Associated top+Higgs production with CMS

Lorenzo Bianchini
ETH Zürich

Sinergia Meeting, Dec. 17th 2015, EPFL

The quark Yukawa sector

The SM Yukawa sector: $\lambda_\psi \bar{\psi}_{\rm L} \psi_{\rm R} H + h.c.$

$$\lambda_\psi = \kappa_\psi \frac{\sqrt{2} m_\psi}{v}$$

=1 in SM

At the LHC, one measures:

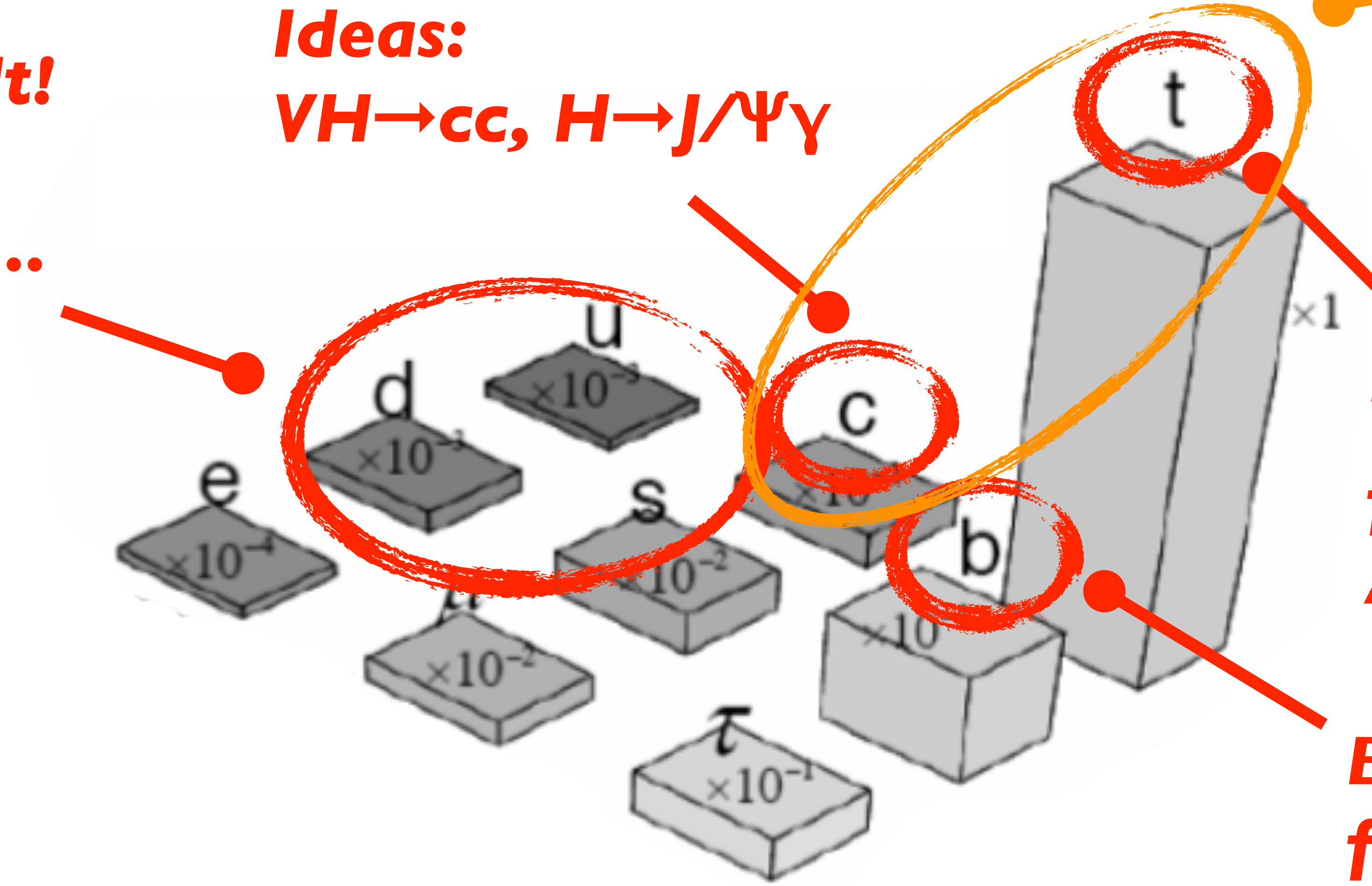
$$\sigma_{xx \to H} \times \mathcal{B}(H \to yy) \longrightarrow$$

- ***ratios of κ's***
- ***κ's*** *(+ model assumptions)*

Very difficult!
Ideas:
H→Φγ, ργ, ...

Difficult!
Ideas:
VH→cc, H→J/Ψγ

FCNC:
t→cH



Top quark:
from H production.
At hand!

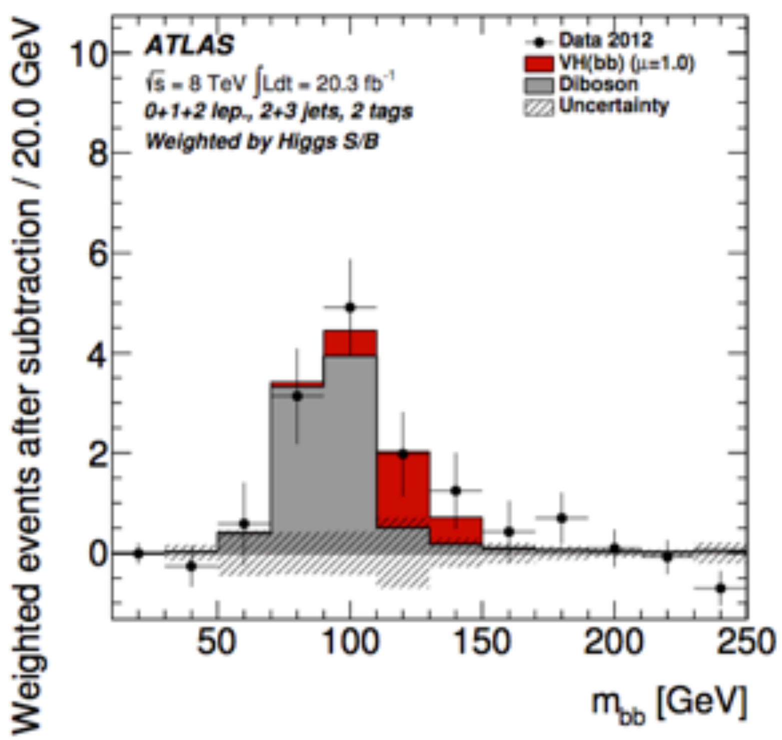
Bottom quark:
from H decay.
At hand!

3rd generation (b)

$(Z,W^{\pm})H \to bb$

- 0,1,2-leptons + jets

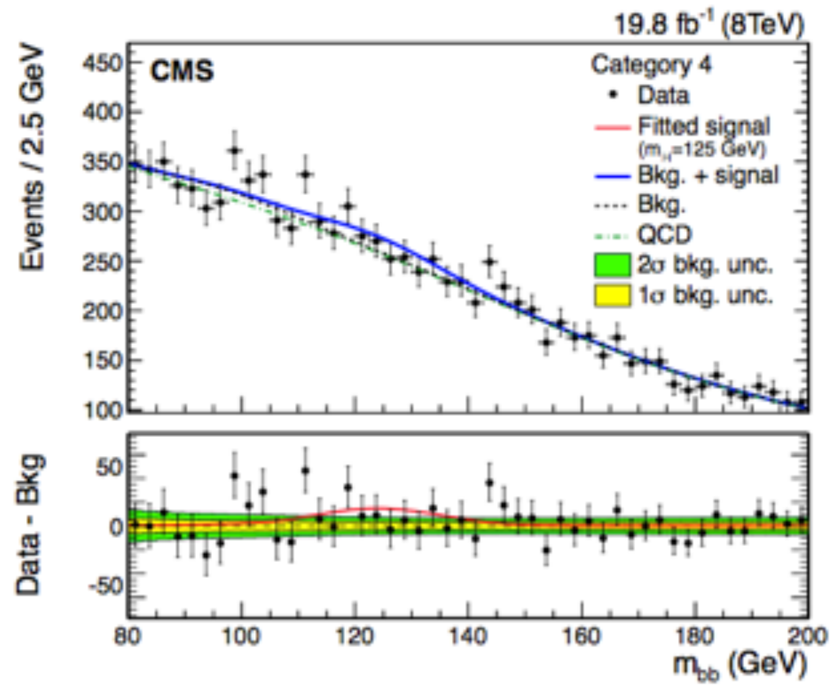
CMS, PRD 89 012003 (2014)
ATLAS, JHEP 01 (2015) 069



$VBF \to bb$

- 0 leptons + jets

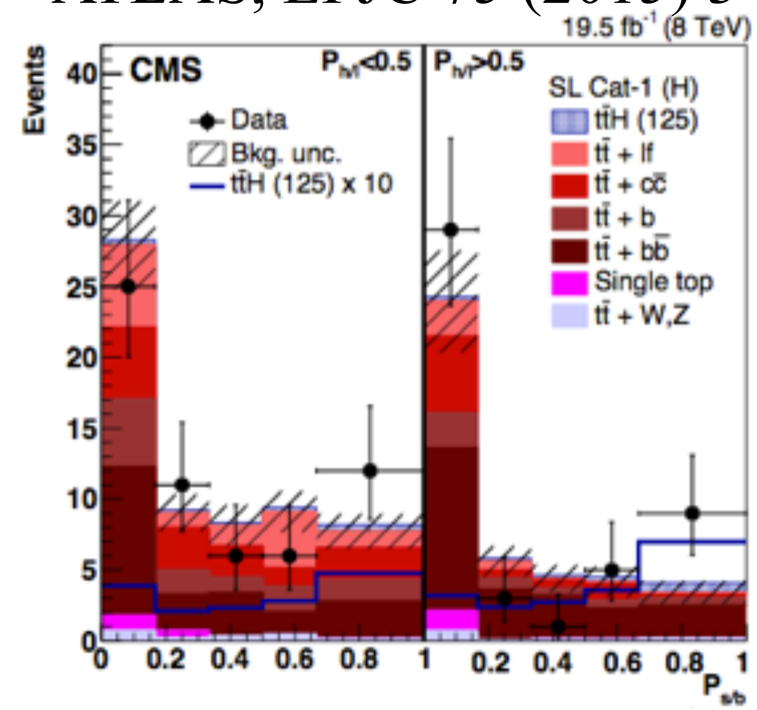
CMS, 1506.01010, *submitted to PRD*



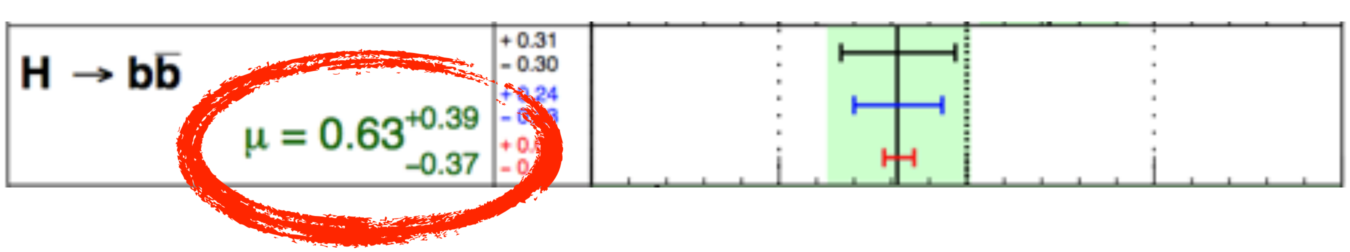
$ttH \to bb$

- 1-2 leptons + jets

CMS, JHEP 09 (2014) 087
CMS, EPJC 75 (2015) 212
ATLAS, EPJC 75 (2015) 349



ATLAS, arXiv:1507.04548, *submitted to EPJC*



CMS, arXiv:1506.01010, *submitted to PRD*

$H \to bb$ Channel	Best fit (68% CL) Observed	Upper limits (95% CL) Observed	Upper limits (95% CL) Expected	Signal significance Observed	Signal significance Expected
VH	0.89 ± 0.43	1.68	0.85	2.08	2.52
tt̄H	0.7 ± 1.8	4.1	3.5	0.37	0.58
VBF	$2.8^{+1.6}_{-1.4}$	5.5	2.5	2.20	0.83
Combined	$1.03^{+0.44}_{-0.42}$	1.77	0.78	2.56	2.70

