Recent Results from CMS

Suvadeep Bose

University of Nebraska Lincoln

(On behalf of CMS collaboration)

Brookhaven Forum
BNL

May 1 , 2013

Outline

Heavy Flavors

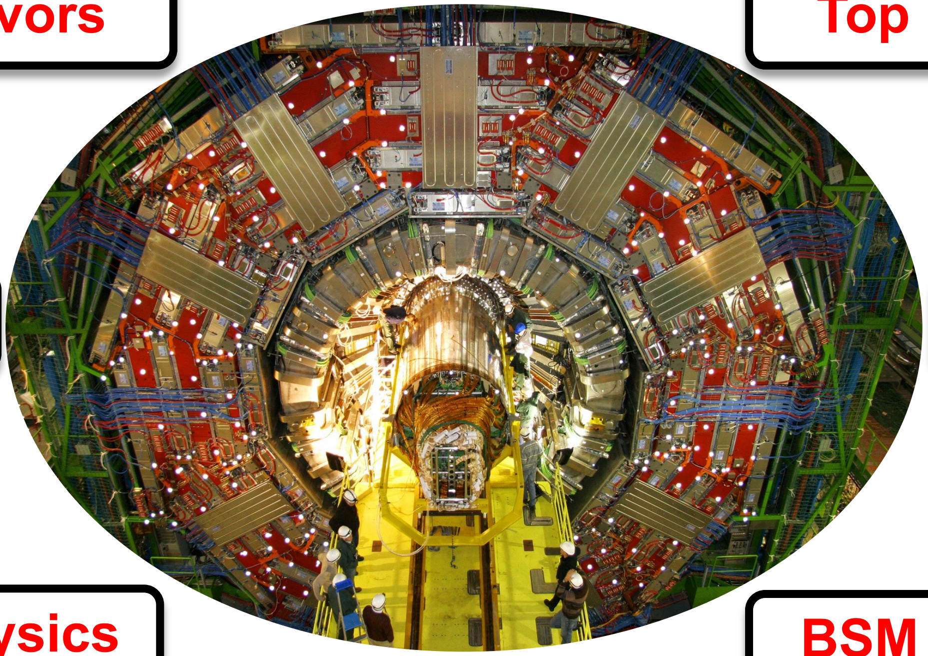
Top Physics

Probing QCD

Higgs Searches

EWK Physics

BSM Physics



What to expect:
- a selection only, with focus on most recent results
- will focus on pp physics only
- see all the specialized talks at this conference for much more details by Yuriy Pakhotin, Norbert Neumeister, Rocio Vilar Cortabitarte

CMS: the detector

Total weight 14000 t
Diameter 15 m
Length 28.7 m

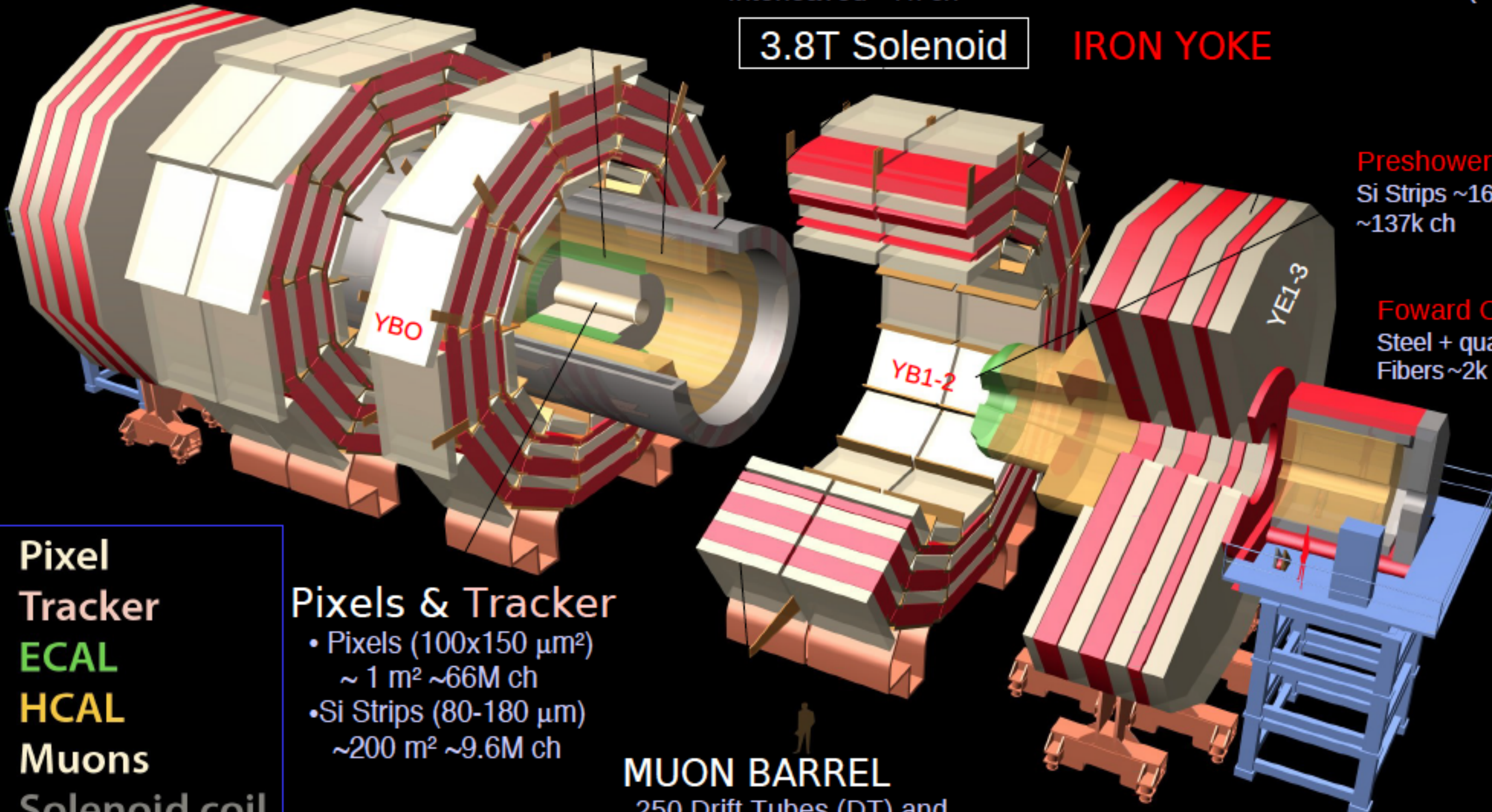
ECAL 76k scintillating $PbWO_4$ crystals

HCAL Scintillator/brass Interleaved ~7k ch

MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)

3.8T Solenoid

IRON YOKE



Preshower
Si Strips ~16 m²
~137k ch

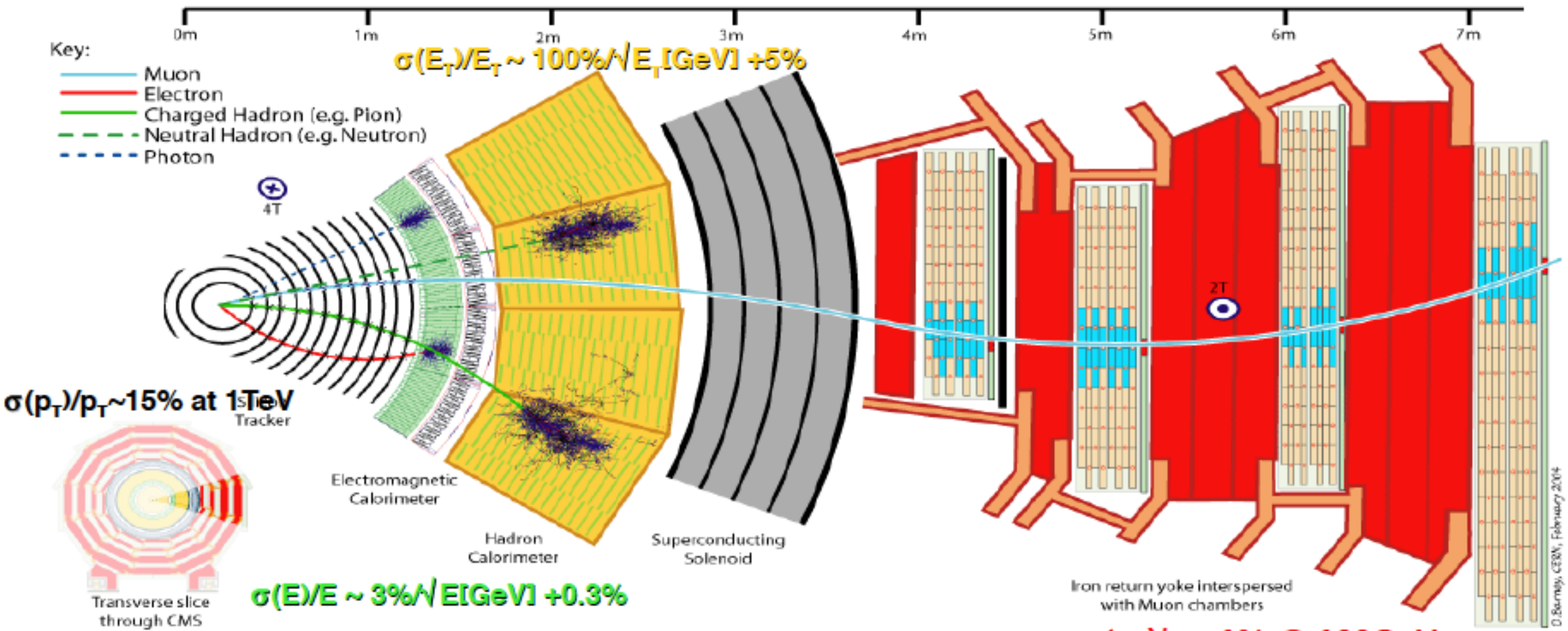
Foward Cal
Steel + quartz
Fibers ~2k ch

Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

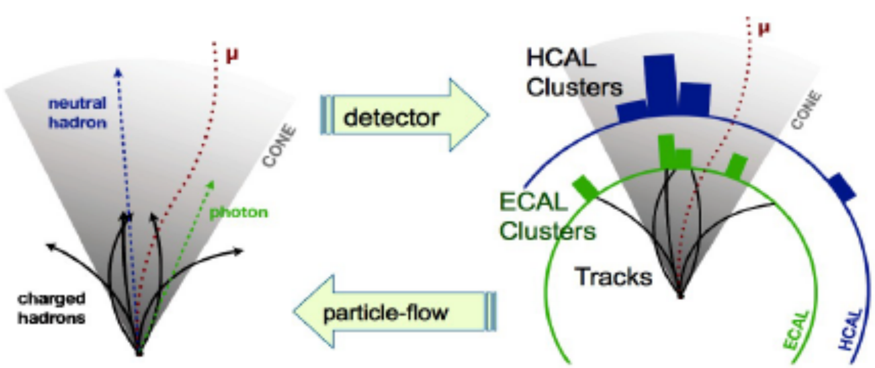
Pixels & Tracker
- Pixels (100x150 μm²) ~ 1 m² ~66M ch
- Si Strips (80-180 μm) ~200 m² ~9.6M ch

MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

CMS: The Physics Objects

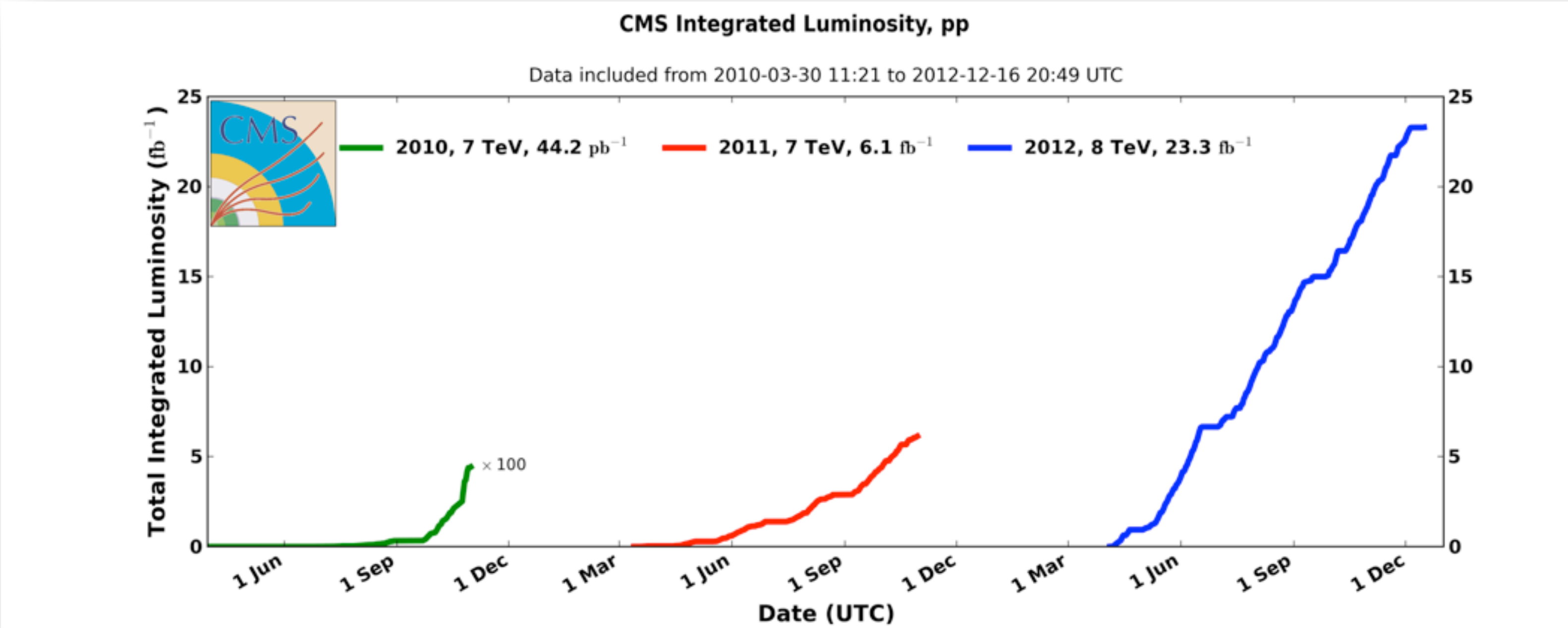


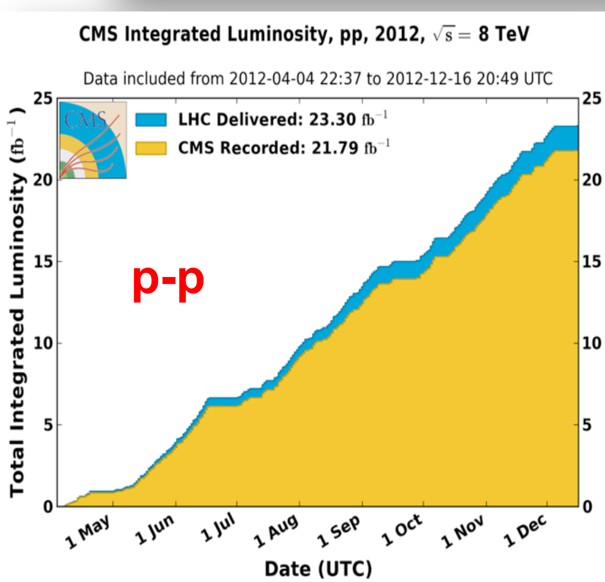
$\sigma(p_T)/p_T < 1\%$ @ 100GeV
$\sigma(p_T)/p_T < 10\%$ @1 TeV

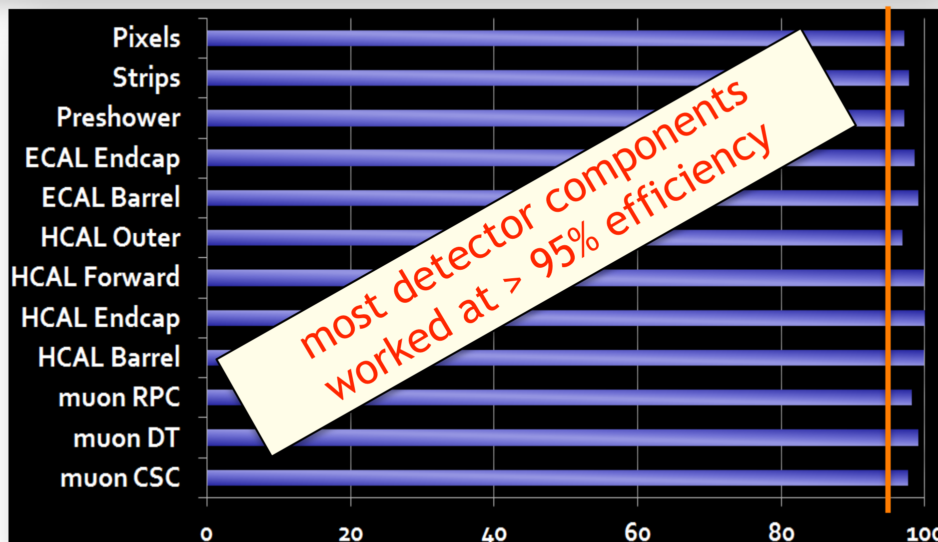


Particle-Flow (PF) algorithms use:
e, μ, γ, charged & neutral hadrons
as building blocks for
jets, b-jets, τ's, ν (miss E_T), isolation

Thanks LHC for Fantastic 3 years!



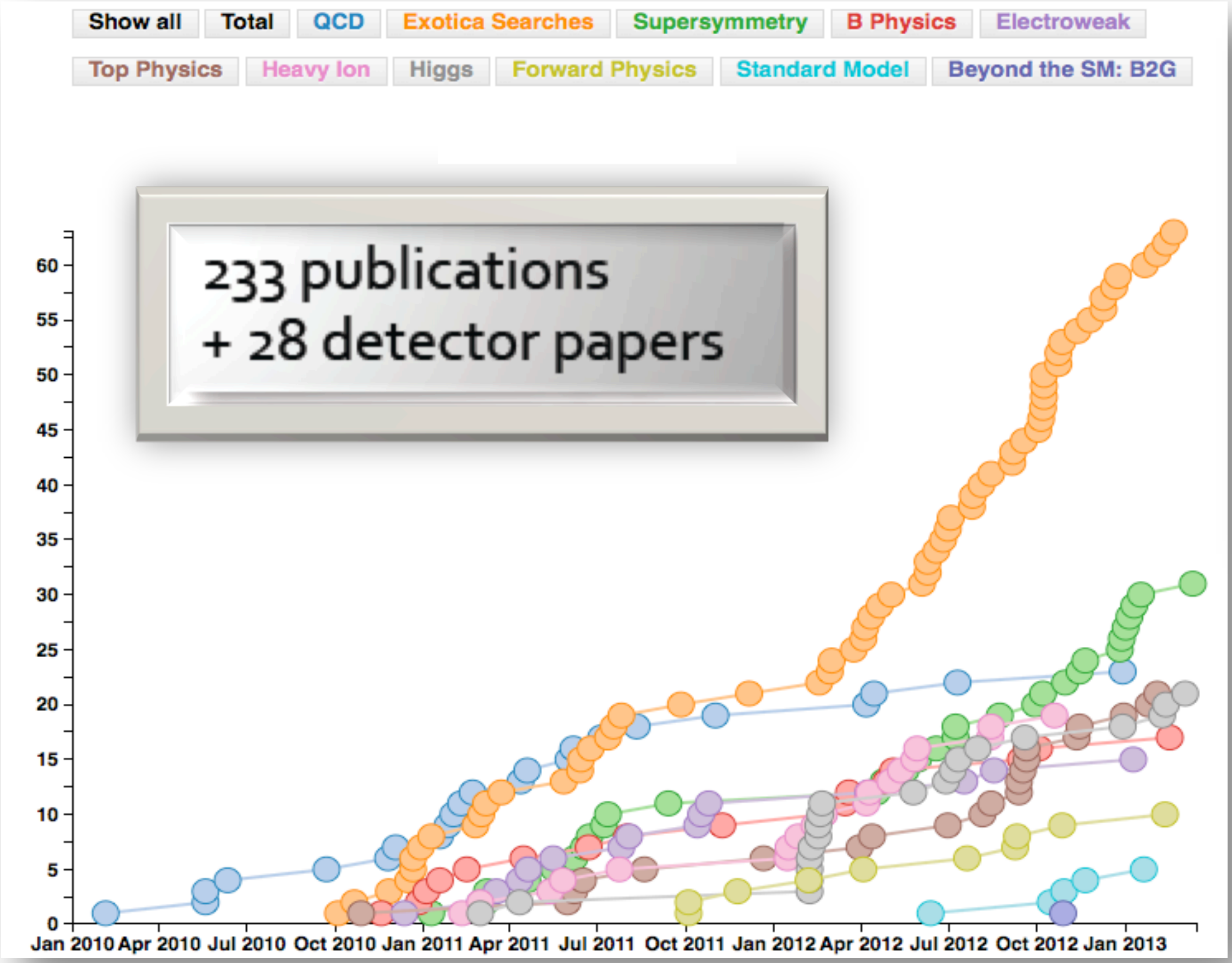


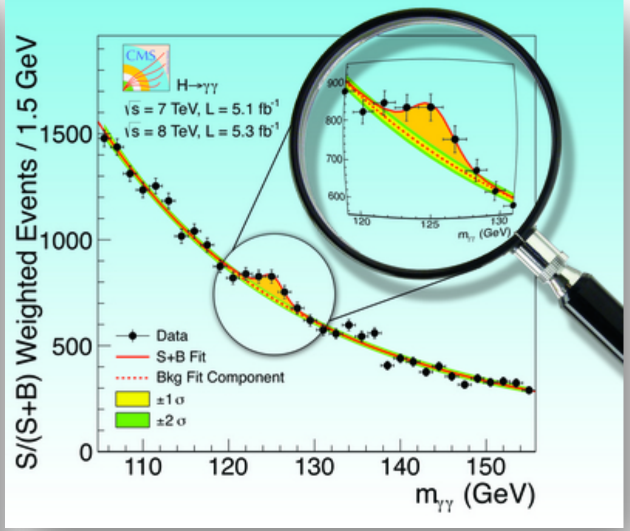


Prolific 3 years

- Public physics results are available at:

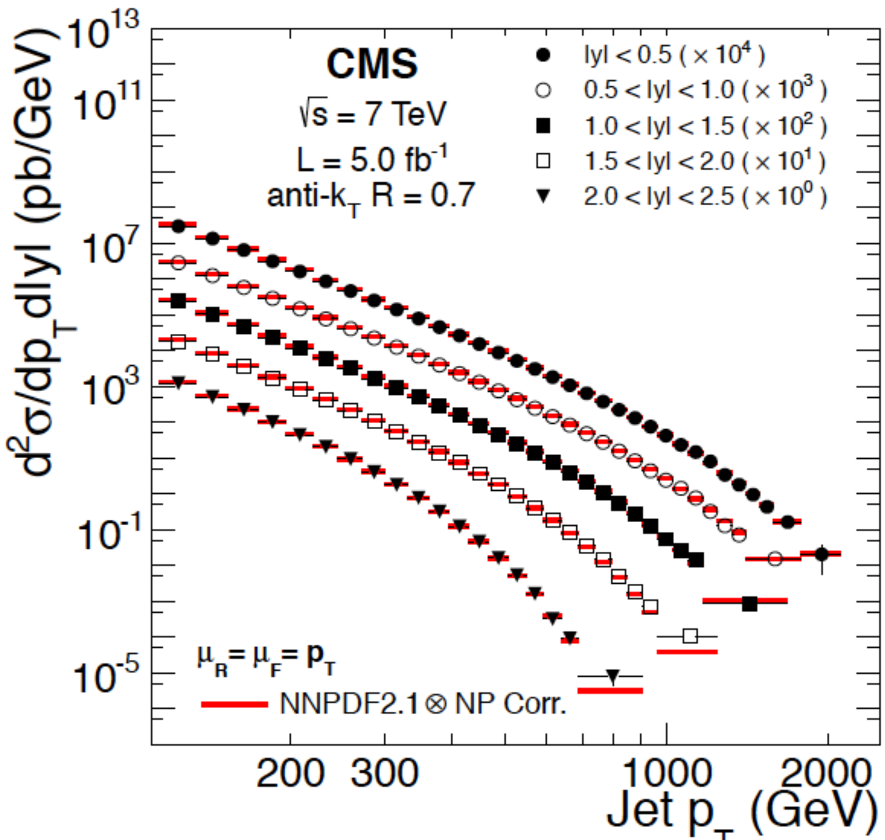
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

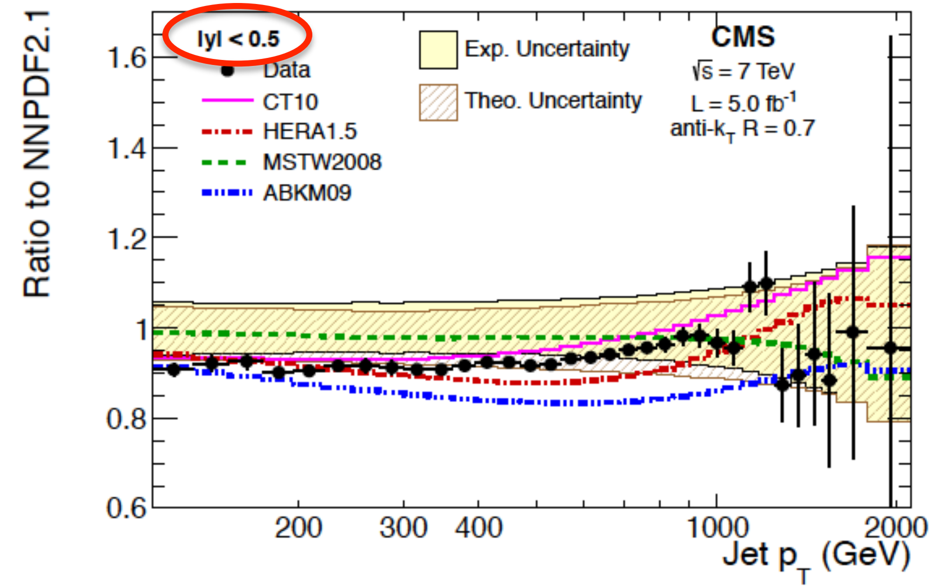


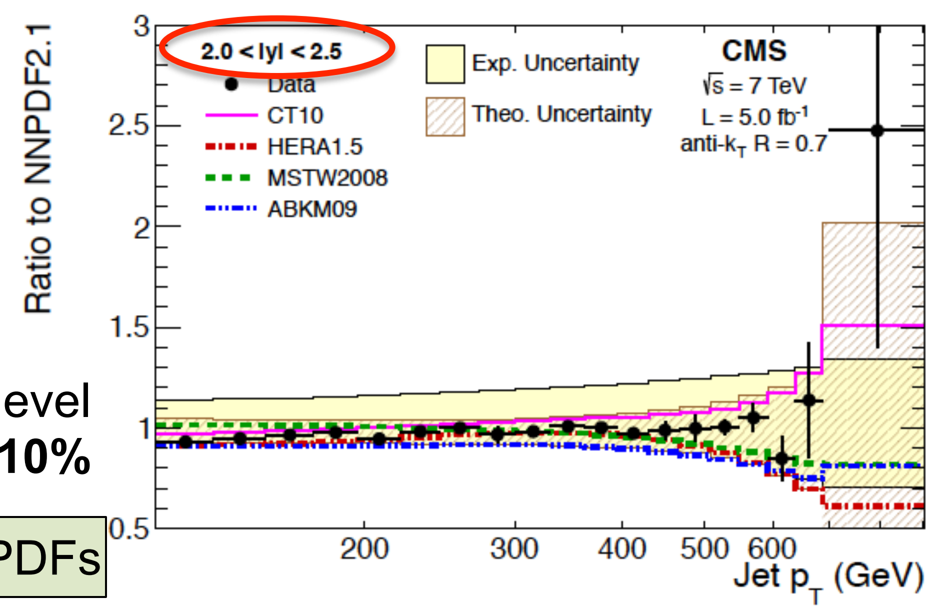


Probing QCD

Hard Jets: Inclusive Jet Production







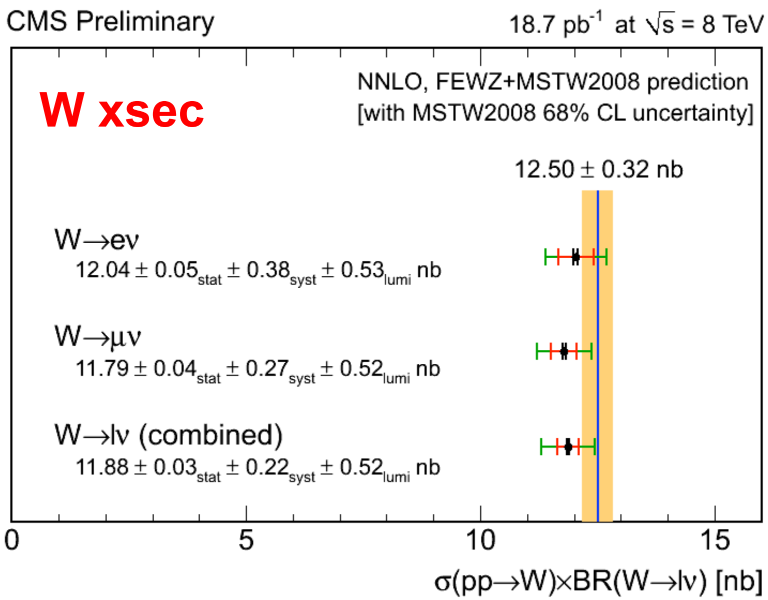
- NLO QCD describes data over ~ 9 orders of magnitude

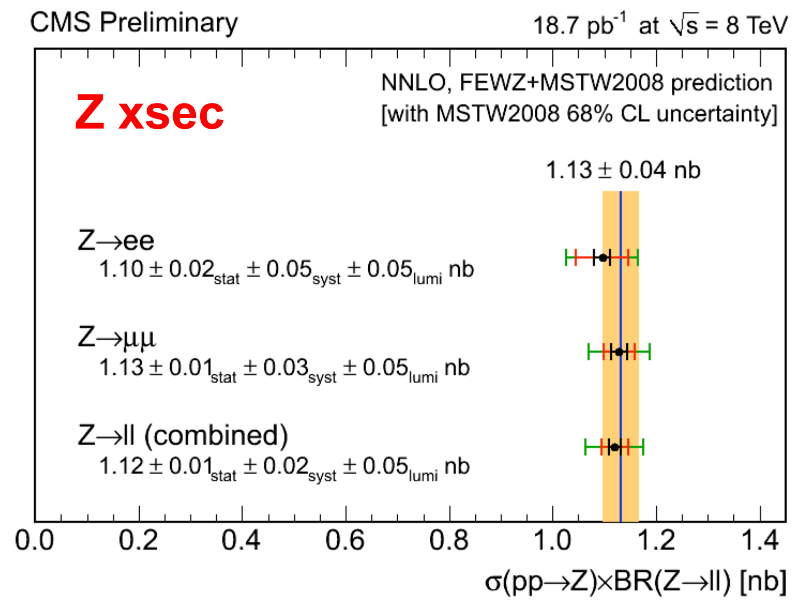
- Jet energy scale uncertainties at the **1-2%** level
- For central |y|: exp. / theo. uncertainties, **5-10%**

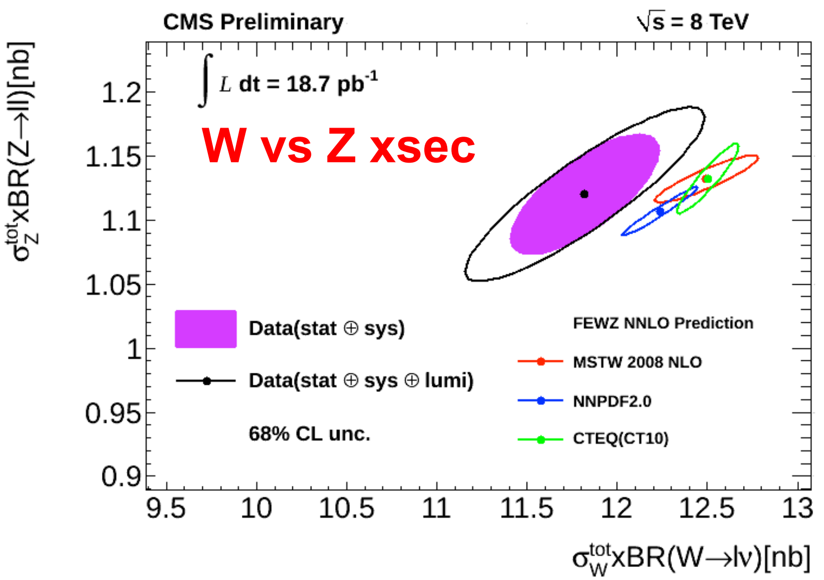
Inclusive jet: Important tool for constraining PDFs

EWK Physics

Inclusive W/Z Production at 8 TeV



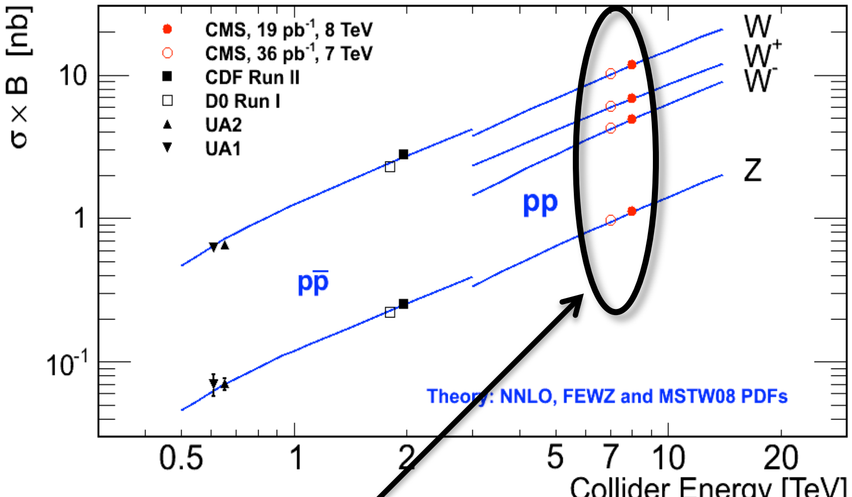




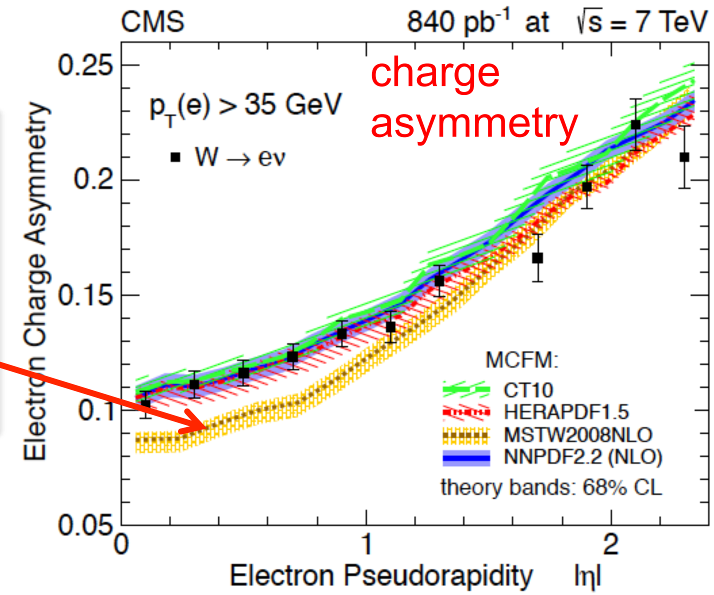
Inclusive cross sections:

- At 7 TeV: experimental precision had reached the 1% level, especially for ratio-observables
- New 8 TeV results from dedicated low-pile up run early in 2012
- Total uncertainty: 2-5 % (4.4 % lumi, 2-3% acceptance, 1.1-1.7% exp)

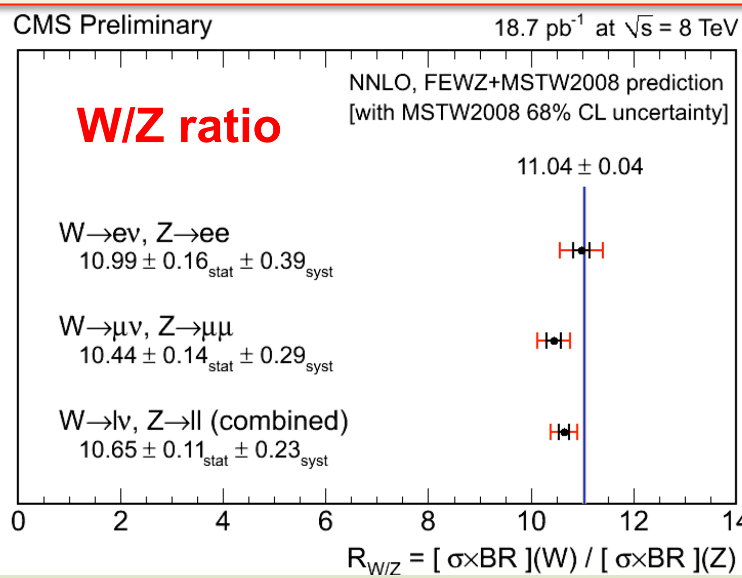
Improving the PDF Knowledge



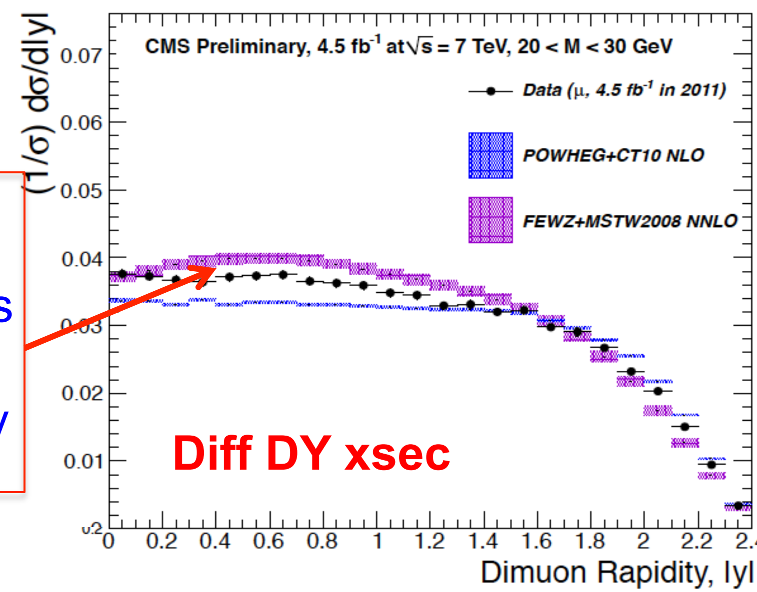
MSTW08 too low for the lepton asymmetry at 7 TeV



