Search for resonant double Higgs production with $bbZZ$ decays in the $bb\ell\ell\nu\nu$ final state

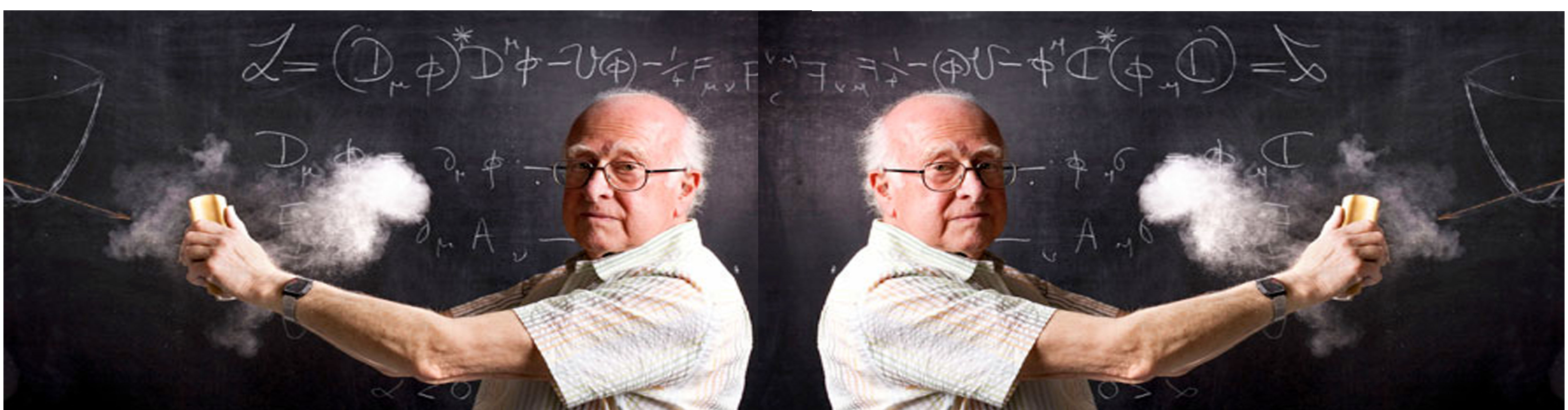
Ph.D. thesis defense (16 July 2019)

Rami Kamalieddin (UNLHEP)

Advisor: Professor Ilya Kravchenko

OUTLINE

- Double Higgs Theory
- Motivation for resonant double Higgs
- CMS detector
- Physics object reconstruction in CMS
- Physics data analysis
- Conclusions



The story

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In BSM, the HH xsex is enhanced and we may be able to see it!

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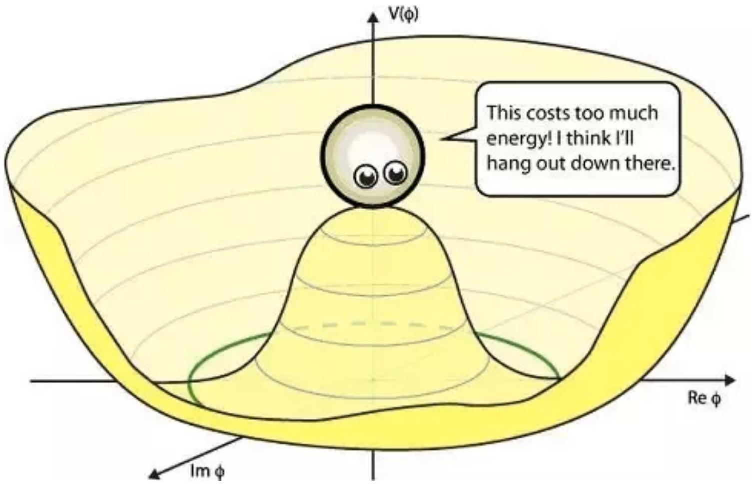
The solution:
In BSM, the HH xsex is enhanced and we may be able to see it!

The action:
Let's use CMSSW, Crab, GRID, Python, C++, Swan, TMVA, RooStats, Matplotlib etc … to DO IT!

Higgs and HH Theory

Higgs potential in the SM

- Want to know the exact form of the Higgs potential
- Need double Higgs to measure λ



$$L_{Higgs} = \frac{1}{2}\partial_\mu H \cdot \partial^\mu H - \mu^2 H^2 - \lambda \upsilon H^3 - \frac{\lambda}{4} H^4$$

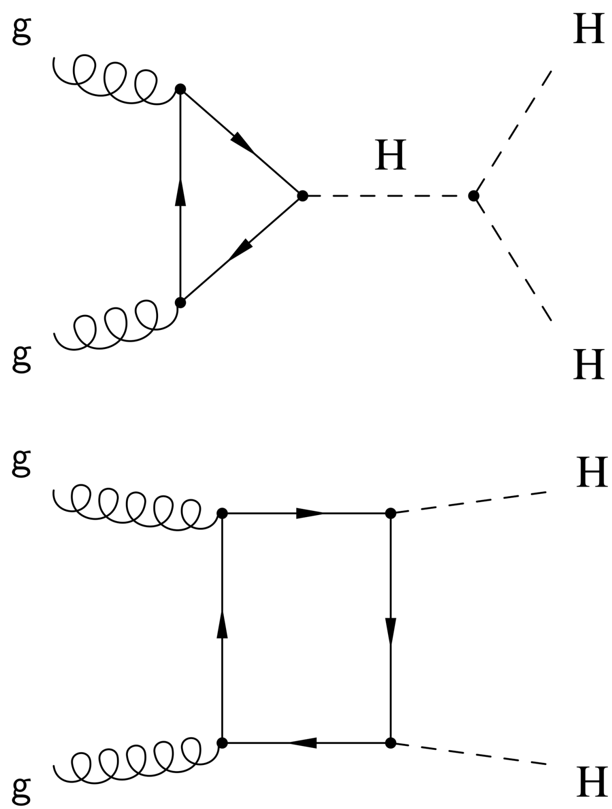
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda \upsilon H^3 + \frac{\lambda}{4} H^4$$

$$\frac{m_H^2}{2} = \lambda \upsilon^2 = \mu^2$$

$$\lambda = \lambda_{HHH} = \lambda_{HHHH}$$

HH Theory in the SM

- In SM, HH production is non-resonant :
  - Two diagrams interfering destructively
  - Low cross section: $\sigma^{HH}{}_{SM} \approx$ 33.45 fb at 13 TeV

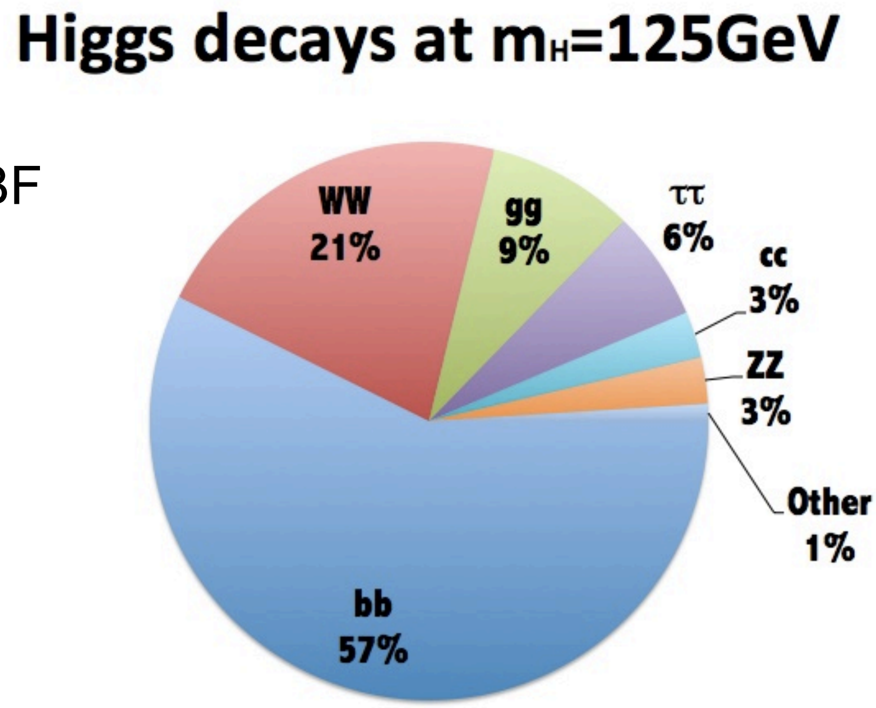


- We are not sensitive to the SM HH with the current LHC data ☹

Higgs boson decays

- bb decay has the highest BF

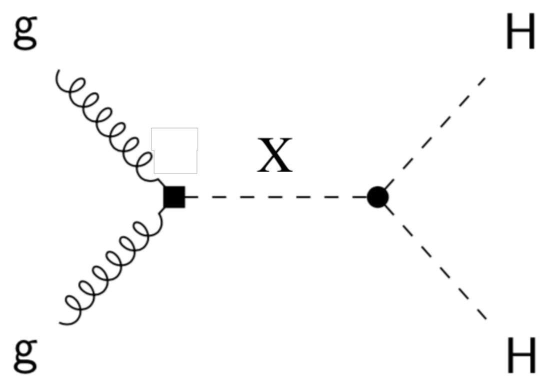
- ZZ* decay with Z to ee/μμ gives handles to improve the sensitivity



Motivation for the resonant double Higgs search

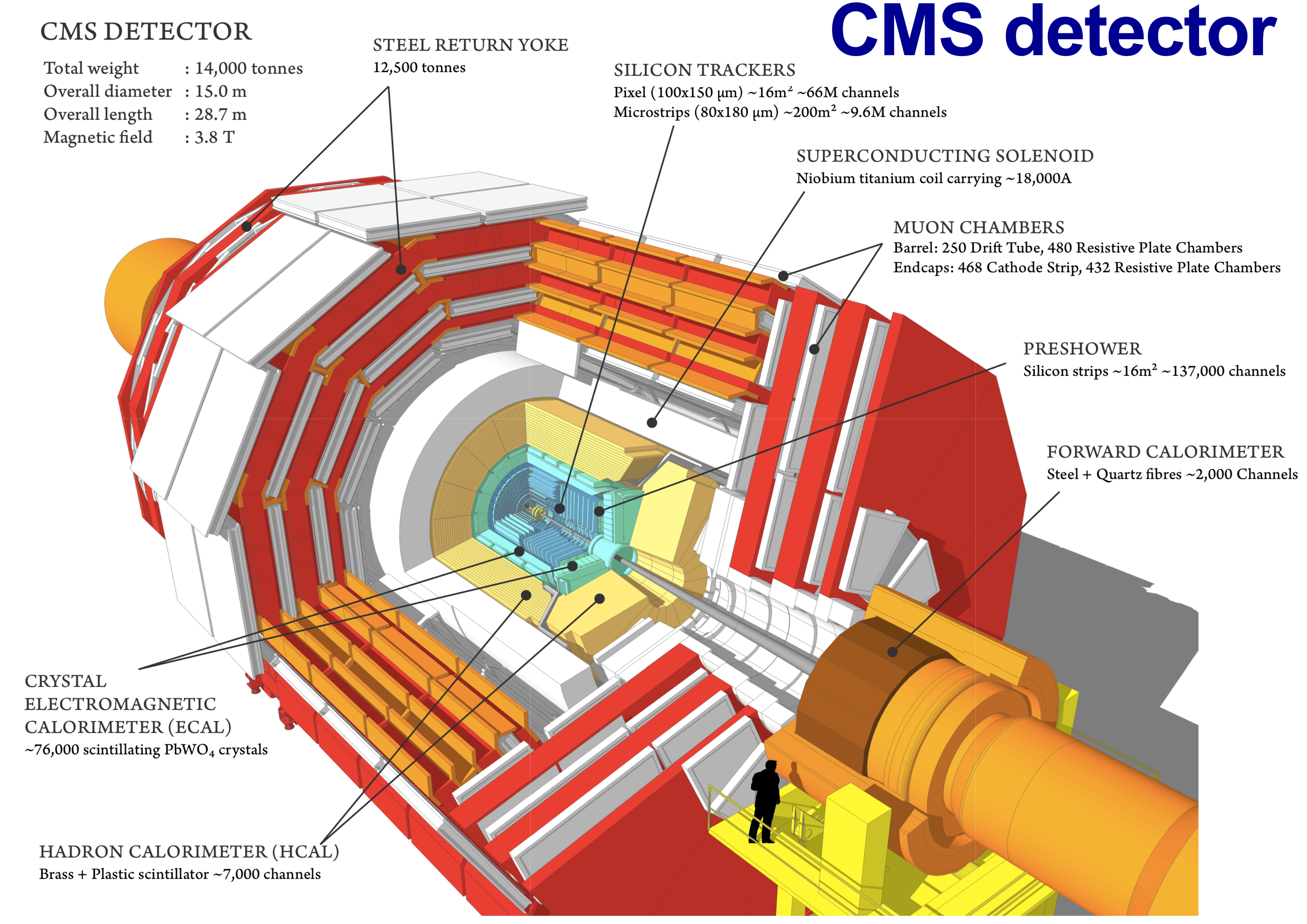
Motivation for the resonant HH

- HH production in BSM could be resonant:
  - Predicted by many BSM theories
  - Modified coupling constants can significantly increase σ^{HH}
  - Two types of particles: spin-0 (radion) and spin-2 (graviton)
  - Model-independent strategy for experimentalists: look for a ‘model independent’ narrow width resonances

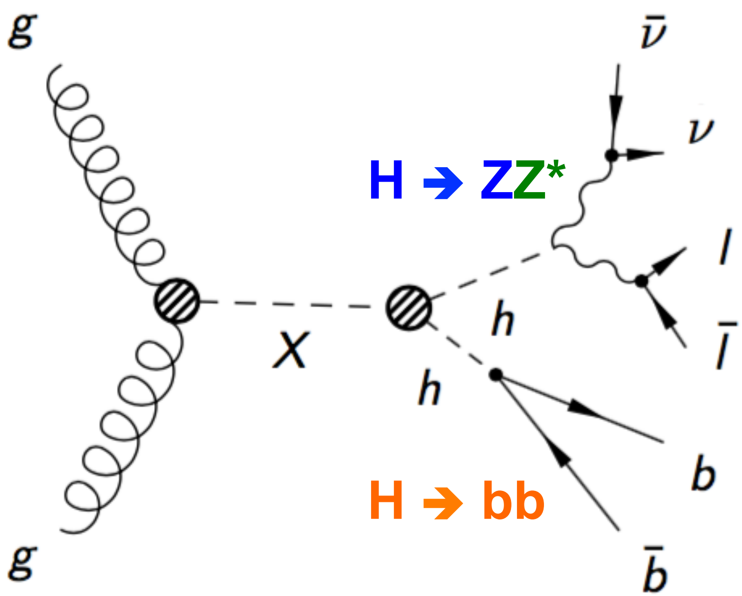


CMS detector

CMS detector



Physics objects of the 2*b* 2*l* 2*ν* signature



- Missing p_T from the off-shell Z* boson
- 2 leptons (ee, μμ) from on-shell Z
- 2 b jets from the Higgs ➔ bb

Reconstructed physics objects

Jets:
Jets are collimated streams of particles. As jets propagate through the CMS detector, they leave tracks in the tracking system and interaction showers in the calorimeter crystals. We have two jets from Higgs to bb decays.

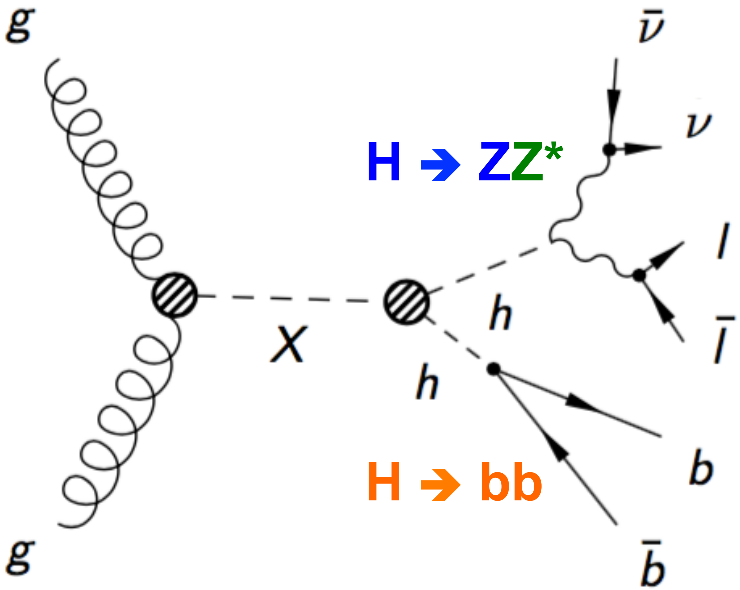
Electrons:
Leave tracks in the tracker and create a shower in the ECAL. Are coming from the on-shell Z boson decays.

Muons:
Leave tracks in the tracker, create a small shower in the ECAL, leave hits in the muon system, and escape the detector. Are coming from the on-shell Z boson decays.

Netrinos or Missing p_T:
Neutrinos from off-shell Z bosons are not detected directly, their presence is inferred using the method of the missing transverse momentum.

