September 26, 2018

Search for physics beyond the standard model in high-mass diphoton events with p-p collisions at $\sqrt{s}$ = 13 TeV with the CMS at LHC

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Peking Univ. (CN)

About the speaker

1) → B.Sc. in Physics & M.Sc. in Particle & Nuclear Physics from Athens (GR)
   → Ph.D. basted at CERN, from Athens (GR)
   [2012-2016] Supersymmetry searches (1l, 2l) and more

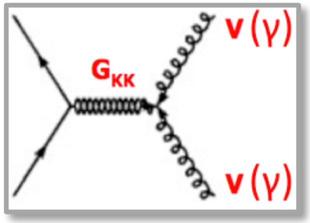
2) Postdoctoral associate at Rutgers Univ. NJ (US),
   [2016-2018] Diphoton search + HCAL service work and more

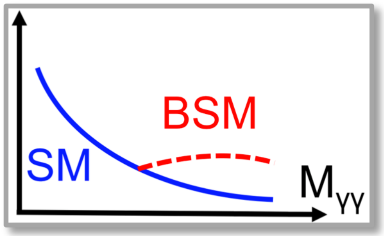
3) Postdoctoral associate at Peking University (CN),
   [2018-2020] Triboson searches (and more to come… soon!)

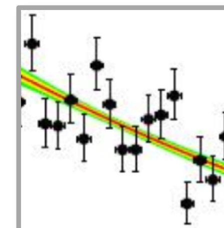
→ Always at CMS experiment [~2008 - till present]

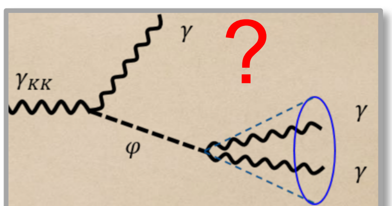
→ Large outreach & science communication activity (guides etc)

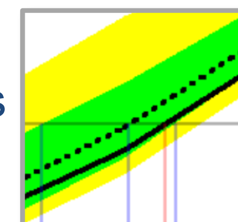
In this talk - Outline







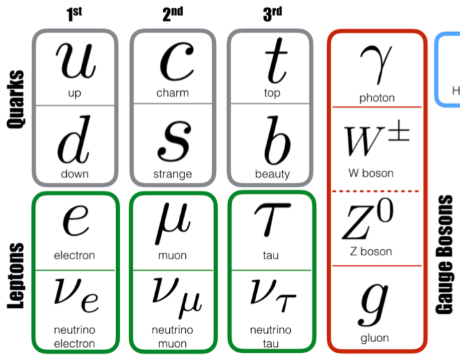


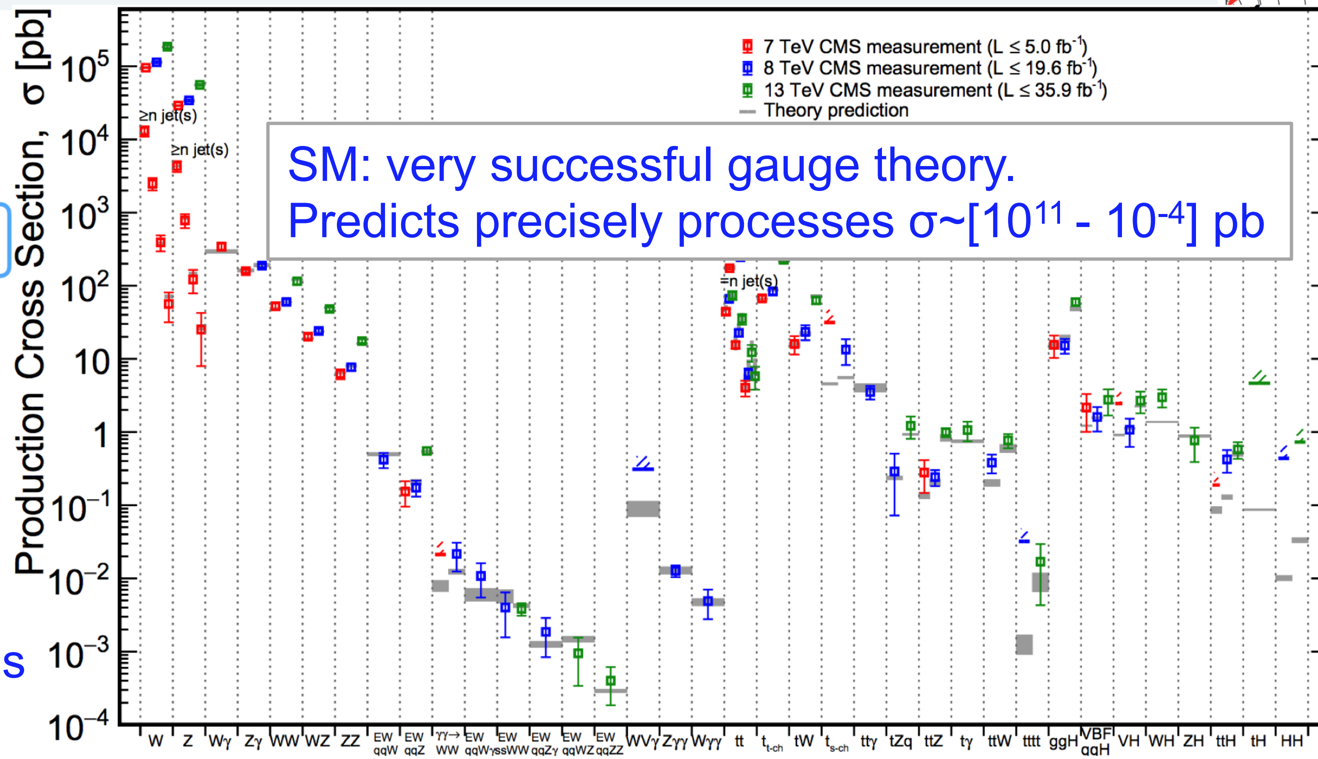


1) Motivation for a γγ search
2) Reconstruction and event selection
3) Signals' generation, simulation & features; MC samples, datasets and triggers used
4) (Data-driven) Background estimate
5) Systematic uncertainties treatment
6) Results' interpretation, limits for 2 models
7) Diphoton next steps and overview

→ Diphoton paper accepted at PRD: arXiv:1809.00327v1 (CWR review and by PKU)
→ This includes also a search for resonant signal
→ CMS "coordinates": EXO-17-017, AN-2017/030, AN-2017/206

SM: successes & shortcomings



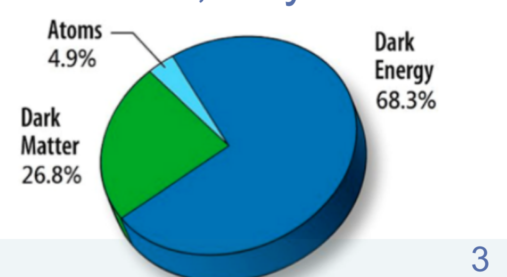


SM: very successful gauge theory.
Predicts precisely processes σ~[10^{11} - 10^{-4}] pb

However SM looks like is not a complete theory:

- m_{Higgs}: renormalizable → $m_{Higgs}^2 = m_{bare}^2 - [\pm\lambda\Lambda_{cut}^2 \pm \ldots] = 125^2\ \mathrm{GeV}^2$
  New Physics at: Λ_{cut}~10^2-10^{18}GeV ←→ "Hierarchy" or "Naturalness" Problem
  Λ_{cut}~10^{18} GeV, Pl.-scale: 125^2 = 123456789012345678901234567890123450 – 123456789012345678901234567889672000
- Unification GUT? Gravity QFT? 25 free parameters, 3 fermion families, why?
- Also shortcomings in Cosmology: Dark Matter, Dark Energy

→ SM looks "effective" rather than fundamental theory



γγ Search Motivation

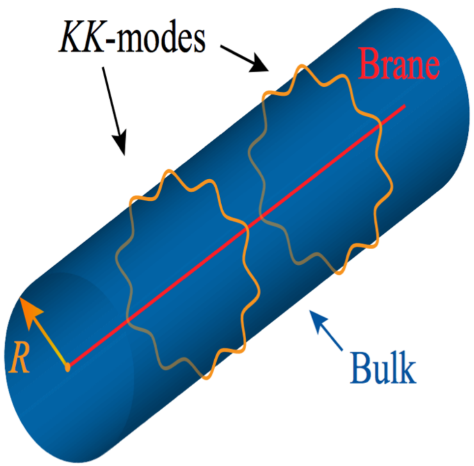
SM shortcomings indicate some kind of BSM physics (at least at Plank scale):

Large Extra Dimension – "ADD" [Arkani-Hamed, Dimopoulos, Dvali]

- Bulk consisting of [3+1] + n_{ED} Extra Dimension (ED)
- ED compactified with average radius R
- SM confined to 4D brane, gravity throughout bulk
- Gravity's strength comparable to the rest forces but dilutes in ED
- Effective M_{Pl} ~TeV-scale: $M_{\rm Pl}{}^2 \sim M_{\rm Pl(4+n)}^{2+n} R^n$
- KK excitations of gravitons (G_{KK}) decay to SM particles

Continuum Clockwork

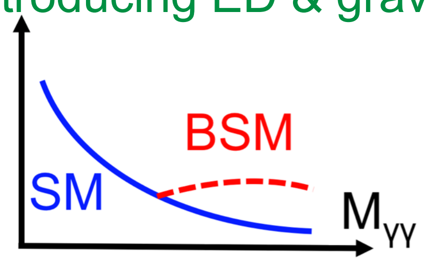
- Coincides with a 5D gravitational theory
- Mechanism that can take large effective interaction scales from dynamics occurring at much lower energies (arxiv:161007962).

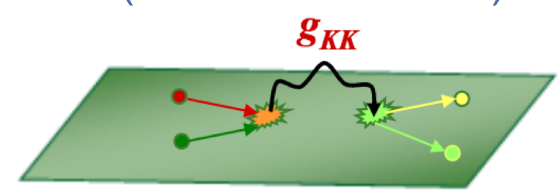


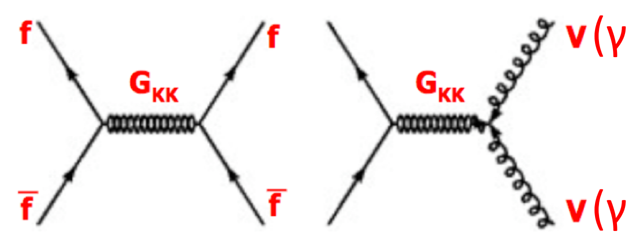
These models are:

→ Solving hierarchy problem by modifying the eff. Pl. scale

→ Introducing ED & graviton





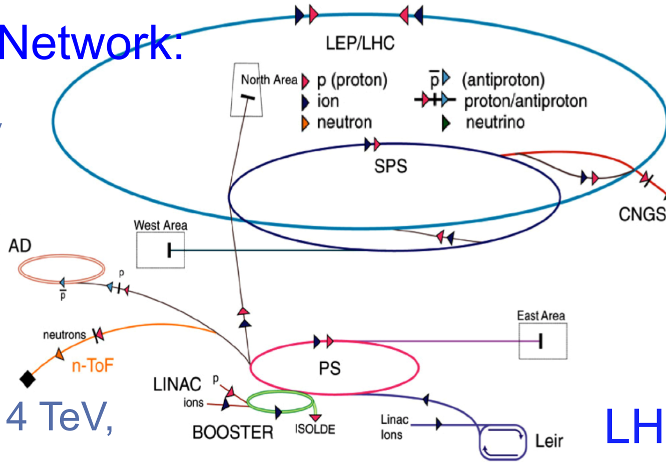


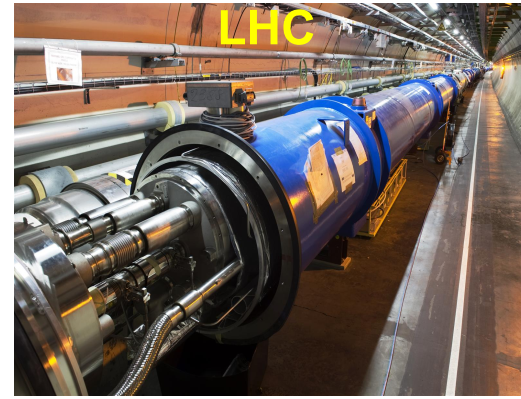
→ Can be visible at TeV-scale, through KK graviton modes, leading to SM (non-resonant) discrepancies in γγ final state

CERN, LHC, pp beams & CMS

CERN's Accelerators Network:

- LINAC2 → 50 MeV
- PS-Booster → 1.4 GeV
- PS-Rink → 26 GeV
- SPS → 450 GeV
- LHC → 7 TeV



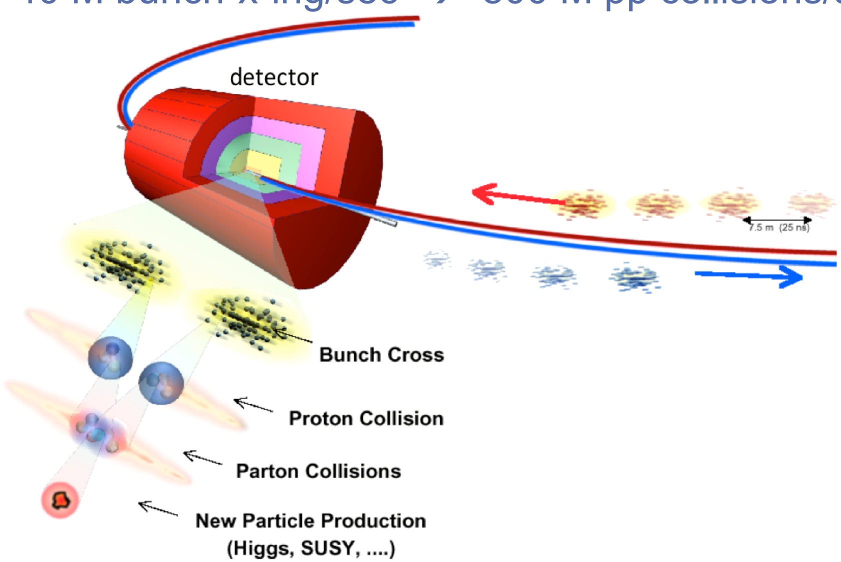


LHC Beams:

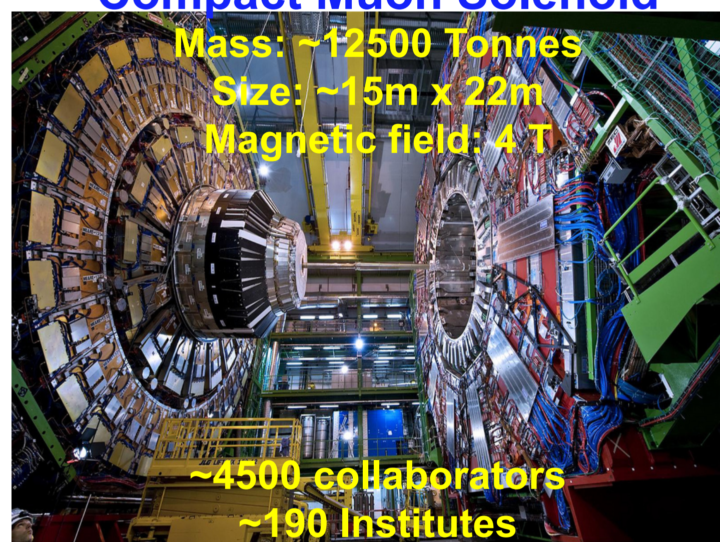
- 2x7 TeV pp beams = 14 TeV,
- L~ 10^{34} $sec^{-1}cm^{-2}$
- ~2800x2 p-bunches,
- 25ns, 7.5m spacing
- 4 collision points: ATLAS, CMS… PU~25-50
- 40 M bunch-x-ing/sec → 800 M pp collisions/s

LHC: 26.7 km, 40-175 m bellow ground

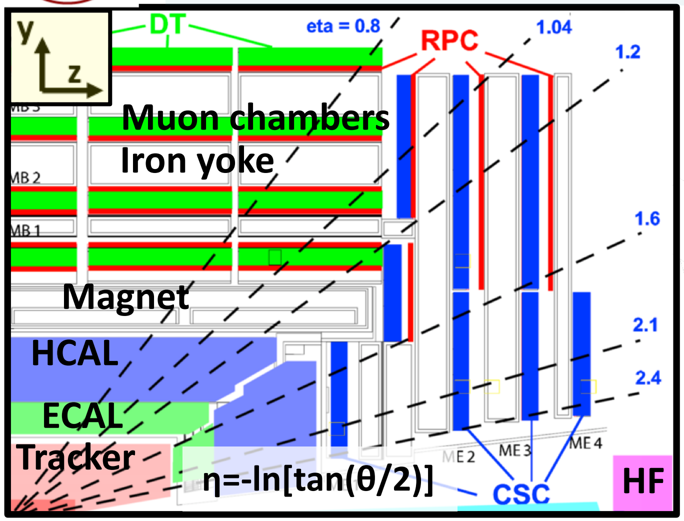
- 1232 dipoles, 392 quadrupoles, 2x8 RF-cav
- B = 8.33 T , I~12 500 Ampere,
- NbTi supercond. T=1.9 K =-271.3 C^o (He)

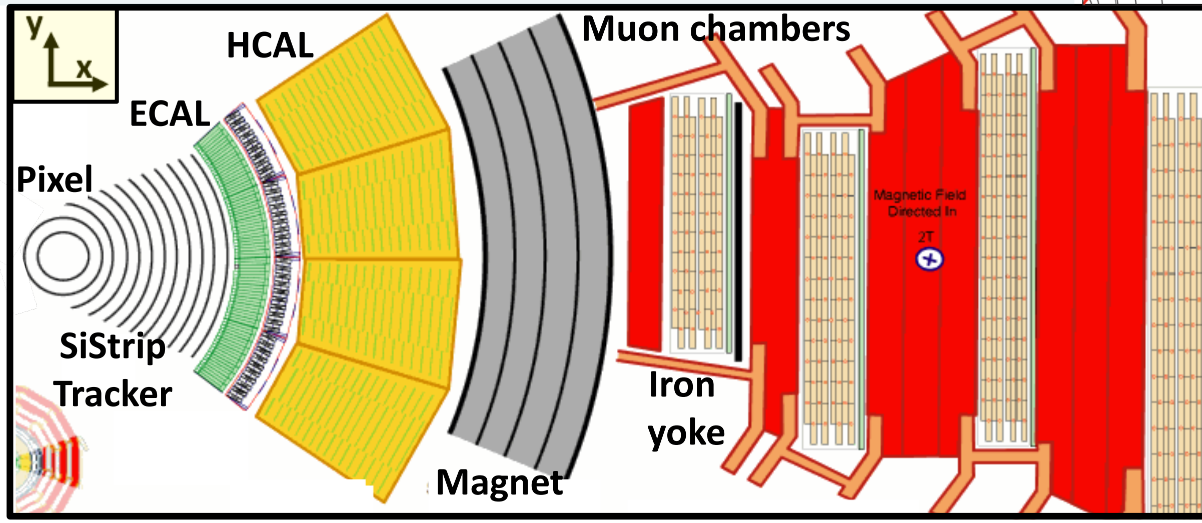


Compact Muon Solenoid

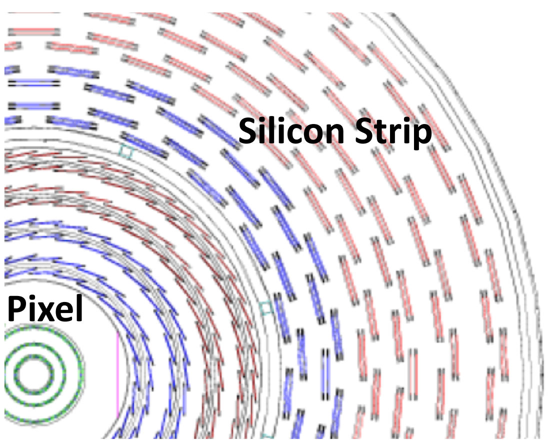


CMS Sub-detectors (a glance)

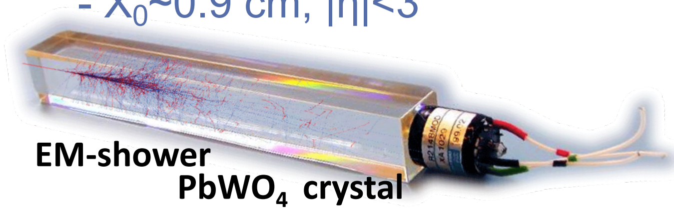




Pixel & Silicon Tracker
- 70M pixels
- “e-holes” pairs→ signal
- |η|<2.5, 2.4 (hits:11 barrel)



ECAL ($e^{\pm}$,γ)
- Lead Tungstate
- 76k crystals $PbWO_4$
- X_0~0.9 cm, |η|<3



HCAL ($p^{\pm}$,n,π,K,Δ…)
- HB, HE (16 leyers), HO, HF
- Plastic scint.:Quartz fibers
- Brass(Cu-Zn) absorber
- X_0~1.5cm, |η|<3

Solenoid Magnet, Iron Yoke
- NiTi, T~1.8K, I~19kA, B~4T

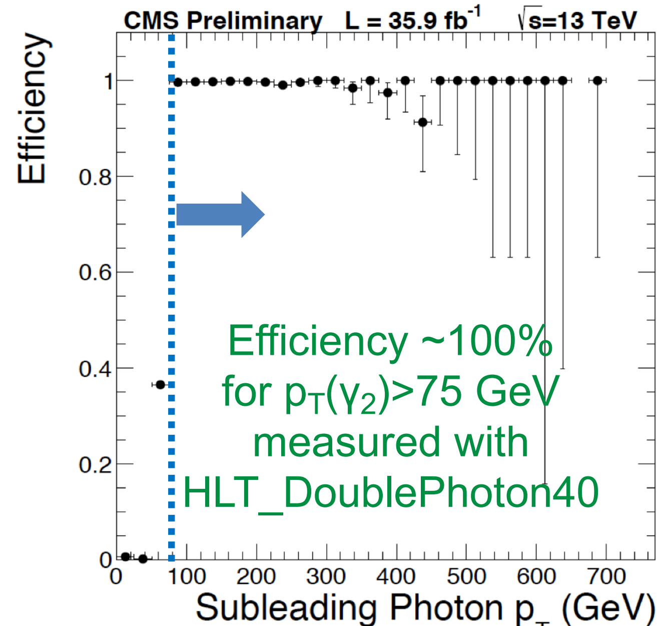
Muon chambers:
- DTs, CSCs, RPCs,|η|<2.4
- Argon-based gasses

Trigger:
- L1→HLT→DAQ
- 40M→40K→~100 ev./s
- Store:Tier-0-1-2→GRID...

Event Reco. & Selection

Triggers: [2016 DoubleEG data, 35.9 fb^{-1}]

- Use HLT_DoublePhoton60 "or" HLT_ECALHT800 for main analysis
- Use HLT_Ele27_WPTight_Gsf for $Z \rightarrow e^+e^-$ control sample (energy scale and efficiency measurement)
- Diphoton vertex identification: Use $H \rightarrow \gamma\gamma$ BDT discriminant

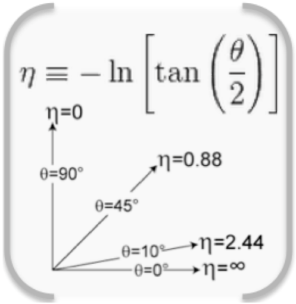


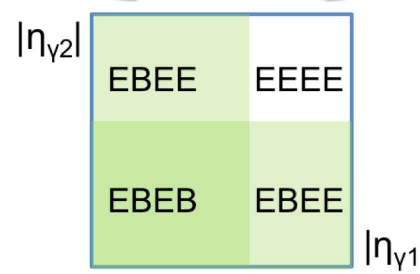
Photon identification (high-p_T γ ID):

1) $\sigma_{i\eta i\eta}$ < 0.0105 [0.0112] for EB
   < 0.028 [0.03] for EE
2) H/E < 0.05
3) Iso_γ^{corr} < 2.75(2.0) GeV for EB(EE), correction for "pileup"
4) Iso_{CH} < 5 GeV in a cone: $\Delta R = \sqrt{(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2}$
5) CSEV: applied (conversion safe $e^\pm$ veto)
6) R_9 > 0.8
   3x3 ECAL cluster E / Seed crystal E

Kinematic selection:

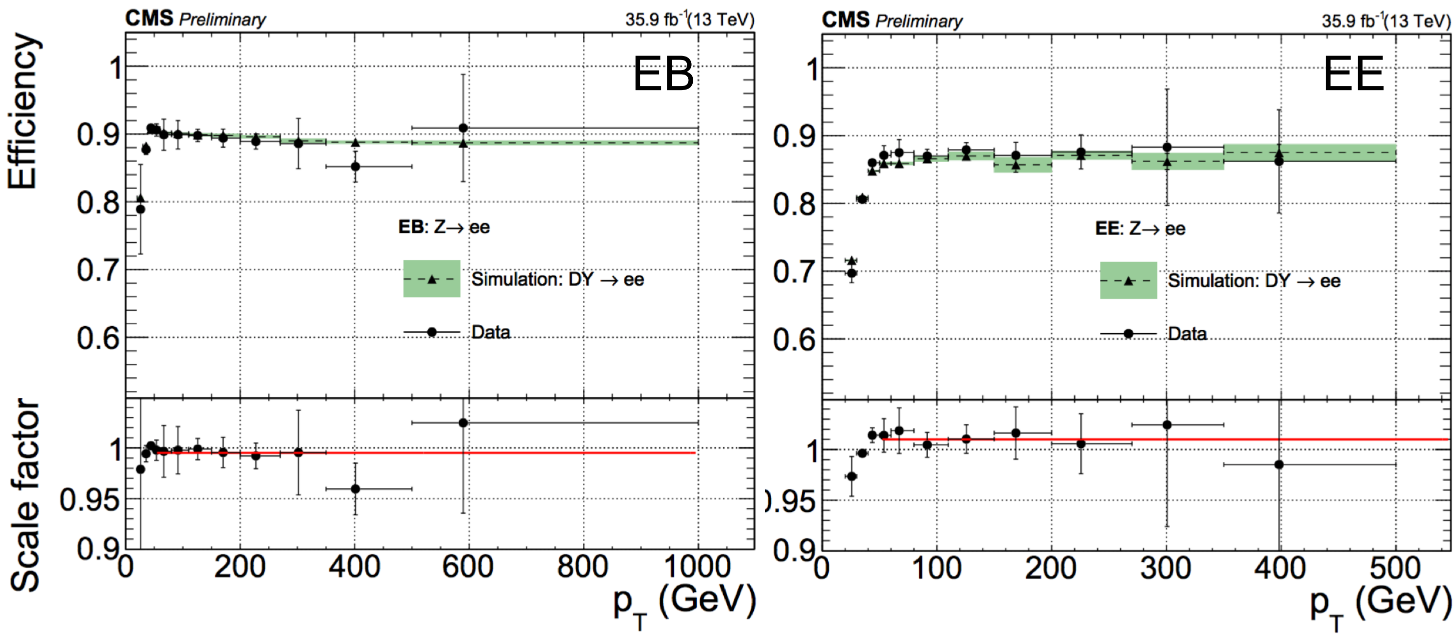
1) $N_\gamma >= 2$,
2) $p_{T\gamma}$ > 75 GeV,
3) $|\eta_\gamma|$: [0, 1.4442] or [1.566, 2.5],
4) At least one γ in EB → EBEB, EBEE
5) $M_{\gamma\gamma}$ > 500 GeV





Photon ID efficiency measurement

- Use MC $Z \rightarrow e^+e^-$ events and SingleElectron dataset
- Photon ID eff. measured with: "Tag & Probe"
  → Tag : tight $e^{\pm}$-ID + M_{ee} cut
  → Probe: loose preselection + analysis ID with inverted CSEV



- Scale Factors are flat vs $p_{T\gamma}$ and are compatible with ~1 (no trend within stat.)
  → Uncertainty per leg ~3% (averaging last 3 bins)
  → Total sys. uncertainty attributed per event: 6%

Signal MC: ADD & C. Clockwork

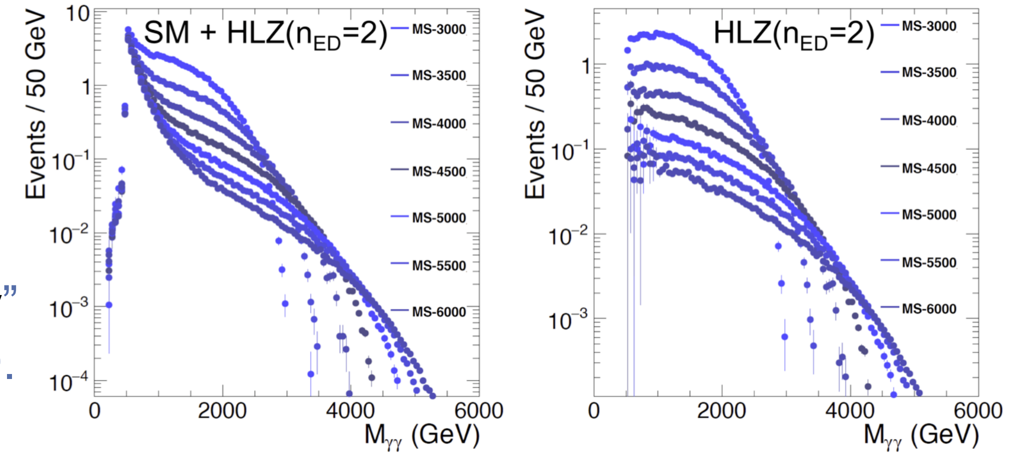
- Total cross section of SM+ADD process: $\sigma_{\text{total}} = \sigma_{\text{SM}} + \frac{\mathcal{F}}{M_S^4}\sigma_{\text{int}} + \frac{\mathcal{F}^2}{M_S^8}\sigma_{\text{ADD}}$

$\mathcal{F}$-conventions:

$$\mathcal{F} = \begin{cases} 1 & \text{(GRW)}, \\ \log\left(\frac{M_S^2}{\hat{s}}\right), \text{ if } n_{ED} = 2 & \\ \frac{2}{n_{ED}-2}, \text{ if } n_{ED} > 2 & \text{(HLZ)}, \\ \pm\frac{2}{\pi} & \text{(Hewett)}, \end{cases}$$

- Parametrization:
  M_S: UV cutoff scale,
  n_{ED} :number of extra dimensions.