Good agreement with NNLO QCD, both @ 7, 8 TeV

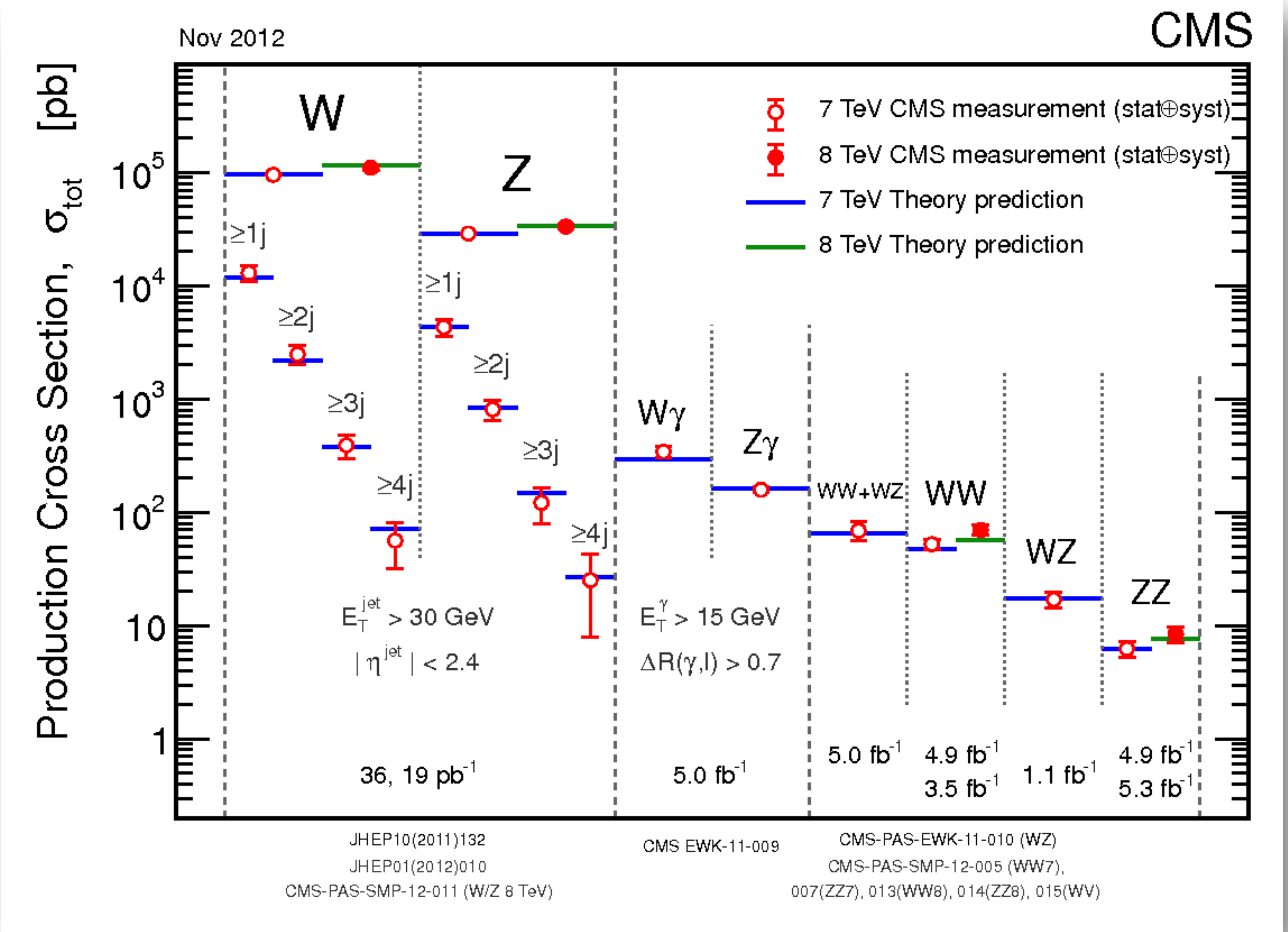


Low-mass Drell-Yan gives interesting PDF sensitivity



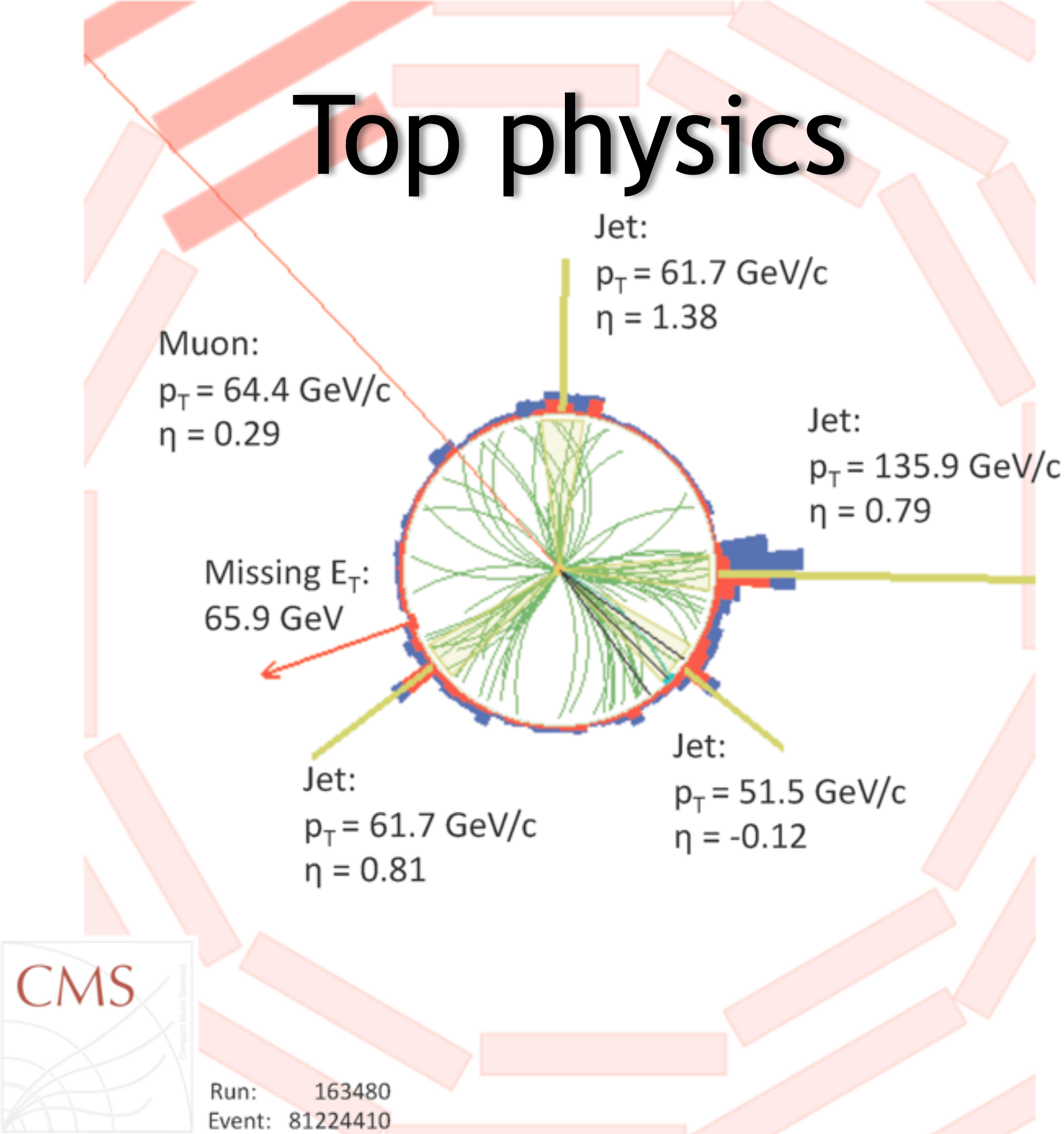
- W/Z ratio at 8 TeV: 1.5 σ difference with MSTW08

The Big Picture



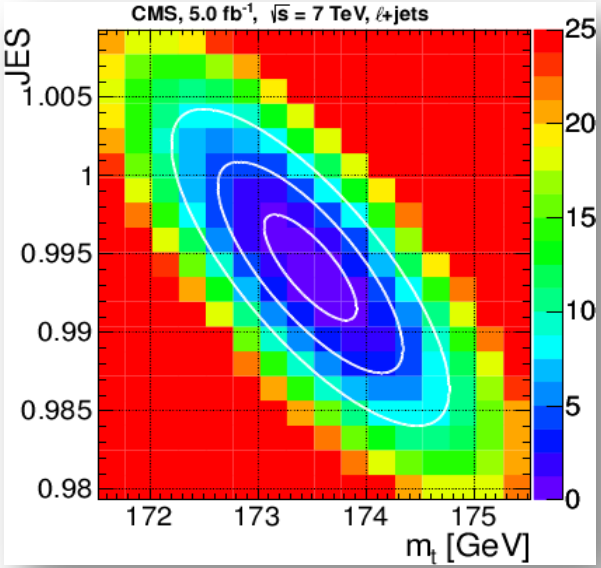
- Overall, the SM works at 7 and 8 TeV centre-of-mass energy

Top physics


Jet:
p_T = 61.7 GeV/c
η = 1.38
Muon:
p_T = 64.4 GeV/c
η = 0.29
Jet:
p_T = 135.9 GeV/c
η = 0.79
Missing E_T:
65.9 GeV
Jet:
p_T = 51.5 GeV/c
η = -0.12
Jet:
p_T = 61.7 GeV/c
η = 0.81
CMS
Run: 163480
Event: 81224410

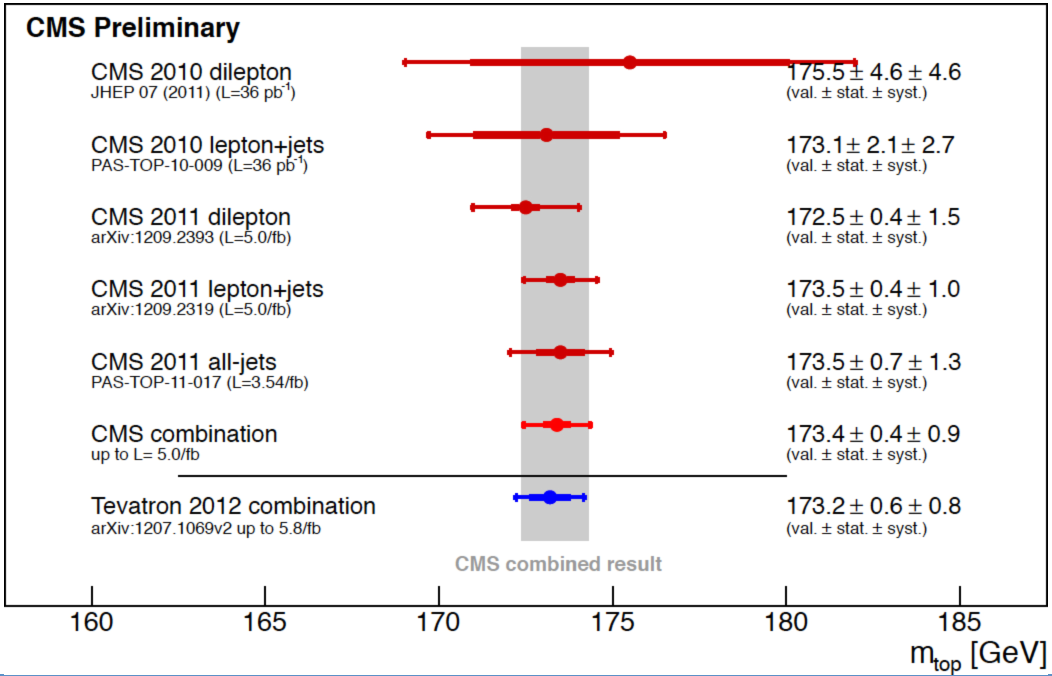
Top-quark Mass

7 TeV



- ❑ Ideogram Method (lepton+jets final state):
  - Reconstruct $m_{t\text{-fitted}}$ via a kinematic fit
  - Event by event likelihood for fit results to be consistent with a given m_t
  - Based on the $p(m_t|m_{t\text{-fitted}})$ given signal (different m_t) and background, accounts all different combinations weighted by the likelihood of the fit

7 TeV



- ❑ Good consistency among all measurements

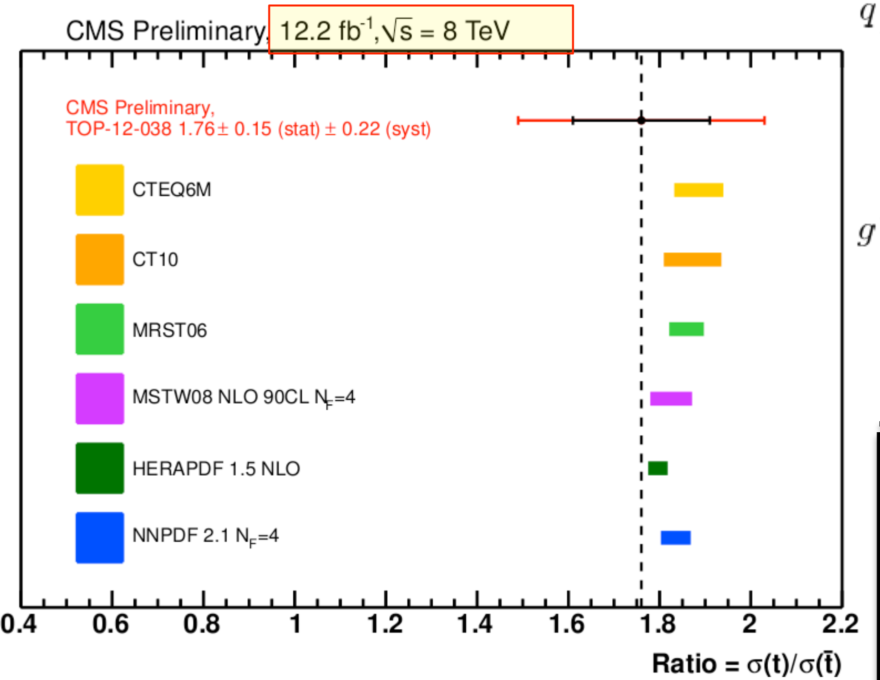
Top mass (GeV):

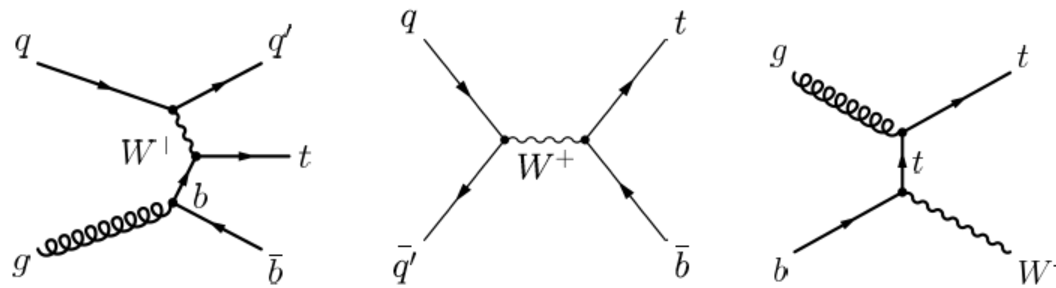
CMS (combination):
173.36 ± 0.38(stat) ± 0.91(syst)

Tevatron (combination):
173.18 ± 0.56(stat) ± 0.75(syst)

New Results: SingleTop and Top-decay (8 TeV)

Single Top





Cross section ratio t/t-bar in t-channel

$R_t = 1.76 \pm 0.14(\text{stat}) \pm 0.21(\text{syst})$

Top decay:

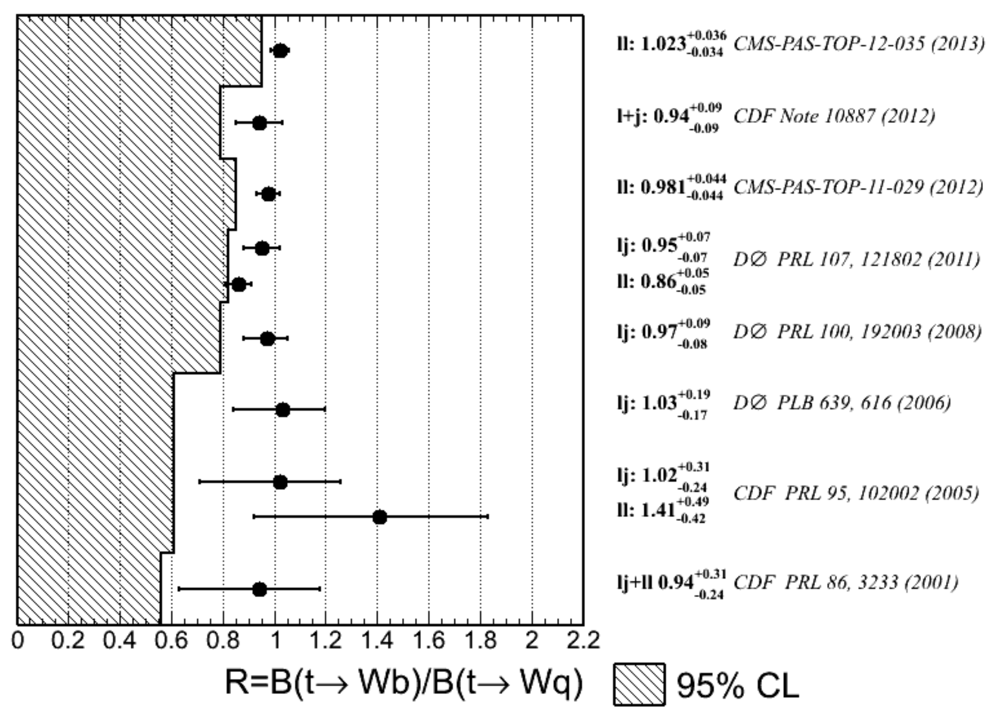
16.7 fb^{-1}

$R = BR(t \to Wb) / BR(t \to Wq)$

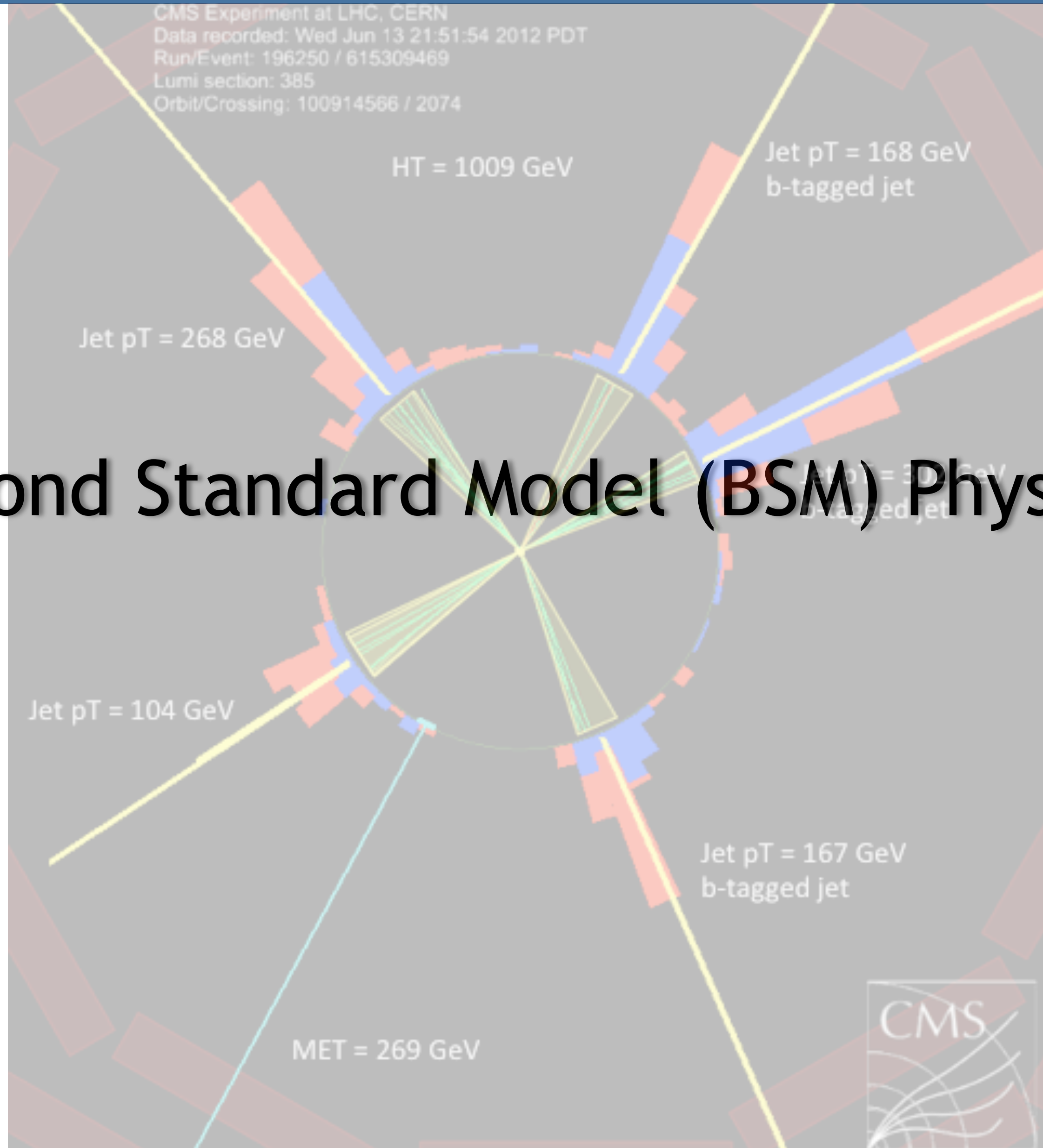
$= 1.023^{+0.036}_{-0.034}$

Good agreement with SM

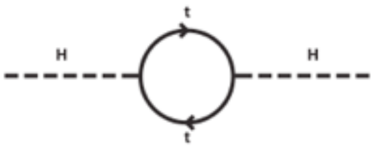
World most precise measurement



Beyond Standard Model (BSM) Physics



- What, if anything, makes the Higgs mass light?
- QFT: $m_H^2 = m_H^{2\ tree} + \Delta m_H^{2\ top} + \Delta m_H^{2\ W,Z} + \Delta m_H^{2\ self} \sim \mathcal{O}(125)\mathrm{GeV}$
- Corrections diverge quadratically $\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{\mathrm{UV}}^2 + \ldots]$
- Either we live in a fine-tuned Universe or QFT is wrong, or there must be some new physics to take care of divergences



$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{\mathrm{UV}}^2 + \ldots]$

$\Delta m_H^2 = \frac{\lambda_s}{8\pi^2}[\Lambda_{\mathrm{UV}}^2 + \ldots]$

- **3 general theoretical solutions:**

(1) Supersymmetry - SUSY:

- Extra “svirtual” contributions stabilize Higgs potential.

(2) Higgs not elementary (Goldstone boson of new gauge group):

- Technicolor, composite-Higgs, ..., (little-Higgs), ...

(3) Quantum gravity sets in at ~TeV:

- Effects from hidden dims (0.1 mm to 10-19 m). ➔ KK-towers, radion, mini-Black Holes, ...

