Probing the Triple Higgs Self-Interaction at the Large Hadron Collider

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IMHEP 2019
January 17-22 2019
Institute of Physics, Bhubaneswar

- Recent update on Flat Extra Dimensions (MUED)
- Probing the Triple Higgs Self-Interaction at the Large Hadron Collider
- My personal perspective on BSM searches at the LHC / HL-LHC (no time to discuss)

Many Variations of UED

- MUED: Minimal Universal Extra Dimensions (cf. mSugra)
- 2UED: Two Universal Extra Dimensions (cf. GMSB)
- nUED: non-minimal Universal Extra Dimensions
  - boundary terms
- SUED: Split Universal Extra Dimensions (cf. Split SUSY)
  - bulk terms
- sUED: UED with singlet extension
- NMUED: Next-to-Minimal UED (cf. pMSSM)
  - (with boundary and bulk terms)
- Many others with larger gauge groups (cf. SU(2)L x SU(2)R)

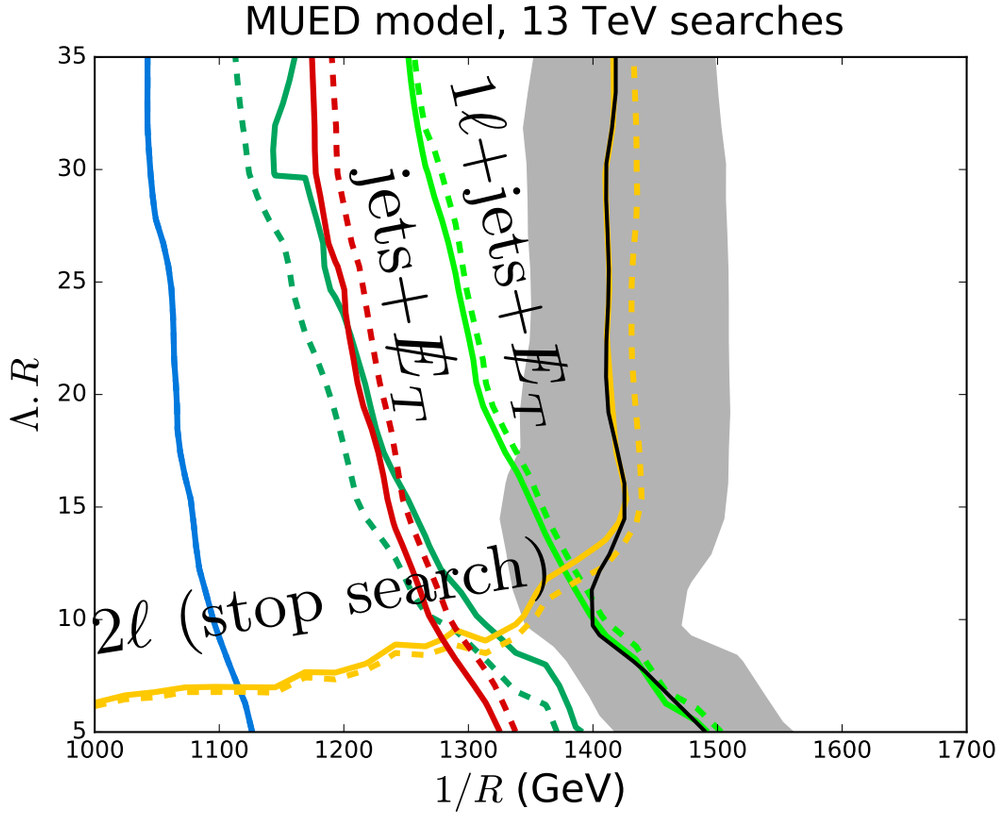
B. Bhattacherjee, M. Guchait,, S. Dasgupta, U. Dey, T. Jha, T. Ray, A. Biswas, A. Shaw, S. Patra, S. Chakraborty, S. Niyogi, K. Sridhar, A. Datta, A. Shaw, K. Ghosh, D. Karabacak, S. Nandi, A. Raychaudhuri, J. Beuria, S. Raychaudhuri, S. Mukhopadhyay, B Mukhopadhyaya, N. Ganguly, D. Choudhury, D. Sachdeva, A. Raychaudhuri, D. Ghosh, P. Bandyopadhyay, A. Kundu . . . . .

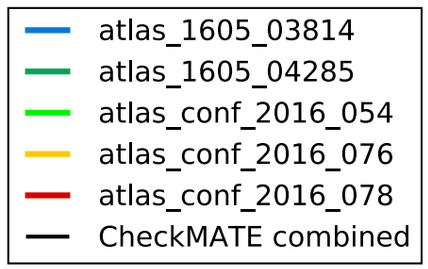
Recent update on Flat Extra Dimensions (MUED)

- MUED: 5 dimensional standard model compactified on an orbifold S1/Z2, with vanishing boundary conditions (at cut=off scale) at two fixed points, and assuming Z2 symmetry along ED.

- Two parameters: cutoff (Lambda) and radius (R)

Omega h^2 ~ 1/sigma ~ Rinv^2





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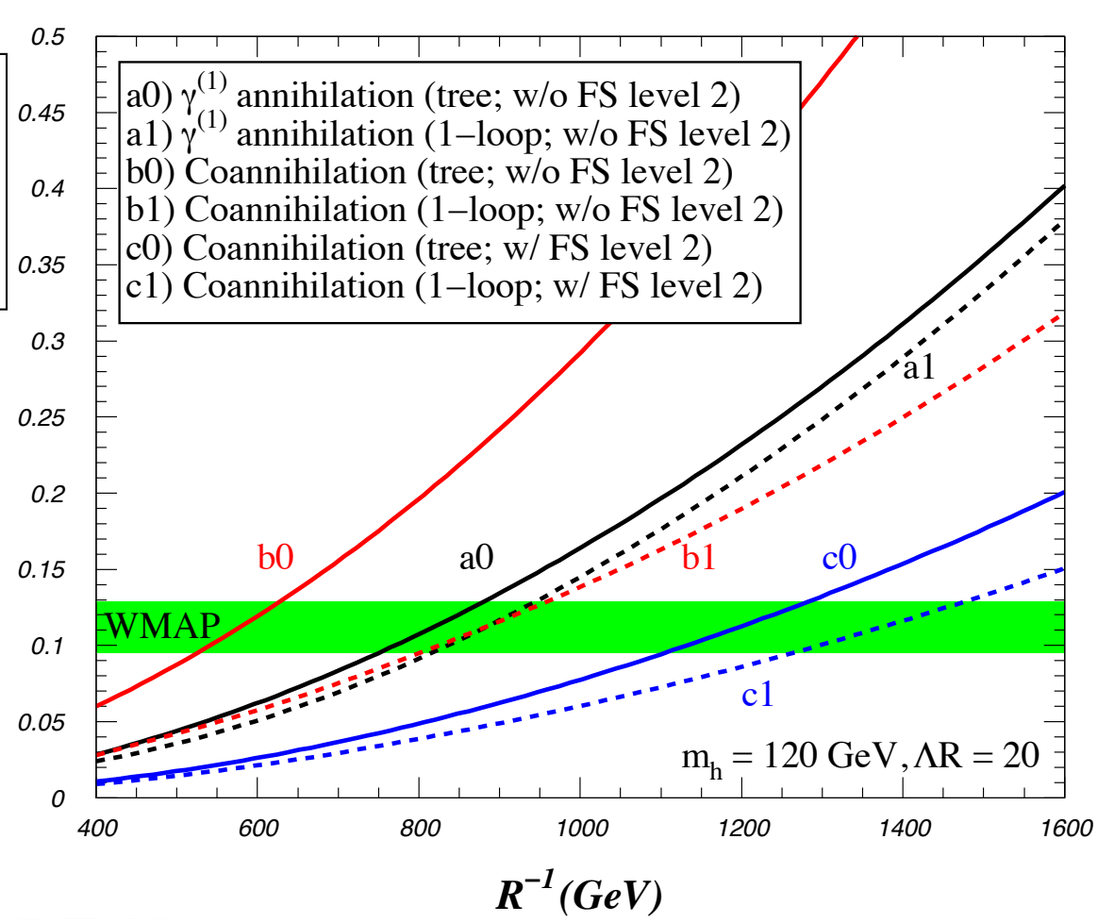
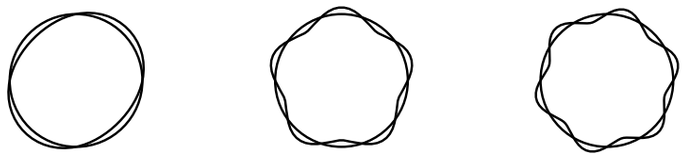


Deutschmann, Flacke, Kim 2017

~1.4 TeV < Rinv < ~1.5 TeV

Belanger, Kakizaki, Pukhov, 2011

One-loop corrected Mass Spectrum

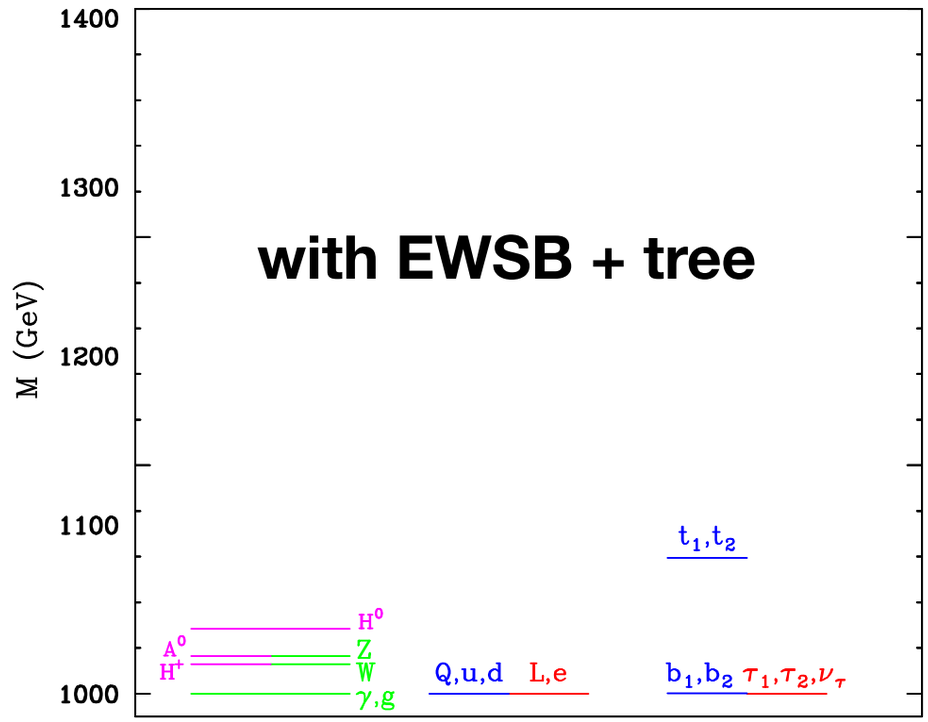


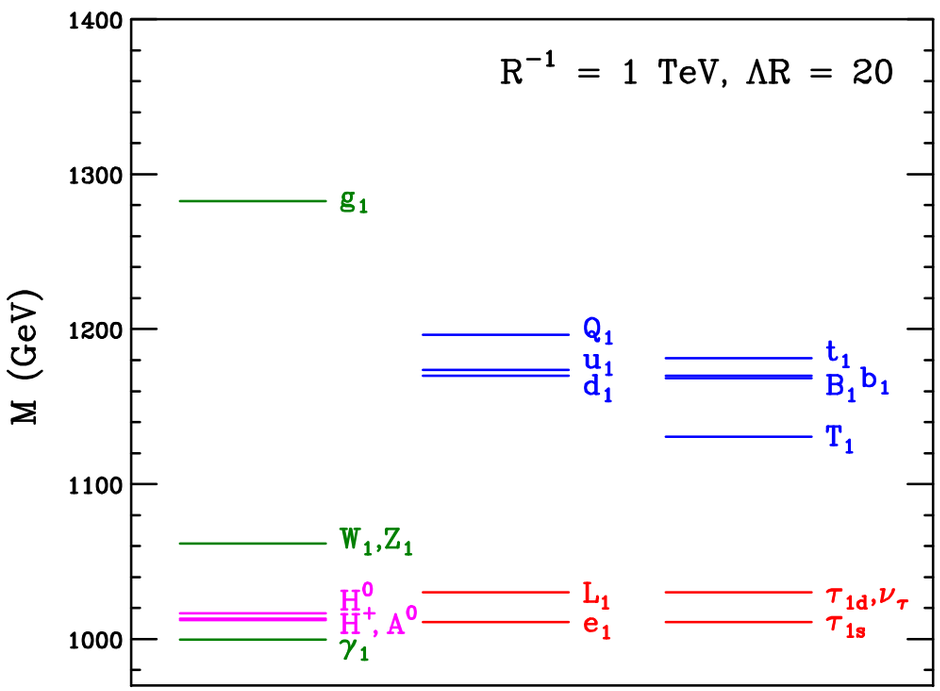
$2\pi R = 2\lambda$ $2\pi R = 5\lambda$ $2\pi R = 6\lambda$

$$E^2 = p_{x_1}^2 + p_{x_2}^2 + p_{x_3}^2 + \frac{n^2}{R^2} + m^2 \equiv \vec{p}^{\,2} + M_n^2$$

$$\lambda = \frac{2\pi R}{n} \Rightarrow p_y = \frac{2\pi n}{2\pi R} = \frac{n}{R} \qquad p_y = \frac{2\pi}{\lambda}$$

$$M_n = \sqrt{\frac{n^2}{R^2} + m^2}$$





w/ EWSB + 1-loop

Finite Corrections

$$\bar{\delta}m_{u_n} = m_n \frac{1}{16\pi^2}\left[g_3^2\left(3L_n\right) + g_1^2\left(L_n\right)\right],$$

$$\bar{\delta}m_{t_n} = m_n \frac{1}{16\pi^2}\left[g_3^2\left(3L_n\right) + g_1^2\left(L_n + \frac{16}{9}\right) - h_t^2\left(\frac{1}{2}L_n + 1\right)\right],$$

$$\bar{\delta}m_{d_n} = m_n \frac{1}{16\pi^2}\left[g_3^2\left(3L_n\right) + g_1^2\left(\frac{1}{4}L_n + \frac{4}{9}\right)\right],$$

$$\bar{\delta}m_{L_n} = m_n \frac{1}{16\pi^2}\left[g_2^2\left(\frac{27}{16}L_n\right) + g_1^2\left(\frac{9}{16}L_n + 1\right)\right],$$

$$\bar{\delta}m_{e_n} = m_n \frac{1}{16\pi^2} g_1^2\left(\frac{9}{4}L_n\right),$$

$$\bar{\delta}m_{Q_n} = m_n \frac{1}{16\pi^2}\left[g_3^2\left(3L_n\right) + g_2^2\left(\frac{27}{16}L_n\right) + g_1^2\left(\frac{1}{16}L_n\right)\right],$$

$$\bar{\delta}m_{Q_{3n}} = m_n \frac{1}{16\pi^2}\left[g_3^2\left(3L_n\right) + g_2^2\left(\frac{27}{16}L_n\right) + g_1^2\left(\frac{1}{16}L_n\right) - h_t^2\left(\frac{1}{4}L_n\right)\right],$$

$$\bar{\delta}m_{H_n}^2 = \overline{m}_H^2 + m_n^2 \frac{1}{16\pi^2}\left[g_2^2\left(\frac{9}{4}L_n\right) + g_1^2\left(\frac{3}{4}L_n\right) - \lambda_H(L_n)\right]$$

$$\bar{\delta}m_{G_n}^2 = m_n^2 \frac{g_3^2}{32\pi^2}\left(23L_n\right),$$

$$\bar{\delta}m_{W_n}^2 = m_n^2 \frac{g_2^2}{32\pi^2}\left(15L_n\right),$$

$$\bar{\delta}m_{B_n}^2 = m_n^2 \frac{g_1^2}{16\pi^2}\left(-\frac{1}{6}L_n\right),$$

$$L_n \equiv \ln(\Lambda^2/m_n^2)$$

Freitas, Kong, Wiegand 2008

H. C. Cheng, K. T. Matchev and M. Schmaltz, Phys. Rev. D **66**, 056006 (2002)

Finite Corrections

$$\bar{\delta}m_{u_n} = m_n \frac{1}{16\pi^2}\left[g_3^2\left(3L_n + \frac{16}{3}\right) + g_1^2\left(L_n + \frac{16}{9}\right)\right],$$

$$\bar{\delta}m_{t_n} = m_n \frac{1}{16\pi^2}\left[g_3^2\left(3L_n + \frac{16}{3}\right) + g_1^2\left(L_n + \frac{16}{9}\right) - h_t^2\left(\frac{1}{2}L_n + 1\right)\right],$$

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$$\bar{\delta}m_{G_n}^2 = m_n^2 \frac{g_3^2}{32\pi^2}\left(23L_n + \frac{154}{3}\right),$$

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$$L_n \equiv \ln(\Lambda^2/m_n^2)$$

Freitas, Kong, Wiegand 2008

H. C. Cheng, K. T. Matchev and M. Schmaltz, Phys. Rev. D **66**, 056006 (2002)

Finite Corrections

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$$\bar{\delta}m_{d_n} = m_n \frac{1}{16\pi^2}\left[g_3^2\left(3L_n + \frac{16}{3}\right) + g_1^2\left(\frac{1}{4}L_n + \frac{4}{9}\right)\right],$$

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3/2 was a mistake.

$$\bar{\delta}m_{G_n}^2 = m_n^2 \frac{g_3^2}{32\pi^2}\left(23L_n + \frac{154}{3}\right),$$

$$\bar{\delta}m_{W_n}^2 = m_n^2 \frac{g_2^2}{32\pi^2}\left(15L_n + \frac{104}{3}\right),$$

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Freitas, Kong, Wiegand 2008

H. C. Cheng, K. T. Matchev and M. Schmaltz, Phys. Rev. D **66**, 056006 (2002)

KK Number Violating Interaction

$\bar{\psi}_0$–ψ_0–V_2^μ coupling: $-iC_{\psi_0\psi_0V_2}\gamma^\mu T^a P_\pm$.

Freitas, Kong, Wiegand 2008

$$C_{\psi_0\psi_0V_2} = \frac{\sqrt{2}g}{64\pi^2}\Bigg[g^2\,C(G)_V\left(\frac{23}{3}L_1+\frac{157}{9}-2\pi^2\right)+\sum_k g_k^2\,C(r_\psi)_k\left(-9L_1-13+\frac{7\pi^2}{4}\right)$$
$$+\,g^2\sum_{i\in\text{scalars}}(-1)^{P_i}T(r_i)_V\left(-\frac{1}{3}L_1-\frac{2}{9}\right)$$
$$+\sum_{i\in\text{scalars}}(-1)^{P_i}h_i^2\left(L_1-1+\frac{\pi^2}{4}+2\frac{C_{\phi_{i0}\phi_{i0}V_0}}{C_{\psi_0\psi_0V_0}}\right)\Bigg]\,,$$

KK Number Violating Interaction

Freitas, Kong, Wiegand 2008

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$\bar{\psi}_2$–ψ_0–V_0^μ **coupling:**

$\bar{Q}_2\gamma^\mu T^a P_L Q_0 A^a_{0\mu}$ **(not allowed)**

$\bar{Q}_2\sigma^{\mu\nu}T^a P_L Q_0 F^a_{0\,\mu\nu}$ **(1/Rinv suppressed?)**

$$-iC_{\psi_2\psi_0V_0}\gamma^\mu T^a P_\pm\,, \qquad -\tilde{D}_{\psi_2\psi_0V_0}\frac{\sigma^{\mu\nu}q_\nu}{2m_{KK}}T^a P_\pm\,,$$

$$pp \to Q_2/q_2 \to q'V, \text{ where } V=\gamma,\, Z,\, W \text{ or } g.$$

KK Number Violating Interaction

Freitas, Kong, Wiegand 2008

$\bar{\psi}_0$–ψ_0–V_2^μ coupling: $-iC_{\psi_0\psi_0 V_2}\gamma^\mu T^a P_\pm$.

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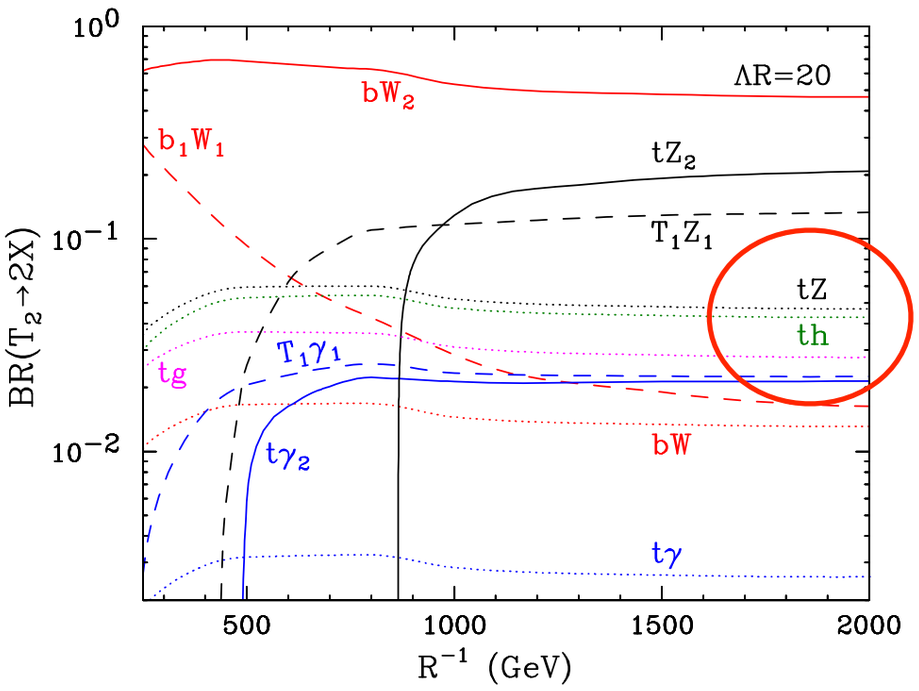
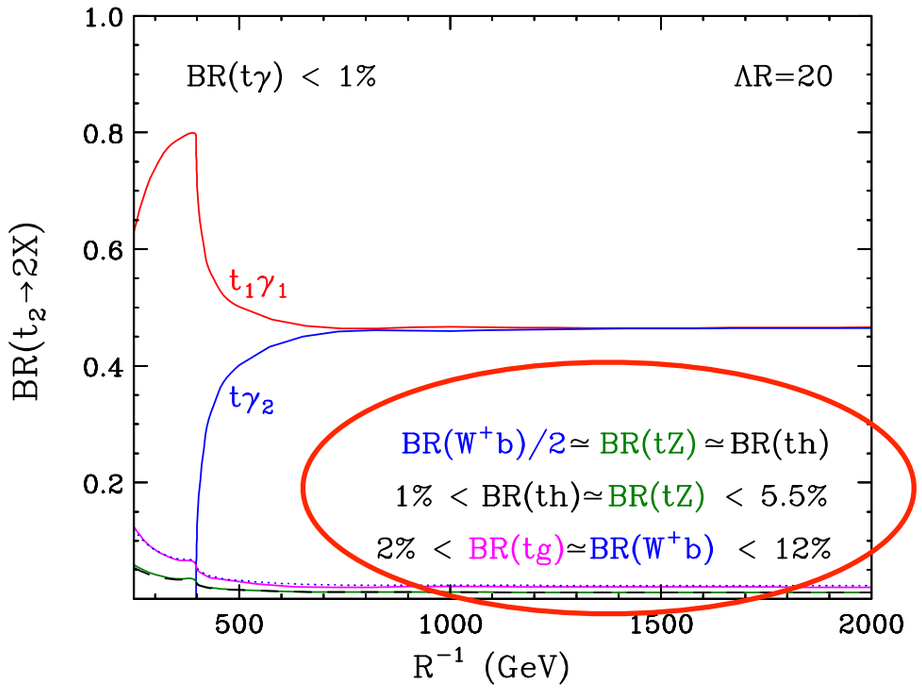
$V_2^{\mu,a}(p)$–$V_0^{\nu,b}(k_1)$–$V_0^{\rho,c}(k_2)$ coupling:
$$f_{abc}\Big\{\big[g_{\mu\nu}(p-k_1)_\rho+g_{\nu\rho}(k_1-k_2)_\mu+g_{\rho\mu}(k_2-p)_\nu\big]C_{V_2V_0V_0}$$
$$+\big[-g_{\mu\nu}k_{1,\rho}+g_{\rho\mu}k_{2,\nu}\big]D_{V_2V_0V_0}+g_{\nu\rho}(k_1-k_2)_\mu\,E_{V_2V_0V_0}\Big\}$$

V_2 decays to $\ell\bar{\ell}$, jj, W^+W^-, $W^\pm Z$, ZZ, $t\bar{t}$.

KK Number Violating Interaction

$\bar{T}_2$–t_0–Φ_0 / $\bar{t}_2$–t_0/b_0–Φ_0 coupling:





$\bar{t}_2$–t_0–h_0 :

$\bar{t}_2$–t_0–Z_L :

$\bar{t}_2$–b_0–W_L^+ :

$\bar{T}_2$–t_0–h_0 :

$\bar{T}_2$–t_0–Z_L :

Φ_2 decay couplings:

$$\bar{t}_0 t_0 h_2 : \quad -i\frac{m_t}{v} C_{t_0 t_0 h_2} ,$$

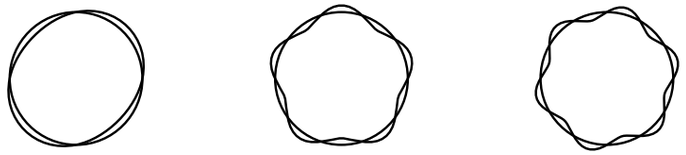
$$\bar{t}_0 t_0 \chi_2 : \quad i\gamma_5 \frac{m_t}{v} C_{t_0 t_0 h_2} ,$$

$$C_{t_0 t_0 h_2} = \frac{\sqrt{2} g_3^2}{64\pi^2} C_F \left[-4L_1 - 4 + \frac{\pi^2}{2} \right].$$

Freitas, Kong, Wiegand 2008

G. Belanger, M. Kakizaki and A. Pukhov, JCAP **1102**, 009 (2011)
M. Kakizaki, S. Matsumoto and M. Senami, Phys. Rev. D **74**, 023504 (2006)

Improved one-loop corrected Mass Spectrum



$2\pi R = 2\lambda$ $\quad 2\pi R = 5\lambda$ $\quad 2\pi R = 6\lambda$

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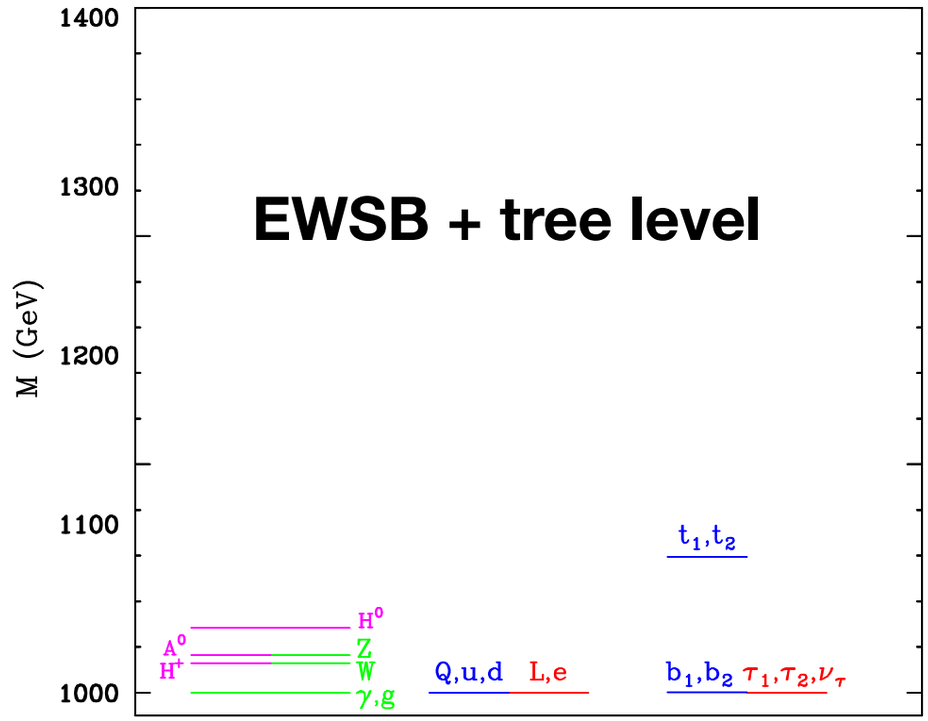