- Include the interference term
  → production "SM+ADD" & "SM-only"
  → Use SHERPA (LO) to extract ADD.



C. Clockwork:

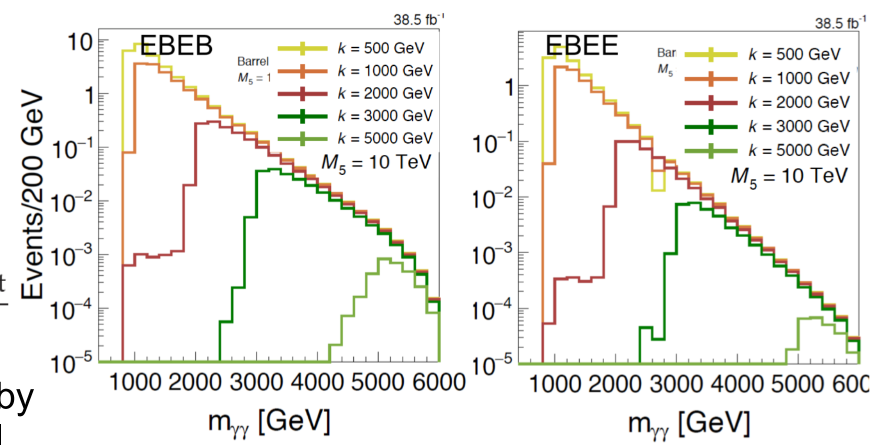
- KK modes all on-shell → no interference
- Use ADD sample [CMS central production]
  → translate in CW → write the x-secs as:

$$\sigma_{\text{Hewett}} = \frac{-2/\pi}{M_S^4}\sigma_{\text{int}} + \frac{4/\pi^2}{M_S^8}\sigma_{\text{ADD}}$$

$$\sigma_{\text{GRW}} = \frac{1}{M_S^4}\sigma_{\text{int}} + \frac{1}{M_S^8}\sigma_{\text{ADD}}$$

$$\frac{\sigma_{\text{ADD}}}{M_S^8} = \frac{\sigma_{\text{GRW}} + \frac{\pi}{2}\sigma_{\text{Hewett}}}{1 + \frac{2}{\pi}}$$

This direct term is scaled by a factor to form CW signal.



[Use only the range $M_{\gamma\gamma}$ > 0.9 TeV]

γγ real background prediction

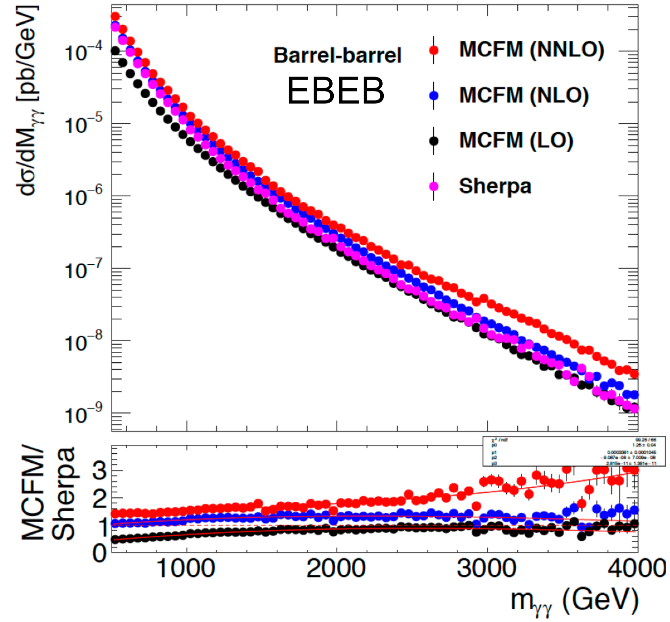
Two different types of BKG mainly contributing:

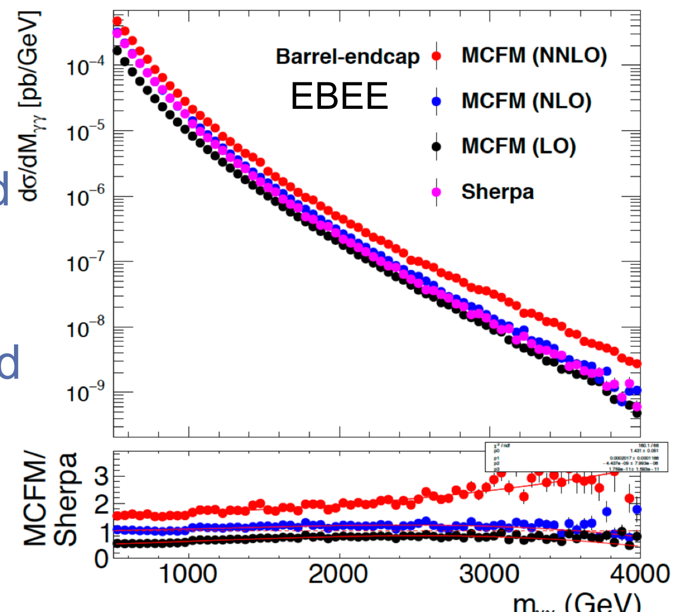
1) prompt (real) γγ 2) fake jγ, jj

- Irreducible prompt SM diphoton "γγ"
  Generated using SHERPA 2.1.1, CT10 PDFs set
  → Box process
  → Born process with up to 3 additional final state jets/partons

- NNLO contribution calculated using the MCFM and corrected by reweighting events at $m_{\gamma\gamma}$ gen-level

- K factor: MCFM^{NNLO} / SHERPA function of $m_{\gamma\gamma}$ used to reweight simulated prompt diphoton (SHERPA) events for prediction.
  → K factor ranges: ~1.4-1.8 for $m_{\gamma\gamma}$<2 TeV EBEB





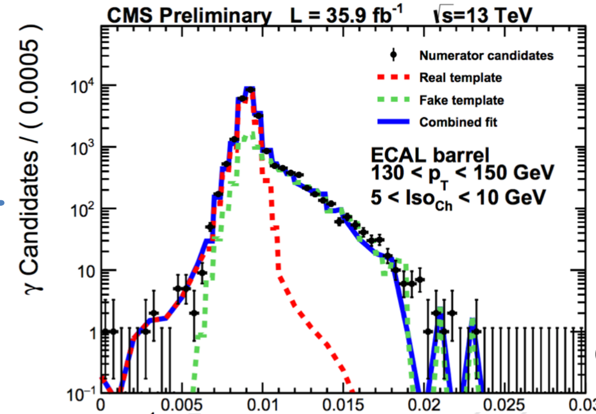
Fake BKG: γj, jj - Rate & estimate

Fake BKG γj, jj. Events where 1,2 jets with large EM activity fake a "γ", typically π^0,η^0

- Define the: Fake Rate (FR): $f = \dfrac{\text{number of jets passing high } p_T \text{ ID}}{\text{number of jets passing denominator definition}}$
- Measure FR in a jet-rich dataset [JetHT, DoubleMu] as a function of $p_{T\gamma}$, EB, EE
- Use FR to reweight data to estimate the fake BKG: $M_{\gamma\gamma}^{Fake}$

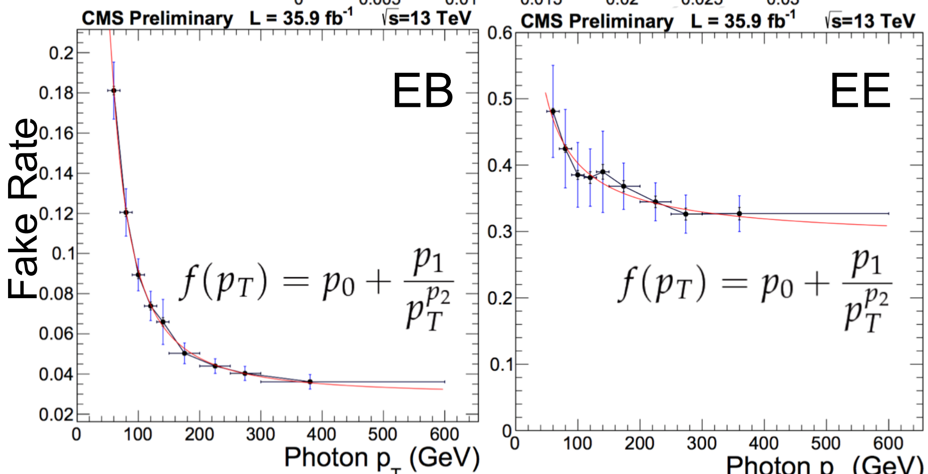
Numerator → must have only fake objects

- Use "fake-sensitive" template variable $\sigma_{i\eta i\eta}$
- Real template from MC
- Fake template from $5<Iso_{CH}<10$ GeV sideband
- MLE-fit in data to get # pure fake numerator objects

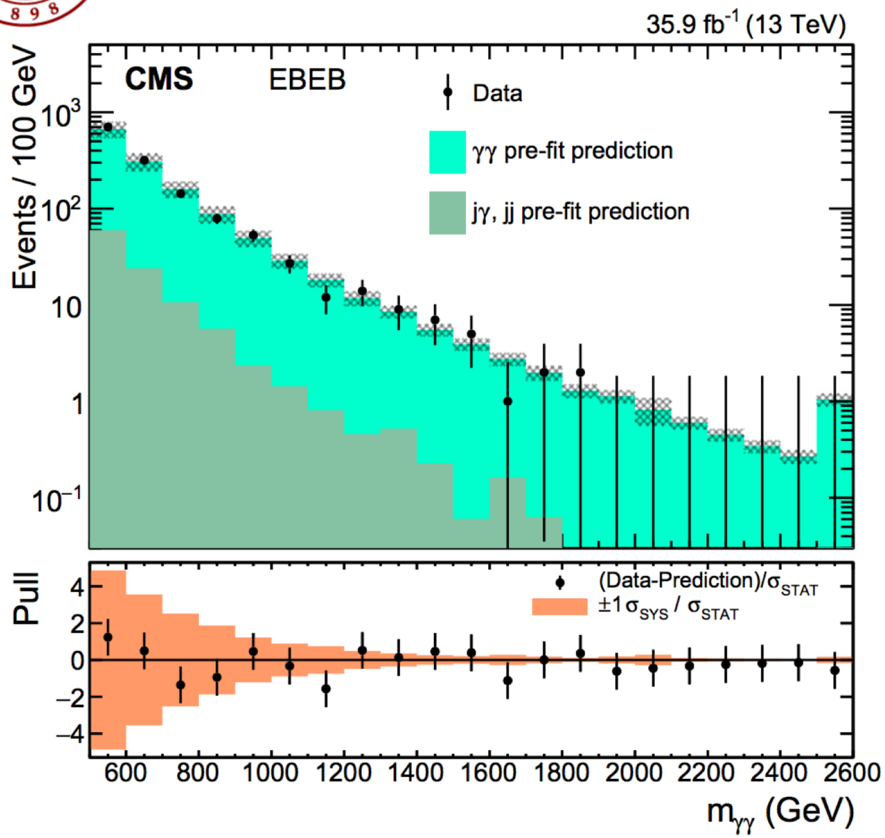


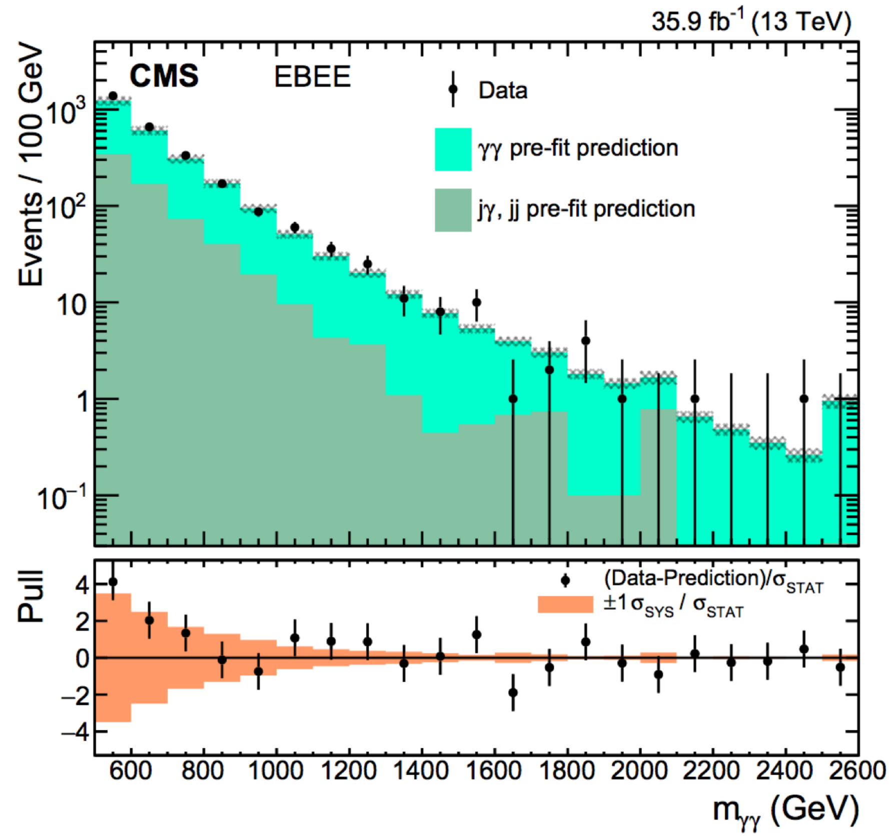
Denominator → γ-like obj. in a loose sel.

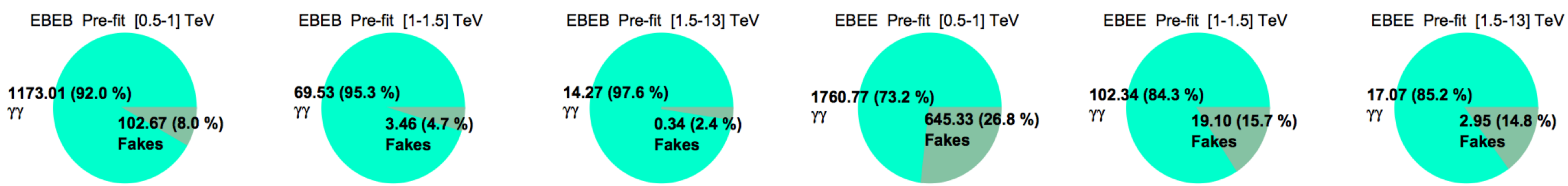
- Pass CSEV
- $Iso_{CH} < 0.2\, p_T$
- $Iso_\gamma^{CORR} < 0.2\, p_T$ (2 GeV) EB(EE)
- H/E < 0.1
- Fail at least 1 "γ ID" cut (orthogonality)



Pre-fit Predicted Spectra







- This pre-fit prediction consist of the 1st of the two "layers" of our prediction
- The 2nd and final predictions comes from the marginalization of nuis. param.
- Good agreement in general (apart from a weak trend at [0.5-1] TeV EBEE)

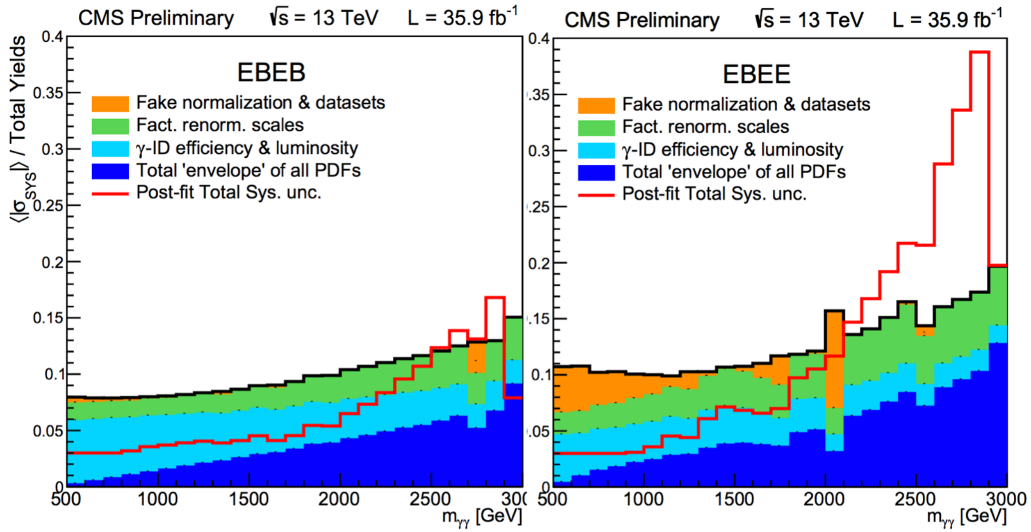
Systematics Unc. / Nuisance param.

The Approach:

- We attribute a nuisance parameter to each source of uncertainty
- Perform "Bayesian Marginalization" (MLE fit) to the data to extract posteriors
- Fit (dominated by low $M_{\gamma\gamma}$) constrains the tails' sys. unc. → Post-fit $M_{\gamma\gamma}$ spectra

Prompt γγ BKG:

- Normalization: float arbitrarily → absorbs uncertainties in higher order terms not included in our NNLO K factor; absorbs Lumi 2.5%, γ-ID eff. 6%
- Scale variations: μ_r , μ_f on K-factor calculation
- PDFs: 26 NLO CT10 eigenvector pair variations using DIPHOX^{NLO}
- Shape difference in MCFM^{NNLO} and MCFM^{NLO} and DIPHOX^{NLO}



Fake BKG:

- Normalization 30% uncertainty (pileup, non-closure)
- Shape differences in fake rate from JetHT and DoubleMuon datasets

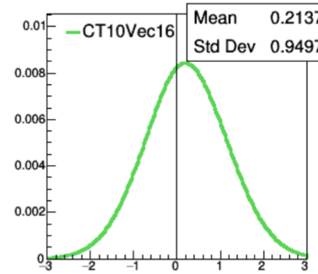
MC signal:

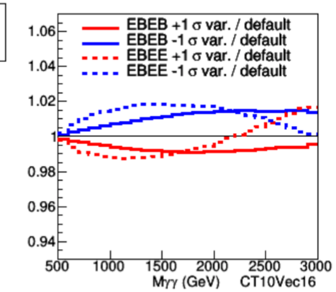
- Lumi. 2.5%, γ-ID eff. 6%
- PDFs: 26 NLO CT10 eigenvector pair variations using DIPHOX at NLO

Nuisance param. Posteriors & Corr.

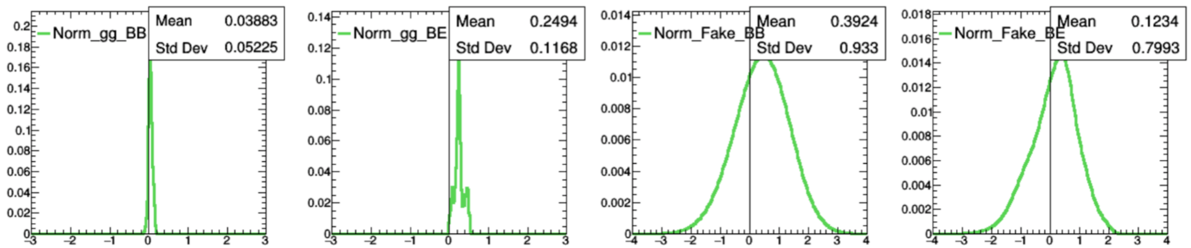
We use in total 35 nuisance parameters.
A few examples of posterior distributions are:

- A typical example (over 26) from the PDF → posteriors (are gaussian-like)

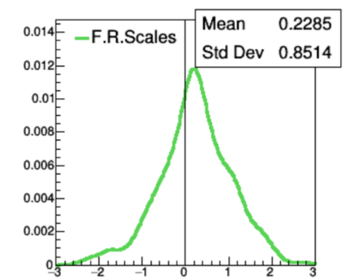


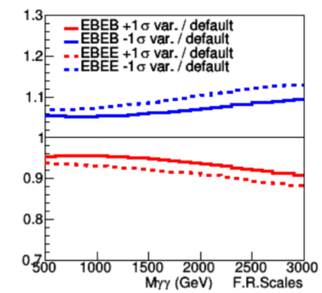


- Four normalization nuisance parameters → (spike-like for real-γγ)

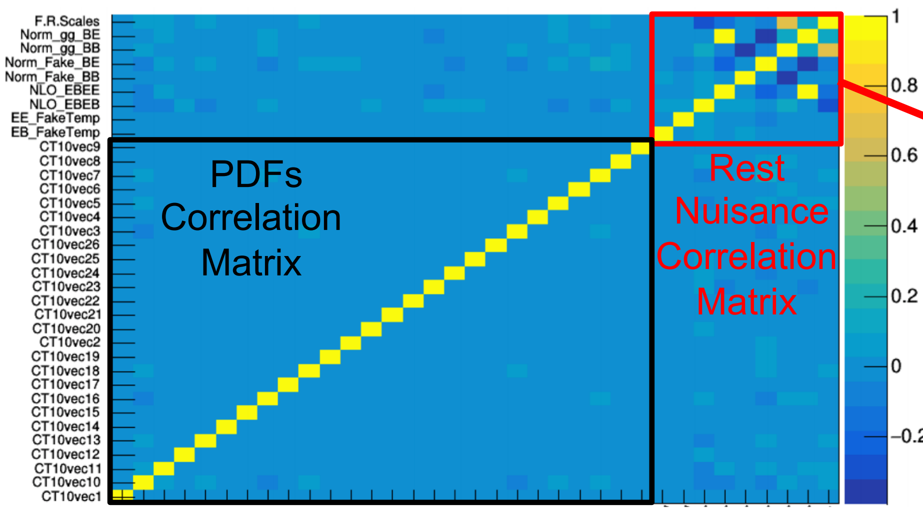


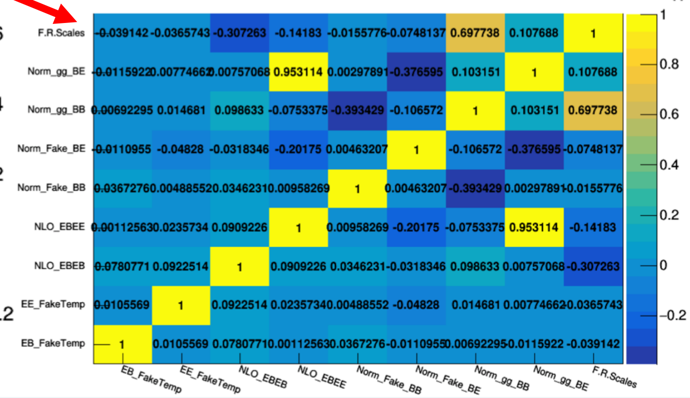
- Scale variations μ_r, μ_f on K-factor calculation→