2.6σ significance

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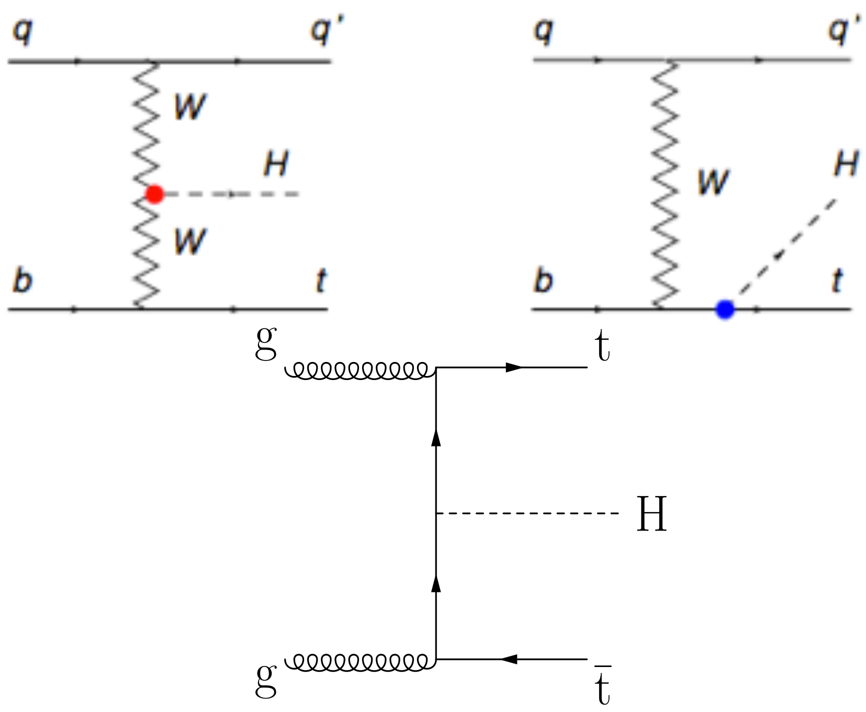
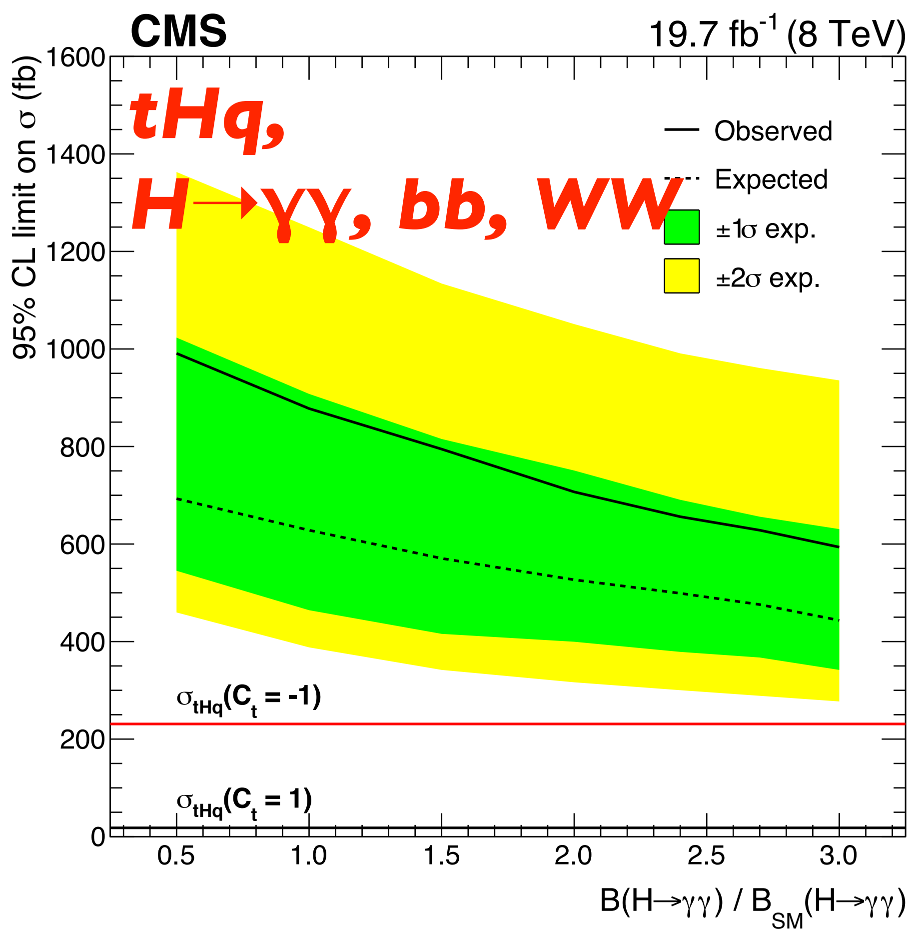
3rd generation (t)

The largest, *O*(1), coupling in the Yukawa sector

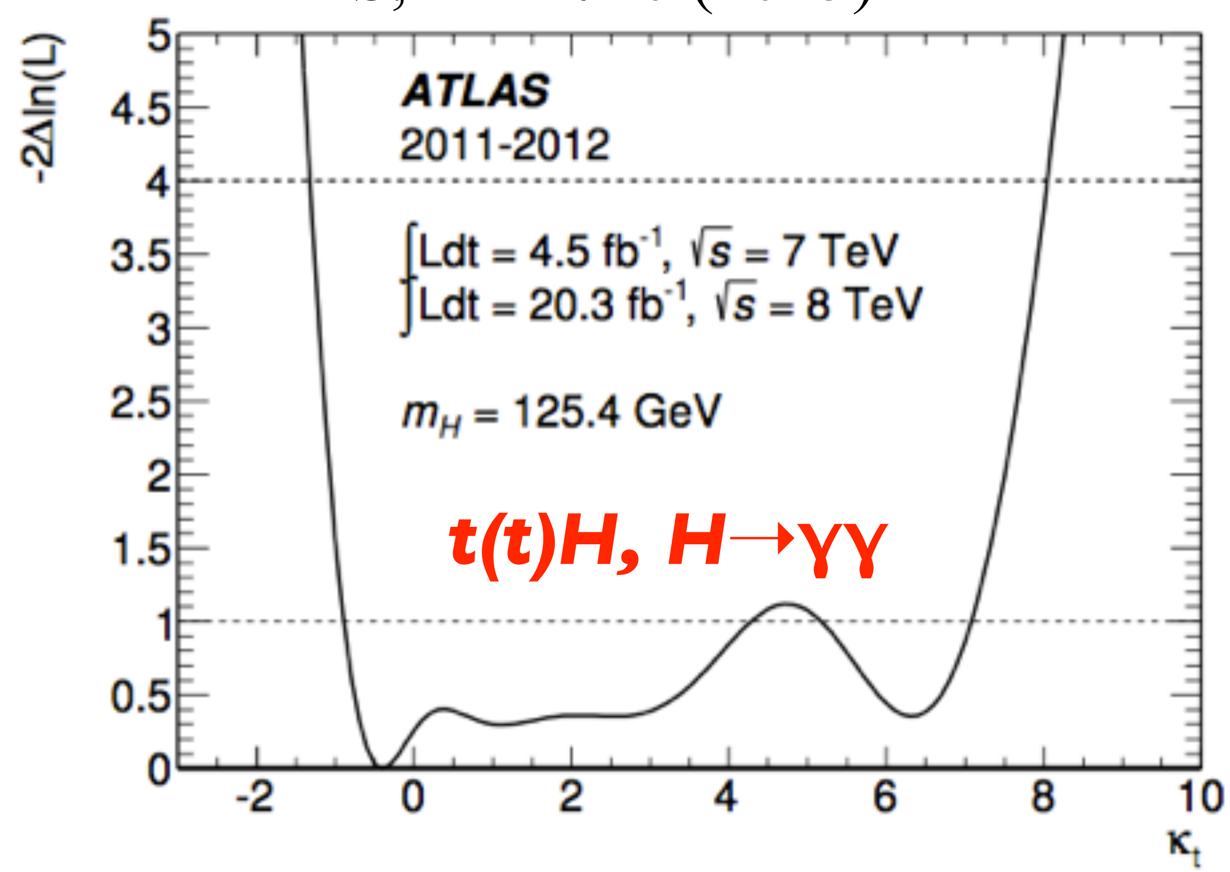
- no direct decay into top quarks
- tightest constraints from *GGF* and *BR(H→γγ)*
  - complement with direct measurement