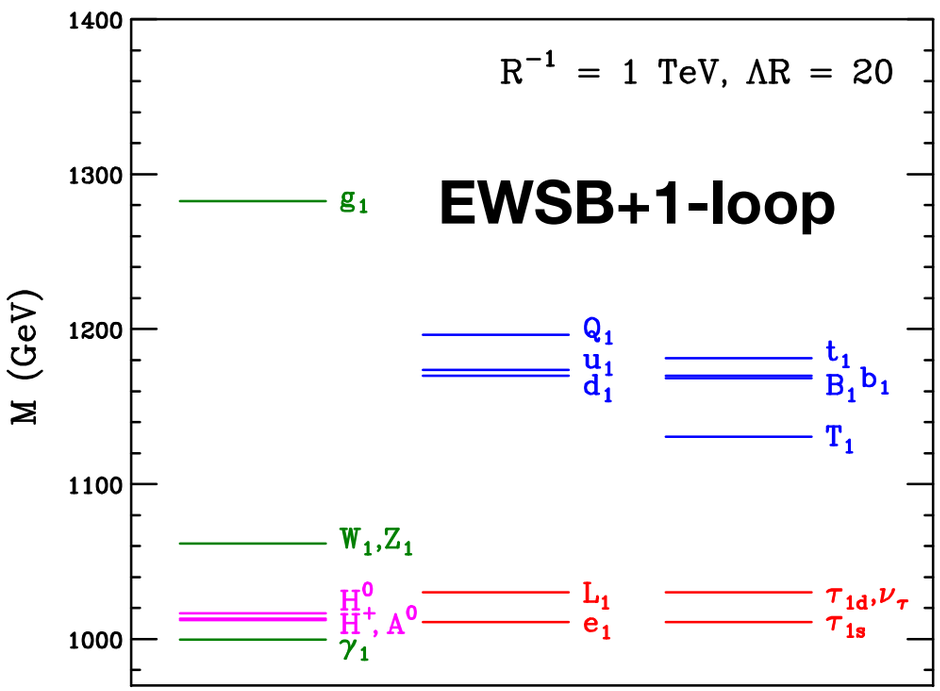

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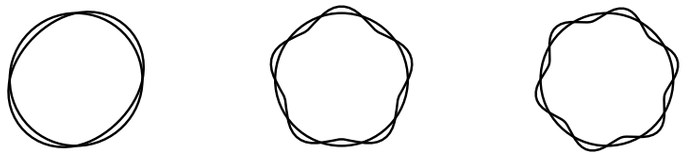

$2\pi R = 2\lambda$ $\quad 2\pi R = 5\lambda$ $\quad 2\pi R = 6\lambda$

$$E^2 = p_{x_1}^2 + p_{x_2}^2 + p_{x_3}^2 + \frac{n^2}{R^2} + m^2 \equiv \vec{p}^{\,2} + M_n^2$$

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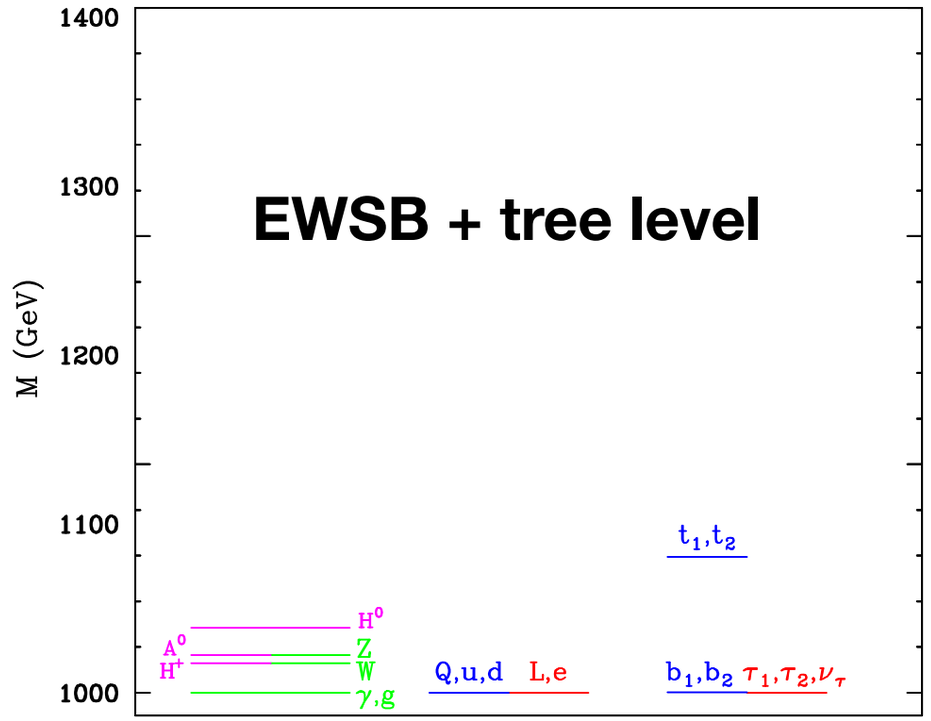
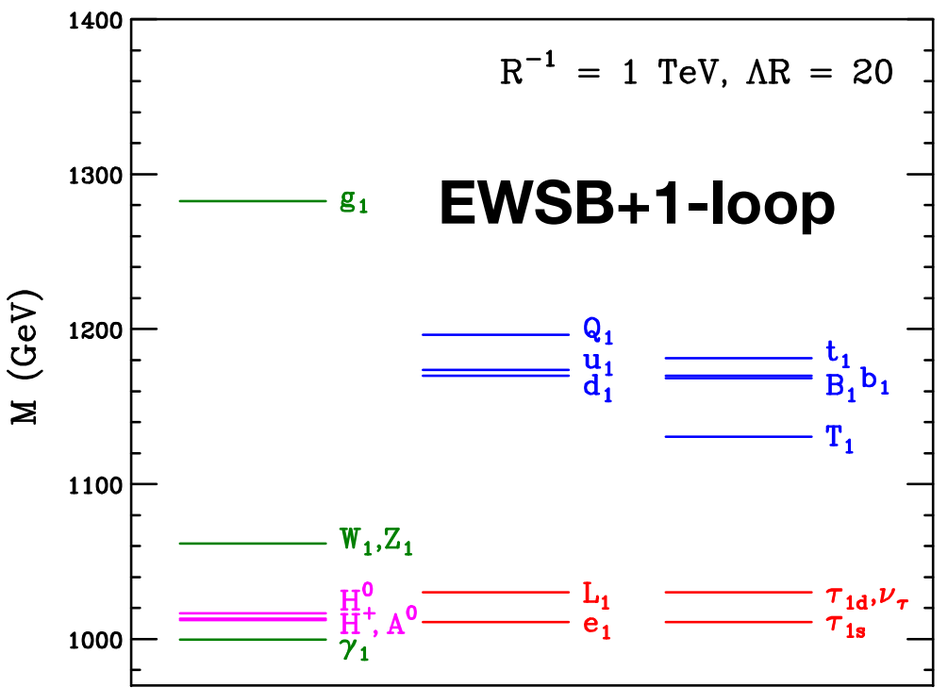
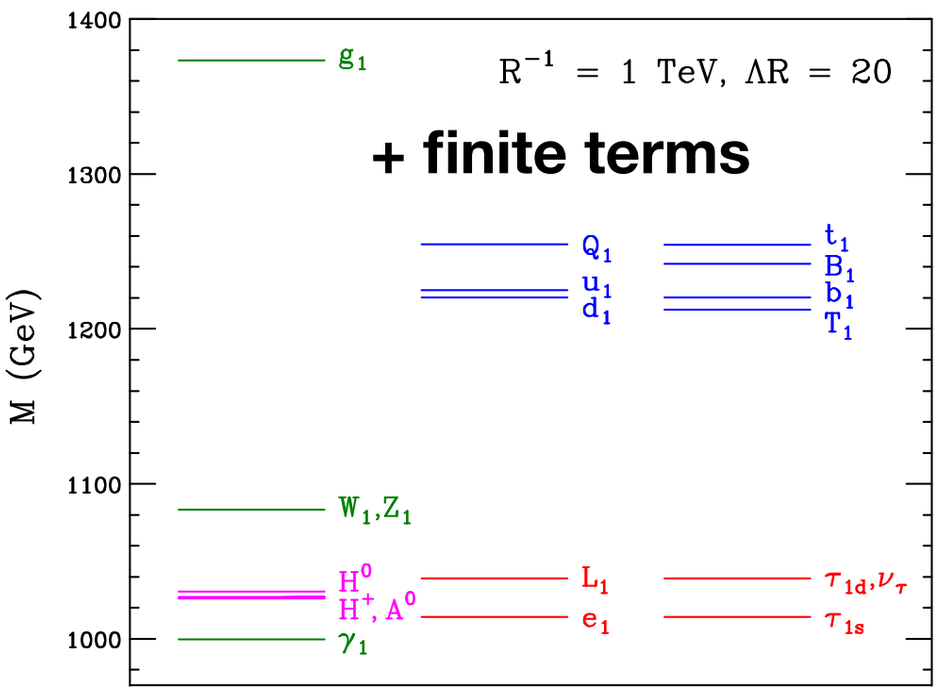
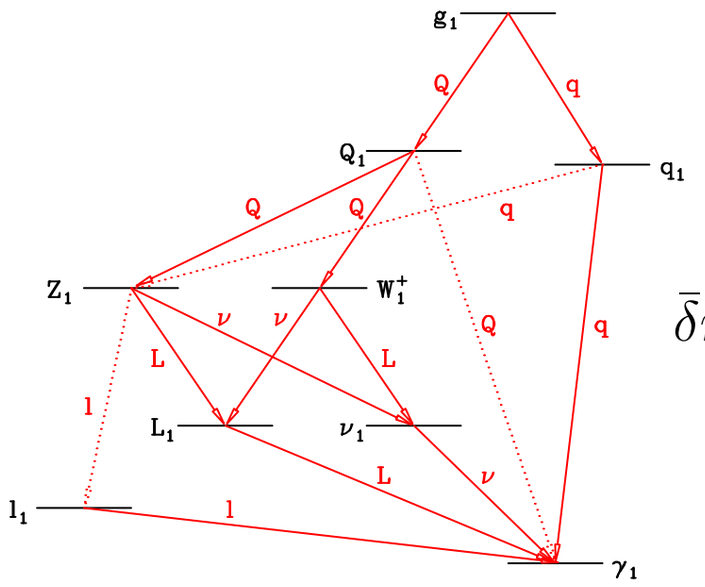




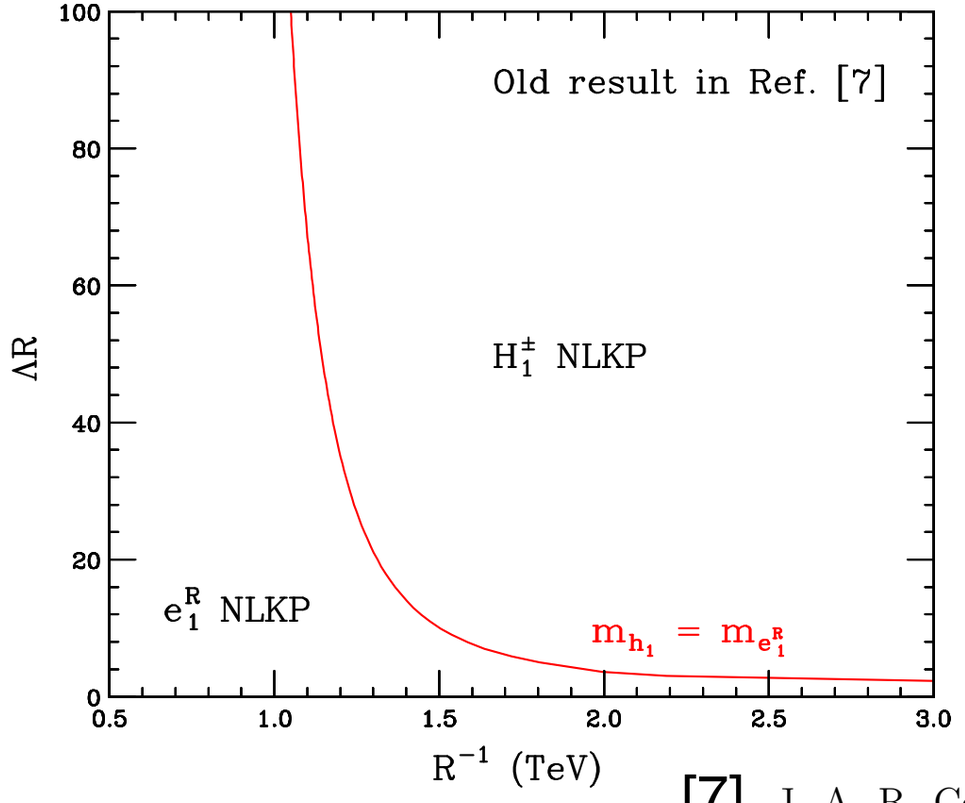


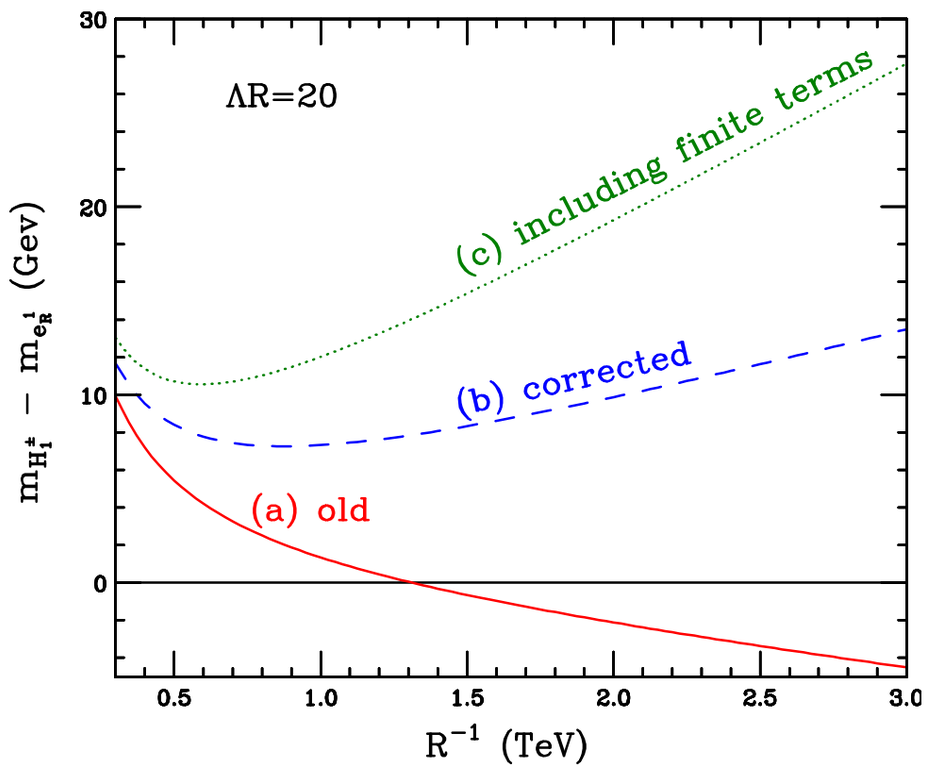
Who is NLKP?



$$\bar{\delta} m^2_{H_n} = \overline{m}^2_H + m^2_n \frac{1}{16\pi^2}\left[g_2^2\left(\frac{9}{4}L_n + 6\right) + g_1^2\left(\frac{3}{4}L_n + 2\right) - \lambda_H(L_n + 1)\right]$$

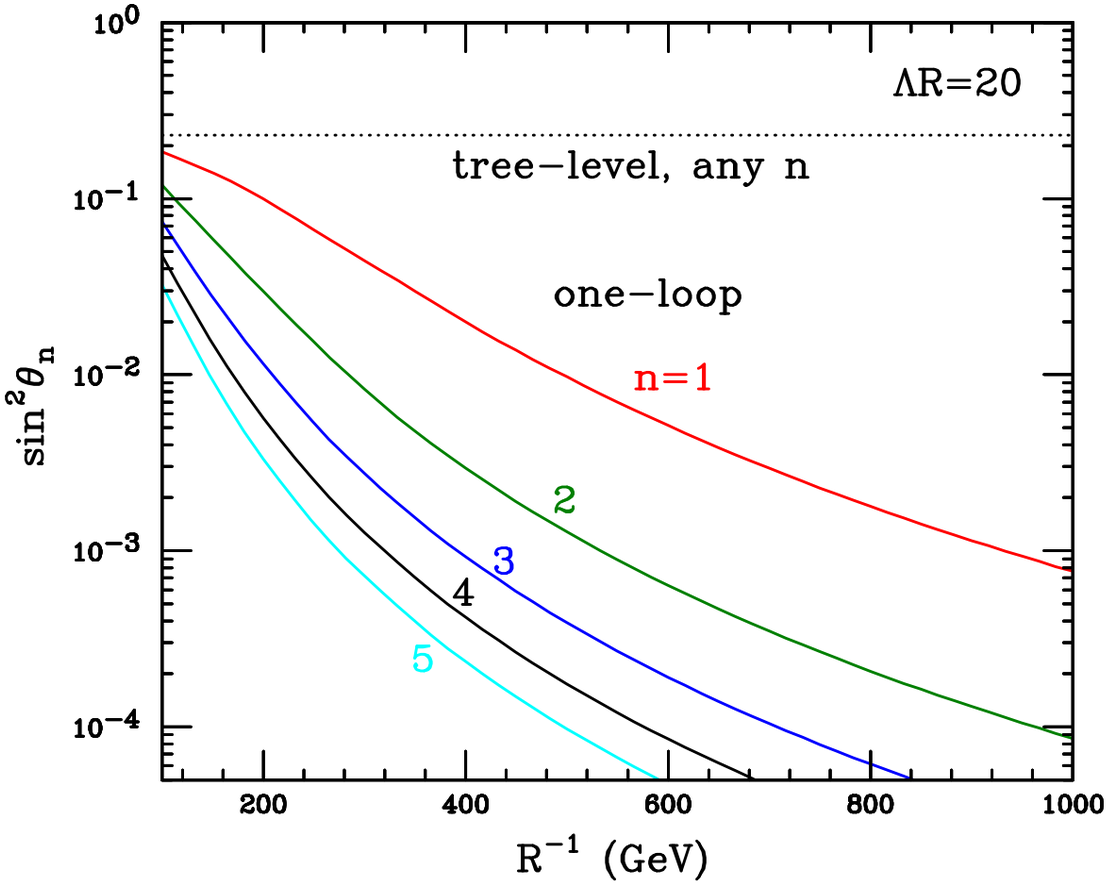
Freitas, Kong, Wiegand 2008

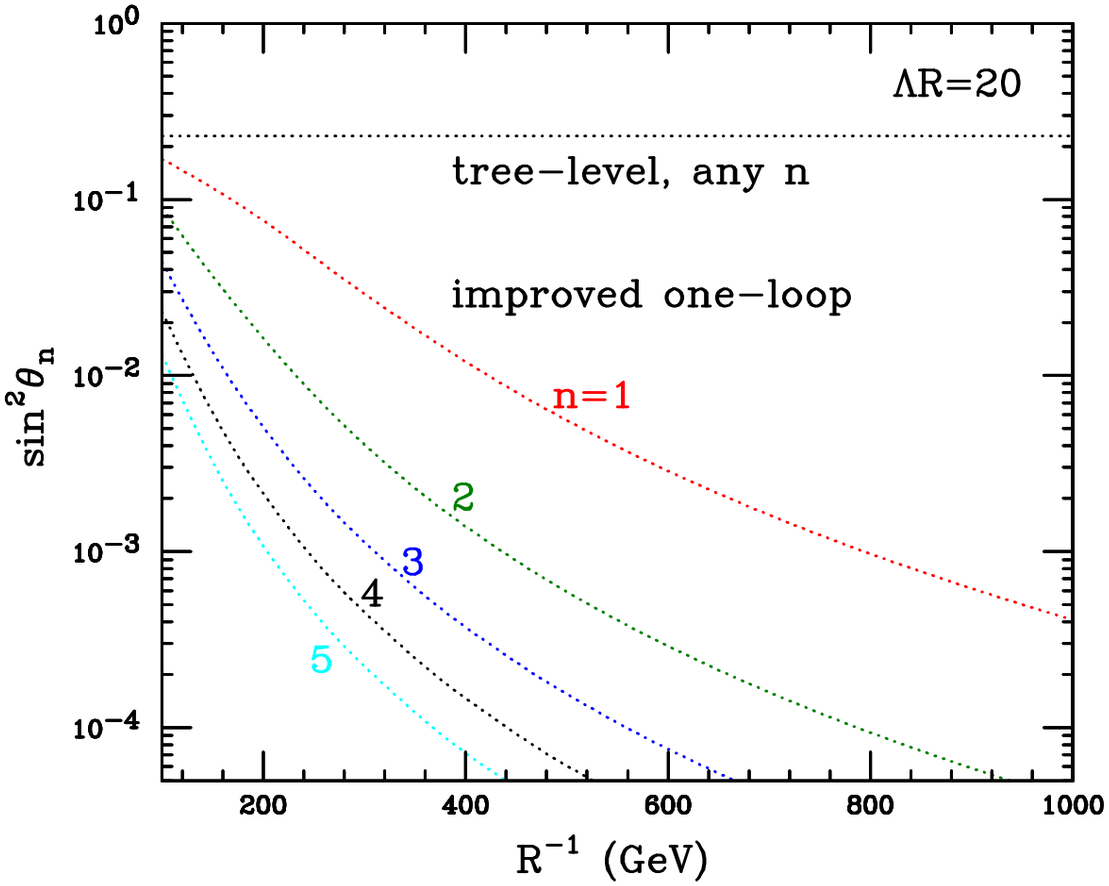




[7] J. A. R. Cembranos, J. L. Feng and L. E. Strigari, Phys. Rev. D **75**, 036004 (2007)

KK Weinberg Angle

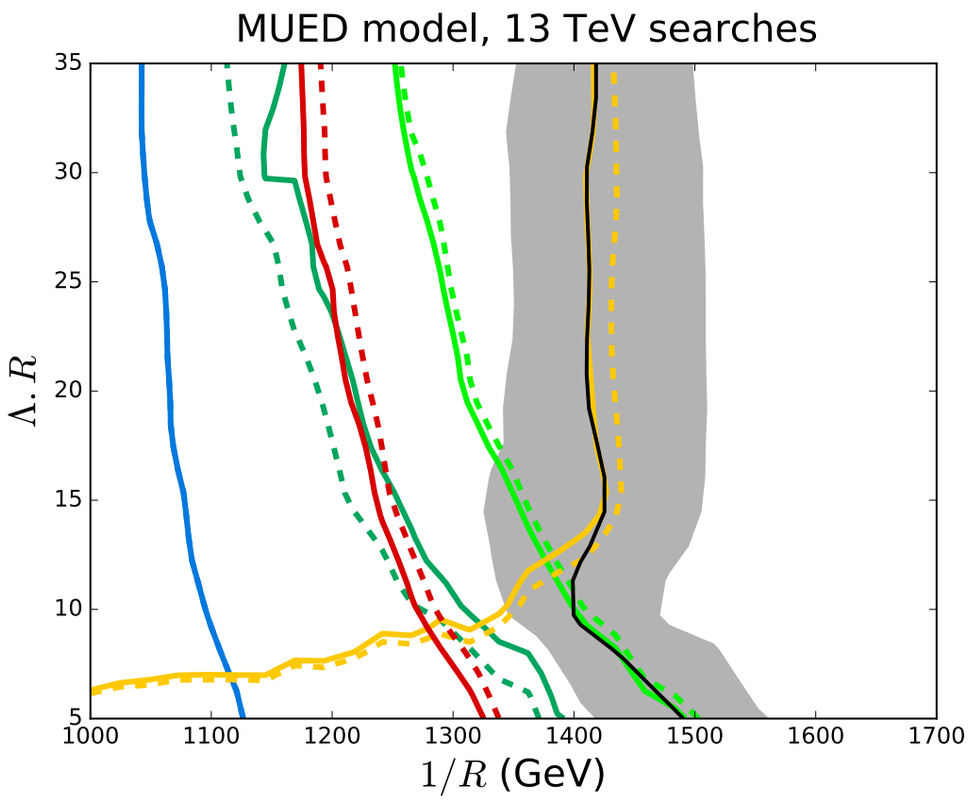




- KK photon is mostly KK hyper charge gauge boson.

Freitas, Kong, Wiegand 2008

Impact on LHC Bounds



- Mass splitting between KK quarks and KK photon increases from ~20% to ~25%.

- Mass splitting between KK gluon and KK photon increases from ~30% to ~40%.

- Heavier spectrum -> smaller cross section -> weaker limit

- Broader spectrum -> harder decay products -> stronger bound

Impact on KKDM relic abundance

- Computation of relic abundance has a rather long history.

- (slightly) Broader spectrum reduce effective cross section in the co-annihilation processes.

$m_{\gamma_1}\downarrow$

$$\frac{e^{-x'_f(m'_1-m'_{\gamma_1})}}{e^{-x_f(m_1-m_{\gamma_1})}} \approx e^{-x_f(m'_1-m_1)} \text{ where } x_f \approx x'_f$$

- Level-2 decays in 11->20 would increase effective cross sections. $m_{\gamma_1}\uparrow$

- Resonance couplings (h2 -> tt) is slightly reduced. $m_{\gamma_1}\downarrow$

- NLKP is always the SU(2) singlet leptons.

- Recent update on Flat Extra Dimensions (MUED)

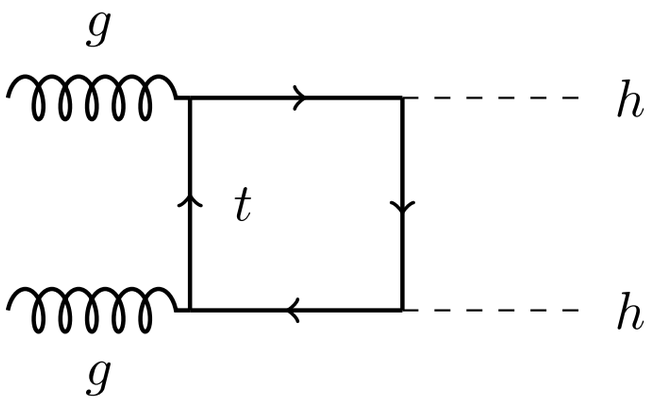
- Probing the Triple Higgs Self-Interaction at the Large Hadron Collider

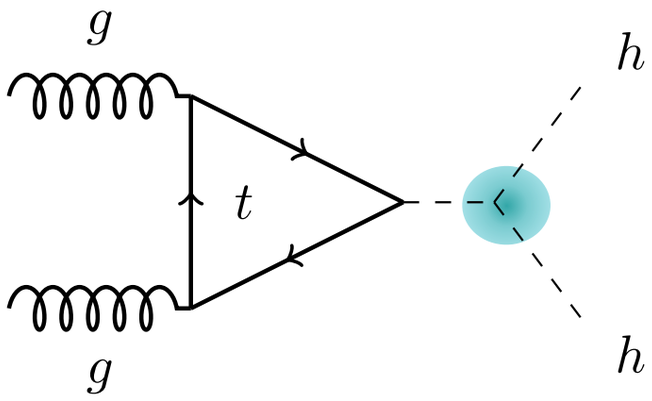
- My personal perspective on BSM searches at the LHC / HL-LHC (no time to discuss)

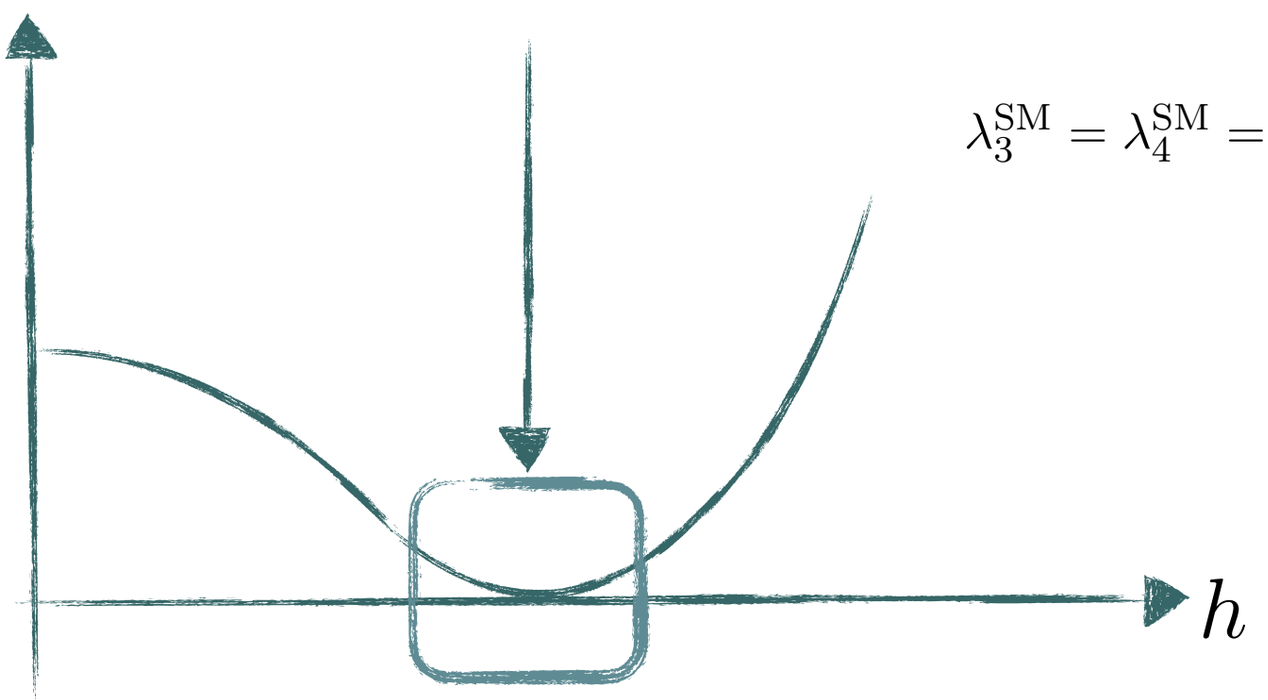
Precision Measurements

- Use Higgs and Top quark for look for new physics.
- Discovery of a Higgs boson jumpstarted a comprehensive program of precision measurements of all Higgs couplings.
- Current results appear to be in agreement with SM predictions.
- Yet, self-couplings are NOT measured.

