Searching for BSM Phenomena at CMS in Run 1 and Run 2

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UC Davis

UCLA Dark Matter Symposium
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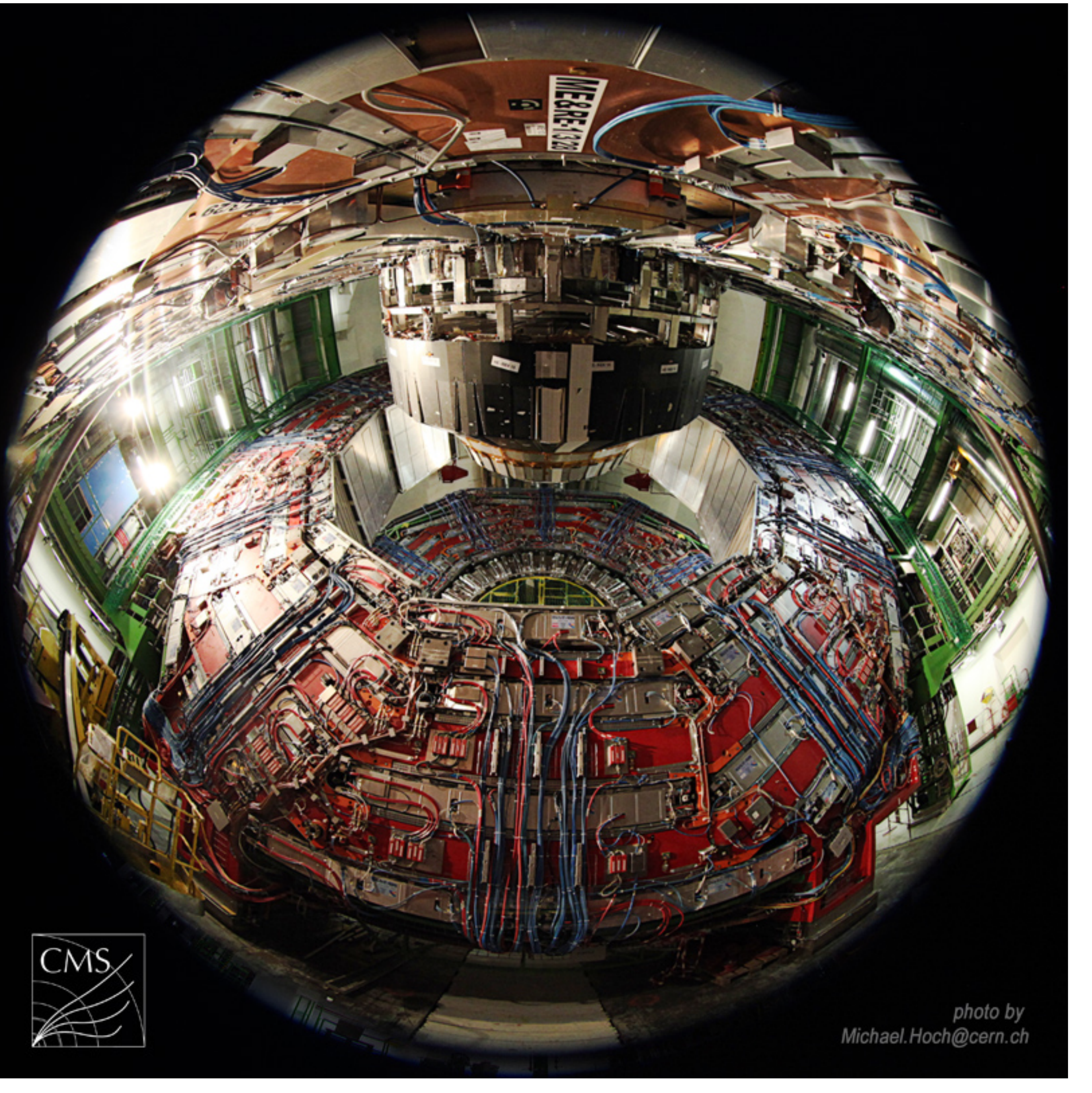


Outline

LHC and CMS Detector

BSM Searches & Results

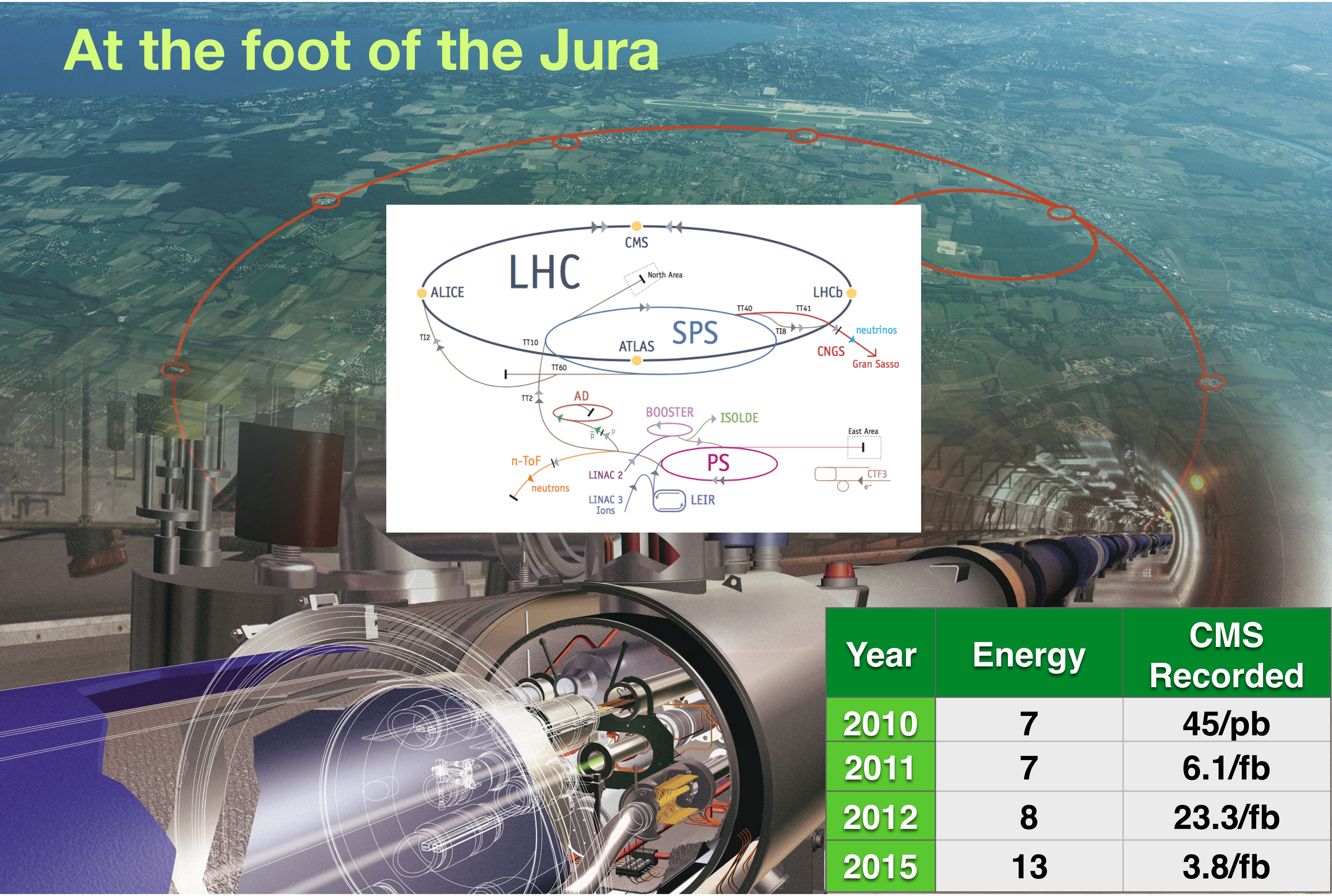
- Higgs status
- Searches for DM
- Searches for additional Higgs bosons
- Searches for resonances
- Searches for SUSY
- Searches for X → top quarks

Coming attractions

Conclusions

- Presenting both Run 1 and Run 2 results

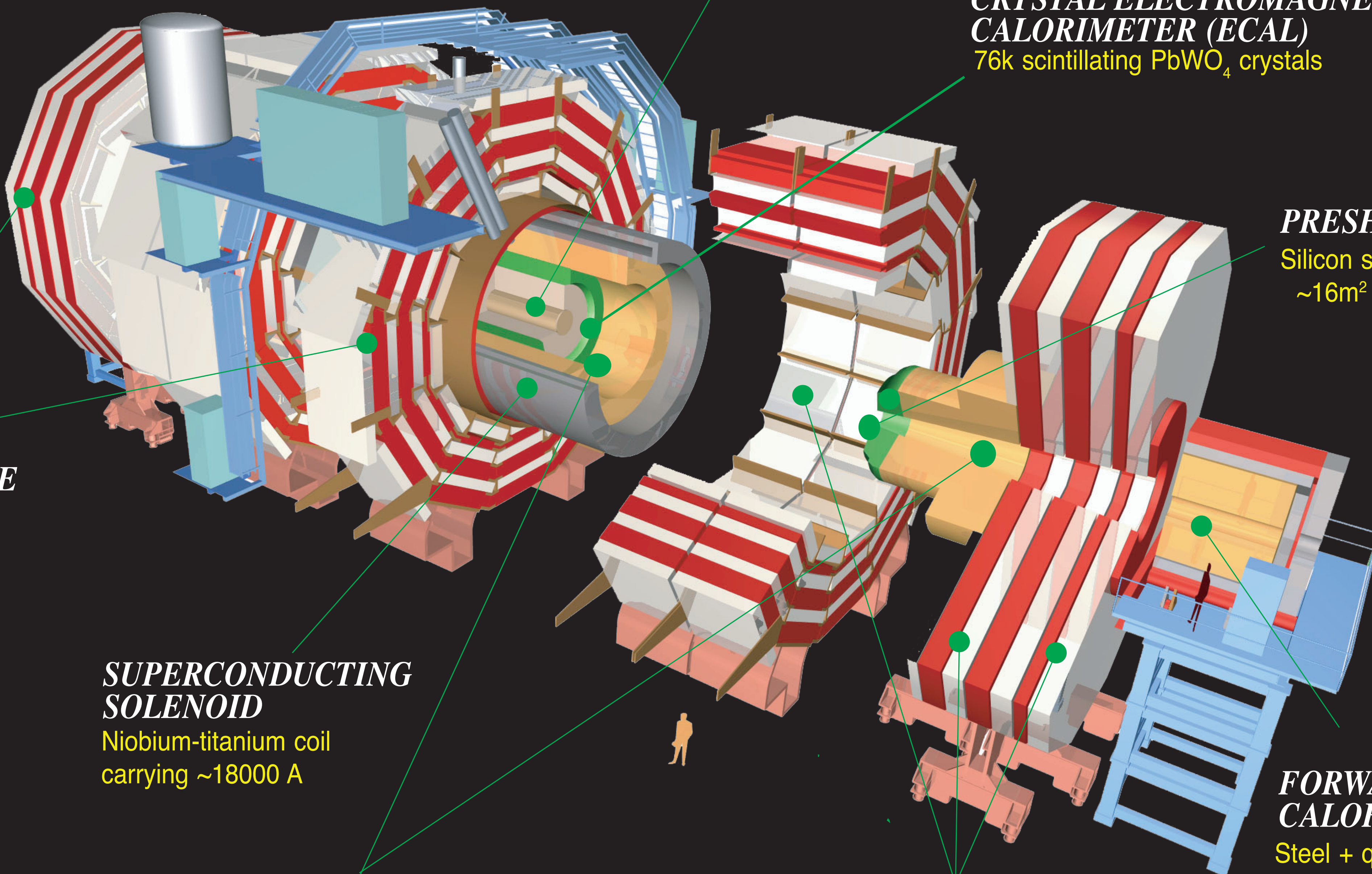
At the foot of the Jura



Year	Energy	CMS Recorded
2010	7	45/pb
2011	7	6.1/fb
2012	8	23.3/fb
2015	13	3.8/fb

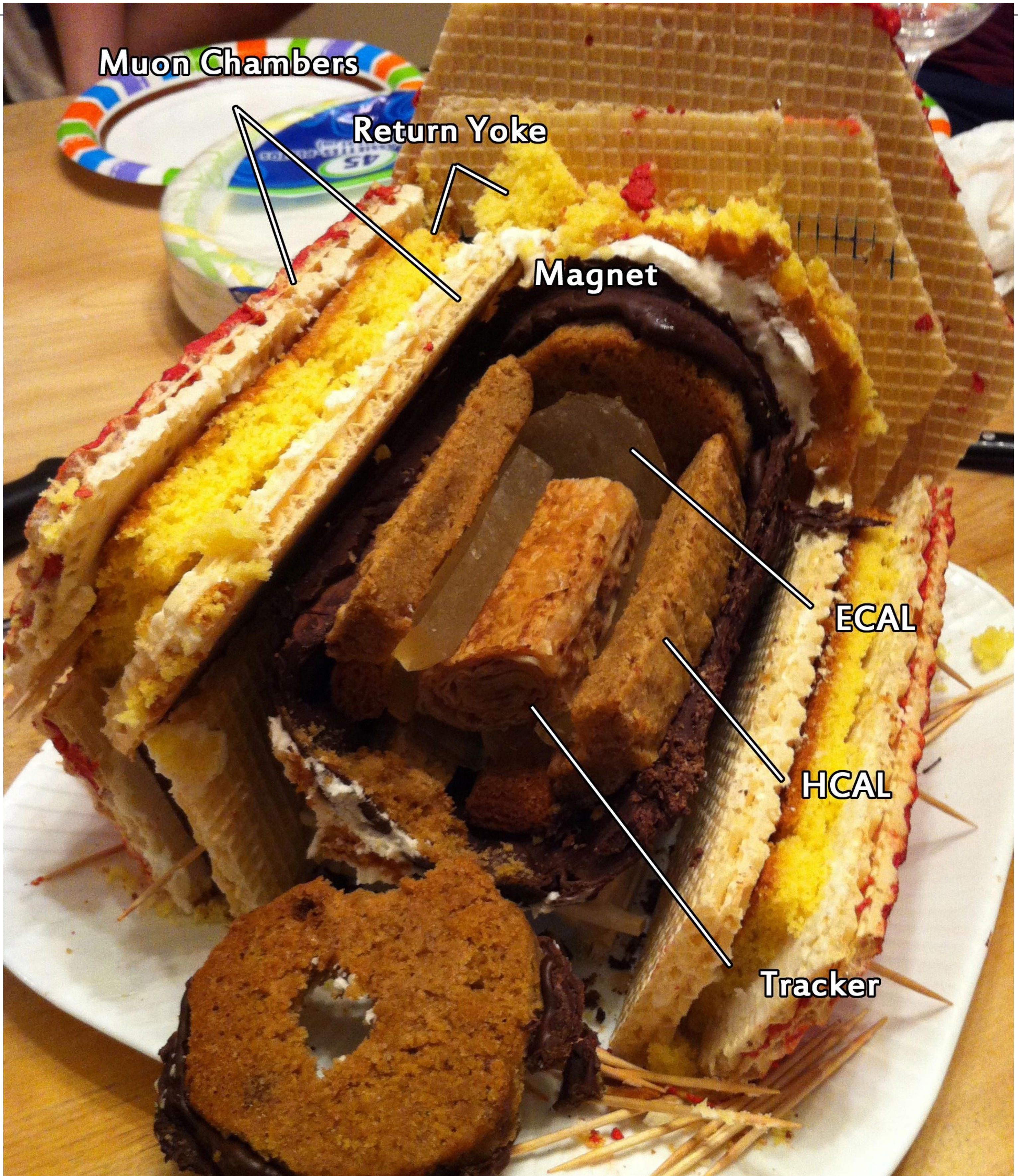
CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

