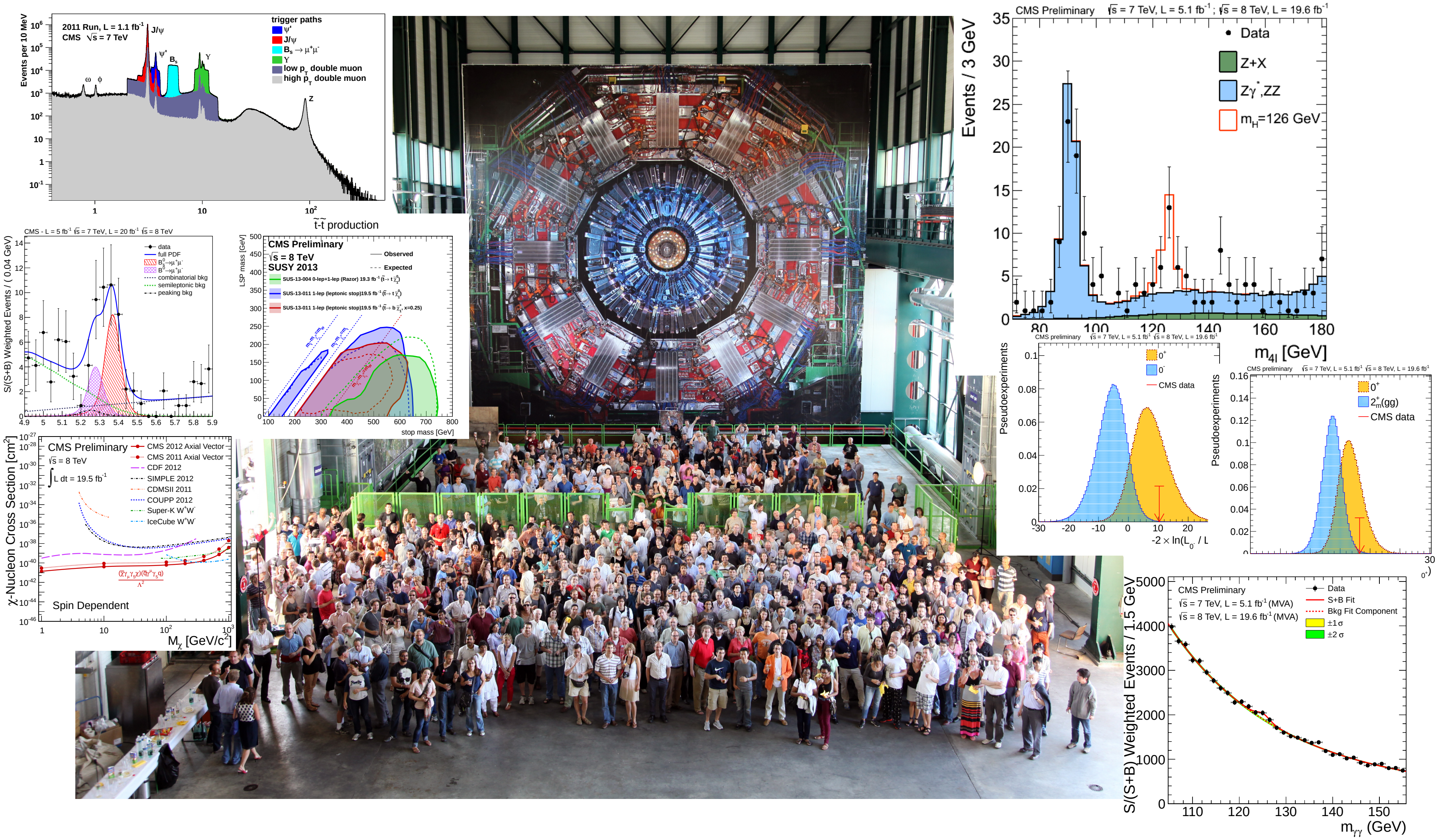
Highlight of Latest Results from CMS

Serguei GANJOUR

CEA-Saclay/IRFU, Gif-sur-Yvette, France

CEA - Saclay

On behalf of the CMS Collaboration



Particles, Strings and Cosmology, PASCOS 2013

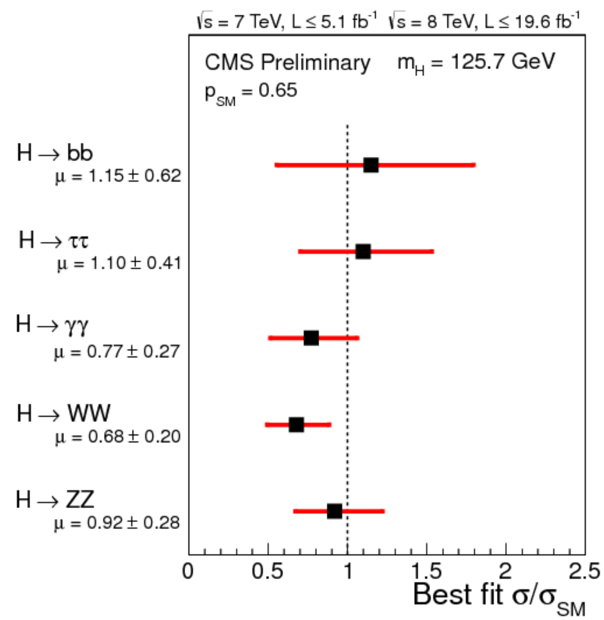
NTU, Taipei, Taiwan
November 20-26, 2013

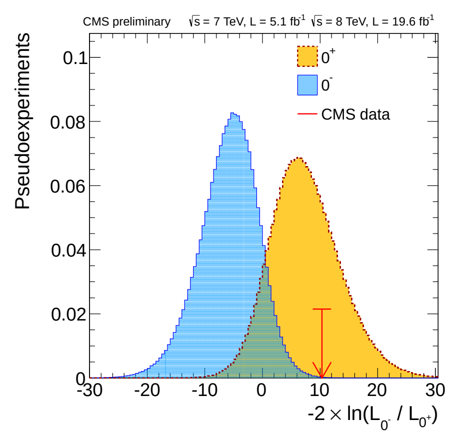
Discovery of a new boson opened the new era at the Energy Frontiers

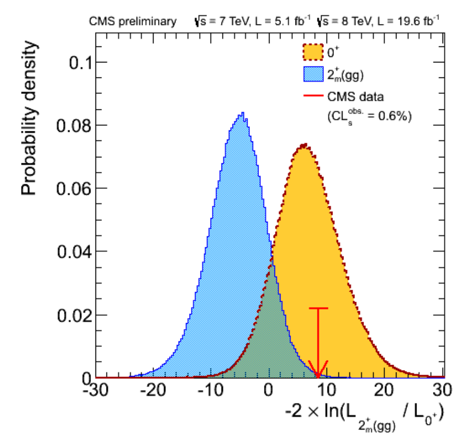
- ☞ The boson that we found looks rather **"standard"** scalar at first sight
- ☞ Unraveling its nature is the major effort

A Higgs Boson→
The Higgs Boson→
The SM Higgs Boson

- ☞ The SM begins to unravel when probed beyond the range of current accelerators
  - ➠ **no hint of New Physics so far**







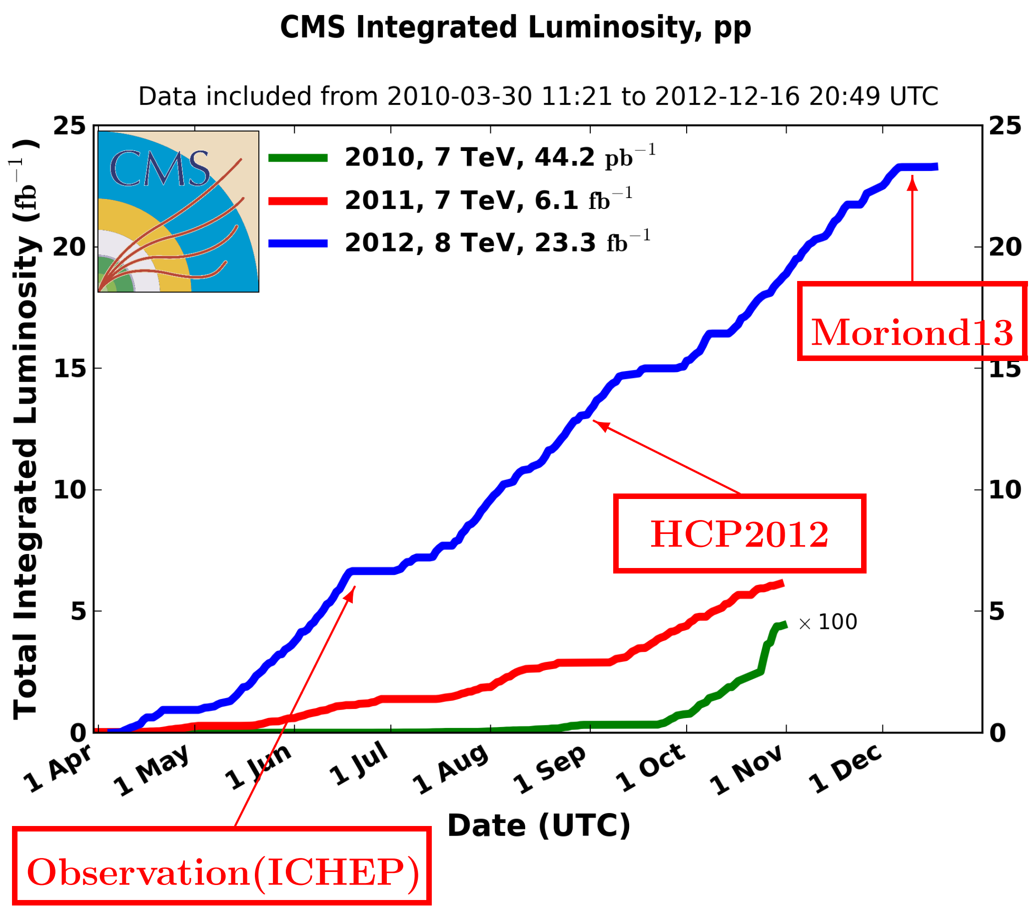
☞ Outline

- ➠ Precision SM
- ➠ Higgs Sector
- ➠ SUSY Searches
- ➠ Dark Matter Search
- ➠ Other BSM searches

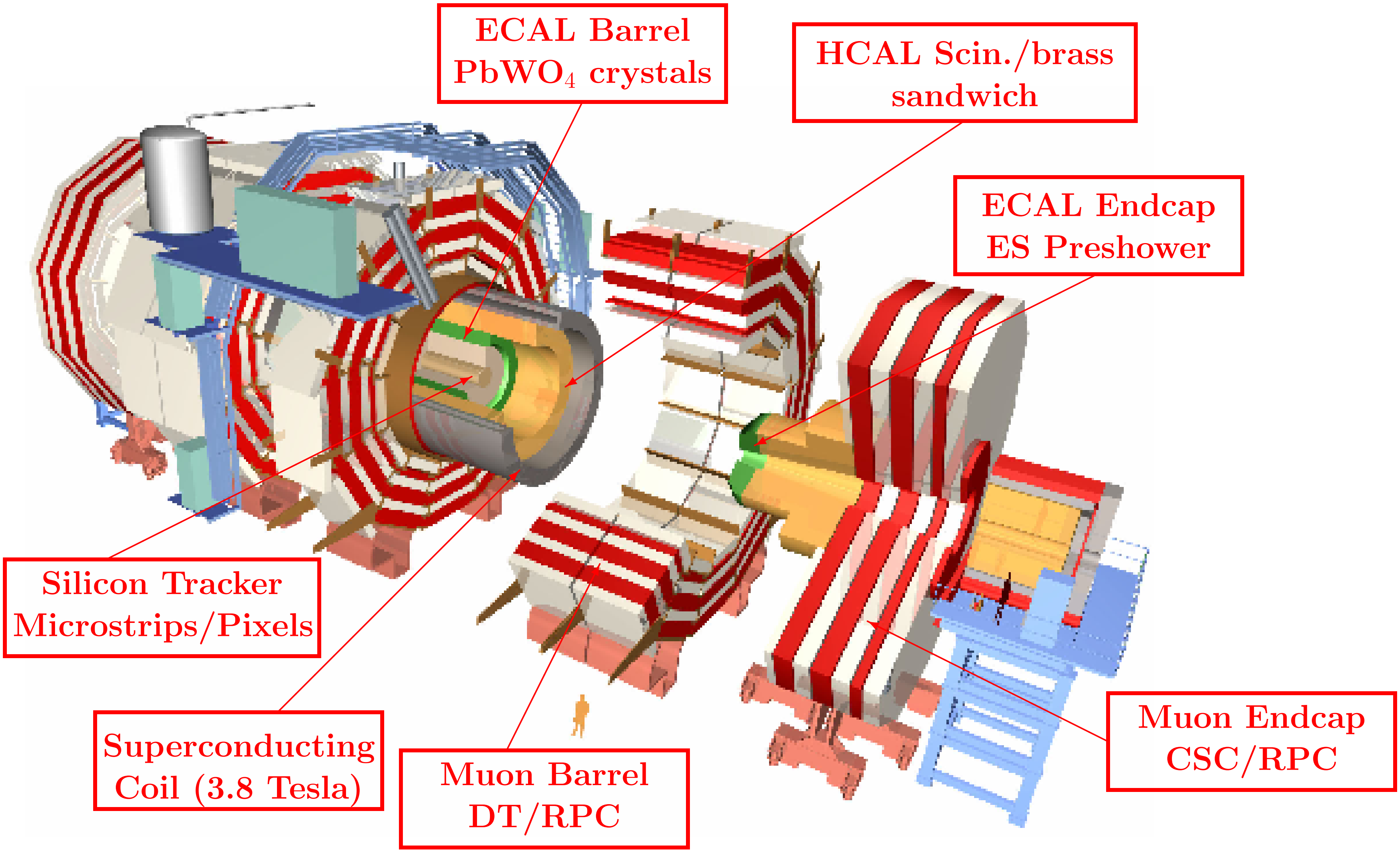
Extremely successful operation of the LHC for these 3 years

- ☞ Started with 7 TeV collisions
- ☞ Upgraded center-of-mass energy to 8 TeV in 2012
- ☞ Available dataset for the analyses with all subdetectors on
  - ➠ **7 TeV:** $\leq$5.1 fb^{-1}
  - ➠ **8 TeV:** $\leq$19.6 fb^{-1}
  - ➠ high detector efficiency

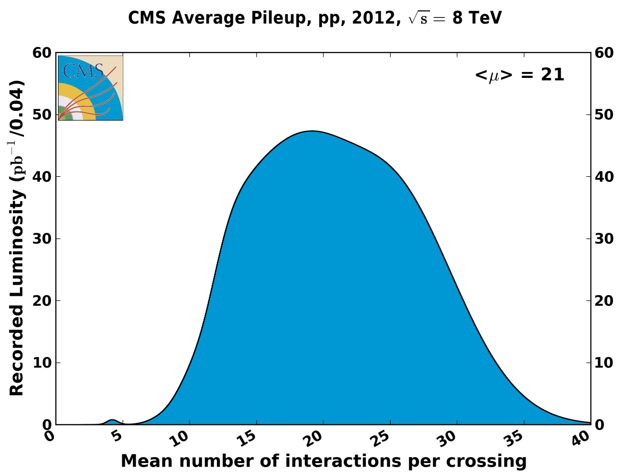
LHC restart in 2015 with a collision energy of ≃13 TeV and increased beam intensity



$\sqrt{s}$=**8 TeV:** *25-30% higher cross section than 7 TeV at low Higgs boson mass*



ECAL Barrel
$PbWO_4$ crystals
HCAL Scin./brass
sandwich
ECAL Endcap
ES Preshower
Silicon Tracker
Microstrips/Pixels
Superconducting
Coil (3.8 Tesla)
Muon Barrel
DT/RPC
Muon Endcap
CSC/RPC



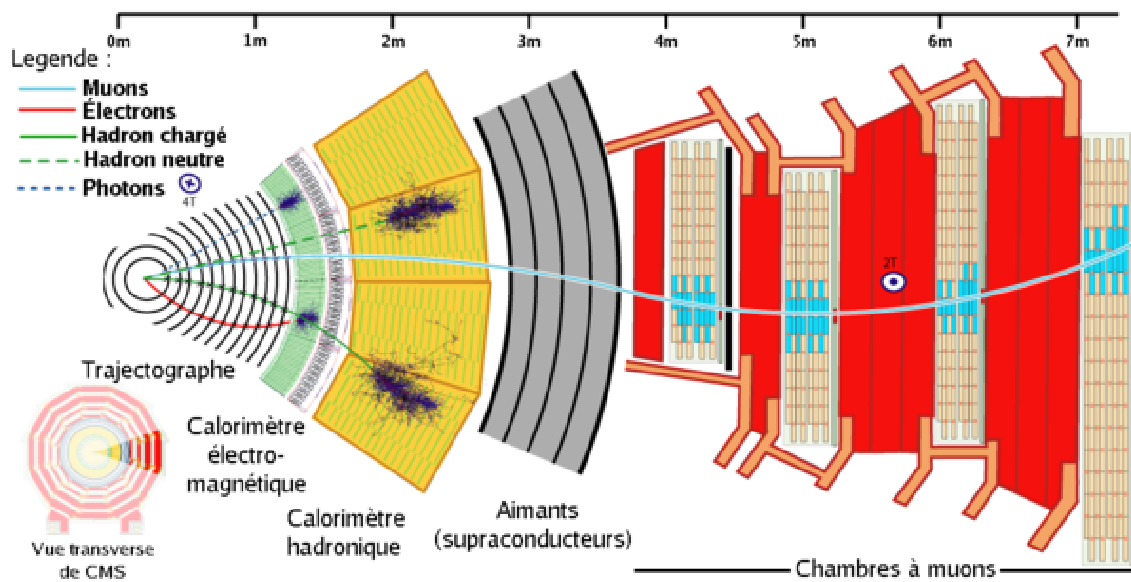
☞ Excellent performance of the CMS experiment in 2012

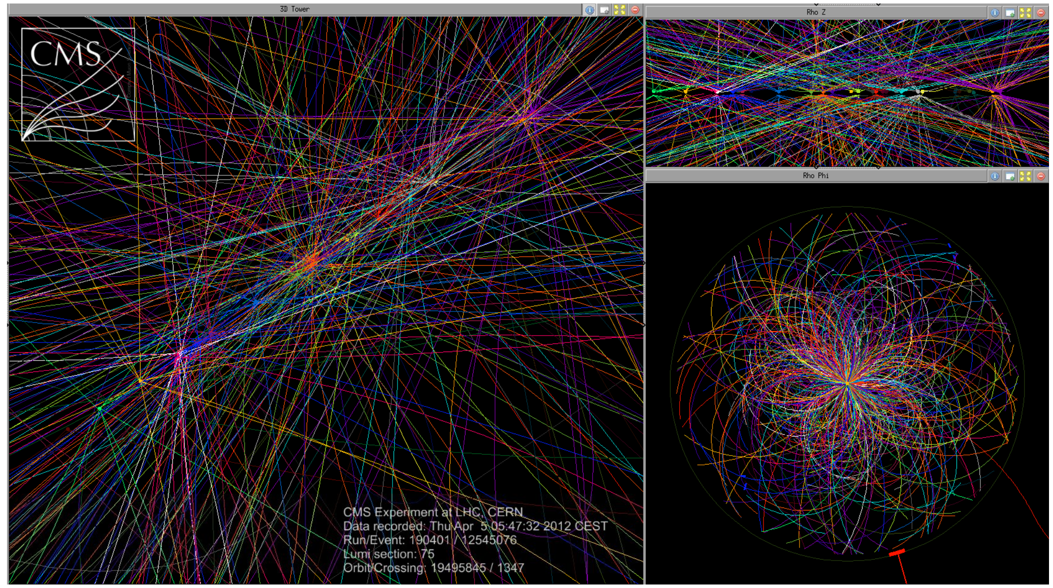
- 90% of recorded data with all subdetectors on
- peak luminosity $7 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 8 TeV CM energy
- **mean pile-up (PU) 21 events**

☞ **Particle Flow** algorithm:

- provides a global event description in form of list of particles
- improvements in jet, τ and E_T^{miss} measurement

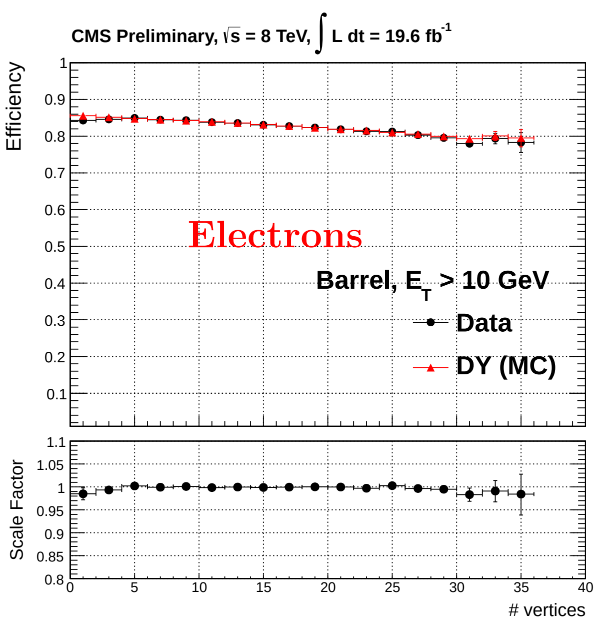
Remarkably improves reconstruction performance at high PU

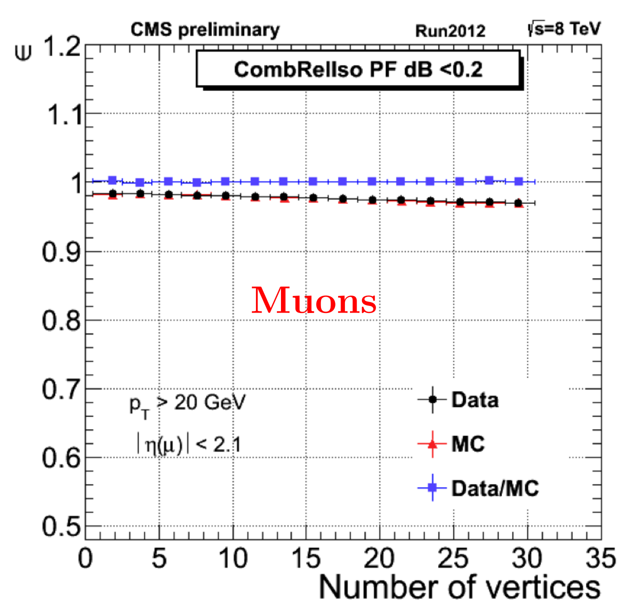


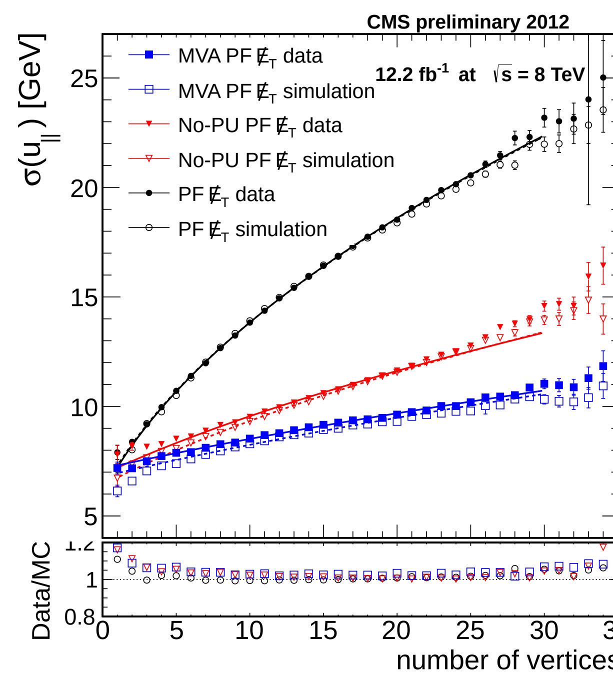


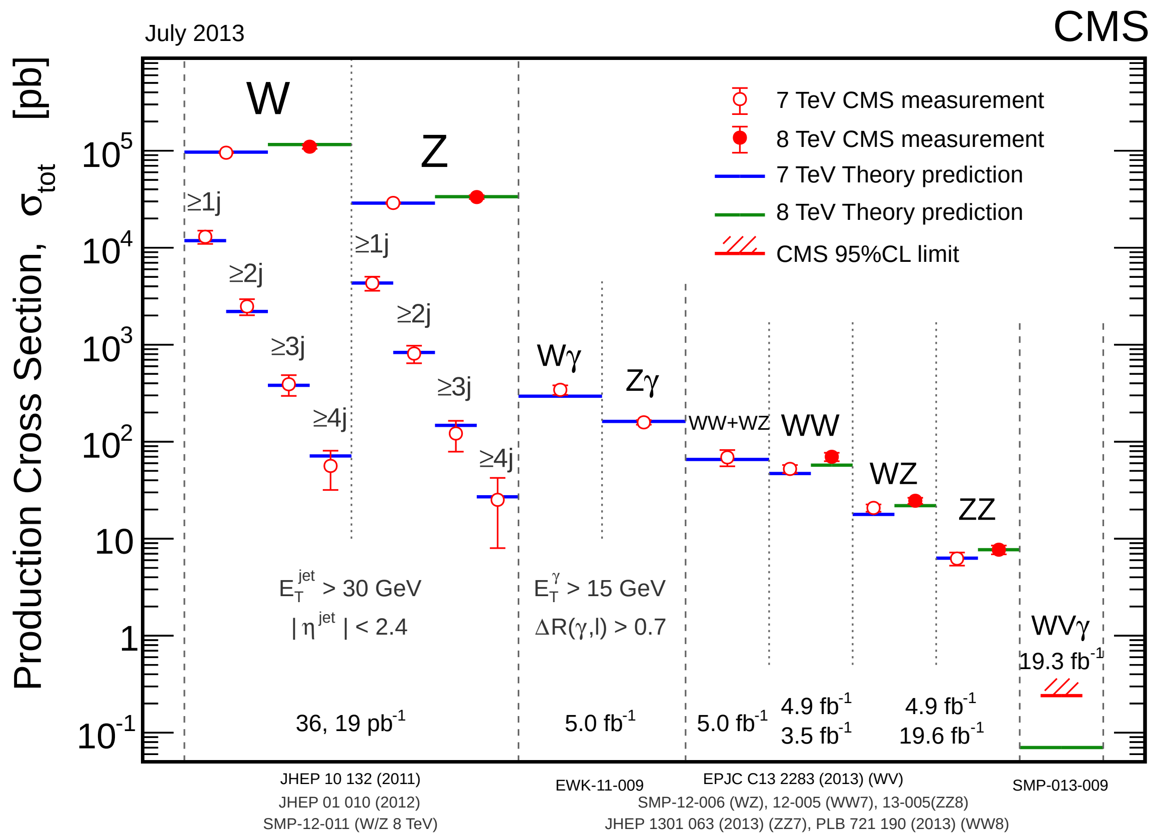
29 distinct vertices have been reconstructed corresponding to 29 distinct collisions within a single crossing of the LHC beam

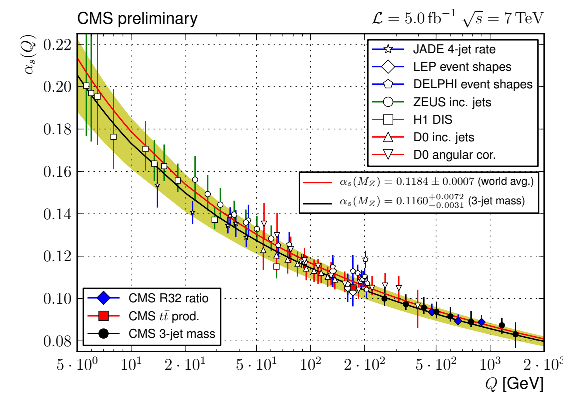
Leptons and MET are almost insensitive to pileup

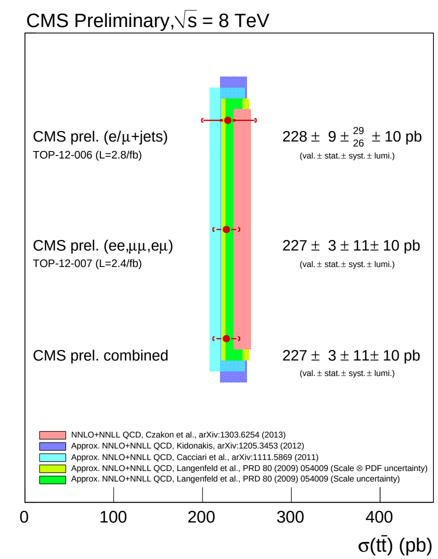












☞ Good understanding of the detector and accurate theory predictions

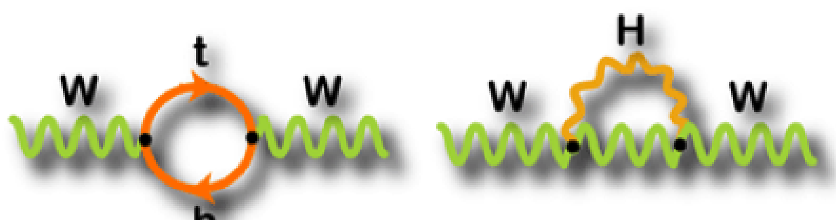
- ➠ **precise measurements** of the SM processes over many orders of magnitude
- ➠ good knowledge of **the background to Higgs analyses and BSM searches**

Higgs Boson

- Standard Model (SM) is confirmed to better than 1% uncertainty by 100's of precision measurements
  - **Higgs boson was the only missing piece of the SM**
- Mass of W boson is a fundamental parameter of the SM (WA $m_W = 80385 \pm 15$ MeV)

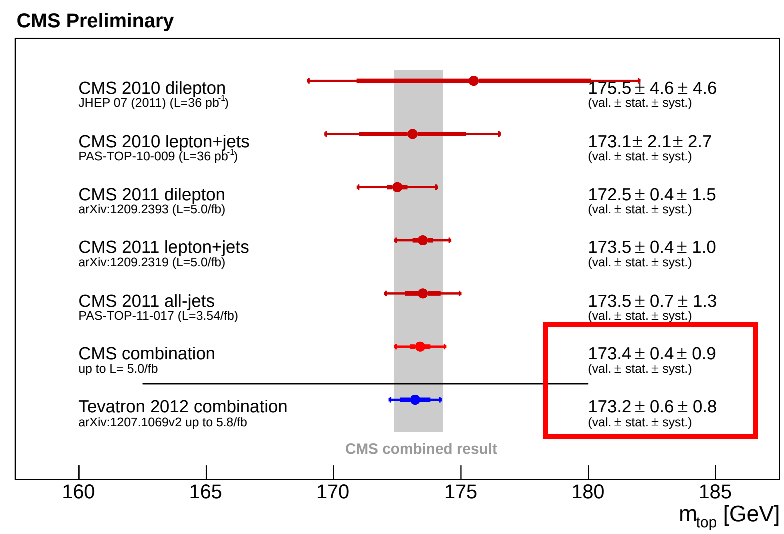
$$m_W = \sqrt{\frac{\pi\alpha}{G_F\sqrt{2}}}\frac{1}{\sin\theta_W\sqrt{1-\Delta R}}$$

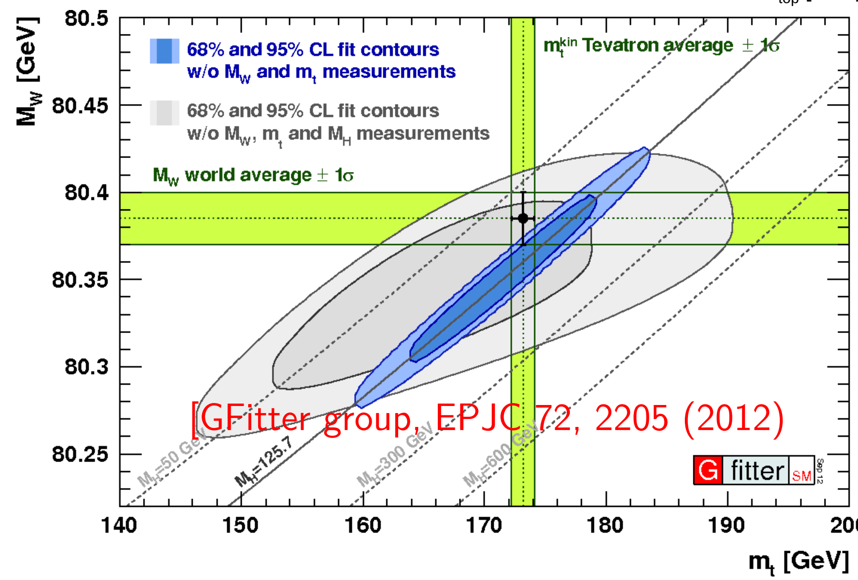
Radiative corrections $\Delta R \sim 4\%$:



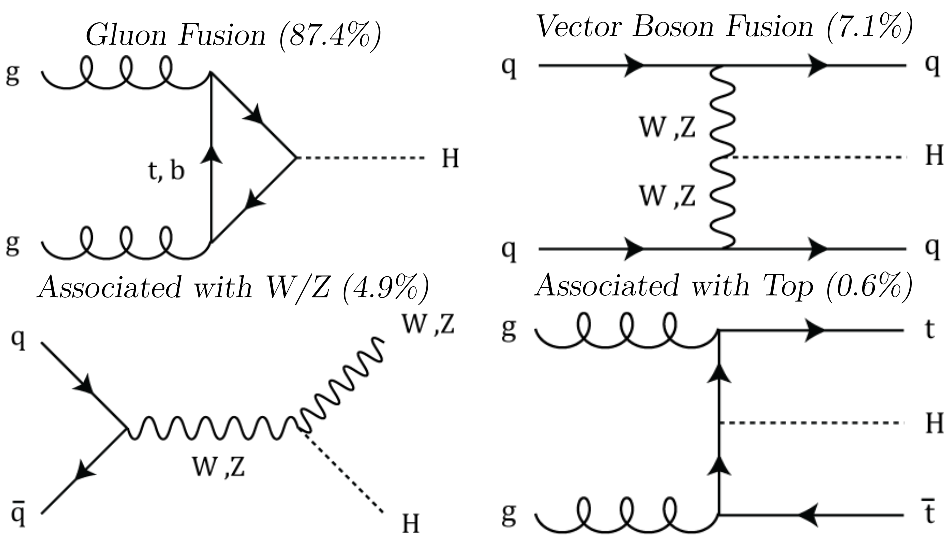
$\Delta R \sim m_t^2$ $\Delta R \sim \log m_H$