Double Higgs







$$V = \frac{m_h^2}{2}h^2 + \kappa_3\lambda_3^{\rm SM} v h^3 + \frac{1}{4}\kappa_4\lambda_4^{\rm SM}h^4$$

$$\lambda_3^{\rm SM} = \lambda_4^{\rm SM} = \frac{m_h^2}{2v^2}$$

- Higgs discovery: 5 fb-1 7 TeV and 5 fb-1 8 TeV
- Higgs properties: 8,13, 14 TeV and lepton collider
- Triple Higgs coupling (Double Higgs production): 14 TeV HL / 27 TeV / lepton collider
- Quartic coupling (triple Higgs production): 100 TeV

Experimental challenges

$\sigma(hh)^{NNLO}_{SM} \simeq 40.7$ fb (14 TeV)

higher branching ratios

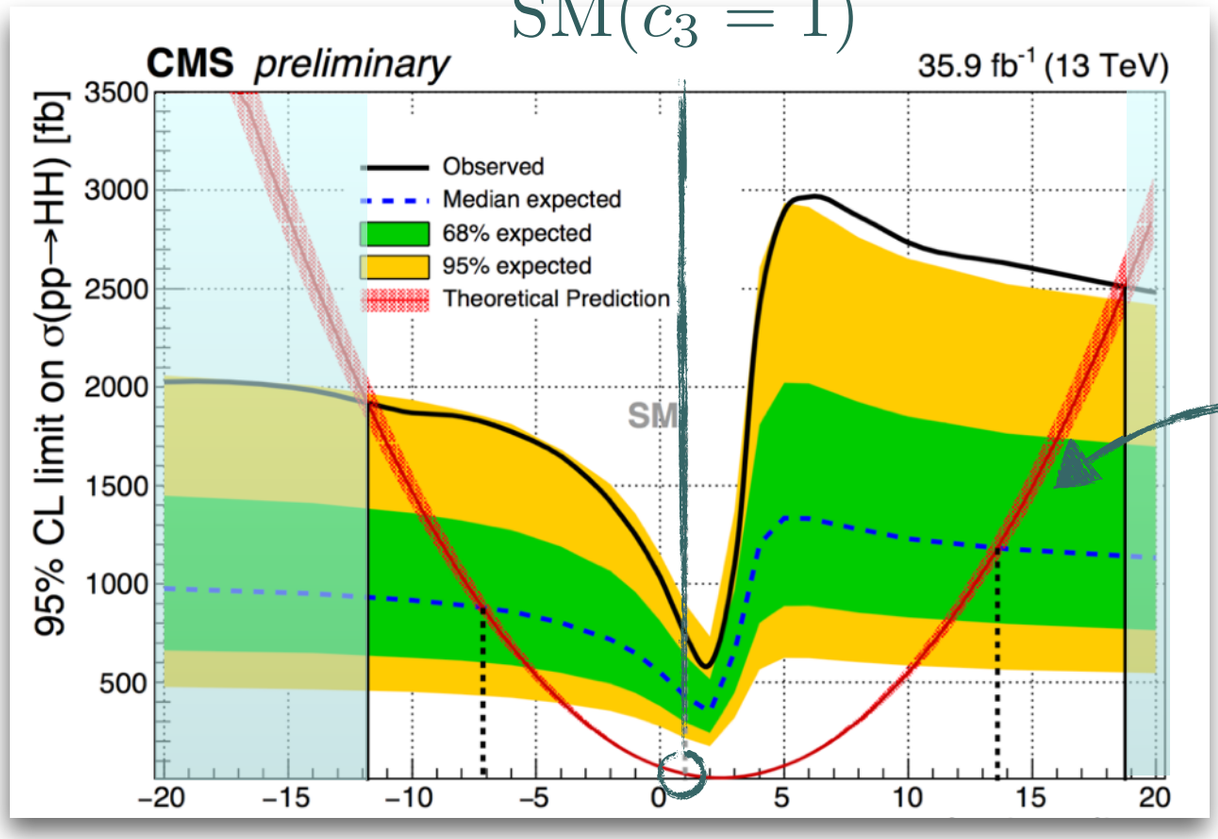
cleaner final state

	bb	WW^*	$\tau\tau$	ZZ^*	$\gamma\gamma$
bb	33%				
WW^*	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ^*	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.1%	0.028%	0.012%	0.0005%

- But, these measurements are challenged by a low σ (hh) and small branching ratios (BR).
- No single channel is expected to reach 5 sigma at HL-LHC.
- The combination of different channels is crucial.

Current status at 13 TeV

$\mathrm{SM}(c_3 = 1)$



CMS PAS HIG-17-030 κ_3

- Allowed range of *hh* cross sections.

$\sigma_{hh}^{observed}/\sigma_{hh}^{SM} = 22$

(12.8 expected)

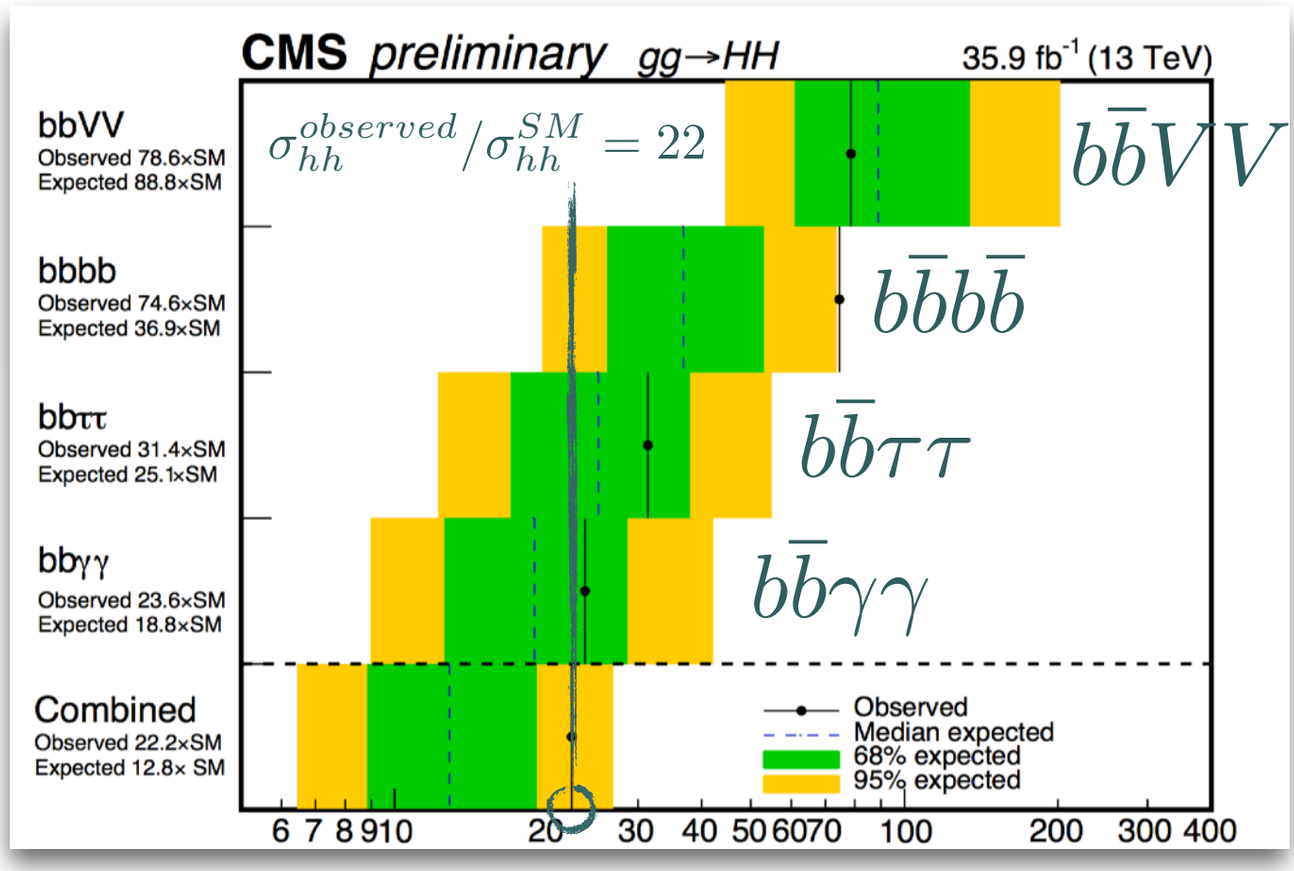
- The $bb\gamma\gamma$ and $bb\tau\tau$ are leading channels.

- Allowed region of κ_3

$-11.8 < \kappa_3 < 18.8$

$(b\bar{b}\gamma\gamma \; + \; b\bar{b}\tau\tau + \; b\bar{b}b\bar{b} \; + \; b\bar{b}VV)$

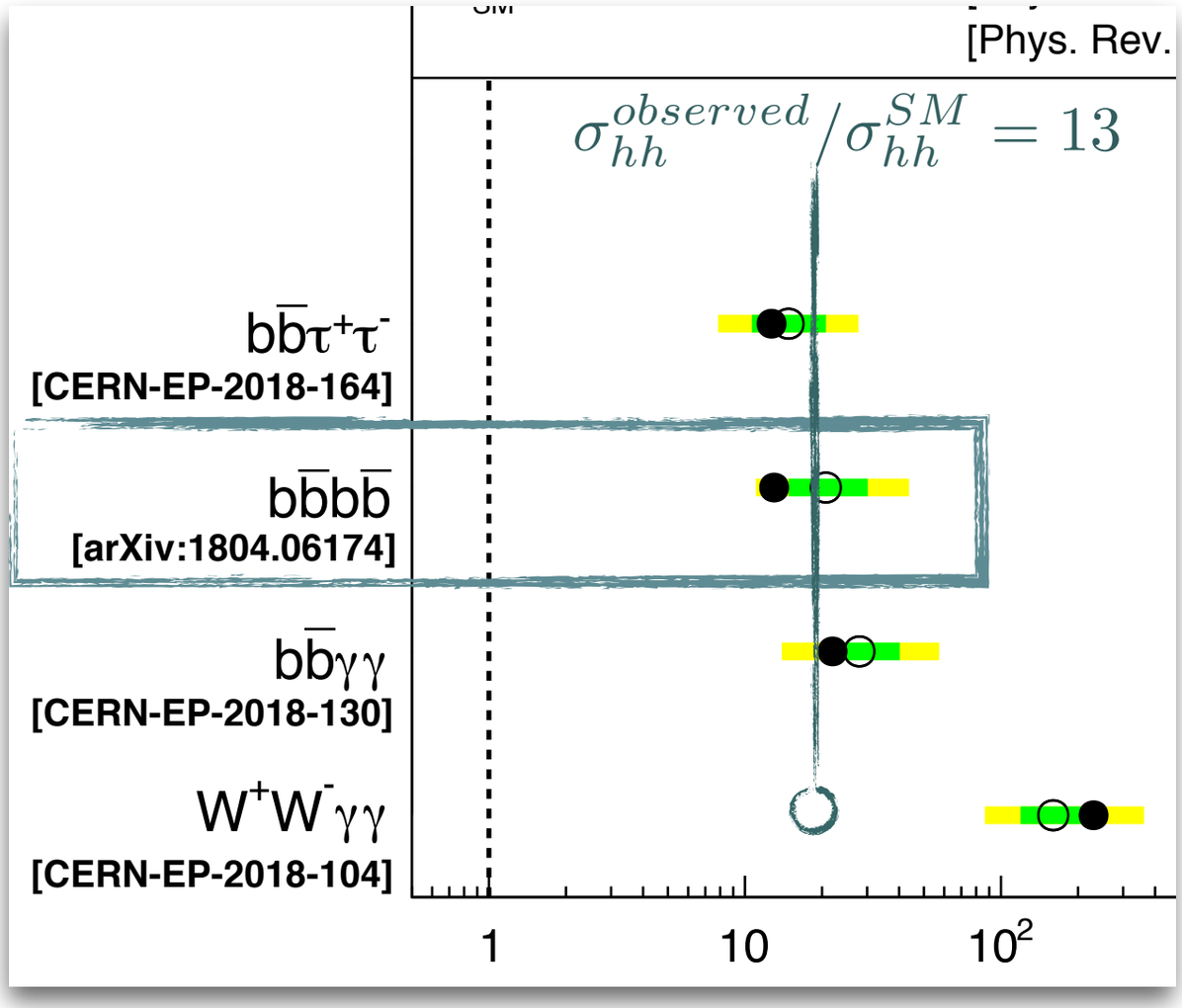
$$\frac{\sigma}{\sigma_{SM}} = A_1\, c_t^4 + A_3\, c_t^2 \kappa_3^2 + A_7\, c_t^3 \kappa_3$$



$95\%\ CL\ on\ \sigma_{hh}/\sigma_{hh}^{SM}$

Current status at 13 TeV

$27.5 - 36.1\ \mathrm{fb}^{-1} (13\ \mathrm{TeV})$



$95\%\ CL\ on\ \sigma_{hh}/\sigma_{hh}^{SM}$

(6.7 observed, 10.4 expected)

ATLAS, PRL 117 (2016) 012001

- The *bbbb* channel is significantly improved!
  - Using an improved *b*-tagging algorithm (multivariate b-tagging algorithm MV2c10)

$$\epsilon_b = 70\ \%$$
$$\epsilon_{c\to b} = 8.3 \sim 14.1\ \%$$
$$\epsilon_{j\to b} = 0.26 \sim 0.83\ \%$$

- Allowed region of κ_3

$$-8.2 \lesssim \kappa_3 \lesssim 13.2 \quad (\text{Using only } b\bar{b}\gamma\gamma)$$

- The bound is weak… The situation at 300 fb^{-1} will be similarly bad…

ATLAS, PRL 117 (2016) 079901

ATLAS/CMS projections at HL-LHC 14 TeV

- Future prospect for HL-LHC, $3\ \mathrm{ab}^{-1}(14\ \mathrm{TeV})$

ATL-PHYS-PUB-2017-001 CMS-FTR-15-002-PAS

		$N(hh)_{SM}$	N_{BKG}	$S/\sqrt{B}$
ATLAS	*bbγγ*	8.4	47.1	1.2
CMS	*bbγγ*	9	26.9	1.7
	bbττ (fully-hadronic)	4.9	30.3	0.89
	bbττ (semi-leptonic)	6.1	122	0.55
	bbWW (di-leptonic)*	37.1	3875	0.60

$cf.$

$\sim 5.0\sigma$

Alves, Ghosh, Sinha 2017

$\sim 4.0\sigma$

Kling, Plehn, Schichtel 2017

$cf.$

$\sim 0.6\sigma$

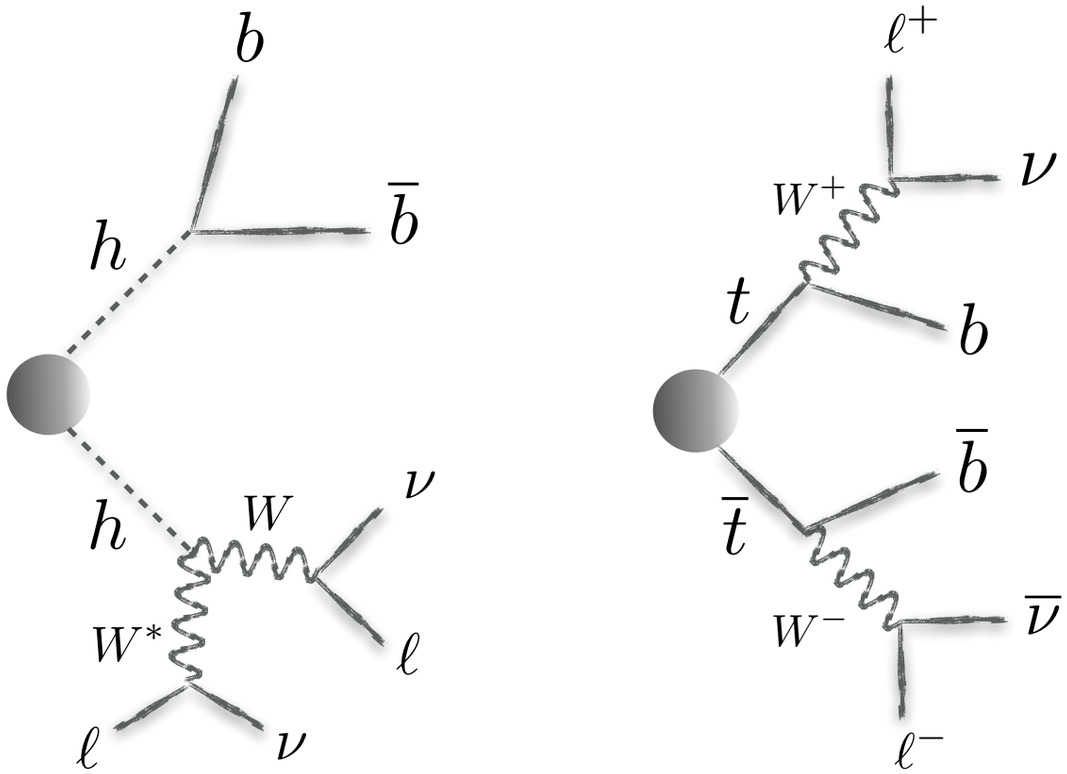
Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi 2017

$\sim 1.5\sigma$

Baglio, Djouadi, Grober, Muhlleitner, Quevillon, Spira 2013

- The *bbWW** seems to be tough channel because of huge backgrounds.

Previously on $hh \rightarrow bbWW^*$



Signal

Major background

- $hh \rightarrow bbWW^*$ channel suffers for the large $t\bar{t}$ background where the final state is identical.
- The sensitivity of signal in the di-leptonic mode is very poor.

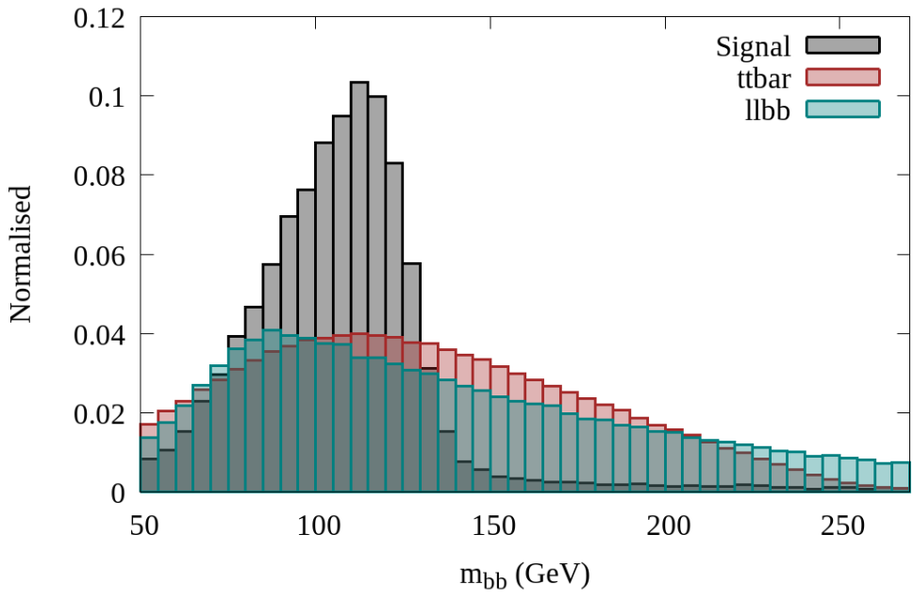
  CMS-FTR-15-002-PAS
- The situation in the semi-leptonic mode is even worse…

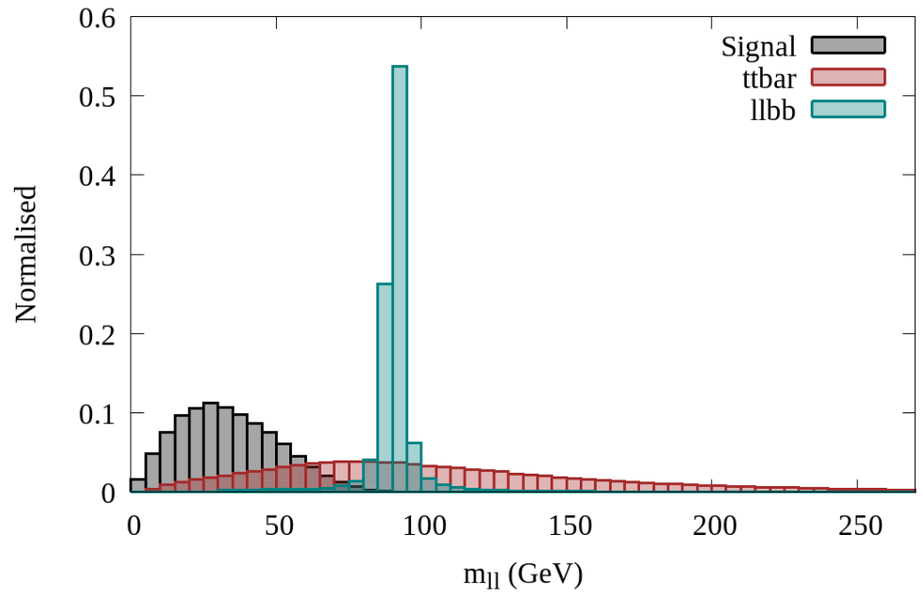
  Dolan, Englert, Spannowsky 2012

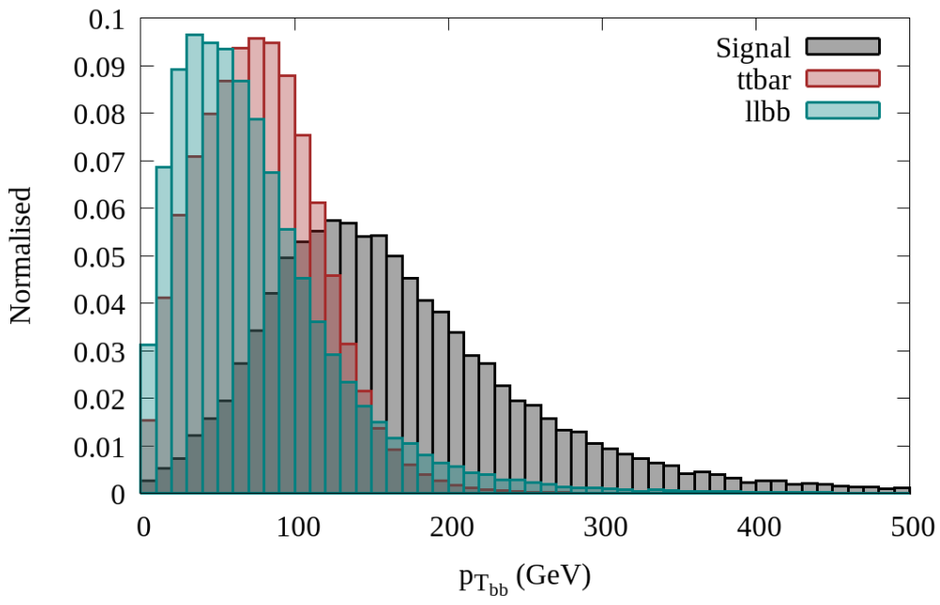
  Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi 2017

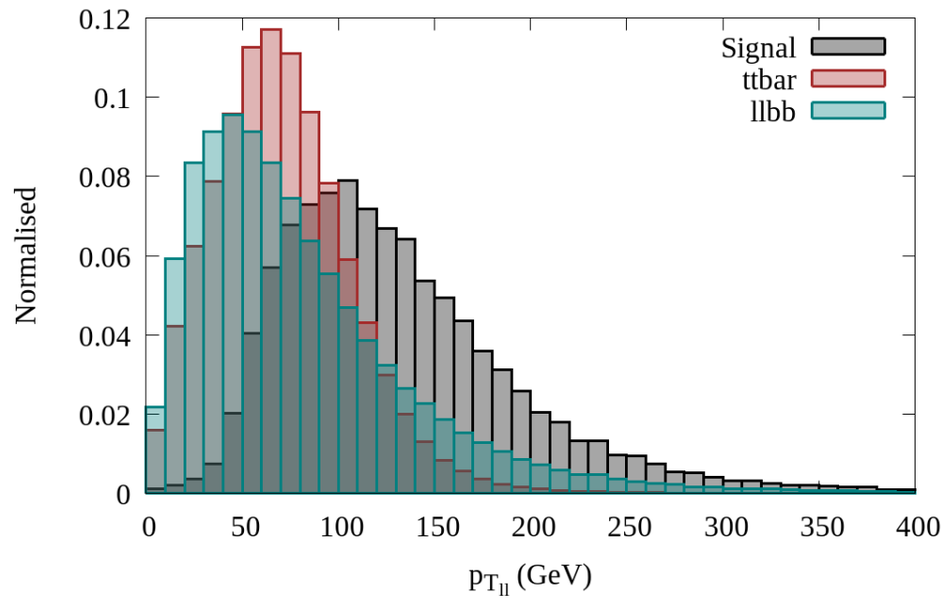
Seemingly it looks hopeless…

$hh \to bbWW^*$: dilepton channel









$$p_{T,\ell_{1/2}},\ \not{E}_T,\ m_{\ell\ell},\ m_{bb},\ \Delta R_{\ell\ell},\ \Delta R_{bb},\ p_{T,bb},\ p_{T,\ell\ell},\ \Delta\phi_{bb\,\ell\ell}$$

Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi 2017

$hh \longrightarrow bbWW^*$: dilepton channel

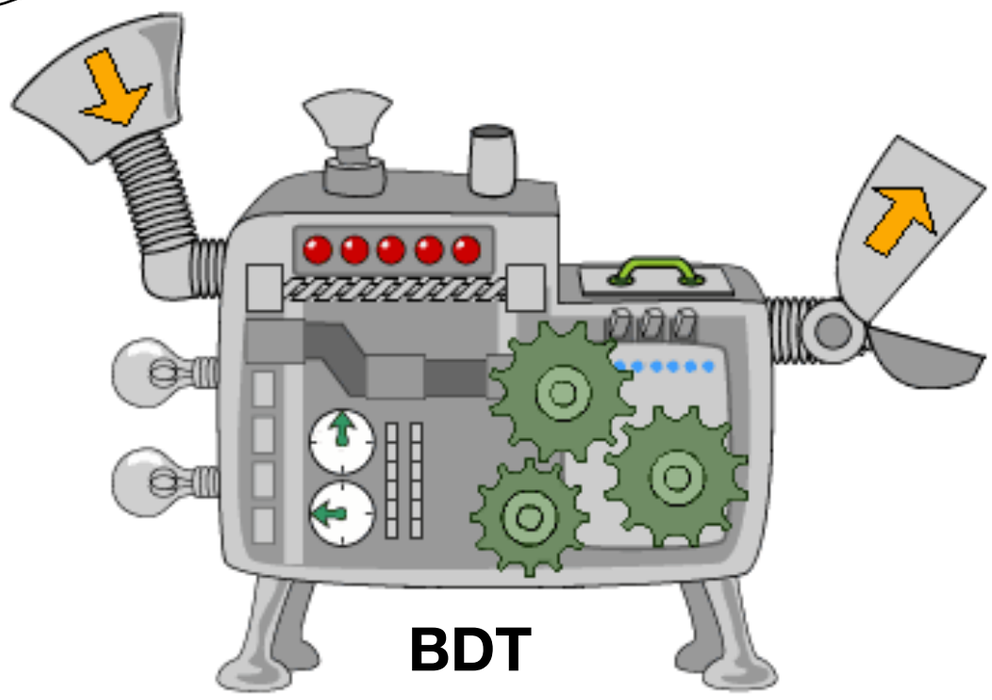
$\not{E}_T$

$p_{T,\ell_{1/2}}$ $\Delta\phi_{bb\,\ell\ell}$

$\Delta R_{\ell\ell}$ ΔR_{bb}

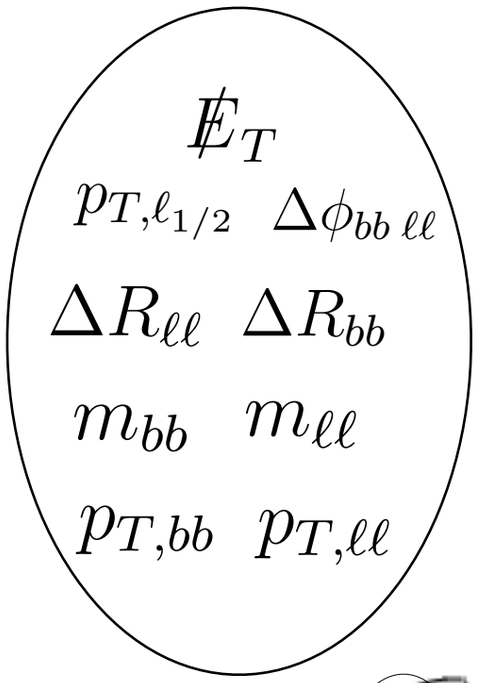
m_{bb} $m_{\ell\ell}$

$p_{T,bb}$ $p_{T,\ell\ell}$

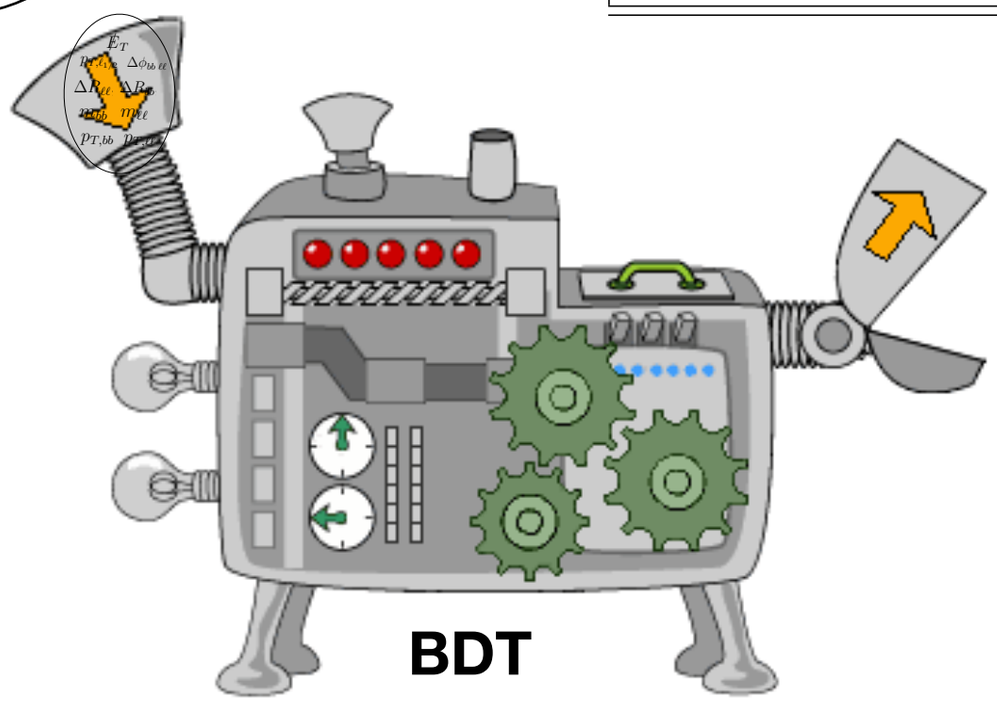


Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi 2017

$hh \longrightarrow bbWW^*$: dilepton channel



Sl. No.	Process	Order	Events
Background	$t\bar{t}$ lep	NNLO [128]	2080.52
	$t\bar{t}h$	NLO [111]	131.66
	$t\bar{t}Z$	NLO [130]	106.31
	$t\bar{t}W$	NLO [129]	35.97
	$hb\bar{b}$	NNLO (5FS) + NLO (4FS) [111]	~ 0
	$\ell\ell b\bar{b}$	LO	842.72
	Total		3197.18
Signal ($hh \to b\bar{b}WW \to b\bar{b}\ell\ell + \not{E}_T$)		NNLO [70]	35.20
Significance ($S/\sqrt{B}$)			0.62



