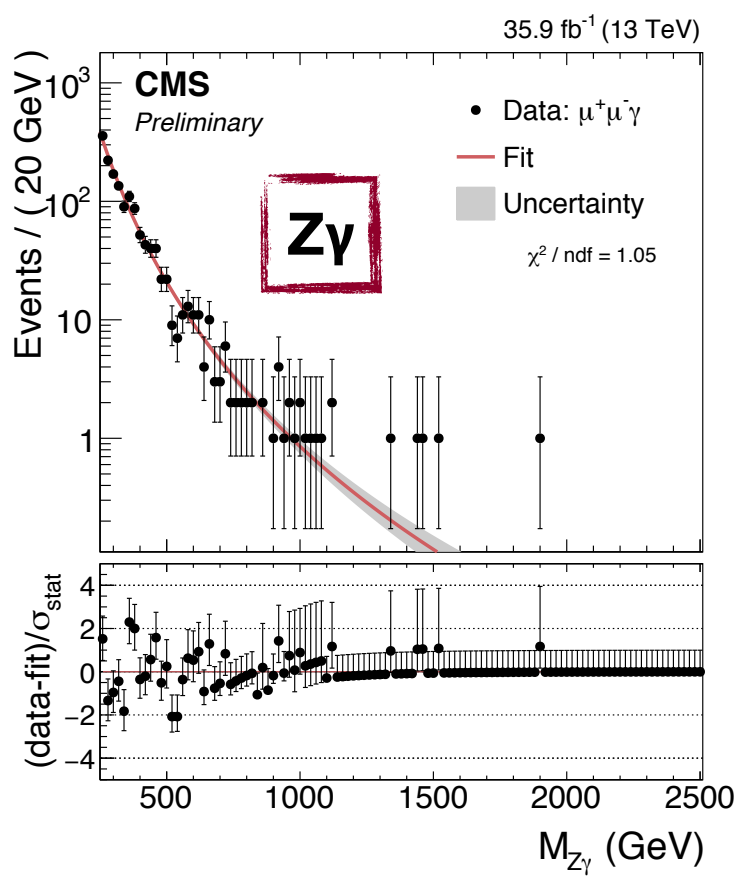
- Supersymmetry is not the **only** solution
  - **Other** models try to solve dark matter and naturalness
  - Many predict existence of new high-mass **resonances**
- Details on cross-section/width/decay depend on **model**
  - Need to have **extensive** resonance-hunting program
  - To be sensitive to a **broad** range of ‘exotic’ models



Bump-Hunting With γγ and Zγ

- Sensitive to **generic** high-mass spin-0 and spin-2 (and spin-1) resonances
  - Background fit directly **from data** → then go bump-hunting