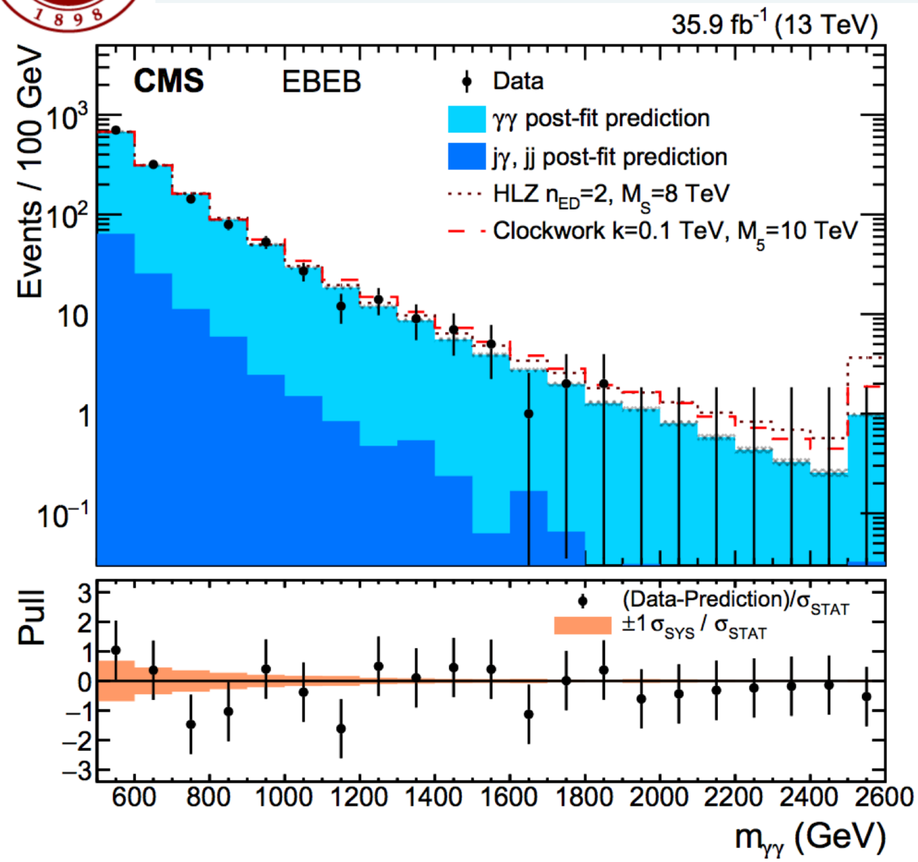
- Correlation Matrix:

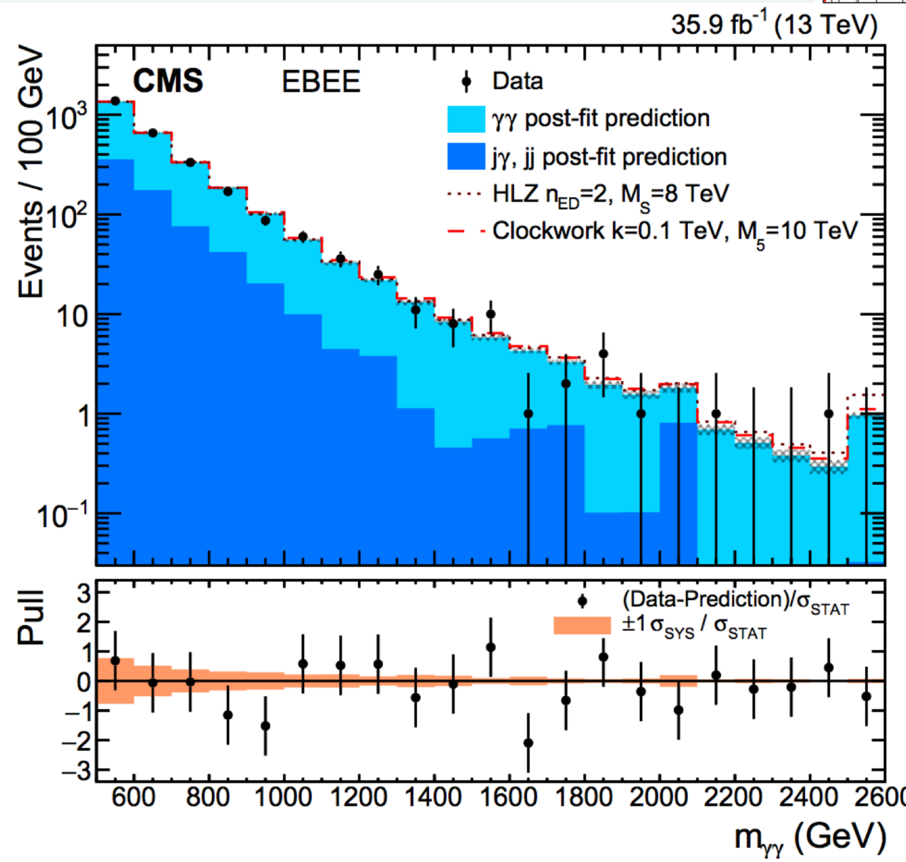


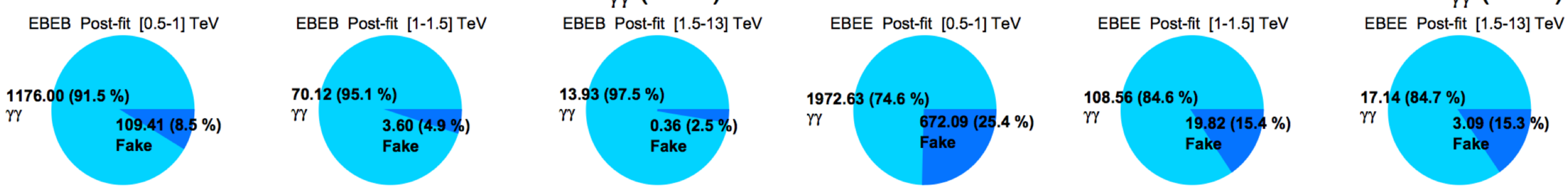


	EB_FakeTemp	EE_FakeTemp	NLO_EBEB	NLO_EBEE	Norm_Fake_BB	Norm_Fake_BE	Norm_gg_BB	Norm_gg_BE	F.R.Scales
F.R.Scales	-0.039142	-0.0365743	-0.307263	-0.14183	-0.0155776	-0.0748137	0.697738	0.107688	1
Norm_gg_BE	-0.0115922	0.00774662	0.00757068	0.953114	0.00297891	-0.376595	0.103151	1	0.107688
Norm_gg_BB	0.00692295	0.014681	0.098633	-0.0753375	-0.393429	-0.106572	1	0.103151	0.697738
Norm_Fake_BE	-0.0110955	-0.04828	-0.0318346	-0.20175	0.00463207	1	-0.106572	-0.376595	-0.0748137
Norm_Fake_BB	0.0367276	0.00488552	0.0346231	0.00958269	1	0.00463207	-0.393429	0.00297891	-0.0155776
NLO_EBEE	0.00112563	0.0235734	0.0909226	1	0.00958269	-0.20175	-0.0753375	0.953114	-0.14183
NLO_EBEB	0.0780771	0.0922514	1	0.0909226	0.0346231	-0.0318346	0.098633	0.00757068	-0.307263
EE_FakeTemp	0.0105569	1	0.0922514	0.0235734	0.00488552	-0.04828	0.014681	0.00774662	-0.0365743
EB_FakeTemp	1	0.0105569	0.0780771	0.00112563	0.0367276	-0.0110955	0.00692295	-0.0115922	-0.039142

Post-fit Predicted Spectra







- This Post-fit prediction consist of the “final layer” of the two of our prediction
- Good agreement within uncertainties.

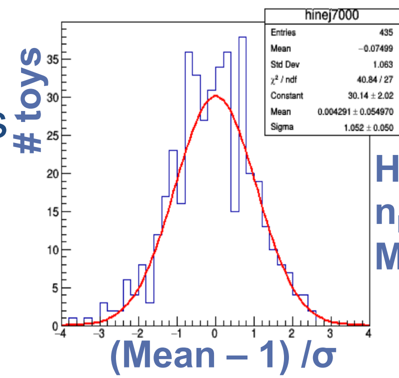
Exclusion limits on ADD & CCW

ADD: no indication of a signal

- We set upper limits on signal strength → lower limits on M_S (UV-cutoff scale):

Signal:	GRW	Hewett negative	Hewett positive	HLZ $n_{ED}=2$	HLZ $n_{ED}=3$	HLZ $n_{ED}=4$	HLZ $n_{ED}=5$	HLZ $n_{ED}=6$	HLZ $n_{ED}=7$
Expected:	$7.1^{+0.7}_{-0.5}$	$5.5^{+0.1}_{-0.3}$	$6.3^{+0.6}_{-0.4}$	$8.4^{+1.3}_{-1.1}$	$8.4^{+0.8}_{-0.6}$	$7.1^{+0.7}_{-0.5}$	$6.4^{+0.6}_{-0.5}$	$6.0^{+0.6}_{-0.4}$	$5.6^{+0.6}_{-0.4}$
Observed:	7.8	5.6	7.0	9.7	9.3	7.8	7.0	6.6	6.2

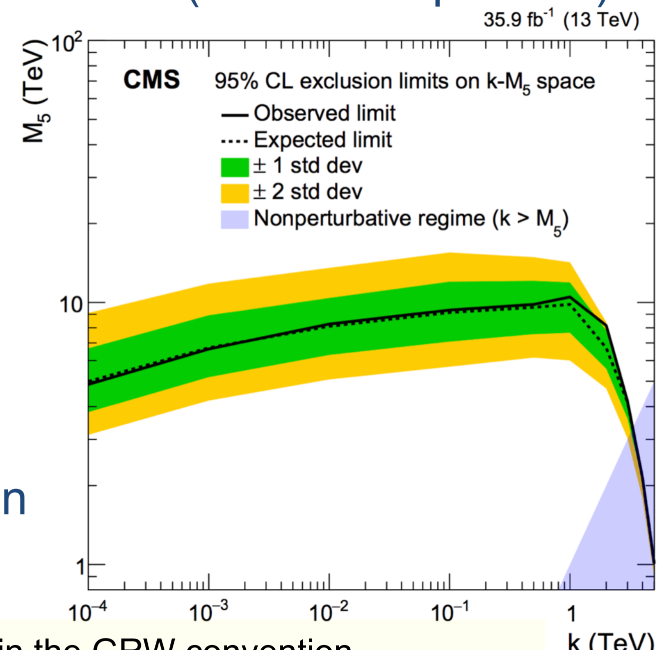
- Obs. limits are ~1σ stronger than the exp. (data under-fluctuation >2TeV)
- Better by ~0.9 TeV wrt ATLAS limits: arXiv:1707.04147 (see back up slides).
- Signal injection tests showed no biases:



HLZ
$n_{ED}=2$
$M_S=7$ TeV

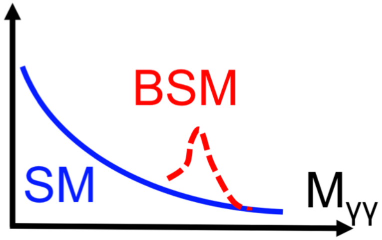
Continuum Clockwork:

- Perform marginalization over $m_{\gamma\gamma} > 0.9$ TeV (due to poor statistics of the ADD model used in signal construction).
- For k = 100 GeV we exclude up to $M_5 < 8$ TeV

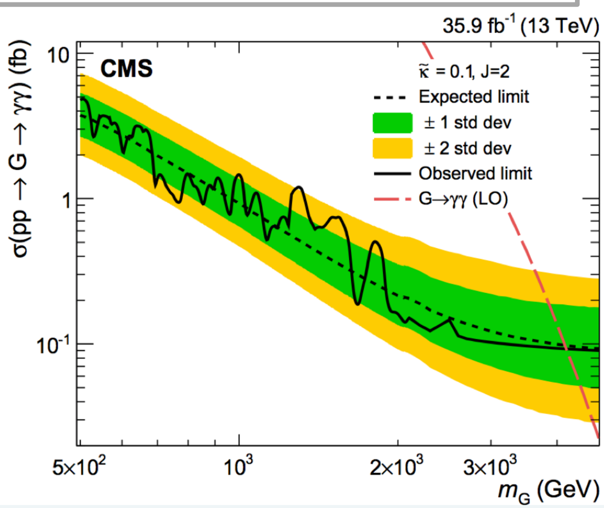


M_S: defined in the GRW convention,
M_5: fundamental scale of the grav. interactions
k: ‘clockwork spring’

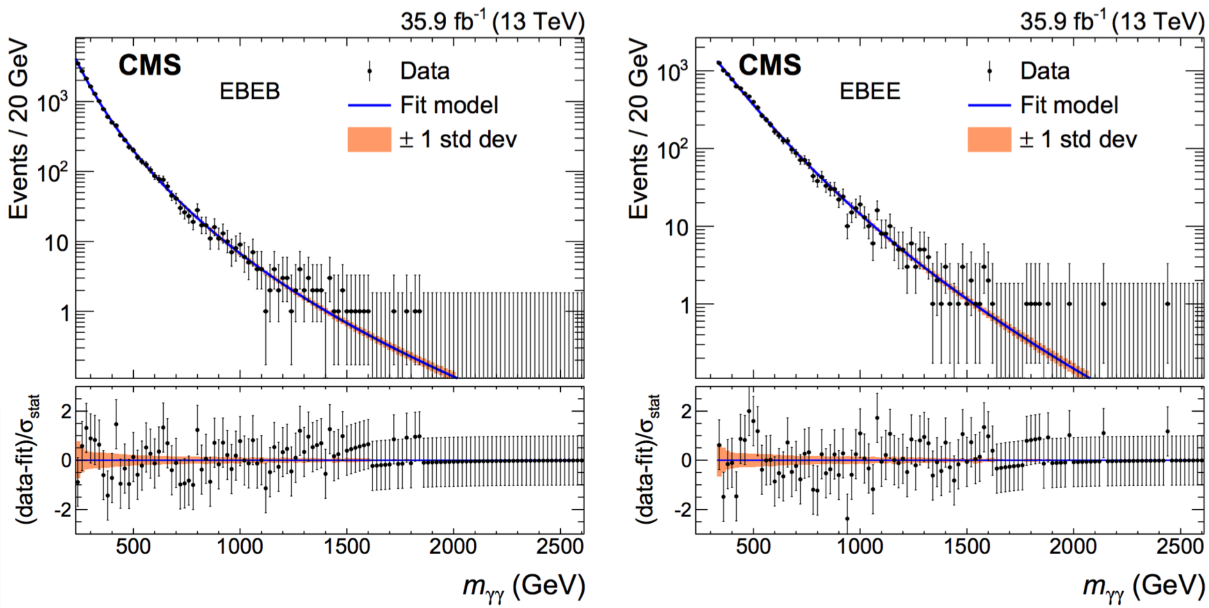
Exclusion limits for Resonant signal



RS graviton (warped ED)
- one extra dimension
- compactified with r_c
- curvature k
- scales masses in 4D as:
  $m = e^{-kr_c\pi} m_0$
- scaling M_{Pl} ~TeV-scale
  (kr_c ~ 11-12)

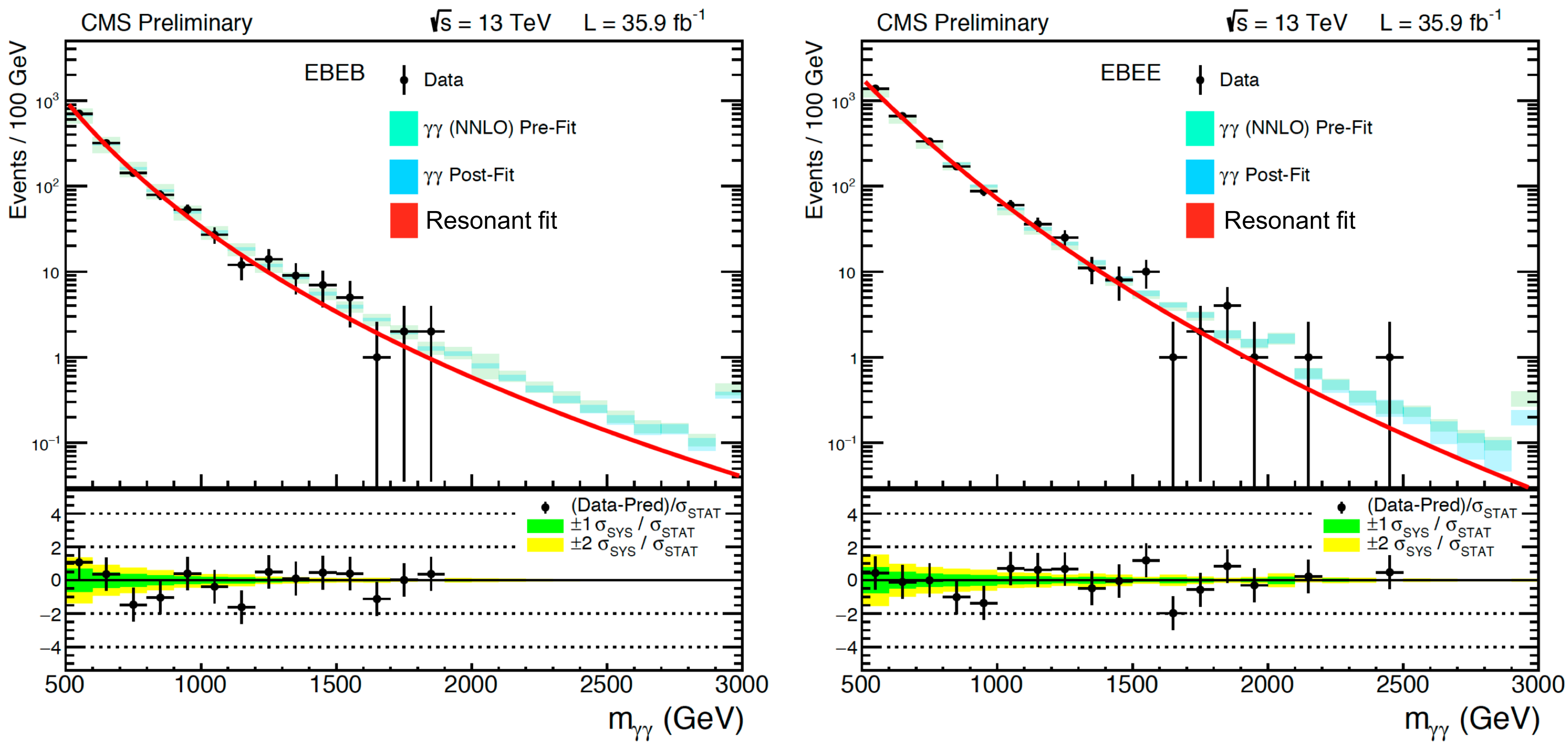


- Having a look at the same data (very similar selection) for a narrow structure:
- SM BKG parametrized as: $g(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\,log(m_{\gamma\gamma})}$
  → 2 param. treated as unconstrained nuisance param. in the unbinned maximum likelihood fit.



- 95% Limits set using: Asymptotic CLs method
- Much more on our paper: arXiv:1809.00327v1 (J=2, J=0, EBEB/EBEE breakdown, various Γ/m_X)

Raw comparison Reso-vs-NonReso

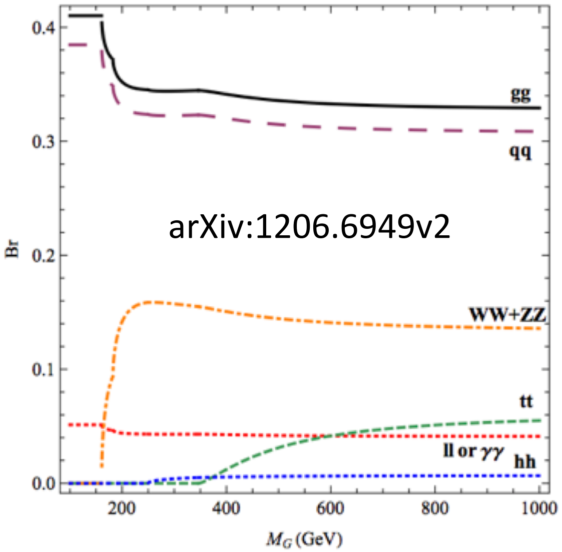


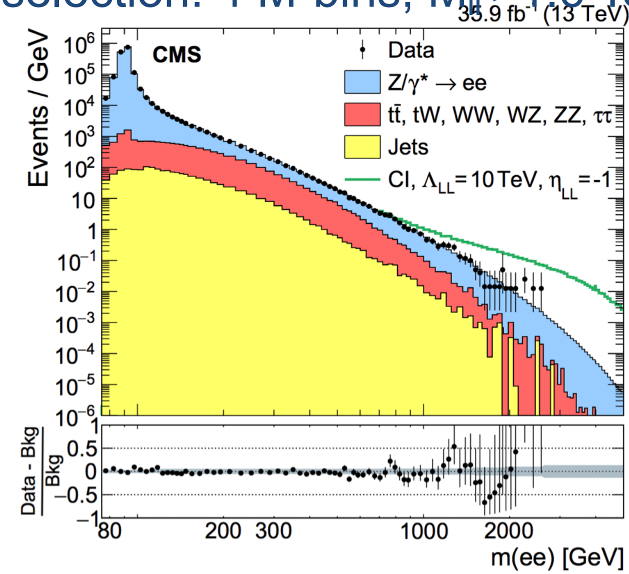
The two approaches/methods for $M_{\gamma\gamma}$ spectra are in a good agreement

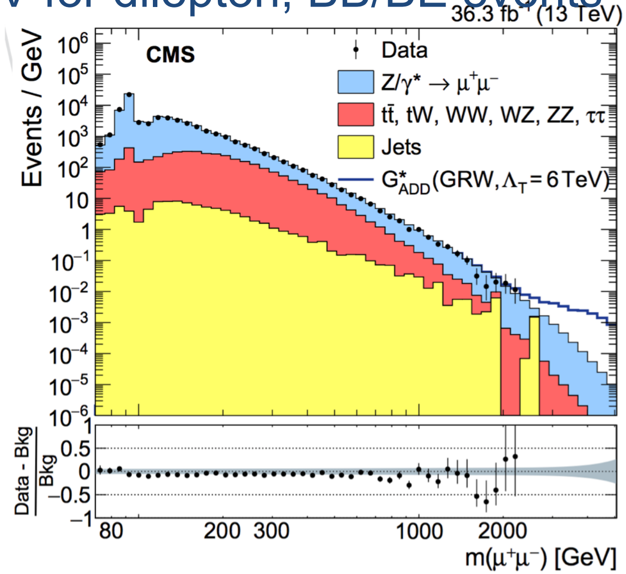
- Good agreement up to ~1.4 TeV
- Small deviations above ~1.7 TeV where we have poor statistics.

ADD Exclusion limits for γγ + μμ + ee

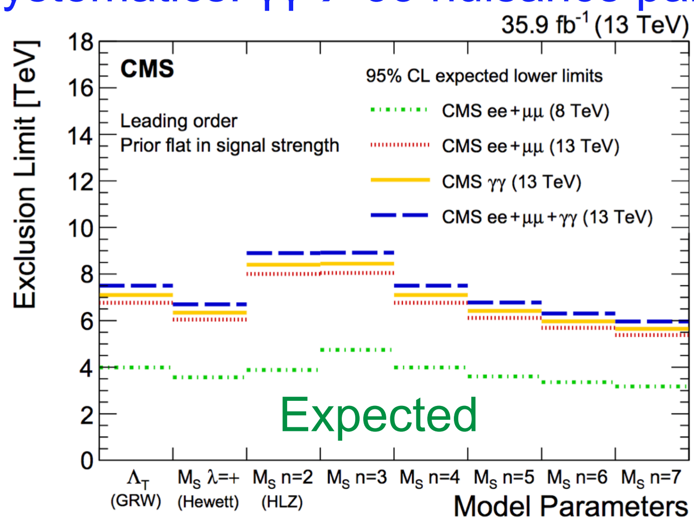
- CMS combined the three channels to set stronger limits
- Similar kinematics/selection: 4 M-bins, M_{ll}>1.6 TeV for dilepton, BB/BE events

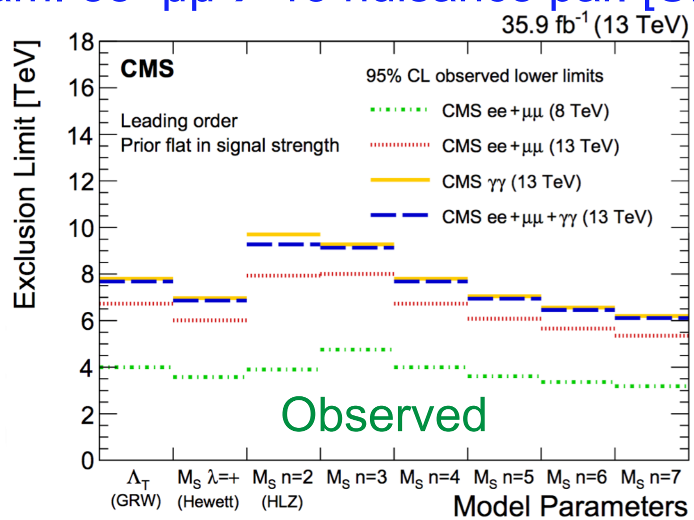






- Systematics: γγ→ 35 nuisance param. ee+μμ→ 13 nuisance par. [Uncorrelated]

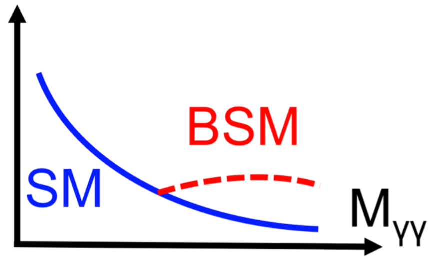




Summary / Conclusions

- A search for BSM physics in diphoton final state has been performed.

- Non-Resonant signatures probed at the tail of $M_{\gamma\gamma}$ distribution:

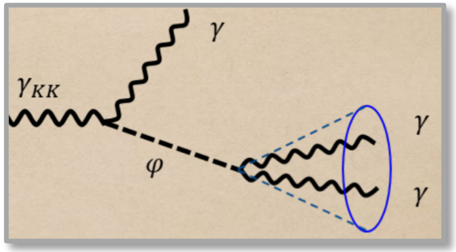


1. ADD with 2,3,…,7 large extra dimension (HLZ, GRW, Hewett±)
2. Continuum Clockwork model

- No indication for BSM physics observed
  → Set exclusion limits at 95%CL
  → The new limits improve current best in γγ Final State

- Combination with ee+μμ → better sensitivity improving by ~0.4TeV the Expected (Observed lim. still dominated by diphotons)

- Graviton / BSM physics strongly constrained at γγ FS,
  → But new idias coming up with 3γ:
  Tri-boson, Di-resonant, coming soon – stay tunned!



Thank you for your attention, interest, and hospitality!