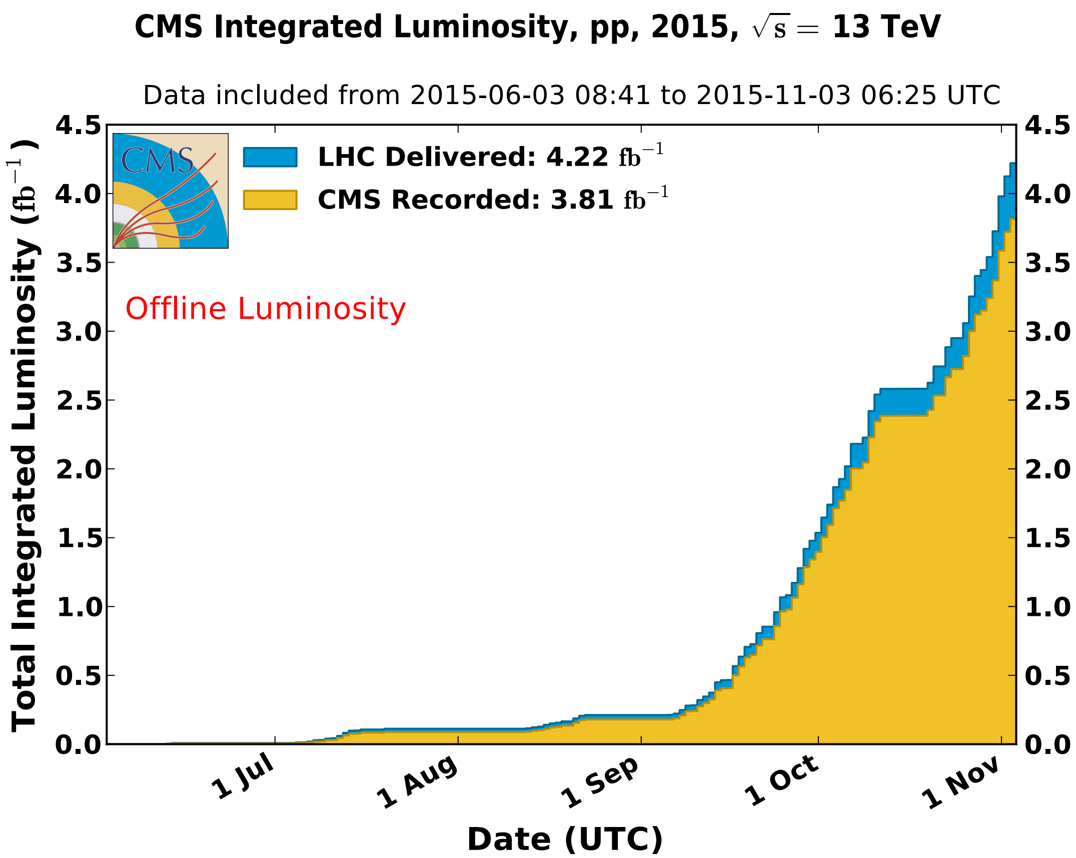


Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

The Compact Muon Solenoid

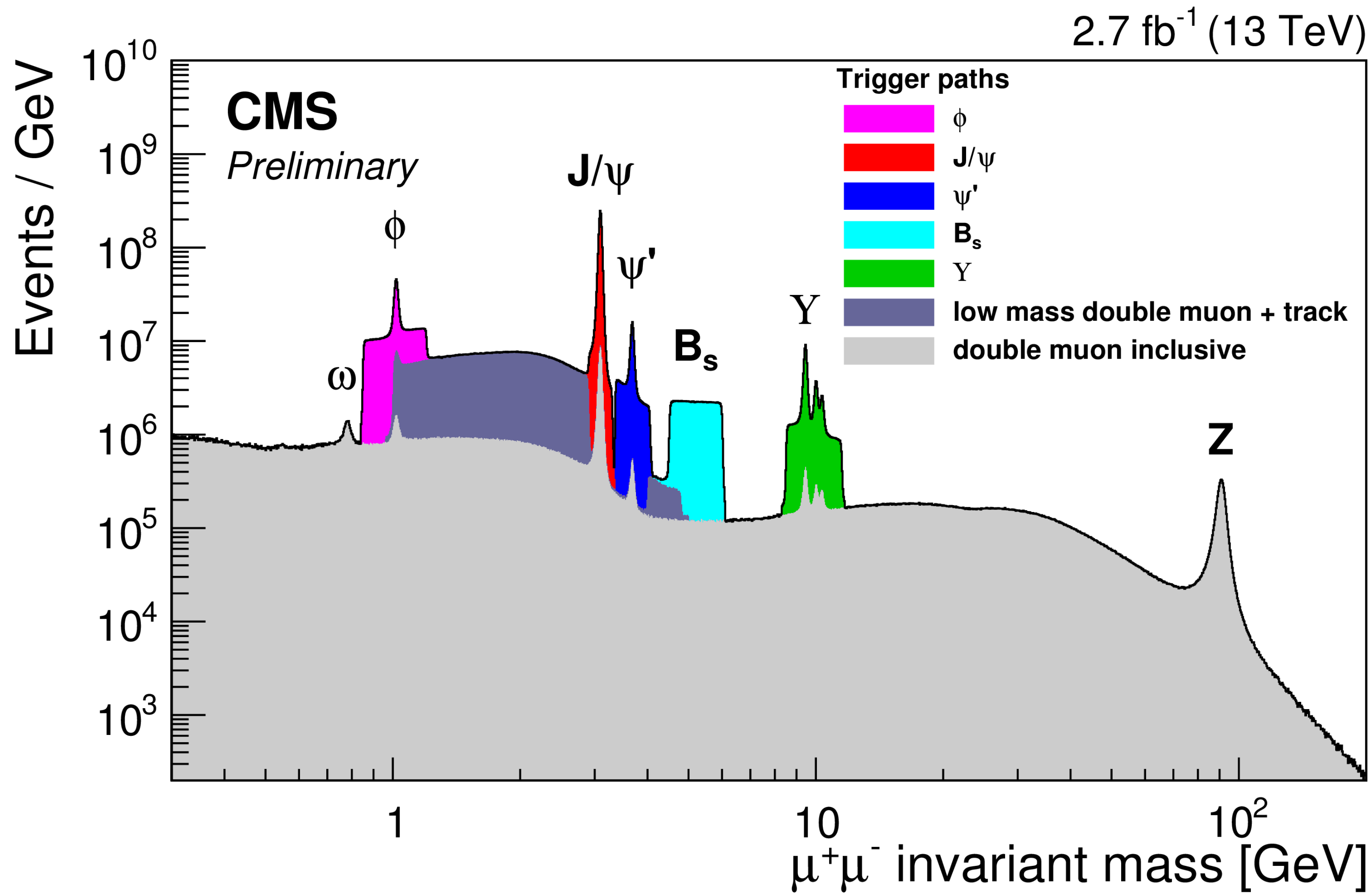


LHC and CMS in 2015

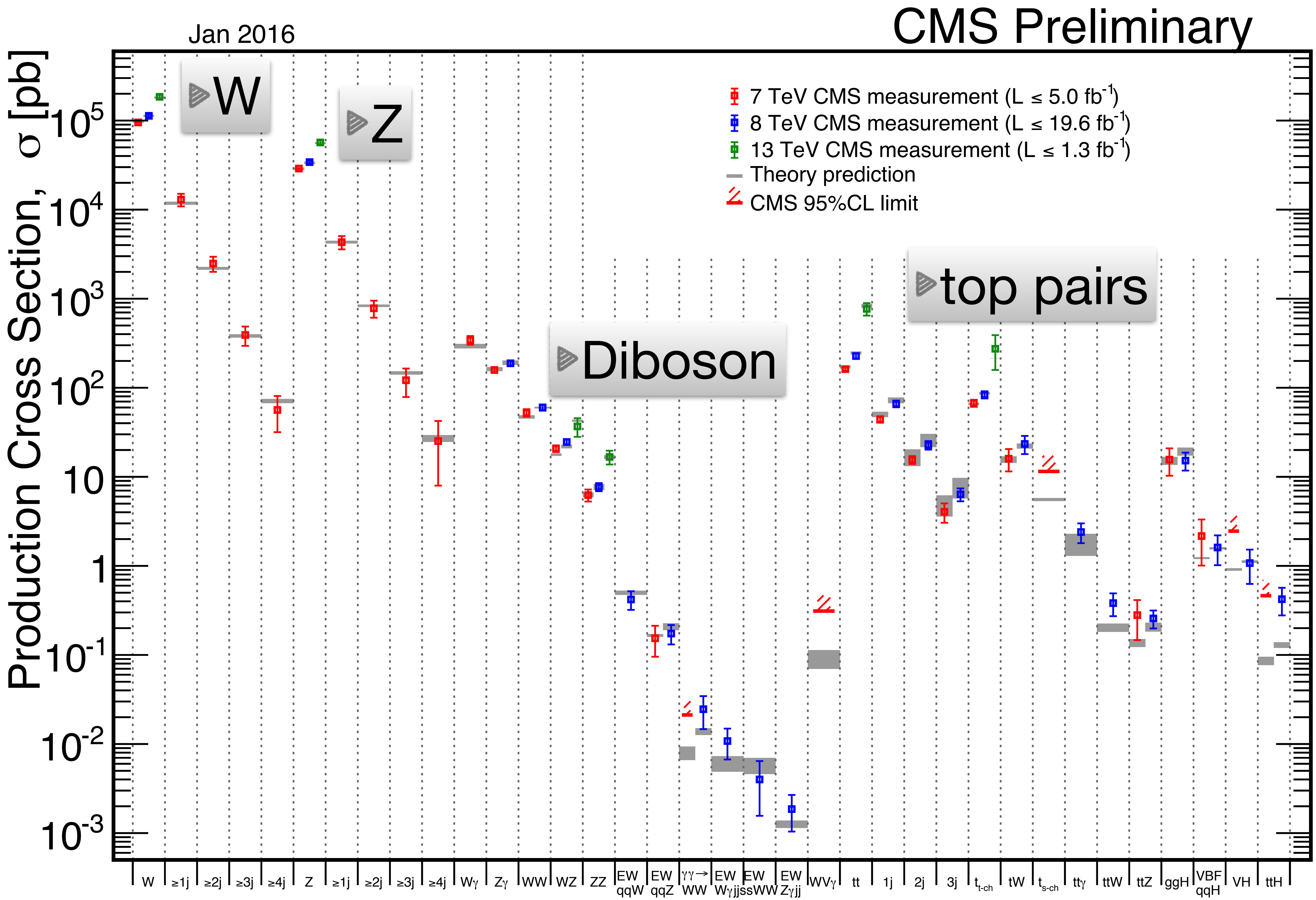


- Recorded at 3.8 T: 2.8/fb
- Good for muons: 2.7/fb
- Golden: 2.2/fb

13 TeV

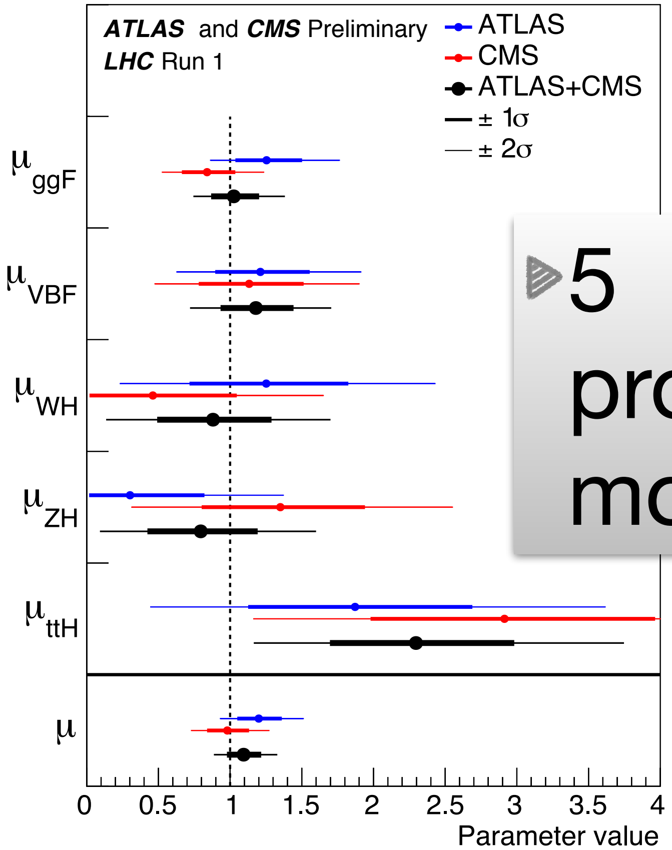


Standard Model Still Going Strong @ 13 TeV

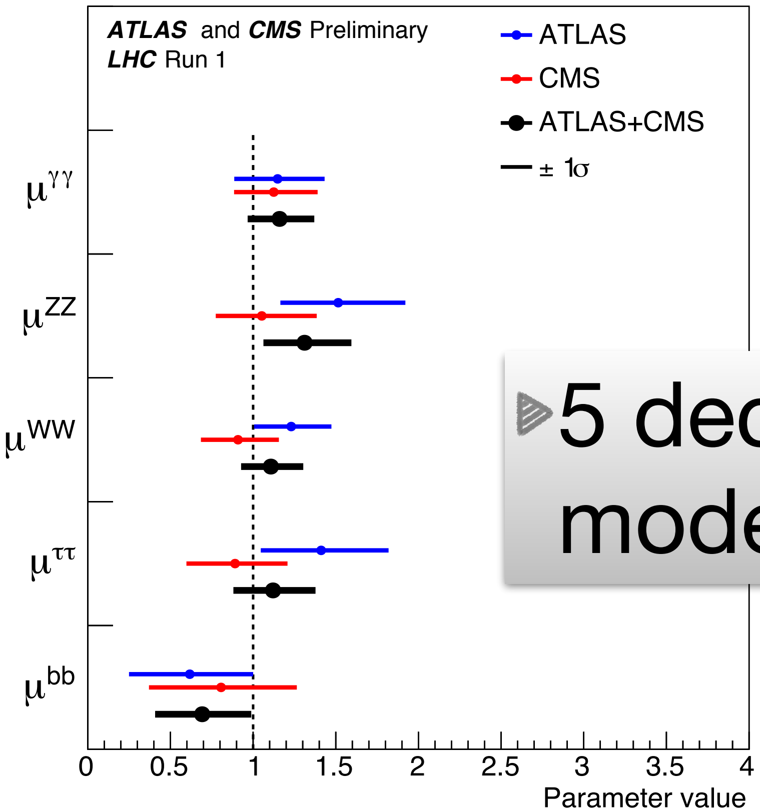


All results at: http://cern.ch/go/pNj7

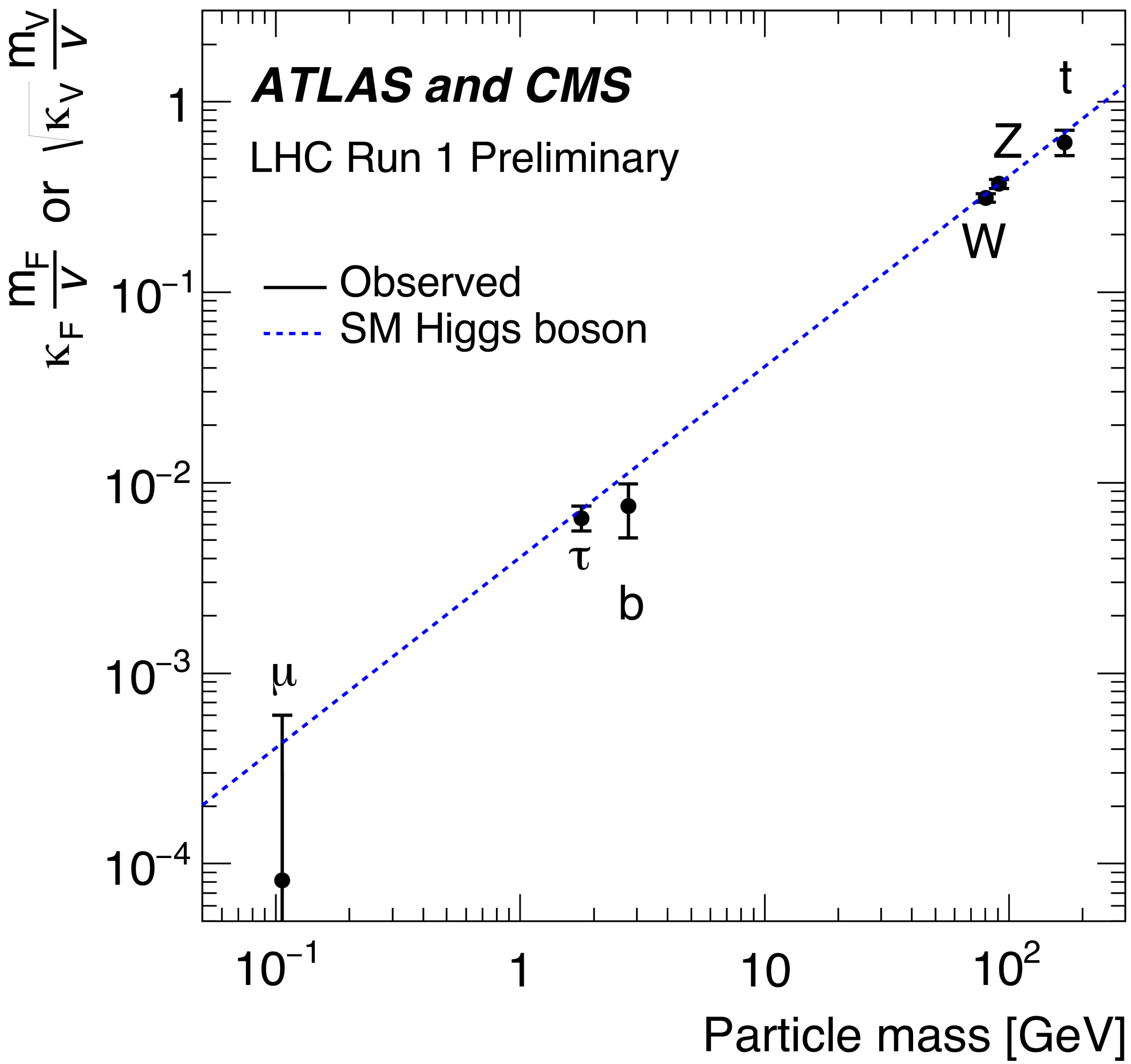
Higgs coupling measurements from Run I



- 5 production modes



- 5 decay modes



- Fit results versus particle mass
- Dashed line is SM prediction

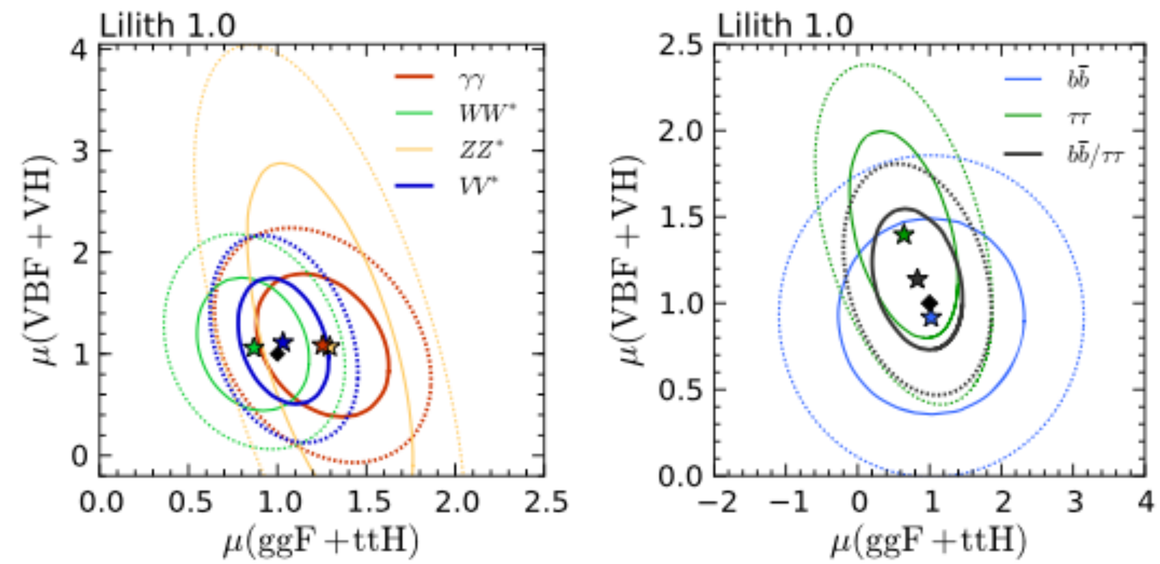
Remaining wiggle room in Higgs Decay BRs

Global fit to Higgs signal strengths and couplings and implications for extended Higgs sectors

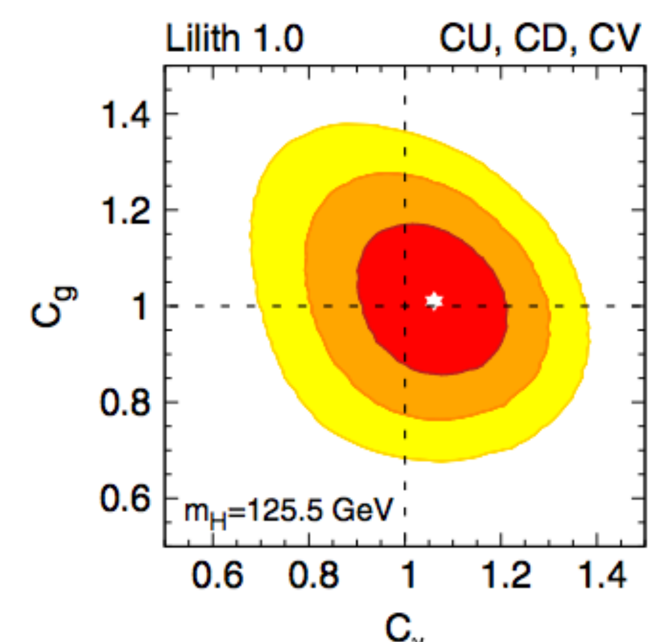
- Bernon, et al, PRD 90, 071301(R) (2014)
- Use published signal strengths μ ≡ σ(best-fit)/σ(SM) and uncertainties, fit for values of Higgs couplings to different SM particles under different assumptions of new physics

At 95% CL, up to 34% allowed branching ratio to as-yet-unseen decays

BERNON, DUMONT, AND KRAML

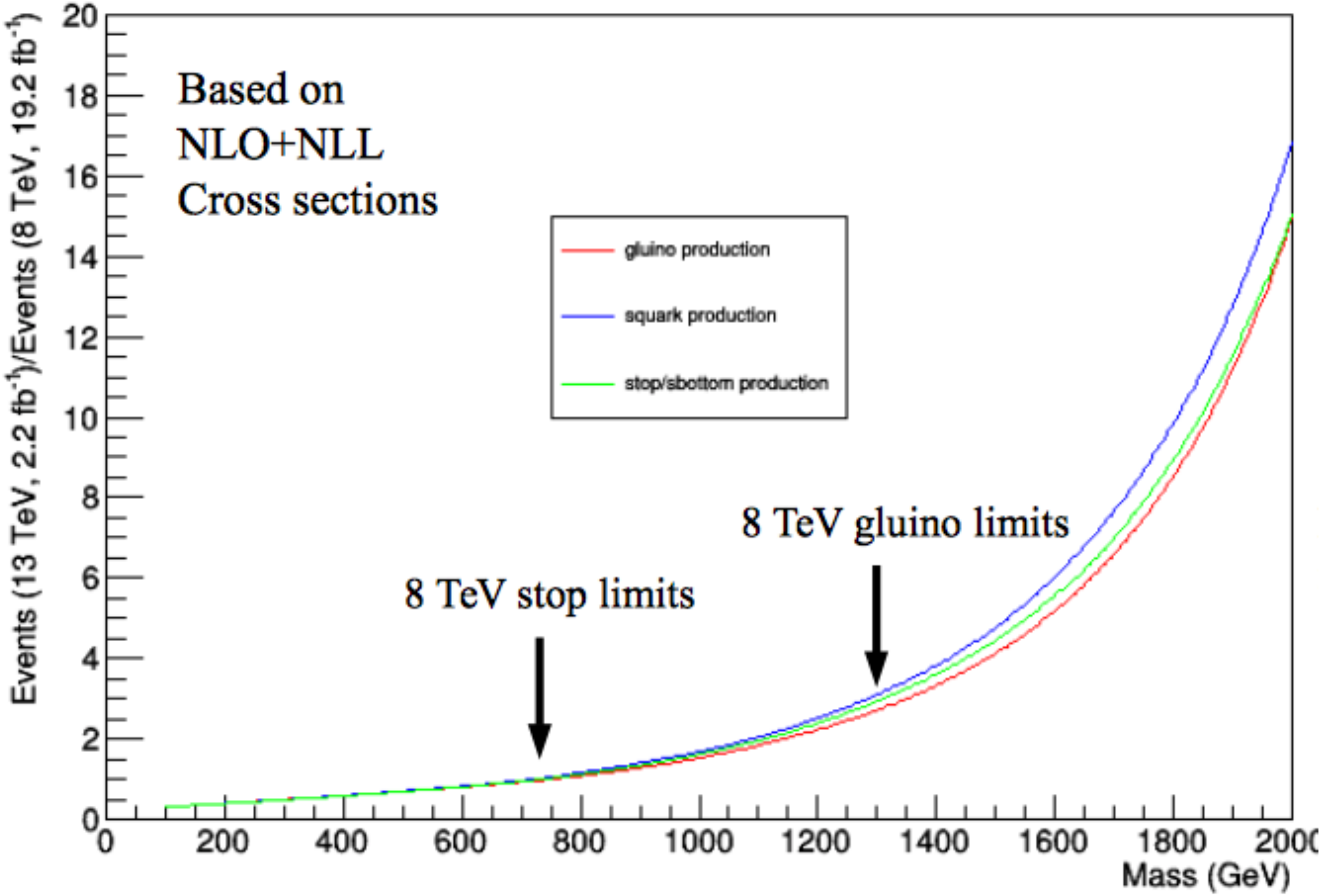


$$\mathcal{L} = \left[C_W m_W W^\mu W_\mu + C_Z \frac{m_Z}{\cos\theta_W} Z^\mu Z_\mu - C_U \frac{m_t}{2m_W} \bar{t}t - C_D \frac{m_b}{2m_W} \bar{b}b - C_D \frac{m_\tau}{2m_W} \bar{\tau}\tau \right] H,$$



- **Direct searches for Higgs decays to exotics still well motivated!**

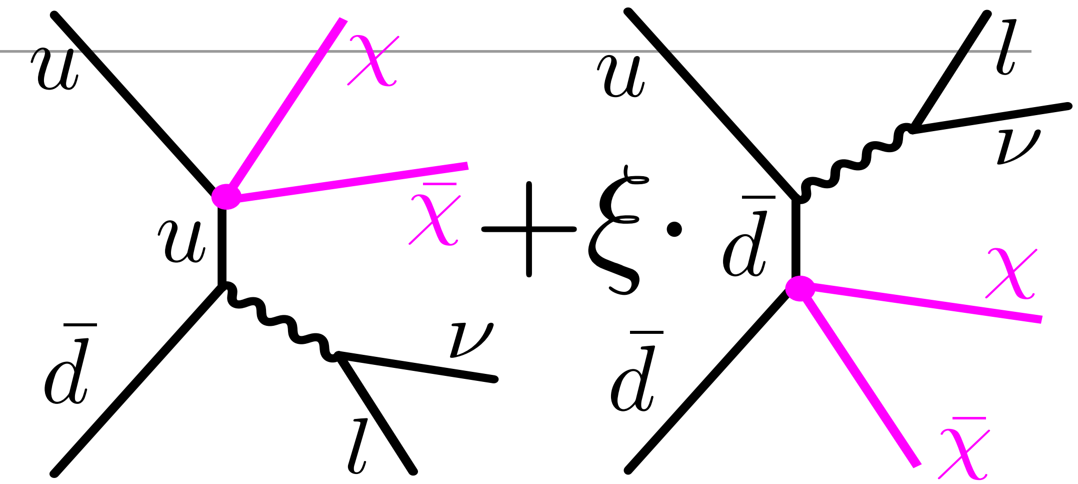
Heavy New Particles: Run II (so far) vs Run I



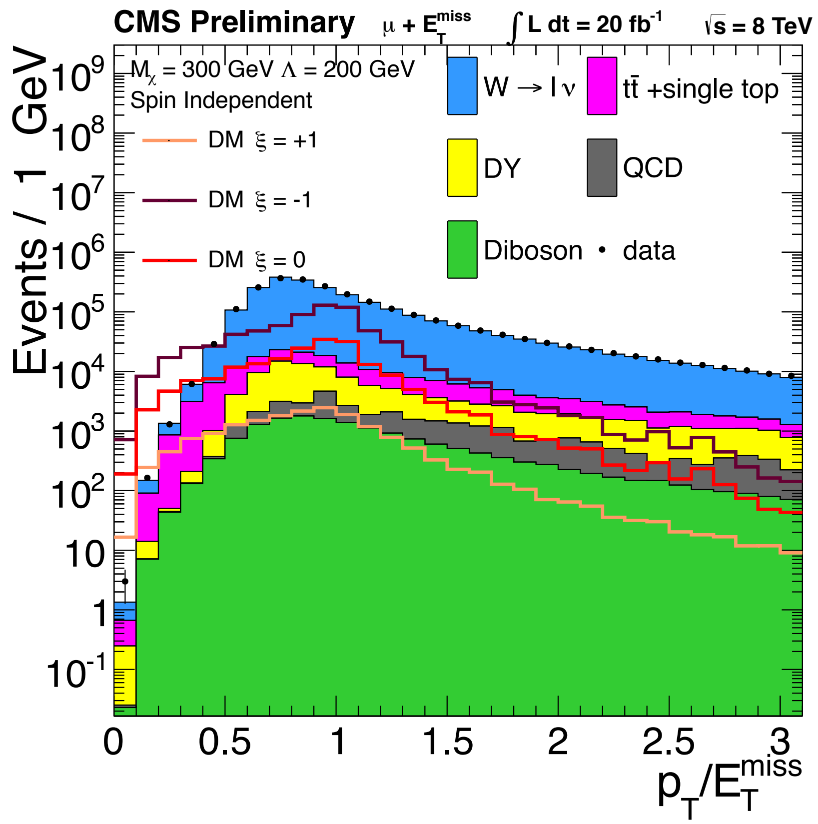
Searches for Dark Matter

CMS-PAS-EXO-13-004

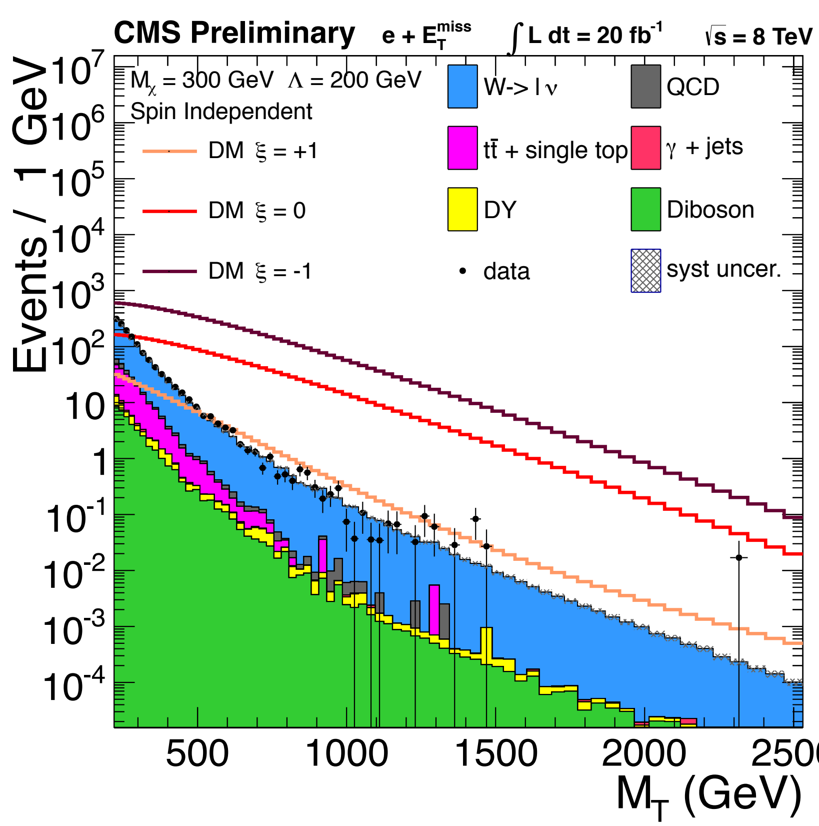
Mono-W (lepton + MET)

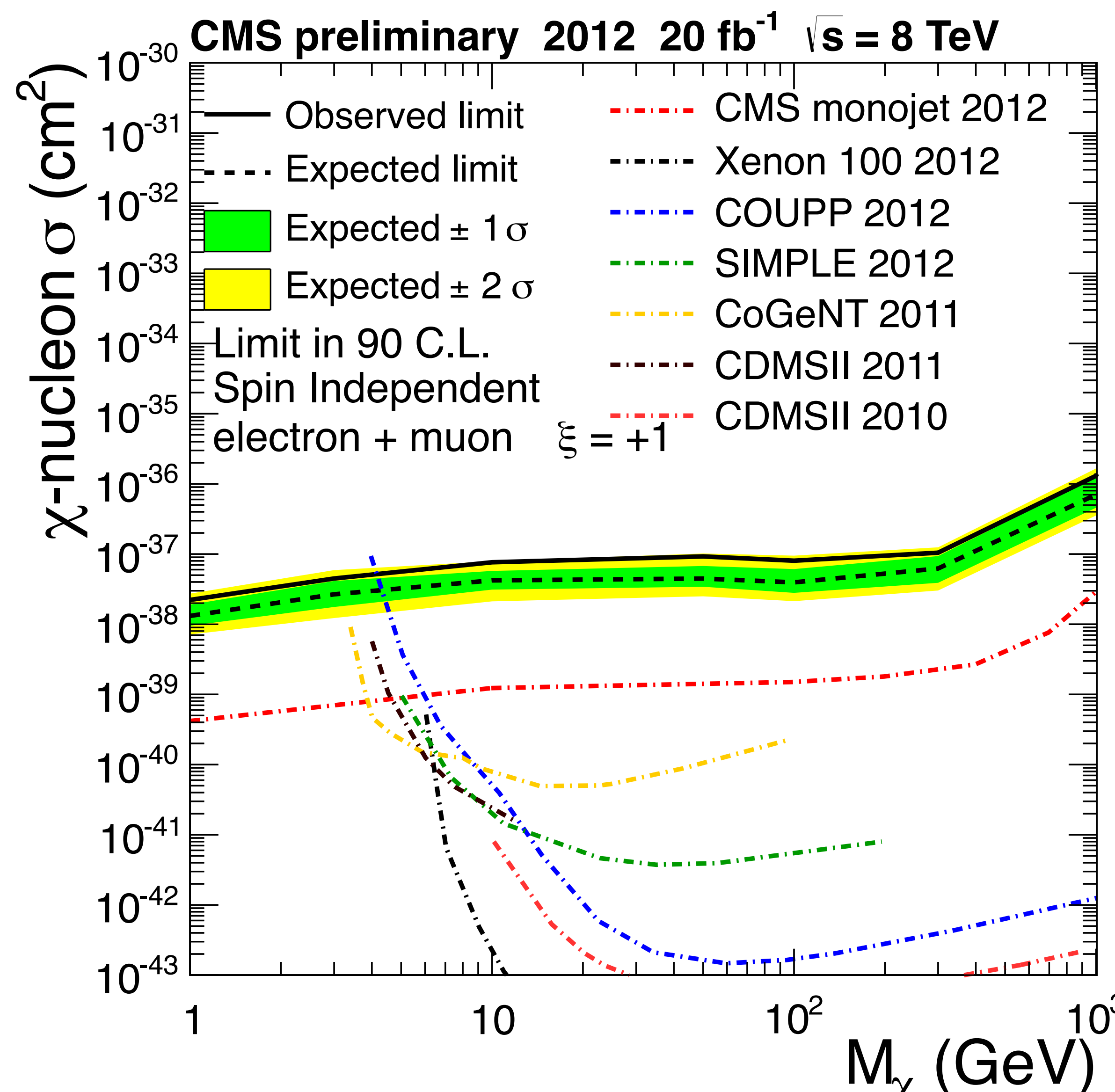


μ channel

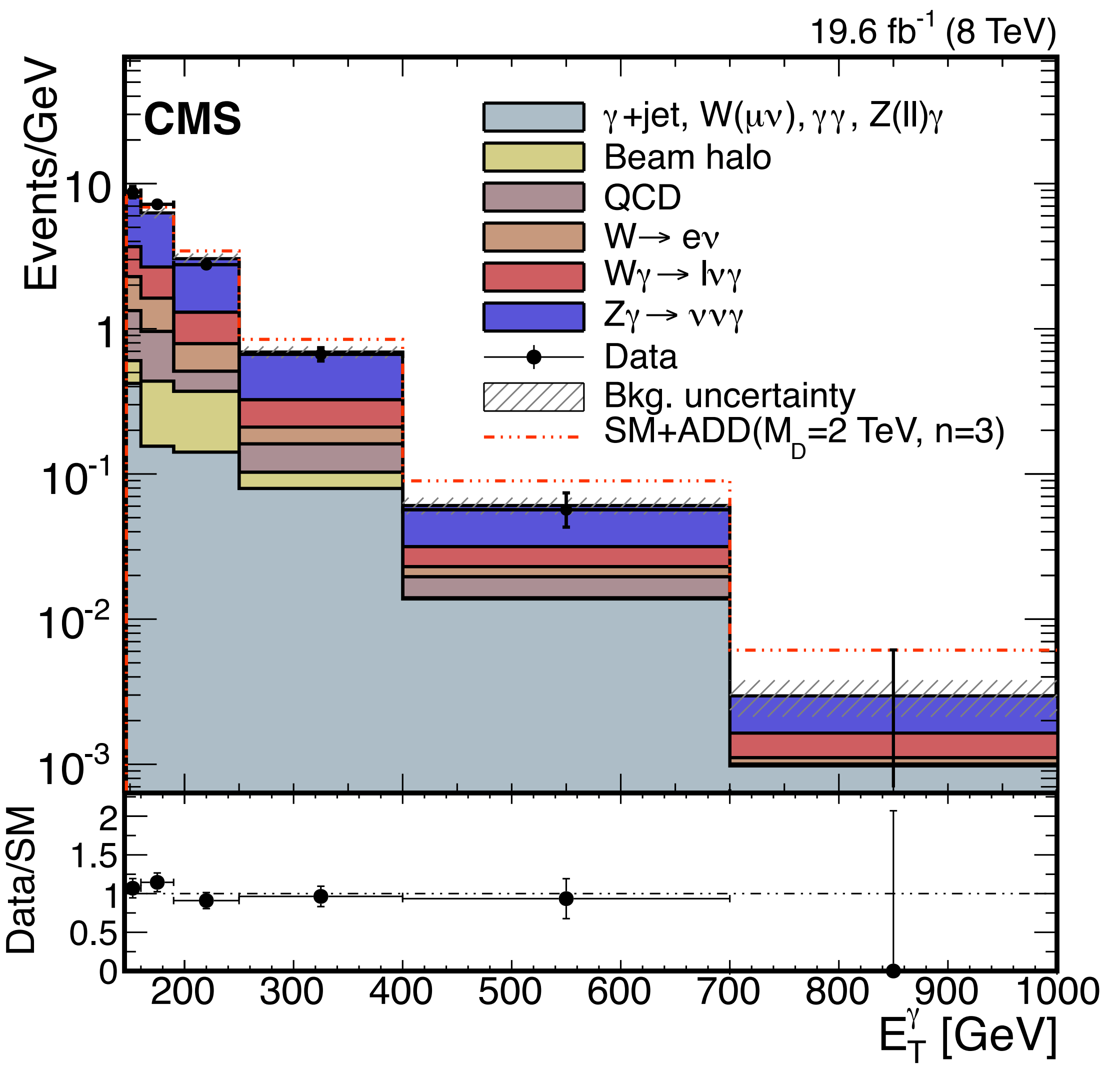


e channel



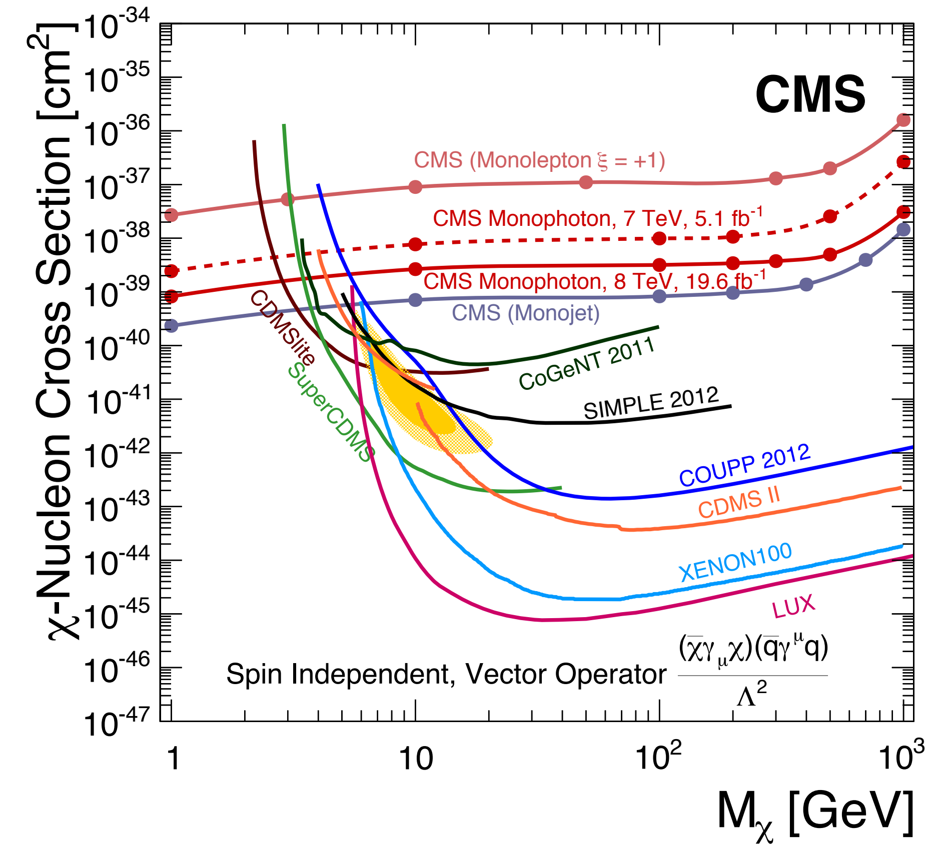


Monophoton (photon + MET)