➢ **All solutions imply new particles at TeV scale !**

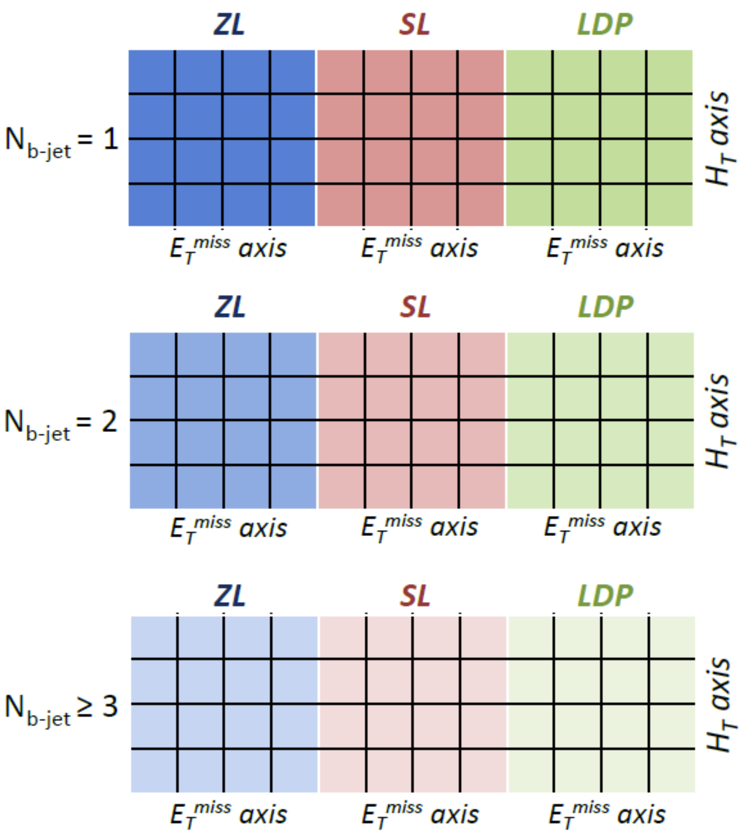
Searching for SUSY

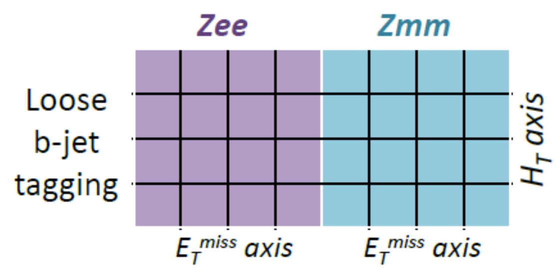
- ❑ Light stops, sbottoms: final states include multiple jets + leptons + MET
- ❑ (b)jets + MET

☑ Use 176 mutual exclusive categories

Event sample legend

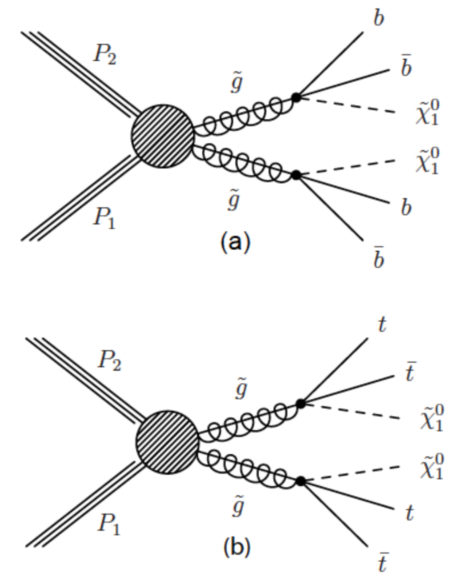
ZL = Zero Lepton; signal sample	SL = Single Lepton; top & W+jets control sample	LDP = low $\Delta\hat{\phi}_{min}$; QCD control sample	Zee = $Z \to e^+e^-$; Z to $\nu\bar{\nu}$ control sample	Zmm = $Z \to \mu^+\mu^-$; Z to $\nu\bar{\nu}$ control sample

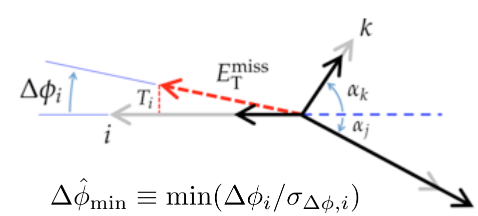




Bin	H_T (GeV)	E_T^{miss} (GeV)
1	400 – 500 (HT1)	125 – 150 (MET1)
2	500 – 800 (HT2)	150 – 250 (MET2)
3	800 – 1000 (HT3)	250 – 350 (MET3)
4	> 1000 (HT4)	> 350 (MET4)

gluino mediated bottom and top-squark production:

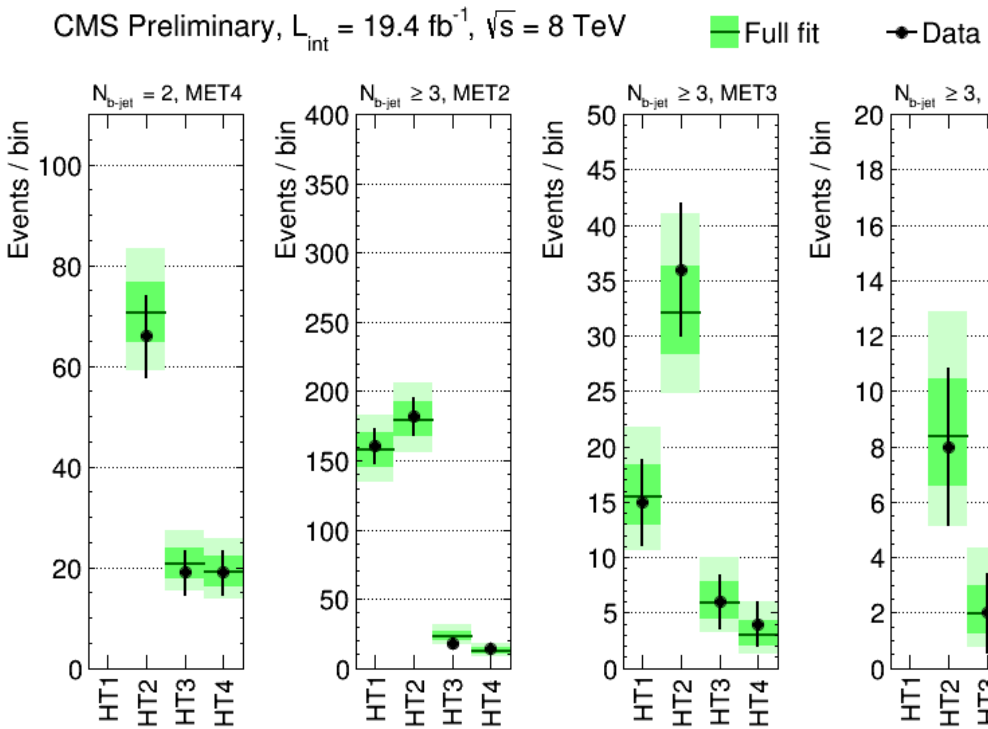


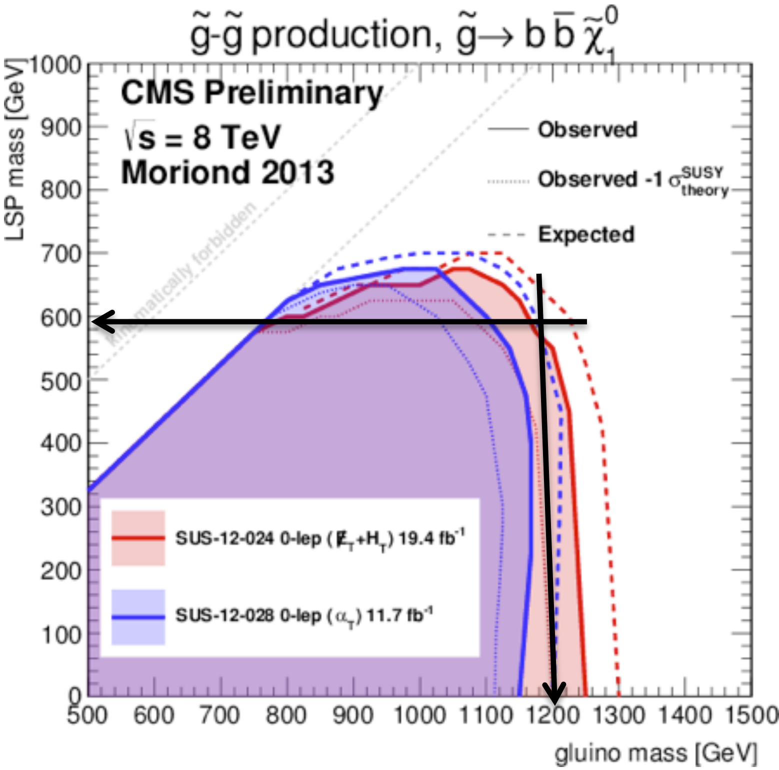


$$\Delta\hat{\phi}_{\min} \equiv \min(\Delta\phi_i/\sigma_{\Delta\phi,i})$$
$$\sigma_{\Delta\phi,i} = \arcsin(\sigma_{T_i}/\mathrm{MET})$$

0-lepton Search for Gluino Mediated Sbottom

- Use global fit to extract contributions from different backgrounds and compare predictions to data in bins most sensitive to signal





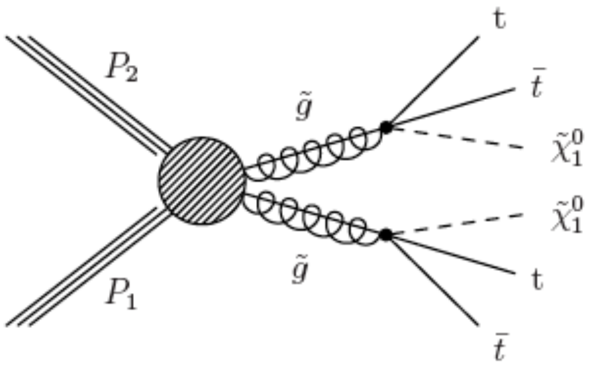
Observed number of events (points with error bars) for the 14 bins with highest signal sensitivity

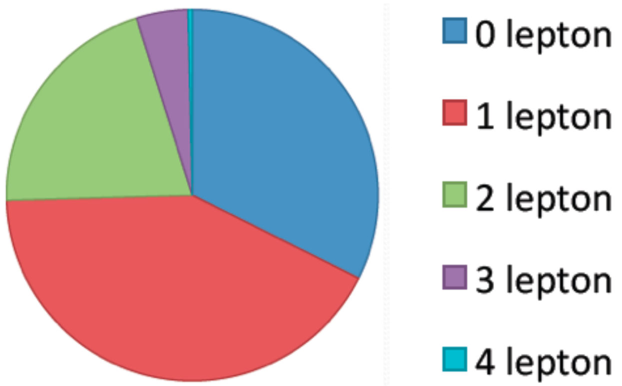
Excluded Gluino masses of 1.2 TeV for LSP masses upto 600 GeV

- No evidence for signal

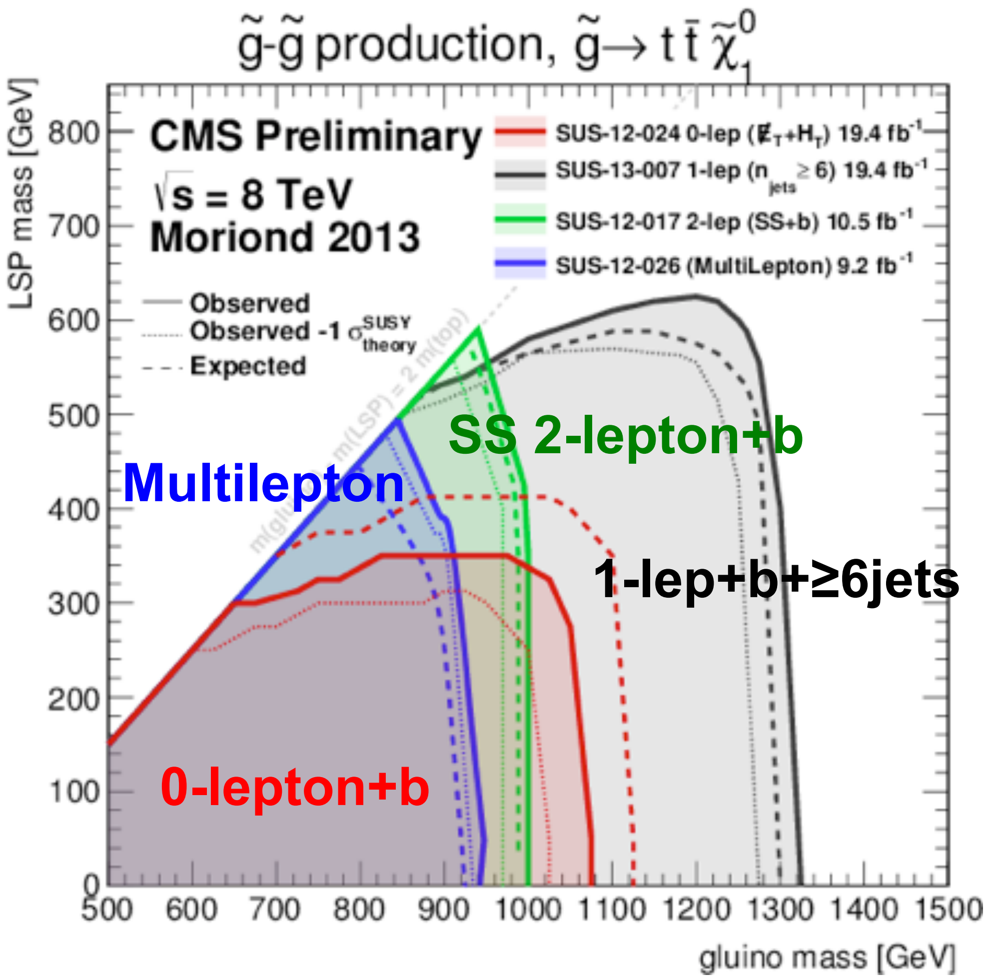
Gluino Mediated Stop Production

Two LSPs ($\tilde{\chi}^0{}_1$) : Large MET





- Searches performed in the final states categorized into 0, 1, SS/OS 2-leptons, multileptons

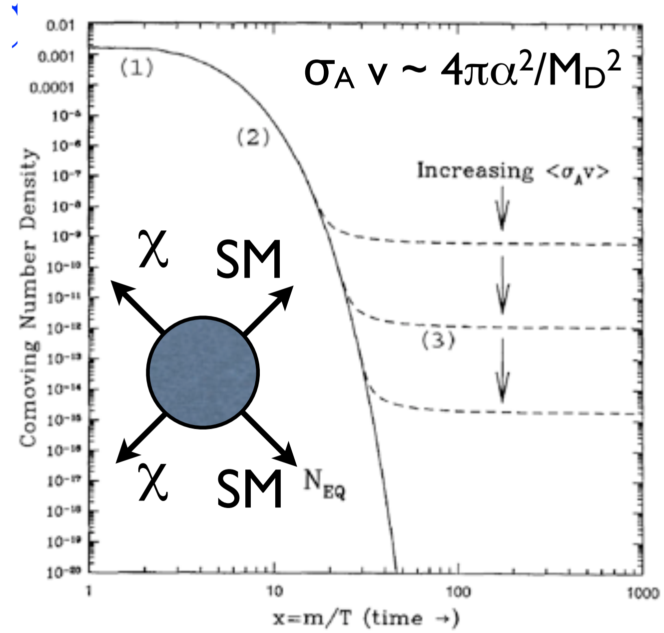


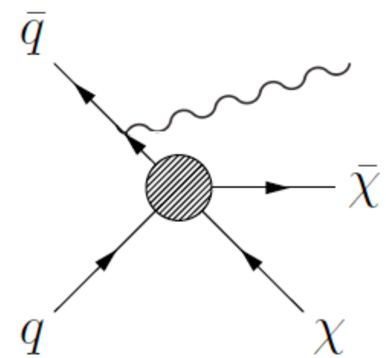
Gluinos of upto masses of 1.3 TeV excluded for LSP mass of a few 100 GeV

Searching for Dark-Matter

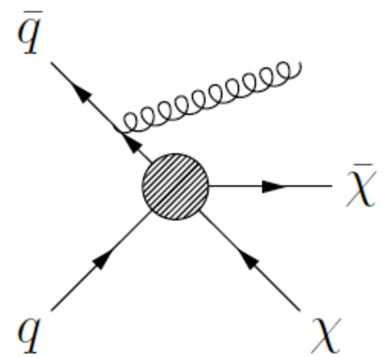
- Dark Matter: assumed to be Dirac fermion, its interactions with SM particles mediated by very heavy particle, treat as point interaction
- Dark matter pair production with a jet from initial state---> Monojet + MET or
  Monophoton + MET
- Same final state can be used to search for a number of interesting phenomena
  - ADD Large Extra Dimensions
  - Unparticle models
  - Light Stop
- Low mass region not accessible to direct detection experiments
- Limited by threshold effects, energy scale, backgrounds
- Bounds from spin-dependent couplings not good
- Crucial to have independent verification from non-astrophysical experiments (such as collider experiments : LHC)

J. Feng 0801.1334v2



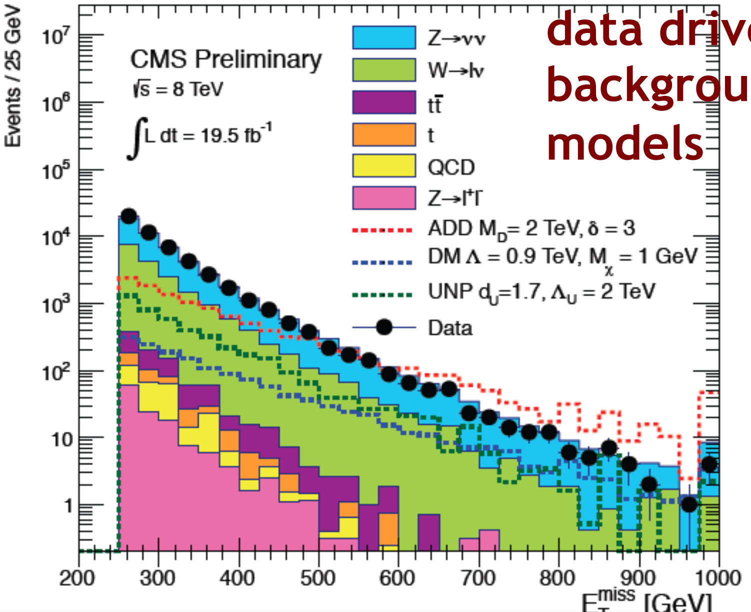


Monophoton + MET

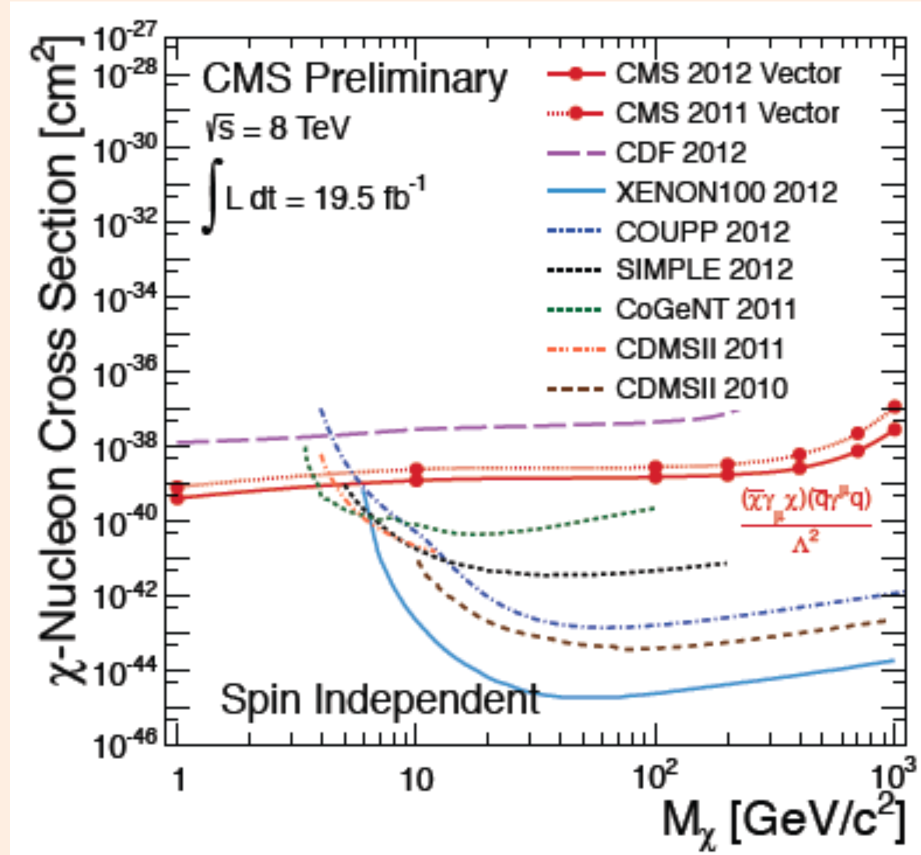


Monojet + MET

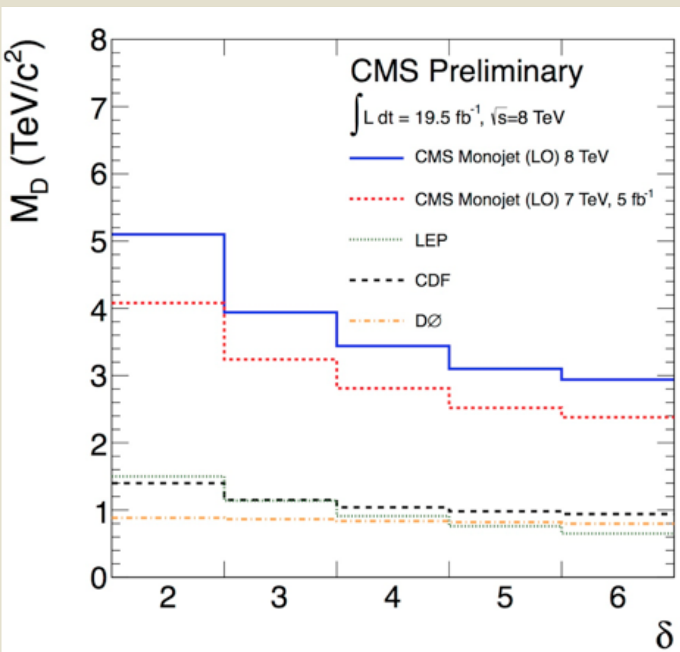
Dark Matter Search: Monojets



data driven background models



90% CL upper limits for Dark matter mass



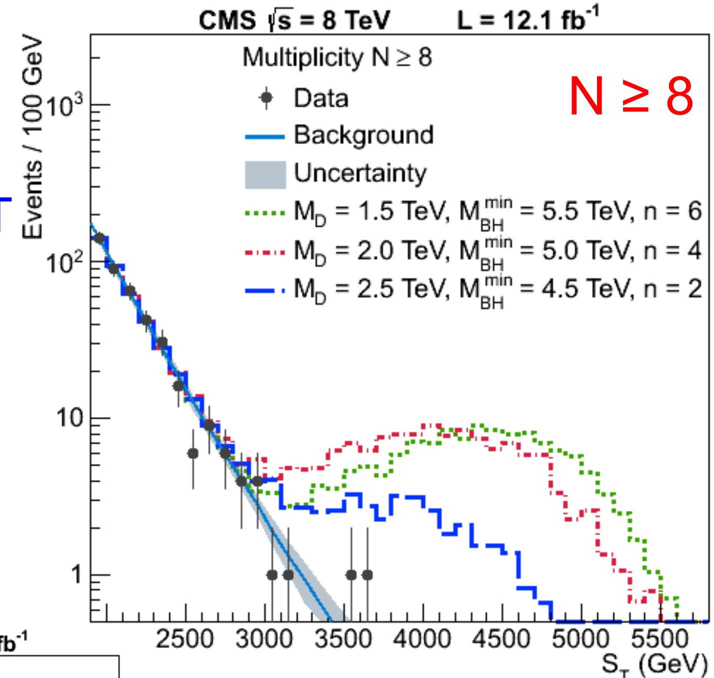
$$M_{Pl}^{2} \approx M_D^{\delta+2} R^{\delta}$$

