Resonant Di-Higgs Production in the bbWW channel: Probing the Electroweak Phase Transition at the LHC

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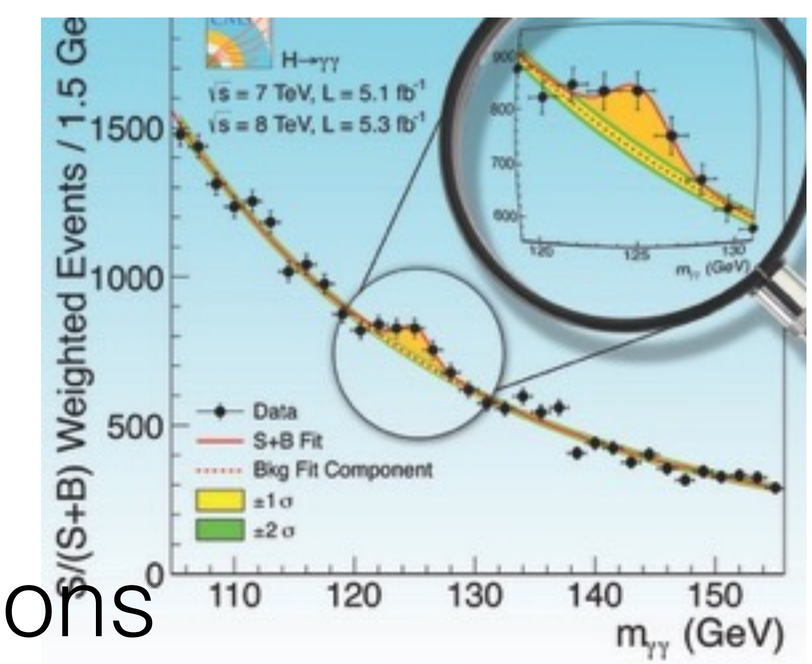
Outline

- Physics motivations
  - Standard Model (SM) and beyond
  - Singlet extension of SM (xSM)
  - Resonant diHiggs production in xSM at LHC
- Analysis strategy
- Event selection: Multivariate analysis (MVA)
- Heavy Mass Estimator: solving the kinematic in presence of 2 neutrinos
- Expected limits on production rates
- Conclusions and Outlook

Standard Model and Beyond

- **The Standard Model (SM) works very well**
  - ➡It describes fundamental particles and interactions among them
  - ➡Higgs boson, predicted in Standard Model, was discovered in 2012 by ATLAS and CMS

- **SM: Theory of Everything? NO Way !**
  - Neutrino Masses: where do they originate from?
  - Dark Matter: what are they?
  - Hierarchy problem: a fine-tuned universe?
  - Matter-antimatter asymmetry? namely baryogenesis: anti-baryons missing during universe evolution ?



No successful model to answer all questions

we will focus on extended Higgs sector

Entending the Higgs sector

- Higgs sector can be extended in more than one way!!

Model	Description	Higgs bosons
SM (one doublet of complex scalar fields)	3 d.o.f. give mass to $W^{\pm}$ and Z, Yukawa couplings generate fermion mass	h
SM + singlet (xSM)	***Used in the context of EWK baryogenesis, DM…***	h, H
2HDM (contains a second doublet)	Prerequisite for SUSY, natural in GUT, DM originating from 2HDM	h, H, A, $H^{\pm}$
2HDM + complex singlet (e.g. NMSSM)	Solve the mu-problem in MSSM (where H(125) is unnaturally heavy)	h_1, h_2, h_3, a_1, a_2, $H^{\pm}$
SM + triplet	Natural explanation for small neutrino masses	h, H, A, $H^{\pm}$, $H^{\pm\pm}$

focus on

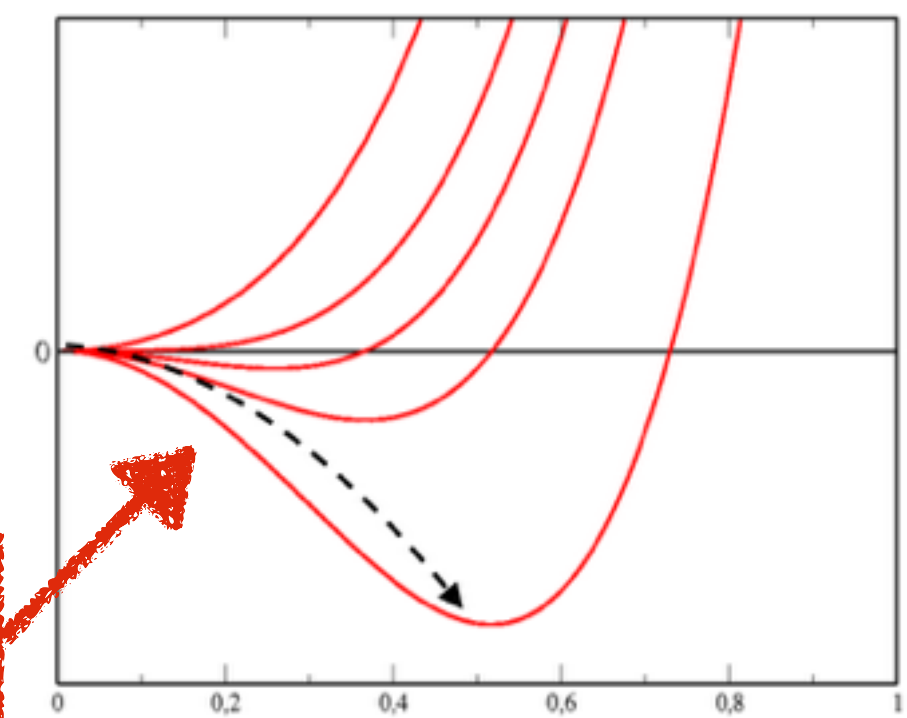
- ✓ Around us: matter domains
- ✓ No anti-matter domain region in universe
  - Cosmic gamma ray and Cosmic microwave background(CMB) observations

$$\eta = \frac{n_B - n_{\bar{B}}}{\gamma} = 6 \times 10^{-10} \ \frac{\text{excess baryons}}{\text{photon}}$$

- Sakharov conditions: resolving baryon asymmetry
  - ✓ Baryon number violation
    - ➡ Sphaleron transition
  - C/CP violation
    - ➡ CKM mixing matrix in SM is too feeble, NOT enough
  - Departure from Thermal equilibrium or breakdown of CPT invariance
    - ➡ 125 GeV SM higgs only results in a smooth cross-over(or second order) ElectroWeak Phase Transition(EWPT)

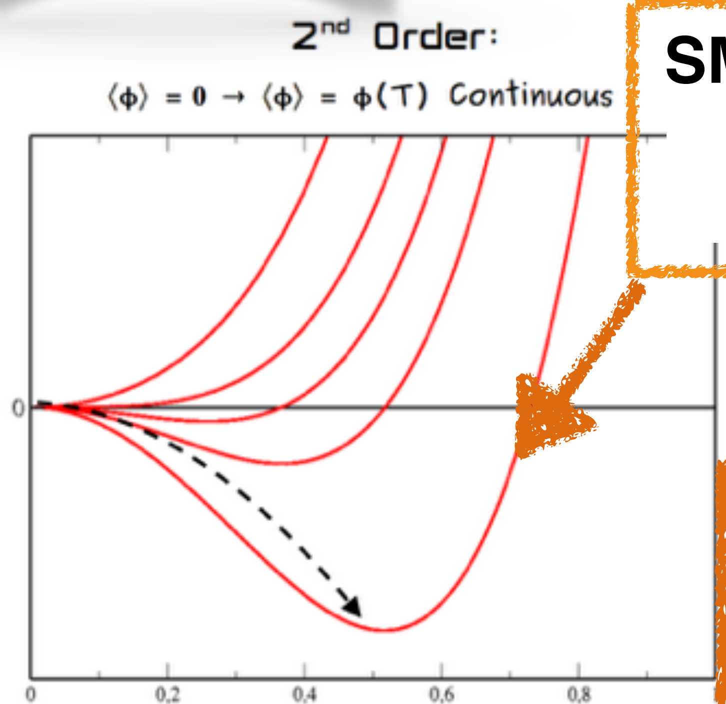
2^{nd} Order:

$\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = \phi(T)$ Continuous



smooth cross-over phase transition: early universe stays in equilibrium

Singlet extension of SM



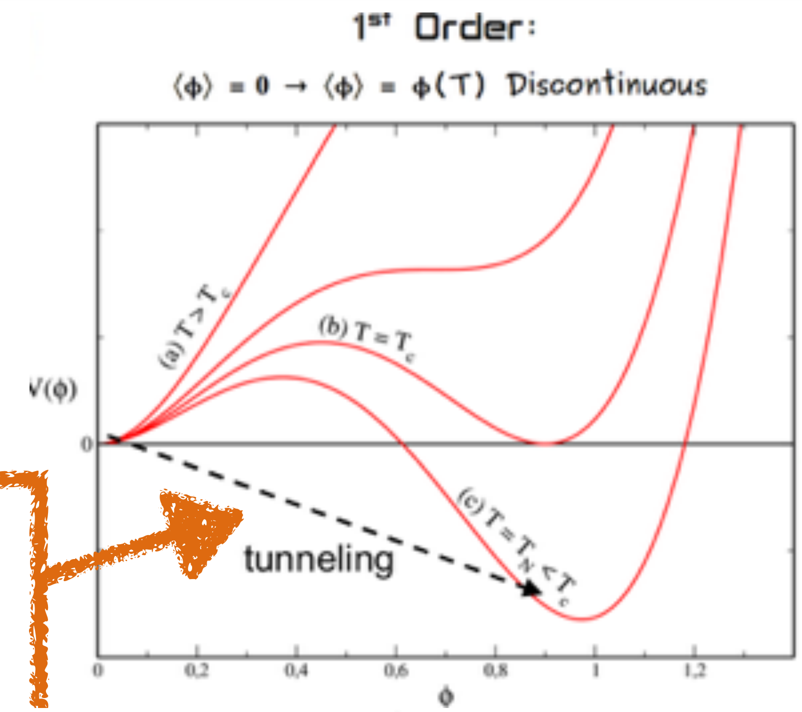
SM: smooth phase transition

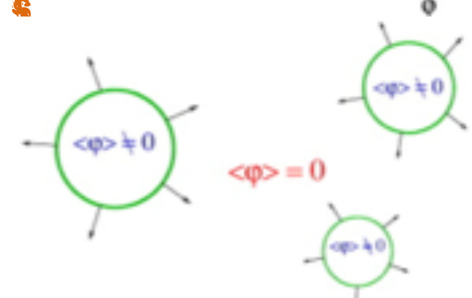
$$V(h,T) = a(T^2 - T_c^2)h^2 + \lambda(T)h^4$$

Add a Singlet

xSM: dramatic phase transition

$$V(h,T) = a(T^2 - T_c^2)h^2 - E(T)h^3 + \lambda(T)h^4$$



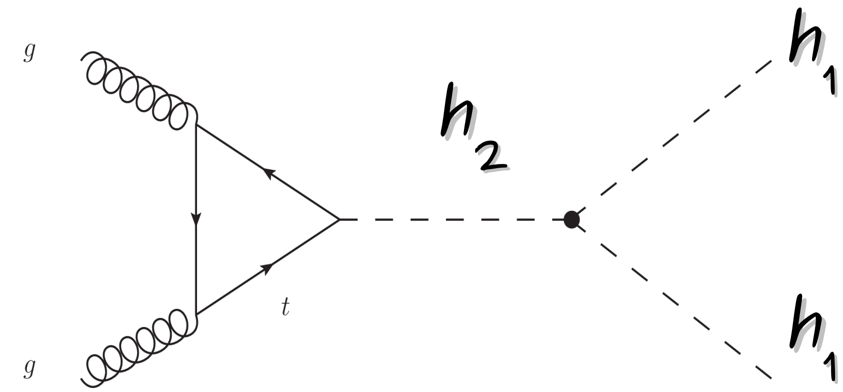


- Extending Higgs sector with new Higgs singlet
  - ✓ Significantly changed the nature and properties of EWPT in early universe -> a strong first order EWPT
  - ✓ Enhanced the sources of CP violation