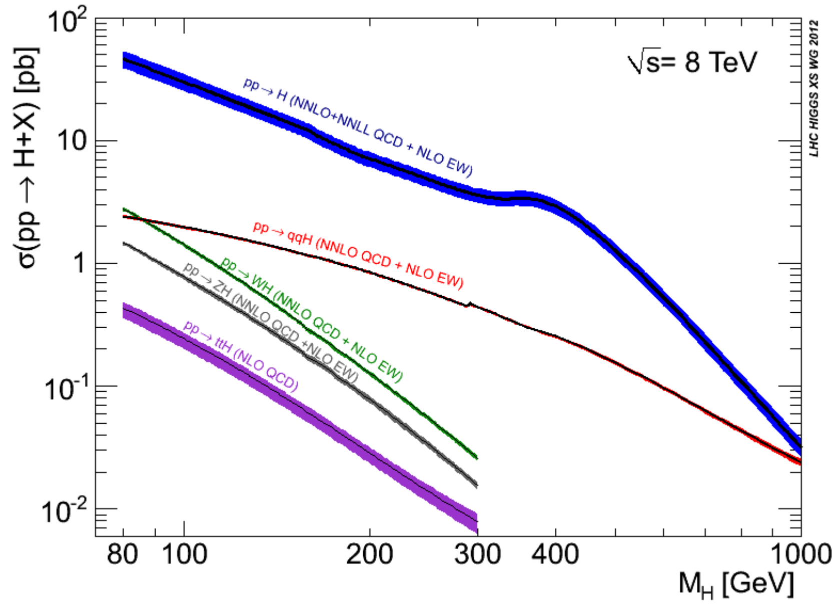
CMS: $m_t = 173.4 \pm 1.0$ GeV
Tevatron: $m_t = 173.2 \pm 0.9$ GeV





Observed agreement demonstrates impressive consistency of the SM



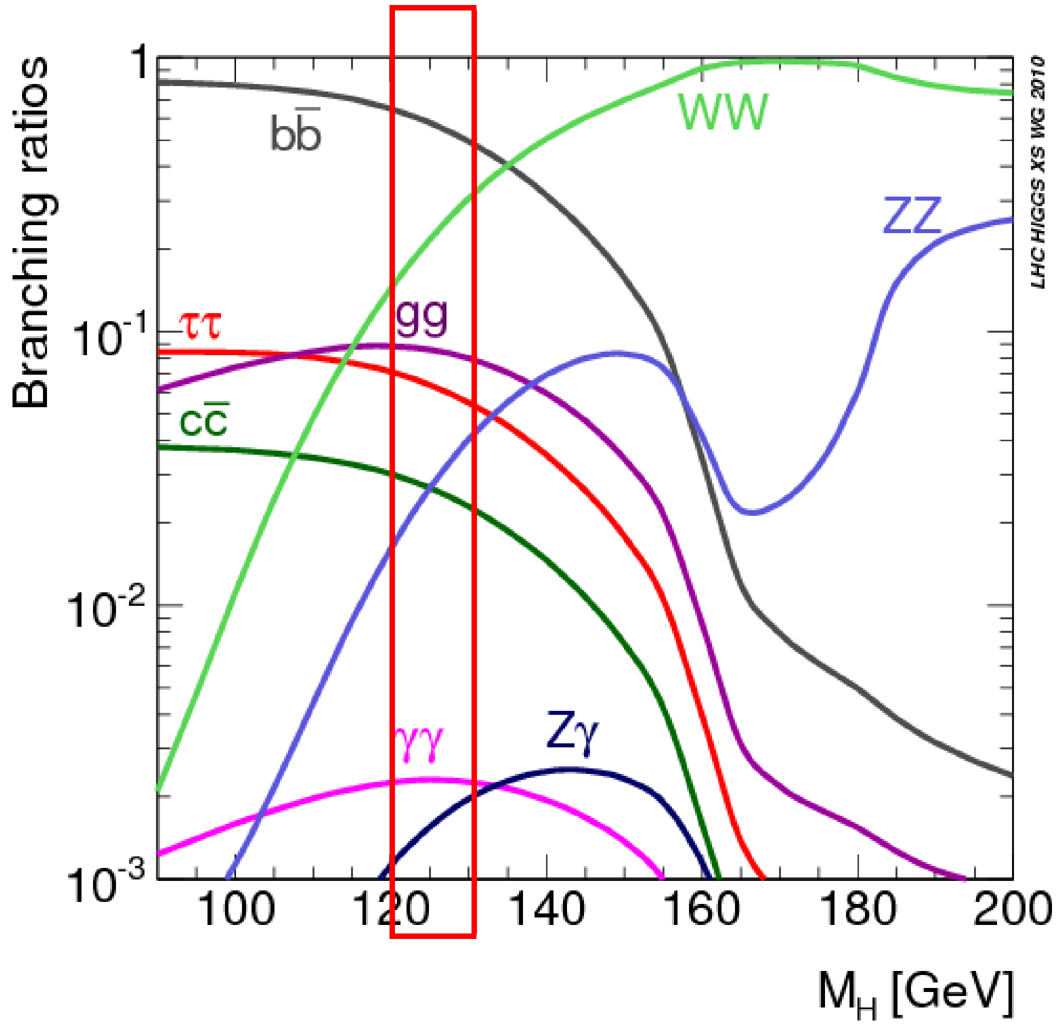


Gluon fusion (GF) *and* **Vector Boson Fusion (VBF)** *are the two most copious Higgs production processes at LHC: they provide wealth of information on its couplings to bosons and fermions today*

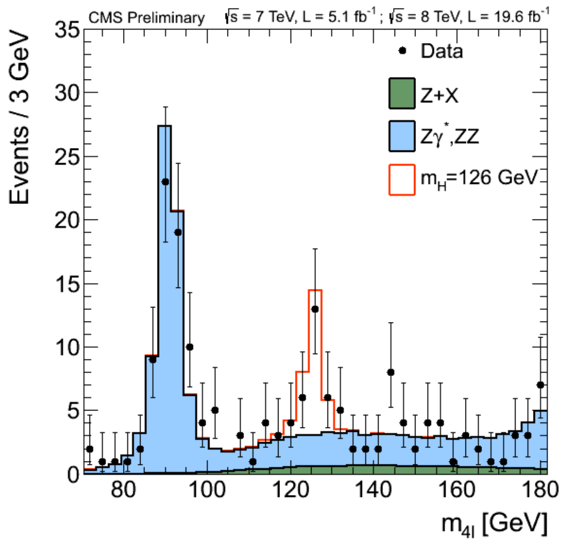
Very rich mass region but also very challenging...

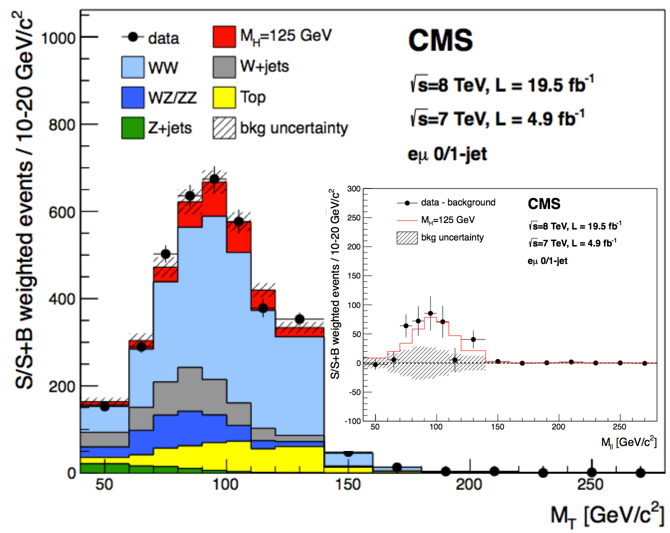
- 5 decay modes exploited: $\gamma\gamma, ZZ, WW, \tau\tau, bb$
- 2 best mass resolution decay modes (~1%): $\gamma\gamma, ZZ$
- Also includes searches in $\mathrm{H} \to \mathrm{Z}\gamma$ and $\mathrm{H} \to \mu^+\mu^-$

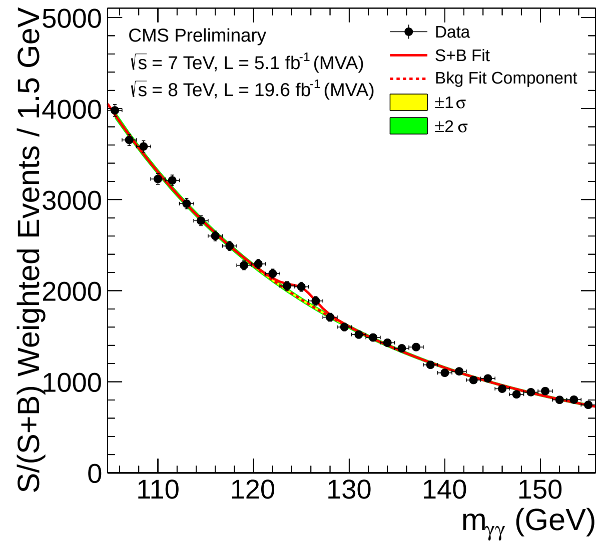
Decay	Exp. Sign. at 125.7 GeV	σ_M/M
H→ $\gamma\gamma$	3.9	1-2%
H→ZZ→4l	7.1	1-2%
H→WW→2l2ν	5.3	20%
H→bb	2.2	10%
H→$\tau\tau$	2.6	10%



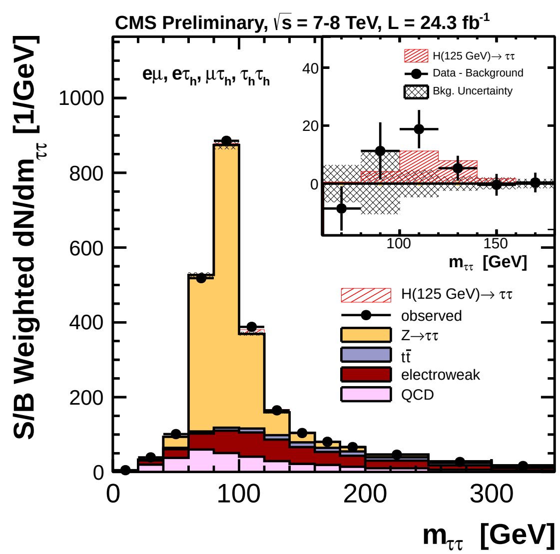
Higgs Results for 5 Main Channels

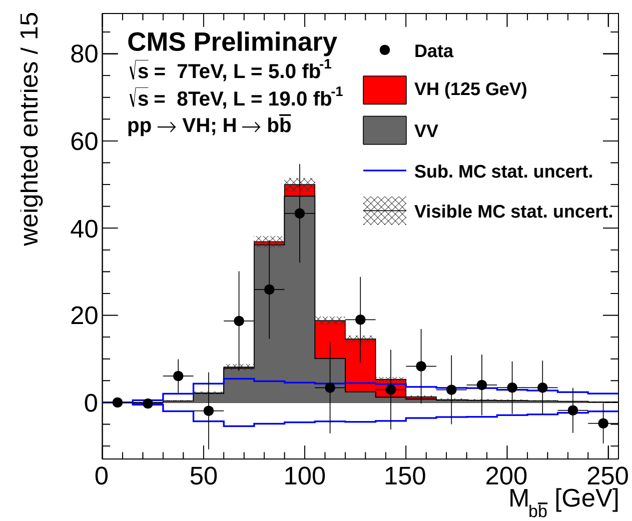






Solid signal in 3 bosonic decay channels and fermionic final states starting to build up excess

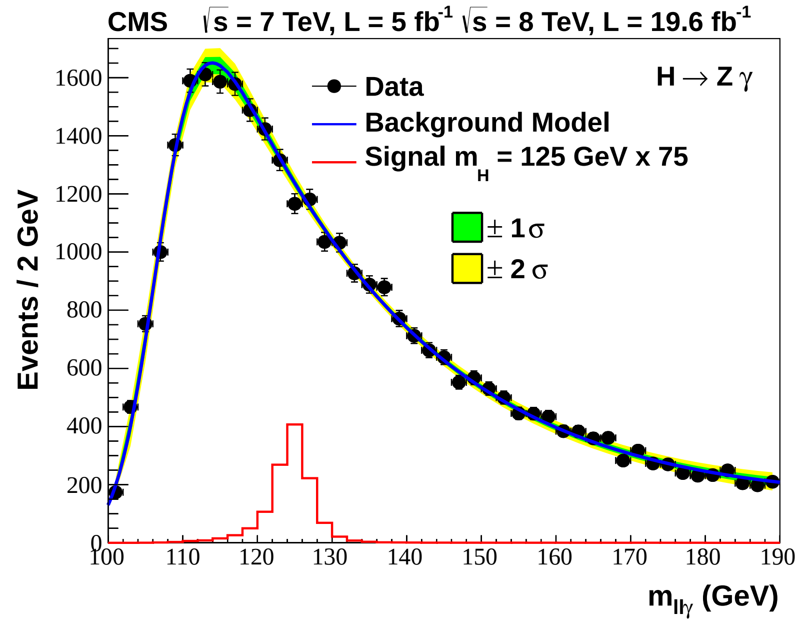


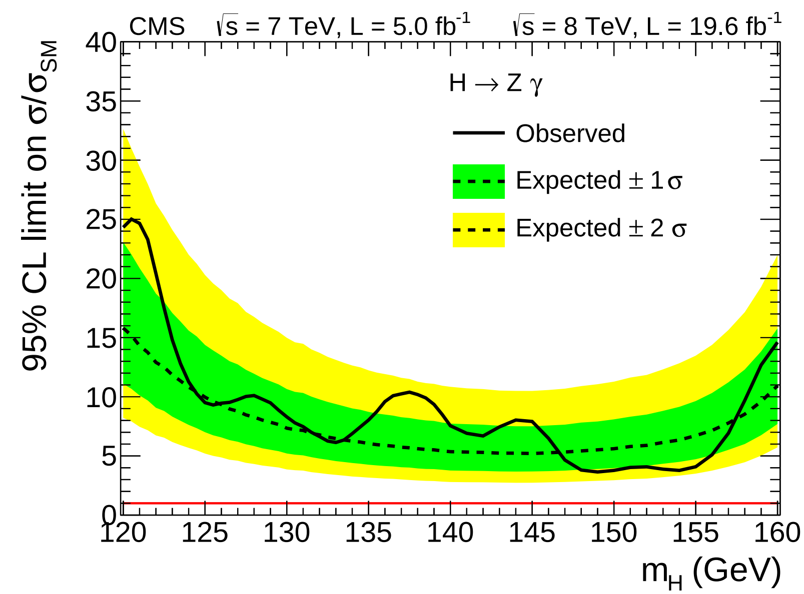


Allows test of many models with alternative EWSB

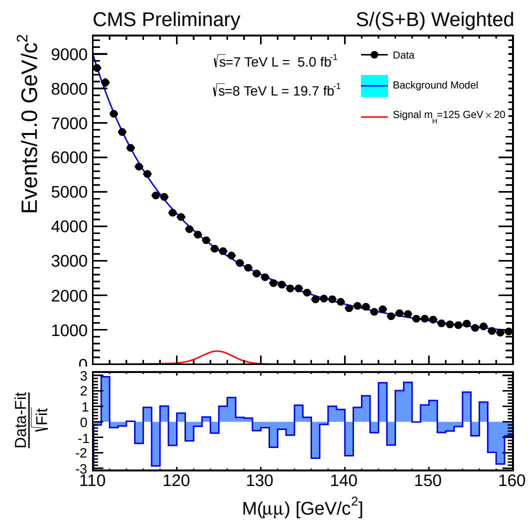
- $\mathcal{B}(\mathrm{H} \to \mathrm{Z}\gamma)$ comparable to $\mathcal{B}(\mathrm{H} \to \gamma\gamma)$, but $\mathcal{B}(\mathrm{Z} \to \mathrm{ll})$ suppresses signal by $\sim$20
- Search for a narrow llγ peak on top of a falling background
  - main backgrounds are pp$\to$Zγ and DY
  - events are classified according to topology of the leptons and the photon, and the photon shower shape
  - also includes **dijet tagged** events with VBF enriched signature

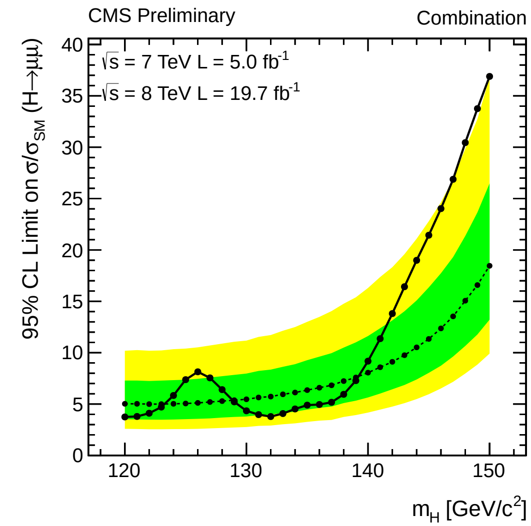
Albeit $\mathrm{H} \to \mathrm{Z}\gamma$ has not yet reached the SM sensitivity to distinguish SM from background, current limit excludes number of models with extended EWSB approaches





[arXiv:1307.5515 accepted by PLB]



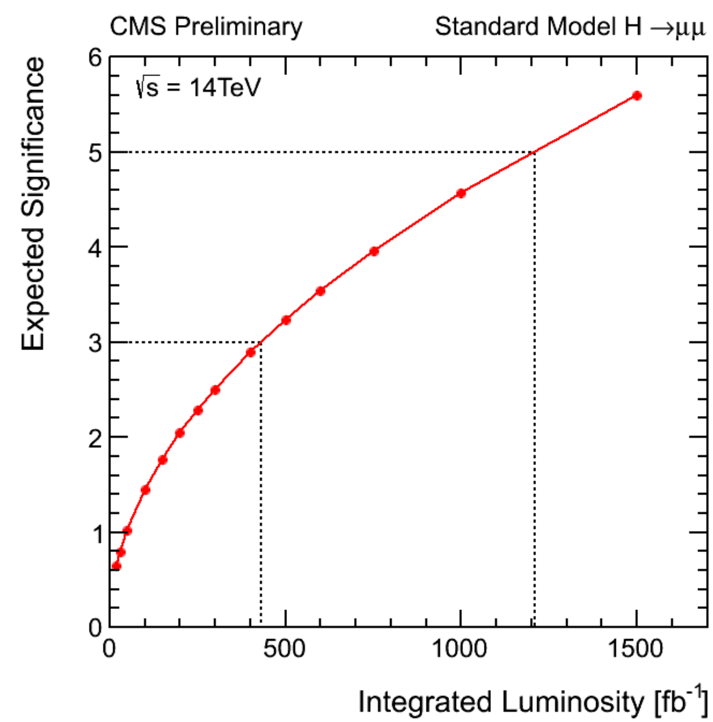


Allows direct study of coupling to two different leptons:

tests lepton flavor violation

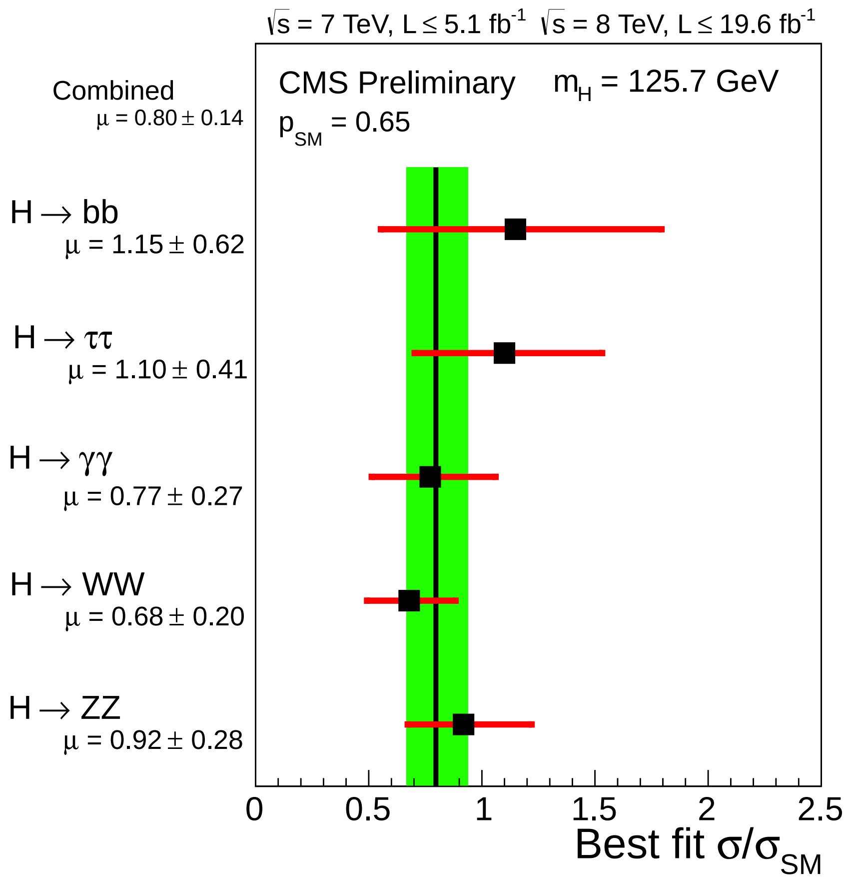
$\mathcal{B}(\mathrm{H} \to \mu\mu)/\mathcal{B}(\mathrm{H} \to \tau\tau) = m_\mu^2/m_\tau^2$

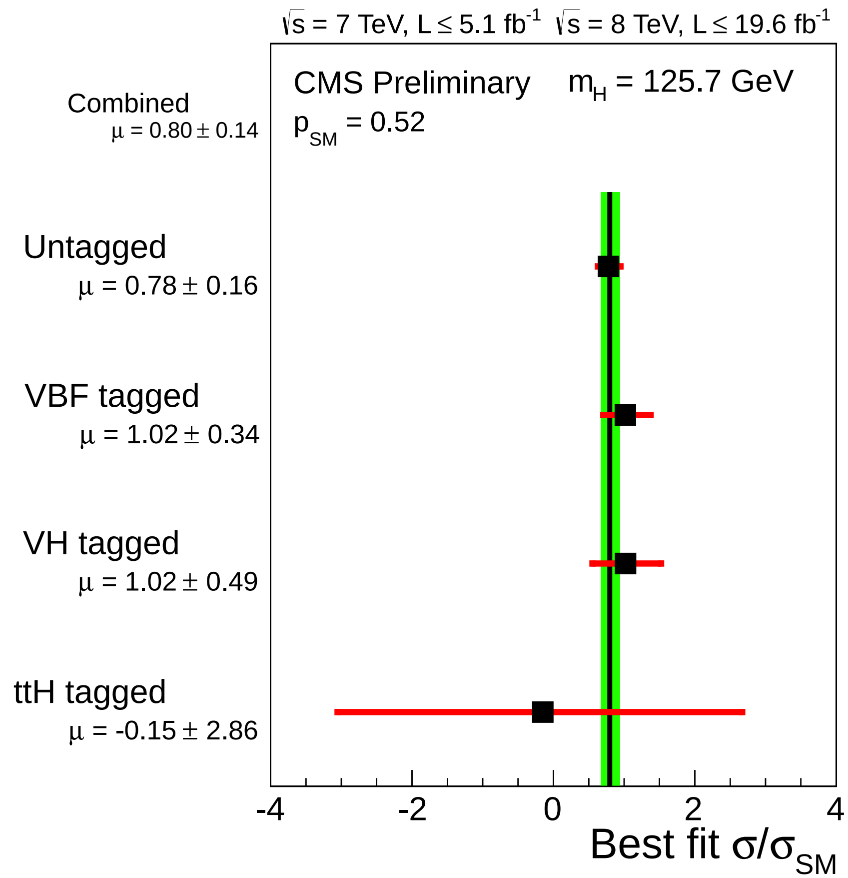
- Search for a narrow $\mu^+\mu^-$ peak on top of a falling background
  - signal to background marginal
  - main background is Drell-Yan
  - events are classified according to number of jets (≤ 2) and p_T $(\mu^+\mu^-)$
  - includes VBF enriched event class



HL-LHC with 3000 fb^{-1} at 14TeV offers new possibilities

[HIG-13-005]





Event yields in different production and decay modes are self-consistent

☞ Overall best-fit signal strength in the combination: $\boldsymbol{\sigma/\sigma_{SM} = 0.80 \pm 0.14}$

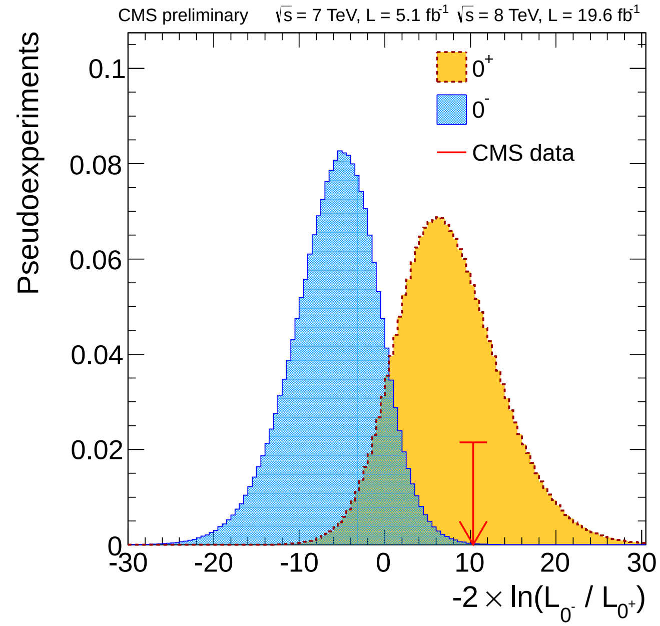
Spin and CP-parity hypotheses are discriminated by angular analysis

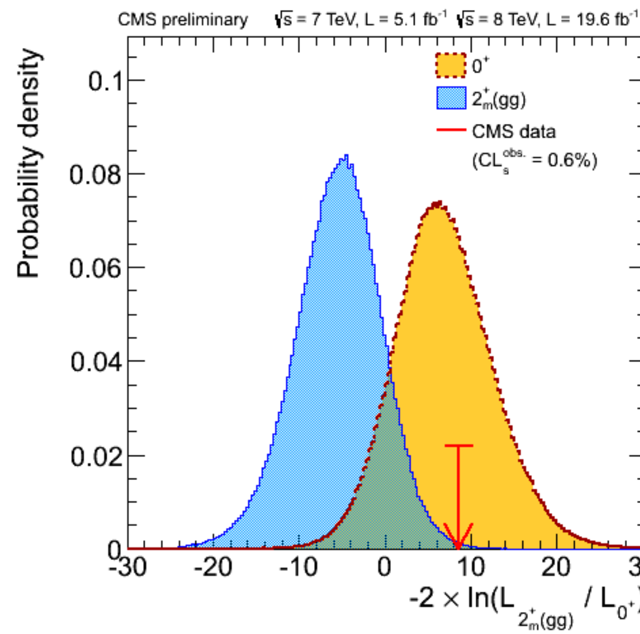
- Spin-0 and 2 are only allowed by $H \rightarrow \gamma\gamma$
- SM Higgs boson has to be CP-even
- WW (0-jet only) is most significant to disentangle spin-0 and spin-2 hypotheses

	ZZ	WW	Comb
exp.	6.8%	1.4%	0.2%
obs.	1.4%	14.0%	0.6%

The data disfavours the 0^- (2^+_m) hypothesis with 99.8% (99.4%) CL

The observation is well compatible with SM Higgs expectations (0^+)





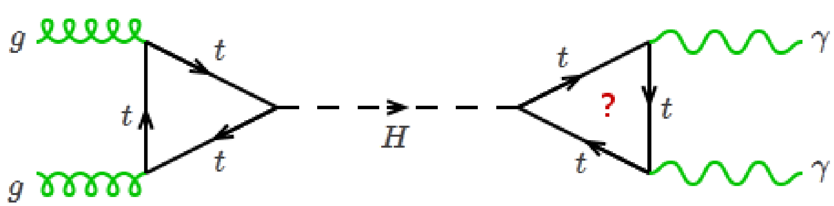
☞ Attach a modifier to the SM prediction

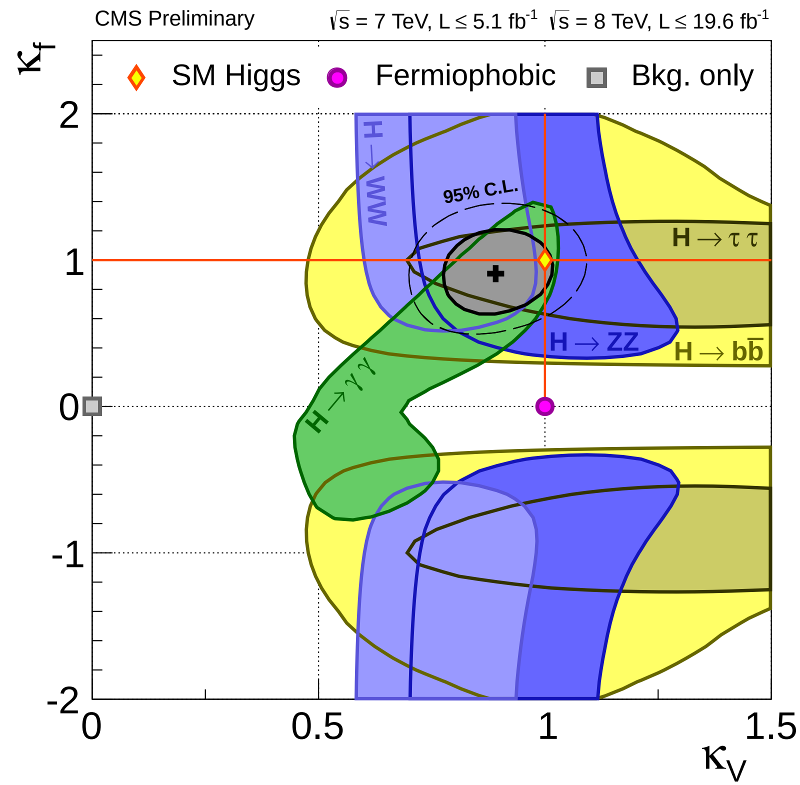
$$\sigma\mathcal{B}(ii \to H \to ff) \sim \frac{\Gamma_{ii}\Gamma_{ff}}{\Gamma_{tot}} = \sigma_{SM} \cdot \mathcal{B}_{SM}\frac{k_i^2 \cdot k_f^2}{k_H^2}$$

☞ Estimate Higgs boson couplings into "**Vectorial**" and "**Fermionic**" sets:

- H$\to$ $\gamma\gamma$ is the only channel that is sensitive to k_V or k_F relative sign
  - ➔ possible to sort out degeneracy

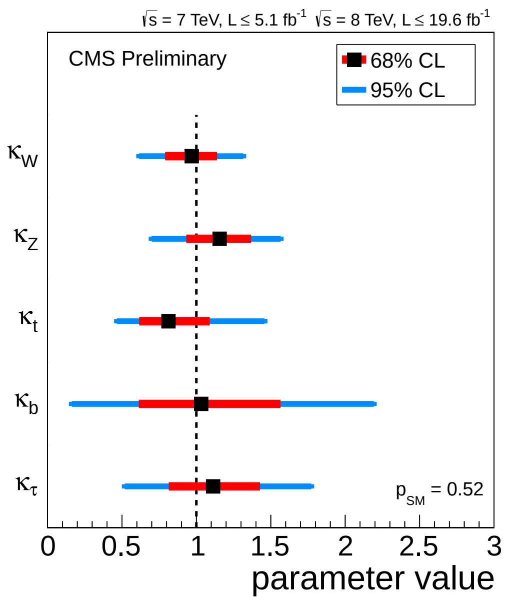
$\Gamma_{gg} \sim k_F^2$ $\Gamma_{\gamma\gamma} \sim |\alpha k_V + \beta k_F|^2$

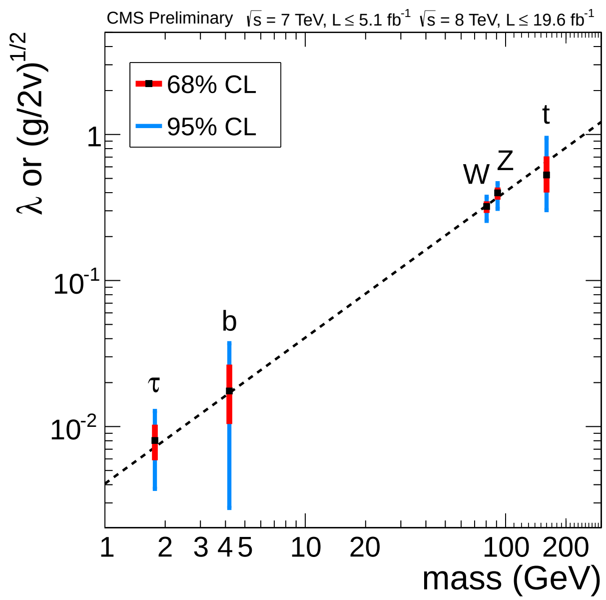


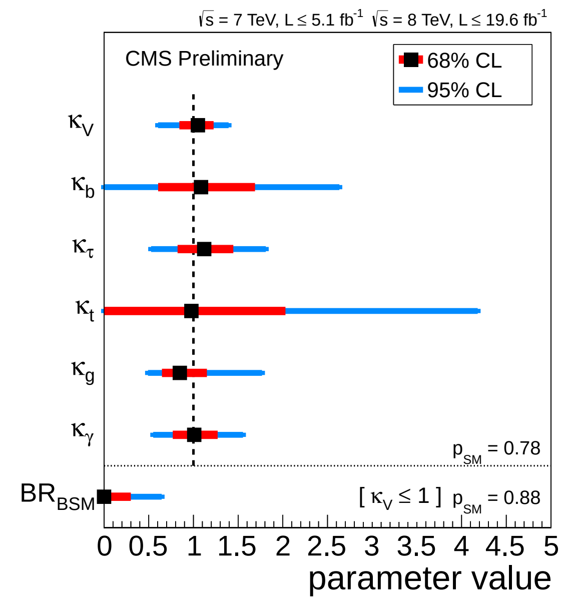


In agreement with the SM within uncertainties

Compatibility with the SM Higgs Boson Couplings







The generic five-parameter model not effective loop couplings
(the SM structure is assumed for loop-induced couplings)