Adhikary, Banerjee, Barman, Bhattacherjee, Niyogi 2017

Distinctive production mechanisms

- A global measure of the $bb\ell\ell$-*system scale* can be estimated by

$$\hat{s}_{min}^{(bb\ell\ell)} = m_{bb\ell\ell}^2 + 2\left(\sqrt{|\vec{P}_T^{bb\ell\ell}|^2 + m_{bb\ell\ell}^2}|\not{\vec{P}}_T| - \vec{P}_T^{bb\ell\ell}\cdot\not{\vec{P}}_T\right)$$

Konar, Kong, Matchev 2008

Barr, Khoo, Konar, Kong, Lester, Matchev, Park 2011

Konar, Kong, Matchev, Park 2010

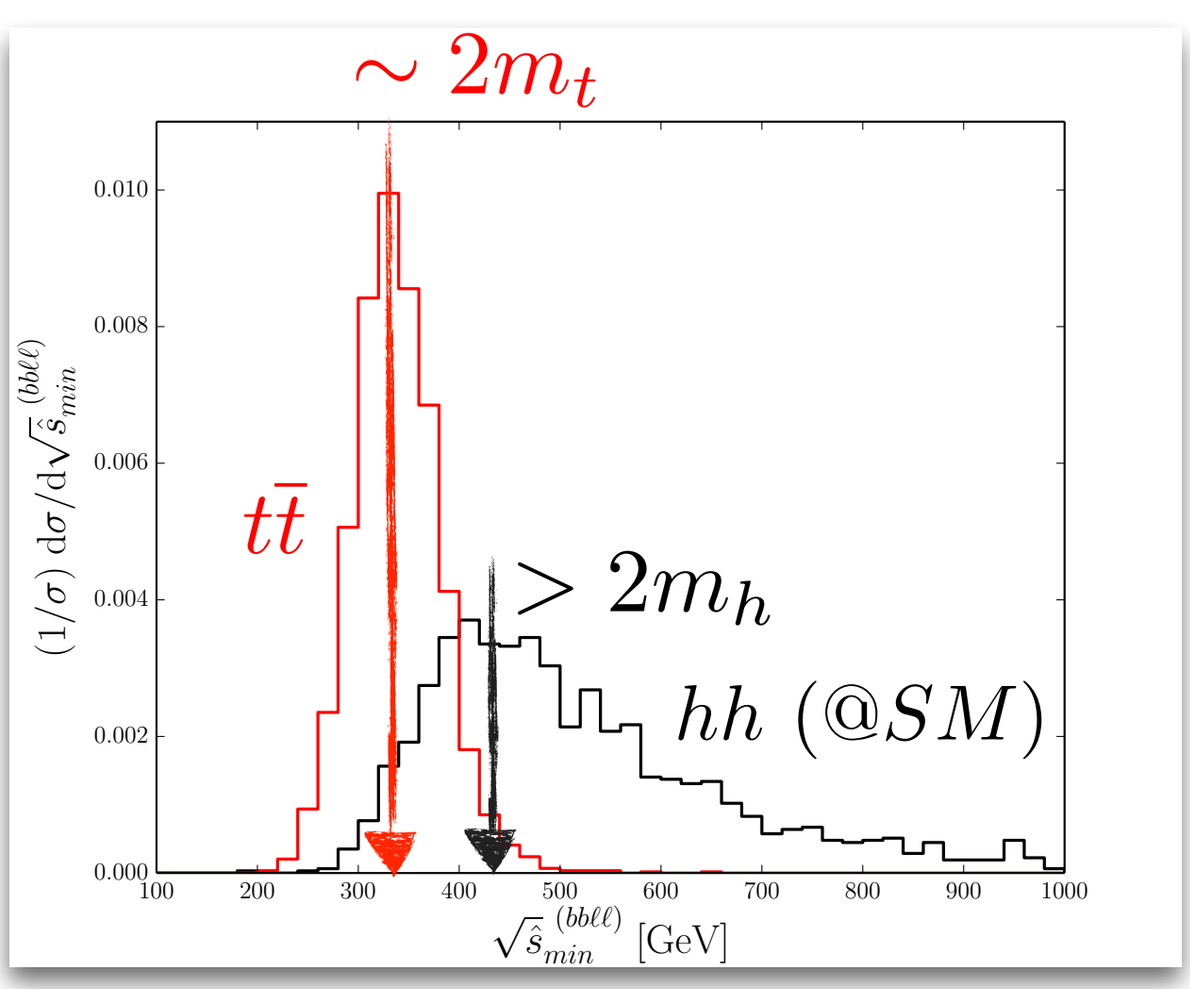
Lozano, Moreno, Park 2015

- Its peak distribution is located at

$$\left(\sqrt{\hat{s}_{min}^{(bb\ell\ell)}}\right)_{\text{peak}} \simeq M_p^{(bb\ell\ell)}$$

Combined mass of initiating system

- $t\bar{t}$ is produced near the threshold ($2m_t$).
- hh (@SM) is produced way above its threshold ($2m_h$).



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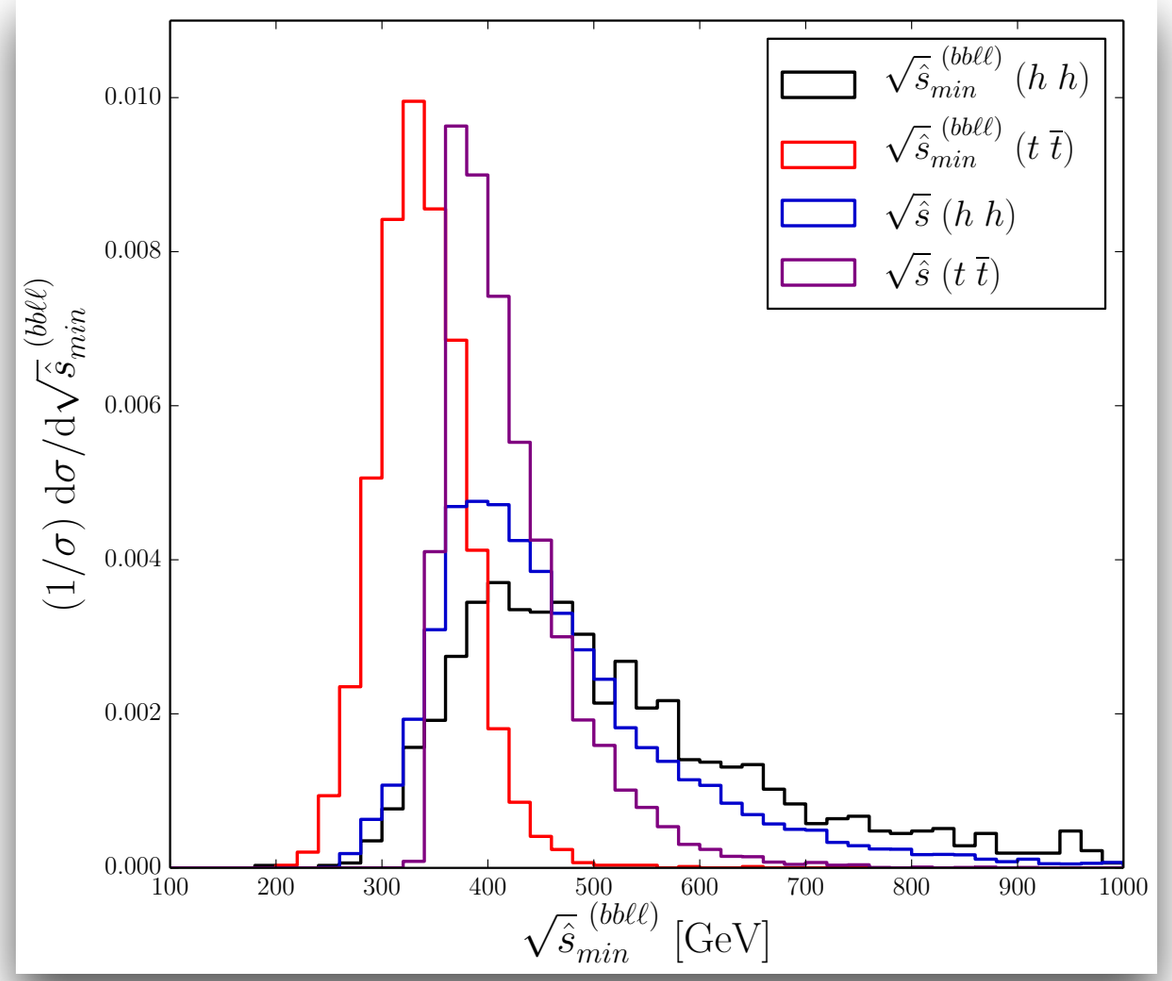
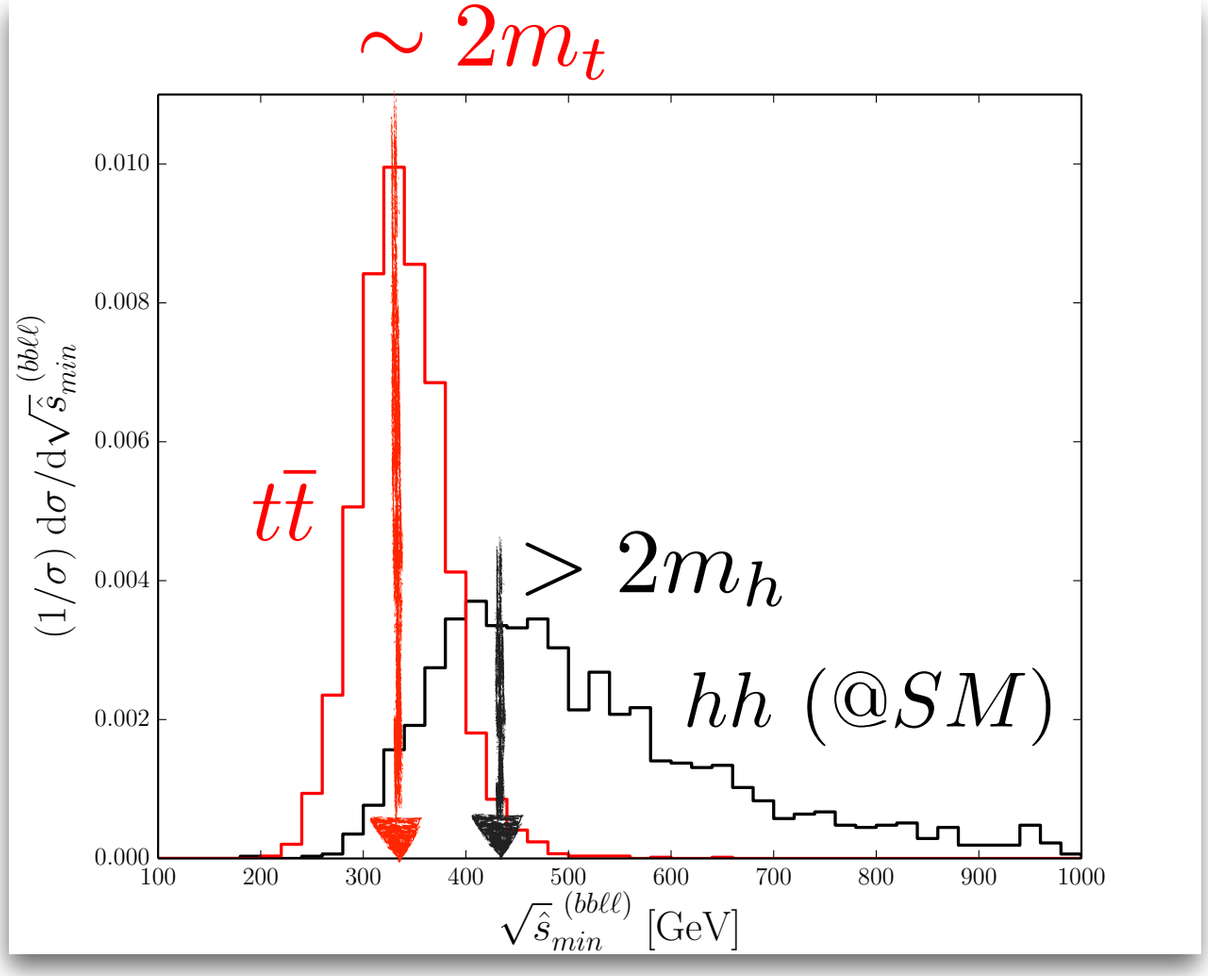
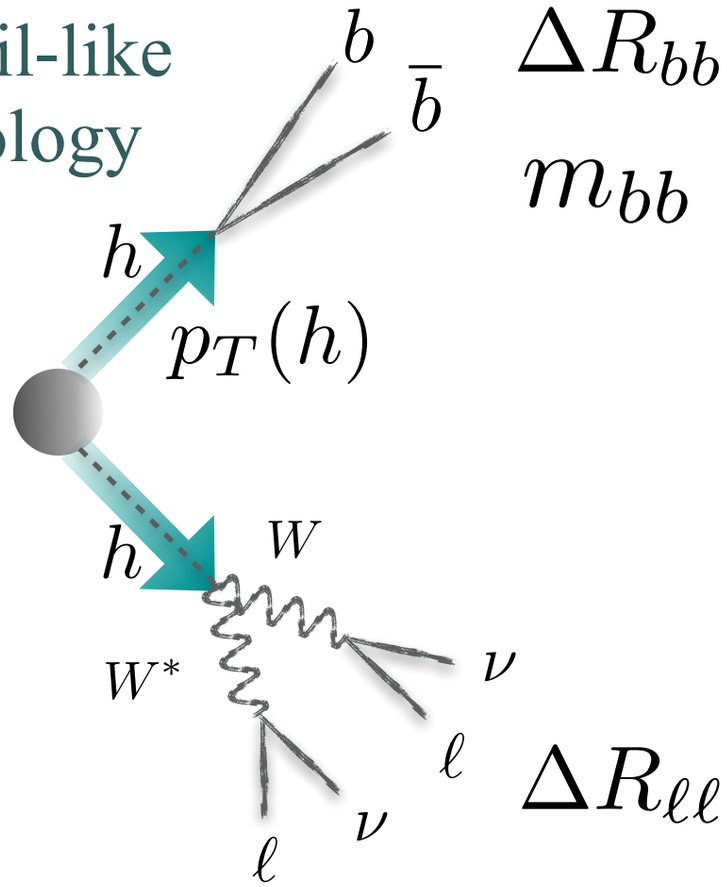




Distinctive production mechanisms

Pencil-like topology

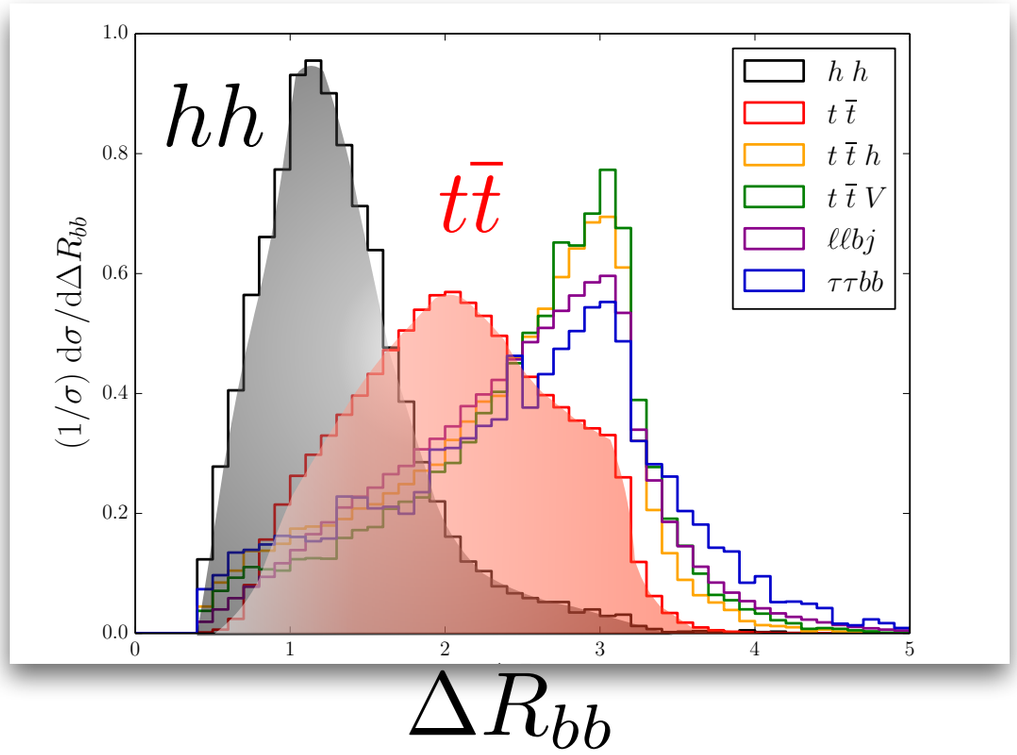


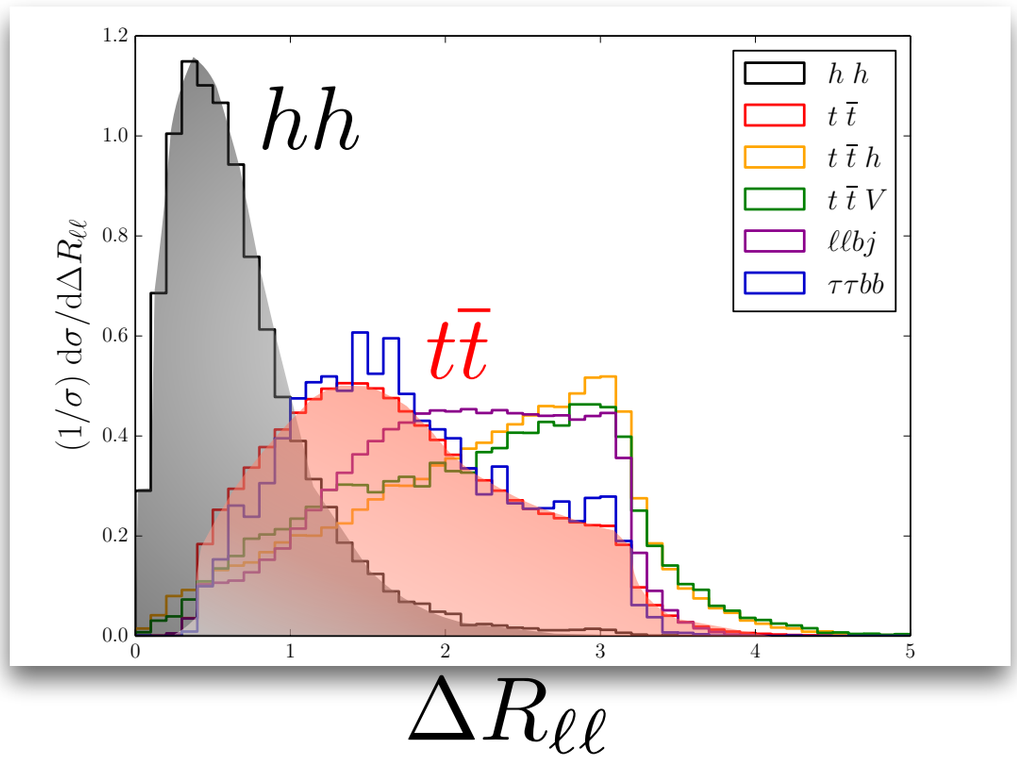
ΔR_{bb}

m_{bb}

$\Delta R_{\ell\ell}$

- Two Higgses are relatively boosted, forming a pencil-like topology, while $t\bar{t}$ is broader.
- It makes sense to use basic angular variables, p_T (h) and m_{bb} to uniquely characterize hh events.





Basic kinematic cuts

hh $t\bar{t}$ $3\ \mathrm{ab}^{-1}(14\ \mathrm{TeV})$ $\sim S/\sqrt{B}$

Signal [fb]	$t\bar{t}$ [fb]	$t\bar{t}h$ [fb]	$t\bar{t}V$ [fb]	$\ell\ell bj$ [fb]	$\tau\tau bb$ [fb]	σ
0.0124	1.1724	0.0297	0.0246	0.0158	0.0379	0.60

Baseline selections: $\not{E}_T > 20$ GeV,
$p_T^\ell > 20$ GeV, $\Delta R_{\ell\ell} < 1.0$, $m_{\ell\ell} < 65$ GeV,
$\Delta R_{bb} < 1.3$, $95 < m_{bb} < 140$ GeV

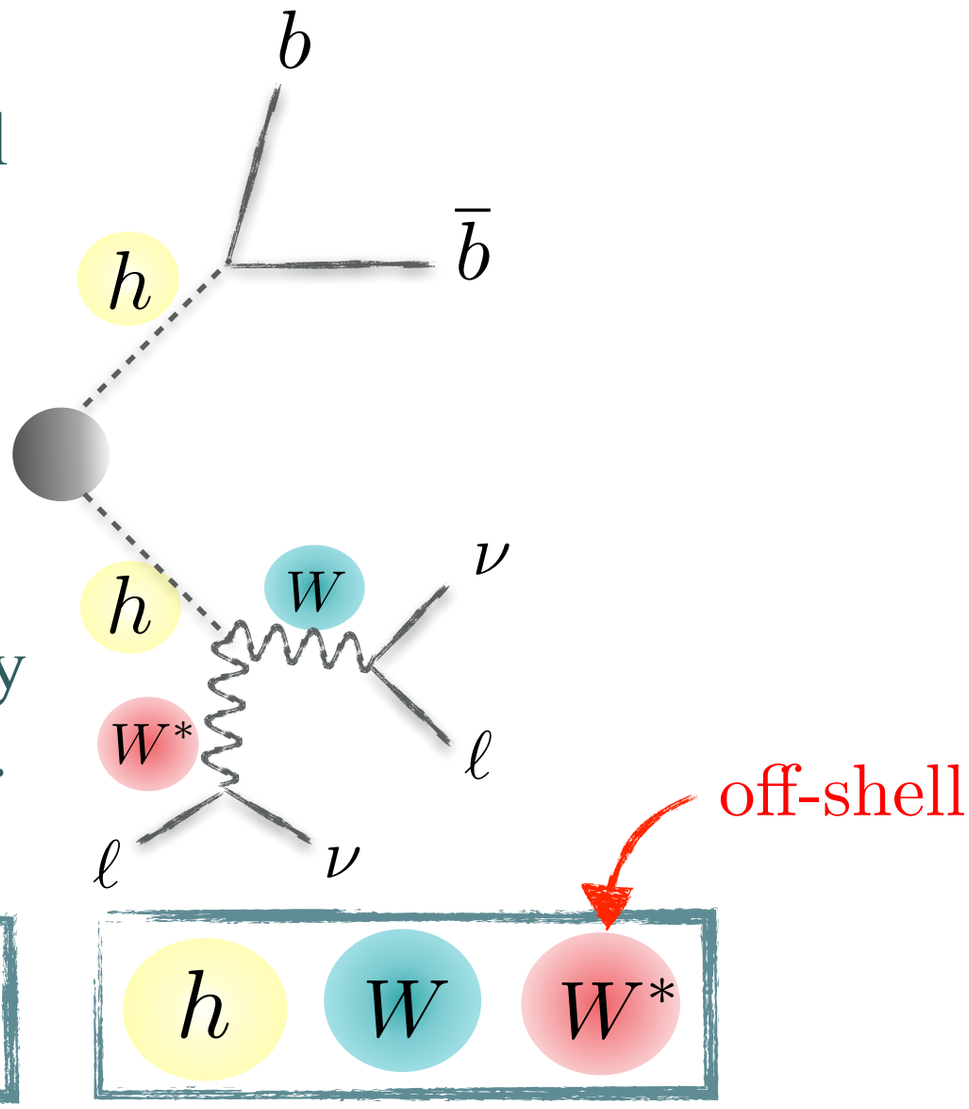
Consistent with the CMS result, previous theory study

- Basic kinematic cuts roughly reproduce the existing result.
- But since these variables are highly-correlated, it is difficult to kill $t\bar{t}$.
- This motivates to consider new orthogonal information, to better suppress the background.

Distinctive mass information

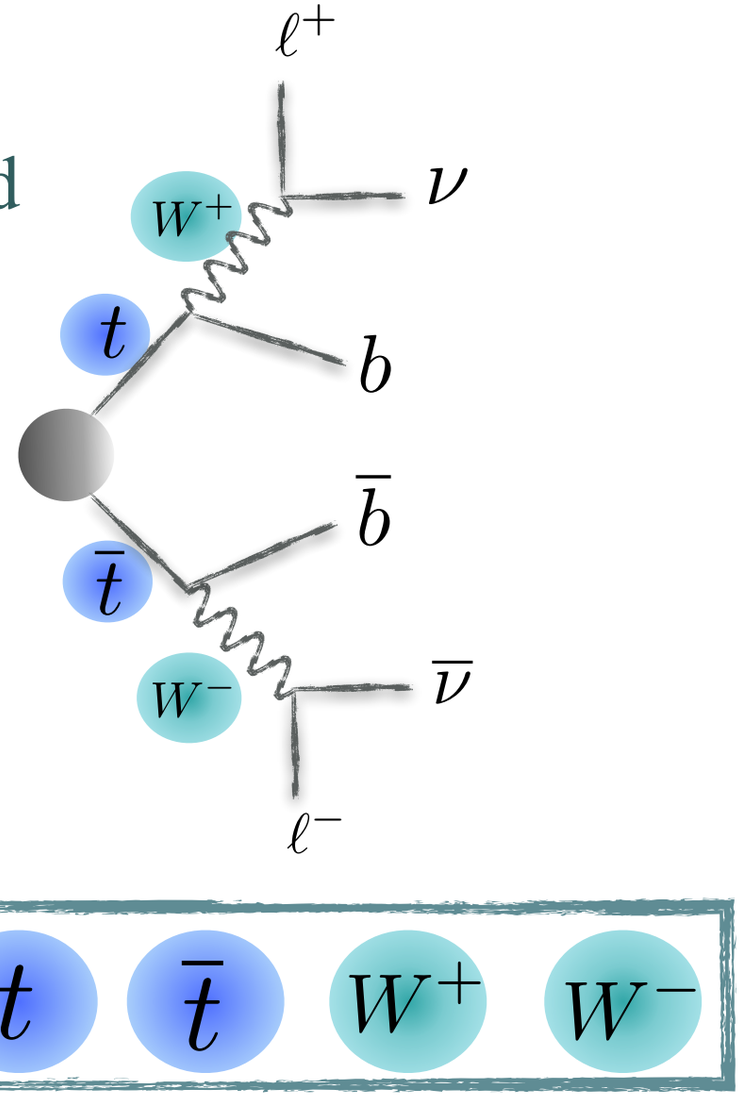
Kim, Kong, Matchev, Park 2018

Signal



Already used…

Major background

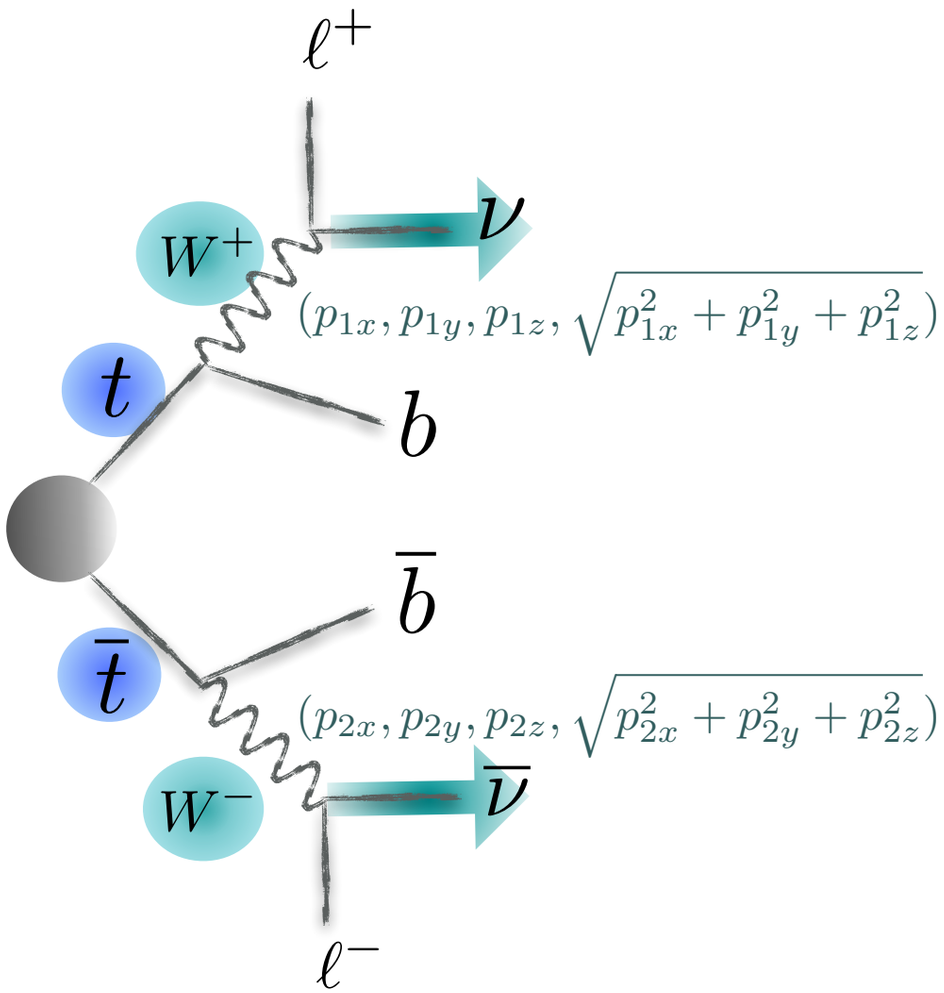


- We think this can be done with on-shell conditions of particles.
- This information is independent of how these particles are produced.
- Therefore less correlated with other kinematic variables.