Physics data analysis

bbZZ: 2b 2l 2ν signature



- MET from the off-shell Z* boson
- 2 leptons (ee, μμ) from on-shell Z
- 2 b jets from the Higgs → bb

Selected HH system decays maximize sensitivity:
- H to bb has the highest BF, thus increases number of candidates
- H to ZZ*, with on-shell Z to ll because resonant Z selection reduces backgrounds

Analysis setup

Analysis in a nutshell

- HH decay in bb ll νν final state
- Analysis flow is optimized for a narrow width (O (GeV)) heavy resonance search in the range 250 to 1000 GeV
- BDTs are trained to optimize SR selection:
  - 2 BDTs are used: low (≤450 GeV) and high mass regions
- Signal extraction:
  - Binned shape analysis
  - To determine DY and TT SFs, simultaneously fit SR and CRs
  - HH_Mt shape is used in the fits to extract limits vs mass
  - 95% CL upper limits on the production σ of $X_{spin\ 0/2}$ to HH to 2b2l2ν
- We combine μμ and ee channels
- Results are compared with the WED theory

Data, MC samples, and Triggers

DATA

- Data collected during 2016:
  - DoubleMuon and DoubleEG data sets

SIGNAL: 250 GeV → 1000 GeV

- Gluon Fusion → X→ HH → bbZZ → 2b2l2ν for 'ZZ part' of signal, this is our signature
- Gluon Fusion → X→ HH → bbWW → 2blνlν for 'WW part' of signal, which also enters our selection

BACKGROUND

- Drell-Yan (DY) in association with 1→4 jets
- top anti-top (TT)
- Single top (ST), Dibosons, and ZH are minor background processes but also pass our selection

- **TRIGGERS**:
  1st Electron has p_T > 23 GeV and 2nd Electron has p_T > 12 GeV
  1st Muon has p_T > 17 GeV and 2nd Muon has p_T > 8 GeV

Physics objects

Physics objects and corrections

Jets:

- Particle Flow anti-k_T (Charged Hadron Subtracted) jets, JES and JER corrections are applied.
- Loose jet ID and PU-ID applied, also p_T > 30 GeV and $|\eta|$ < 2.4

b tagging

- CMVAv2 algorithm that uses 6 simpler taggers, WP Medium is applied
- b tagging/mistagging scale factors applied as weights

Electrons:

- MVA Identification WP Loose, p_T > 25/15 GeV and $|\eta|$ < 2.5. Identification (ID), Isolation (ISO), High-level Trigger (HLT) scale factors (SFs) are applied
- Particle Flow relative isolation < 0.06 (ρ-subtracted, cone $\Delta R = 0.3$)

Muons:

- Loose global muon, p_T > 20/15 GeV and $|\eta|$ < 2.4, ID, ISO, TRK, HLT SFs
- Particle Flow relative isolation < 0.15 ($\Delta\beta$-subtracted, cone $\Delta R = 0.4$)

Missing p_T:

- Particle Flow missing p_T with all needed corrections

Event selection

Event selection

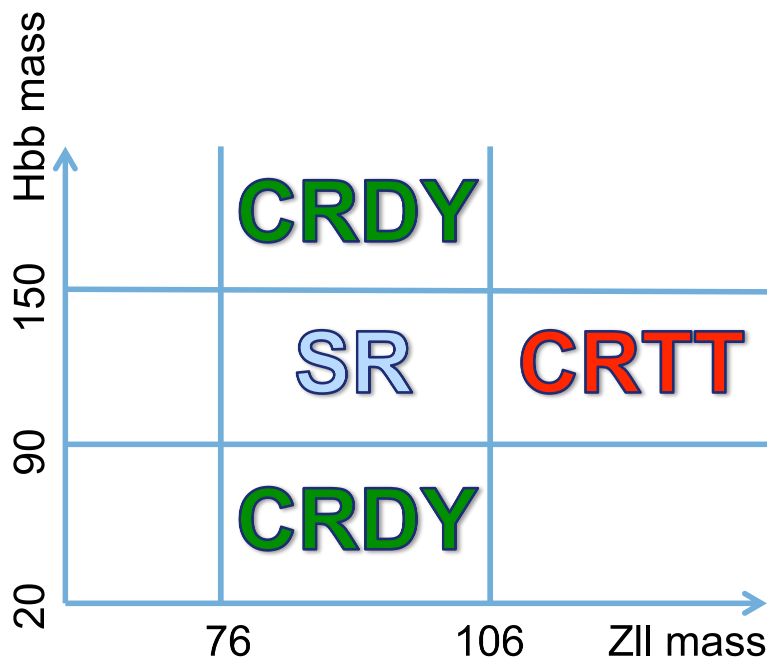
- Z boson and Higgs boson candidates:
  - $Z(\mu\mu)$: two opposite-sign muons with $p_T > 20/15$ GeV
  - $Z(ee)$: two opposite-sign electrons with $p_T > 25/15$ GeV
  - $H(bb)$: a pair of b-jets with the highest CMVAv2 discriminant value

- On the way to HH system:
  - $\geqq$ 2 b-jets
  - 20 GeV < H_{bb} mass
  - 2 leptons
  - 76 GeV < Z_{ll} mass to be orthogonal to bbWW measurement
  - Missing p_T selection to be orthogonal to bbZZ in 2b2l2q state
  - Z_{ll} + H_{bb} + missing $p_T \approx$ HH candidate
  - Requirement on the pseudo-transverse mass of HH $\geqq$ 100 GeV $\quad \tilde{M}_T(HH) = \sqrt{E^2 - p_z^2}$

Signal and control regions

Three regions are defined:

- Signal Region (**SR**): Z_{ll} mass = [76, 106], H_{bb} mass = [90, 150]
- Control region DY (**CRDY**): Z_{ll} mass = [76, 106], H_{bb} mass =]90-150[
- Control region TT (**CRTT**): Z_{ll} mass > 106, H_{bb} mass = [90, 150]

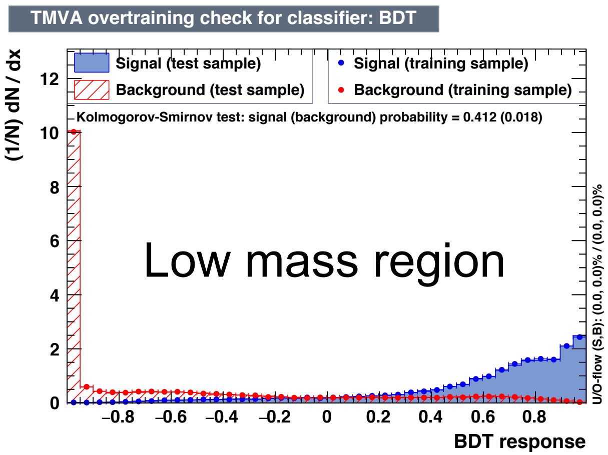


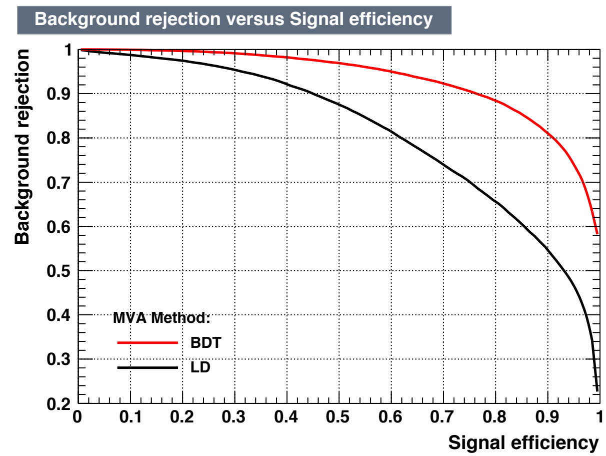
Background reduction

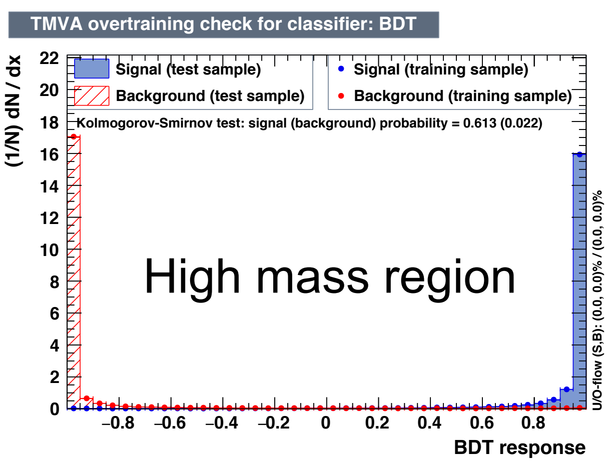
BDT discriminant

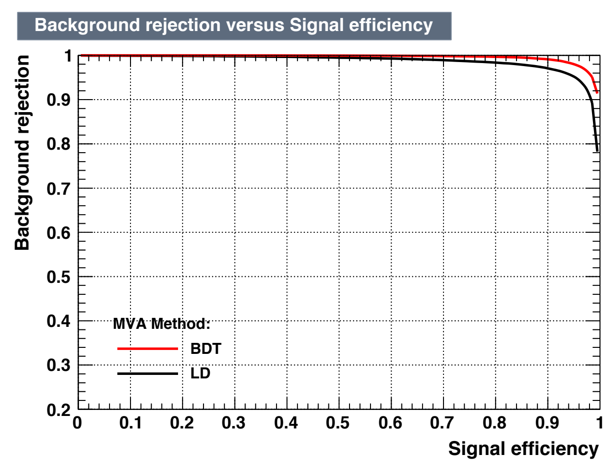
- To reduce background contamination in the SR: require a BDT selection
- BDTs are trained on bbZZ signal vs DY&TT events
- BDT selections are optimized for each mass hypothesis in 250 → 1000 GeV and each channel (ee/μμ) separately to yield the lowest limit
- The mass range is split into two:
  - Low mass (250 → 450 GeV)
  - High mass (500 → 1000 GeV)
- The input to BDT is a set of nine variables:
  - M_T and p_T of Z boson and Higgs boson candidates
  - ΔR between leptons and ΔR between b jets
  - Missing p_T (MET)

BDT Performance







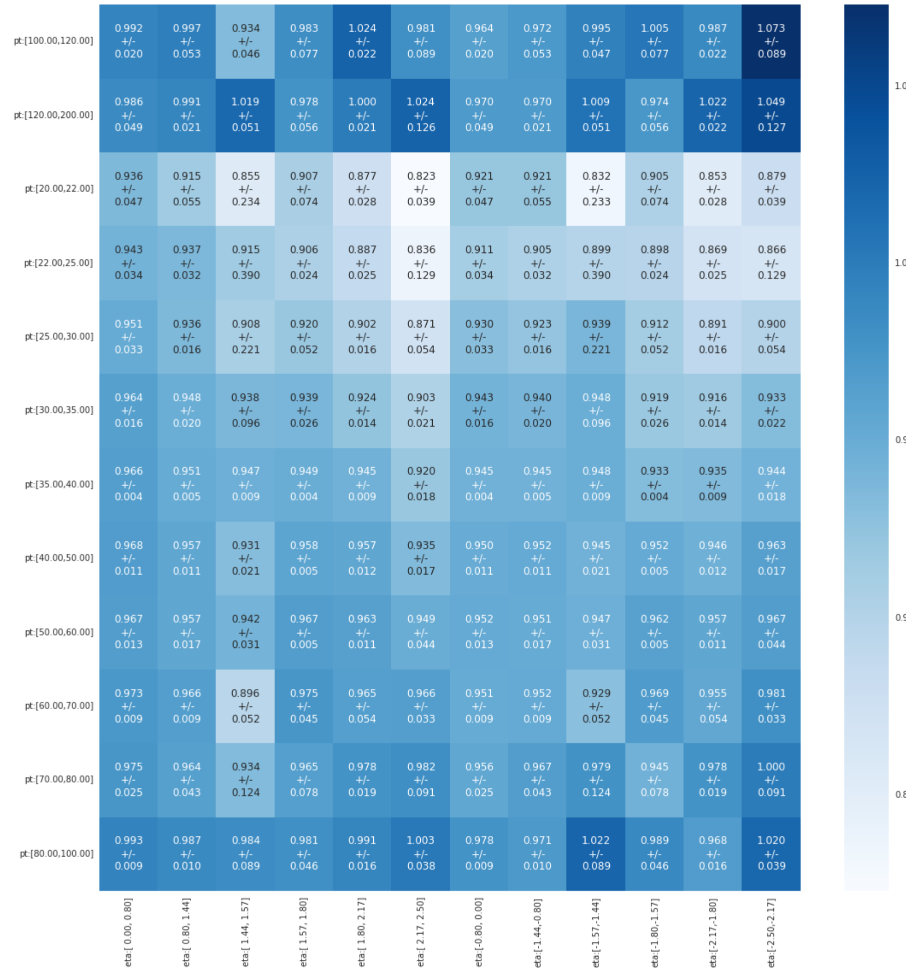


Di-electron channel, gravion hypothesis

Data-MC disagreements

Data-MC discrepancies

- Lepton efficiencies
- b tagging and light flavor mistagging probability
- Kinematic reweighting of the DY plus jets samples
  - $\Delta\eta_{bb}$
  - $p_T(Z)$



Maximum likelihood fit

$$L(r_{signal}, r_k \mid data) = \prod_{i=1}^{Nbins} \frac{\mu_i^{n_i} \cdot e^{-\mu_i}}{n_i!} \cdot \prod_{j=1}^{Nnuisances} e^{-\frac{1}{2}\vartheta_j^2}$$

$$\mu_i = r_{signal} S_i + \sum_{k=1}^{Nbackgrounds} r_k B_{k,i}$$

Index i is reserved for bins of the input distributions

Index j is reserved for uncertainties

n_i is the number of observed data events in the bin i

Index k refers to the background process k, and $B_{k,i}$ is the content of the bin i of the background shape for a process k, and S_i is the content of the bin i of the signal shape

The parameter r_k sets the normalization of the background process k, while r_{signal} is the signal strength parameter

All r parameters float freely in the fit

Systematics

Uncertainties

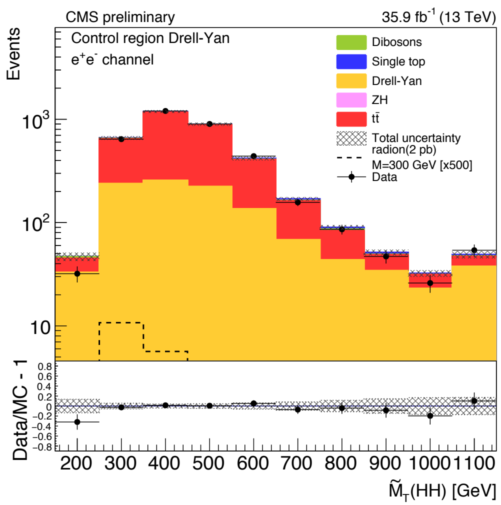
Normalization:
- Luminosity
- PDF uncertainties
- QCD scale variations
- Cross section normalization
- Pile up
- MET
- Drell-Yan and TT normalizations

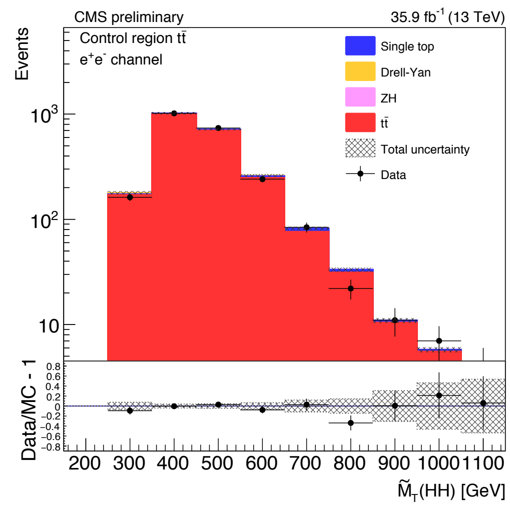
Shape:
- Lepton Scale factors: split into all components
- Jet Energy Scale
- Jet Energy Resolution
- Tagging of a b jet
- Mistagging of a b jet
- **Bin-by-Bin** MC uncs