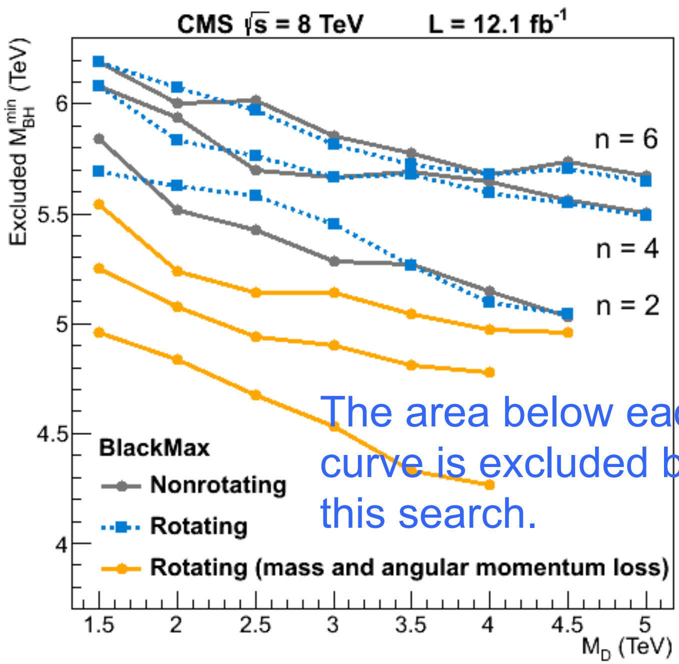
M_D< 5 TeV excluded for ADD n=2

M_D< 2.9 TeV excluded for ADD n=6

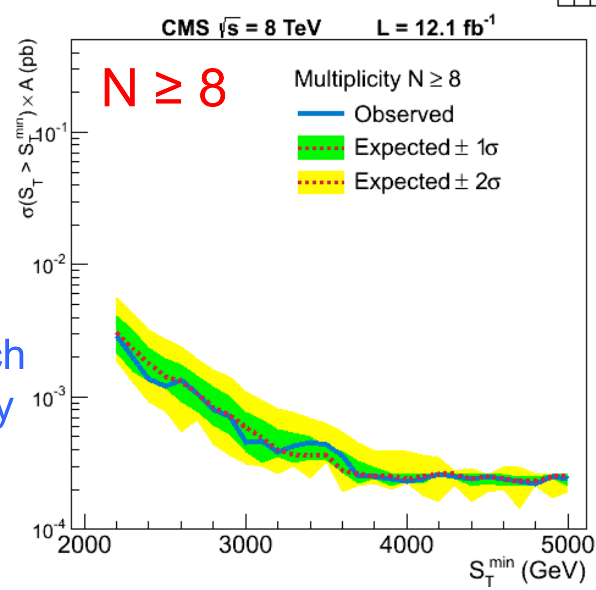
Microscopic Black Holes

- Smoking gun signature of TeV scale quantum gravity
- BH produce large number of energetic objects
- S_T = scalar sum of all objects with p_T>50 GeV+MET
- Search for deviation in S_T distribution in bins of object multiplicity (N at least > 2)
- Use ST spectrum from N=2 to predict QCD background at N≥3,4,5,6,7,8,9,10 where signal would be present





The area below each curve is excluded by this search.

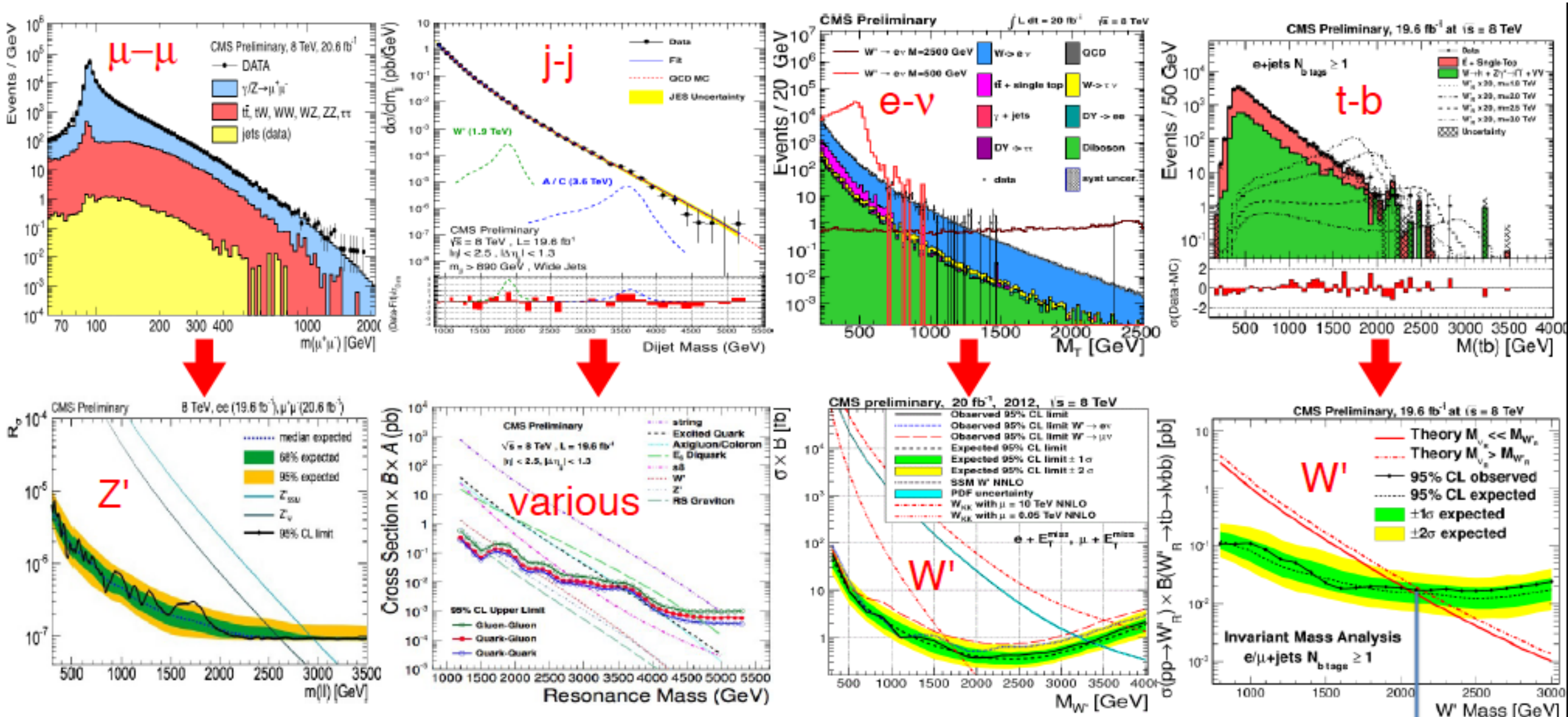


- ❑ No excess observed in data
- ❑ Set model independent upper limit on the minimum BH mass of 4.3 – 6.2 TeV

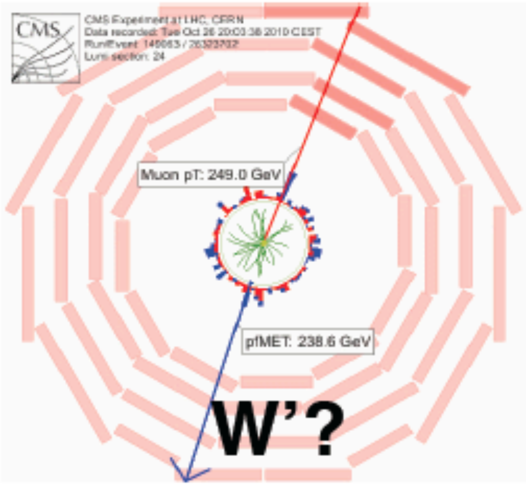
BSM Searches: High-Mass Resonances

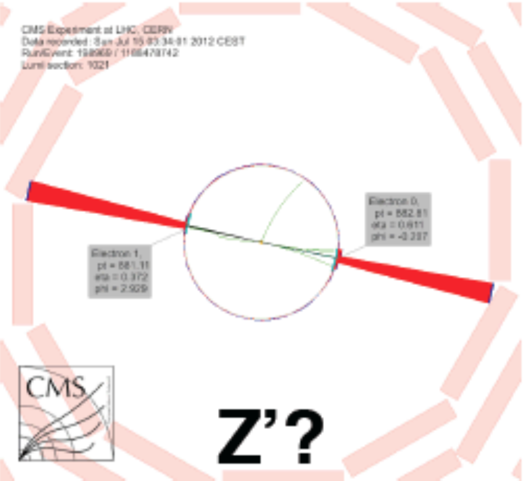
- ”Simple” procedure:

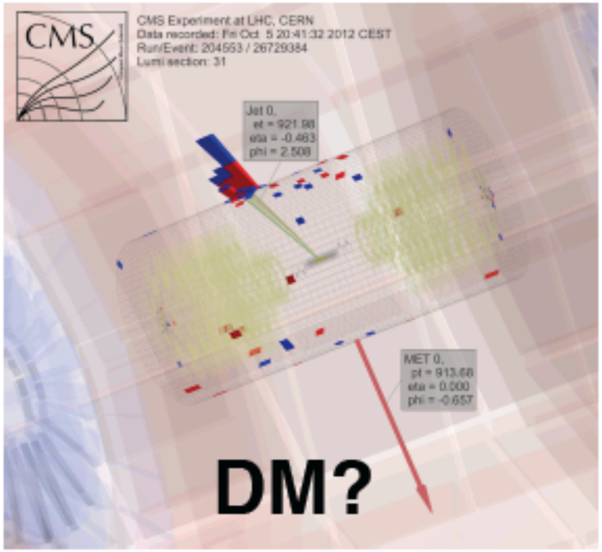
1. Reconstruct pairs of high-pT objects: jets, leptons, bosons, ...
2. Look at invariant mass tails for deviations from smooth SM backgrounds.
3. Interpret (lack of) excess within (simplified) BSM models: **Set limits to New physics**

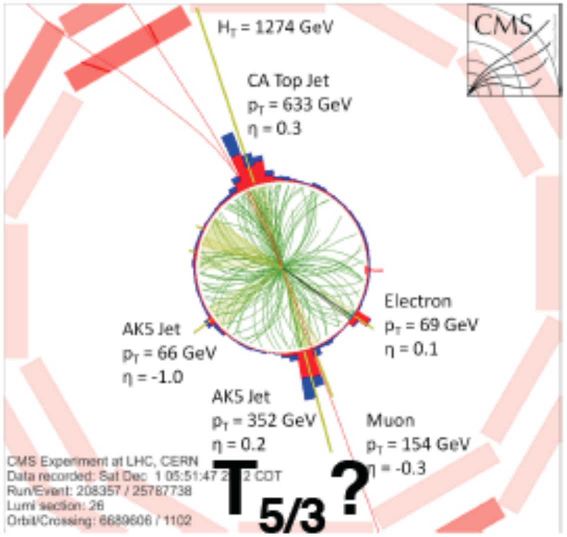


Looking forward to see more of these events…



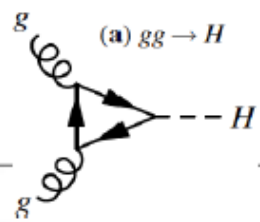




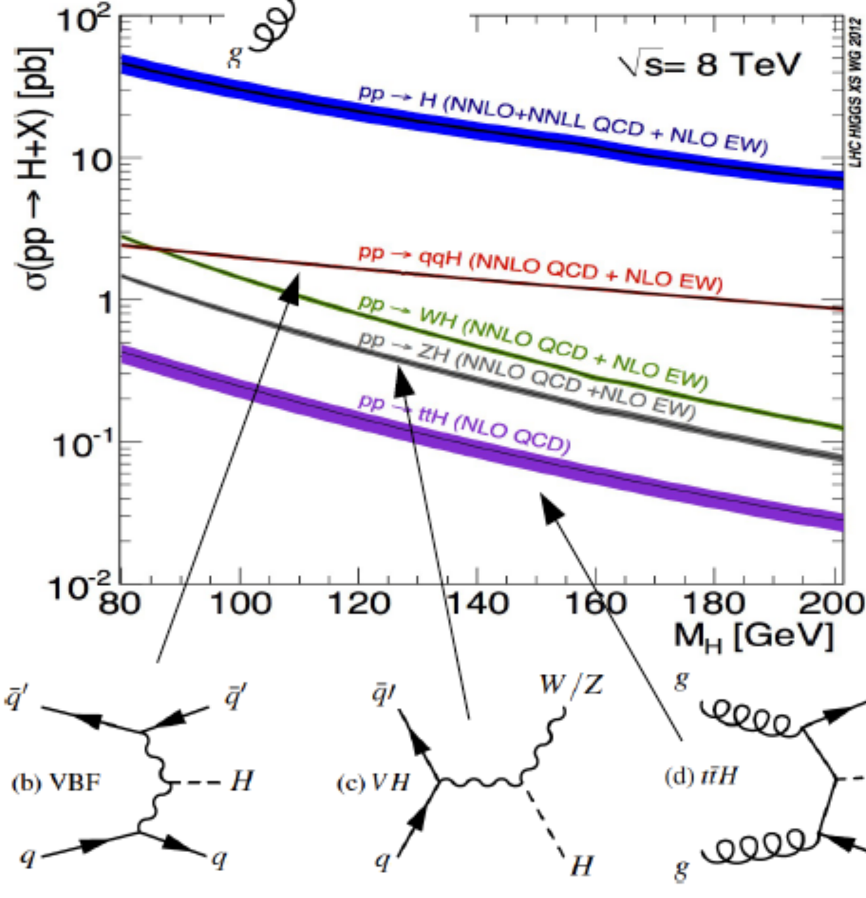


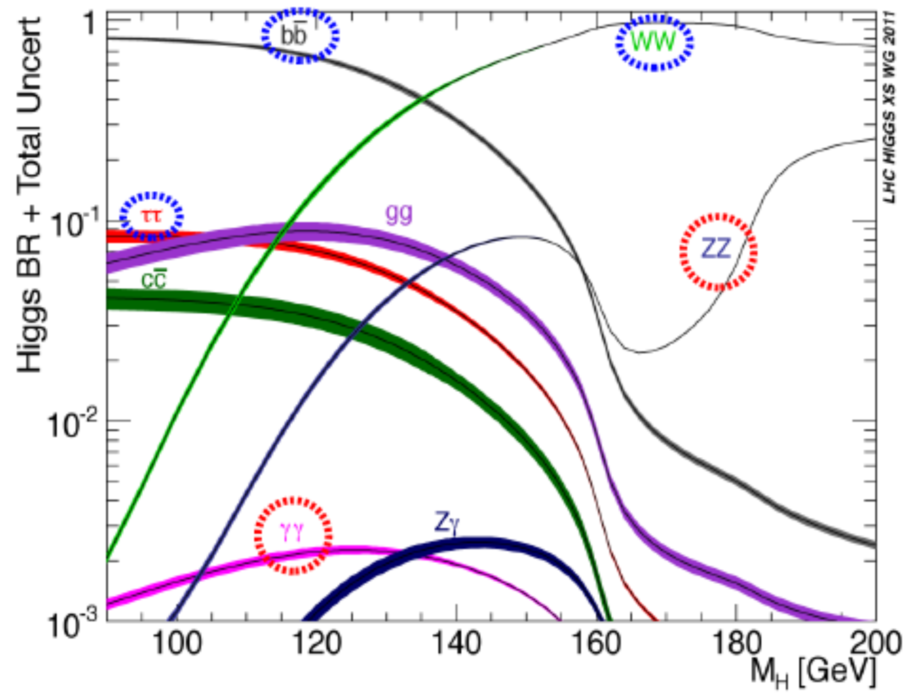
Slide Courtesy: S Lee

Higgs Results



Gluon-fusion: dominant





«Cleanest» channels: H → γ's, leptons

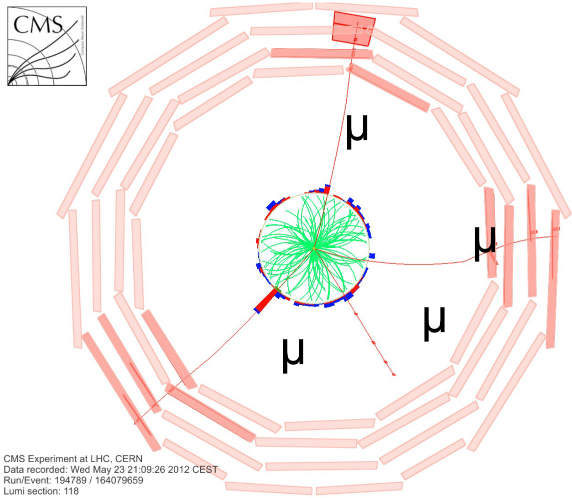
Large x-section channels: H → WW,ττ,bb

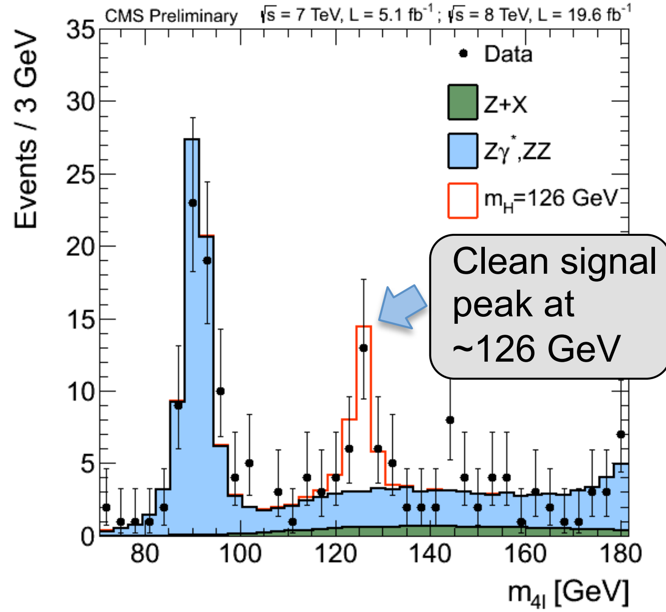
VBF & associated prod.: harder H, more jets

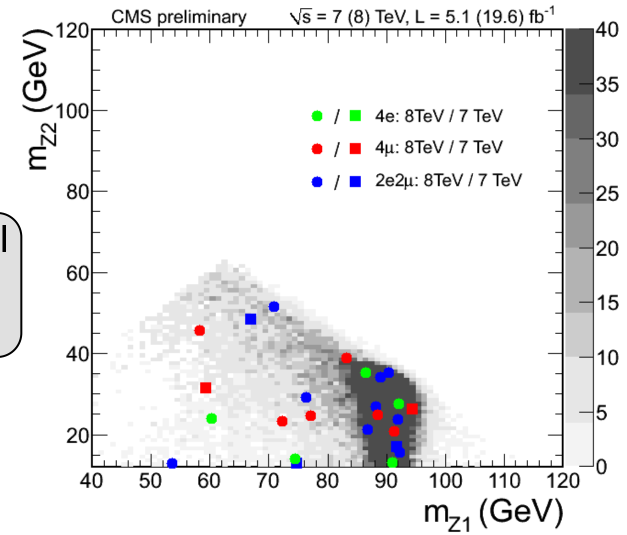
At a Glance .. Higgs Decay Channels

@ 125GeV	signature	S/B	Mass Resol.	N events in $20fb^{-1}$	Good For
$H \to bb$	two b-jets, Z or W, bb inv. mass	low O(0.1)	10%	$\sim 10^5$ ~50 (sel)	couplings to fermions
$H \to \tau\tau$	had tau, leptons, MET	low O(0.1)	15%	$\sim 10^4$ ~40 (sel)	couplings to fermions ★
$H \to WW$	two leptons with opposite charge MET	medium O(1)	-	$\sim 10^3$ ~120 (sel)	cross section, BR, couplings to V ★
$H \to \gamma\gamma$	two photons peak in inv. mass	low O(0.1)	2%	800 ~400 (sel)	H mass, couplings $K_V K_F$, discovery ★
$H \to ZZ$	four leptons with right charge peaks in inv. mass (Z_1 and Higgs)	high >1	1-2%	40 ~12 (sel)	H mass, discovery ★