Topness (T)

M. L. Graesser and J. Shelton 2012

Kim, Kong, Matchev, Park 2018



$$\chi^2_{ij} \equiv \min_{\vec{\not{p}}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{b_i \ell^+ \nu} - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m^2_{\ell^+ \nu} - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m^2_{b_j \ell^- \bar{\nu}} - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m^2_{\ell^- \bar{\nu}} - m_W^2\right)^2}{\sigma_W^4} \right]$$

$$T \equiv min\left(\chi^2_{12}\,,\, \chi^2_{21}\right)$$

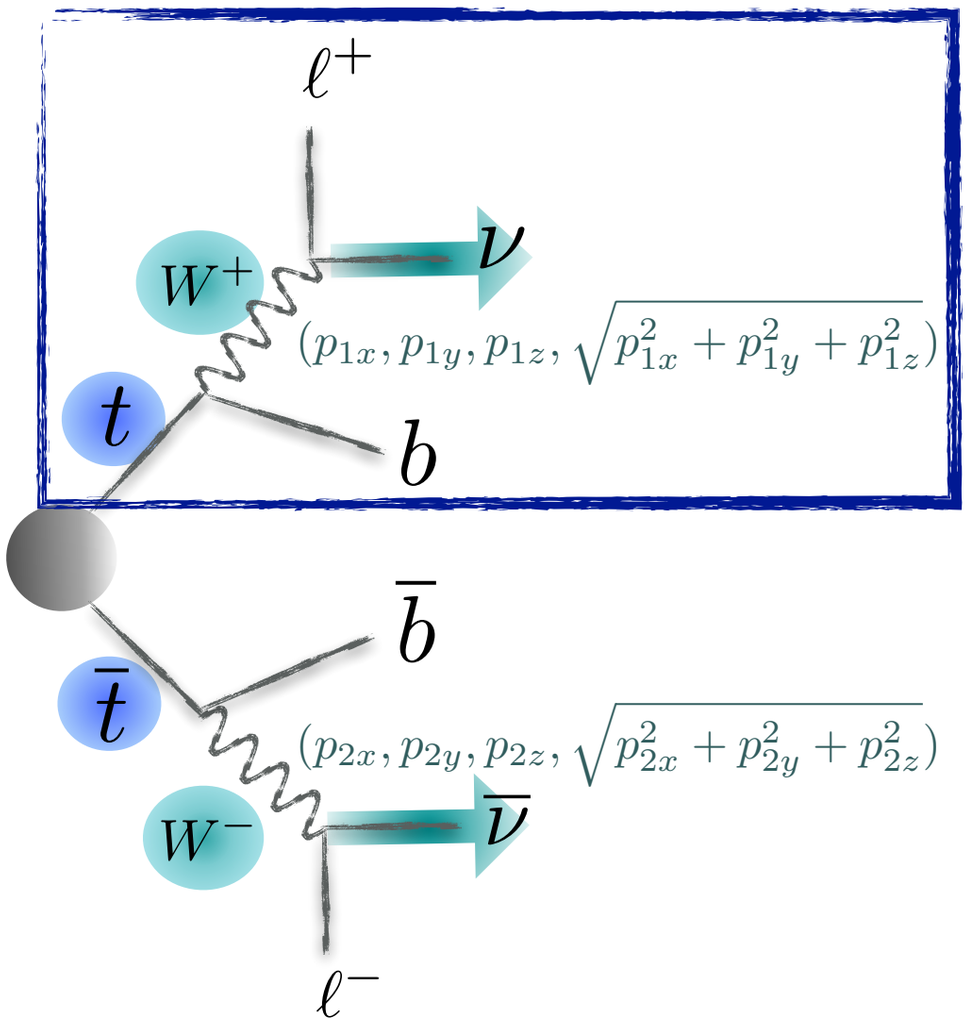
two possible ways of paring b and ℓ

- Topness provides a degree of consistency to dileptonic $t\bar{t}$ production.
- It scans over 6 unknowns of neutrino momenta with four on-shell masses and missing E_T constraints.
- And find a minimum of the likelihood function.

Topness (T)

M. L. Graesser and J. Shelton 2012

Kim, Kong, Matchev, Park 2018



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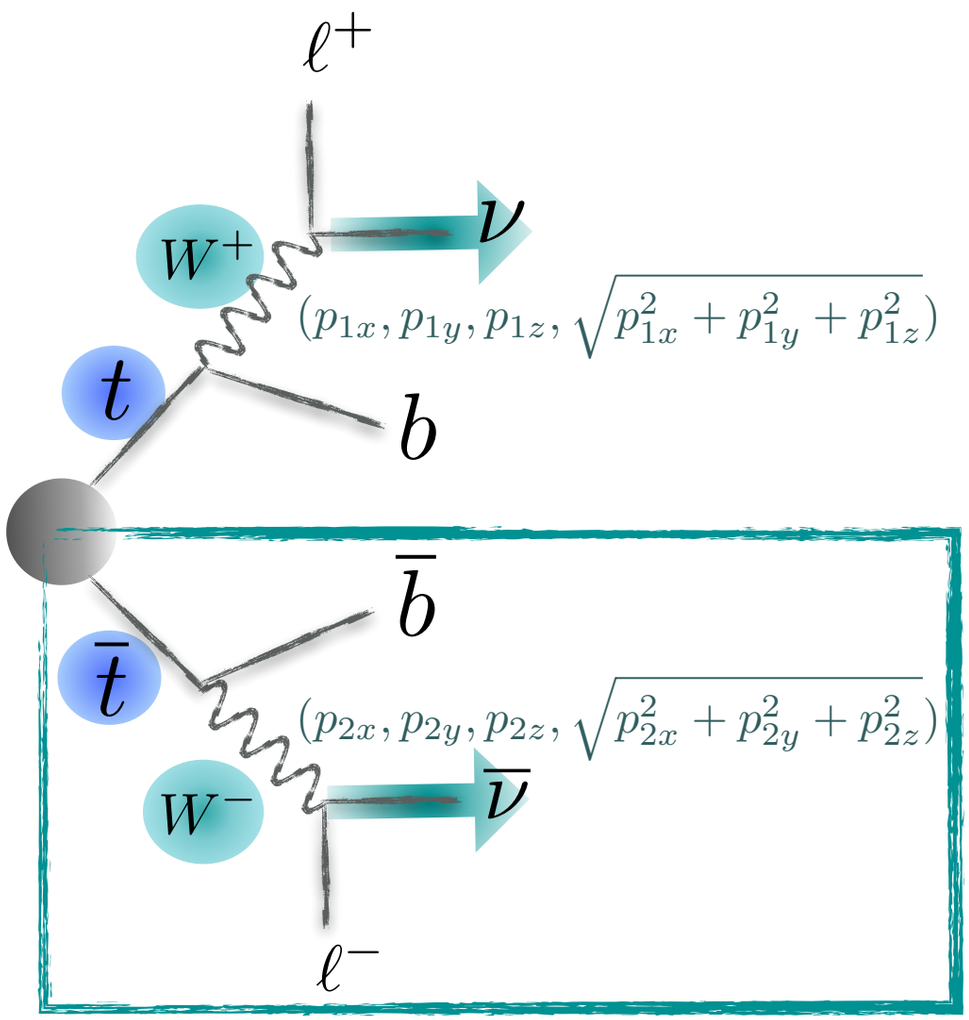
M. L. Graesser and J. Shelton 2012

Kim, Kong, Matchev, Park 2018



$$\chi^2_{ij} \equiv \min_{\vec{\not{p}}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{b_i \ell^+ \nu} - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m^2_{\ell^+ \nu} - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m^2_{b_j \ell^- \bar{\nu}} - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m^2_{\ell^- \bar{\nu}} - m_W^2\right)^2}{\sigma_W^4} \right]$$

$$T \equiv min\left(\chi^2_{12}\,,\, \chi^2_{21}\right)$$

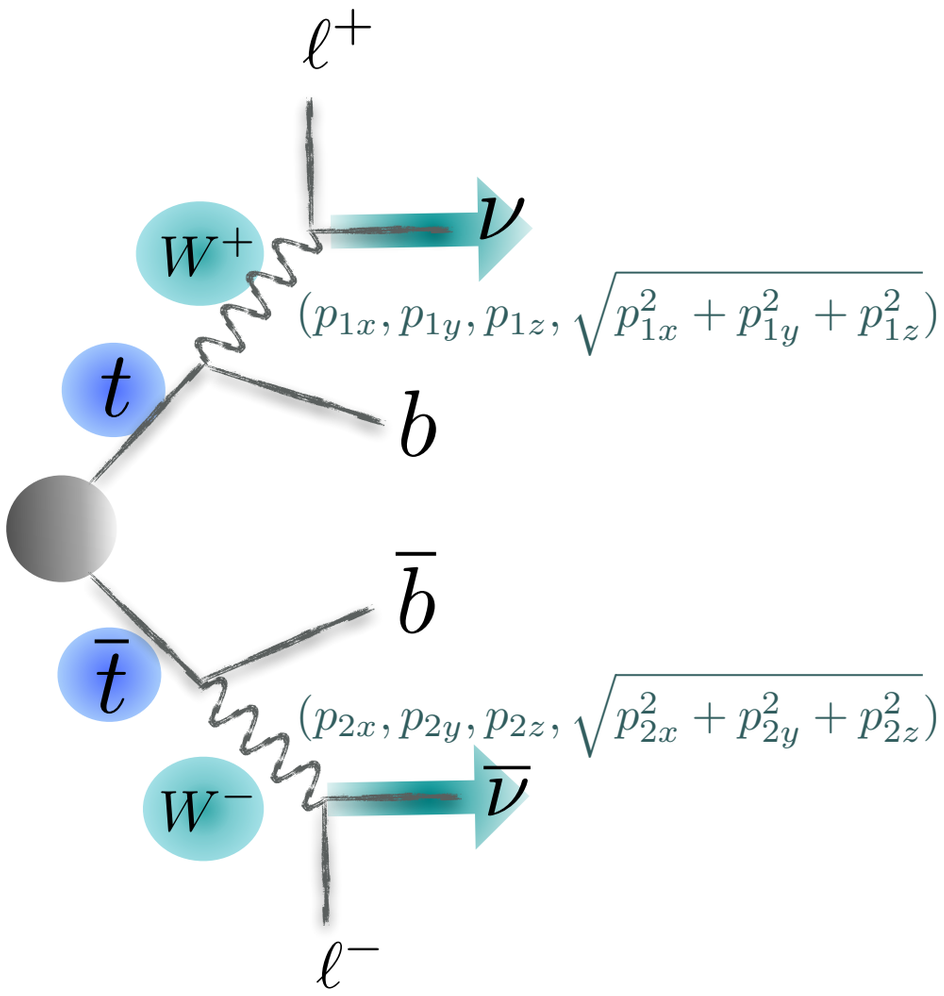
two possible ways of paring b and ℓ

- Topness provides a degree of consistency to dileptonic $t\bar{t}$ production.
- It scans over 6 unknowns of neutrino momenta with four on-shell masses and missing E_T constraints.
- And find a minimum of the likelihood function.

Topness (T)

M. L. Graesser and J. Shelton 2012

Kim, Kong, Matchev, Park 2018



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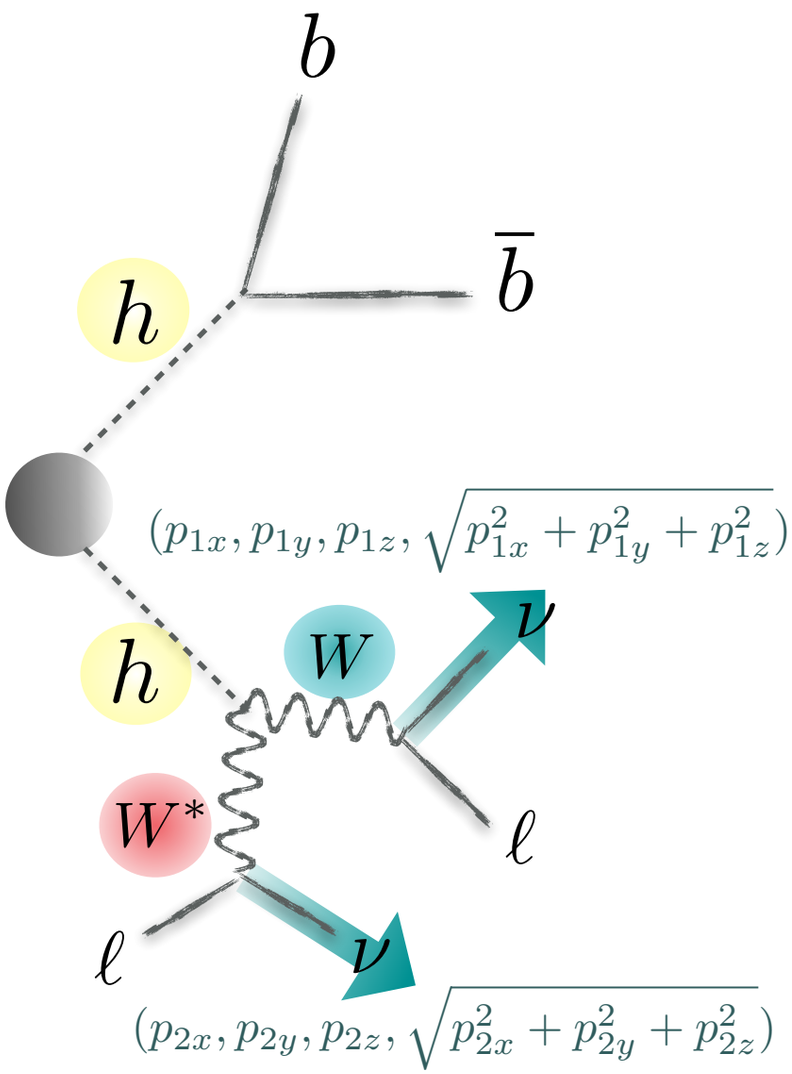
Higgsness (H)



Kim, Kong, Matchev, Park 2018

$$H \equiv \min_{\vec{\not{p}}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{\ell^+\ell^-\nu\bar{\nu}} - m_h^2\right)^2}{\sigma^4_{h_\ell}} + \frac{\left(m^2_{\nu\bar{\nu}} - m^2_{\nu\bar{\nu},peak}\right)^2}{\sigma^4_{\nu}} \right.$$

$$+min \left(\frac{\left(m^2_{\ell^+\nu} - m_W^2\right)^2}{\sigma^4_W} + \frac{\left(m^2_{\ell^-\bar{\nu}} - m^2_{W^*,peak}\right)^2}{\sigma^4_{W_*}} , \right.$$

$$\left. \left. \frac{\left(m^2_{\ell^-\bar{\nu}} - m_W^2\right)^2}{\sigma^4_W} + \frac{\left(m^2_{\ell^+\nu} - m^2_{W^*,peak}\right)^2}{\sigma^4_{W_*}} \right) \right] ,$$

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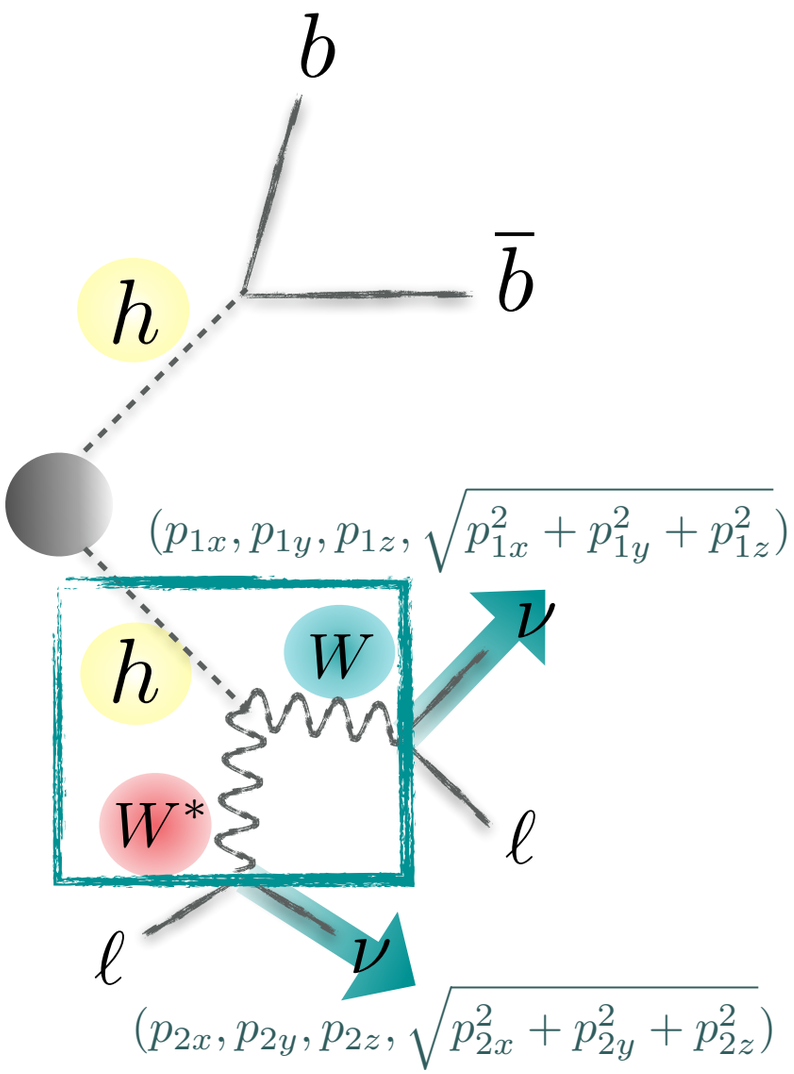

Kim, Kong, Matchev, Park 2018

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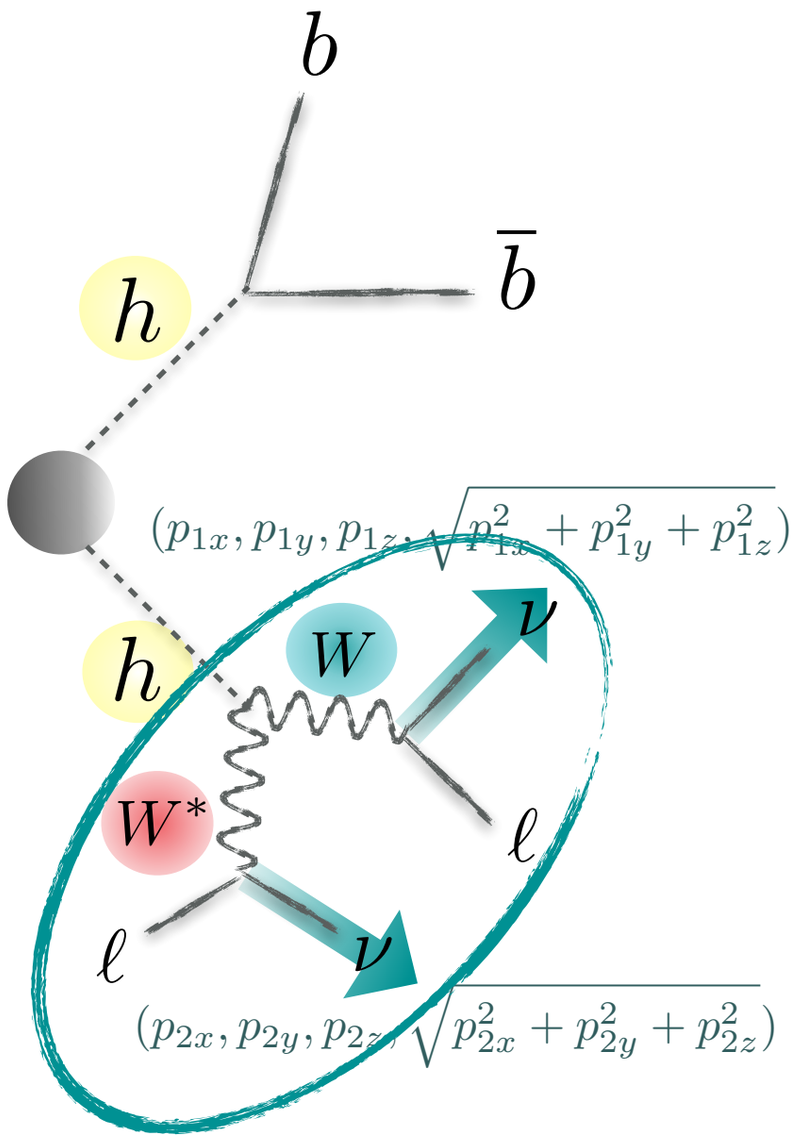
Kim, Kong, Matchev, Park 2018



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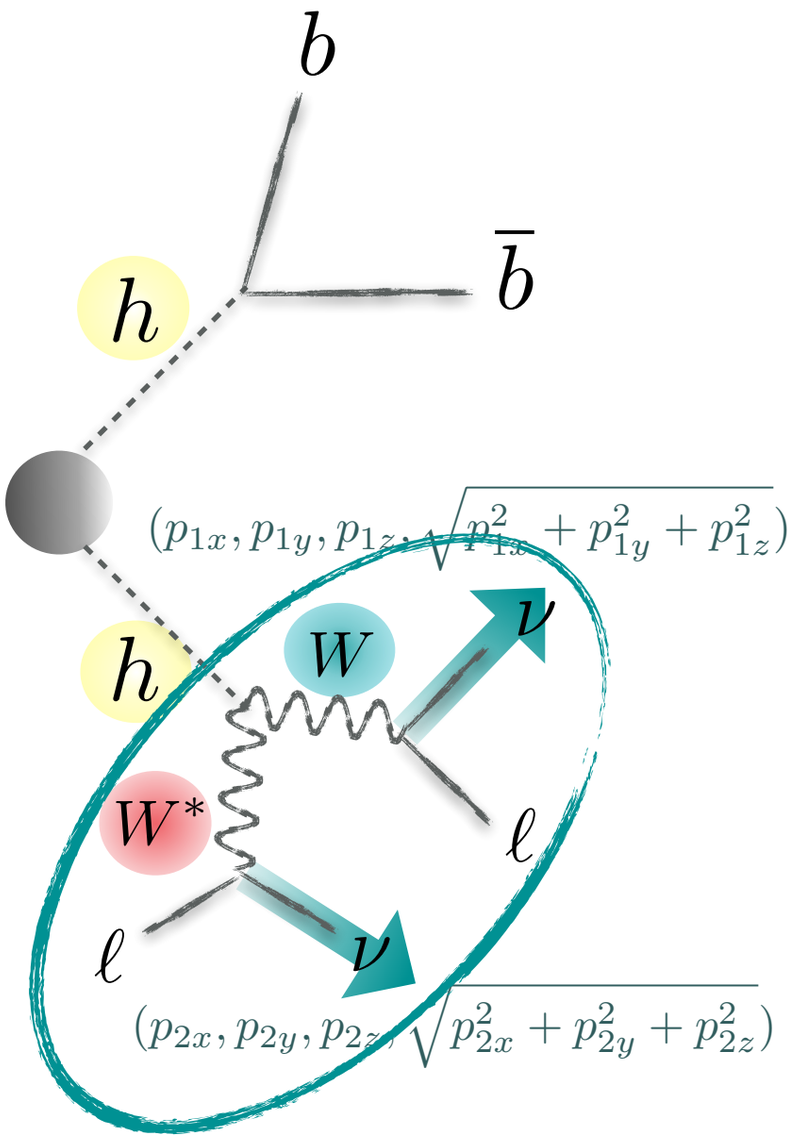
Kim, Kong, Matchev, Park 2018



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Kim, Kong, Matchev, Park 2018

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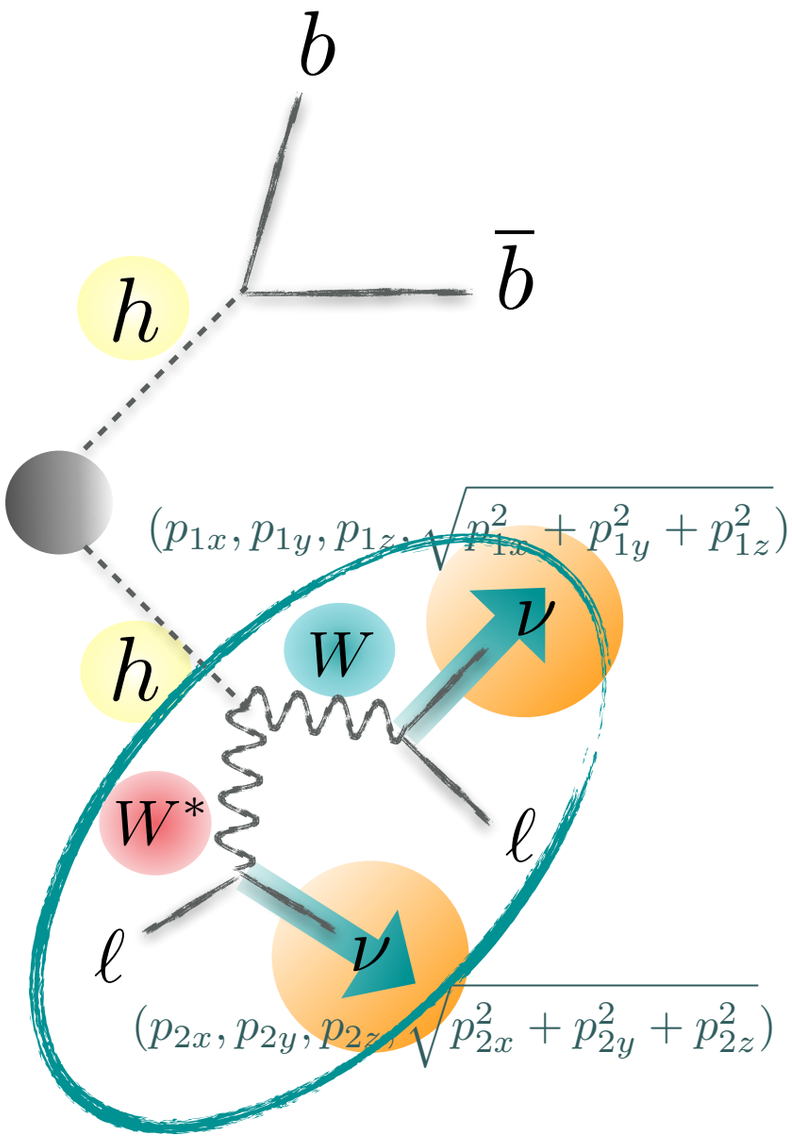