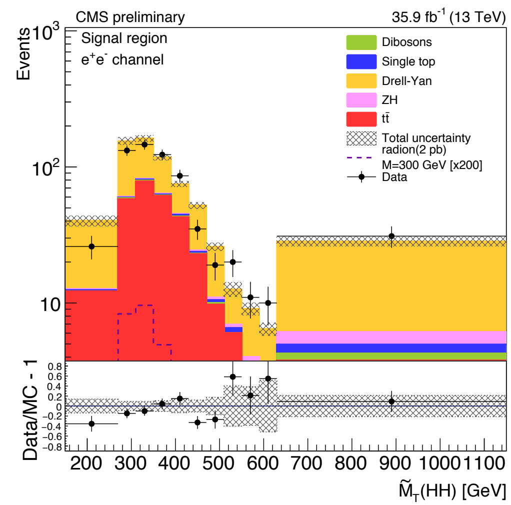
Results

Post-fit HH_Mt in SR and CRs

e+e-







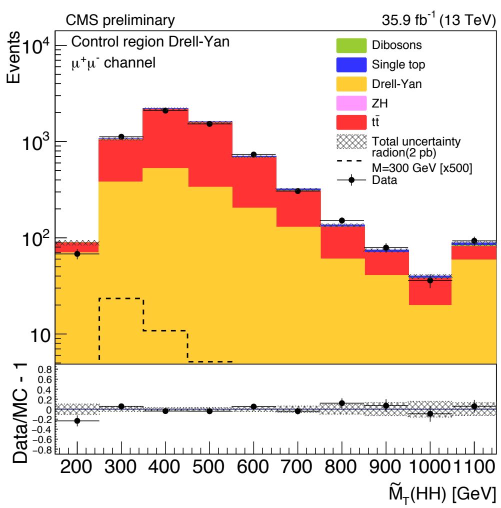
CRDY

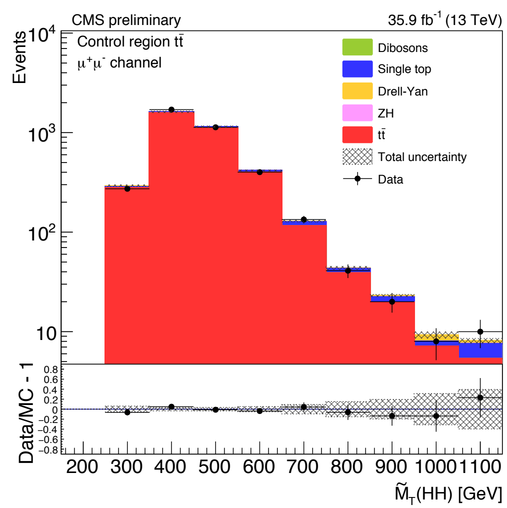
CRTT

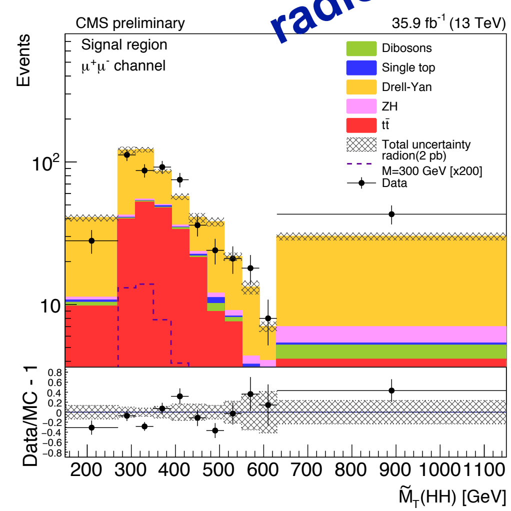
SR

radion (spin 0)

m+m-

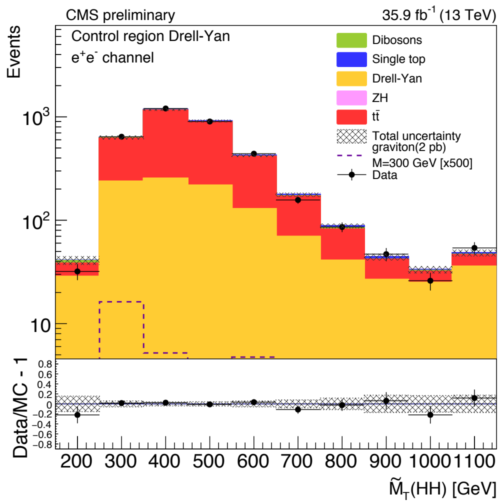


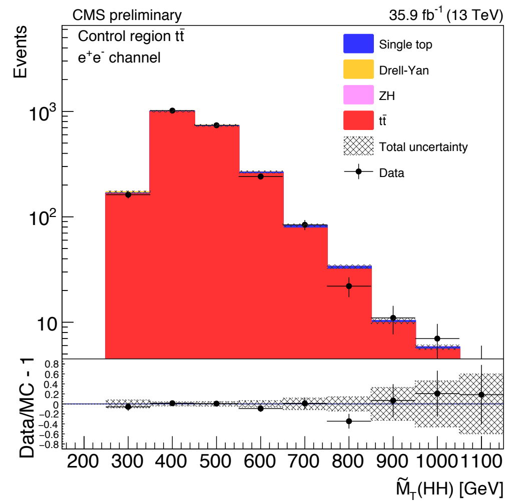


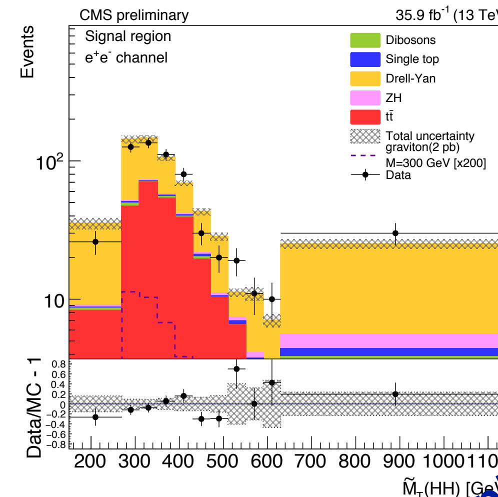


Post-fit HH_Mt in SR and CRs

e+e-



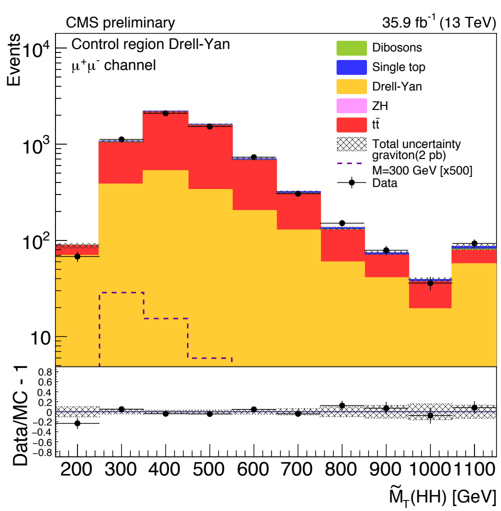


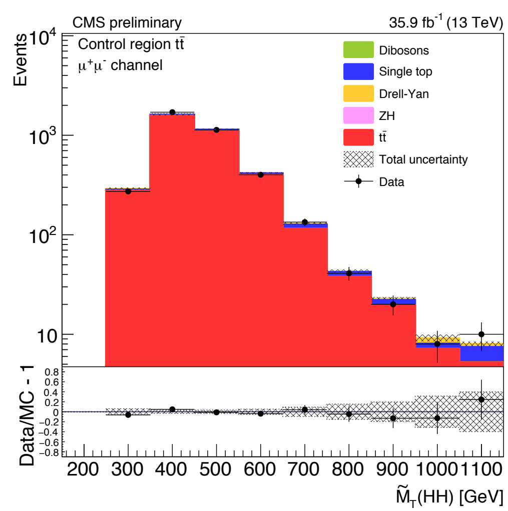


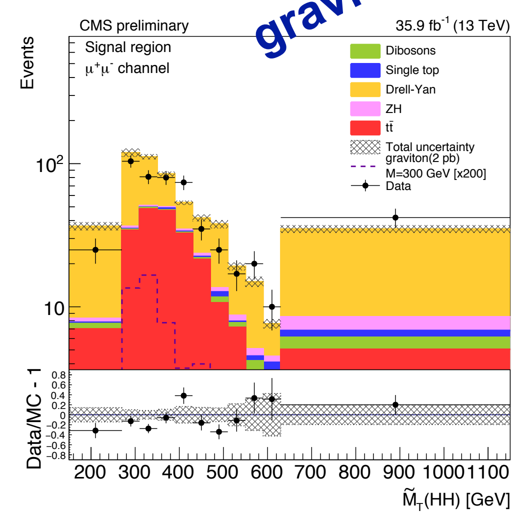
CRDY CRTT SR

graviton (spin 2)

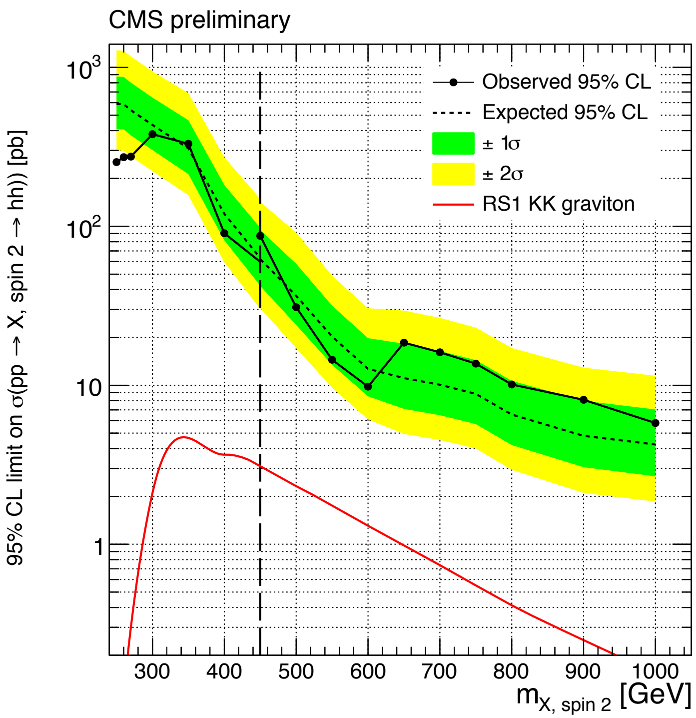
m+m-







95 % CL upper limits

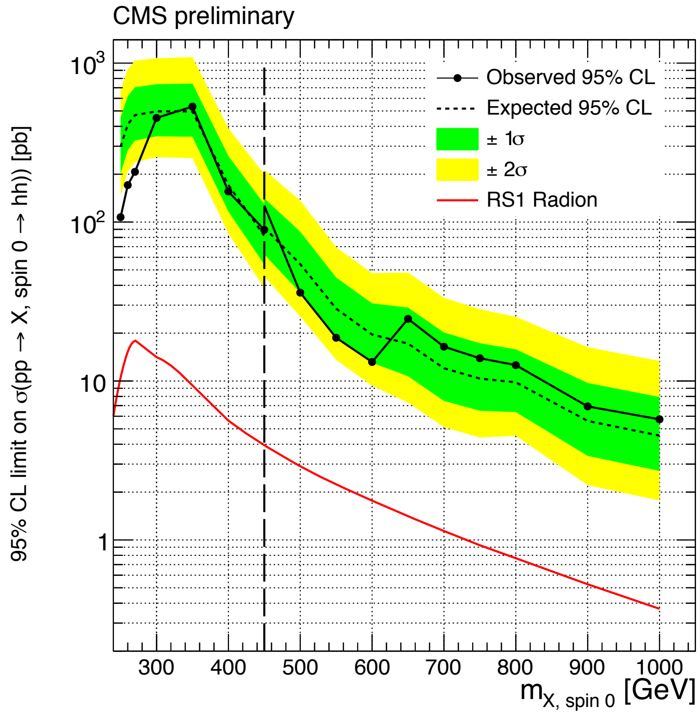


Mass, GeV	Observed Limit (pb)	Expected Limit (pb)
250	253.5	589.1
260	272.2	585.9
270	274.4	537.5
300	380.0	434.4
350	330.6	309.4
400	90.4	119.9
450	59.8	63.3
500	31.0	36.6
550	14.5	20.2
600	9.8	12.7
650	18.5	11.1
700	16.1	10.1
750	13.7	8.8
800	10.1	6.5
900	8.1	4.8
1000	5.8	4.2

graviton(spin 2)

http://cds.cern.ch/record/2648796?ln=en

95 % CL upper limits



Mass, GeV	Observed Limit (pb)	Expected Limit (pb)
250	107.3	297.7
260	170.8	410.9
270	207.0	470.3
300	451.7	496.9
350	532.6	496.9
400	155.7	171.1
450	89.3	82.0
500	36.0	54.4
550	18.7	28.5
600	13.2	19.6
650	24.6	17.2
700	16.4	12.0
750	13.9	10.4
800	12.6	9.8
900	6.9	5.6
1000	5.7	4.5

radion (spin 0)

http://cds.cern.ch/record/2648796?ln=en

Summary

- We have presented the search for resonant HH production with bbZZ decays in 2b2l2ν final state using 35.9 fb^{-1} of data collected in 2016

- Main backgrounds are DY and TT: fit simultaneously (ML fit) signal and control regions to determine their normalizations

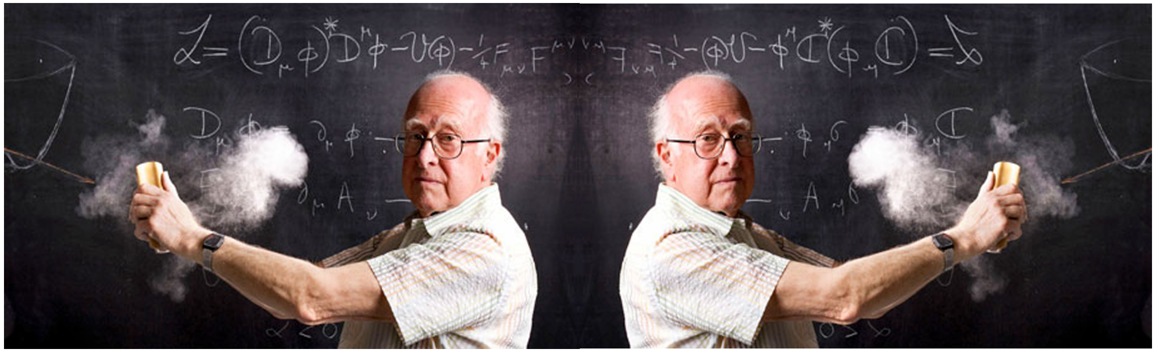
- Use BDTs to reduce background contamination in the signal region

- Combination of ee and μμ channels was used to derive expected limits as a function of mass of a narrow width spin 0/2 resonance decaying to HH

- Interpretation of results is done in WED theory

- This is the world-first search for double Higgs boson production in the bbZZ intermediate channel

Backup material



Triggers

Triggers for dimuon and dielectron analysis channels both at L1 and HLT levels.

Channel	L1 Seeds	HLT Paths
$Z(\mu\mu)\ Z(\nu\nu)H \rightarrow b\overline{b}$	L1_SingleMu20	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v⋆ OR HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_v⋆ OR HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v⋆ OR HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v⋆
$Z(ee)\ Z(\nu\nu)H \rightarrow b\overline{b}$	L1_SingleEG30 OR L1_SingleIsoEG22er OR L1_SingleIsoEG24 OR L1_DoubleEG_15_10	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ

MC samples

Signal samples and DY are at LO using MadGraph5_aMC@NLO, Pythia for parton showering and hadronization

DY is reweighted to NLO using $\Delta\eta_{bb}$ and $p_T(Z)$

Top quark at NLO:
1) t-channel, tW, tt using POWHEG
2) s-channel using MadGraph5_aMC@NLO

Single top is rescaled to NNLO

Dibosons at LO using Pythia and rescaled to NLO

ZH at NLO using MadGraph5_aMC@NLO and rescaled to NNLO

DY plus 1 Jet	MadGraph5_aMC@NLO-PYTHIA
DY plus 2 Jets	MadGraph5_aMC@NLO-PYTHIA
DY plus 3 Jets	MadGraph5_aMC@NLO-PYTHIA
DY plus 4 Jets	MadGraph5_aMC@NLO-PYTHIA
WW	PYTHIA
WZ	PYTHIA
ZZ	PYTHIA
ZH with $H \to b\bar{b}$ and $Z \to \ell\ell$	MadGraph5_aMC@NLO
$t\bar{t}$	POWHEG-PYTHIA
top quark tW channel	POWHEG-PYTHIA
$\bar{t}$ quark tW channel	POWHEG-PYTHIA
top quark t-channel	POWHEG-PYTHIA
$\bar{t}$ t-channel	POWHEG-PYTHIA
top quark s-channel	MadGraph5_aMC@NLO-PYTHIA

DY and TT SFs from the fit

Normalization for backgrounds, final numbers after the application of all the nui-sances during the postfit procedure. Electron channel. All regions are used.

channel,mass	TT_SF	DY_SF
ee 300 GeV	0.80 +/- 0.09	1.62 +/- 0.23
ee 900 GeV	0.79 +/- 0.08	1.64 +/- 0.18

Normalisation for backgrounds in the unblinded SR only, final numbers after the applica-tion of all the nuisances during the postfit procedure. Electron channel.

channel,mass	TT_SF	DY_SF
ee 300 GeV	0.8 +/- 0.1	1.58 +/- 0.25
ee 900 GeV	0.9 +/- 0.33	1.75 +/- 0.49

Normalization for backgrounds, final numbers after the application of all the nui-sances during the postfit procedure. Muon channel. All regions are used.

channel,mass	TT_SF	DY_SF
mm 300 GeV	0.91 +/- 0.07	1.44 +/- 0.13
mm 900 GeV	0.91 +/- 0.07	1.43 +/- 0.13

Normalisation for backgrounds in the unblinded SR only, final numbers after the applica-tion of all the nuisances during the postfit procedure. Muon channel.

channel,mass	TT_SF	DY_SF
mm 300 GeV	0.91 +/- 0.07	1.49 +/- 0.15
mm 900 GeV	0.91 +/- 0.19	1.53 +/- 0.42

HLT SFs for dimuon triggers

HLT_BIT_HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v or
HLT_BIT_HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v
or HLT_BIT_HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_v
or HLT_BIT_HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v

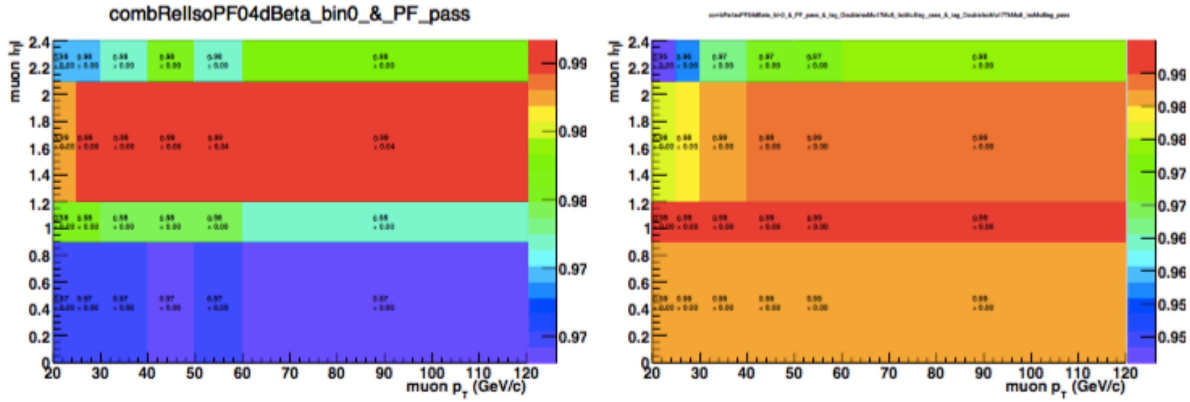


Figure 3: Scale factors in p_T and η bins for 2016 data runs B, C, D, E, F, G for the HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v* OR HLT_Mu17_TrkIsoVVL_TkMu8_TrkIs oVVL_v* triggers. Left: Scale factors for 8 GeV leg. Right: Scale factors for 17 GeV leg, provided that the subleading leg passed 8 GeV cut.