CMS, arXiv:1509.08159, *submitted to JHEP*

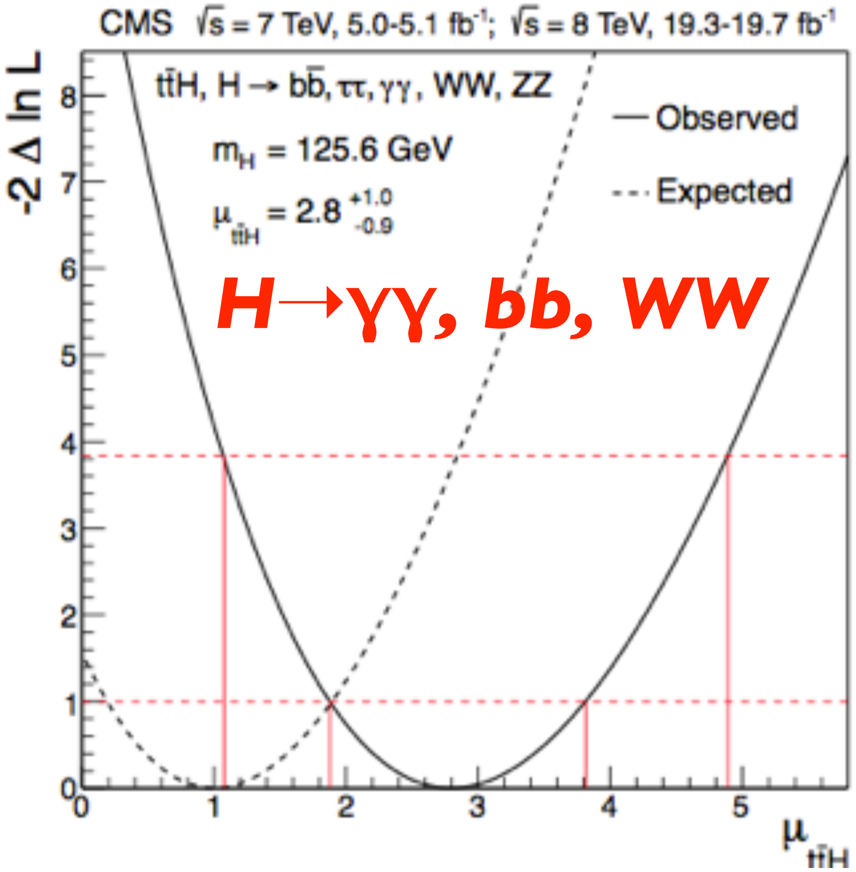


ATLAS, PLB 740 (2015) 222

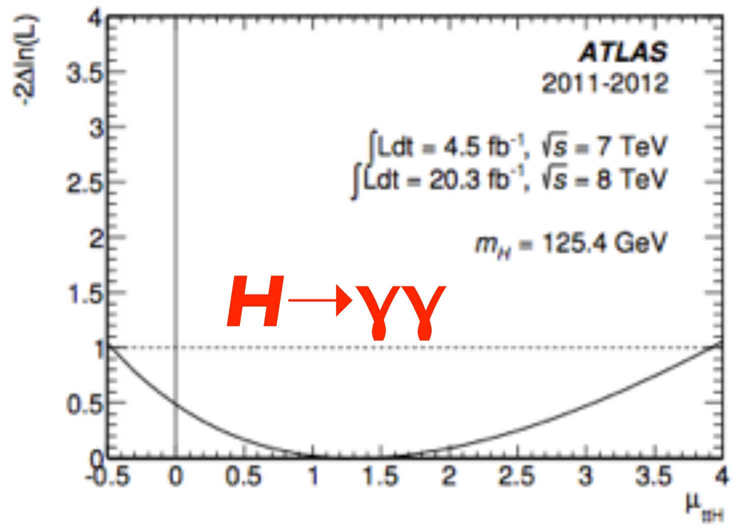


TTbar + Higgs

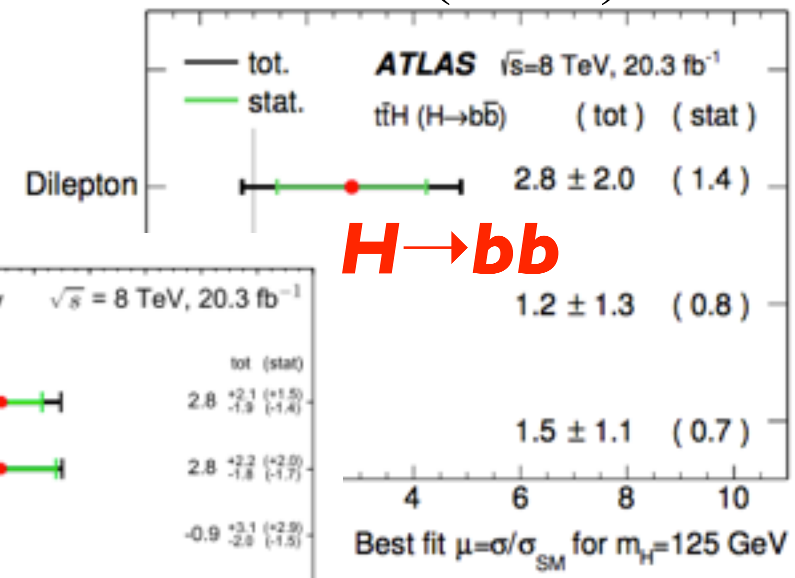
JHEP 09 (2014) 087

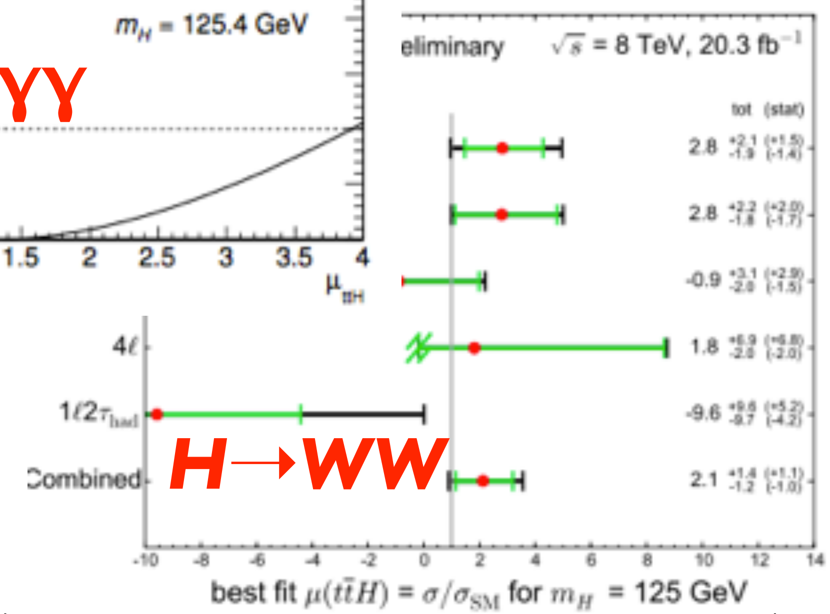


PLB 740 (2015) 222



EPJC 75 (2015) 349





arXiv:1506.05988,
accepted by PLB

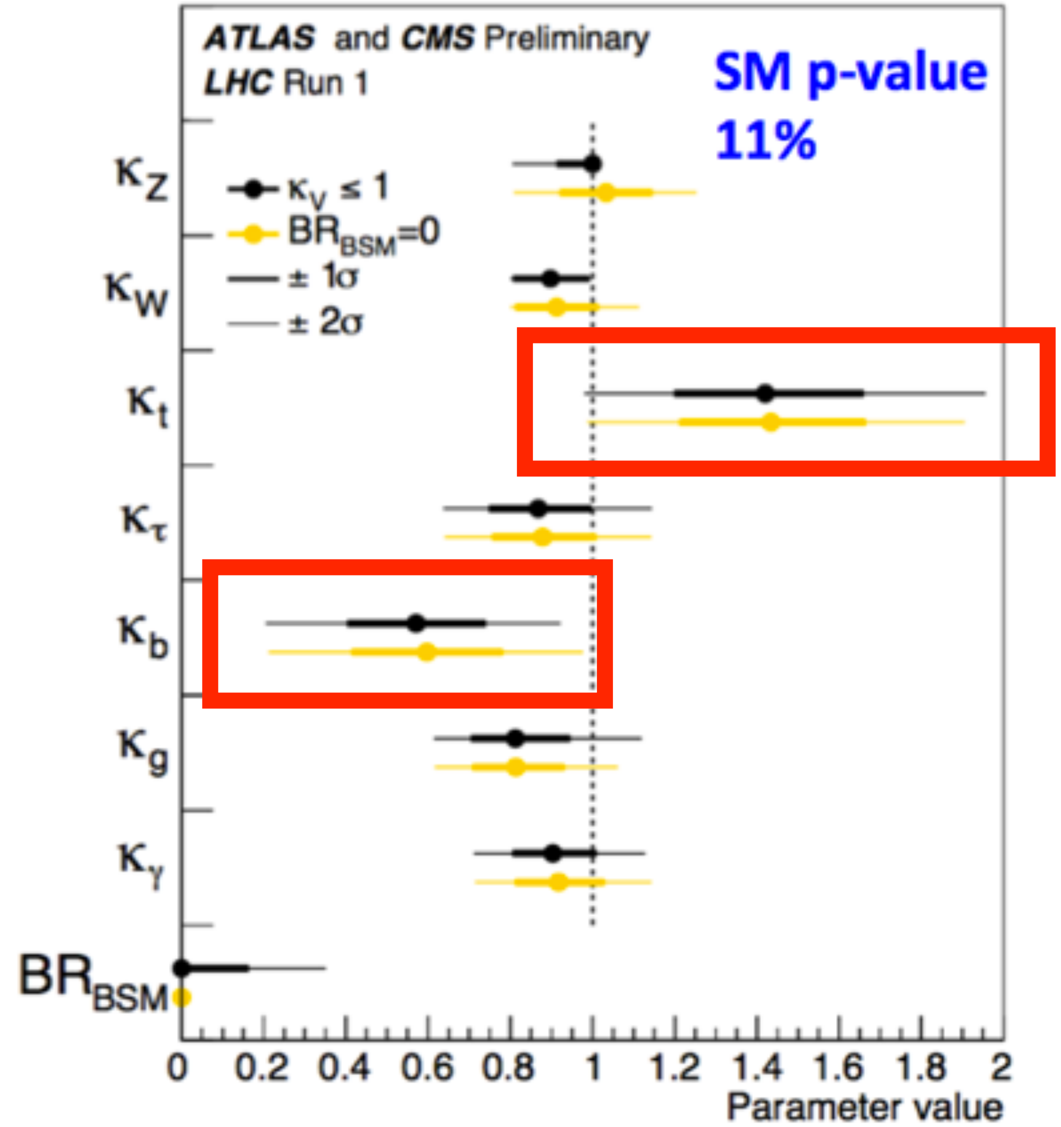
	Experiment	obs. (exp.) limit 95% CL	best-fit value (±1σ)
H → hadrons	CMS	< 4.1 (3.5)	$0.7^{+1.9}_{-1.9}$
	ATLAS	< 3.4 (2.2)	$1.5^{+1.1}_{-1.1}$
H → photons	CMS	< 7.4 (4.7)	$2.7^{+2.6}_{-1.8}$
	ATLAS	< 6.7 (4.9)	$1.4^{+2.1}_{-1.4}$
H → leptons	CMS	< 6.6 (2.4)	$3.7^{+1.6}_{-1.4}$
	ATLAS	< 4.7 (2.4)	$2.1^{+1.4}_{-1.2}$

ATLAS+CMS: Run I legacy

7+8 TeV "grand combination" of ATLAS+CMS. Largest pulls:

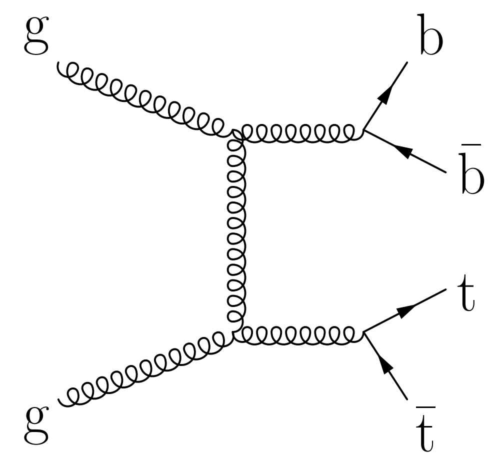
- $\sigma(ttH)$ at **2.3σ** from SM
- BR^{bb}/BR^{ZZ} at **2.4σ** from SM

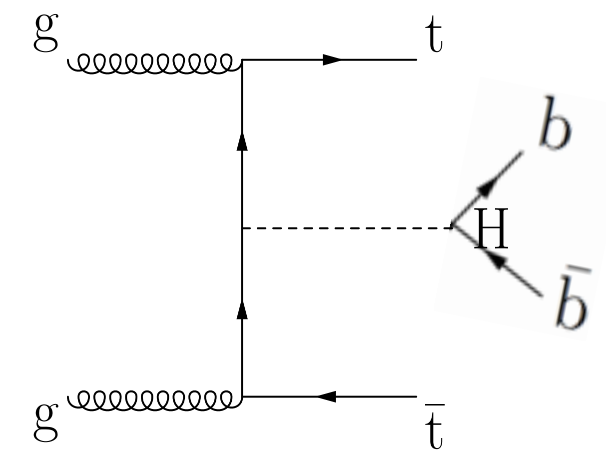
Production process	Observed Significance(σ)	Expected Significance (σ)
VBF	**5.4**	**4.7**
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
H→ττ	**5.5**	**5.0**
H→bb	2.6	3.7