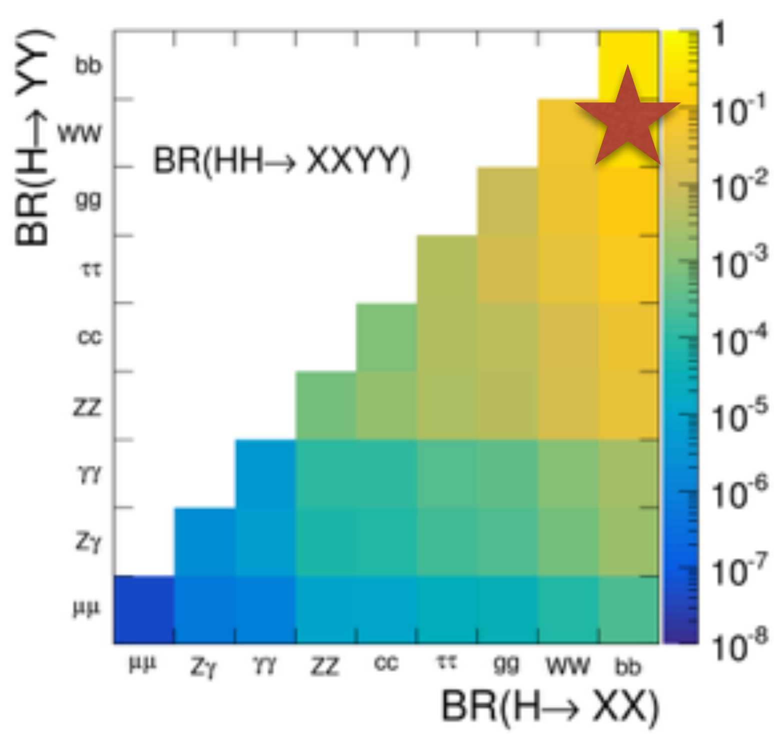
	SM	xSM
Baryon violation (sphaleron)	✓	✓
C & CP violation	✓/✗	✓
out of equilibrium or CPT violation	✗	✓

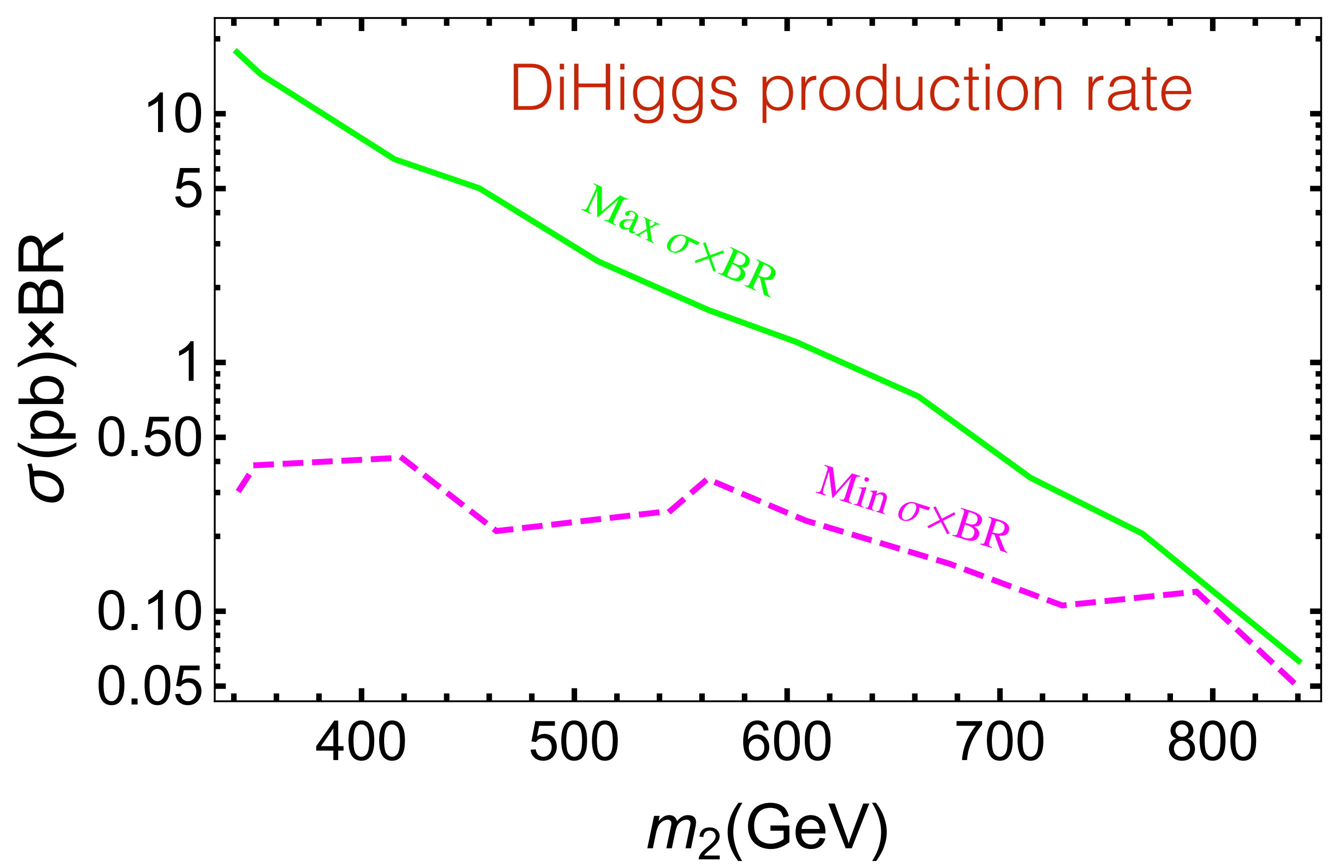
Resonant DiHiggs Production at LHC

- xSM: Singlet scalar extension of the SM
  - Two flavor Higgs bosons mixing:
    - Higher mass: Heavy Higgs
    - Lower mass: SM-like Higgs



  - M_H>250 GeV: H->hh, resonant diHiggs production
  - Production rate: optimistic and pessimistic
- Final states: two SM Higgs decays
  - bbττ, bbWW, bbγγ, bbbb…
  - We focus on bbWW→bbμνμν





More About xSM at LHC

- Signal from xSM:12 benchmarks

	$\cos\theta$	m_2 (GeV)	Γ_{h_2} (GeV)	x_0 (GeV)	λ	a_1 (GeV)	a_2	b_3 (GeV)	b_4	λ_{111} (GeV	λ_{211} (GeV)	σ (pb)	BR
B1	0.961	258	0.68	307	0.52	-266	0.26	-138	0.26	3.43	-0.70	1.19	0.50
B2	0.976	341	2.42	257	0.92	-377	0.39	-403	0.77	204	-150	0.59	0.74
B3	0.982	353	2.17	265	0.99	-400	0.45	-378	0.69	226	-144	0.44	0.76
B4	0.983	415	1.59	54.6	0.17	-642	3.80	-214	0.16	44.9	82.5	0.36	0.33
B5	0.984	455	2.08	47.4	0.18	-707	4.63	-607	0.85	46.7	93.5	0.26	0.31
B6	0.986	511	2.44	40.7	0.18	-744	5.17	-618	0.82	46.6	91.9	0.15	0.24
B7	0.988	563	2.92	40.5	0.19	-844	5.85	-151	0.08	47.1	104	0.087	0.23
B8	0.992	604	2.82	36.4	0.18	-898	7.36	-424	0.28	45.6	119	0.045	0.30
B9	0.994	662	2.97	32.9	0.17	-976	8.98	-542	0.53	44.9	132	0.023	0.33
B10	0.993	714	3.27	29.2	0.18	-941	8.28	497	0.38	44.7	112	0.017	0.20
B11	0.996	767	2.83	24.5	0.17	-920	9.87	575	0.41	42.2	114	0.0082	0.22
B12	0.994	840	4.03	21.7	0.19	-988	9.22	356	0.83	43.9	83.8	0.0068	0.079

- How challenging the analysis is :
  - Top pair production(tt) can have same final states

→ σ(tt)·Br(μνμνbb) ~ 9.53 pb → N_{ev}(300 fb^{-1}) ~ 3000,000 events

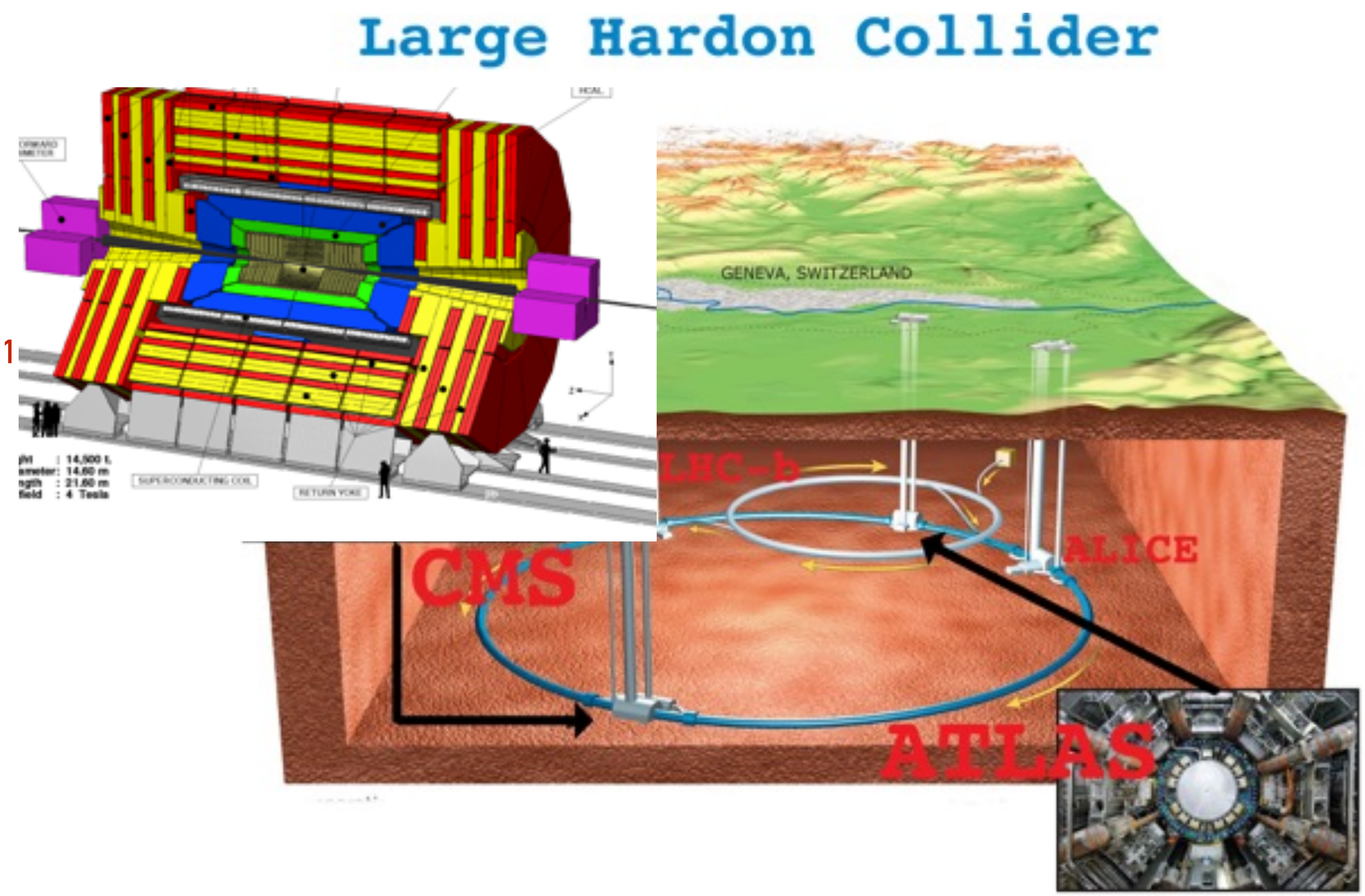
→ σ(B1)·Br(μνμνbb) ~ 0.002 pb → N_{ev}(300 fb^{-1}) ~ 600 events (0.02% N_{tt})

→ σ(B6)·Br(μνμνbb) ~ 0.0001 pb → N_{ev}(300 fb^{-1}) ~ 30 events (0.001% N_{tt})

→ σ(B12)·Br(μνμνbb) ~ 1.5e-6 pb → N_{ev}(300 fb^{-1}) ~ 0.5 events (0.00002% N_{tt})

Introduction to LHC and CMS

- LHC: Large Hadron Collider, can accelerate and collide protons at high energy and luminosity