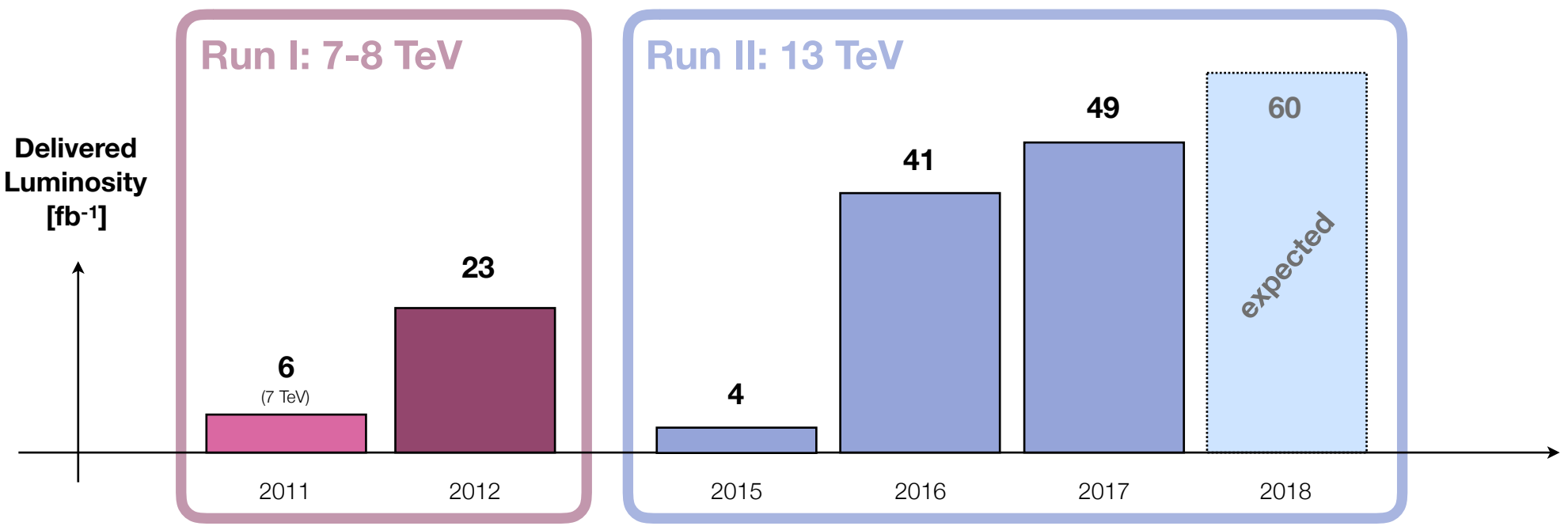




No Signs of New Physics Yet

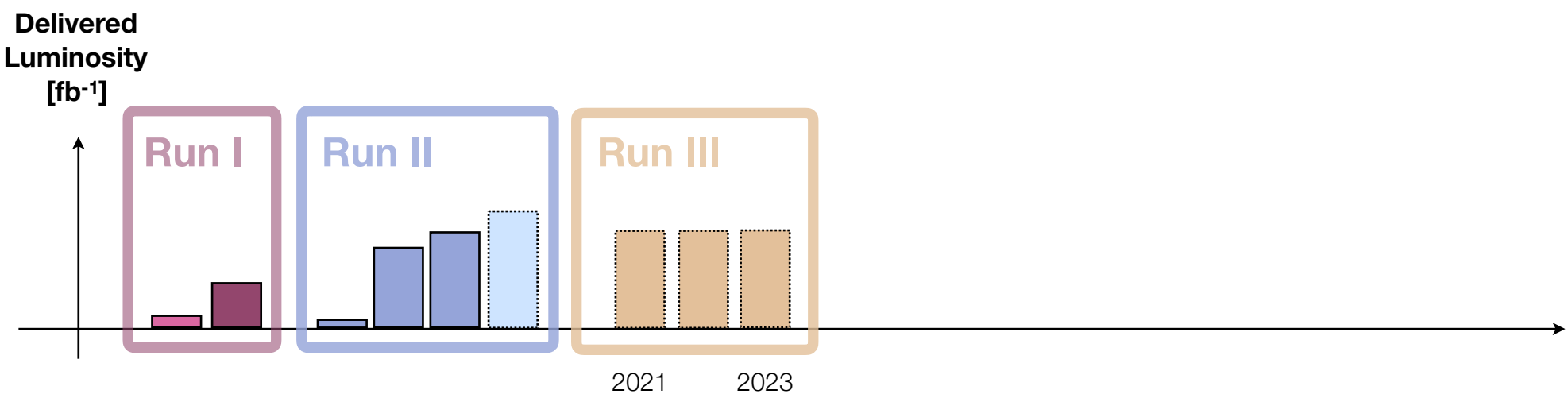
- Many models predict existence of new particles at the **TeV scale**
  - Yet **no** conclusive sign of new physics found at the LHC
- Possible explanations:
  - Mass scale **higher** than current reach
  - Cross section **lower** than expected
  - Too **similar** to known processes (difficult signatures)
- Are **conventional** direct searches still cutting-edge?
  - …or do we need to look **differently**?

From the Energy to the Luminosity Frontier



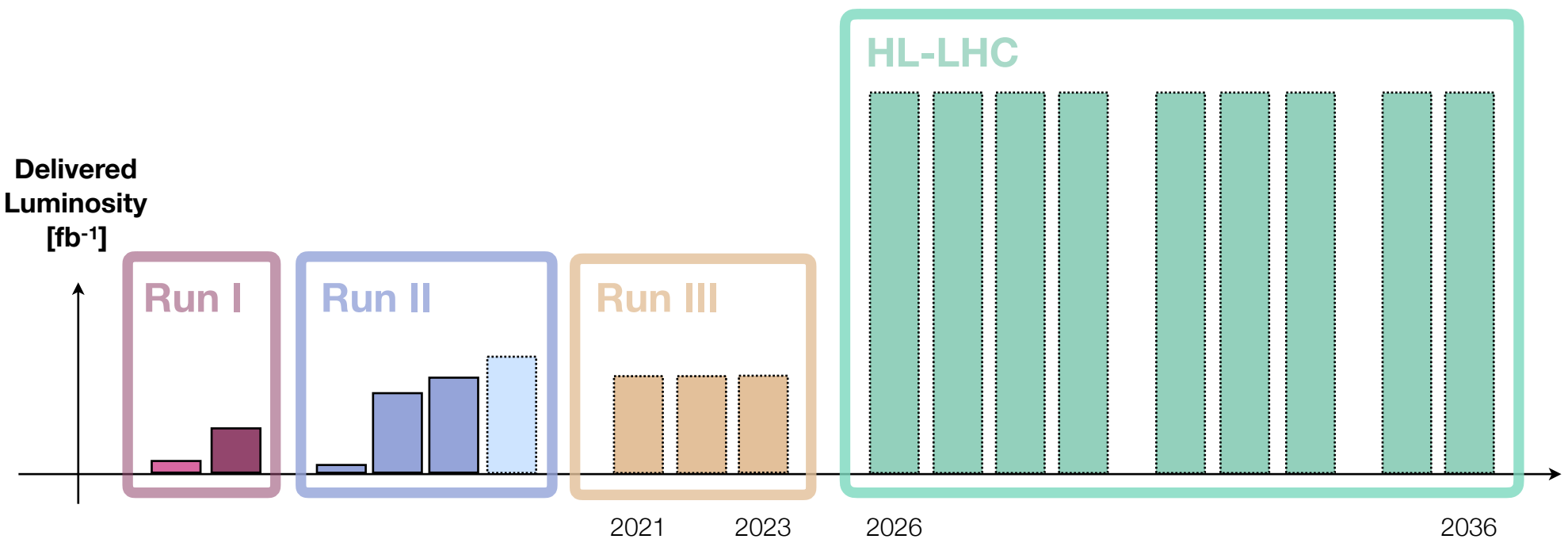
From the Energy to the Luminosity Frontier