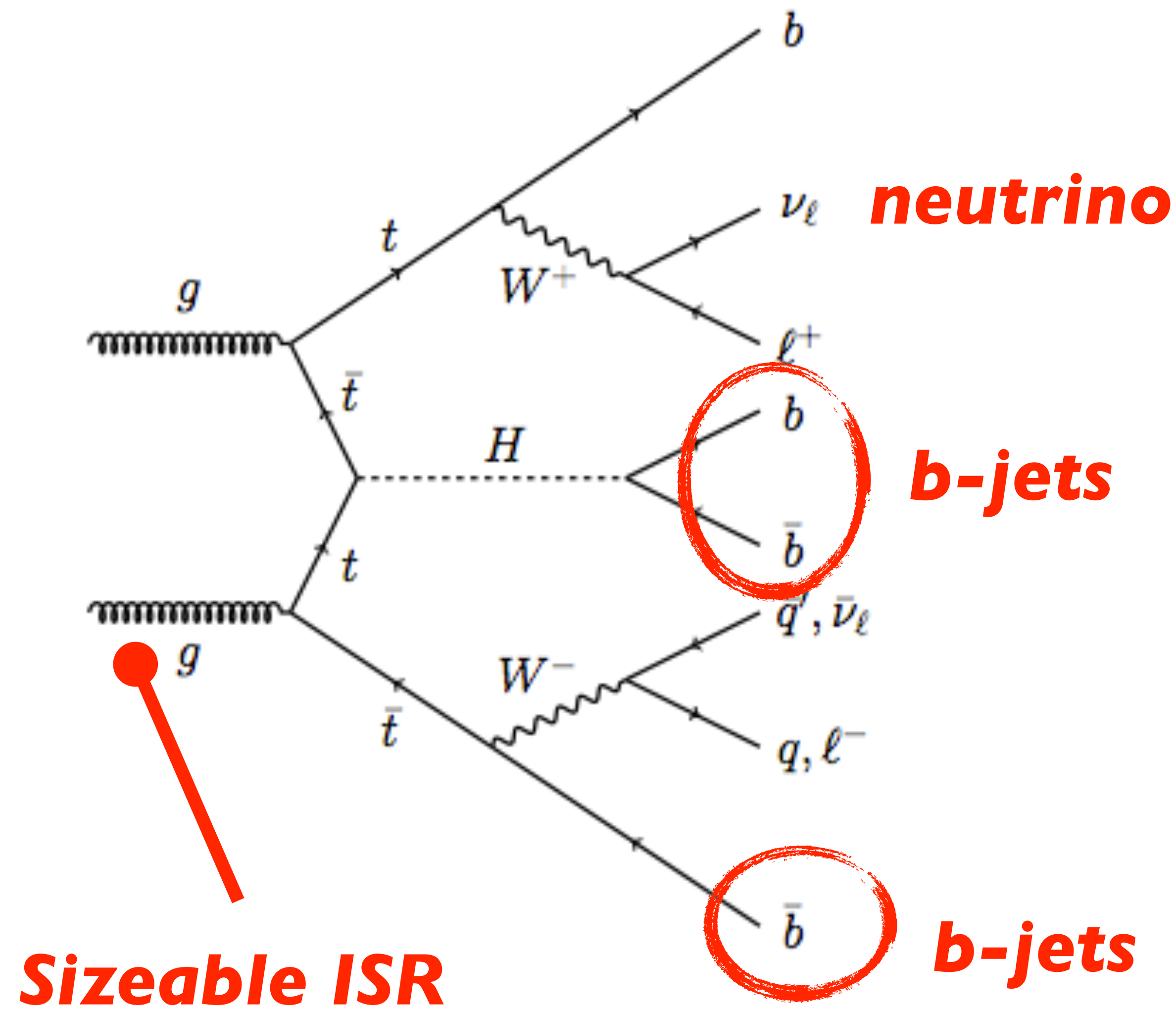
Search for ttH→bb

- Challenges:
  - large irreducible background
    - same final state, similar diagrams
  - combinatorial background
    - not just a bump hunting
  - jets not always come from top/ Higgs decay
    - allow for ISR jets and partial event reconstruction





Pursue an analysis strategy based on an analytical Matrix Element Method



CMS-PAS-HIG-14-010

CMS, EPJC 75 (2015) 212

General formulation of the MEM

Assign each reconstructed event with its probability:

$$\text{Prob}\{\vec{y} \in [\vec{y}_0, \vec{y}_0 + d\vec{y}] \mid S, \theta\} = p_S(\vec{y}_0; \theta) d\vec{y}$$

$$\int_{\mathcal{A}} p_S(\vec{y}\,; \theta) d\vec{y} = 1$$

- (normalised) differential cross section: $p_S(\vec{y}\,;\theta) = \frac{1}{\sigma_S(\theta)} \frac{d\sigma_S}{d\vec{y}}(\vec{y}\,;\theta)$

$$d\sigma_S(\vec{y}\,;\theta) = \left[\int d\Phi(\vec{x}) dx_a dx_b \sum_{i,j} \frac{f_i(x_a) f_j(x_b)}{(1+\delta_{ij}) x_a x_b s} |\mathcal{M}_S(\vec{x}, \theta)|^2 W(\vec{y}, \vec{x}; \theta) \right] d\vec{y}$$

$$\prod_i \frac{d^3\vec{p}_i}{(2\pi)^3 2E_i}$$

Numerical integration (e.g. VEGAS***)***

Parton density functions (e.g. LHAPDF***)***

Scattering amplitude (e.g. MCFM, MG5***)***

Detector transfer function (MC simulation)

General formulation of the MEM

Assign each reconstructed event with its probability:

$$\mathrm{Prob}\{\vec{y} \in [\vec{y}_0, \vec{y}_0 + d\vec{y}] \mid S, \theta\} = p_S(\vec{y}_0; \theta) d\vec{y} \qquad \int_{\mathcal{A}} p_S(\vec{y}\,; \theta) d\vec{y} = 1$$

- (normalised) differential cross section: $$p_S(\vec{y}\,;\theta) = \frac{1}{\sigma_S(\theta)} \frac{d\sigma_S}{d\vec{y}}(\vec{y}\,;\theta)$$

$$d\sigma_S(\vec{y}\,;\theta) = \left[\int d\Phi(\vec{x}) dx_\mathrm{a} dx_\mathrm{b} \sum_{i,j} \frac{f_i(x_\mathrm{a}) f_j(x_\mathrm{b})}{(1+\delta_{ij}) x_\mathrm{a} x_\mathrm{b} s} |\mathcal{M}_S(\vec{x}, \theta)|^2 W(\vec{y}, \vec{x}; \theta) \right] d\vec{y}$$

- multi-channel processes: $$p(\vec{y}\,;\theta) = \lambda_S(\theta) p_S(\vec{y}\,;\theta) + \sum_j \lambda_{Bj} p_{Bj}(\vec{y})$$

- sample likelihood: $$\mathcal{L}(\vec{y}\,;\theta) = \left[\prod_{i=1}^{N} p(\vec{y}_i\,;\theta) \right] \frac{e^{-\mathcal{N}(\theta)} \mathcal{N}(\theta)^N}{N!}$$

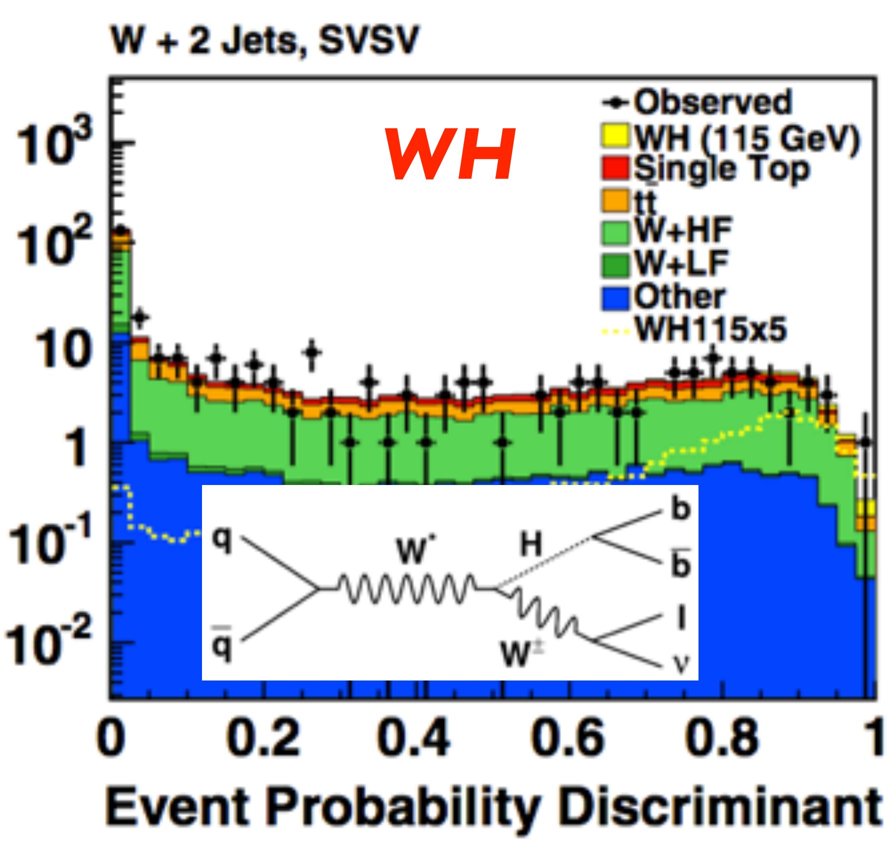
MEM for hypothesis testing

Ratio of MEM probability densities is a powerful test statistic

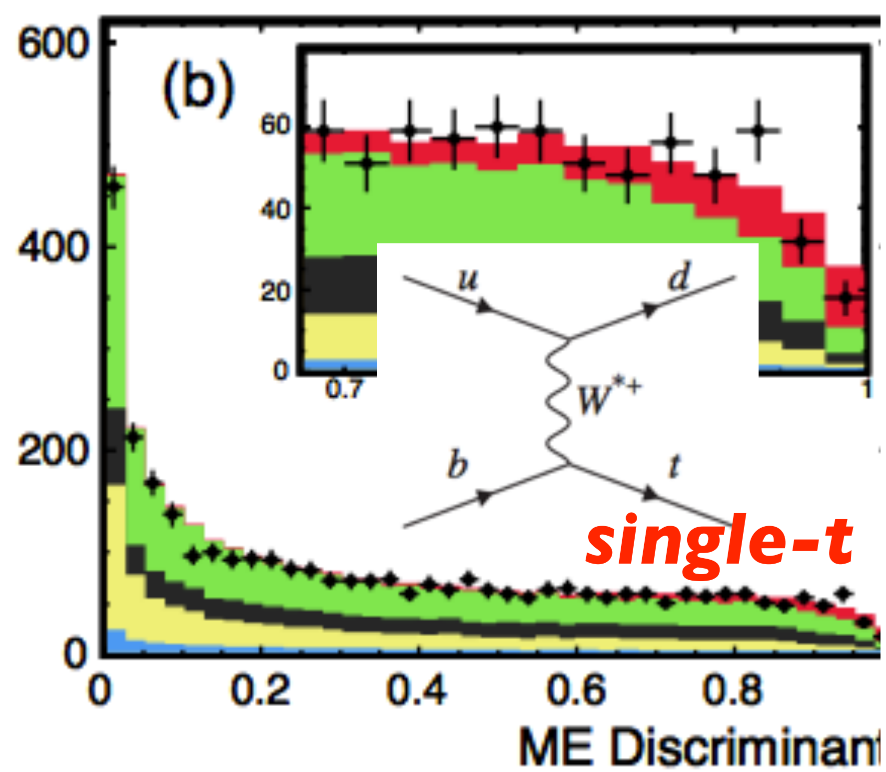
- optimal properties (largest power at fixed error) L. Neyman, Phil. Trans. Royal Soc. London 236 (1937) 333

$$\mathrm{LR} = \frac{\lambda_S p_S}{\sum_j \lambda_{B_j} p_{B_j}} \quad \text{or} \quad \frac{1}{1+\mathrm{LR}} \in [0,1]$$