Not effective loop couplings as function of the mass

New particles can modify the loop-mediated couplings and contribute to the total width

$$\Gamma_{tot} = \sum \Gamma_{i(SM)} + \Gamma_{BSM}$$

No significant deviations from the SM Higgs boson are found so far

A non-zero partial decay width to invisible particles could provide evidence for NP

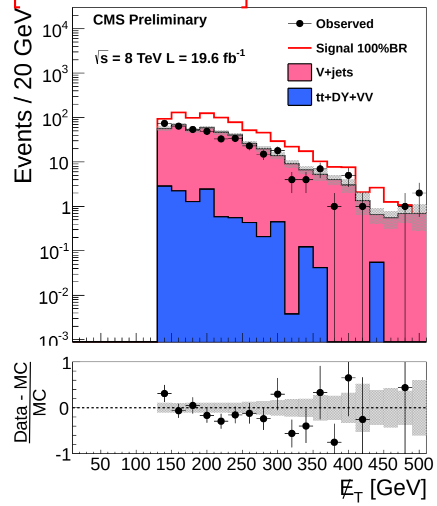
☞ Current direct 95% CL on $\mathrm{BR_{inv}}$ using **VBF and VH channels:**

Channel	obs.	exp.
VBF	0.69	0.53
VH	0.75	0.91
Comb.	0.54	0.46

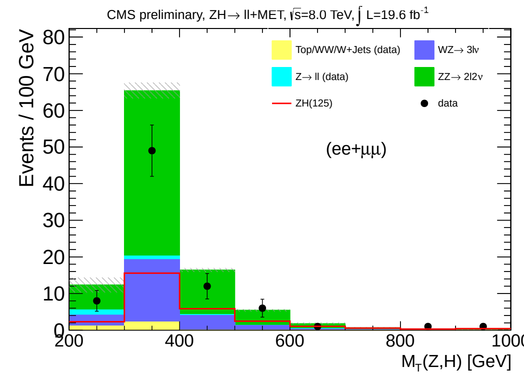
☞ Projected sensitivity to $\mathrm{BR_{inv}}$ for **ZH, Z $\rightarrow$** ll channel

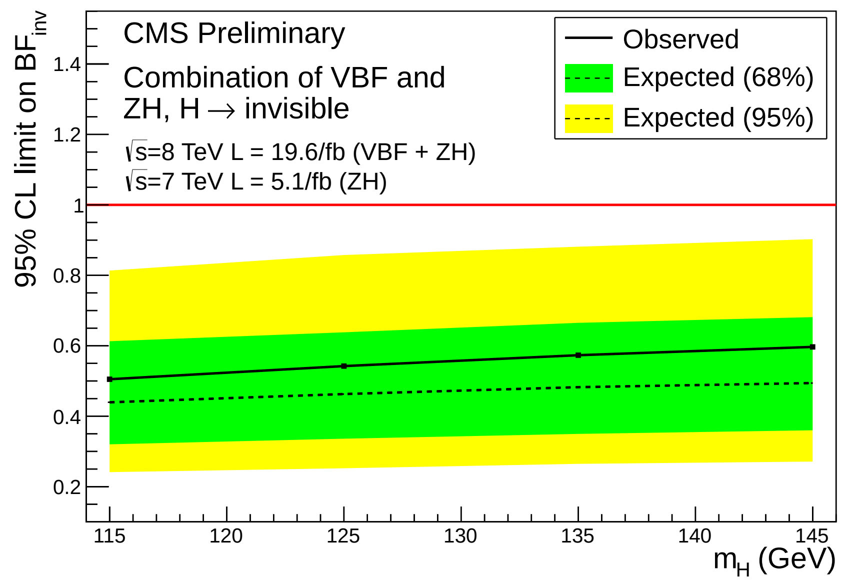
- ➠ about 10% with $3\mathrm{ab}^{-1}$ (HL-LHC)
- ➠ if it is combined with the other SM channels, precision could be **pinned down to 5%**

[HIG-13-013] VBF

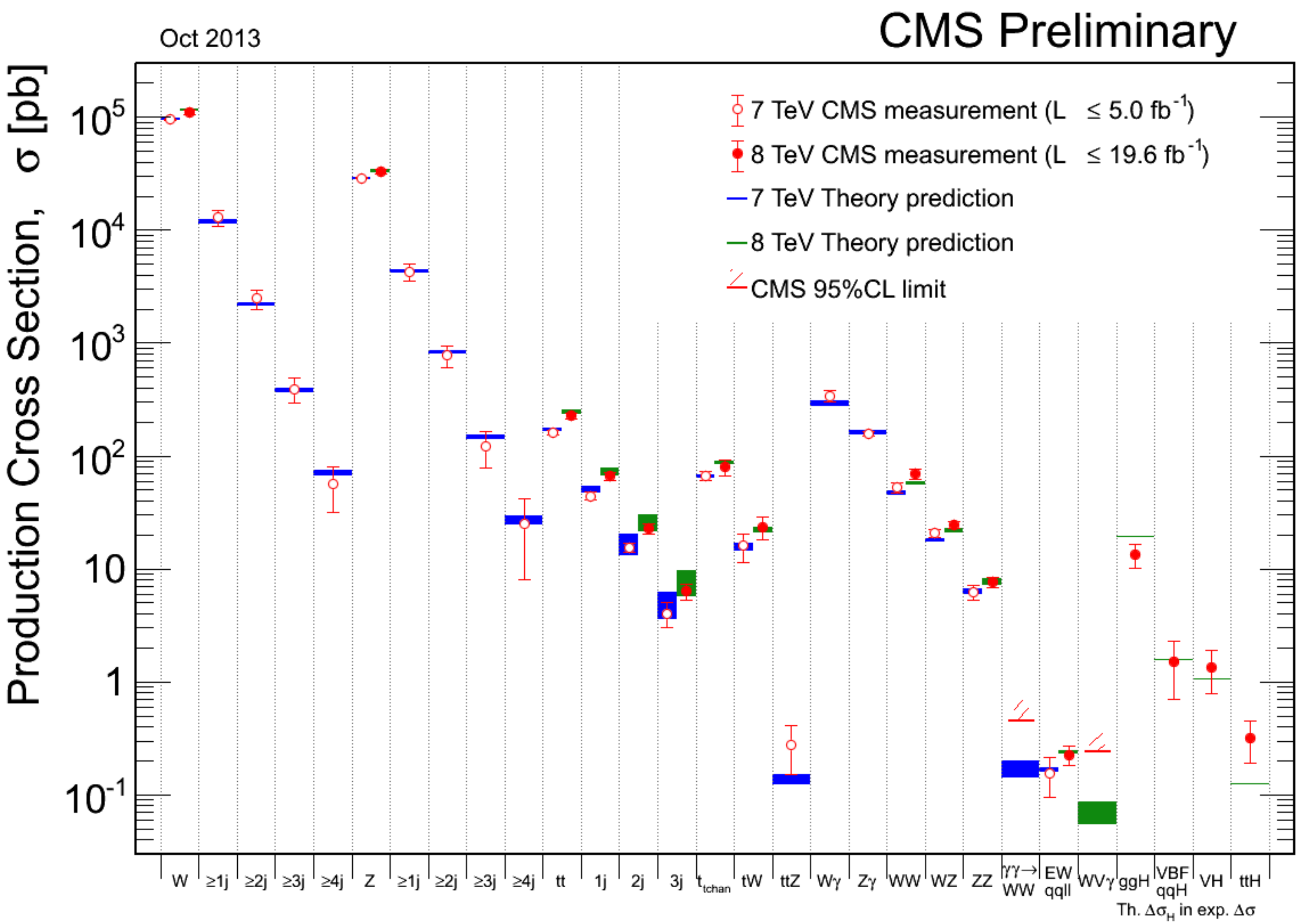


[HIG-13-018] VH





Consistent with global coupling fit: $\mathrm{BR_{inv}} < 0.52$ at 95% CL



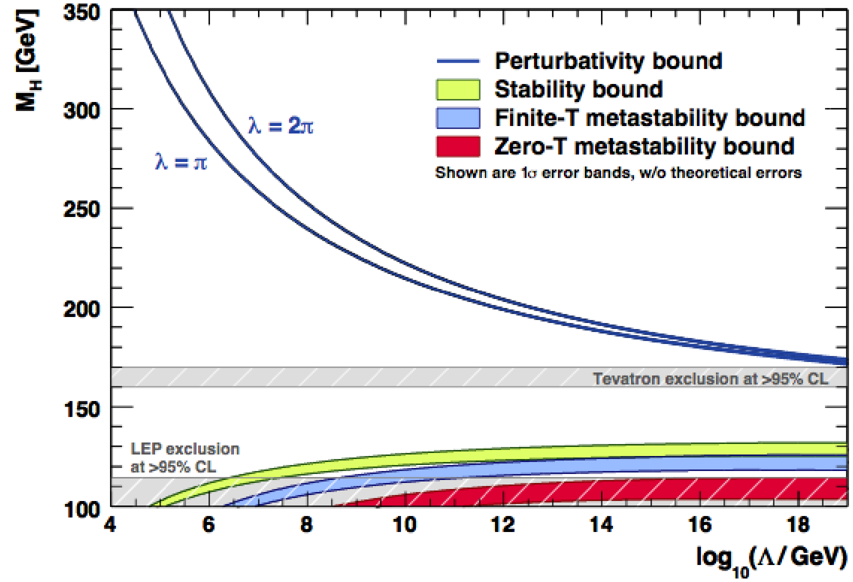
Dedicated test of the SM at new energy regime including the Higgs sector

The boson that we found looks rather "standard" scalar at first sight:

Unstable vacuum at the Plank scale!

- Experimental clues of the BSM physics
  - Dark Matter
  - Baryogenesis
  - Neutrino mass

[J.Ellis, et al., Phys. Lett. **B679**:369-375 (2009)]

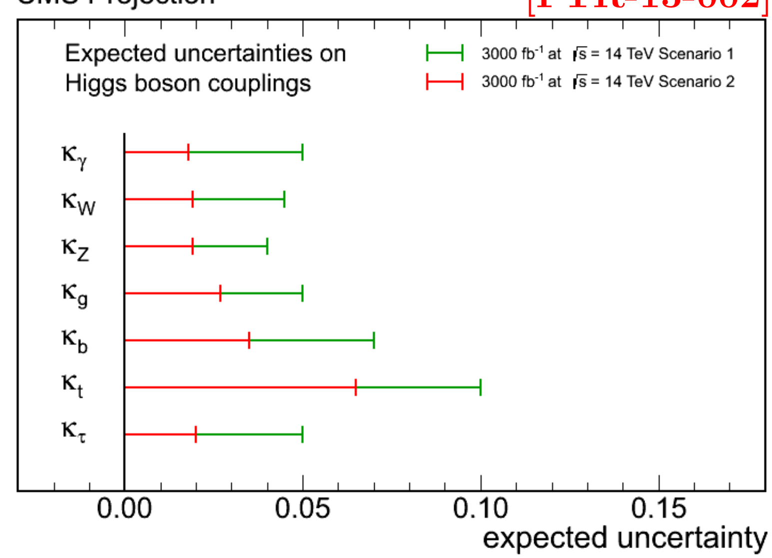


- **Indirect Searches**
  - precision coupling measurement

$$\Delta k/k \propto 1/M_{\Lambda}^2$$

  - extended Higgs sector
  - $B_{s,d} \to \mu^+\mu^-$, TGC, etc

CMS Projection [FTR-13-002]

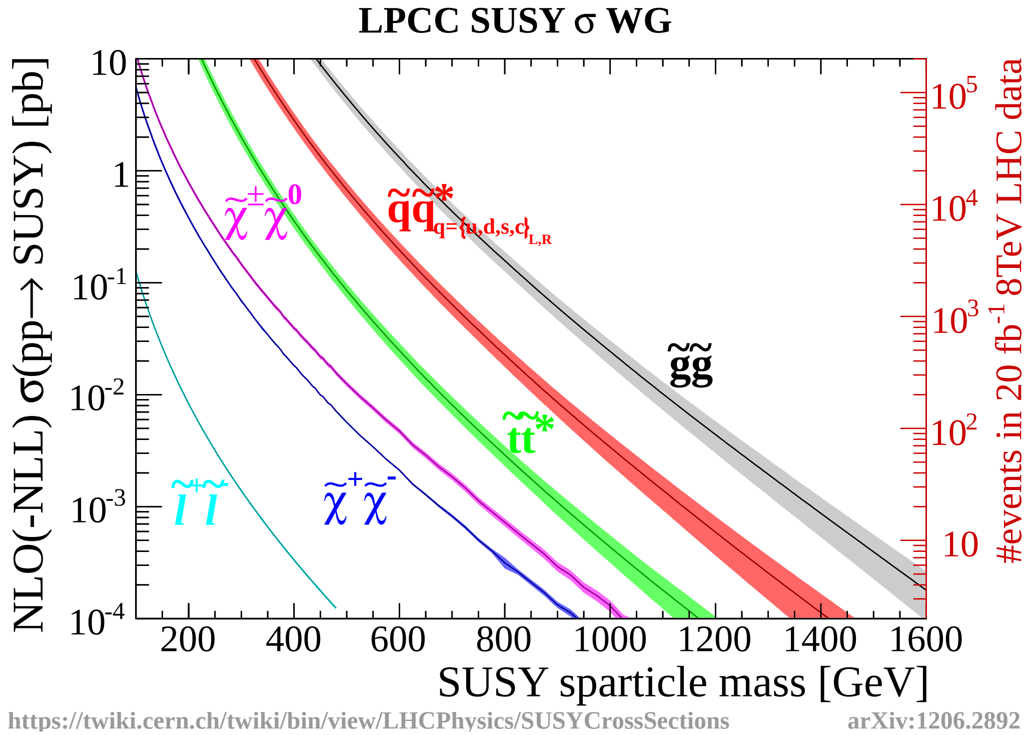


- **Direct Searches of BSM**
  - SUSY, DM, heavy resonances

$\Delta k/k$ ~10(1)%⇒ M_{Λ} ~1-1.5(3-4) TeV

SUSY Searches

- ☞ Constrained SUSY models like the **CMSSM** are put under the pressure by the LHC limits: $m_{\tilde{q}} \simeq m_{\tilde{g}} \geq 1.4$ TeV
- ☞ Interpretation shifts towards "**Natural SUSY**", i.e. 3rd generation squark searches
  - ➠ assumes 100% BR for decays considered in **RPC**

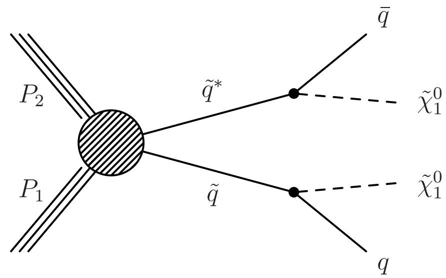


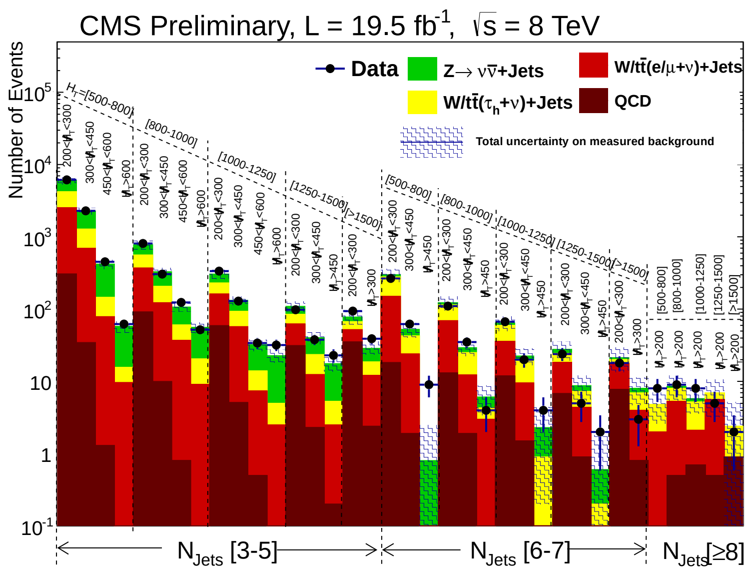
[arXiv:1110.6926]

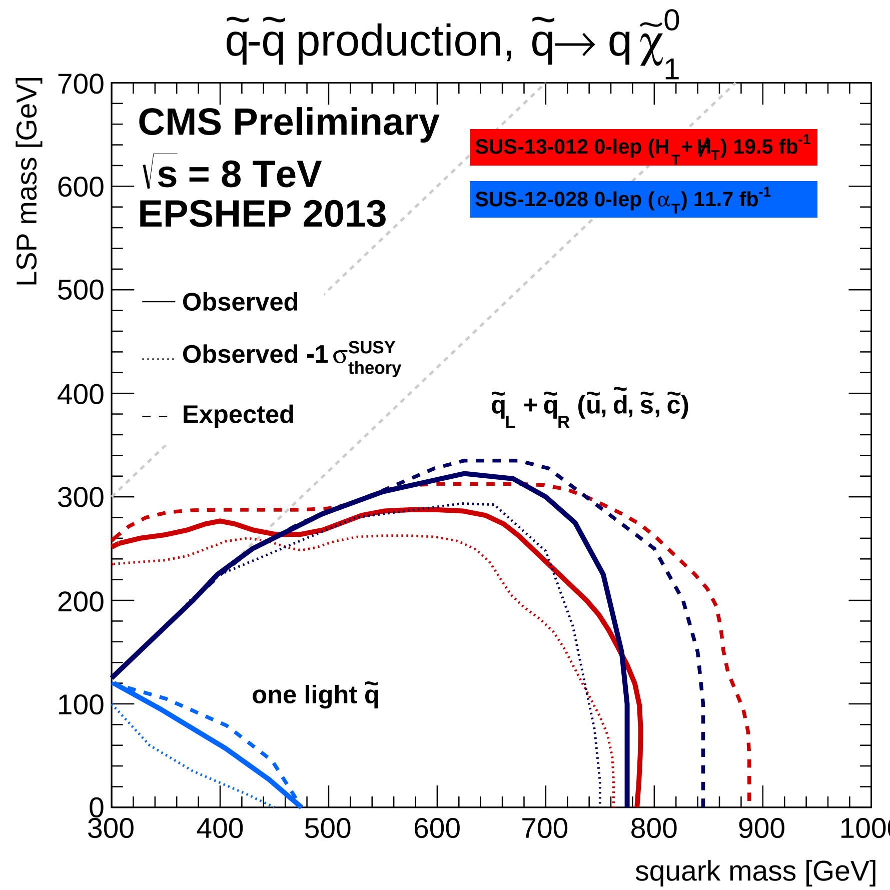
$$m_{\tilde{g}} \leq 1500 \text{ GeV}$$
$$m_{\tilde{t},\tilde{b}_L} \leq 700 \text{ GeV}$$
$$m_{\tilde{\chi}^0_{1,2},\tilde{\chi}^+_1} \leq 350 \text{ GeV}$$

Large 1st and 2nd generation squarks, bino/wino, sleptons can be heavy without compromising **naturalness**

- ☞ **"Stong SUSY":** $pp \to \tilde{q}\tilde{q}/\tilde{g}\tilde{g}$
  - ➠ **large σ, jets, E_T^{miss}, (leptons)**
- ☞ **"Elektroweak SUSY":** $pp \to \tilde{\chi}^{\pm}\tilde{\chi}^{0(\mp)}/\tilde{l}\tilde{l}$
  - ➠ **small σ, lepton(s)+E_T^{miss}**







☞ Traditional $\mathbf{Jets}+\boldsymbol{E}_{\boldsymbol{T}}^{\mathbf{miss}}$ search

➠ uses simple kinematic variables to categorize events

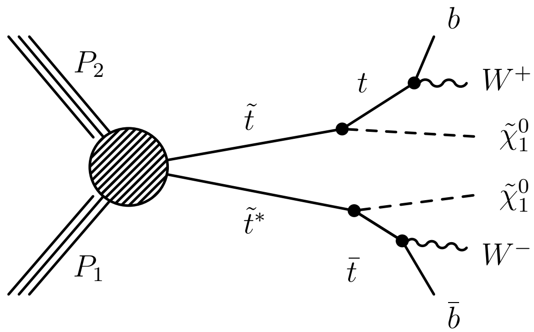
Observed numbers of events are consistent with the SM expectations

Exclusion limit for squark in GeV

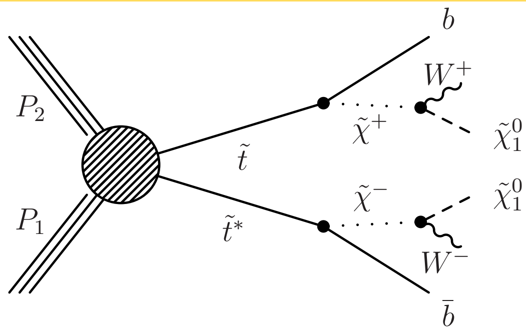
$\mathrm{m_{SUSY}} = \mathrm{m_{\tilde{q}}}$	$\tilde{u}_L \to q\tilde{\chi}_1^0$	$\tilde{q} \to q\tilde{\chi}_1^0$
Squark limit	500	750
No limit for $\mathrm{m_{LSP}}$	120	300

[SUS-13-011]

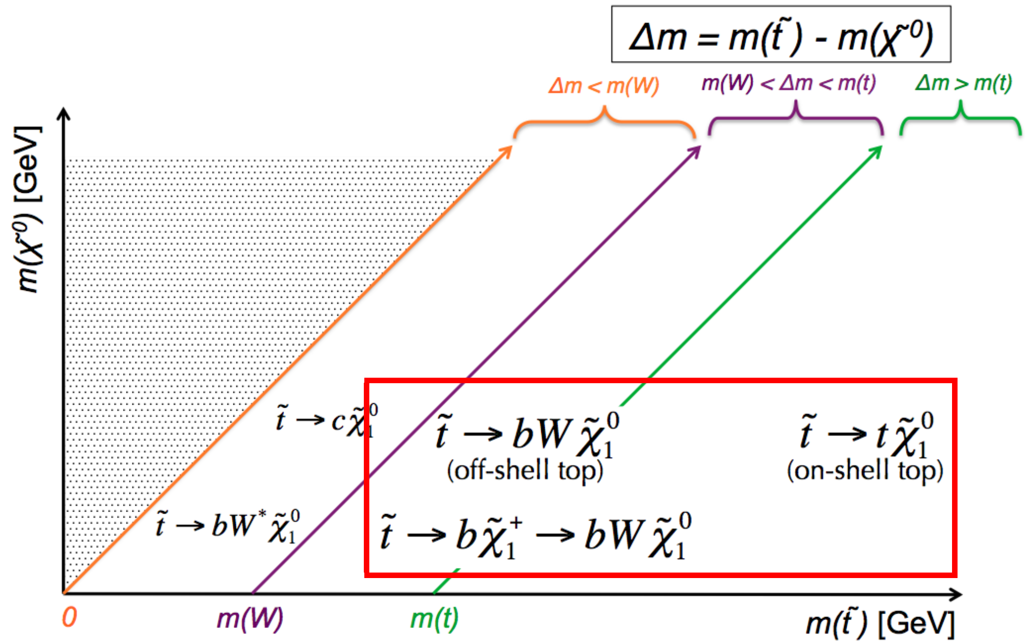
$\tilde{t}\tilde{t} \to t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$



$\tilde{t}\tilde{t} \to b\bar{b}\tilde{\chi}_1^+\tilde{\chi}_1^- \to b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$



Model Parameter Space

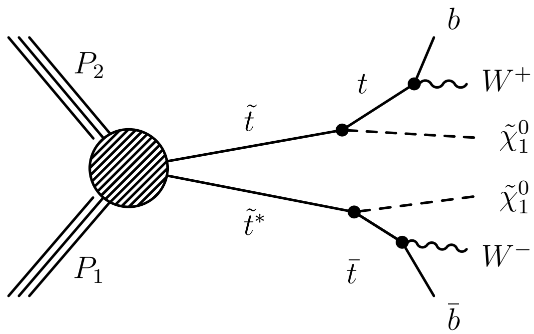


- Similar to $t\bar{t}$ signature with MET from undetected $\tilde{\chi}_1^0$ LSP
  - focus on 1e/μ channel $\to$ large $\mathcal{B}$ and clean

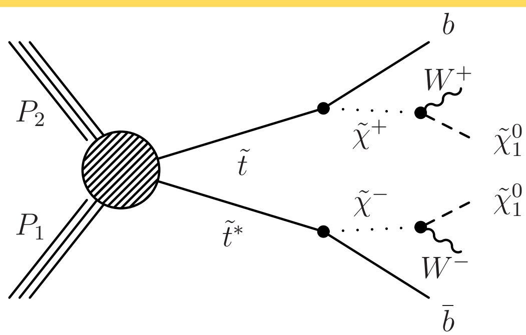
- **Analysis challenge**
  - **small mass** ($\sim$ m_t): sizable XS, large $t\bar{t}$
  - **high mass** ($>>$ m_t): different kin., low XS

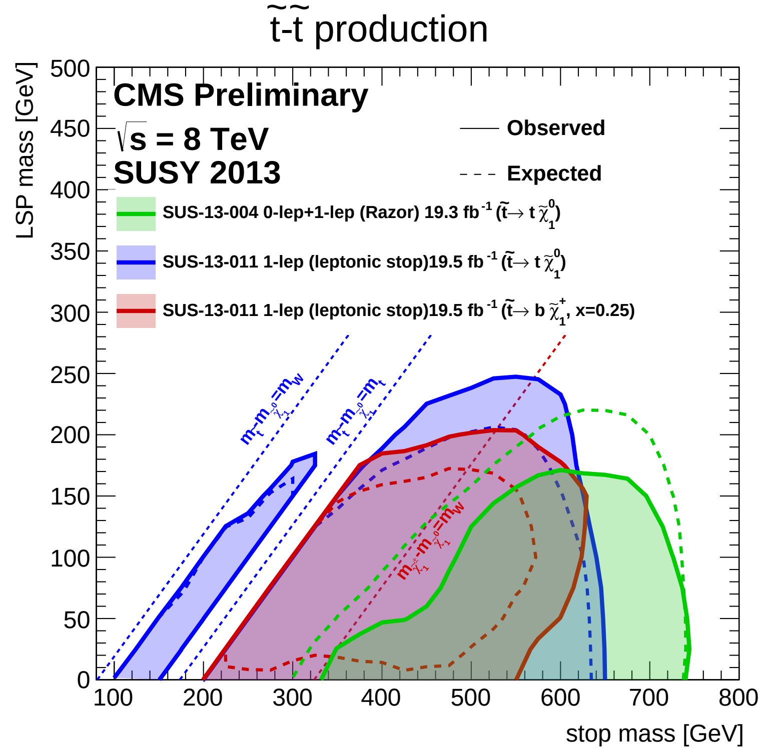
Discriminate against background using BDT optimizatior for kinematical variables

$\tilde{t}\tilde{\bar{t}} \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$



$\tilde{t}\tilde{\bar{t}} \rightarrow b\bar{b}\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$





☞ Similar to $t\bar{t}$ signature with MET from undetected $\tilde{\chi}_1^0$ LSP

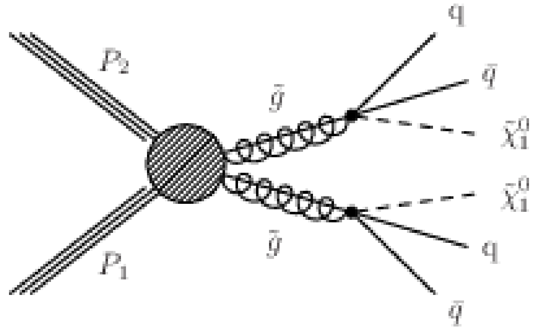
➠ focus on 1e/μ channel $\rightarrow$ large $\mathcal{B}$ and clean

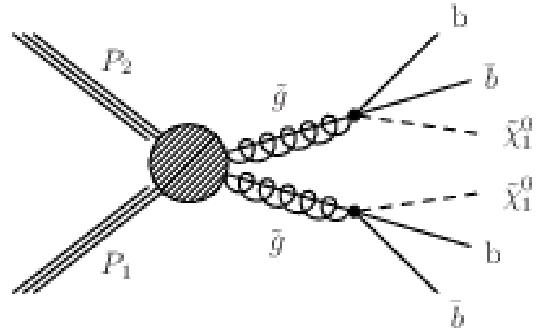
☞ Analysis sensitive to $\Delta M > m_t$ and $\Delta M < m_t$ **but not $\Delta M \sim m_t$**

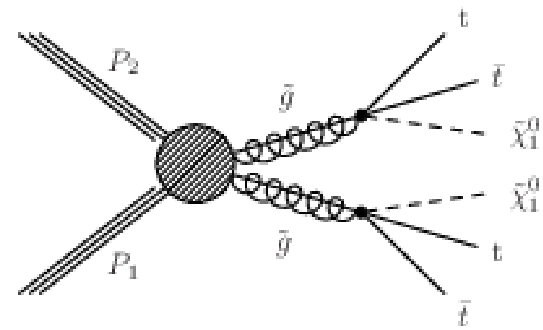
Exclusion limit for stop in GeV

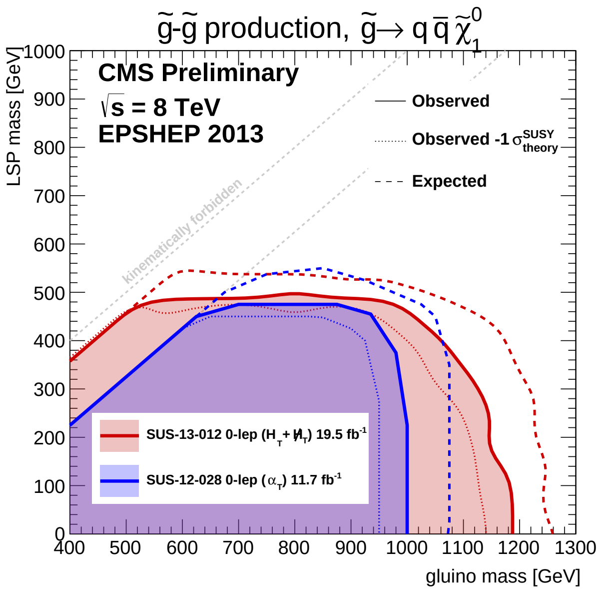
$m_{SUSY} = m_{\tilde{t}}$	$\tilde{t} \rightarrow t\tilde{\chi}_1^0$
Stop limit	625
No limit for m_{LSP}	225

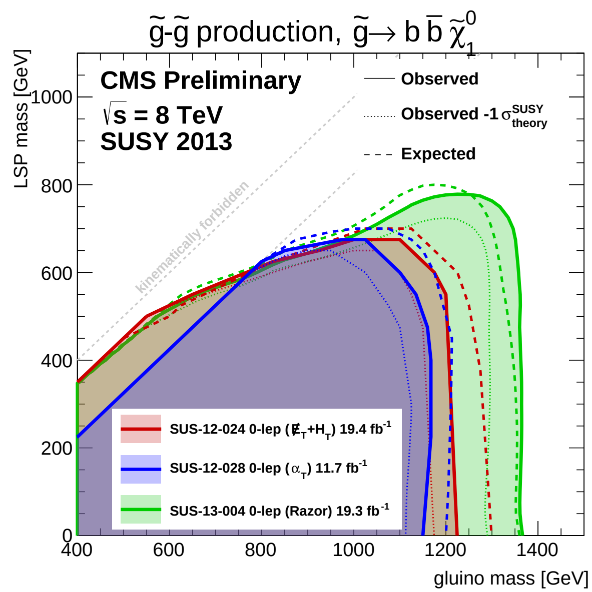
Gluino Mediated Production of Squarks

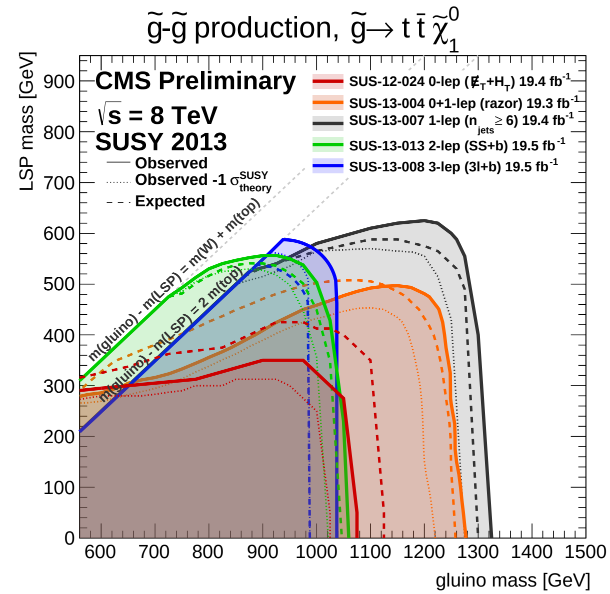












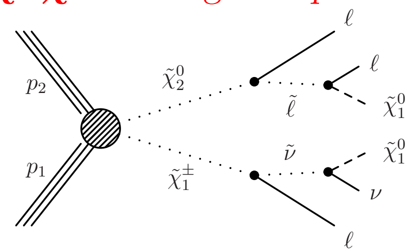
Signature:	Signature:	Signature:
$\mathbf{Jets + H_T + E_T^{miss}}$	$\mathbf{Jets + btag + E_T^{miss}}$	$\mathbf{0/1lep + 2btag + E_T^{miss}}$

$\mathrm{m_{SUSY} = m_{\tilde{g}}}$	$\tilde{q} \to q\tilde{\chi}_1^0$	$\tilde{b} \to b\tilde{\chi}_1^0$	$\tilde{t} \to t\tilde{\chi}_1^0$
Gluino limit	1200	1350	1300
No limit for $\mathrm{m_{LSP}}$	500	800	600