- LHC Run III will start in 2021
  - **Three** more years of ~50 fb^{-1} per year
  - Possible **bump** in energy: 13 → 14 TeV (would benefit searches)
  - Will have a total of **300 fb^{-1}** of LHC Runs II+III



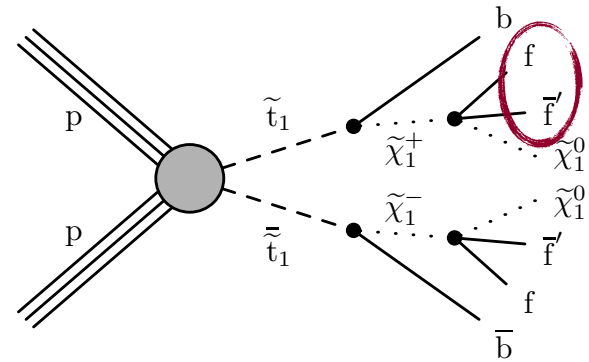
From the Energy to the Luminosity Frontier

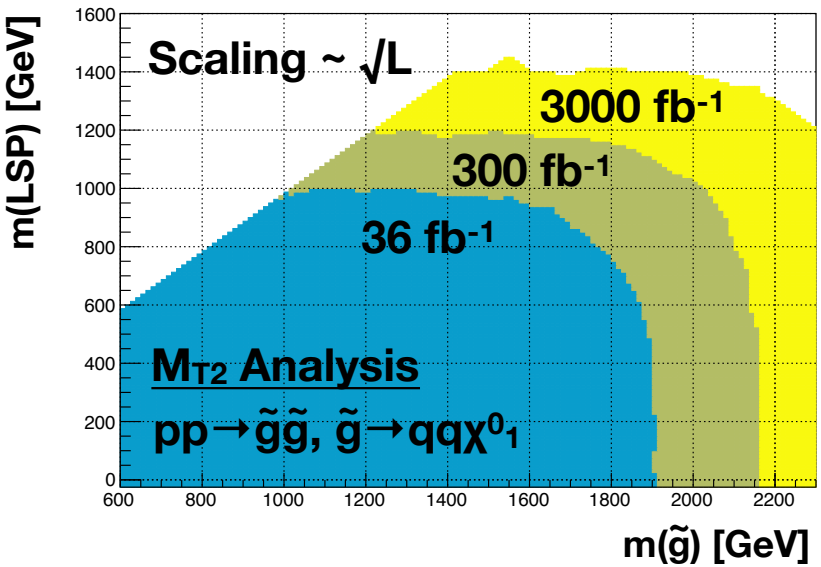
- Looking **further** in the future of LHC: HL-LHC starts in 2026
  - **Big** jump in instantaneous luminosity: up to 10^{35} $cm^{-2}s^{-1}$
  - Plan to collect 300 fb^{-1} per year, total of **3000 fb^{-1}** in ten years
  - How to best exploit such an **enormous** dataset?

