Overview of recent CMS results

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LIP Lisbon

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Instituto Superior Técnico, Lisbon

DISCRETE 2012 - Third Symposium on Prospects in the Physics of Discrete Symmetries

On behalf of the CMS Collaboration

Outline

- Jets, W&Z, top
- Higgs
- SUSY
- Other searches
- (Prospects)

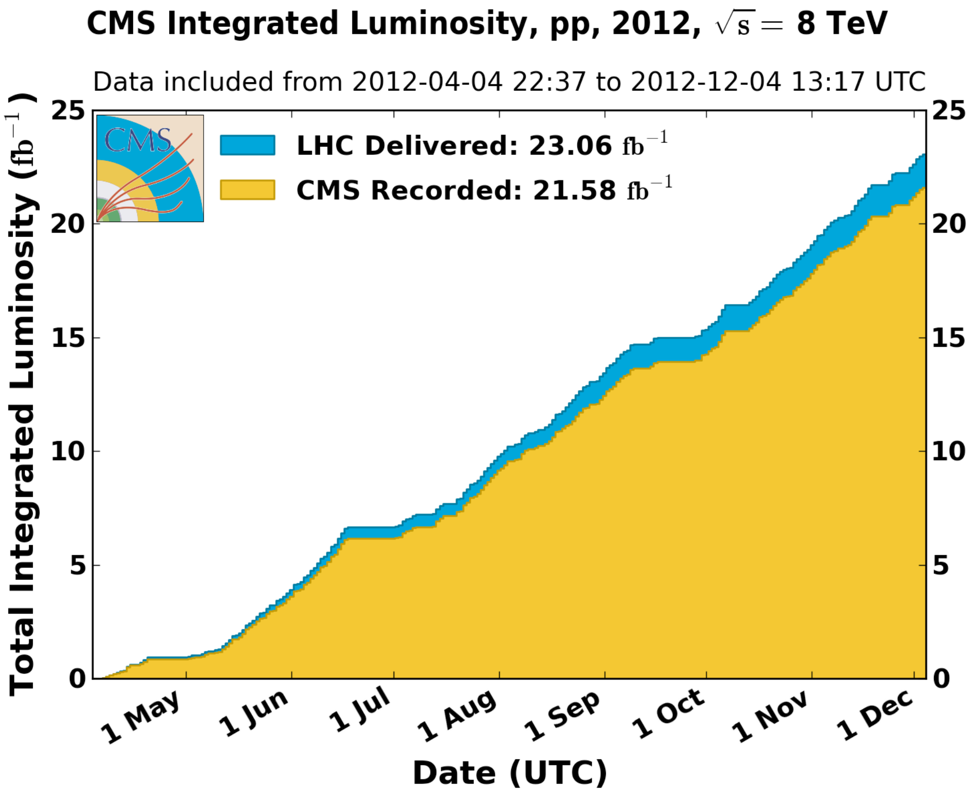
Related talks at this conference:

- Top quark physics, M. Gallinaro
- Measurements of the top-quark mass and production cross section at CMS, P. F. Silva
- Results on the Search for MSSM Neutral and Charged Higgs bosons (CMS), M. Tosi
- Searches for SM Higgs boson decaying into two photons, ZZ and two τs in CMS, M. Meneghelli

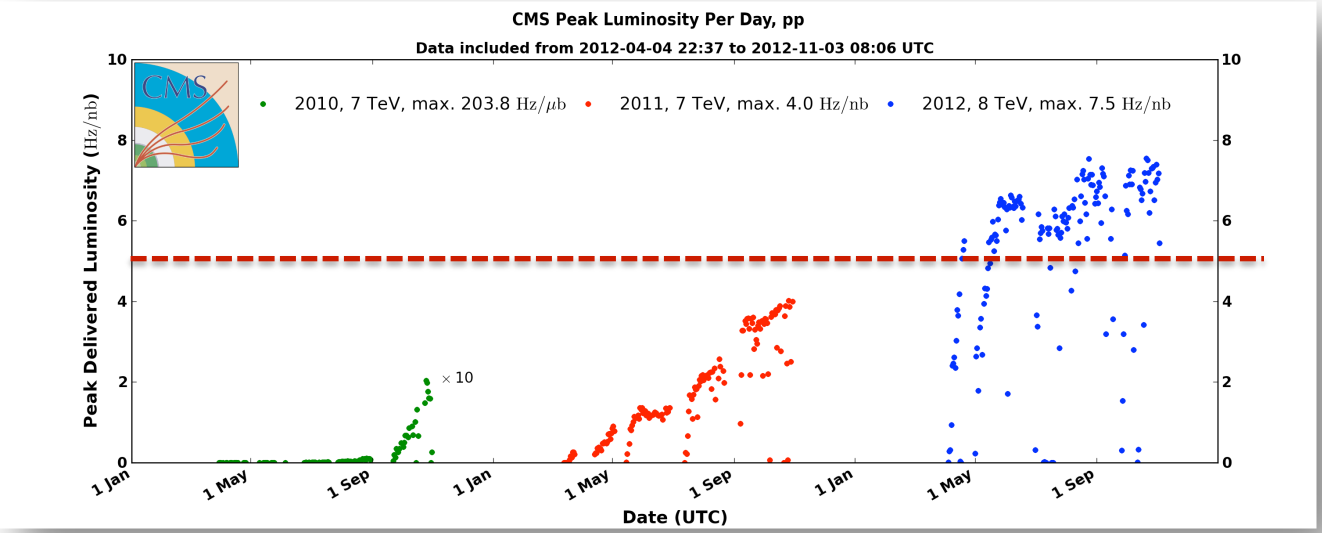
8 TeV data in 2012

Until December 4:

- Delivered 23.1 fb^{-1}
- Recorded 21.6 fb^{-1} (94%)
- Certification ~ 90% of data delivered is used for physics

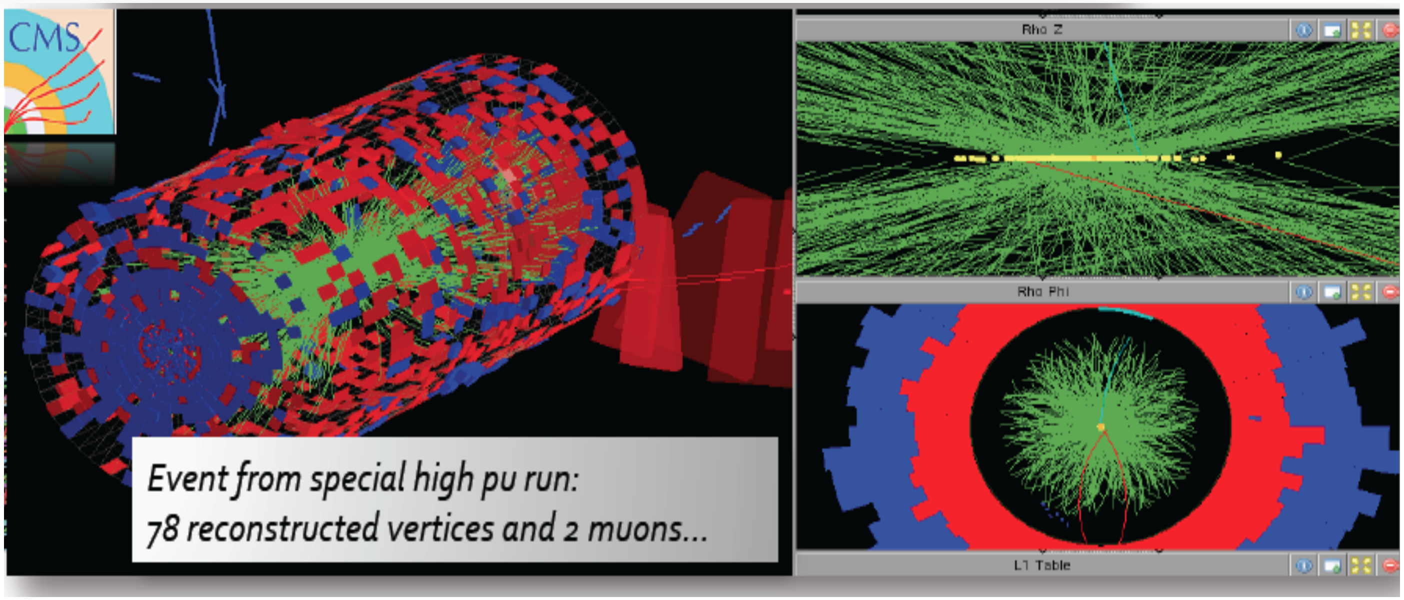


Pileup in 2012



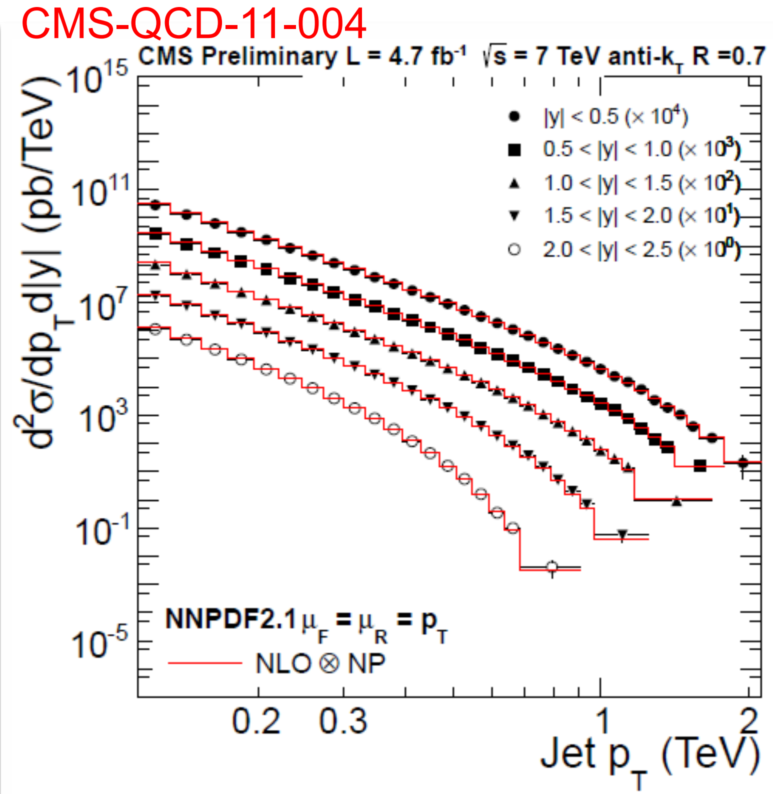
Peak: 37 pileup events

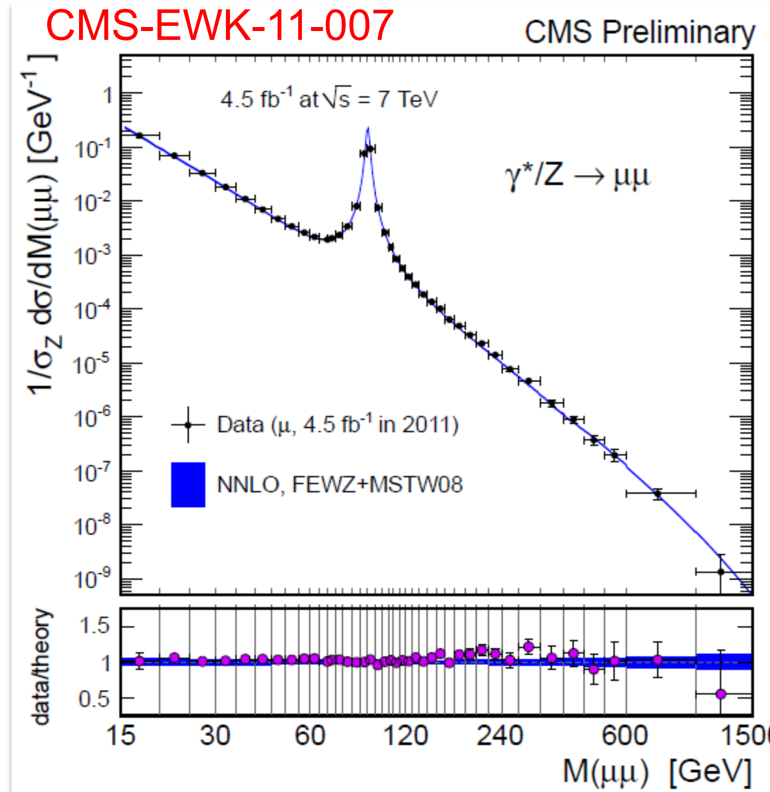
Design value
25 pileup events
(L=10^{34}, 25 ns)



2011-12 Datasets: Jets, W&Z, top

Standard model: Jets, γ^*/Z





Inclusive jet and dijets:

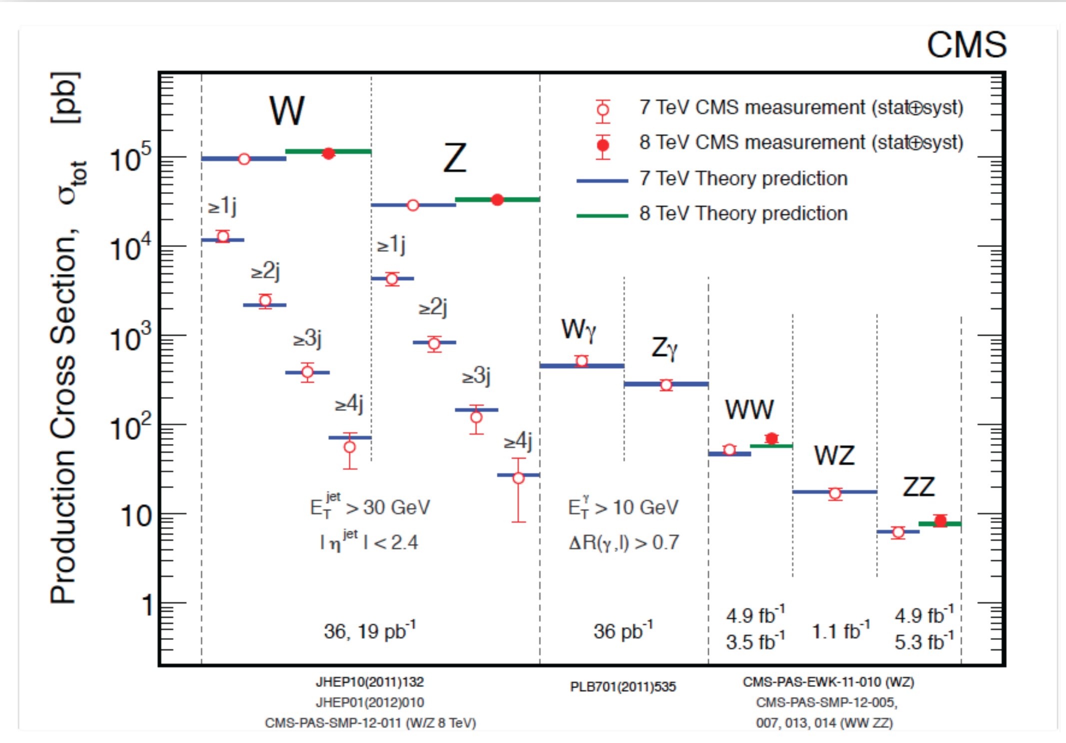
- NLO QCD describes data over ~9 orders of magnitude!
- 1-2% JES.
- Constrains gluon PDF up to x=0.6

Differential Drell-Yan cross section:

- 2.5M $\mu\mu$ pairs tests NNLO cross sections and PDFs

Vector boson pairs

W, Z, WW, and ZZ cross sections at 8 TeV
(Special Low PU runs used for W,Z at 8 TeV)

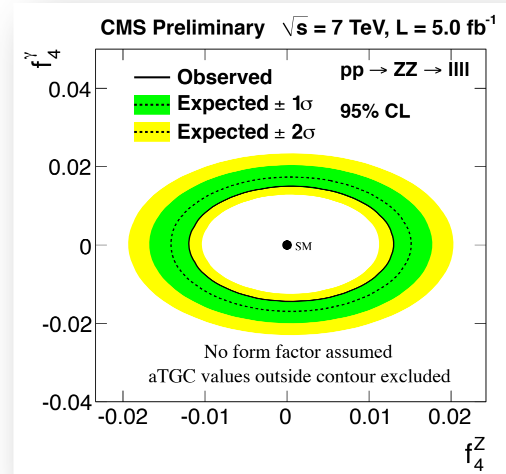


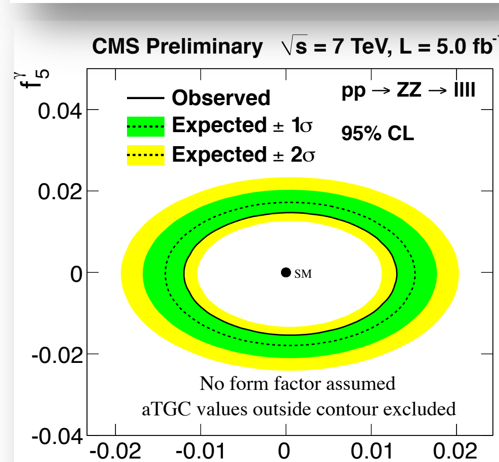
Measured σ (ZZ) = 8.4 ± 1.3 pb
SM (NLO) σ (ZZ) = 7.7 ± 0.4 pb

Measured σ (WW) =69.9 ± 7.0 pb
SM (NLO) σ (WW) = 57.3 ± 2.0 pb

SMP-12-011
SMP-12-013
SMP-12-014

Limits on anomalous ZZZ/ZZγ couplings:

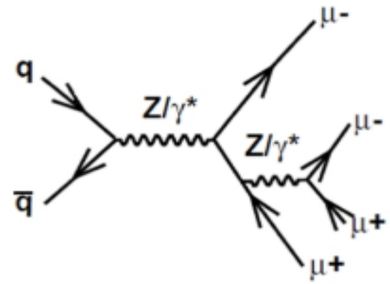


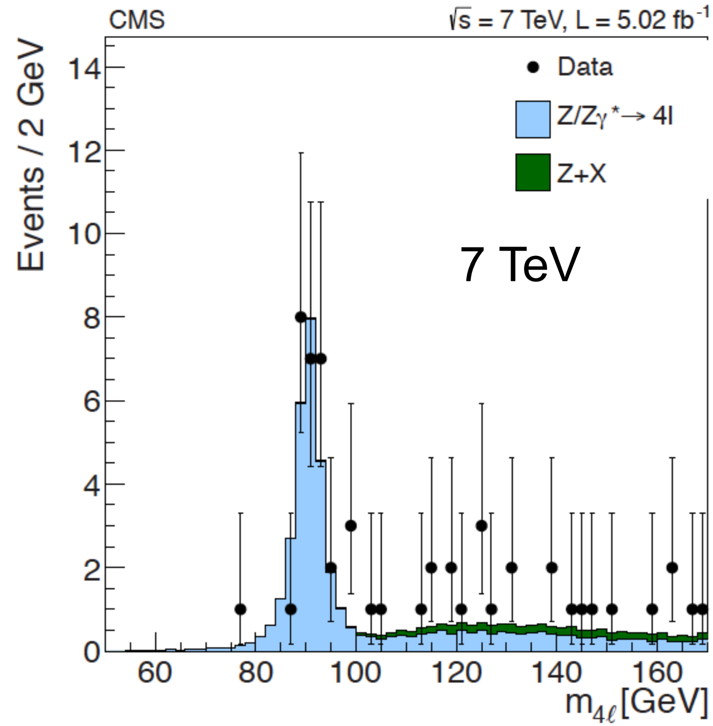


SMP-12-007

Observation Z→ 4l decay

9.7 σ significance





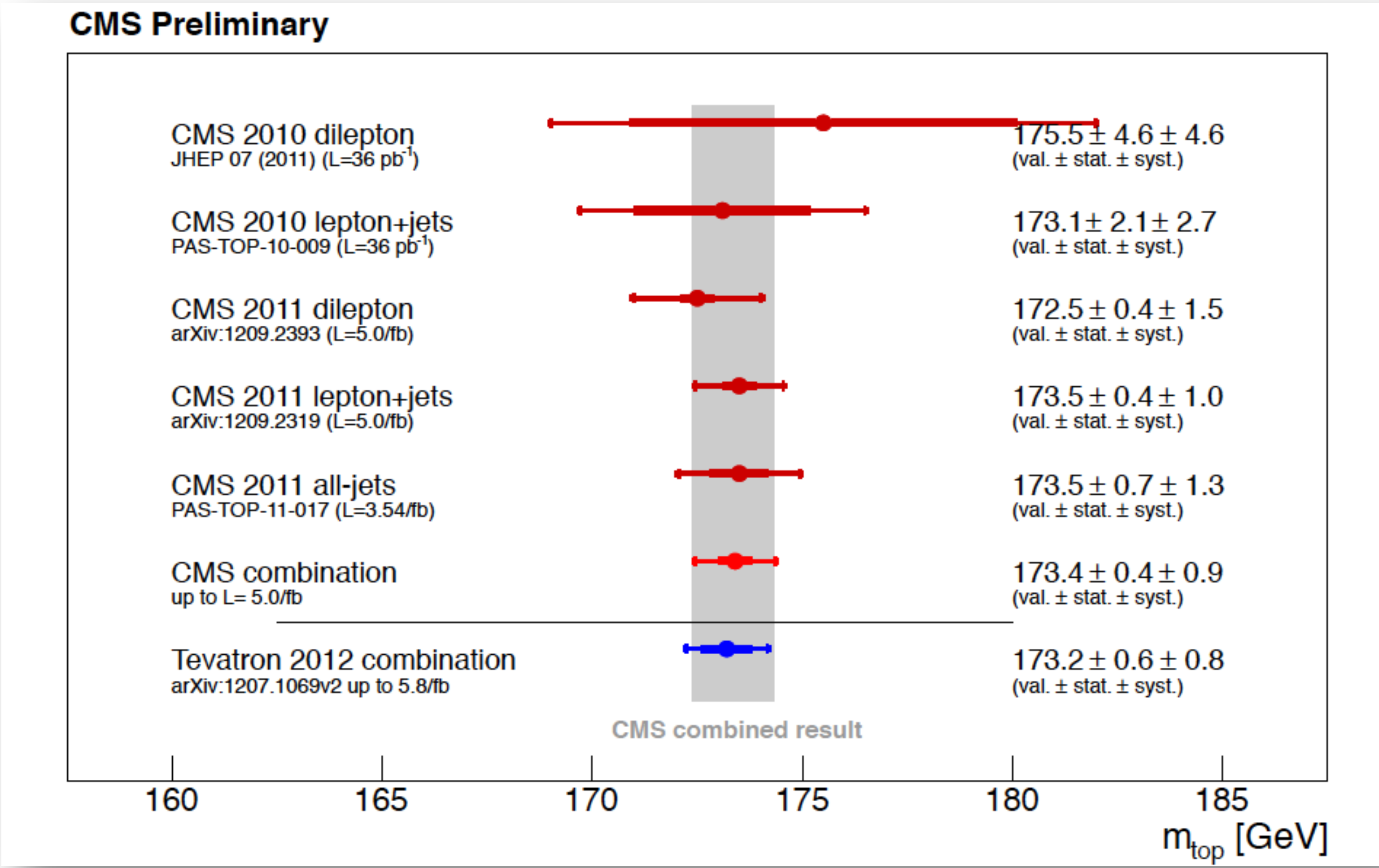
- Standard candle
  - $H \rightarrow ZZ \rightarrow 4l$
  - 10x more events
- Current statistics
  - ±0.5% on m_{4l} scale

Final state channels	4e	4μ	$2e2\mu$	4ℓ
Irreducible background ($pp \rightarrow Z\gamma^* \rightarrow 4\ell$)	0.07	0.25	0.14	0.46 ± 0.05
Other (reducible) backgrounds	0.01	0.01	0.05	0.07 ± 0.1
Expected signal ($pp \rightarrow Z \rightarrow 4\ell$)	3.8	13.6	12.0	29.4 ± 2.6
Total expected (simulation)	3.9	13.9	12.2	30.0 ± 2.6
Observed events	2	14	12	28
Yield from fit to the observed mass distribution	-	13.6 ± 3.8	11.5 ± 3.1	27.3 ± 5.4

arXiv:1210.3844

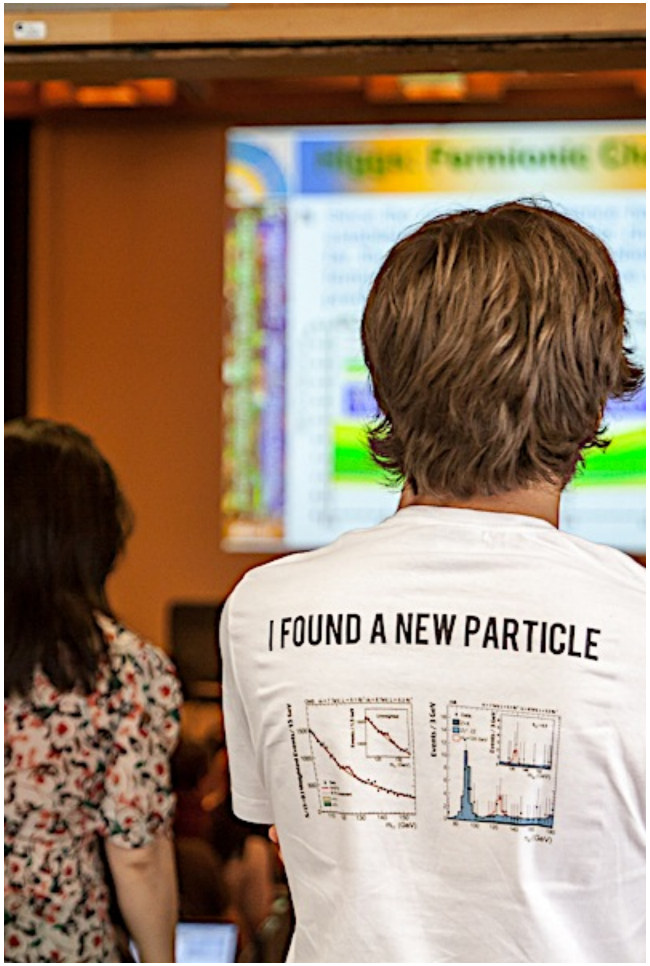
Top quark mass in CMS

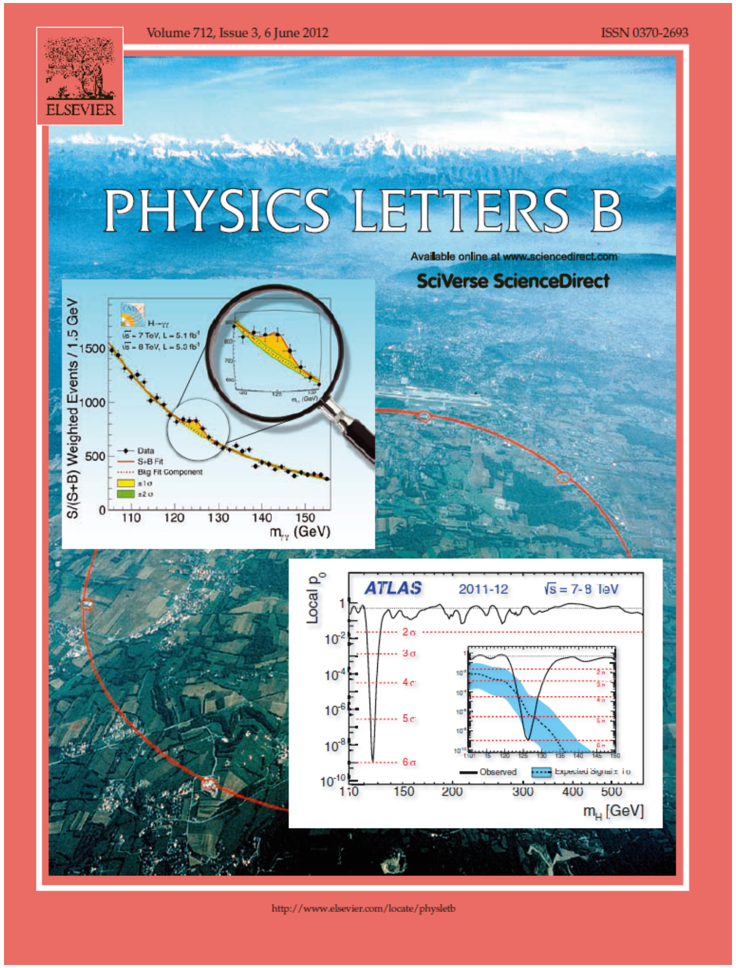
m_{top} = 173.4 ± 0.4 (stat) ± 0.9 (syst) GeV



CMS PAS TOP-11-018

2011-12 Datasets: Higgs

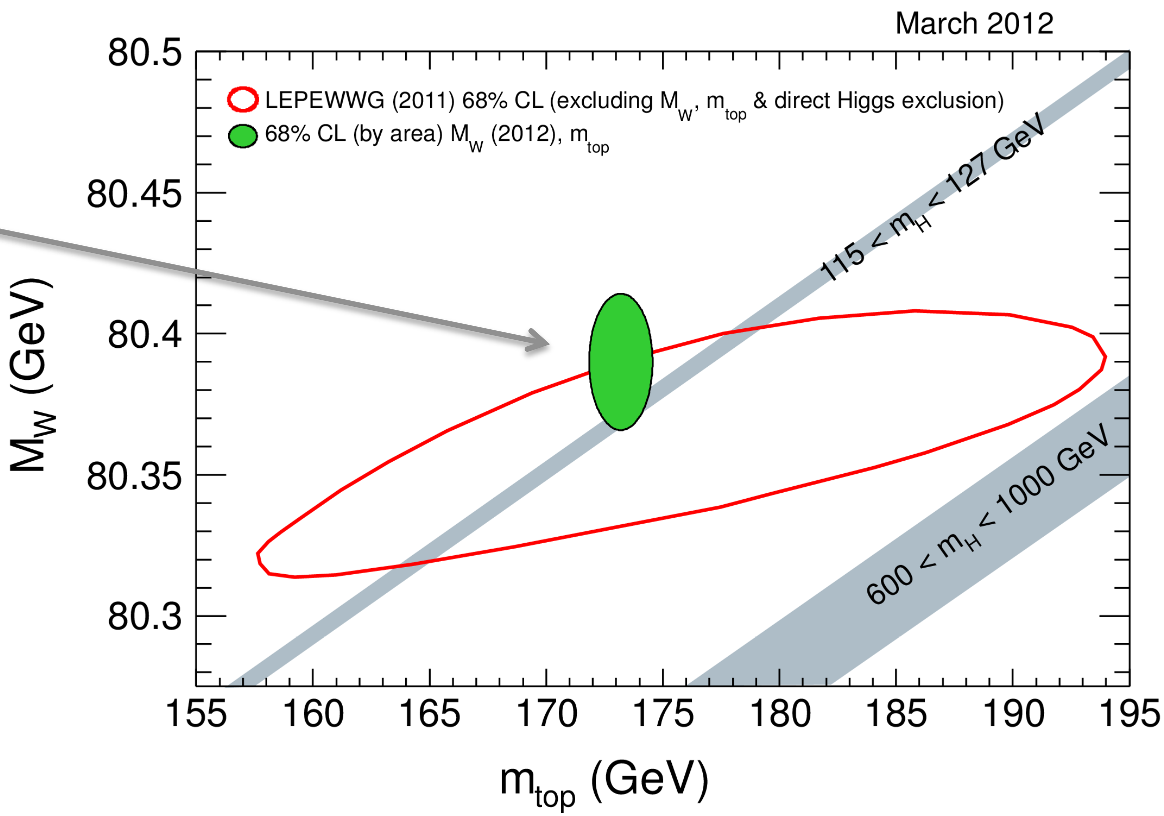




Very precise measurement of M_W = 80.390 ± 0.016 GeV, driven mainly by the Tevatron.

Much of the SM Higgs range had been ruled out by 2011 LHC running.