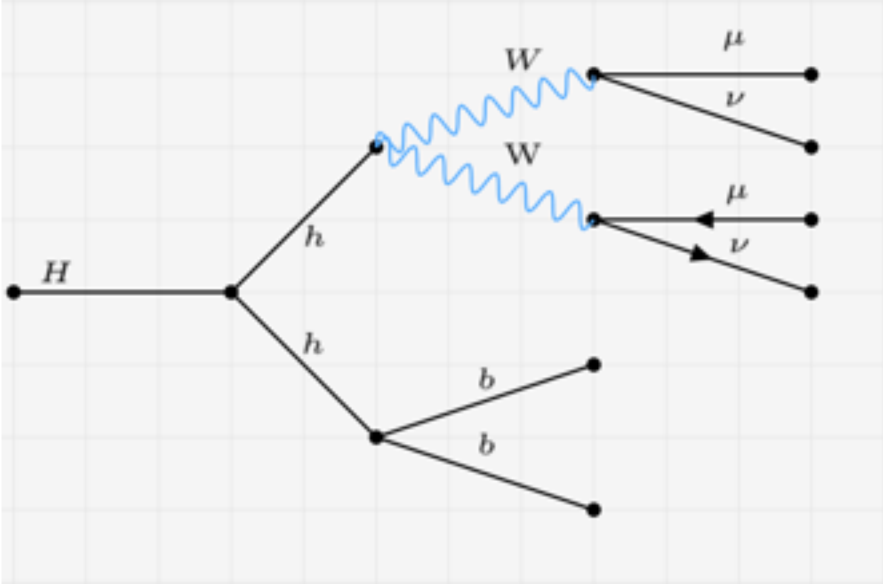
- Run 2: 2015-2018
  - Center of mass energy = 13TeV
  - integrated luminosity ~40 fb^{-1}
  - Expected integrated luminosity ~300 fb^{-1}
- After upgrade: HL-LHC, 2023-2028
  - Instantaneous luminosity: ~5 times nominal one
  - Higher center of mass energy (14TeV)
  - Expected integrated luminosity ~ 3000 fb^{-1}

- CMS, Compact Muon Solenoid, is a general purpose detector on LHC, able to reconstruct all SM particles except neutrinos, which are partially estimated by momentum imbalance in transverse plane
- Delphes is used to simulate CMS response in this study

Analysis strategy

Event Preselection

- 2 isolated muons (p_T>10 GeV and |η|<2.4), opposite sign
- 2 jets (P_T>30 GeV and |η|<2.5), at least one medium+one loose b-tagging
  - ➡ medium b-tagging: Eff ~75%, Mistag~1.5%
  - ➡ loose b-tagging: Eff ~85%, Mistag~10%
- Missing Transverse Energy (E_T^{miss}) > 20 GeV



Multivariate analysis (MVA)

optimizing selection by boost decision tree

Heavy mass estimator (HME)

event reconstruction by solving the kinematic

SM backgrounds:

→ Top-pair production (tt): large cross section (σ) + same final states
→ Drell-Yan (DY): very large σ, no jets at Leading Order, and no E_T^{miss}
→ tW: small σ + same final state
→ Non resonant hh: very small σ (negligible)

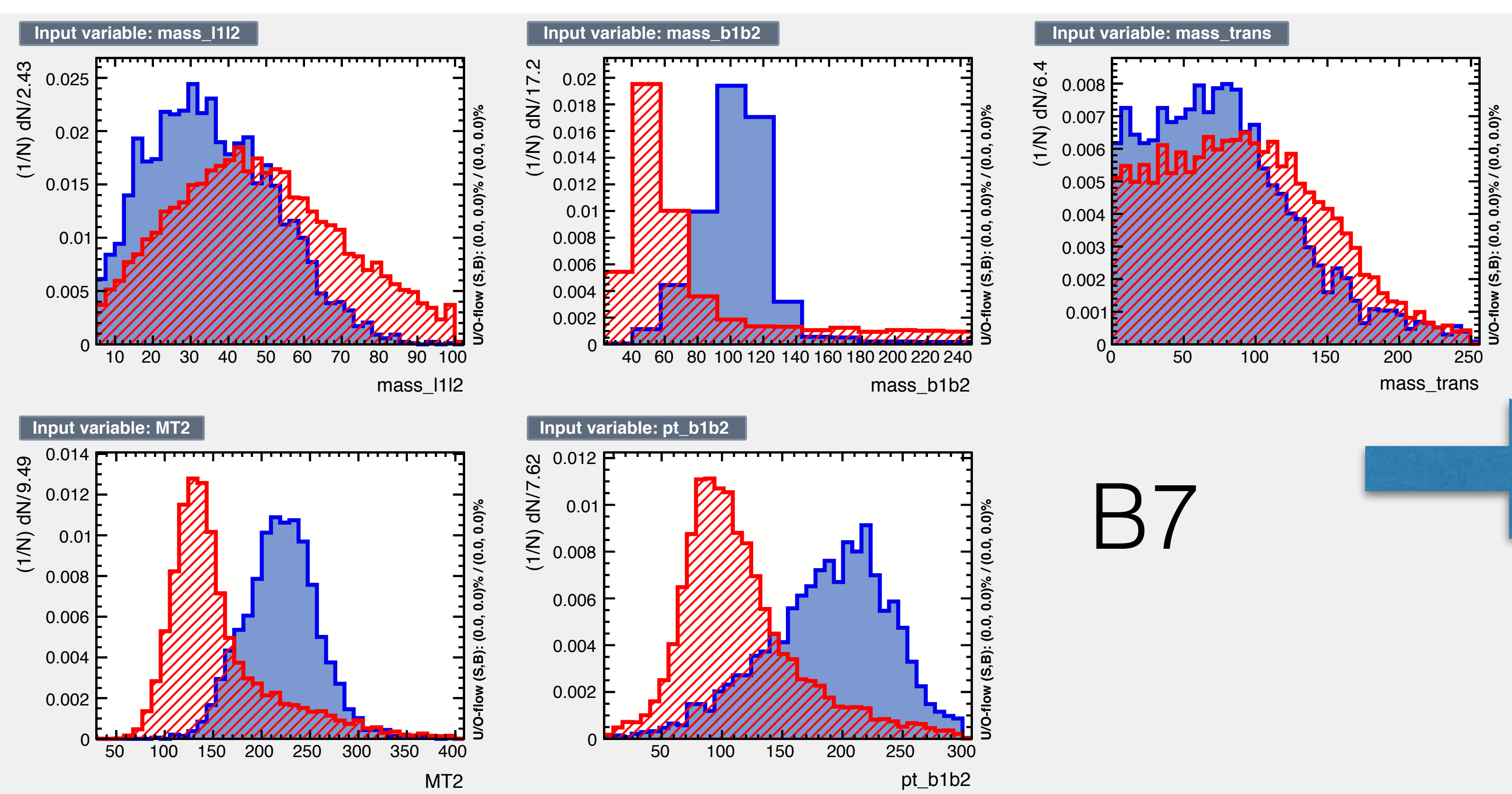
Major Background: Top-pair production (our focus)

Analysis Optimization: MVA

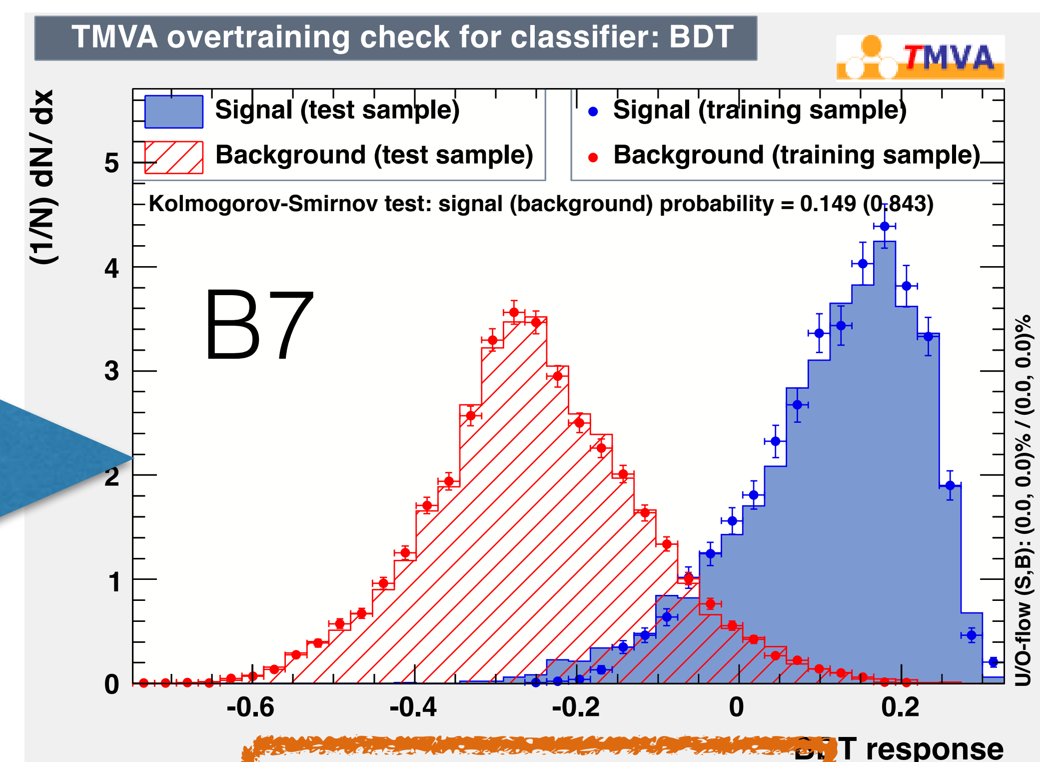
- Kinematic selection: before MVA
  - loose cut
  - the same for each signal benchmark point
  - efficient for signal: above 96%
  - tt efficiency: ~ 60%
- 12 kinematic variables as inputs for MVA
- Some input variables (B7 shown):

kinematic selection

Variable	Cut
$\Delta R(l,l)$	$0.07 < \Delta R(l,l) < 3.3$
$\Delta R(j,j)$	$\Delta R(j,j) < 5.0$
$M(l,l)$	$5 < M(l,l) < 100$ GeV
$M(j,j)$	$M(j,j) > 22$ GeV



MVA output: final discriminator



Boosted Decision Tree

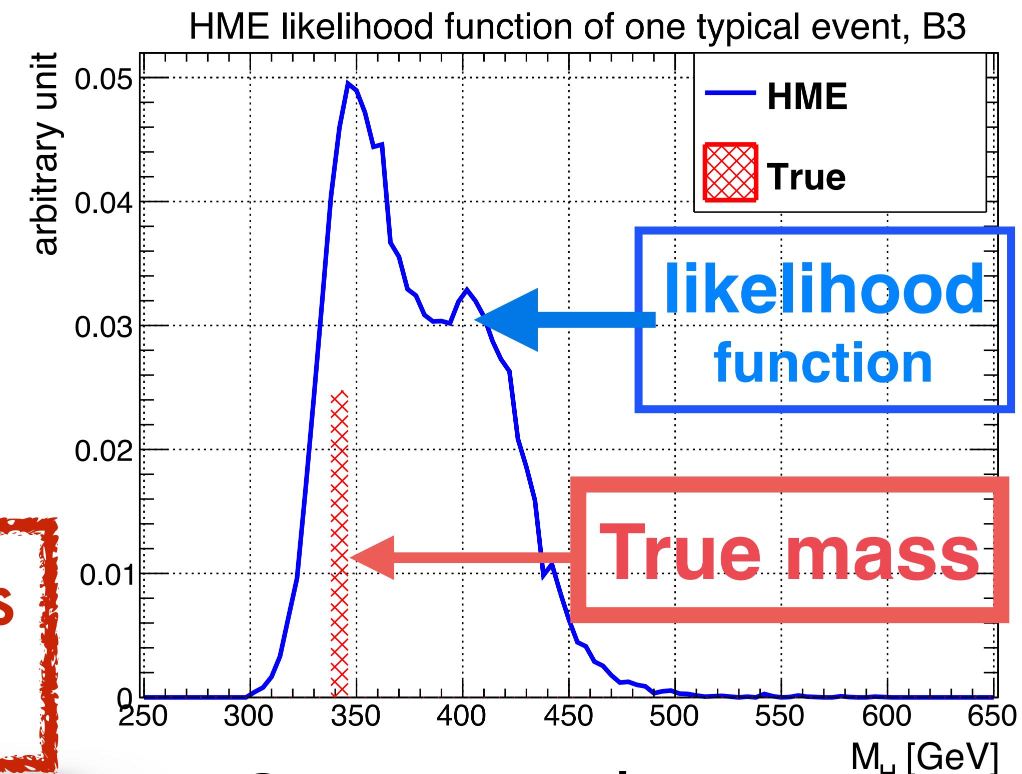
Heavy Mass Estimator(HME)

1. Mass reconstruction is not straightforward, due to the existence of two neutrinos
   - ➡ Two neutrinos contribute 6 unknown parameters
2. This channel provides 4 constraints
   - ➡ Reduce 6 unknowns to 2
3. We randomly generate 2 unknowns
   - ➡ η and φ of one neutrino

$$\not{E}_{Tx} = p_x(\nu_1) + p_x(\nu_2)$$
$$\not{E}_{Ty} = p_y(\nu_1) + p_y(\nu_2)$$
$$\sqrt{p_4^2(\ell_1,\nu_1)} = M_W, 20 < \sqrt{p_4^2(\ell_2,\nu_2)} < 45 \text{ GeV}$$
$$(p_4(\ell_1) + p_4(\ell_2) + p_4(\nu_1) + p_4(\nu_2))^2 = M_h^2$$