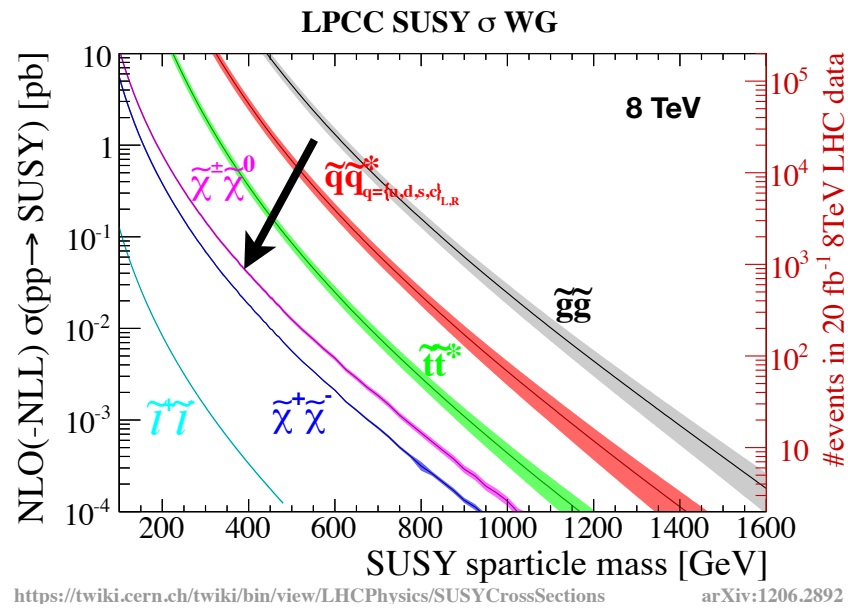


300 fb^{-1}: New Directions for SUSY

- Increasing luminosity → **diminishing returns** for inclusive searches
- Could we have missed it?
  - **Compressed** spectra: low ME_T → tag with soft leptons
  - Long lifetimes → **displaced** signatures
  - Lower cross sections: **electroweak** SUSY