Excess of events in the low mass region seen in ATLAS and CMS

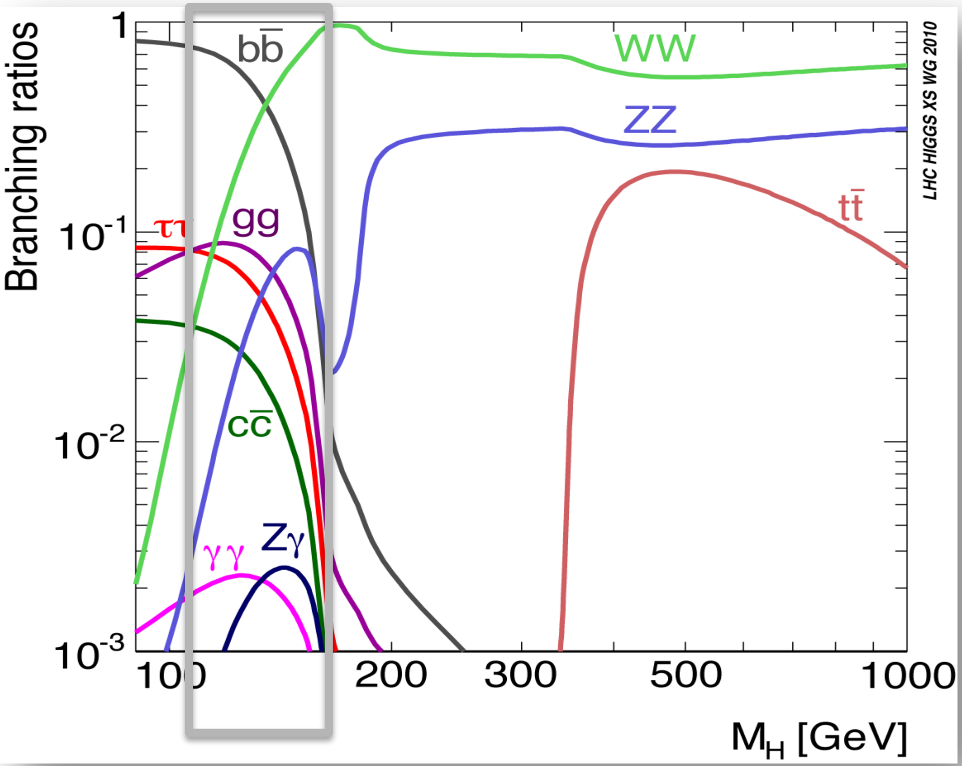


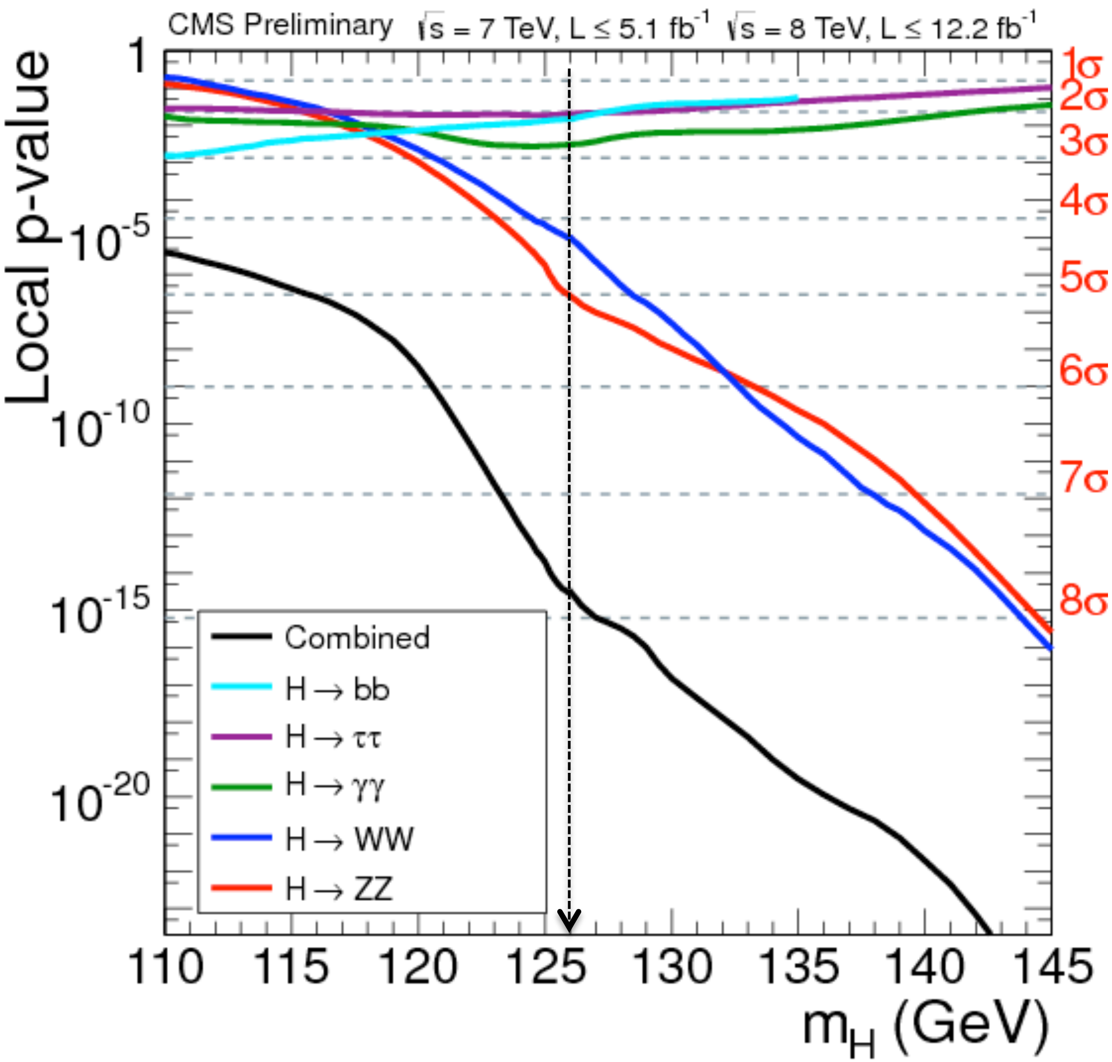
Exclusions of M_H:

- LEP < 114 GeV (arXiv:0602042v1)
- Tevatron [156,177] GeV (arXiv:1107.5518)
- LHC [~127, 600] GeV arXiv:1202.1408 (ATLAS) arXiv:1202.1488 (CMS)

5 decay modes exploited

- bb, ττ, WW, ZZ, γγ
- Low mass region is very rich but also very challenging:
  main decay modes (bb, ττ) are hard to identify in the huge background
- Very good mass resolution (1%): H→γγ and H→ZZ→4l

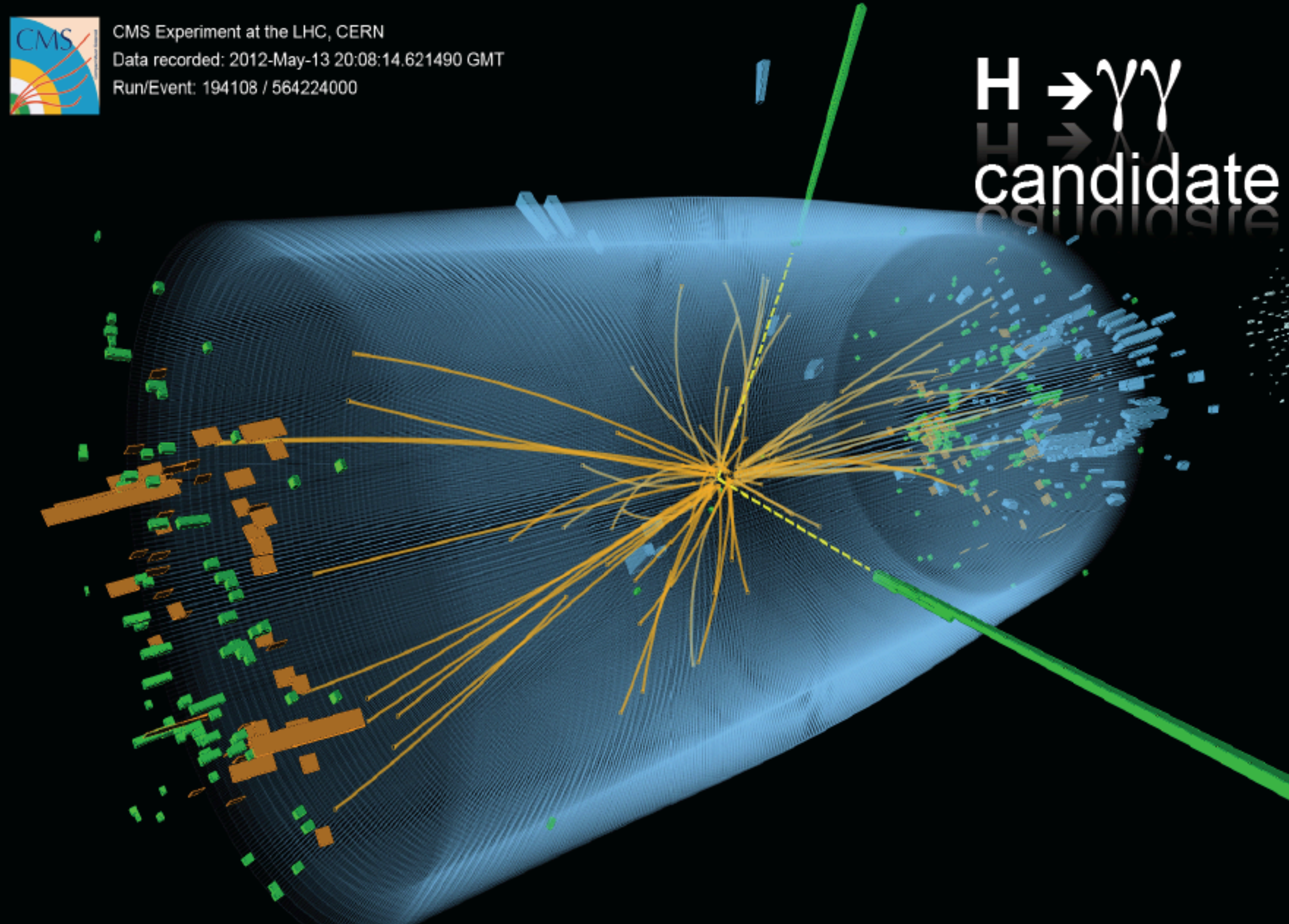




Expected sensitivity at 126 GeV: **7.8 sigma**

Datasets

Channel	m_H range [GeV/c^2]	data set [fb^{-1}]	Data used CMS [fb^{-1}]	m_H resolution
1) $H \to \gamma\gamma$	110-150	5+5/fb	2011+12	1-2%
2) $H \to$ tau tau	110-145	5+12/fb	2011+12	15%
3) $H \to$ bb	110-135	5+12/fb	2011+12	10%
4) $H \to WW \to l\nu l\nu$	110-600	5+12/fb	2011+12	20%
5) $H \to ZZ \to 4l$	110-1000	5+12/fb	2011+12	1-2%

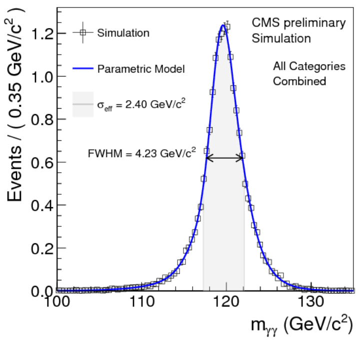

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H →γγ
candidate

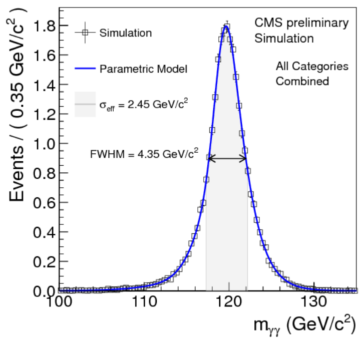
$H \rightarrow \gamma\gamma$

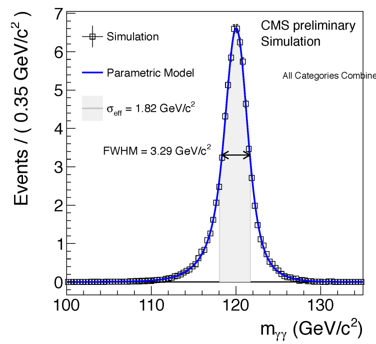
- No update since ICHEP
- Photon energy resolution is crucial
- Multi-Variate Analysis (MVA) for photon ID and event classification
  - Divide events into non-overlapping samples of varying S/B based on properties of the reconstructed photons
- Two VBF categories:
  - presence of di-jets in VBF process

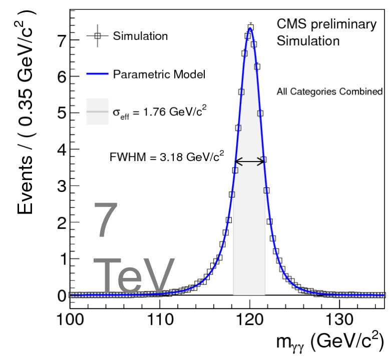
ECAL response and $m_{\gamma\gamma}$ resolution

EPS – Jul 2011	LP – Aug 2011	Moriond – Feb 2012	ICHEP – Jul 2012
FWHM = **4.23 GeV** →	**4.35 GeV** →	**3.29 GeV** →	**3.18 GeV** →









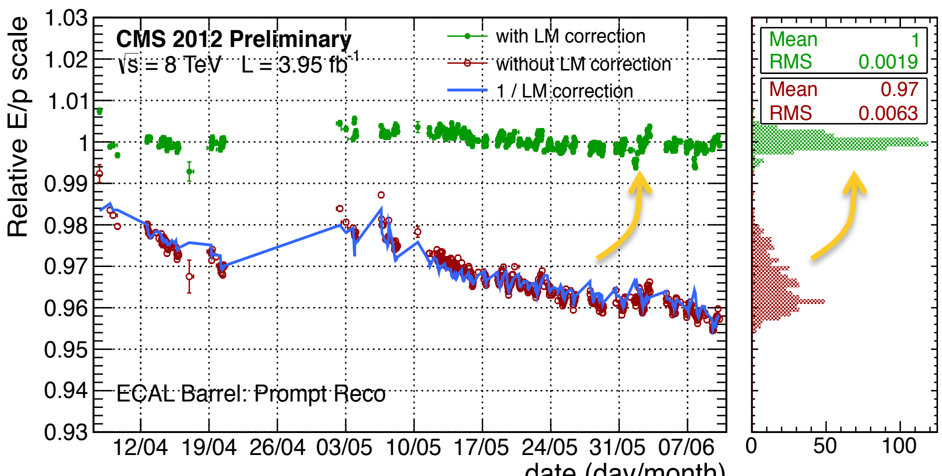
Even better performance

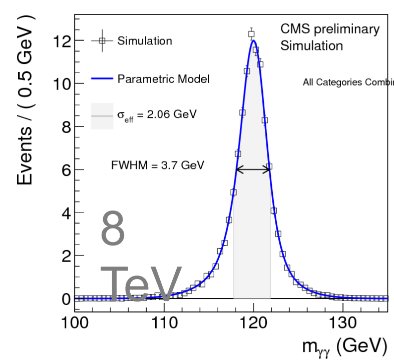
7 TeV: 25% improvement over one year

3.7 GeV →

Stable laser calibration:

Automated 48-hour calibration loop.





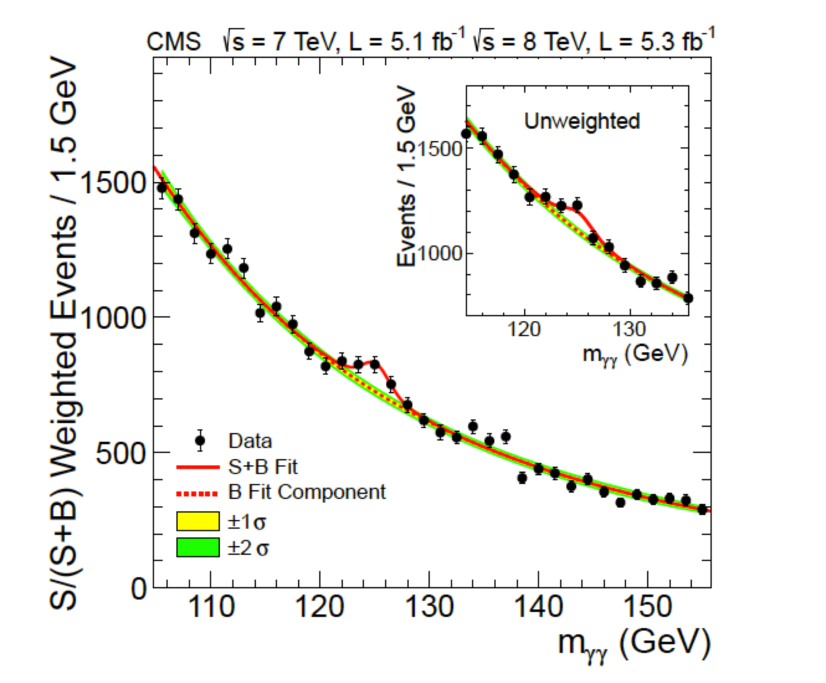
[CMS-DP-2012-015]

Expected yield for SM Higgs

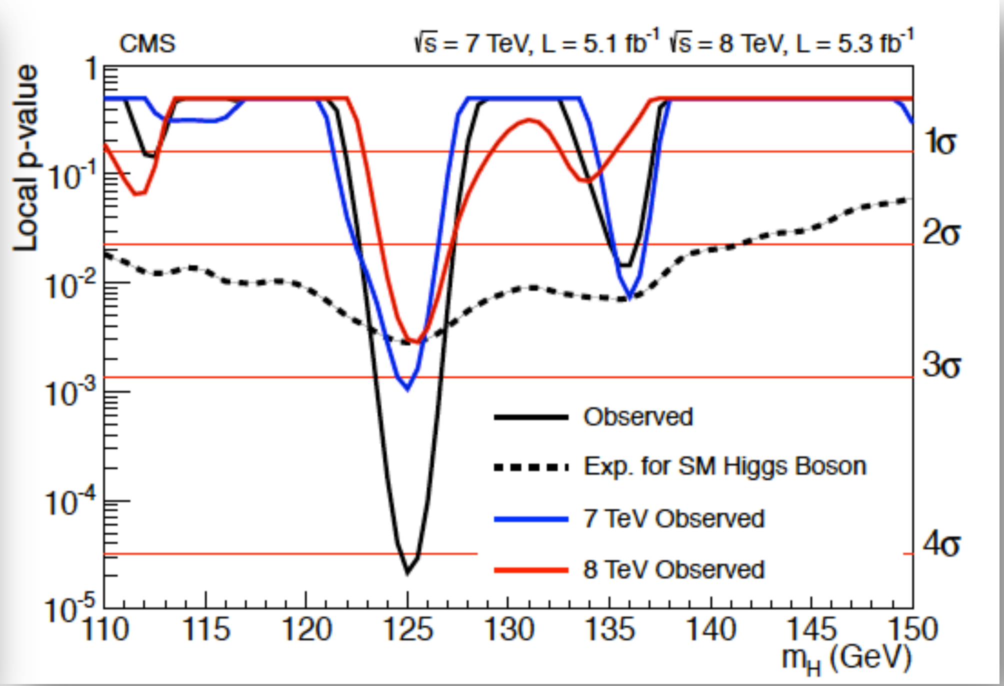
Event categories		SM Higgs boson expected signal ($m_H = 125$ GeV)							Background $m_{\gamma\gamma} = 125$ GeV (events/GeV)
		Events	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	
7 TeV, 5.1 fb^{-1}	BDT 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 ± 0.4
	BDT 1	16.3	88%	6%	6%	–	1.26	1.08	37.5 ± 1.3
	BDT 2	21.5	92%	4%	4%	–	1.59	1.32	74.8 ± 1.9
	BDT 3	32.8	92%	4%	4%	–	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	27%	72%	1%	–	1.73	1.37	1.7 ± 0.2
8 TeV, 5.3 fb^{-1}	BDT 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 ± 0.6
	BDT 1	21.0	87%	6%	6%	1%	1.53	1.31	54.7 ± 1.5
	BDT 2	30.2	92%	4%	4%	–	1.94	1.55	115.2 ± 2.3
	BDT 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 ± 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 ± 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 ± 0.4

H→γγ mass spectrum and p-values

Sum of mass distributions for each event class, weighted by S/(S+B)



p-values



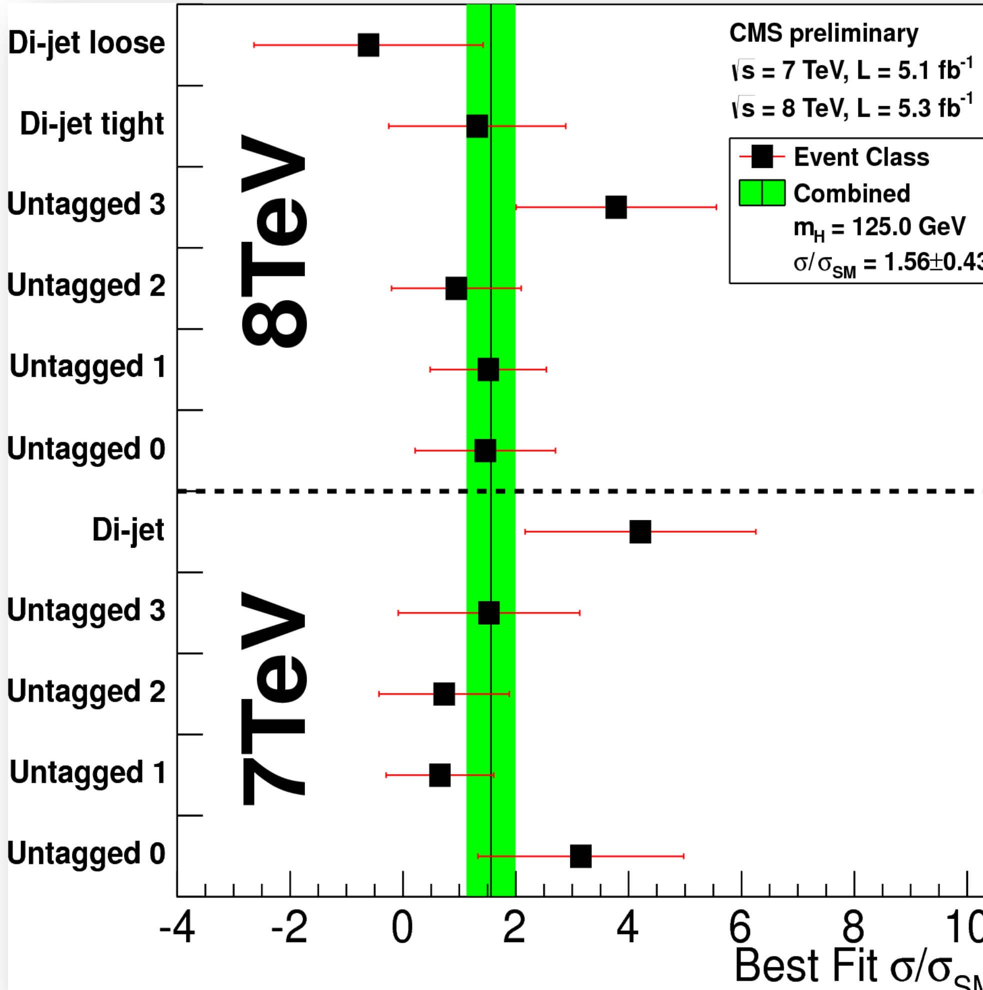
Significance based on local p-value: 4.1σ

Significance based on global p-value: 3.2σ (110-150) GeV

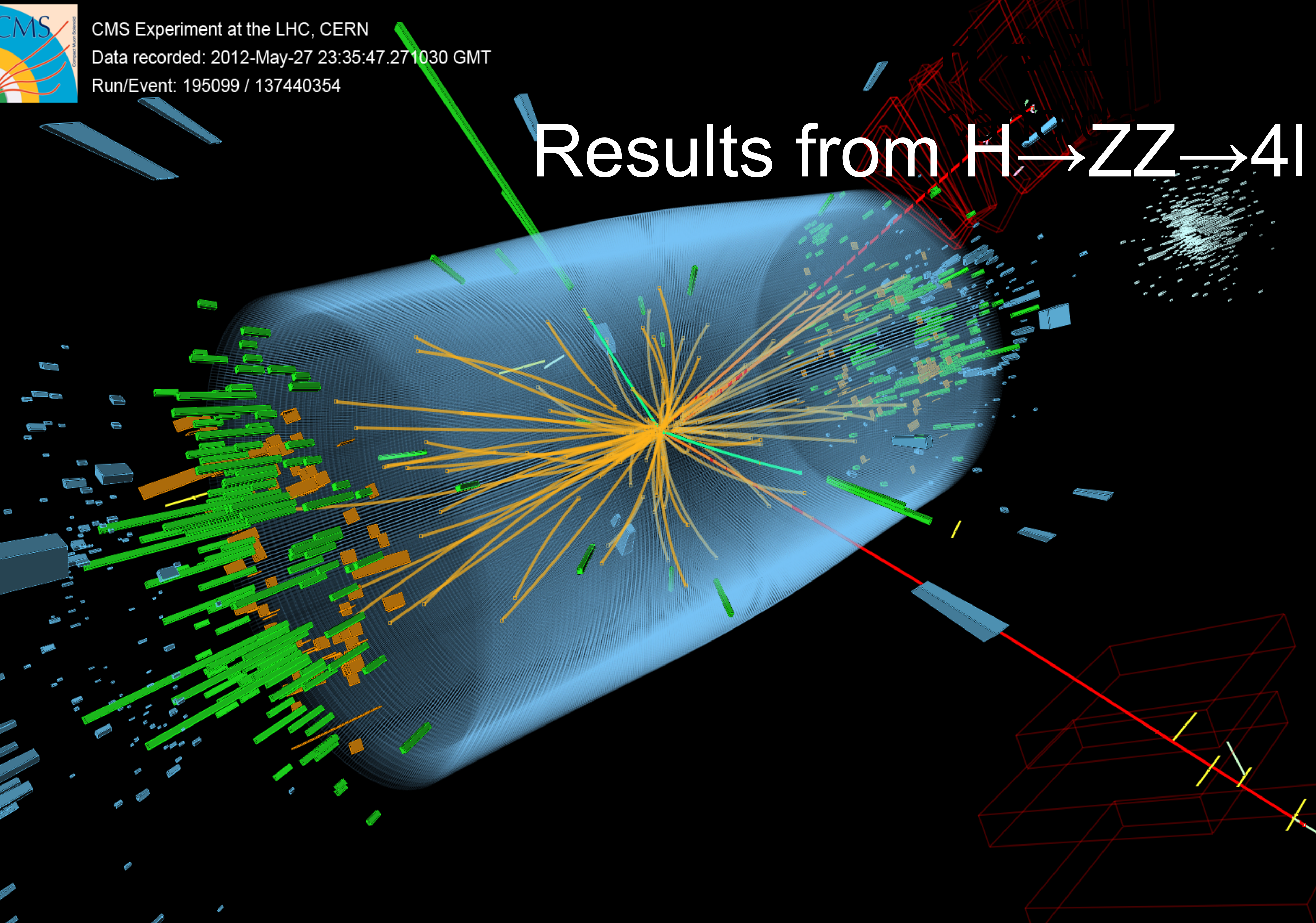
H→γγ signal strength

Best fit signal strength consistent between different classes

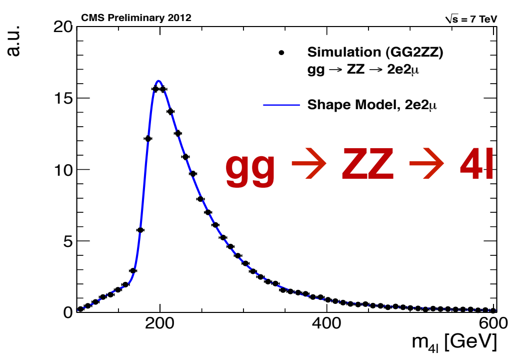
Combined best fit signal strength (m_H=125 GeV):
σ/σ_{SM} = 1.56±0.43 x SM

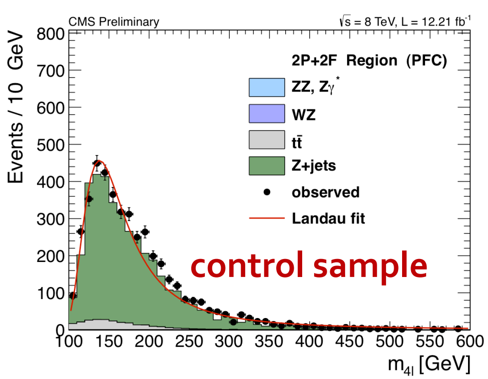


Results from H→ZZ→4l



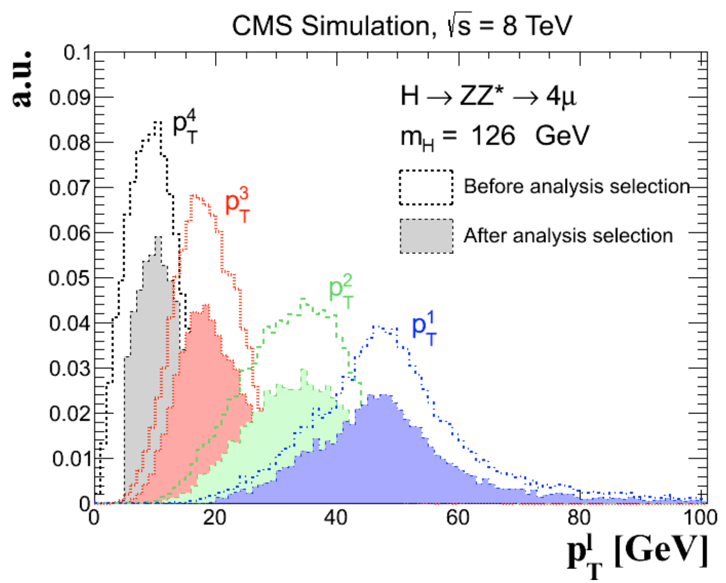
- Background models:
  - irreducible $ZZ^{(*)}$
    - Estimated using simulation
    - Corrected for data/simulation scale
  - reducible Z+jets, ttbar, WZ
    - Estimated from control samples





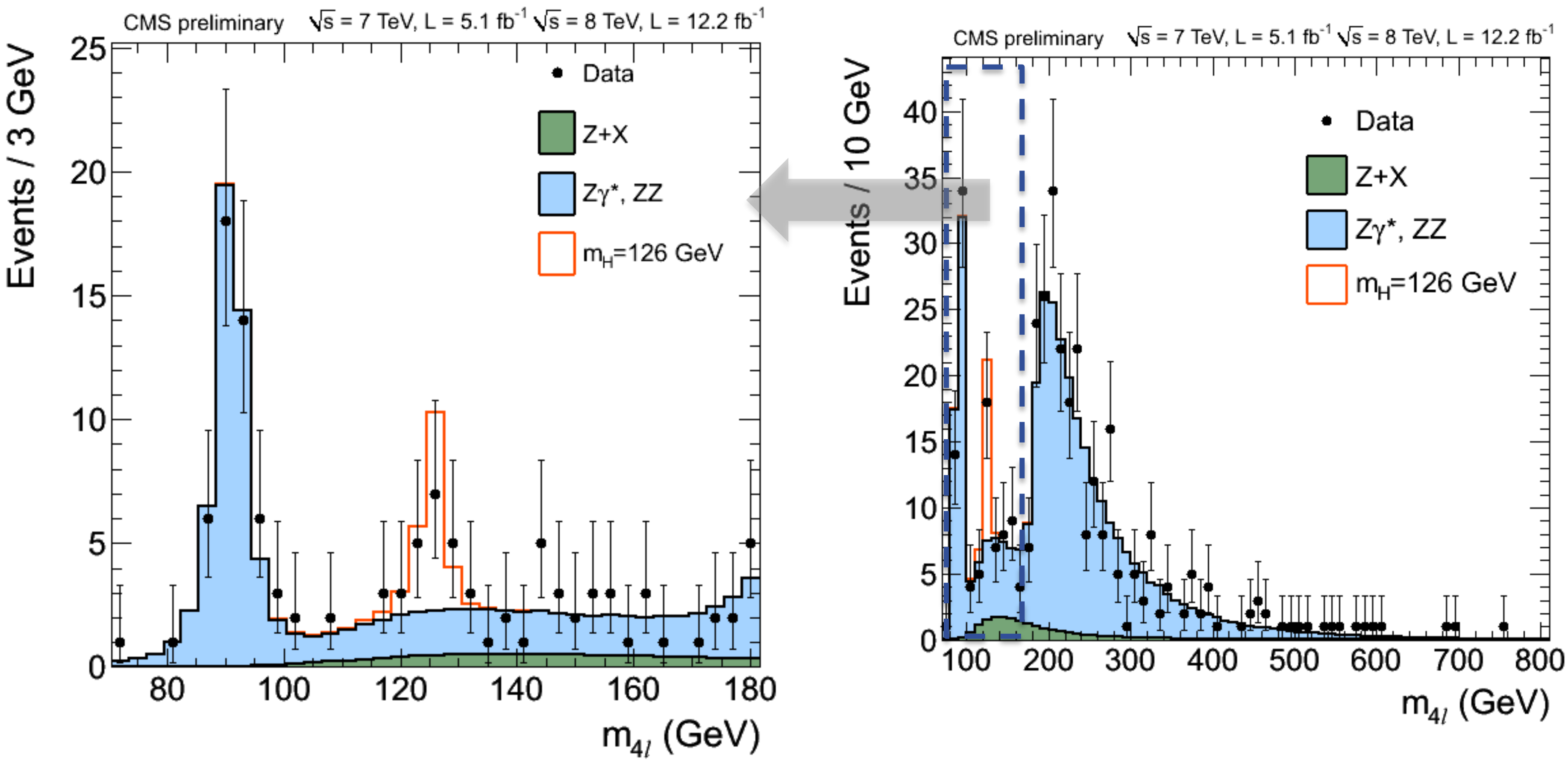
Event selection:

requires the highest possible efficiencies (lepton Reco/ID/ Isolation).



Four lepton mass spectrum

Mass distribution for the four leptons (two pairs of electrons, or two pairs of muons, or the pair of electrons and the pair of muons).



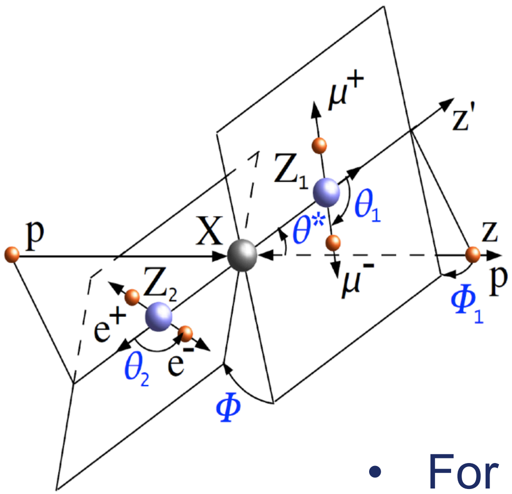
H→ZZ Signal and Background

Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	4.7 ± 0.6	9.6 ± 1.0	12.5 ± 1.4	26.8 ± 1.8
Z+ X	$3.4^{+3.0}_{-2.3}$	$1.6^{+1.2}_{-0.9}$	$5.6^{+5.4}_{-3.6}$	$10.6^{+5.3}_{-4.4}$
All backgrounds	$8.0^{+3.1}_{-2.3}$	$11.2^{+1.6}_{-1.4}$	$18.1^{+5.6}_{-3.8}$	$37.3^{+6.6}_{-4.7}$
$m_H =$ 125 GeV	2.4 ± 0.4	4.6 ± 0.5	5.9 ± 0.7	12.9 ± 0.9
$m_H =$ 126 GeV	2.7 ± 0.4	5.1 ± 0.6	6.6 ± 0.8	14.4 ± 1.1
Observed	12	16	19	47

- Integrated in the mass range from 110 to 160 GeV

- Z +X background is estimated from data;
- ZZ is estimated from simulation

Matrix element likelihood analysis

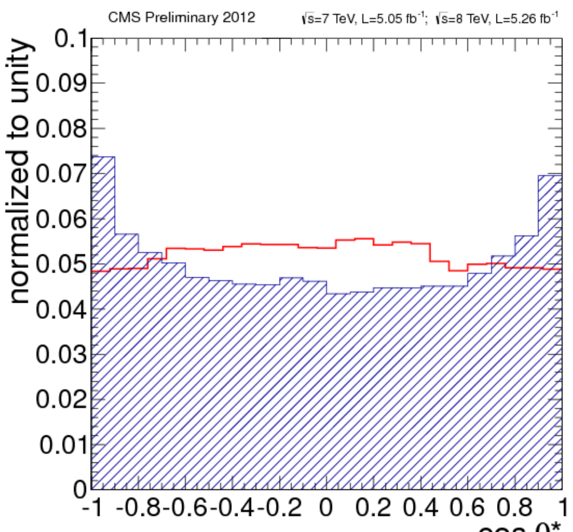


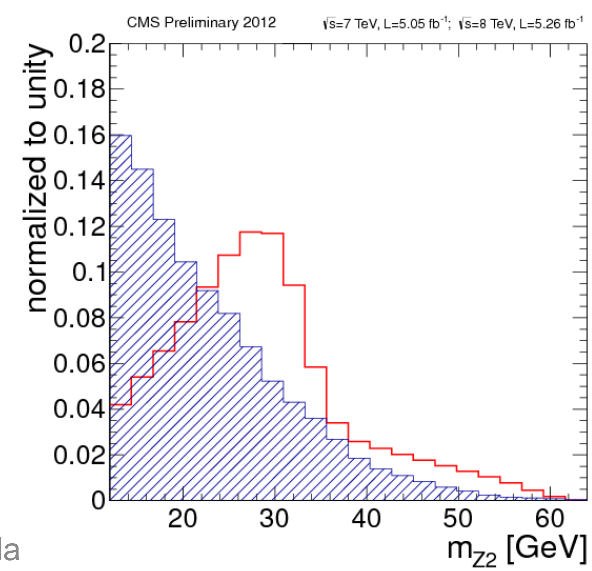
Matrix Element Likelihood Analysis:
uses kinematic inputs for signal to background discrimination

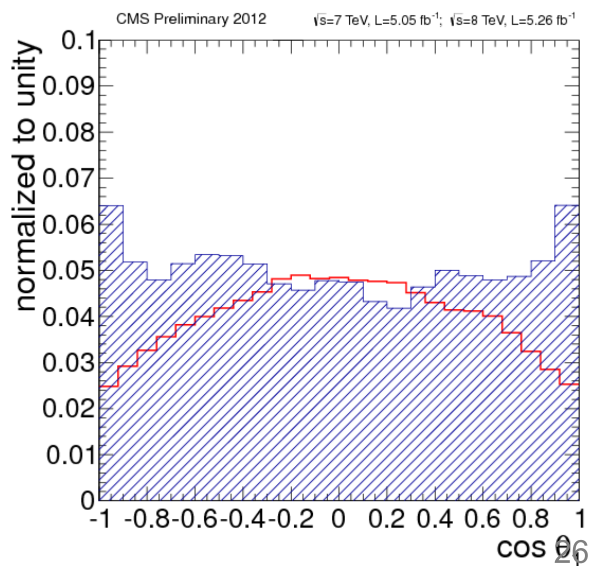
$$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$$

$$K_D = \left[1 + \frac{\mathcal{P}_{\rm bkg}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\rm sig}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

- For the signal, use a fully analytic parameterization
- For the use a simulation of the process $q\bar{q} \rightarrow ZZ/Z\gamma$