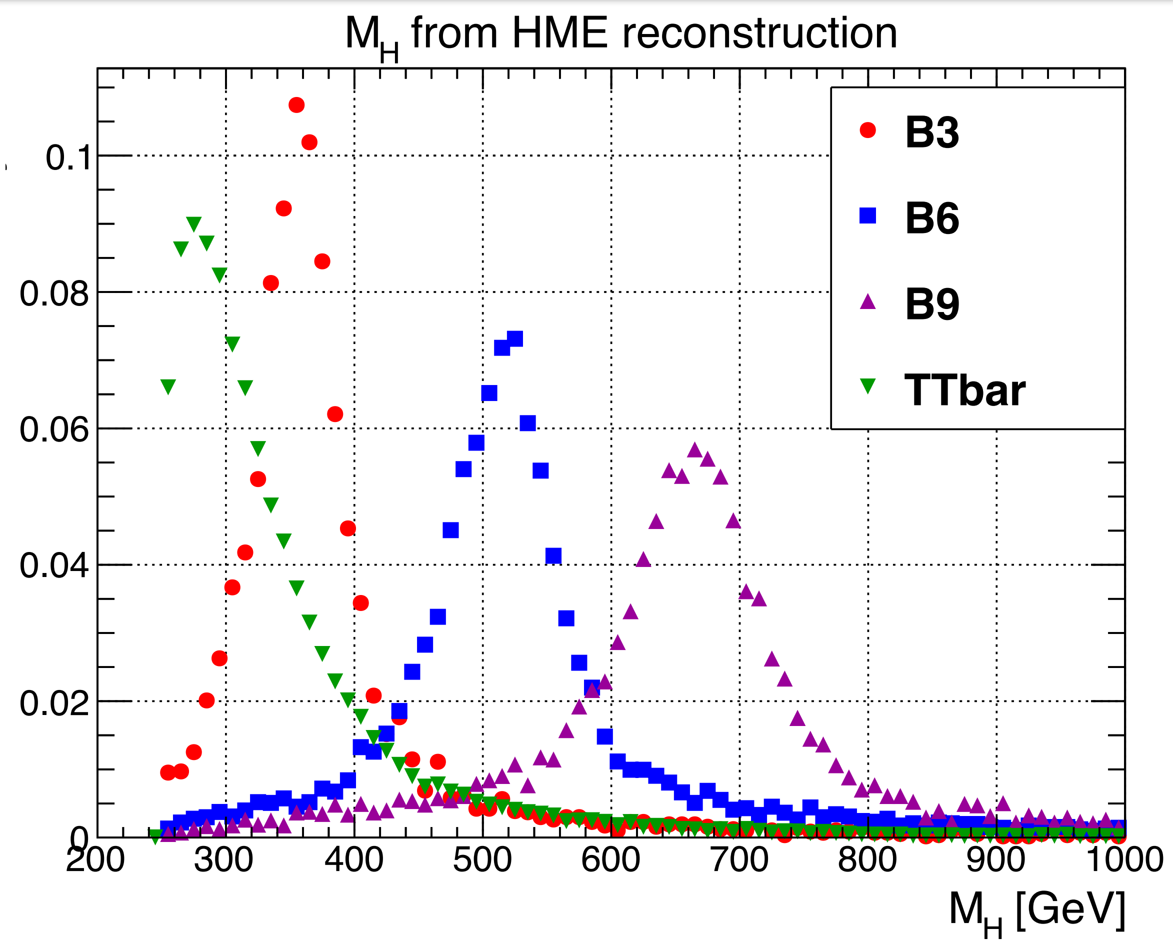
4. If generated 2 unknowns are in kinematic allowed region, system is fully solved and we get one estimator of M_H value
   - ➡ Otherwise drop this generation
5. Repeat above procedure many times, and likelihood function is built in each single event according to the distribution of M_H estimator

Mass value with maximum likelihood is taken as the final M_H estimator in single event



One Typical Event

Heavy Mass Estimator (2)

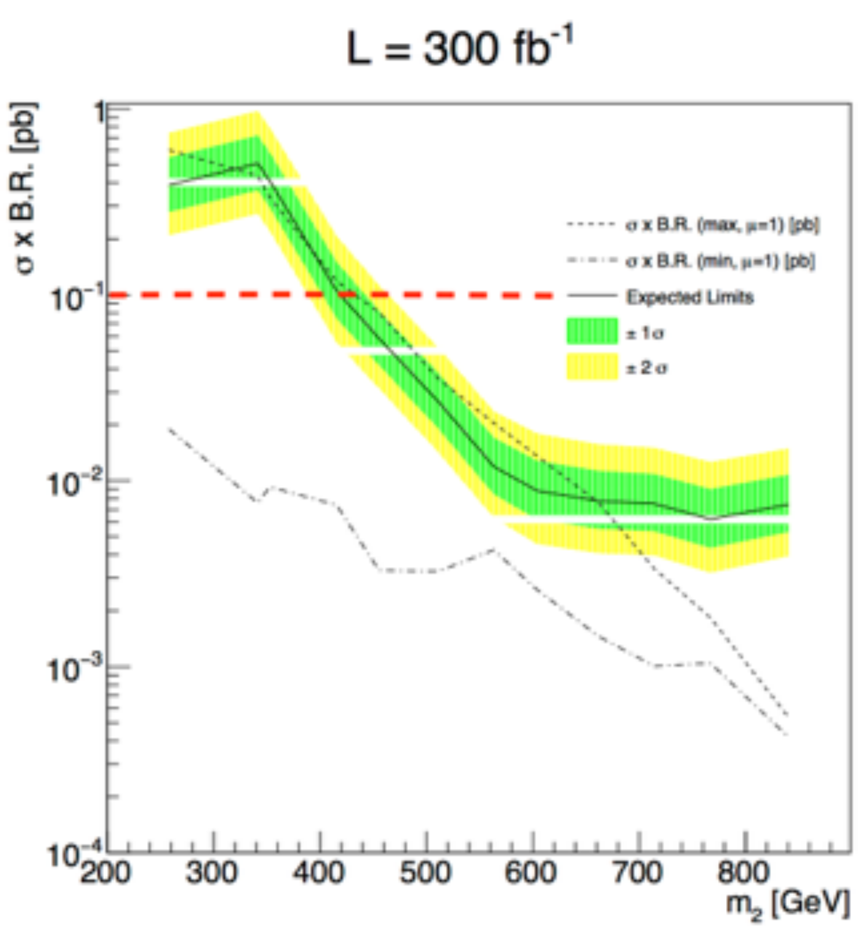


- After preselection + MVA selection, HME is used to reconstruct events
- Resolution of HME reconstruction depends on heavy Higgs mass
- Reconstructed mass shape can largely improve analysis sensitivity
  - Powerful discriminant against tt
  - Shape analysis, rather than simple cut and count analysis

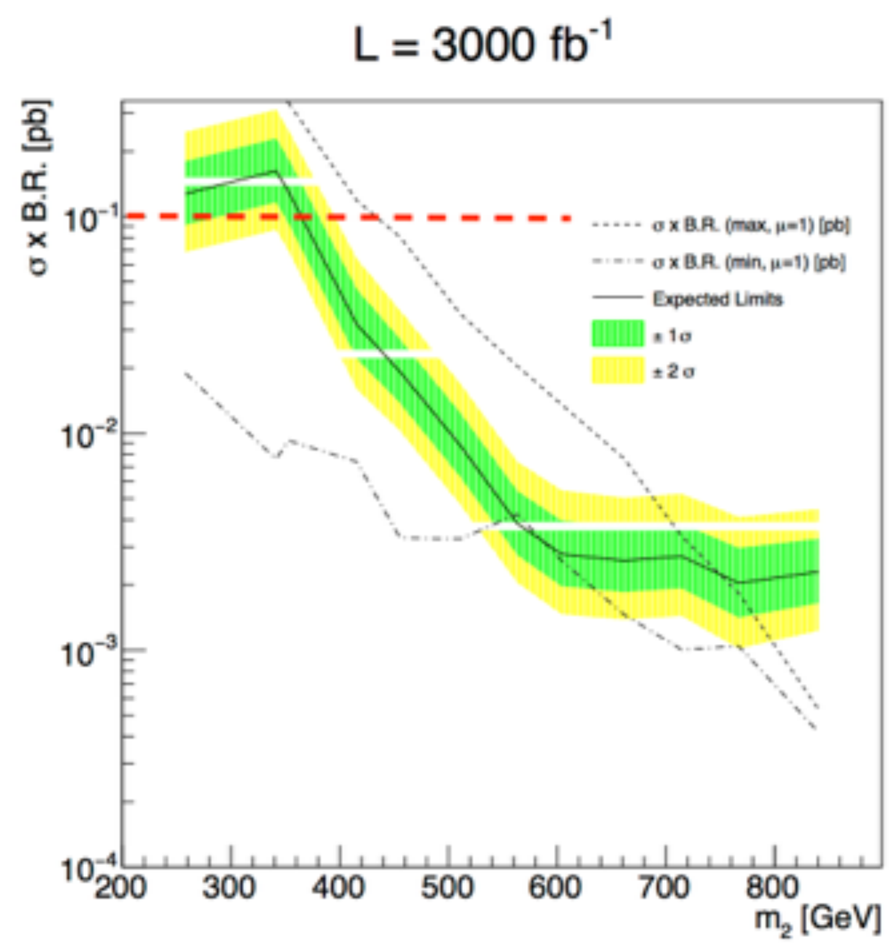
Expected Upper Limits

- Expected limits are derived by asymptotic Confidence Level(CLs) method
  → Relies on an asymptotic approximation of the distributions of the LHC test-statistic, which is based on a profile likelihood ratio

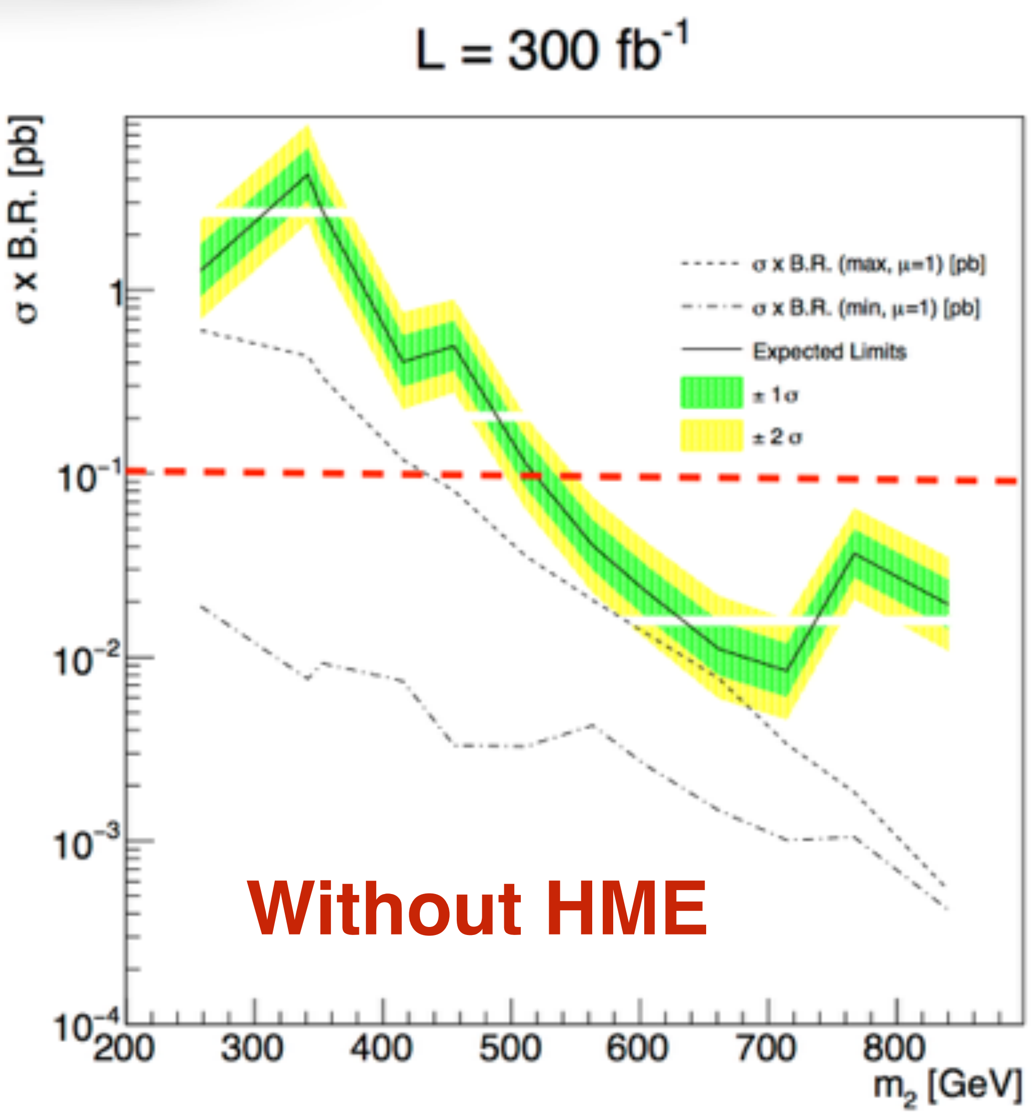
- Almost full heavy Higgs mass range exclusion with 3000 fb^{-1}
  → Considering CMS+ATLAS (including e+mu, e+e, mu+mu)
  → Limit is compared to the cross section from the optimistic and pessimistic predications