Back-up slides and more

ADD G_{KK} BRs

TABLE I. Branching ratio for the massive graviton to SM particle with $l = e, \mu$ and $q = u, d, s, c, b$.

channels	HH	gg	$\gamma\gamma$	W^+W^-	ZZ	$t\bar{t}$	$q\bar{q}$	l^+l^-
$\mathcal{B}r$	2/293	96/293	12/293	24/293	12/293	16/293	90/293	12/293

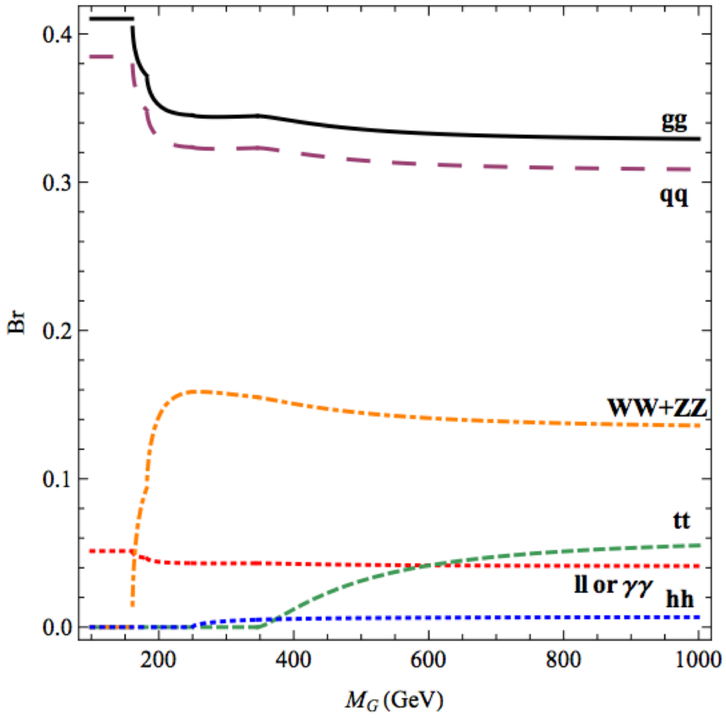
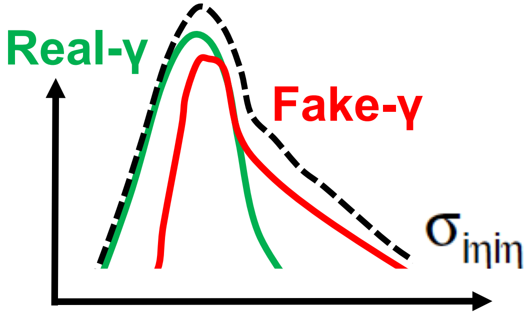


FIG. 3. Branching ratios, where $q = u, d, c, s, b$ and $l = e, \mu$. We have $Br(G \to ll) \simeq Br(G \to \Gamma\Gamma)$ as shown above.

γ-ID, variables

- $\sigma_{i\eta i\eta}$, the 2nd moment of the cluster about its average "η" position:

$$\sigma^2_{i\eta i\eta} = \frac{\sum_i^{5\times5} (0.0175\eta_i + \eta_{\text{seed}} - \bar{\eta}_{5\times5})^2 \times w_i}{\sum_i^{5\times5} w_i} \quad ; \quad w_i = max\{0.0,\, 4.7 + \ln \frac{E_i}{E_{5\times5}}\}$$



- i is the enumeration index of a crystal in a 5×5 array centered on the highest energy crystal,
- η_i is the pseudorapidity of the i^{th} crystal,
- η_{seed} is the pseudorapidity of the seed crystal,
- $\bar{\eta}_{5\times5}$ is the average pseudorapidity of the crystals in the 5×5 array,
- $E_i, E_{5\times5}$ are the i-crystal and the full 25 crystals energy deposites, respectuvely.

- R_9 = 3x3 ECAL cluster Energy / Seed crystal Energy.

- ρ-Corrected Iso:

$$\overline{\text{Iso}}_\gamma = \alpha + Iso_\gamma - \rho A - \kappa p_{\text{T}}$$

Detector region	α [GeV]	A	κ
$\lvert\eta_{SC}\rvert < 0.9$	0.99	0.15	0.0016
$0.9 < \lvert\eta_{SC}\rvert < 1.4442$	0.99	0.13	0.0016
$1.566 < \lvert\eta_{SC}\rvert < 2.0$	0.77	0.093	0.00075
$2.0 < \lvert\eta_{SC}\rvert < 2.2$	0.77	0.15	0.00075
$2.2 < \lvert\eta_{SC}\rvert < 2.5$	0.77	0.21	0.00075

ρ-Corrected Iso

The presence of additional pp interactions in the same bunch crossing, known as 'pileup', will increase the energy deposited in the calorimeter and the detector occupancy. It has been shown in the resonant diphoton analysis that pileup only appreciably affects the measurement of photon isolation. The photon isolation is rho corrected using the 'fixedGridRhoAll' rho value from the MiniAOD. There is also an additional correction based on the photon p_T. The definition of the corrected photon isolation $\overline{\mathrm{Iso}}_\gamma$ is summarized in Equation 8

$$\overline{\mathrm{Iso}}_\gamma = \alpha + Iso_\gamma - \rho A - \kappa p_T \quad (8)$$

where Iso_γ is the uncorrected photon isolation, A is the effective area, κ is a coefficient giving the p_T dependence of the correction, and α is an empirical constant chosen to make the corrected isolation peak near 0. The parameters α, A, and κ depend on the supercluster pseudorapidity $|\eta_{SC}|$ and are listed in Table 7.

Where appropriate, variables are corrected for data/MC discrepancies. This is the case regarding $\overline{\mathrm{Iso}}_\gamma$; a so-called "stochastic correction" was used. Details on the this correction can be found in Appendix A of [19]. In addition, we apply the 8_0_X version of the standard EGamma energy regression as well as the energy smearing and scaling corrections to MC and data, respectively.

Detector region	α [GeV]	A	κ
$\|\eta_{SC}\| < 0.9$	0.99	0.15	0.0016
$0.9 < \|\eta_{SC}\| < 1.4442$	0.99	0.13	0.0016
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$2.0 < \|\eta_{SC}\| < 2.2$	0.77	0.15	0.00075
$2.2 < \|\eta_{SC}\| < 2.5$	0.77	0.21	0.00075

Using Eq. (6.175), one can calculate cross sections for various processes relevant to collider experiments. For instance, the cross section with two photons in the final state is

$$\frac{d\sigma}{dt}(f\bar{f} \to \gamma\gamma) = \frac{\pi}{N_f s^2}\left[\alpha Q_f^2 G_1\left(\frac{t}{s}\right) + \frac{s^2}{M_S^4} G_2\left(\frac{t}{s}\right)\right]^2 \tag{6.176a}$$

$$\frac{d\sigma}{dt}(gg \to \gamma\gamma) = \frac{\pi}{512}\frac{s^2}{M_S^8} G_3\left(\frac{t}{s}\right) \tag{6.176b}$$

where $G_1 \sim G_3$ are given in Appendix C [467]. A similar expression can be obtained for $f\bar{f} \to f\bar{f}$. A generic form often used for data fitting for the sum of the SM and KK processes can be written as [593]

$$\frac{d^2\sigma}{d\cos\theta^* dM} = f_{\rm SM} + f_{\rm int}\left(\frac{F}{M_S^4}\right) + f_{\rm KK}\left(\frac{F}{M_S^4}\right)^2$$

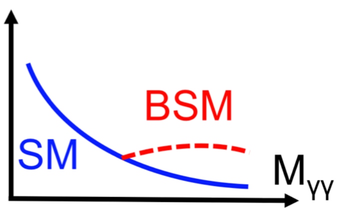
$$F = \begin{cases} 1 & \text{GRW [467]} \\ \begin{cases} \ln \frac{M_S^2}{M^2} & \delta = 2 \\ \frac{2}{\delta - 2} & \delta > 2 \end{cases} & \text{HLZ [594]} \\ \frac{2\lambda}{\pi} = \pm\frac{2}{\pi} & \text{Hewett [595]} \end{cases} \tag{6.177}$$

- Taken from: Nagashima, Beyond the SM of Elementary Particle Physics.

Outline

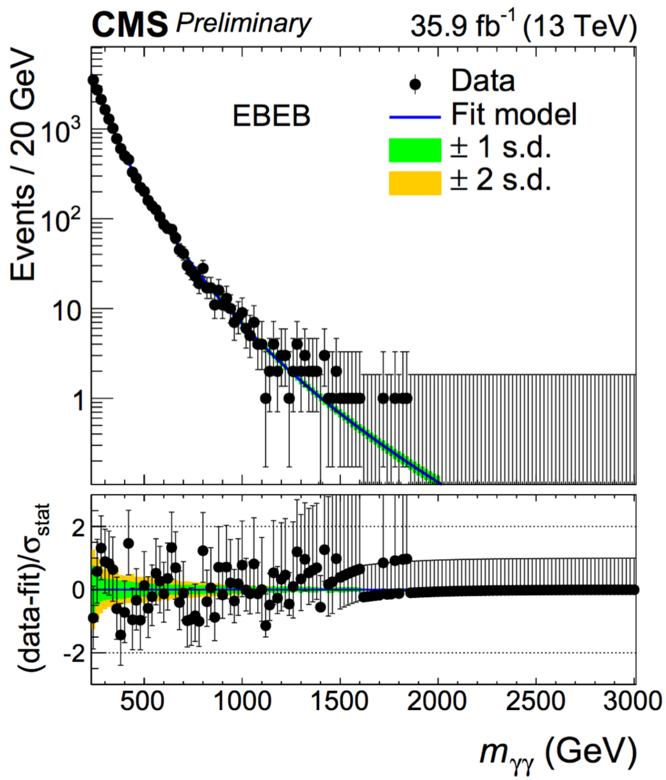
AN-17-030 | PAPER EXO-17-017 | AN-17-206

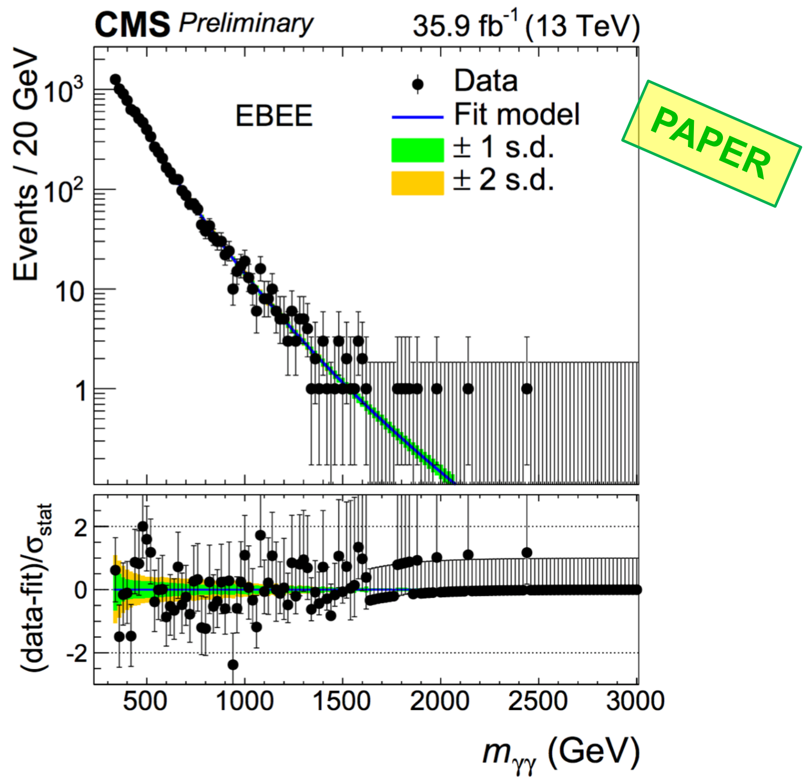
- The goal of these "twin analyses" is to search for evidence of BSM physics in pp → γγ events using $M_{\gamma\gamma}$
- Search for non-resonant signal: → ADD extra dimensions →
  → Continuum clockwork →



1) Reconstruction and event selection
2) Signals' generation, simulation & features; MC samples, datasets and triggers used
3) Background estimate
4) Systematic uncertainties treatment
5) Results interpretation / limits

- SM background parametrized as: $g(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\,log(m_{\gamma\gamma})}$
  → 2 parameters treated as unconstrained nuisance parameters in the unbinned maximum likelihood fit.





- No statistically significant structures on the data
  → No indication for BSM physics.

Signal MC: ADD (x-sec, production)

- Total cross section of SM+ADD process:

$$\sigma_{\text{total}} = \sigma_{\text{SM}} + \frac{\mathcal{F}}{M_S^4}\sigma_{\text{int}} + \frac{\mathcal{F}^2}{M_S^8}\sigma_{\text{ADD}}$$

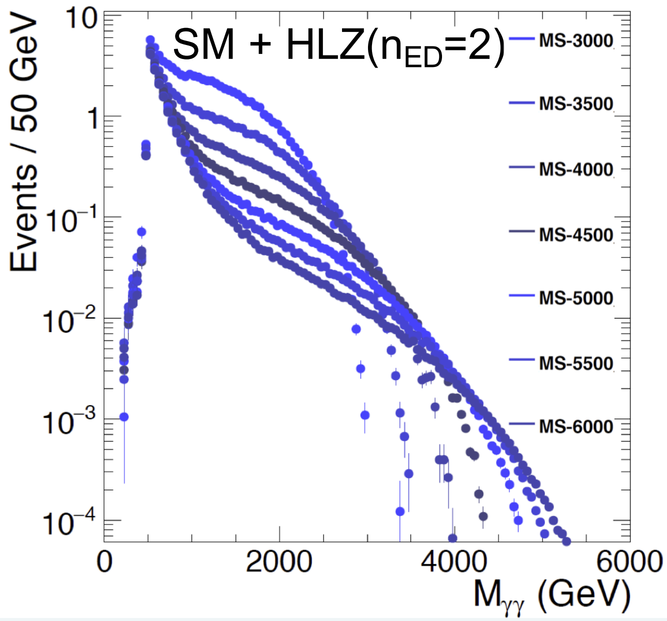
$$\mathcal{F} = \begin{cases} 1 \quad (\text{GRW}), \\ \log\left(\frac{M_S^2}{\hat{s}}\right), \text{ if } n_{ED} = 2 \\ \frac{2}{n_{ED}-2}, \text{ if } n_{ED} > 2 \\ \pm\frac{2}{\pi} \quad (\text{Hewett}), \end{cases} \quad (\text{HLZ}),$$

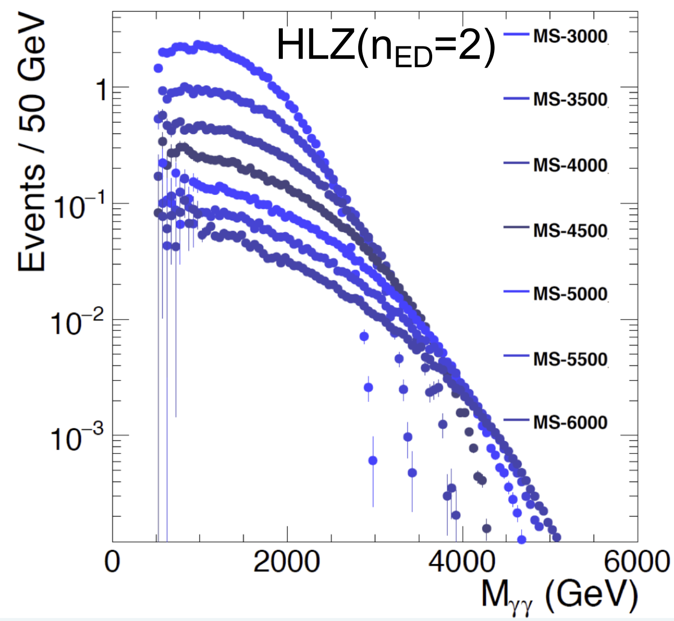
- Conventions for F: GRW, HLZ, Hewett
  Our parametrization: M_S: UV cutoff scale, n_{ED} :number of extra dimensions.

- Include the interference term → production "SM+ADD" and "SM-only"
  → Use SHERPA (LO) to extract ADD signal.
  (Computationally not feasible to include additional final state partons into SM+ADD)

- HLZ example → similar with the rest

- Scan parameter space:
  M_S: 3-11 TeV
  n_{ED}: 2, 3, …, 7





Signal MC: Continuum Clockwork

- Use the ADD sample [CMS central production] → to translate in CW

$$\sigma_{\text{total}} = \sigma_{\text{SM}} + \frac{\mathcal{F}}{M_S^4}\sigma_{\text{int}} + \boxed{\frac{\mathcal{F}^2}{M_S^8}\sigma_{\text{ADD}}}$$

M_S: defined in the GRW convention,
M_5: fundamental scale of the gravitational interactions
k: 'clockwork spring', (Perturbativity constrains $k < M_5$)

- Direct term can be rescaled by:

$$\theta(m_{\gamma\gamma} - k)\frac{30 M_S^8}{283\pi M_5^3}\sqrt{1 - \frac{k^2}{m_{\gamma\gamma}^2}}\frac{1}{m_{\gamma\gamma}^5}\left[1 + \frac{5^2 \cdot 7 \cdot 17}{283 \cdot 2^8}\left(1 - \frac{k}{m_{\gamma\gamma}}\right)^9\sqrt{\frac{m_{\gamma\gamma}}{k}}\right]^{-1}$$

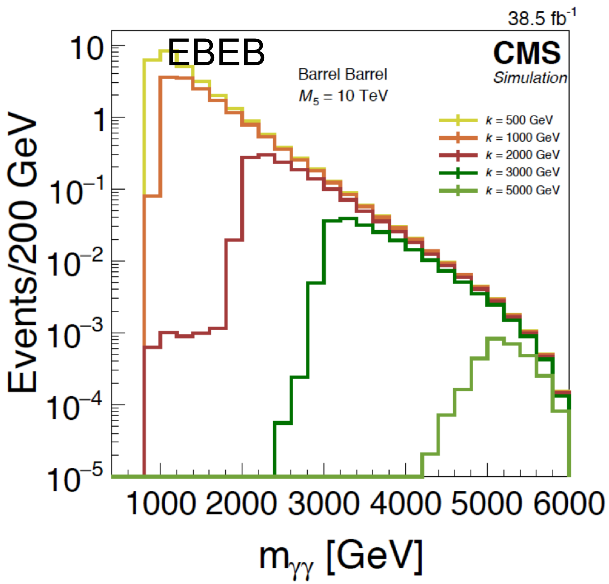
- Write the x-secs as: and extract direct term

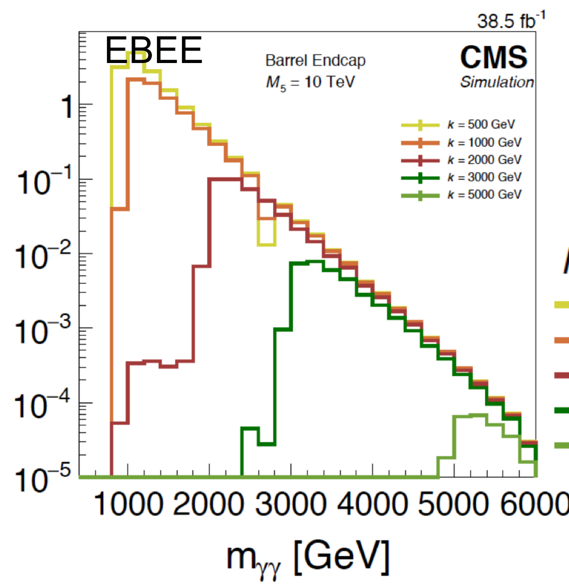
$$\sigma_{\text{Hewett}} = \frac{-2/\pi}{M_S^4}\sigma_{\text{int}} + \frac{4/\pi^2}{M_S^8}\sigma_{\text{ADD}}$$

$$\sigma_{\text{GRW}} = \frac{1}{M_S^4}\sigma_{\text{int}} + \frac{1}{M_S^8}\sigma_{\text{ADD}}$$

$$\frac{\sigma_{\text{ADD}}}{M_S^8} = \frac{\sigma_{\text{GRW}} + \frac{\pi}{2}\sigma_{\text{Hewett}}}{1 + \frac{2}{\pi}}$$

This direct term is scaled by the factor to form CW signal





M_5 = 10 TeV
k = 500 GeV
k = 1000 GeV
k = 2000 GeV
k = 3000 GeV
k = 5000 GeV

$M_{\gamma\gamma} > 0.9$ TeV

Continuum Clockwork arxiv:161007962

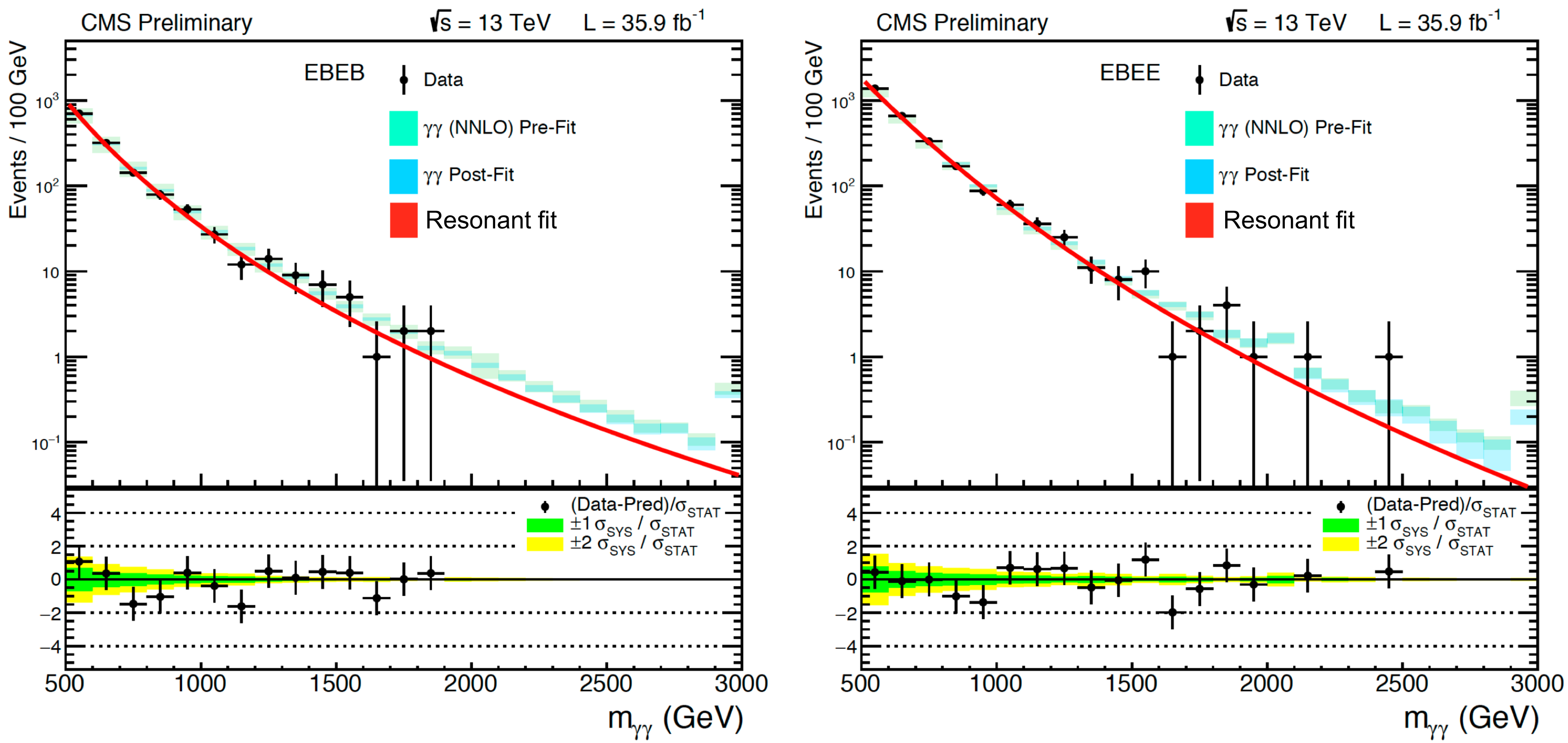
A third proposed solution to the hierarchy problem that we consider in this paper is the continuum clockwork mechanism [8], which coincides with a 5D gravitational theory on a linear dilaton background [9, 10]. The clockwork [11, 12] is a general mechanism that can introduce large effective interaction scales from dynamics occurring at much lower energies. This is achieved by introducing N copies of some particle content on different sites forming a one-dimensional lattice in theory space. The physical mass spectrum consists of a single massless mode localized on the end site of the lattice and a set of massive modes ('gears') distributed along the sites. In the continuum limit of the clockwork with $N \to \infty$, this lattice is interpreted as a physical extra dimension.

No additional samples are needed to generate the clockwork signal; instead the ADD signal samples are reinterpreted to produce the clockwork prediction. In the clockwork model, the KK modes are all on shell, so there is no interference effect, while the ADD prediction includes both a direct term and an interference term. The GRW and negative Hewett models have opposite signs for the interference term, so the direct term can be isolated by linearly adding, with appropriate weights, the predictions assuming the GRW and negative Hewett conventions. The direct term is then rescaled by Eq. (2), provided by the authors of Ref. [14]:

$$\theta(m_{\gamma\gamma} - k)\frac{30M_S^8}{283\pi M_5^3}\sqrt{1-\frac{k^2}{m_{\gamma\gamma}^2}}\frac{1}{m_{\gamma\gamma}^5}\left[1+\frac{(5^2)(7)(17)}{(283)(2^8)}\left(1-\frac{k}{m_{\gamma\gamma}}\right)^9\sqrt{\frac{m_{\gamma\gamma}}{k}}\right]^{-1}. \quad (2)$$

Here, M_S is defined in the GRW convention, M_5 is the fundamental scale of the gravitational interactions, and k is the 'clockwork spring', which, phenomenologically, controls the energy scale at which the KK modes can be excited. To solve the hierarchy problem, M_5 should be close to the electroweak scale. Demanding perturbativity of the theory imposes the constraint $k < M_5$.

Raw comparison Reso-vs-NonReso



The two approaches/methods for $M_{\gamma\gamma}$ spectra are in a good agreement

- Good agreement up to ~1.4 TeV
- Small deviations above ~1.7 TeV where we have poor statistics.