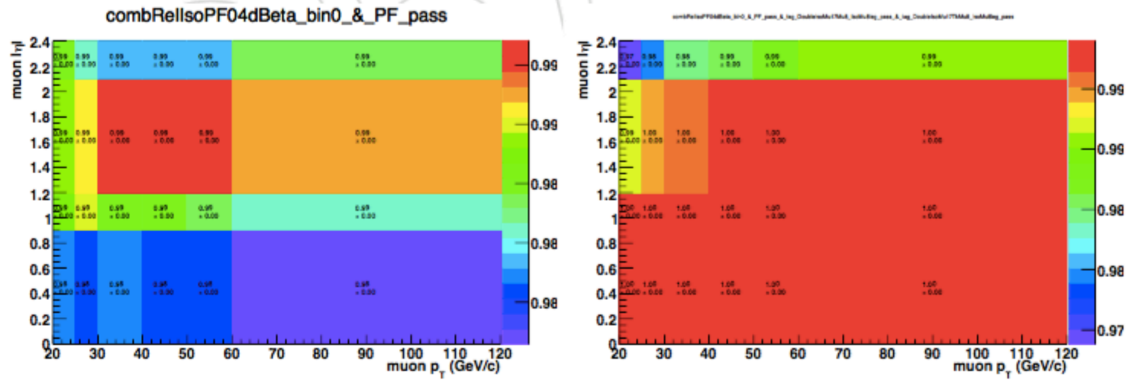


Figure 4: Scale factors in p_T and η bins for 2016 data run H for the HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v* OR HLT_Mu17_TrkIsoVVL_TkMu8_TrkIs oVVL_v* triggers. Left: Scale factors for 8 GeV leg. Right: Scale factors for 17 GeV leg, provided that the subleading leg passed 8 GeV cut.

HLT SFs for dimuon triggers, dZ requirement

HLT_BIT_HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v or
HLT_BIT_HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v
or HLT_BIT_HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_v
or HLT_BIT_HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v

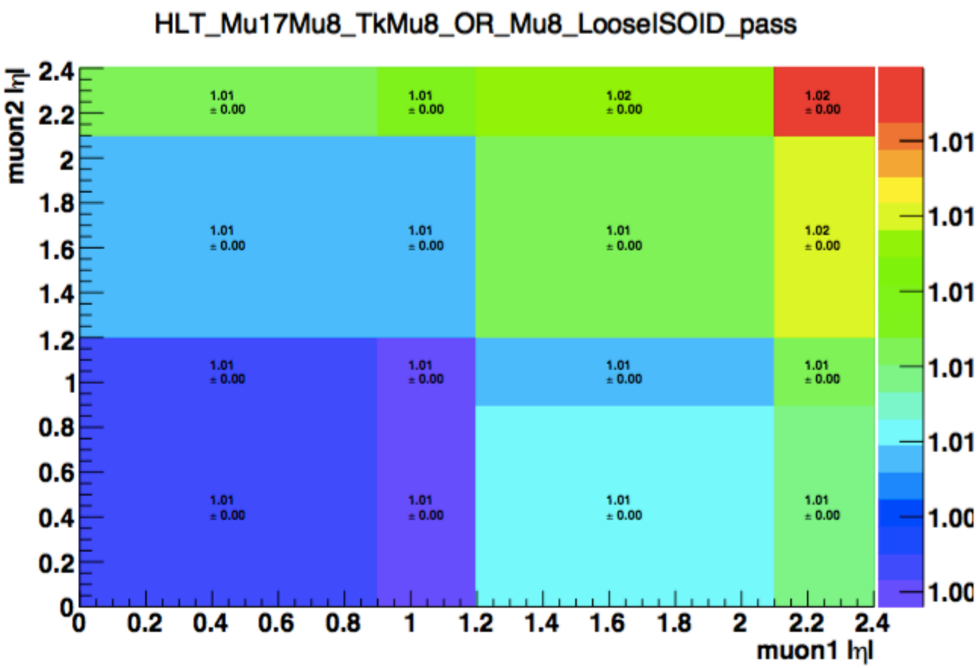
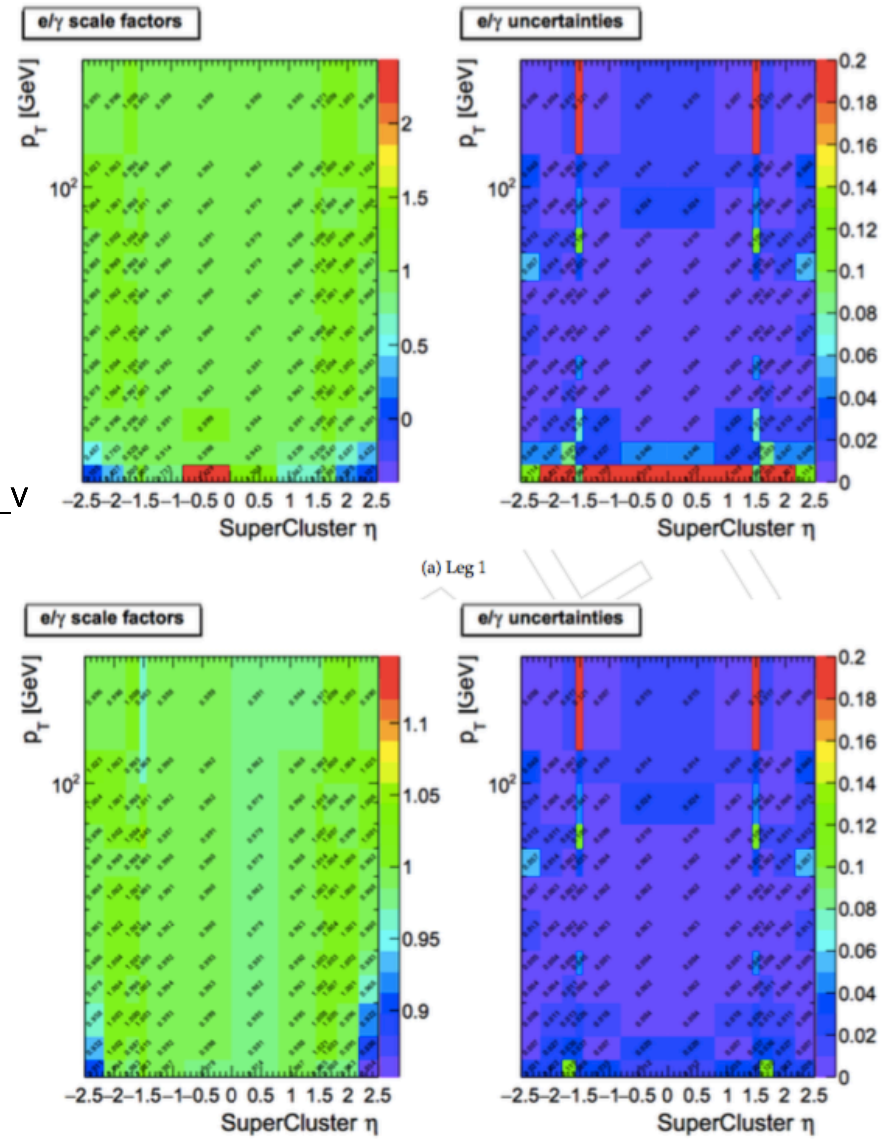


Figure 5: Scale factors in η bins of the leading and subleading muons for 2016 data set for dZ requirement, measured after muons have passed the HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v* OR HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_v* triggers.

https://indico.cern.ch/event/636555/contributions/2577291/attachments/1453162/2241537/TnP_DoubleMuSF_03_05_17.pdf

HLT SFs for dielectron trigger

HLT_BIT_HLT_Ele23_Ele12_
CaloIdL_TrackIdL_IsoVL_DZ_v



(a) Leg 1

(b) Leg 2

Figure 2: Scale factors in p_T and η bins for 2016 data set for the HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ trigger. ID cut (general purpose MVA WP90) and ISO cuts are applied, then the scale factors are measured. Taken from [20]

https://indico.cern.ch/event/604949/contributions/2543520/attachments/1439974/2216426/VHbb_TnP_SFs_egamma_april.pdf#search=vhbb%20AND%20cerntaxonomy%3A%22Indico%2FExperiments%2FCMS%20meetings%2FPH%20%2D%20Physics

Analysis strategy

Object selection → Select Candidate → Prepare input to Combine → Limits

Requirements on leptons, jets and met

BDT with nine variables

'Simple shape' of HH_m_T

Derive the best limits we can

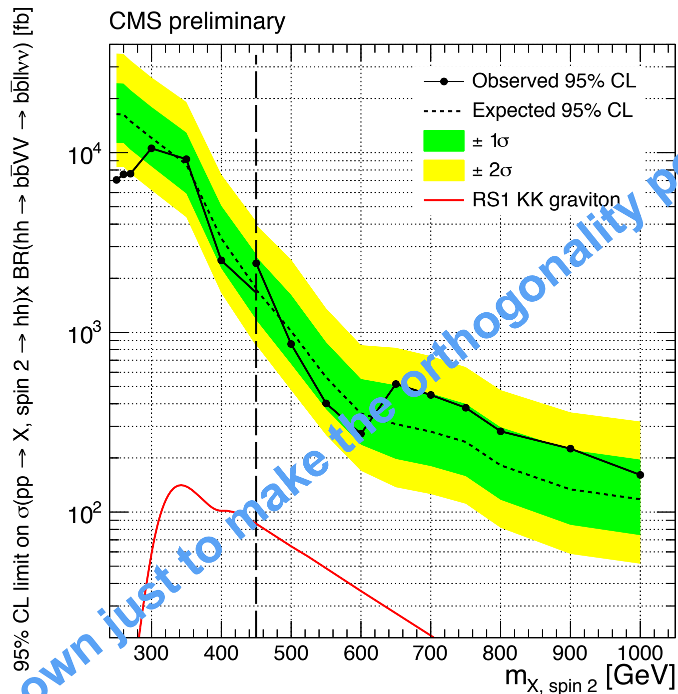
Our objective is:

- Set 95% CL upper limit on σ(pp ⟶ **X** ⟶ HH) vs mass of **X** (where X is the spin 0/2 narrow width resonance)

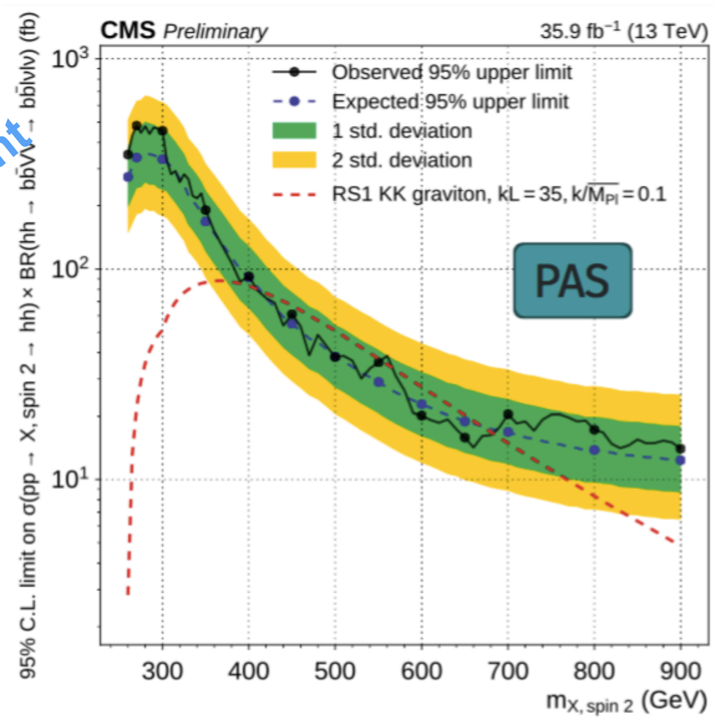
The method we will use to achieve it:

- Binned shape analysis using Higgs Combination Tool

Zll cut to be orthogonal to bbWW



bbZZ



bbWW is O(20) more sensitive

Shown just to make the orthogonality point

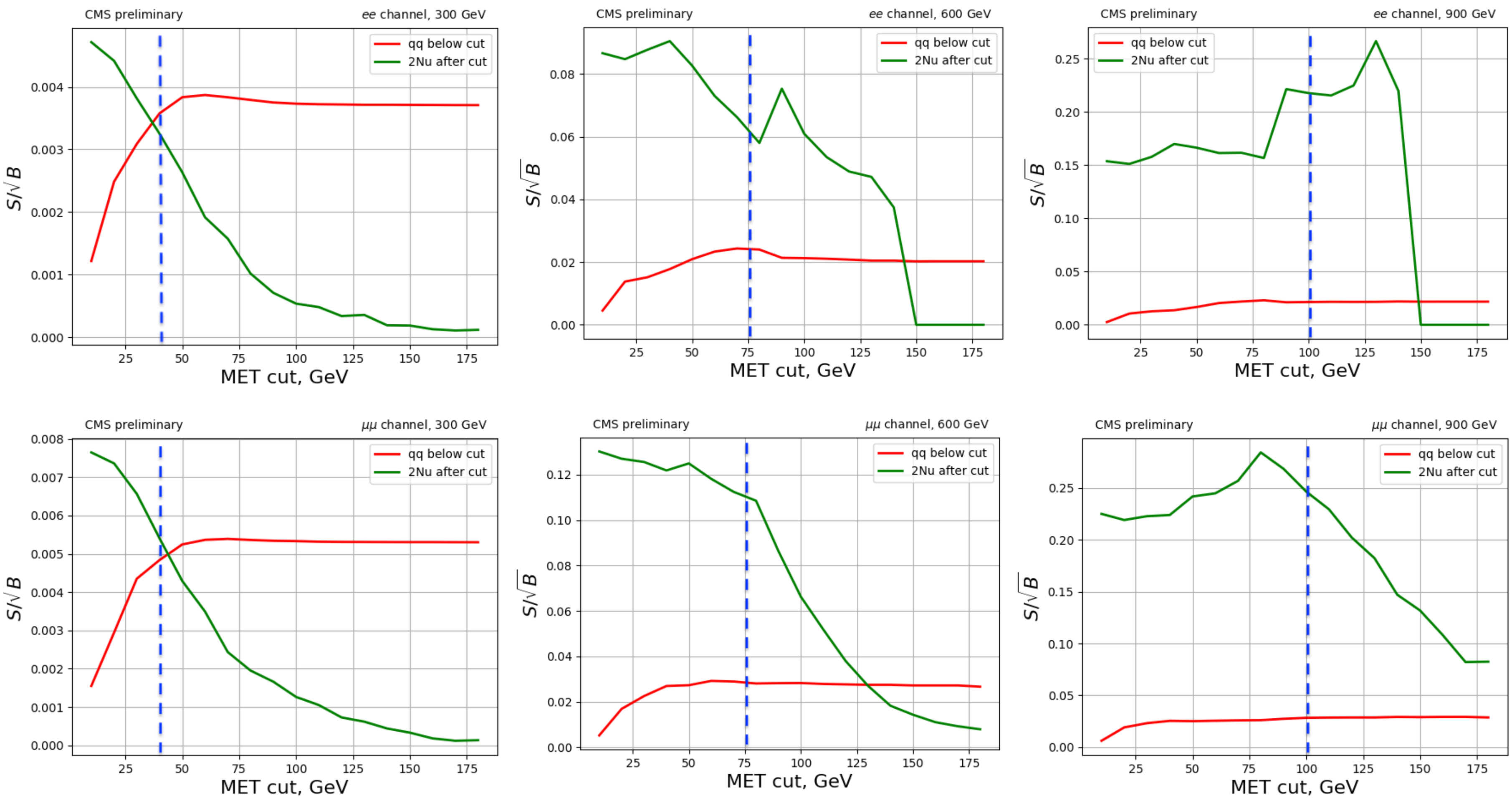
- Known approved bbVV (bbWW) analysis operates strictly in the range Z_{ll} mass < 76 GeV
- We work in the region Z_{ll} mass > 76 GeV
- In our analysis space bbWW to bbZZ fraction is 1 to 4

MET cut to be orthogonal to 2b2l2q

MET selection for us (and for 2b2l2q) was developed by both teams together to achieve the best limit for the bbZZ combination

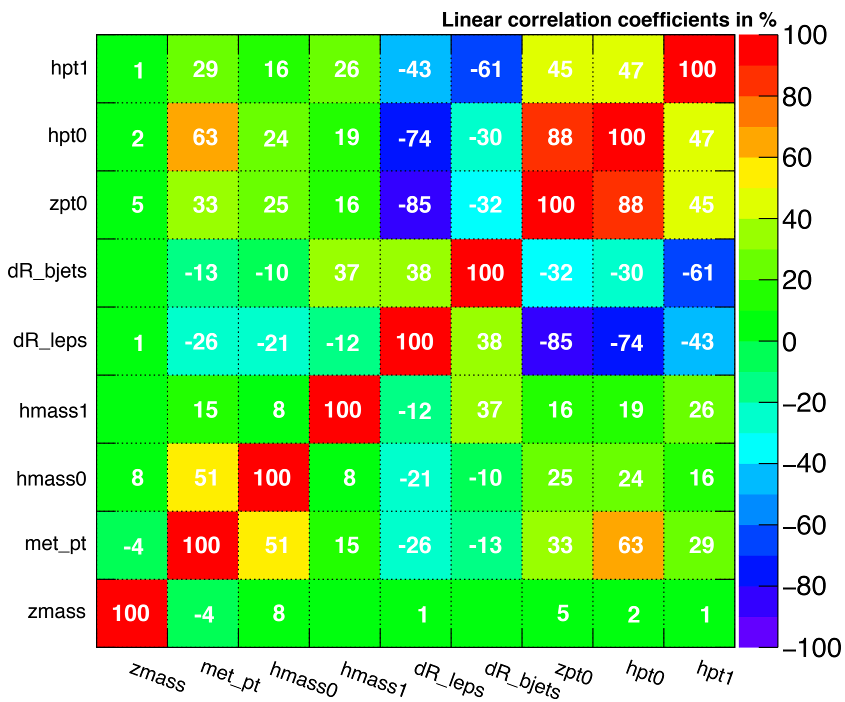
Signal mass, GeV	$\not{E}_T$ cut, GeV
260-300	> 40
350-600	> 75
650-1000	> 100

MET cut to be orthogonal to 2b2l2q, cont.