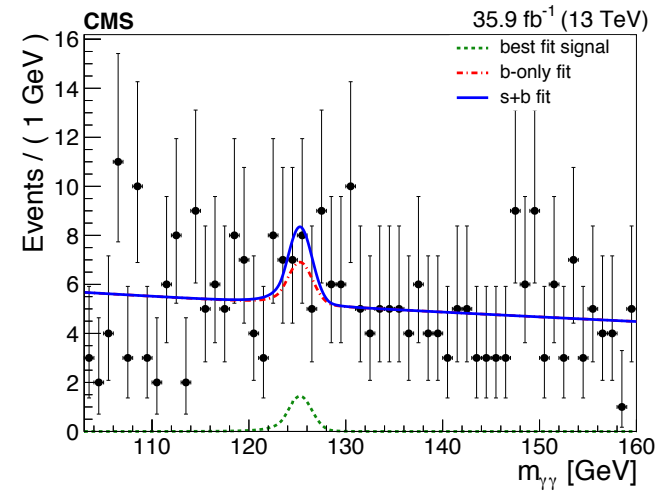


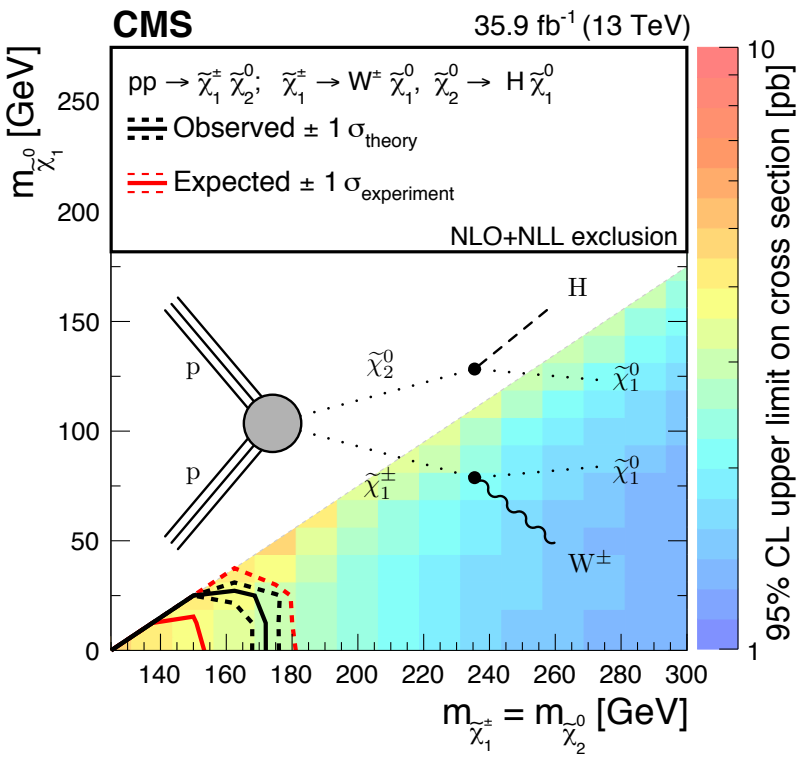


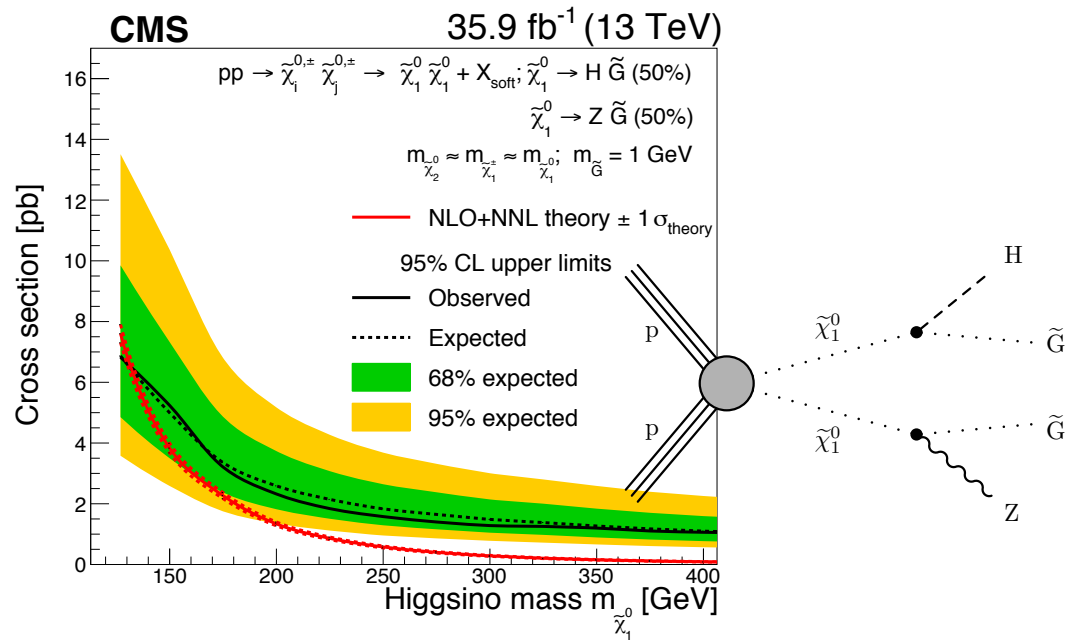


Using the Higgs to Probe Electroweak SUSY

- H→γγ can be used to **tag** EW SUSY events
  - Clean, high-resolution - but **low BR** (0.2%)
  - Will need 300 fb^{-1} to achieve **sensitivity**