SUSY: EWK SUSY Production with Leptons

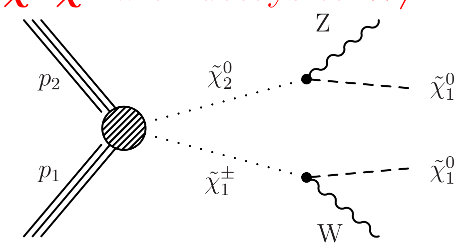
Search for Electroweak SUSY Production chargino, neutralino and sleptons using leptonic states

$\tilde{\chi}^{\pm}\tilde{\chi}^{0}$ *with light sleptons*



3l, same-sign 2l

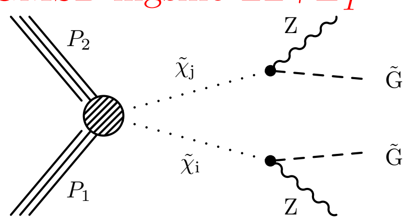
$\tilde{\chi}^{\pm}\tilde{\chi}^{0}$ *with decays to W/Z*



3l, Z(ll)V(jj)

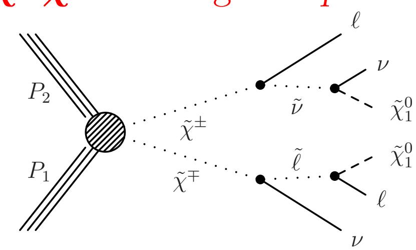
Broad array of searches targeting variety of final states

GMSB higsino ZZ+E_T^{miss}



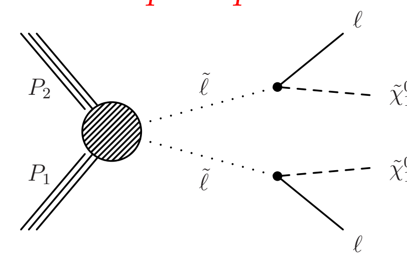
4l, 3l, Z(ll)V(jj)

$\tilde{\chi}^{+}\tilde{\chi}^{-}$ *with light sleptons*

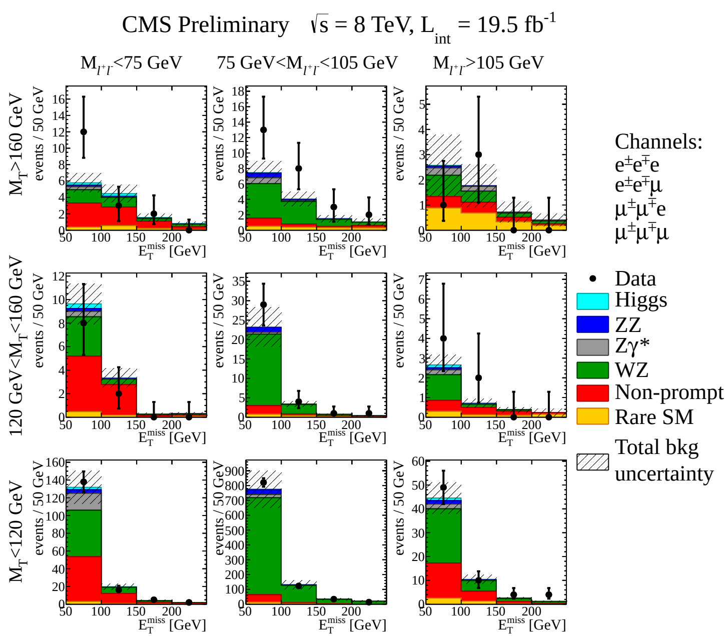


opposite-sign 2l

Direct slepton production



opposite-sign 2l

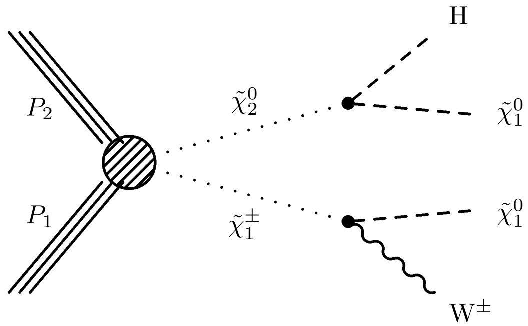


☞ Lepton flavor categories:

- ➠ 3l, OSSF pair (shown)
- ➠ 3l, no OSSF pair
- ➠ SS 2l+τ_{had}
- ➠ OS eμ+τ_{had}

Data consistent with background over range of kinematical regions, lepton categories

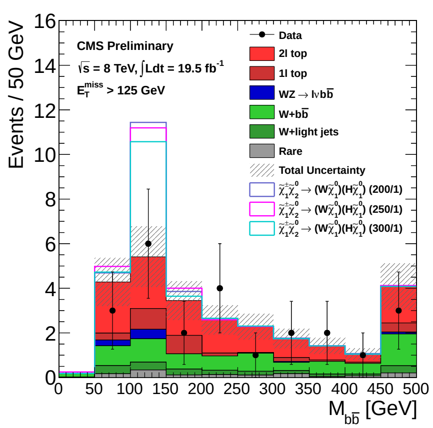
Novel effort search for Electroweak SUSY Production chargino, neutralino using *in final states with a Higgs boson*

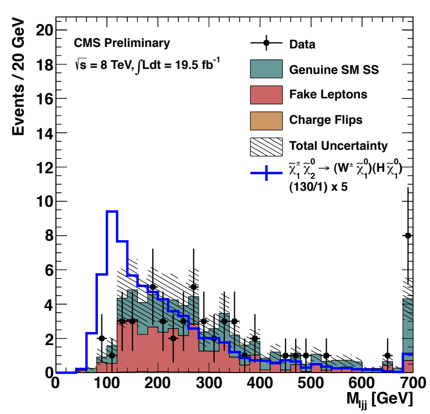


Unexplored final state WH+E_T^{miss}

☞ $\mathrm{H} \to \mathrm{bb}, \mathrm{W(l\nu)W(jj)}, ZZ, \tau\tau$

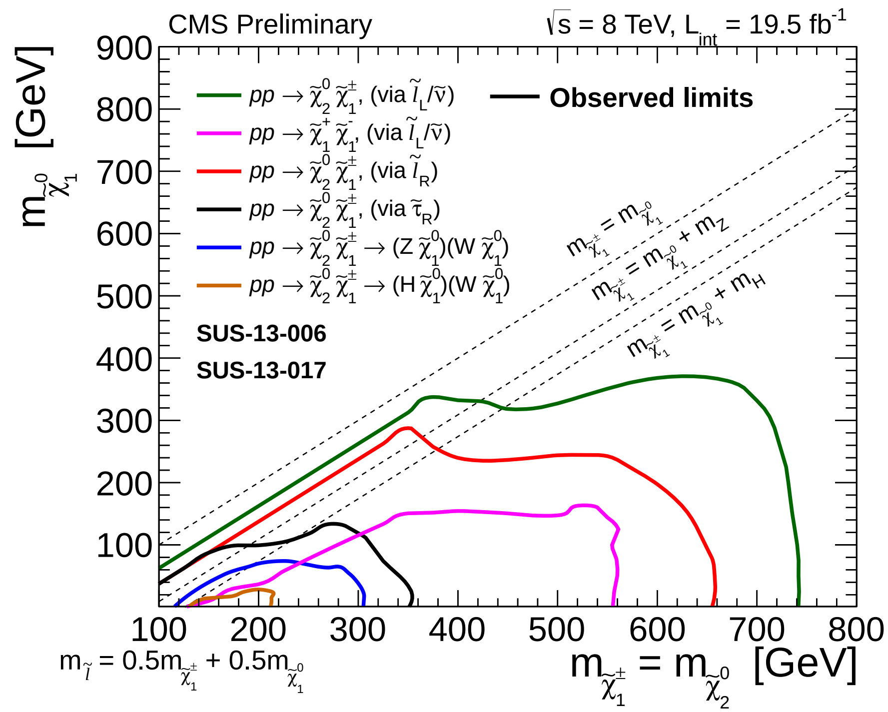
➠ signature: 1l, SS 2l, $\geq$ 3l





No evidence for a peak in m_{bb}, m_{ljj}

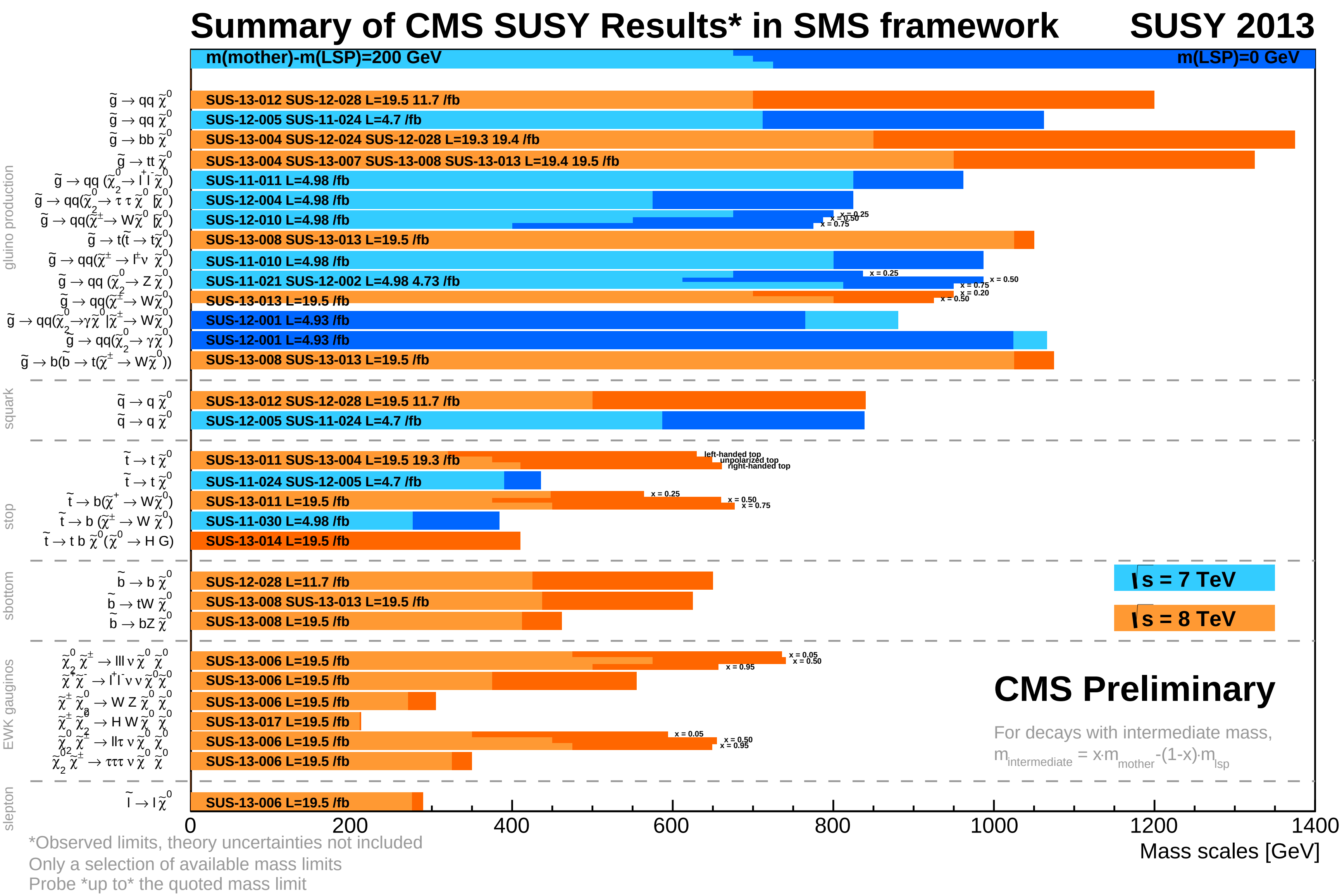
Search for Electroweak Production of Gaugino and Sleptons



Exclusion limit for gaugino in GeV

$m_{SUSY} = m_{\tilde{\chi}^\pm}$	$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$	$pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$
Gaugino limit	750	550
No limit for m_{LSP}	400	200

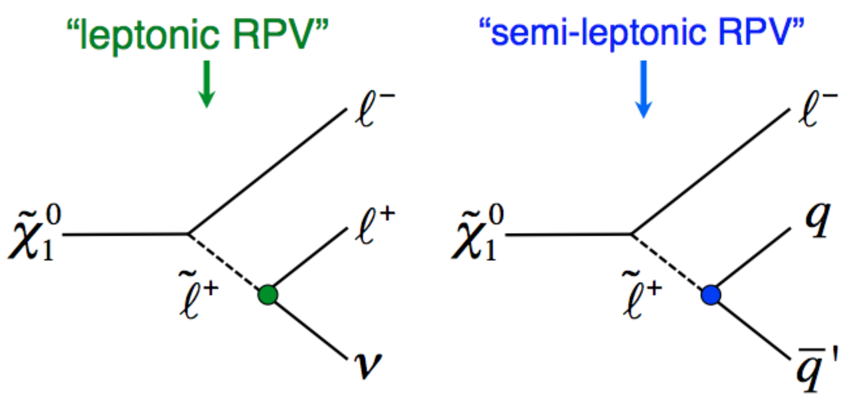
Probe sleptons up to $m_{\tilde{l}}$ ~280 GeV



Impressive variety of SUSY searches have been peformed, but only limits so far...

- ☞ **Proton stability** forbids simultaneous $\not{L}$ and $\not{B}$
  - ➠ impose R-parity in MSSM
  - ➠ two other possibilities $\not{L}$ or $\not{B}$
  - ➠ LSP is not stable (DM candidate?)
- ☞ $\not{L}$: LSP will decay to two leptons

$$\Delta L_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \ldots$$

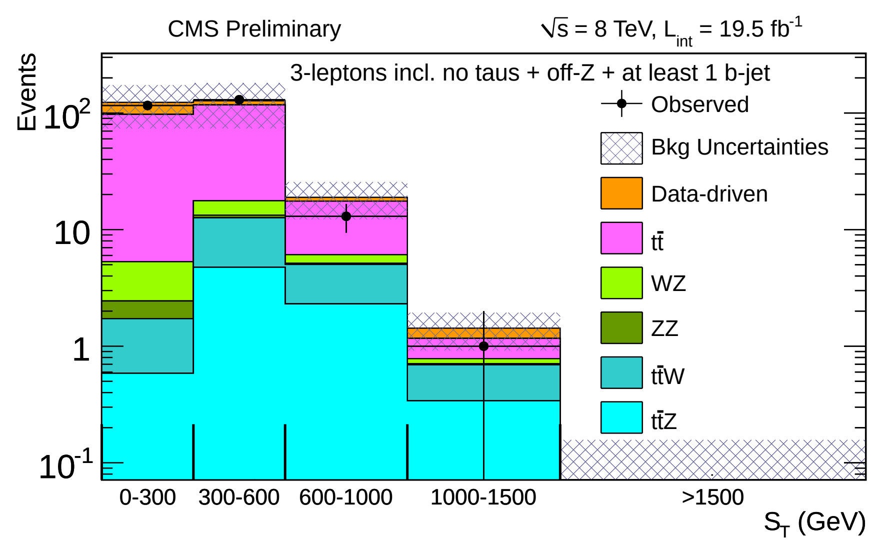


Unstable LSP significantly reduces MET, additional objects

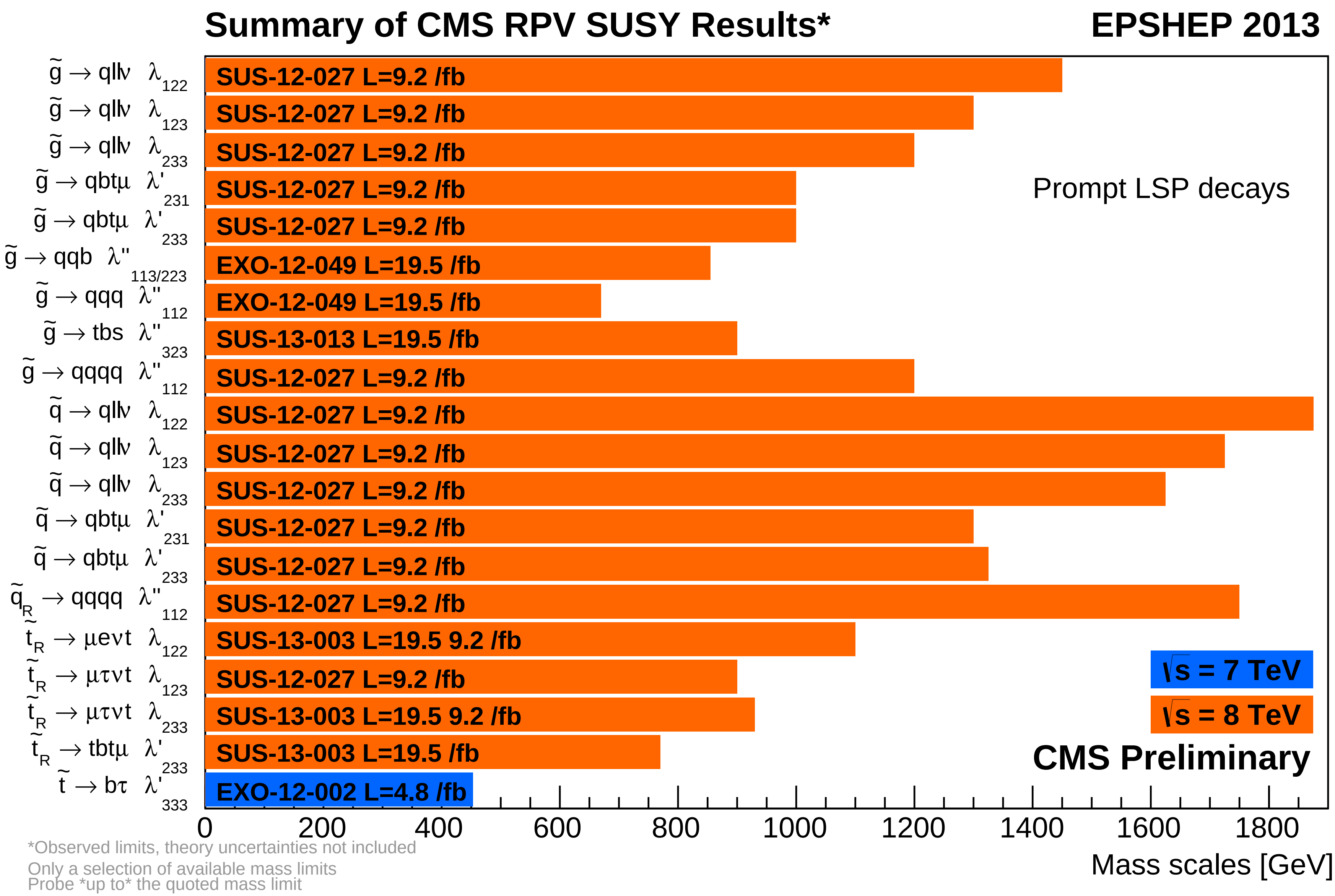
- ☞ Search for anomalous production with **≥3-leptons and at least 1 b-jet**
- ☞ Use event energy scale as sensitive observable

$$\mathbf{S_T = \Sigma_{jet}\, p_T + \Sigma_{lep}\, p_T + MET}$$

[SUS-13-003]



No excesses above the SM background expectation, no evidence for RPV stops



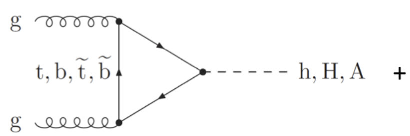
RPV searches are probing the 1 TeV scale and even beyond...

☞ EWSB through 2 isospin Higgs doublets in MSSM $\phi \to \tau\tau(\phi = \mathrm{h}, \mathrm{H}, \mathrm{A})$:

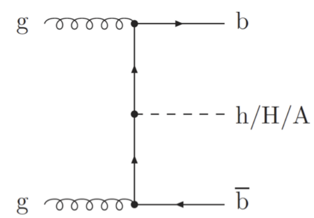
$$\sigma \times \mathcal{B} \sim \tan^2 \beta$$

➠ event categorization by number of b-jets and tau lepton final states

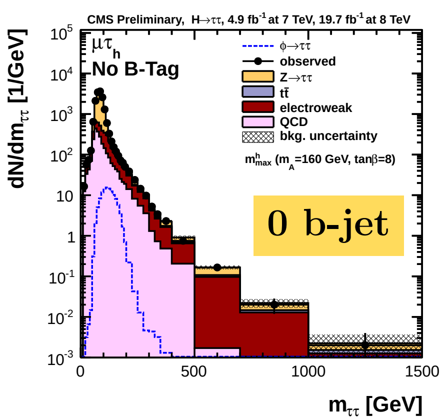
- 2 main Production Processes:

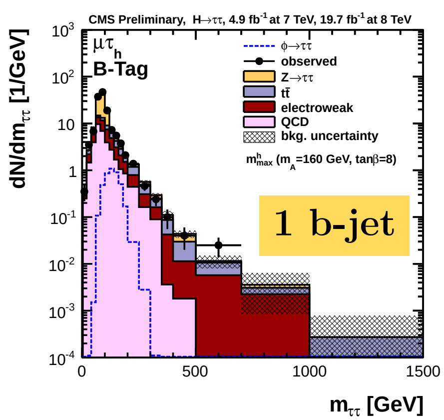


+



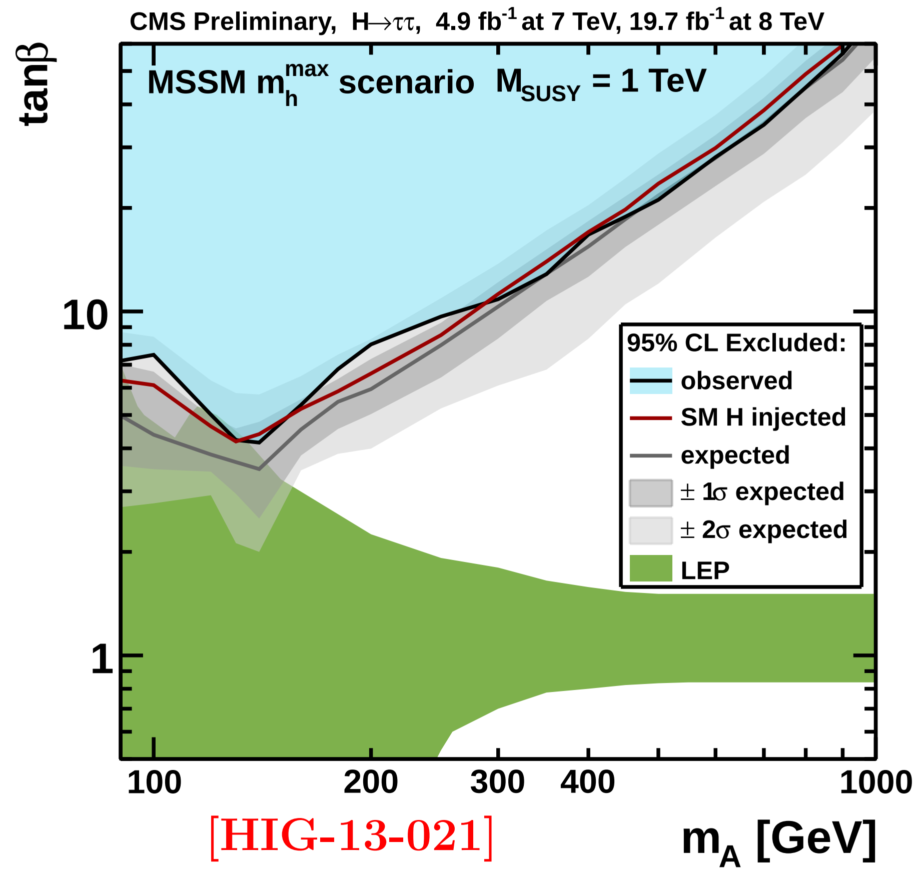
- Cross-section increases ~tan β²





No excess is observed in the tau-pair invariant mass spectrum

Exclusion limits in the MSSM parameter space of $\mathrm{m_A}$ *and* $\tan\beta$ *in the* $\mathrm{m_{h_{max}}}$ *scenario*



[HIG-13-021]

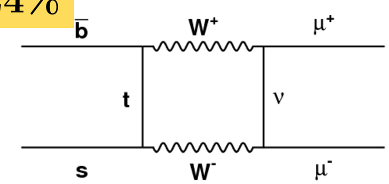
SUSY modifies tree-level couplings

A is difficult to find at moderate $\tan\beta \sim 5$

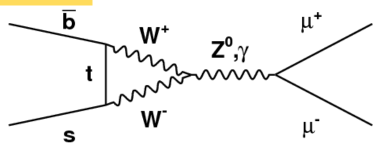
Largest effect $\Delta k_{\tau,b}/k_{\tau,b} \sim 100\%/\mathrm{m_A^2}$

- Rare SM decay known to 10% accuracy
  - V_{tq} and helicity suppression
  - $\mathcal{B}(B_s \to \mu^+\mu^-) \sim 3.8 \times 10^{-9}$

24%



75%

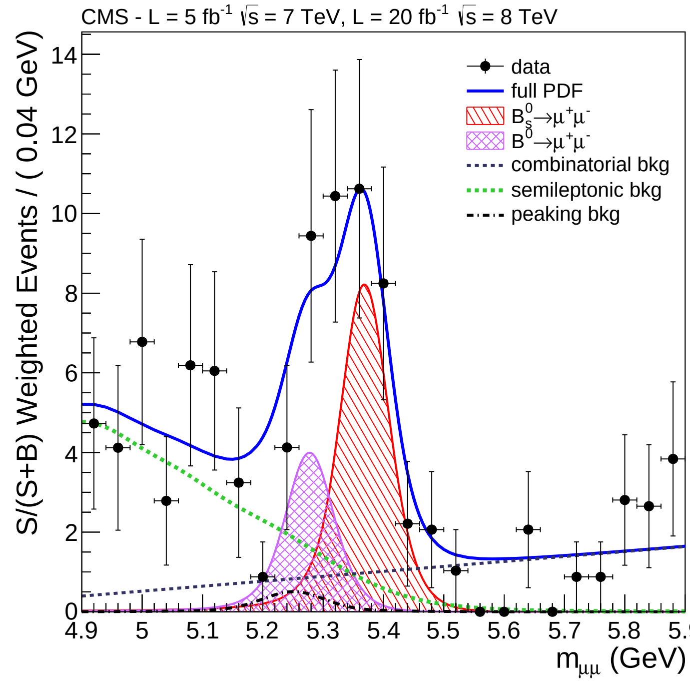


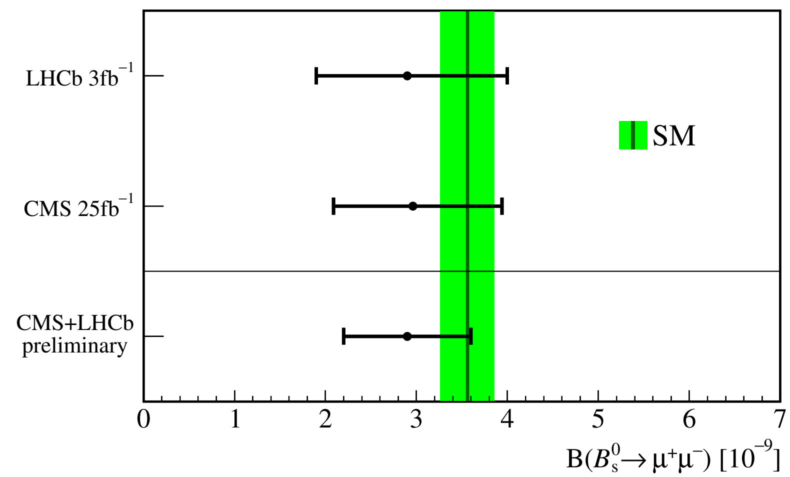
- Large Sensitivity to New Physics, e.g.

$$\mathcal{B}_{MSSM}(B_q \to l^+l^-) \propto \frac{M_b^2 M_l^2 \tan^6\beta}{M_A^4}$$

- Mass resolution is a key aspect for future
  - $\mathcal{B}(B_d \to \mu^+\mu^-)/\mathcal{B}(B_s \to \mu^+\mu^-)$

An excess of events with respect to background is observed with a significance of 4.3σ and consistent with the SM prediction





$$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

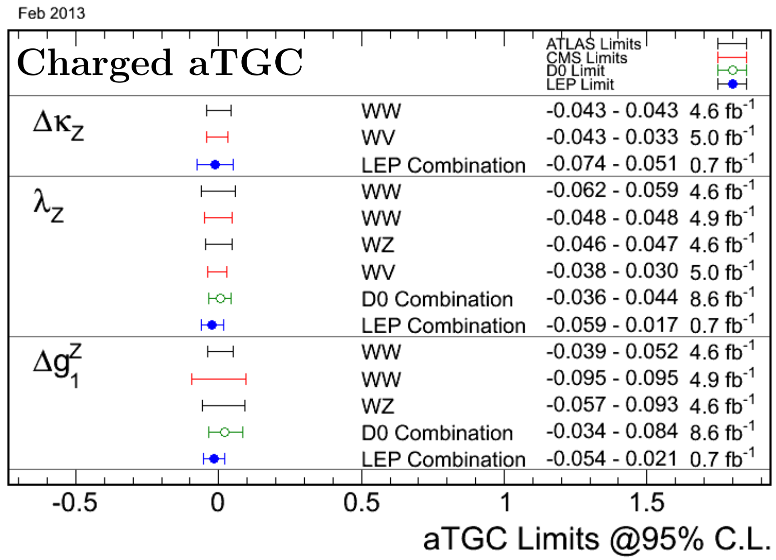
New Physics via effective Lagrangians

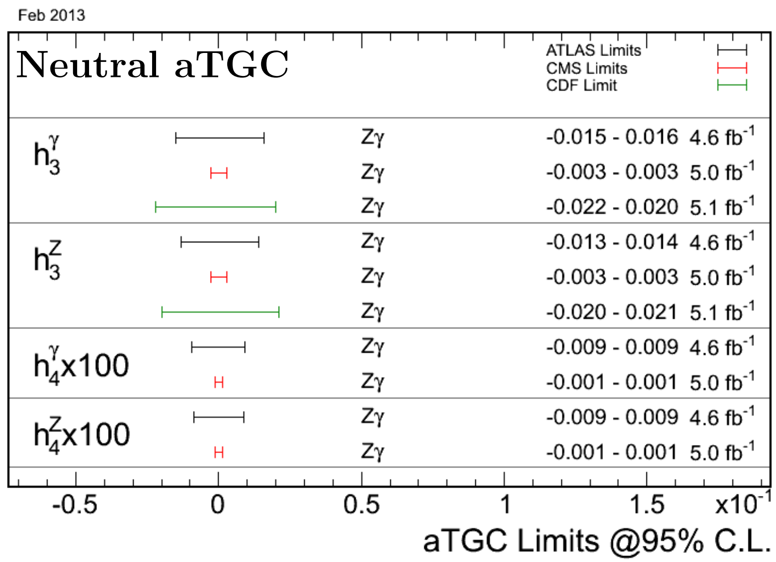
- A different way to look for deviations:
  - no particular model assumed
  - access to higher energy scales
- Extending the SM Lagrangian in a linear way:

$$\mathcal{L}(\sqrt{s} \ll \Lambda) = \mathcal{L}_{SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{n-4}} \sum_j f_j^n \mathcal{O}_j^n$$

- Respect $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ gauge invariance
- Set limits on charged and neutral anomalous Triple Gauge Couplings (aTGC) couplings from **diboson production**
  - parameterization assumes all parameters are zero in the SM
  - LHC can potentially probe a few TeV scale

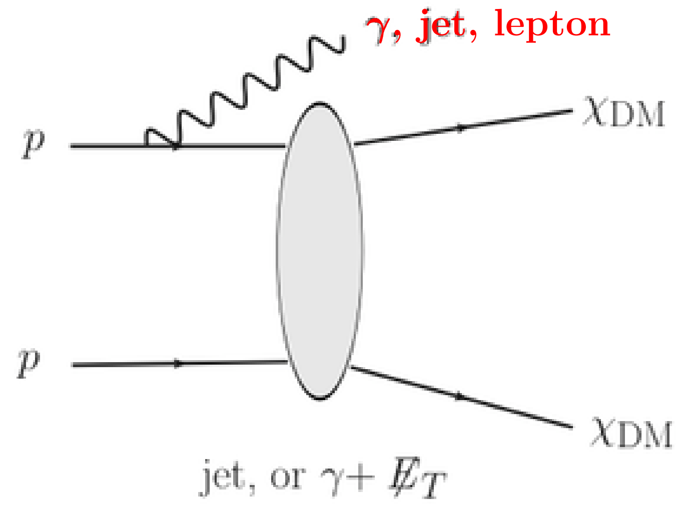
[Eur.Phys.J. C39 (2005) 293]





No deviations from zero are observed so far...