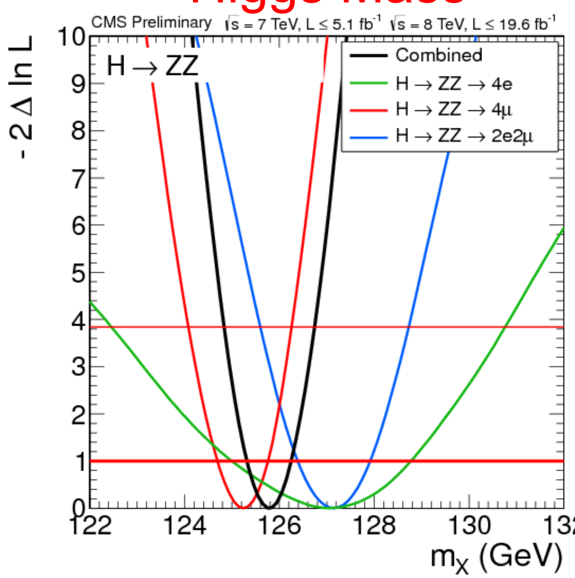
H->ZZ>4l

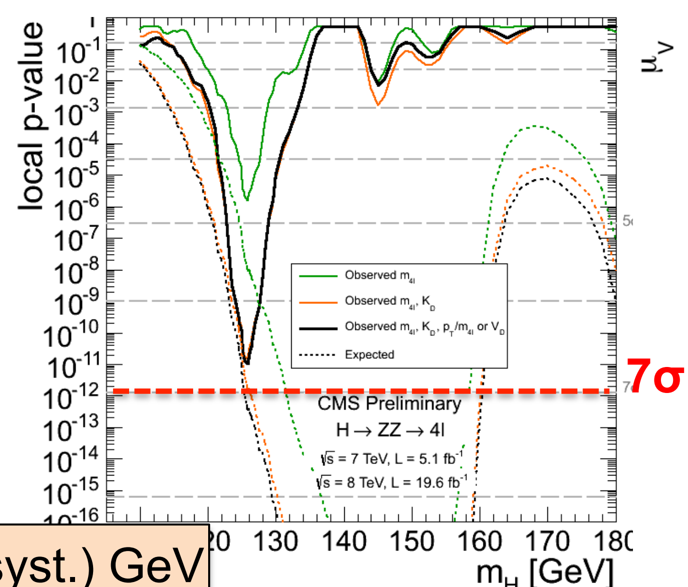






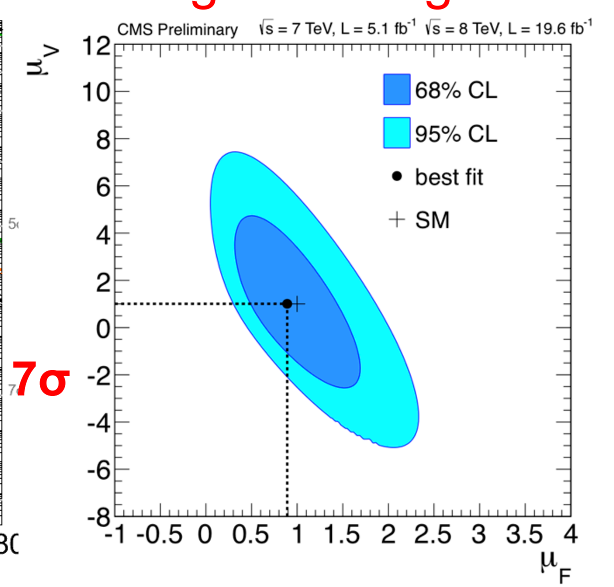
Higgs Mass

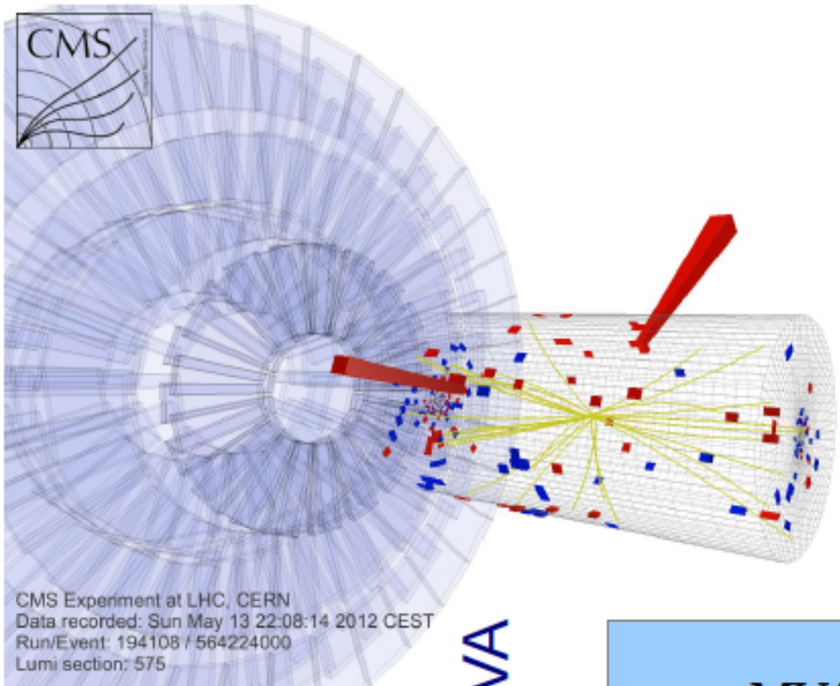




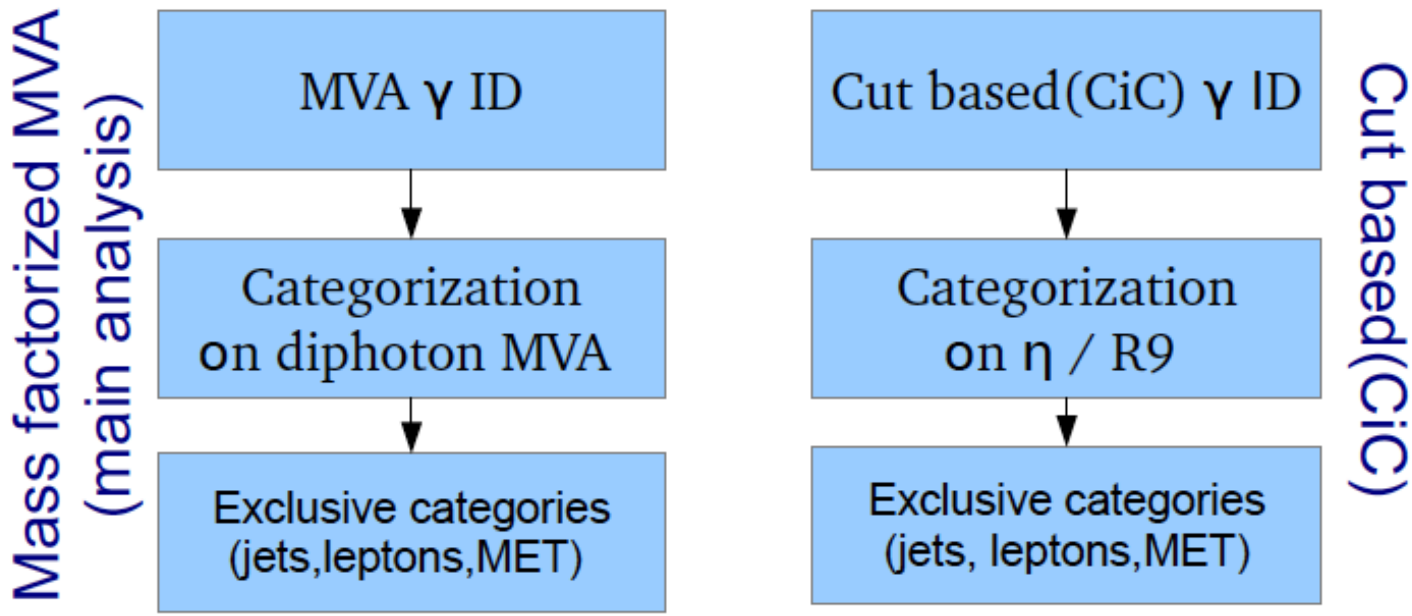
$m_H = 125.8 \pm 0.5(\text{stat.}) \pm 0.2(\text{syst.})$ GeV

Signal strength

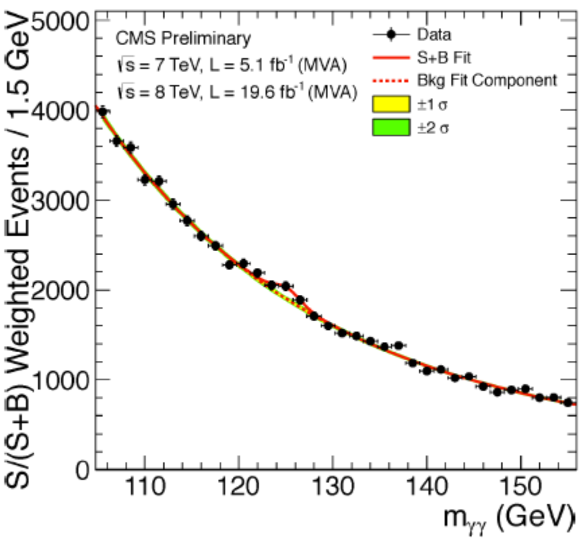


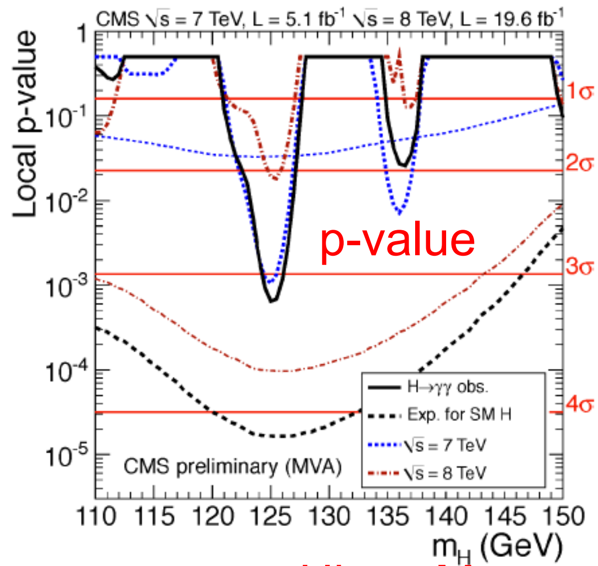


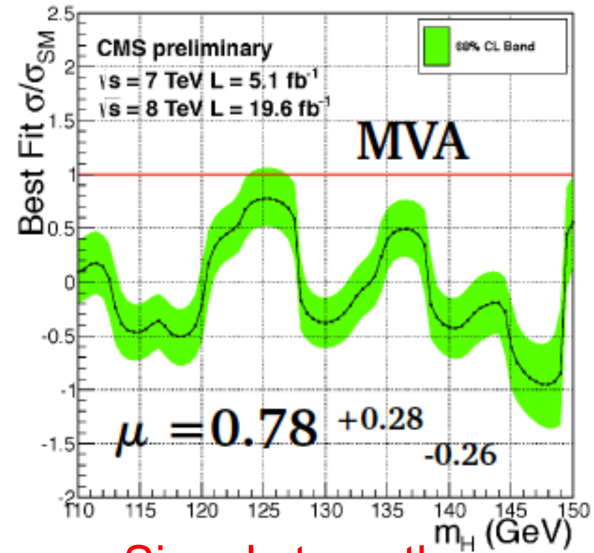
- Two energetic isolated photons
- Very good mass resolution
- Backgrounds
  - Direct $\gamma\gamma$ production
  - Fake photons
- Two independent analyses pubic with full data



H->γγ



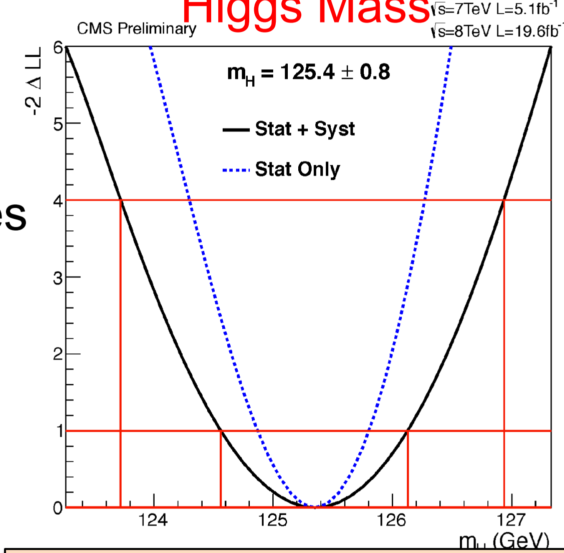


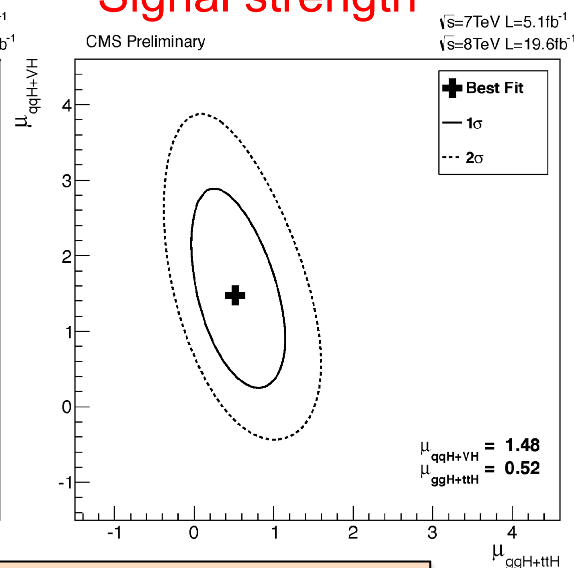


Signal strength

Higgs Mass

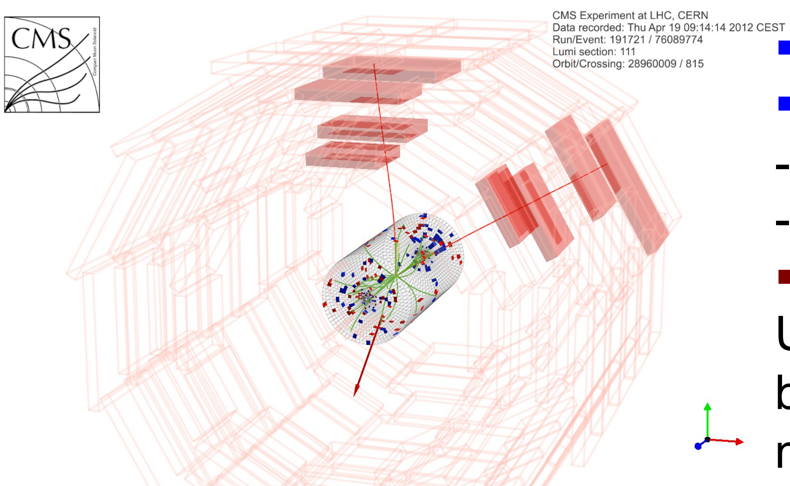
Peak visible @ ~ 125 GeV
Expected 4.2 σ ,Observed 3.2 σ





- Difference between the analyses
  - Due to fluctuations of the large background
- Signal strength compatibility estimated with Jackknife resampling within 1.5σ (for both 7+8 TeV)

m_H = 125.4 ± 0.5(stat.) ± 0.6(syst.) GeV (MVA)

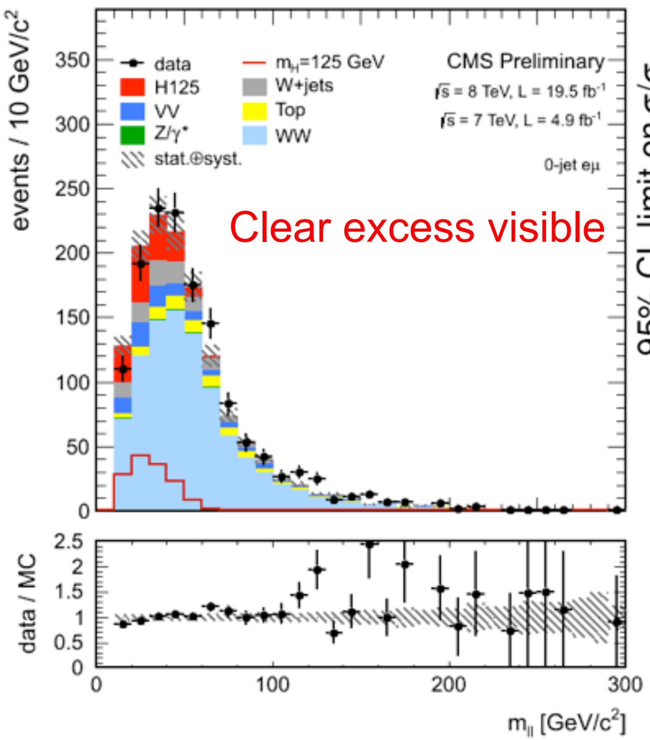


- Two high-p_T isolated leptons and moderate MET
- Split data into two categories

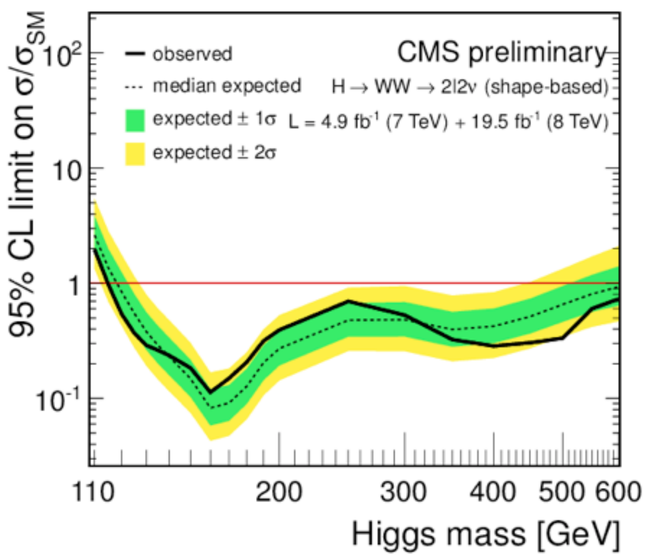
- Different-Flavor (DF), Same-Flavor (SF)
- No jet, 1-jet

- Two approaches: cut-based and shape-based

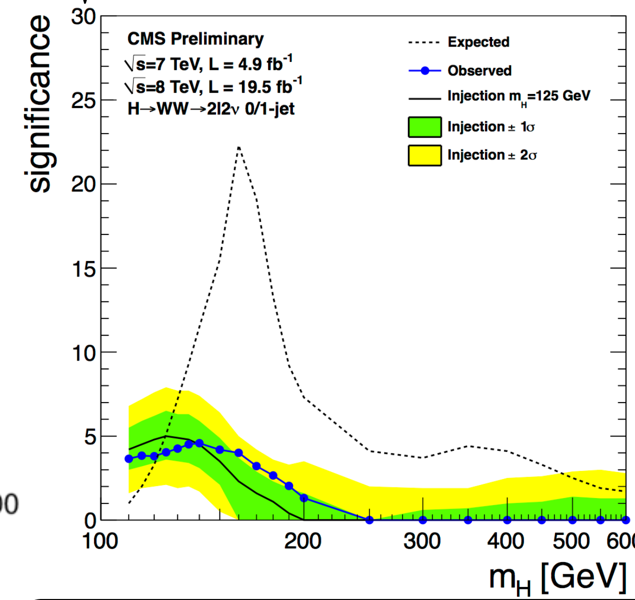
Use 2D ($M_{\ell\ell}$ – M_T) to separate signal from background for DF shape-based analyses, counting method for the rest; $M_T = \sqrt{2p_T^{\ell\ell}\ \mathrm{MET}\ cos\Delta\phi_{\ell\ell-\mathrm{MET}}}$



Clear excess visible

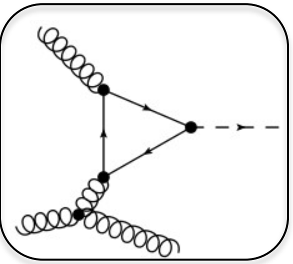


Exclude 128-600 GeV at 95% C.L

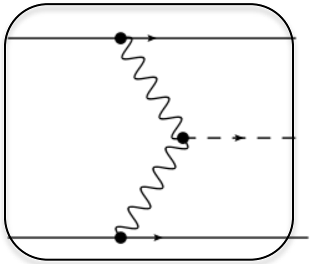


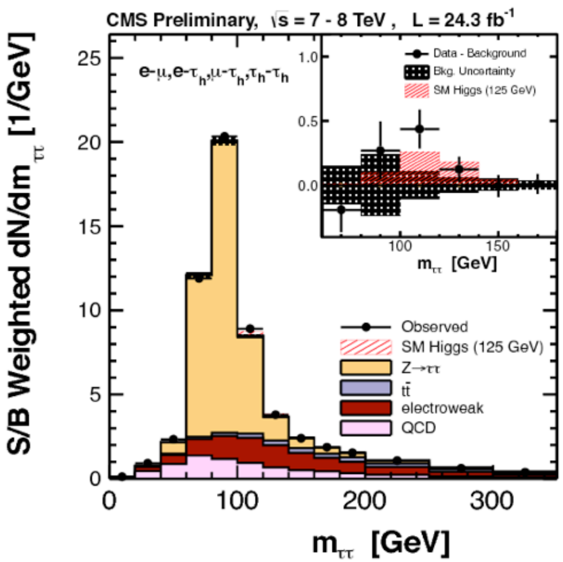
5.0 σ expected , 4.1 σ observed
Second most sensitive final state!