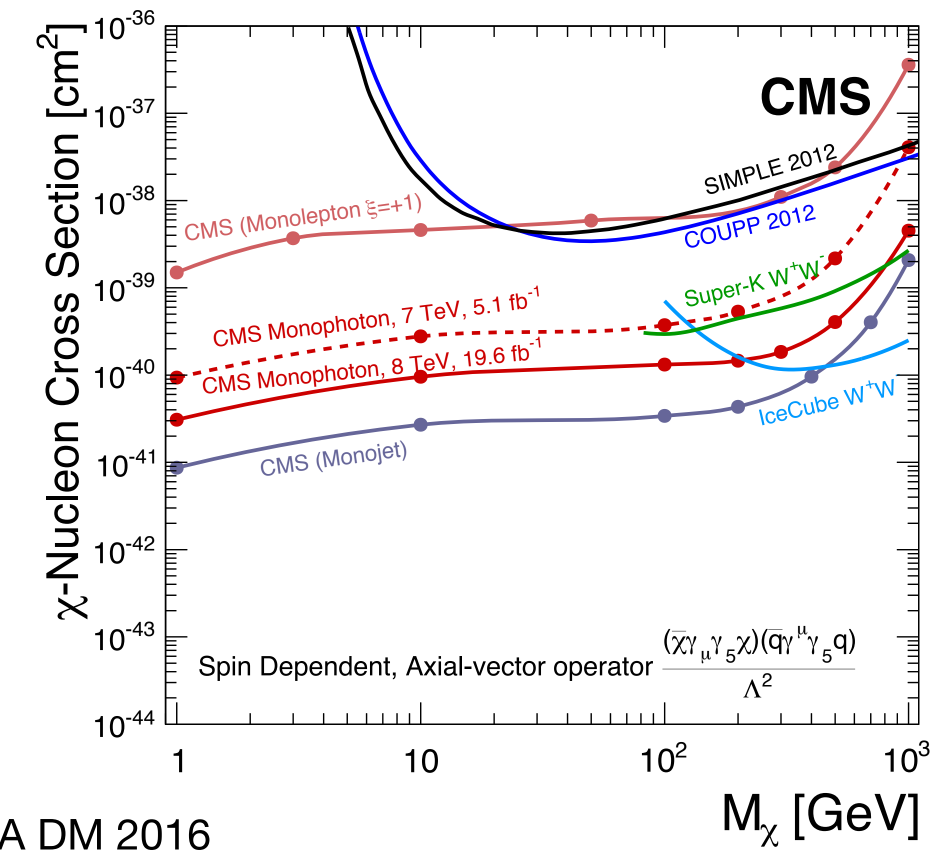


Process	Estimate
$Z(\to \nu\bar{\nu}) + \gamma$	345 ± 43
$W(\to \ell\nu) + \gamma$	103 ± 21
$W \to e\nu$	60 ± 6
jet $\to \gamma$ MisID	45 ± 14
Beam halo	25 ± 6
Others	36 ± 3
Total background	614 ± 63
Data	630

spin independent

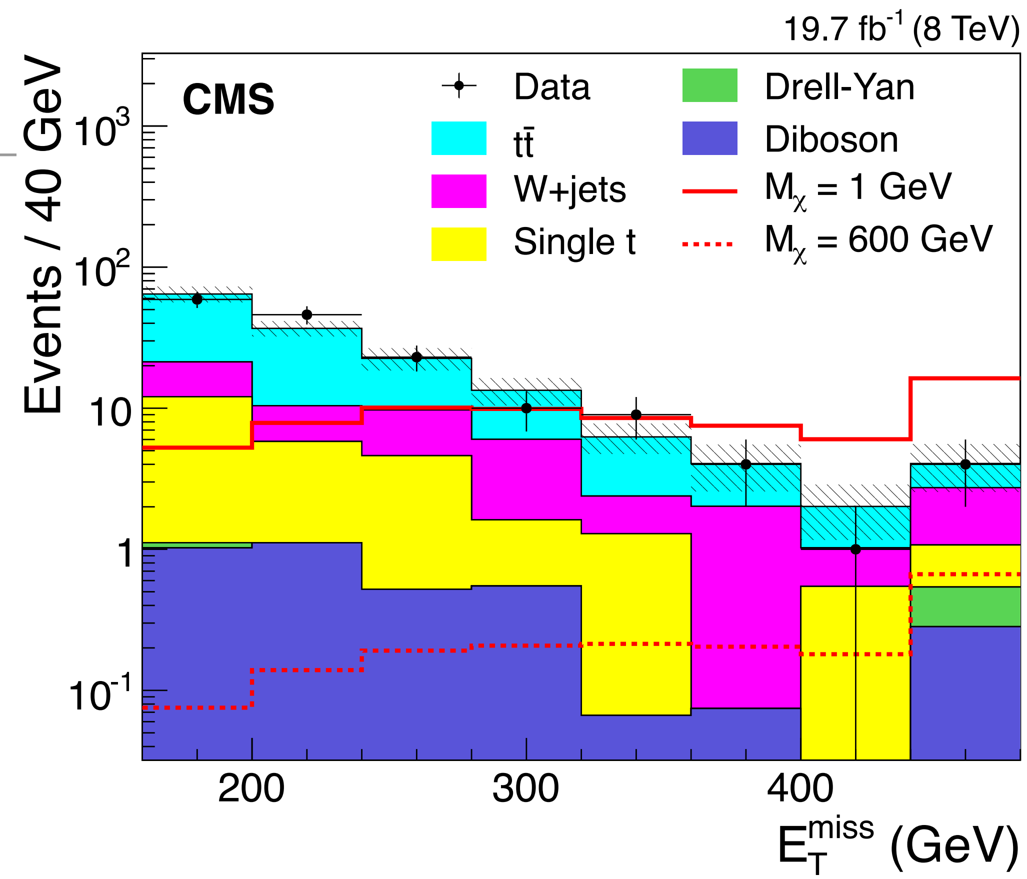


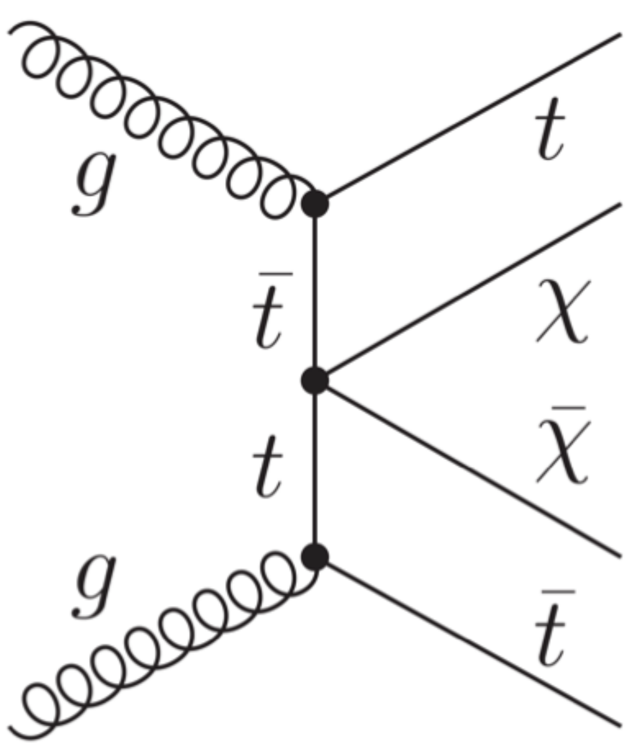
spin dependent

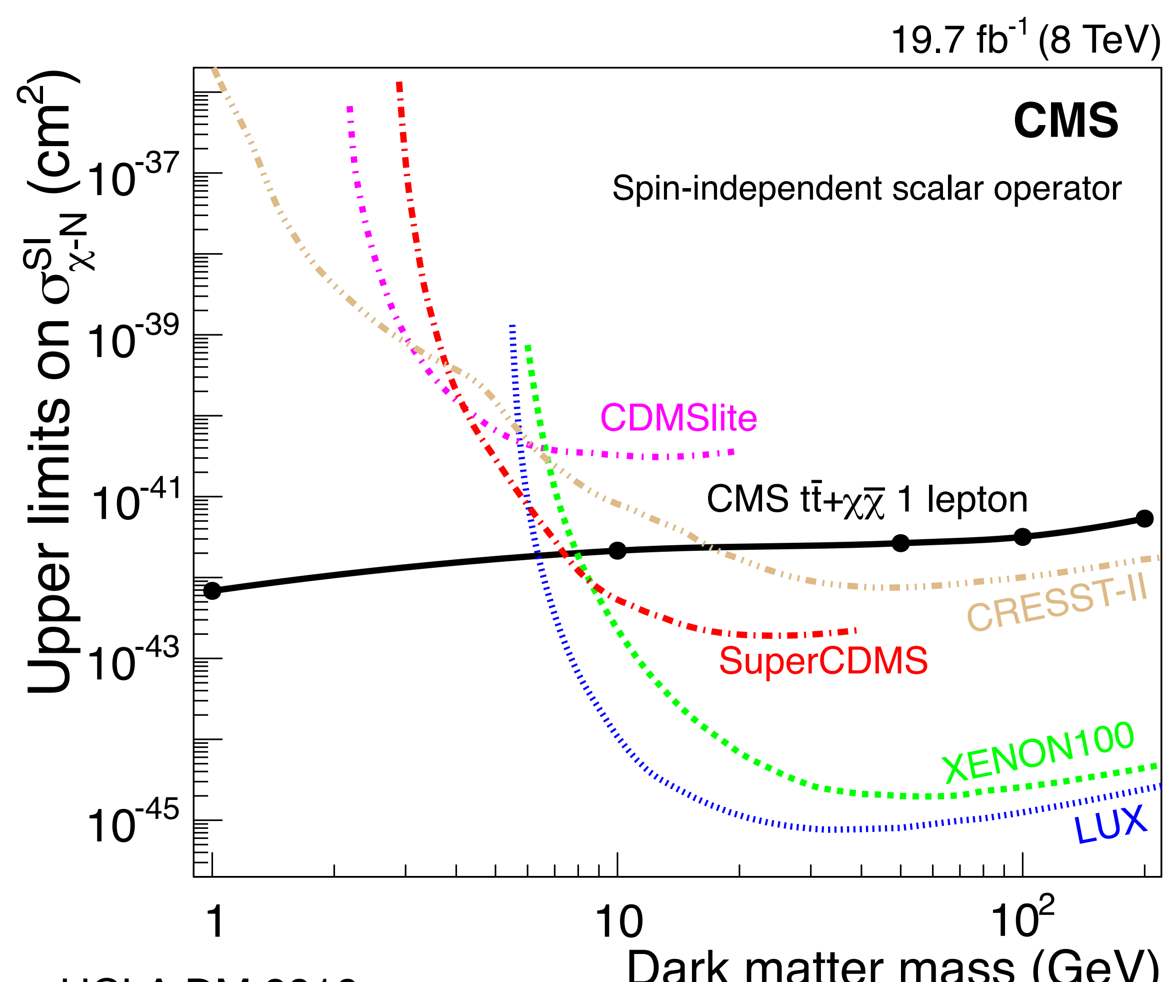


DM with top quarks

- Assume DM is Dirac fermion
- Coupling depends on mass of DM particle and interaction scale (M*)
- Couplings to 3rd generation quarks poorly constrained



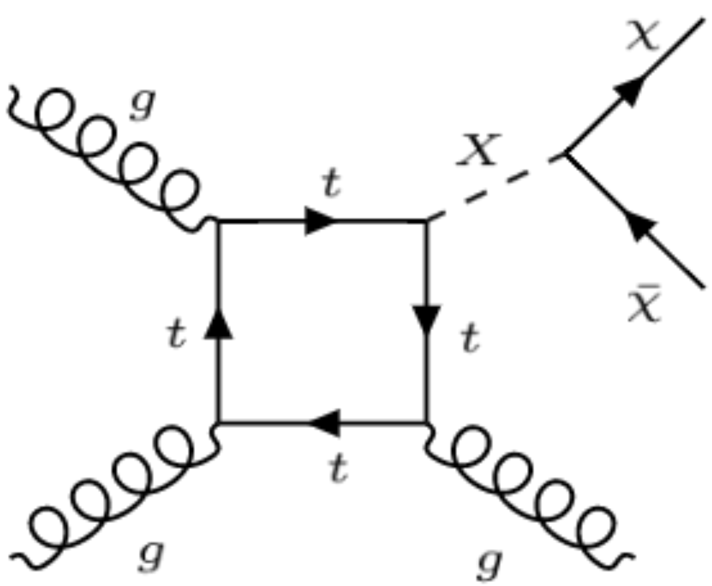


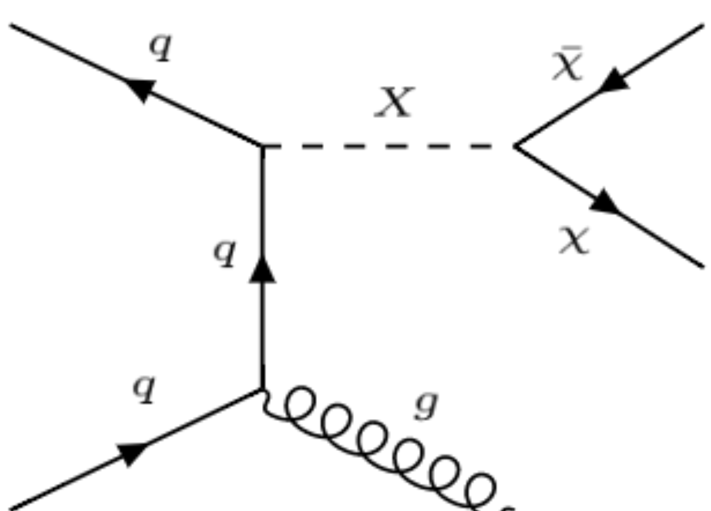


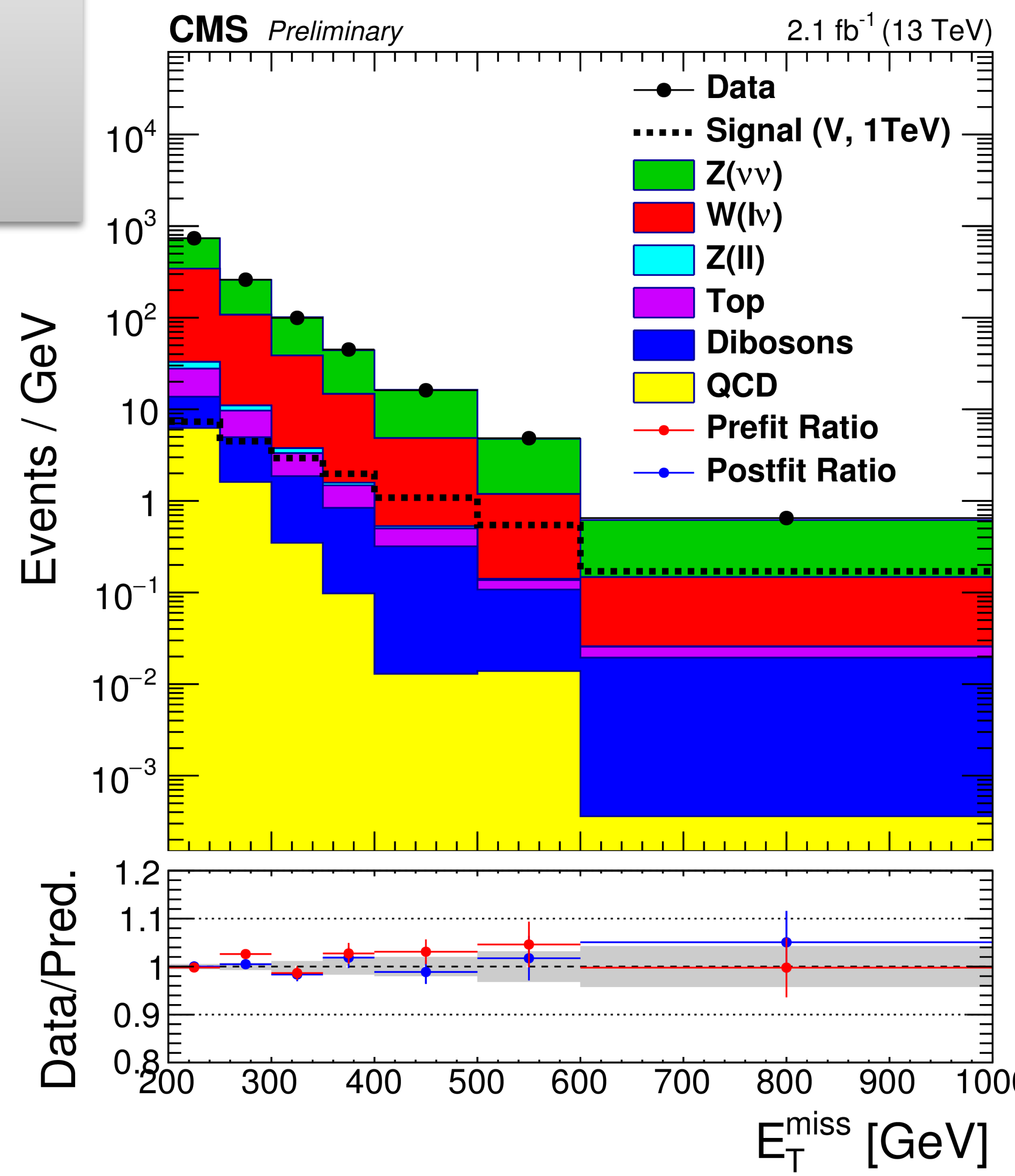
DM with Jets and MET

13 TeV

- Search for generic DM
- Monojets → Multijets expected from DM pairs
- arising from vector mediator X→ $\chi\chi$
- p_T(j)>100 GeV, MET > 200 GeV