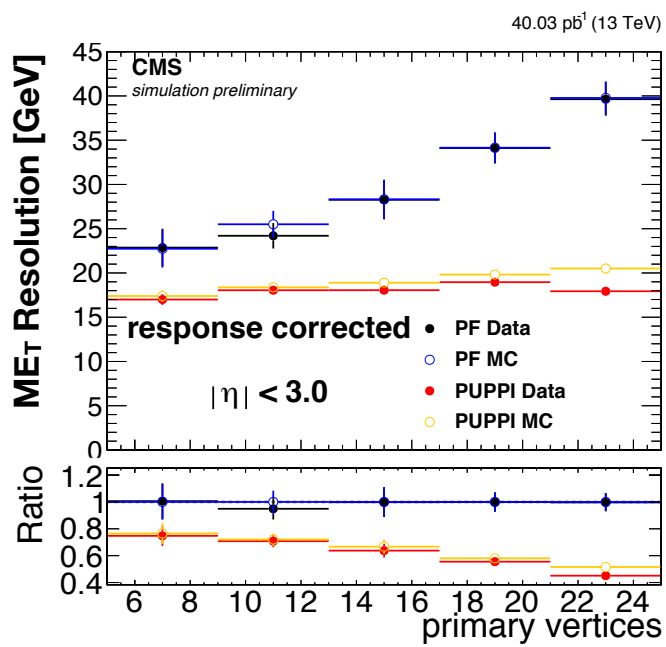




HL-LHC: It Won't Be a Free Lunch

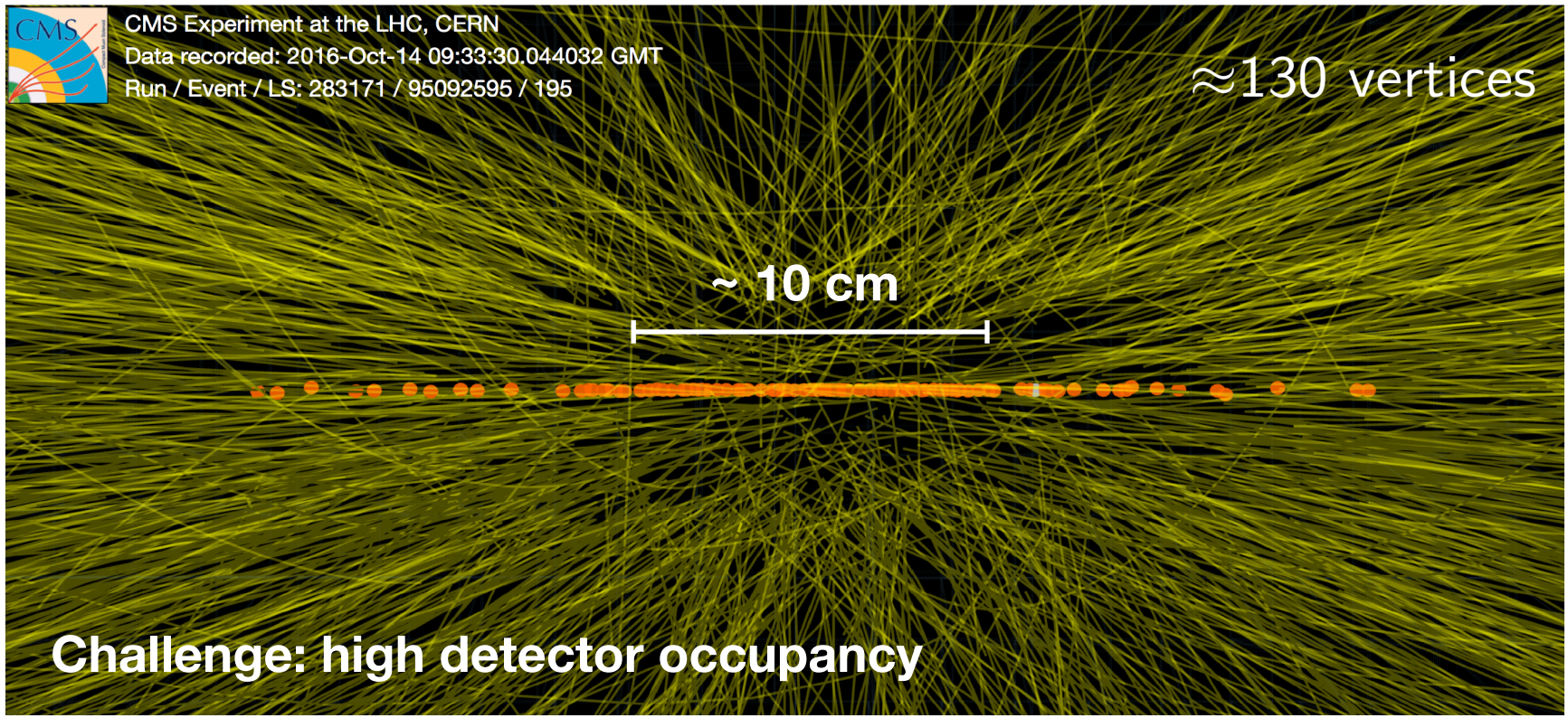
- To achieve such high luminosity, experimental conditions will be **harsher**
  - High **pile up**: 140 (or 200!) simultaneous collisions on **average** (currently 40)
  - High **radiation**: up to ×10 higher hadron fluence (especially forward)
- Will pose serious **challenges** to detectors
  - Trigger/reconstruction need to have **same level** of performance as Run II
  - High **radiation hardness**, especially forward

	Run2	HL-LHC
$\sqrt{s}$ [TeV]	13 or 14	13 or 14
L [$cm^{-2}\ s^{-1}$]	2×10^{34}	10^{35}
Int. L [fb^{-1}]	300	3000
γ dose rate [Gy/h]	0.3 (η=0) 10 (η=3)	1.5 (η=0) 50 (η=3)
Hadron fluence [cm^{-2}]	4×10^{11} (η=0) 10^{14} (η=3)	4×10^{12} (η=0) 10^{15} (η=3)



Already Working On It

- **High intensity** LHC run in 2016 created “HL-LHC” conditions
  - High-pileup data to be used for **future** performance studies