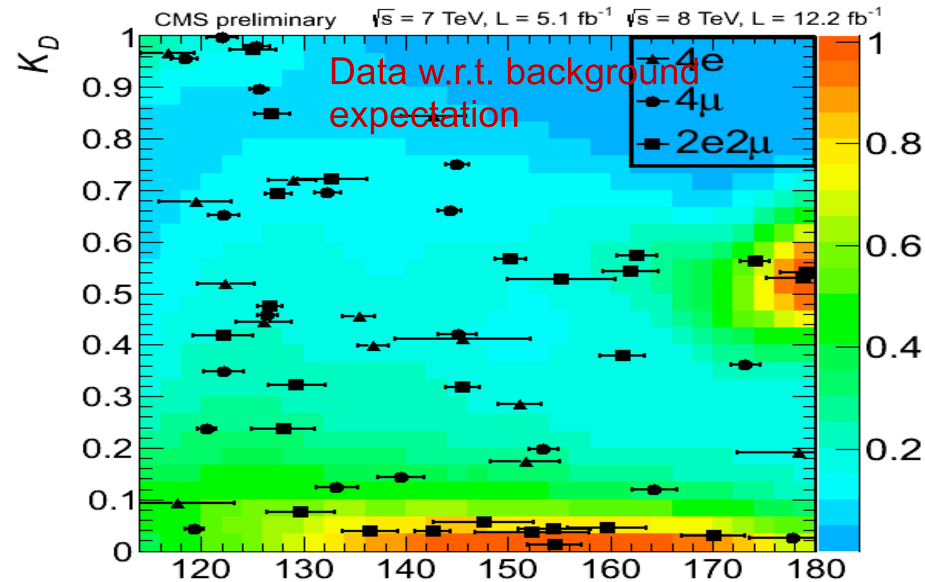


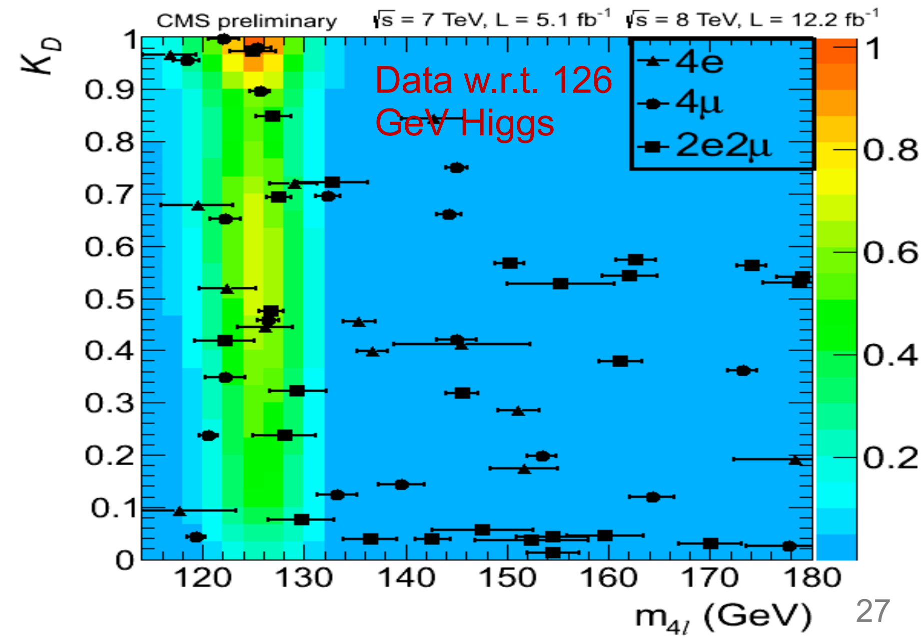


K_D versus m_{4l} distributions

K_D discriminant versus m_{4l}

- Data points shown with per-event mass uncertainties
  - Top: Data w.r.t. background expectation
  - Bottom: Data w.r.t 126 GeV Higgs expectation
- Six simultaneous two-dimensional maximum likelihood fits for each value of m_H , in the variables m_{4l} and K_D .
- K_D distribution for signal is similar for a scalar, pseudo-scalar, or a spin-two resonance with the minimal couplings, at a mass around $m_H = 126$ GeV

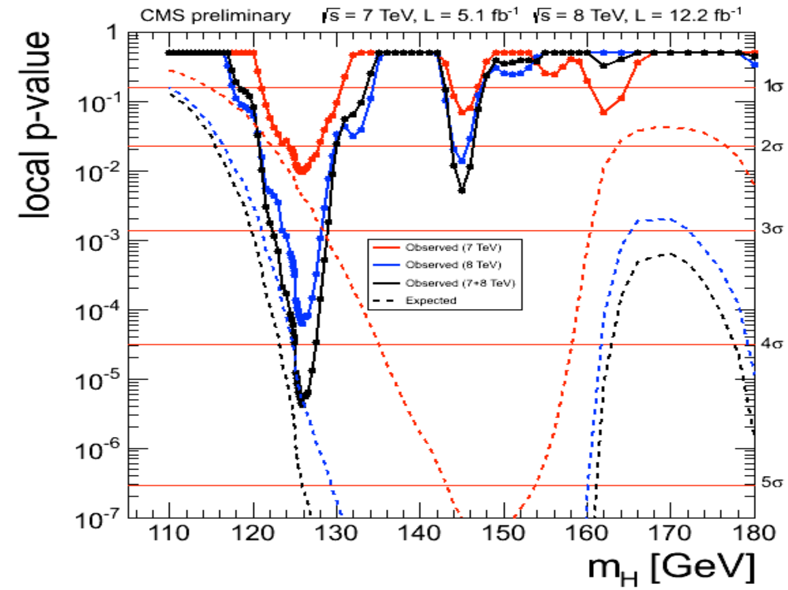




Results from H→ZZ analysis

2D fit results (K_D - m_{4l}) :

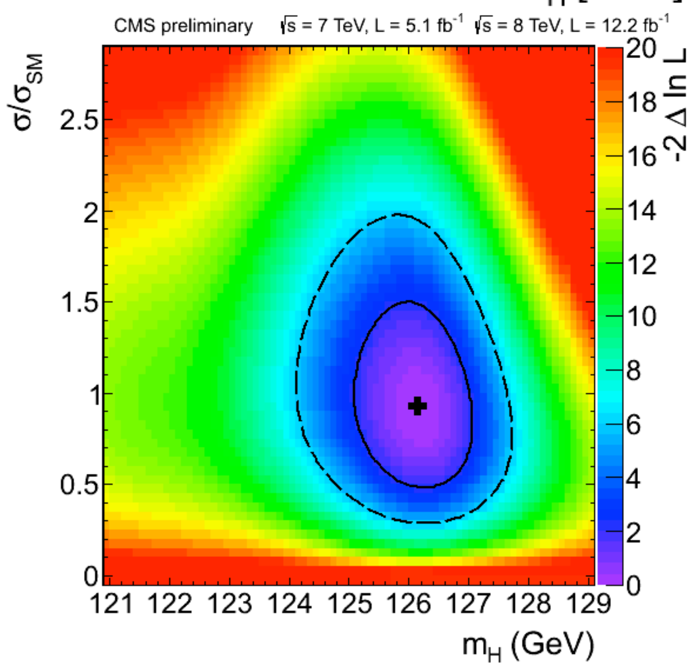
- The minimum local p-value has a significance of **4.5 sigma**
- The signal strength relative to SM is μ **= 0.80**$^{+0.35}_{-0.28}$ at 126 GeV.



Mass measurement

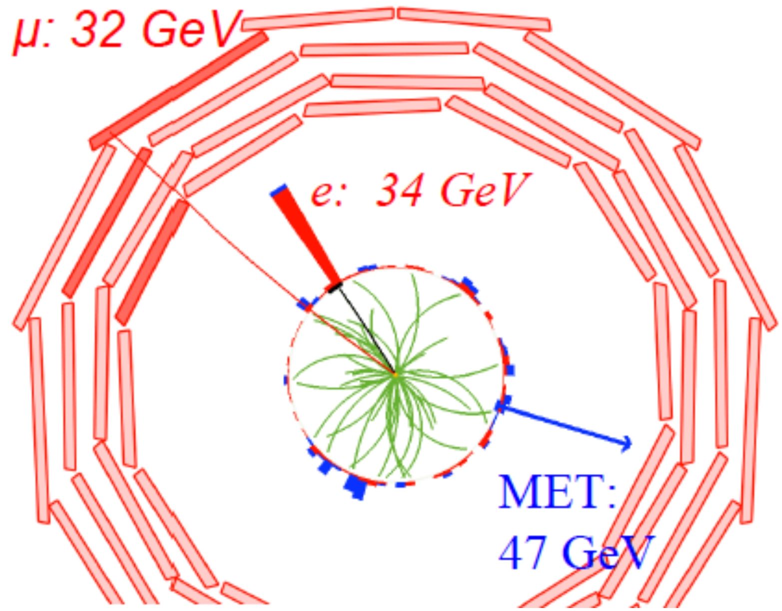
A simultaneous fit of the mass and of signal strength gives:

m_H **= 126.2** ±0.6(stat)±0.2(syst) GeV



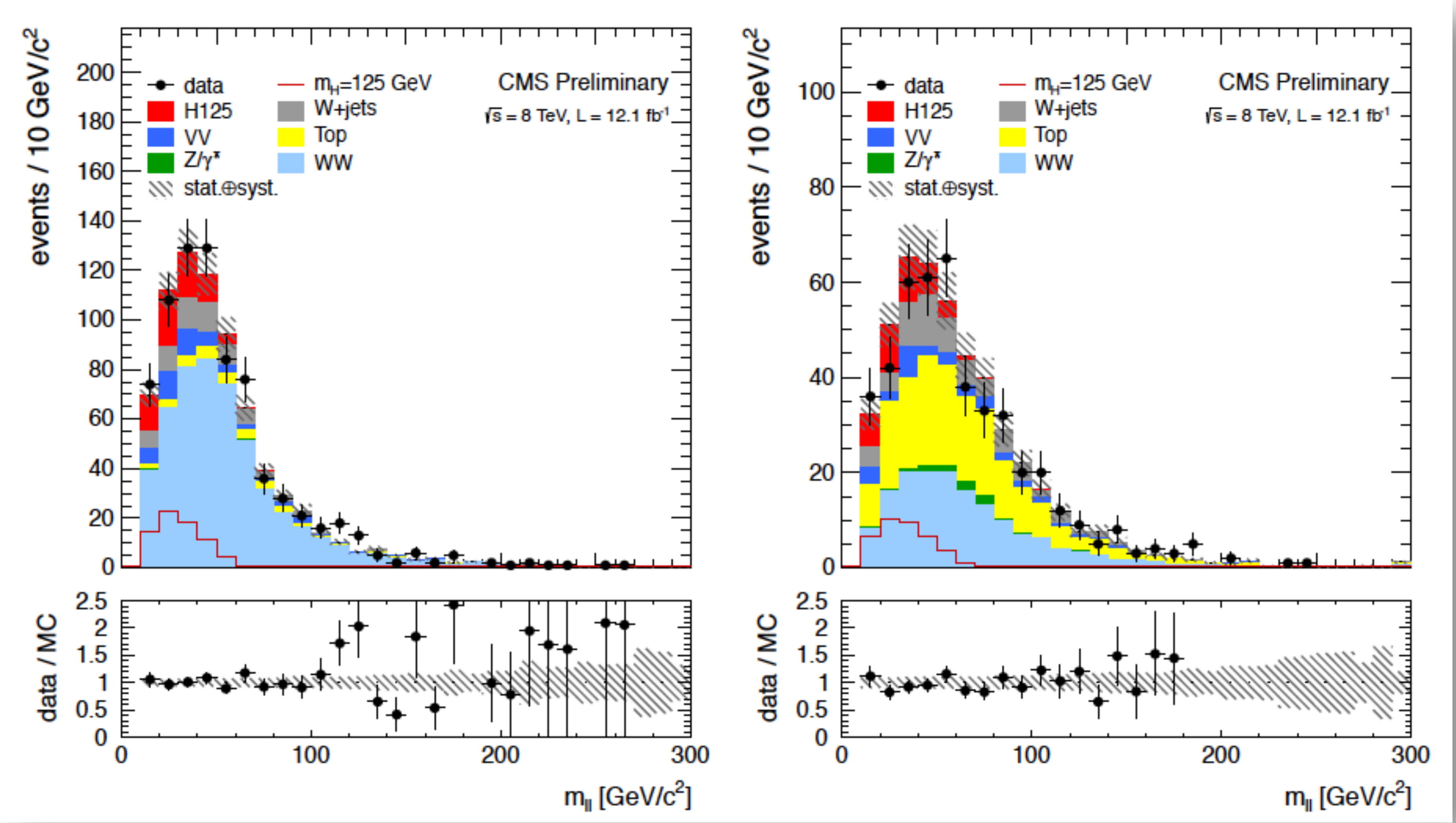
$H \rightarrow WW \rightarrow 2l\ 2\nu$

- Signature
  - 2 opposite charged leptons (only e, μ)
  - 2 neutrinos == missing transverse energy (MET)
    - no Higgs mass peak
- Analysis challenges
  - understand backgrounds
    - normalize to control regions
  - backgrounds: WW, W+jets, top, DY



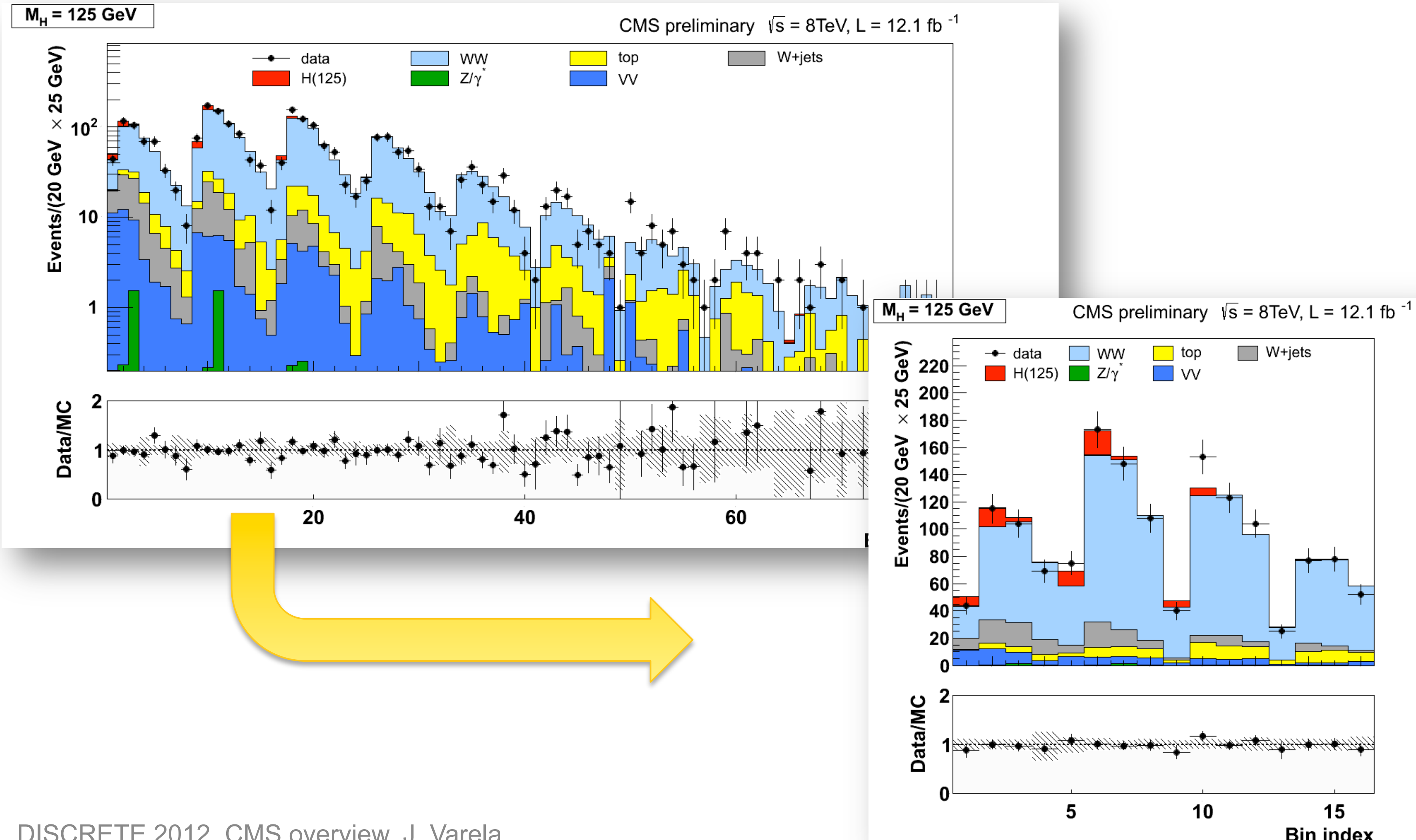
- Different flavor (DF) channels are the most sensitive
  - same flavor has substantial DY background
  - gluon fusion: 0 and 1 jet categories
  - VBF: 2 jet category
- Cut-based and Shape analysis in (m_{ll}-m_T) plane

e-μ mass in the 0-jet category   e-μ mass in the 1-jet category



H→WW shape analysis

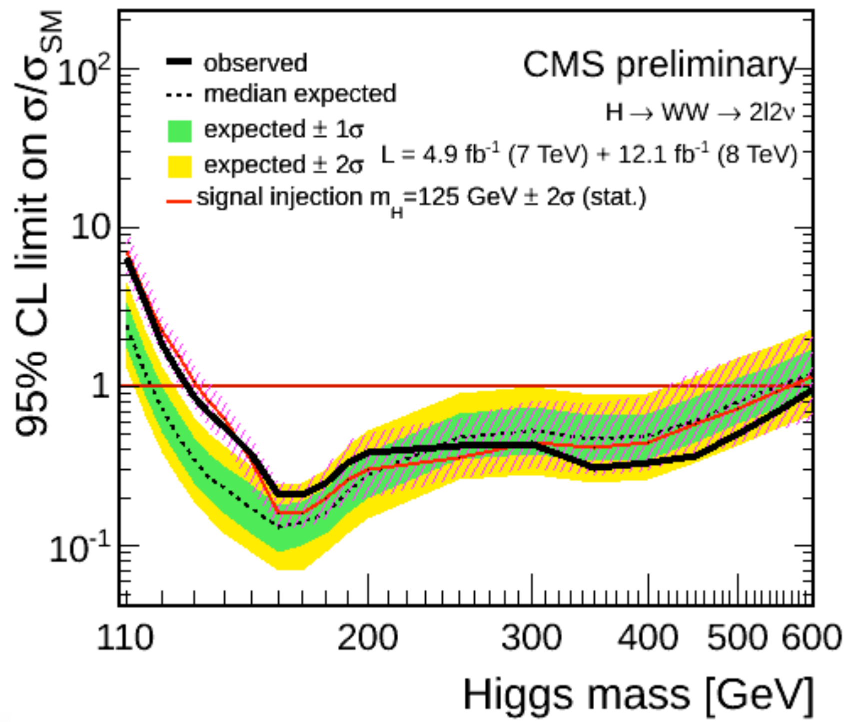
- Two-dimensional m_T-m_{ll} distribution unrolled in one-dimension
- 0-jet bin after the CLs fit for the mH = 125 GeV Higgs signal hypothesis



Results from H→WW analysis

For a mass of 125 GeV:

- Observed signal significance: 3.1 sigma
- Signal strength σ/σ_{SM} : 0.74±0.25



expected/observed significance		
8 TeV cut-based	8 TeV shape-based	7+8 TeV shape-based
2.4/1.7	3.7/2.9	4.1/3.1
best fit value		
8 TeV cut-based	8 TeV shape-based	7+8 TeV shape-based
0.80 ± 0.45	0.77 ± 0.28	0.74 ± 0.25

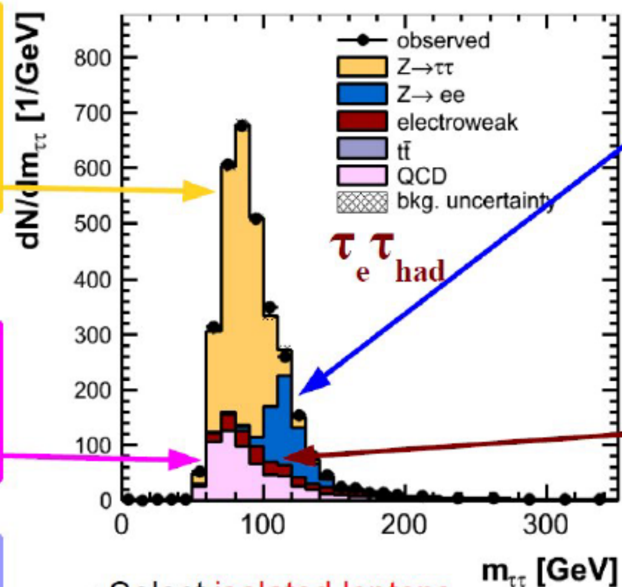
H → ττ analysis

- Reconstructed τ decays: e, μ, τ_{had}
- Event categories: 0 and 1 jet, VH, VBF
- Main ingredients of the analysis:
  - tau pair mass resolution
  - good understanding of the backgrounds

Z→ττ:
- Embedding: in Z→μμ, replace μ by sim. τ decay.
- Normalized from Z→μμ events.

QCD:
- Normalization & shape taken from LS/OS or fakerate.

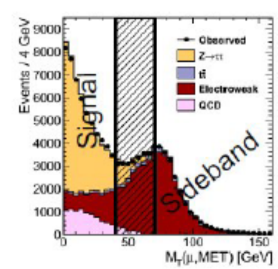
ttbar:
- From madgraph.
- Normalization from sideband.



- Select isolated leptons.
- Restrict $\not{E}_T$ (supp. W+jets, ttbar).
- Discriminate signal from background based on $m_{\tau\tau}$.

Z→ee(/μμ):
- From powheg.
- Corrected for jet→τ, e/μ→τ fakerate.

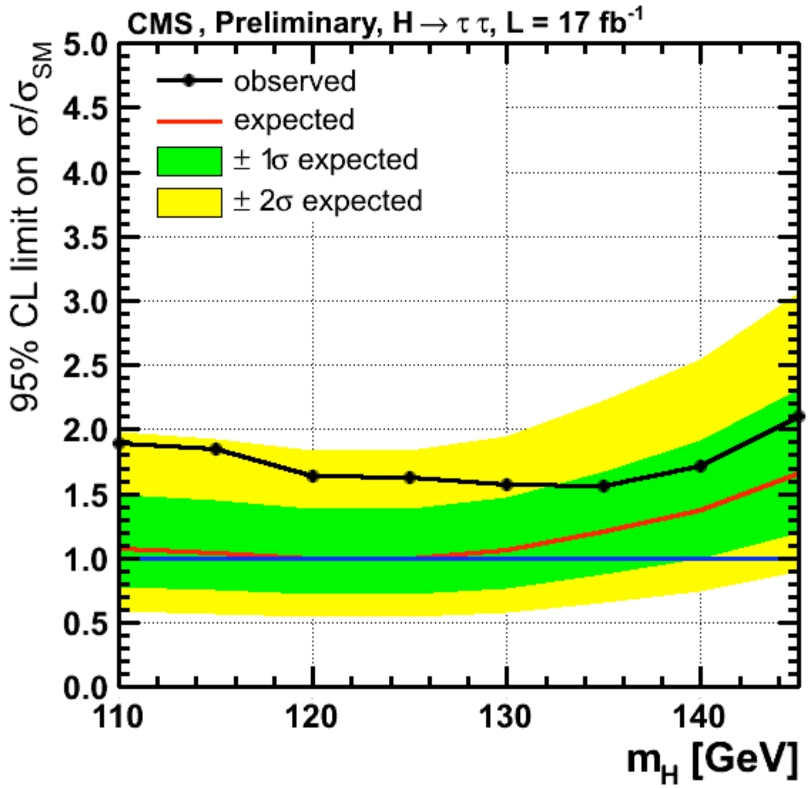
Diboson/W+jets:
- From madgraph.
- Normalization from sideband.



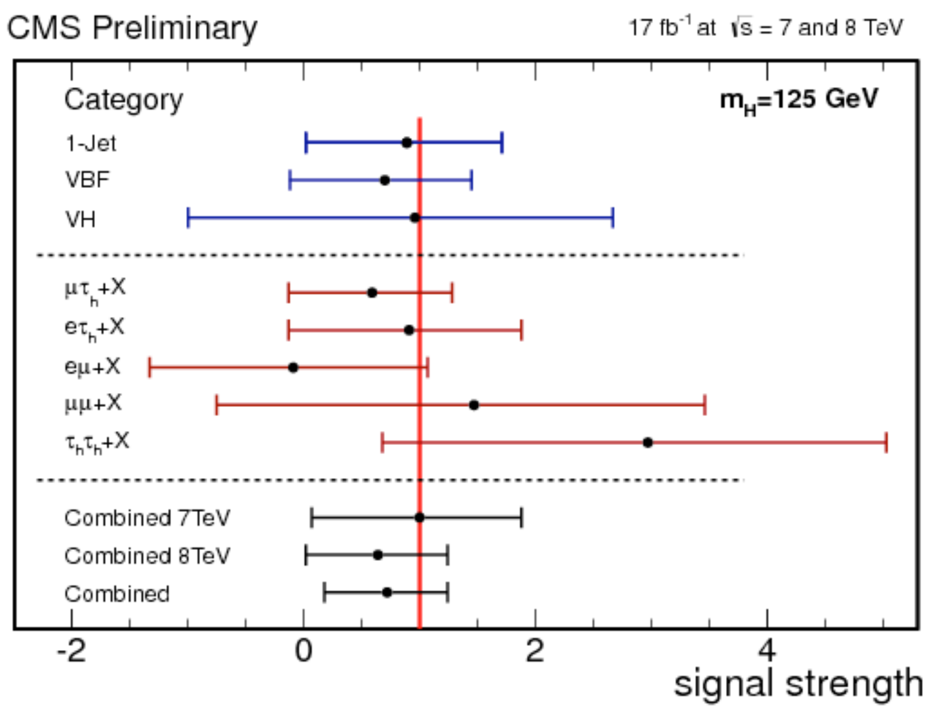
from C. Pauss
HCP 2012

Results from H → ττ analysis

7 and 8 TeV data; all categories combined



Best-fit signal strength values, σ/σ_{SMH}



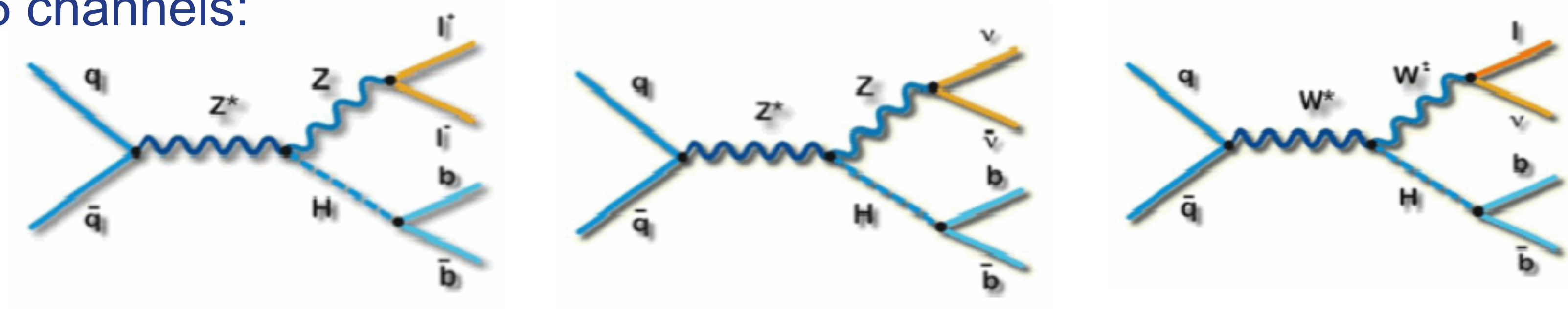
Sensitivity ~1 times SM

Mild excess at low mass ~ 1.5 sigma

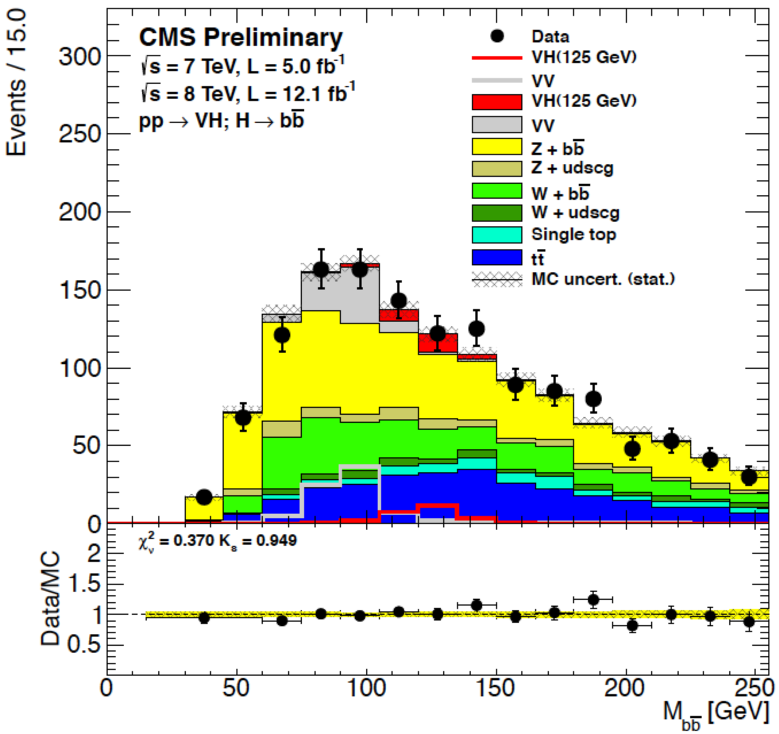
Combined σ/σ_{SMH} at m_H = 125 GeV: 0.7±0.5

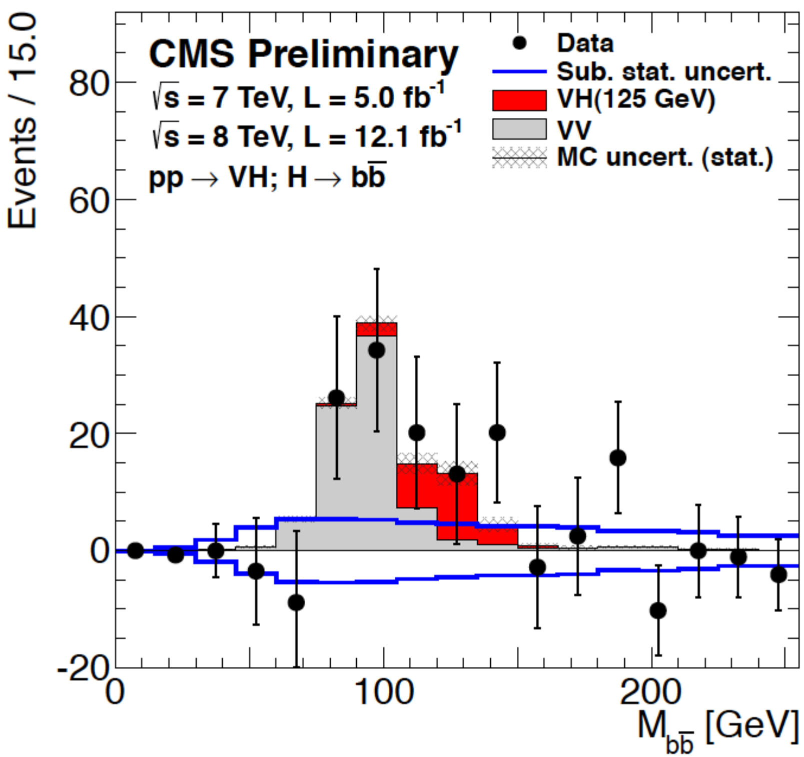
VH → Vbb analysis

5 channels:

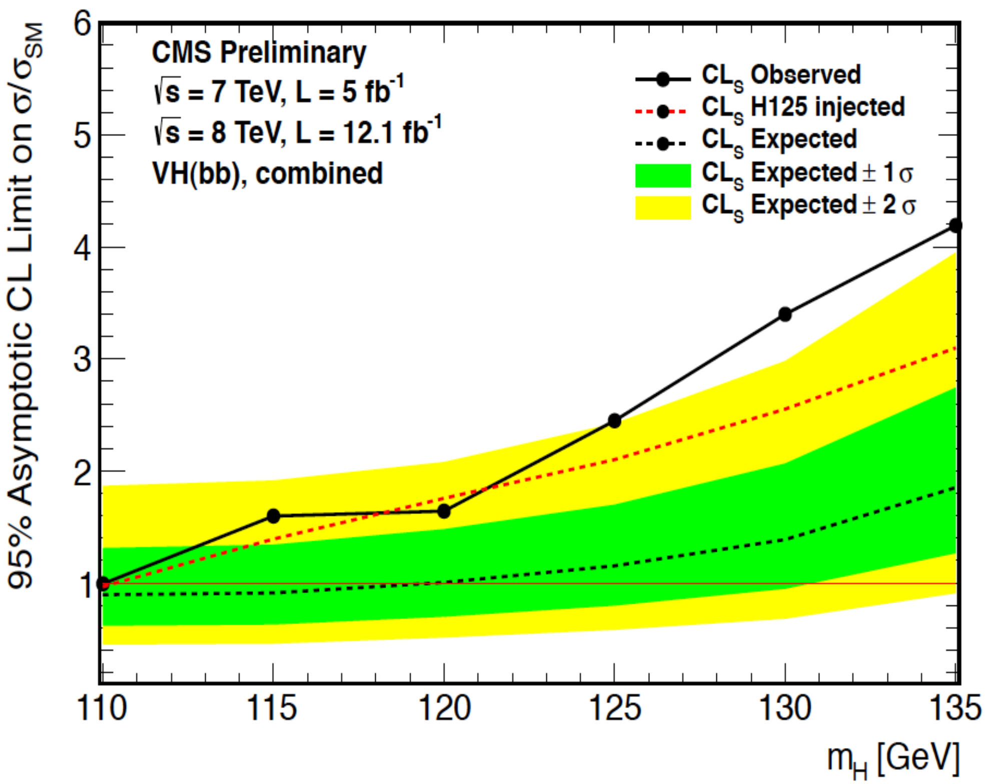


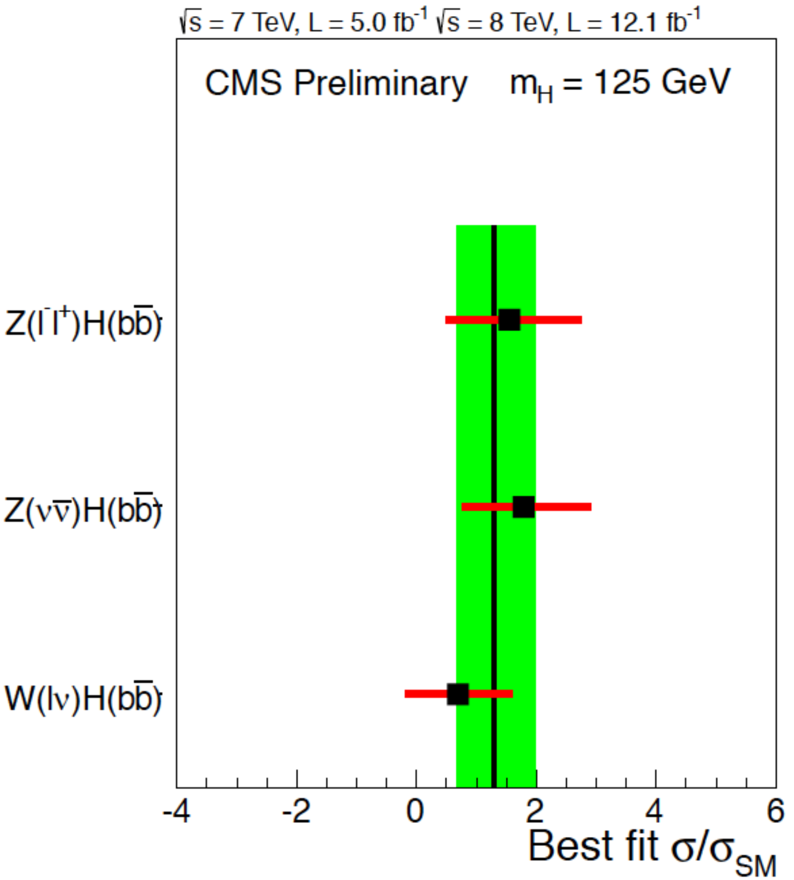
All channels combined:





Results from VH → Vbb analysis





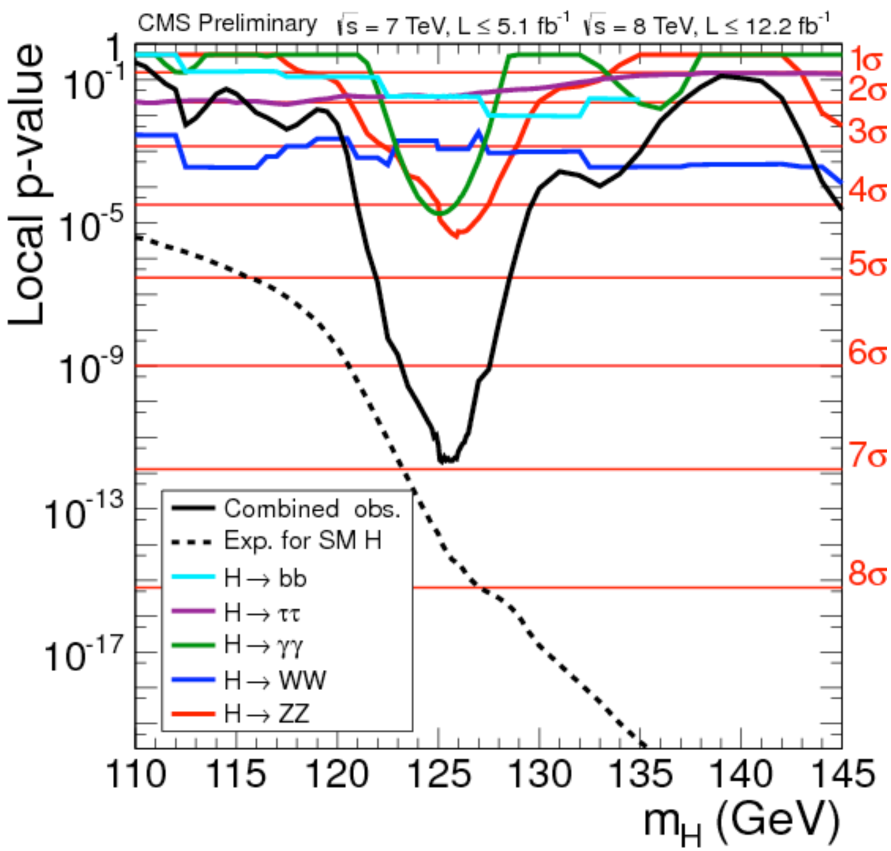
At 125 GeV:

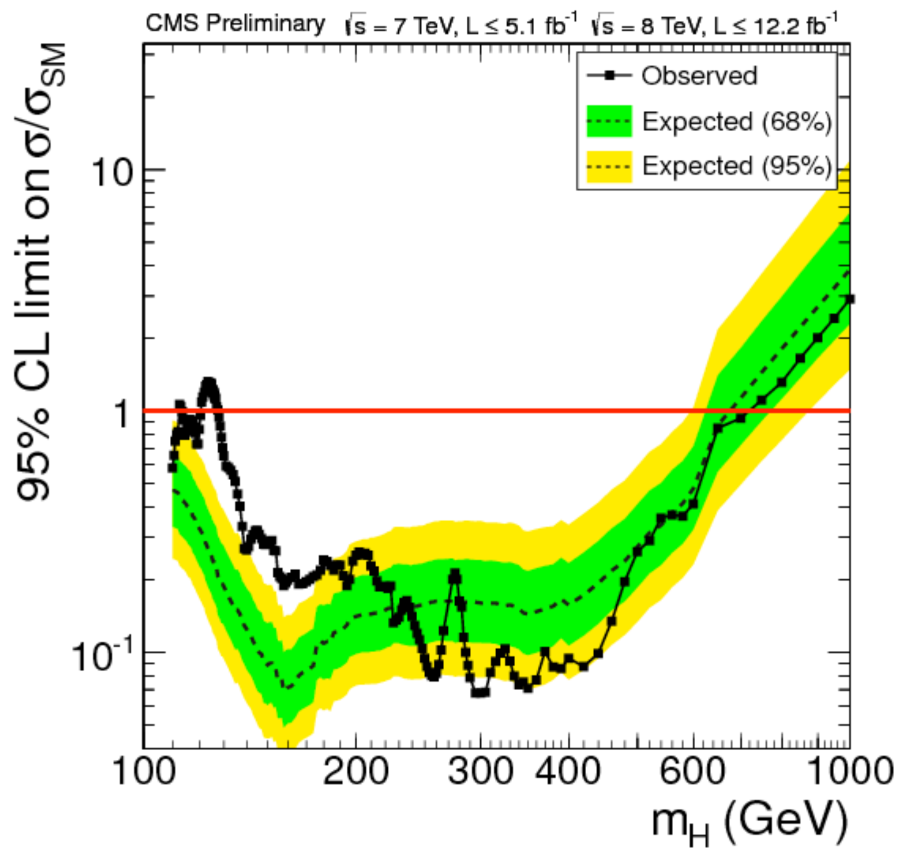
- Expected limit 1.2 times SM
- The significance of the excess is 2.2 σ

Combined signal strength: $1.3^{+0.7}_{-0.6}$

Higgs combined results

Combination of 5 channels: bb, ττ, WW, ZZ, γγ



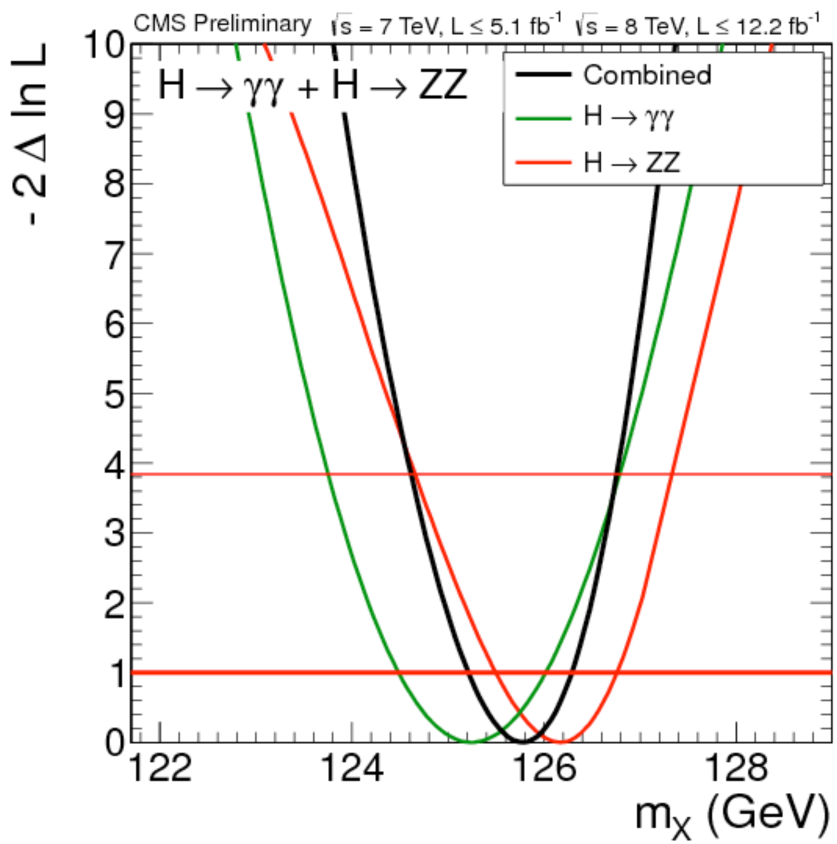


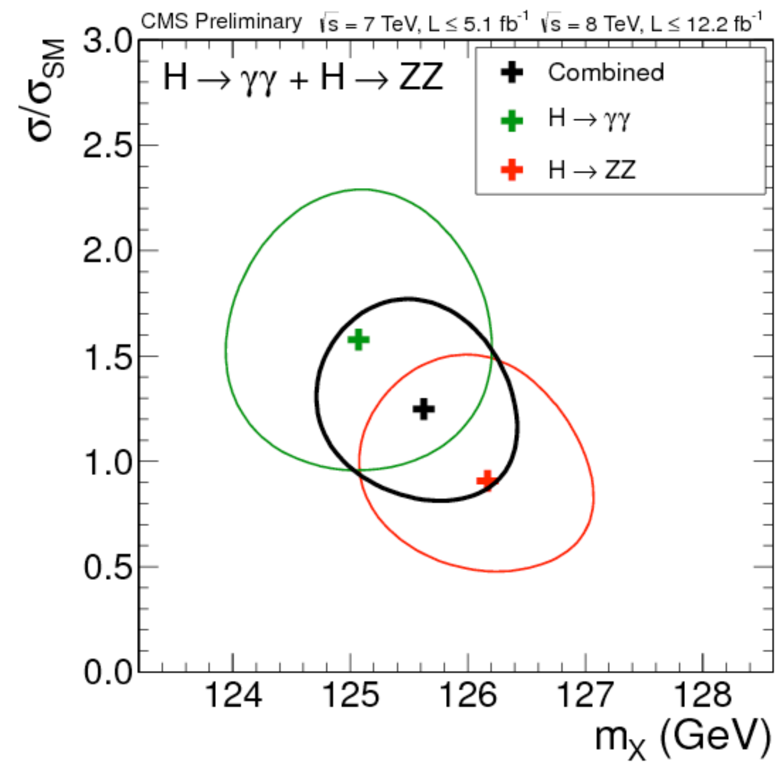
Significance 6.9σ versus 7.8σ expected.

Mass of the new resonance

Model independent mass measurement from the two high-resolution channels:

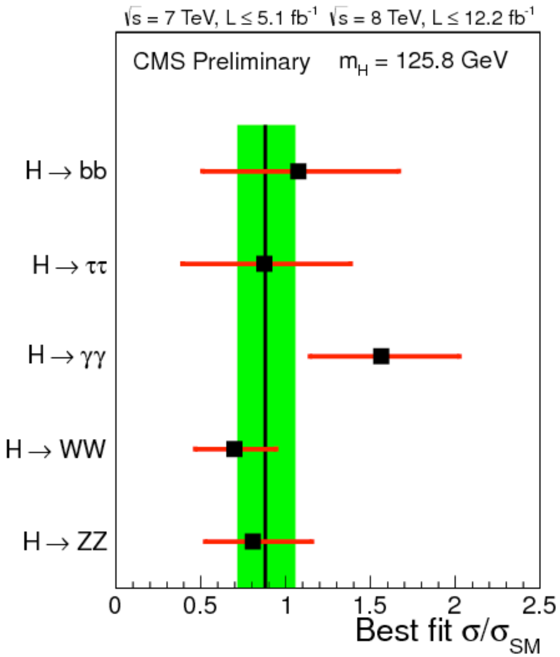
$m_X = 125.8 \pm 0.4$ (stat) ± 0.4 (syst) GeV





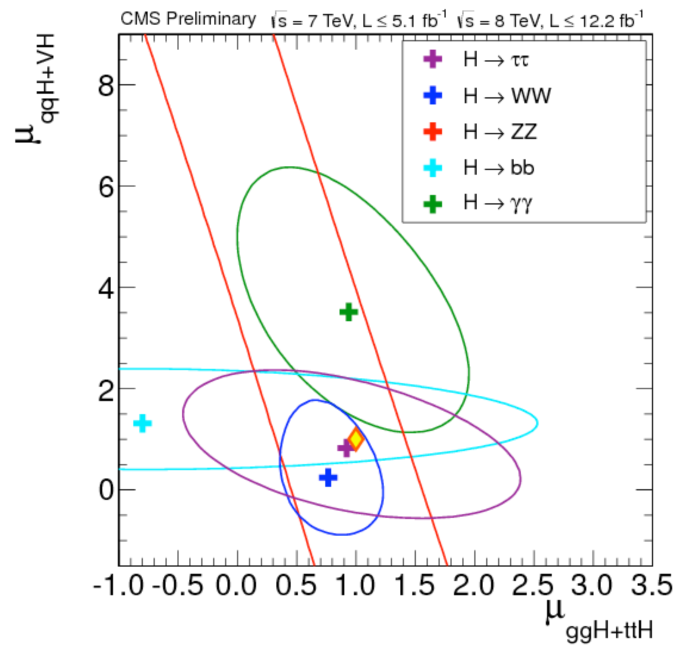
The combined 68% CL contour assumes that the relative event yields among the three channels are those expected from the standard model

Signal strength at m_H=125.8 GeV



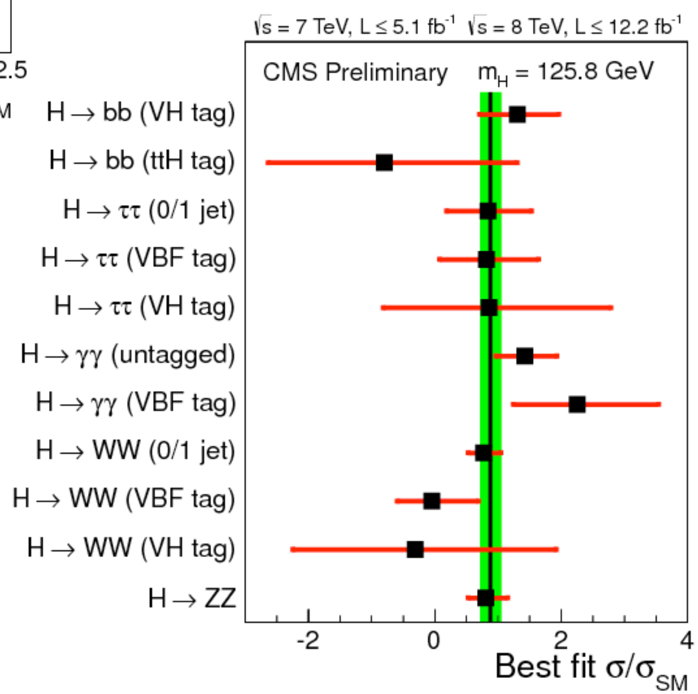
Overall best-fit signal strength in the combination:

σ/σ_{SM} = 0.88±0.21



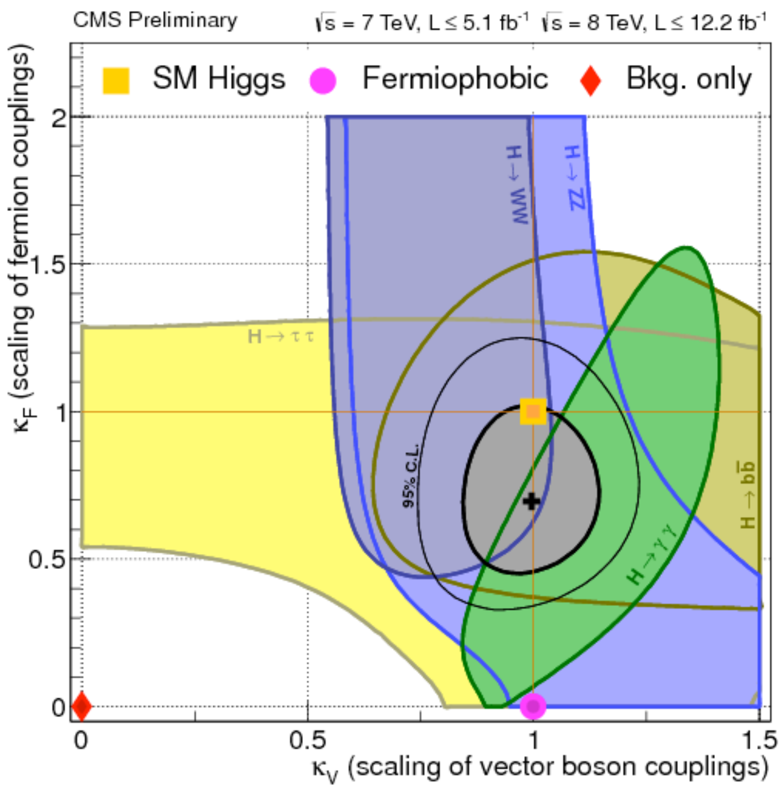
signal strength in gluon fusion + ttH v.s. VBF + VH production mechanisms

Signal strengths consistent with each other and with SM

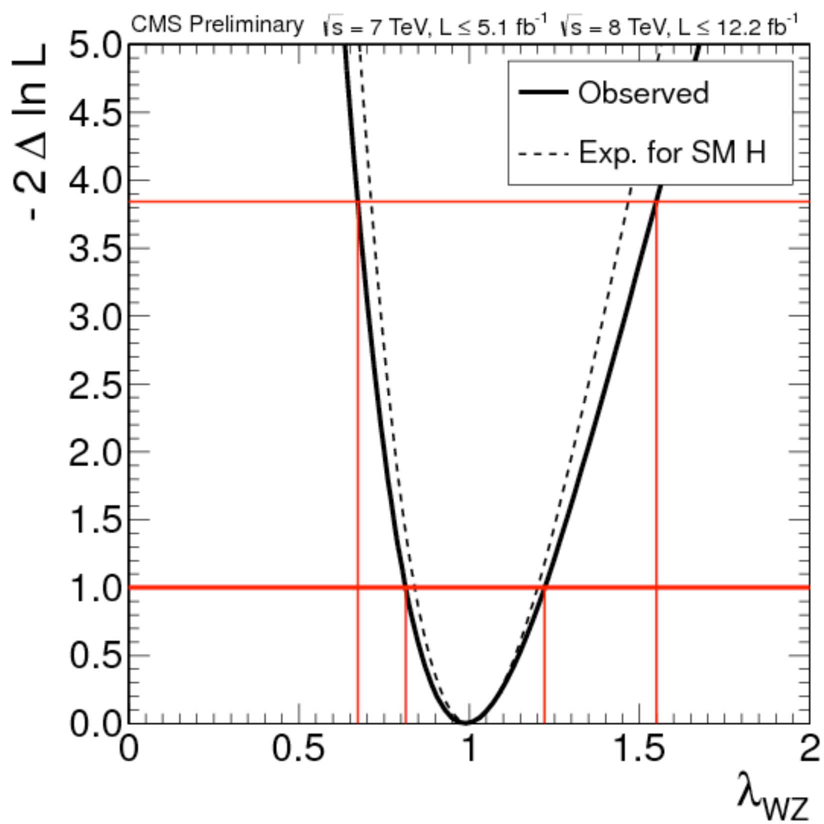


Couplings to fermions and bosons

Fermion and Vector Boson Couplings



Custodial Symmetry $\lambda_{WZ} = \kappa_W/\kappa_Z$

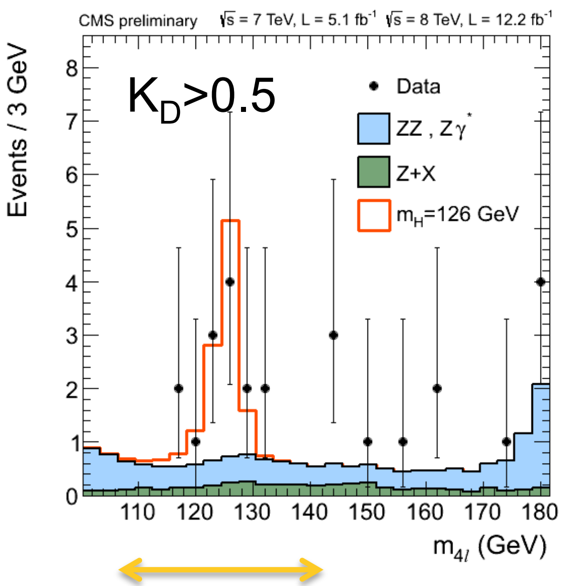


Couplings look consistent with SM Higgs

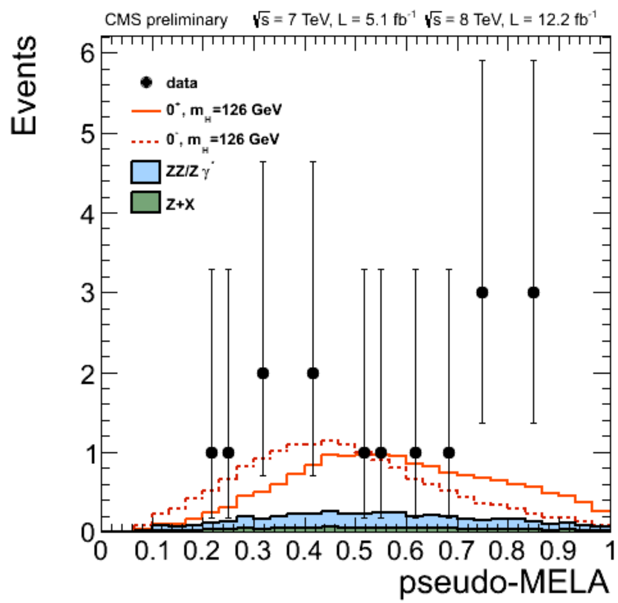
Spin-parity analysis

- Expected separation between 0+ and 0-: 2 standard deviations
- Scalar (0+): data consistent (0.6 standard deviations)
- Pseudoscalar (0-): data different by 2.5 standard deviations

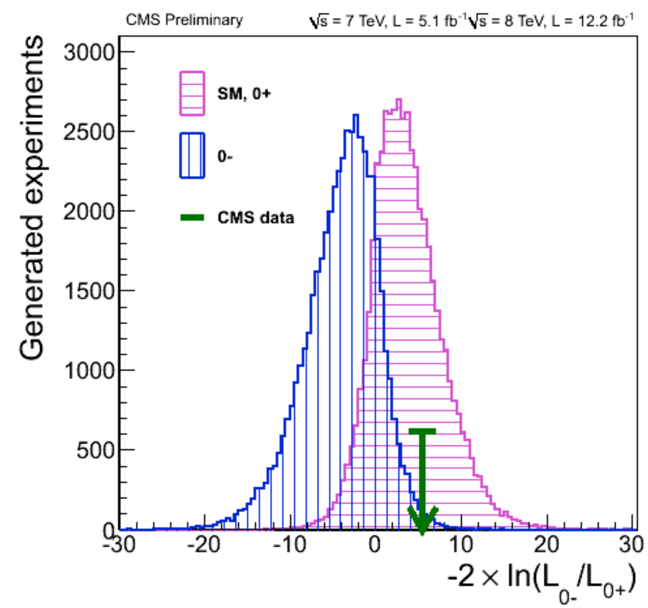
$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm SM}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$



$106<m_{4l}<141$ GeV



Distribution of D_{0-} for $106<m_{4l}<141$ GeV and $D_{bkg}>.5$



Expected log-likelihood distributions for the 0+ and 0- hypothesis. The observation in the data is shown by the green arrow.

2011-12 Datasets: SUSY

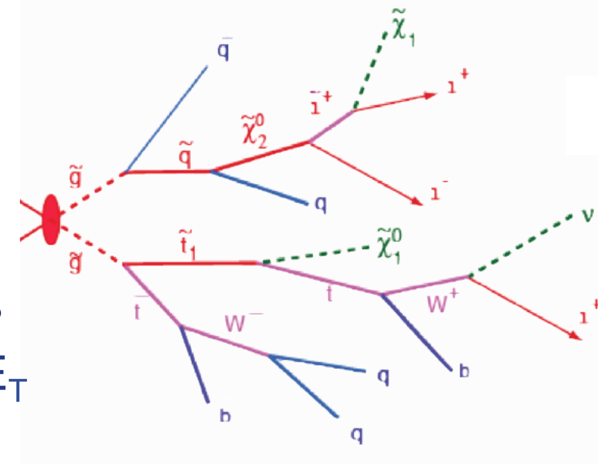
SUSY searches at 7 TeV

The initial SUSY program at CMS was designed to be

1. Generic

- Signature based searches not tuned to a particular SUSY model

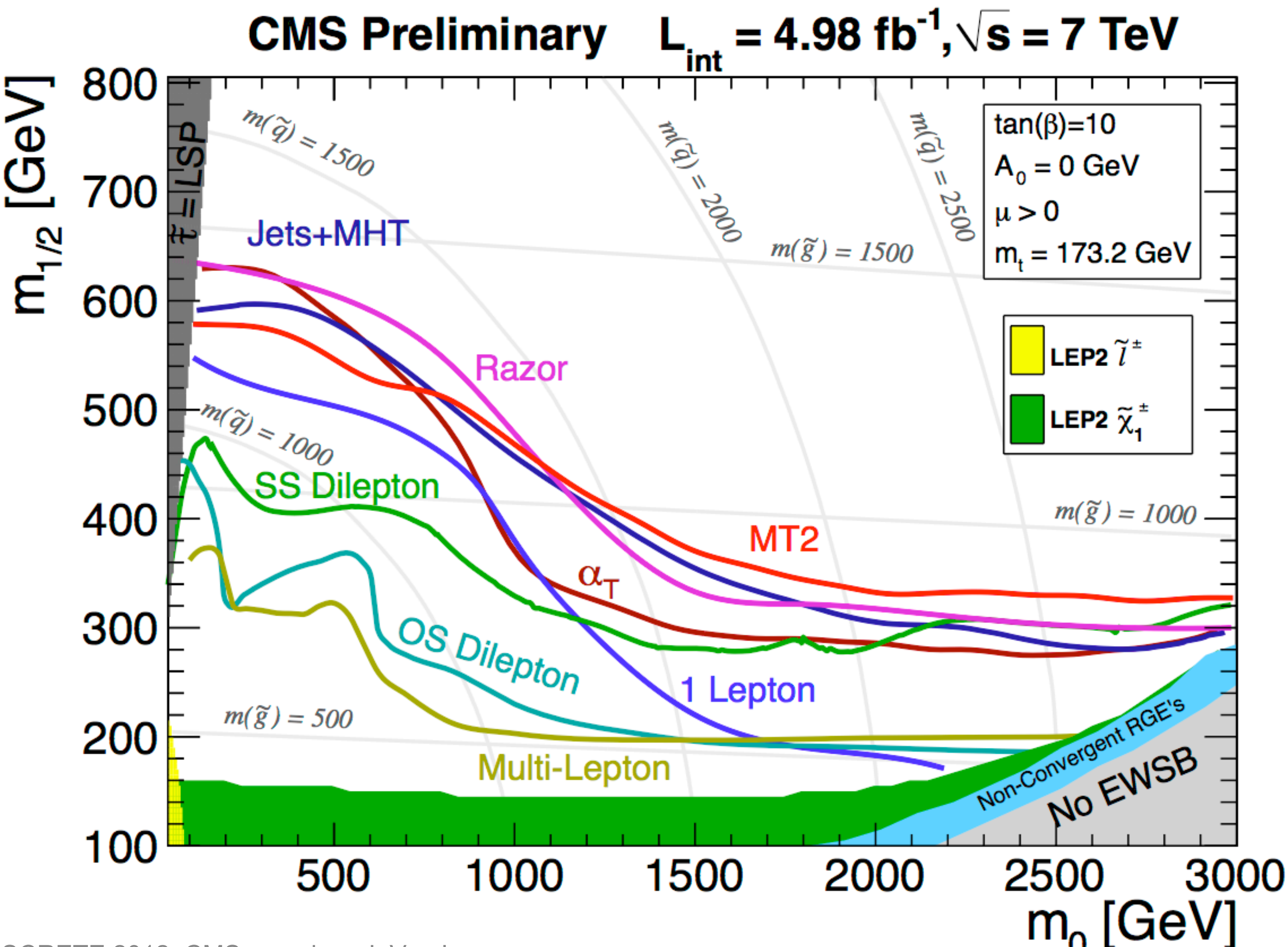
1. Broad



- Cover many possible signatures
  - Fully hadronic final state
  - Final states with leptons; final states with photons
  - Assume stable LSP: all final states with missing E_T
  - Most of the searches have a version with b-tag
- Use different methods
  - eg: four methods for the all hadronic channel (α_T, MHT, MT2, razor)
  - Counting as well as shapes analysis

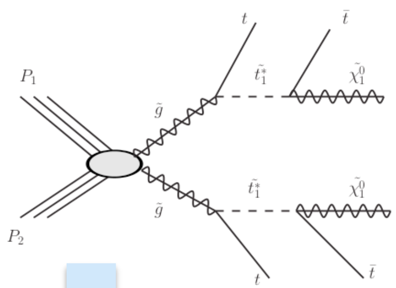
1. Robust

- Background estimated from data as much as possible

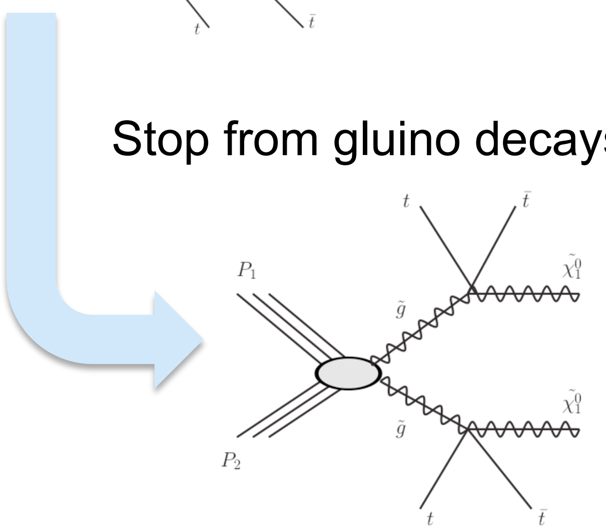

CMS Preliminary $L_{int} = 4.98\ fb^{-1}, \sqrt{s} = 7\ TeV$
$m_{1/2}$ [GeV]
m_0 [GeV]
$\tilde{\tau}$ = LSP
$m(\tilde{q}) = 1500$
$m(\tilde{q}) = 2000$
$m(\tilde{q}) = 2500$
$m(\tilde{g}) = 1500$
$m(\tilde{q}) = 1000$
$m(\tilde{g}) = 1000$
$m(\tilde{g}) = 500$
tan(β)=10
A_0 = 0 GeV
μ > 0
m_t = 173.2 GeV
LEP2 $\tilde{l}^{\pm}$
LEP2 $\tilde{\chi}_1^{\pm}$
Jets+MHT
Razor
SS Dilepton
MT2
α_T
OS Dilepton
1 Lepton
Multi-Lepton
Non-Convergent RGE's
No EWSB

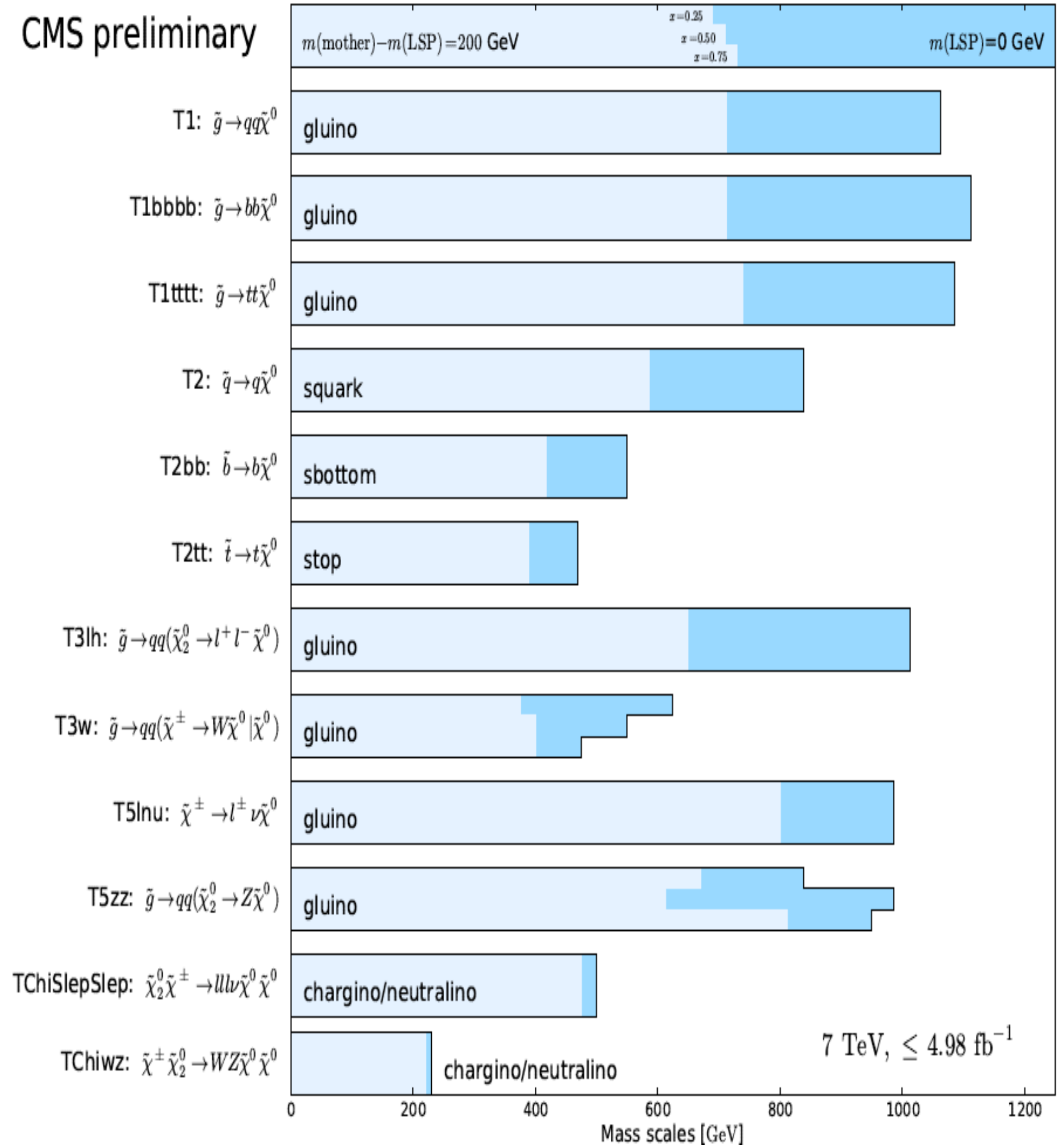
SMS interpretation

Simplified models:



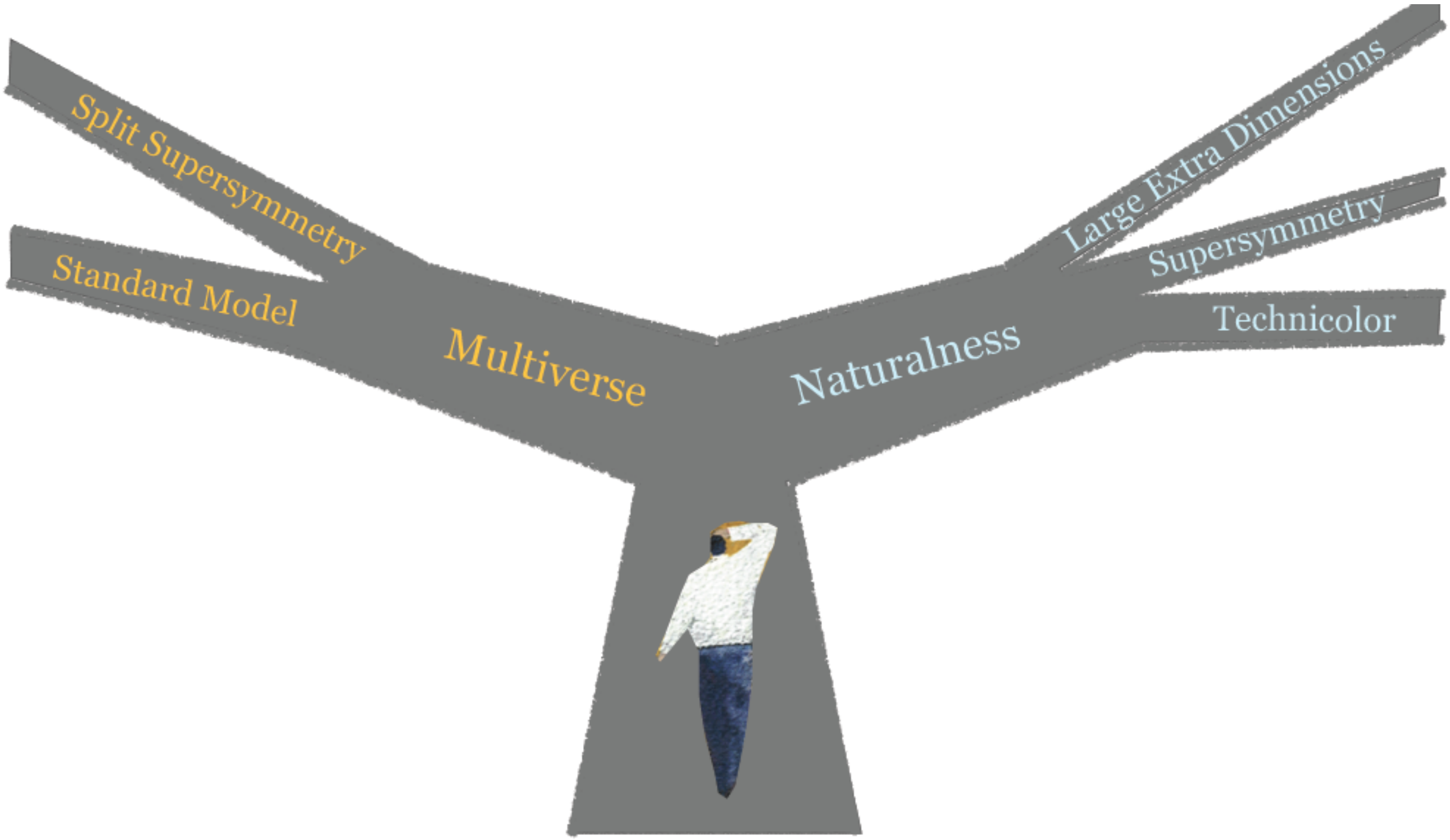
Stop from gluino decays





CMS searches have excluded light squarks and gluinos up to ~ 1 TeV

At a Crossroad



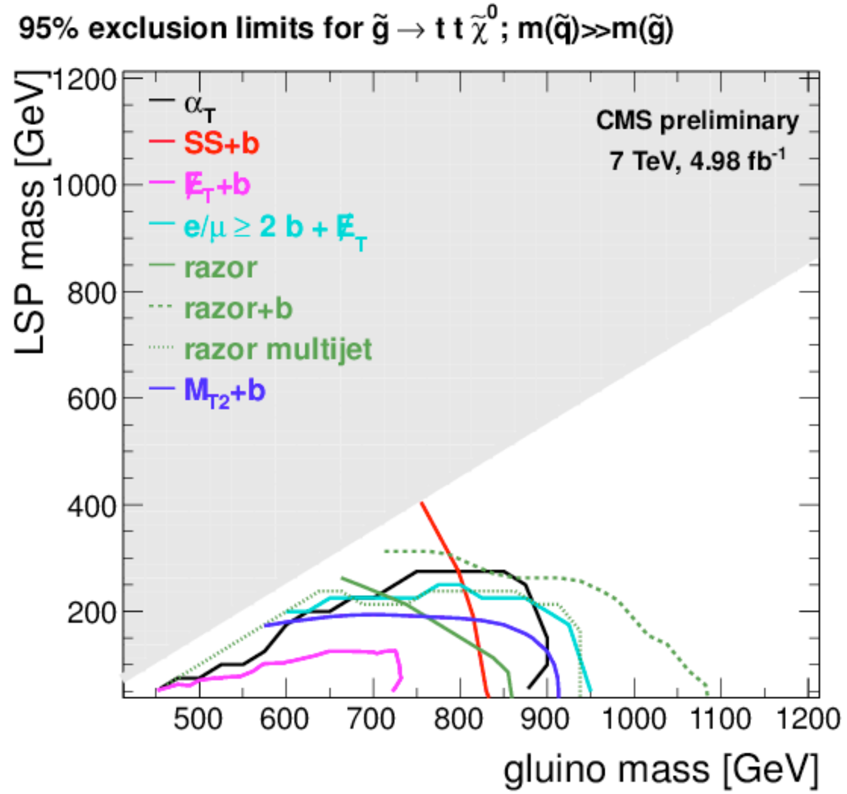
Savas Dimopoulos, CERN Colloquium, Sep 20, 2012

Looking for natural SUSY

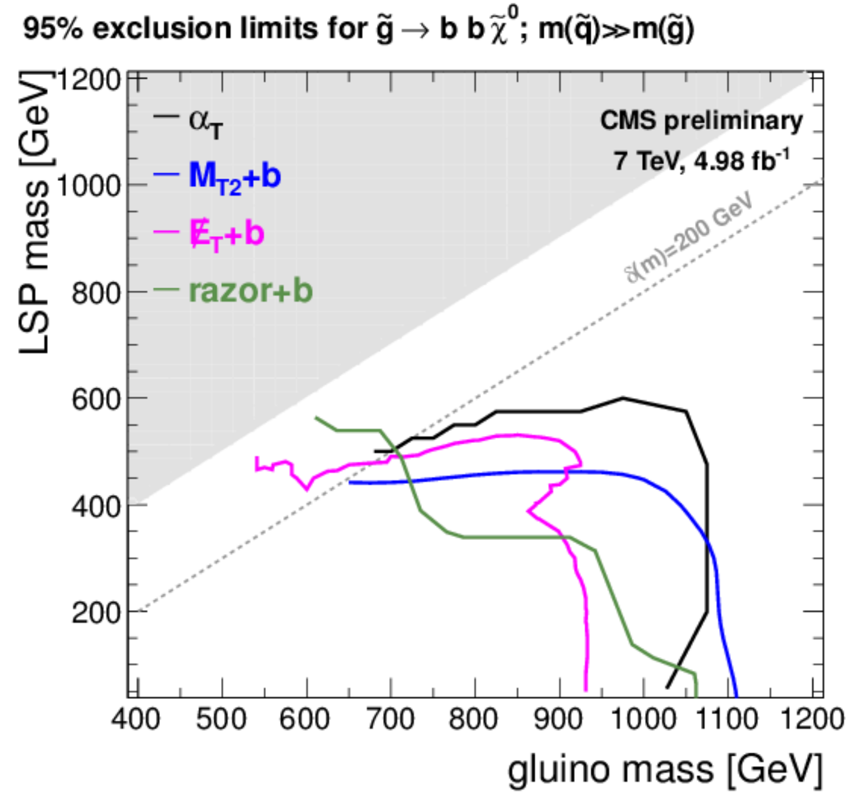
- Search for stops and sbottoms in gluino decays
  - Relatively light stops are needed for naturalness
  - In natural SUSY the gluino cannot be too heavy
  - If the other squarks are very heavy, then the gluino will decay into sbottoms and stops with high BR
- Search for direct stop and sbottom pair production
  - To close the loophole that the “gluino is too heavy”
- Existing “generic” searches can be re-interpreted in this context
- New targeted searches have been developed for pair production

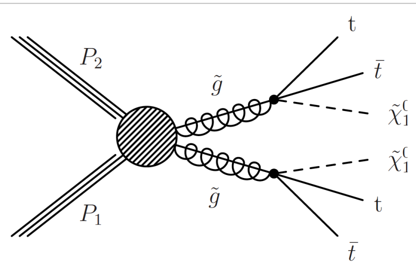
Stop and sbottom in gluino decays

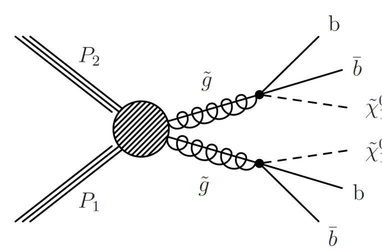
$\tilde{g} \rightarrow t\,t\,\tilde{\chi}^0$; $m(\tilde{q}) \gg m(\tilde{g})$



$\tilde{g} \rightarrow b\,b\,\tilde{\chi}^0$; $m(\tilde{q}) \gg m(\tilde{g})$



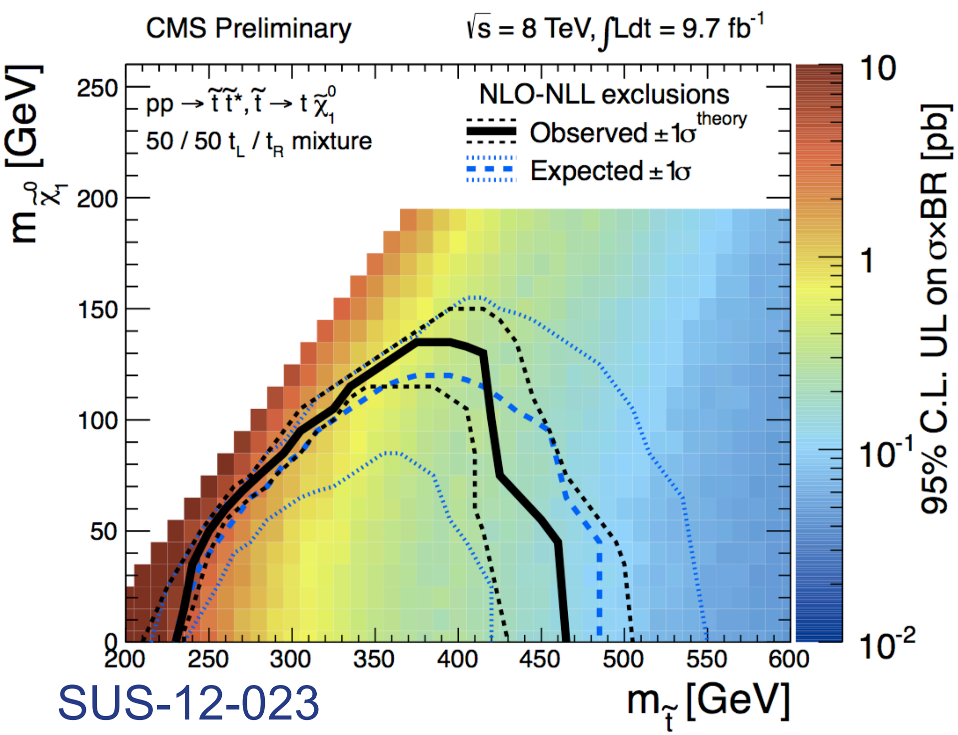




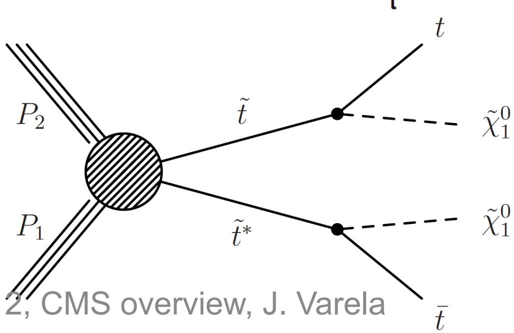
Direct stop and sbottom pair production

Single lepton + missing E_T

$$\tilde{t} \rightarrow t\chi_1^0 \text{ and } \tilde{t} \rightarrow b\chi_1^+ \rightarrow bW\chi_1^0$$

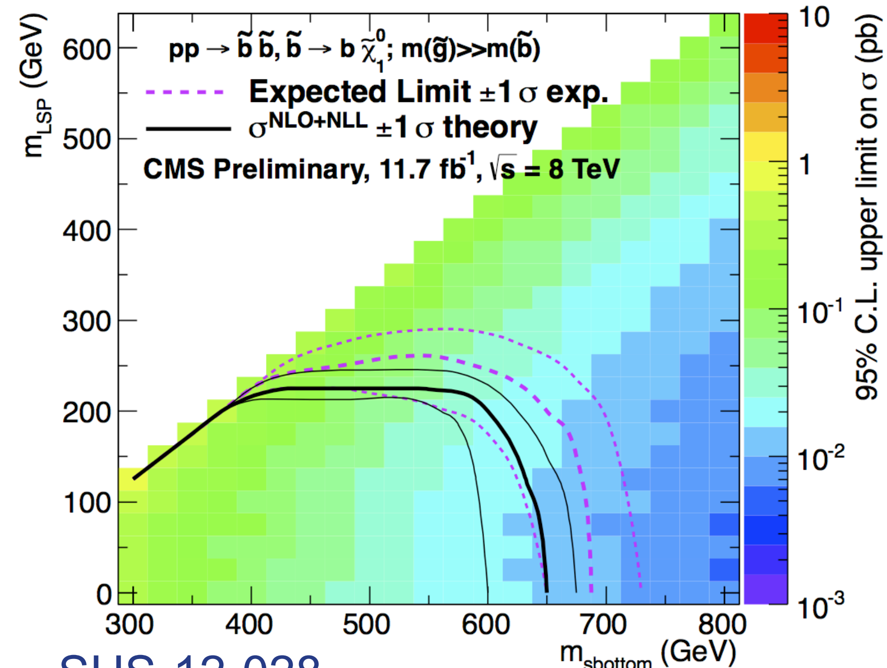


SUS-12-023

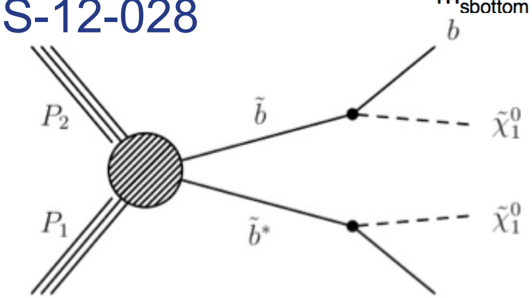


Missing E_T and b jets

$$\tilde{b} \rightarrow b\,\tilde{\chi}_1^0$$

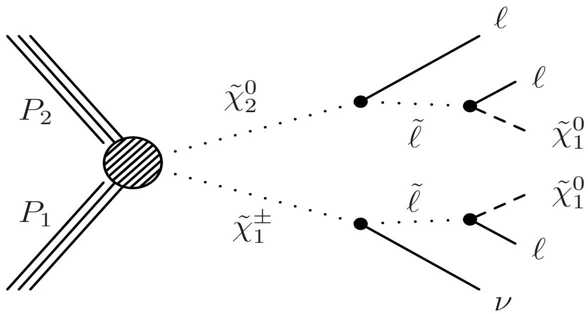


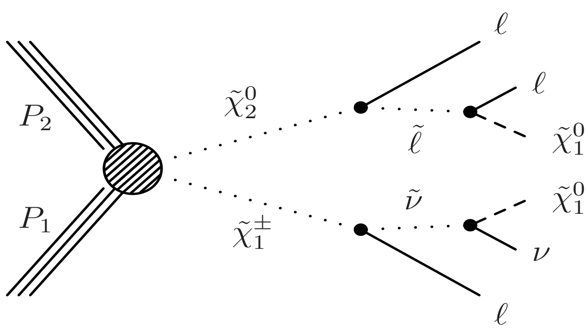
SUS-12-028



EWK production

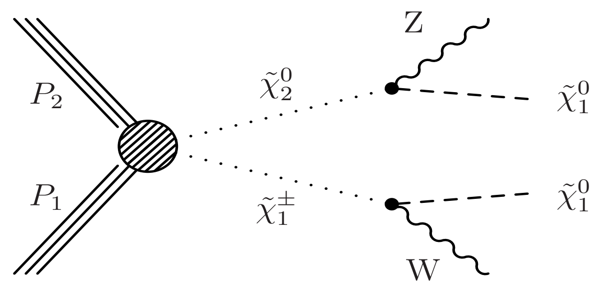
Models with decays into sleptons

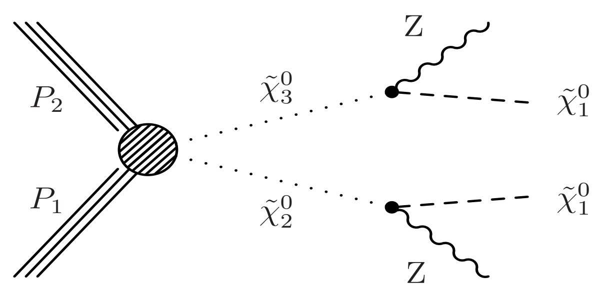




- Trilepton + MET final states
- Same-sign dileptons

Models with decays into W and Z

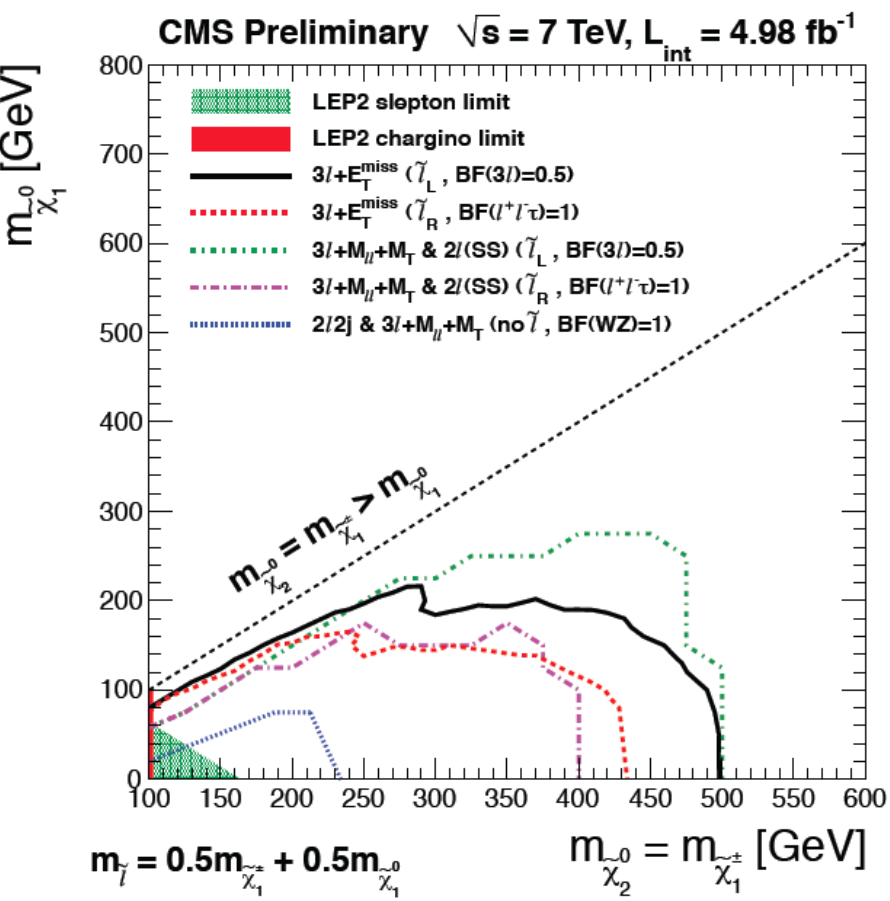




- Z→ℓℓ + ℓ + MET
- Z→ℓℓ + W/Z→jet-jet + MET
- Four leptons

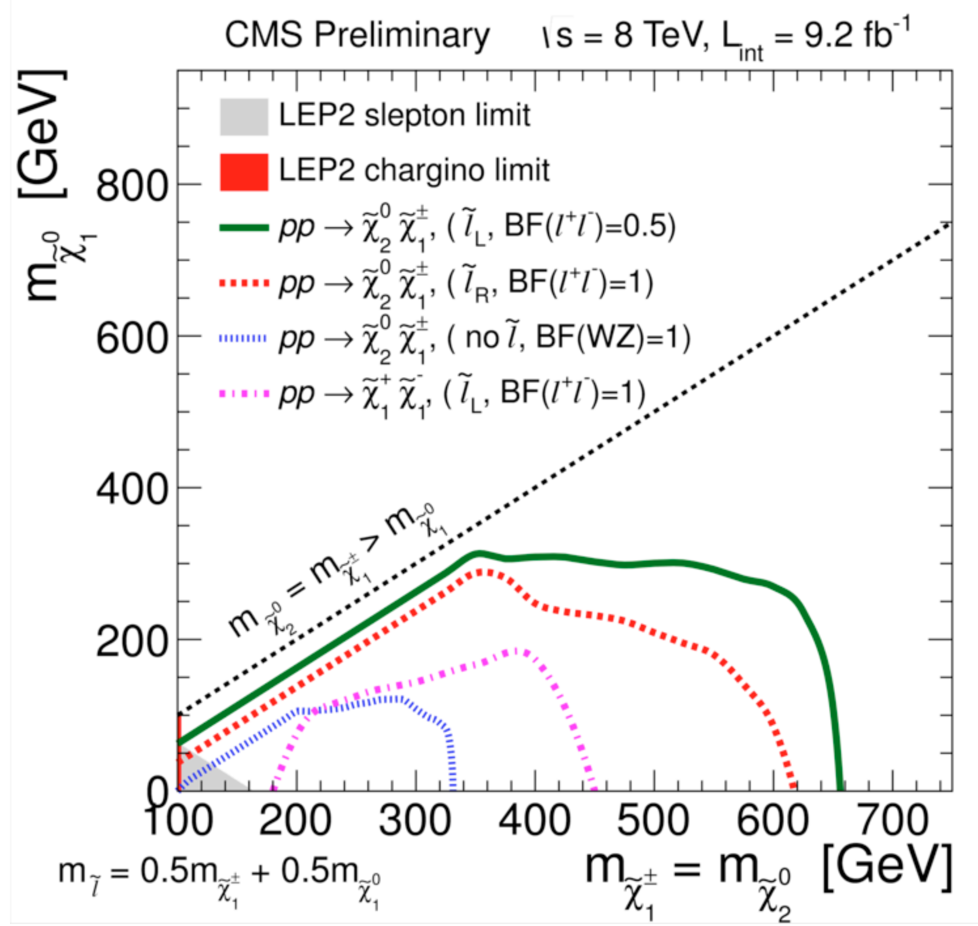
$\chi^+\chi^0$ exclusion limits

7 TeV result

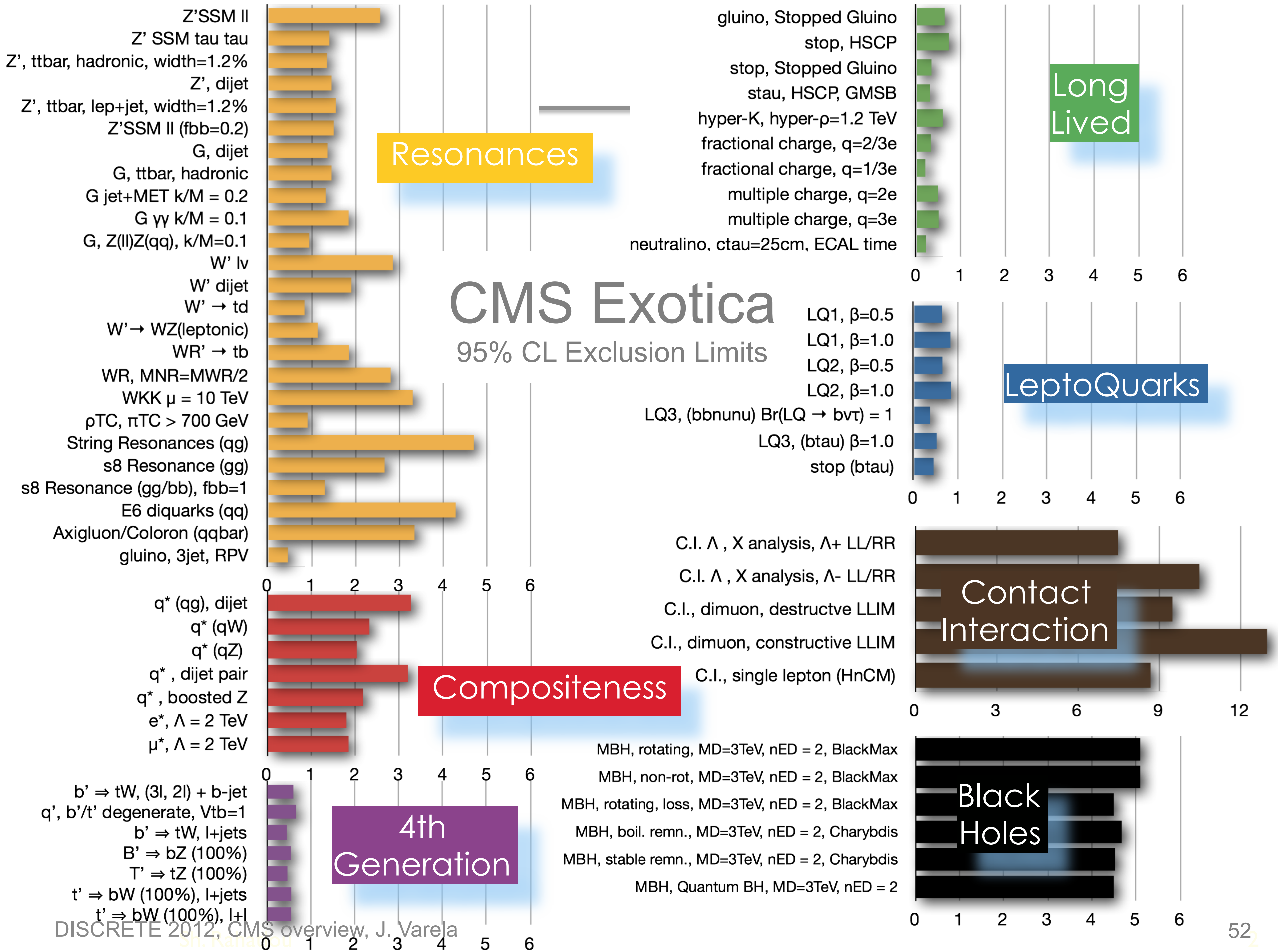


SUS-12-006

New 8 TeV result



SUS-12-022



CMS Exotica
95% CL Exclusion Limits
Resonances
Z'SSM ll
Z' SSM tau tau
Z', ttbar, hadronic, width=1.2%
Z', dijet
Z', ttbar, lep+jet, width=1.2%
Z'SSM ll (fbb=0.2)
G, dijet
G, ttbar, hadronic
G jet+MET k/M = 0.2
G γγ k/M = 0.1
G, Z(ll)Z(qq), k/M=0.1
W' lν
W' dijet
W' → td
W'→ WZ(leptonic)
WR' → tb
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
s8 Resonance (gg/bb), fbb=1
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
0 1 2 3 4 5 6
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
0 1 2 3 4 5 6
4th Generation
b' ⇒ tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' ⇒ tW, l+jets
B' ⇒ bZ (100%)
T' ⇒ tZ (100%)
t' ⇒ bW (100%), l+jets
t' ⇒ bW (100%), l+l
0 1 2 3 4 5 6
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
fractional charge, q=2/3e
fractional charge, q=1/3e
multiple charge, q=2e
multiple charge, q=3e
neutralino, ctau=25cm, ECAL time
0 1 2 3 4 5 6
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3, (bbnunu) Br(LQ → bντ) = 1
LQ3, (btau) β=1.0
stop (btau)
0 1 2 3 4 5 6
Contact Interaction
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., dimuon, destructve LLIM
C.I., dimuon, constructive LLIM
C.I., single lepton (HnCM)
0 3 6 9 12
Black Holes
MBH, rotating, MD=3TeV, nED = 2, BlackMax
MBH, non-rot, MD=3TeV, nED = 2, BlackMax
MBH, rotating, loss, MD=3TeV, nED = 2, BlackMax
MBH, boil. remn., MD=3TeV, nED = 2, Charybdis
MBH, stable remn., MD=3TeV, nED = 2, Charybdis
MBH, Quantum BH, MD=3TeV, nED = 2
0 1 2 3 4 5 6

Prospects

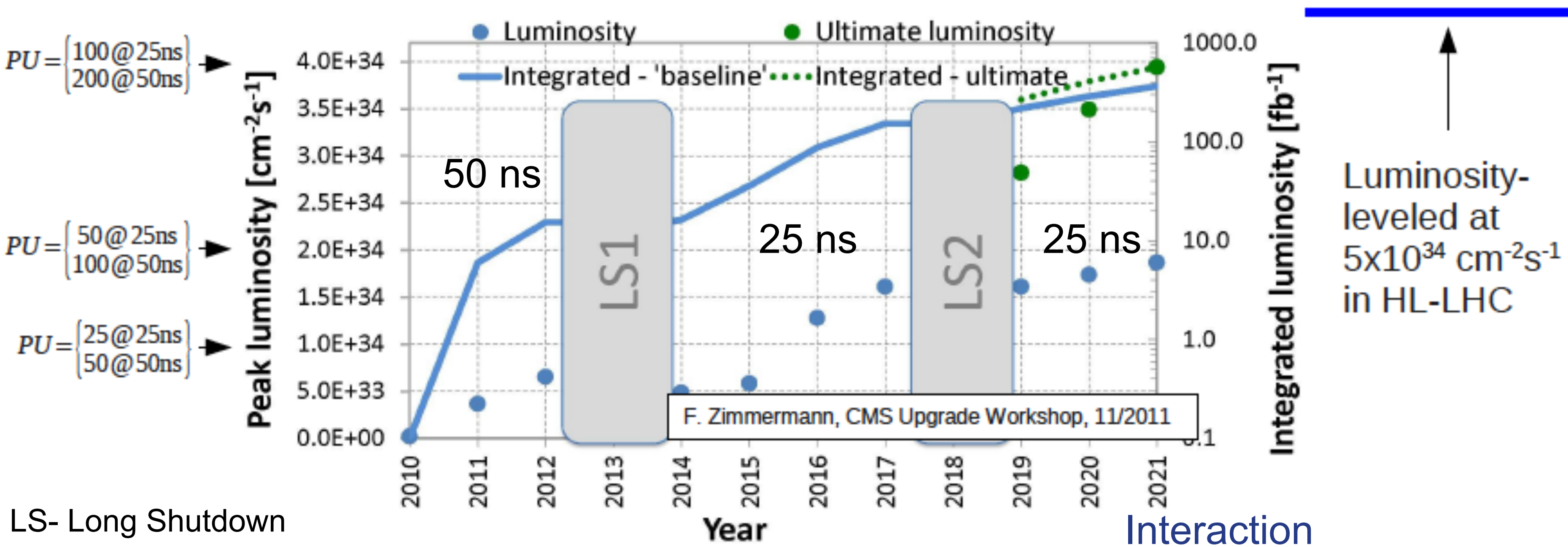
LHC and HL-LHC projections

LHC

Energy increase
8 TeV to 13/14 TeV

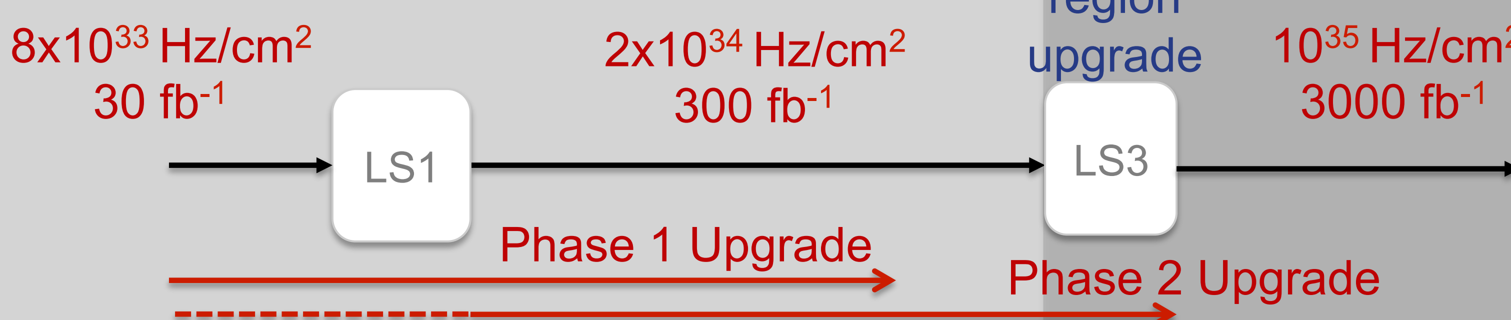
Injection upgrade

HL-LHC



LS- Long Shutdown

Interaction region upgrade



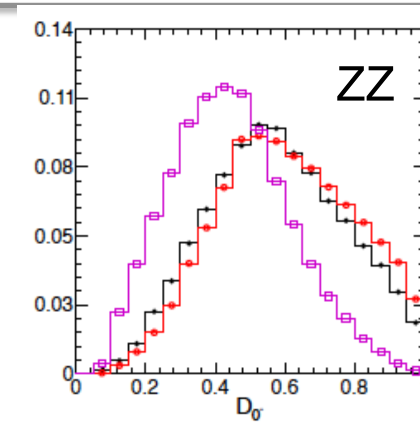
Spin-parity: H→ ZZ, WW, γγ with 30 fb^{-1}

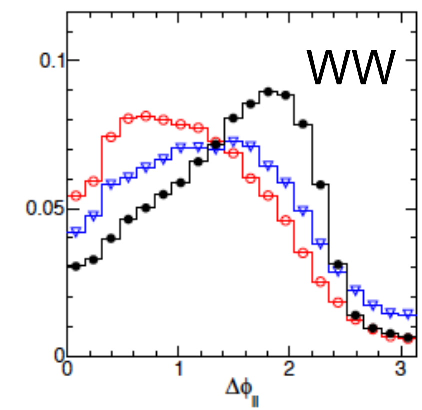
- Simplified generator study
  - S.Bolognesi et al., arXiv:1208.4018
  - ZZ: likelihood discriminator
  - WW feature: angle between leptons
  - γγ: production angle

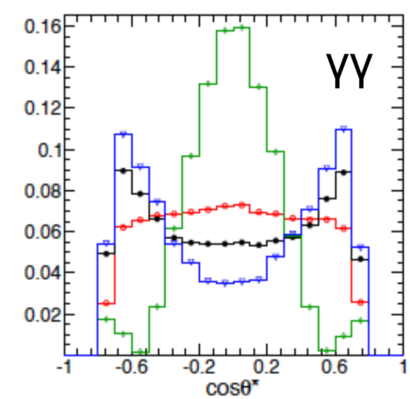
For 5+30 fb^{-1}:

scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$	combined
0_m^+ vs bkg	7.1	4.5	5.2	9.9
0_m^+ vs 0^-	4.1	1.1	0.0	4.2
0_m^+ vs 2_m^+	1.6	2.5	2.5	3.9

- Up to 4σ separation possible in 2012
  - for both odd parity and spin-2
  - ATLAS+CMS combined

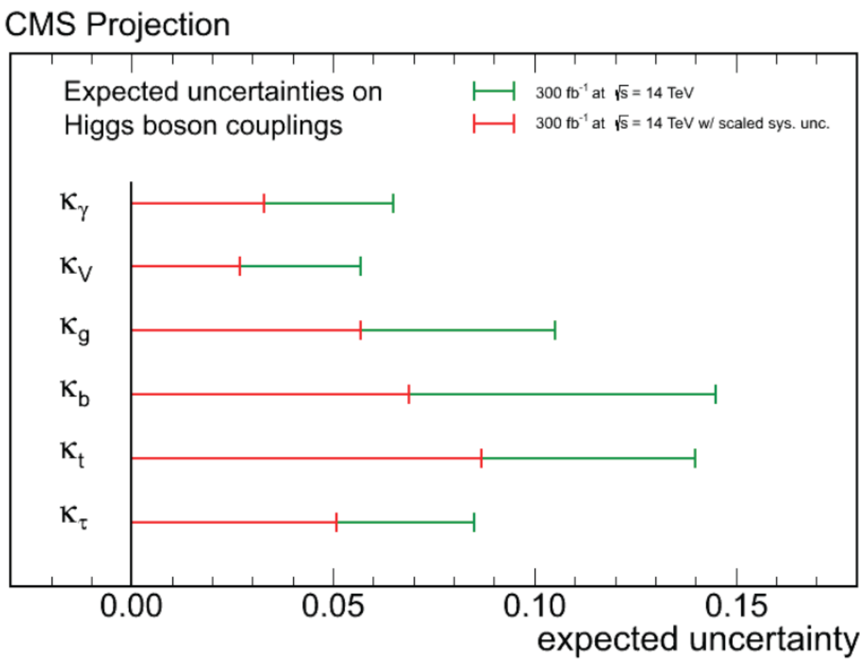




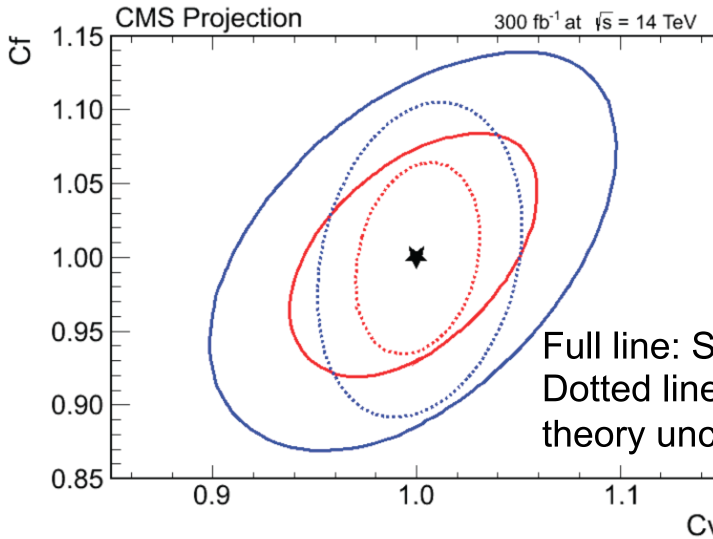


Projected Higgs couplings with 300 fb^{-1}

- Two scenarios:
  - Scenario 1: same systematics as in 2012
  - Scenario 2: theory systematics scaled by a factor ½, other systematics scaled by $1/\sqrt{L}$