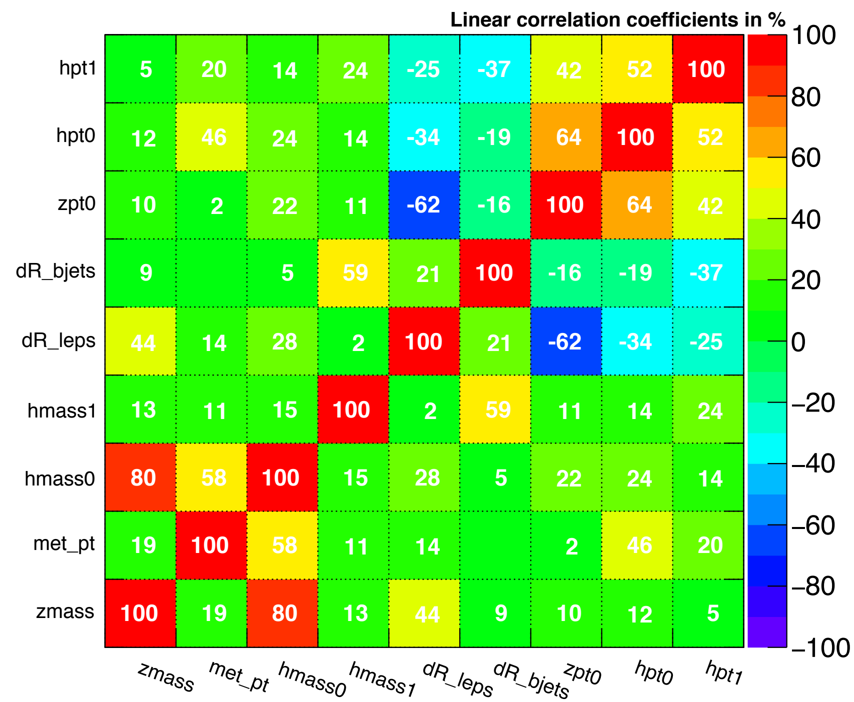


Correlations, ee, low

Correlation Matrix (signal)

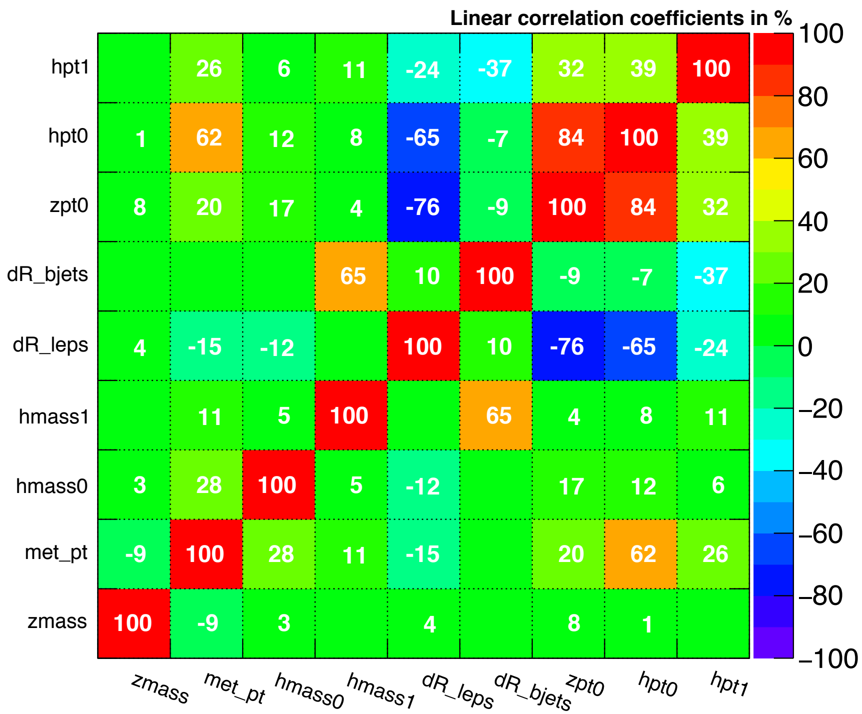


Correlation Matrix (background)

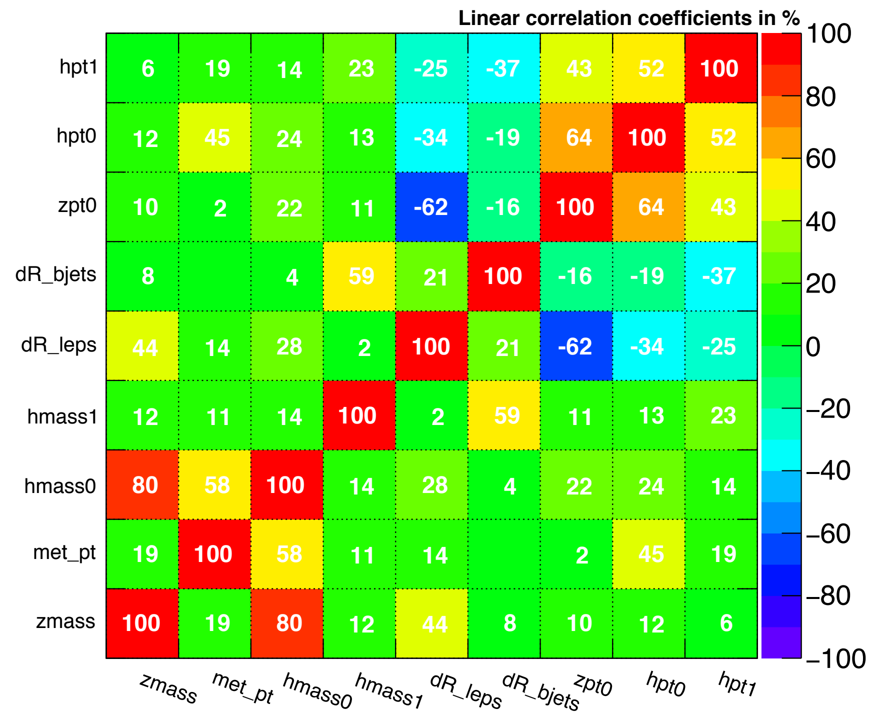


Correlations, ee, high

Correlation Matrix (signal)

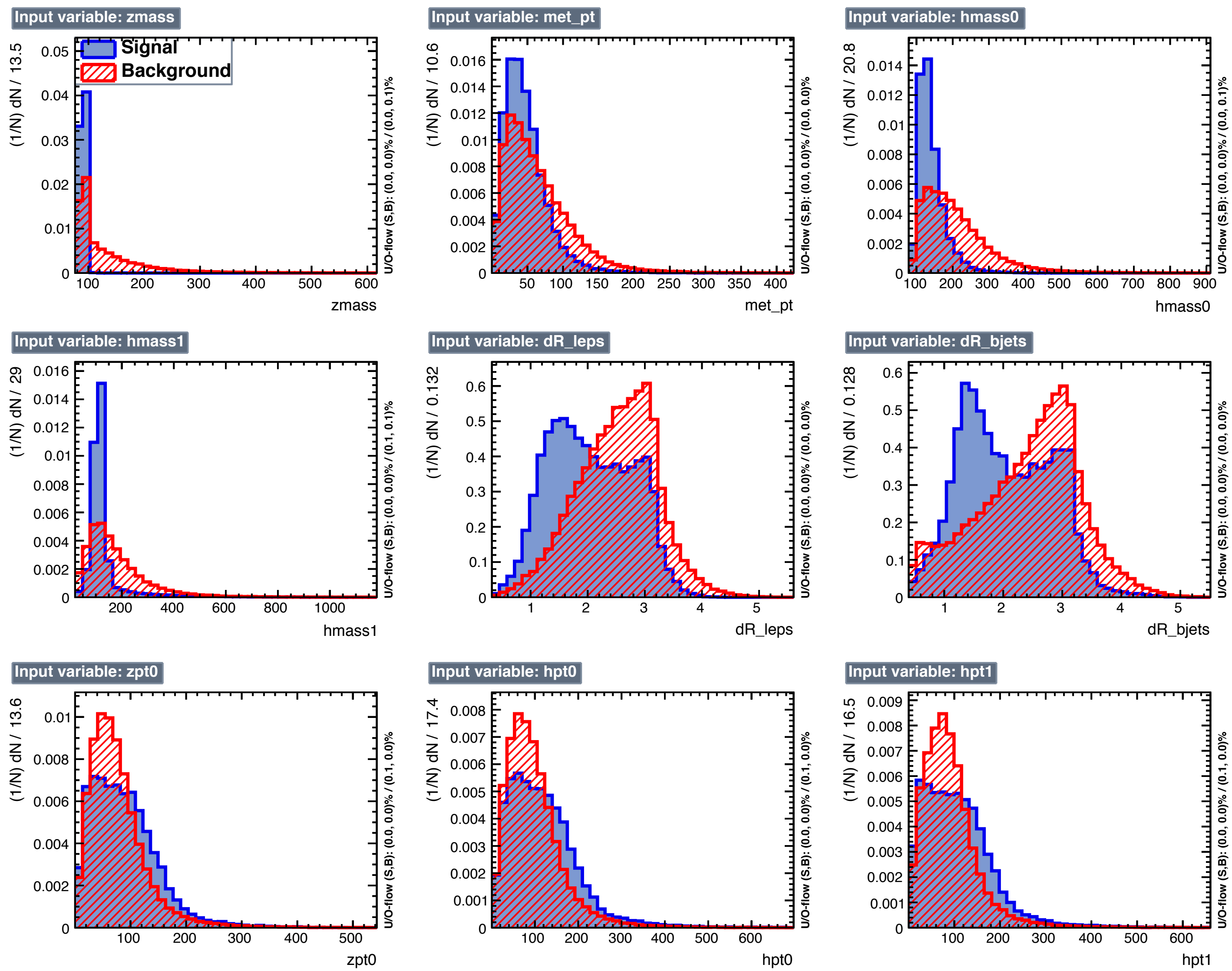


Correlation Matrix (background)



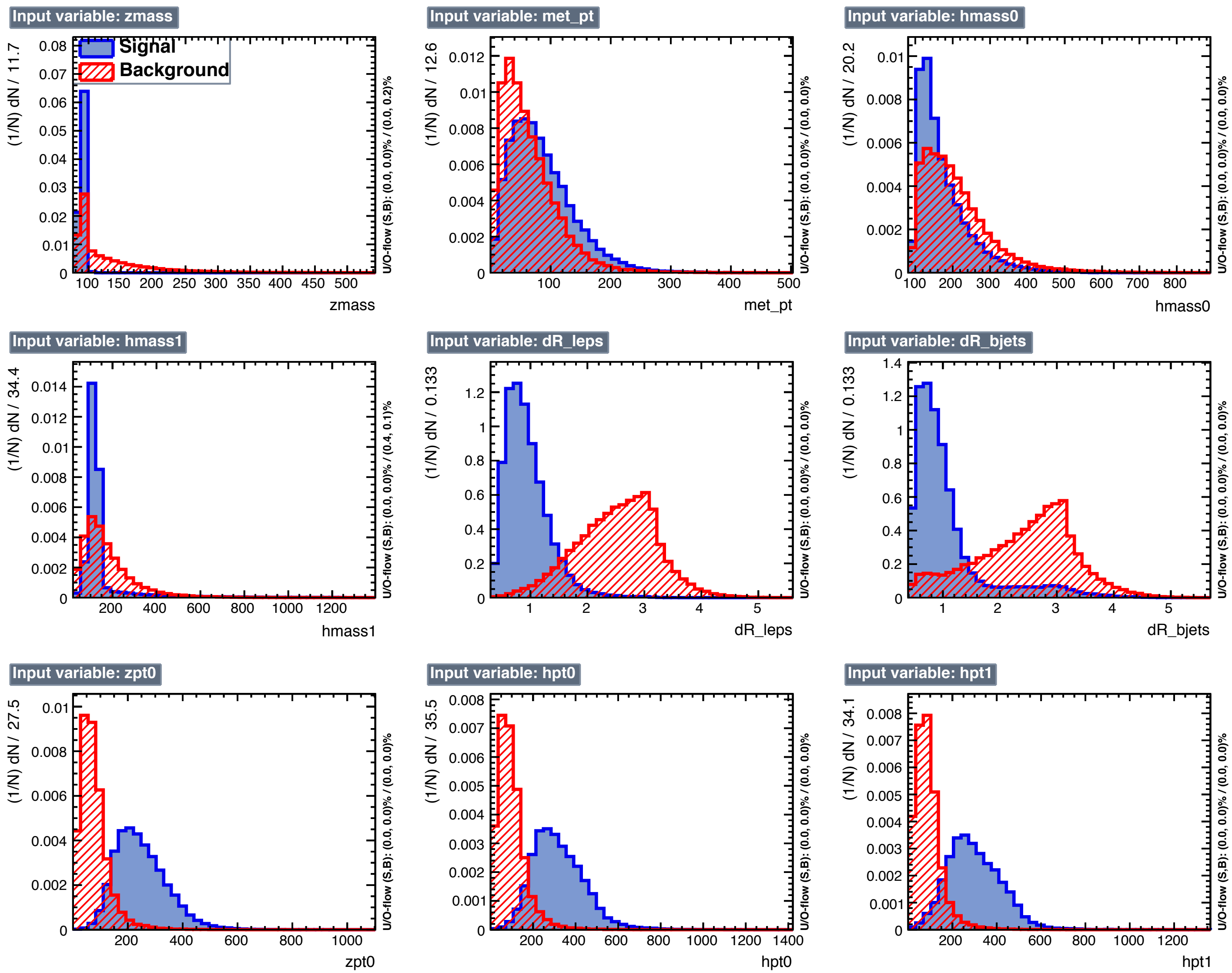
Variables, graviton, ee, low

Index '1' refers to H → bb decay and index '0' refers to H → ZZ decay.



Variables, graviton, ee, high

Index '1' refers to H → bb decay and index '0' refers to H → ZZ decay.



Event selection in the SR before BDT

Fraction of events surviving the candidate selection and kinematic requirements. Efficiencies are given for bbZZ and bbWW contributions in the SR and are normalised to the initial event counts before any selection is applied. A di-muon channel is presented. Numbers for the di-electron channel have the same trend but lower values, because in CMS efficiencies for electrons are lower than for muons.

Process	Mass (GeV)	Efficiency (%)
bbWW	300	0.2
bbZZ	300	10.4
bbWW	900	0.1
bbZZ	900	15.1

Importance of BDT variables, ee

Relative importance of the input variables in the low mass BDT training.

Rank	Variable	Importance (%)
1	$\Delta R_{b\ jets}$	13.9
2	MET	12.1
3	Mass of H $\rightarrow b\bar{b}$ candidate	11.9
4	$p_T^{ZZ^*}$	11.0
5	$\Delta R_{leptons}$	10.9
6	p_T of H $\rightarrow b\bar{b}$ candidate	10.7
7	p_T of Z boson candidate	10.2
8	Mass of ZZ^* system	10.1
9	Mass of Z boson candidate	9.26

Relative importance of the input variables in the high mass BDT training.

Rank	Variable	Importance (%)
1	$\Delta R_{leptons}$	14.1
2	Mass of H $\rightarrow b\bar{b}$ candidate	13.7
3	$\Delta R_{b\ jets}$	13.2
4	p_T of H $\rightarrow b\bar{b}$ candidate	12.1
5	p_T of Z boson candidate	11.5
6	$p_T^{ZZ^*}$	11.3
7	MET	10.3
8	Mass of ZZ^* system	7.7
9	Mass of Z boson candidate	6.1

Importance of BDT variables, μμ

Relative importance of the input variables in the low mass BDT training.