FR: x-checks & closure test in MC

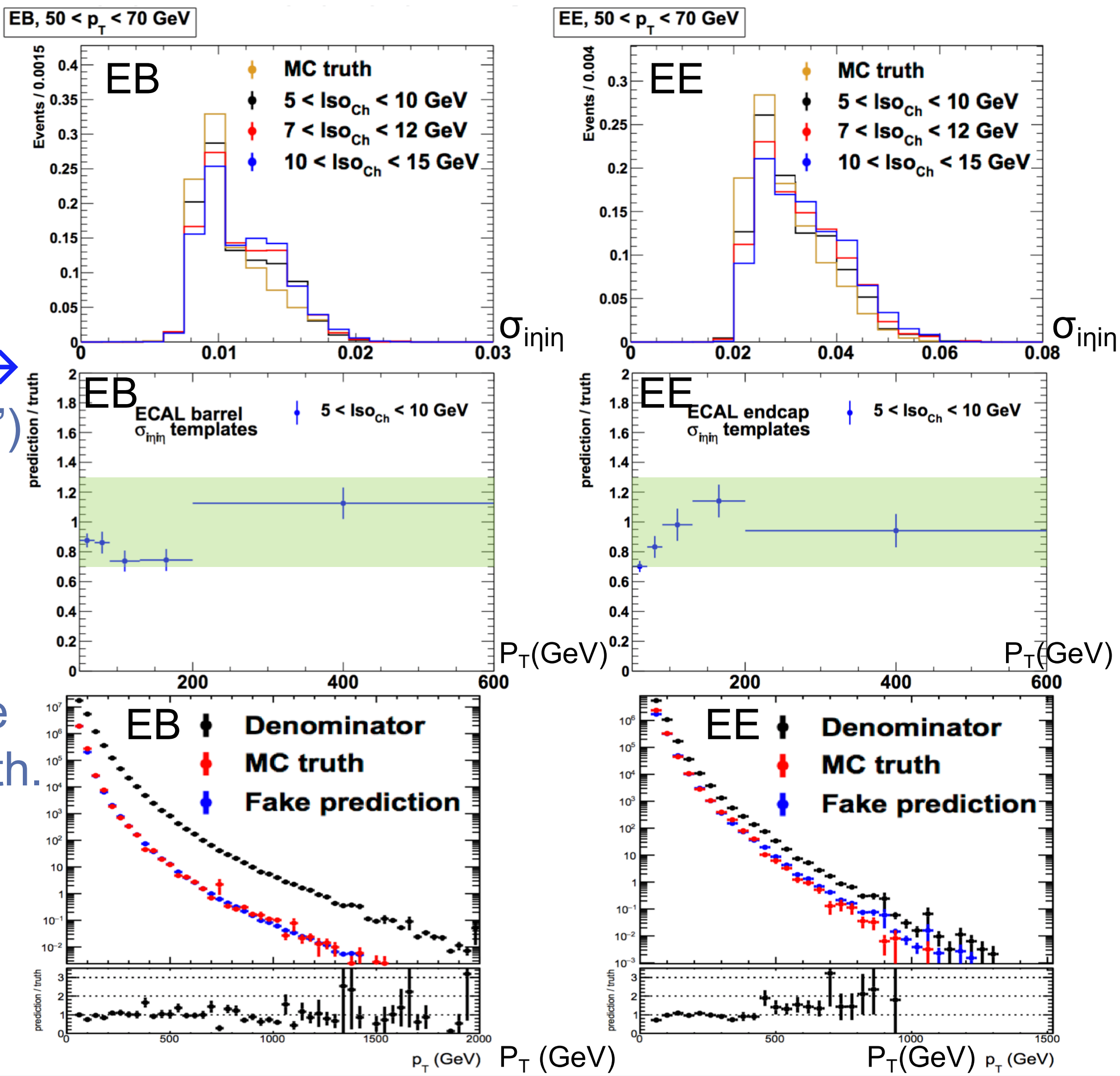
- We can use MC events, treating them exactly as data to extract FR. Which can be compared to the known fakes in MC sample using the MC truth info

- Test the "Fake Templates" derived from the template MLE-fit vs MC-truth.

- Test the FR forming Ratio = Pred / Truth→ (ie: "fake yields from fit / true")
- Closure within ~30% → attribute systematic unc.

- Kinematic distribution closure p_T re-weighting events vs truth.

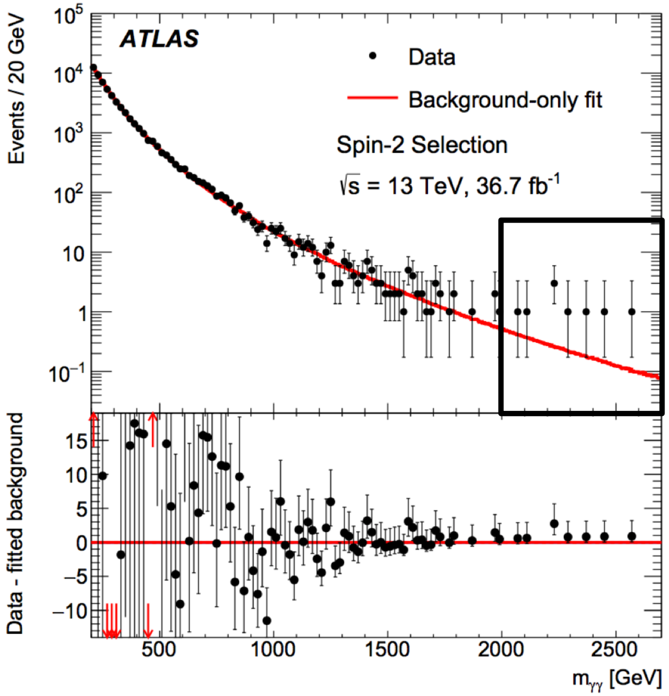
- Good closer in general (much more on AN…)

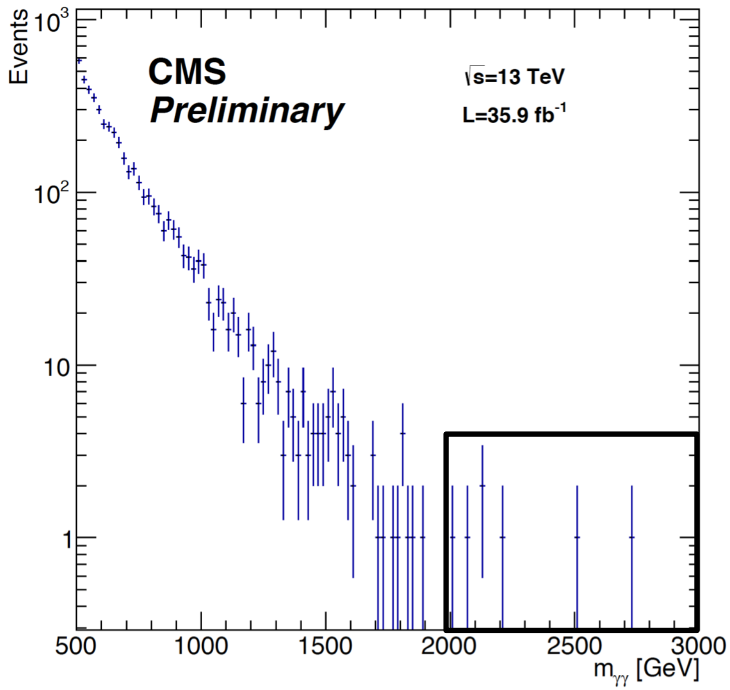


Atlas vs CMS spectra comparision

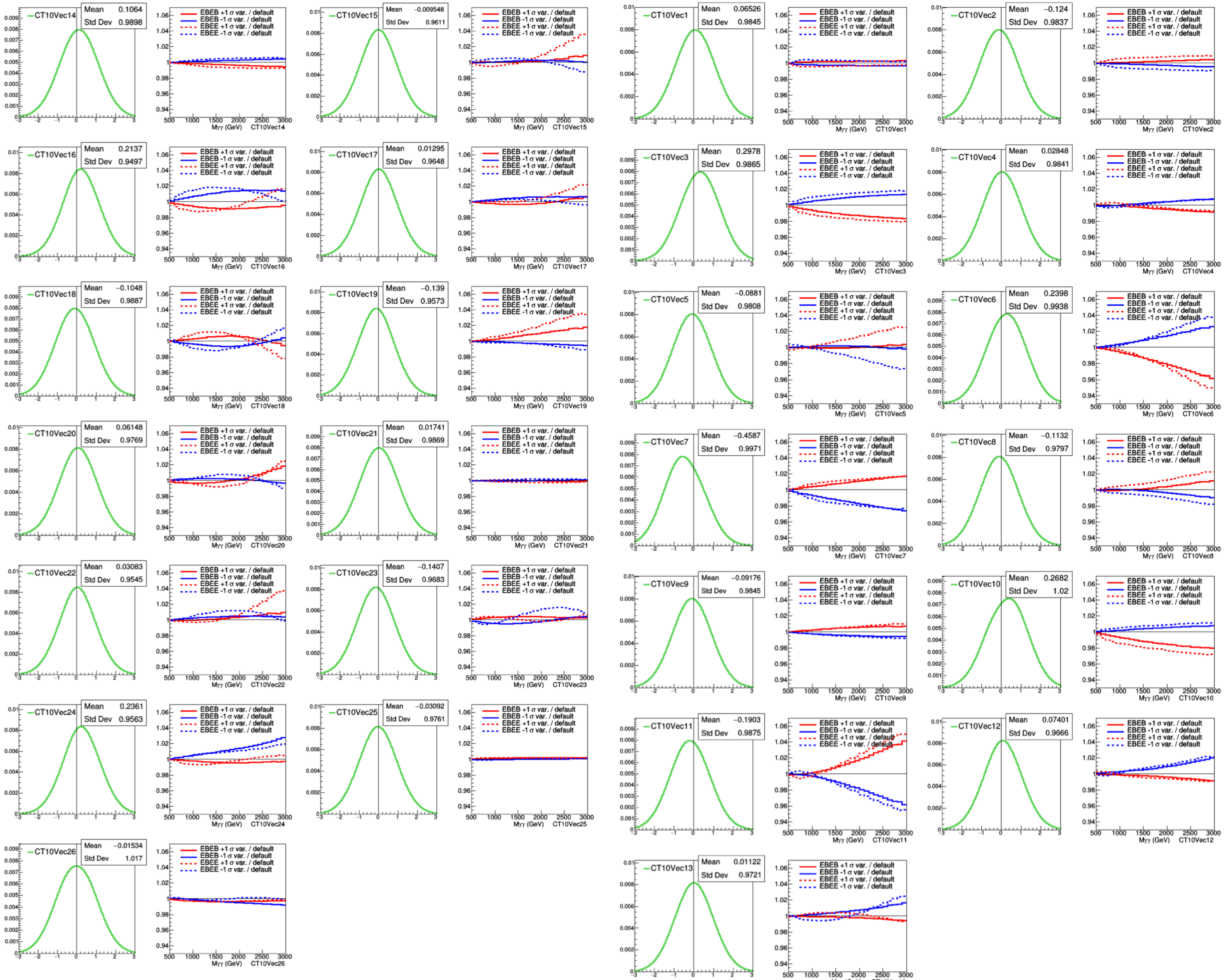
Atlas:
EBEB + EBEE + EEEE
9 events for $M_{\gamma\gamma}$>2 TeV

CMS:
EBEB + EBEE $_{[|\eta|<2.37]}$ + EEEE$_{[|\eta|<2.37]}$
7 events for $M_{\gamma\gamma}$>2 TeV

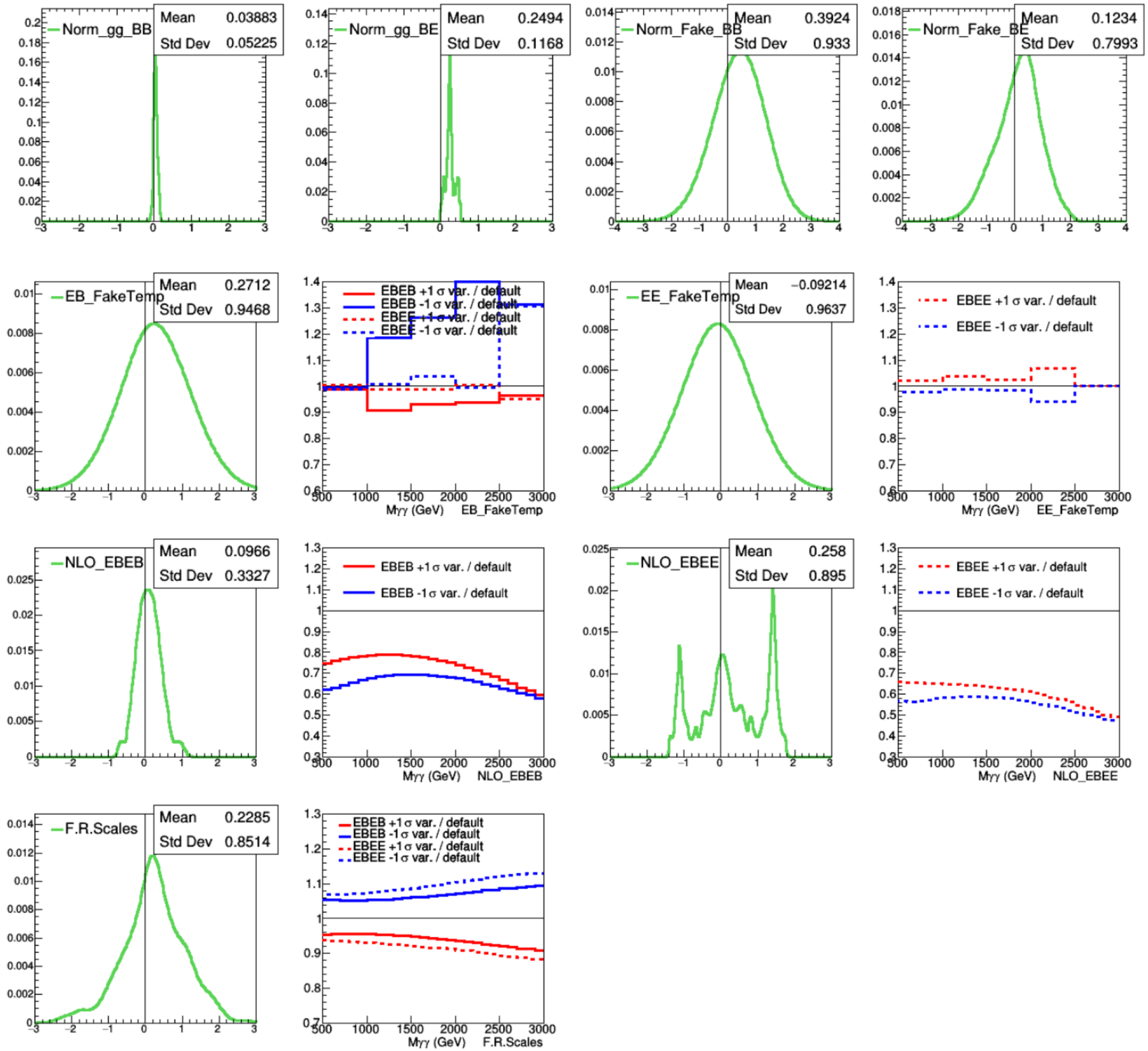




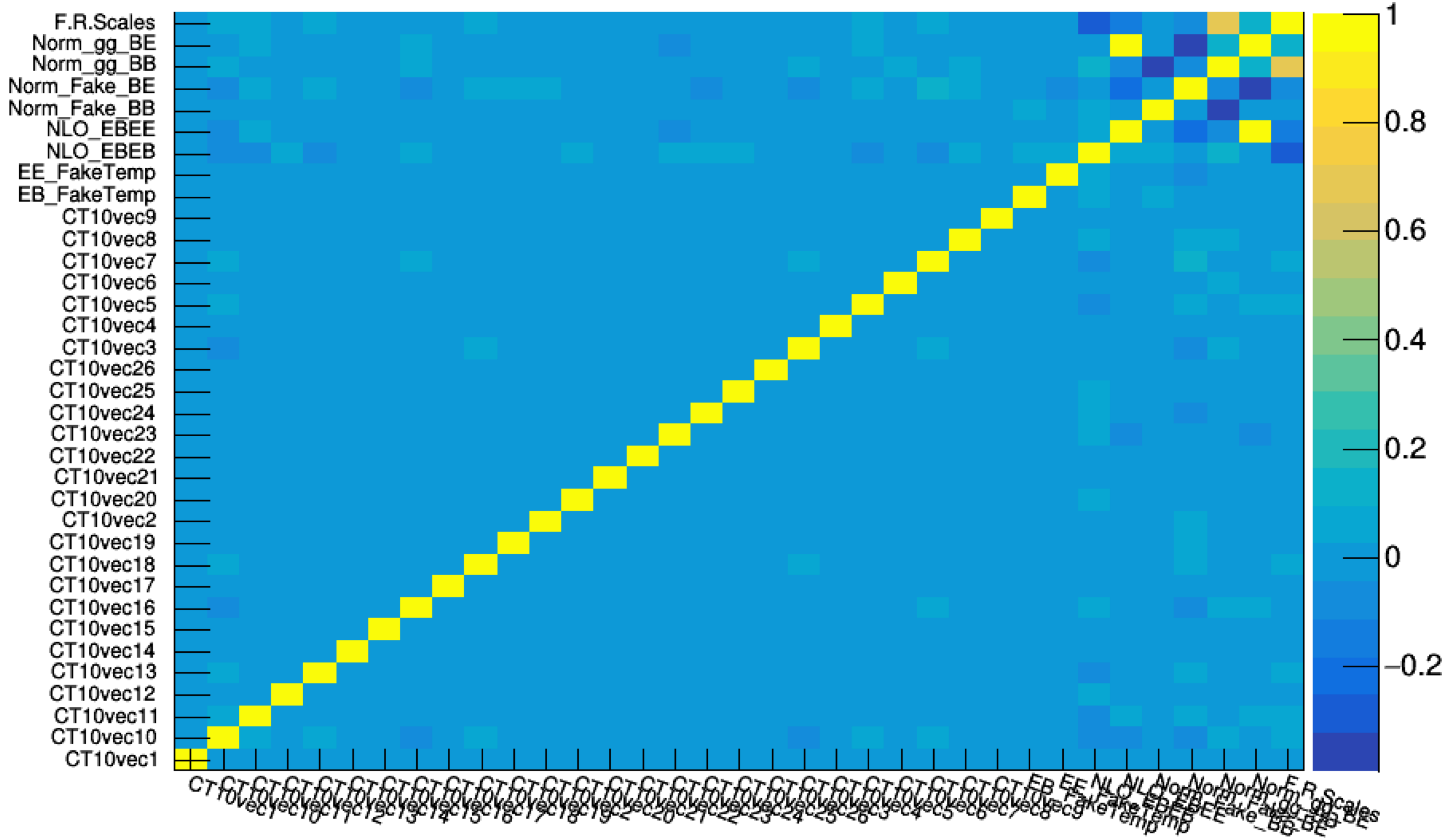
PDFs Posterior Distributions



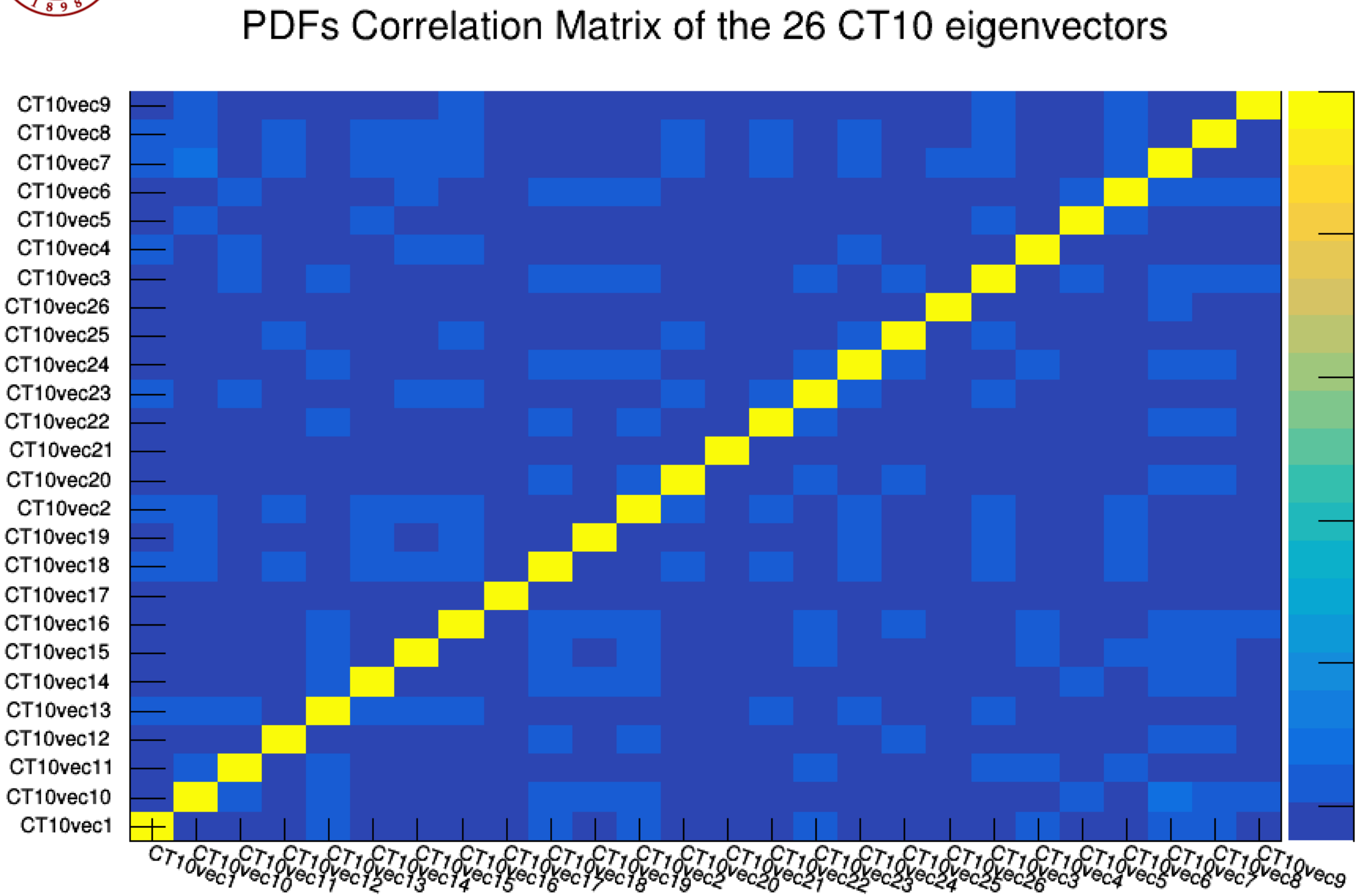
Non-PDF Posterior Distributions



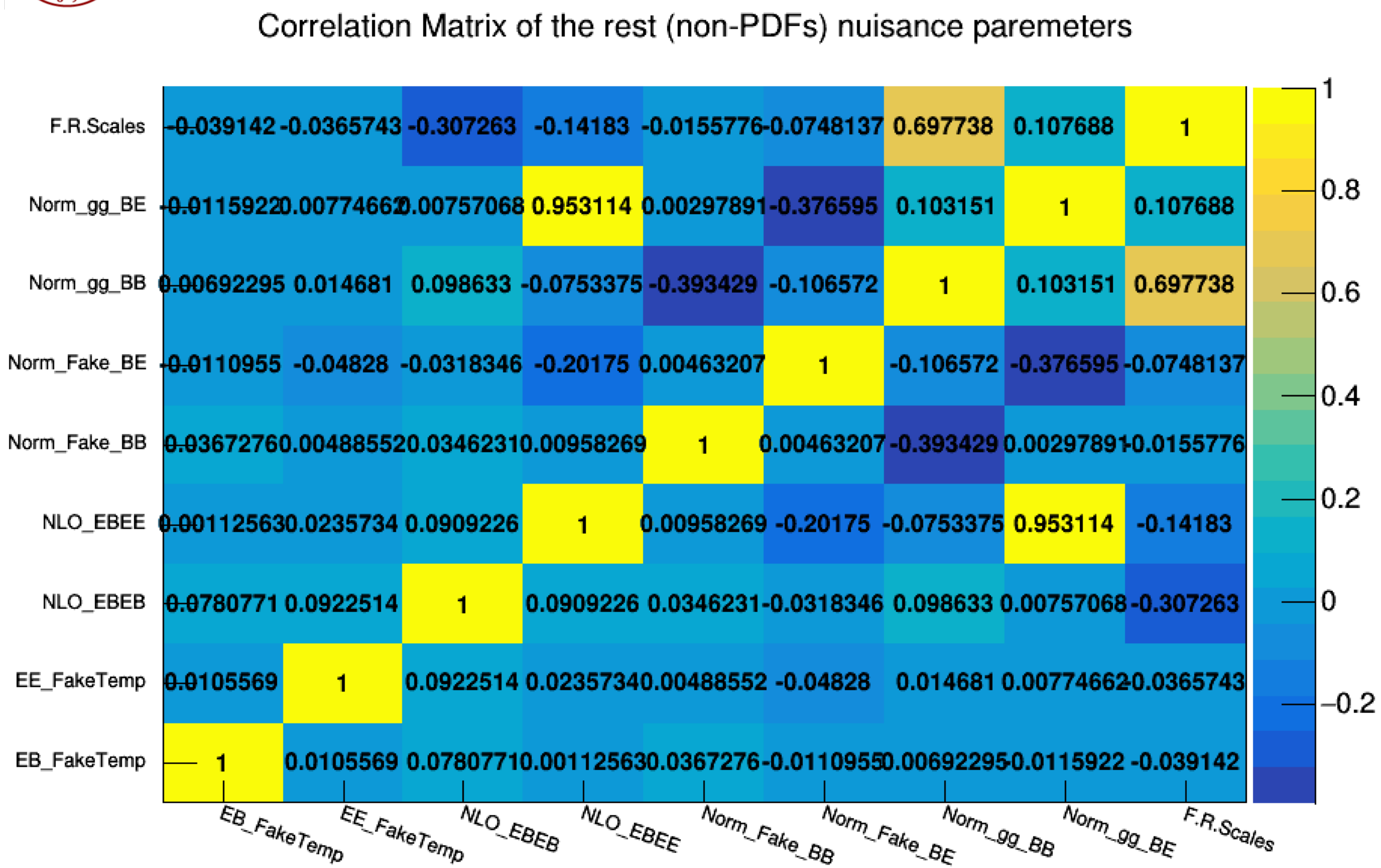
Correlation matrix of 35 nu.param.



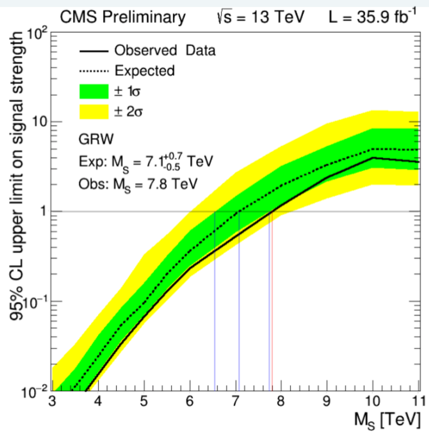
Correlation matrix of 26 nu.param.