300 fb^{-1} 14 TeV, Scenario 1
300 fb^{-1} 14 TeV, Scenario 2



With 300 fb^{-1} the uncertainties of the Higgs couplings are expected in the range $\sigma(\kappa_V) \sim 3\text{-}6\%$
$\sigma(\kappa_b) \sim 7\text{-}15\%$

HL-LHC: Higgs couplings with 3000 fb^{-1}

- Extrapolation by two orders of magnitude to higher luminosity
  - is subject to large uncertainties
  - scenarios 1 and 2 provide likely upper and lower bounds
- Experience at LEP and Tevatron indicates that scaling with 1/√L is not unrealistic

- With 3000 fb^{-1} the Higgs couplings can possibly be determined with high precision (1-3%)
- The decay H→μμ can be observed with a significance of 5 sigma
  - measurement of the Hμμ coupling with a precision of ~10%.
- Measurement of multiple Higgs boson production is possible
  - The SM cross section for di-Higgs boson production is 33 fb at 14 TeV.
  - Measurement of the Higgs potential

Coupling	Uncertainty (%) 3000 fb^{-1} Scenario 1	Uncertainty (%) 3000 fb^{-1} Scenario 2
κ_γ	5.4	1.5
κ_V	4.5	1.0
κ_g	7.5	2.7
κ_b	11	2.7
κ_t	8.0	3.9
κ_τ	5.4	2.0

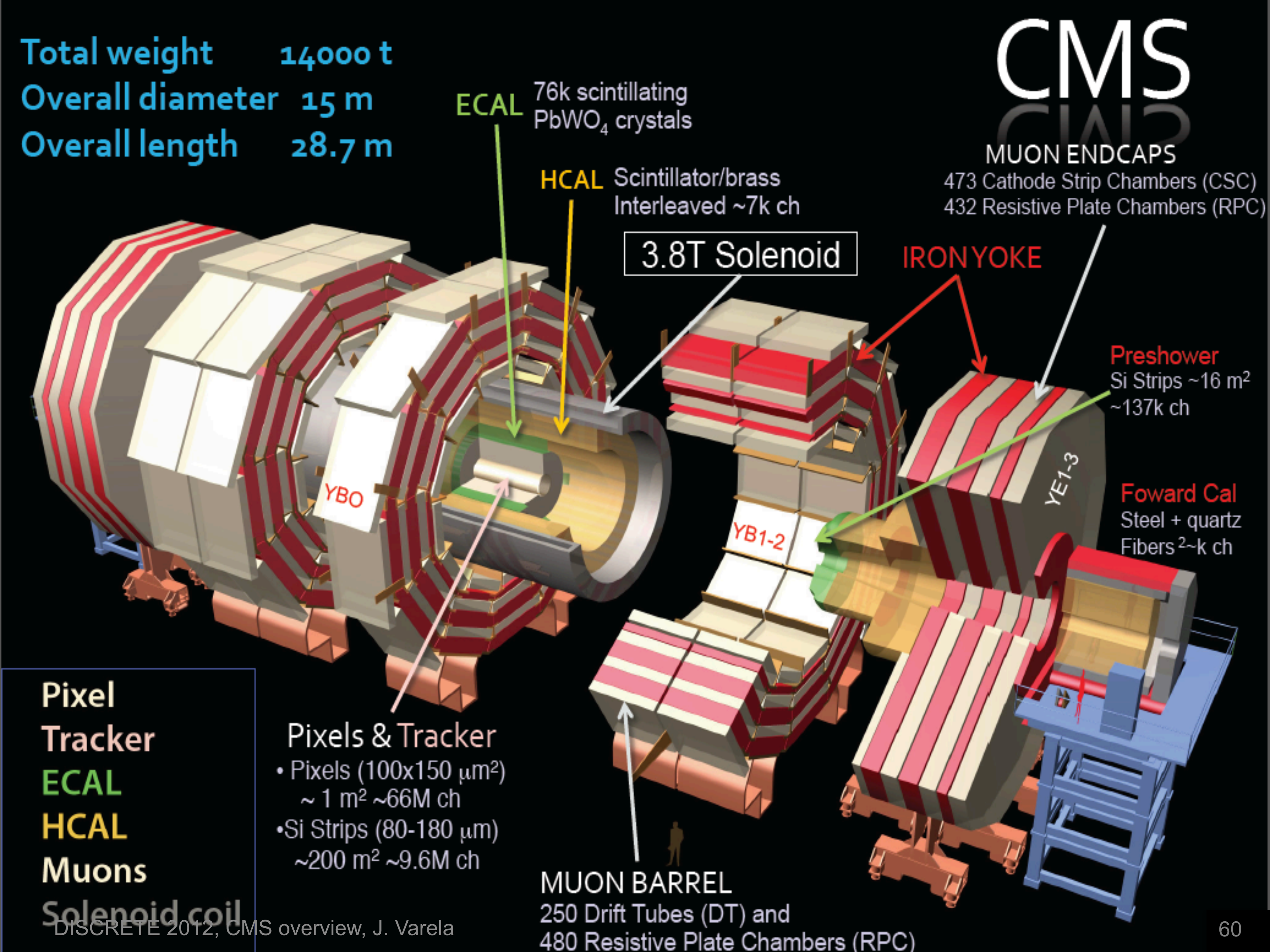
Scenario 1:
- 2012 systematics

Scenario 2:
- theory syst: scaled by a factor ½
- other systematics scaled by 1/√L

Outlook

- The LHC experiments have exceeded the design performance, showing that precision physics can be made at high luminosity and pileup.
- Impressive performance of the standard model describing the LHC data. This is a tribute to decades of hard and rigorous theoretical work.
- As of today, the 125 GeV resonance is compatible with the SM Higgs boson
- Bright prospects for physics at LHC with higher energy and luminosity. We are just at the beginning.

BACKUP

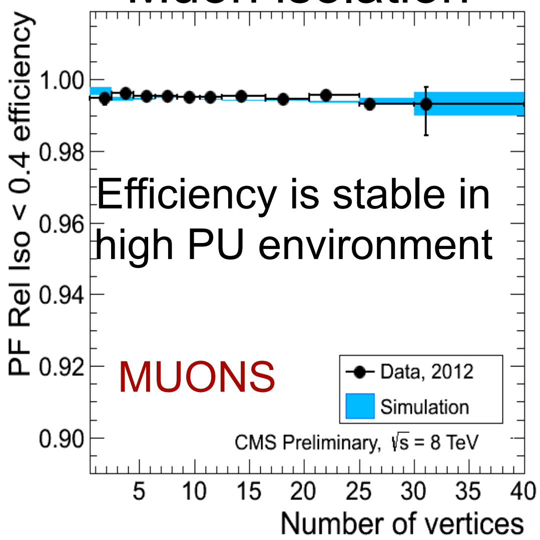

Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
CMS
ECAL
76k scintillating
$PbWO_4$ crystals
HCAL
Scintillator/brass
Interleaved ~7k ch
3.8T Solenoid
IRON YOKE
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
Preshower
Si Strips ~16 m^2
~137k ch
YE1-3
Foward Cal
Steel + quartz
Fibers 2~k ch
YB0
YB1-2
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 ~66M ch
•Si Strips (80-180 μm)
~200 m^2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

Pileup challenges

Reconstruction of hard collisions in high pileup environment requires detectors with very high granularity:

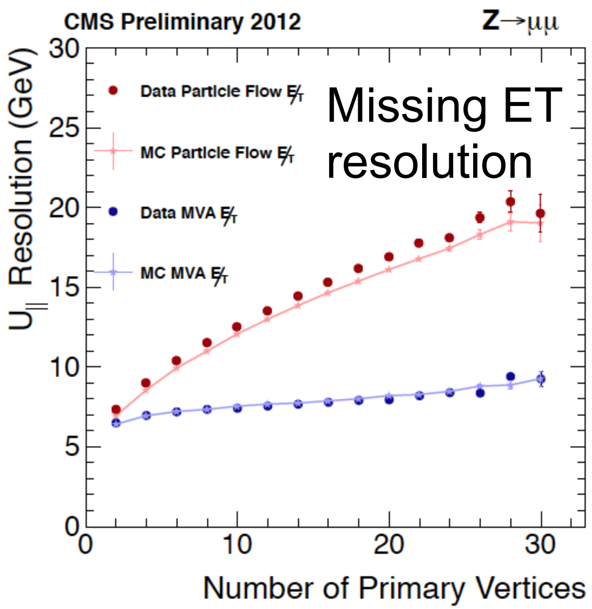
- efficient association of charged tracks to collision vertices
- reconstruction of charged and neutral particles in jets
- pileup neutrals corrected w/global energy density (ρ)

Muon isolation



Physics with high pileup requires full particle flow reconstruction assuring:

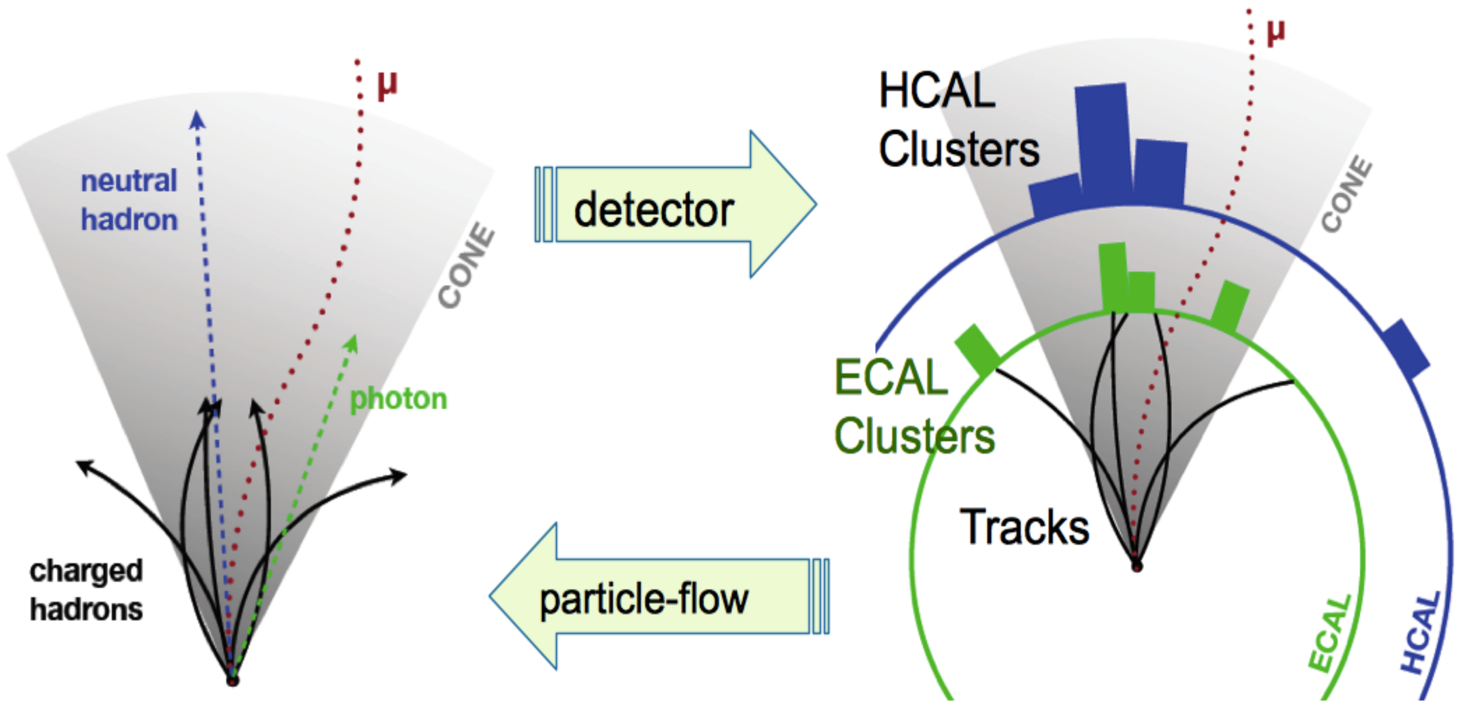
- precise jet energy correction
- robust missing energy measurement
- efficient lepton isolation



Very efficient reconstruction code is needed to stay within computing budget

Event Reconstruction

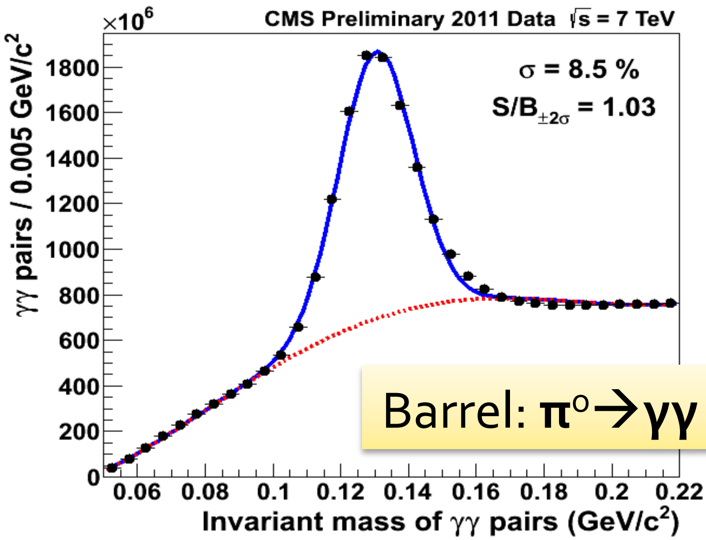
Particle Flow

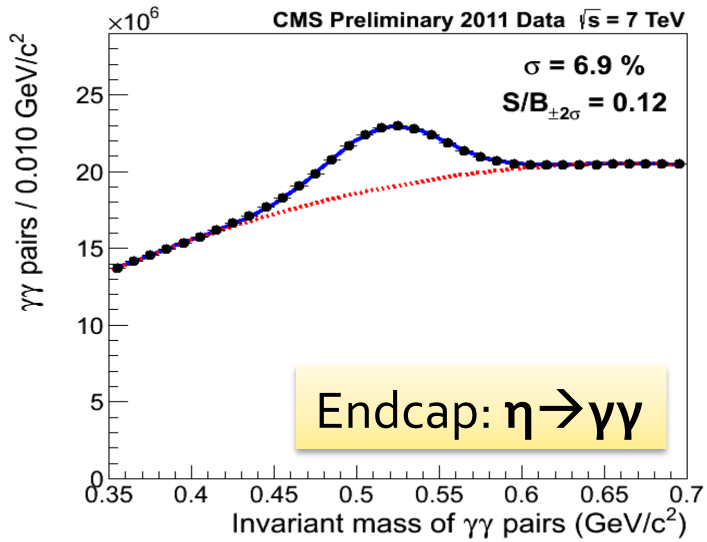


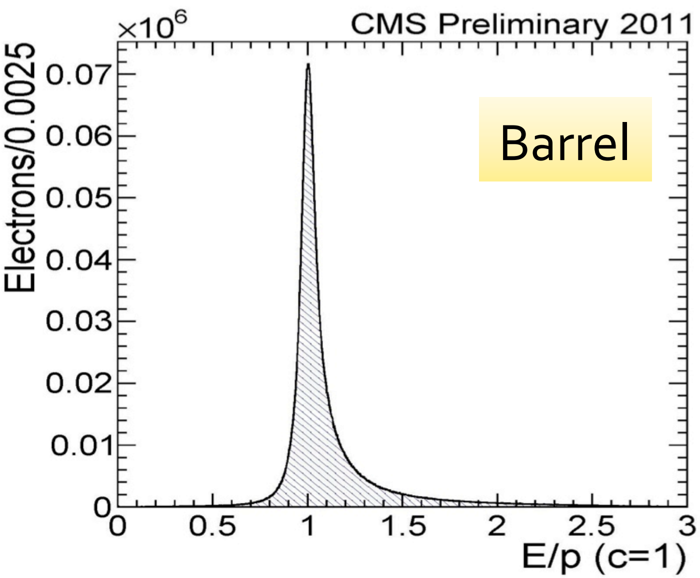
Stable particles in the event are reconstructed by a sophisticated algorithm that combines information from all sub-detectors.

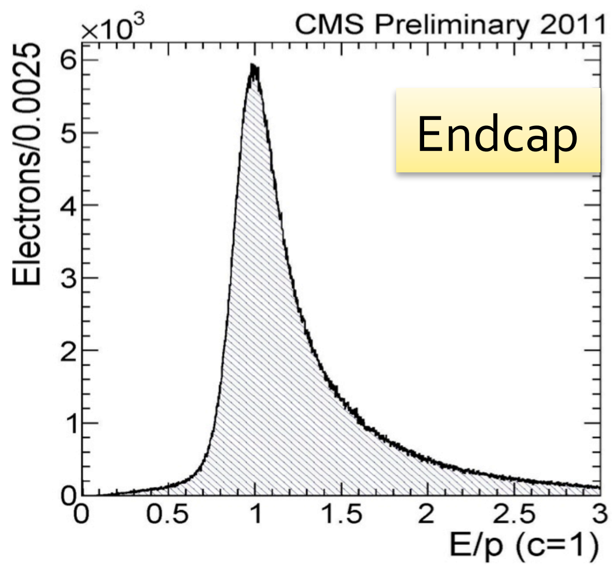
This exploits the fine-grained nature of CMS.

Photons (EM Calorimetry)



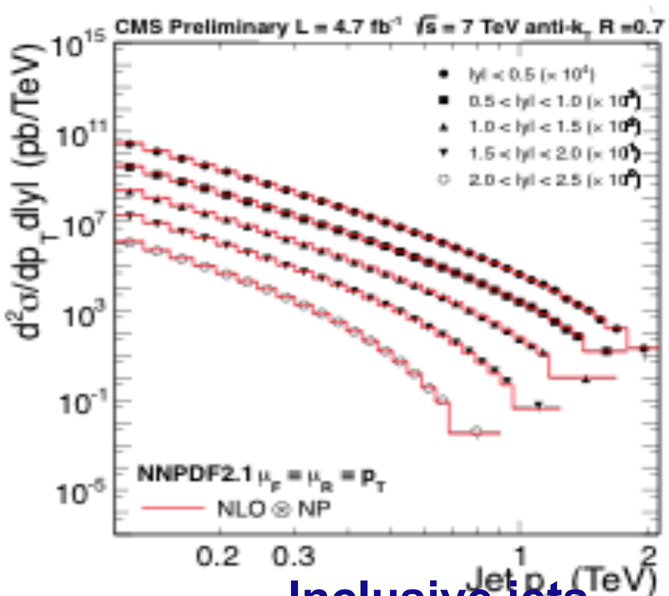




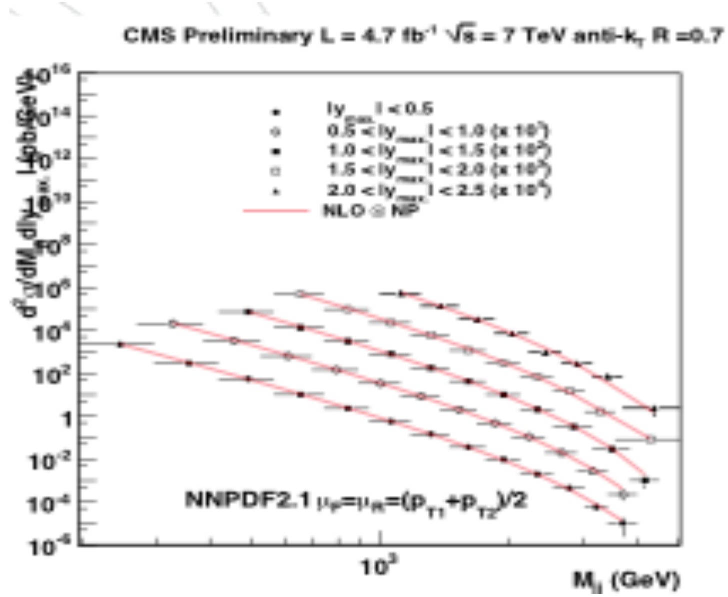


Calibration is a key issue for H→γγ

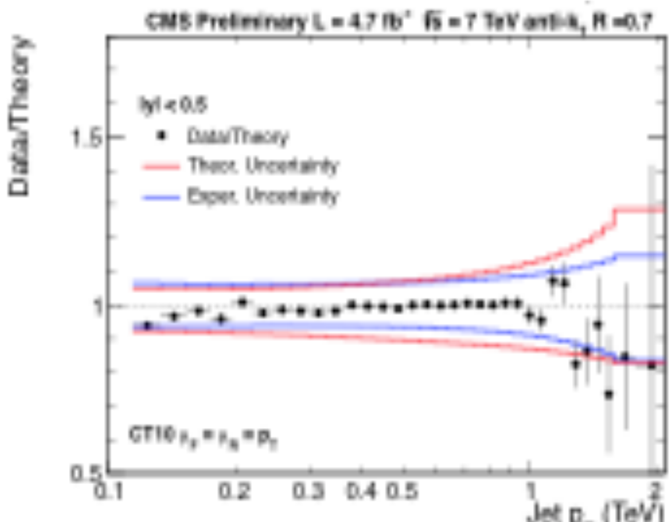
Jet Studies with 2011 Dataset

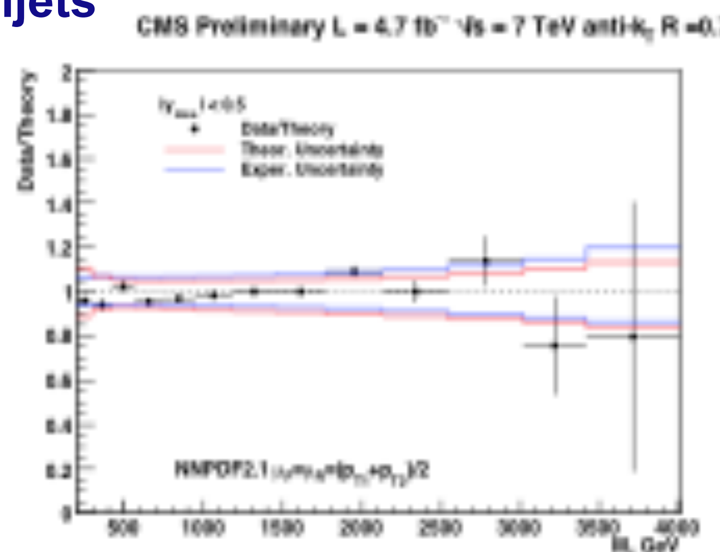


Inclusive jets



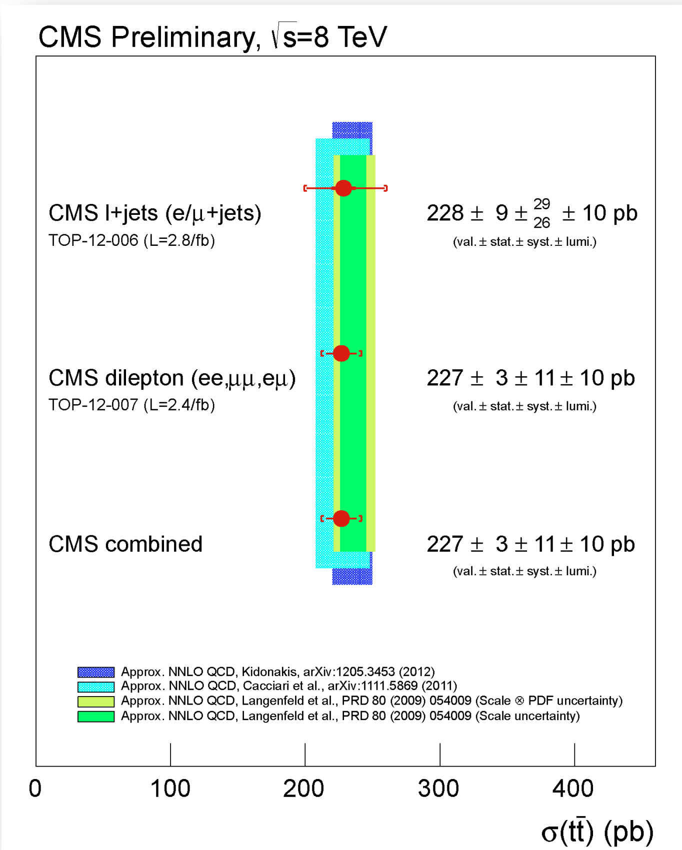
Dijets

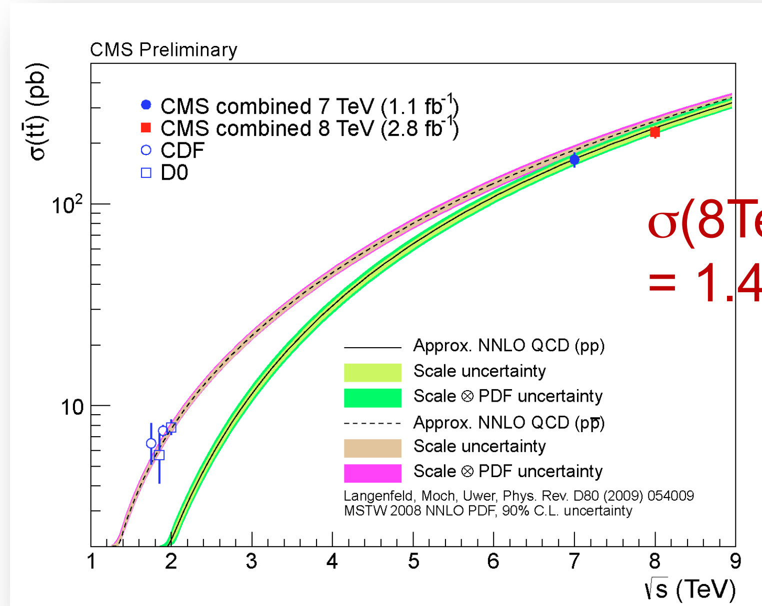




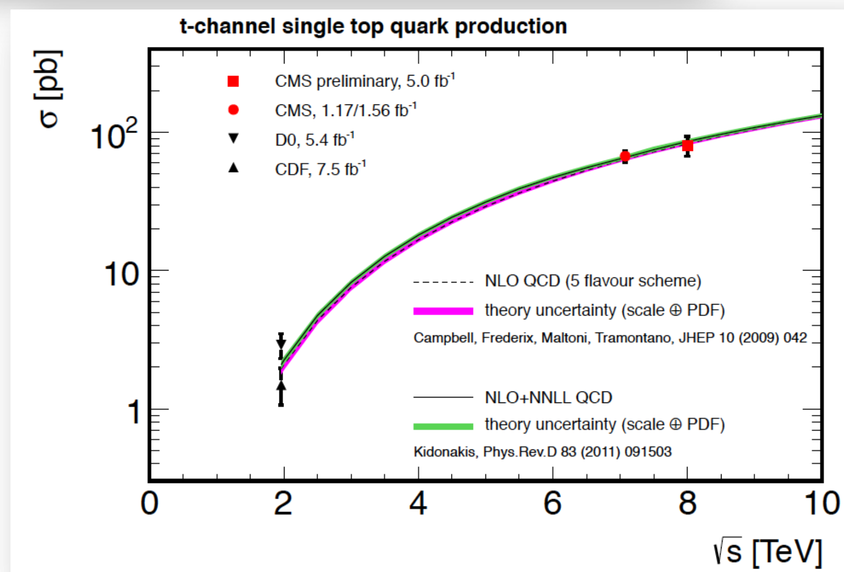
Top cross sections at √s= 8 TeV

CMS-TOP-12-006/7





σ(8TeV)/σ(7TeV)
= 1.41 ± 0.11

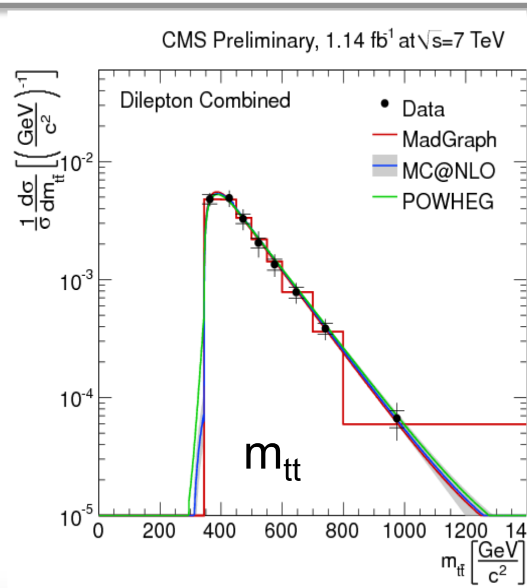


σ = 227 ± 3 (stat) ± 11 (syst) ± 10 (lumi) pb

σ_{tt}(NLO) = 225.2 pb calculated using MCFM

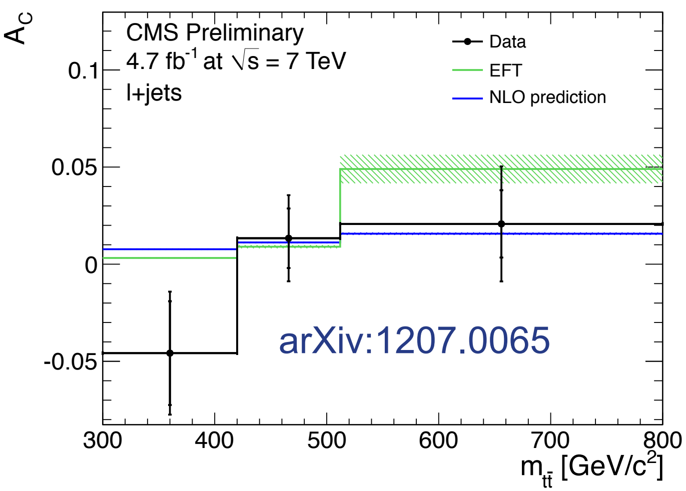
Top properties highlights

tt differential measurement



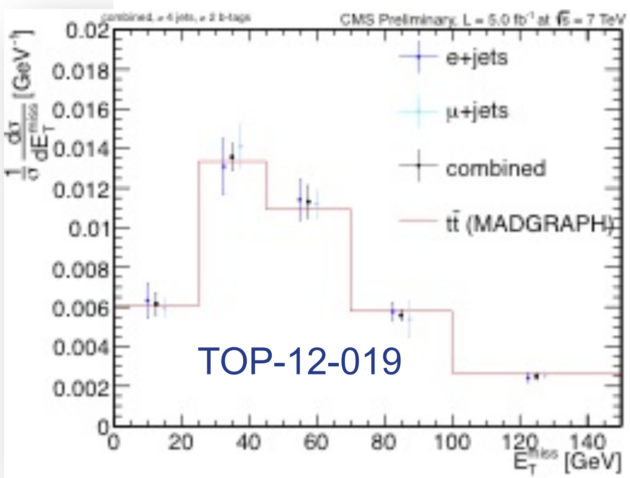
Charge asymmetry:

TOP-11-030



$A_C = 0.004 \pm 0.016$
SM: 0.012 ± 0.001

Associated production
tt+ME$_T$



R=B(t→Wb)/B(t→Wq):

R=0.98±0.04 TOP-11-029

Associated production ttbb

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 3.6 \pm 1.1(stat.) \pm 0.9(sys.)\%$$

CMS Inclusive Razor

- Razor variables:
  - Form 2 mega-jets: j1 and j2
  - Boost to Razor "R" frame: $p_z = 0$
  - Define M_R, M_T^R and R

Search in 0,1,2 lepton events

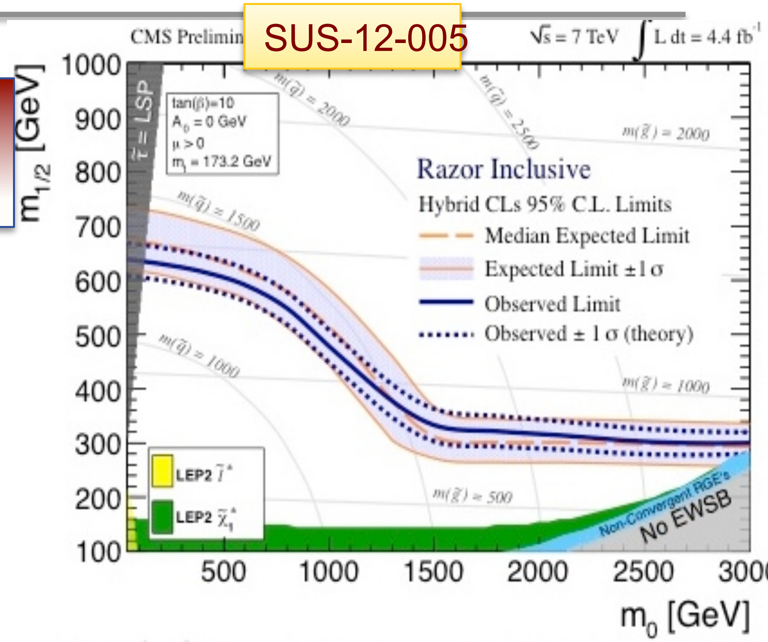
$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$

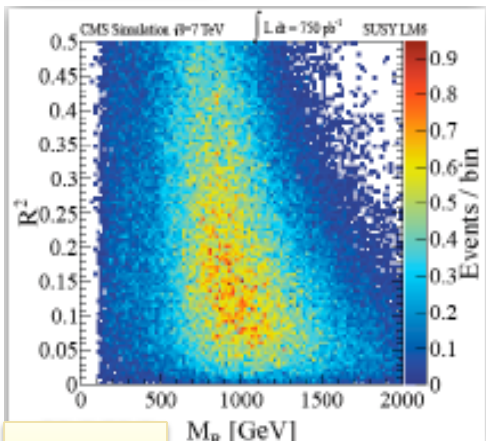
$$R \equiv \frac{M_T^R}{M_R}$$

•$M_R \approx$ Energy of the 2 LSP's in rest frame of the mother sparticle
•$M_T^R \approx$ Average transverse mass of LSP's

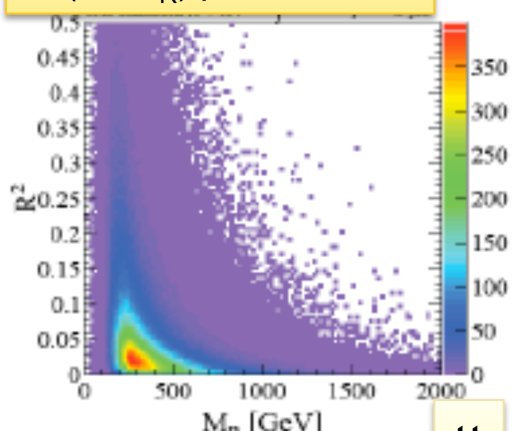
SUS-12-005



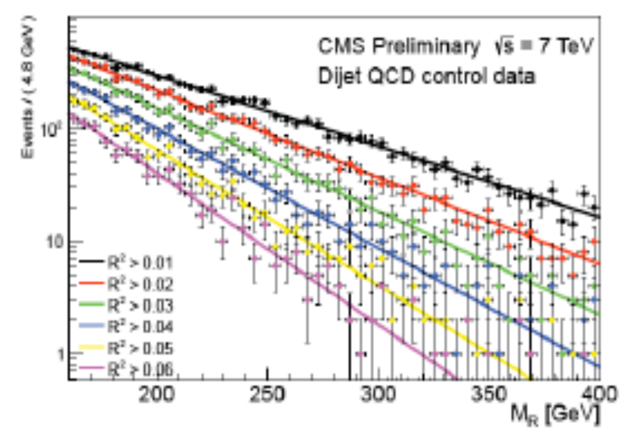
Great Signal/ Background Separation in (R^2, M_R) plane