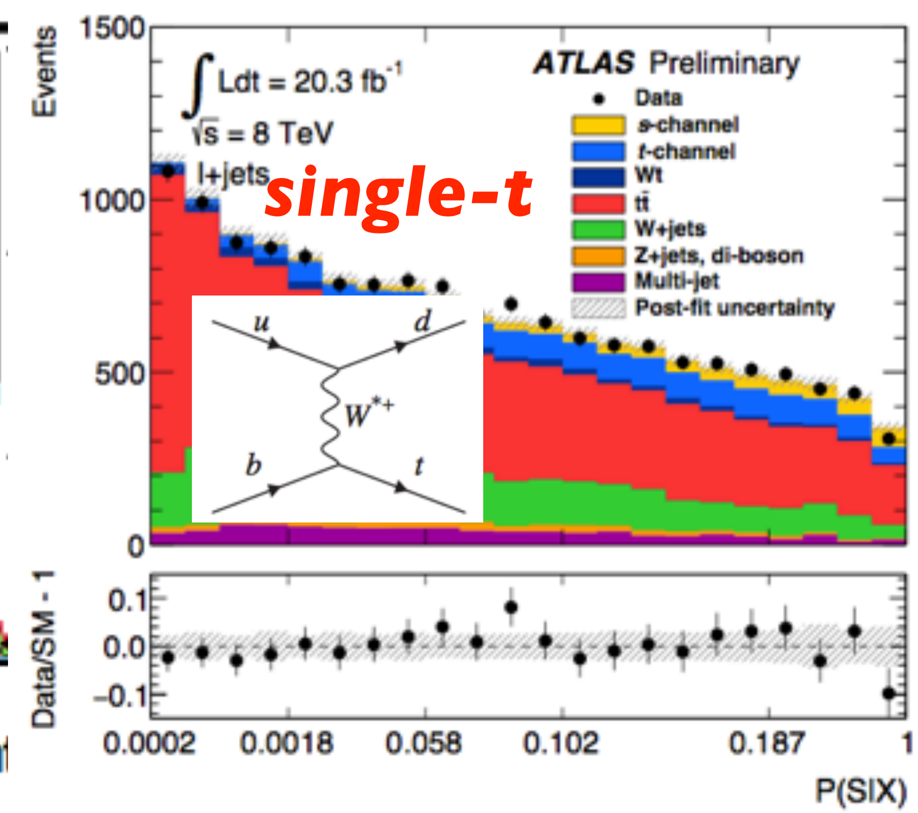
CDF, PRD 85 072001 (2012)



CDF, PRL 103 (2009) 092002



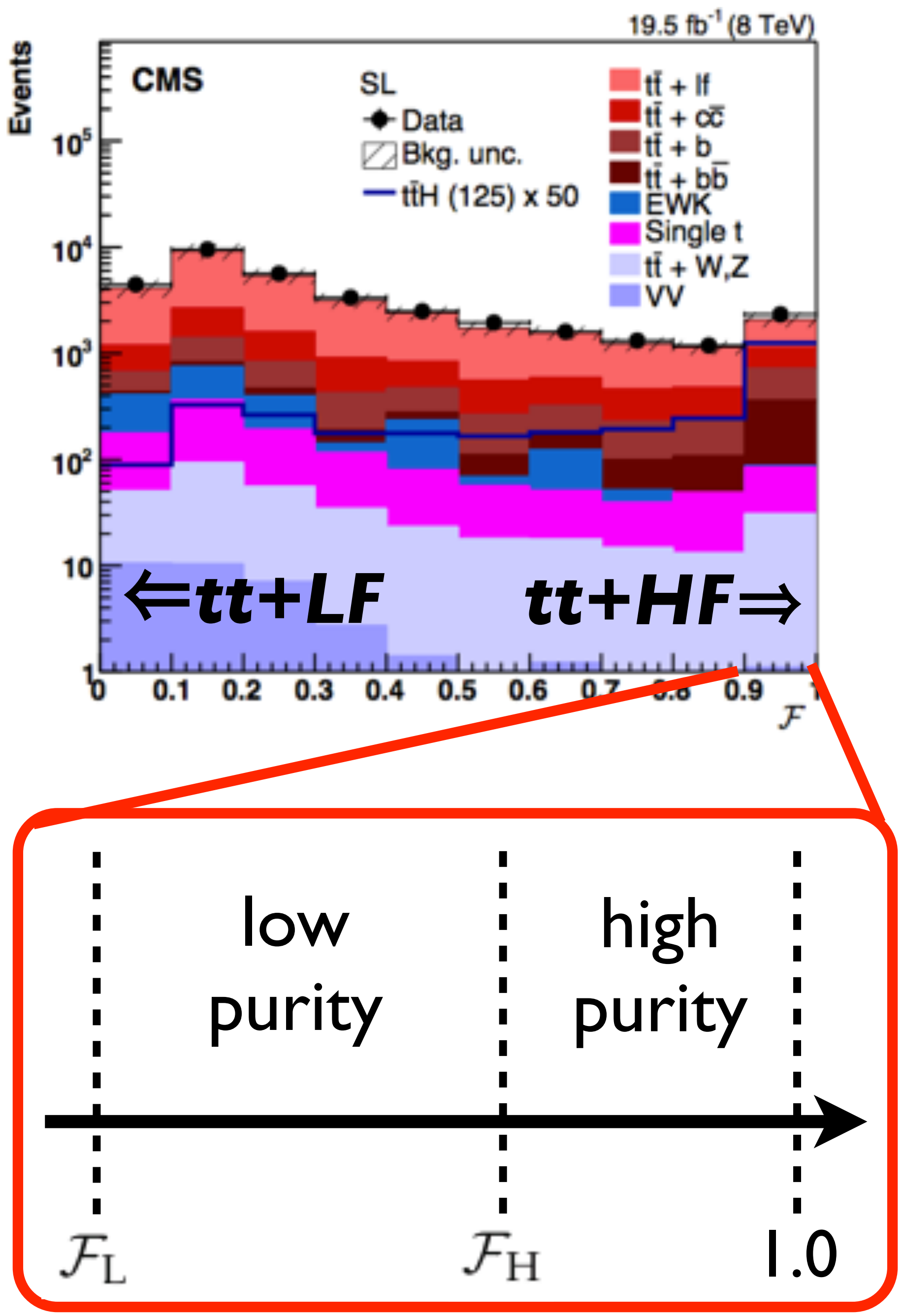
ATLAS-CONF-2015-047



Analysis strategy

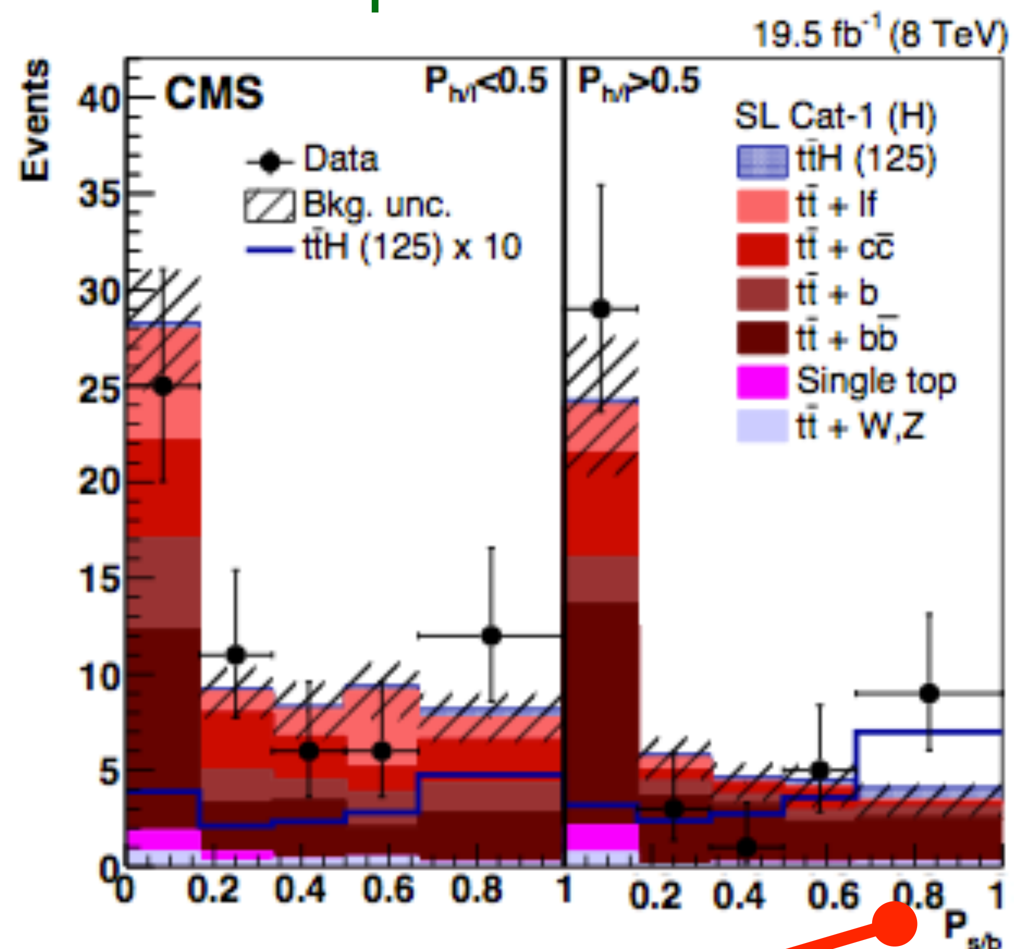
Select high-purity events

- use only b-tag values of jets



Fit full MEM discriminant shape

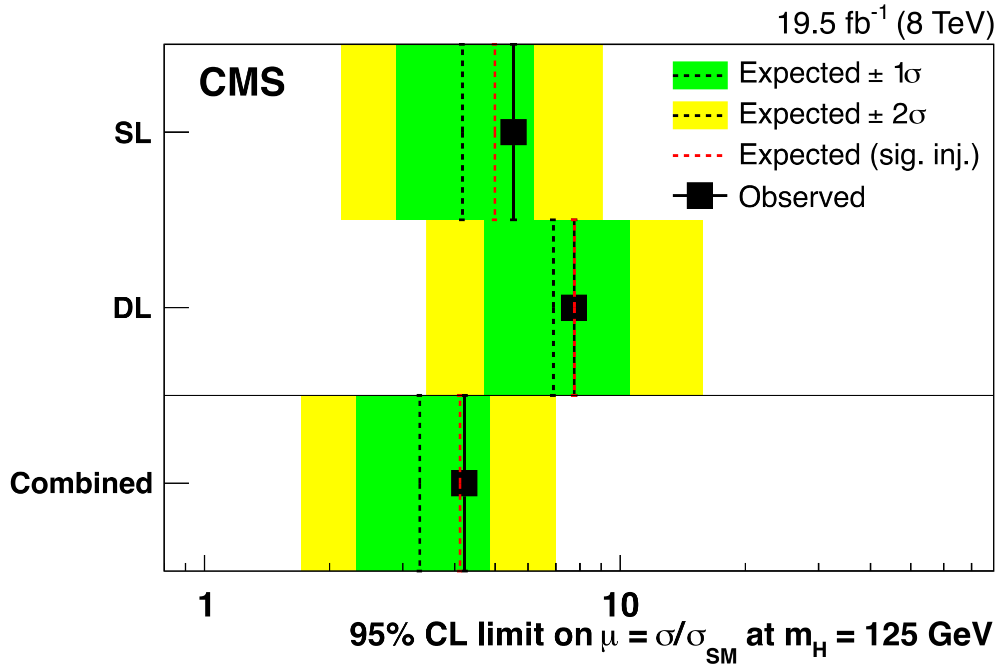
- split into categories of "event interpretation":
  - SL & full reconstruction
  - SL & incomplete reconstruction
  - dileptonic