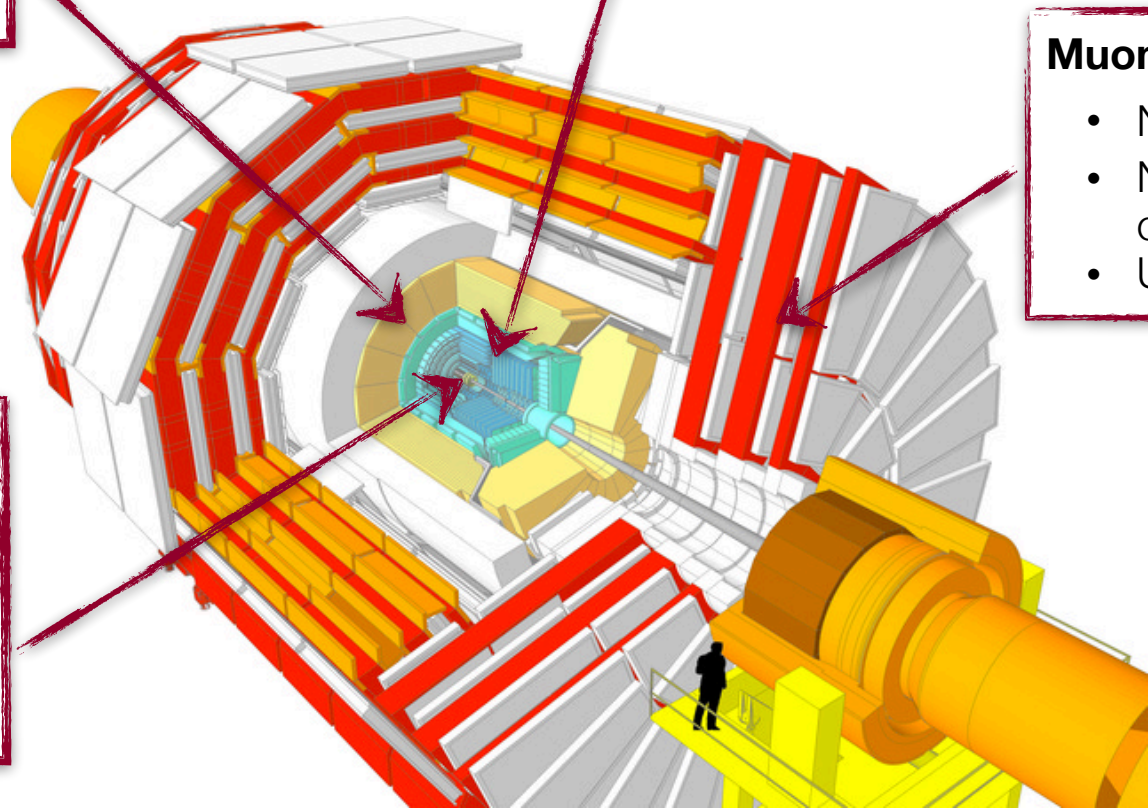
CMS Upgrade Program for HL-LHC

New Forward Calorimetry

- Entirely made of silicon
- Radiation tolerant
- '5D' measurement

Central ECAL

- New electronics
- Lower operating temperature (10°C)



Muon System

- New electronics
- New forward chambers
- Up to $|\eta| = 3$

New Tracker

- Radiation tolerant
- Light
- Full-blown tracking at trigger level
- Pixels up to $|\eta| = 4$

Couplings: How Much Precision Do We Need?

- Deviation from expected SM couplings would prove Higgs **exotic**
  - Amount of deviation depends on **specific model**

Extra Higgs, singlet in SM, breaks symmetry in a 'hidden' sector, mixes with SM H

Higgs not elementary and pseudo-Goldstone boson of a new force with scale » m_H

Supersymmetry: deviations even if all other sparticles out of LHC reach

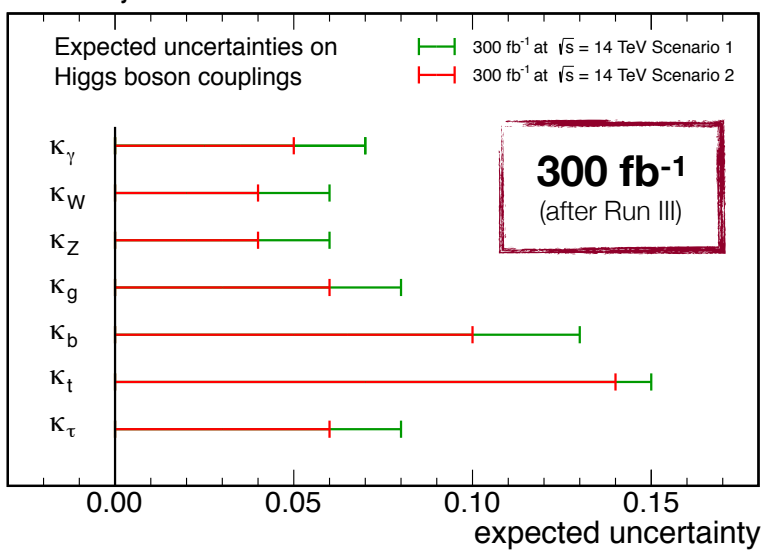
Expected deviation from SM couplings:

	ΔhVV	*Δhtt*	*Δhbb*
Mixed-in Scalar	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
MSSM	< 1%	3%	10-100%