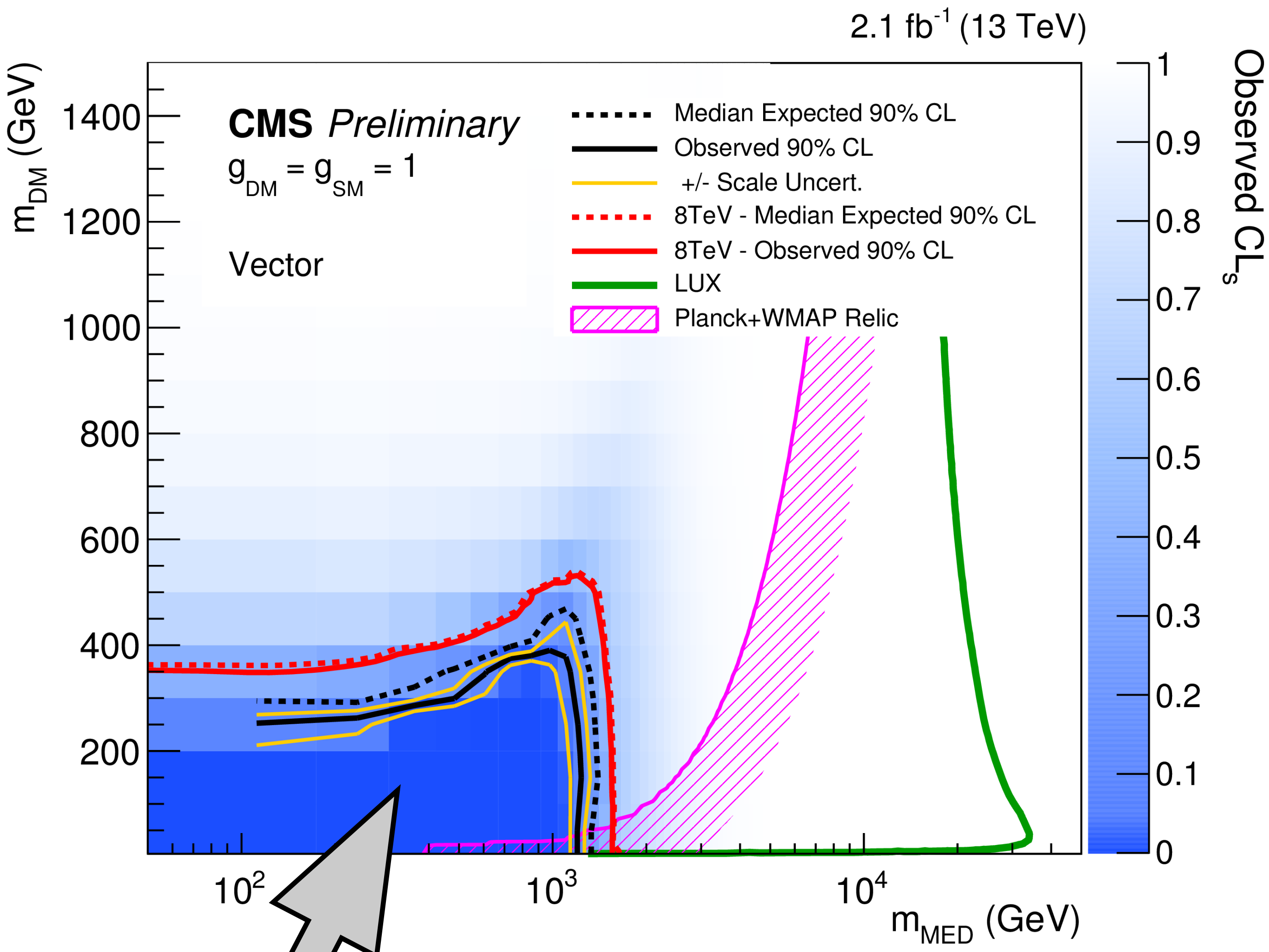




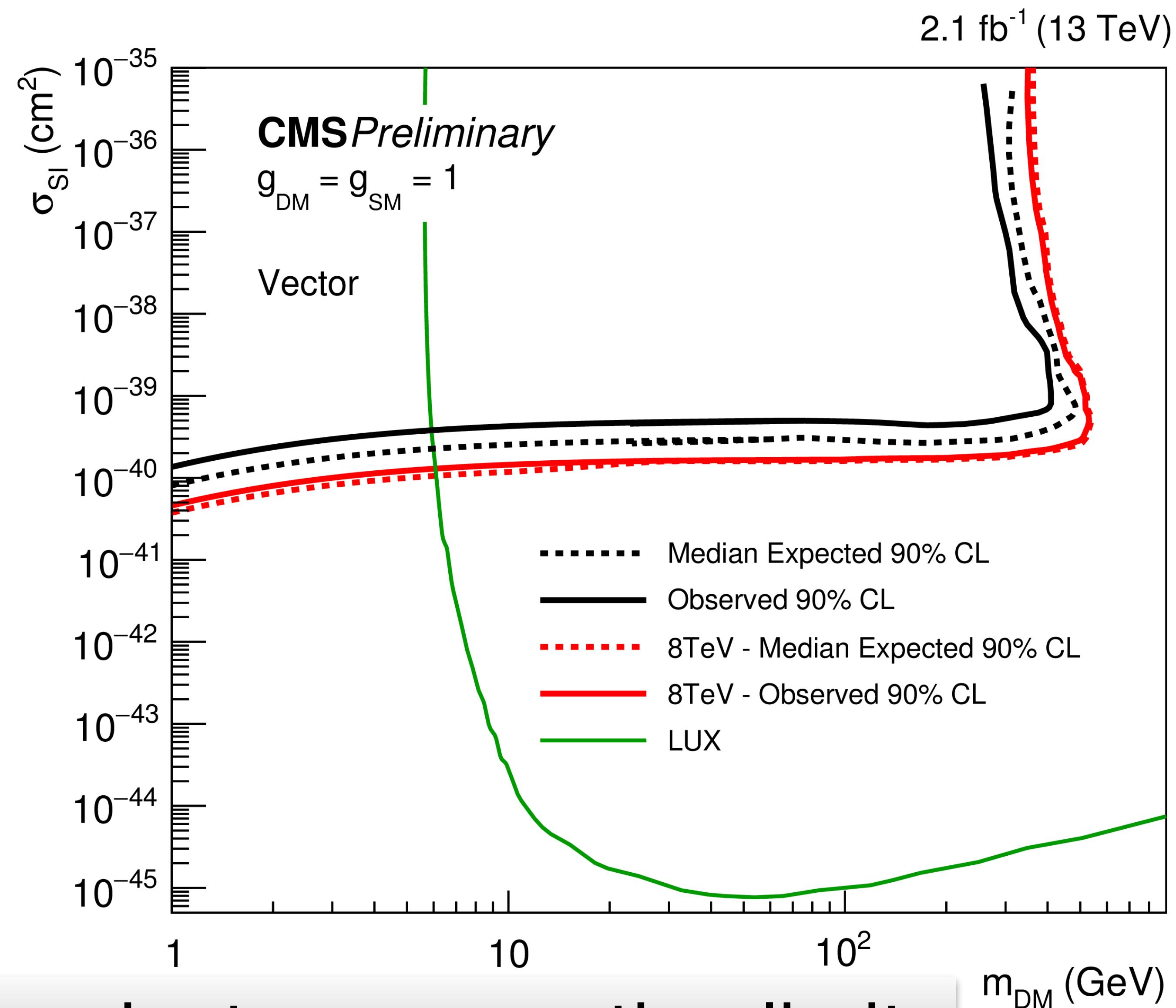


DM with Jets and MET

- m_{DM} vs m_{MED} mass plane



13 TeV

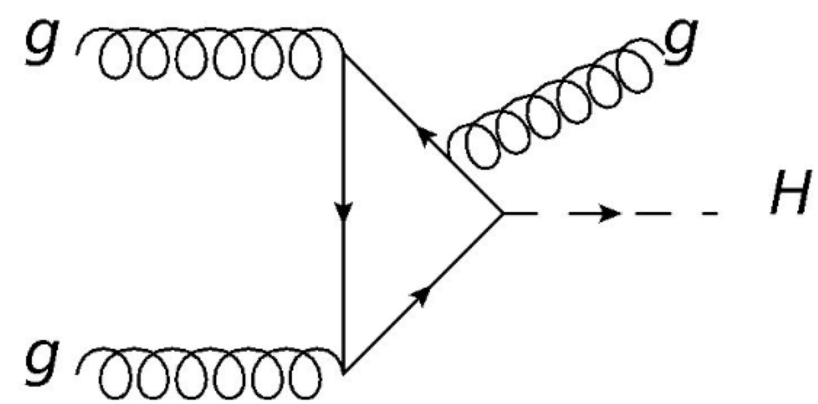


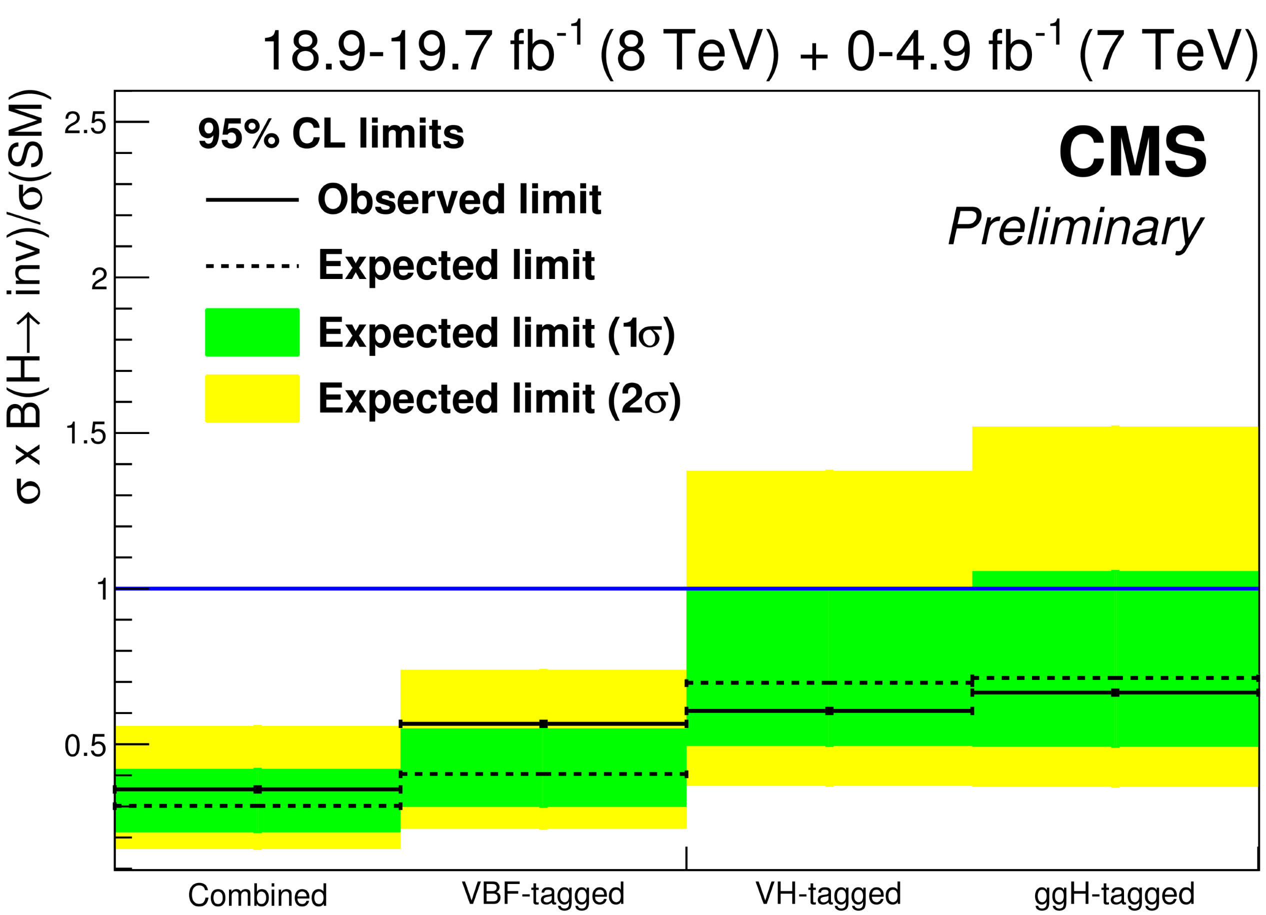
- Excluded !
- Approaching Run 1 sensitivity

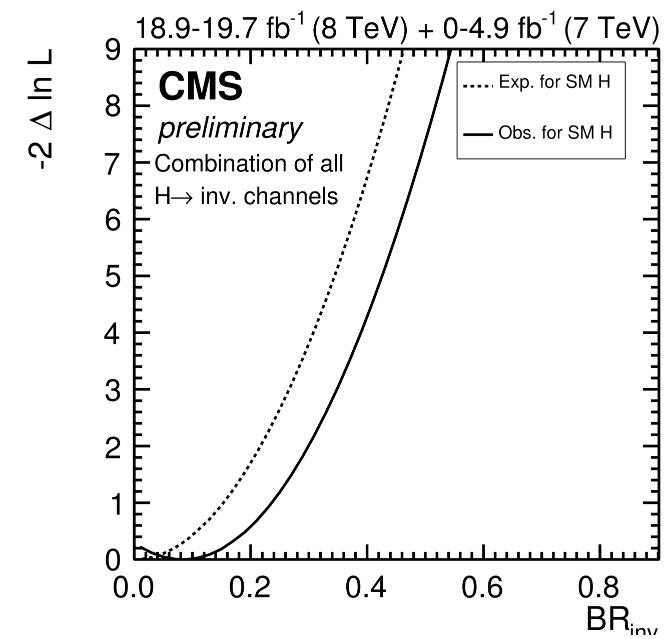
- spin-independent cross section limits

Invisible Higgs Decays in Run 1

- Invisible = χ, graviscalars, etc.
  - not visible, exotic…
- Combine 3 different H production channels: ggH, VBF, VH





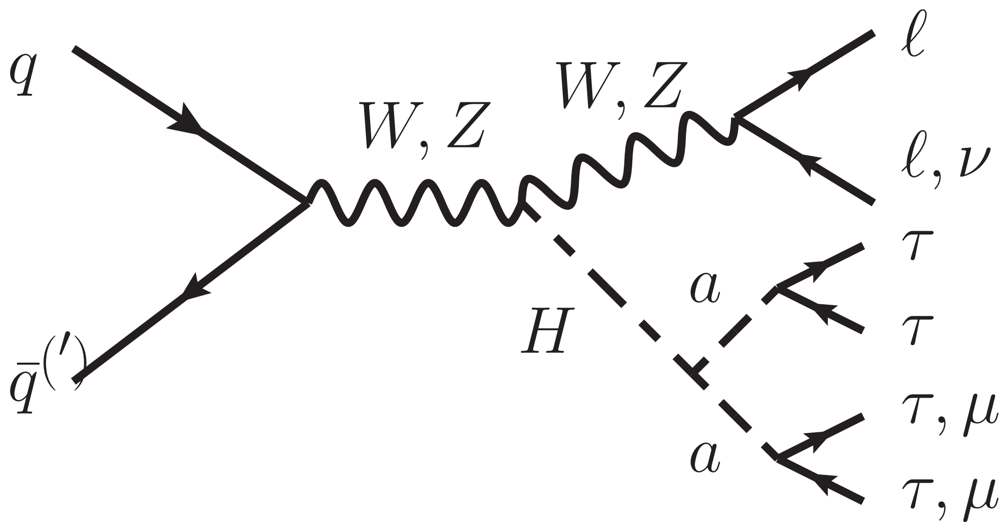


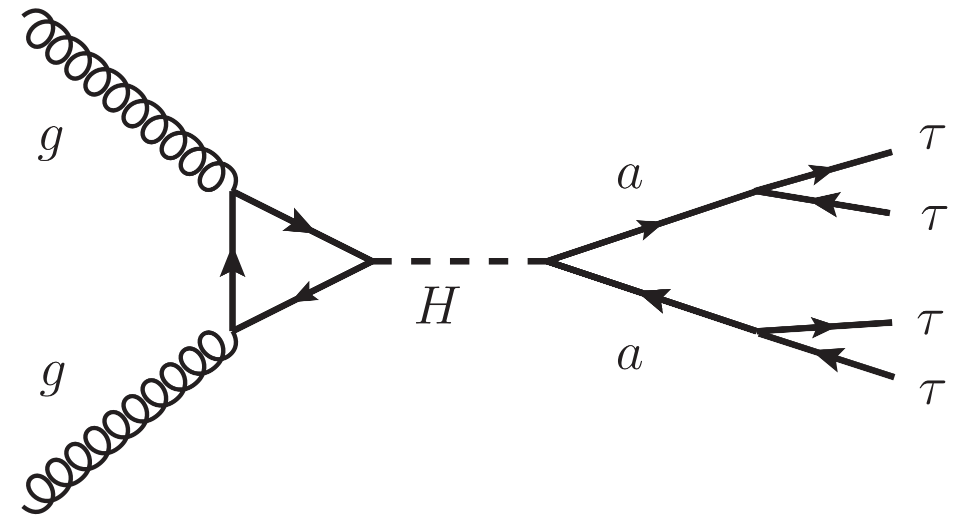
Channel	Observed (expected) upper limits on $\frac{\sigma}{\sigma_{SM}} \cdot \mathcal{B}(\mathrm{H} \to \mathrm{inv})(\%)$
VBF-tagged	57 (40)
VH-tagged	60 (69)
ggH-tagged	67 (71)
Combined	36 (30)

- Combined Result: 36% (obs) 30% (expected)

Searches for additional Higgs bosons

Search for light pseudoscalar Higgs bosons



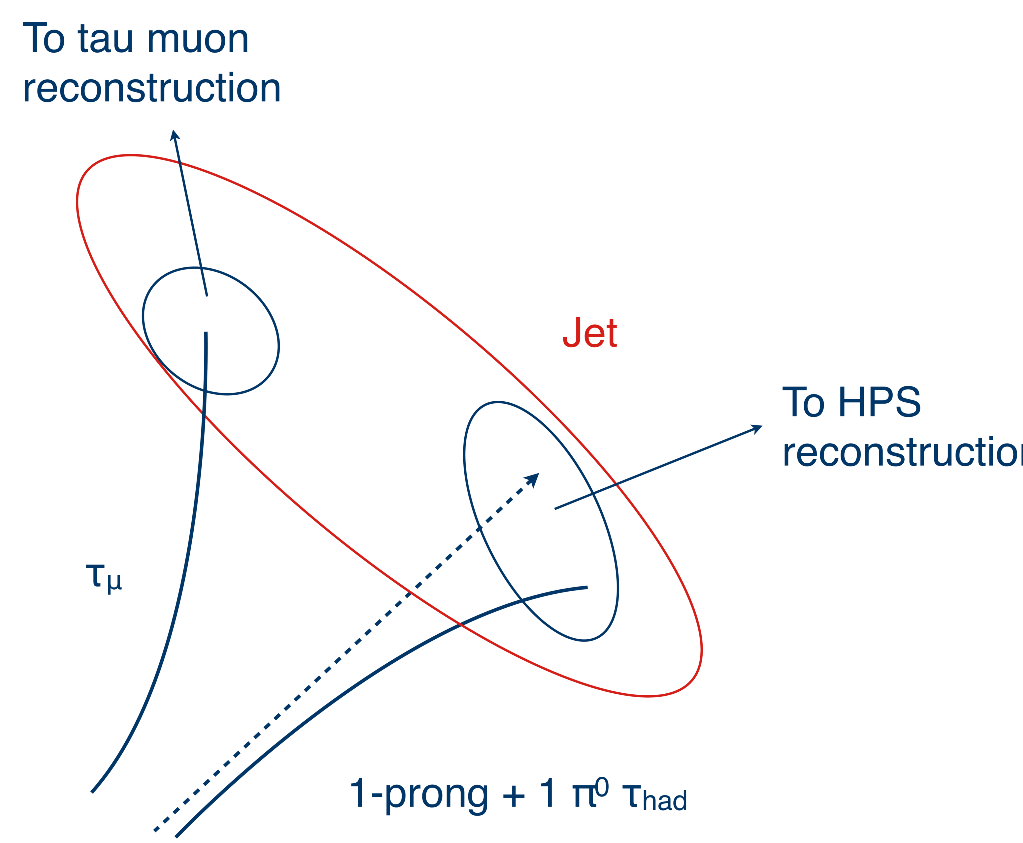


H(125) →*aa* →4τ

5 < m_a < 15 GeV

Thus, boosted *a*, overlapping τ

- **→ modify standard hadronic τ id**

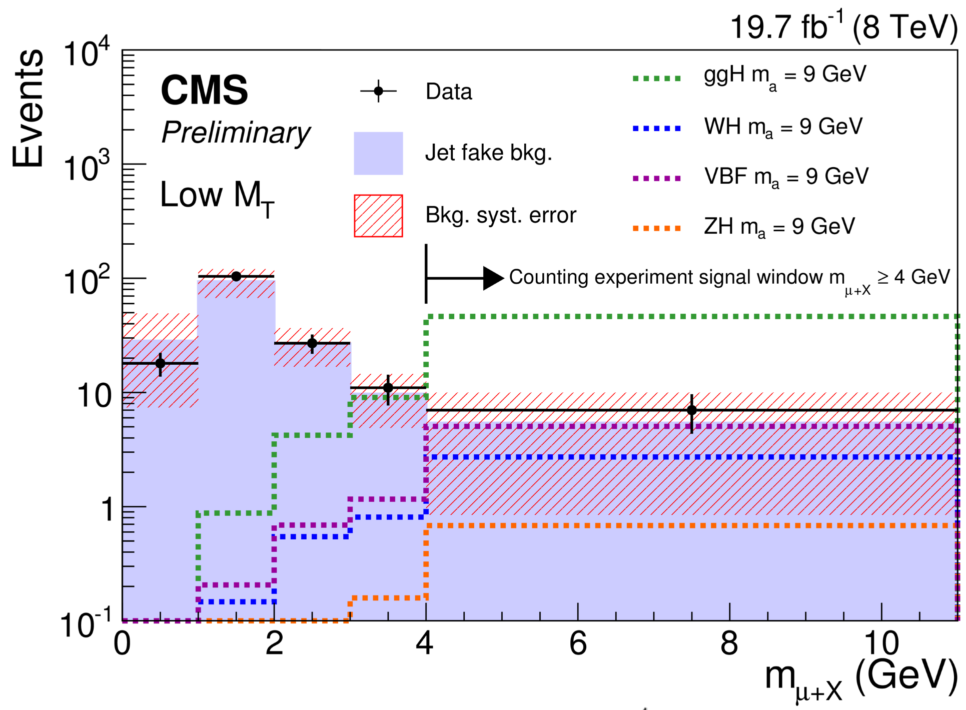


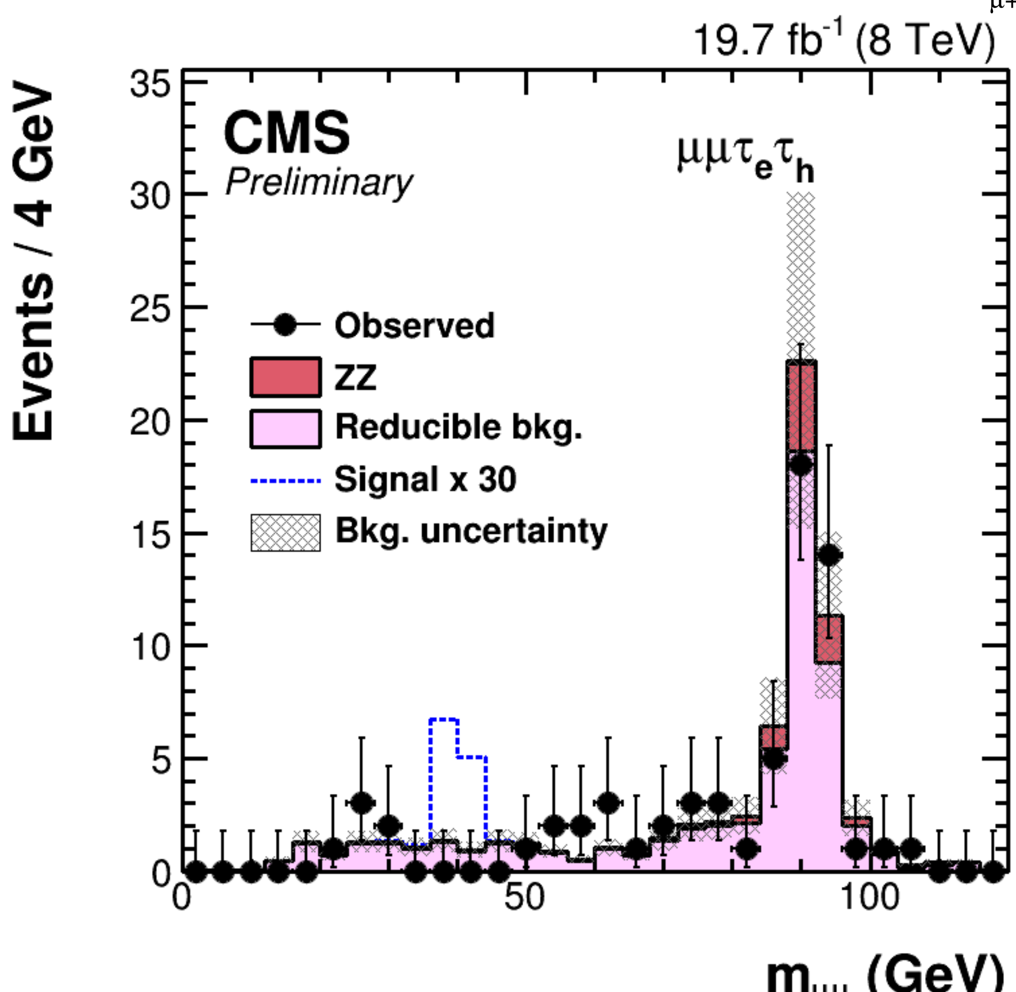
H(125) →*aa* →2τ2μ

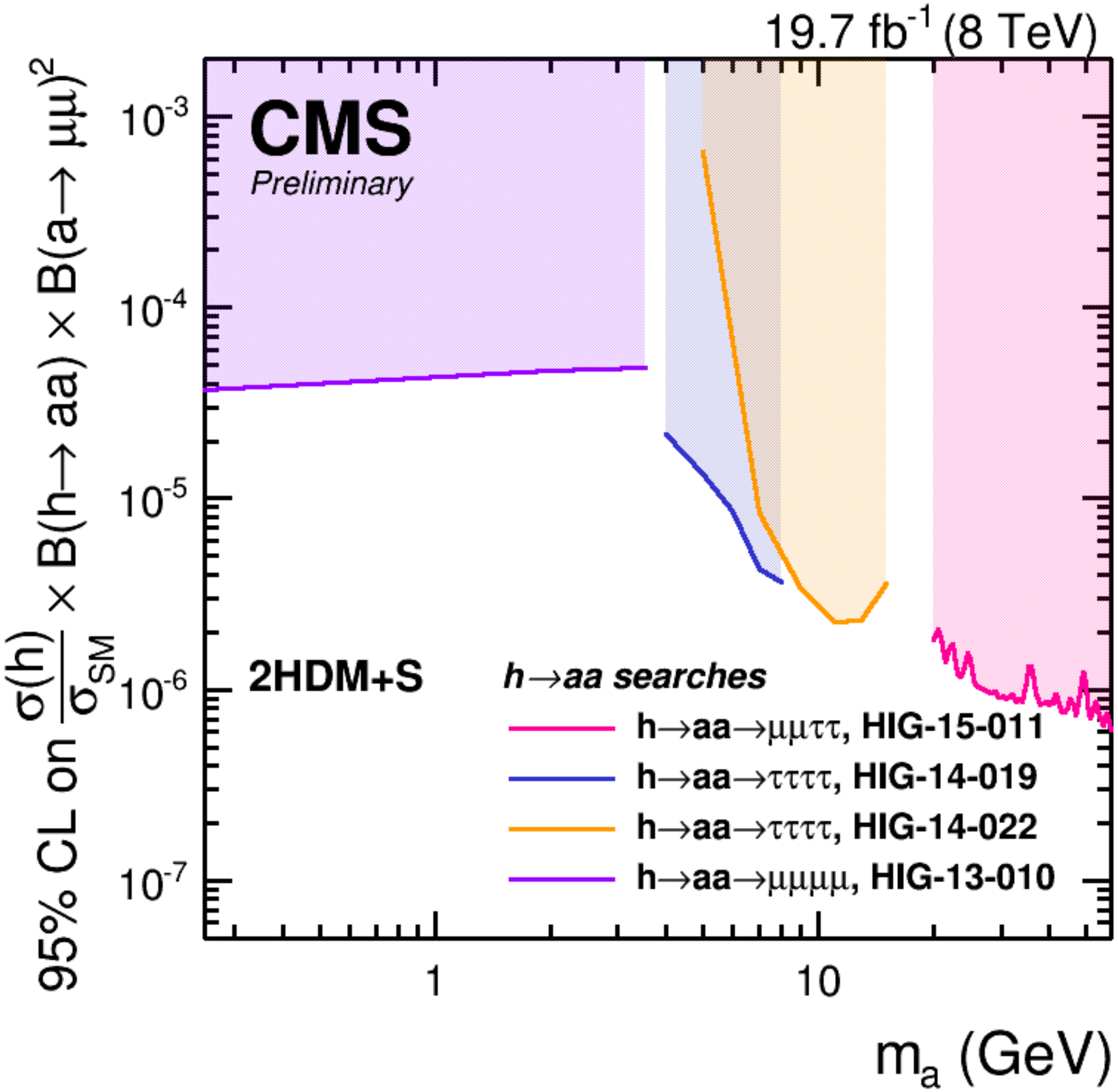
20 < m_a < 62.5 GeV

no appreciable boost

Search for light pseudoscalar Higgs bosons

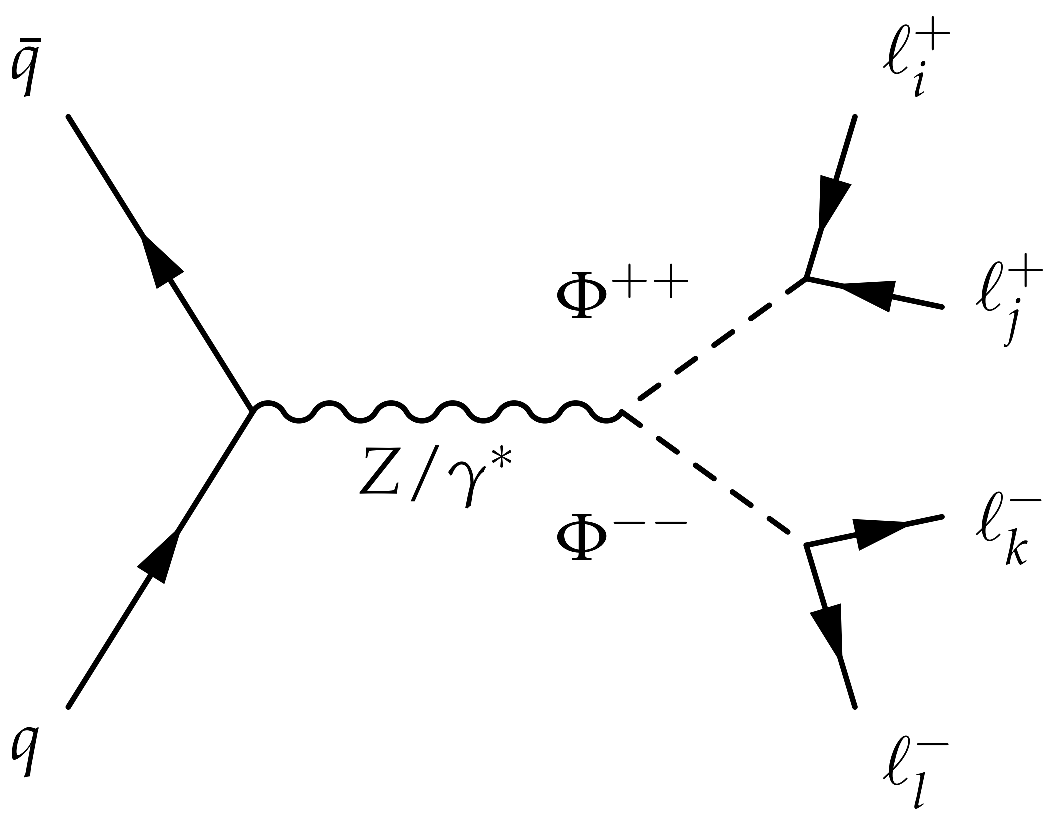


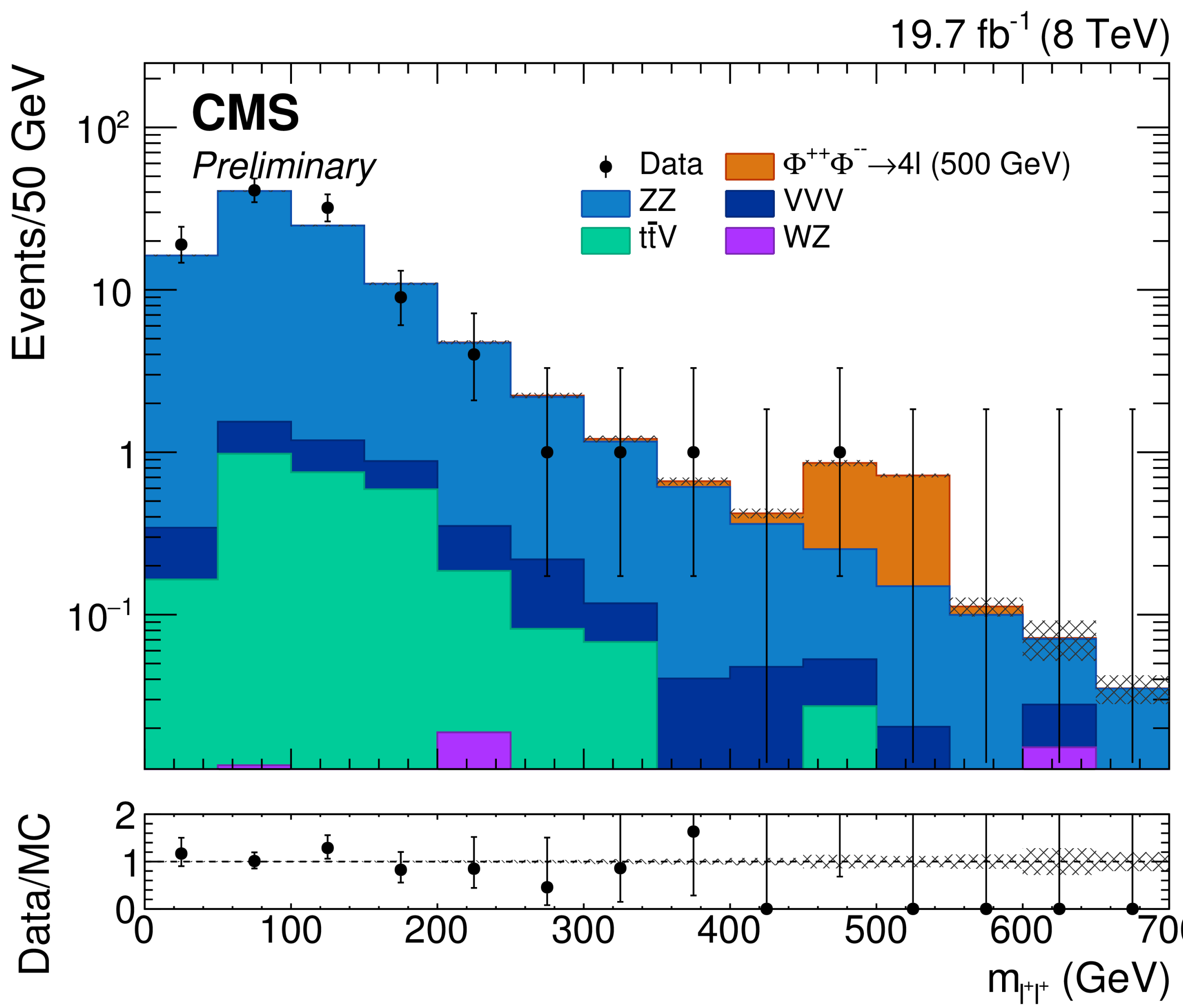




Doubly-charged Higgs

- Minimal see-saw model to explain ν masses
  - includes scalar triplet: Φ^{++}, Φ^{+}, Φ^{0}
  - search: 3 or 4 leptons with p_T > 20 GeV