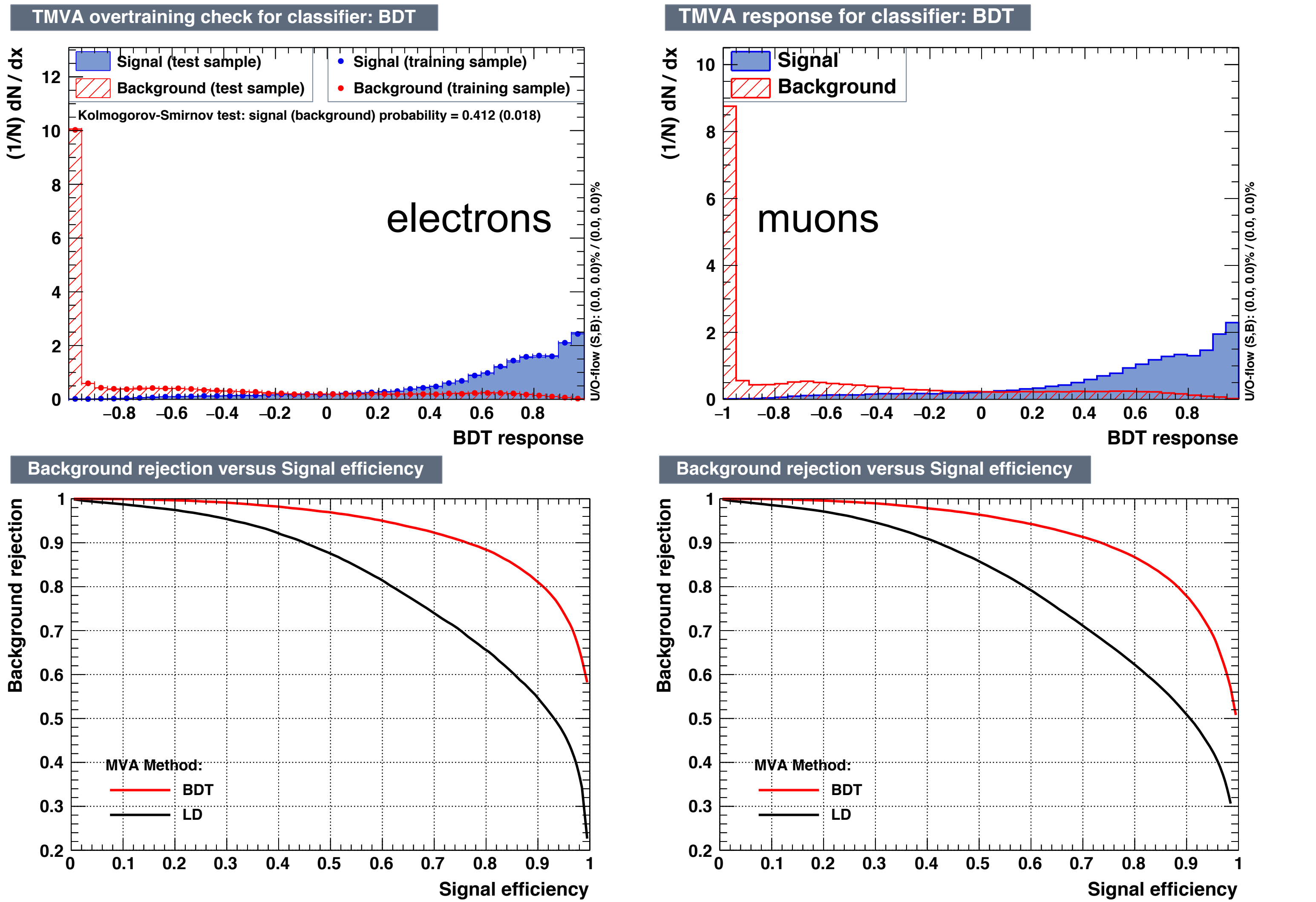
Rank	Variable	Importance (%)
1	$\Delta R_{b\ jets}$	13.0
2	MET	12.2
3	Mass of H $\rightarrow b\bar{b}$ candidate	11.9
4	p_T of H $\rightarrow b\bar{b}$ candidate	11.3
5	p_T of Z boson candidate	11.1
6	$p_T^{ZZ^*}$	10.9
7	$\Delta R_{leptons}$	10.5
8	Mass of ZZ^* system	9.7
9	Mass of Z boson candidate	9.5

Relative importance of the input variables in the high mass BDT training.

Rank	Variable	Importance (%)
1	Mass of H $\rightarrow b\bar{b}$ candidate	13.8
2	$\Delta R_{b\ jets}$	13.1
3	$\Delta R_{leptons}$	12.9
4	p_T of H $\rightarrow b\bar{b}$ candidate	11.7
5	$p_T^{ZZ^*}$	11.3
6	p_T of Z boson candidate	11.1
7	MET	11.0
8	Mass of ZZ^* system	8.8
9	Mass of Z boson candidate	6.2

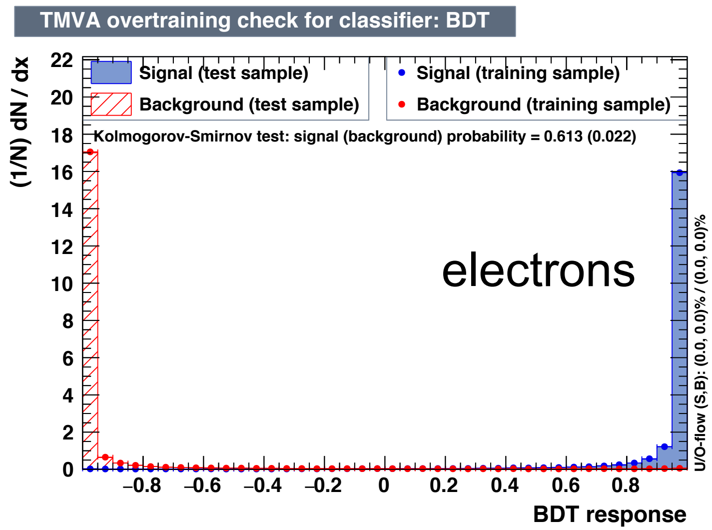
Low mass BDT

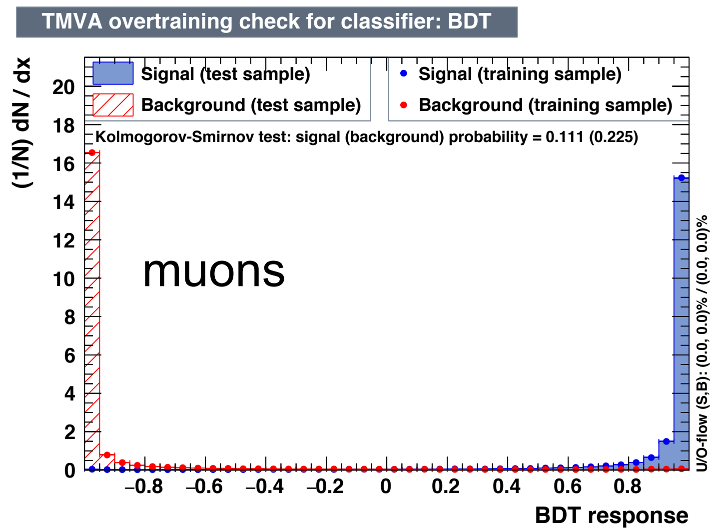
This is the region where backgrounds look very much signal-like, hard to get very high performance

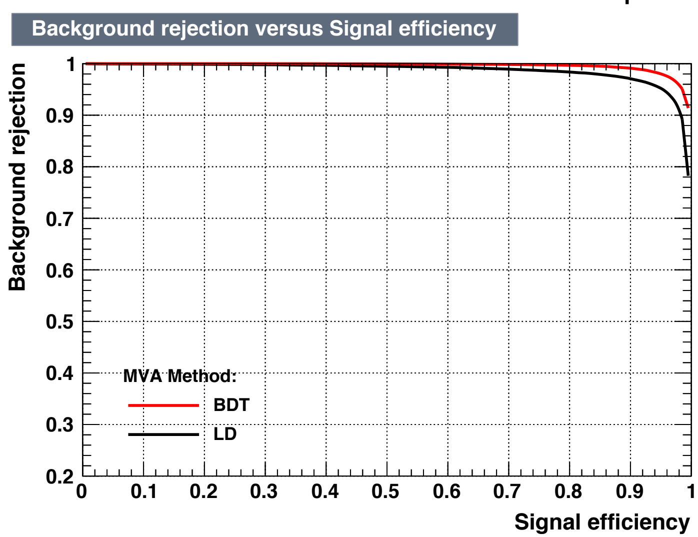


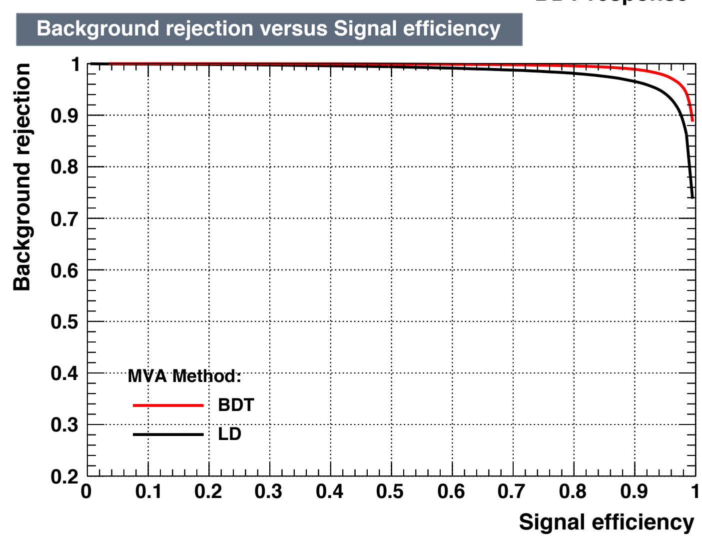
High mass BDT

This is the region where signal is highly boosted, performance is noticeably higher

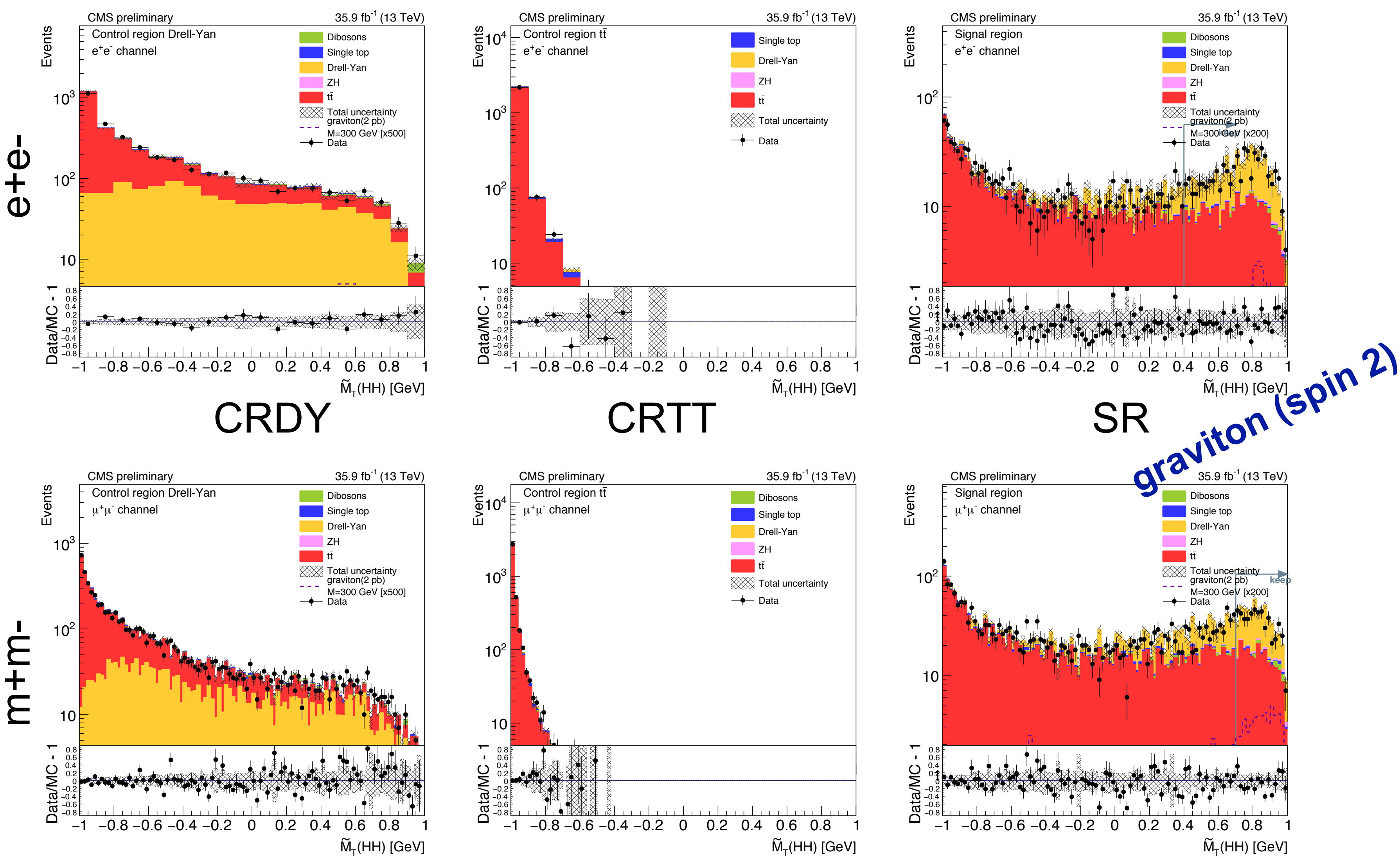








BDT distributions



BDT optimization

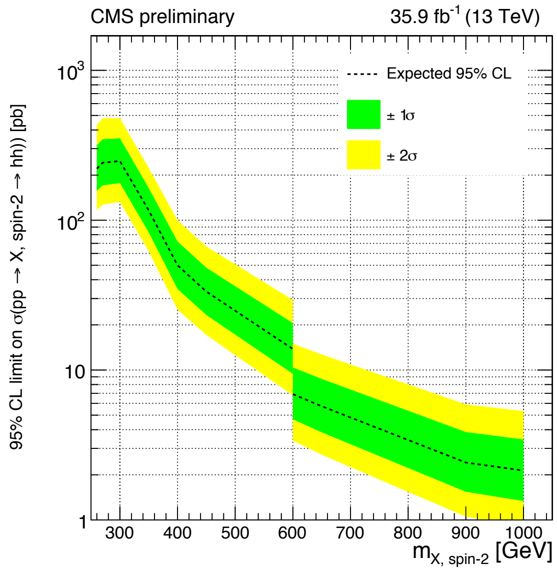
- We are statistics dominated, so keep all uncertainties as lnN, otherwise it will take absurdly long to compute the result.

- Optimize each channel separately.

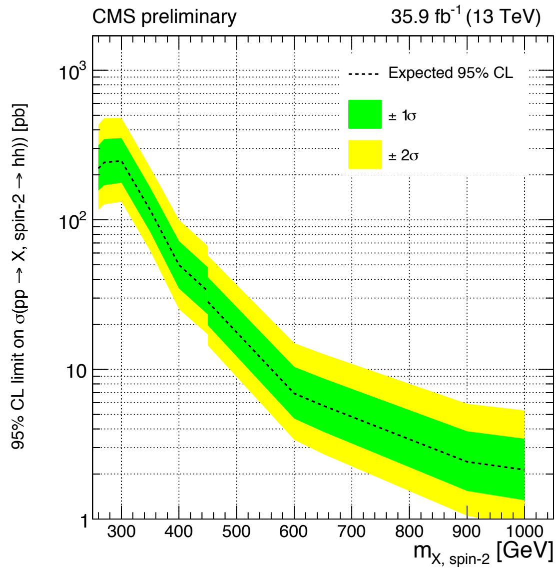
- Use as few cuts across the whole mass range as possible **if** it does not hurt the performance **but** helps to simplify the analysis and/or to avoid wasting weeks of computing time.

Channel	260 and 270 GeV	300 and 350 GeV	400 and 450 GeV	500 to 1000 GeV
Di-muon	0.1	0.7	0.7	0.99
Di-electron	0.4	0.4	0.925	0.99

Cross check of BDTs and mass regions



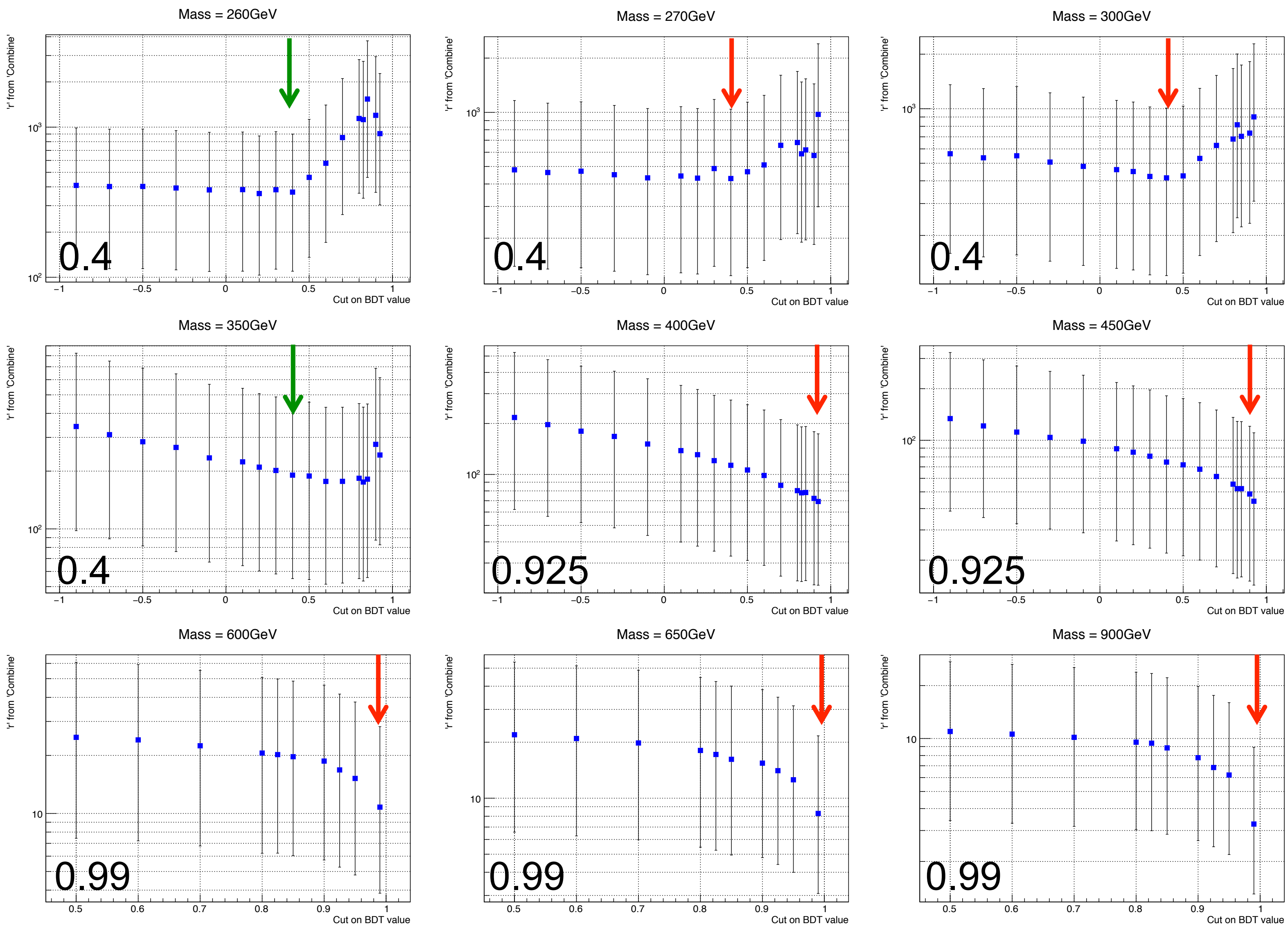
Low mass BDT applied at high mass region - worse!