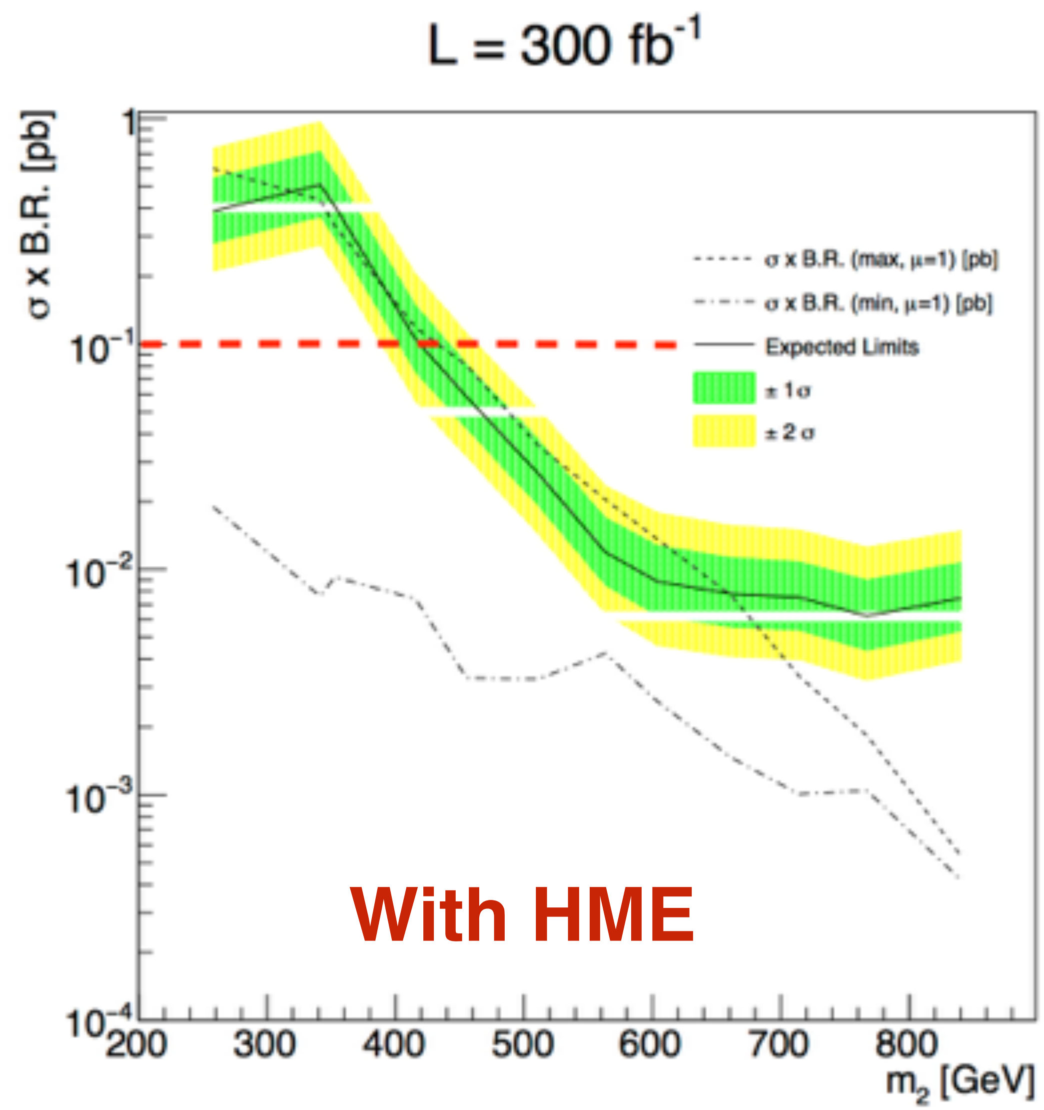


end of HL-LHC



Impact of HME On Expected Limits

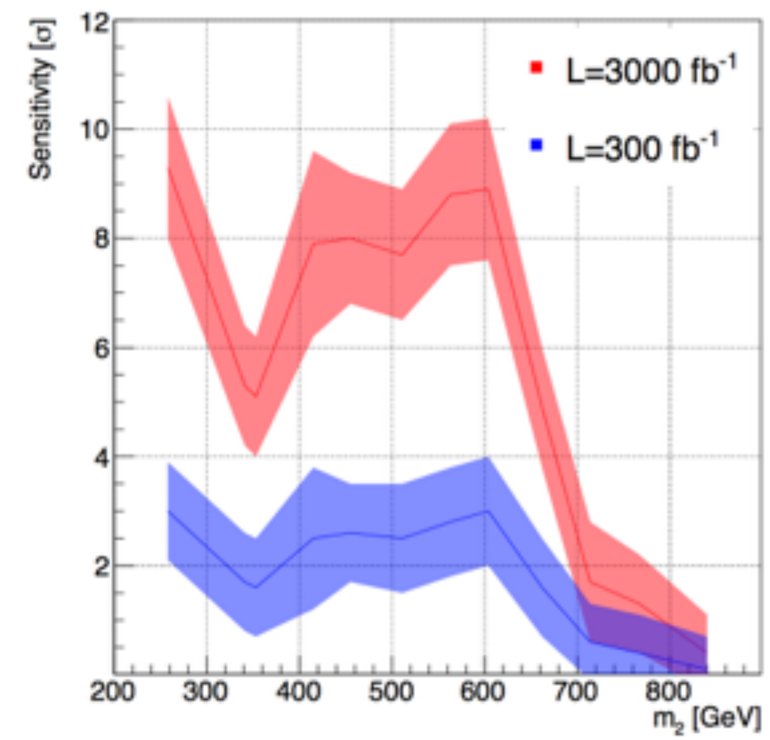




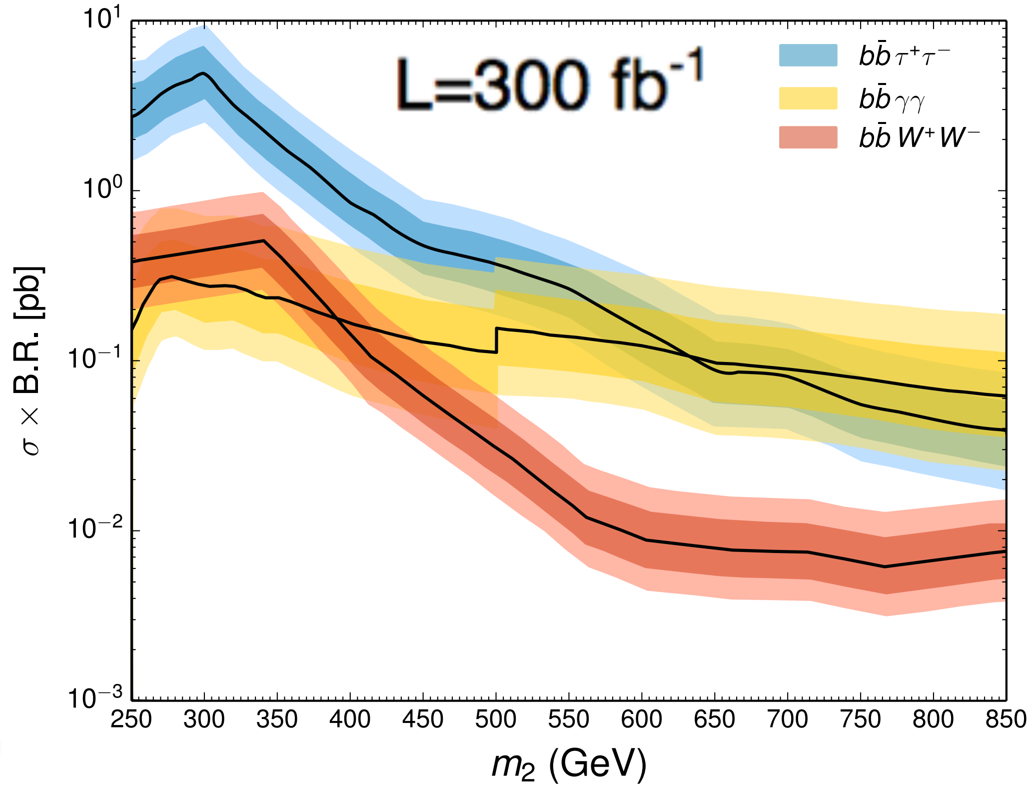
HME largely improves analysis sensitivity and analysis with HME gives a stronger constraint on xSM with same dataset

Conclusions and Outlook

- Very challenging channel, but
  - ➡ Despite the huge background, the analysis can set upper limits up to 700 GeV
  - ➡ 5σ discovery of an eventual new resonance can be reached with 3000 fb^{-1} data
- Competitive with other decay Channels



- Future improvements:
  - MVA could be further improved: advanced Neural Networks
  - Make full use of HME likelihood (rather than maximum)
  - Define several control regions to better estimate tt



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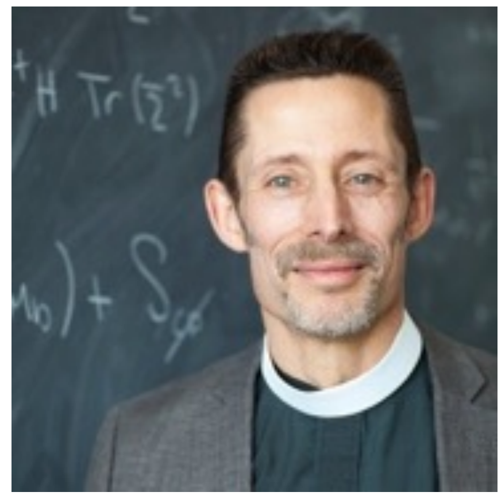

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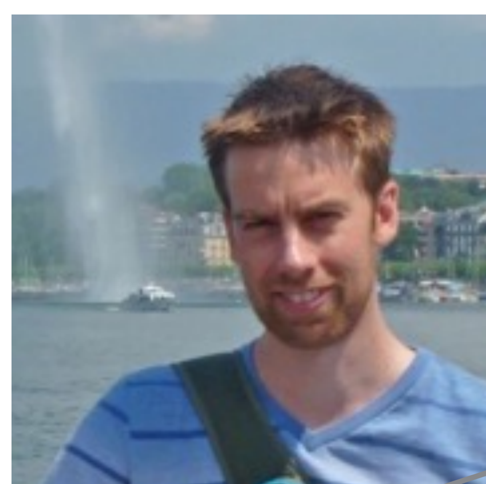

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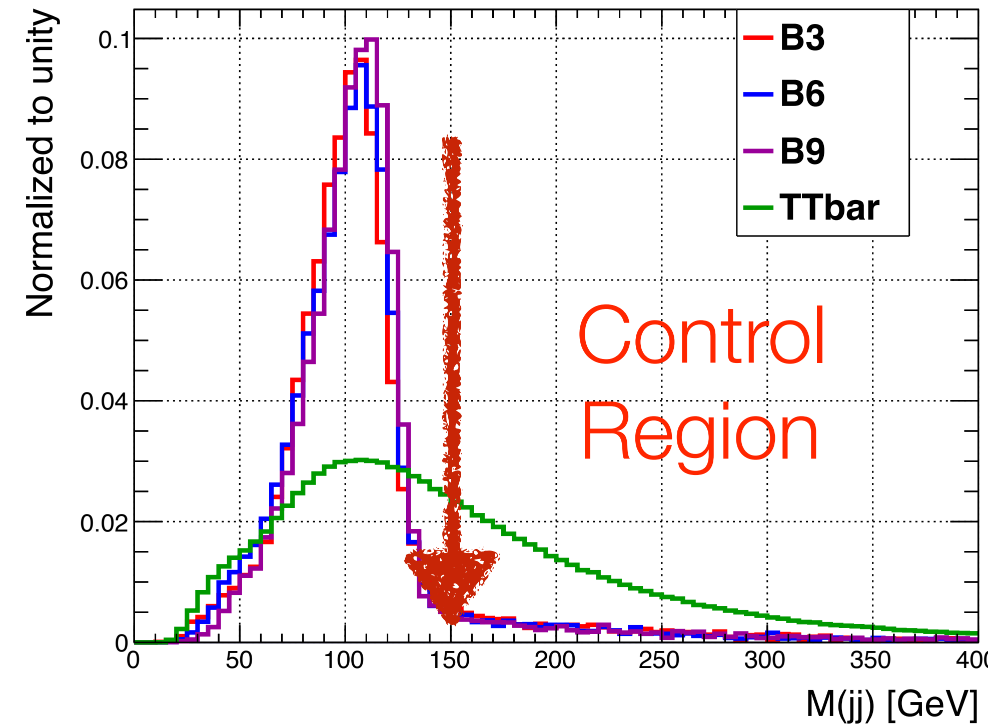
Thanks!