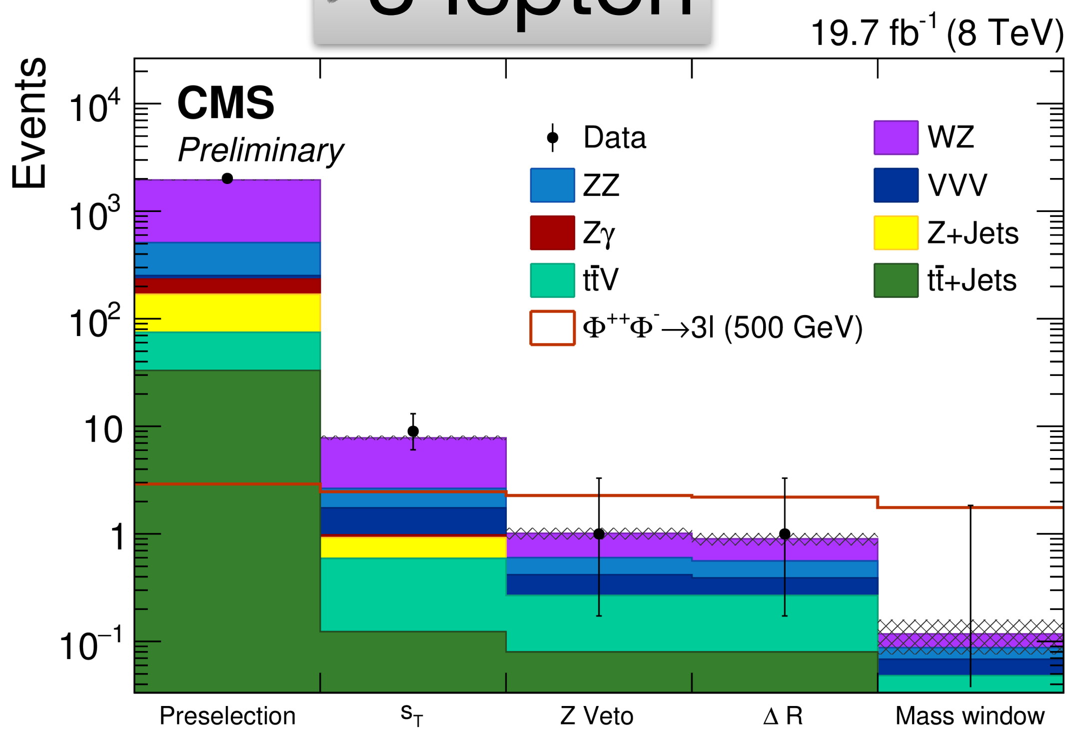




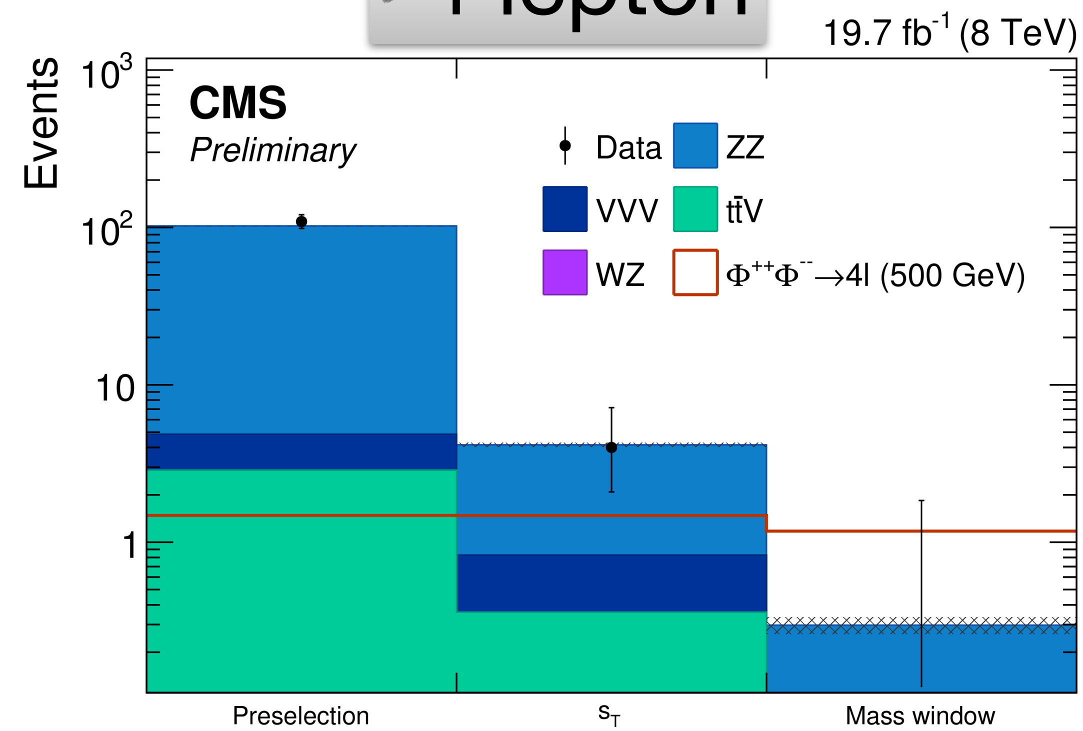
- LS dilepton mass

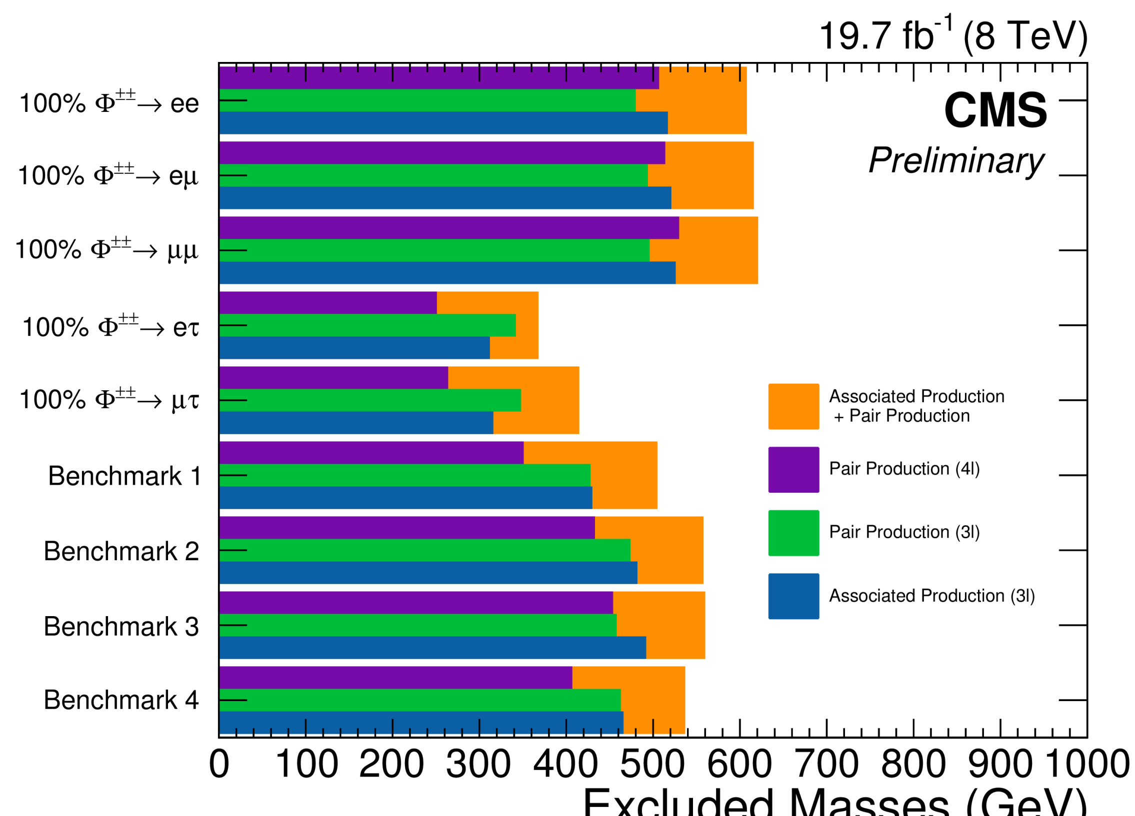
Doubly-charged Higgs

3 lepton



4 lepton

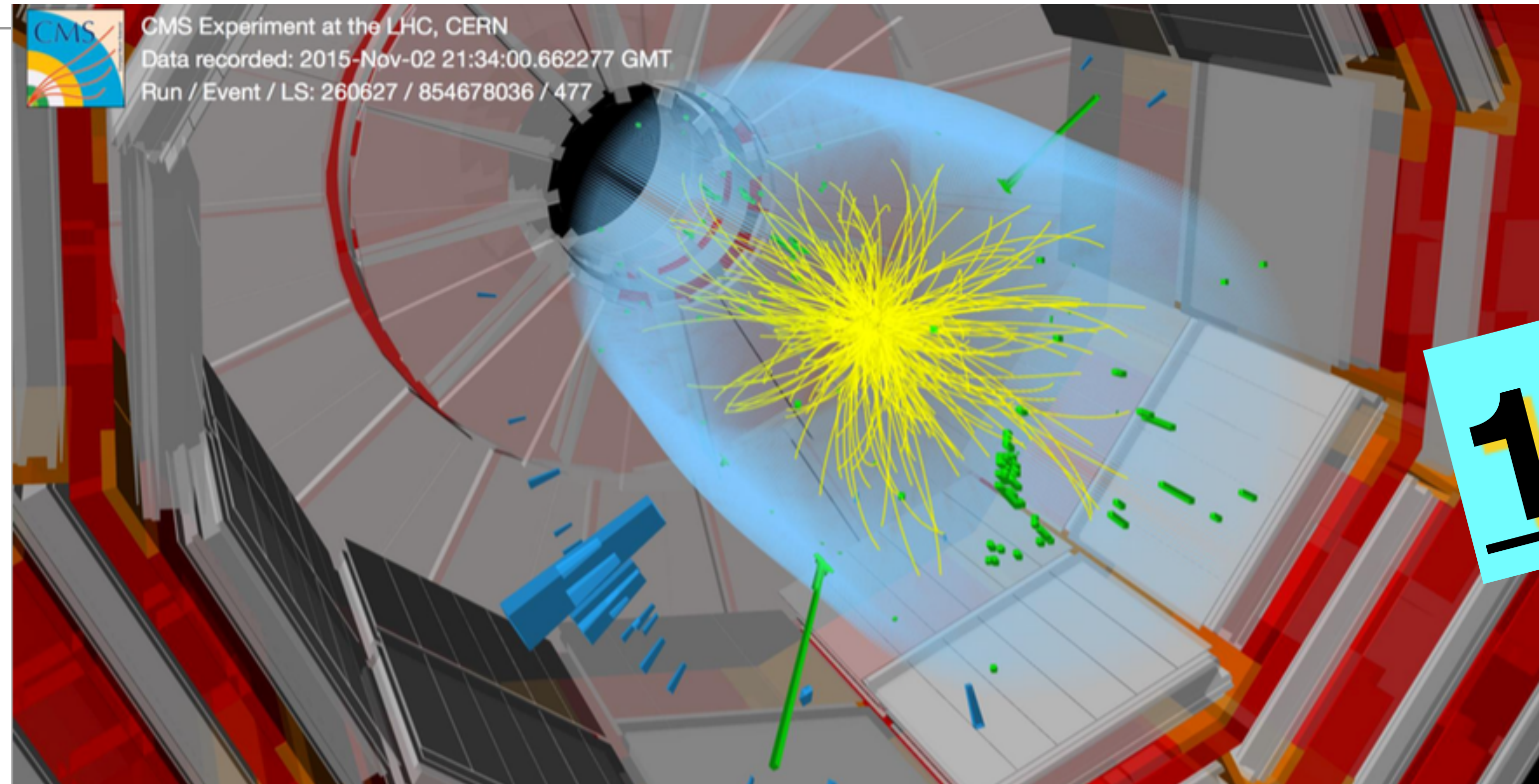




Searches for resonances

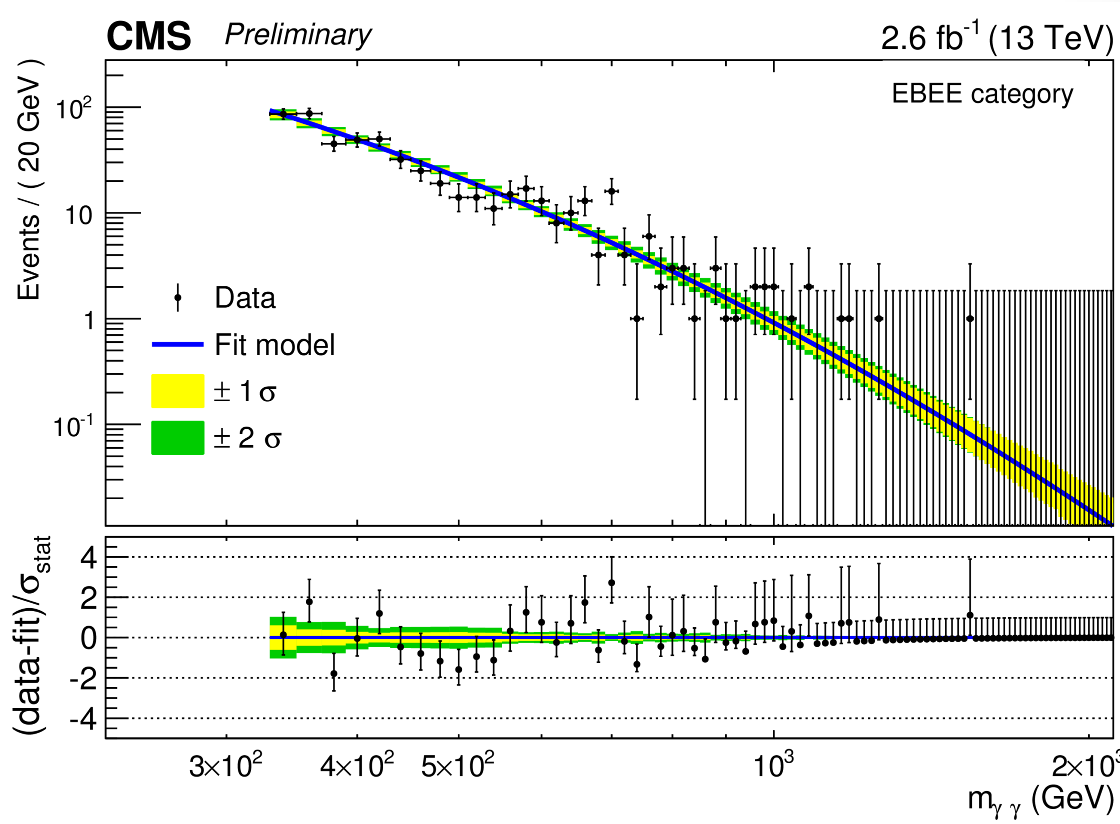
CMS-PAS-EXO-15-004

Diphoton Resonances



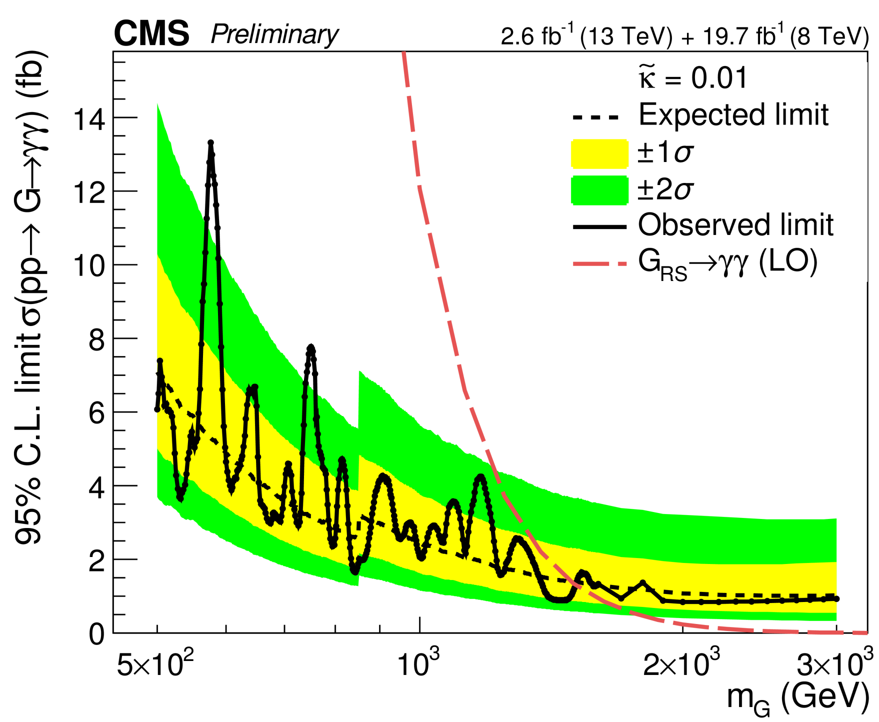
13 TeV

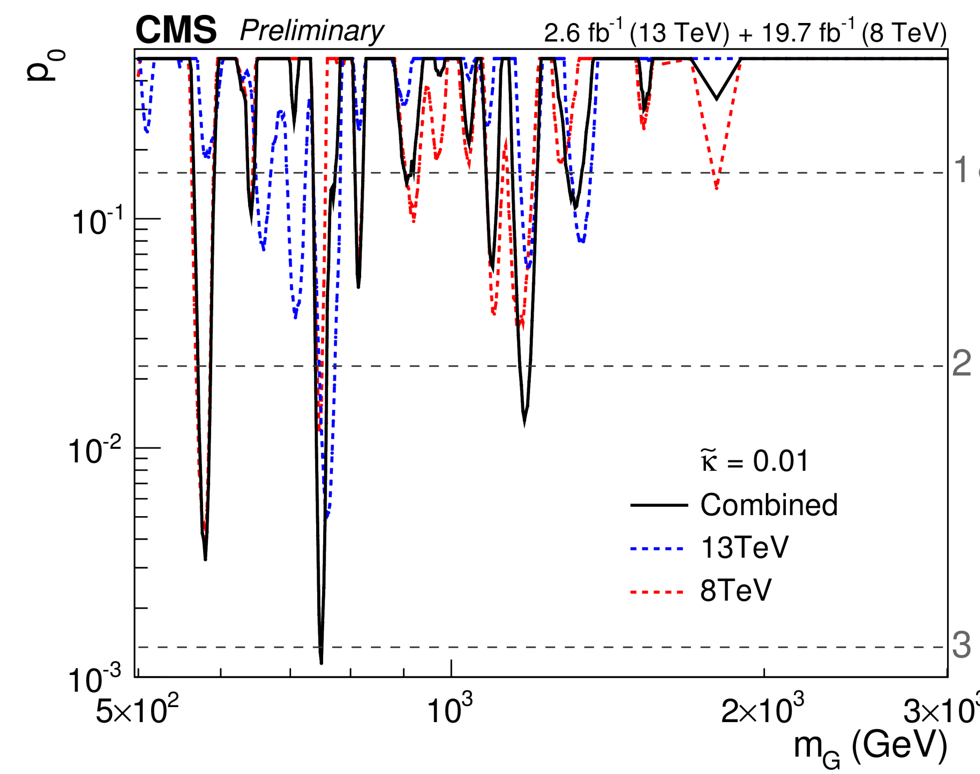
Diphoton event with m(γγ) = 745 GeV

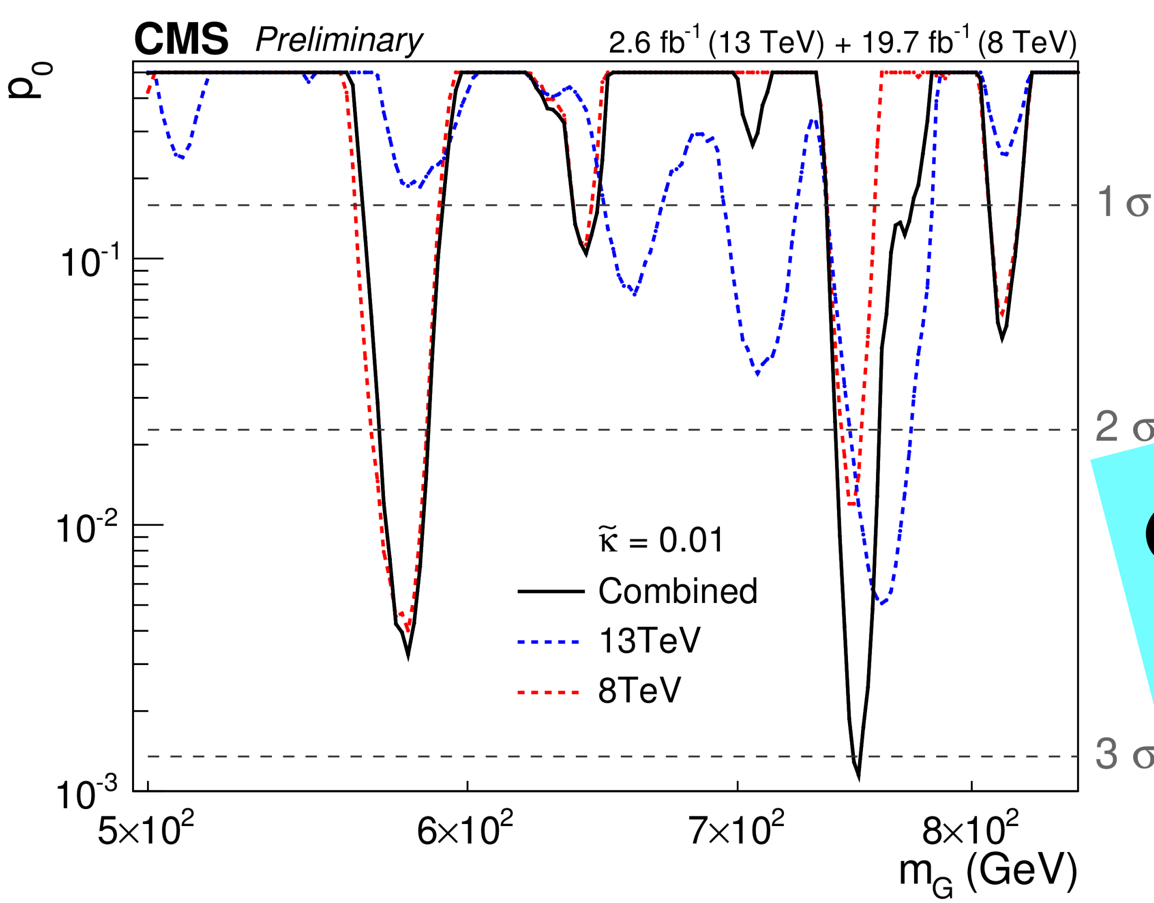


- Barrel + Endcap spectrum

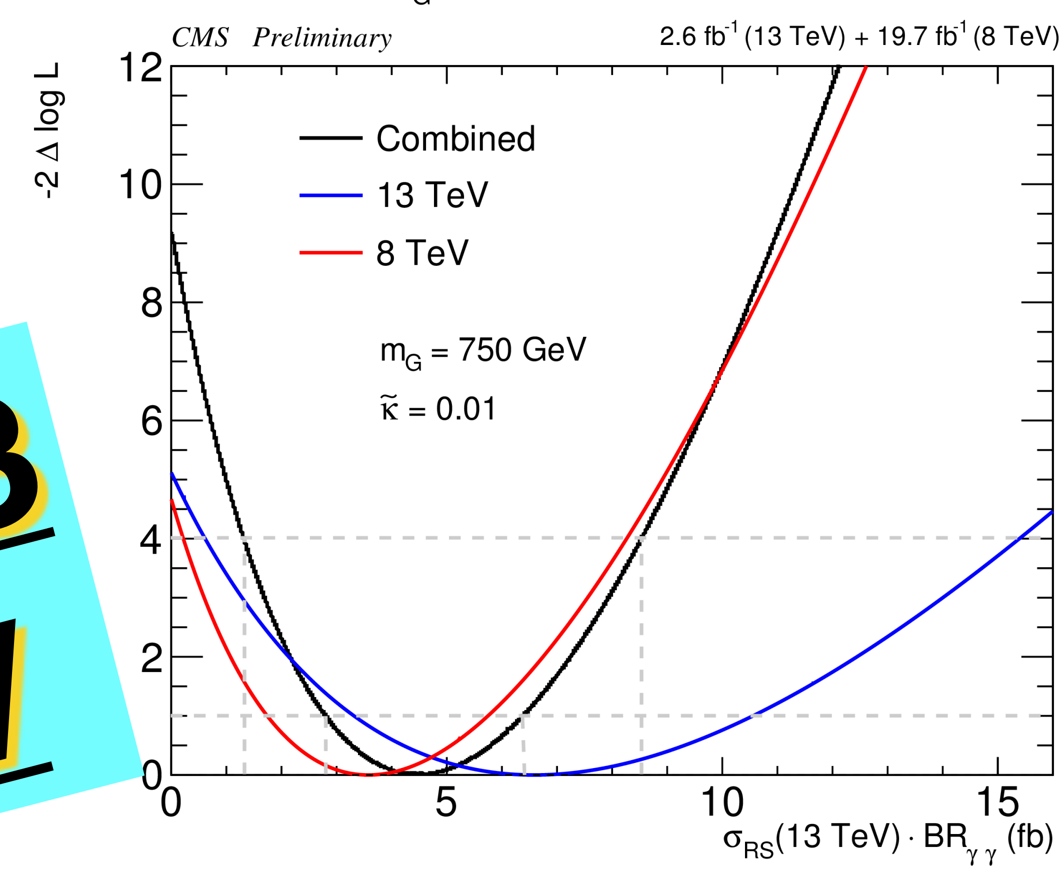
Diphoton Resonances: 8+13 TeV combination