SUSY



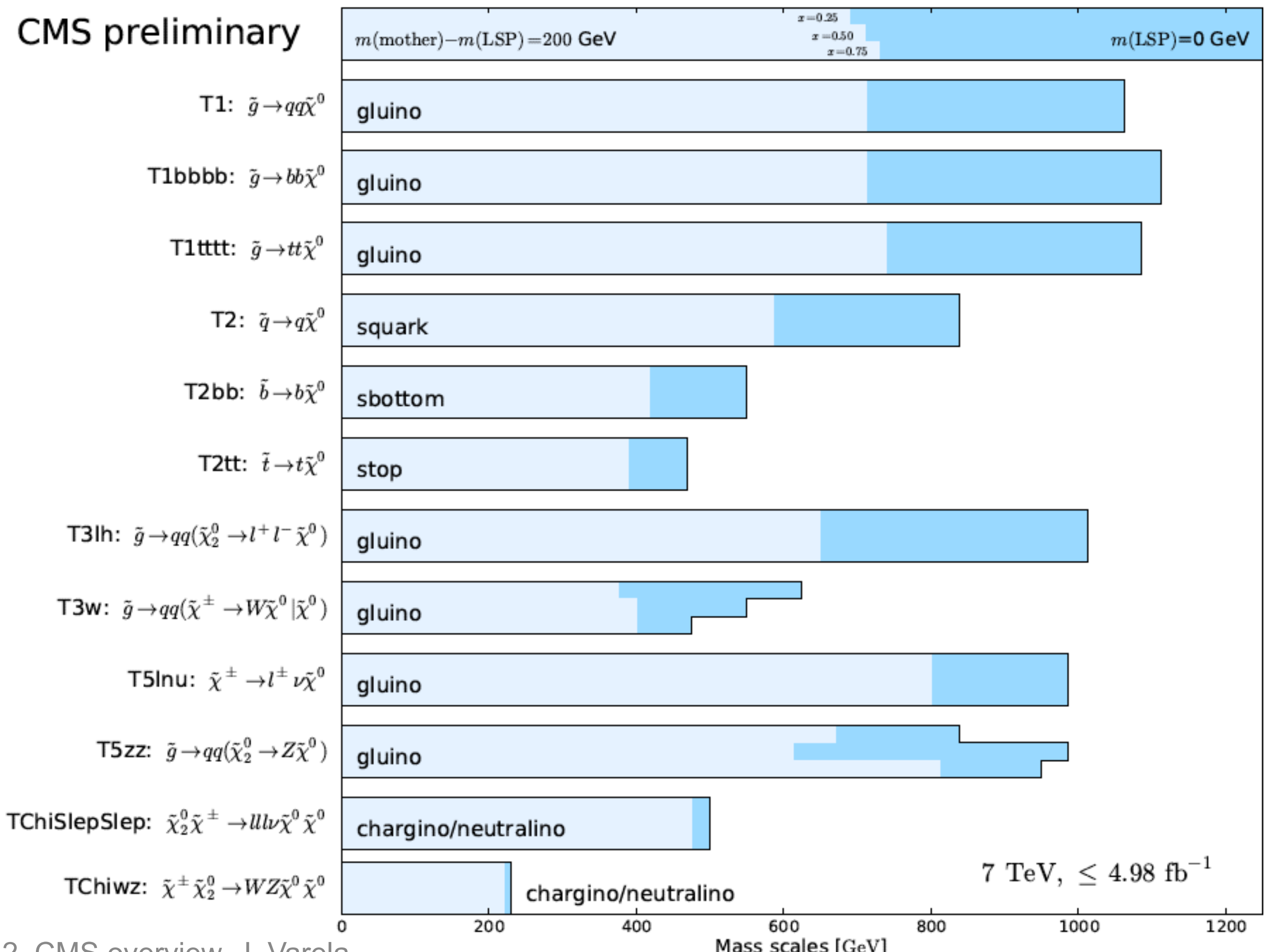
tt



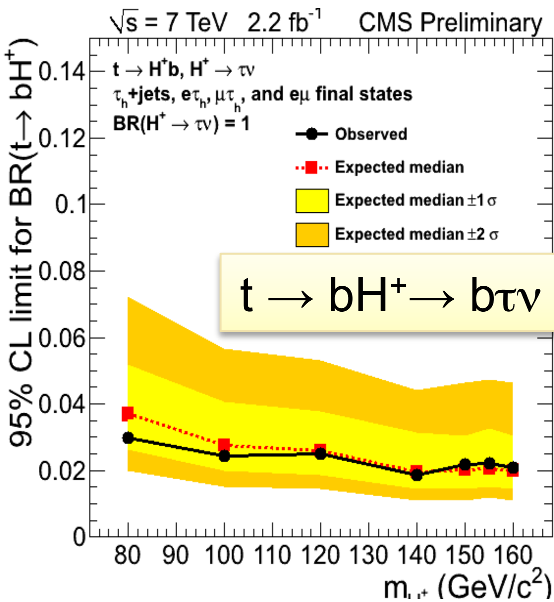
For various cuts on M_R (R), the differential distribution of R (M_R) has simple single or double exponential shape for backgrounds

SMS interpretation

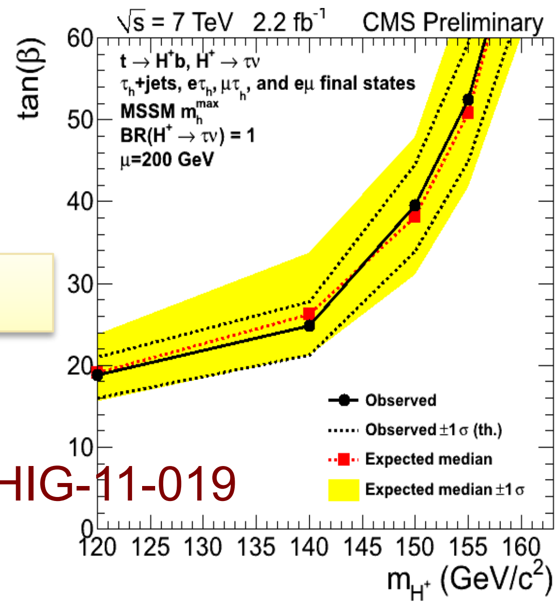
CMS searches have excluded light squarks and gluinos up to ~ 1 TeV



Charged and doubly charged Higgs



t → bH⁺→ bτν

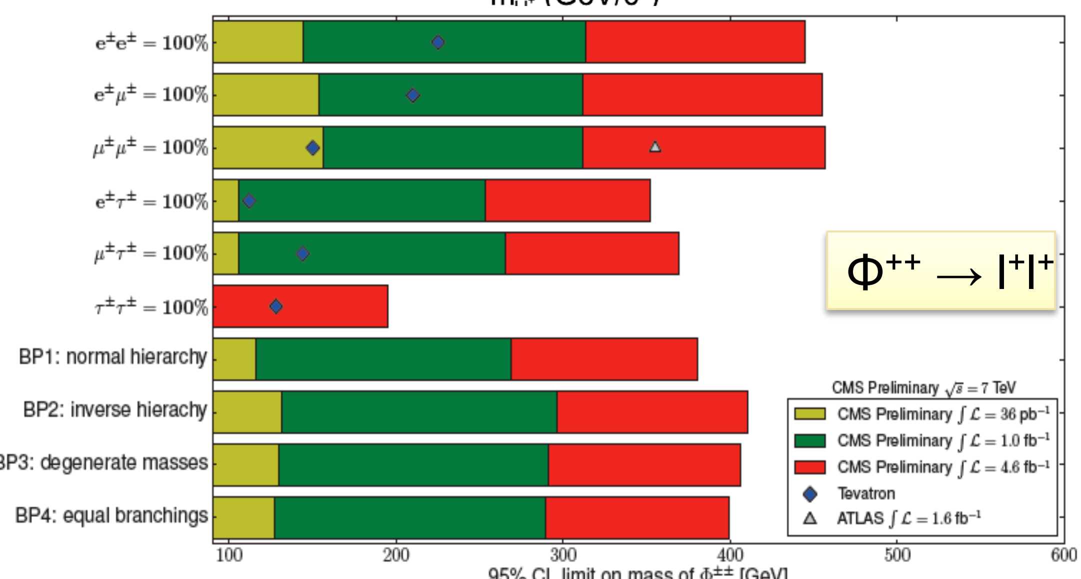


HIG-11-019

$t\bar{t} \to H^+bW^-b$, H^+bH^-b
With $H^+ \to \tau\nu$
Search channels
1. τ_h + jets
2. τ_h + e, τ_h + μ
3. eμ

Systematics limited
⇒ only 2.2 fb^{-1} used

HIG-12-005

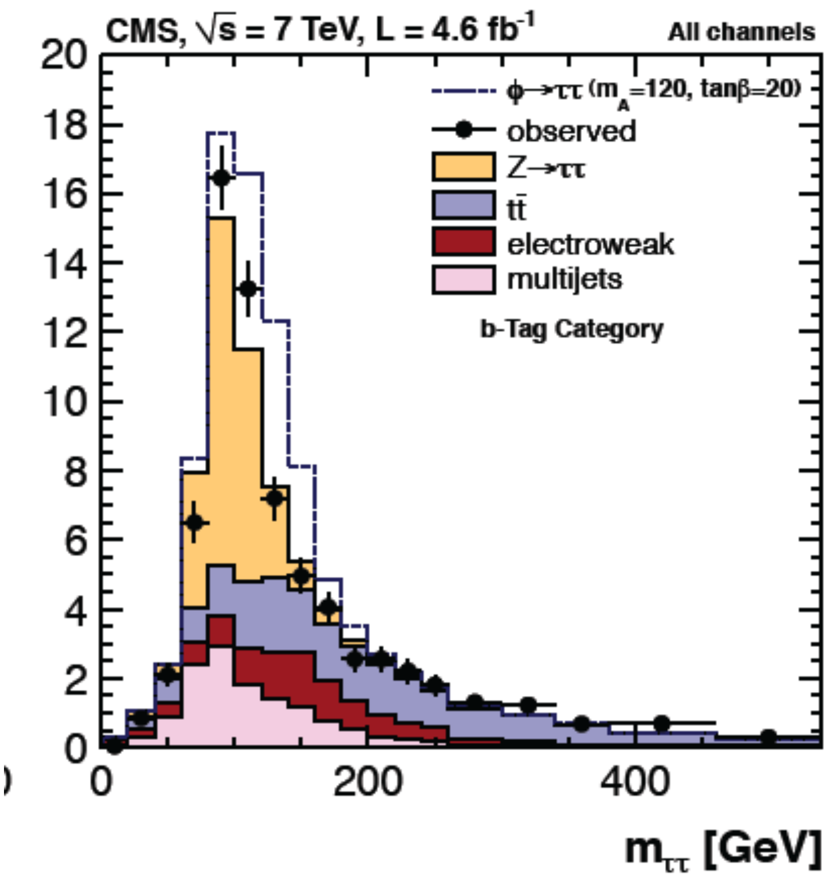


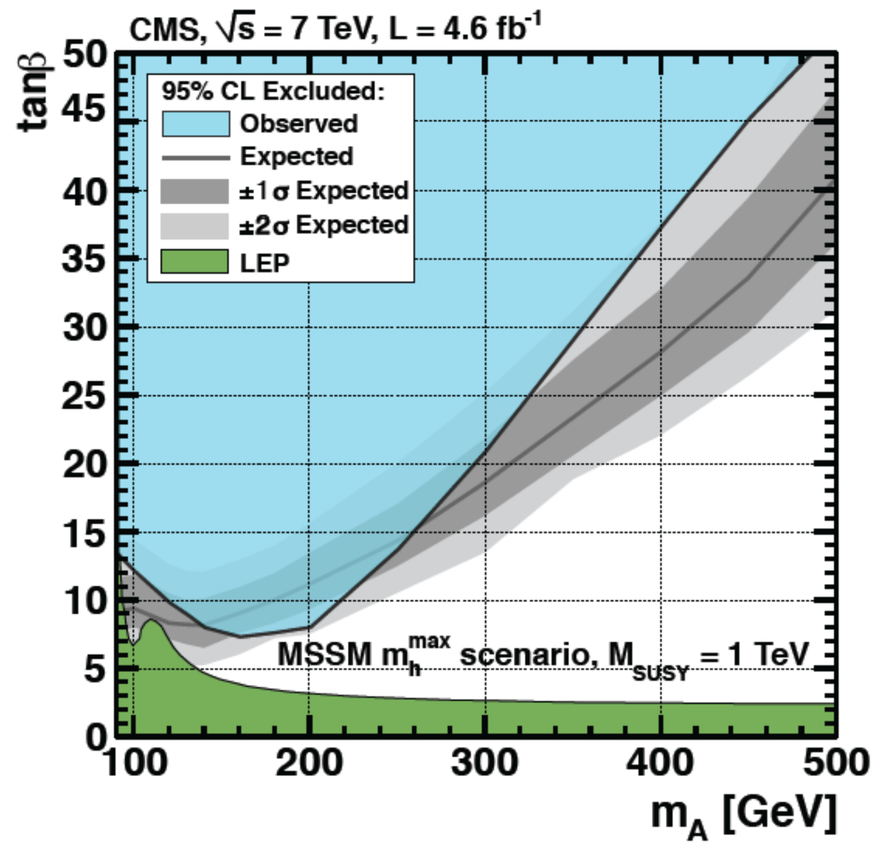
$\Phi^{++} \to l^+l^+$

- Doubly charged Higgs
  - No signal unfortunately
    - But in all channels CMS has world's best limits
    - New: $\Phi^{++} \to \tau^+\tau^+$ decay

MSSM Higgs in tau pairs

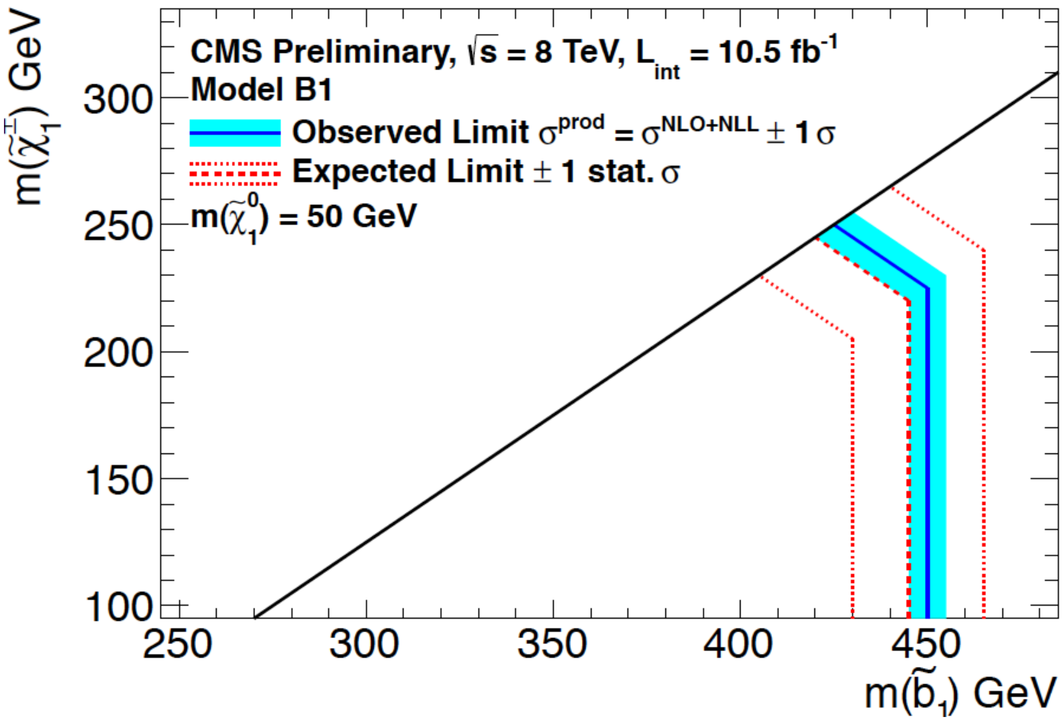
- Tau pair mass (l+h and ll decays)
- Two categories: non-b-tagged and b-tagged (to enhance bbΦ)

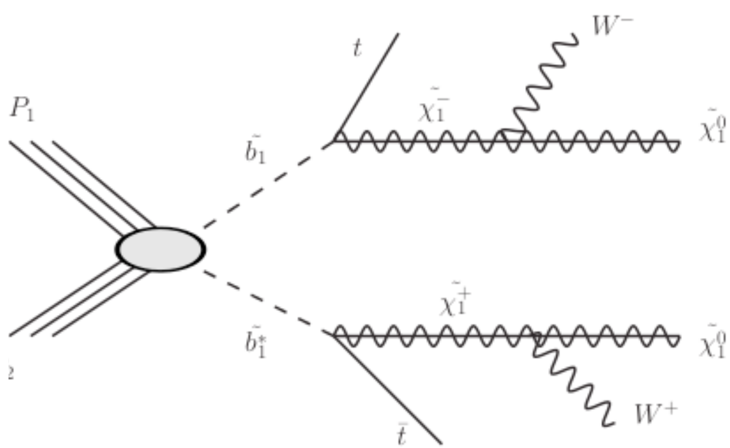




Sbottom pair production

Same-sign dileptons and b jets





SUS-12-029

- Dilepton analyses split into off and on Z resonance:
  - Different backgrounds and different model sensitivity

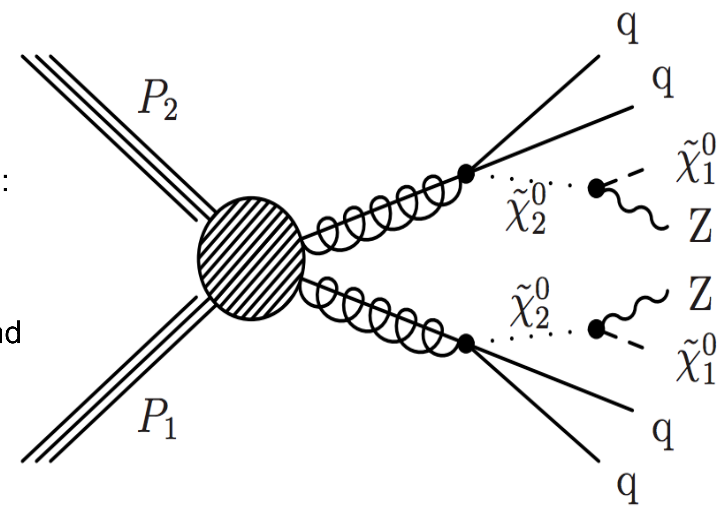
Complementary search methods based on orthogonal data control samples:

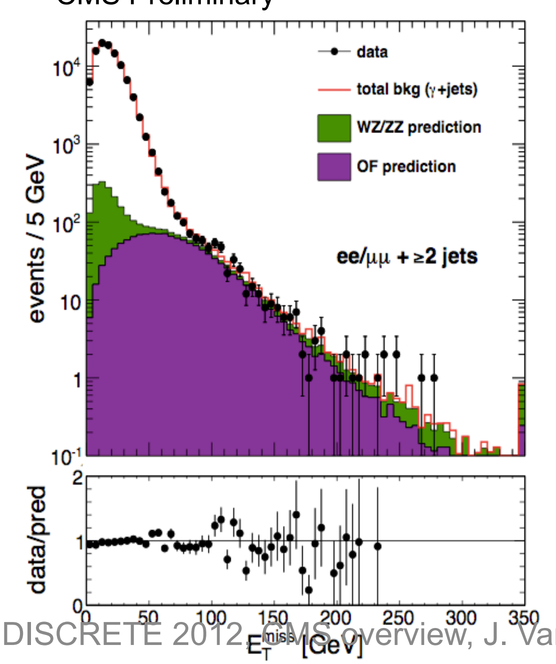
MET and; Jet-Z-Balance $= \left|\sum_{\text{jets}} \vec{p}_T\right| - \left|\vec{p}_T^{\,(Z)}\right| = \left|-\vec{E}_T^{\text{miss}} - \vec{p}_T^{\,(Z)}\right| - \left|\vec{p}_T^{\,(Z)}\right|$

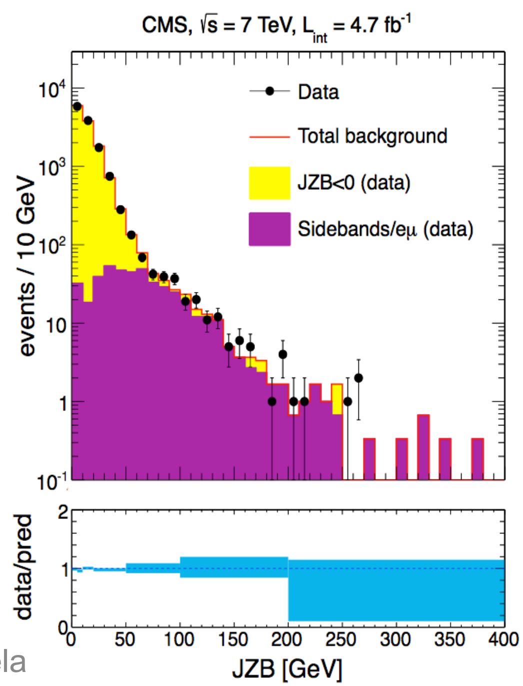
tt background predicted from shapes in eμ events and M(ee)/M(μμ) sideband data

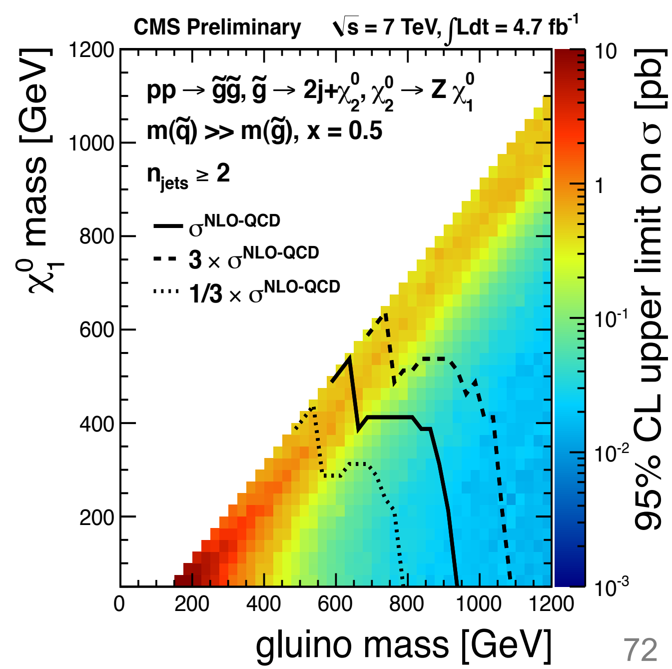
Z+artificial MET predicted from data-derived MET resolution templates.

Z+artificial JZB predicted from symmetry in negative→positive tails of JZB.



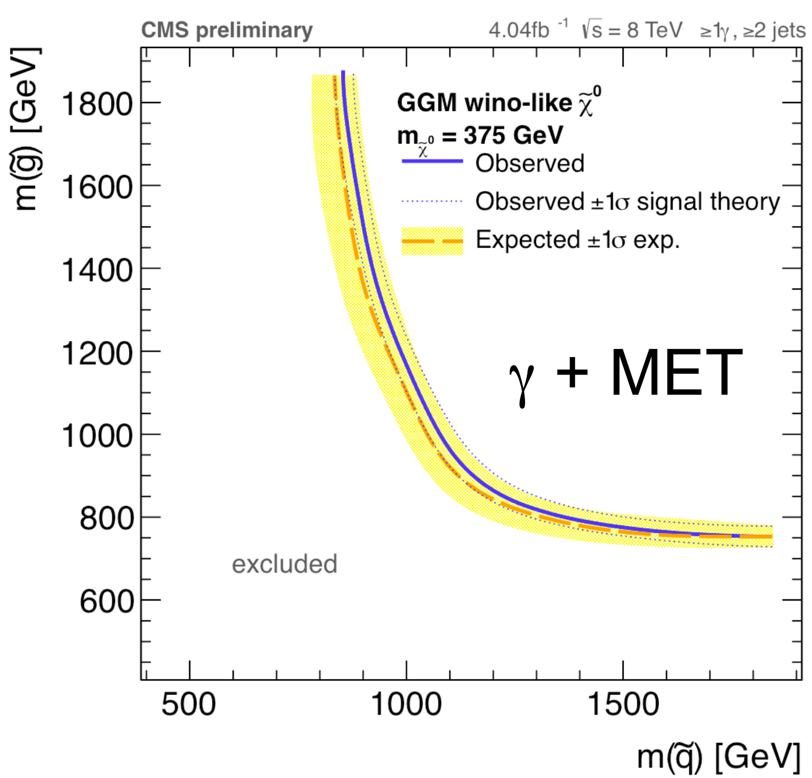


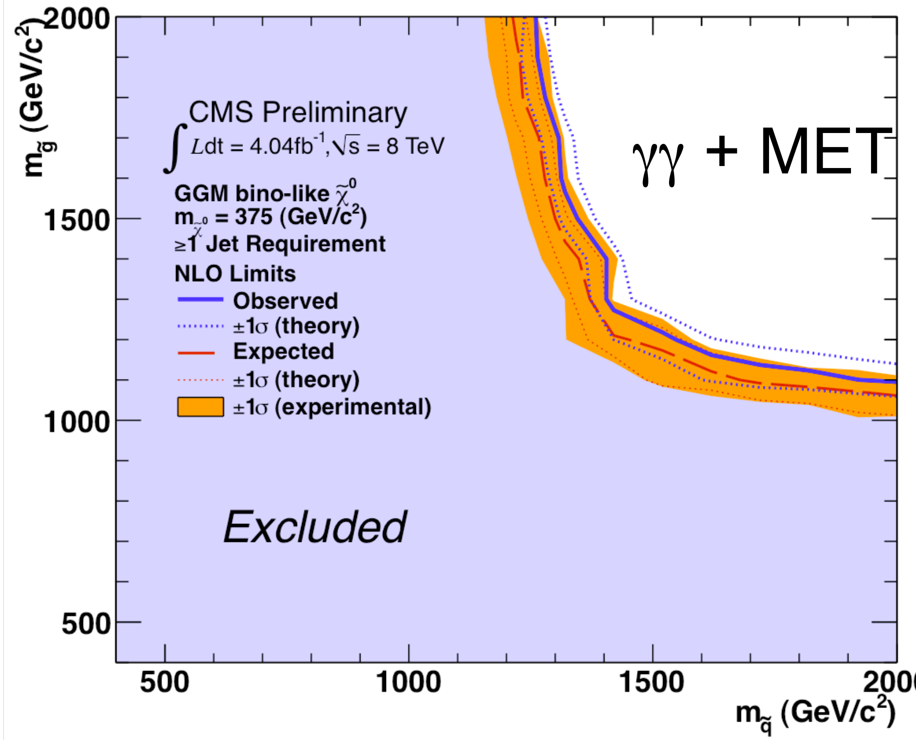




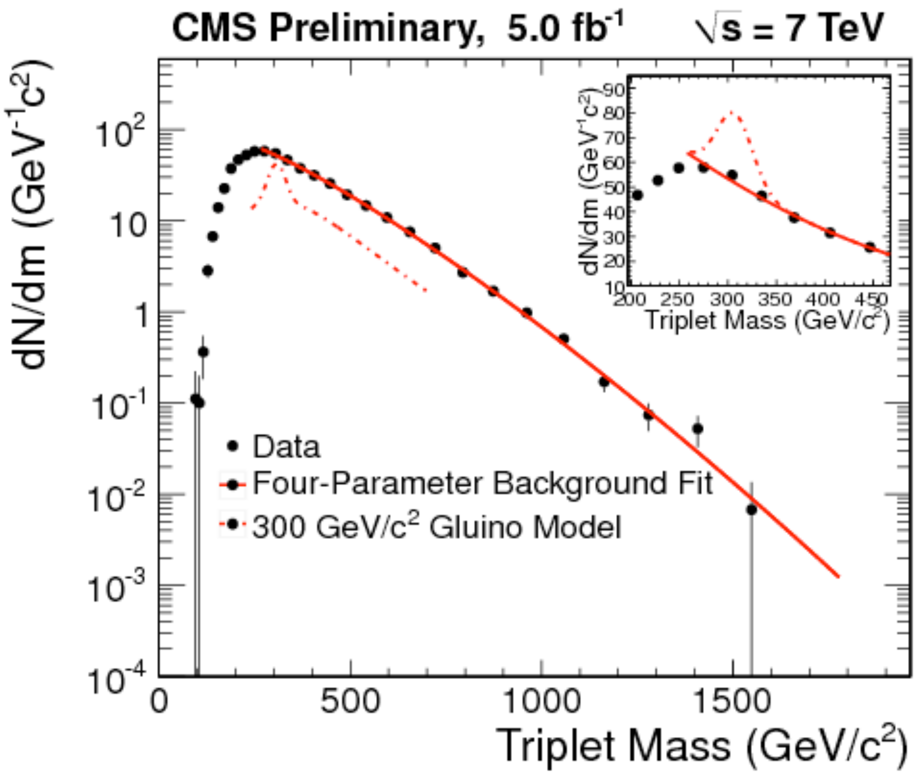
Depending on the nature of χ^0, single or double photon final states can dominate

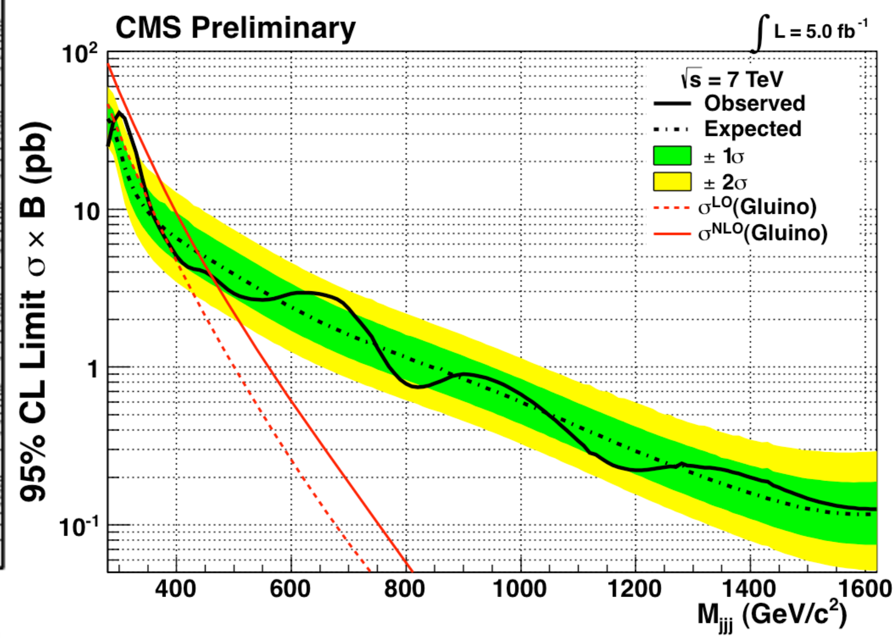
Early 8 TeV results





An RPV example: gluino→3 quarks





Exclude gluino masses below 460 GeV (assuming 100% BR into three jets)

W' → lν in 8 TeV Data

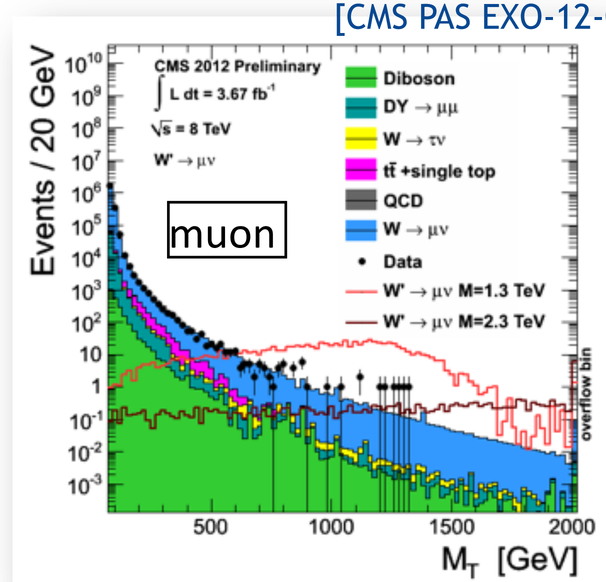
[CMS PAS EXO-12-010]

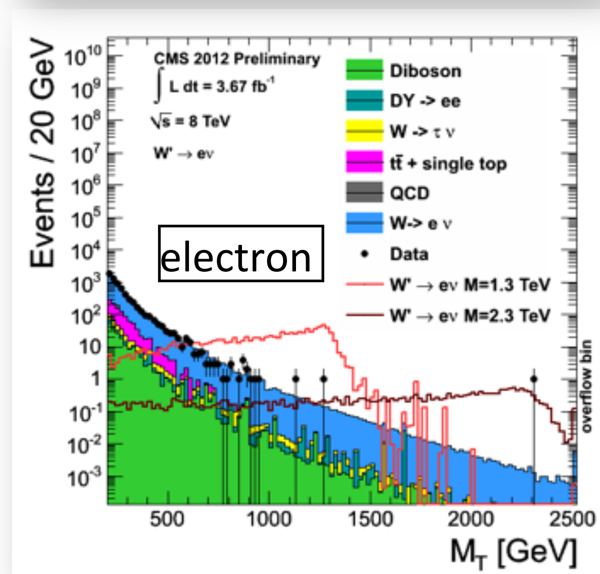
- Search for a new heavy gauge boson W' decaying to a charged lepton (μ or e) and ν

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

- Many models possible
  - right-handed W' bosons with standard-model couplings
  - left-handed W' bosons including interference
  - Kaluza-Klein W'_{KK}-states in split-UED
  - Excited chiral boson (W*)

$M(W'_{SSM})$ 95% CL	Luminosity	Expected	Observed
ATLAS e+μ, 2011	4.7	> 2.55 TeV	> 2.55 TeV
CMS e+μ, 2012	3.7	> 2.80 TeV	> 2.85 TeV
CMS e+μ, 2011+2012	5.0 + 3.7	> 2.85 TeV	> 2.85 TeV

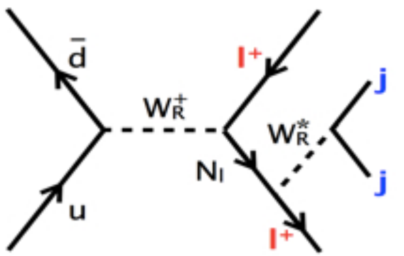




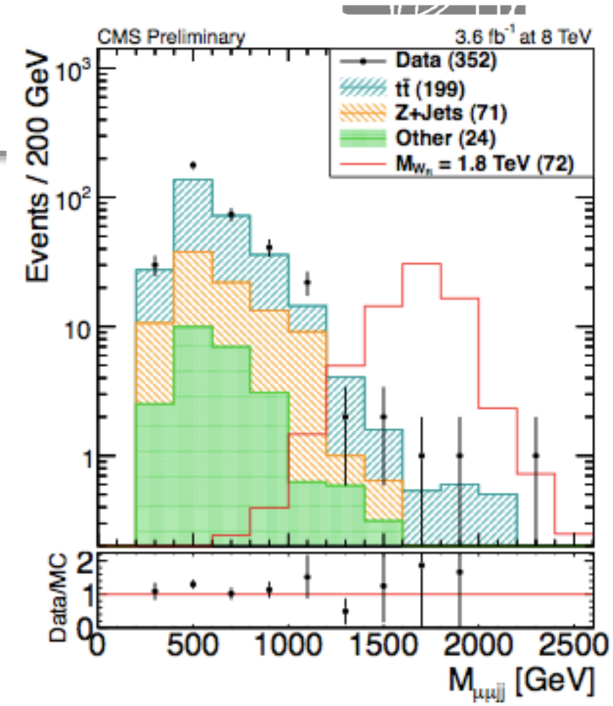
Heavy Neutrino in 8 TeV

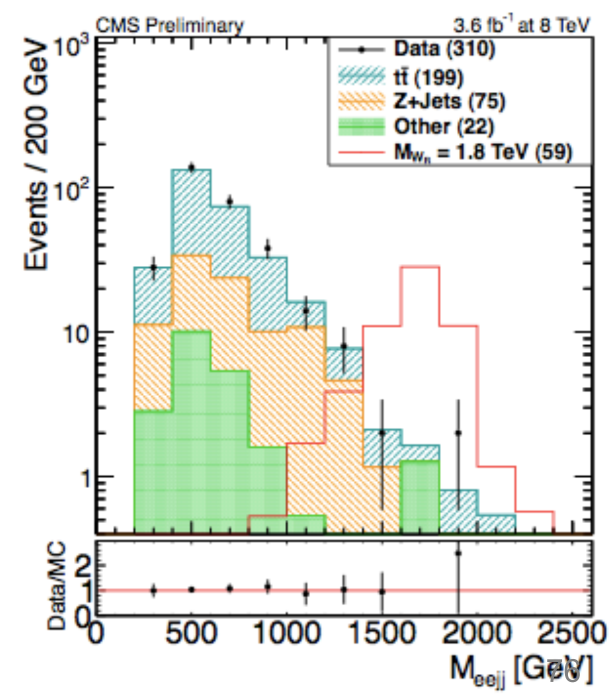
[CMS PAS EXO-12-017]