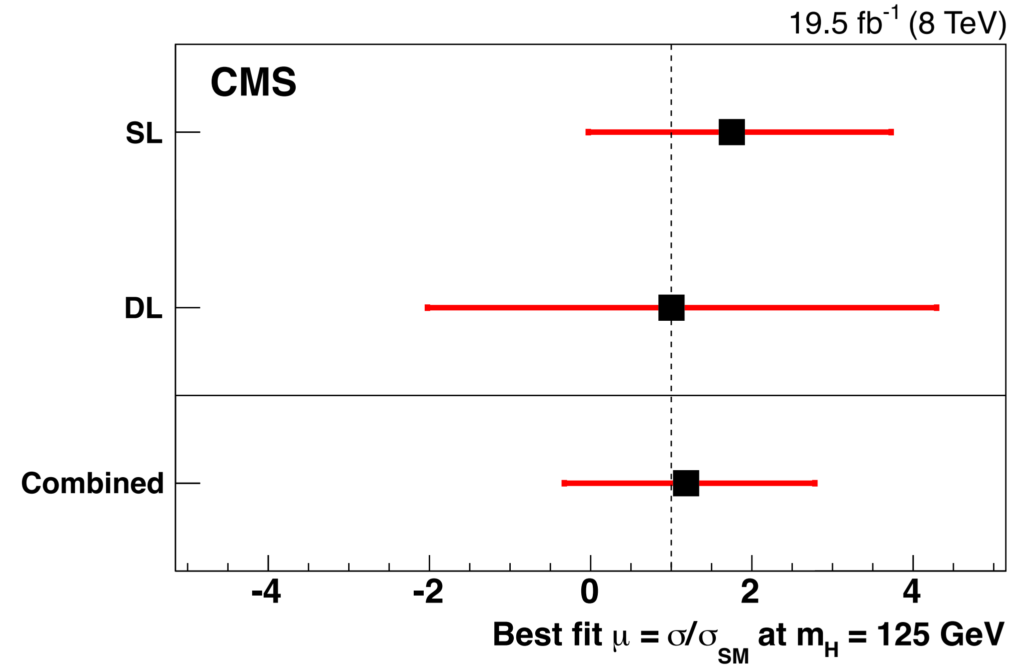


$P_{s/b}$ = [1 + p(tt+bb)/p(ttH)]$^{-1}$

CMS, EPJC 75 (2015) 212

Results: 8 TeV





Channel	Best-fit μ	Observed UL	Median exp. UL (signal injected)	Median exp. UL (background only)	$\pm 1\sigma$ CL interval	$\pm 2\sigma$ CL interval
SL	$+1.7^{+2.0}_{-1.8}$	5.5	5.0	4.2	[2.9, 6.2]	[2.1, 9.1]
DL	$+1.0^{+3.3}_{-3.0}$	7.7	7.8	6.9	[4.7, 10.6]	[3.4, 15.8]
Combined	$+1.2^{+1.6}_{-1.5}$	4.2	4.1	3.3	[2.3, 4.9]	[1.7, 7.0]

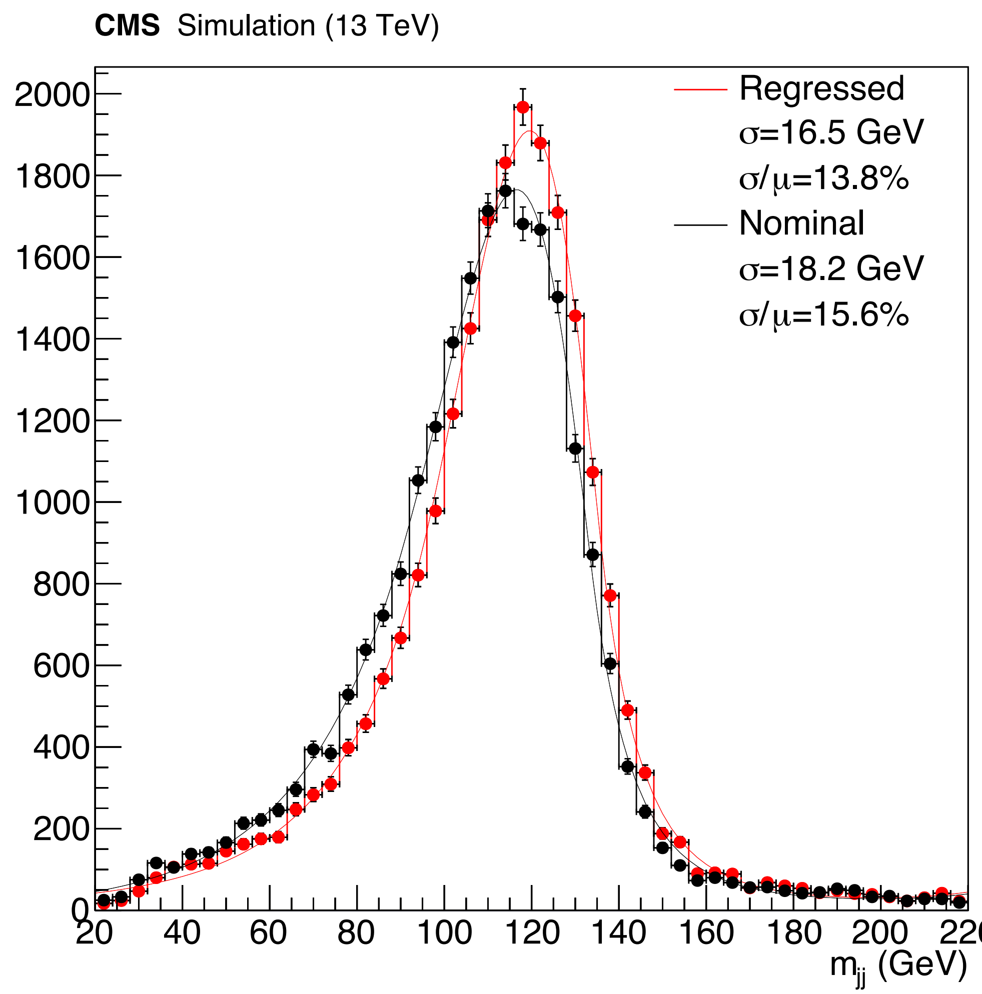
Key feature:

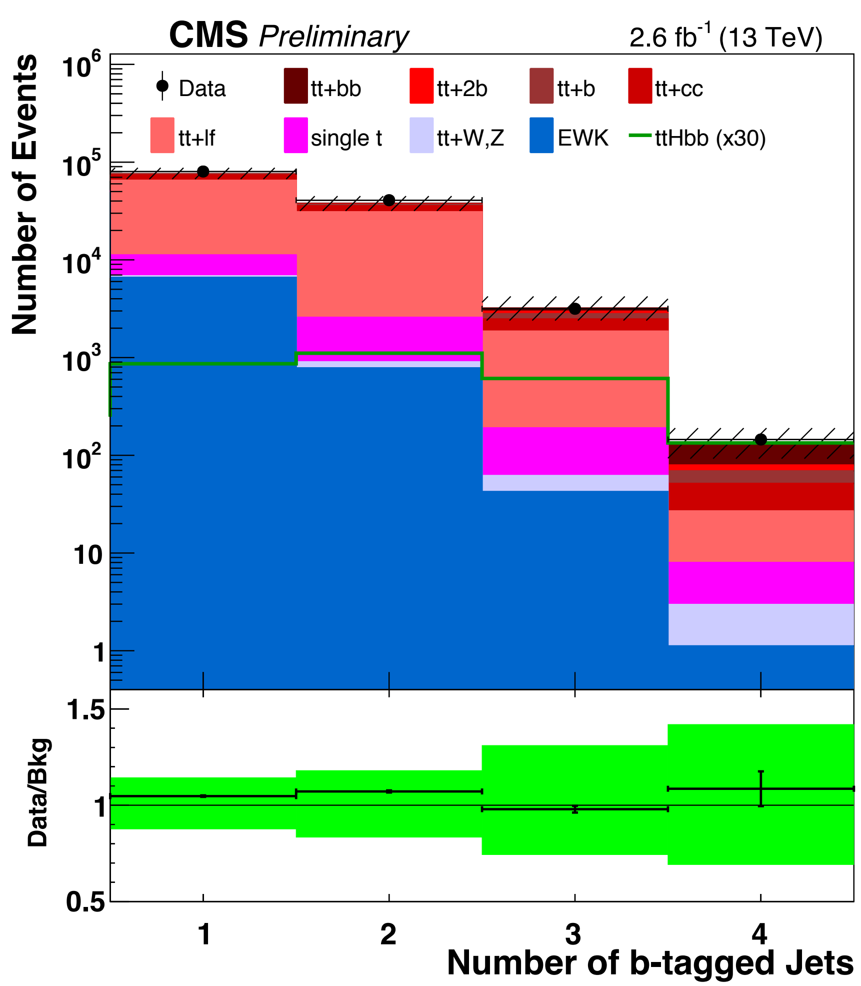
- large ttbb/ttH separation => less sensitivity to ttbb normalisation
  - less sentitive to *a priori* tt+bb theory uncertainty
  - after-fit, tt+bb uncertainty is ~20%

CMS, EPJC 75 (2015) 212

Looking ahead: Run 2

- New MC simulations
  - NLO generators, new parton-showers (PY8), new tunes.
    - under validation
- Detector calibration
  - b-jet energy regression, b-tagging SF
    - well progressed

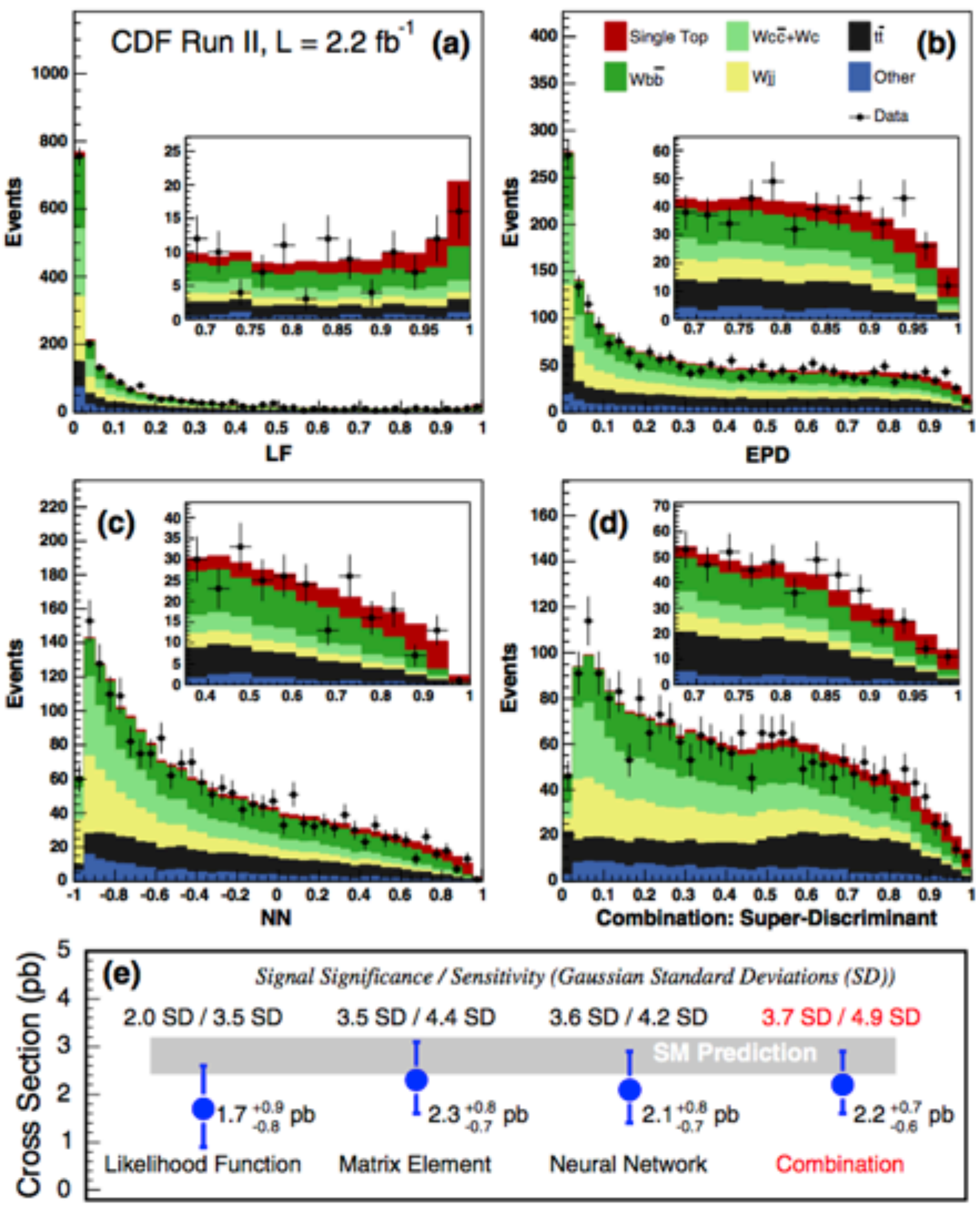




- Recent ETH+UZH activity:
  - new b-tagger (~30% less fake rate)
  - fully hadronic ttH
  - boosted top tagging
  - extending MEM using neural-networks

MEM meets aNN

CDF, PRL 101 (2008) 252001



σ(single-t): 10% improvement compared to single-best discr.