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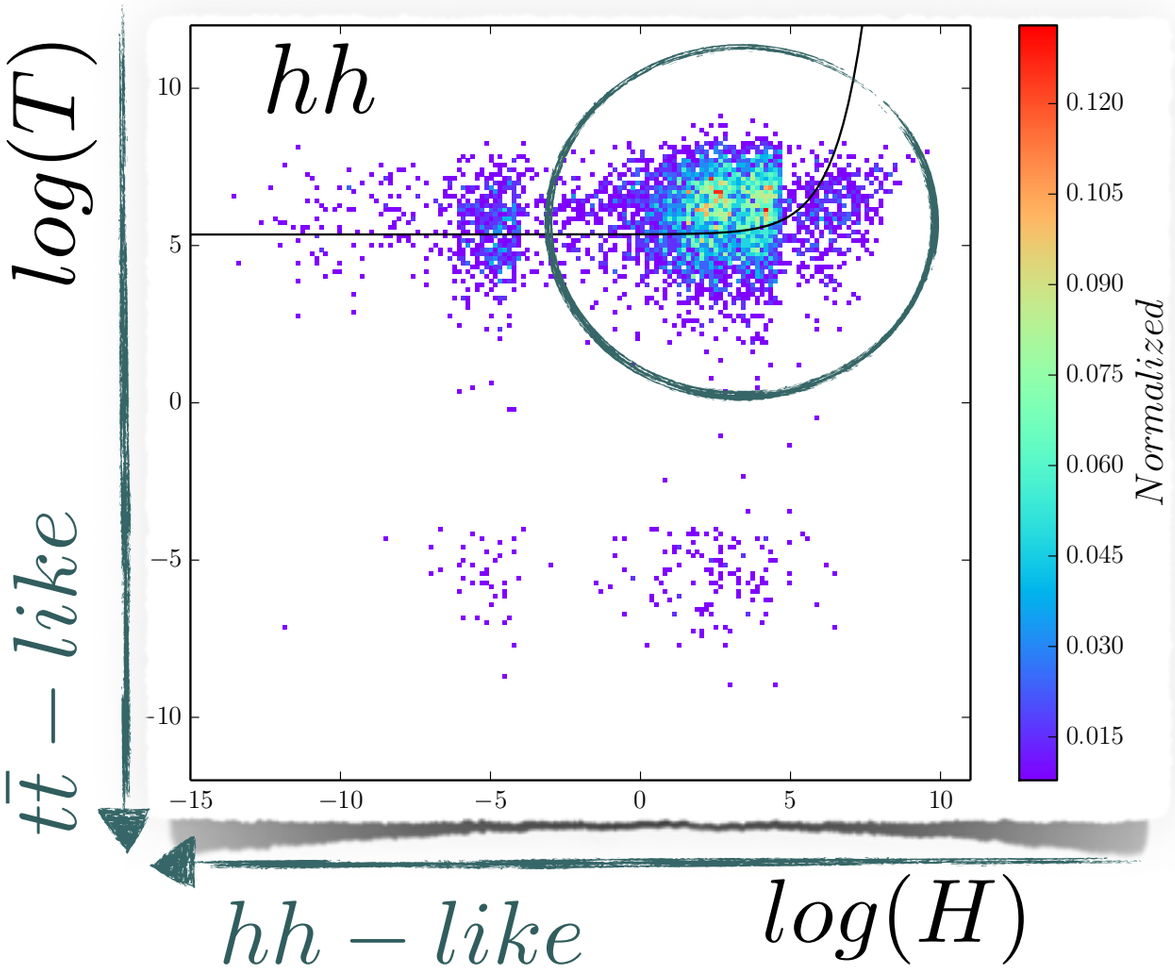
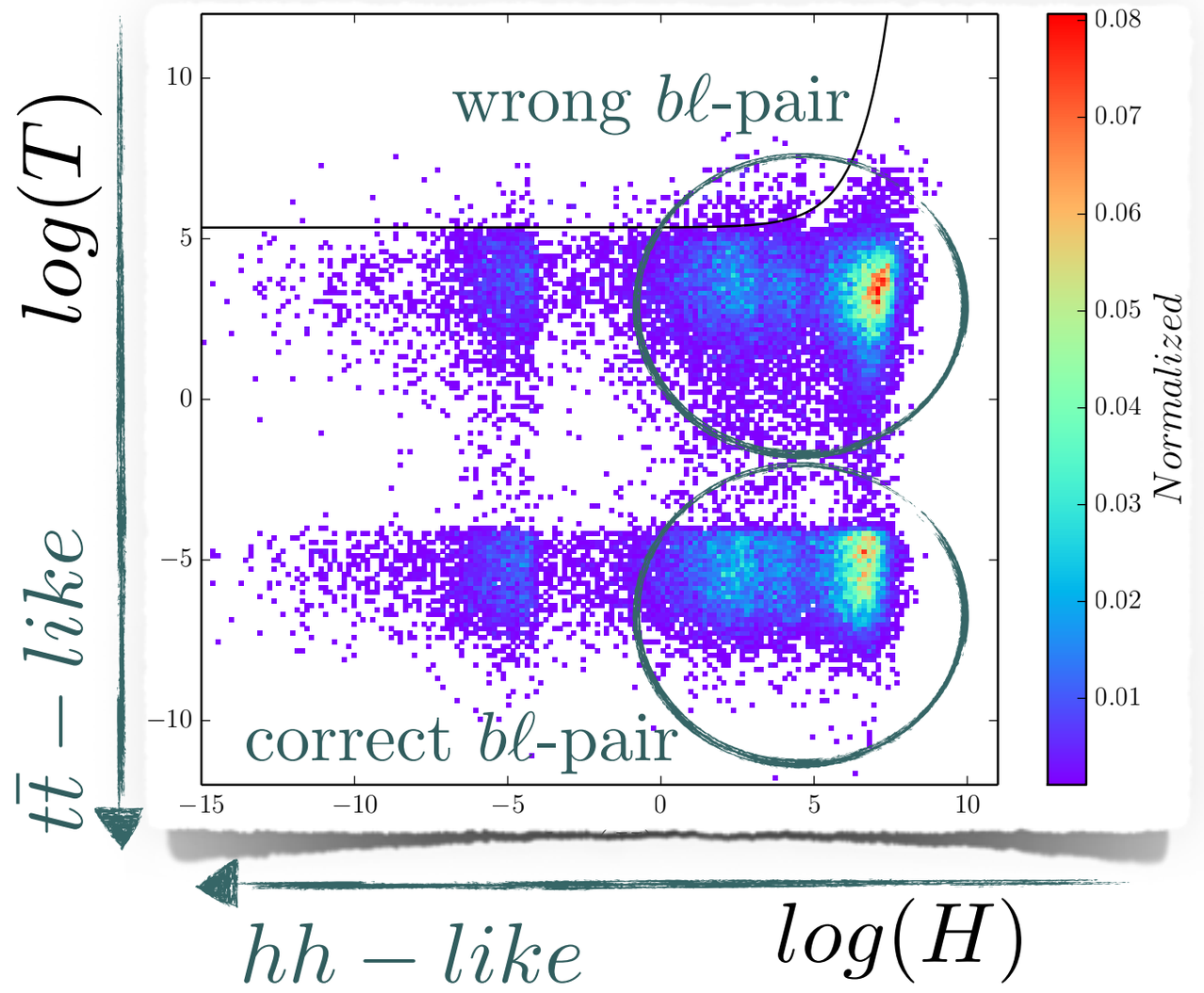
Distributions of (*log H* , *log T*) after baseline selection cuts

Kim, Kong, Matchev, Park 2018



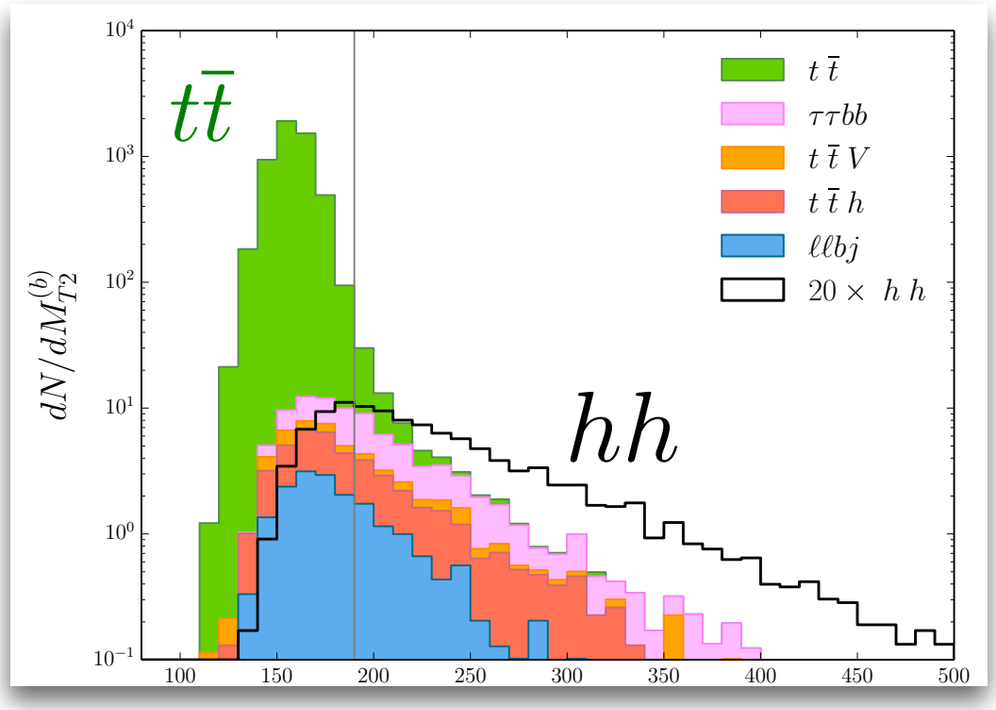
- A clear separation between *hh* and backgrounds ($t\bar{t}$ is dominant)



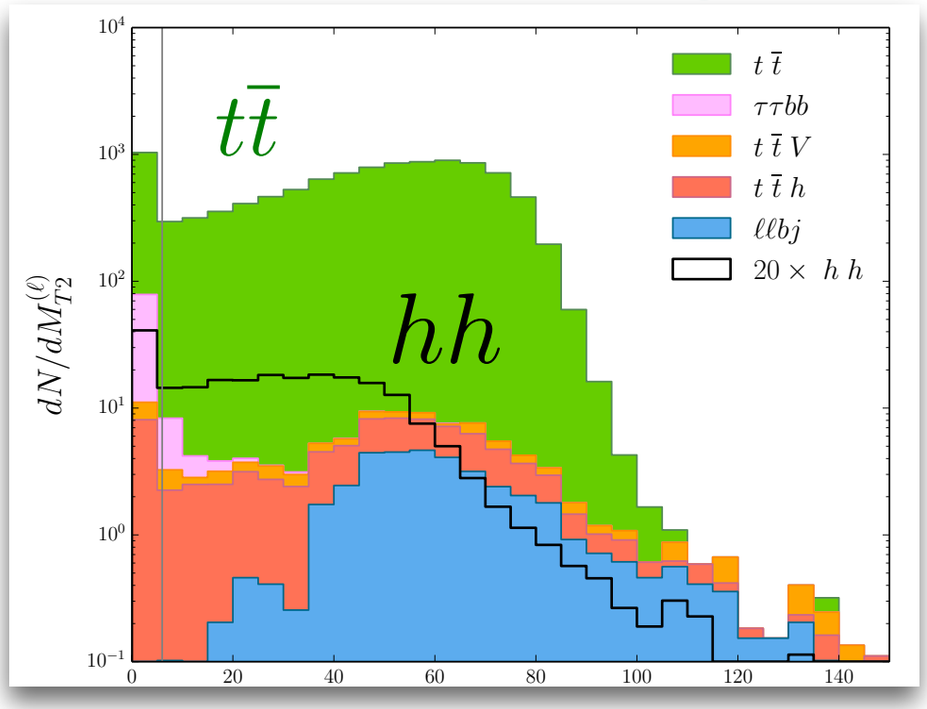
- Since there is a two-fold ambiguity in $b\ell$-paring, Topness displays the island-nature.

Other reinforcements…

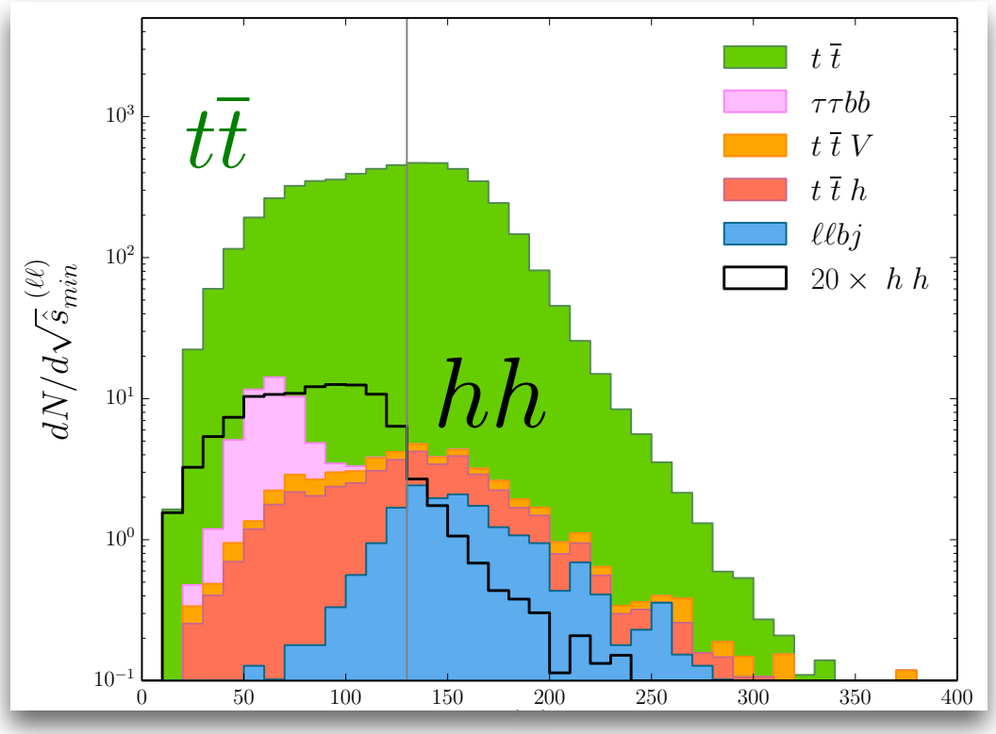
Kim, Kong, Matchev, Park 2018



$M_{T2}^{(b)}$



$M_{T2}^{(\ell)}$



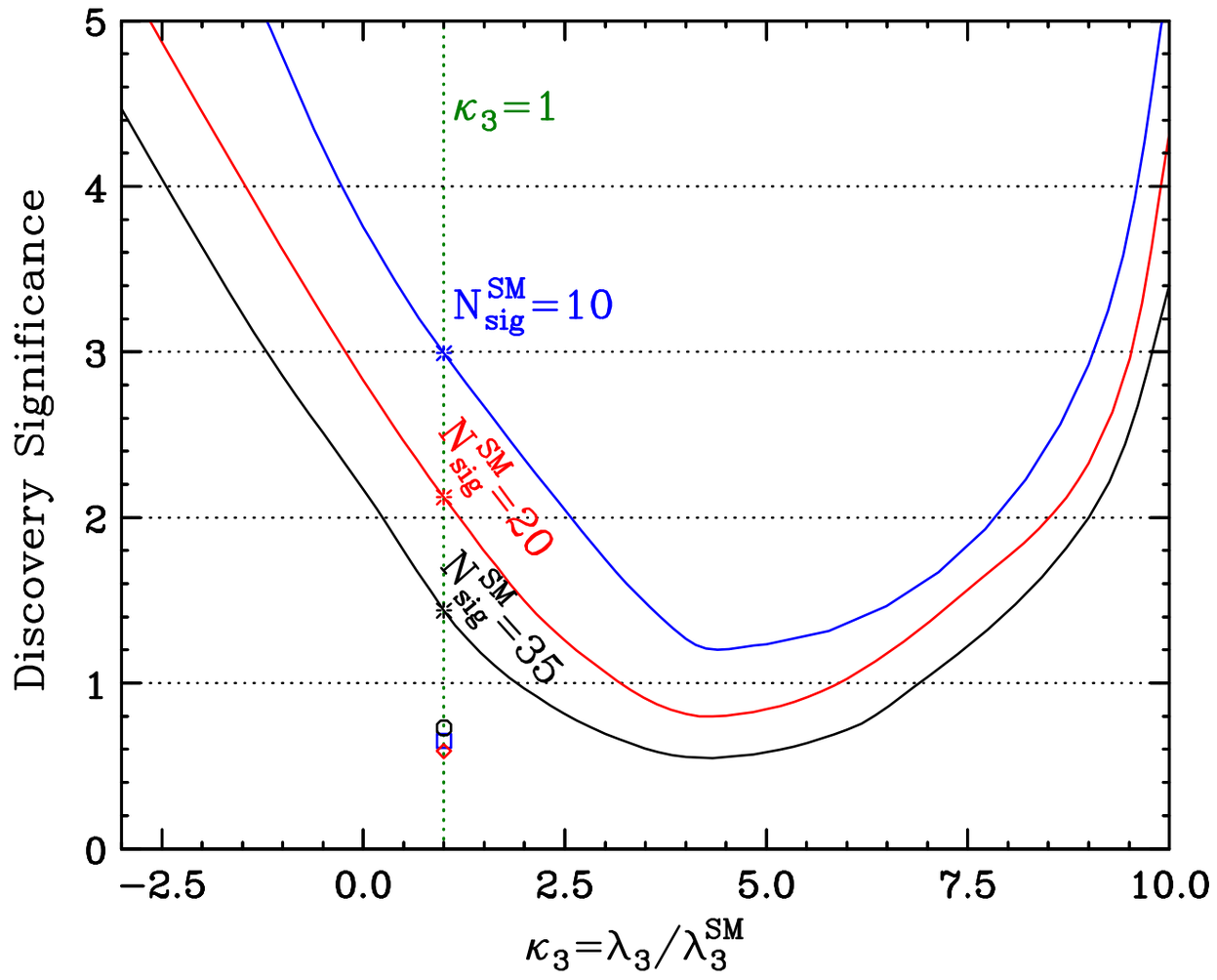
$\sqrt{\hat{s}_{min}^{(\ell\ell)}}$

- $M_{T2}^{(b)}$ is designed to specifically kill $t\bar{t}$.
- $M_{T2}^{(\ell)}$ is designed to specifically kill $\tau\tau b\bar{b}$.
- $\sqrt{\hat{s}_{min}^{(\ell\ell)}}$ can be used to suppress $t\bar{t}$ further.
- They are correlated with Topness and Higgsness.

Final $hh \to bbWW^*$ significance

$3\ \mathrm{ab}^{-1}(14\ \mathrm{TeV})$

Kim, Kong, Matchev, Park 2018



- $S/\sqrt{B} \sim 2$ seems to be achievable depending on how many signal events we want to keep.

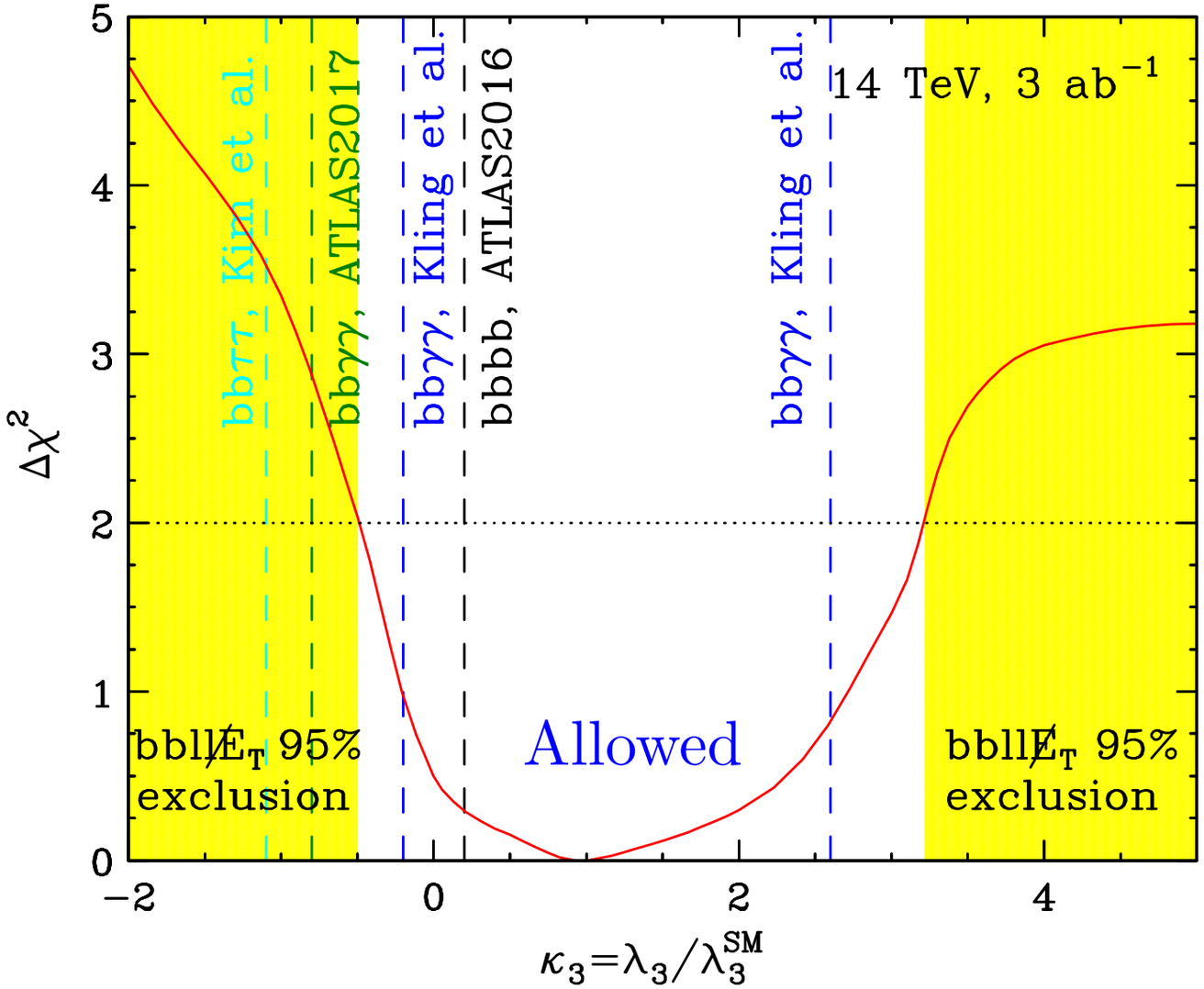
- To validate our analysis, we first reproduced the CMS significance 0.6σ using the same BDT.

	Signal [fb]	$t\bar{t}$ [fb]	$t\bar{t}h$ [fb]	$t\bar{t}V$ [fb]	$\ell\ell bj$ [fb]	$\tau\tau bb$ [fb]	σ	S/B
Baseline selections: $\not{E}_T > 20$ GeV, $p_T^\ell > 20$ GeV, $\Delta R_{\ell\ell} < 1.0$, $m_{\ell\ell} < 65$ GeV, $\Delta R_{bb} < 1.3$, $95 < m_{bb} < 140$ GeV	0.0124	1.1724	0.0297	0.0246	0.0158	0.0379	0.60	9.7×10^{-3}
Higgsness $\oplus$ Topness $\oplus$ $M_{T2}^{(b)}$ $\oplus$ $M_{T2}^{(\ell)}$ $\oplus$ $\sqrt{\hat{s}}_{min}^{(\ell\ell)}$	0.0065	0.0090	0.0073	0.0051	2.4×10^{-4}	0.0046	2.1	0.25

~1/2 ~1/200

Precision of the triple Higgs coupling

Kim, Kim, Kong, Matchev, Park arXiv:1902.XXXX



- How precisely can we distinguish different value of κ_3 with respect to the SM?
- $\Delta\chi^2 = 1$ interval on κ_3 turns out to be:

$$-0.3 < \kappa_3 < 3.0 \quad \cup \quad 6.1 < \kappa_3 \lesssim 11$$

$0.2 < \kappa_3 < 1.8$ (27 TeV)

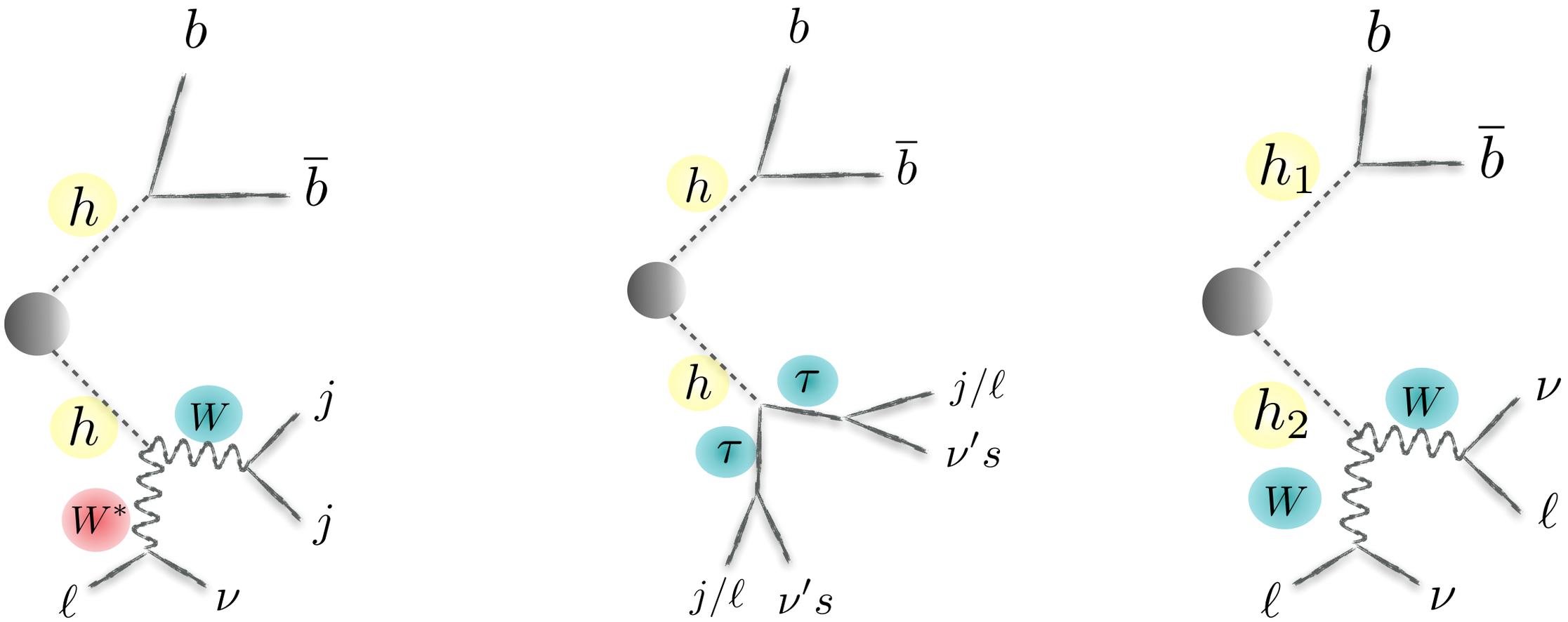
- The appearance of two islands is attributed to the fact that $\Delta\chi^2$ is a quartic function in terms of κ_3

$$\Delta\chi^2 \sim (\mu - 1)^2$$

$$\mu = \frac{\sigma}{\sigma_{SM}} \sim A_3 \kappa_3^2 + A_7 \kappa_3 + A_1$$

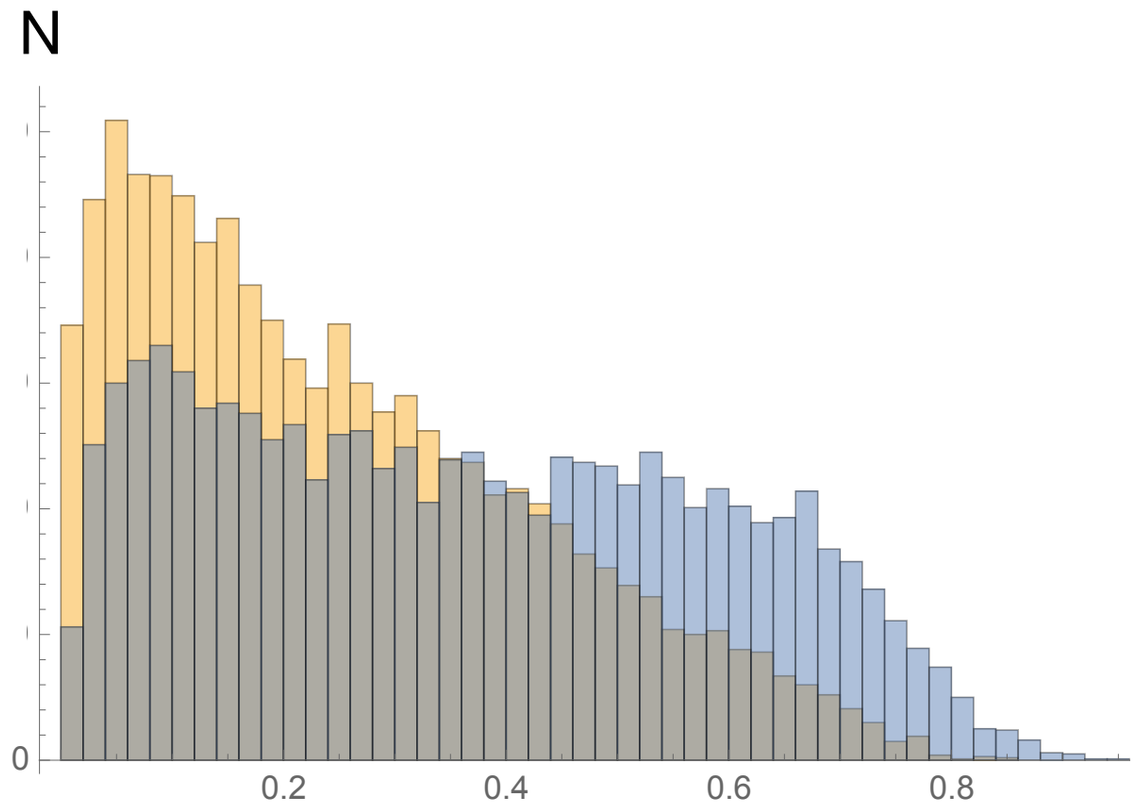
- The expected precision is comparable with the *bbγγ* and *bbττ*.
- The best result will come by combining *bbγγ*, *bbττ*, *bbWW**, and *bbbb*.
- We have a hope to discover *hh* and probe *kappa3* at HL-LHC.