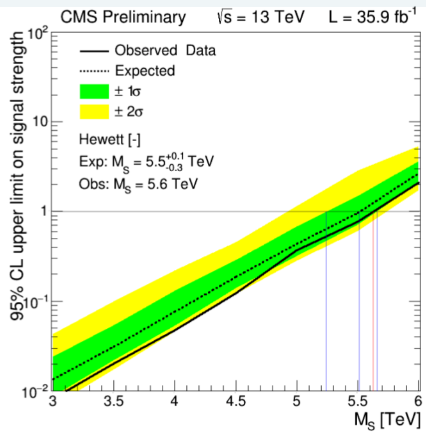


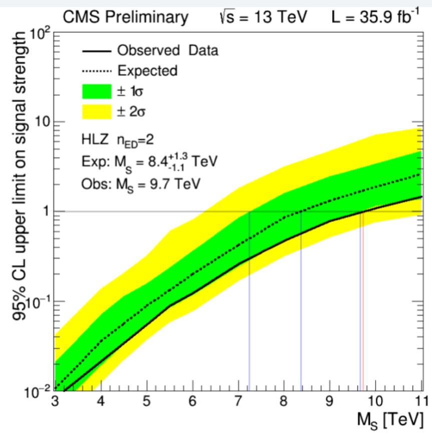
Correlation matrix of 9 nu.param.



Exclusion (lower) limits on M_s







Signal:	GRW	Hewett negative	Hewett positive	HLZ n_{ED}=2	HLZ n_{ED}=3	HLZ n_{ED}=4	HLZ n_{ED}=5	HLZ n_{ED}=6	HLZ n_{ED}=7
Expected:	$7.1^{+0.7}_{-0.5}$	$5.5^{+0.1}_{-0.3}$	$6.3^{+0.6}_{-0.4}$	$8.4^{+1.3}_{-1.1}$	$8.4^{+0.8}_{-0.6}$	$7.1^{+0.7}_{-0.5}$	$6.4^{+0.6}_{-0.5}$	$6.0^{+0.6}_{-0.4}$	$5.6^{+0.6}_{-0.4}$
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	ADD formalism Parameter	GRW	Hewett positive	HLZ $n=3$	HLZ $n=4$	HLZ $n=5$	HLZ $n=6$
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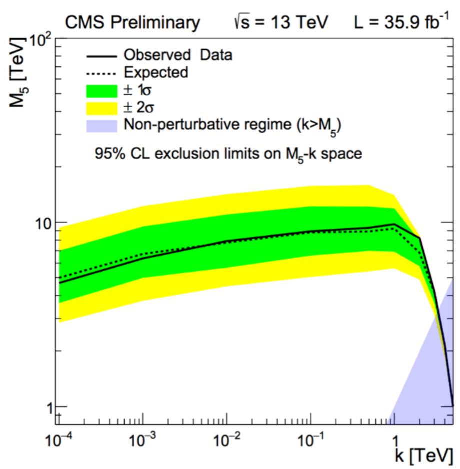
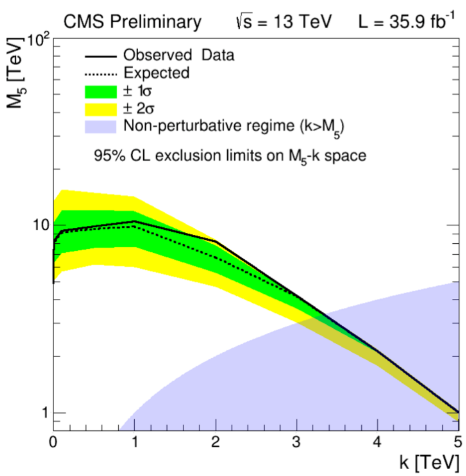
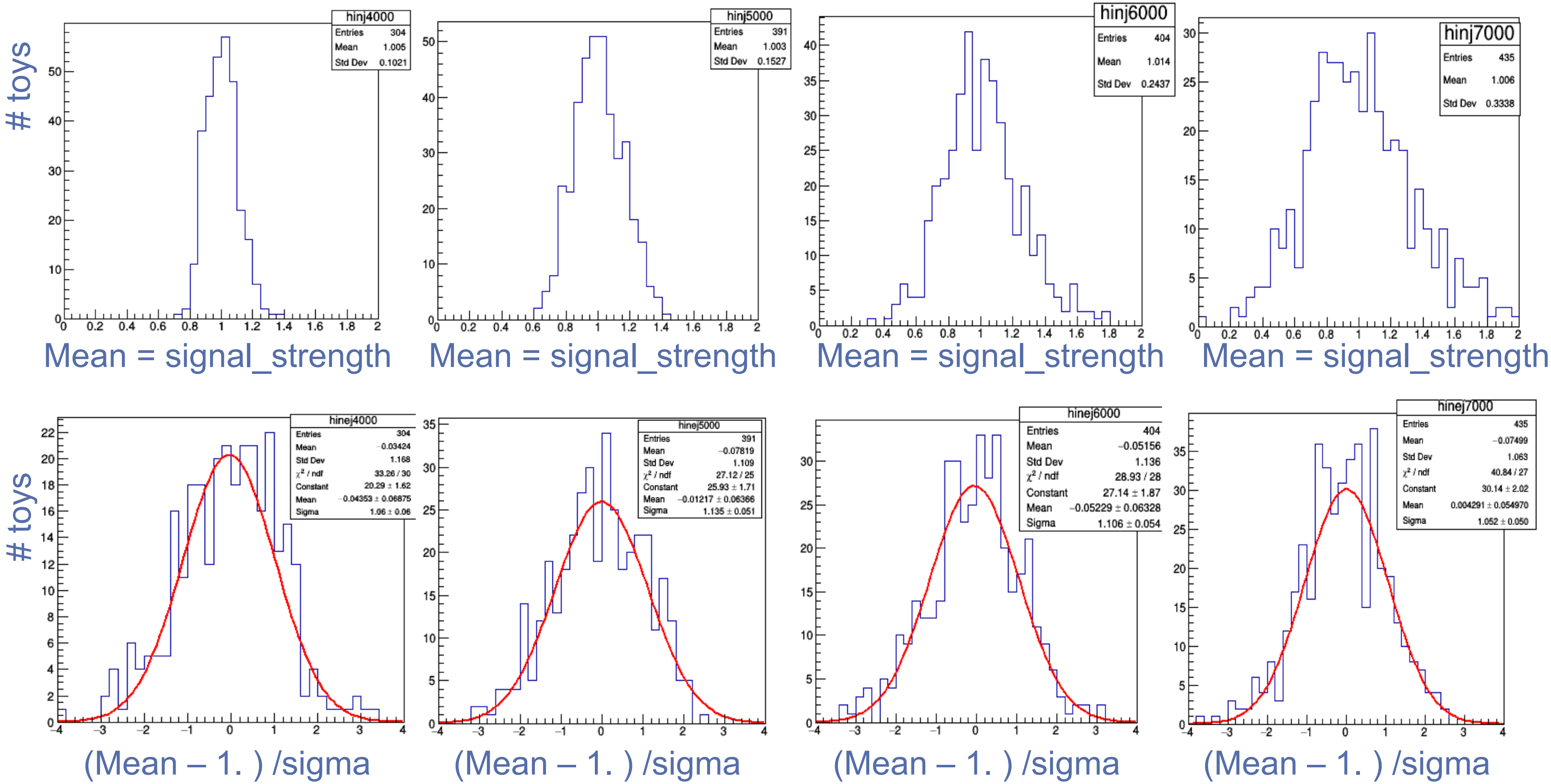




Signal injection HLZ n_D=2 (1k toys)

Ms: 4 TeV | Ms: 5 TeV | Ms: 6 TeV | Ms: 7 TeV



Extra Dim. Motivation & Signature

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  - M_H^{bare} undergoes Q-corrections up to M_{Pl}~10^{19} GeV where Q-gravity is involved.
  - Whereas we observed (surprisingly) low M_H~10^2 GeV.

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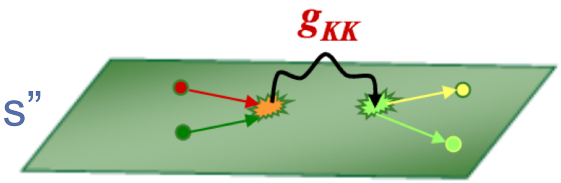

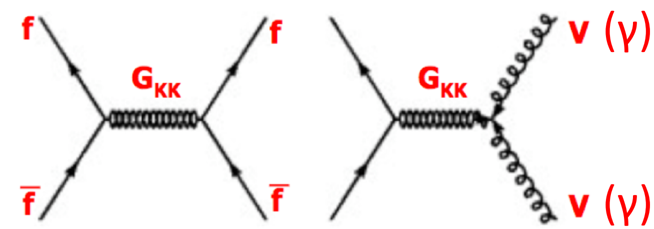

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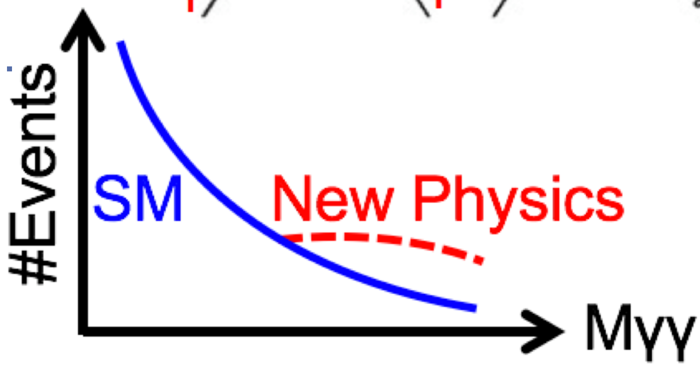
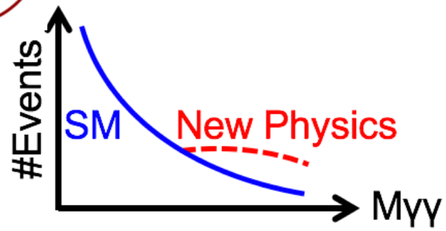
- Both models has a high mass γγ system as a final state.



Datasets & MC

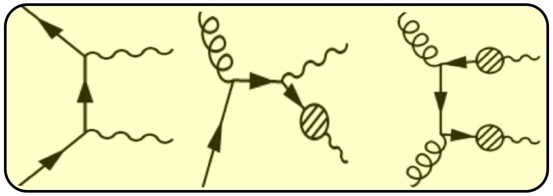


- We probe the high mass diphoton events' shape.
- DATA 2016:
  - Dataset: /DoubleEG/2016*…./ → 35.9/fb
  - Global tag: 80X_dataRun2_2016SeptRepro_v7

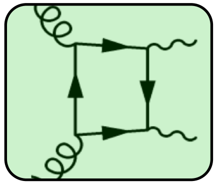
Data period	Good run JSON
2016, Run B–G	Collisions16/13TeV/ReReco/Final/Cert_271036-284044_13TeV_23Sep2016ReReco_Collisions16_JSON.txt
2016, Run H	Collisions16/13TeV/Final/Cert_271036-284044_13TeV_PromptReco_Collisions16_JSON.txt

/DoubleEG/Run2016B-03Feb2017_ver2-v2	5.788	fb^{-1}
/DoubleEG/Run2016C-03Feb2017-v1/MINIAOD	2.573	fb^{-1}
/DoubleEG/Run2016D-03Feb2017-v1/MINIAOD	4.248	fb^{-1}
/DoubleEG/Run2016E-03Feb2017-v1/MINIAOD	4.009	fb^{-1}
/DoubleEG/Run2016F-03Feb2017-v1/MINIAOD	3.102	fb^{-1}
/DoubleEG/Run2016G-03Feb2017-v1/MINIAOD	7.540	fb^{-1}
/DoubleEG/Run2016H-03Feb2017_ver2-v1/MINIAOD	8.391	fb^{-1}
/DoubleEG/Run2016H-03Feb2017_ver3-v1/MINIAOD	0.215	fb^{-1}

- Dominant BKG: "γγ"-real,
  → SHERPA 2.1.1, CT10, [LO +3partons +box].



- Subdominant BKG: "γj", "jj" fake.

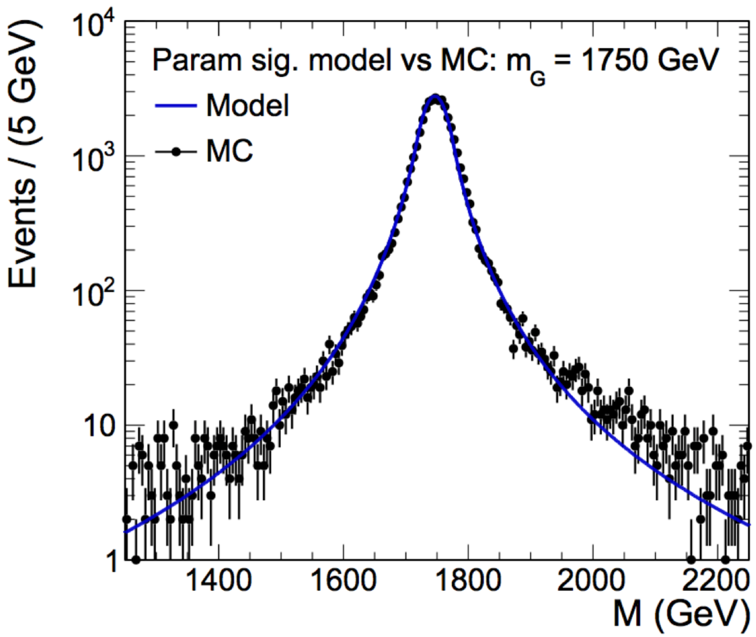


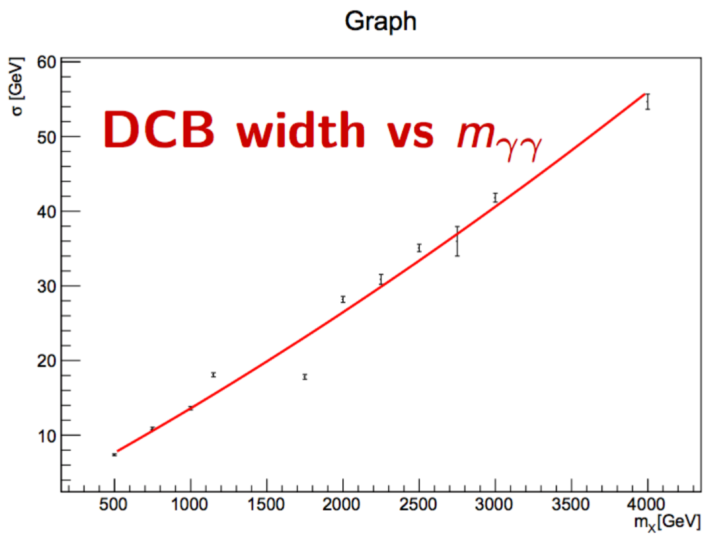
MC samples used:

γγ: DiPhotonJets_MGG-80toInf_13TeV_amcatnloFXFX_pythia8
GGJets_M-***To***_Pt-50_13TeV-sherpa
γ,jet: Gjets_HT-***To***_TuneCUETP8M1 13TeV-madgraphMLM-pythia8
jets: QCD_Pt-***to***_EMEnriched_TuneCUETP8M1_13TeV_pythia8

Signal Model

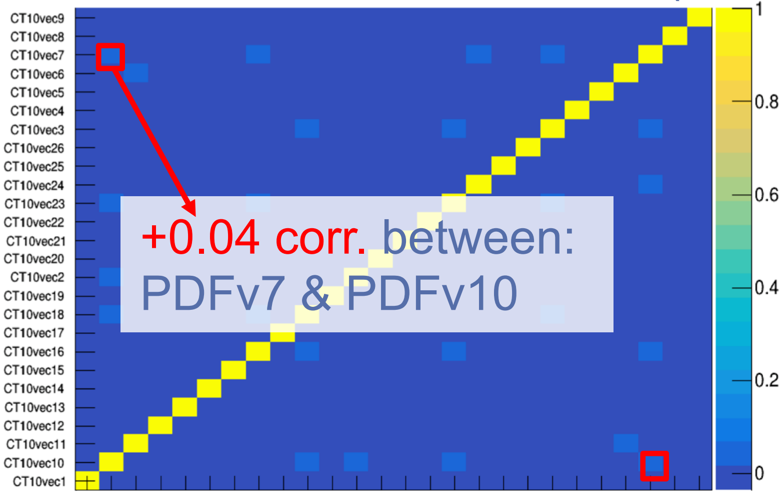
- **Signal shape** from simulation:
  - → The reconstructed signal shape is fitted with the convolution of a double-sided crystal ball (detector response) and the theoretical line-shape.
  - → Energy corrections from Egamma (in bins of E_T, η, R_9 and ECAL gain of seed channel).
  - → The signal shape is then described uniquely with a DCB obtained from fit to Asymov dataset generated from the previous fit.
  - → **DCB coefficients evolution as a function of $m_{\gamma\gamma}$ parametrized with a polynomial**.

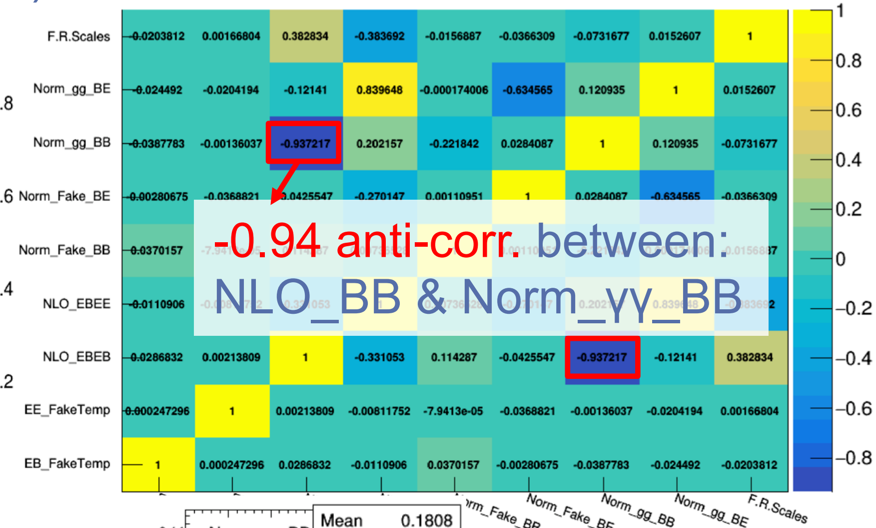


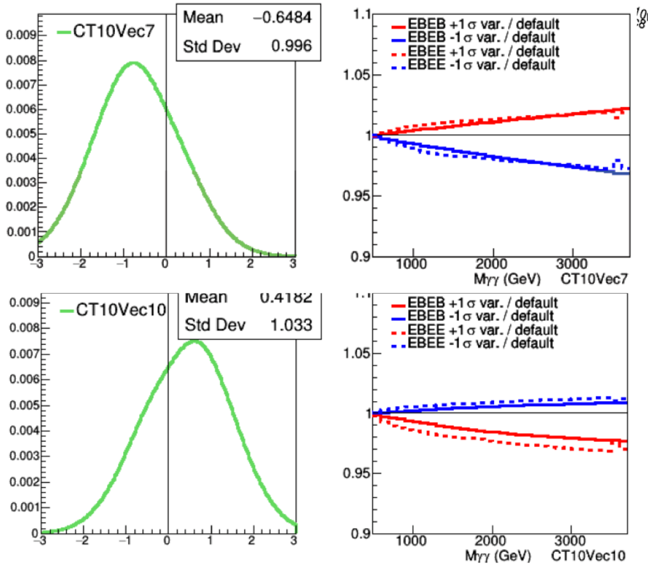


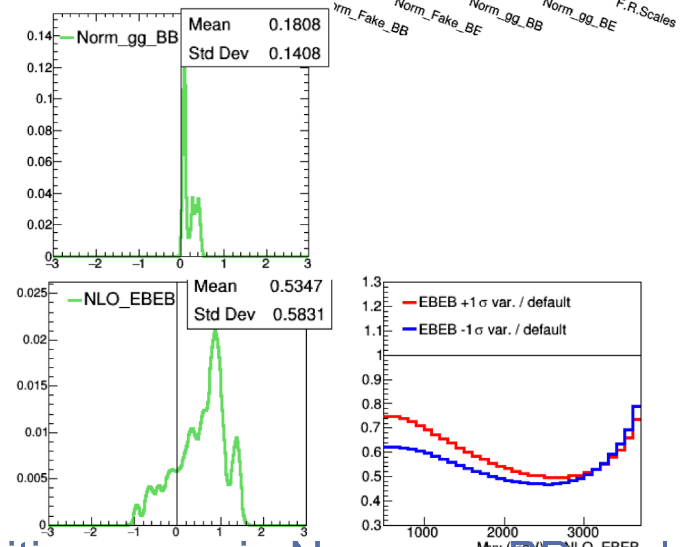
Do we understand correlations?

Pick an extreme cases (value) from each correlation matrix:



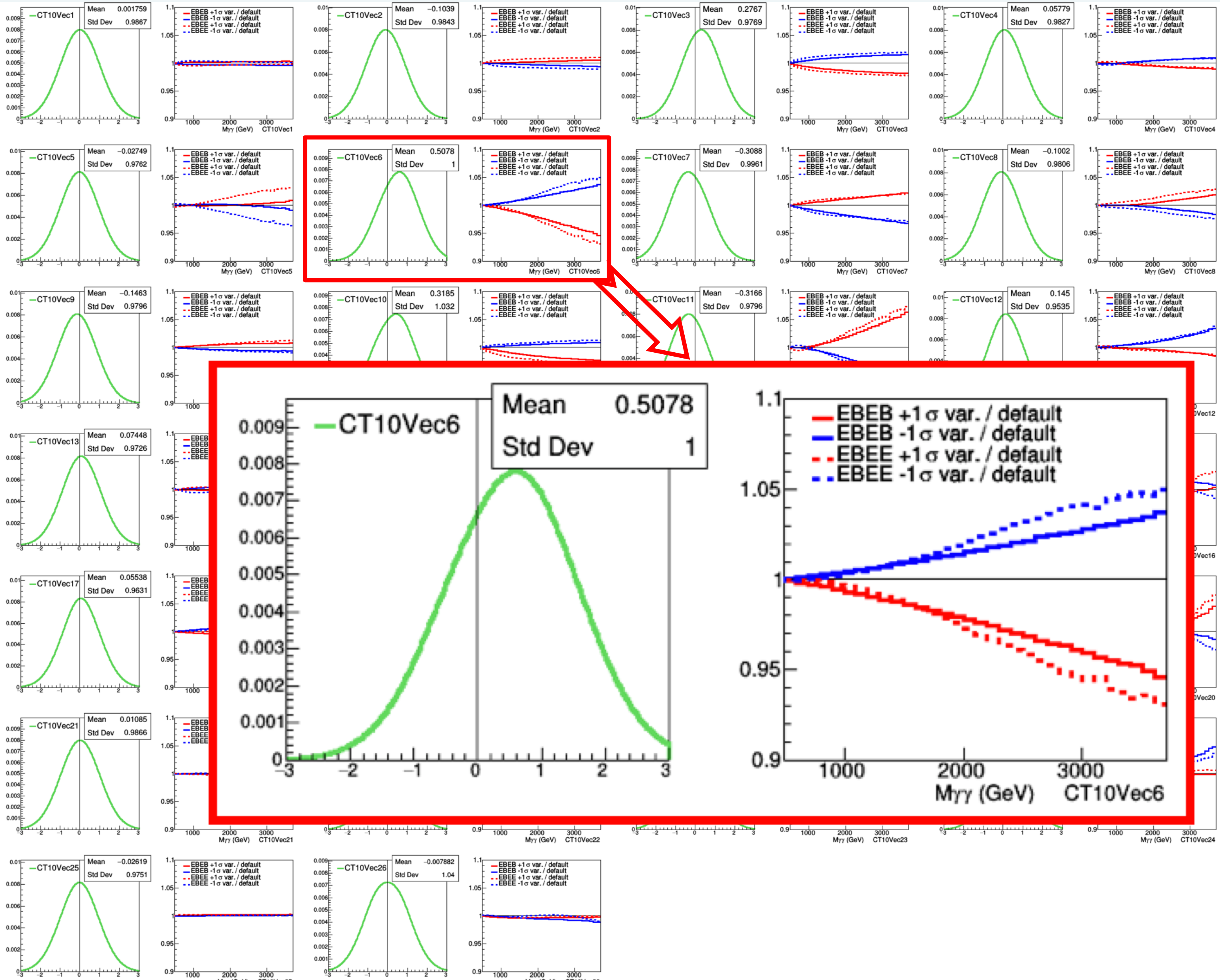






- Posteriors ”point” coherently to steeper falling Mγγ spectra.
- Positive mean in Norm_γγ_BB scales Mγγ yields up, whereas positive NLO_BB does the opposite.

26 PDFs' posterior distributions



DIPHOX 1.1.3: some of its structure

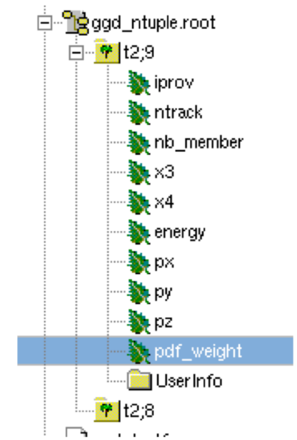
perl start.pl --parameter parameter.indat --histo param_histo.indat

- start.pl: Makes the *.exe scripts
- parameter.indat: Input 58 parameters for the process
- param_histo.indat: 9 parameters & histo definitions

◆ Configurable parameters / our default choices:

- PDF set used → CT10nlo.Lhgrid
- All PDF error sets → False/True
- Value of cm initial state factorization scale → 1.0
- Value of cm renormalization scale → 1.0
- Value of cm final state factorization scale → 1.0
- α_{EM}→0 const., α_s →0=LHAPDF
- Number of active flavors → 5
- For the direct → "born level" + "H.O."
- Contributions → direct: dir & fragment. onef, twof.
- Cross-section calculation at: LO+HO = NLO
- ΔR iso. cone → 0.3, Abs_Iso < 5 GeV
- …and much more...