ATLAS, EPJC 75 (2015) 349

Variable	Definition	NN rank			
		$\geq 6j, \geq 4b$	$\geq 6j, 3b$	$5j, \geq 4b$	$5j, 3b$
$D1$	Neyman–Pearson MEM discriminant (Eq. (4))	1	10	-	-
Centrality	Scalar sum of the p_T divided by sum of the E for all jets and the lepton	2	2	1	-
p_T^{jet5}	p_T of the fifth leading jet	3	7	-	-
$H1$	Second Fox–Wolfram moment computed using all jets and the lepton	4	3	2	-
ΔR_{bb}^{avg}	Average ΔR for all b-tagged jet pairs	5	6	5	-
SSLL	Logarithm of the summed signal likelihoods (Eq. (2))	6	4	-	-
$m_{bb}^{min\ \Delta R}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	7	12	4	4
$m_{bj}^{max\ p_T}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_T	8	8	-	-
$\Delta R_{bb}^{max\ p_T}$	ΔR between the two b-tagged jets with the largest vector sum p_T	9	-	-	-
$\Delta R_{lep-bb}^{min\ \Delta R}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	10	11	10	-
$m_{uu}^{min\ \Delta R}$	Mass of the combination of the two untagged jets with the smallest ΔR	11	9	-	2
Aplan$_{b-jet}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor[92] built with only b-tagged jets	12	-	8	-
N_{40}^{jet}	Number of jets with $p_T \geq 40GeV$	-	1	3	-
$m_{bj}^{min\ \Delta R}$	Mass of the combination of a b-tagged jet and any jet with the smallest ΔR	-	5	-	-
$m_{jj}^{max\ p_T}$	Mass of the combination of any two jets with the largest vector sum p_T	-	-	6	-
H_T^{had}	Scalar sum of jet p_T	-	-	7	-
$m_{jj}^{min\ \Delta R}$	Mass of the combination of any two jets with the smallest ΔR	-	-	9	-
$m_{bb}^{max\ p_T}$	Mass of the combination of the two b-tagged jets with the largest vector sum p_T	-	-	-	1
$p_{T,uu}^{min\ \Delta R}$	Scalar sum of the p_T of the pair of untagged jets with the smallest ΔR	-	-	-	3
$m_{bb}^{max\ m}$	Mass of the combination of the two b-tagged jets with the largest invariant mass	-	-	-	5
$\Delta R_{uu}^{min\ \Delta R}$	Minimum ΔR between the two untagged jets	-	-	-	6
m_{jjj}	Mass of the jet triplet with the largest vector sum p_T	-	-	-	7

ttH: combination of MEM discriminant + other variables using an artificial NN

Looking (even more) ahead

ATL-PHYS-PUB-2014-016
CMS-NOTE-13-002

* [no theory, full theory]

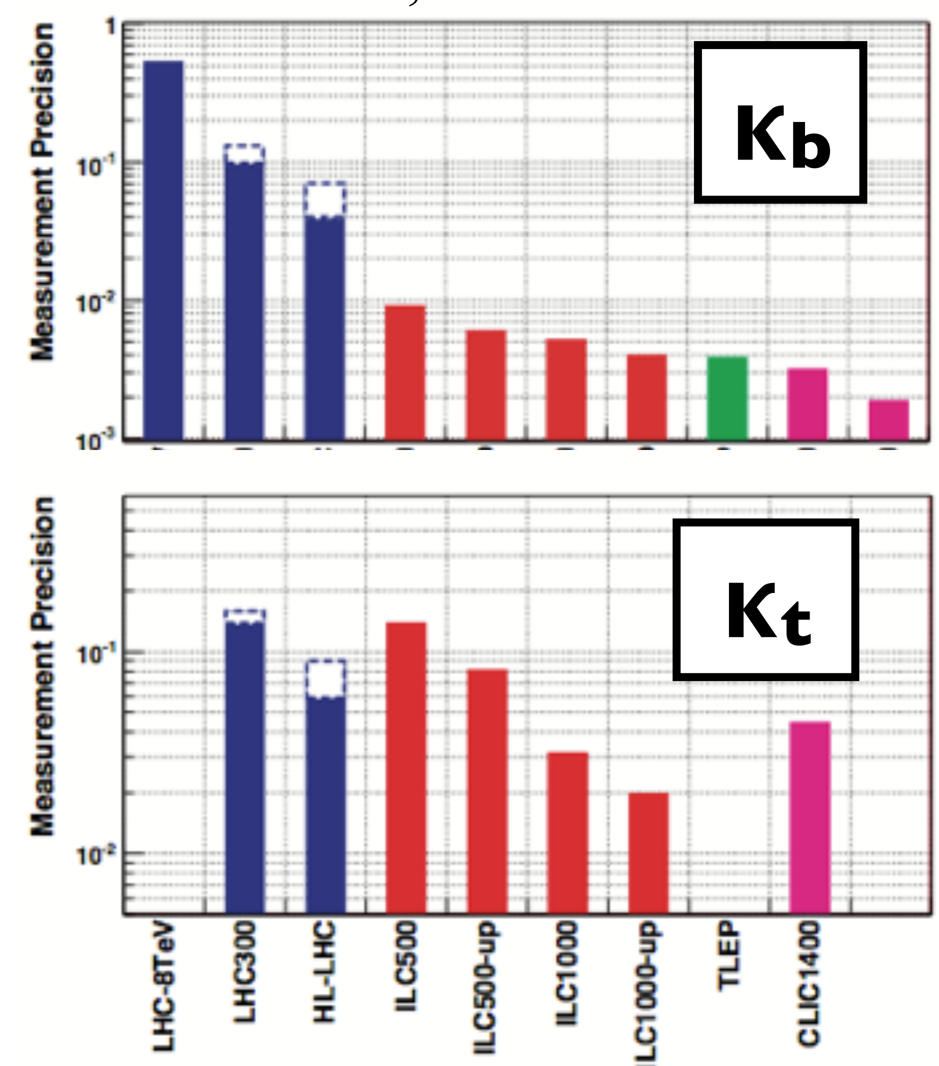
**[1/2 theory & 1/√L sys., Run 1 syst.]

	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ	BR_{BSM}
*ATLAS**	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]	[10,14]
*CMS***	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]	[7,11]

Optimistic scenario:

	$\delta\kappa/\kappa$	
κ_V, κ_γ	**3%**	**Gauge bosons**
κ_b	**4%**	**Bottom Yukawa**
κ_t	**5%**	**Top Yukawa**
κ_τ	**3%**	**Leptons**
κ_μ	**5%**	**2nd family**

Snowmass, arXiv:1310.8361



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Conclusions

- Released our ttH→bb search with Run 1 data
  - proof of principle of the method
    - a few spin-offs inside CMS
  - very performing, but not yet sensitive to SM

- Run 1 showed overall agreement with SM Higgs hypothesis
  - but not all channels measured with conclusive evidence yet
    - no evidence of H→bb: a ~2σ under-fluctuation?
    - "unexpected" evidence of ttH: a ~2.3σ over-fluctuation?

- We are continuing our effort on ttH→bb
  - detector commissioning is done
  - consolidating new improvements
  - first preliminary results by Moriond2016
    - 2015 data alone is like adding ~20% sensitivity to Run 1
    - need ~15 fb^{-1} to reach 3σ ⟺ end of 2016

Back up

1^{st} and 2^{nd} generation

- H → cc challenging at LHC
  - recast VH→bb analysis into VH→cc

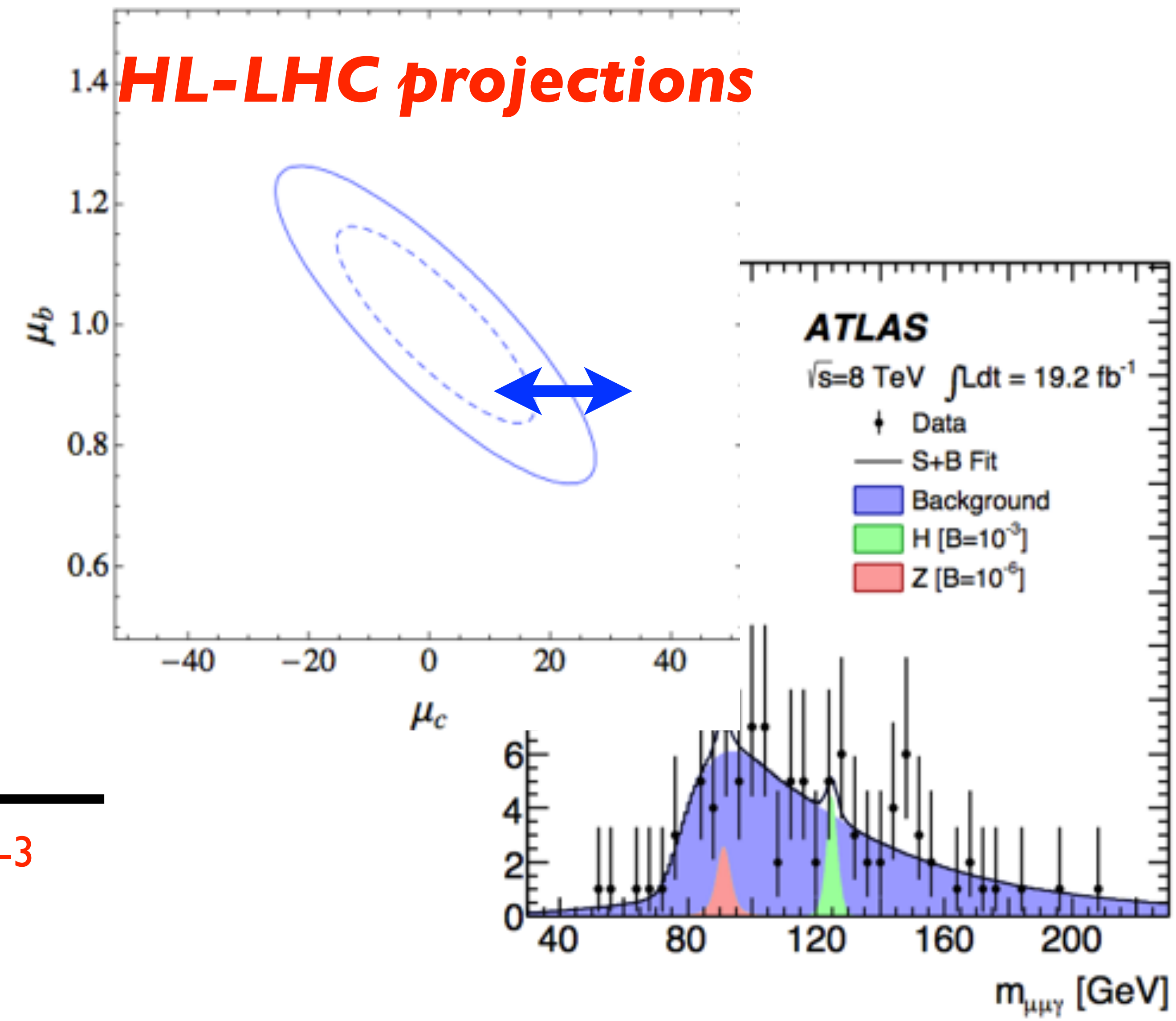
$$\mu_b = \frac{\sigma \mathrm{BR}_b}{[\sigma \mathrm{BR}_b]^{\mathrm{SM}}} \to \mu_b + \left(\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\right)\frac{\mathrm{BR}_c^{\mathrm{SM}}}{\mathrm{BR}_b^{\mathrm{SM}}}\mu_c$$