BackUp

Systematics

- Define a control region (CR) to estimate tt:
  - only a very small fraction of tt are selected
  - uncertainty on tt on QCD scale (~10-15%) affect drastically sensitivity
  - better estimation is necessary
- Scale Factors will be extracted in the CR and applied to the SR
  → uncertainty on the SF is driven by the statistic in the CR
  → using more CR allows to cross check the SF
  → better to be conservative, we assume:
  B1-B2-B3: 3% B4: 5% B5: 10%
  B6-B7-B8-B9: 12% B10-B11-B12: 15%



- Signal uncertainty:
  - this is just a feasibility study, No data to compute realistic systematics
  - assuming general CMS systematics for Higgs searches: ~10%

Source of uncertainties	Error, %
Integrated luminosity	2.6%
Muon HLT	1.5%
Muon ID	$4 \times 1\%$
Muon tracking	$4 \times 0.2\%$
Overlapping in Tracker	$2 \times 1.2\%$
Overlapping in Muon System	$2 \times 1.3\%$
Dimuons mass consistency	1.5%
NNLO Higgs p_T re-weighting	2.0%
PDF+α_s	3.0%
Total	7.3%

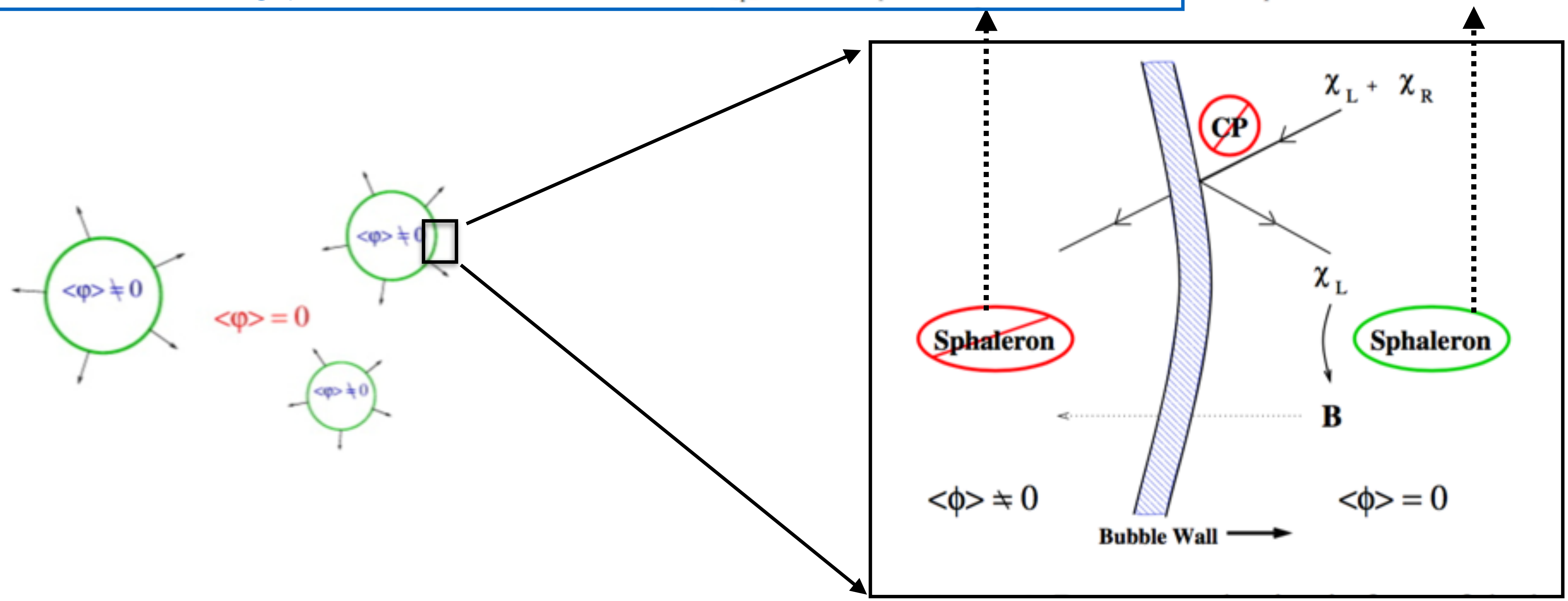
Example:CMS collaboration.Phys. Lett B 752 (2016) 146,

ElectroWeak Phase Transition and Baryogenesis

$E_{Sph}/T_N > 1$, sufficiently suppress sphaleron transition in broken phase
->strong phase transition

$\Gamma^b_{Sph} \sim Exp(-E_{Sph}/T_N) \sim$ SUPPRESSED

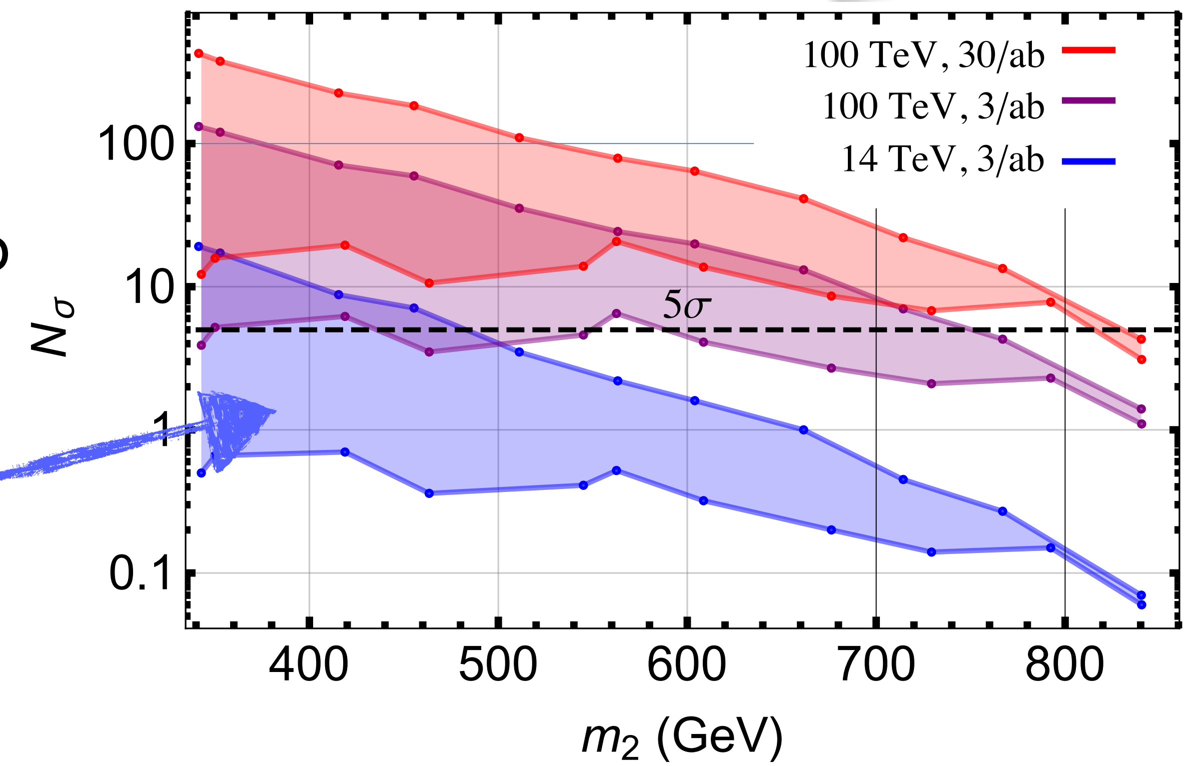
$\Gamma^S_{Sph} \sim \alpha^5_W T^4_N \sim$ UNSUPPRESSED