◆ Tree product content:



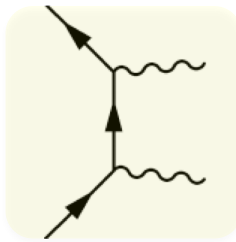
◆ Basic cuts at the ntuple level & more:

1) PT(γ) > 50 GeV
2) |η|(γ) < 2.5
3) M(γγ) > 200 GeV
4) Iso_{abs}(ΔR:0.3) < 5 GeV
5) 8M events / ntuple

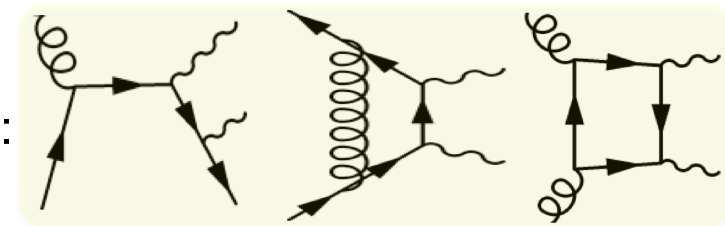
DIPHOX processes

- Diphox covers both:
  direct and indirect (hadron "fragmentation" originated photons) productions.

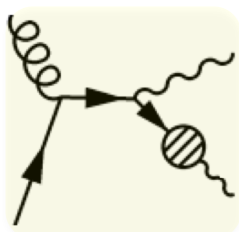
Direct LO:



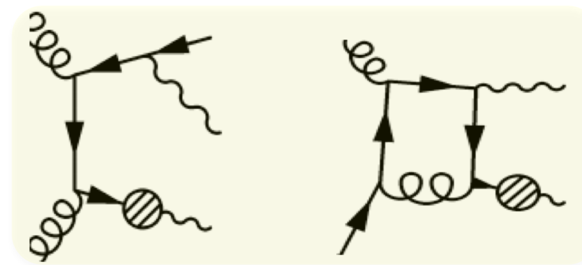
Direct HO:



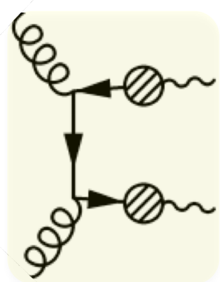
Single fragm. LO:



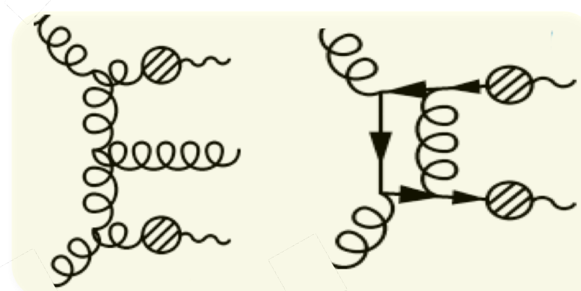
1-frag.HO:



Double fragm. LO:



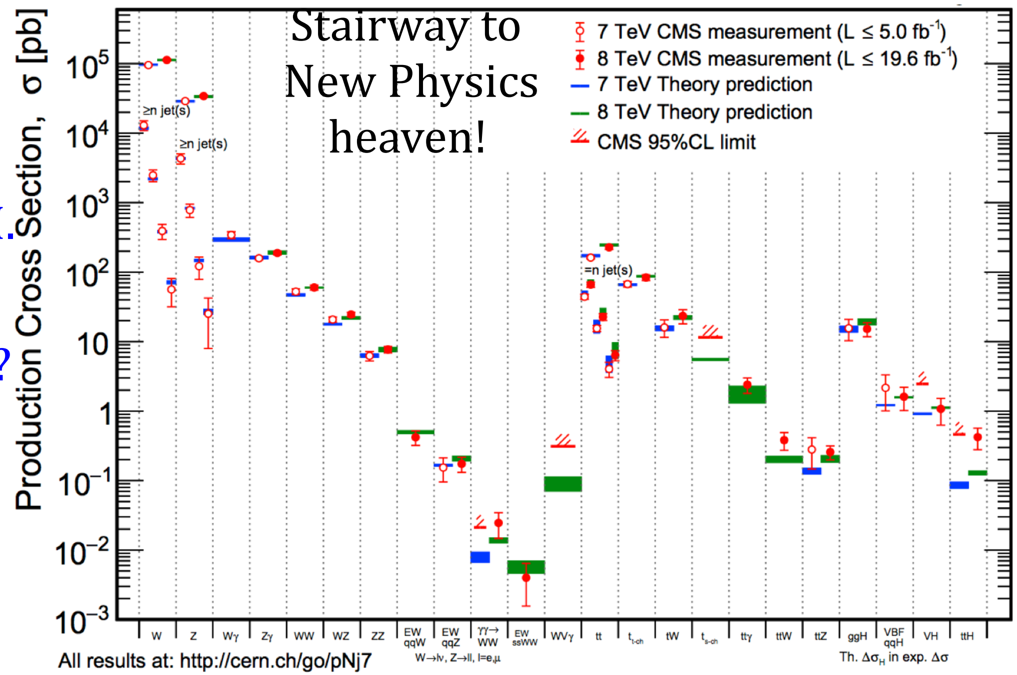
2-frag.HO:



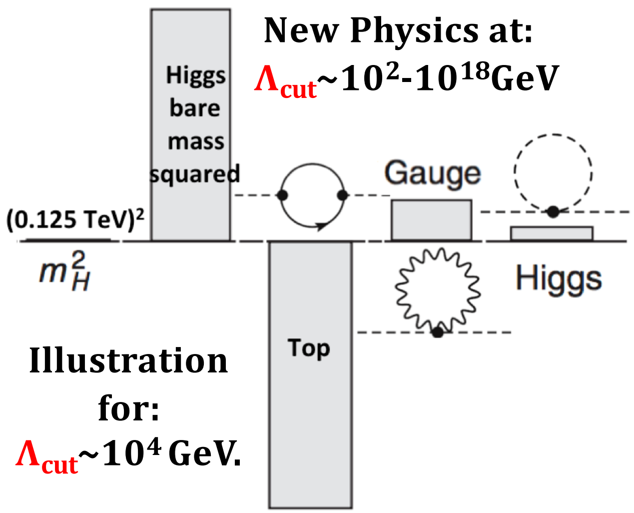
- DIPHOX produces separate x-sec calculation for "LO" and "HO" per M(γγ) range.
  (Typically HO is ~x10 higher than the LO.)

SM: Successes & Shortcomings

- SM: Very successful theory:
  - Precisely pred.: σ~[10^{11} - 10^{-3}] pb
  - Successful pred. of Higgs BRs.
  - No evidence for deviation from SM.
- But SM seams not a "final theory":
  - "Hierarchy/Naturalness" problem?
  - GUT Unification?
  - Gravity QFT ?
- Dark Matter & Dark Energy ?

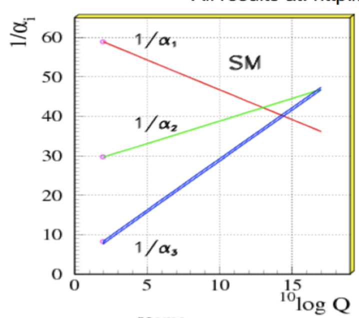


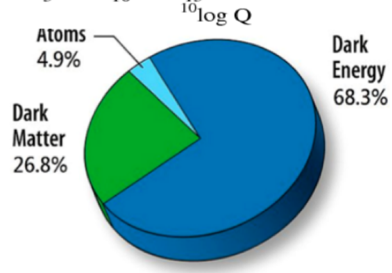
$m_{Higgs}^2 = m_{bare}^2 - [\pm\lambda\Lambda_{cut}^2 \pm ...] = 125^2\ GeV^2$

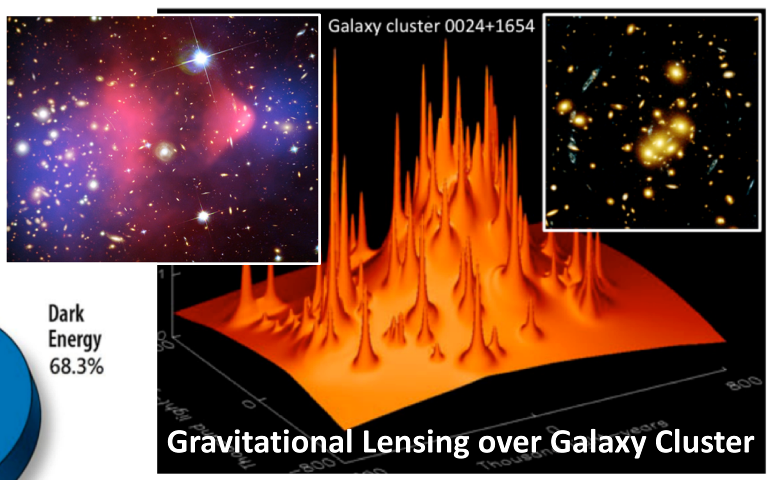


New Physics at:
Λ_{cut}~10^2-10^{18}GeV

Illustration for:
Λ_{cut}~10^4 GeV.

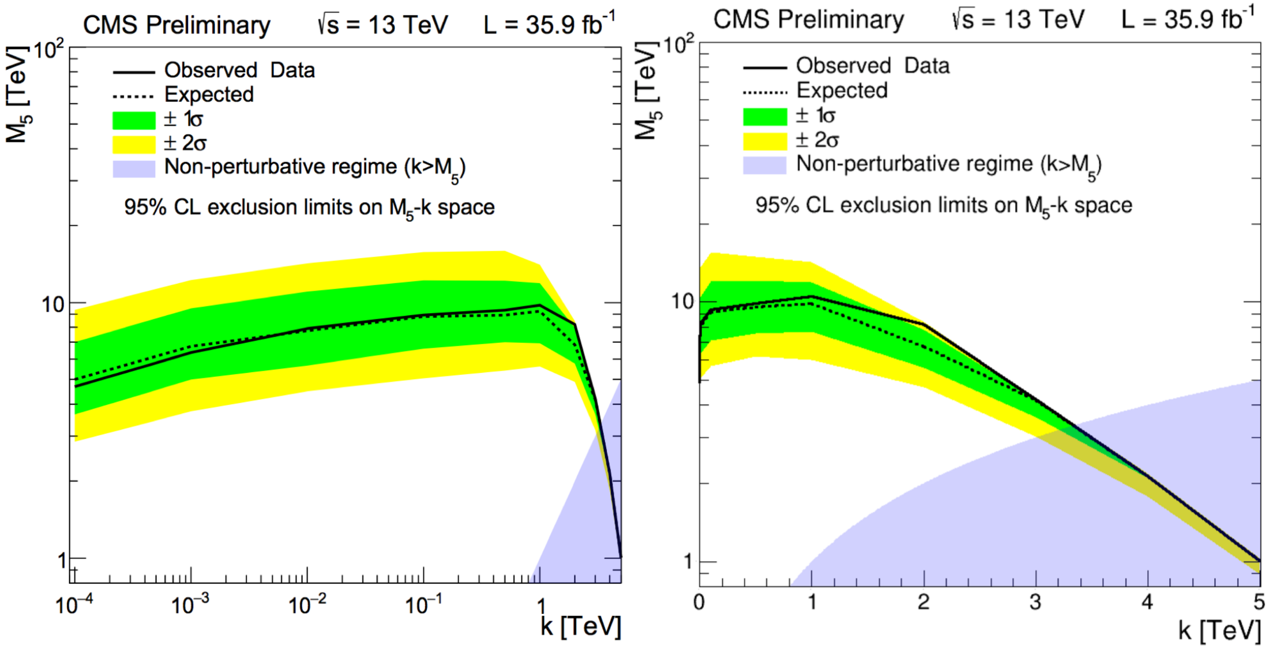






X-checks

- A search for



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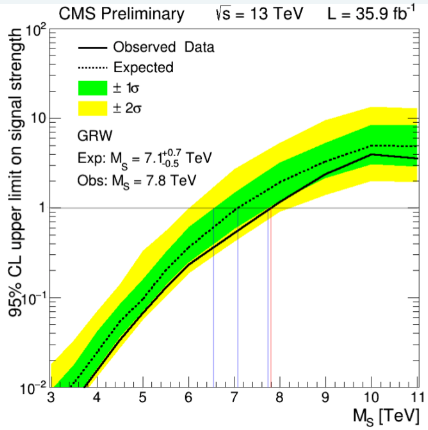

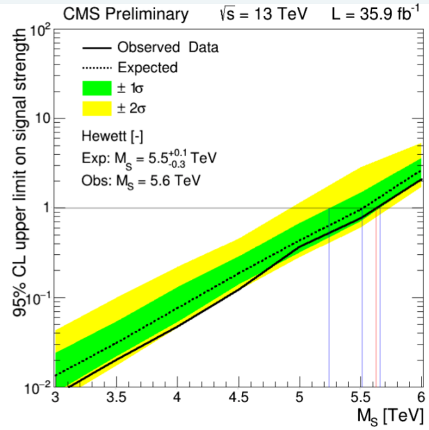

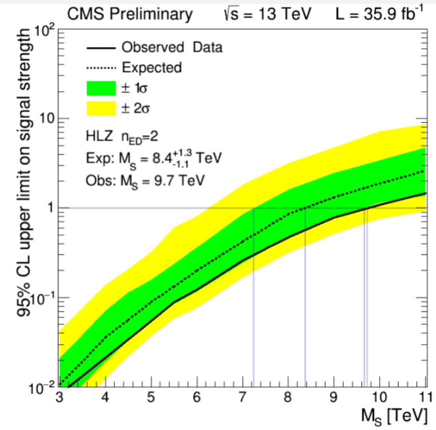

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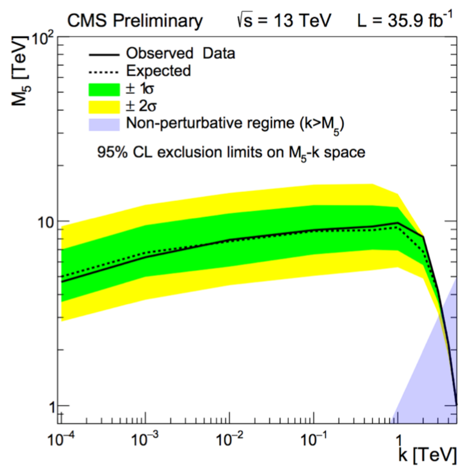

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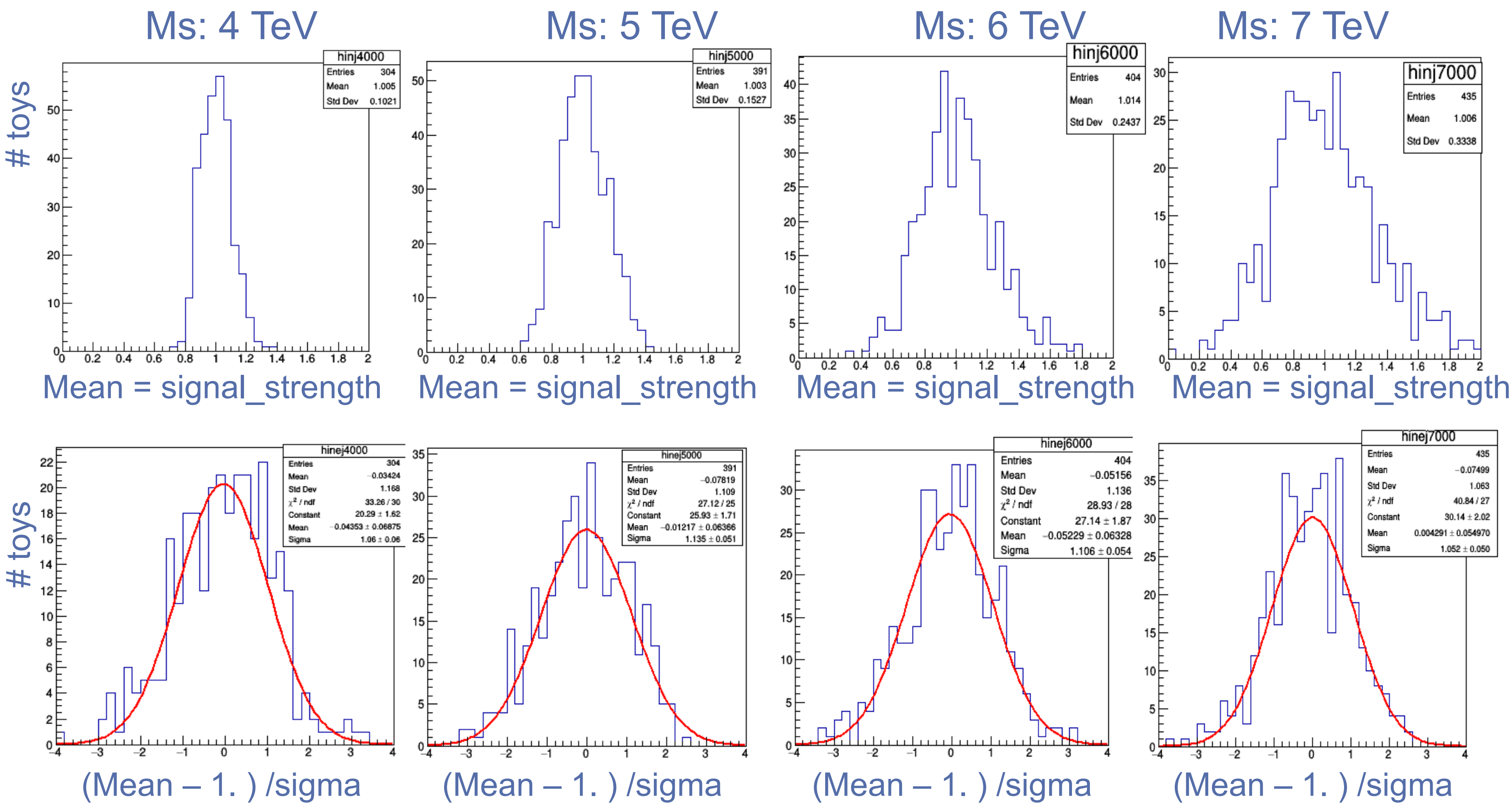

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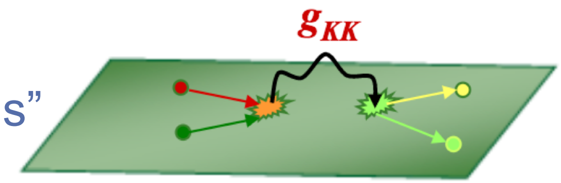

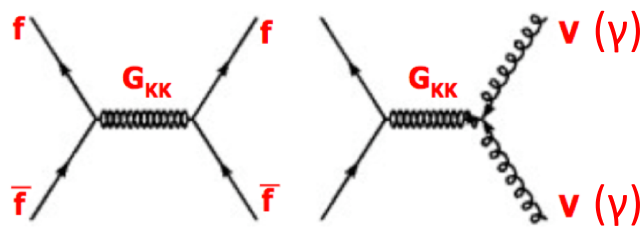

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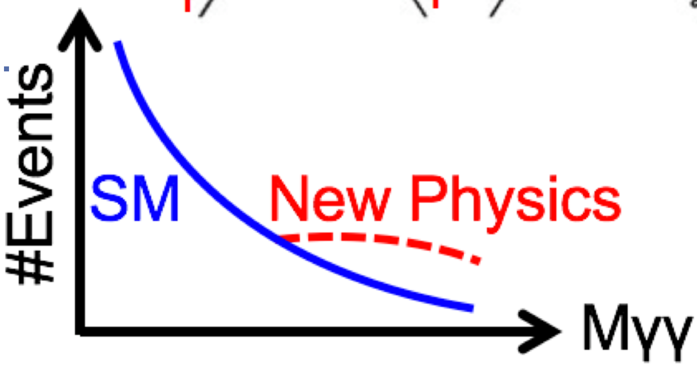

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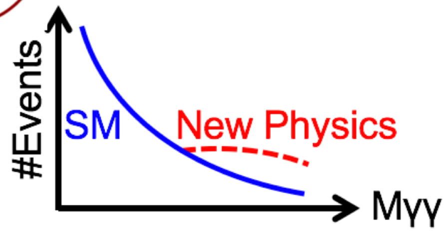

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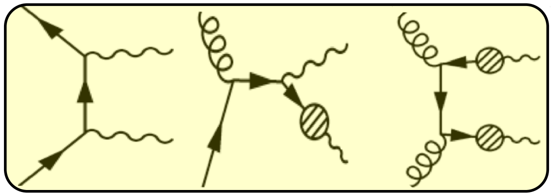

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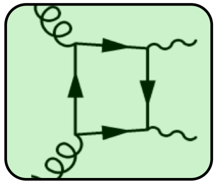
  → SHERPA 2.1.1, CT10, [LO +3partons +box].
- Subdominant BKG: "γj", "jj" fake.



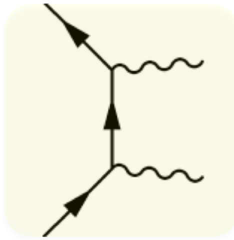
MC samples used:

γγ: DiPhotonJets_MGG-80toInf_13TeV_amcatnloFXFX_pythia8
GGJets_M-***To***_Pt-50_13TeV-sherpa
γ,jet: Gjets_HT-***To***_TuneCUETP8M1 13TeV-madgraphMLM-pythia8
jets: QCD_Pt-***to***_EMEnriched_TuneCUETP8M1_13TeV_pythia8

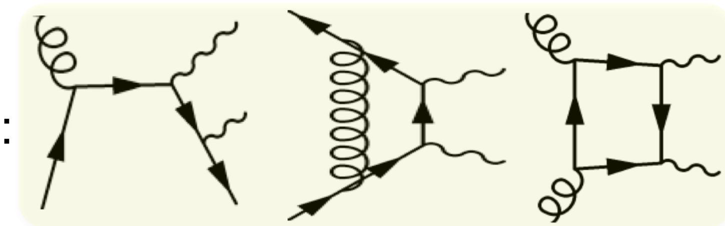
DIPHOX processes

- Diphox covers both:
  direct and indirect (hadron "fragmentation" originated photons) productions.

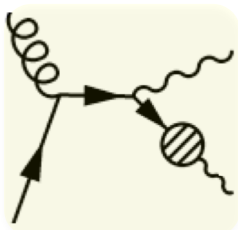
Direct LO:



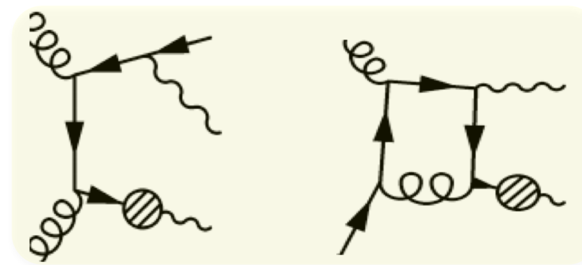
Direct HO:



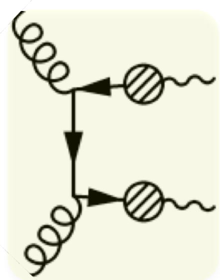
Single fragm. LO:



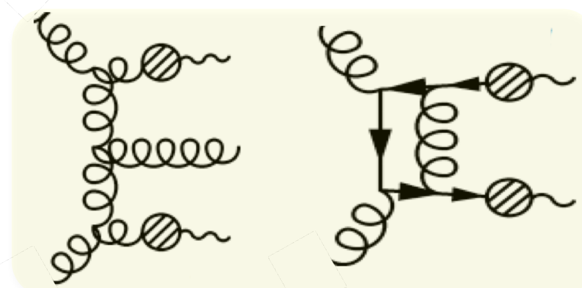
1-frag.HO:



Double fragm. LO:



2-frag.HO:



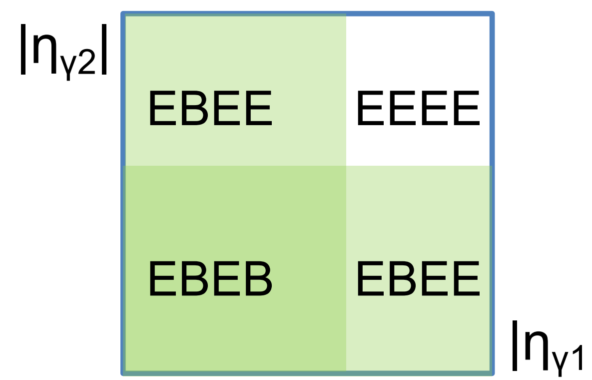
- DIPHOX produces separate x-sec calculation for "LO" and "HO" per M(γγ) range.
  (Typically HO is ~x10 higher than the LO.)

Event Selection Summary

- γ identifications (high-p_T photon ID)
  1) $\sigma_{i\eta i\eta}$ < 0.0105 [0.0112], (0.028 [0.03]) for EB(EE)
  2) H/E < 0.05
  3) "Conversion-safe electron-veto": applied.
  4) Iso_γ (corrected) < 2.75(2.0) GeV for EB(EE)
  5) Iso_{CH} < 5 GeV
  6) R_9 > 0.8

- Std primary Vertex selection:
  1) n_{dof} >=4,
  2) $|z|$ < 24 cm,
  3) d_0 < 2 cm

- Kinematics:
  1) N_γ >= 2,
  2) $p_{T\gamma}$ > 75 GeV,
  3) $|\eta_\gamma|$: [0, 1.4442] || [1.566, 2.5],
  4) At least one "γ" in EB → EBEB, EBEE.
  5) Mγγ > 0.5 TeV



Fake (γj,jj) BKG, rate & estimate

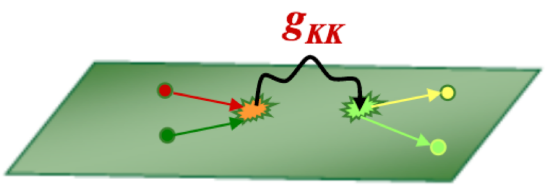
- Reducible Fake (γj,jj) BKG.
  Events where 1,2 jets with large EM activity fake a "γ", typically π^0,η^0)

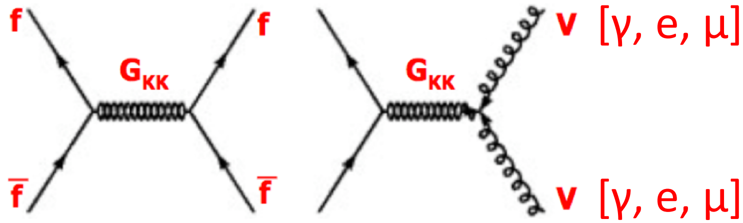
- We define the: *Fake Rate:* $$f = \frac{\text{number of jets passing high } p_T \text{ ID}}{\text{number of jets passing denominator definition}}$$

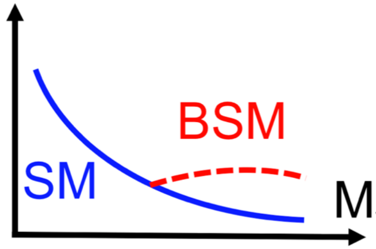
- Real photon are removed from numerator.
- Real and fake photon templates are fit to data in a fake photons sensitive variable template: $\sigma_{i\eta i\eta}$
- *Fake Rate* measured in a jet-rich dataset (JetHT, DoubleMu)
- as a function of $p_T(\gamma)$ in EB and EE.