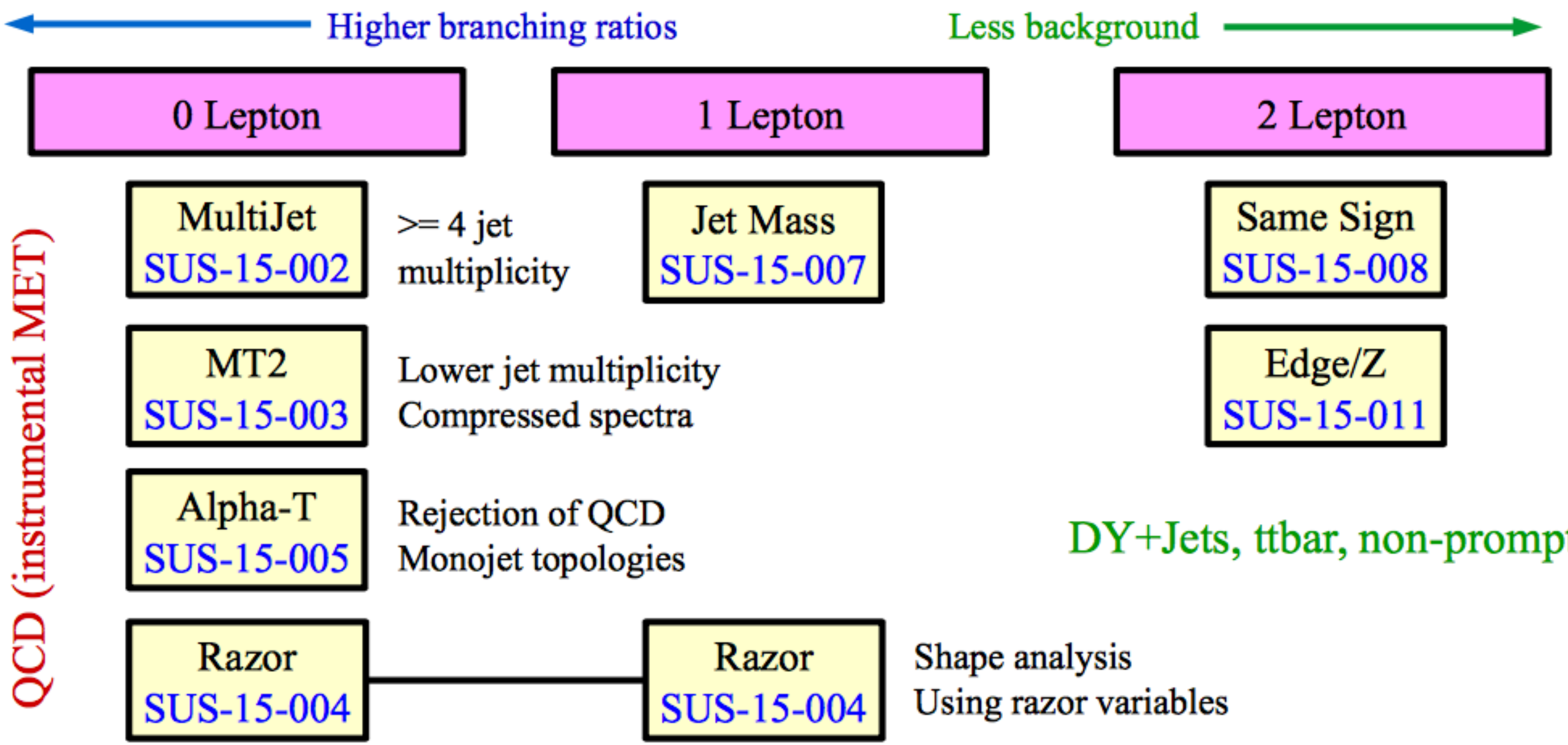
8&13 TeV



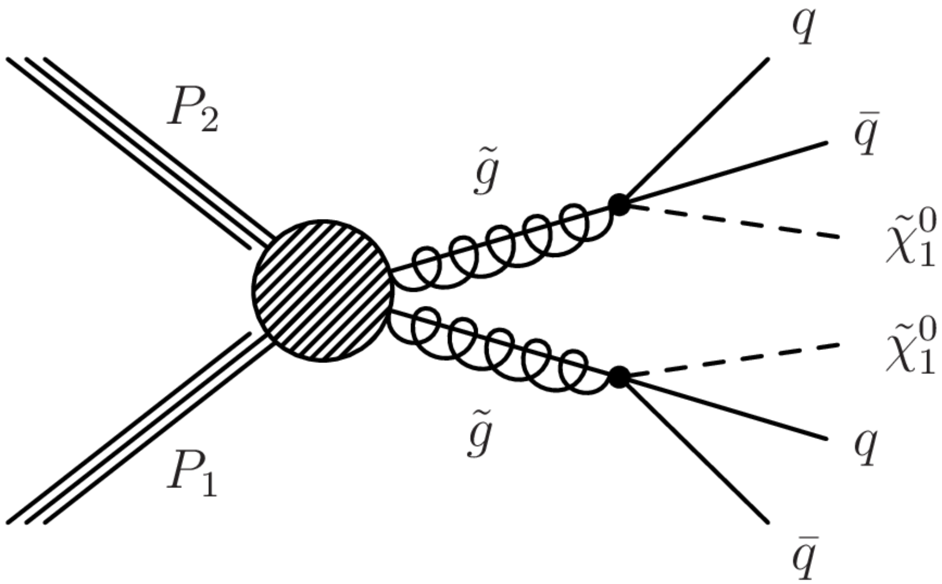
Searches for Supersymmetry

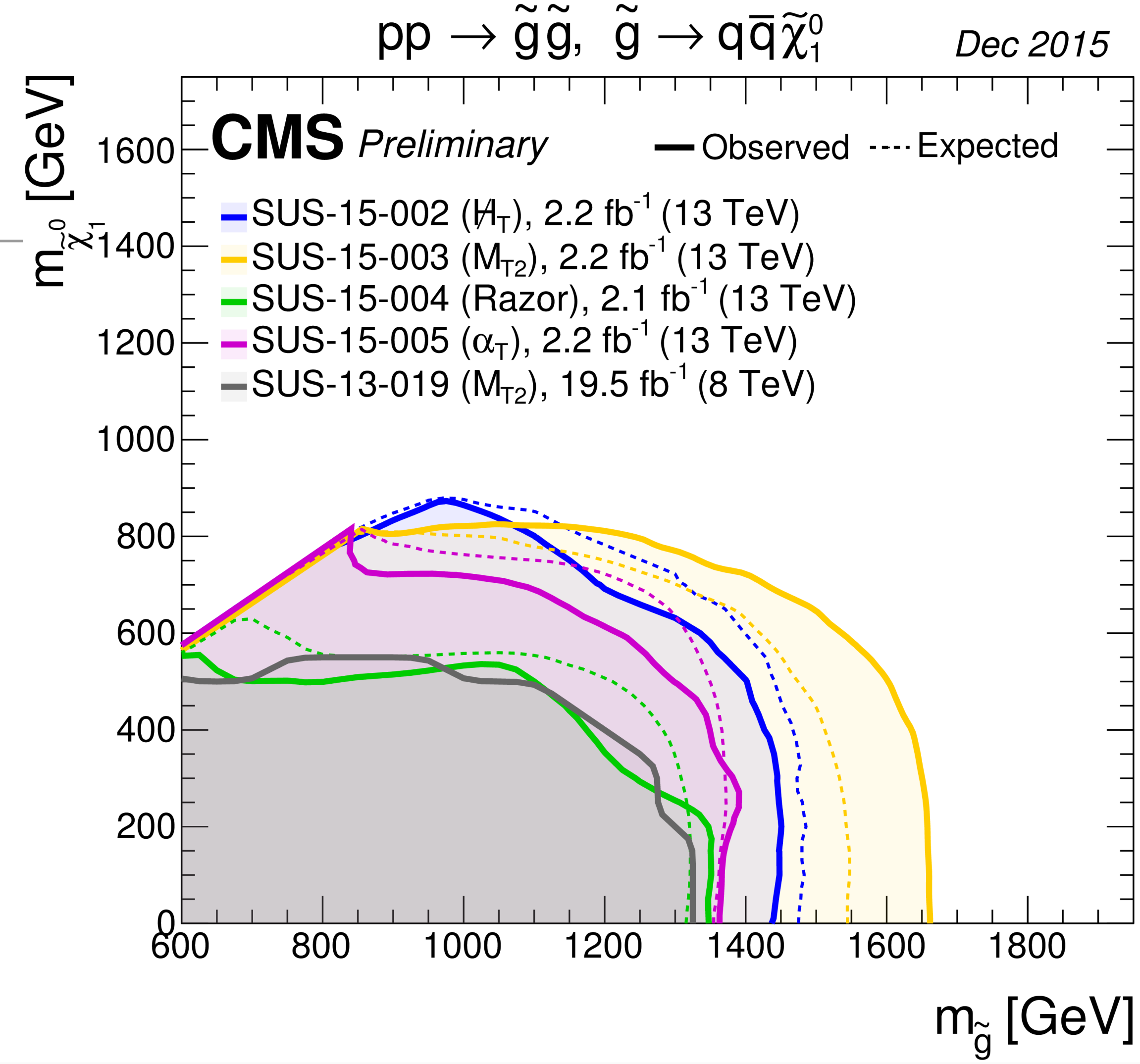
SUSY searches at 13 TeV

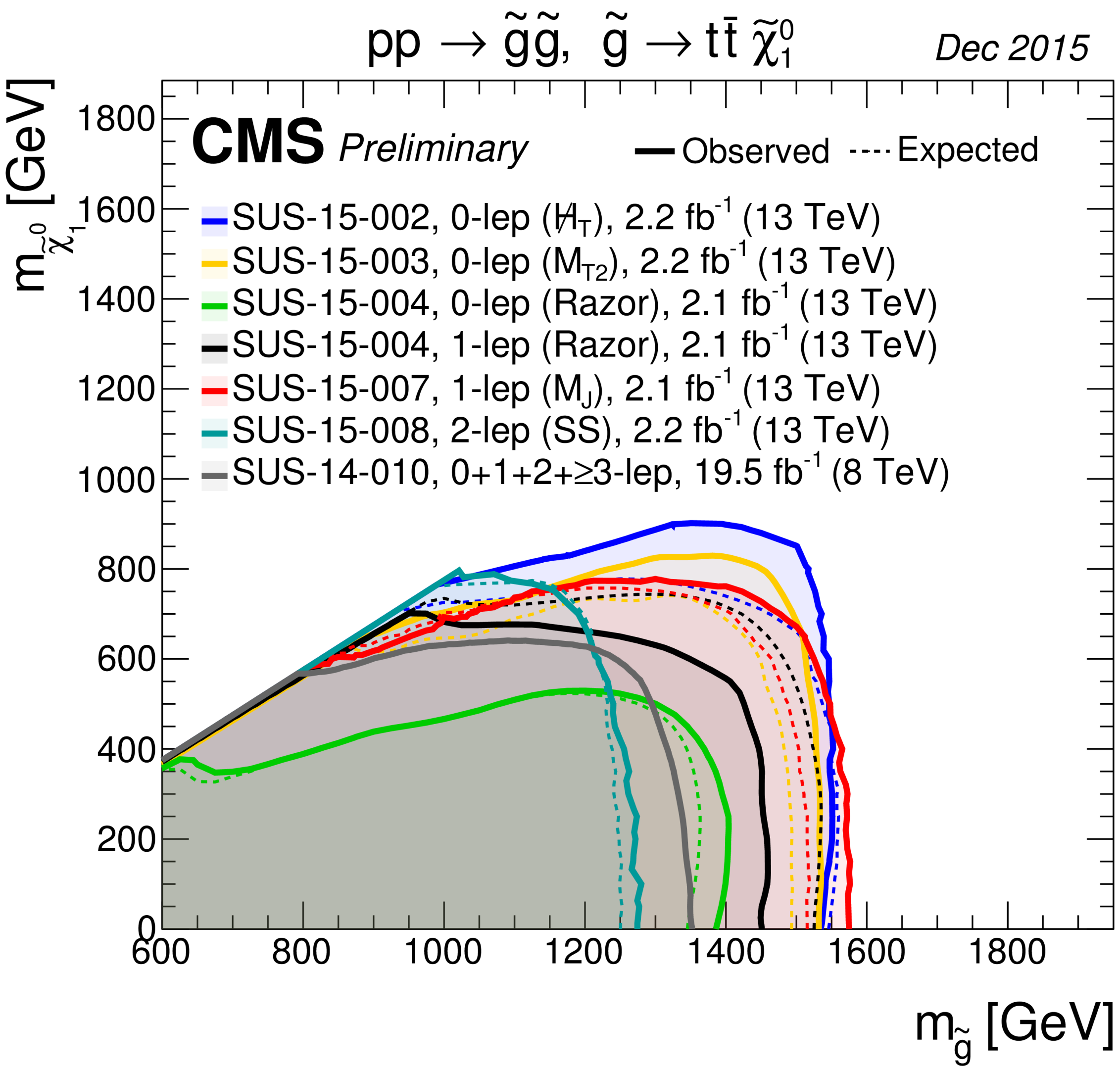
- Focus (so far) on gluino pair production with 2015 data



Gluinos in Run II





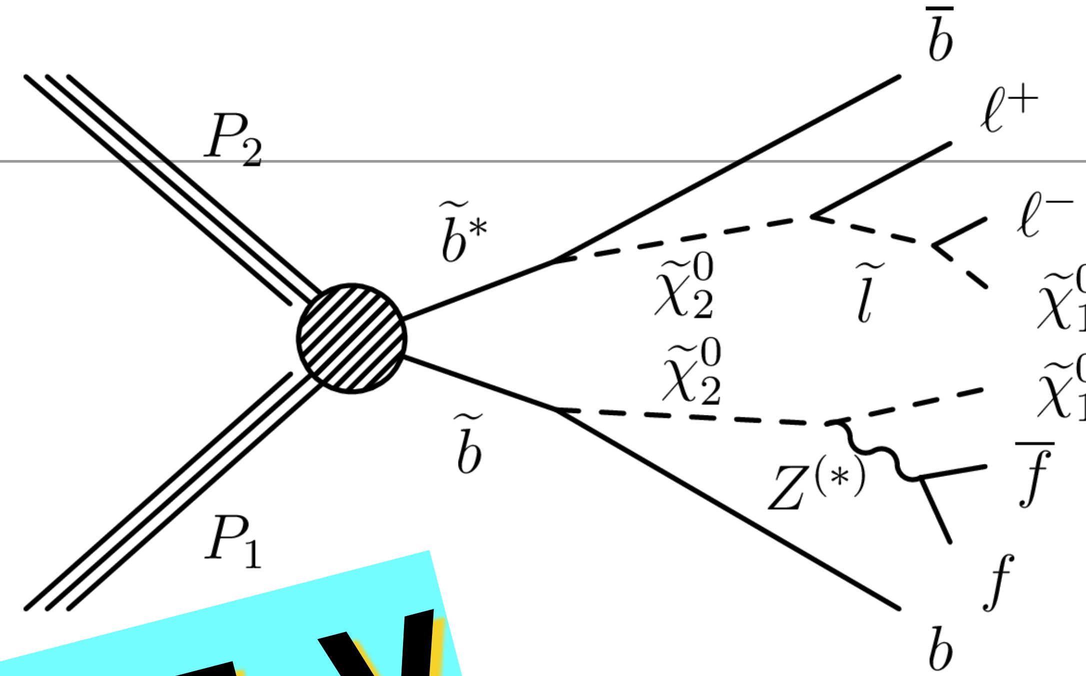


- CMS-PAS-SUS-[002 - 005]
- Using optimized kinematic variables
- Gluino mass limits already 100-400 GeV higher than Run 1 with full data

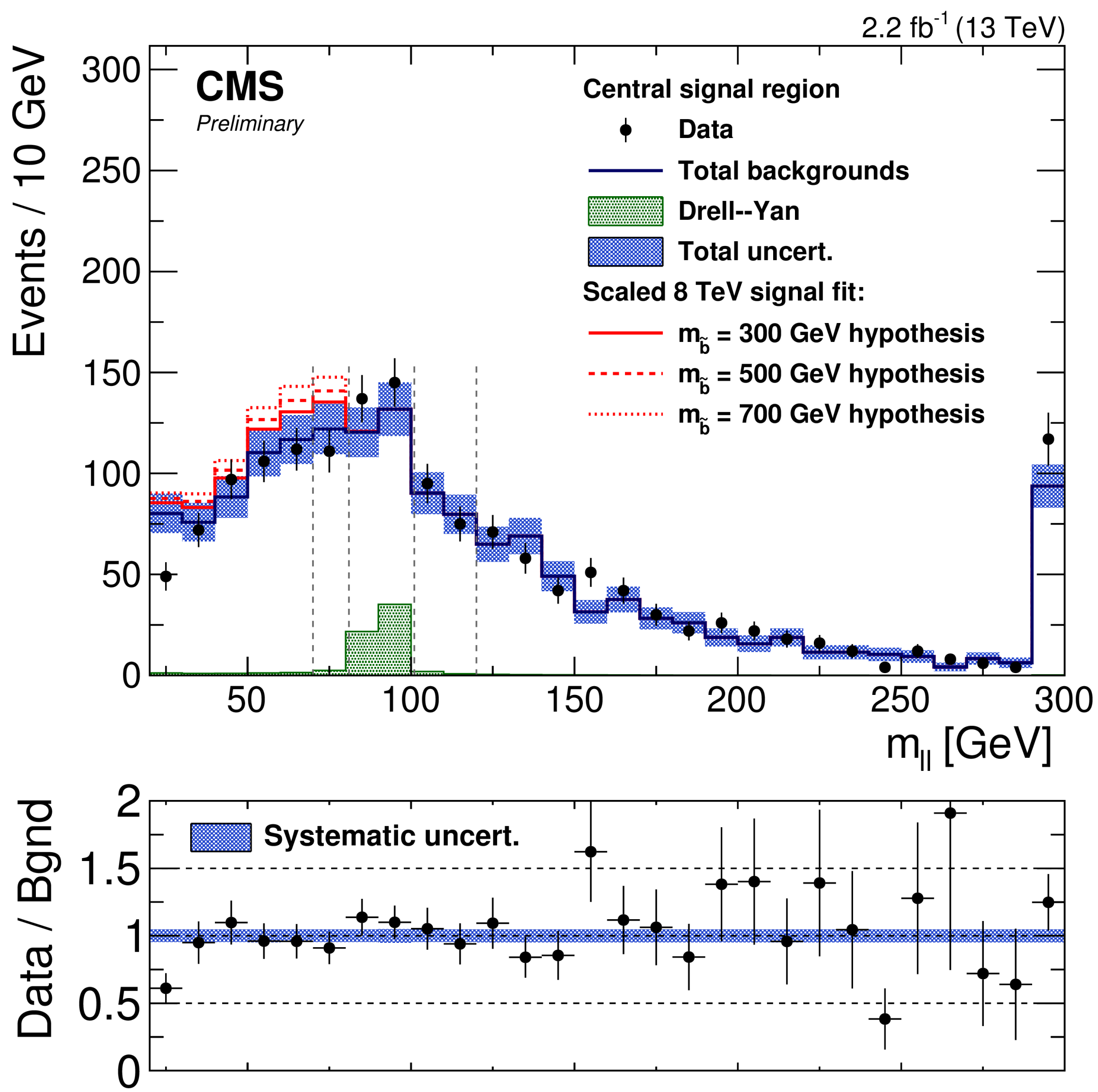
13 TeV

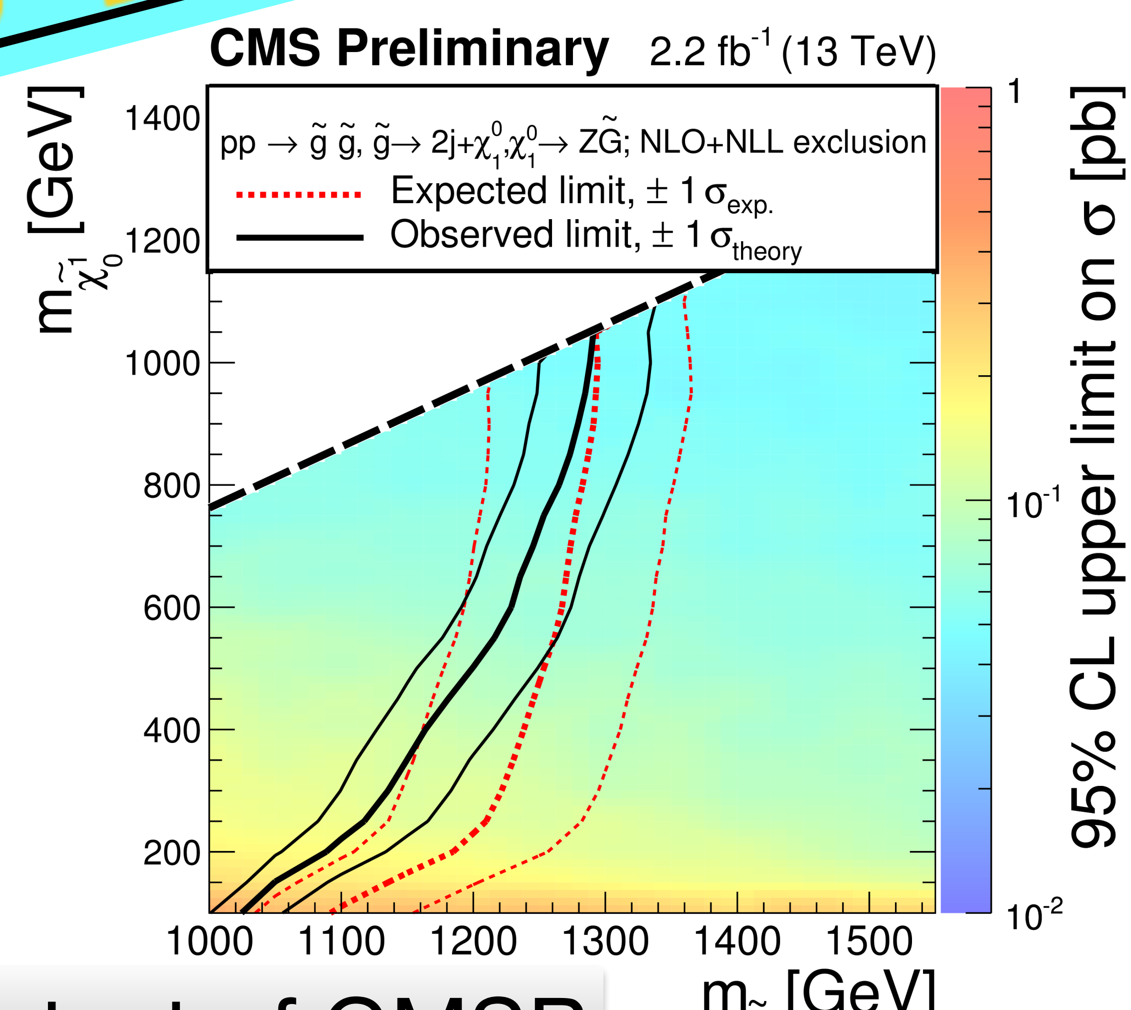
SUSY Dilepton “Edge”

- Classic SUSY signature
  - N_2 → slepton + lepton
  - slepton → lepton + LSP
  - Mass of Edge function of: ΔM(N_2,slepton),ΔM(slepton,LSP)