High mass BDT applied at 450 GeV mass region: good!

Apply high BDT all the way to the left until it is worse than low BDT.
Answer - already at 400 GeV the limit with:
Original (low mass) BDT: $r < 49.97$
High mass BDT applied : $r < 81.88$

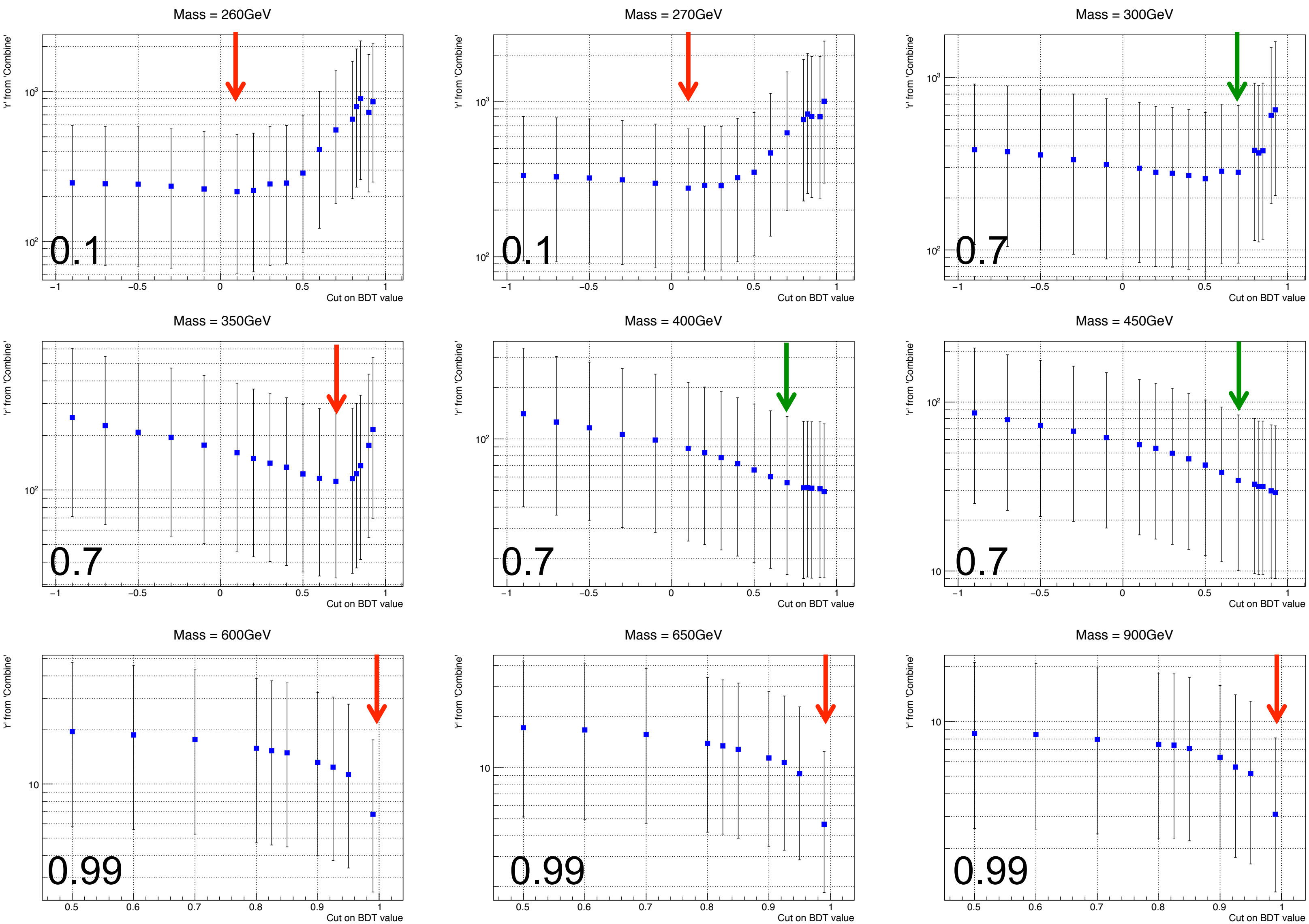
Electron channel



Cuts:
Best
Subopt.

Numbers represent cuts used in the analysis

Muon channel



Cuts:
Best
Subopt.

BDT efficiency

Efficiency of the BDT selection in two mass regions and for two channels: ee channel (top) and μμ channel (bottom). BDT selection at 300 GeV is 0.4(ee) and 0.7(μμ)

sample	Efficiency at 300 GeV (%)	Efficiency at 900 GeV (%)
signal (bbZZ)	89.2	94.9
signal (bbWW)	75.0	88.4
$t\bar{t}$	28.8	0.2
Drell-Yan	74.2	1.2
Single top	33.1	1.1
ZH	88.8	10.7
Dibosons	90.0	5.0

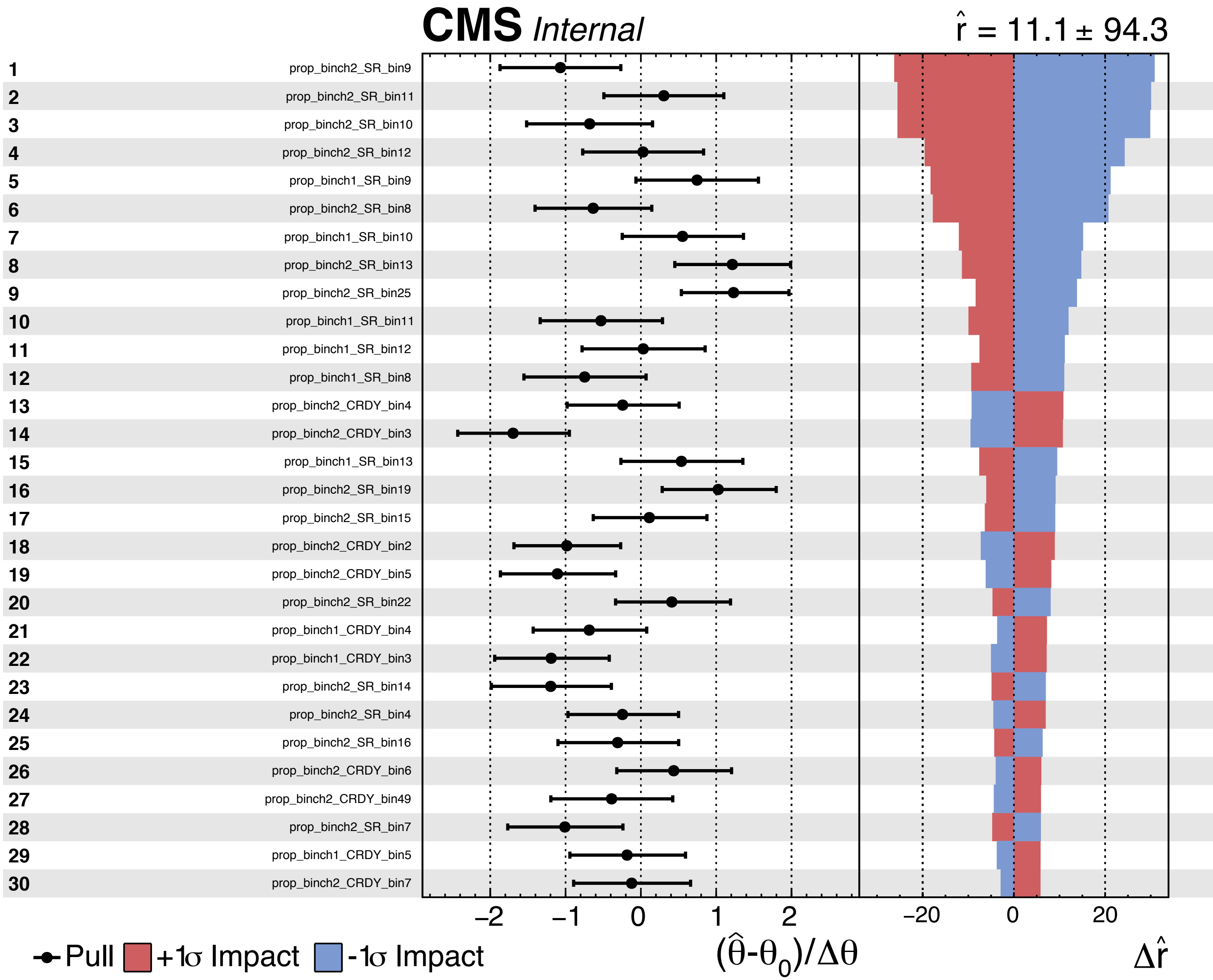
sample	Efficiency at 300 GeV (%)	Efficiency at 900 GeV (%)
signal (bbZZ)	58.1	91.1
signal (bbWW)	25.9	96.3
$t\bar{t}$	13.6	0.2
Drell-Yan	39.0	0.8
Single top	13.0	0.2
ZH	56.0	8.4
Dibosons	51.4	6.2

Expected event yield

Expected event yields and observed data counts in the SR, split by channel.
300 GeV graviton mass hypothesis.
Signal is normalized to 1 pb cross section. BDT selection is 0.4 for the ee, and 0.7 for μμ.

Process	ee channel	$\mu\mu$ channel
Signal	0.09	0.12
DY	341.55	318.32
$t\bar{t}$	261.42	216.85
ZH	7.27	10.62
Single top	6.79	5.99
Dibosons	7.64	9.08
Data	598	513

Systematics: impacts



Leading systematic uncertainties

The effect of leading systematic uncertainties on the total event yield for main signal and background processes, ee channel, 300 GeV graviton mass hypothesis.

Sample	b-tagging	mistagging	electron ID and ISO	electron tracker eff.	electron trigger eff.	JER	JEC
DY	4.3	7.4	5.4	1.1	2.1	0.2	5.3
$t\bar{t}$	0.5	7.4	4.7	1.1	1.9	0.0	0.5
Signal (bbZZ)	0.2	7.6	5.0	1.1	2.0	0.7	5.8
Signal (bbWW)	0.0	7.6	6.7	1.1	2.9	0.0	1.6

The effect of leading systematic uncertainties on the total event yield for main signal and background processes, μμ channel, 300 GeV graviton mass hypothesis.

Sample	b-tagging	mistagging	muon ID	muon ISO	muon tracker eff.	muon trigger eff.	JER	JEC
DY	4.9	7.0	0.2	0.1	0.1	0.4	0.2	9.4
$t\bar{t}$	0.9	7.2	0.2	0.1	0.0	0.4	0.6	0.7
Signal (bbZZ)	0.3	7.7	0.2	0.1	0.0	0.4	0.5	4.4
Signal (bbWW)	0.0	9.2	0.2	0.1	0.0	0.1	0.0	8.5

Derivation of the expected limits

- Normalize signal samples to HH xsec of 1pb

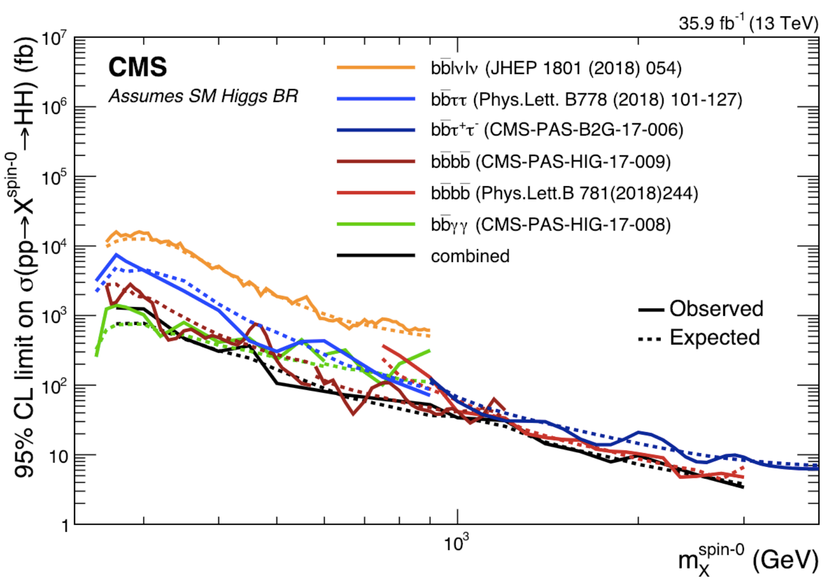
- Use bbZZ (~0.0012) and bbWW(~0.0266) known BFs

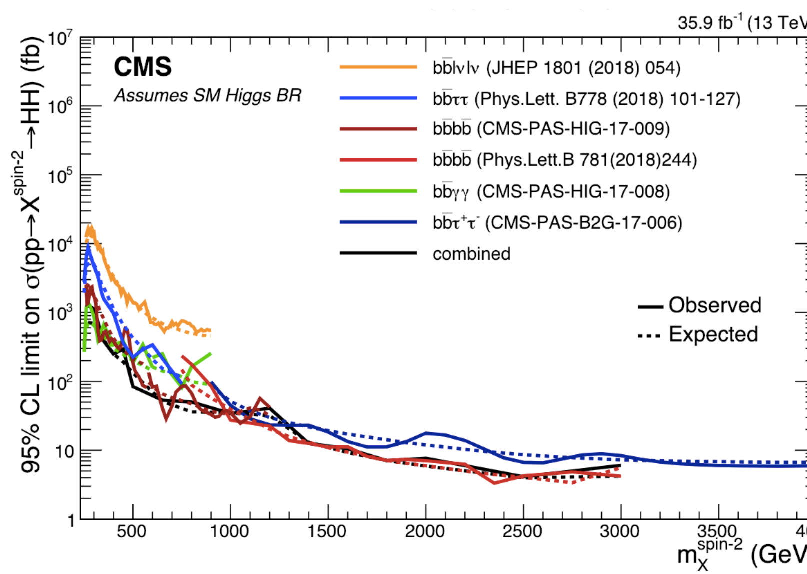
- A fit of all regions simultaneously in order to extract the signal strength as well as the normalization of DY and TT backgrounds

- Obtained value of ‘r’ is 95% CL upper limit on σ(pp ➔ **X** ➔ HH) in pb

Combination of HH channels

Combination of HH channels using 2016 data. Expected (dashed) and observed (solid line) 95% CL exclusion limits are shown. The results describe the production cross section of a narrow width spin 0 (left) and spin 2 (right) resonance decaying into a pair of SM Higgs bosons.