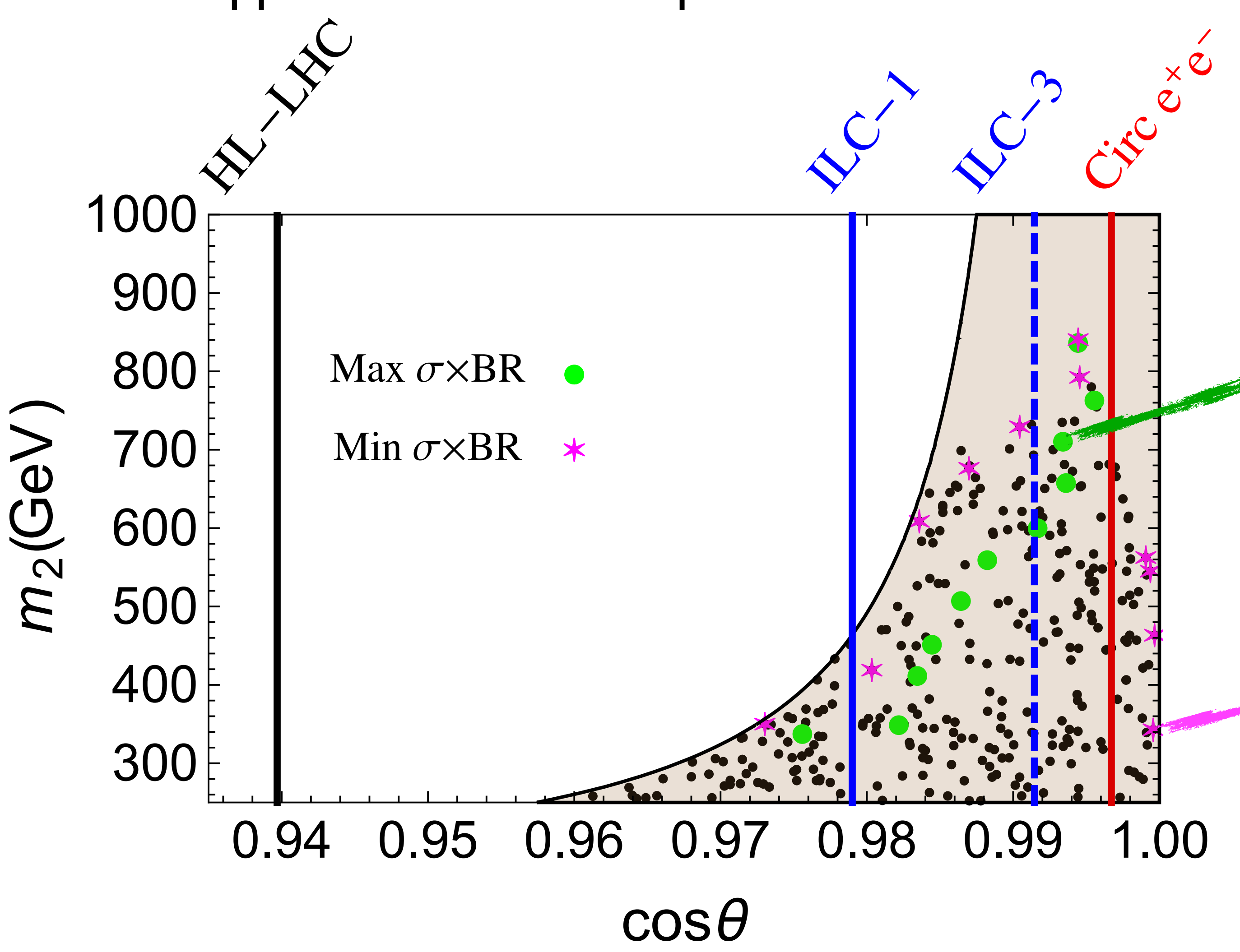


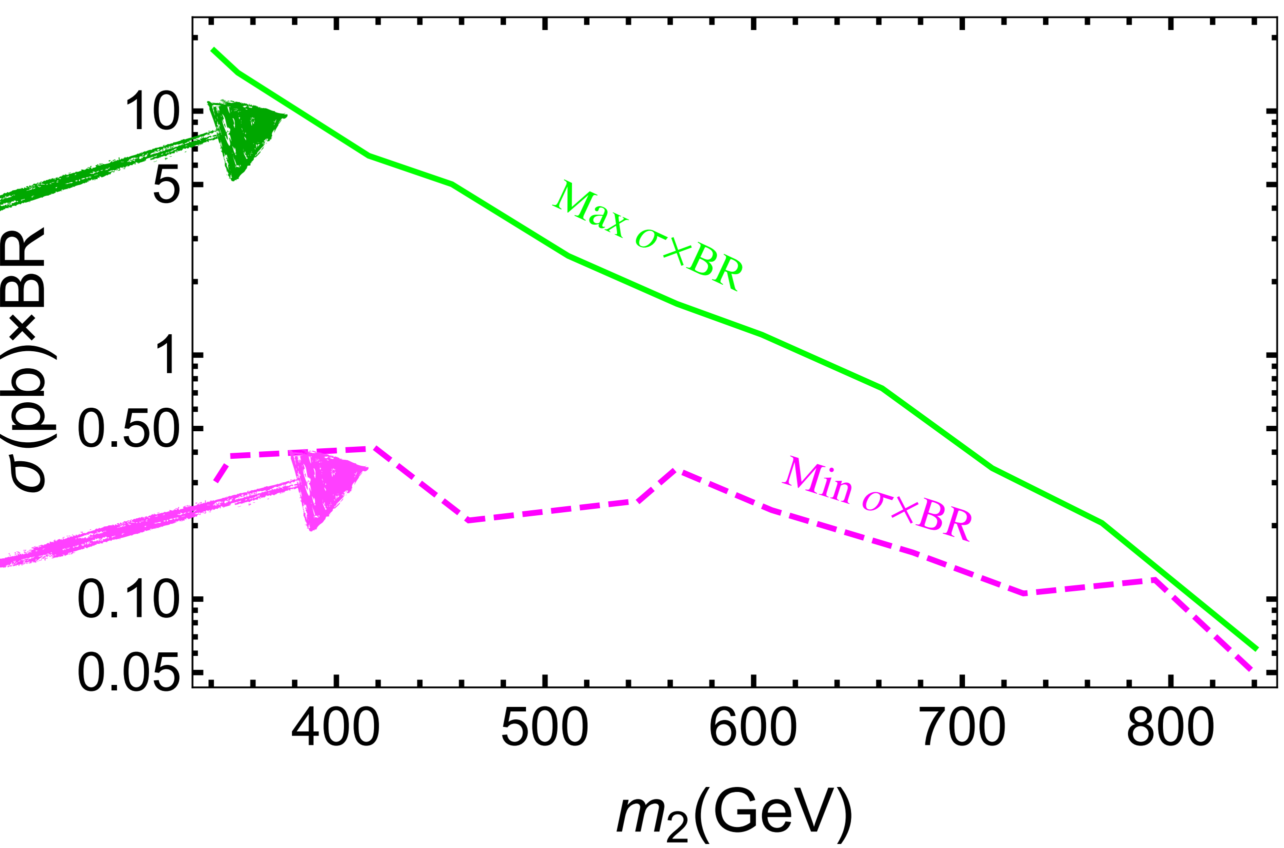
Signal cross section:

From Luca

- Among all strong first order EWPT points, two different benchmark models have been selected: **Optimistic** and **Pessimistic** scenario
- LHC is sensitive only at medium-low masses in bbγγ. We want to improve it with bbWW

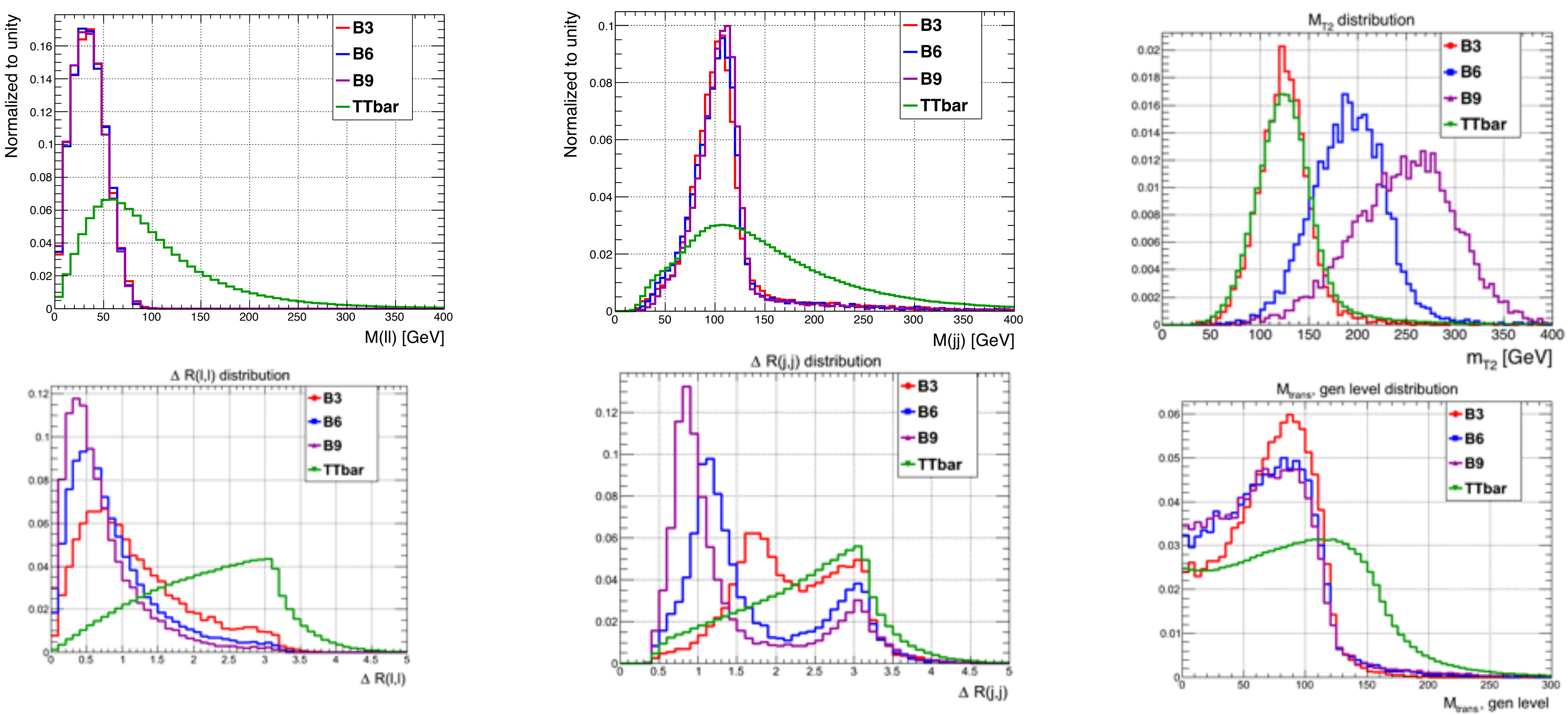




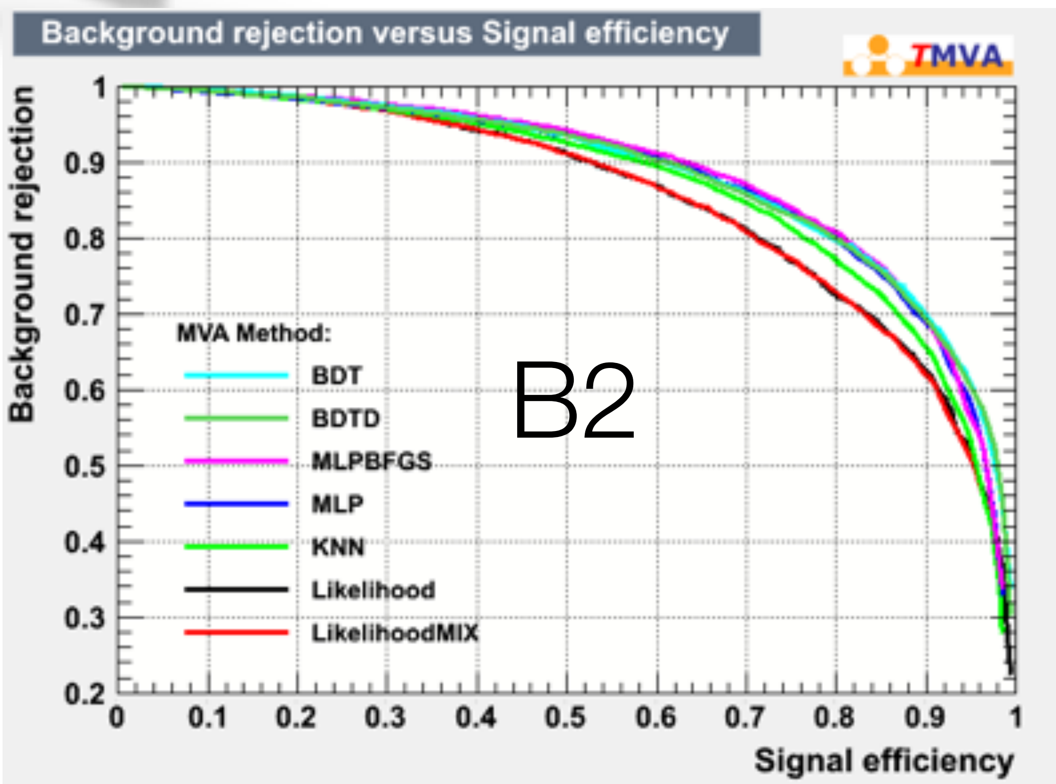


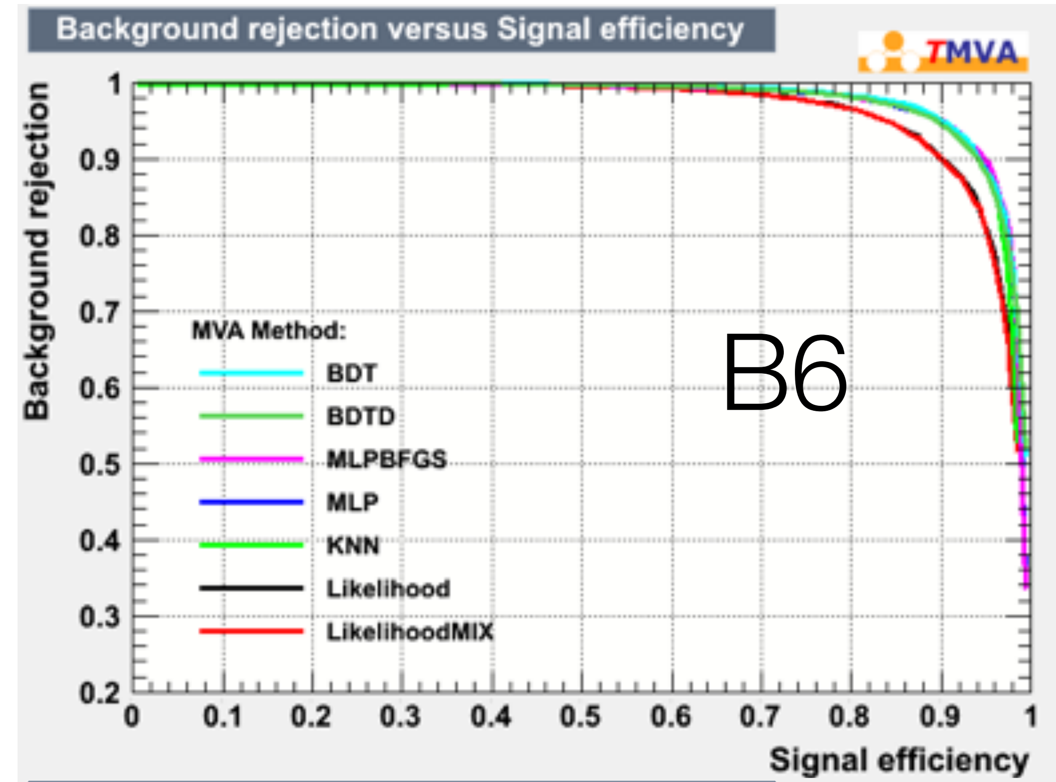
Kinematic Distributions

- Signal and background have different kinematic!!!
  - e.g. Di-lepton and Di-jet invariant mass
- Make full use of kinematic distributions: Multi-variate Analysis(MVA)