BSM Searches



Dark matter (DM) existence is well established based on gravitational effects

☞ DM particles are produced in pairs after ISR

➠ signature: MET and mono-jet/photon/W/Z

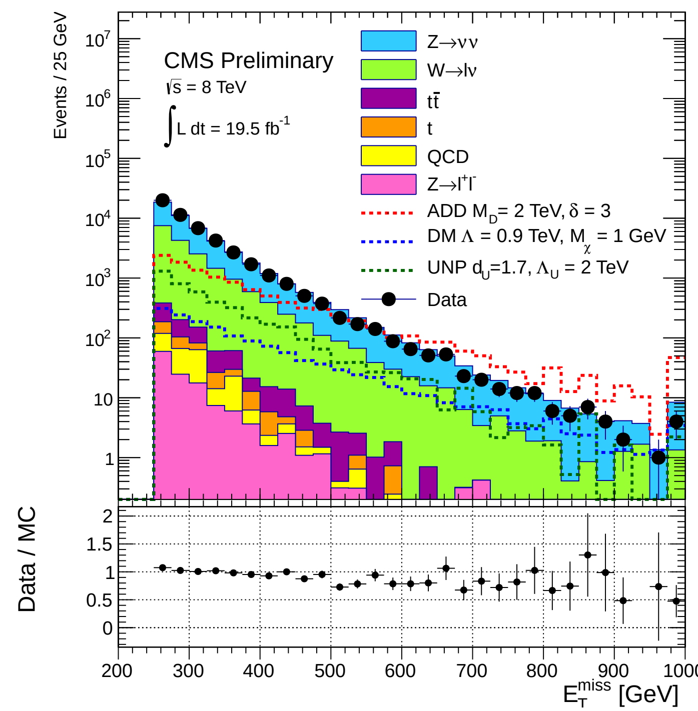
➠ dominant background is $\mathbf{Z \to \nu\nu + X}$

☞ Couplings between SM and DM can be probed and compared with direct detection results

➠ interpretation in spin (in)dependent EFT

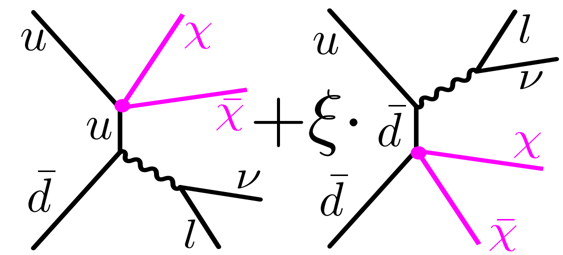
☞ Search for non-SM contribution of **hard jets** recoiling against something invisible

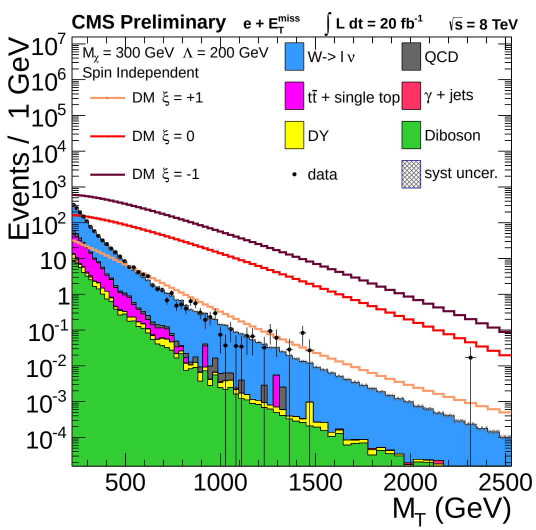
Data are consistent with Standard Model background expectation

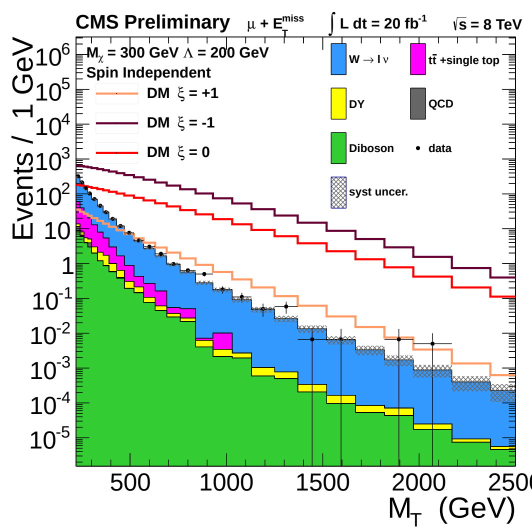


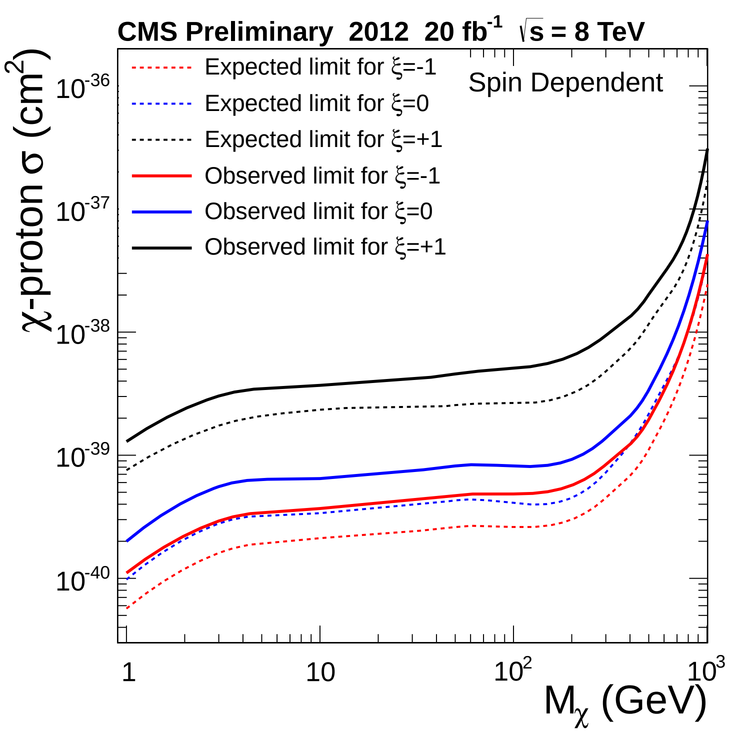
- Search for non-SM contribution of **isolated leptons** from leptonic decays of W's recoiling against something invisible
  - measure transverse mass spectrum
  - Data/MC agreement over orders of magnitude

Interference illustration





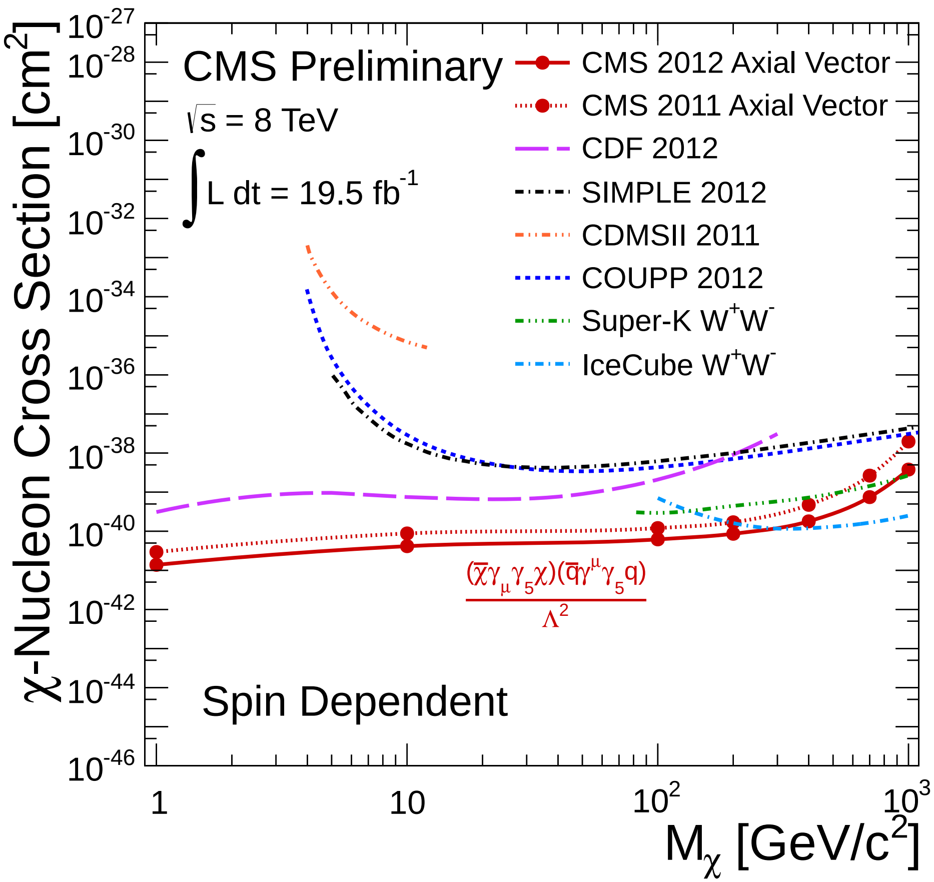




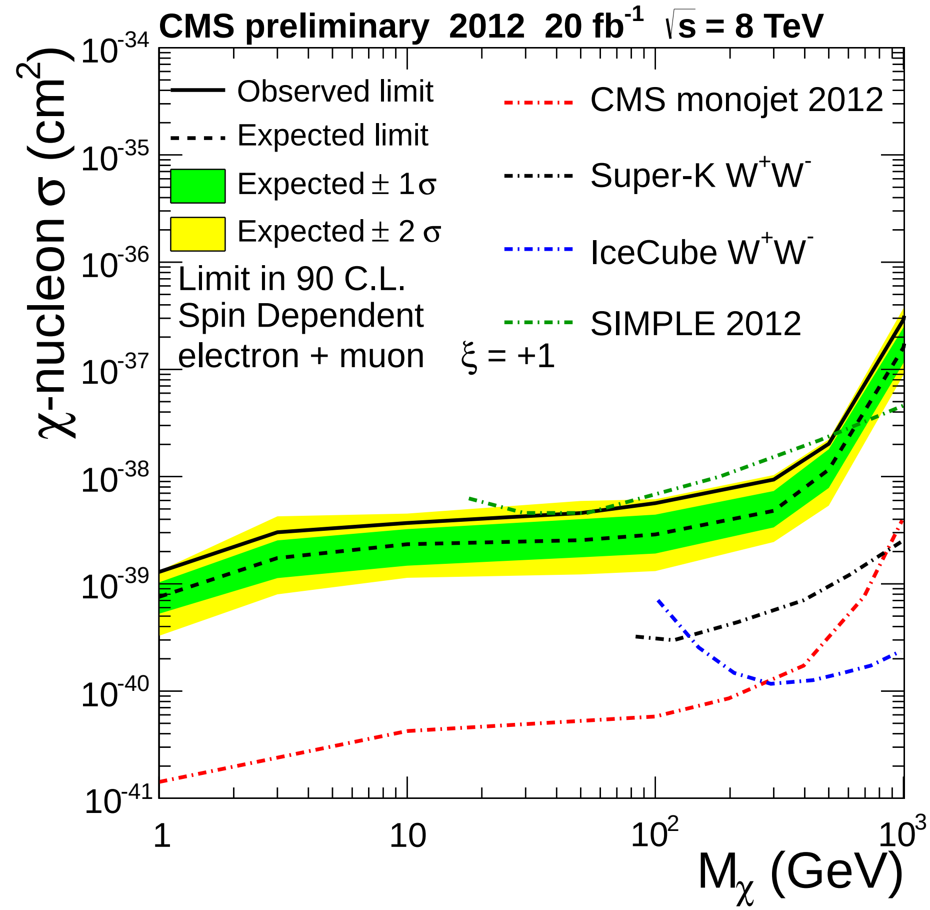
No deviations from background estimate was observed

Limit improves when interference is considered

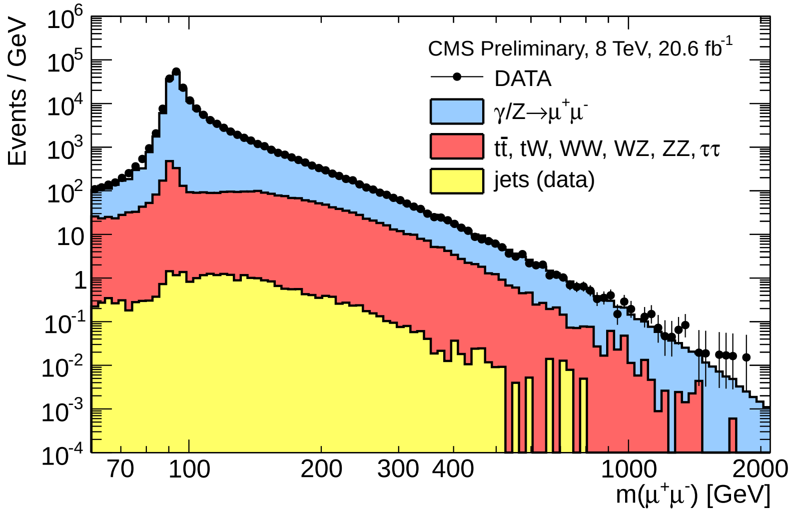
[EXO-12-048]

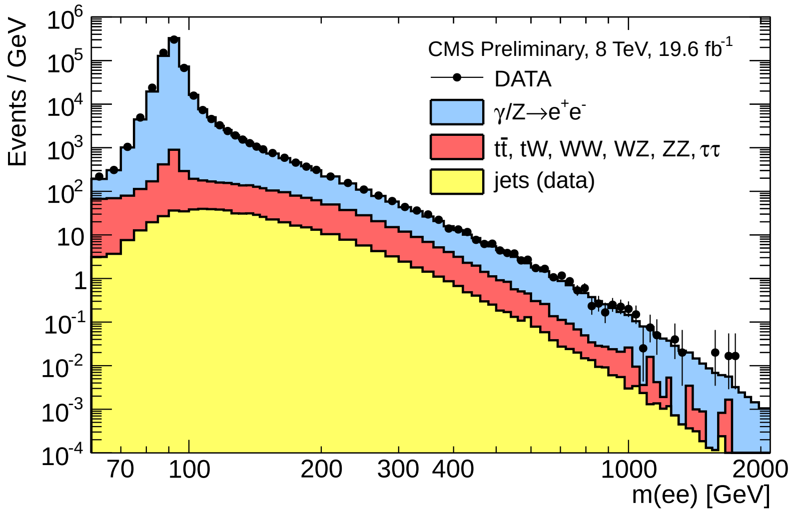


[EXO-13-004]



- It is assumed that the DM particles are Dirac fermions
- Collider results **dominate in spin dependent searches**
- **Cover low mass range** for spin independent searches



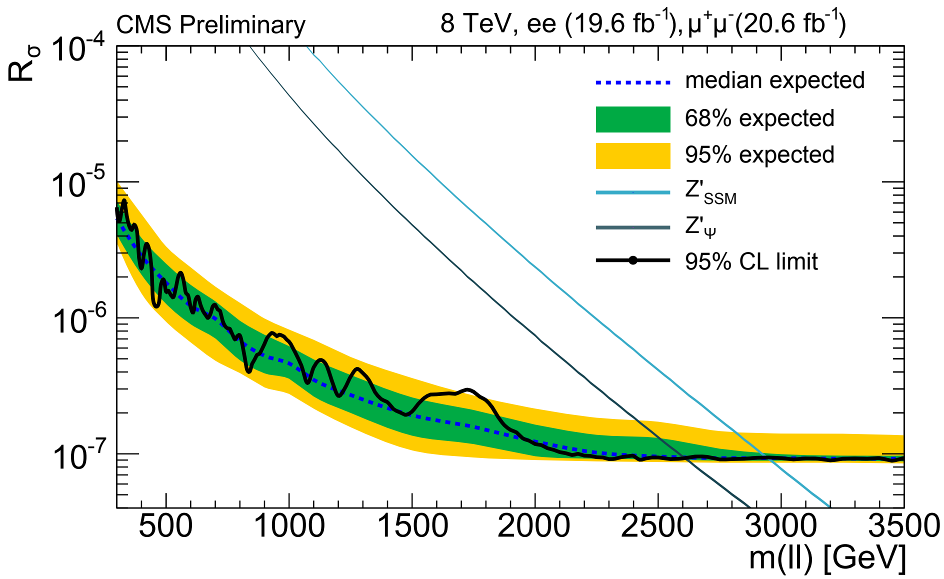


Data/MC agreement over many orders of magnitude: **no deviations from background estimate**

[EXO-12-061]

Many systematic uncertainties cancel out in ratio

$$R_\sigma = \frac{\sigma(pp \to Z' + X \to ll + X)}{\sigma(pp \to Z + X \to ll + X}$$



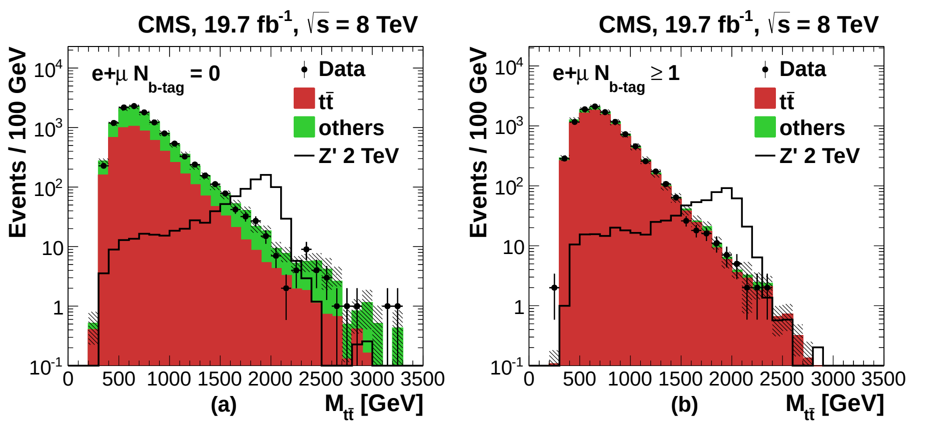
SM-like couplings: $m_{Z',SSM} > 2.96$ TeV

Superstring-inspired: $m_{Z',\psi} > 2.6$ TeV

[B2G-13-001]

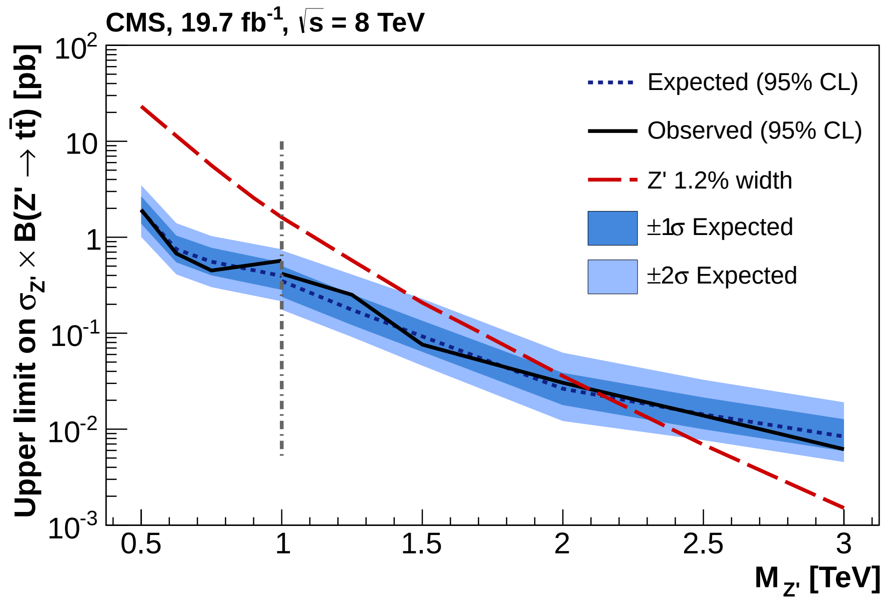
☞ Two dedicated searches:

- optimized for $t\bar{t}$ production at the kinematic production threshold
- optimized for $t\bar{t}$ production produced with high Lorentz boosts

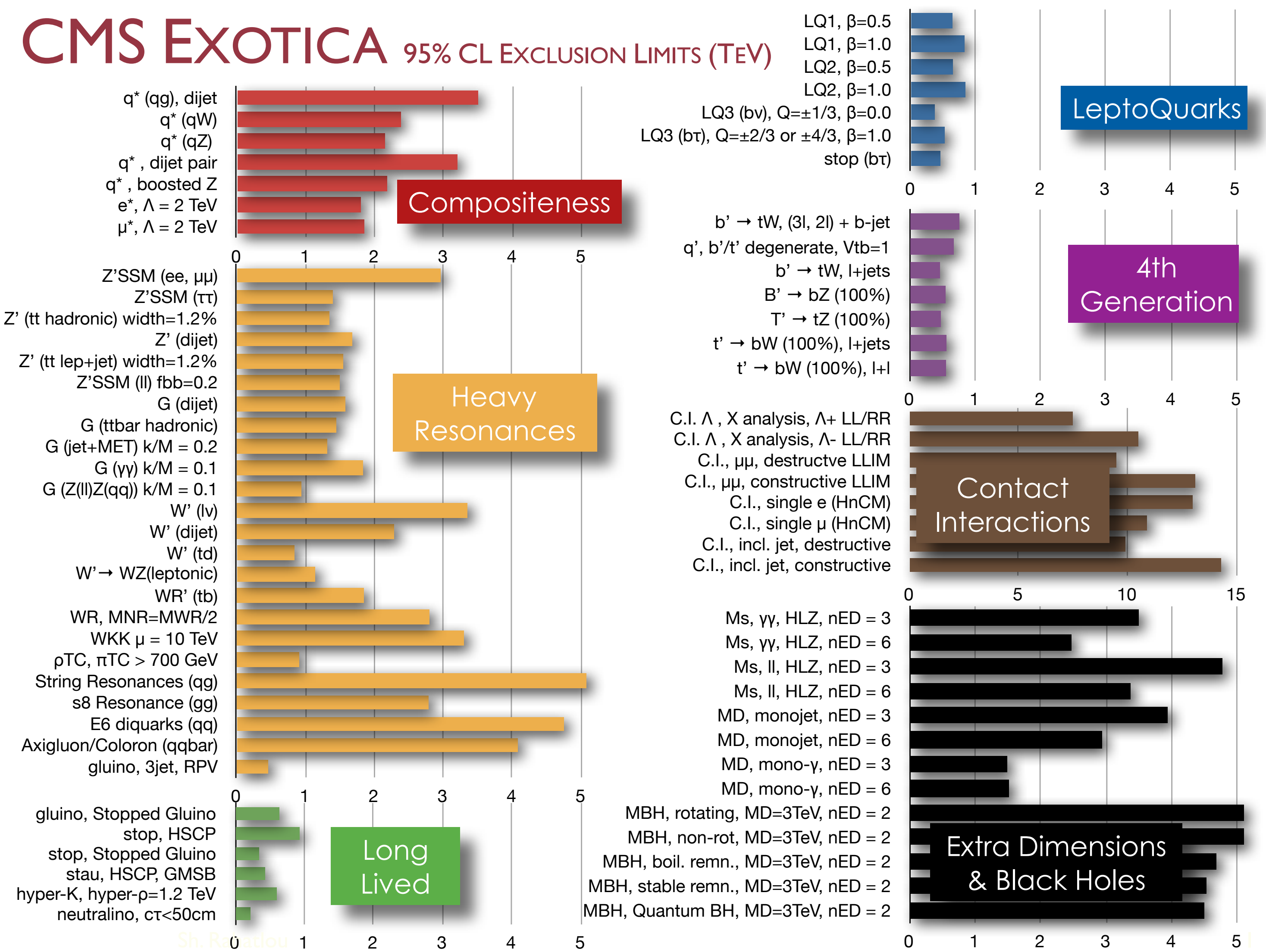


Data/MC agreement over many orders of magnitude: **no deviations from background estimate**

The 95% CL upper limits on production cross-section



Topcolor Z', width 1.2%: $m_{Z'} > 2.1$ TeV
Topcolor Z', width 10%: $m_{Z'} > 2.7$ TeV
KK excitation of the gluon: $m_{g_{KK}} > 2.7$ TeV



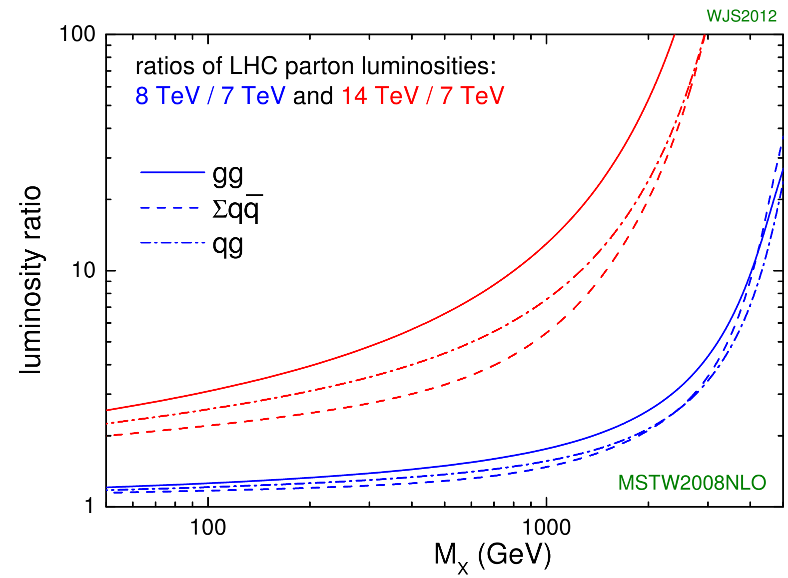
Impressive variety of BSM searches have been peformed, but only limits so far...

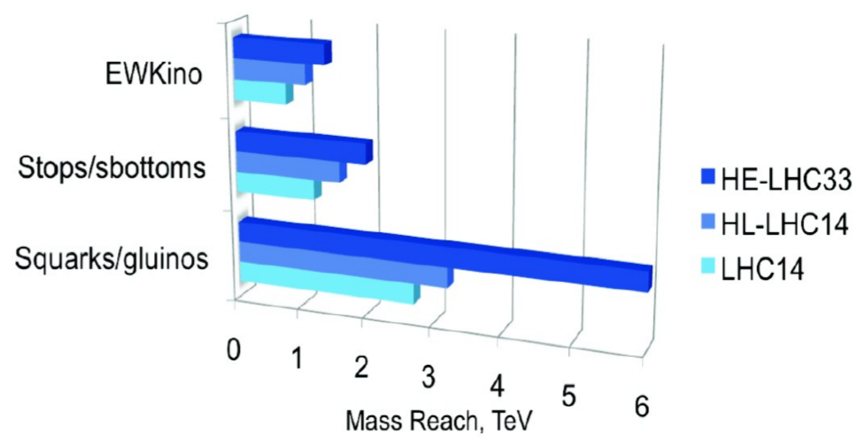
Explored a very vast range of masses, parameters, signatures
… but let us leave no stone unturned

- **It is to early put away a new physics at the TeV-scale**
  - always assumptions involved to derive "absolute" SUSY limits (Simplified Model)
  - limits decrease if assumptions are given up
  - a lot of room to look for more signatures and models

- **LHC reuse with ≃13-14 TeV will be a new game**
  - significant step toward both **small couplings** and **large masses**
  - improve sensitivity on **mass scale about x2** with respect to 8 TeV searches

Parton Luminosities:
rise due to steep fall-off of the lower energy PDF at large x



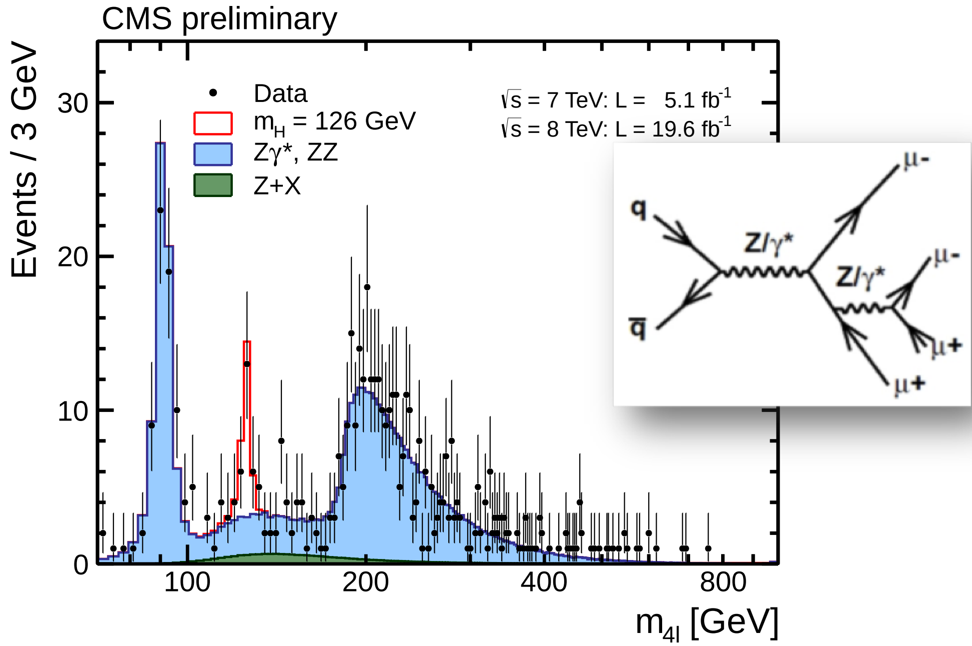


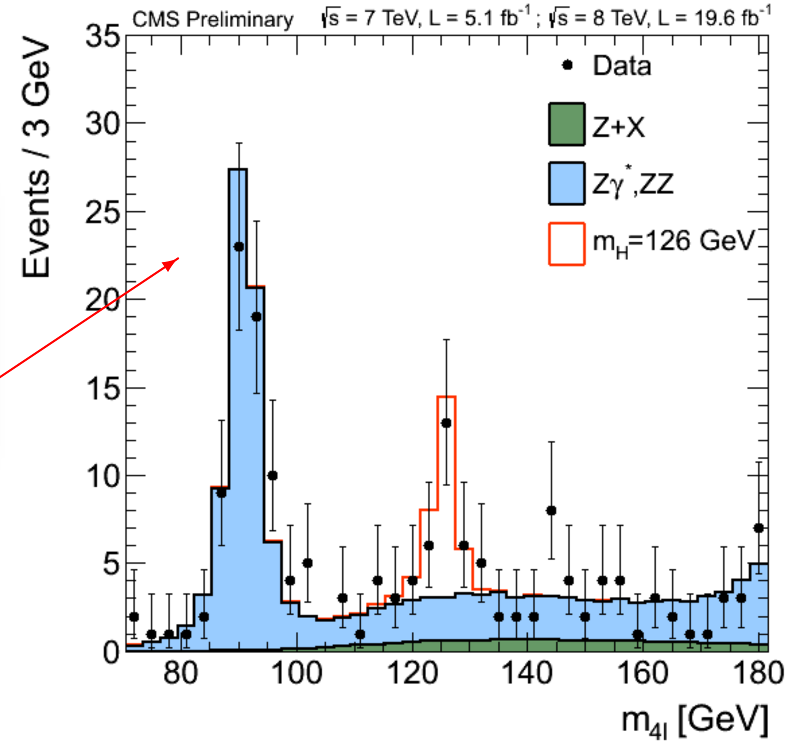
- ☞ **Vigorous update of the main results with the full statistics is available**
- ☞ **The boson that we found looks rather "standard" scalar at first sight**
  - ➠ **data disfavor the pseudo-scalar 0^- and spin-2 hypotheses**
  - ➠ couplings are in agreement within uncertainties with the SM predictions
- ☞ **Focusing on the 3rd Generation SUSY → no evidence for SUSY**
  - ➠ searches for "**light**" sbottom/stop target "**natural**" **SUSY** scenarios
    - ➔ probe stops **m(stop) ≥ 650 GeV**
    - ➔ probe gluinos **m(gluino) ≥ 1300 GeV**
    - ➔ probe sbottoms **m(sbottom)≥ 600 GeV**
  - ➠ RPV searches target multileptons and low MET signature
- ☞ No deviations from the SM in **rare B decays and diboson** production observed
- ☞ Broad array of **Dark Matter and heavy resonance** searches
  → no evidence for BSM signal

Overall we see so far is very well compatible with the Standard Model

The "14" TeV revamp of LHC will enable us to probe heavier particles, and potentially open up a new realm of Particle Physics

Backup





4-lepton mass resolution 1-2%

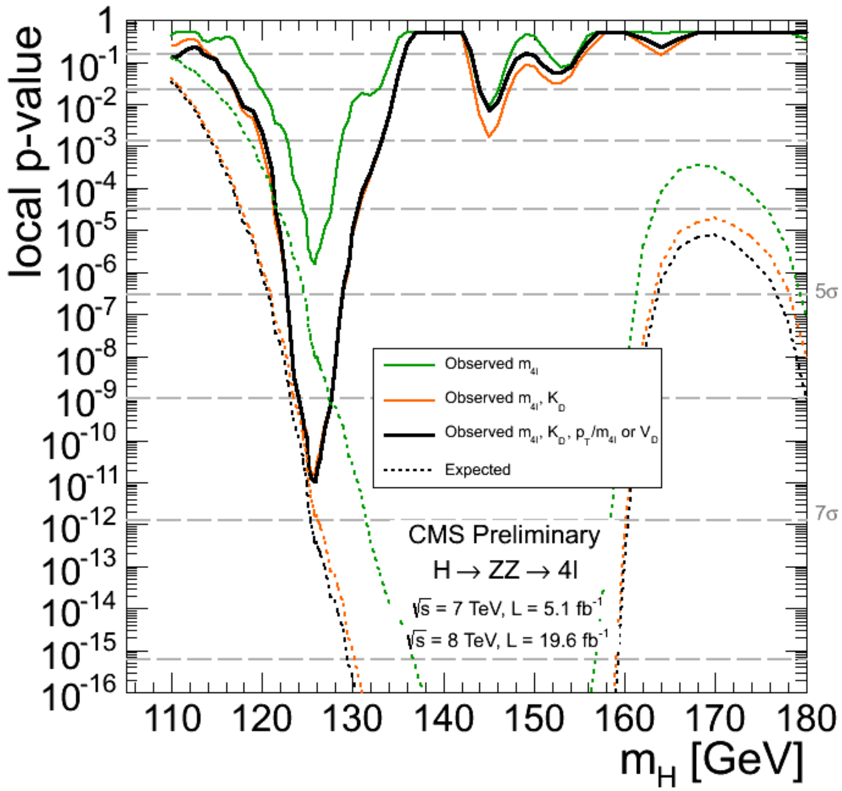
One of the best performing channels in the whole mass range

Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	6.6 ±0.8	13.8 ±1.0	18.1 ±1.3	38.5 ±1.8
Z+ X	2.5 ± 1.0	1.6 ± 0.6	4.0 ± 1.6	8.1 ±2.0
All background expected	9.1 ± 1.3	15.4 ± 1.2	22.0 ± 2.0	46.5 ±2.7
m_H = 125 GeV	3.5 ±0.5	6.8 ±0.8	8.9 ±1.0	19.2 ±1.4
m_H = 126 GeV	3.9 ±0.6	7.4 ±0.9	9.8 ±1.1	21.1 ±1.5
Observed	16	23	32	71

Event yields in 110-160 GeV →

- ☞ Extremely demanding channel for selection, requiring the highest possible efficiencies (lepton Reco/ID/Isolation)
- ☞ Straightforward for spin/parity measurements and includes VBF channel