Particles traversing CMS

Interactions with the detector material

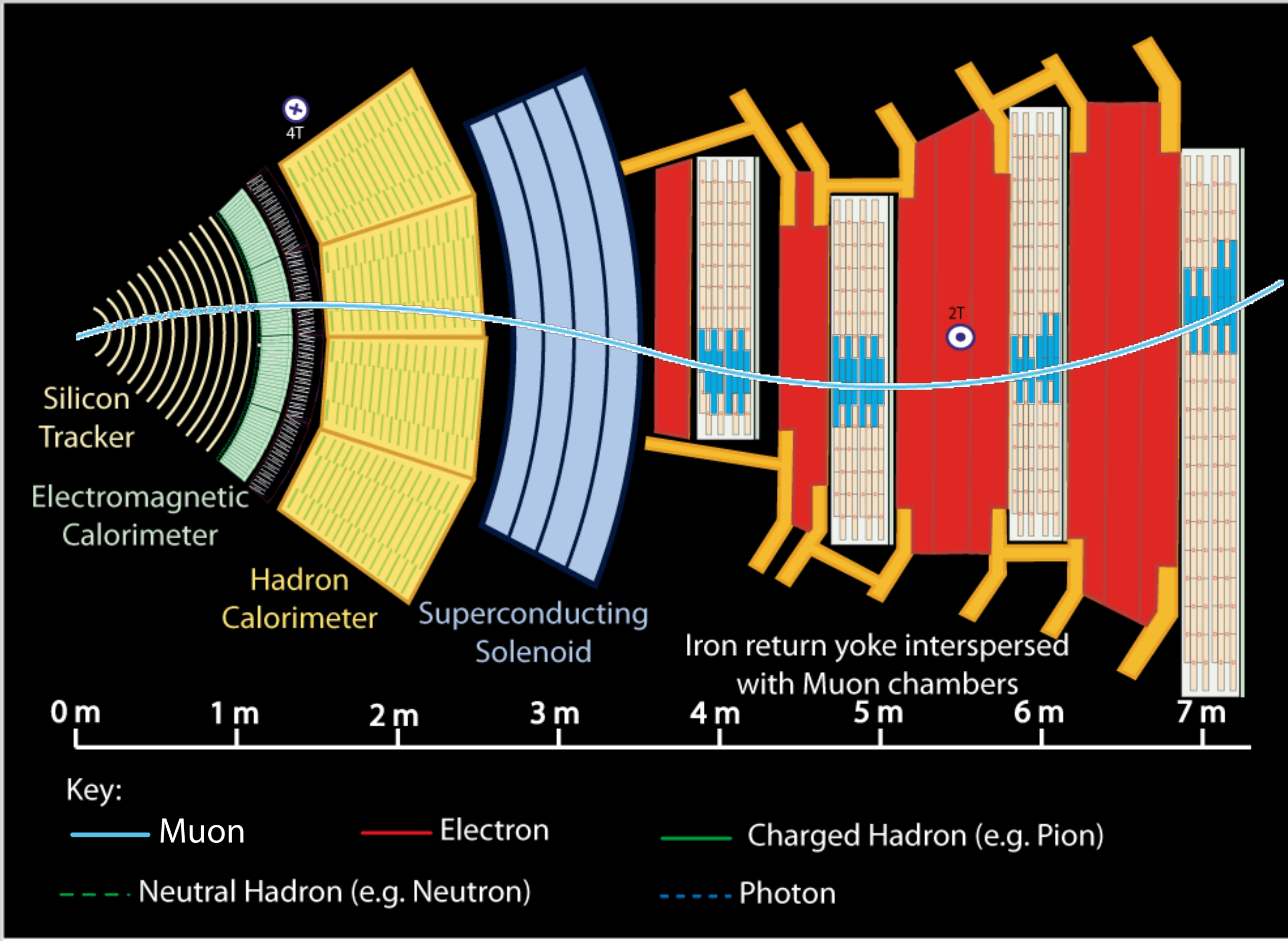
Muon: passing through CMS, bending in the field (both ways, depending on when it is inside or outside of the solenoid) leaving hits in the Tracker layers and the muon chambers before escaping completely

Electron: Bending in the magnetic field, leaving hits in the tracker layers and being “stopped” by the electromagnetic calorimeter

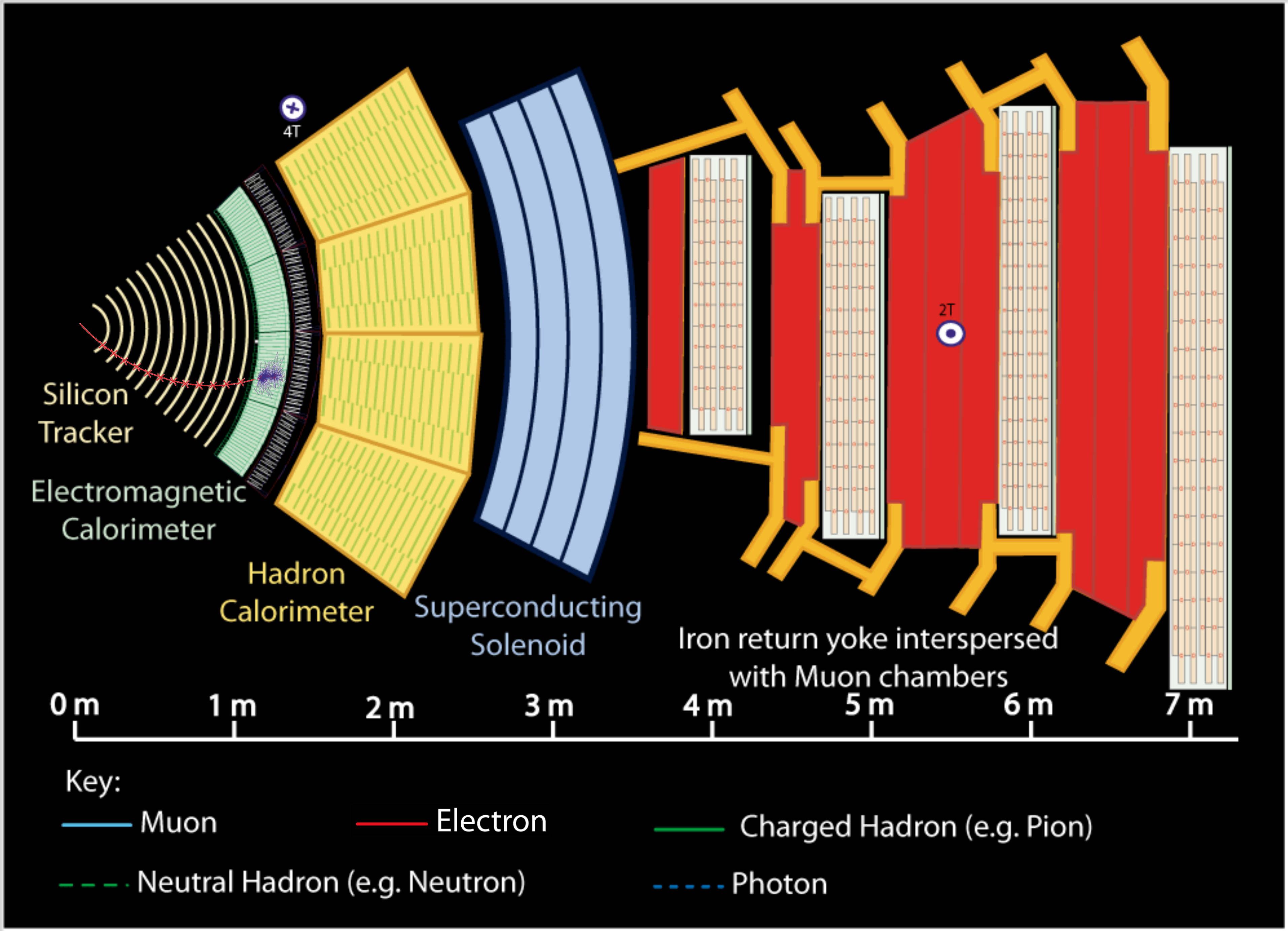
Charged hadron: Bends in the magnetic field and leaves signals in the tracker layers; passes through the electromagnetic calorimeter leaving essentially no signal, and is “stopped” by the hadron calorimeter

Neutral hadron: Does not bend in the magnetic field and does not leave any signal in the tracker layers; passes through the electromagnetic calorimeter leaving essentially no signal, and is “stopped” by the hadron calorimeter

Photon: passes through the tracker without bending in the magnetic field or leaving hits, is “stopped” by the electromagnetic calorimeter



4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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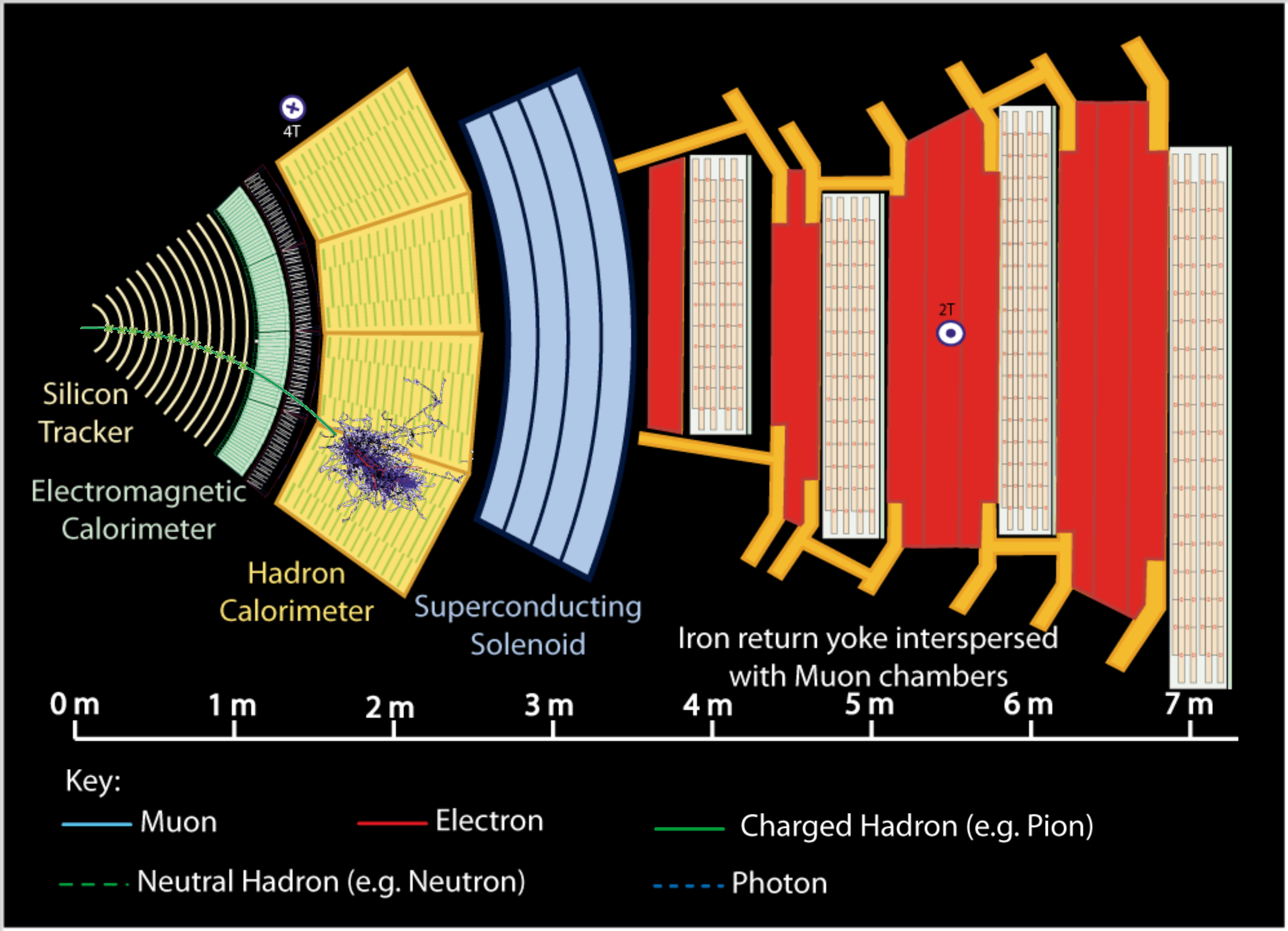
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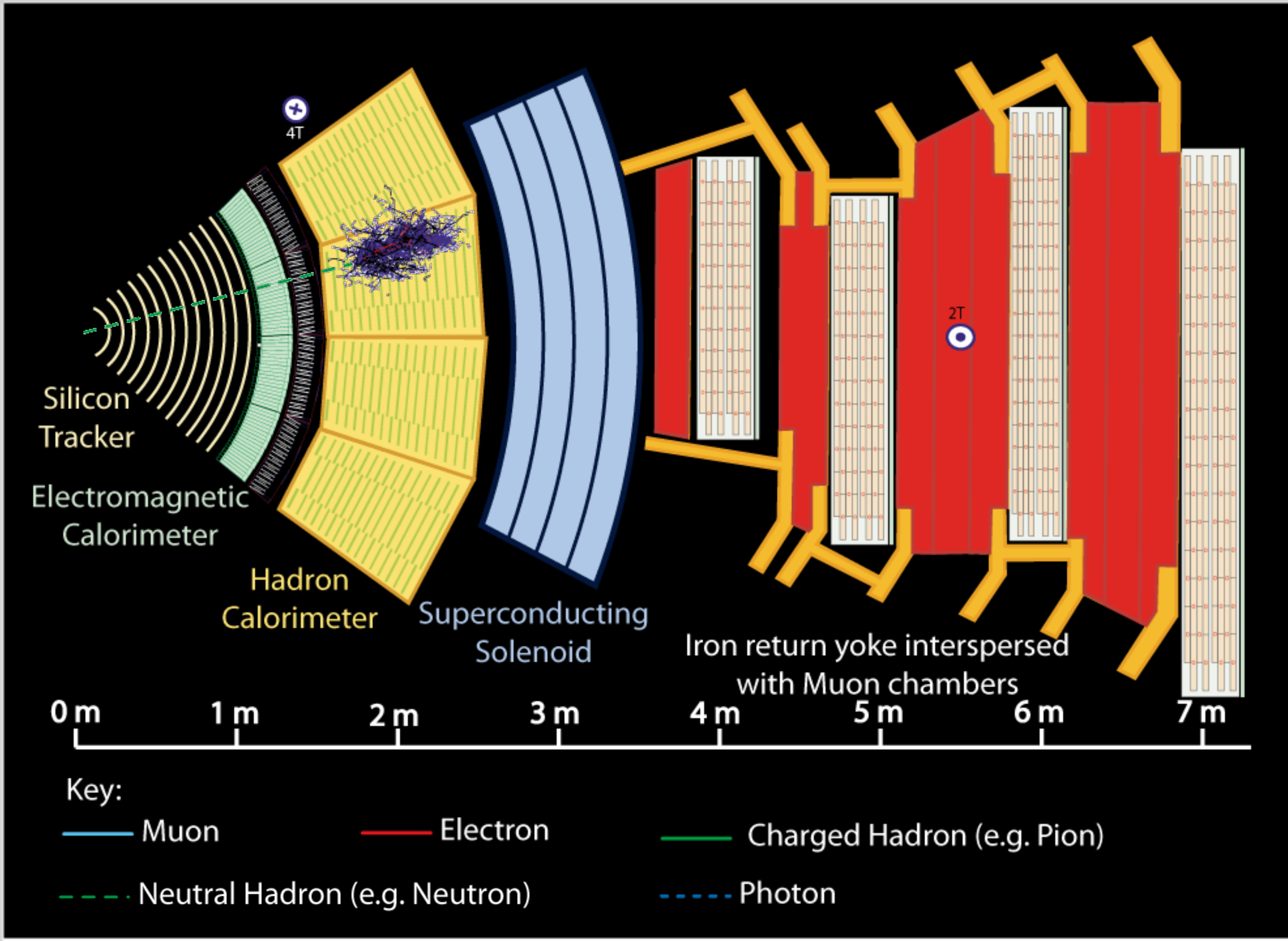
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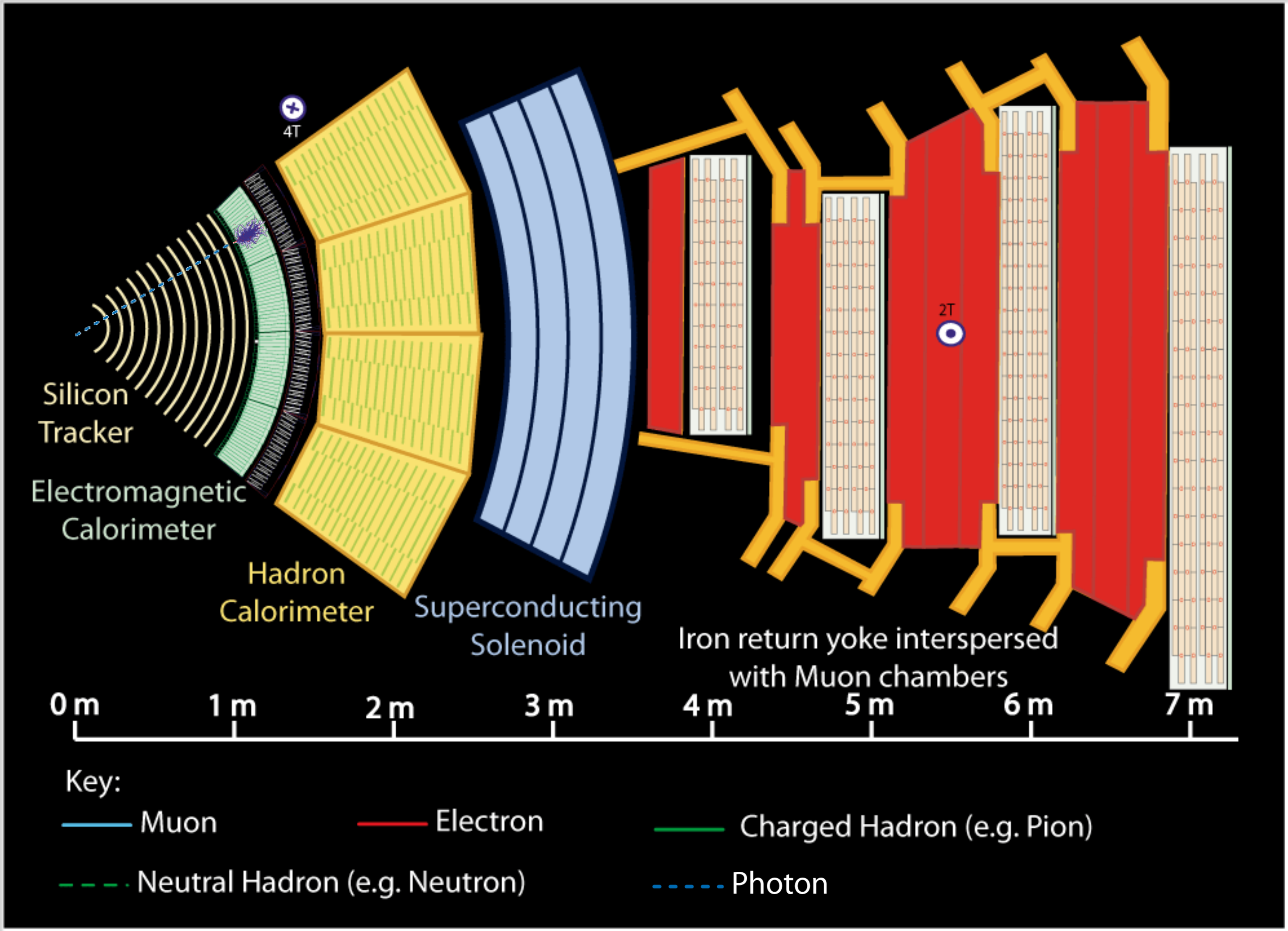

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