Future & On-going directions

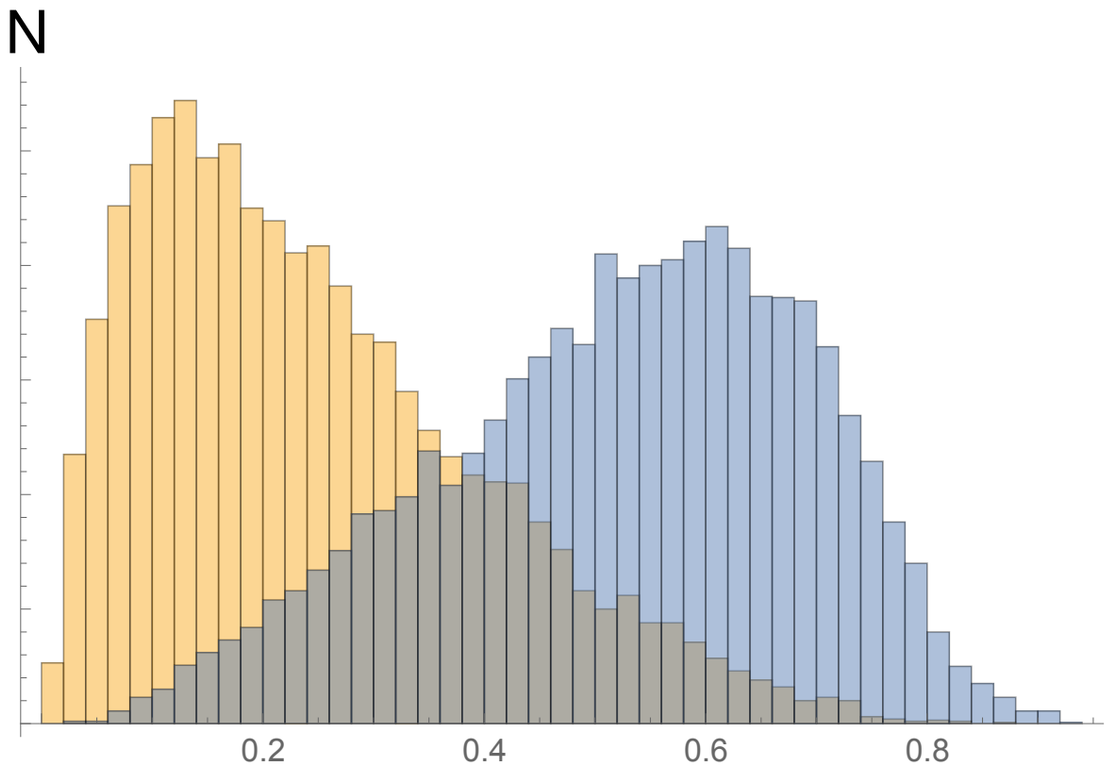


- Our method has a wide applicability to improve other channels.
- The semi-leptonic $hh \longrightarrow bbWW^*$ channel.
- The $hh \longrightarrow bb\tau\tau$ channel.
- The BSM Higgs searches $h_1\, h_2 \longrightarrow bbWW$

Shape variables



Sphericity in lab frame



Sphericity in CM frame

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i \mid p_i \mid^2}, \qquad \lambda_1 + \lambda_2 + \lambda_3 = 1$$

$$\lambda_1 \geq \lambda_2 \geq \lambda_3$$

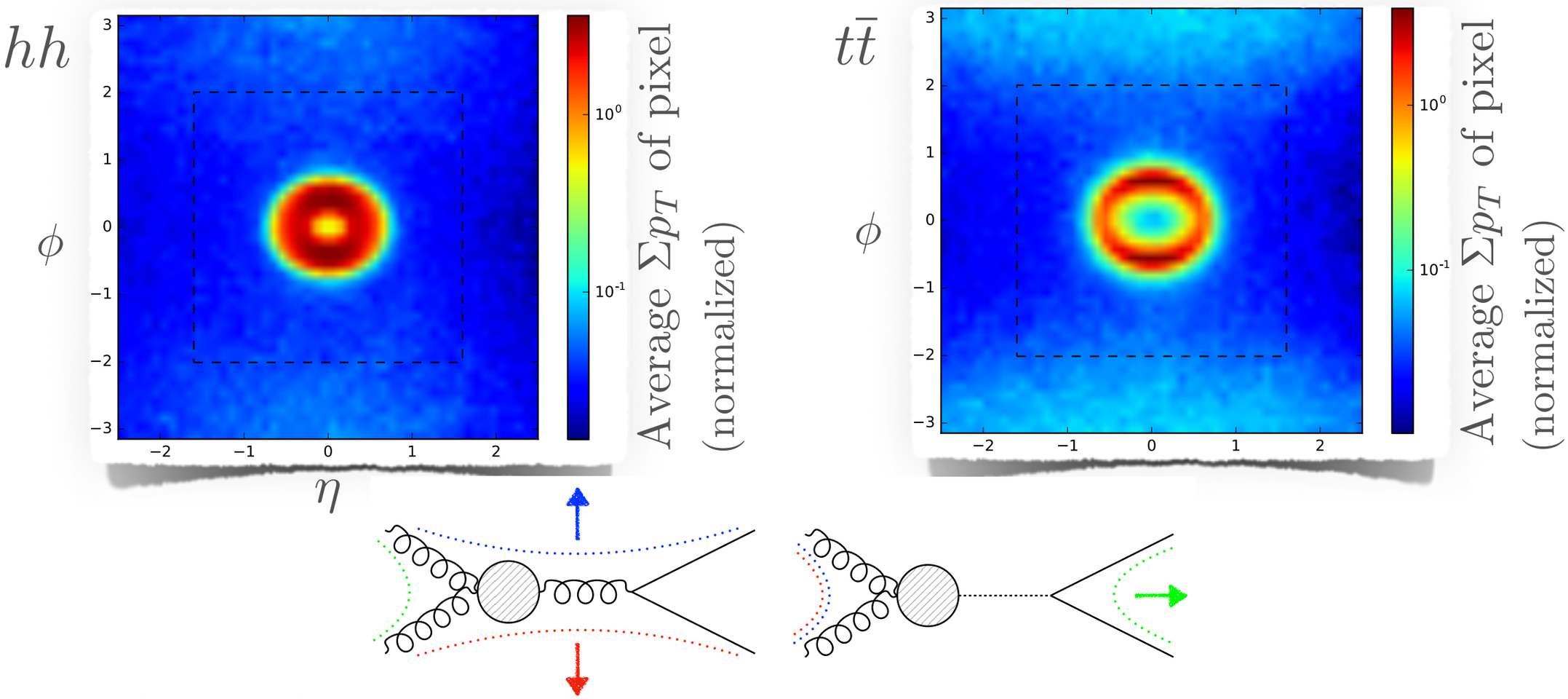
$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

- S -> 0: pencil-like event
- S -> 1: isotropic event

$hh \to bbWW^*$ meets jet-images

J. Gallicchio and M. D. Schwartz 2010

Kim, Kim, Kong, Matchev, Park arXiv:1902.XXXX

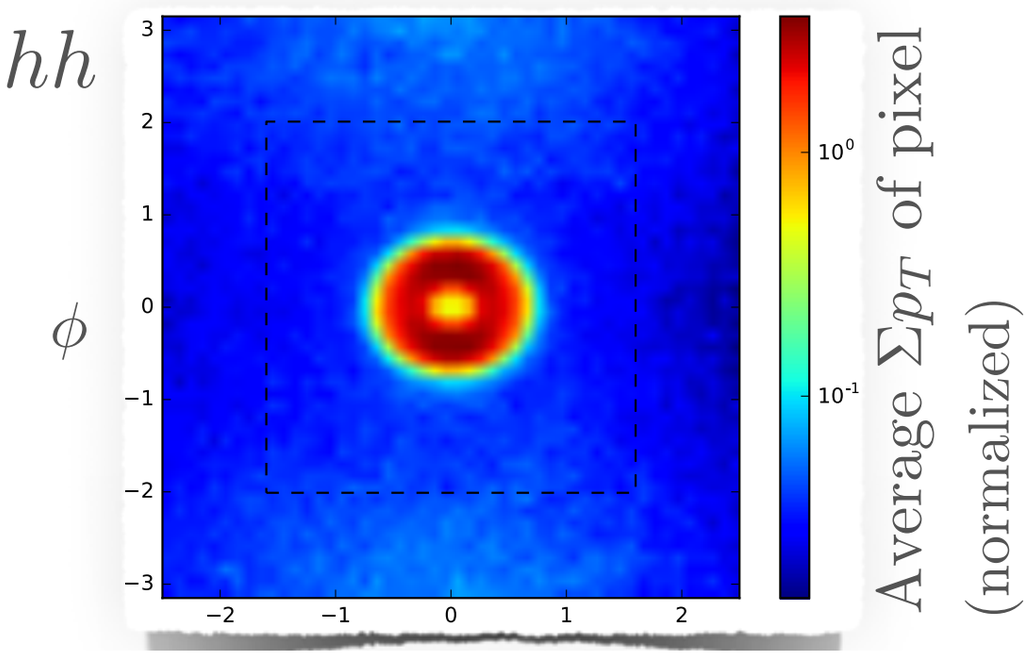


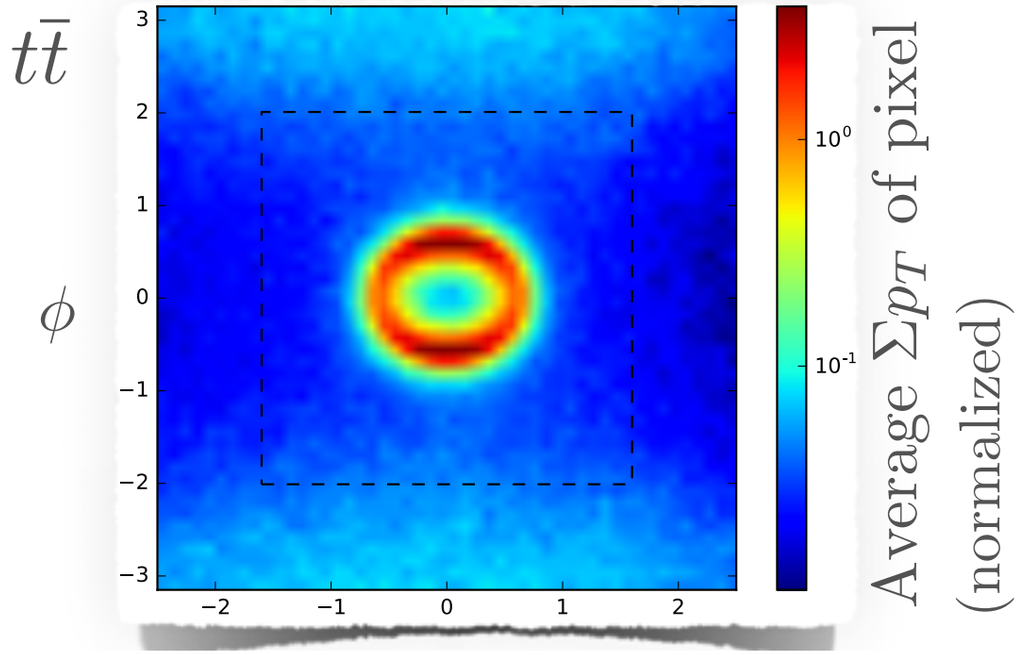
- Jets have color, and they are connected to each other.
- The signal and background have different color-flows
- b-jets from $t\bar{t}$ background are pulled toward the beam direction.
- One can think of constructing a global event shape to discriminate hh/tt.

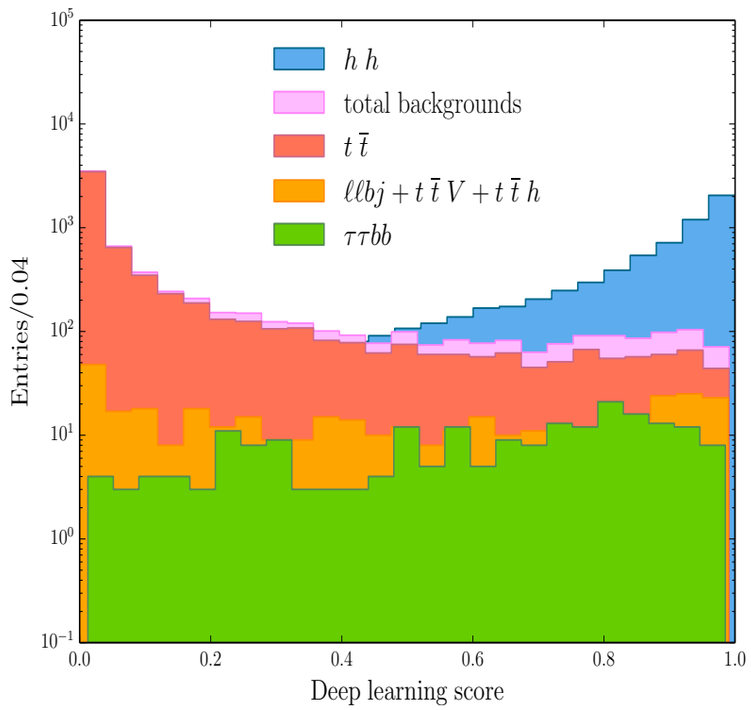
$hh \to bbWW^*$ meets jet-images

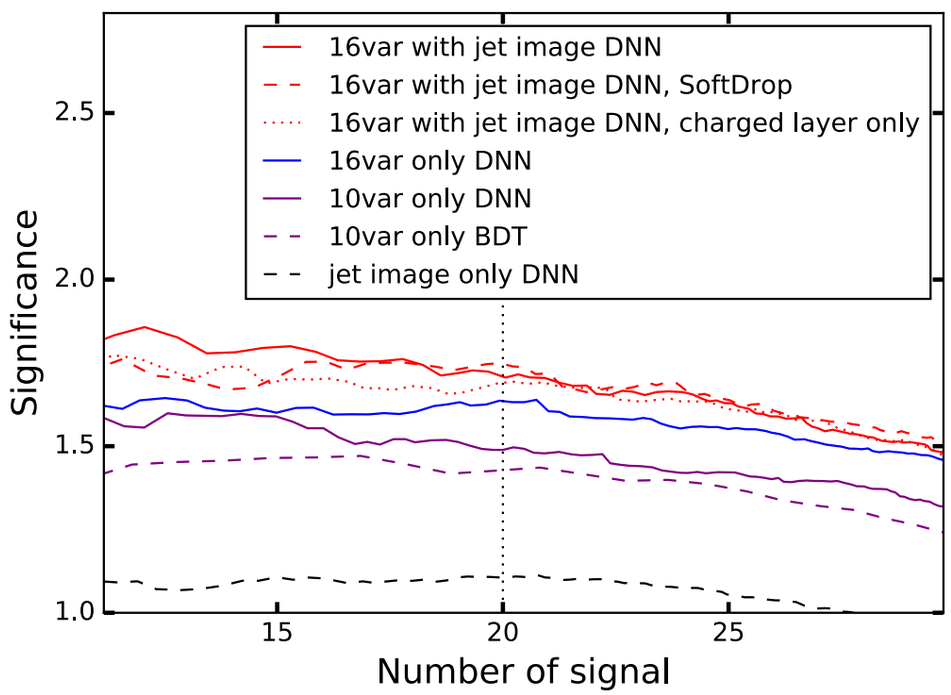
J. Gallicchio and M. D. Schwartz 2010

Kim, Kim, Kong, Matchev, Park arXiv:1902.XXXX



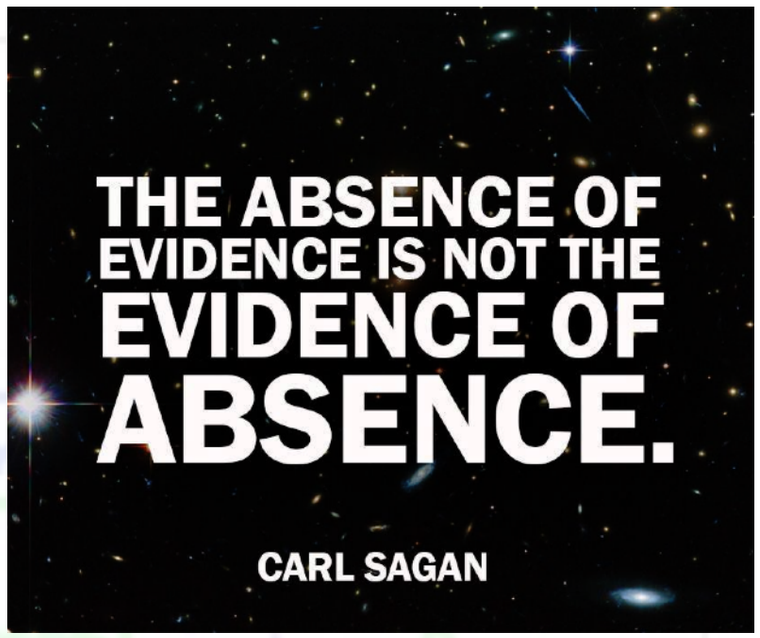






- Recent update on Flat Extra Dimensions (MUED)
- Probing the Triple Higgs Self-Interaction at the Large Hadron Collider
- My personal perspective on BSM searches at the LHC / HL-LHC (no time to discuss)

Summary

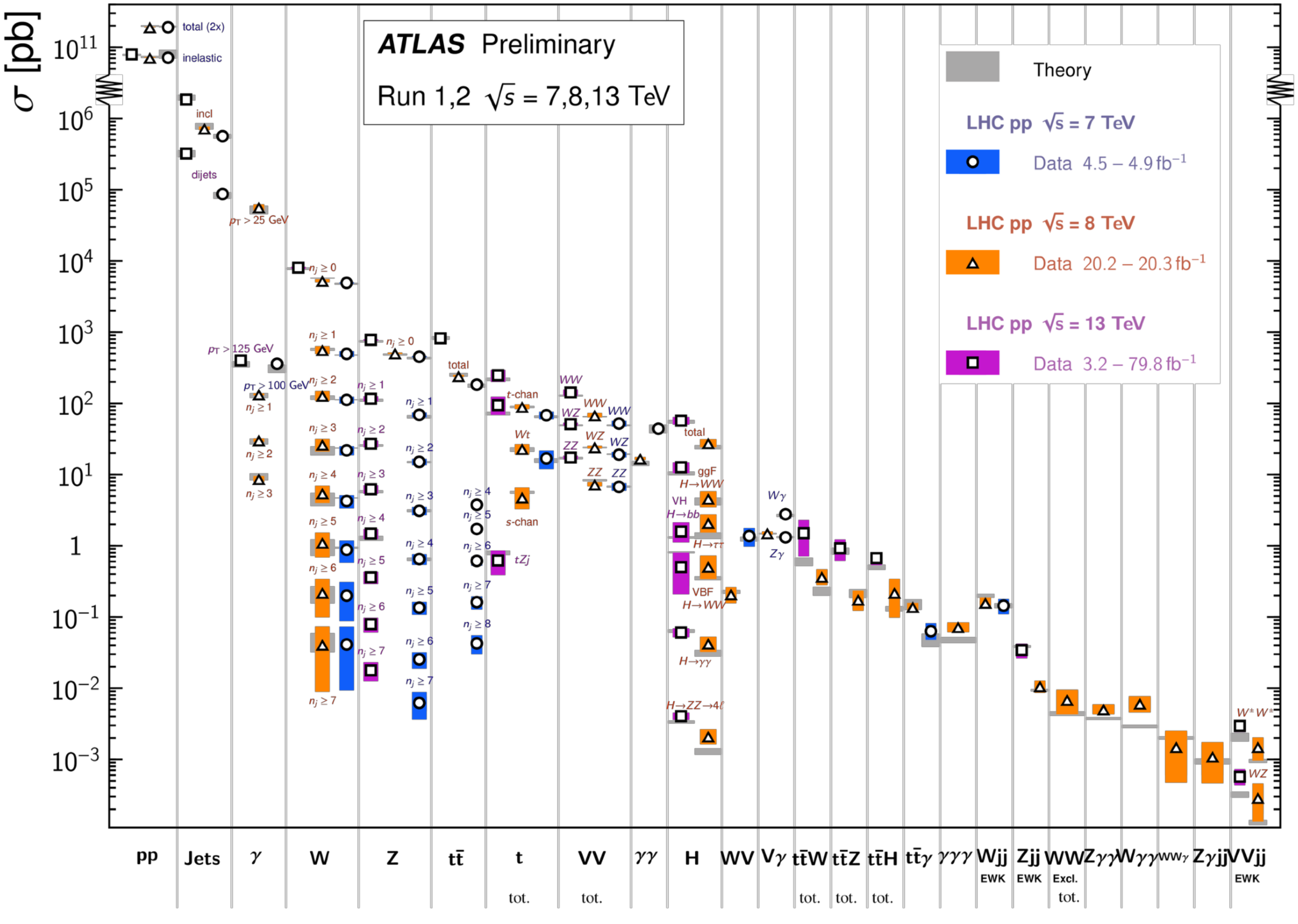


- Discussed recent update on MUED.
- Worth revisiting collider/DM phenomenology with the improved mass spectrum including finite terms.
- Higgs self-interaction is guaranteed physics at HL-LHC and it might provide important clues for BSM searches.
- Discussed new method useful for especially in the dilepton final state.
- Topness/Higgness have many applications.

My personal perspective on BSM searches at the LHC / HL-LHC

Standard Model Production Cross Section Measurements

Status: July 2018



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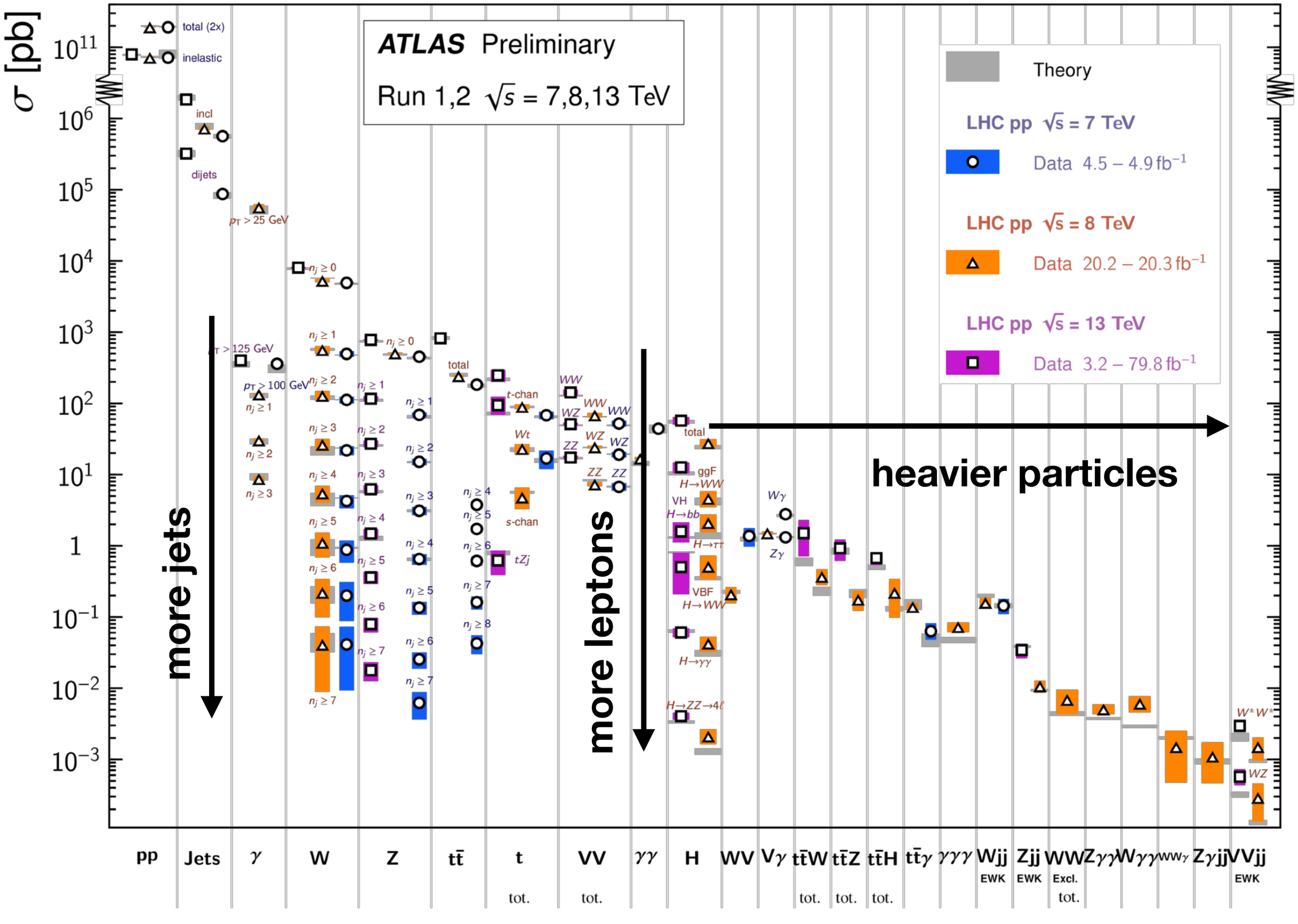


ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Mass limit	$\sqrt{s}$ = 7, 8 TeV / $\sqrt{s}$ = 13 TeV	Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 / 1.55	m($\tilde{\chi}_1^0$)<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 / 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	m($\tilde{\chi}_1^0$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.85	m($\tilde{\chi}_1^0$)<800 GeV	1706.03731
		$ee, \mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 0.98	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}_1^0$)<200 GeV	1711.01901
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1706.03731
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1, M_2 = 2\times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	m($\tilde{\chi}_1^0$)=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.6-0.8	m($\tilde{\chi}_1^0$)=300 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$	0	2c	Yes	36.1	$\tilde{t}_1$ 0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.6	m($\tilde{\chi}_1^0$)=0	1403.5294, 1806.02293
		$ee, \mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.17	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=10 GeV	1712.08119
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.26	m($\tilde{\chi}_1^0$)=0	1501.07110
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^0/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.76	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
						$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.22	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=100 GeV, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$ 0.5	m($\tilde{\chi}_1^0$)=0	1803.02762
		2 e,μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0	≥ 3b	Yes	36.1	$\tilde{H}$ 0.13-0.23 / 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0	Yes	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 / 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 0.44	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, m($\tilde{\chi}_1^0$)=1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82 / 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 / 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 / 2.0	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}, \tilde{g}\to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 / 2.1	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 / 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 / 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544

10^{-1} 1 **Mass scale [TeV]**

**Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (3.2 – 79.8) fb^{-1} $\sqrt{s}$ = 8, 13 TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	79.8	V' mass 4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass 3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.0 TeV	η_{LL}^-	1707.02424
	CI $tttt$	≥1 e, μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-XXX
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-XXX
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt) = 1$, $c(T_{5/3}Wt) = 1$	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	3.2	Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb) = 1$, $c(YWb) = 1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	0 e, μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	$\kappa_B = 0.5$	ATLAS-CONF-2018-XXX
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

10^{-1} 1 10 **Mass scale [TeV]**

**Only a selection of the available mass limits on new states or phenomena is shown.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 36.1)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	Signature	$\int \mathcal{L}\, dt$ [fb^{-1}]	Lifetime limit		Reference
SUSY	RPV $\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displaced lepton pair	20.3	χ_1^0 lifetime	7-740 mm	$m(\tilde{g})$= 1.3 TeV, $m(\chi_1^0)$= 1.0 TeV	1504.05162
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced vtx + jets	20.3	χ_1^0 lifetime	6-480 mm	$m(\tilde{g})$= 1.1 TeV, $m(\chi_1^0)$= 1.0 TeV	1504.05162
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced dimuon	32.9	χ_1^0 lifetime	0.029-18.0 m	$m(\tilde{g})$= 1.1 TeV, $m(\chi_1^0)$= 1.0 TeV	CERN-EP-2018-173
	GMSB	non-pointing or delayed γ	20.3	χ_1^0 lifetime	0.08-5.4 m	SPS8 with Λ= 200 TeV	1409.5542
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	20.3	$\chi_1^\pm$ lifetime	0.22-3.0 m	$m(\chi_1^\pm)$= 450 GeV	1310.3675
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	36.1	$\chi_1^\pm$ lifetime	0.057-1.53 m	$m(\chi_1^\pm)$= 450 GeV	1712.02118
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	large pixel dE/dx	18.4	$\chi_1^\pm$ lifetime	1.31-9.0 m	$m(\chi_1^\pm)$= 450 GeV	1506.05332
	Stealth SUSY	2 ID/MS vertices	19.5	$\tilde{S}$ lifetime	0.12-90.6 m	$m(\tilde{g})$= 500 GeV	1504.03634
	Split SUSY	large pixel dE/dx	36.1	$\tilde{g}$ lifetime	> 0.9 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	CERN-EP-2018-198
	Split SUSY	displaced vtx + $E_{\text{T}}^{\text{miss}}$	32.8	$\tilde{g}$ lifetime	0.03-13.2 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	1710.04901
	Split SUSY	0 ℓ, 2 – 6 jets + $E_{\text{T}}^{\text{miss}}$	36.1	$\tilde{g}$ lifetime	0.0-2.1 m	$m(\tilde{g})$= 1.8 TeV, $m(\chi_1^0)$= 100 GeV	ATLAS-CONF-2018-003
Higgs BR = 10%	$H \to ss$	2 low-EMF trackless jets	20.3	s lifetime	0.41-7.57 m	$m(s)$= 25 GeV	1501.04020
	$H \to ss$	2 ID/MS vertices	19.5	s lifetime	0.31-25.4 m	$m(s)$= 25 GeV	1504.03634
	FRVZ $H \to 2\gamma_d + X$	2 $e-, \mu-$jets	20.3	γ_d lifetime	0-3 mm	$m(\gamma_d)$= 400 MeV	1511.05542
	FRVZ $H \to 2\gamma_d + X$	2 $e-, \mu-, \pi-$jets	3.4	γ_d lifetime	0.022-1.113 m	$m(\gamma_d)$= 400 MeV	ATLAS-CONF-2016-042
	FRVZ $H \to 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	3.4	γ_d lifetime	0.038-1.63 m	$m(\gamma_d)$= 400 MeV	ATLAS-CONF-2016-042
	$H \to Z_d Z_d$	displaced dimuon	32.9	Z_d lifetime	0.009-24.0 m	$m(Z_d)$= 40 GeV	CERN-EP-2018-173
Scalar	VH with $H \to ss \to bbbb$	1 – 2ℓ + multi-b-jets	36.1	s lifetime	0-3 mm	$\mathcal{B}(H \to ss)$= 1, $m(s)$= 60 GeV	1806.07355
	Φ(300 GeV) $\to ss$	2 low-EMF trackless jets	20.3	s lifetime	0.29-7.9 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1501.04020
	Φ(300 GeV) $\to ss$	2 ID/MS vertices	19.5	s lifetime	0.19-31.9 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1504.03634
	Φ(600 GeV) $\to ss$	2 low-EMF trackless jets	3.2	s lifetime	0.09-2.7 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	ATLAS-CONF-2016-103
	Φ(900 GeV) $\to ss$	2 low-EMF trackless jets	20.3	s lifetime	0.15-4.1 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1501.04020
	Φ(900 GeV) $\to ss$	2 ID/MS vertices	19.5	s lifetime	0.11-18.3 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1504.03634
	Φ(1 TeV) $\to ss$	2 low-EMF trackless jets	3.2	s lifetime	0.78-16.0 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 400 GeV	ATLAS-CONF-2016-103
Other	HV Z'(1 TeV) $\to q_v q_v$	2 ID/MS vertices	20.3	s lifetime	0.1-4.9 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1504.03634
	HV Z'(2 TeV) $\to q_v q_v$	2 ID/MS vertices	20.3	s lifetime	0.1-10.1 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1504.03634