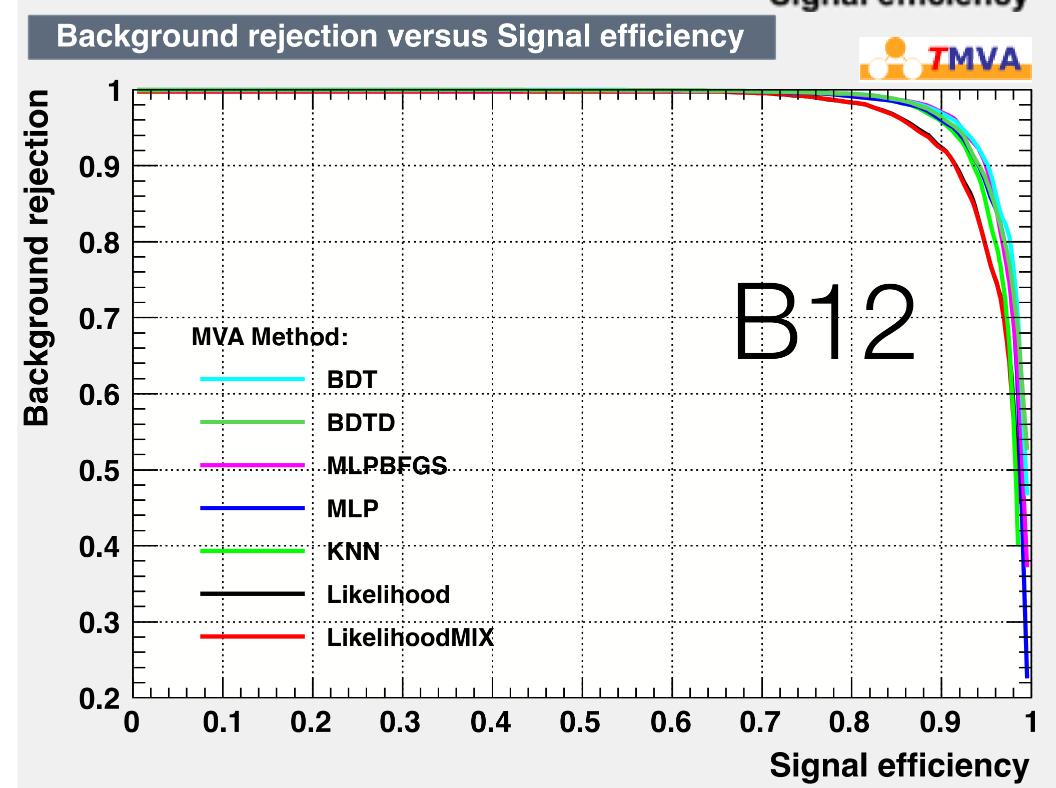


MVA Performance



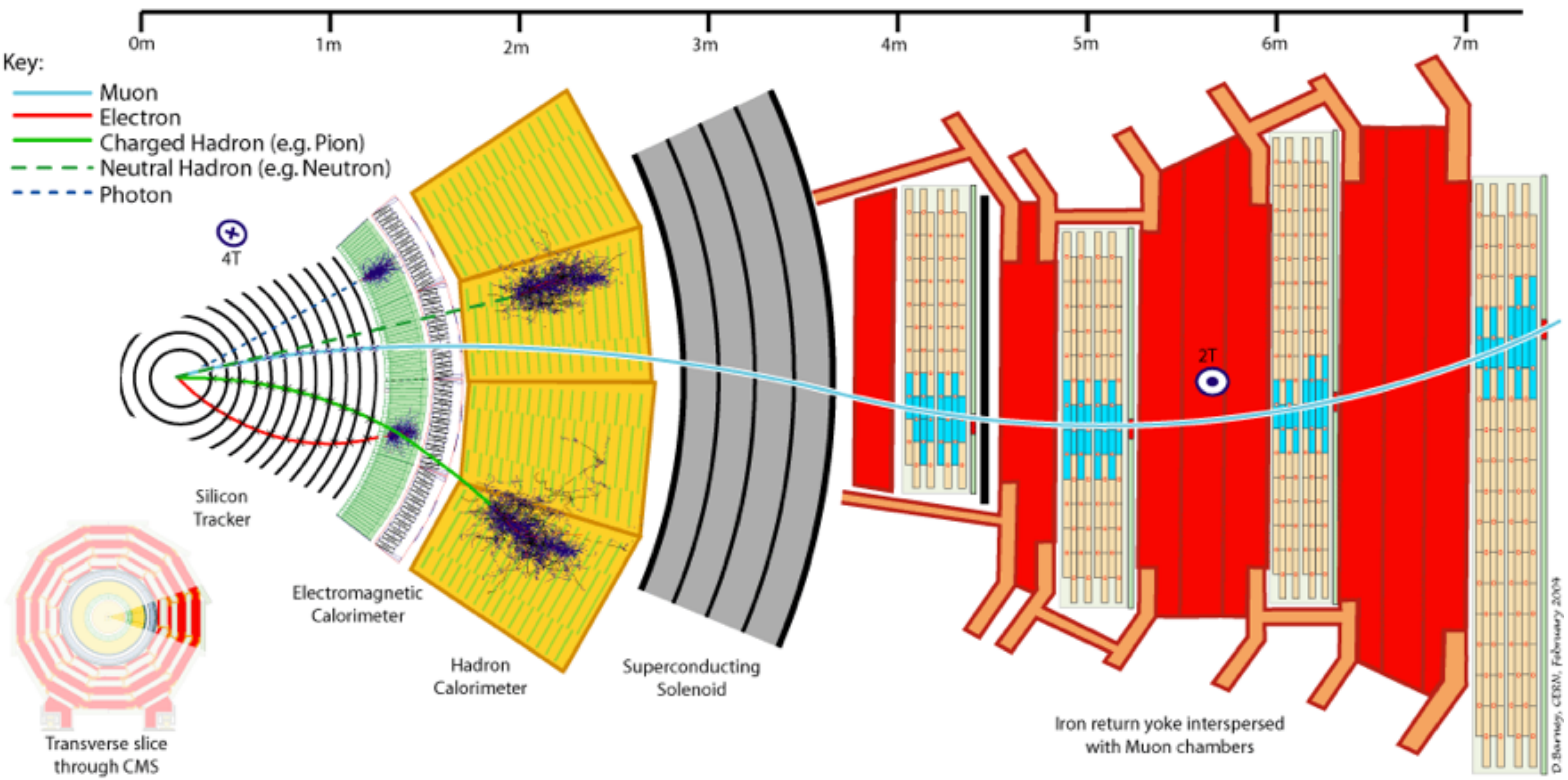


- MVA performs better at high mass point
  - however higher mass point has smaller production rate
- High Mass Estimator is designed to reconstruct mass shape
  - improves sensitivity of this analysis



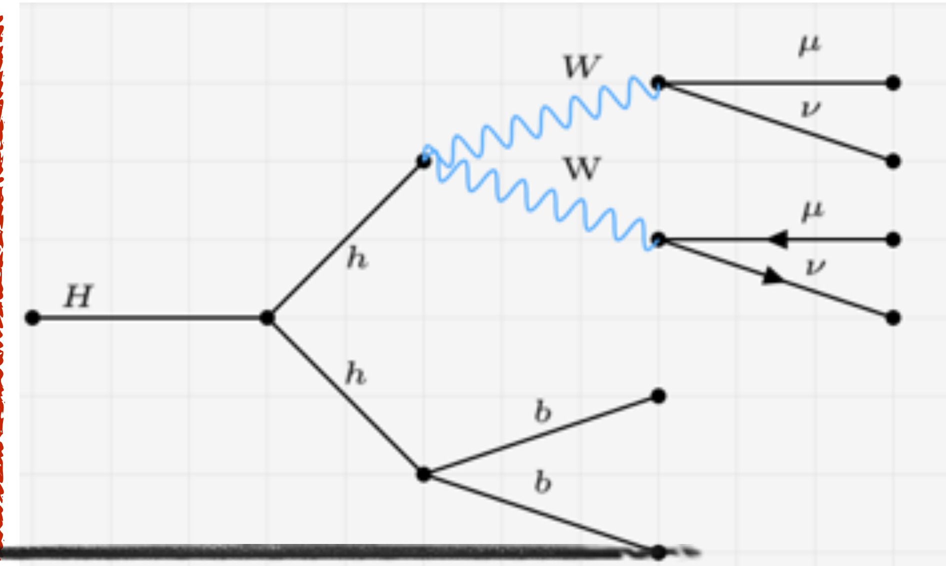
Compact Muon Solenoid

- CMS: general purpose detector on LHC: able to reconstruct all SM particles except neutrinos, which are estimated by momentum unbalance

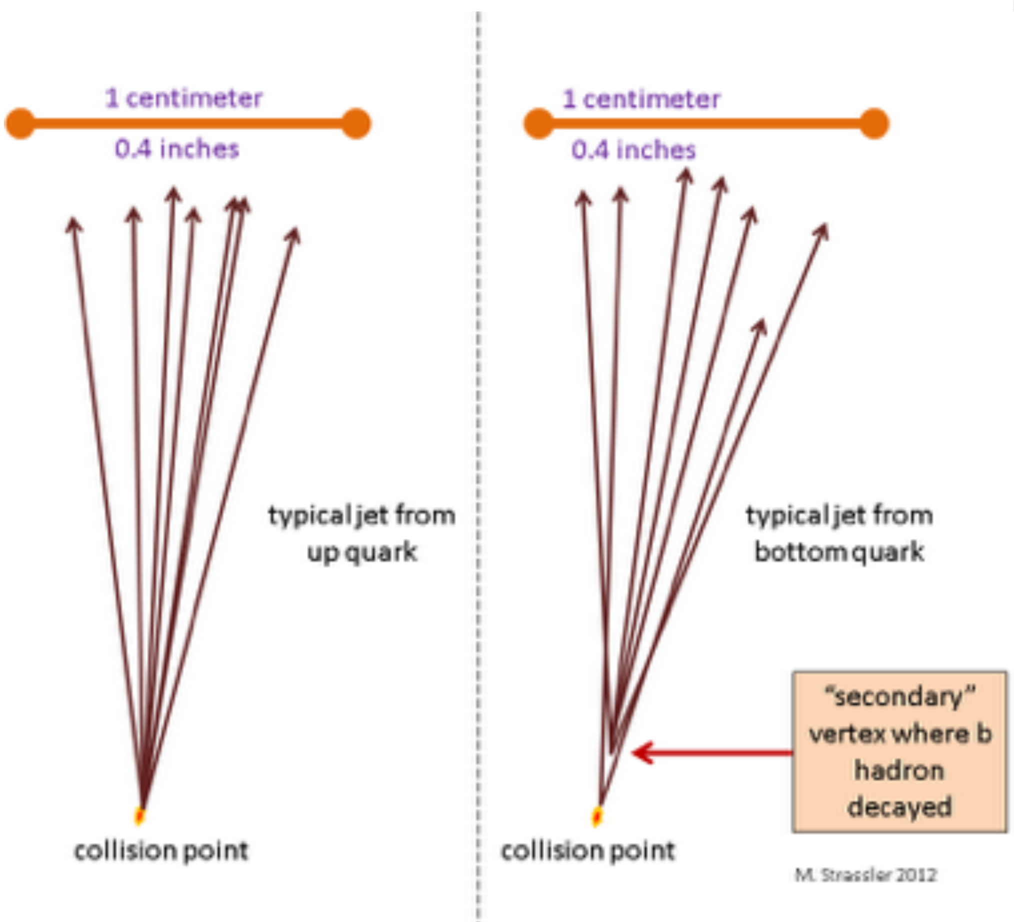


Event Preselection

- Preselection
  - 2 isolated muons (P_T>10 GeV and $|\eta|$<2.4), opposite sign
  - 2 jets (P_T>30 GeV and $|\eta|$<2.5)
    - ➡ 1 b-tagged jet (medium working point, WP)
    - ➡ 1 b-tagged jet (medium or loose working point)
  - Missing Transverse Energy (E_T^{miss}) > 20 GeV



- b-tagging algorithm:
  - → In delphes eff. and mistag are parametrized (vs p_T and η)
  - → Medium WP: eff.~70%, mistag~1.5%
  - → Loose WP: eff.~85%, mistag~10%



SM backgrounds:

→ Top-pair production (tt): large cross section (σ)

→ Drell-Yan (DY): very large σ, no jets at Leading Order, and no E_T^{miss}

→ tW: small σ, could produce the same final state

→ Non resonant hh: very small σ (negligible)

Major Background: Top-pair production (our focus)

	SM	xSM
Baryon violation (sphaleron)	✓	✓
C & CP violation	✓ ✗	✓
out of equilibrium or CPT violation	✗	✓