Inclusive



VH

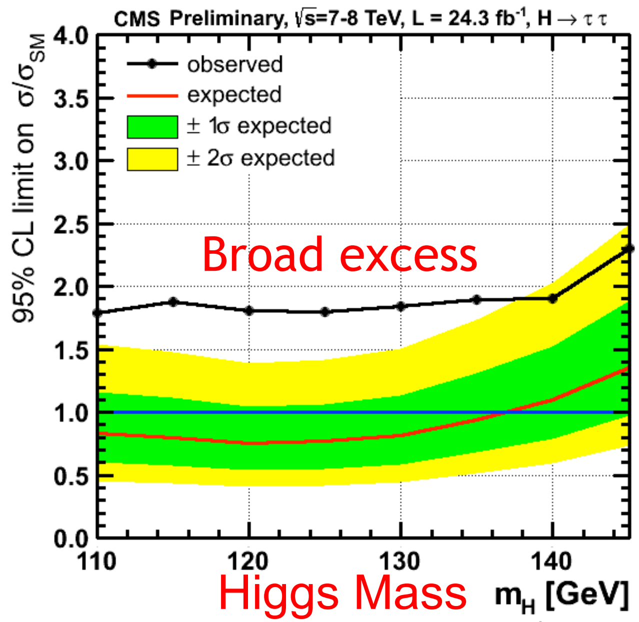




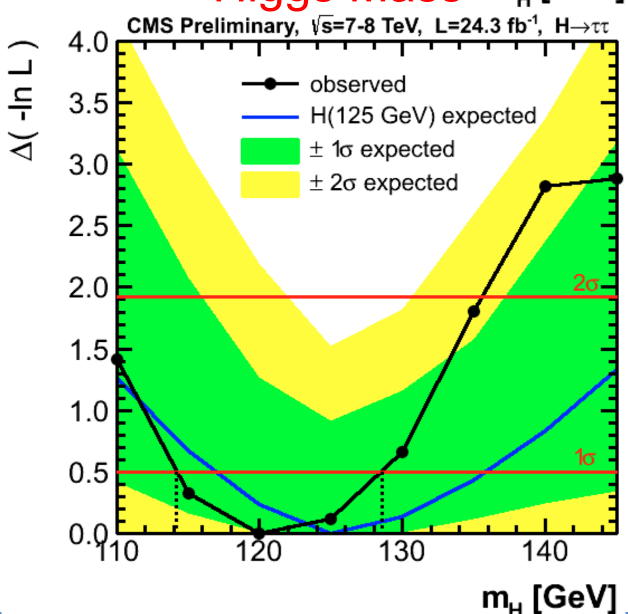
1-jet and VBF categories for eμ, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$

$m_H = 120^{+9}_{-7}$ (stat+syst) GeV

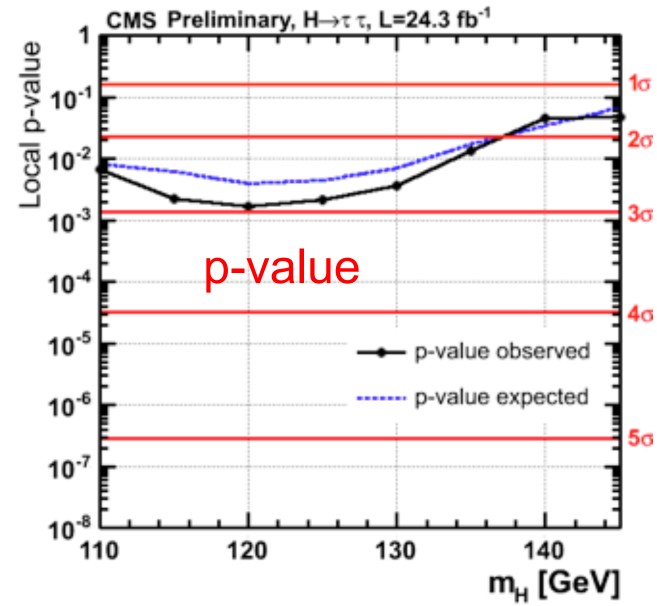
Broad excess



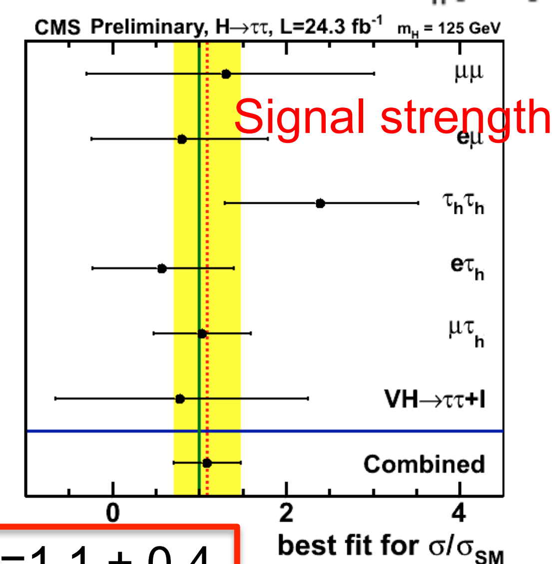
Higgs Mass



p-value

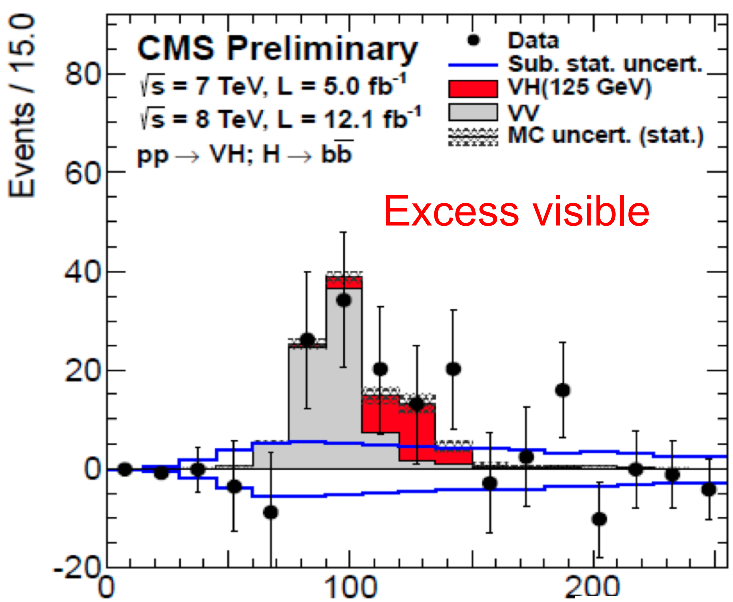


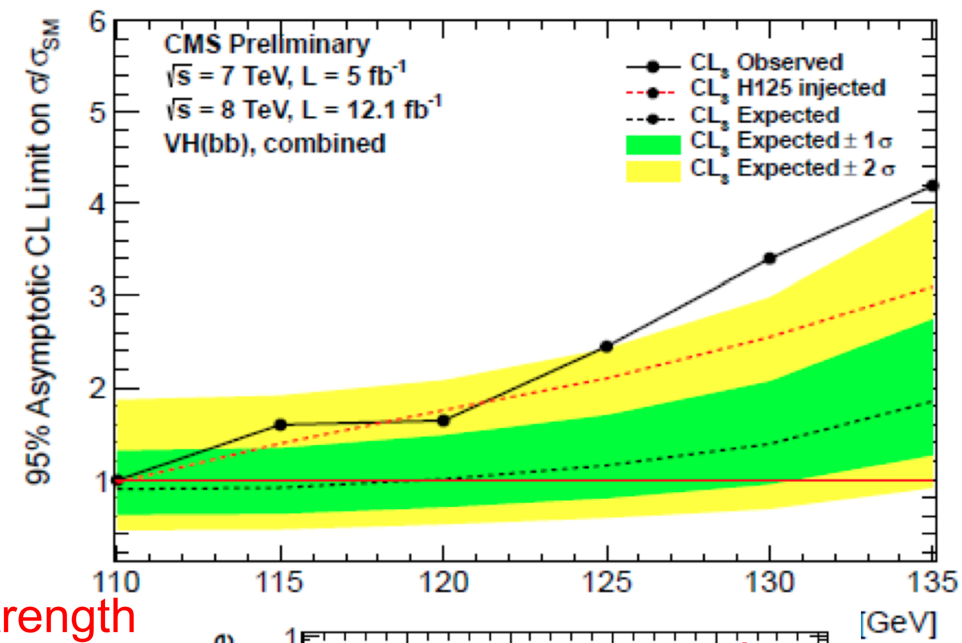
Signal strength



μ=1.1 ± 0.4

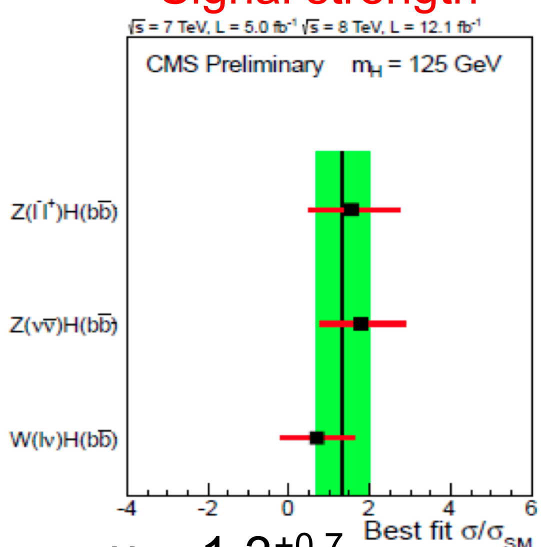
H->bb



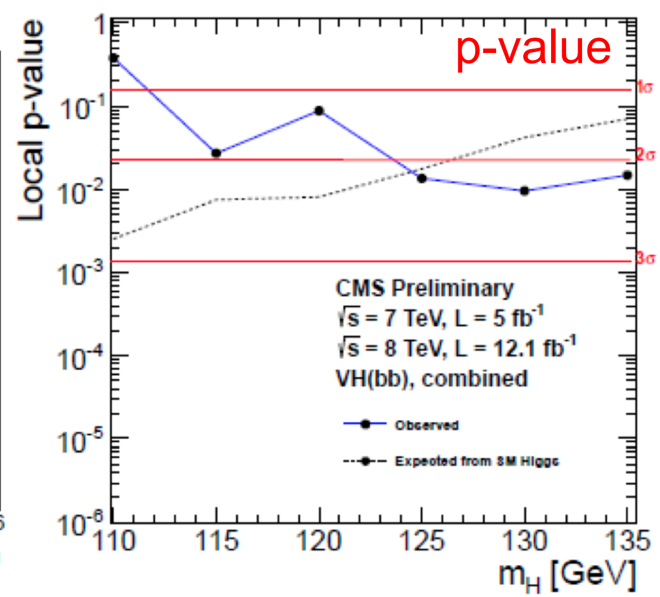


at 125 GeV sig = 2.2σ $\mu = 1.3^{+0.7}_{-0.67}$

Signal strength



$\mu = 1.3^{+0.7}_{-0.67}$

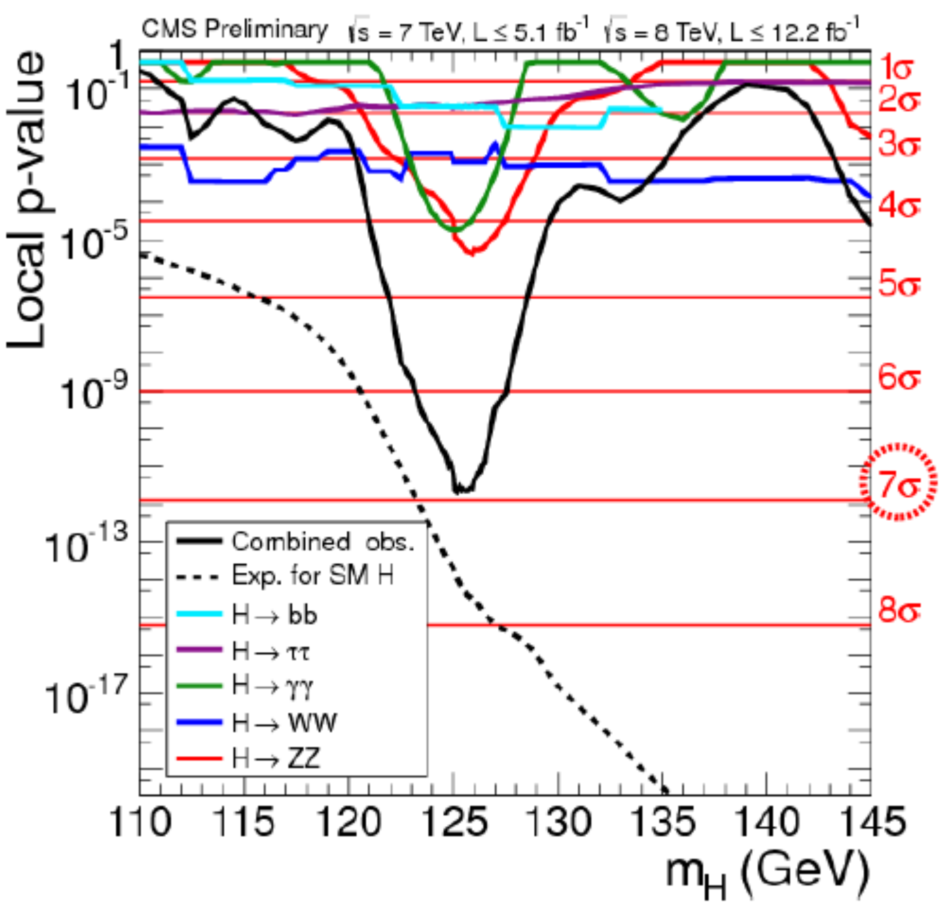


- Soon will be updated with full statistics

Summary of all channels

Decay	Expected	Observed
H → ZZ	7.1 σ	6.7 σ
H → γγ	3.9 σ	3.2 σ
H → WW	5.3 σ	3.9 σ
H → bb ✪	2.2 σ	2.0 σ
H → ττ	2.6 σ	2.8 σ
H → ττ and H → bb	3.4 σ	3.4 σ

Combined significance (local p-value):



✪ will be updated by LHCP

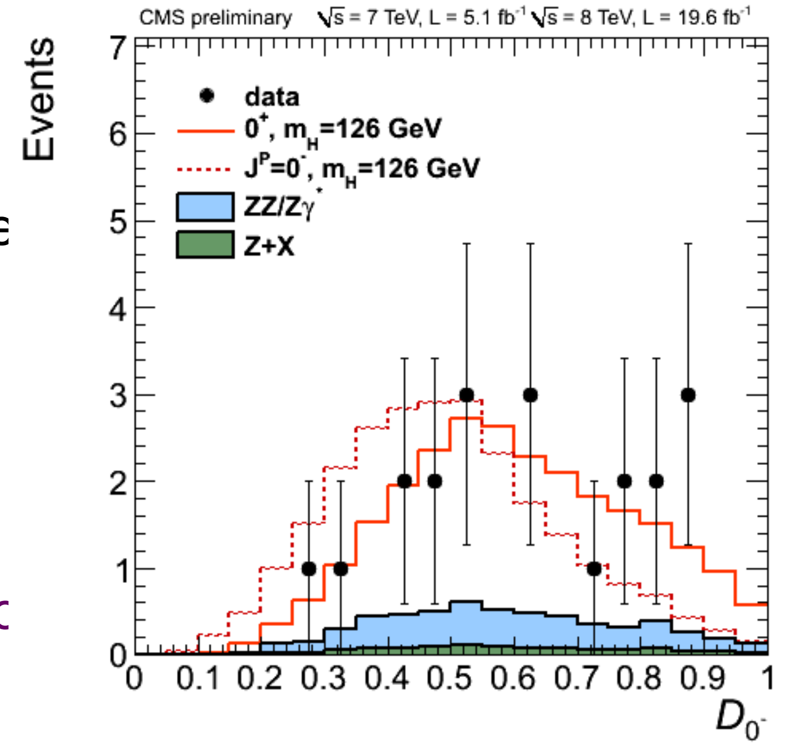
Spin parity

- ❑ So far we know the observed particle (assuming just one particle)
  - X is a boson (decays to γγ, 4l etc)
  - X can not be spin 1 (decays to γγ + Landau-Yang theorem)
  - X can not be 100% 0^- (from 4l correlations) [PRL 110, 081803 (2013)]

❑ Further tests in ZZ(4l) and WW(lνlν) channels with full data on a few reasonably well motivated J^P hypothesis ("pure" states only) w.r.t. SM Higgs

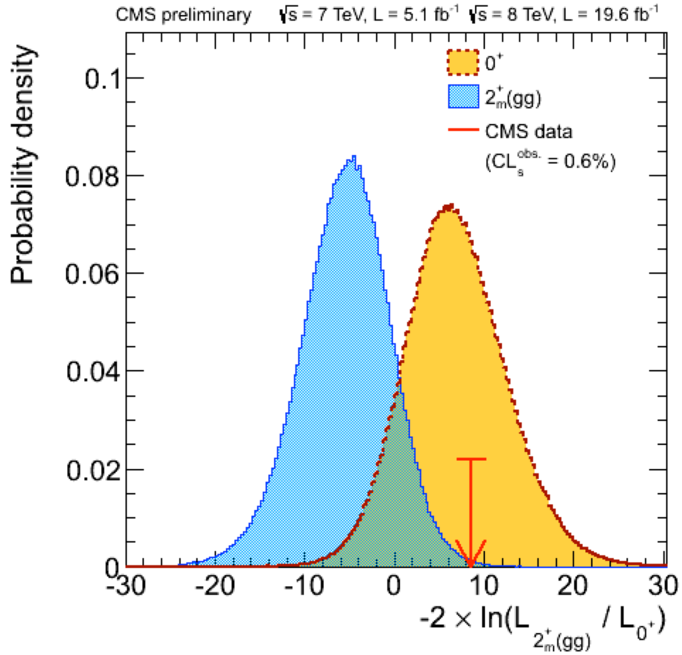
- Using kinematic distributions to distinguish different signal models
  - – Probe different amplitude structures
- Test compatibility of data with distinct mode (*Neyman-Pearson hypothesis testing*)
  - ➢ Null Hypothesis always SM Higgs

- ○ Discriminator D_{JP} to separate SM Higgs hypothesis from alternative hypothesis
- ○ Discriminator D_{bkg} to separate SM Higgs frc backgrounds



Spin Parity (combination)

J^P	production	comment
0^-	$gg \rightarrow X$	pseudoscalar
0^+_h	$gg \rightarrow X$	higher dim operators
2^+_{mgg}	$gg \rightarrow X$	minimal couplings
$2^+_{mq\bar{q}}$	$q\bar{q} \rightarrow X$	minimal couplings
1^-	$q\bar{q} \rightarrow X$	exotic vectors
1^+	$q\bar{q} \rightarrow X$	exotic pseudovector