- We search for the decay of $W_R \rightarrow$ μμjj and eejj, as in a Left-Right Symmetric Model



- Selection
  - Lepton p_T >60/40 GeV, motivated by W decay
  - Jet p_T > 40 GeV
  - M(ll) > 200 GeV to reduce DY+jets.
- Background
  - Top: data-driven from eμjj
  - DY+jets: normalised to data, MC shape in Z peak
  - QCD: data-driven fake rate
  - VV, Single top: from MC



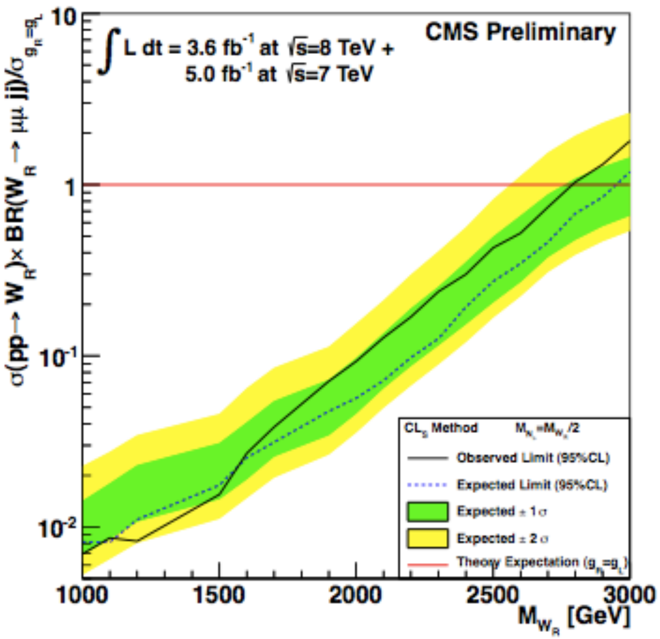


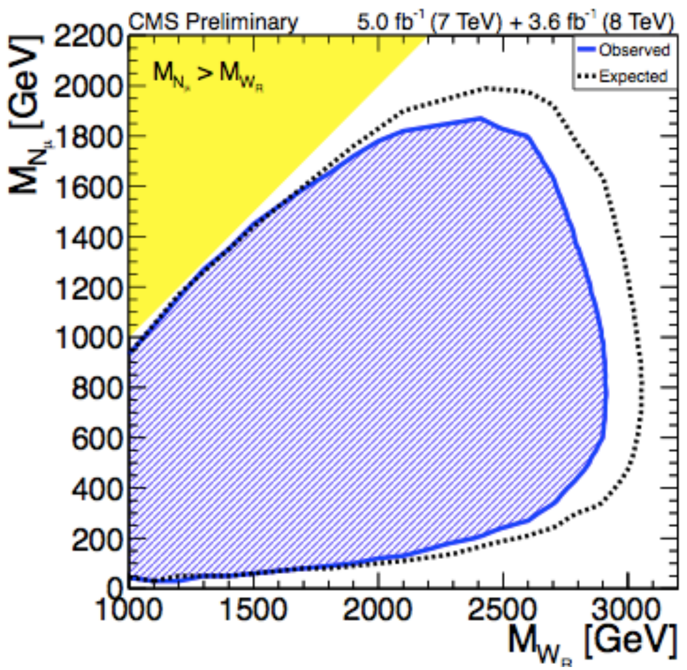
Heavy Neutrino in 8 TeV Data

- Search assumes small W_R–W_L and N_l–$N_{l'}$ mixing angles, only one lepton channel kinematically accessible
- Primary Systematic Uncertainties
  - Signal Eff.: 6-10% from lepton
  - Background: ~50% from DY+jets shape, ~16% from top shape

For M(N)=M(W_R)/2; M(W_R) > 2.8 TeV

[CMS PAS EXO-12-017]





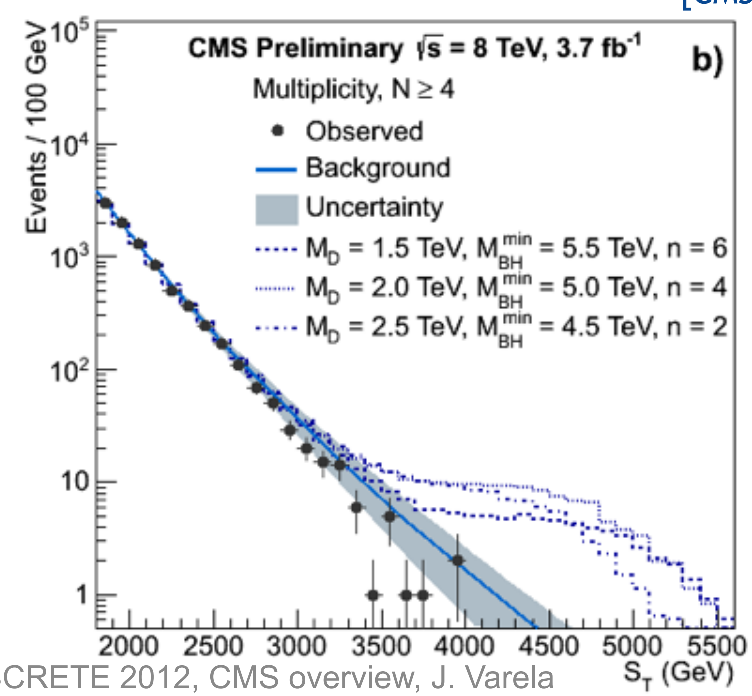
Black Holes in 8 TeV Data

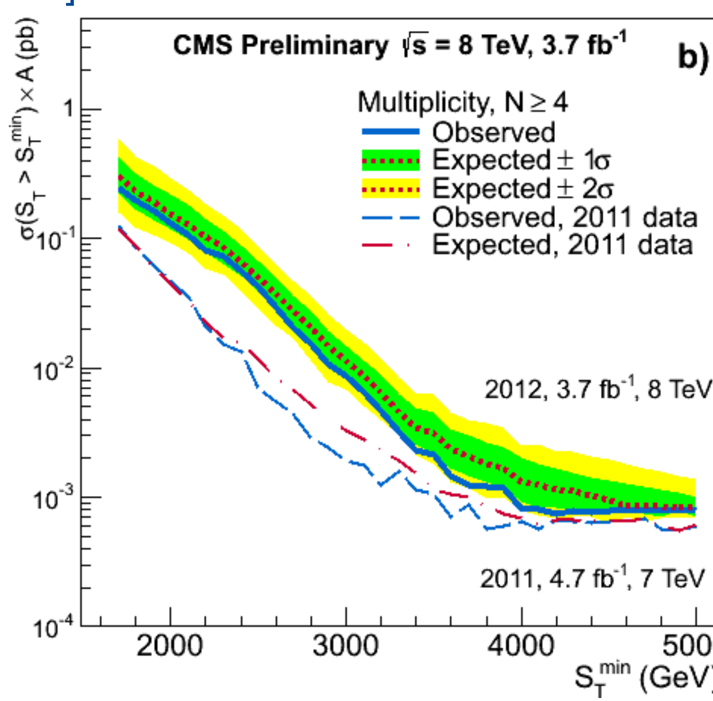
- Hypothetical BH would evaporate into many high-p_T objects
  - Estimate by S_T, the p_T sum of physics objects with p_T > 50 GeV
- Main background of QCD estimated by fit to n=2 distribution
  - Normalised for each multiplicity bin separately at S_T = 1.8–2.2 TeV
  - Model-independent limits vs S_T and multiplicity

$$S_T = \sum_{j,e,\mu,\gamma,MET}^{N} p_T$$

Large improvement in sensitivity (~10-20%) with respect to 2011 analysis

[CMS PAS EXO-12-009]



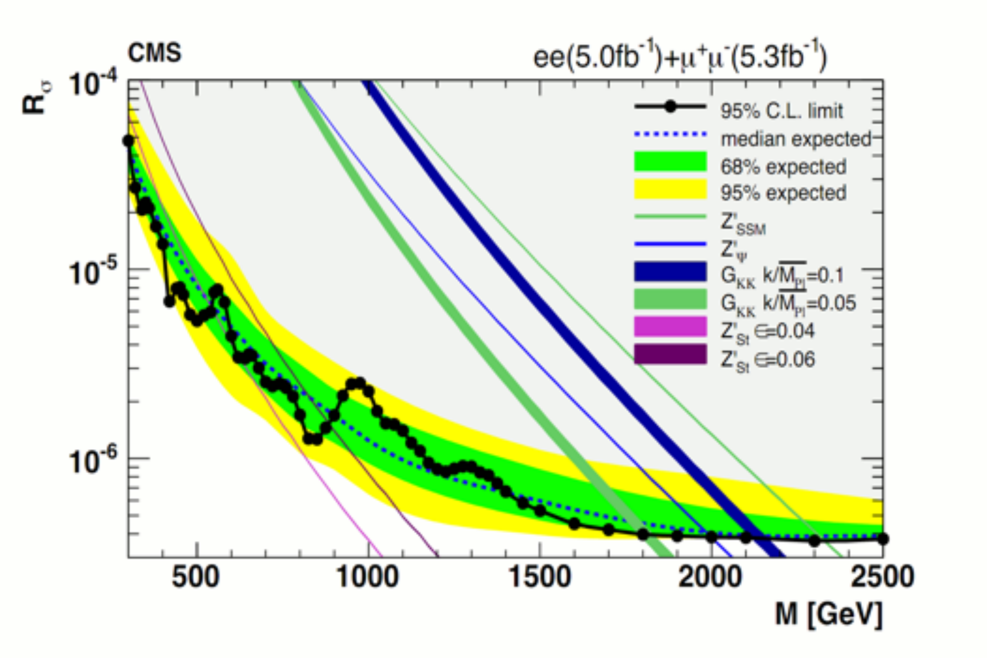


Z' in 2011 Data?

- Search for Z-like narrow resonances decaying to dileptons
- Interesting features in dilepton spectra
  - around 2σ each for CMS & ATLAS in e+μ
  - similar in scale to 2011 Higgs excess

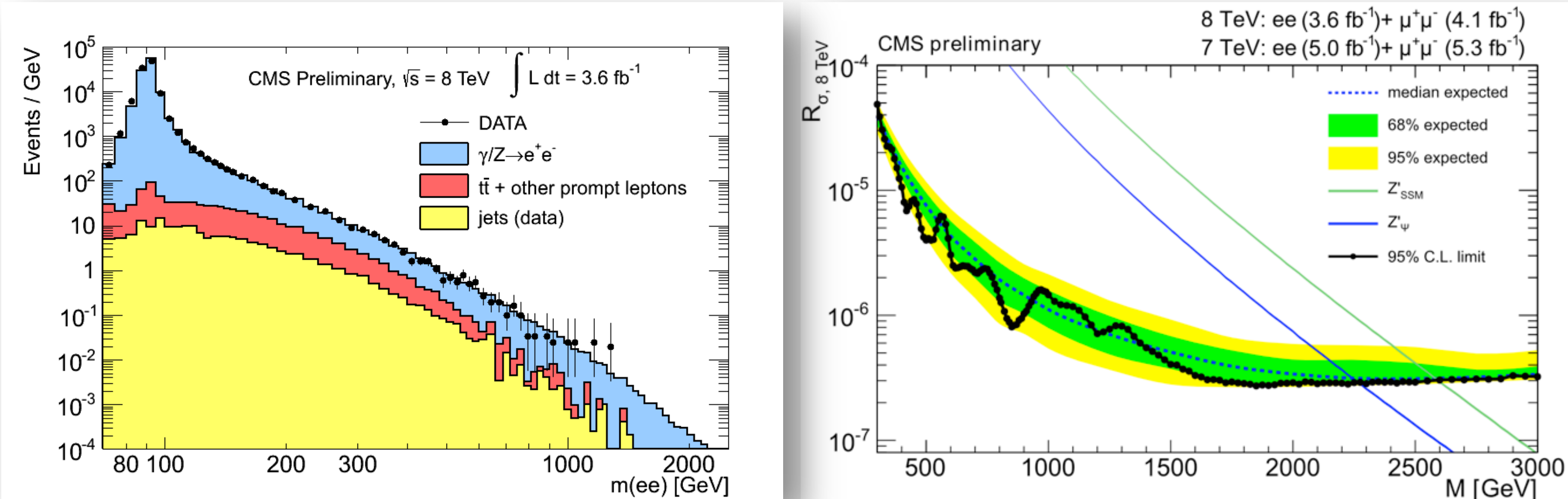
[hep-ex 1206.1849]

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



Today: Z' in 8 TeV Data

CMS EXO-12-015



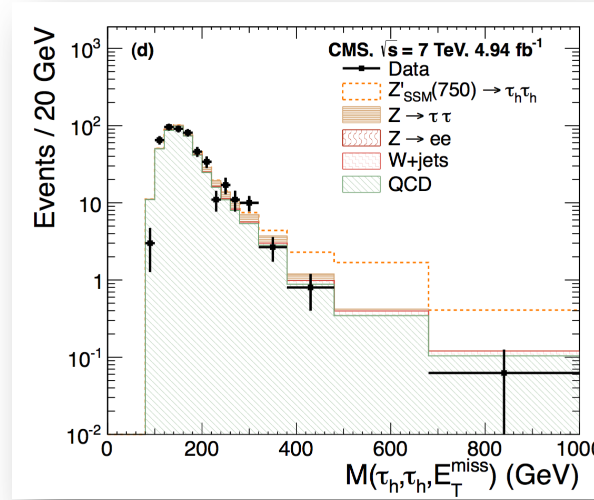
Limits on the combined 7 TeV and 8 TeV data from 2011+2012

- $M(Z'_{SSM}) > 2590$ GeV at 95% C.L.
- $M(Z'_{\psi}) > 2260$ GeV at 95% C.L.

Excess just below 1 TeV all but gone in CMS data

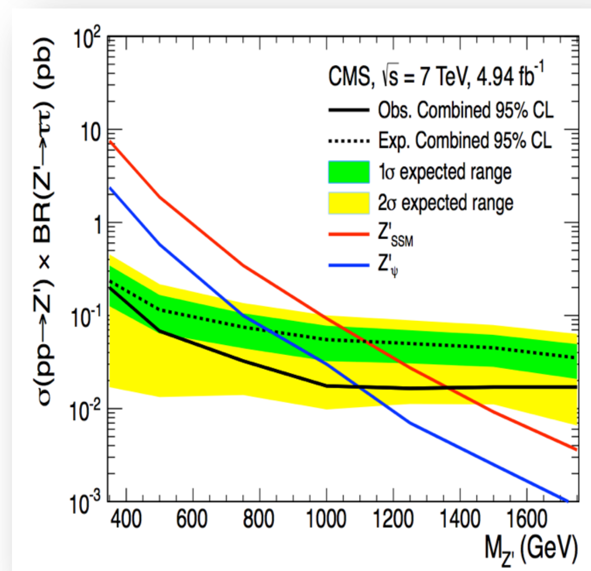
Z' → τ τ (7 TeV data)

[CMS EXO-11-031, hep-ex 1206.1725]



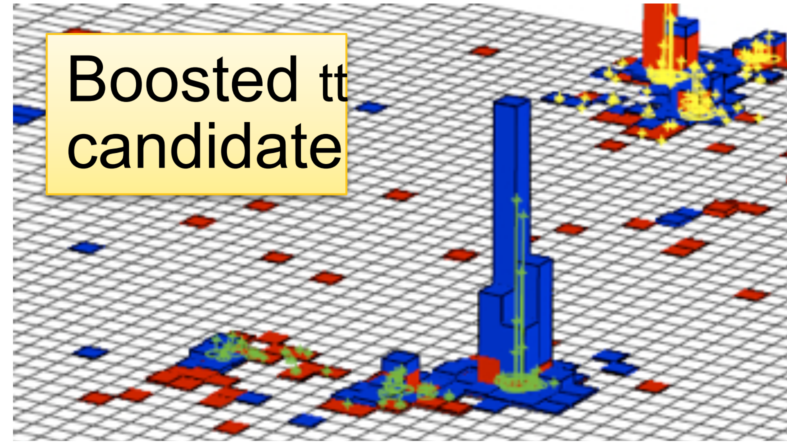
- Z' might couple preferentially to third-generation fermions
  - 5 fb-1 at √s = 7 TeV
  - Study: $\tau_e\tau_\mu$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$
  - plot effective (visible) mass
- Backgrounds:
  - DY Z → ττ, W+jets, tt, VV, QCD
  - estimated from data where possible

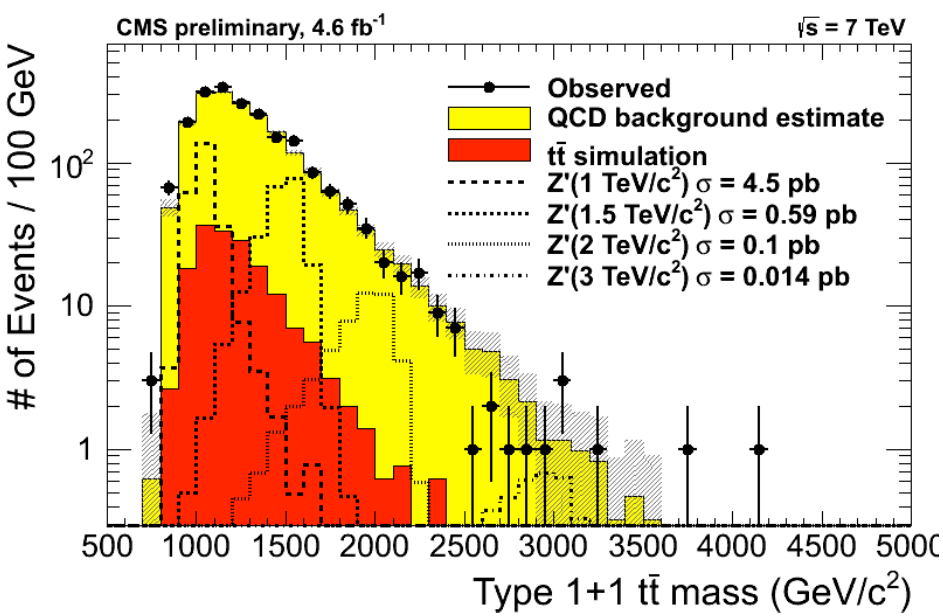
$M(Z'_{SSM})$	expected	observed
CMS	> 1.1 TeV	> 1.4 TeV
ATLAS	> 1.4 TeV	> 1.3 TeV

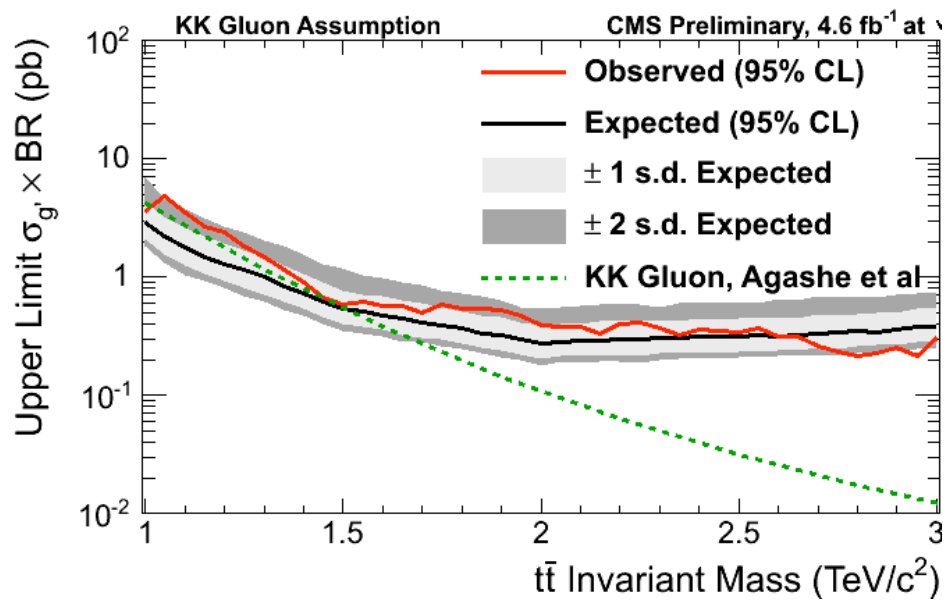


Boosted top pairs

- Boosted top events
  - Pioneered by CMS
  - Strong limits on Kaluza-Klein gluons and Z' -like objects decaying to top pairs



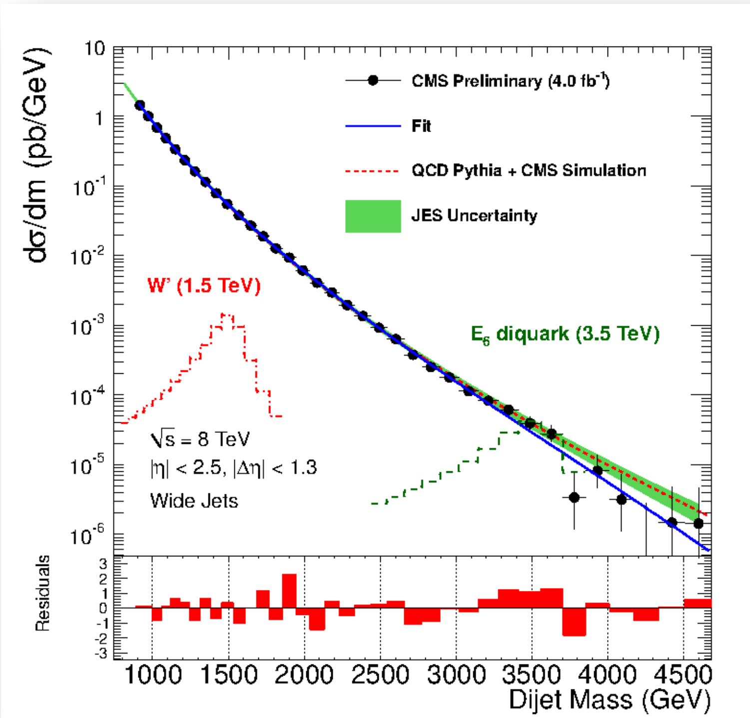


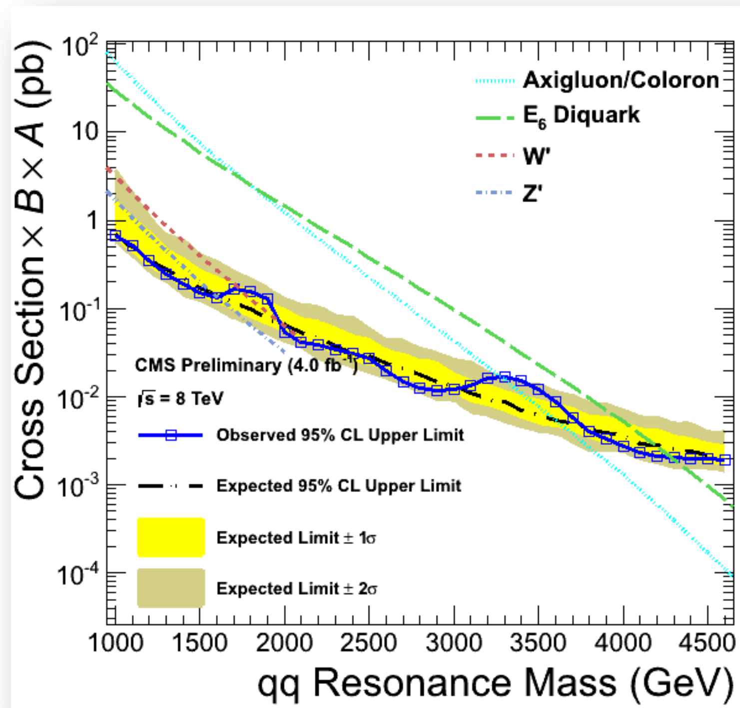


Dijets in 8 TeV Data

- Search for dijet resonance in smoothly falling mass spectrum
  – leading jet mass m_{jj} > 0.9-1 TeV from trigger and other constraints
  – Background estimated from smooth functional fit

[CMS PAS EXO-12-016]

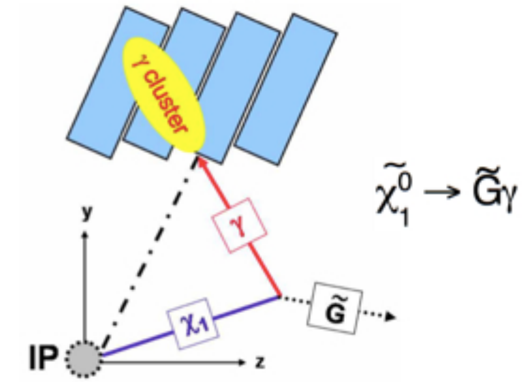




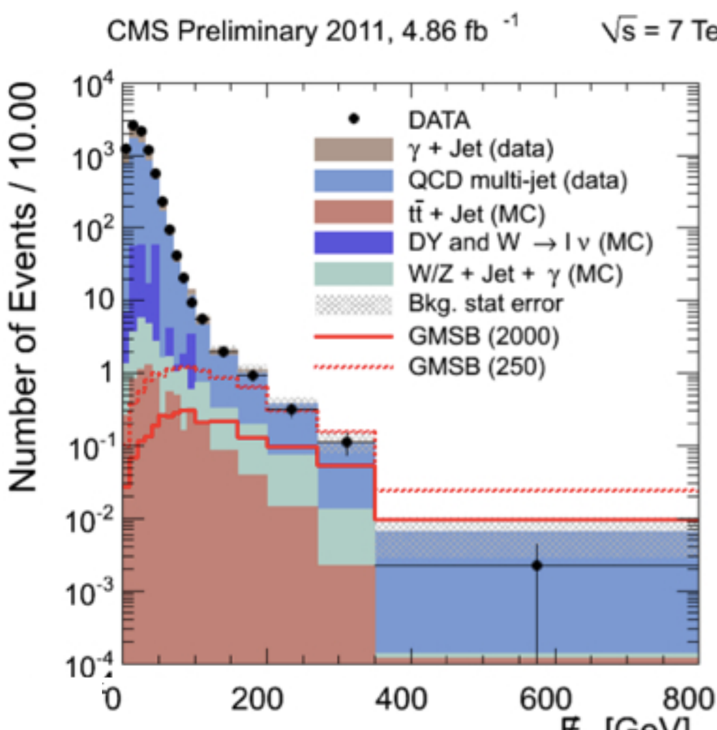
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

GMSB with Displaced Photon

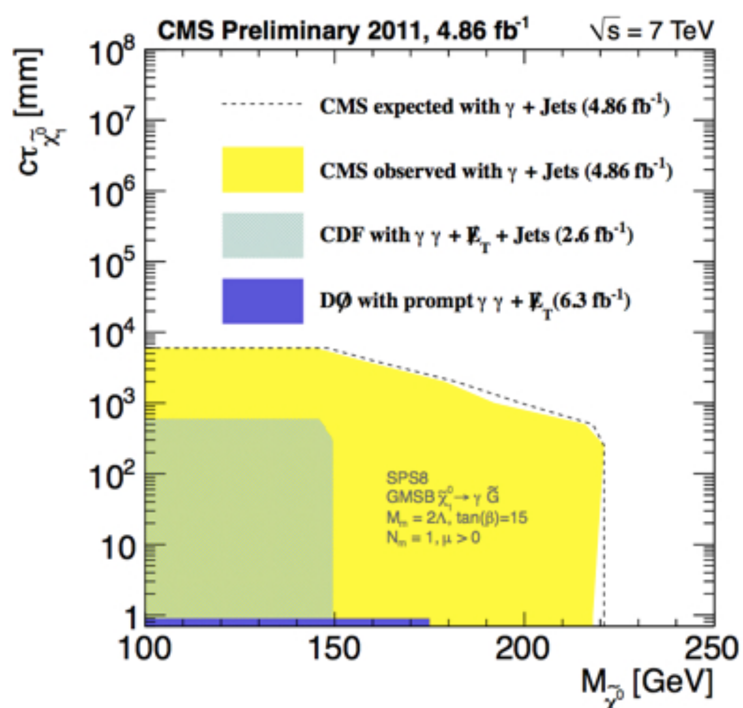
- GMSB (SUSY) decays typically include many jets
- Selection: photon with E_T > 100, three jets with p_T > 35
  - relaxed ECAL timing and shower-shape cuts
  - E_T^{miss} and ECAL timing main discriminants



Much-improved sensitivity to long-lived neutralino

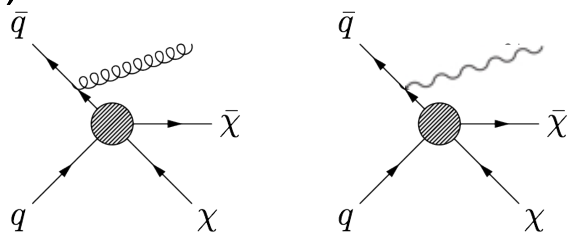


[CMS PAS EXO-11-035]



Monojet and Monophoton

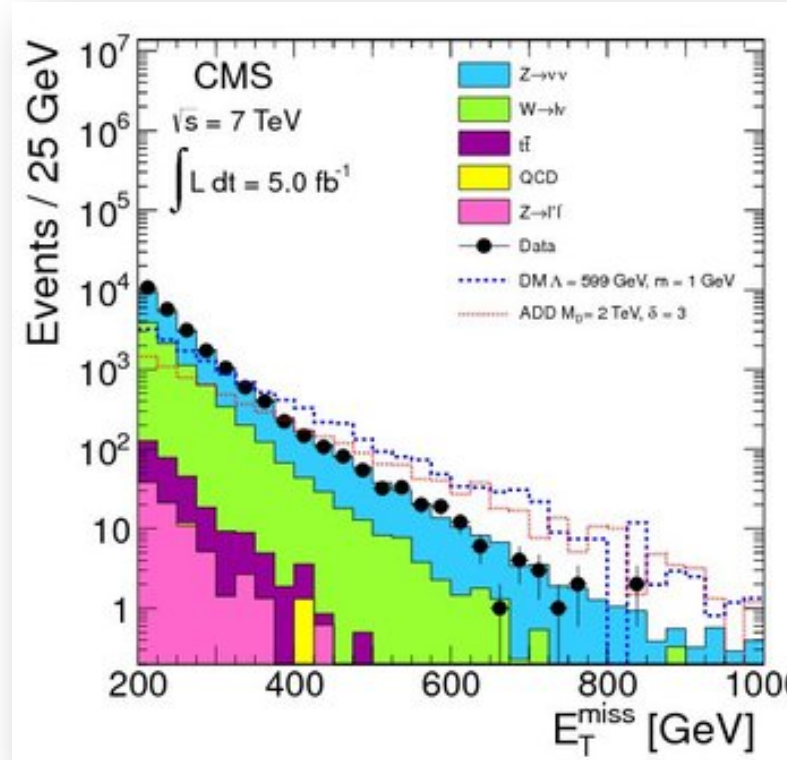
- Look for missing energy and radiated jet (photon)



- Monojet Selection:
  - Leading jet pT > 120 GeV, |η| < 2
  - allow a second jet if not back-to-back
  - veto isolated leptons

- Backgrounds and Uncertainties
  - Z + (jets/γ) --> νν+(jets/γ)
  - W + (jets/γ) --> lν+(jets/γ)
  - smaller backgrounds from top, QCD, non-collision

- Missing Energy (ETmiss) to distinguish signal



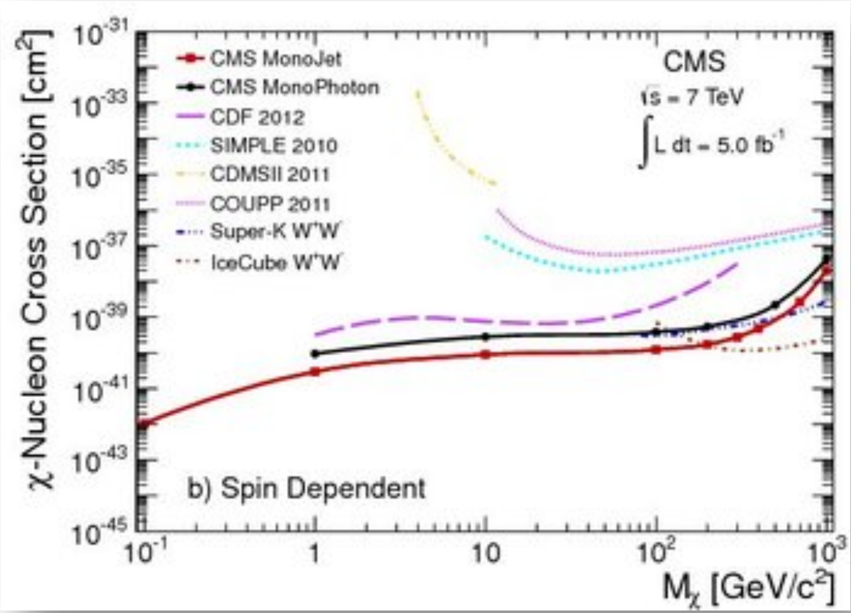
Spin-dependent couplings

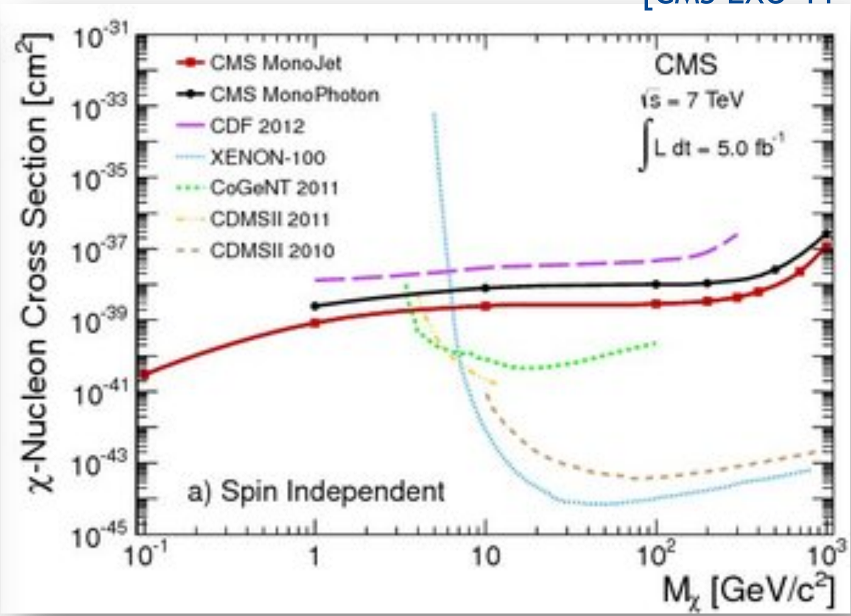
– Limits extend well below Direct DM (DD) searches

Spin-independent couplings

– competitive at low masses where nuclear recoil imposes a threshold for detection in DD case

[CMS EXO-11-059]





Parton Luminosities