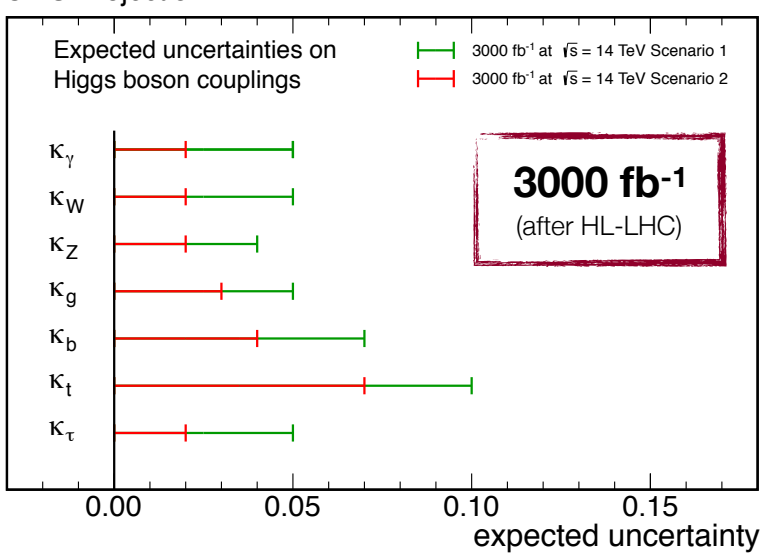
Phys. Rev. D **86**, 095001

Can We See New Physics with Higgs Couplings?

CMS Projection



CMS Projection



- CMS projections for:
  - After LHC Run III (300 fb^{-1})
  - After 10 years of HL-LHC (3000 fb^{-1})
- Two scenarios:
  - **Scenario 1:** systematic uncertainties left same as current analyses
  - **Scenario 2:** 50% of theoretical uncertainties, experimental uncertainties scaled with √L

Can We See New Physics with Higgs Couplings?

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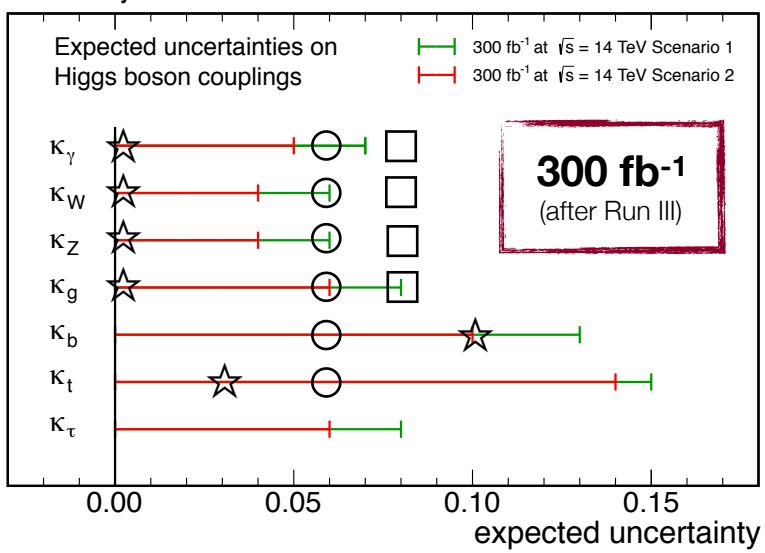
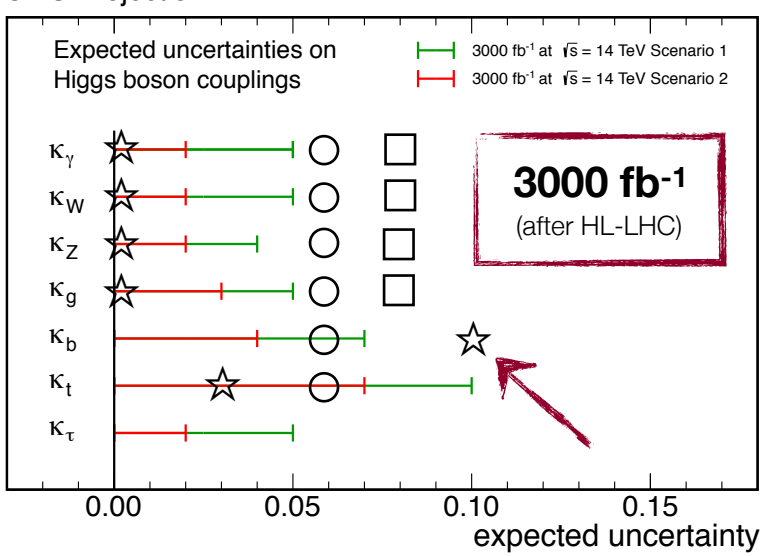


CMS Projection



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- Two scenarios:
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Deviations expected from: ☆: MSSM ☐: Composite Higgs ○: Mixed-in Scalar

- Need HL-LHC to reach sensitivity to new physics

Conclusions

- CMS has **vast** search program for physics beyond the Standard Model
  - **Direct:** Supersymmetry, high-mass resonances, exotic signatures, …
  - **Indirect:** precision measurement of Higgs couplings
- The **luminosity frontier** is approaching: large datasets await us!
  - 300 fb^{-1} in 2023, up to 3000 fb^{-1} in 2036
- Will allow us to search in **new directions**
  - 300 fb^{-1}: probe **compressed** and **electroweak** Supersymmetry
  - 3000 fb^{-1}: **Higgs couplings** will be sensitive to new physics
- Exciting times ahead of us!