- Expected results with μ=1

ZZ	WW	Comb
6.8%	1.4%	0.2%

obs. value weaker than exp. for WW due to best fit μ < 1

- Observed results at measured μ

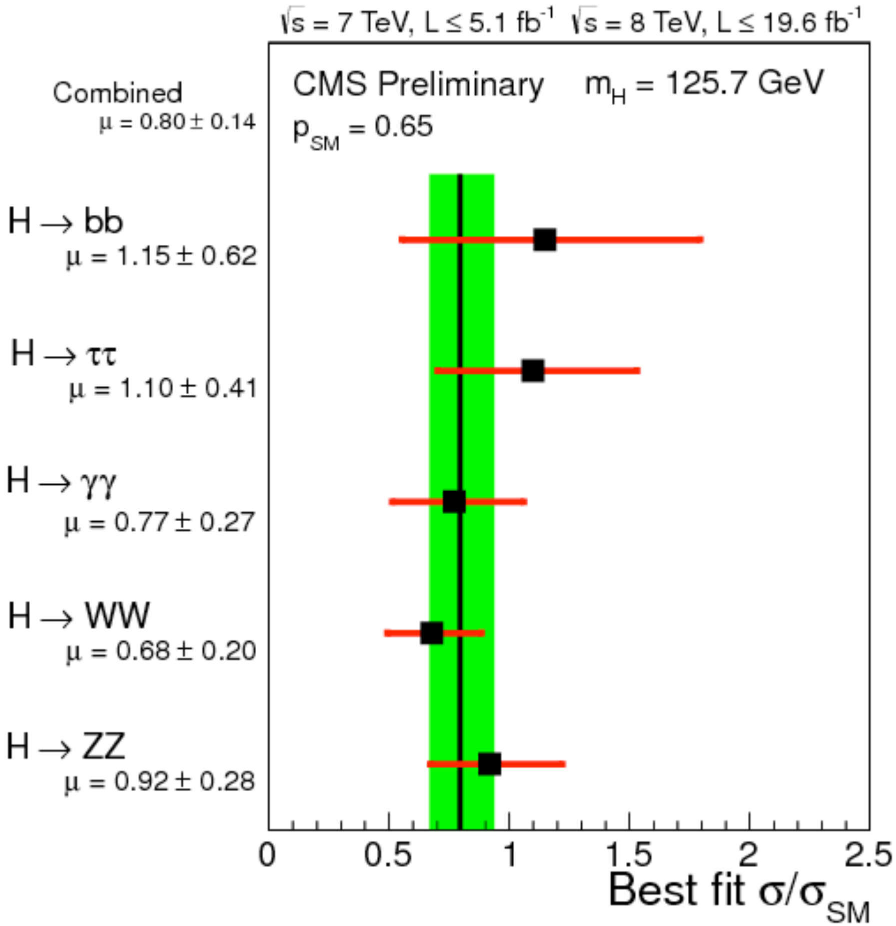
ZZ	WW	Comb
1.4%	14%	0.6%

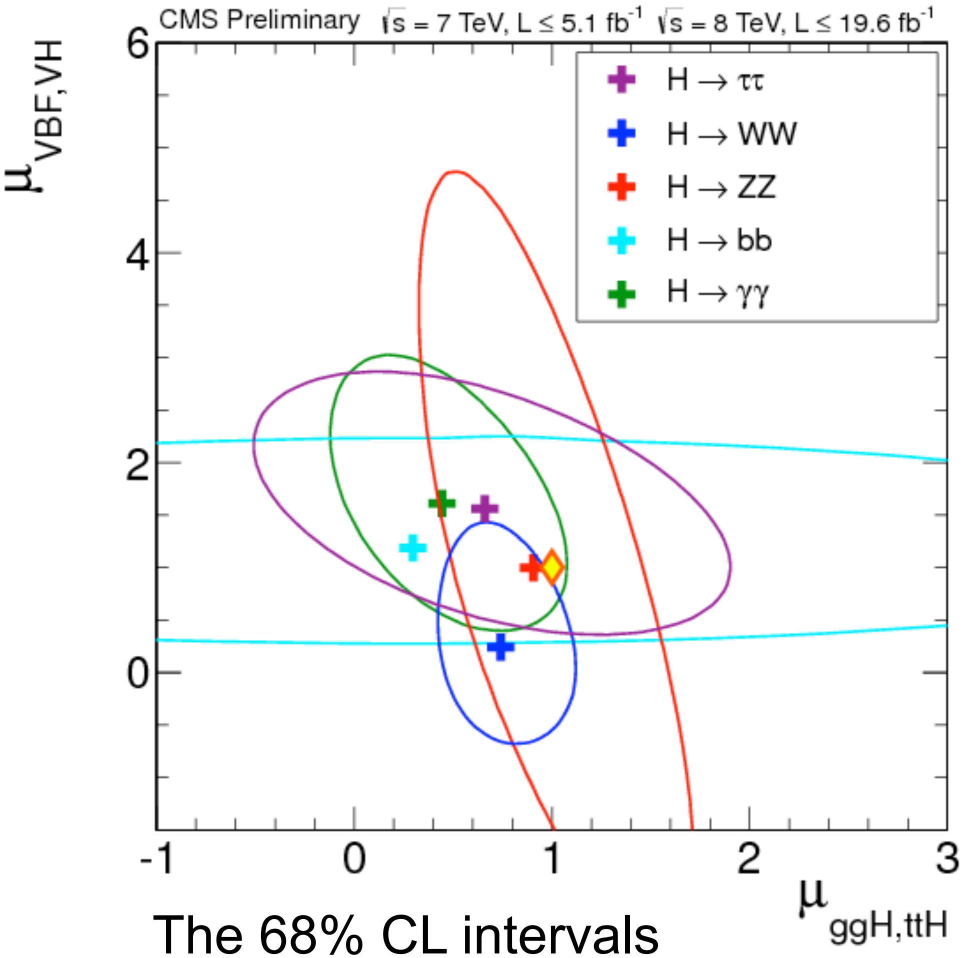
obs. value better than exp. for ZZ due to a fluctuation

- ☑ **The observation is very compatible with SM Higgs expectations (0^+)**
- Data disfavors the 2^+_m (gg) hypothesis with a CL_s value of 0.6%

Compatibility with SM Higgs Boson

- ❑ Signal strengths are consistent with SM prediction

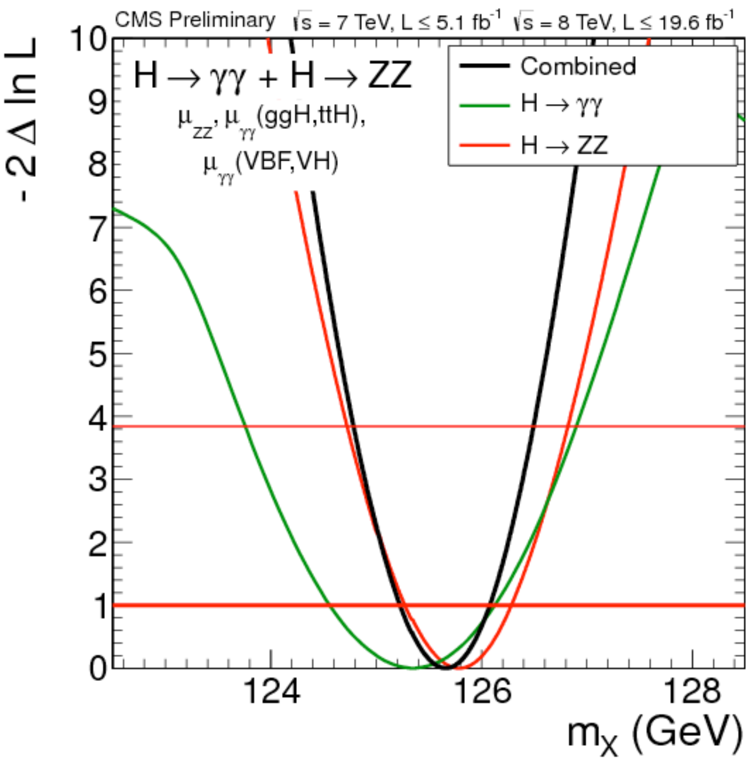




μ=0.80±0.14

The 68% CL intervals for signal strength

The Mass of the Observed State



$H \rightarrow ZZ \rightarrow 4l$:

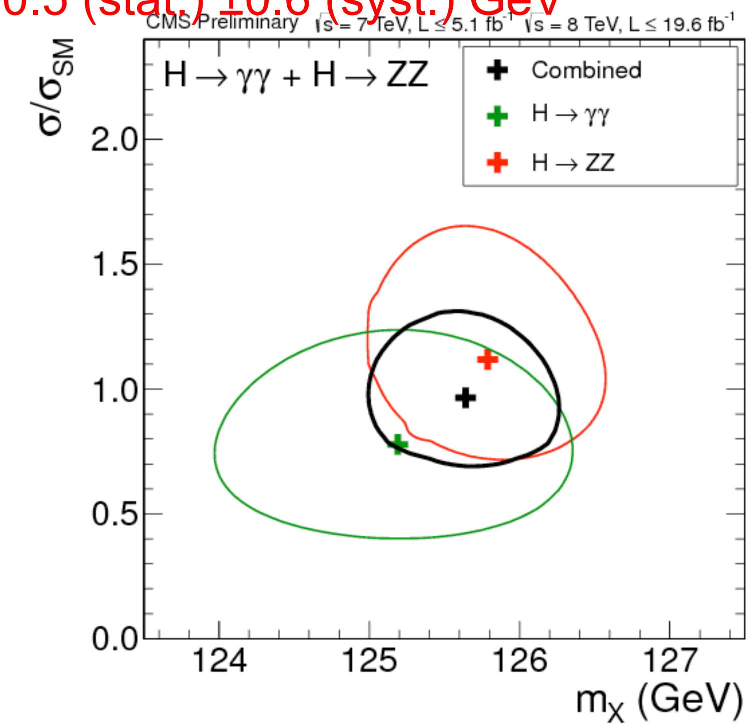
Very small systematics due the very good control of the leptons scale and resolution:

m_H = 125.8 ± 0.5 (stat.) ±0.2 (syst.) GeV

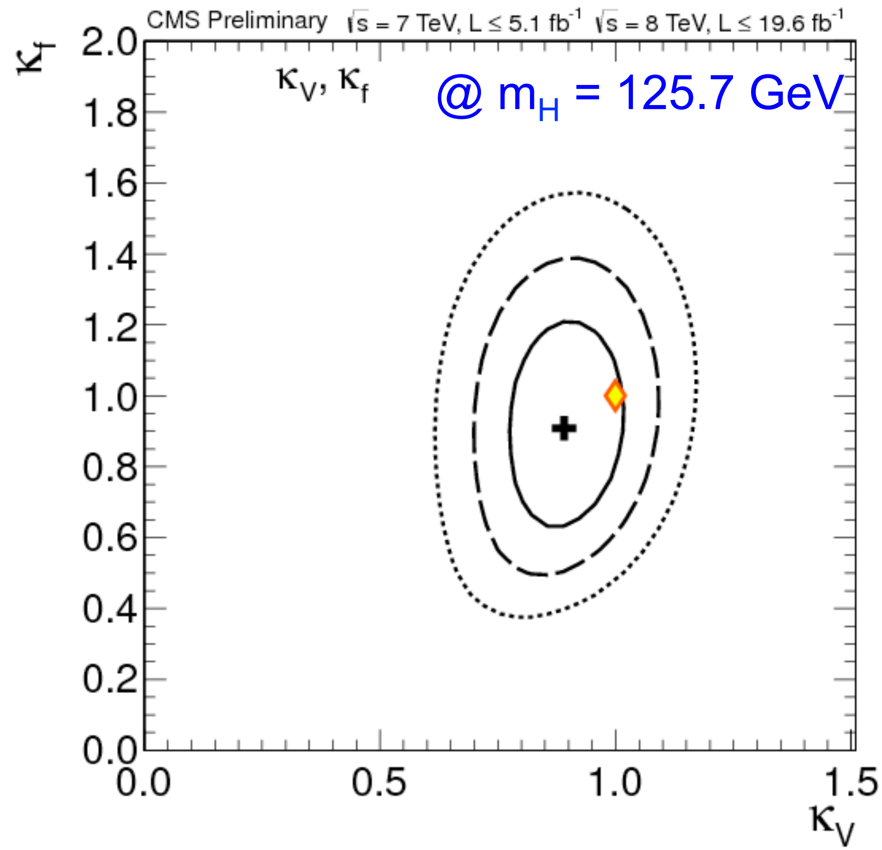
$H \rightarrow \gamma\gamma$:

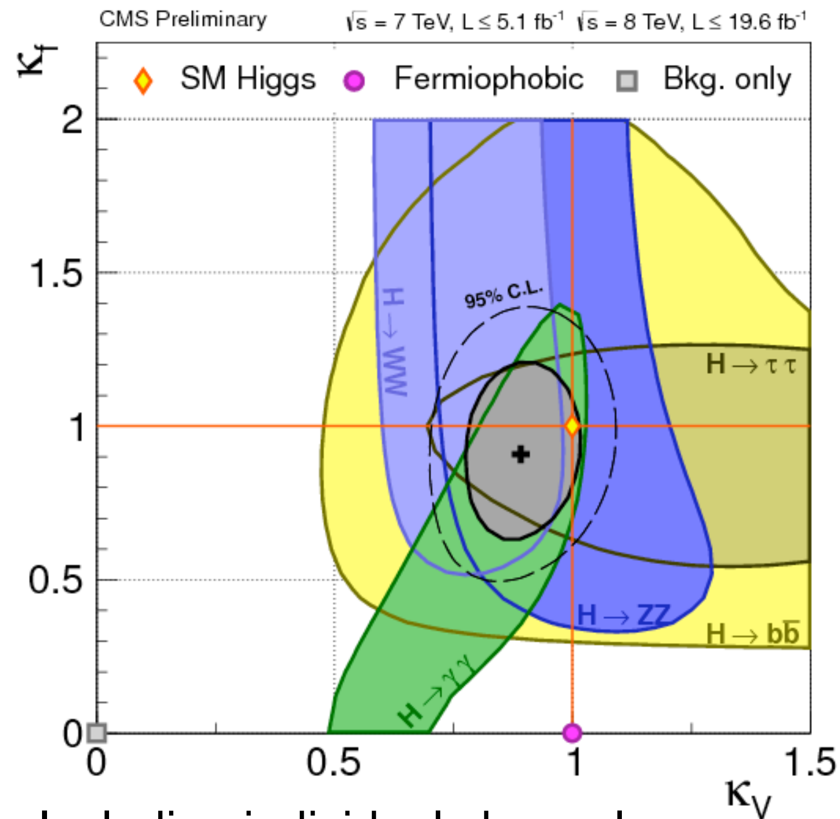
Systematics on the extrapolation from the Z → ee to H → γγ (0.25% (e to γ), 0.4% (Z to H))

m_H = 125.4 ± 0.5 (stat.) ±0.6 (syst.) GeV



m_X = 125.7 ± 0.3(stat) ± 0.3(syst) GeV
= 125.7 ± 0.4 GeV





Including individual channel

$\Gamma(H\text{->}\gamma\gamma) \sim |\alpha\, \kappa_V + \beta\, \kappa_f|^2$
$\alpha/\beta = -\,0.2$
$\Gamma_{BSM} = 0$

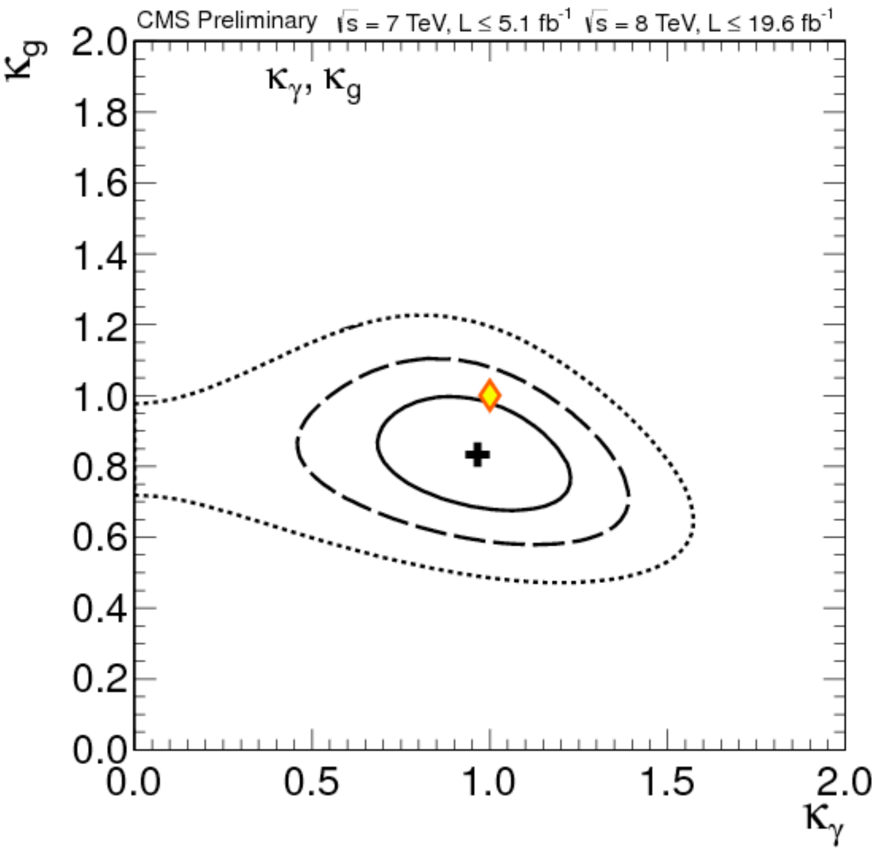
- Consistent with SM prediction

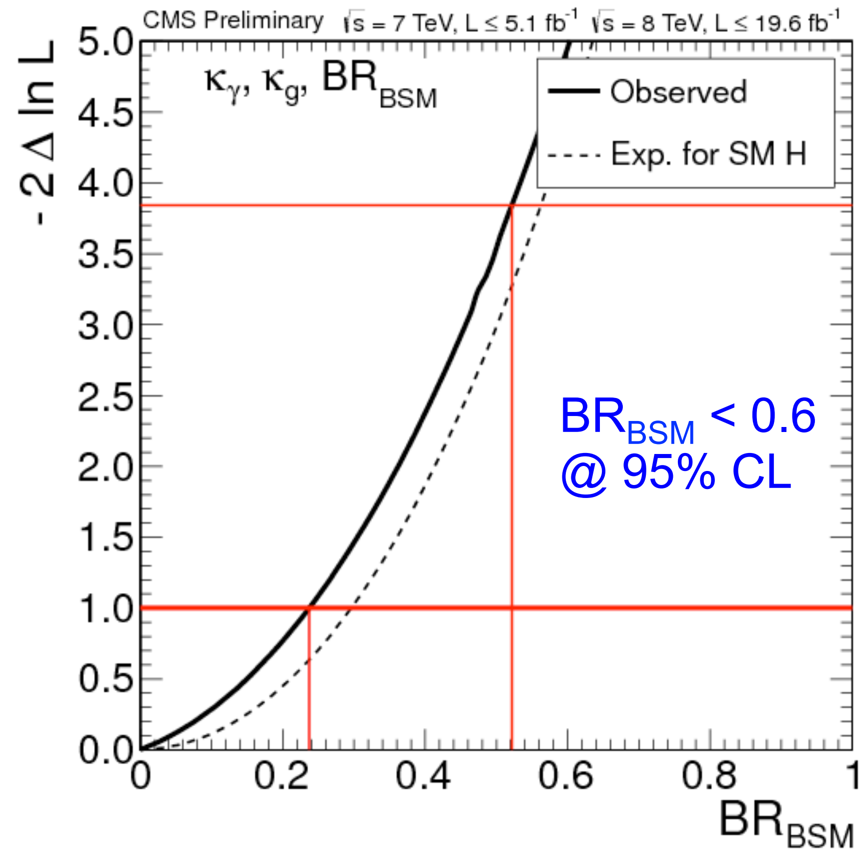
Conclusions and Outlook

- CMS has contributed in a significant manner to probing nature at the TeV scale
- CMS have given extensive proof of being able to deliver, at high quality and over short time scales
  - this promises well also for the coming years
- CMS discovered the first fundamental scalar field
- Spin-parity results are consistent with the SM Higgs and disfavor other considered scenarios
- Signal strengths are consistent with the SM prediction as well.
- Mass of the new boson is **125.7 ± 0.4 GeV**
- *More results to follow later this summer*
- A lot of experience with data analyses at Run 1
- Rather complex searches, pushing capabilities of the hardware to its fullest (but still a lot of things can be improved for Run 2)
- No evidence for physics beyond the SM so far – searches will continue
- Is new physics that control the Higgs mass is right around the corner? Or do we live in a very unnatural Universe?

Current Physics Landscape

Back up slides





Effective couplings to gluons and photons. Note best fit κ_γ ~1, with κ_g < 1 in line with μ < 1 in VV modes as well.
$\Gamma_{BSM} = 0$.

Loop-induced couplings free (κ_γ,κ_g profiled). Allowed for extra particles in loop, i.e. extra width

Comparison of latest CMS & ATLAS results

Channel	ATLAS Lumi [1/fb]	CMS Lumi [1/fb]	Specialty	Inclusive signature	σ Obs. (Exp.)	mass [GeV]	Signal Strength μ	Spin/ Parity
H → ZZ → 4l	4.6+20.7	5.1+19.6	mass, discovery, spin/parity	4 leptons	6.6 (4.4)	124.3 ±0.6 (stat) ±0.5 (sys)	1.5 ± 0.4	√
					6.7 (7.2)	125.8 ±0.5 (stat) ±0.2 (sys)	0.91+0.30-0.24	√
H → WW → 2l2ν	4.6+20.7	4.9+19.5	cross section, coupling	2 leptons, MET	3.8 (3.7)	consistent	1.01 ± 0.31	√
					4.0 (5.1)	consistent	0.76 ± 0.21	√
H → γγ	4.8+20.7	5.1+19.6	mass, discovery, couplings	two photons	7.4 (4.1)	126.8 ±0.2 (stat) ±0.7 (sys)	1.6 ± 0.3	√
					3.2 (4.2)	125.4 ±0.5 (stat) ±0.6 (sys)	0.78+0.28-0.26	-
H → bb	4.7+13.0	5.0+12.1	coupling to fermions	two b-jets	-	consistent	-0.4 ± 1.0	-
					2.2 (2.1)	consistent	1.3+0.7-0.6	-
H → ττ	4.6+13.0	4.9+19.4	couplings to leptons	hadronic taus, leptons, MET	1.1 (1.7)	consistent	0.8 ± 0.7	-
					2.9 (2.6)	120+9-7	1.1 ± 0.4	-

CMS (shaded rows) ATLAS (unshaded rows)