13 TeV



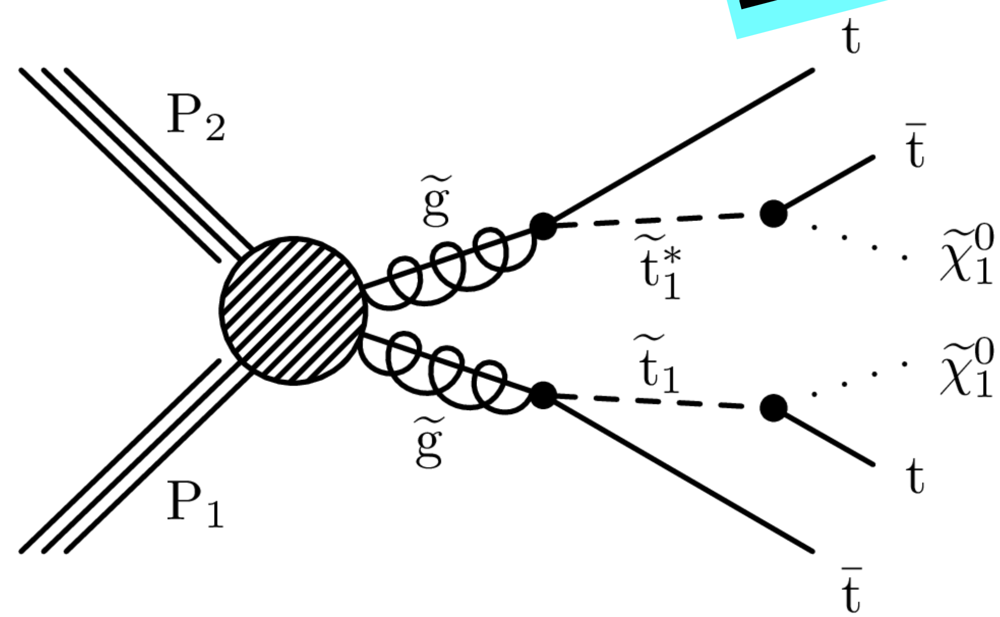


- context of GMSB

SUSY Single Lepton, LS Dileptons

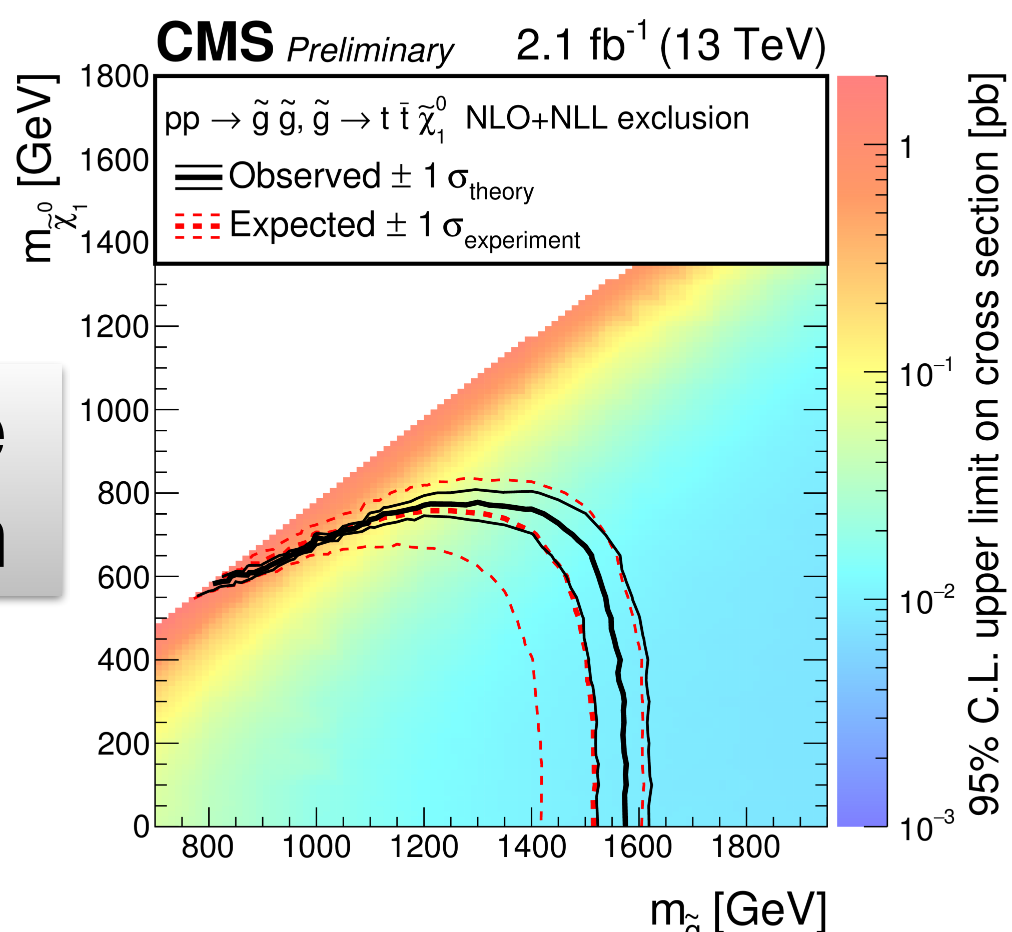
13 TeV

- Single Lepton: require large scalar sum of masses for jets (from top), large MET
- LS dilepton: gluino Majorana! Reduces ttbar, D-Y substantially

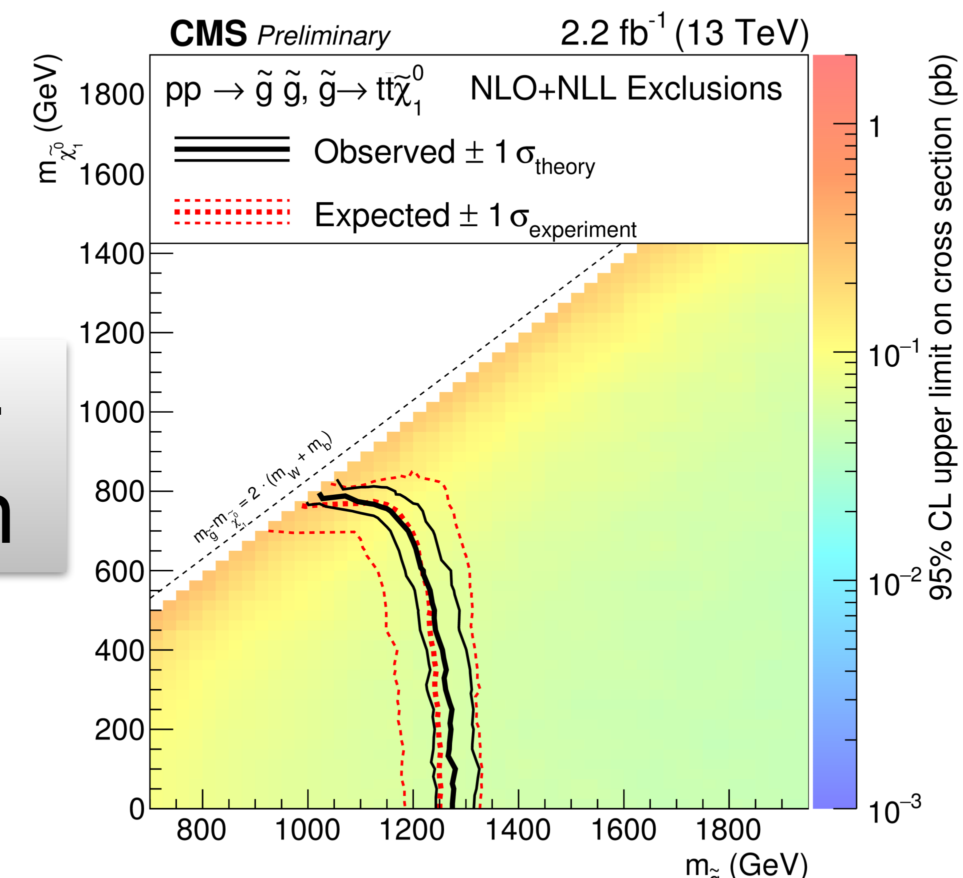


- CMS-PAS-SUS-15-007
- CMS-PAS-SUS-15-008

- Single lepton

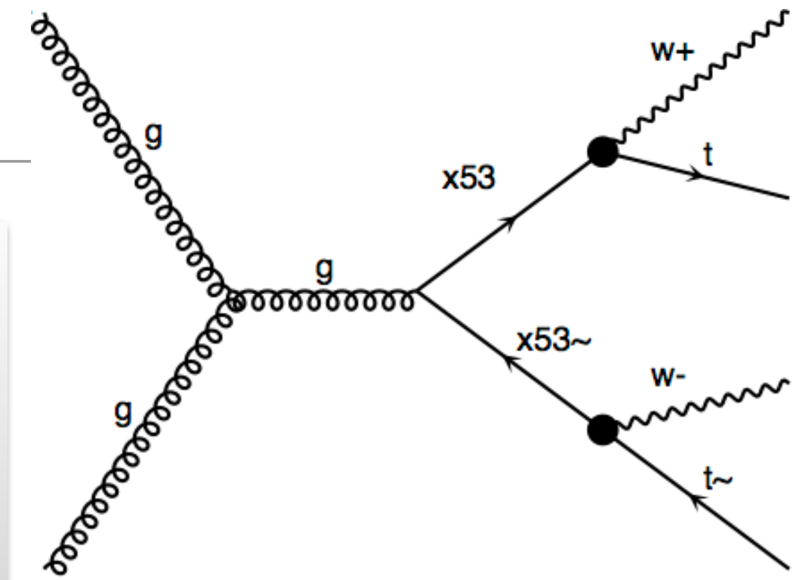


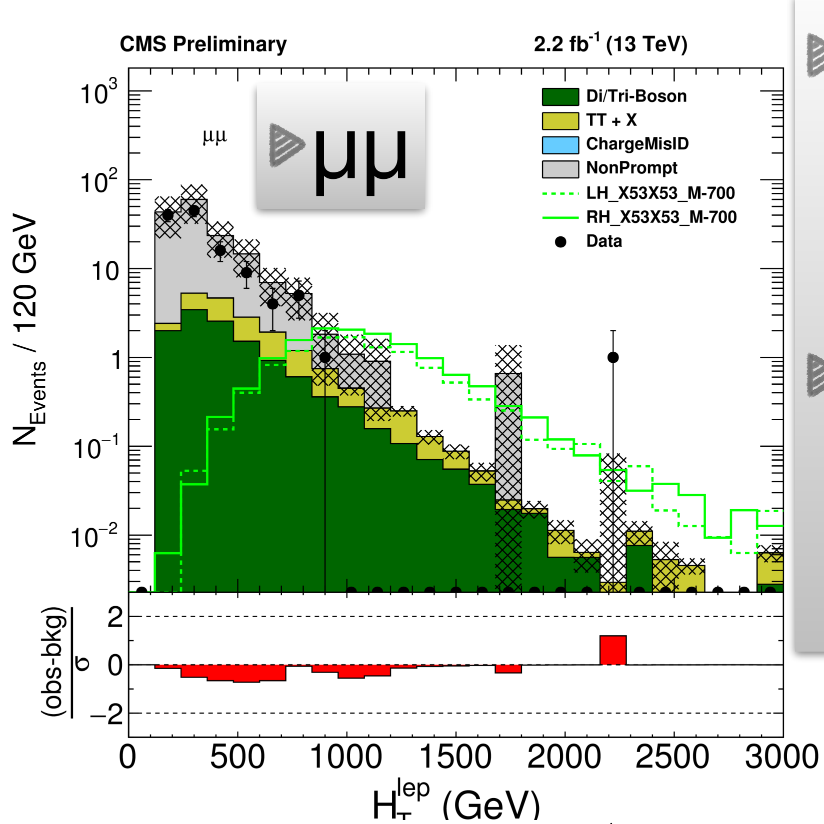
- LS di-lepton



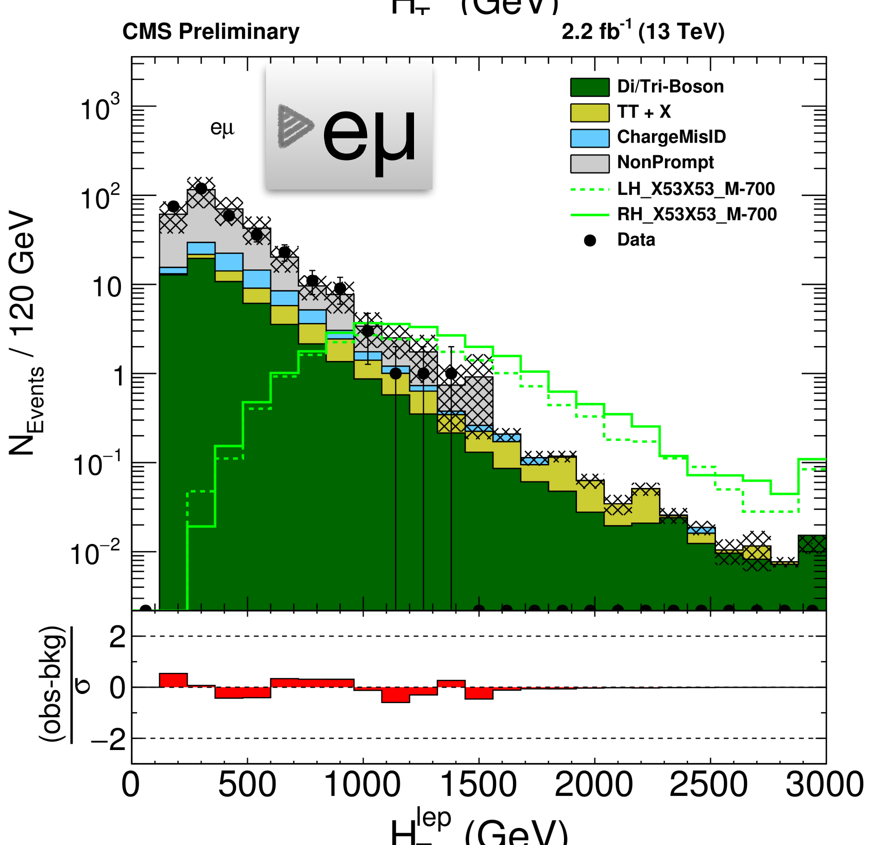
Searches for X → Top Quarks

Top quark partners



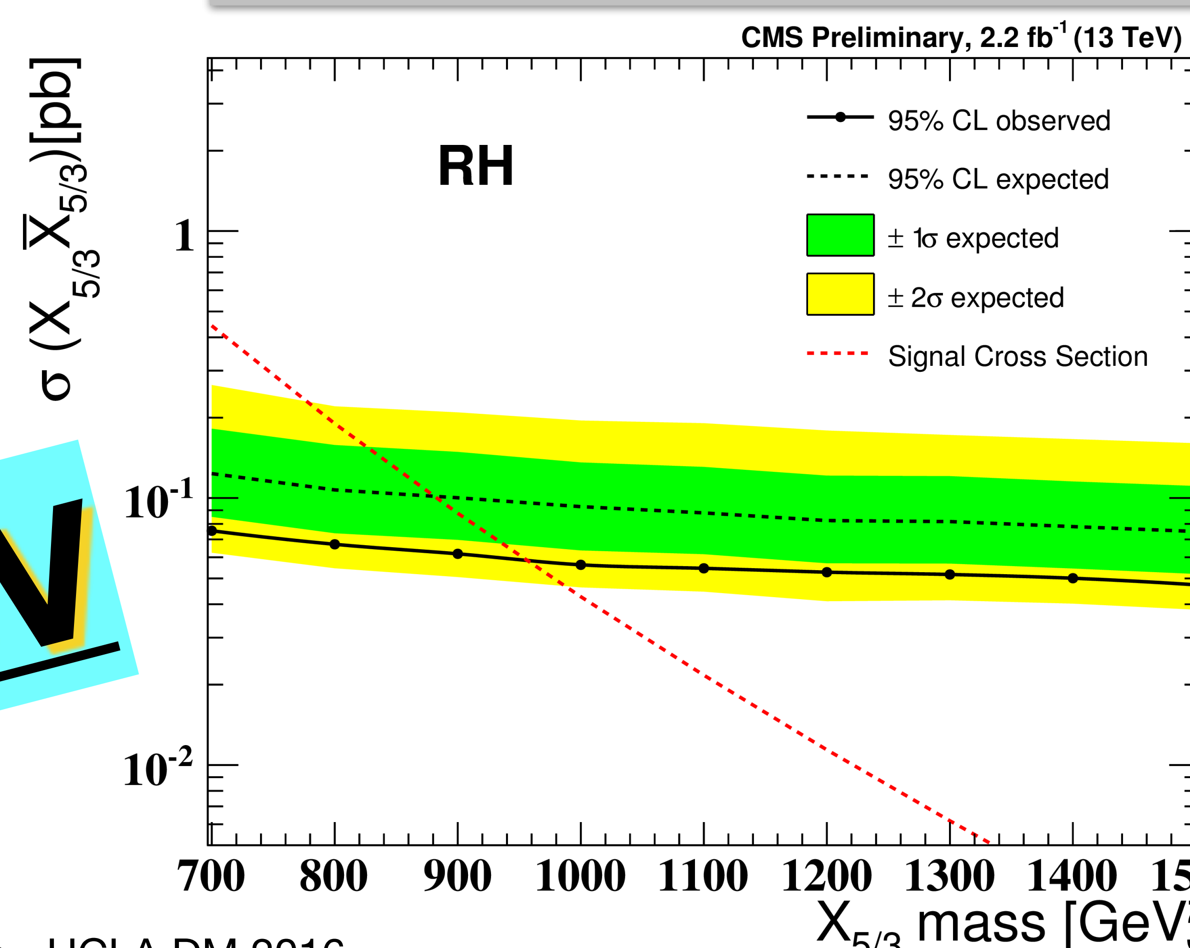


- Idea: solve hierarchy problem with heavy top partners
- |q|=5e/3 avoids interference with ggH coupling



- combined LS dileptons, leptons+jets

13 TeV

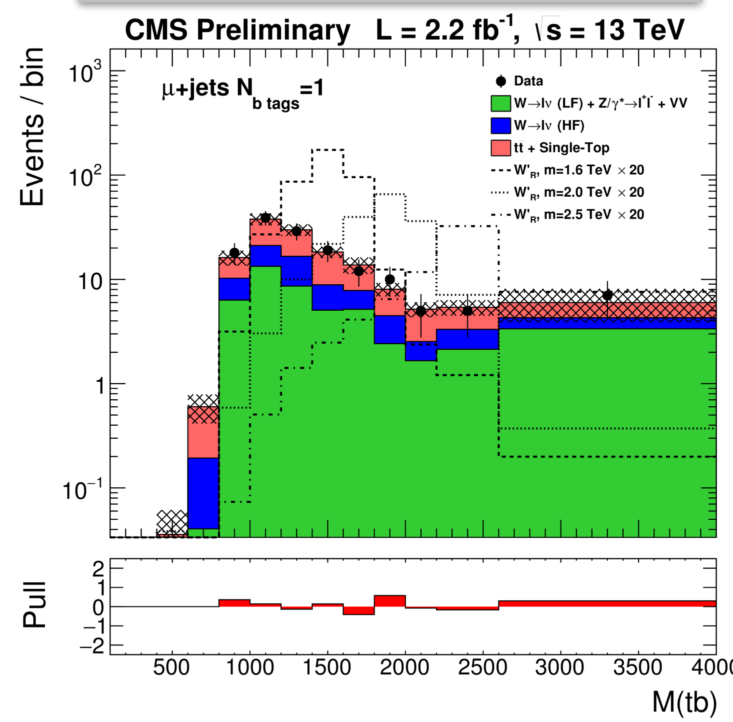


W’ → tb

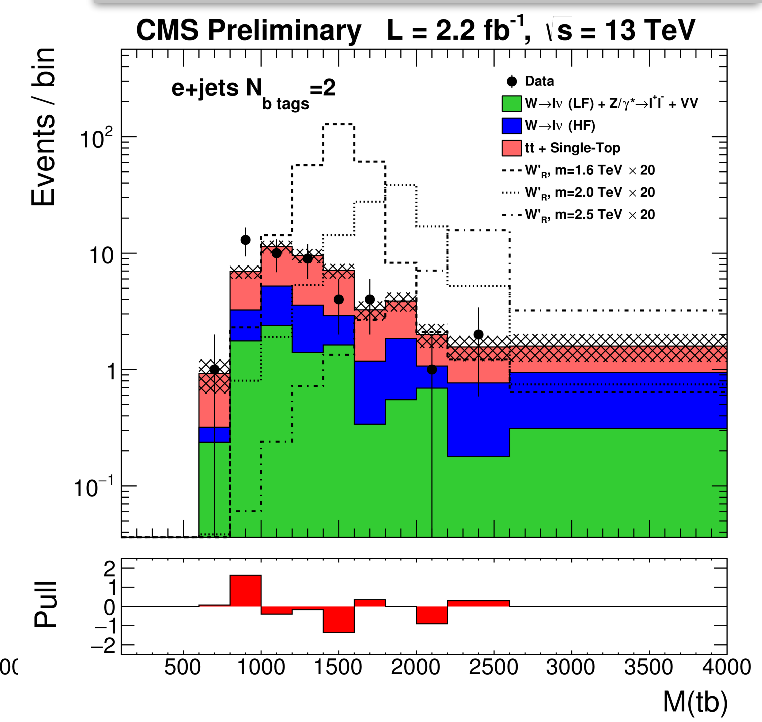
CMS-PAS-B2G-15-004

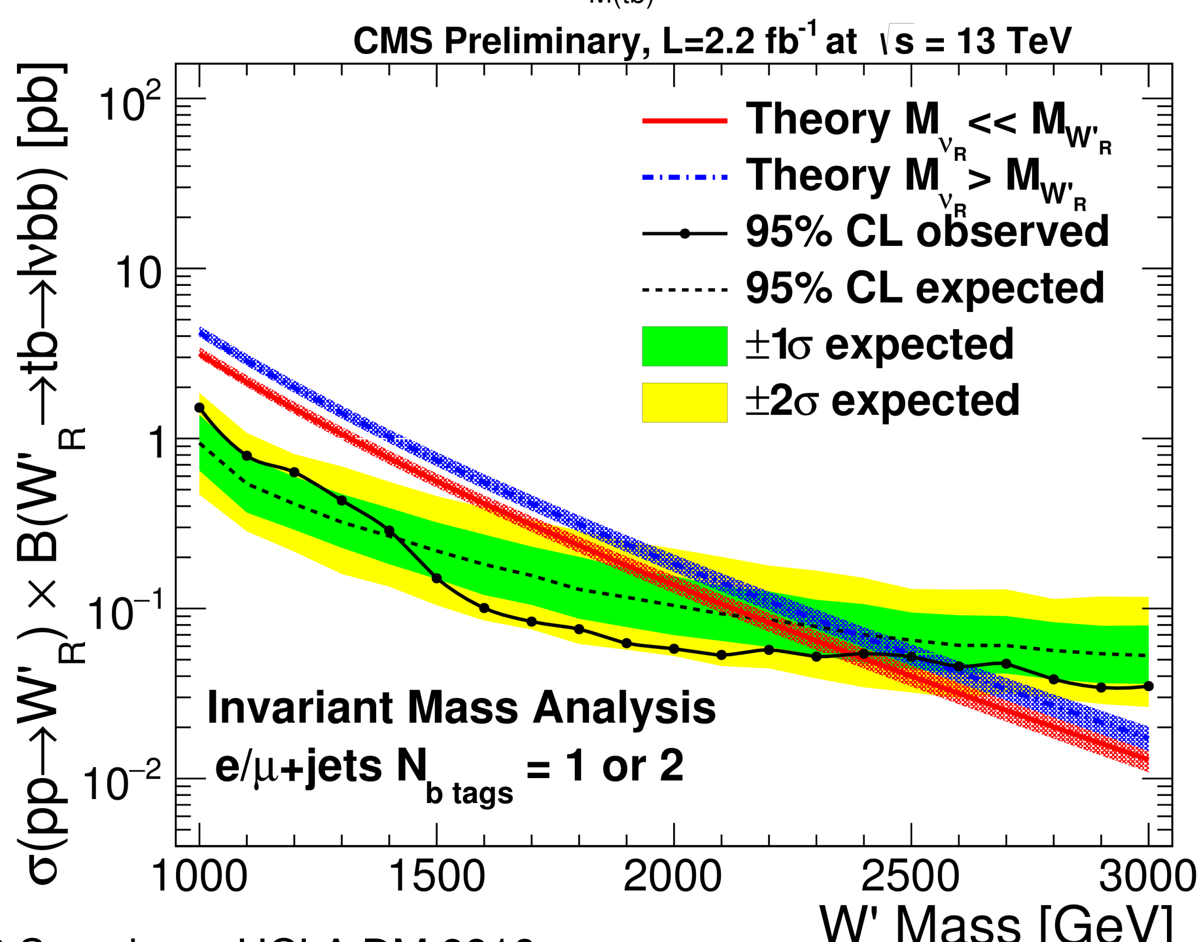
- Predicted in various BSM models
- Tend to couple more strongly to 3rd generation fermions
- Search in leptons + jets + MET