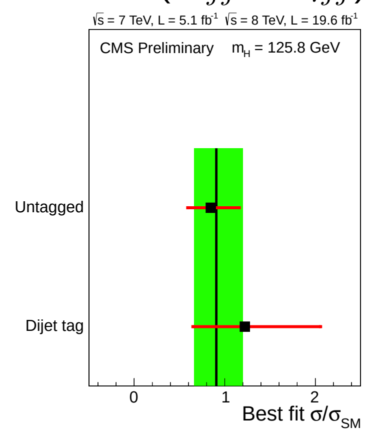
Zoomed mass range

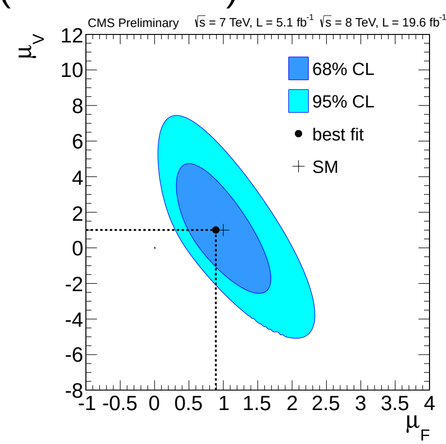


Jet categories to measure couplings

Untagged (0/1 jet): use $p_{T_{4l}}/m_{4l}$ (VBF ∼5%)

Dijet tagged (≥2 jets): use Fisher Discr. (m_{jj}, $\Delta\eta_{jj}$) (VBF ∼20%)



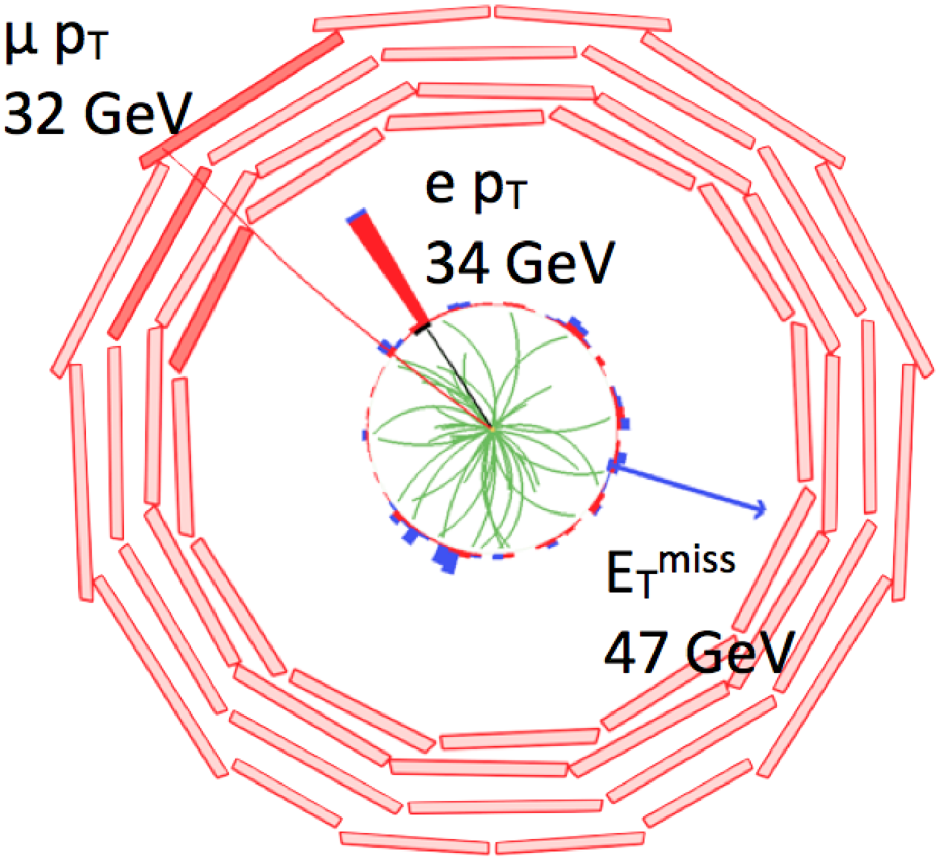


Expected significance at 126 GeV: $\boldsymbol{7.1\sigma}$

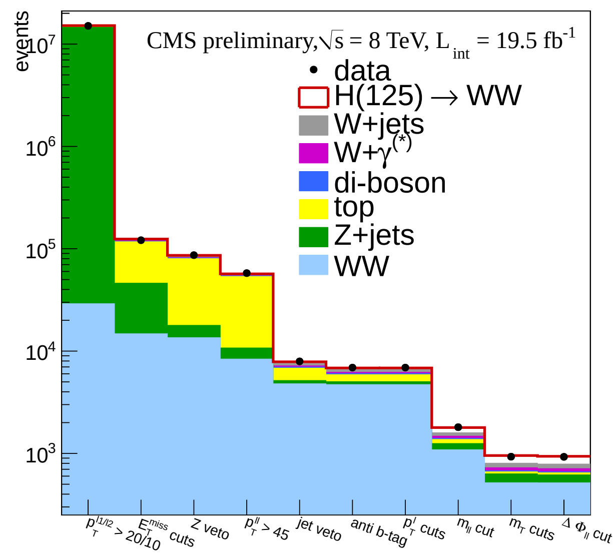
Observed significance at 126 GeV: $\boldsymbol{6.7\sigma}$

Measured signal strength at 126 GeV: $\boldsymbol{\mu = 0.92 \pm 0.28}$

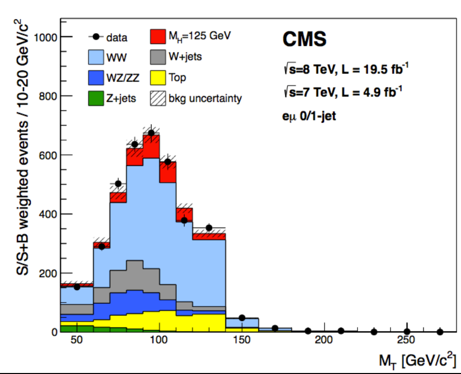
High sensitivity, but low mass resolution channel

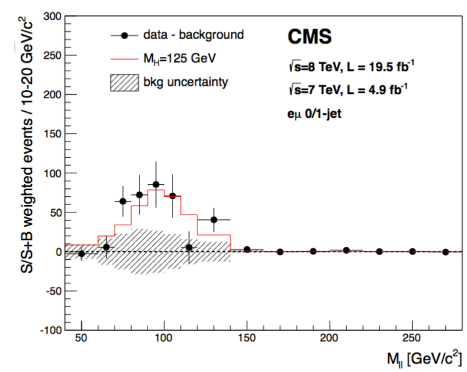


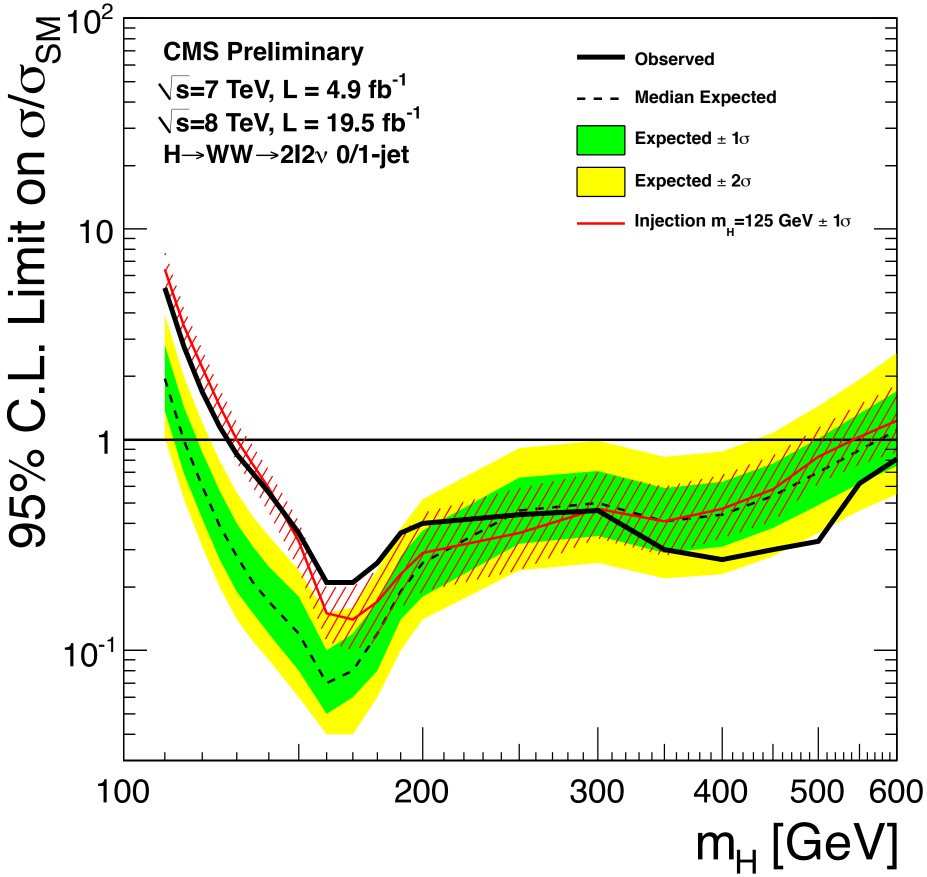
- ☞ Background estimation is the most important part of analysis

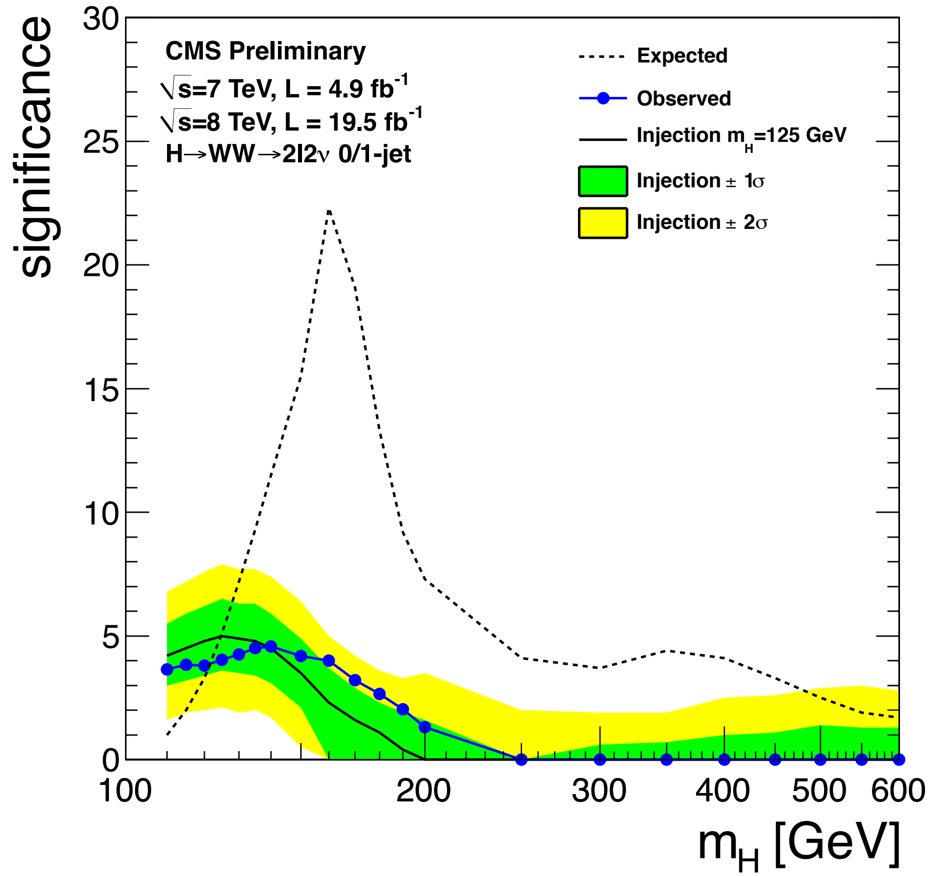


Signature with two isolated leptons (electrons or muons) and large Ãěmissing energy (E_T^{miss})









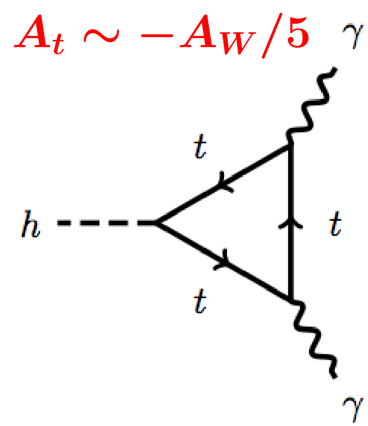
Measured signal strength at 125 GeV: $\mu = 0.76 \pm 0.21$

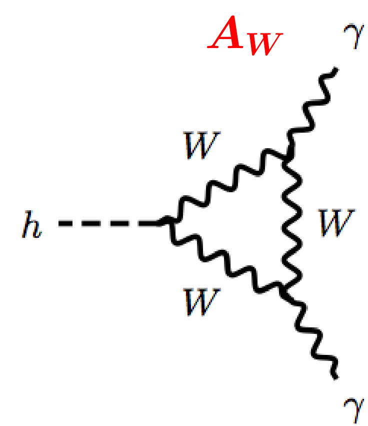
Expected significance at 125 GeV: $\mathbf{5.1\sigma}$

Observed significance at 125 GeV: $\mathbf{4.0\sigma}$

Consistent with a SM Higgs boson with a mass around 125 GeV

$H \to \gamma\gamma$ (HIG-13-001)



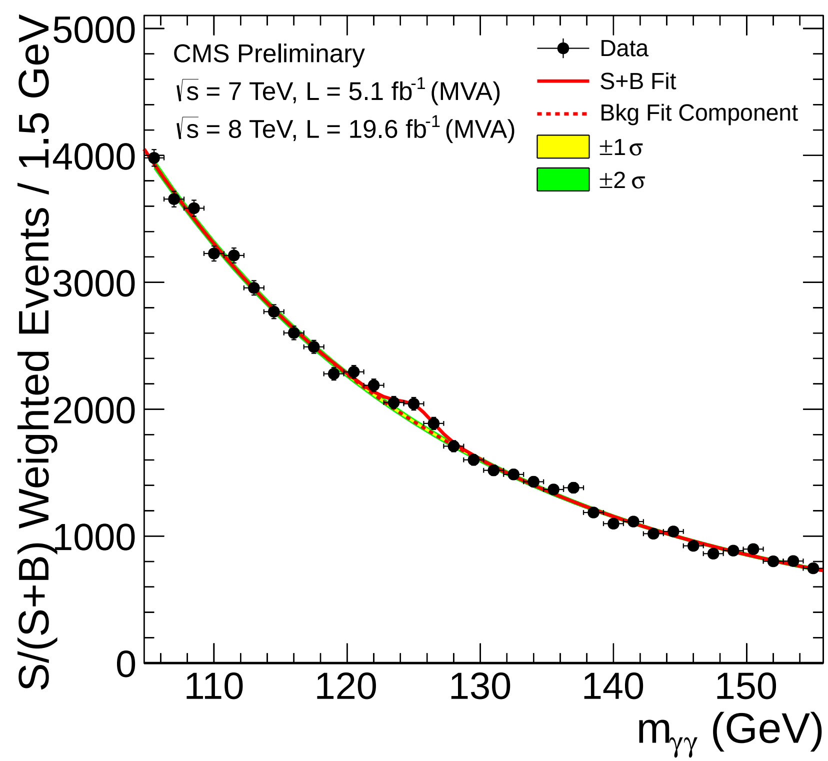


A discovery channel at low masses

- **Low signal rate $\mathcal{B} \sim 10^{-3}$**
  - decay involves virtual loops
  - has **negative** contribution from the top quark loop
- **Clean signature in the detector**
  - identified as a narrow peak on the top of continuous background

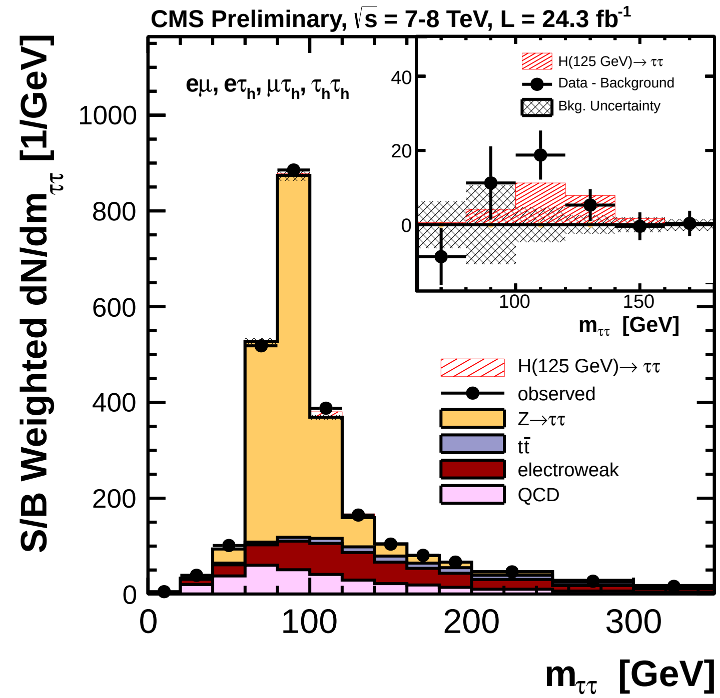
Good performance of ECAL and photon reconstruction are cornerstones of the analysis

- Best fitted signal strength at 125 GeV
  $\boldsymbol{\sigma/\sigma_{SM} = 0.78 \pm 0.28 \pm 0.26}$



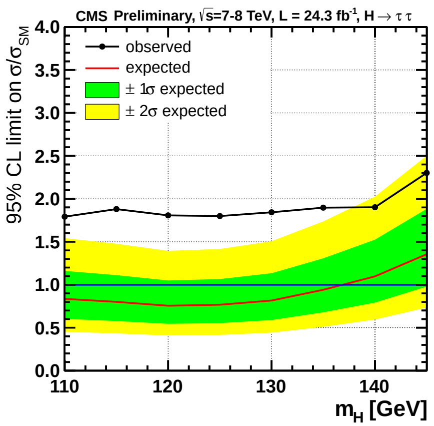
$H \to \tau\tau$ probes coupling to leptons

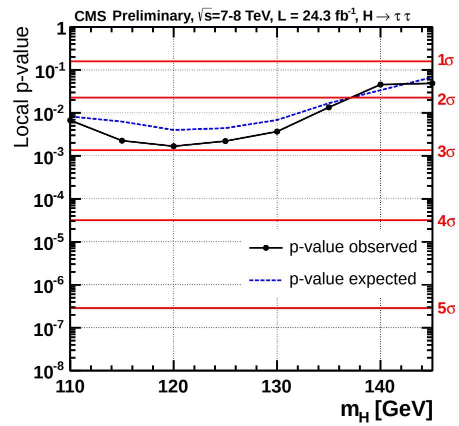
- Analyze decays of tau pairs: $e\mu$, $\mu\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- **Full $m(\tau\tau)$ reconstruction**
  - event-by-event estimator of true $m(\tau\tau)$ likelihood

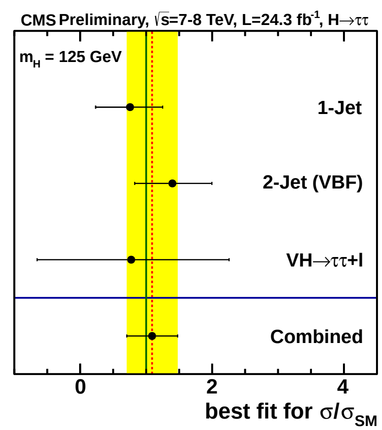


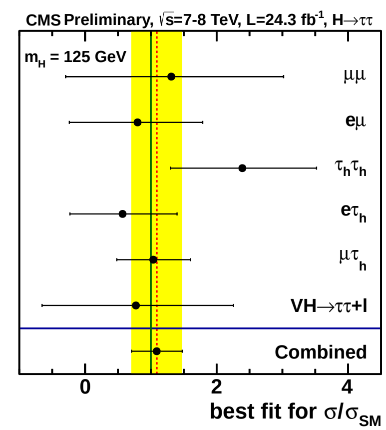
Events are classified according to jet multiplicity

(all categories are fit simultaneously)



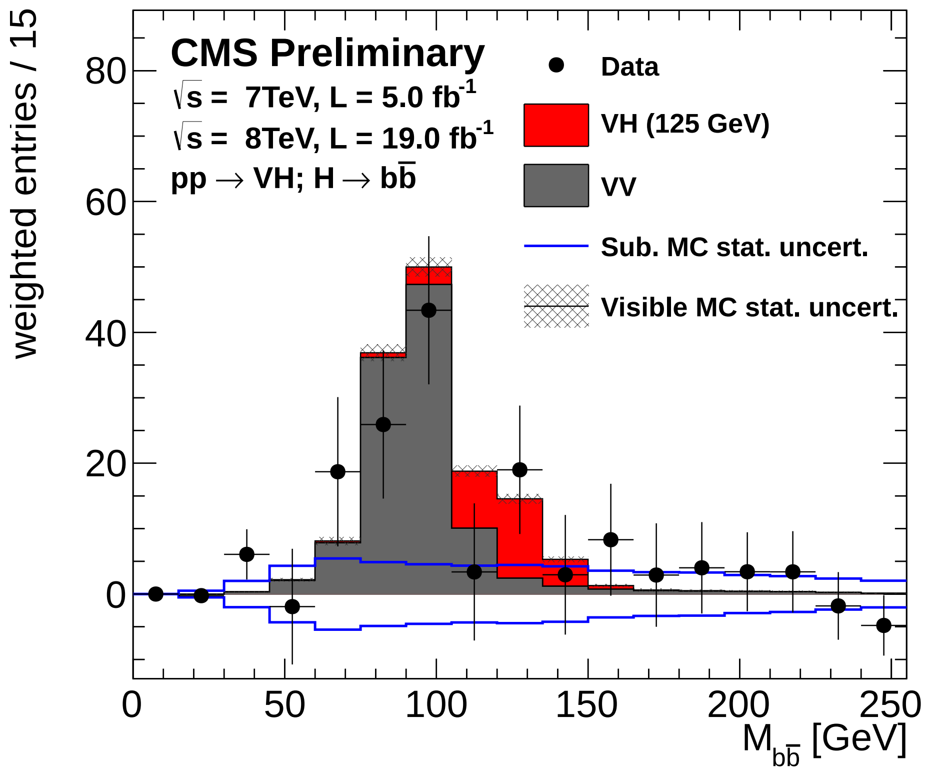


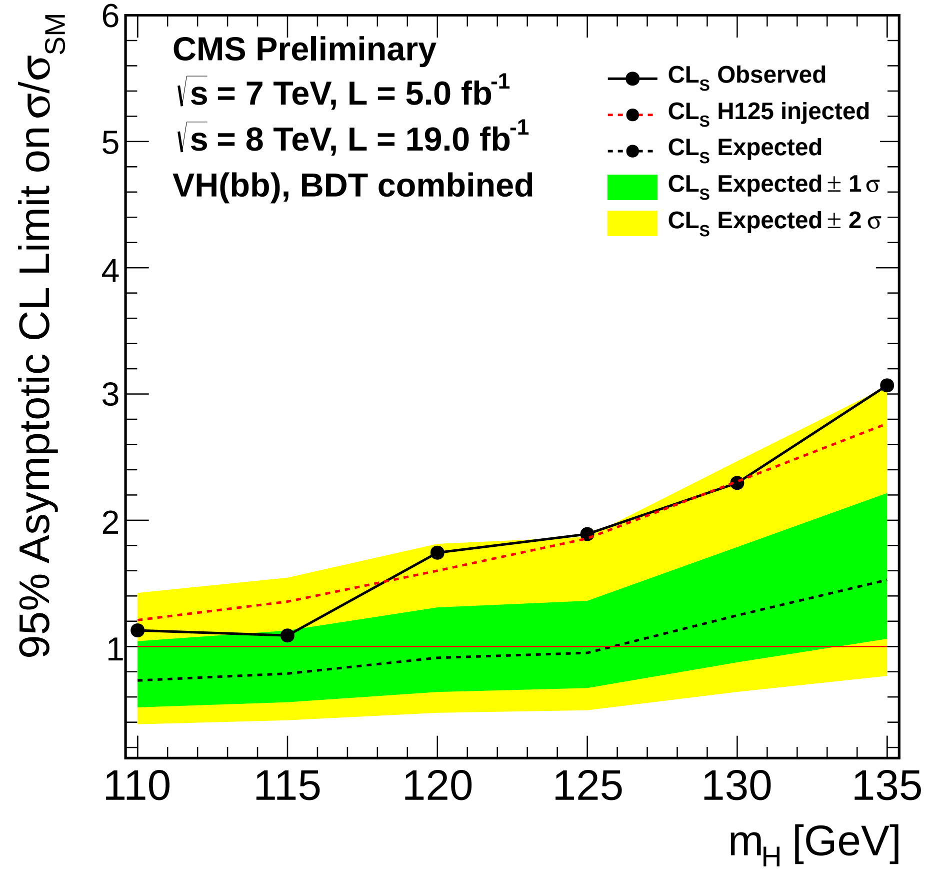




Reached **1xSM** sensitivity: **clear excess 2.9σ at 125 GeV**

Measured signal strength at 125 GeV: $\mu = 1.1 \pm 0.4$





$H \to b\bar{b}$ is a key piece of the observation puzzle

- Challenge: $\sigma(b\bar{b}) \sim 10^7 \sigma\mathcal{B}(H \to b\bar{b})$
- Search in associated production with W/Z

- Reached SM sensitivity below 125 GeV

Observed excess about 2.1σ is compatible with a SM Higgs boson with a mass around 125 GeV

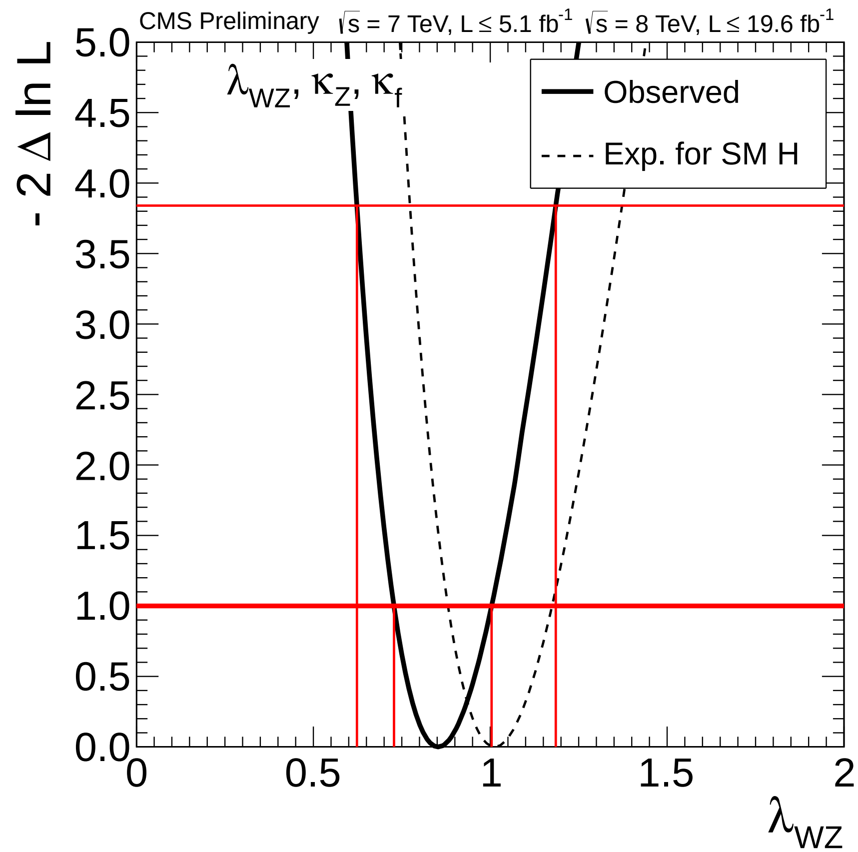
- Combination of “inclusive” WW (0/1jet) and ZZ yields gives the ratio of the Higgs couplings to WW and ZZ, g_W/g_Z, which is protected by **custodial symmetry**

$$\rho = \frac{M_W}{M_Z \cos\theta_W} = \frac{g_W}{g_Z \cos\theta_W} = 1$$

  - $\rho \neq 1$ **is possible in new physics models**

- Perform combination of all channels to assess $\lambda_{WZ} = k_W/k_Z$
  - likelihood scan versus 3 n.d.f.: λ_{WZ}, k_Z, and k_F gives

$\boldsymbol{\lambda_{WZ} = [0.62 - 1.19]}$ at 95% CL



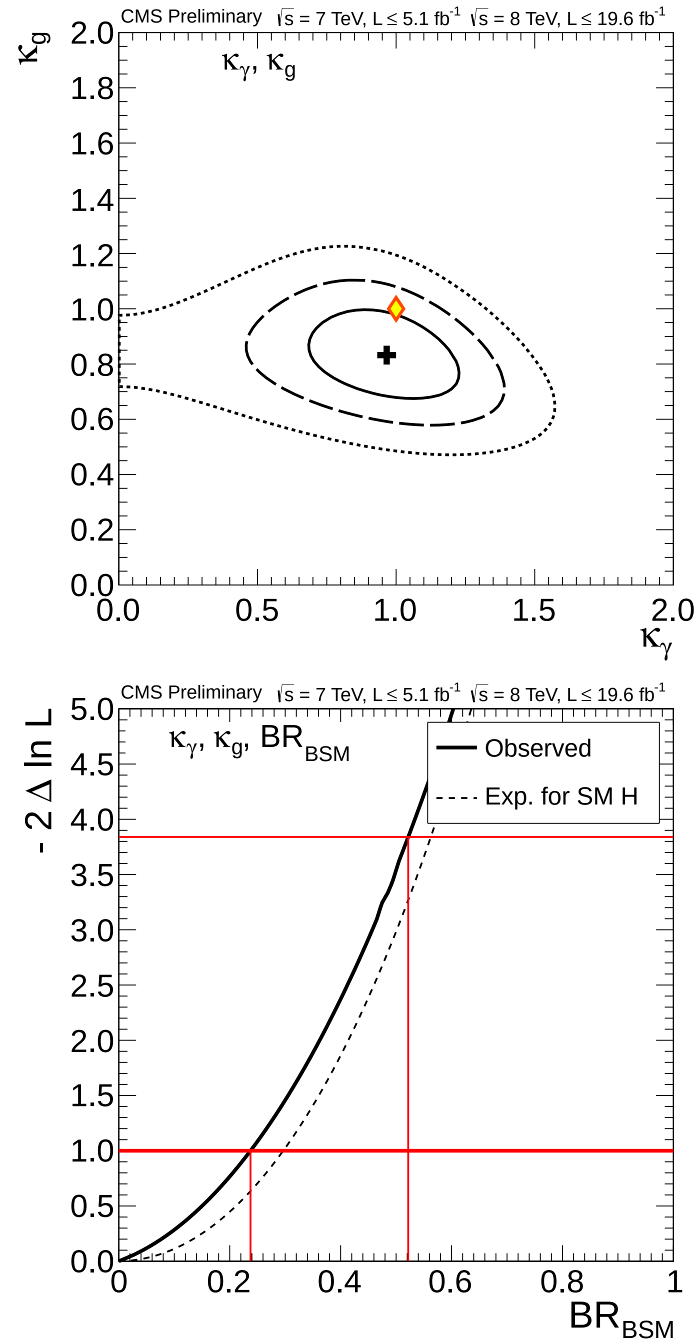
Consistent with the SM expectation

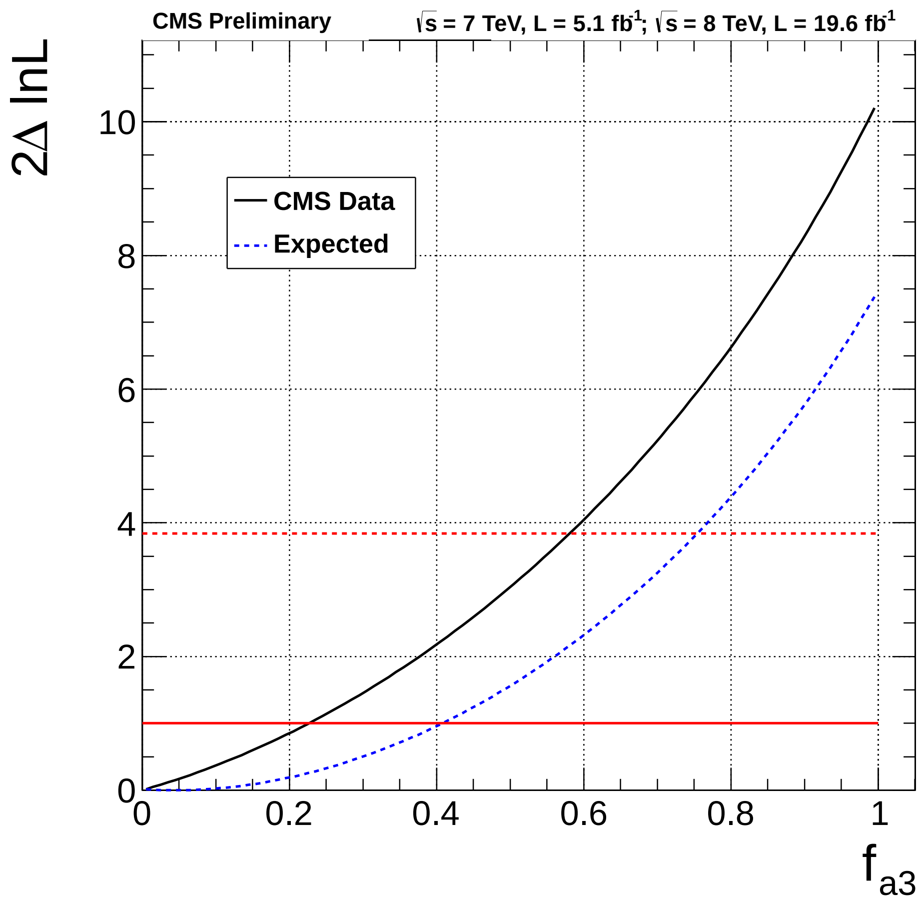
- New particles can modify the loop-mediated couplings and contribute to the total width