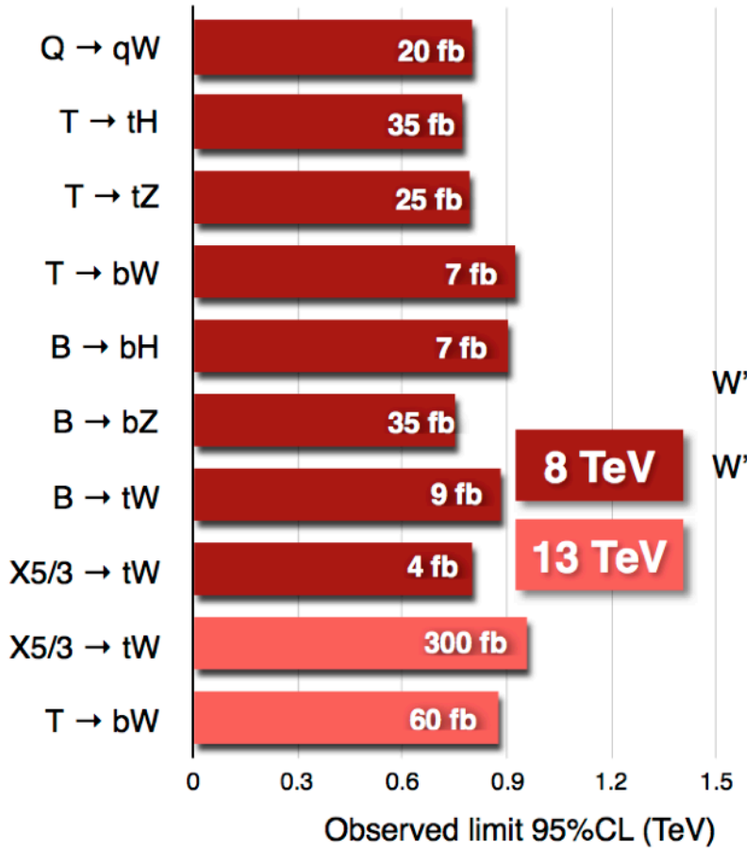
0.01 0.1 1 10 100 $c\tau$ [m]

$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

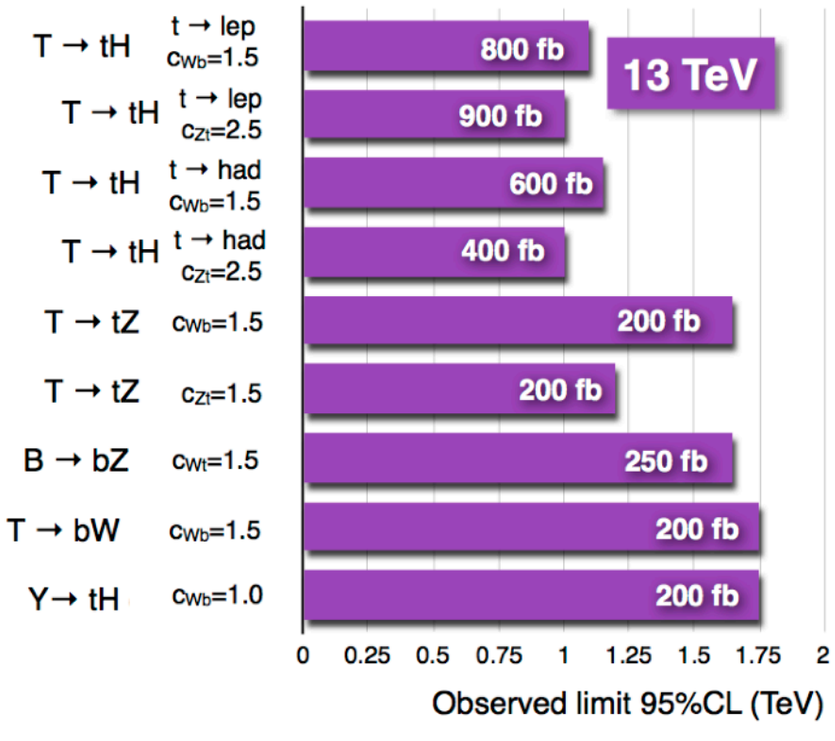
**Only a selection of the available lifetime limits on new states is shown.*

$(\gamma\beta = 1)$

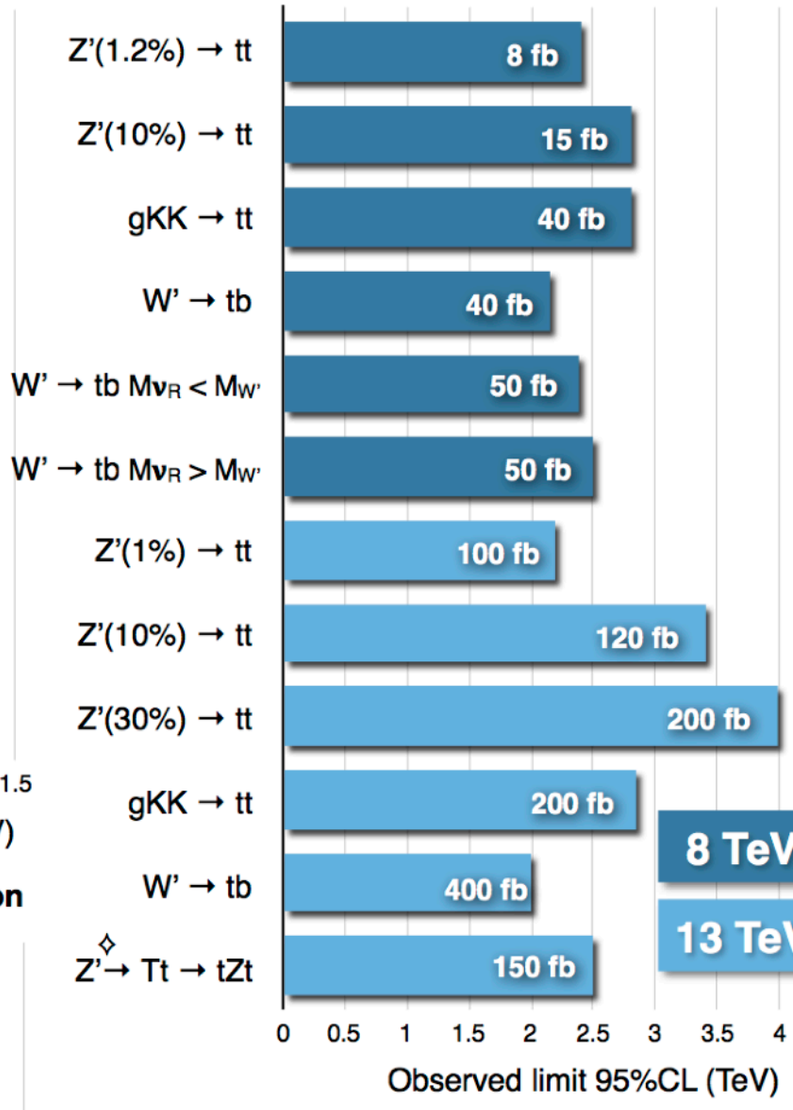
Vector-like quark pair production



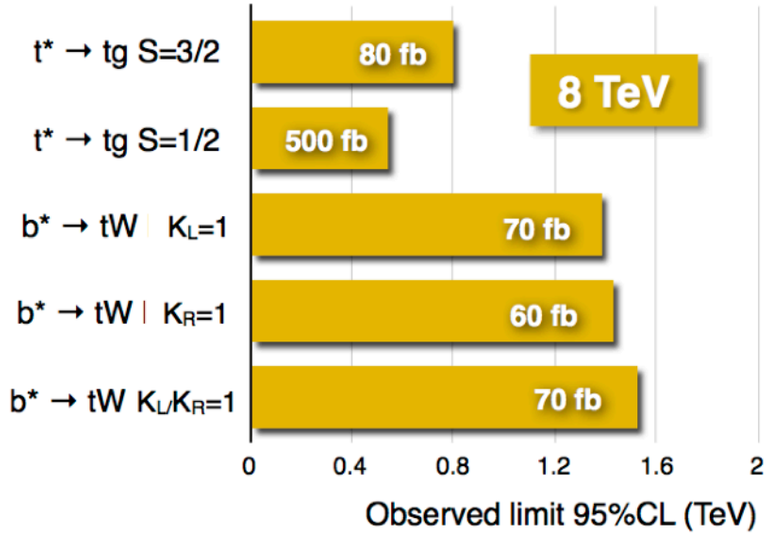
Vector-like quark single production



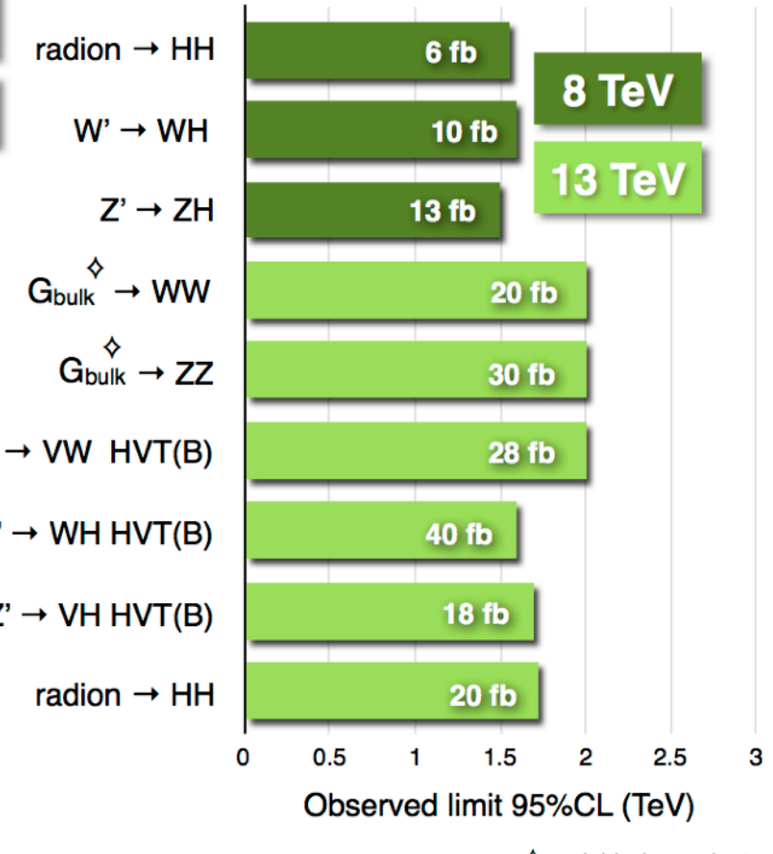
Resonances to heavy quarks



Excited quarks



Resonances to dibosons



B2G
new physics searches with heavy SM particles

CMS

✧model-independent

My personal (incomplete, biased and self-indulgent) perspective on BSM searches at the LHC / HL-LHC

- Limits are strong.

- No obvious hints for BSM physics.

- Are we covering all possible scenarios?

- Have we missed anything?

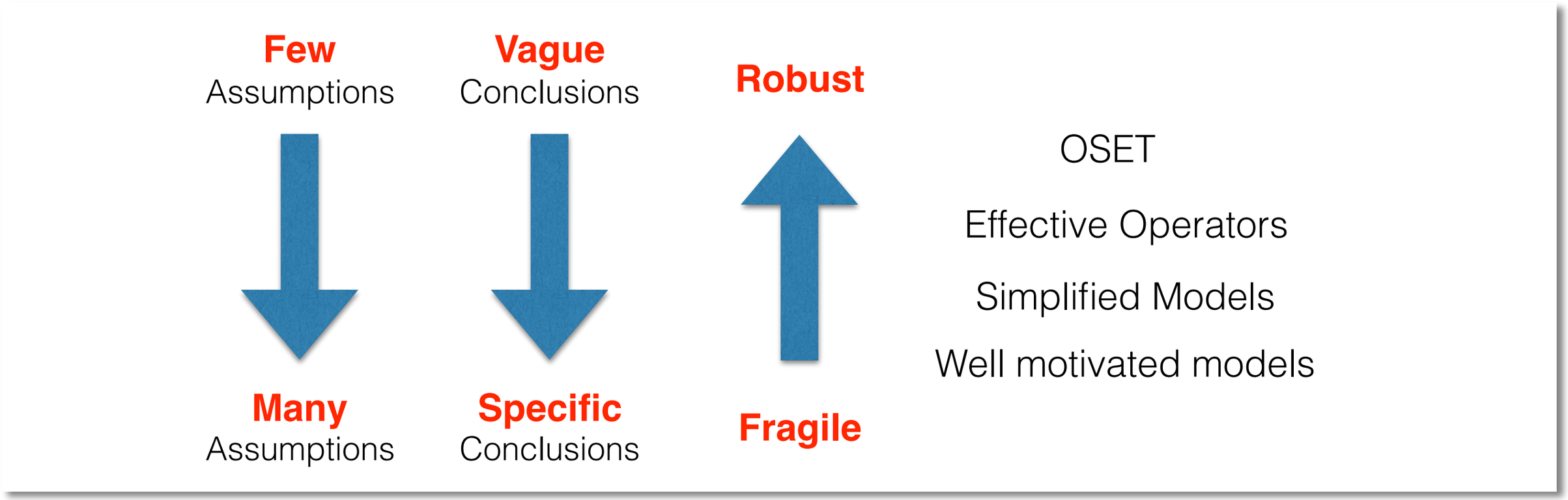
- We learned “what is NOT BSM.” and have a long way to go.

NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
TC-TC
composite Higgs
hypercolor
supercolor
technicolor
extended TC
pseudo NGB
6th gen
5th gen
4th gen
S.T.U
vector-like family
lepto quark
sterile ν
heavy Majorana
fractionally charged
shadow matter
mirror symmetry
MSSM +νR
NMSSM
unification
unmotivated SM
axigluon
Z'LR
Z'ψ
W'R
Z'SM
Z'χ
Z'η
X
Y
milli-charged
mono-pole
triplet Higgs
double charged Higgs
general 2HDSM
Type II
Type I
spontaneous CP
Majoron
axion
familon
NGB
superweak
milli-weak
Weinberg's 3HD
quintessence
K-essence
composite W,Z
contact
string
N=2
N=4
N=8
heterotic
IIB
IIA
M
F
I
extra dim

H. Murayama

How to Search for BSM

- There isn't a unique way. No right or wrong approach.
- Start with precision measurement of SM. Use Higgs / top quark.
- We have many "templates" for BSM physics.
- Well "motivated" models: Supersymmetry, extra dimensions, strong dynamics etc
- OSET: On-Shell Effective Theories (event topology with kinematics only)
- Effective Operators
- Simplified Models
- Alternatively, we propose a strategy for searching for theoretically-unanticipated new physics which avoids a large trials factor by focusing on experimental strengths. Searches for resonances decaying into pairs of visible particles are experimentally very powerful due to the localized mass peaks and have a rich history of discovery.
    - Yet, due to a focus on subsets of theoretically-motivated models, the landscape of such resonances is far from thoroughly explored.



- Well "motivated" models: Supersymmetry, extra dimensions, strong dynamics etc

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Unexplored Landscape of Two-Body Resonances

- Let us consider all possible combinations of two reconstructed objects (putting aside theoretical constraints.)

	e	μ	τ	γ	j	b	t	W	Z	h
e										
μ										
τ										
γ										
j										
b										
t										
W										
Z										
h										

Unexplored Landscape of Two-Body Resonances

- Let us consider all possible combinations of two reconstructed objects (putting aside theoretical constraints.)

	e	μ	τ	γ	j	b	t	W	Z	h
e	$Z', H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, e_{KK}	L^*
μ		$Z', H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, μ_{KK}	L^*
τ			$Z', H, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, τ_{KK}	L^*
γ			$H, G_{KK}, \mathcal{Q}$	Q^*	Q^*	Q^*	$W_{KK}, \mathcal{Q}$	$H, \mathcal{Q}$	Z_{KK}	
j				Z', ρ, G_{KK}	$W', \not{R}$	$T', \not{R}$	Q^*, Q_{KK}	Q^*, Q_{KK}	Q'	
b					Z', H	$W', \not{R}, H^{\pm}$	T', Q^*, Q_{KK}	Q^*, Q_{KK}	B'	
t						H, G', Z'	T'	T'	T'	
W							H, G_{KK}, ρ	$W', \mathcal{Q}$	$H^{\pm}, \mathcal{Q}, \rho$	
Z								H, G_{KK}, ρ	A, ρ	
h									H, G_{KK}	

TABLE II. Theory models motivating two-body final state resonance searches. Here Z' and W' denote additional gauge bosons, $\not{R}$ denotes R-parity violating decays of sparticles in supersymmetry, $H^{\pm\pm}$ denotes doubly-charged Higgs bosons, H denotes additional neutral scalar or pseudoscalar Higgs bosons, L^* and Q^* denote excited fermions, X_{KK} denote various Kaluza-Klein excitations of gravitons or Standard Model fields, ρ denotes neutral or charged techni-rhos, LQ denotes leptoquarks, T', B', Q' denote vector-like top, bottom, and light-flavor quarks, and $\mathcal{Q}$ denotes quirks. See also [38].

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Unexplored Landscape of Two-Body Resonances

	ℓ	γ	q	g	b	t	W^+	Z	h
ℓ	$(\mathbf{1},2)^*$	$[\mathbf{1},1]^*$	$(\bar{\mathbf{3}},{}^{1(4)}/_3)^{\diamondsuit\heartsuit}$	$[\mathbf{8},1]^*$	$(\bar{\mathbf{3}},{}^4/_3)^{\diamondsuit\heartsuit}$	$(\bar{\mathbf{3}},{}^1/_3)^{\diamondsuit\heartsuit}$	$[\mathbf{1},0]^*$	$[\mathbf{1},1]^*$	$[\mathbf{1},1]^*$
$\bar{\ell}$	$(\mathbf{1},0)$	$[\mathbf{1},-1]^*$	$(\bar{\mathbf{3}},-{}^{2(5^*)}/_3)^{\diamondsuit\heartsuit}$	$[\mathbf{8},-1]^*$	$(\bar{\mathbf{3}},-{}^2/_3)^{\diamondsuit\heartsuit}$	$(\bar{\mathbf{3}},-{}^5/_3)^*$	$[\mathbf{1},-2]^*$	$[\mathbf{1},-1]^*$	$[\mathbf{1},-1]^*$
γ	$[\mathbf{1},1]^*$	$(\mathbf{1},0)$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{8},0)$	$[\bar{\mathbf{3}},{}^1/_3]$	$[\bar{\mathbf{3}},-{}^2/_3]$	$(\mathbf{1},-1)$	$(\mathbf{1},0)$	$(\mathbf{1},0)$
q	$(\bar{\mathbf{3}},{}^{1(4)}/_3)^{\diamondsuit\heartsuit}$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{3},{}^{-1(2)(-4)}/_3)$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{3},{}^{-1(2)}/_3)$	$(\mathbf{3},{}^{-1(-4)}/_3)$	$[\bar{\mathbf{3}},-{}^{2(-5^*)}/_3]$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$
$\bar{q}$	$(\mathbf{3},{}^{2(5^*)}/_3)^{\diamondsuit\heartsuit}$	$[\mathbf{3},{}^{-1(2)}/_3]$	$(\mathbf{1}(\mathbf{8}),0(-1))$	$[\mathbf{3},{}^{-1(2)}/_3]$	$(\mathbf{1}(\mathbf{8}),0(-1))$	$(\mathbf{1}(\mathbf{8}),0(-1))$	$[\mathbf{3},{}^{-1(-4^*)}/_3]$	$[\mathbf{3},{}^{-1(2)}/_3]$	$[\mathbf{3},{}^{-1(2)}/_3]$
g	$[\mathbf{8},1]^*$	$(\mathbf{8},0)$	$[\bar{\mathbf{3}},{}^{1(-2)}/_3]$	$(\mathbf{1}(\mathbf{8}),0)$	$[\bar{\mathbf{3}},{}^1/_3]$	$[\bar{\mathbf{3}},-{}^2/_3]$	$(\mathbf{8},-1)$	$(\mathbf{8},0)$	$(\mathbf{8},0)$
b		$[\bar{\mathbf{3}},{}^1/_3]$	$(\mathbf{3},{}^{-1(2)}/_3)$	$[\bar{\mathbf{3}},{}^1/_3]$	$(\mathbf{3},{}^2/_3)$	$(\mathbf{3},-{}^1/_3)$	$[\bar{\mathbf{3}},-{}^2/_3]$	$[\bar{\mathbf{3}},{}^1/_3]$	$[\bar{\mathbf{3}},{}^1/_3]$
$\bar{b}$			$(\mathbf{1}(\mathbf{8}),0(-1))$	$[\mathbf{3},-{}^1/_3]$	$(\mathbf{1}(\mathbf{8}),0)$	$(\mathbf{1}(\mathbf{8}),-1)$	$[\mathbf{3},-{}^4/_3]^*$	$[\mathbf{3},-{}^1/_3]$	$[\mathbf{3},-{}^1/_3]$
t				$[\bar{\mathbf{3}},-{}^2/_3]$	$(\mathbf{3},-{}^1/_3)$	$(\mathbf{3},-{}^4/_3)$	$[\bar{\mathbf{3}},-{}^5/_3]^*$	$[\bar{\mathbf{3}},-{}^2/_3]$	$[\bar{\mathbf{3}},-{}^2/_3]$
$\bar{t}$					$(\mathbf{1}(\mathbf{8}),1)$	$(\mathbf{1}(\mathbf{8}),0)$	$[\mathbf{3},-{}^1/_3]$	$[\mathbf{3},{}^2/_3]$	$[\mathbf{3},{}^2/_3]$
W^+						$[\bar{\mathbf{3}},-{}^5/_3]^*$	$(\mathbf{1},-2)^*$	$(\mathbf{1},-1)$	$(\mathbf{1},-1)$
W^-							$(\mathbf{1},0)$	$(\mathbf{1},1)$	$(\mathbf{1},1)$
Z							$(\mathbf{1},0)$		$(\mathbf{1},0)$
h									$(\mathbf{1},0)$

( ): boson resonance

[ ]: fermionic resonance

$*$: no possible initial state at the LHC

$\diamondsuit$ $\Delta B = 1$
$\heartsuit$ $\Delta L = 1$
(if couples to q / g)

Possible (QCD, EM) quantum numbers of each 2-body resonance

indicates the existence of a resonant production via tree-level decay coupling, loop-induced processes involving the decay coupling, or the inclusion of additional couplings to quarks / gluons (allowed by quantum numbers).

indicate the leading production mode in association with 1, 2, 3 and 4 SM particles using the same coupling for production and decay (in 4 flavor scheme).

indicates the unavoidable existence of a pair production mode.

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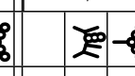
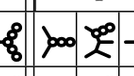
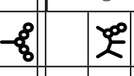
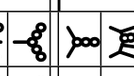
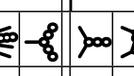
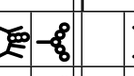
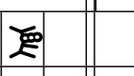
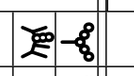
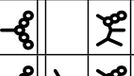
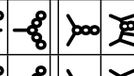
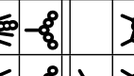
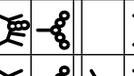
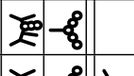
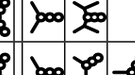
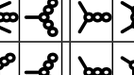
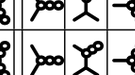
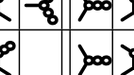
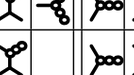
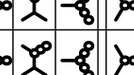
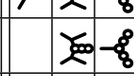
	ℓ	γ	q	g	b	t	W^+	Z	h
ℓ									
$\bar{\ell}$									
γ									
q									
$\bar{q}$									
g									
b									
$\bar{b}$									
t									
$\bar{t}$									
W^+									
W^-									
Z									
h									

Survey of n=2 Final State at the LHC

	e	μ	τ	γ	j	b	t	W	Z	h
e	$Z', H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, e_{KK}	L^*
μ		$Z', H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, μ_{KK}	L^*
τ			$Z', H, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, τ_{KK}	L^*
γ				$H, G_{KK}, \mathcal{Q}$	Q^*	Q^*	Q^*	$W_{KK}, \mathcal{Q}$	$H, \mathcal{Q}$	Z_{KK}
j					Z', ρ, G_{KK}	$W', \not{R}$	$T', \not{R}$	Q^*, Q_{KK}	Q^*, Q_{KK}	Q'
b						Z', H	$W', \not{R}, H^{\pm}$	T', Q^*, Q_{KK}	Q^*, Q_{KK}	B'
t					H, G', Z'	T'	T'	T'	T'	
W						H, G_{KK}, ρ	$W', \mathcal{Q}$	$H^{\pm}, \mathcal{Q}, \rho$		
Z							H, G_{KK}, ρ	A, ρ		
h								H, G_{KK}		

Survey of n=2 Final State at the LHC

	e	μ	τ	γ	j	b	t	W	Z	h
e										
μ										
τ										
γ										
j										
b										
t										
W										
Z										
h										

Survey of n=2 Final State at the LHC

	e	μ	τ	γ	j	b	t	W	Z	h
e	$\pm\mp$[4],$\pm\pm$[5]	$\pm\pm$[5, 6] $\pm\mp$[6, 7]	[7]	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$
μ		$\pm\mp$[4],$\pm\pm$[5]	[7]	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$
τ			[8]	$\varnothing$	$\varnothing$	$\varnothing$	[9]	$\varnothing$	$\varnothing$	$\varnothing$
γ				[10]	[11–13]	$\varnothing$	$\varnothing$	[14]	[14]	$\varnothing$
j					[15]	[16]	[17]	[18]	[18]	$\varnothing$
b						[16]	[19]	$\varnothing$	$\varnothing$	$\varnothing$
t						[20]	[21]	$\varnothing$	$\varnothing$	
W							[22–25]	[23, 24, 26, 27]	[28–30]	
Z								[23, 25, 31]	[28, 30, 32, 33]	
h									[34–37]	

- Existing two-body exclusive final state resonance searches at 7 and 8 TeV LHC, with striking features that most diagonal entries have existing searches, whereas most off-diagonal entries do not. (Numbers represent ATLAS/CMS references.)

- $\varnothing$ symbol indicates no existing searches at the LHC (7 and 8 TeV).

- No Tevatron analyses included. No 13 TeV analyses included.

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Survey of n=2 Final State at the LHC

	e	μ	τ	γ	j	b	t	W	Z	h
e	$\pm\mp$[4],$\pm\pm$[5]	$\pm\pm$[5, 6] $\pm\mp$[6, 7]	[7]	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$
μ		$\pm\mp$[4],$\pm\pm$[5]	[7]	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$
τ			[8]	$\varnothing$	$\varnothing$	$\varnothing$	[9]	$\varnothing$	$\varnothing$	$\varnothing$
γ				[10]	[11–13]	$\varnothing$	$\varnothing$	[14]	[14]	$\varnothing$
j					[15]	[16]	[17]	[18]	[18]	$\varnothing$
b						[16]	[19]	$\varnothing$	$\varnothing$	$\varnothing$
t							[20]	[21]	$\varnothing$	$\varnothing$
W								[22–25]	[23, 24, 26, 27]	[28–30]
Z									[23, 25, 31]	[28, 30, 32, 33]
h										[34–37]

- Existing two-body exclusive final state resonance searches at 7 and 8 TeV LHC, with striking features that most diagonal entries have existing searches, whereas most off-diagonal entries do not. (Numbers represent ATLAS/CMS references.)

- $\varnothing$ symbol indicates no existing searches at the LHC (7 and 8 TeV).

- No Tevatron analyses included. No 13 TeV analyses included.

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