μ+jets, 1b tag



e+jets, 2b tags





13 TeV

Run II searches not covered here

Black Holes

- CMS-PAS-EXO-15-007

Heavy Stable Charged Particles

- CMS-PAS- EXO-15-010

13 TeV

Dijet resonances

- CMS-PAS-EXO-15-001, 009

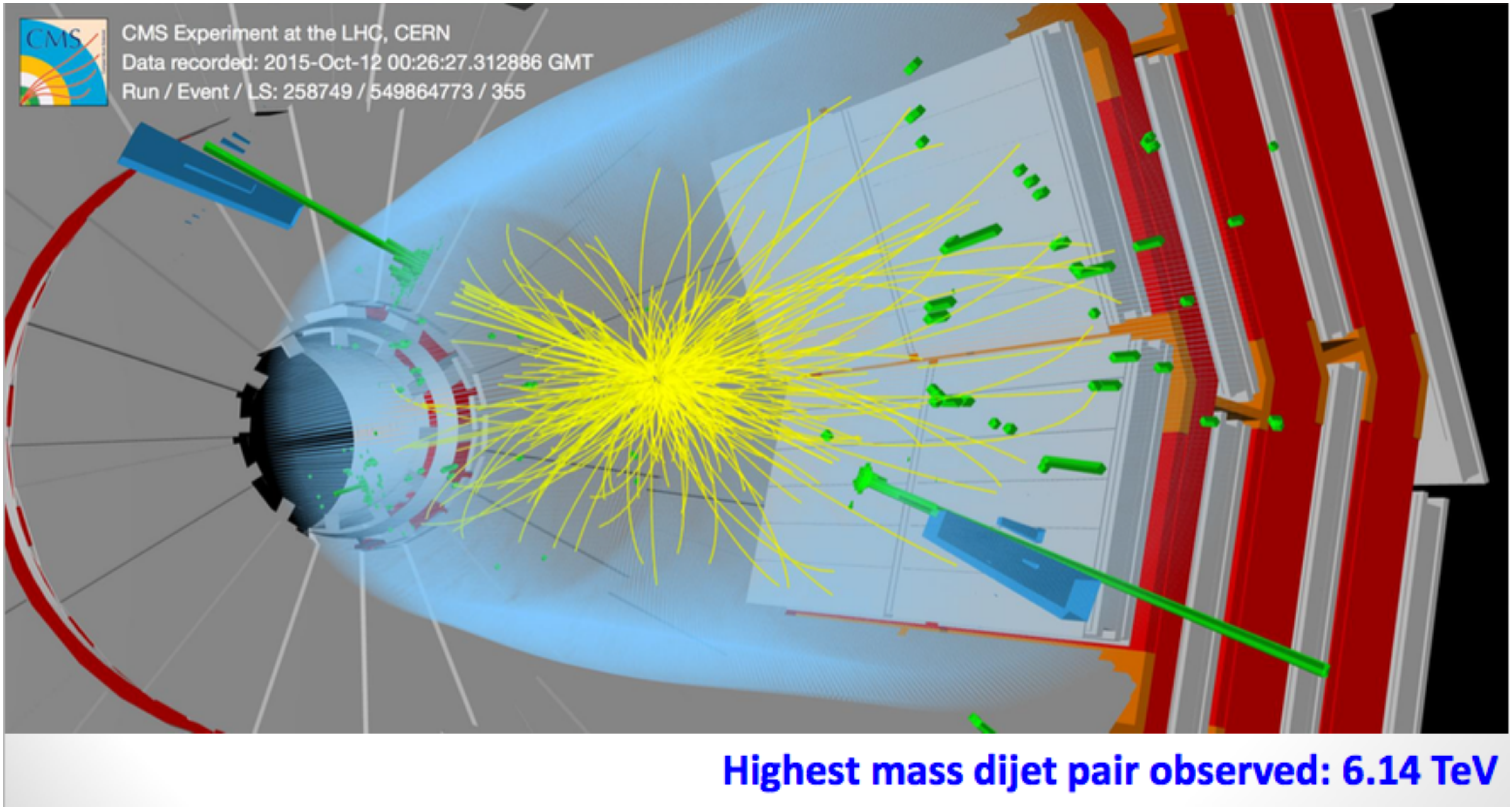
Dilepton resonances

- CMS-PAS-EXO-15-005

http://cms.web.cern.ch/news/cms-physics-results

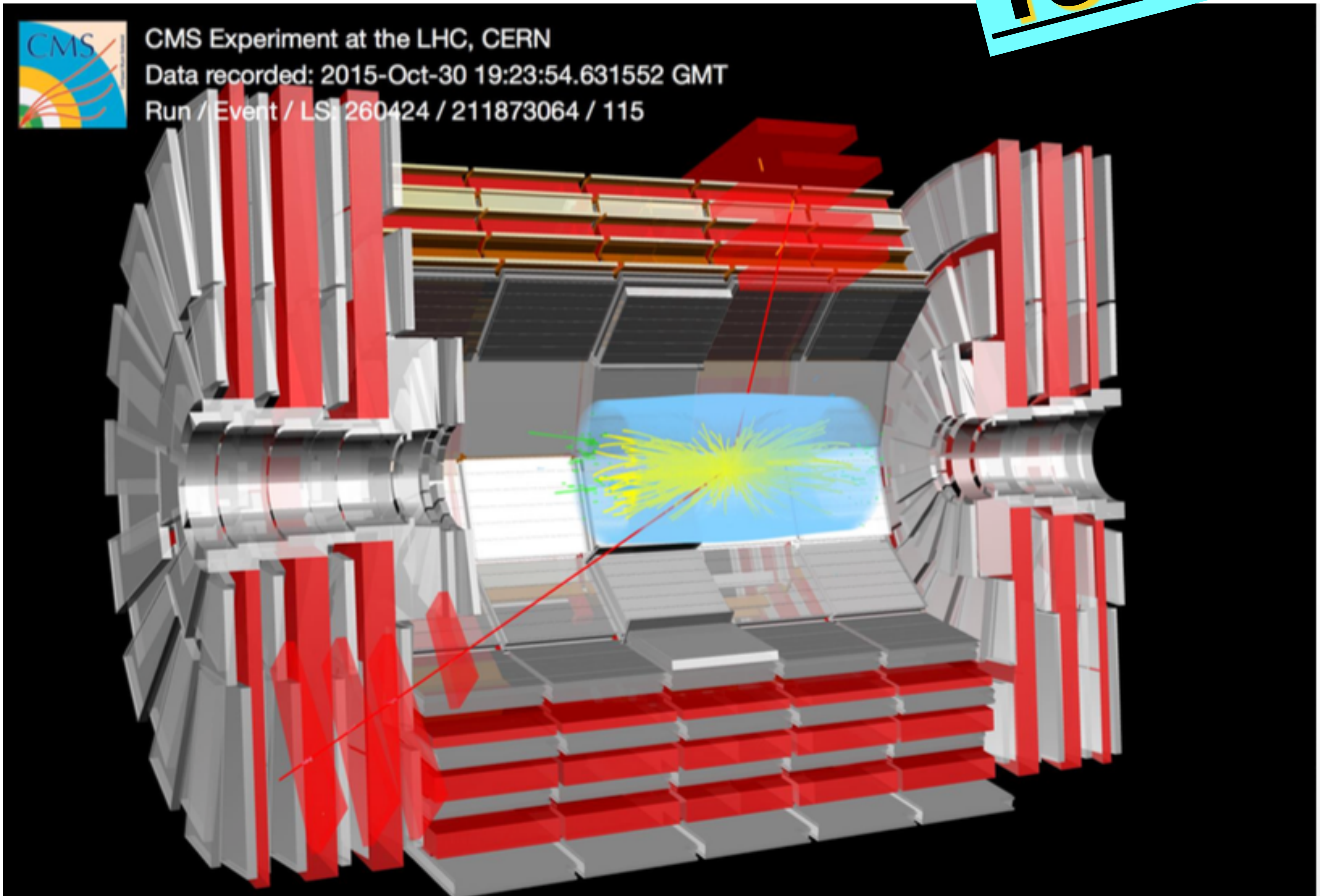
Dijet resonance

13 TeV



Dimuon resonance

13 TeV



Highest mass dimuon pair observed: 2.4 TeV

Coming Attractions

Higgs in Run II

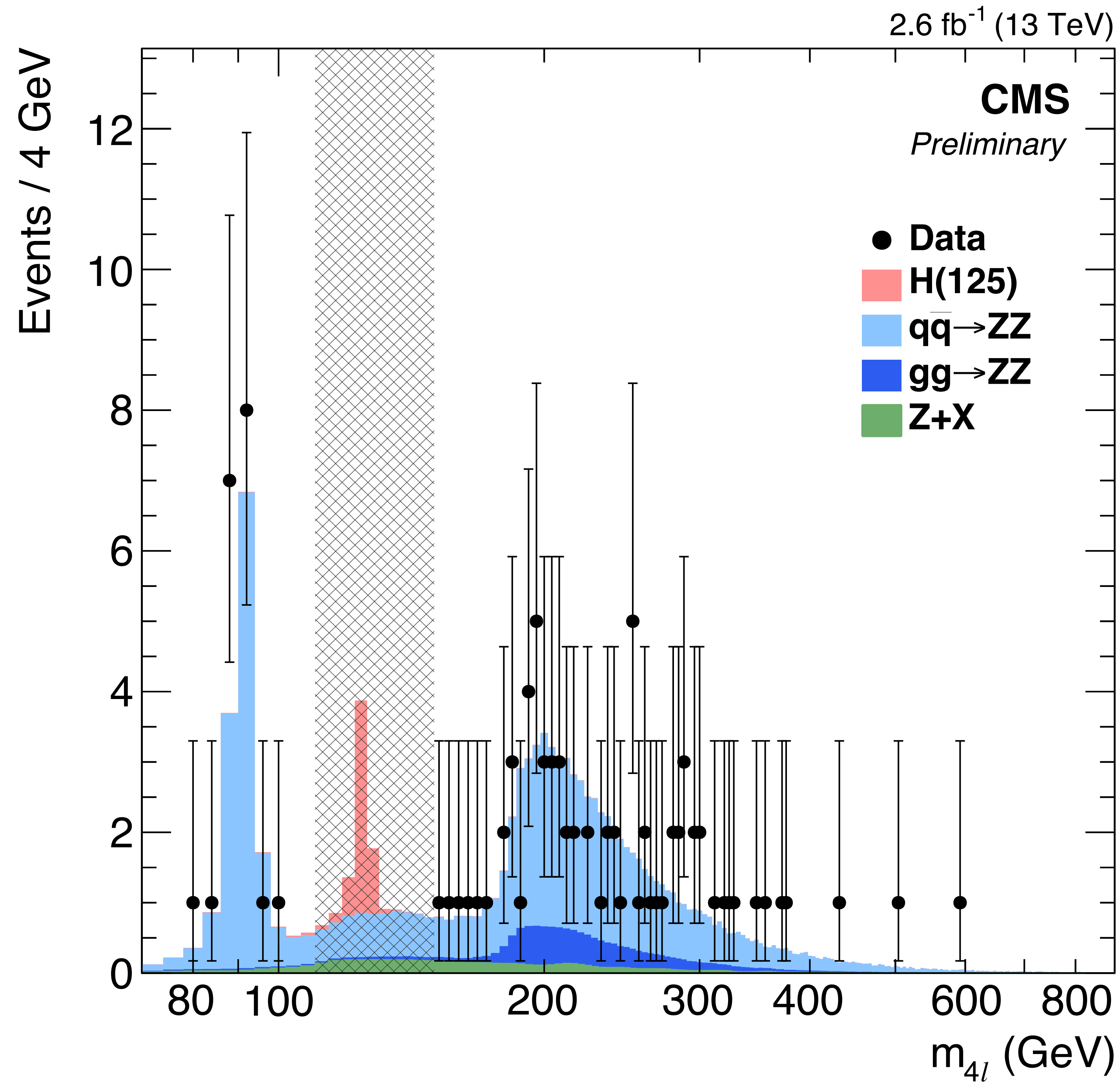
13 TeV

13 TeV vs. 8 TeV

- ggH, VBF cross sections up 2.6x
- Discovery channels visible with ~ 5/fb
- ttH cross section up ~ 4x
- Heavy Higgs partner production would be much higher

Busy with preparations now

- All CMS Higgs analyses blinded at present!



Conclusions

Higgs discovery opens new chapter for BSM physics

CMS continues the hunt

- **Wrapping up Run 1 searches**
- **Polishing up preparations for high-statistics Run 2 searches**

  Expecting ~ 30/fb in 2016

In Backup: Detector and Accelerator upgrades will keep us busy searching (and hopefully measuring!) for two decades

- **Phase 1 upgrades will all be in place by early next year. Instrumental in BSM search reach with 300/fb @ 13 TeV**
- **HL-LHC: 10x data @ 14 TeV**

  Push LHC searches for heavy particles, precision Higgs measurements

  Substantial radiation and pileup: detector R&D critical

Backup Slides

Phase 1 Upgrades

Over next few years, expect to collect ~ 300/fb @ 13 TeV. This will enable unprecedented reach in BSM searches

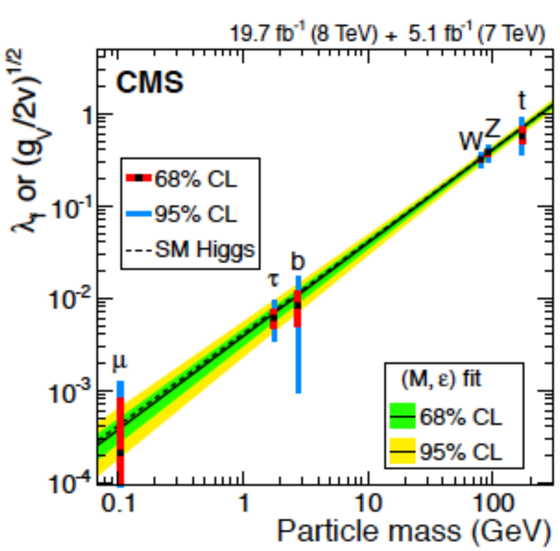
Detector upgrades necessary to maintain performance in increasingly difficult environment:

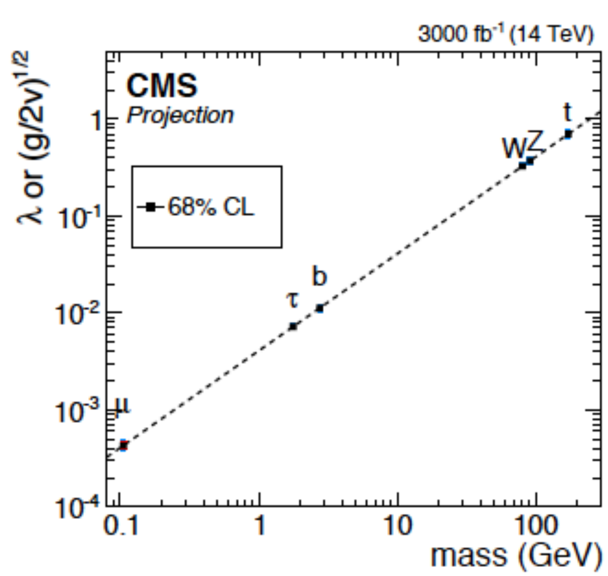
- **New pixel tracker**
- **Upgraded Level-1 trigger**
- **Upgraded electronics for Hadron Calorimeter**

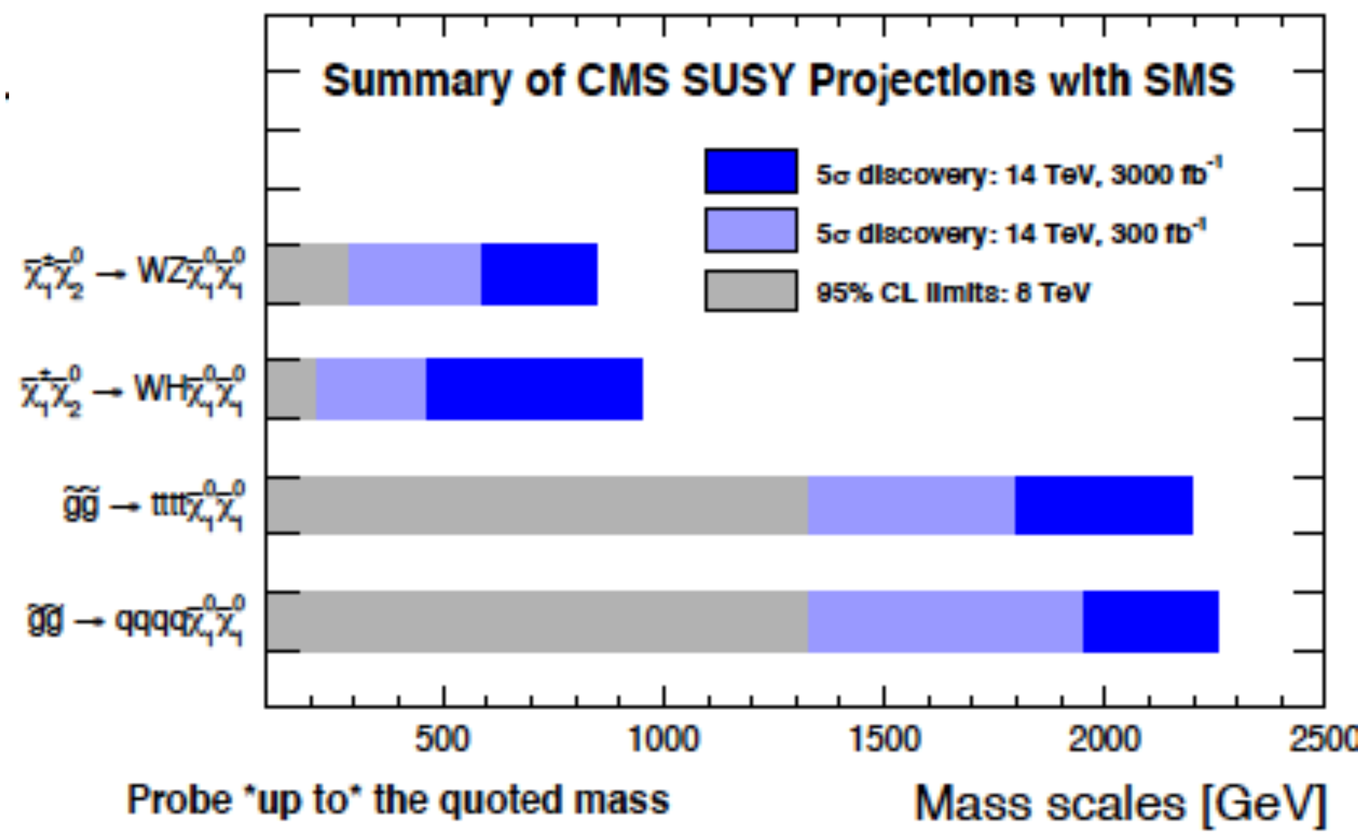
High-Luminosity LHC: The Future

Exploit LHC ultimate potential

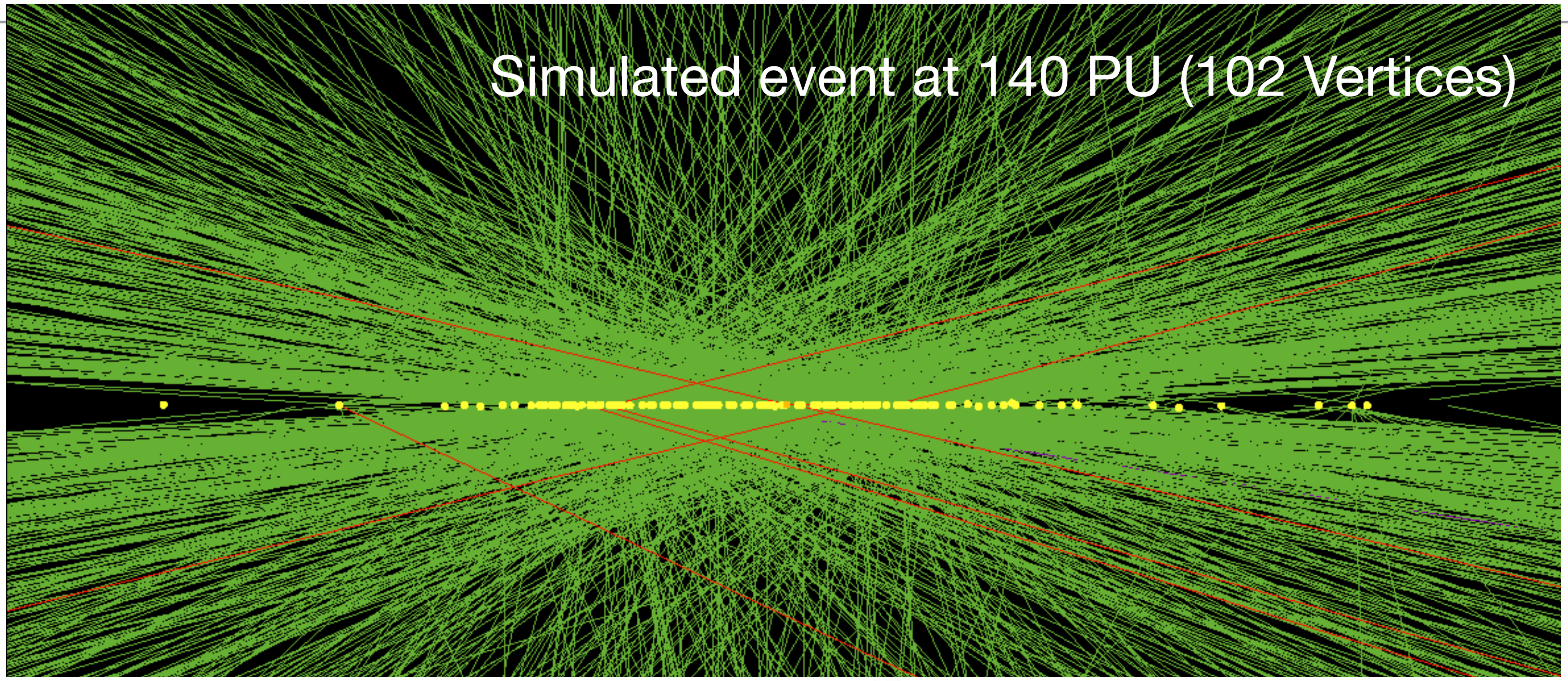
- 3000/fb @ 14 TeV
- Methodical continued search for new particles with access to small cross sections
- Precision Higgs couplings
- P5: Highest priority!

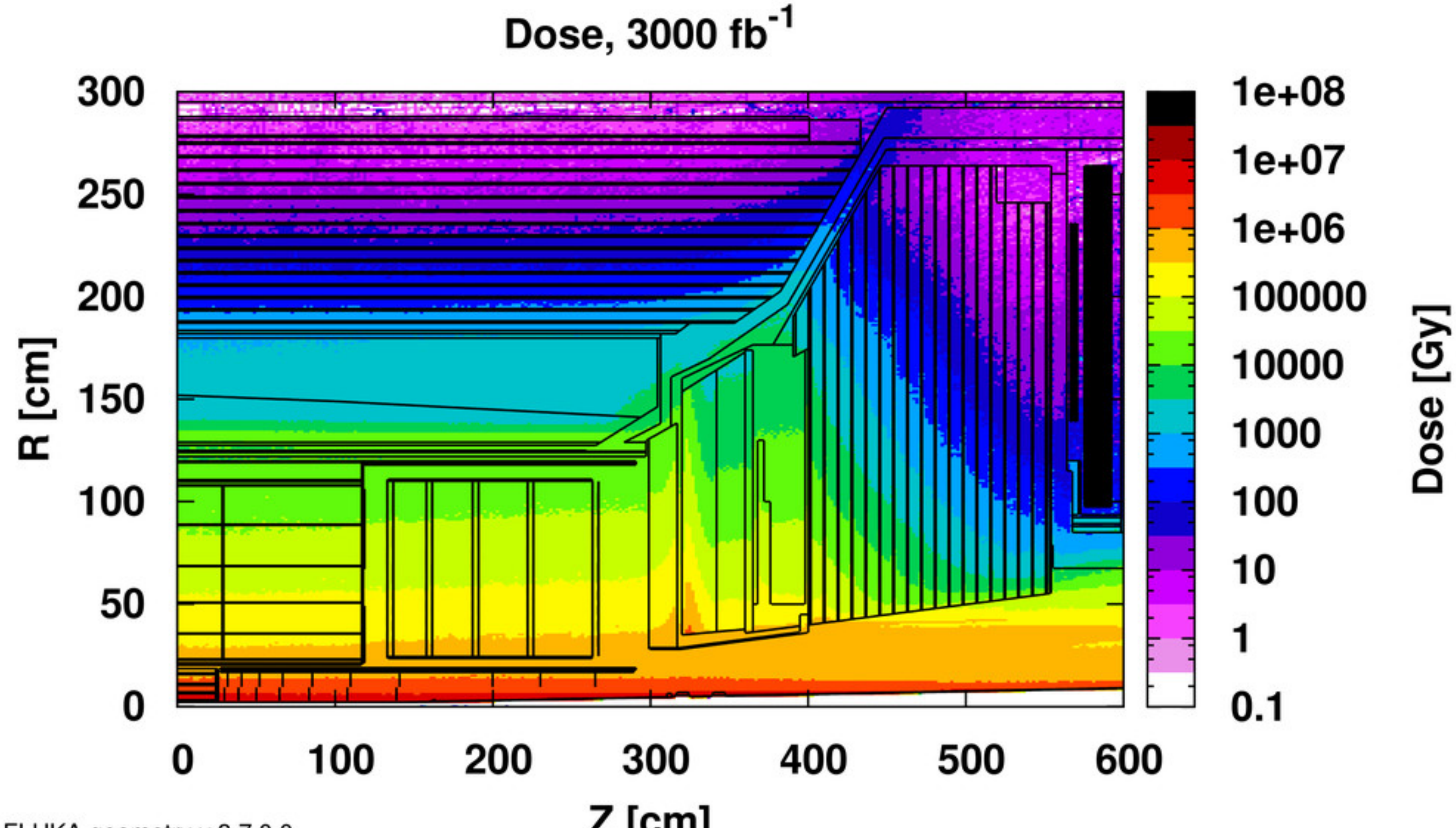






HL-LHC: The Future looks bright

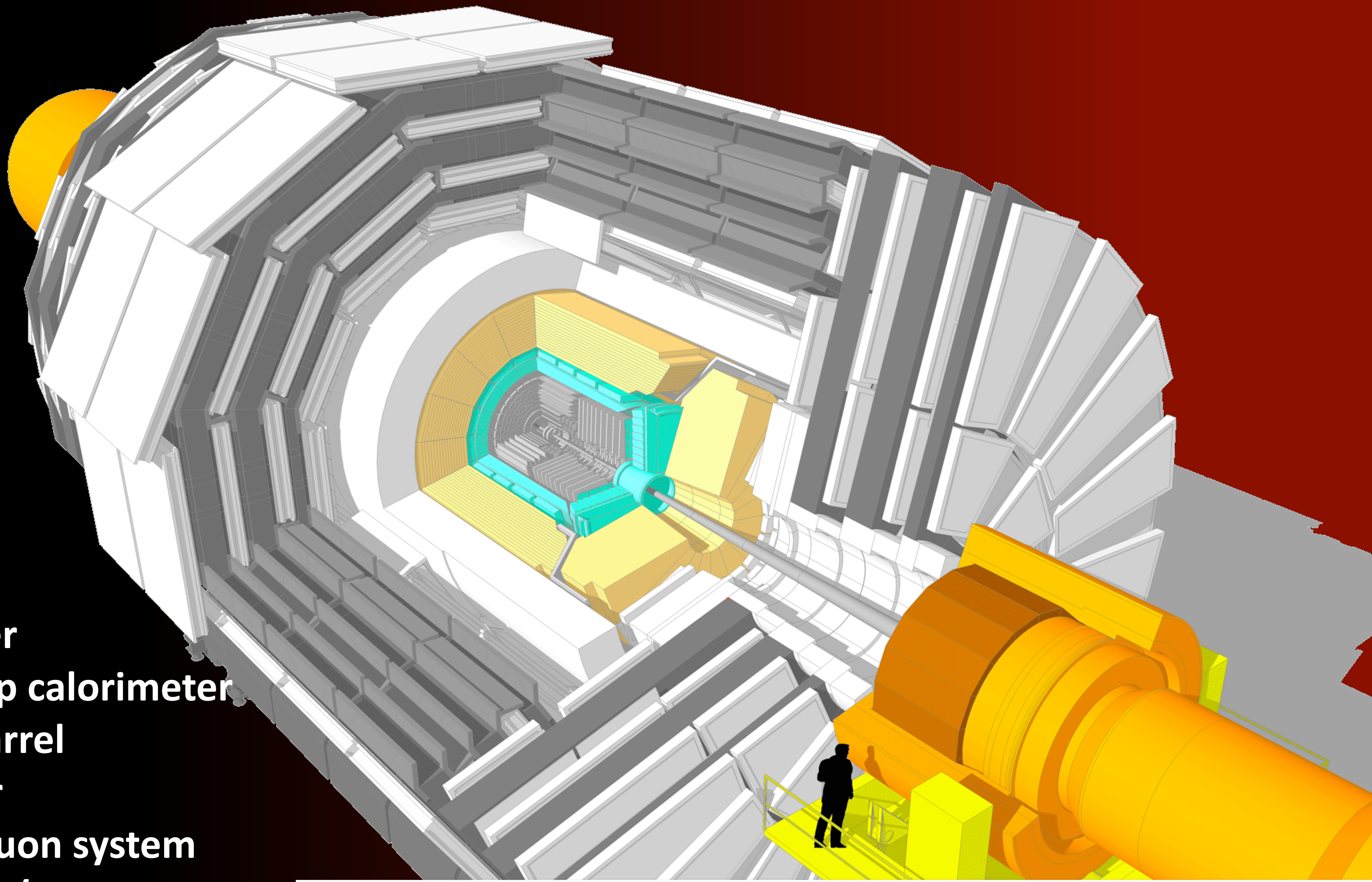




CMS FLUKA geometry v.3.7.0.0

High-Luminosity LHC Detector

- Large components of the current CMS detector must be replaced for HL-LHC



- New Tracker
- New Endcap calorimeter
- Upgrade barrel calorimeter
- Upgrade muon system
- New Trigger/DAQ

Technical Proposal: CERN-LHCC-2015-010, http://cds.cern.ch/record/2020886

Kinematic variables in gluino searches

H_T: scalar sum of jet transverse momenta (p_T)

$H_{T,miss}$: |vector sum of jet p_T|

M_{T2}: generalization of M_T. Good for QCD multijet rejection

$$M_{T2}(m_{\tilde{\chi}}) = \min_{\vec{p}_T^{\tilde{\chi}(1)} + \vec{p}_T^{\tilde{\chi}(2)} = \vec{p}_T^{\text{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$

Razor variables: M_R, R^2 characterize energy mass, energy flow for pair-produced particles:

$$M_R \equiv \sqrt{(P_{j_1} + P_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2} \quad M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1} + p_T^{j2}) - \vec{p}_T^{miss} \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})}{2}} \quad R^2 \equiv \left(\frac{M_T^R}{M_R} \right)^2$$

α_T: $p_T(j2)/M_T$

$\Delta\phi^*_{min}$: minimum angle between a jet and $H_{T,miss}$ vector formed by others