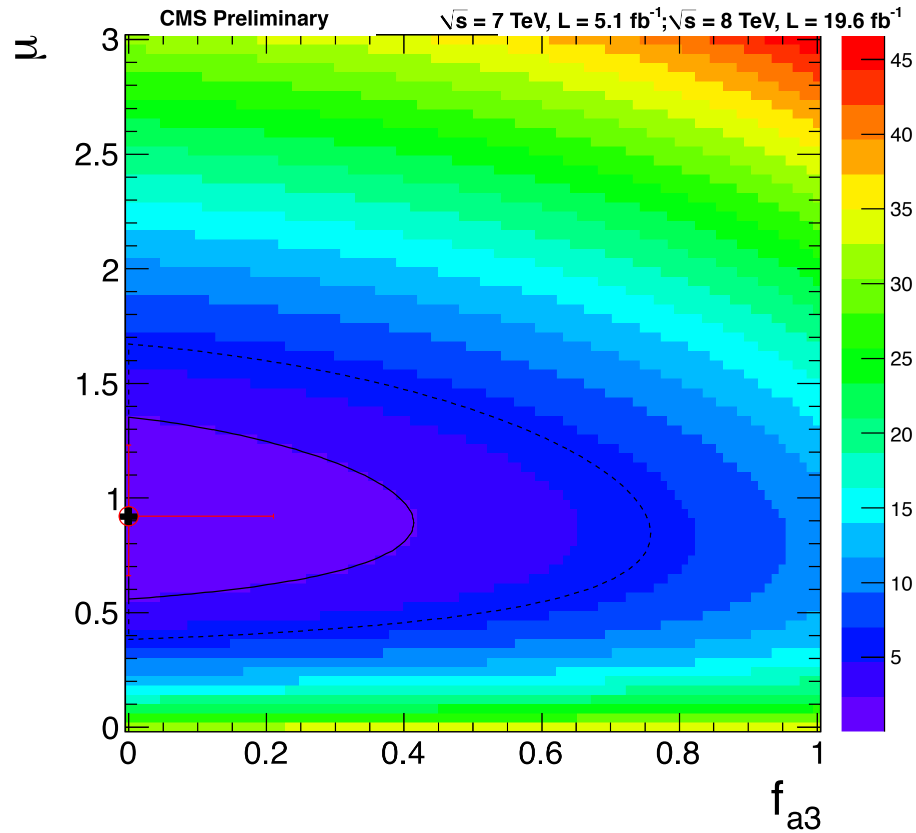
$$\Gamma_{tot} = \sum \Gamma_{i(SM)} + \Gamma_{BSM}$$

- Parametrize the photon and the gluon loops with effective scale factors (k_g,k_γ)
- Allow total width to scale as 1/(1-$\mathcal{B}_{\rm inv}$)

No large invisible branching fraction







Expected separation between SM 0^+ and 0^- is 2σ

Fraction of CP-violating combination to the decay amplitude: $f_{a3} = 0^{+0.2}_{-0.0}$

Data disfavor $J^P = 0^-$ at 2.5σ ($< 3\%$ CL)

$J^P = 0^+$ is consistent with observation (0.6σ)

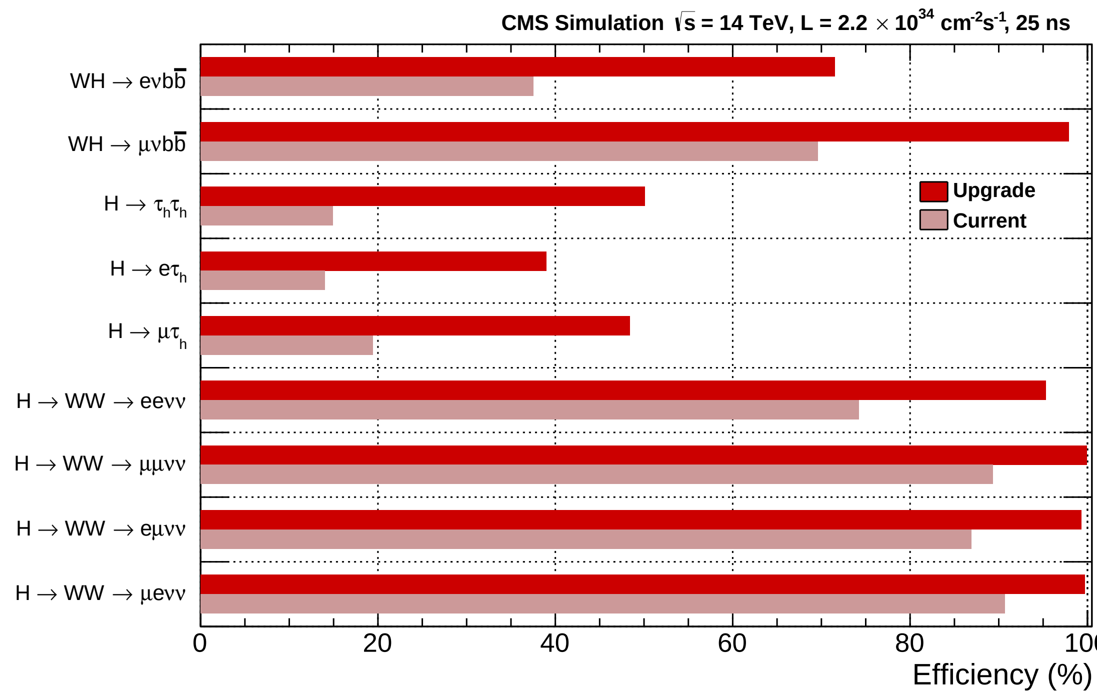
☞ Detector upgrade needed

- to withstand radiation damage and pileup
- to maintain or enhance the current physics performance

☞ CMS will undergo a series of detector and trigger upgrades

- several subdetectors will be improved or replaced
- trigger is a key component
  - ➔ mandated by need to study the Higgs boson
  - ➔ thresholds not too dissimilar to today

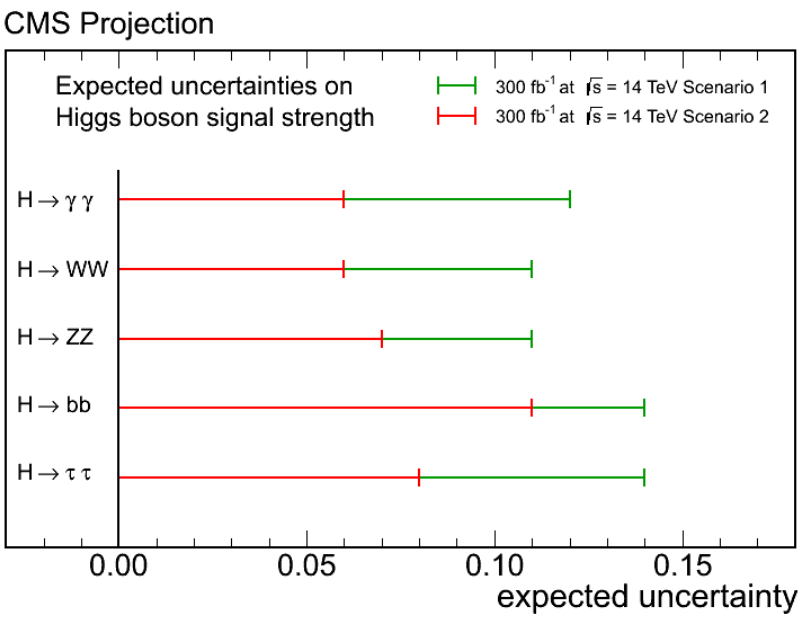
[CMS-NOTE-13-002, arXiv:1307.7135]

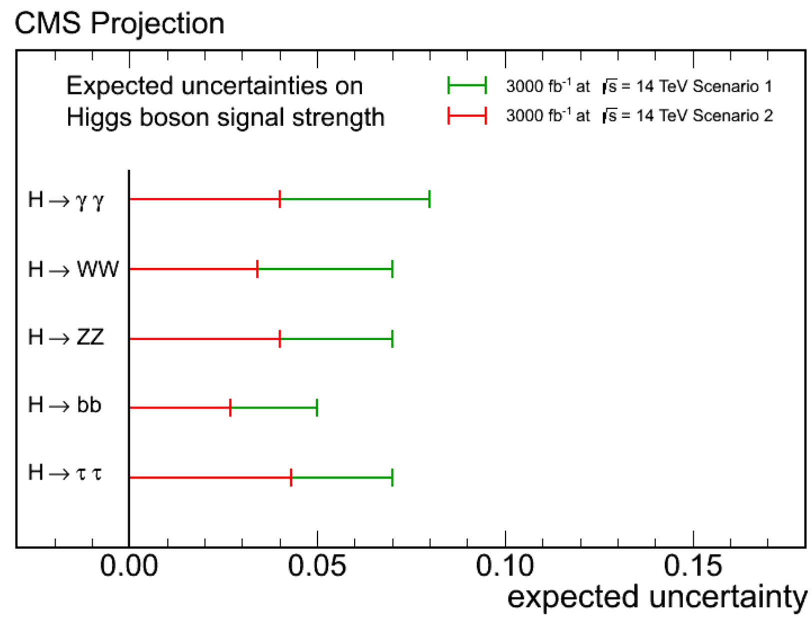


Current and Phase 1 trigger efficiency: upgraded trigger system available for data taking in 2016

☞ First step to assess **compatibility to SM**

- perform single parameter fit, signal strength $\boldsymbol{\mu = \sigma/\sigma_{\rm SM}}$
- group decay channels together and express results as $\boldsymbol{\sigma_\mu/\mu}$





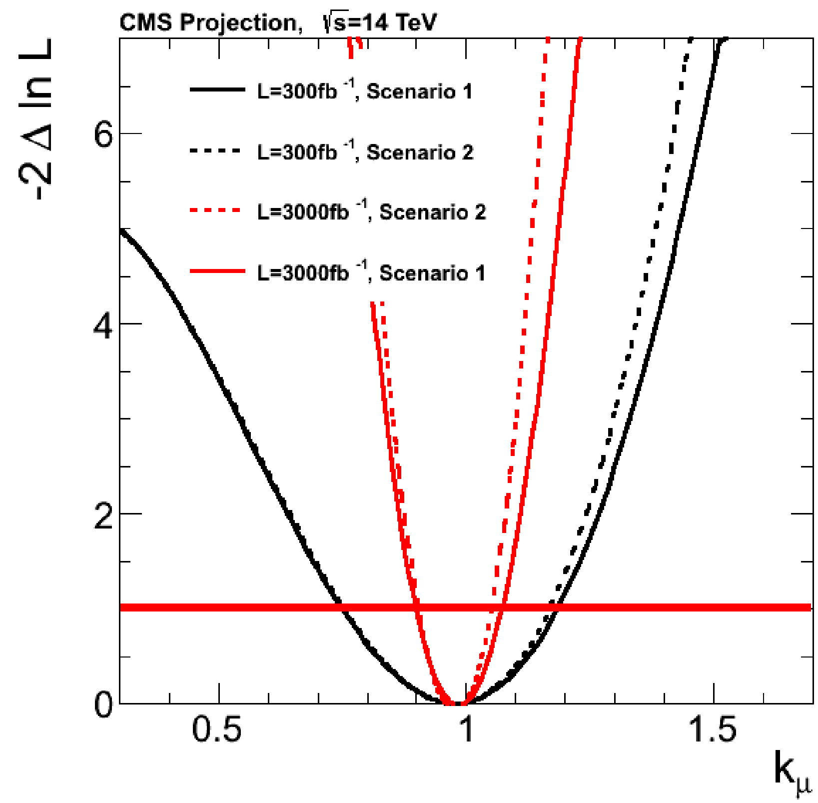
[Scenario 2, Scenario 1]

L ($\rm fb^{-1}$)	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[14,20]	[6, 17]

Not always straightforward to interpret: worth separation of production modes

Extracting Higgs couplings requires assumptions at LHC

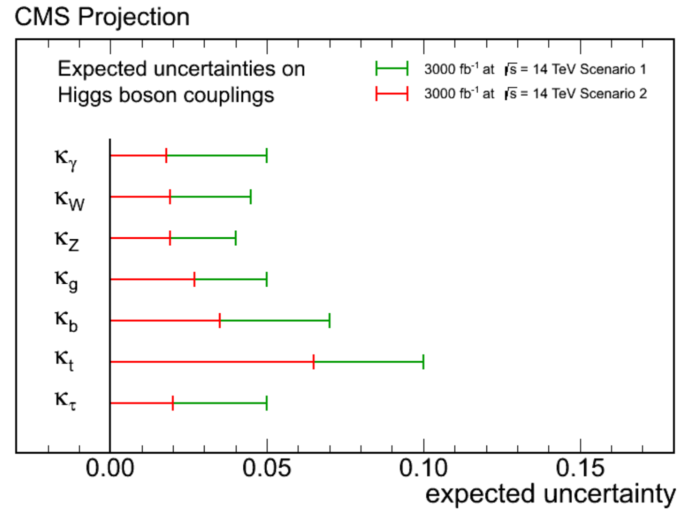
- Total width $\Gamma_{\rm H} \sim k_H^2$ is not measurable
  - not possible to measure directly a production cross section as at **a e^+e^- collider**
- Follow recommendations and fit models described in Yellow Report 3 [arXiv:1307.1347]
  - assumed $k_H = \Sigma\, k_i BR_i$, only for i in SM
    - ➔ total width controlled by $\rm H \to bb$
    - ➔ $\rm H \to cc$ is a 5% unaccessible contribution (assumed to scale with bb)
    - ➔ no contributions from BSM
- **Global fits targeting the k factors**
  - do not resolve loops, effective coupling instead (k_γ, k_g and $k_{Z\gamma}$)



Results reported in terms of 68% uncertainties (-2$\Delta \ln L$=1) on k

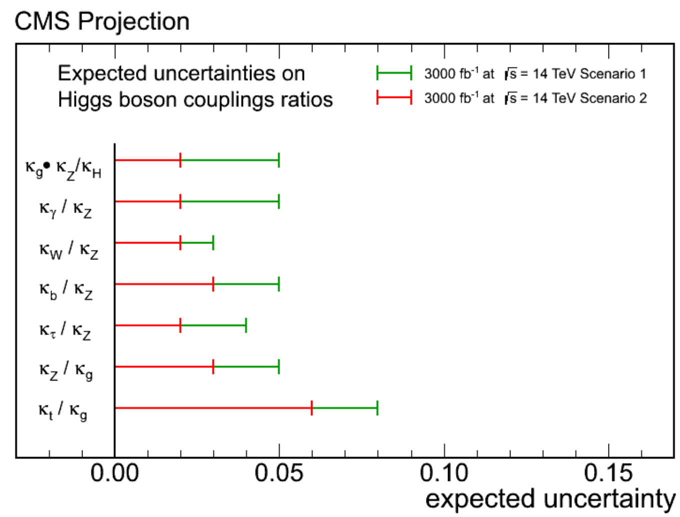
☞ **Assume no new undetectable modes**

➠ in an ambitious scenario, ultimate precision is about 2% for couplings involved in the main decay modes



☞ Results are more “stable” if total width absorbed by a reference scale factor

➠ look at **ratios of couplings** for direct comparison



HL-LHC can lead to an accuracy of about 5-8% for many coupling constants in scenario conservatively covering the range of future performances

[**Scenario 2, Scenario 1**]

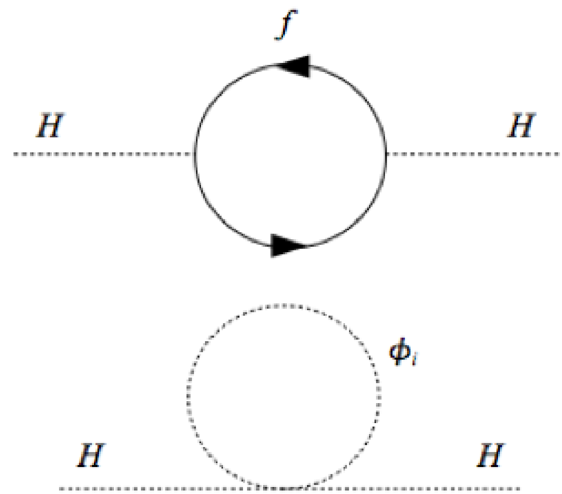
L (fb^{-1})	k_γ	k_W	k_Z	k_g	k_b	k_t	k_τ	$k_{Z\gamma}$	$k_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

☞ Hierarchy Problem

➠ in the SM the quantum corrections for the mass of the Higgs boson require a miraculous cancellation as

$$\mathcal{O}(10^{30}) - \mathcal{O}(10^{30}) \sim \mathcal{O}(10^{4})$$

Fine-tuning in MSSM→ Natural SUSY



$$\Delta M_H^2 \sim \frac{\lambda_f^2}{4\pi^2}[(m_f^2 - m_S^2)\log(\frac{\Lambda}{m_S})]$$

Little hierarchy problem:
large mass of squarks re-introduce fine-tuning

☞ Dark Matter

$$\mathbf{P_R} = (\mathbf{-1})^{\mathbf{2S+3B+L}} \begin{cases} S- & \text{spin} \\ B- & \text{barion number} \\ L- & \text{lepton number} \end{cases}$$

$P_R = -1$ for spart.
$P_R = +1$ for SM part.

R-Parity Conservation (RPC):

1. lightest sparticle (LSP) stable
2. sparticles are produced in pairs
3. cascade decay down to the LSP (DM candidate)

☞ Gauge Unification

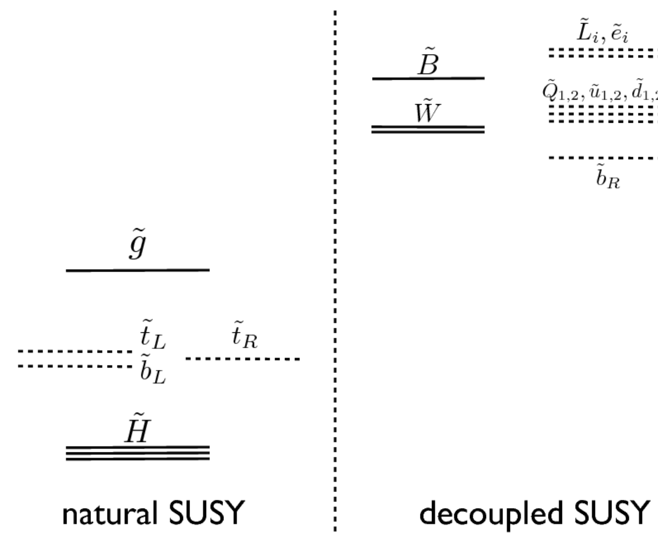
SUSY: Search Strategy

[arXiv:1110.6926]

☞ Disclaimers:

- SUSY is broken by unknown mechanism
- introduces many free parameters in theory
- results are presented in a given model using assumptions
- most current results are given in Simplified Models: single decay chain, 100% BR, etc

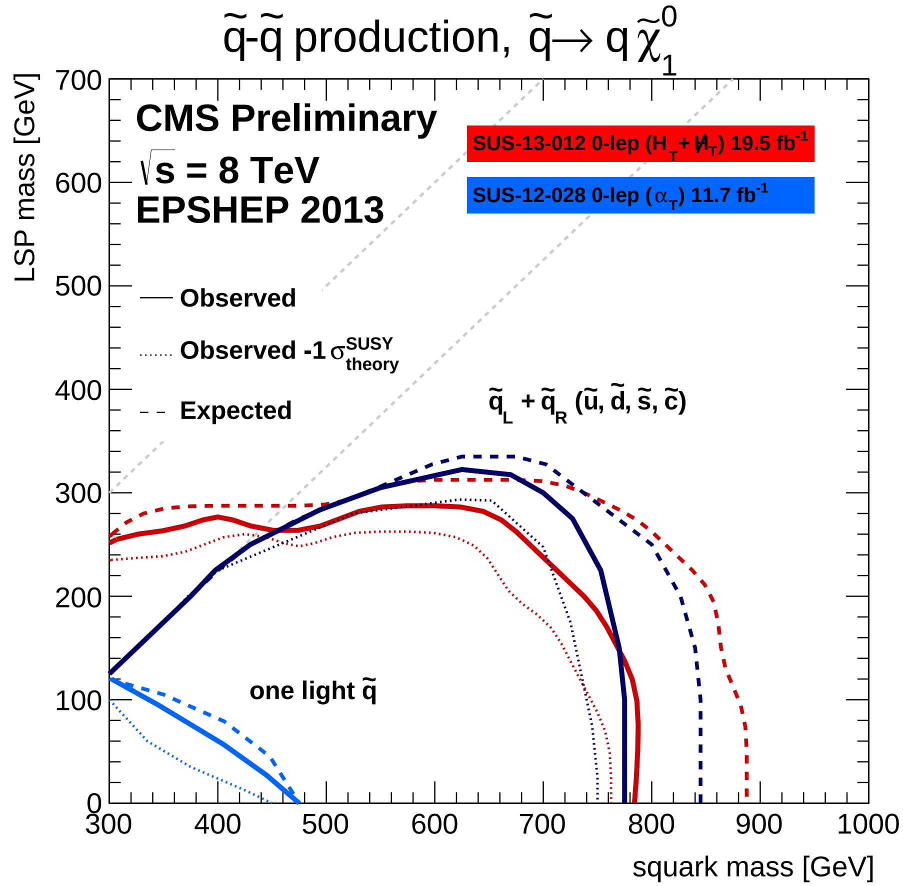
$$\begin{aligned} m_{\tilde{g}} &\leq 1500 \text{ GeV} \\ m_{\tilde{t},\tilde{b}_L} &\leq 700 \text{ GeV} \\ m_{\tilde{\chi}^0_{1,2},\tilde{\chi}^+_1} &\leq 350 \text{ GeV} \end{aligned}$$

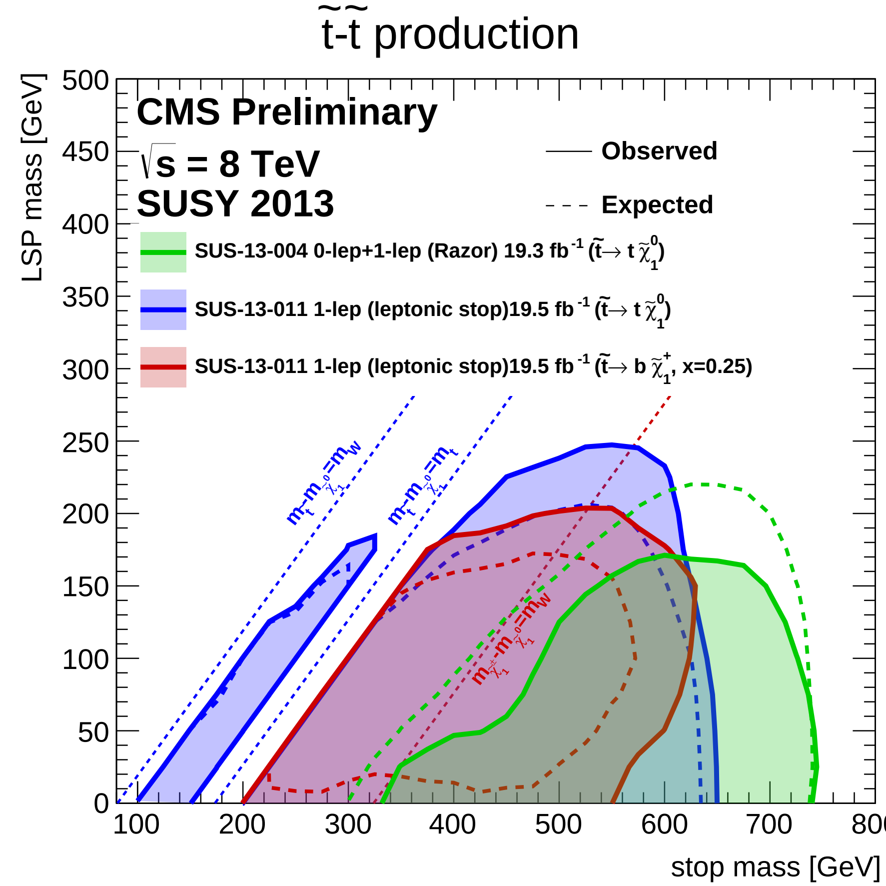


Large 1st and 2nd generation squarks, bino/wino, sleptons can be heavy without compromising **naturalness**

☞ Strategy is based on phenomenology oriented approach:

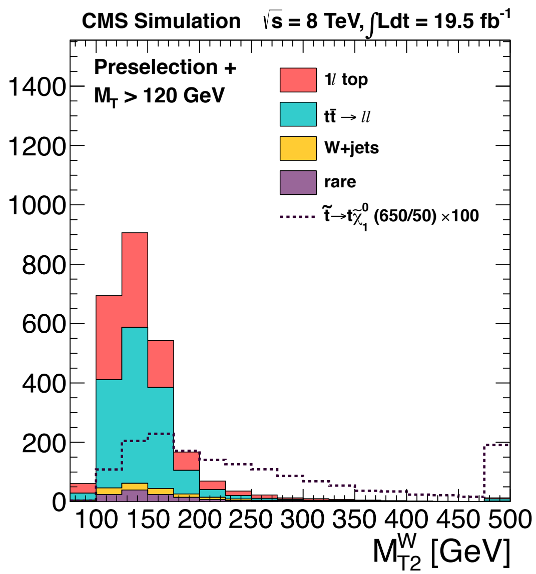
- **natural spectrum** in RPC scenario
- strong production in RPC scenario
- R-Parity Violation (RPV) scenario
- extended Higgs sector in SUSY: h,H,A,$H^{\pm}$
- indirect searches: $B_{s,d} \rightarrow \mu^+\mu^-$, TGC



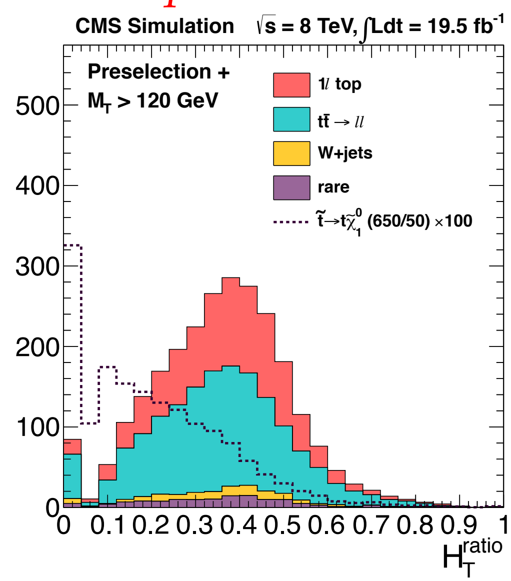


- ☞ Traditional **Jets**+$\boldsymbol{E_T^{\text{miss}}}$ search
  - ➠ uses simple kinematic variables to categorise events
  - ➠ main backgrounds QCD, W/Z+jet and $t\bar{t}$ are estimated using data-driven techniques
- ☞ Focus on **1 lepton** channel
- ☞ Analysis sensitive to $\Delta\text{M} > \text{m}_\text{t}$ and $\Delta\text{M} < \text{m}_\text{t}$ **but not** $\boldsymbol{\Delta\text{M} \sim \text{m}_\text{t}}$
  - ➠ search for stops in gluino-mediated cascade processes
  - ➠ precise subtraction of $t\bar{t}$ background

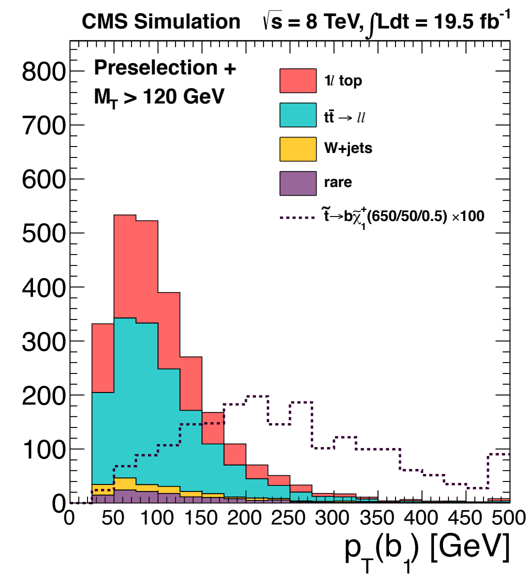
M_{T2}^{W} [JHEP07 (2012) 110]

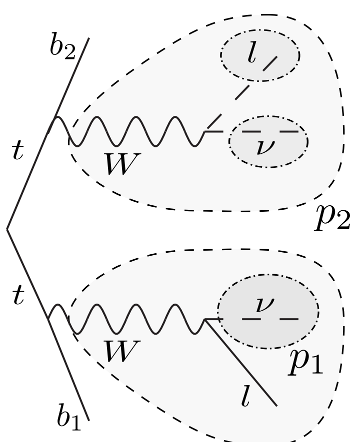


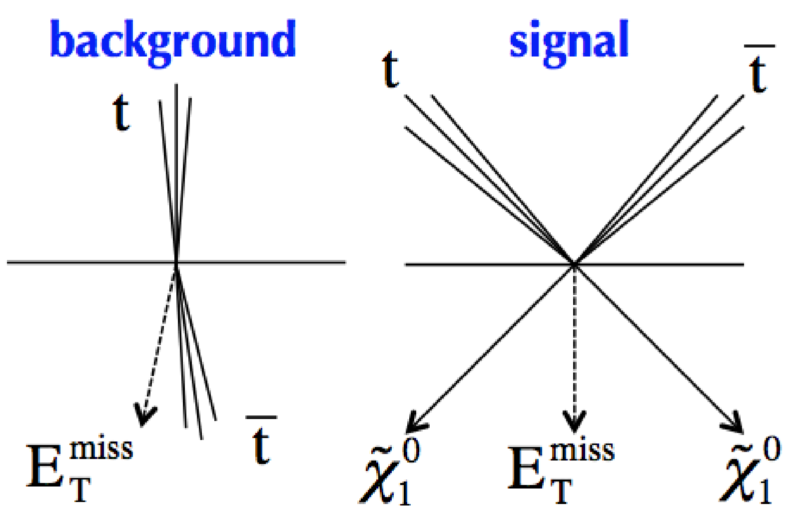
Fraction of H_T in same hemisphere as MET

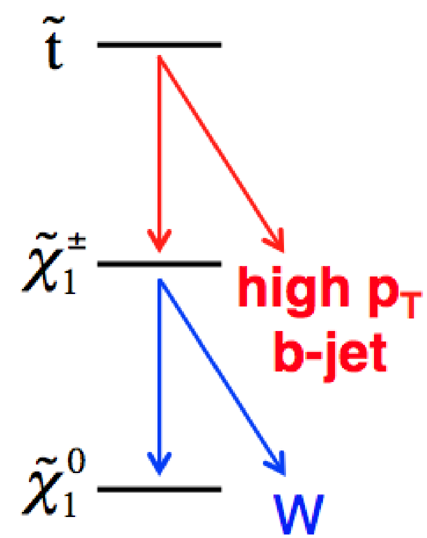


Leading b-jet p_T

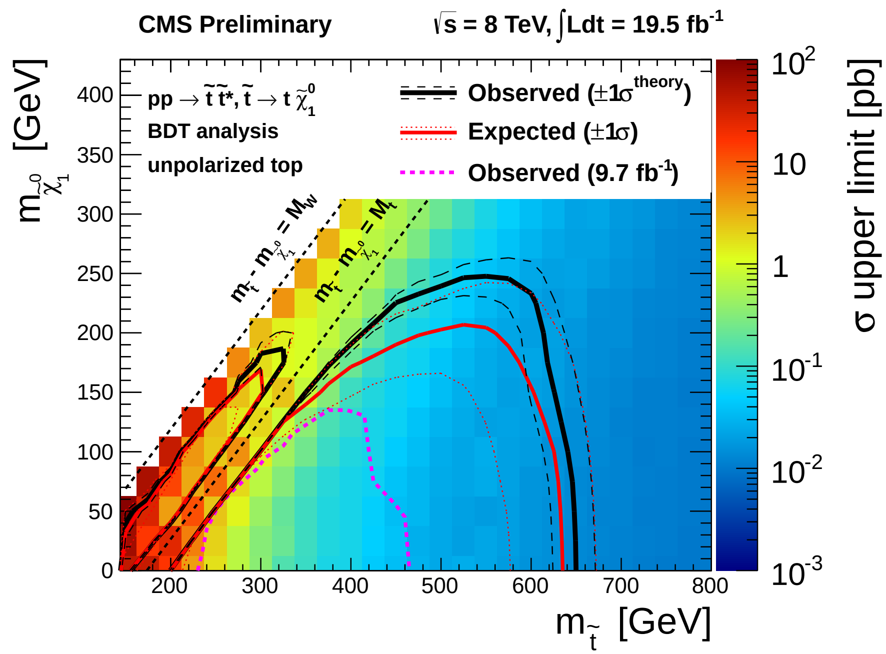




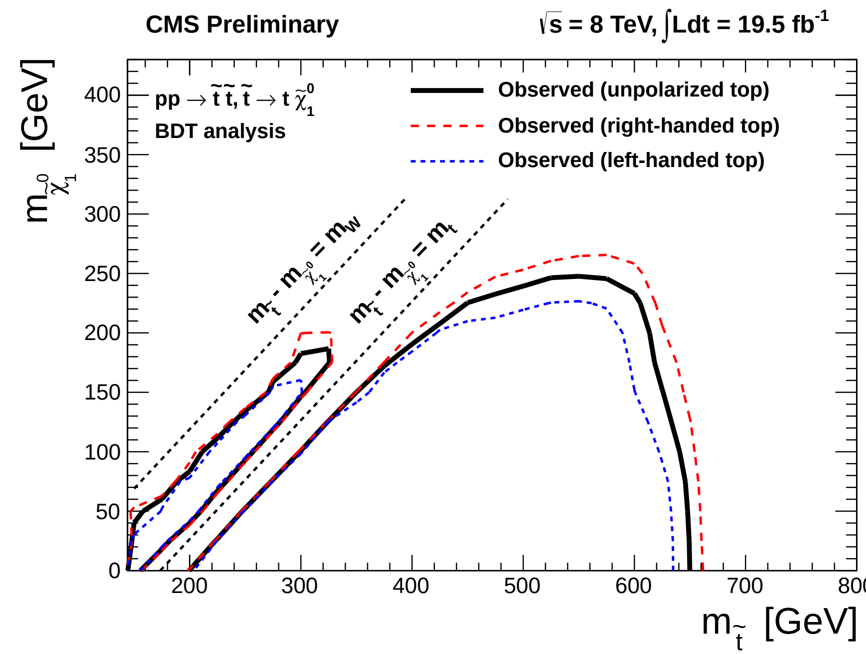




Limits from BDT signal regions



Polarization Dependence



- Analysis sensitive to $\Delta M > m_t$ and $\Delta M < m_t$ **but not $\Delta M \sim m_t$**
  - search for stops in gluino-mediated cascade processes
  - precise subtraction of $t\bar{t}$ background