- Apply the *Fake Rate* to the data to estimate the fake BKG:
- Identify denominator object in data → reweight by the Fake rate → form $M_{\gamma\gamma}^{Fake}$.

Glimpse on Selection, kinematics, M-spectra



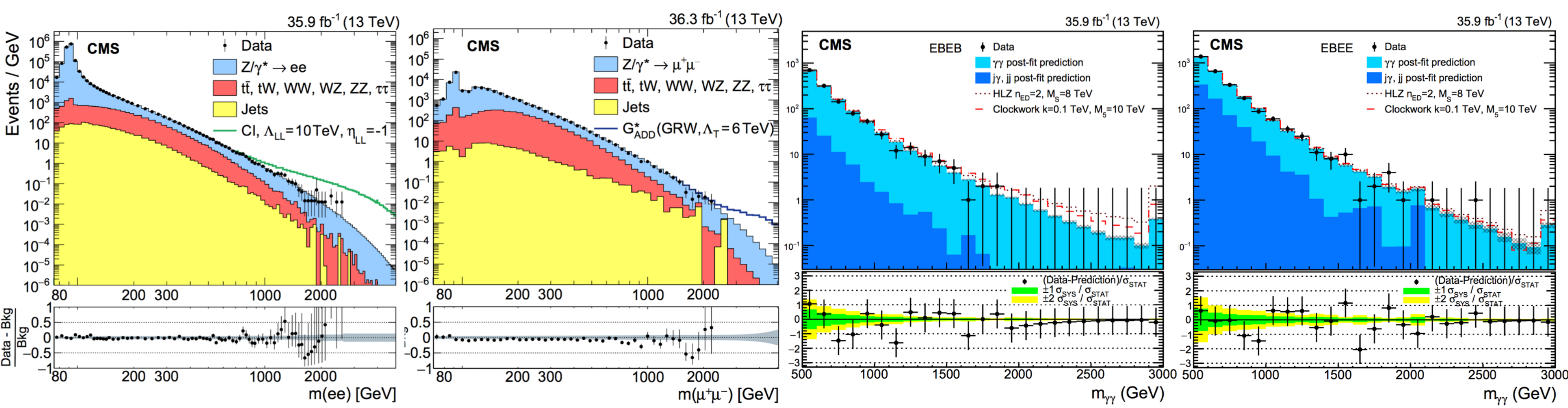




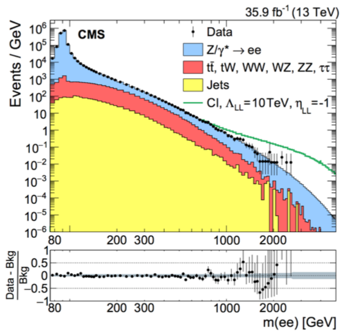
(Similar) Kinematic selection:

1) $N_{\gamma,e,\mu} = 2$,
2) Hight p_T objects (γ,e,μ)
3) |η|: [0, 1.4442] or [1.566, 2.5],
4) At least one obj. in Barrel → BB, BE (rejecting EE)
5) $M_{\gamma\gamma} > 0.5$ TeV, $M_{ee} > 1.8$ TeV, $M_{\mu\mu} > 1.8$ TeV

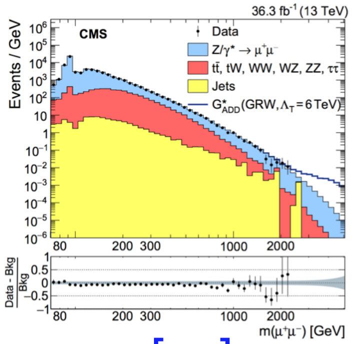
(Different) object definitions: we will not expand here – see EXO-17-017 & EXO-17-025.



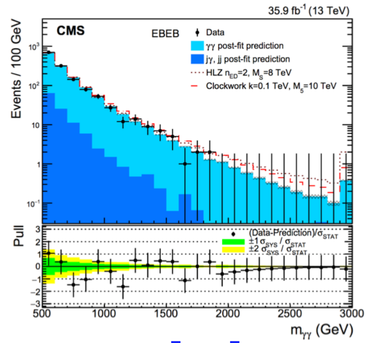
Combination binning break-down



[ee]



[μμ]



[γγ]

	[ee]	[μμ]	[γγ]
|η|:	BB, BE	BB, BE	BB, BE
Mass →	[1.8, 2.2] TeV [2.2, 2.6] TeV [2.6, 3.0] TeV [3.0, Λ_T] TeV	[1.8, 2.2] TeV [2.2, 2.6] TeV [2.6, 3.0] TeV [3.0, Λ_T] TeV	[0.5,0.6] TeV [0.6, 0.7] TeV … 0.1 TeV binning … […, 13.0] TeV

We set up limits in two different binning configurations:

1. with a single-bin for dileptons: M_{ll}>3 TeV, and
2. with the M_{ll}-multibin approach → This is supposed to be the “official”.

Comb. Sys.Unc. & Limits setting

- γγ Diphoton Sys. Unc. → Exactly as in γγ paper → 35 nuisance parameters.
  (26 for the individual PDFs + other 9 unc. See backups for more)

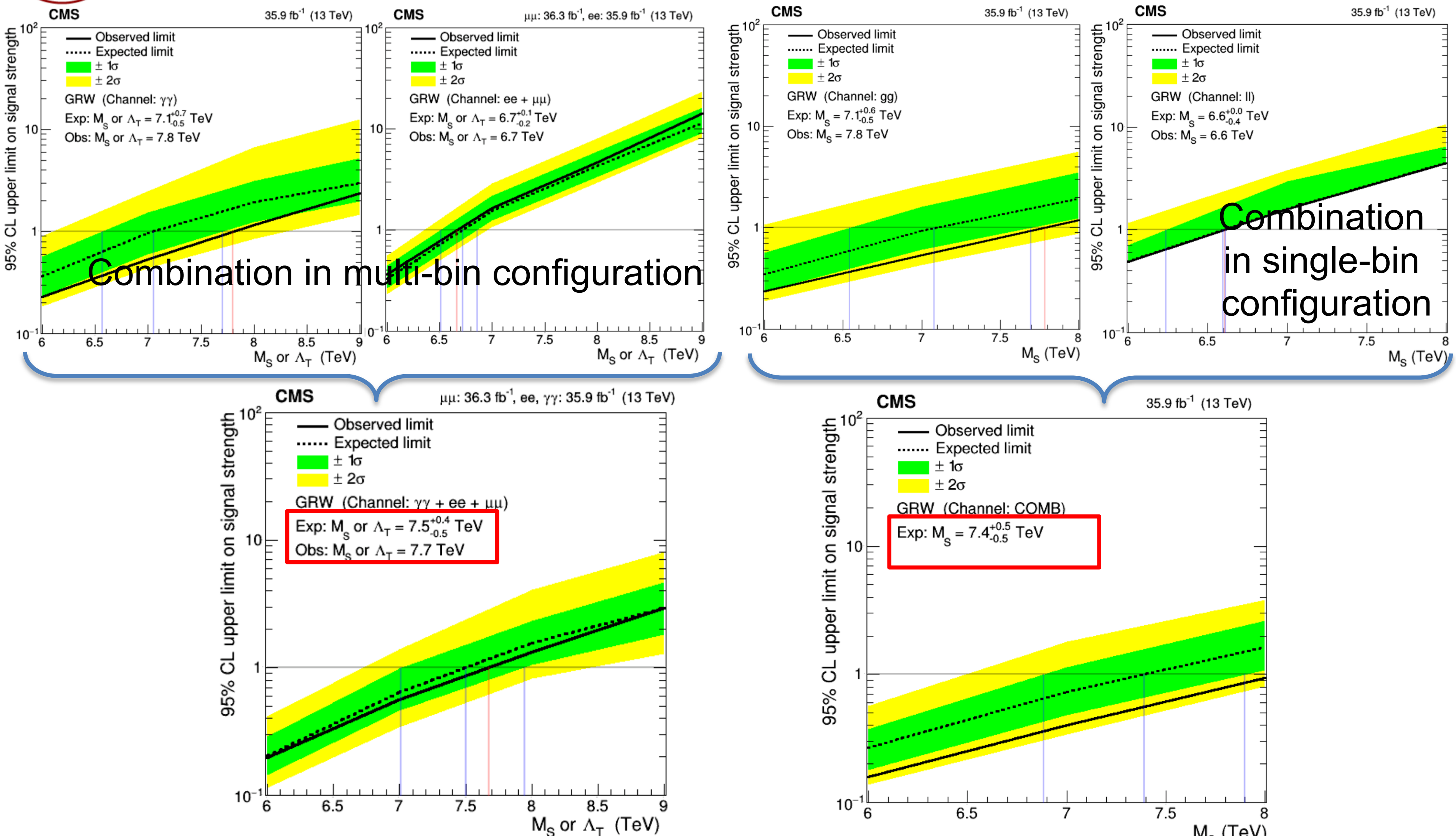
- ee, μμ Dilepton Sys. Unc. → 13 different sources (diff. nuisance parameters):
  [*EleEt , EleID , Gen_systPileup , Muon_systReconstruction , Muon_systResolution , Muon_systScale , crosssections , ddriven , lumi , mcstat , normalization , pdf_total , trigger*]
  → We use the same (lnN) prior of the 4 diff. M_{ll} bins.
  - Max of the 4-mass-bins for all sources (apparat from "mcstat")
  - Min of the 4-mass-bins for "mcstat"

- All nuisance par. are assumed uncorrelated with each other (including PDFs).
  → Different approaches (γγ/ee,μμ) makes difficult the addressing of correlations.

- Limits setting approach in Combination (exactly as in γγ-paper):
  Perform "Bayesian Marginalization" (MLE fit) to the data to extract posteriors.
  → Extract signal strength posterior,
  → plot the 95% CL upper limit on signal strength per mass point,
  → translate it to lower limits on M_S or Λ_T

- In this slides we set limits only on GRW → to be translated in HLZ, & Hewett.

γγ + ee + μμ Limits combination



- Finally, the **GRW exp. limits is: 7.50$^{+0.44}_{-0.49}$ TeV** (to be used in HLZ & Hewett)
- **Observed: 7.68 TeV.** (Multi-bin gain ~100 GeV here).

γγ+ee+μμ Obs. Limits combination

Order	GRW Λ_T [TeV]	Hewett M_S [TeV]	HLZ M_S [TeV] $n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
ee for $m_{ee} > 1.8$ TeV								
LO	6.1 (6.4)	5.5 (5.7)	7.0 (7.5)	7.3 (7.6)	6.1 (6.4)	5.5 (5.8)	5.1 (5.4)	4.9 (5.1)
LO ×1.3	6.3 (6.5)	5.7 (5.8)	7.3 (7.7)	7.5 (7.8)	6.3 (6.5)	5.7 (5.9)	5.3 (5.5)	5.0 (5.2)
$\mu\mu$ for $m_{\mu\mu} > 1.8$ TeV								
LO	6.7 (6.5)	6.0 (5.8)	7.9 (7.6)	7.9 (7.7)	6.7 (6.5)	6.0 (5.9)	5.6 (5.5)	5.3 (5.2)
LO ×1.3	6.8 (6.6)	6.1 (5.9)	8.1 (7.8)	8.1 (7.9)	6.8 (6.6)	6.2 (6.0)	5.7 (5.6)	5.4 (5.3)
Combined ee and $\mu\mu$ for $m_{\ell\ell} > 1.8$ TeV								
LO	6.7 (6.8)	6.0 (6.0)	7.9 (8.0)	8.0 (8.0)	6.7 (6.8)	6.1 (6.1)	5.7 (5.7)	5.4 (5.4)
LO ×1.3	6.9 (6.9)	6.1 (6.2)	8.2 (8.2)	8.2 (8.2)	6.9 (6.9)	6.2 (6.2)	5.8 (5.8)	5.5 (5.5)
Combined ee, $\mu\mu$, and $\gamma\gamma$ for $m_{\ell\ell} > 1.8$ TeV and $m_{\gamma\gamma} > 500$ GeV								
LO	7.7 (7.5)	6.9 (6.7)	9.3 (8.9)	9.1 (8.9)	7.7 (7.5)	6.9 (6.8)	6.5 (6.3)	6.1 (6.0)

Summary & Conclusion on Comb.

→ Inclusion of BE events improves limits by ~0.1 TeV (wrt BB-only) in all individual channels: γγ, ee, μμ.

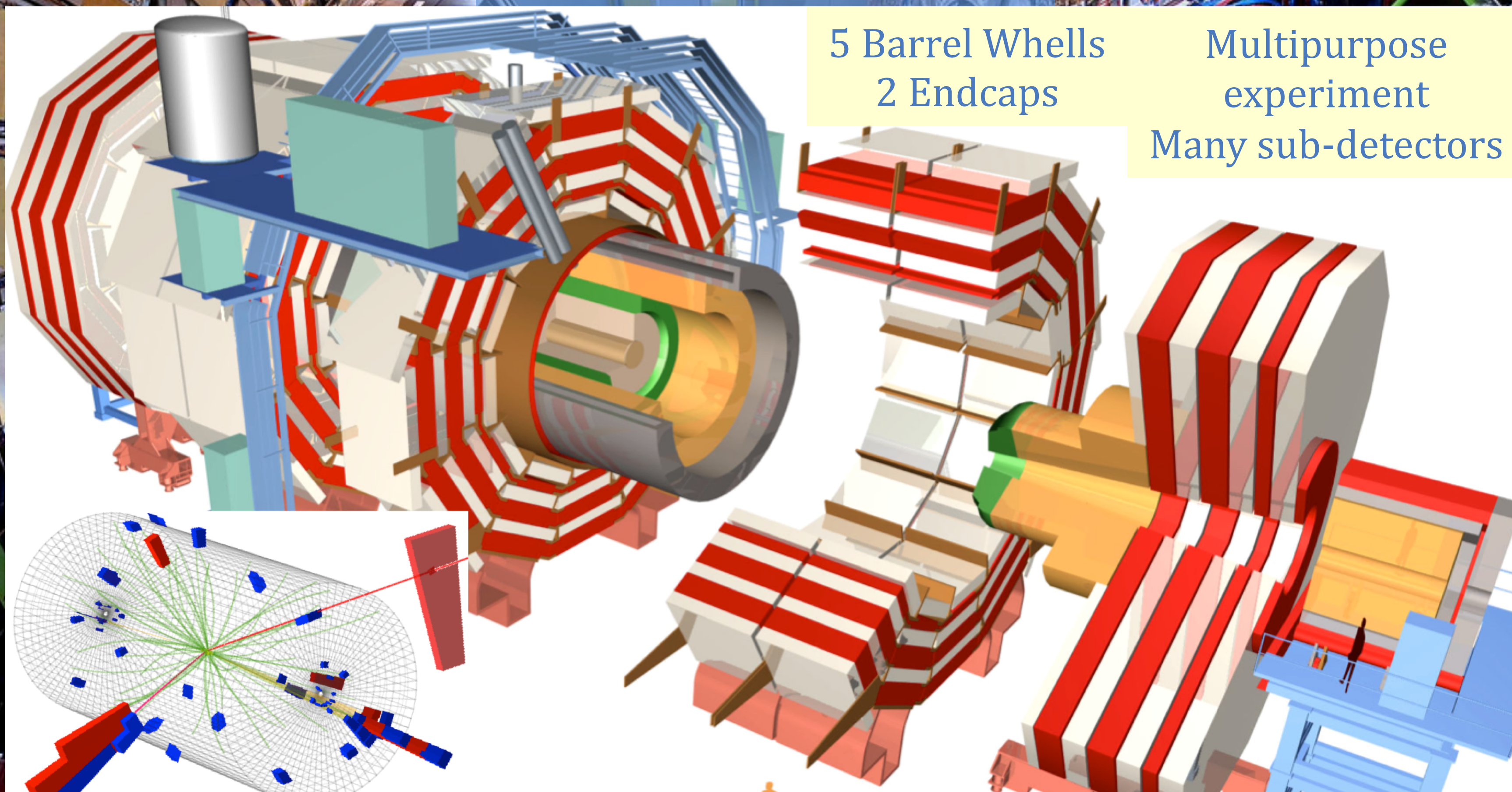
→ Multi-bin approach improves limits by ~0.3 TeV (wrt single-bin) in the individual channels: ee, μμ.

→ Diphoton & Dilepton combinations improves by ~0.4 TeV the γγ-result and by the ~0.8 TeV the dilepton result.

- GRW excluded at (95% CL) bellow 7.5(7.7) TeV exp.(obs.).
  (γγ observed limits still stronger by 0.1TeV due to data under-fluctuation in BB).
- Next steps:
  → Translate the results into HLZ & Hewett models.
  (HLZ n=2 needs a separate set of signal cards; everything else can be translated naively using the usual formula)
  → Translation to "1.3 K-factored signal" is straight forward, intersecting s-strength bands with 1.3 (instead of 1.0). Assuming s-strength scale linearly with normalization.

CMS Detector/Experiment

Compact Muon Solenoid
~4500 collaborators
~190 Institutes
Mass: ~12 500 Tonnes
Size: ~15m x 22m
Magnetic field: ~4 T



5 Barrel Whells
2 Endcaps

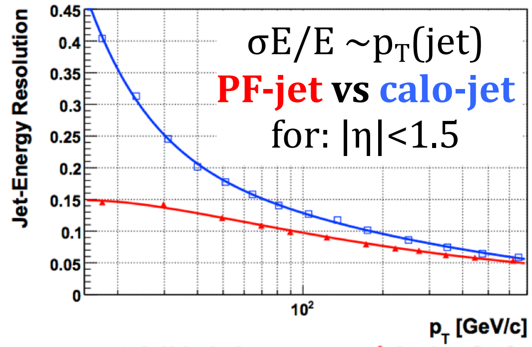
Multipurpose experiment
Many sub-detectors

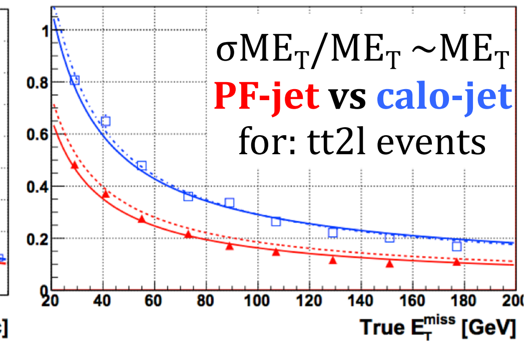
From Signals → Physics Objects Reco 1/2

◆ **Main Strategy:"Particle Flow".**

- Input: vertices/tracks/calo-clast.
- Clusterise to: **γ, $e^\pm$, $\mu^\pm$, $had^{\pm,0}$**.

(more on PF performance→ backups)

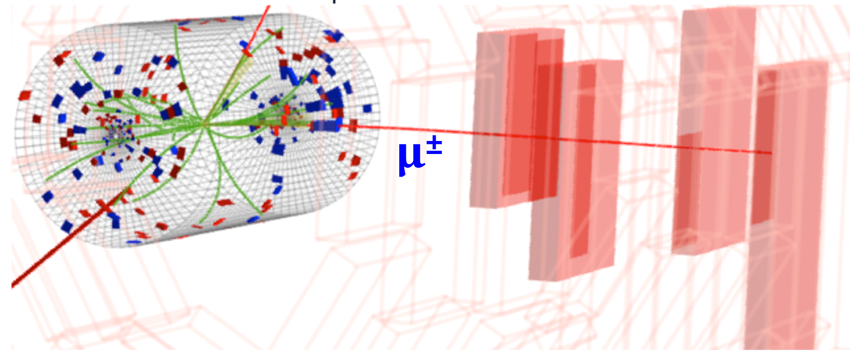




LEPTONS:

◆ **Muons [$\mu^\pm$]** (~stable, helical track)

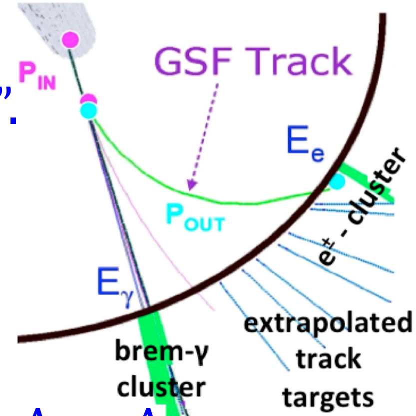
- Reco: Tracker & μ-chambers info.
- Purity-Eff. enhance with cuts: hits, Iso, d_z...

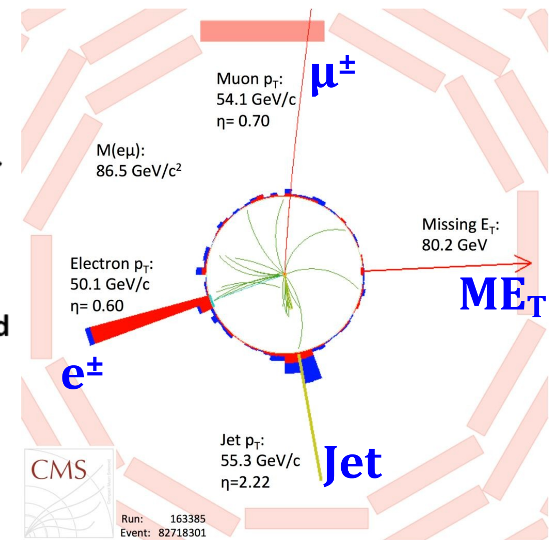


◆ **Electrons [$e^\pm$]**

- $e^\pm$ interact with tracker → radiates "γ".
- Reco: ECAL & Tracker info.
- Correct for brem-γ → fit to get "$e^\pm$".
- Reject γ-conversion.
- Purity-Eff. enhance cuts: χ^2/ndf, hits, Iso, $d_{z,xy}$, E/p-match, E/H, $\Delta\varphi_{in}$,$\Delta\eta_{in}$

→ Correct MC eff-SF.

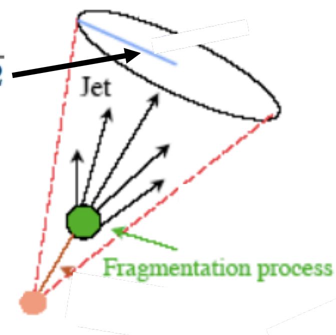


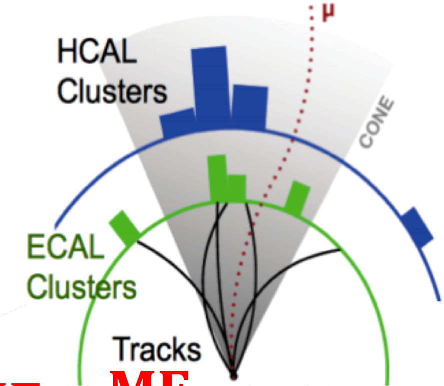


From Signals → Physics Objects Reco 2/2

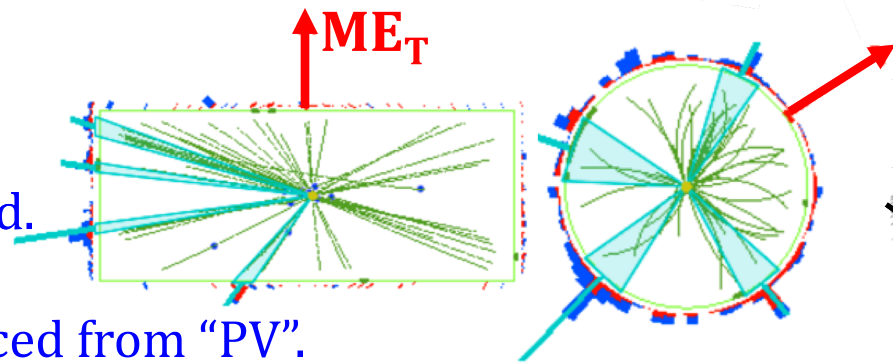
COMPOSITE OBJECTS

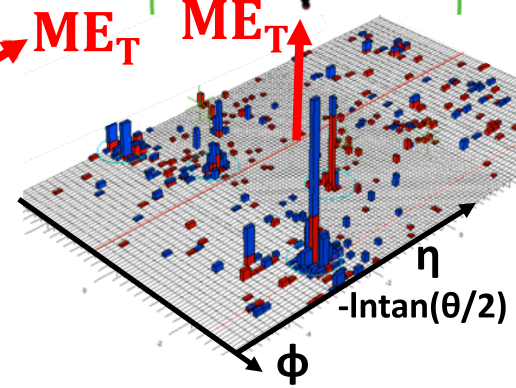
$$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$



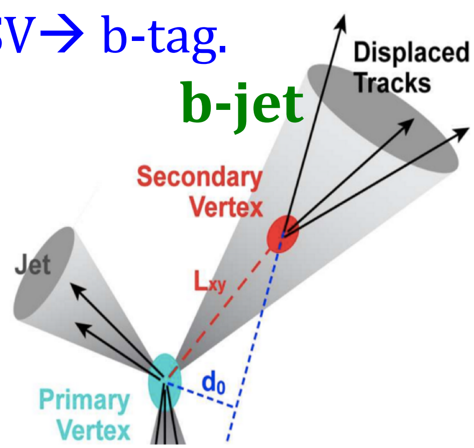


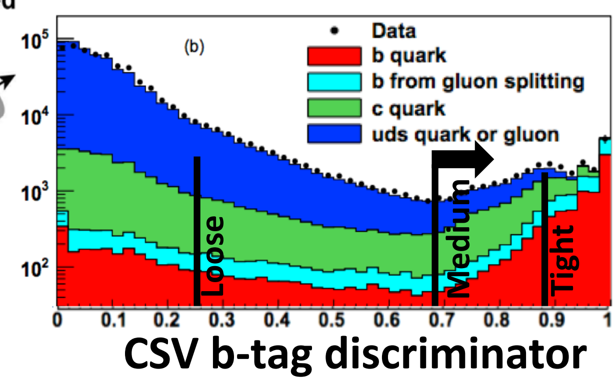
- **Jets =** hadronized q,g.
- Flow in cone: ΔR, η-φ plane:
- Jet = "PF-objects" + clustering algorithm.
- "anti-k_T", ΔR=0.5.





- **b-jets**
- b-hadrons: long-lived.
- Fly ~mm. b→Wc/u.
- Produce "SV" displaced from "PV".
- Identify "SV" → build variables CSV→ b-tag.





- **ME_T**
- Momentum imbalance in "xy"-plane using all PF-objects:

$$\vec{\not{E}}_T \equiv -\sum_i \vec{p}_T$$

(I will skip "γ", "τ_h", g-tagger, t-tagger, performance plots & calibr. Technics)