Exclude stops $m_{\tilde{t}} \leq 625$ GeV for neutralinos $m_{\tilde{\chi}_1^0} \leq 225$ GeV

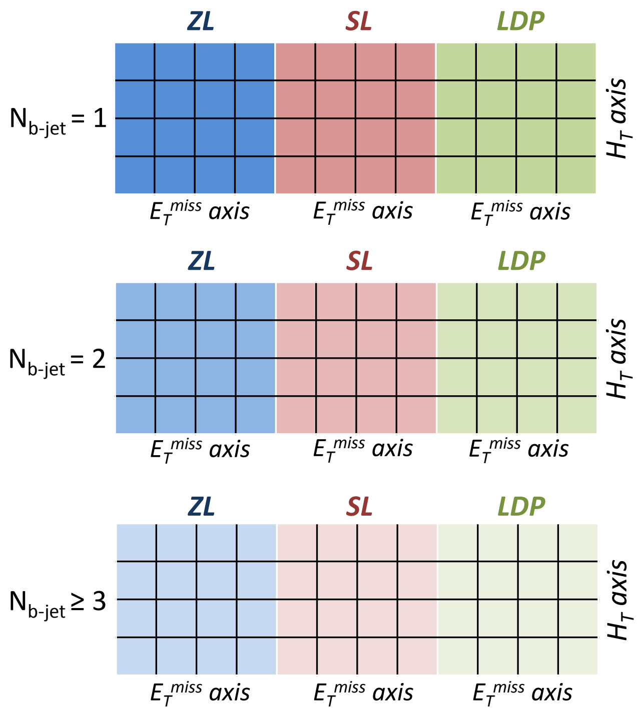
- Signal acceptance depends on top polarization from $\tilde{t} \to t\tilde{\chi}_1^0$
  - depends on left/right stop mixing and $\tilde{\chi}^0$ composition
  - compare mass limits for unpolarized (nominal) vs. left/left-handed tops
  - impact on mass limits about 20 GeV

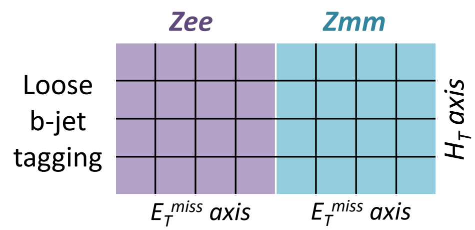
☞ **Gluino mediated** pair production of $\tilde{b}$ and $\tilde{t}$ squarks [arXiv:1305.2390] subm. to PLB

- hadronic final state: $\geq$3jets, $\geq$1 b-jets plus MET
- event categorization by $\mathrm{H_T} = \Sigma_{jet}\, p_T$, MET and $\mathrm{N_{b-jets}}$

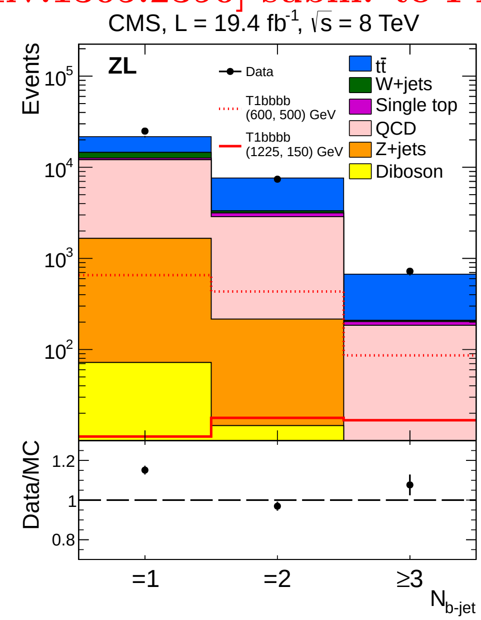
Event sample legend

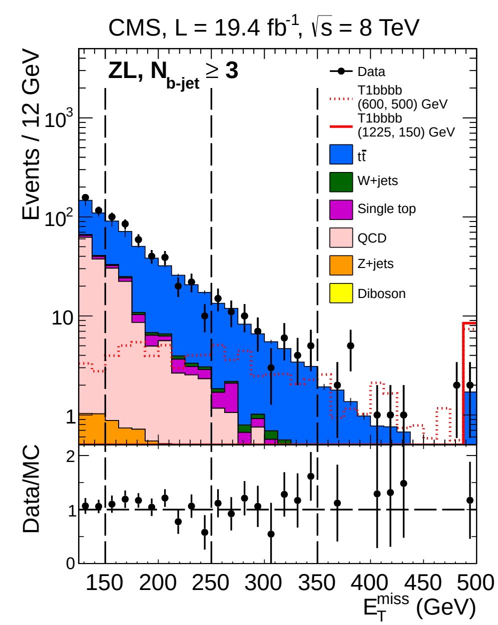
ZL = Zero Lepton; signal sample	*SL* = Single Lepton; top & W+jets control sample	*LDP* = low $\Delta\hat{\phi}_{min}$; QCD control sample	*Zee* = Z → e^+e^-; Z to $\nu\bar{\nu}$ control sample	*Zmm* = Z → $\mu^+\mu^-$; Z to $\nu\bar{\nu}$ control sample





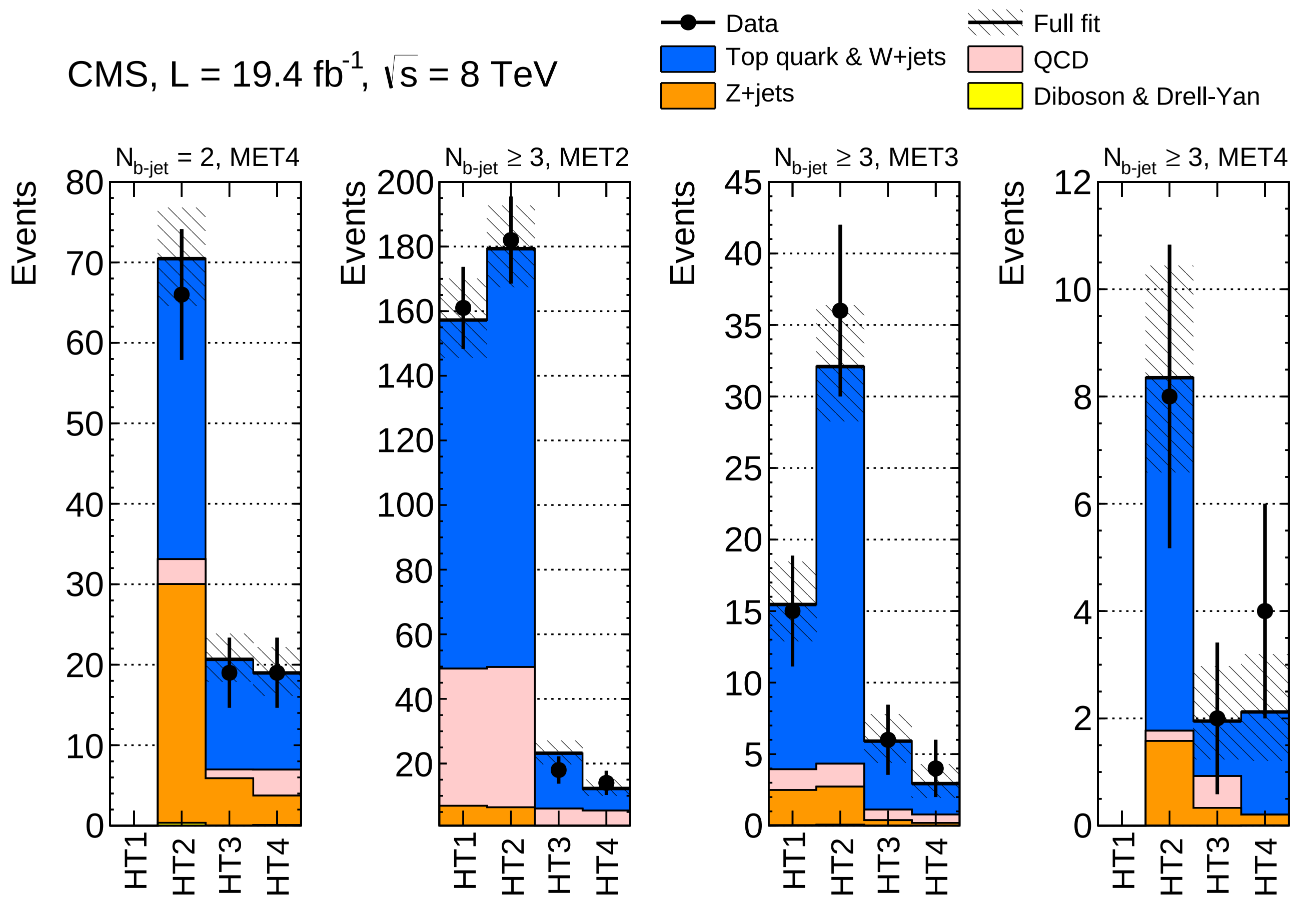
Bin	H_T (GeV)	E_T^{miss} (GeV)
1	400 – 500 (HT1)	125 – 150 (MET1)
2	500 – 800 (HT2)	150 – 250 (MET2)
3	800 – 1000 (HT3)	250 – 350 (MET3)
4	> 1000 (HT4)	> 350 (MET4)





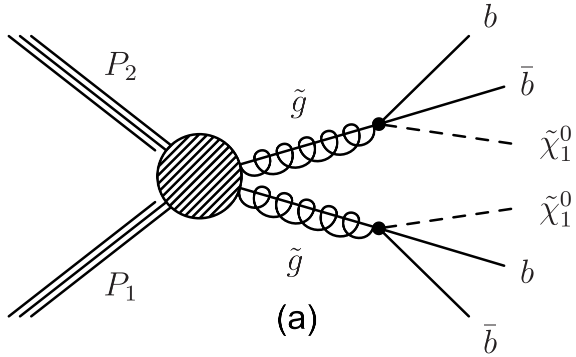
Background estimated from data control samples: e/μ+jets (SL), invert $\Delta\phi^{min}$ (LDP), Z→ll (Zee, Zmm)

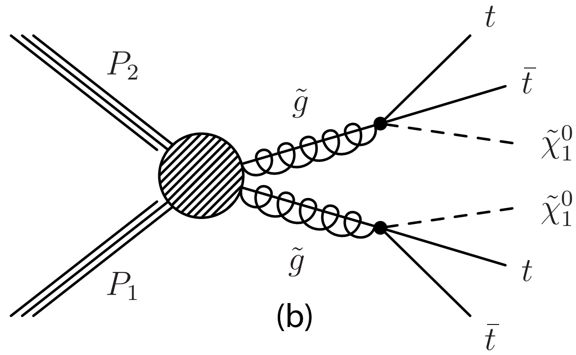
Binned likelihood fit performed simultaneously over all $\mathrm{H_T}$, MET and $\mathrm{N_{b-jets}}$ bins in signal and control regions

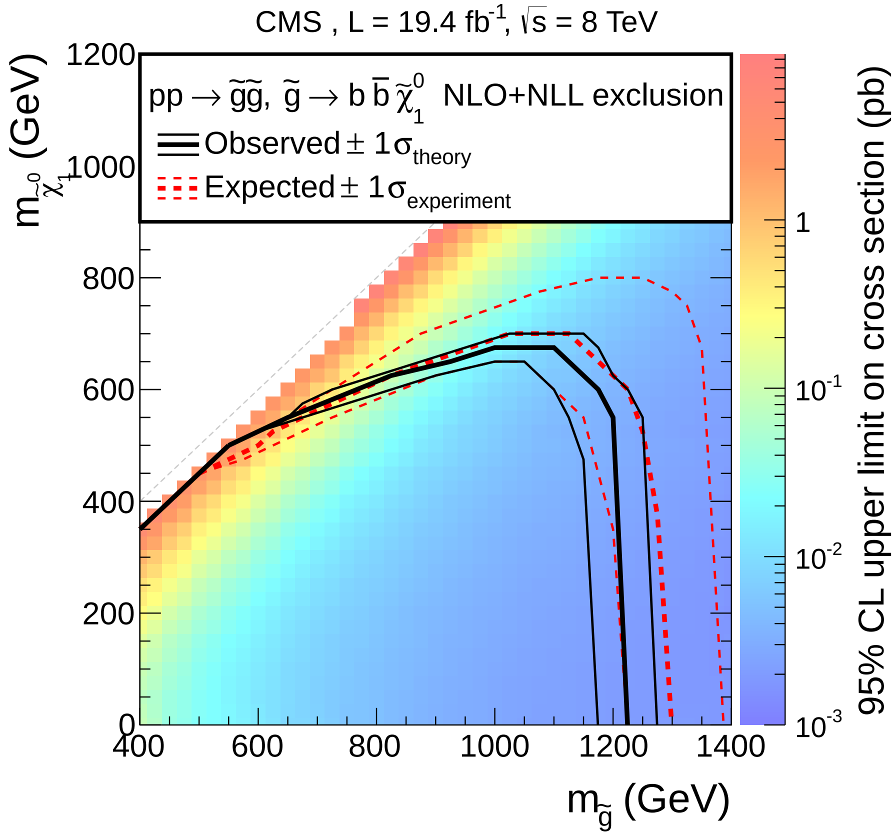


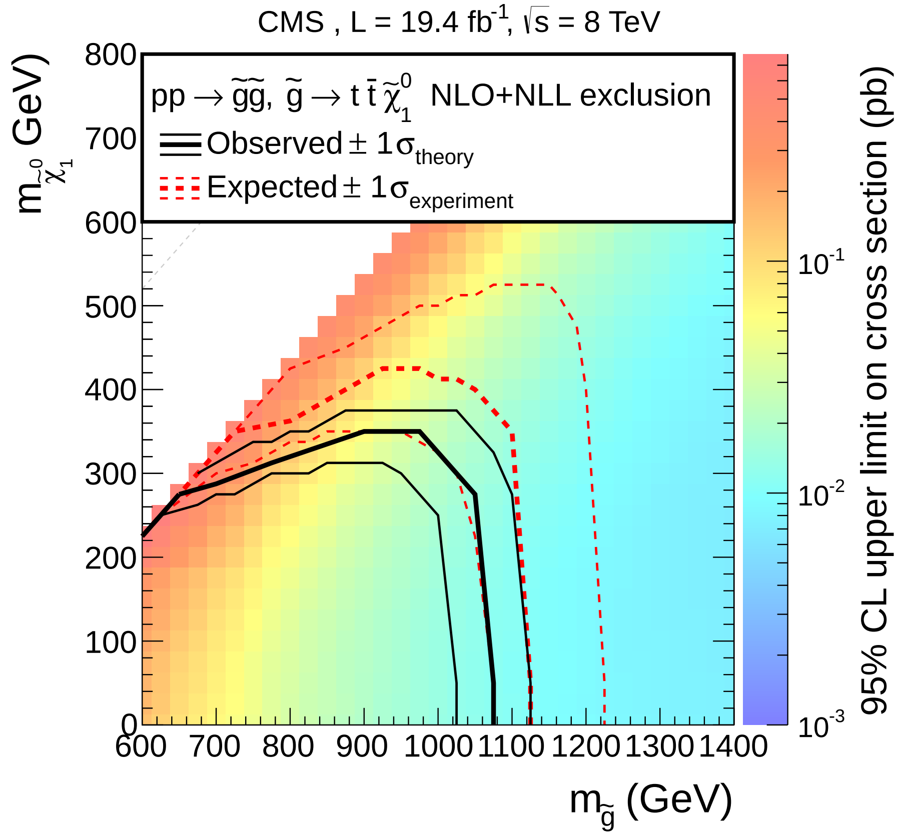
Events with $\mathrm{N_{b-jets}} \geq 3$: most sensitive to the signal

No significant excess in data observed







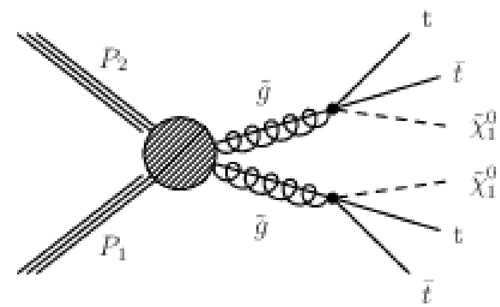


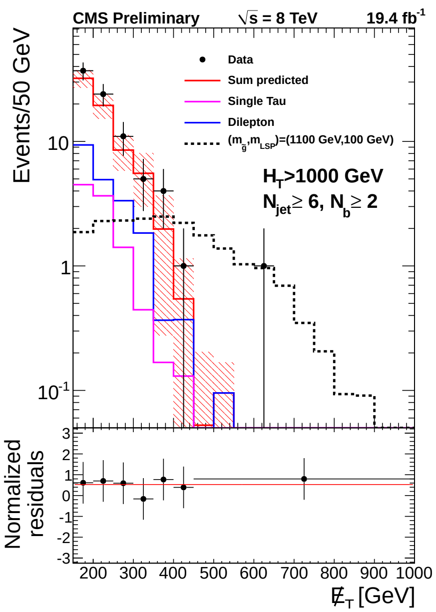
$m_{gluino} > 1200(1025)$ GeV at low mass LSP for 4b (4t) final state

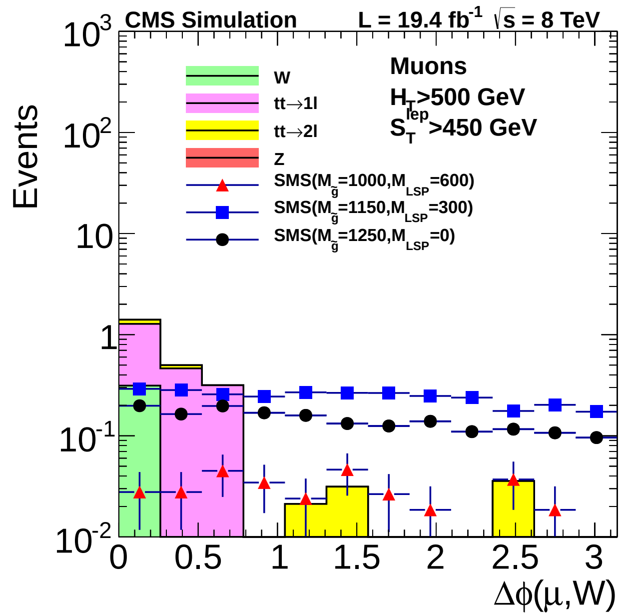
[SUS-13-007]

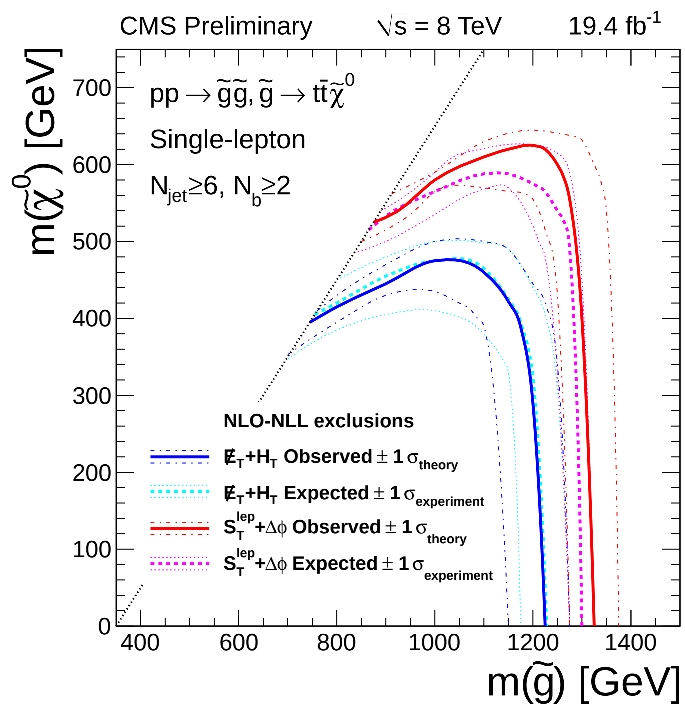
☞ Involve strong production processes and cascade decays to the LSP and a single lepton ($\tilde{g} \to \tilde{t}t, \tilde{b}b$)

- hadronic objects ≥6jets, ≥2 b-jets plus MET
- event categorization by $\mathrm{H_T}$, MET and $\mathrm{N_{b-jets}}$
- Two complementary approaches:
  Lepton Spectrum: MET>250 GeV
  Delta Phi: $\mathrm{S_T} = p_T{}^{\mathrm{lep}}$+MET for $\Delta\phi$(W,l)>1







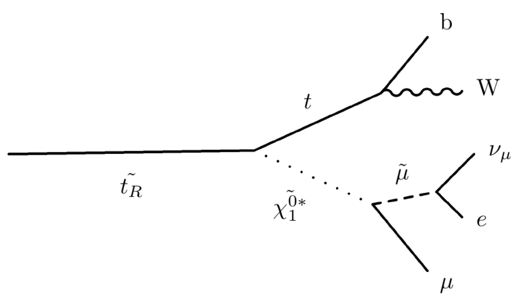


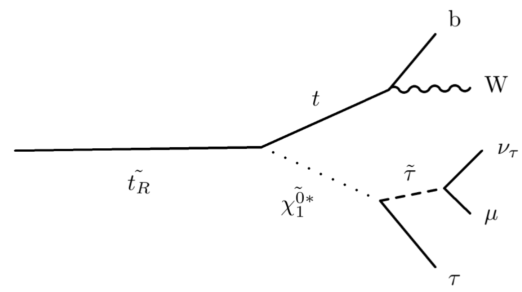
Background uncertainty from the MET scale and MC statistics on the single lepton scale factor

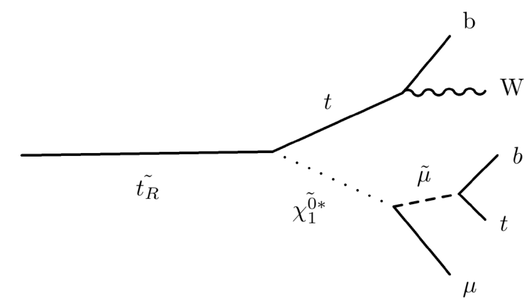
$\mathbf{m_{gluino}}$ < 1.3 TeV are excluded for neutralino masses below 0.5 TeV

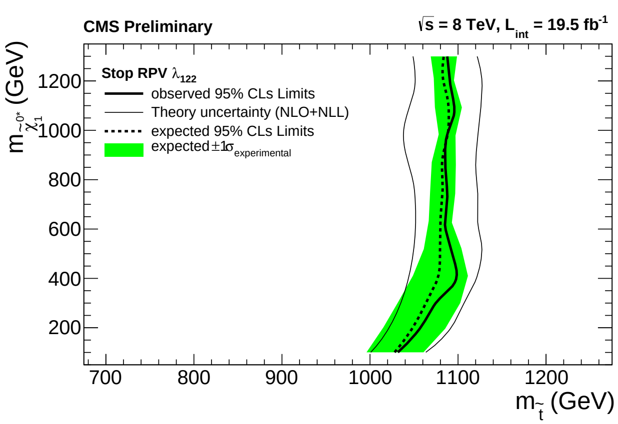
[SUS-13-003]

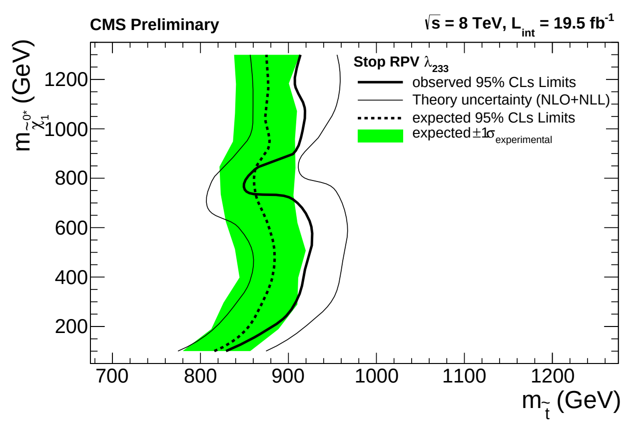
Leptonic RPV	*Leptonic RPV*	*Semi-leptonic RPV*
λ_{122}: e, μ– *enriched*	λ_{233}: μ, τ– *enriched*	λ'_{233}: μ, b, τ– *enriched*

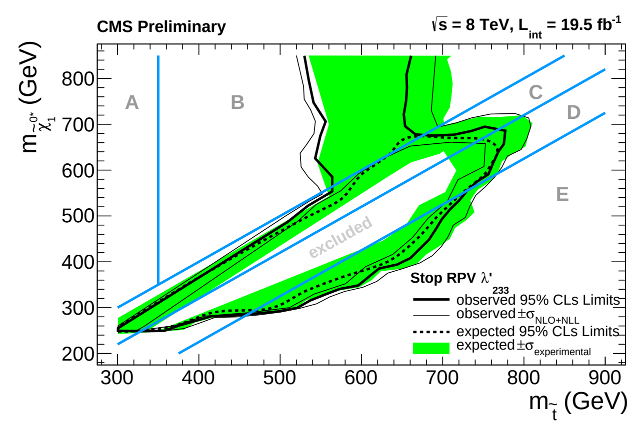












Probe stop up to kinematic limit about 1.1 TeV

R-Parity Violating SUSY with 4l

[SUS-13-010]

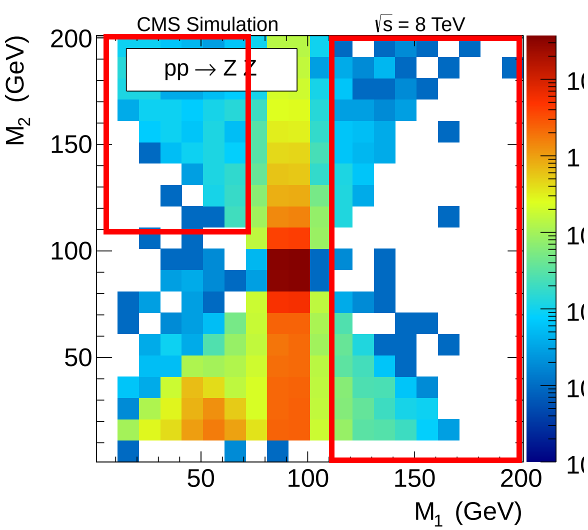
LRPV naturally gives multilepton signatures

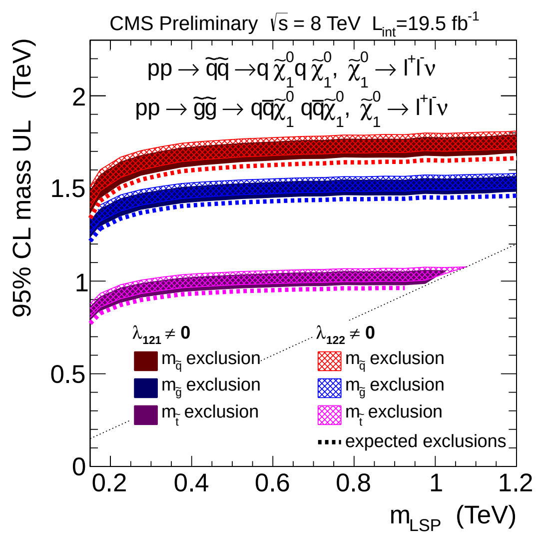
$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to 4l$

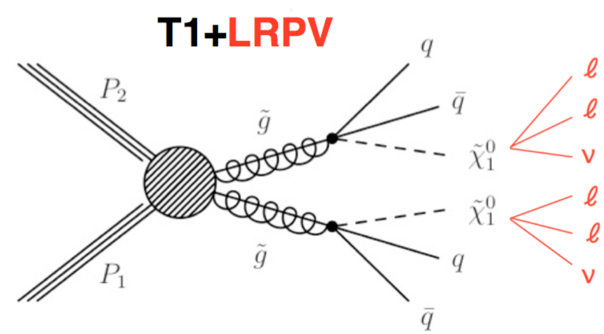
- Search for anomalous production with 4 leptons
  - M_1 - mass of opposite-sign, same-flavor dilepton around M_Z
  - M_2 - mass of the other lepton pair
- Define signal regions in M_2 versus M_1 plane
  - suppress ZZ background

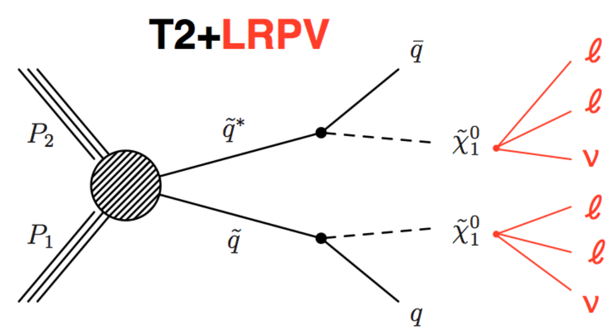
$\lambda_{121} > 0$: electron-enriched

$\lambda_{122} > 0$: muon-enriched









$N_{bkg} = 3.0 \pm 0.6$ev., $N_{data} = 1$ev. $\to$ **upper limit 3.4 events**

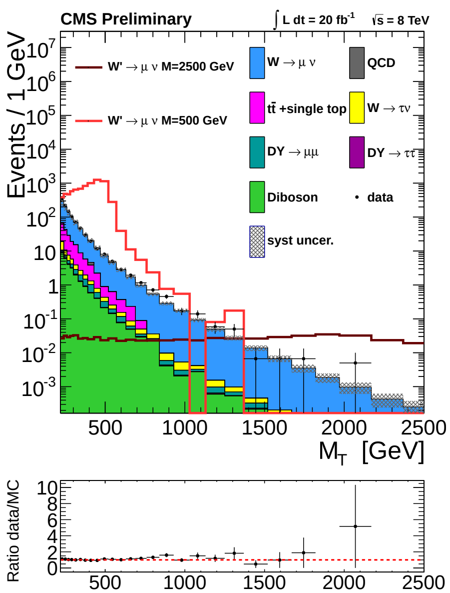
Probe $m_{\tilde{g}} \sim 1.5$ TeV, $m_{\tilde{t}} \sim 1.0$ TeV, $m_{\tilde{q}} \sim 1.7$ TeV

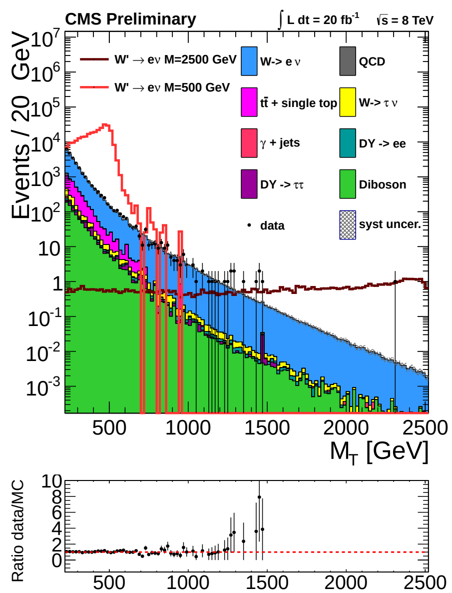
Lepton+MET W' Searches

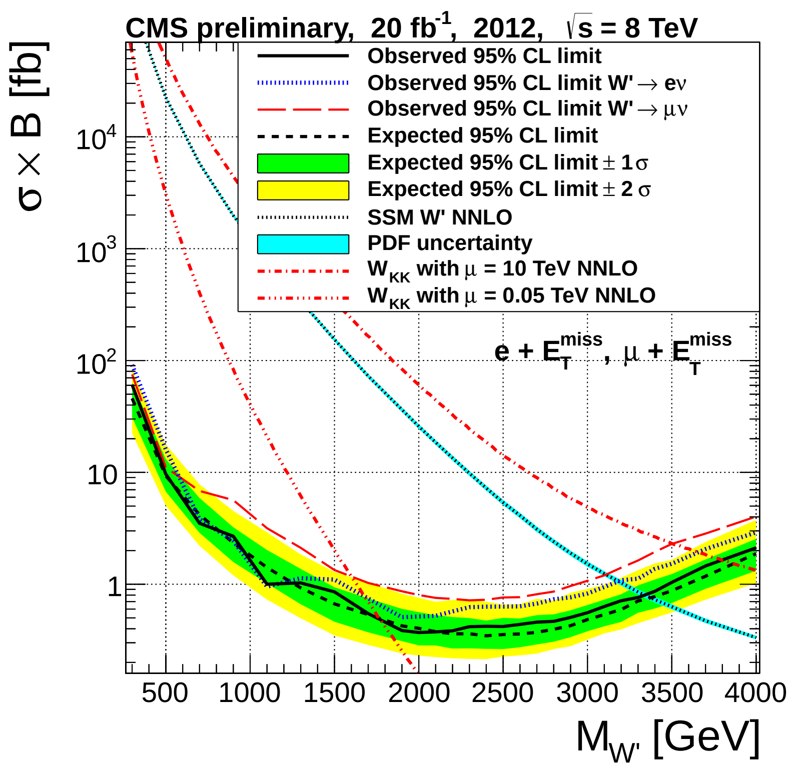
Look for Jacobian peak on falling $\mathrm{M_T}$ *distribution:*

$$\mathrm{M_T} = \sqrt{2 \cdot p_T{}^{l} \cdot \mathrm{E_T^{miss}} \cdot (1 - \cos\Delta\phi_{l,\nu})}$$

[EXO-12-060]







☞ Background prediction given by MC

➠ fit to background with empirical function: $\mathrm{f_{M_T}} = \frac{\mathrm{a}}{(\mathrm{M_T^3} + \mathrm{bM_T} + \mathrm{c})^{\mathrm{d}}}$

SM-like couplings: $\mathrm{m_{W',SSM}} > 3.35\ \mathrm{TeV}$

UED second KK excitation $(\mathrm{W^2_{KK}})$: $\mathrm{m} > 1.7(3.7)\ \mathrm{TeV}$ for μ=0.05(10) TeV

No significant deviations from background expectation