  - from radiative decay H → J/ψ γ
    ↳ μμ

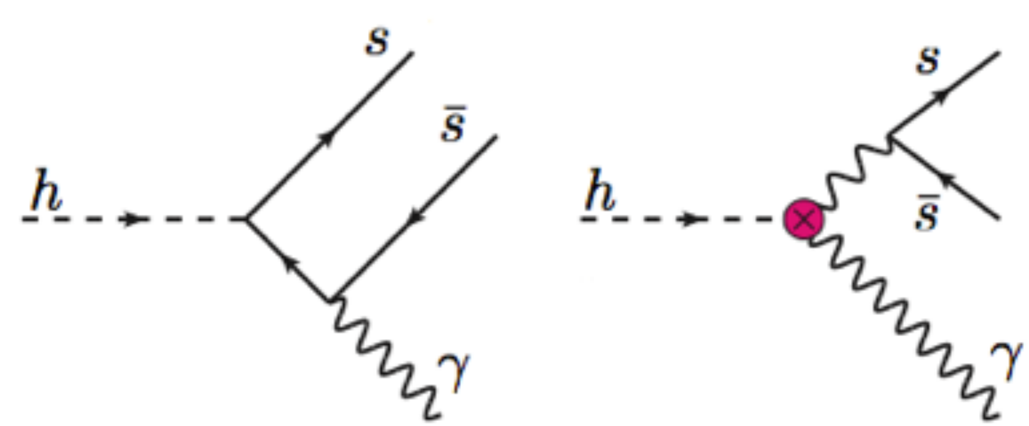
ATLAS, PRL 114 121801 (2015)
CMS, arXiv:1507.03031 (2015)

B(H→J/ψγ)	SM	Obs. (Exp.)
95% CL U.L.	~3 · 10^{-6}	1.5 (1.2) · 10^{-3}

Y. Soreq, FCC-ee Workshop



- What about even-lighter quarks?
  - radiative decays: H→Φγ, ργ, ...
    - sensitive to $\kappa_{s/d/u}$



$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma[(3.0\pm0.3)\kappa_\gamma - 0.78\bar{\kappa}_s]}{0.57\bar{\kappa}_b^2}\times 10^{-6}$$

3^{rd} generation (t)

The largest, *O*(1), coupling in the Yukawa sector

- no direct decay into top quarks
- tightest constraints from *GGF* and *BR($H\to\gamma\gamma$)*
  - complement with direct measurement

	$H\to VV, qq$	$H\to\gamma\gamma$
σ_{GGF}	κ_t^2 *[loop]*	$\lvert\kappa_t \mathcal{M}_a + \kappa_V \mathcal{M}_b\rvert^2$ *[loop]*
σ_{ttH}	κ_t^2 *[tree]*	
σ_{tH}	$\lvert\kappa_t \mathcal{M}_a + \kappa_V \mathcal{M}_b\rvert^2$ *[tree]*	

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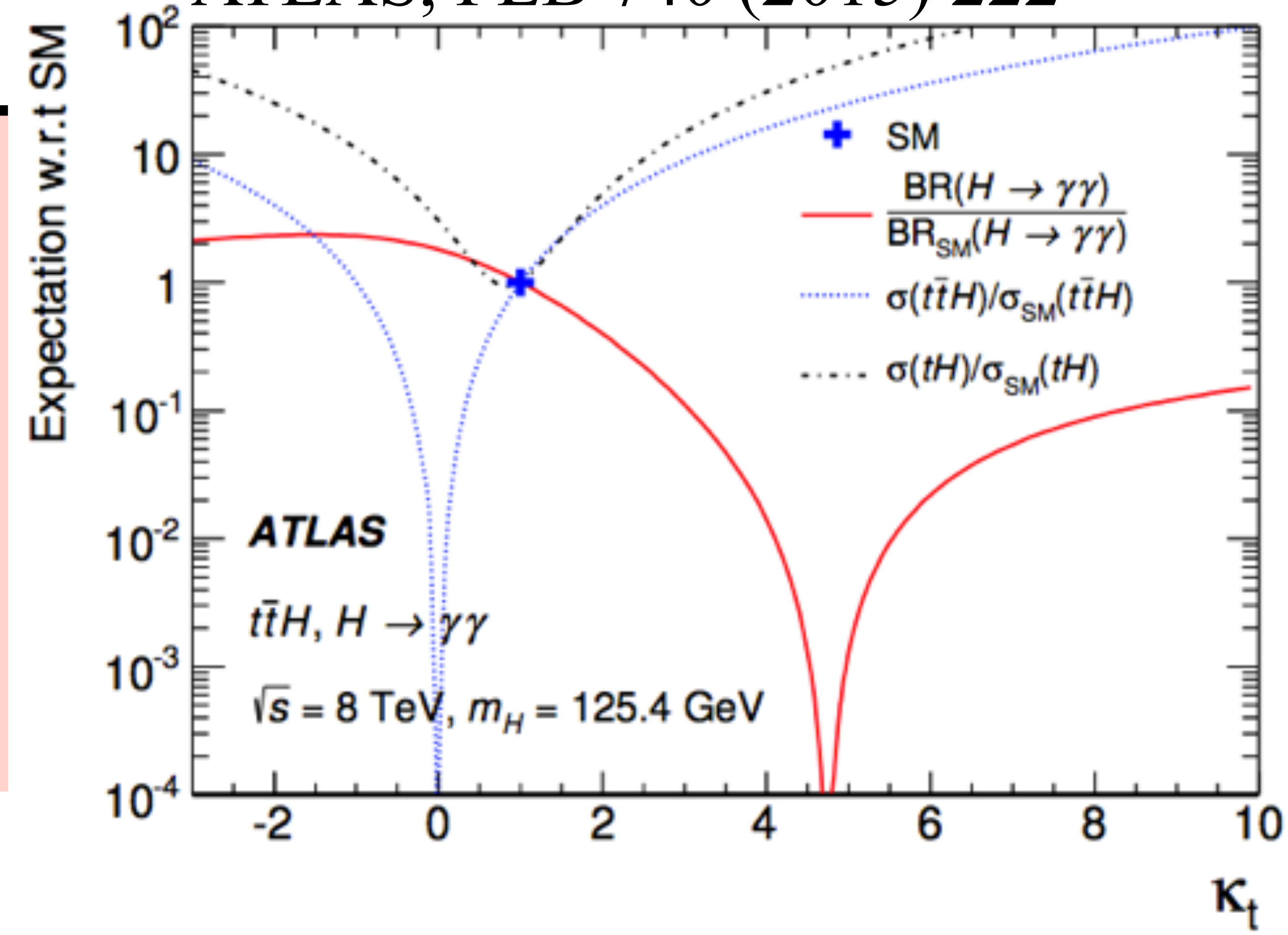
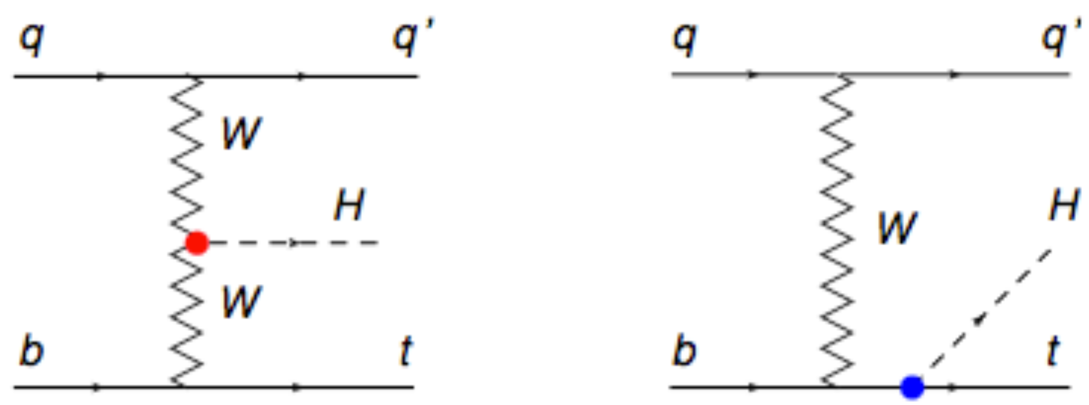


Single top + Higgs

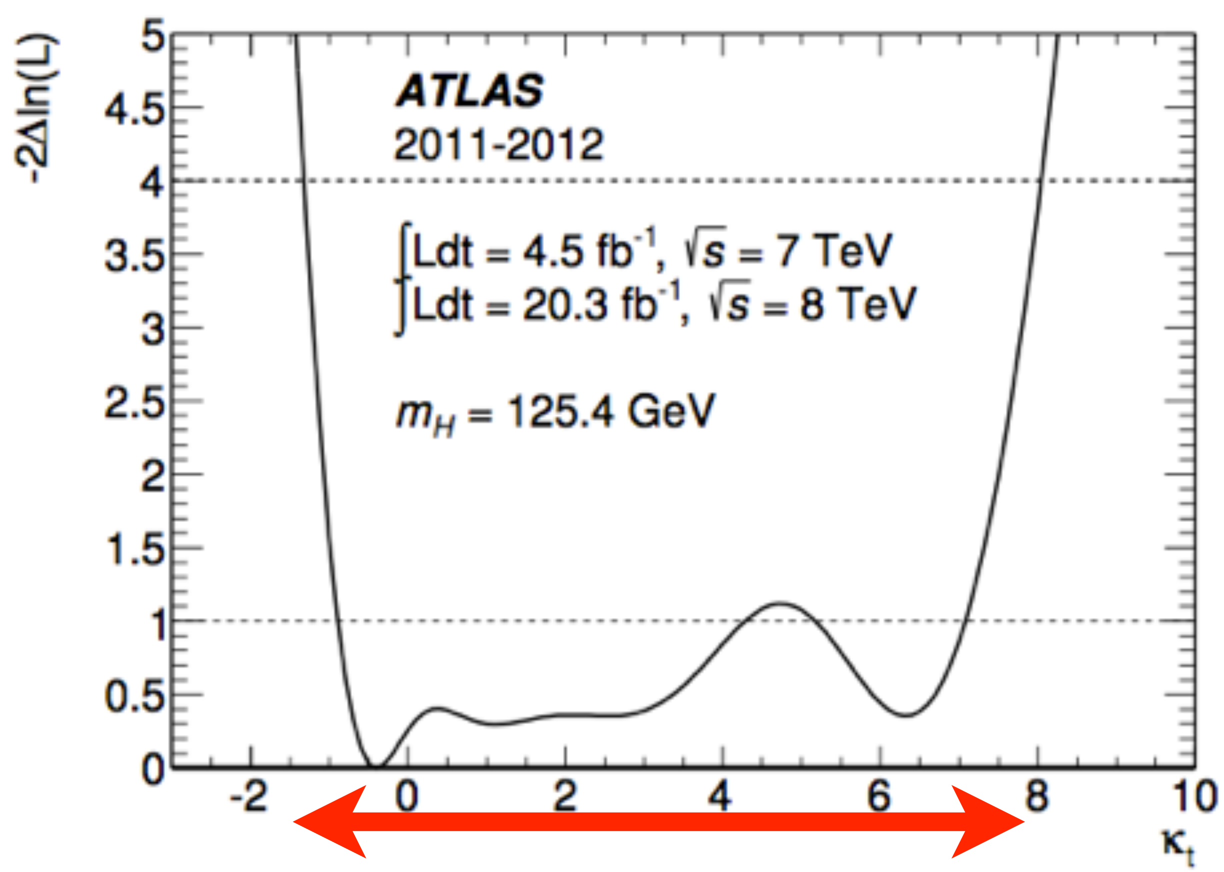
Search for tH production (t- & tW channel)

- small in SM (σ_{NLO}~18 fb)
- sensitive to *sign*(g_{HWW} × y_t)

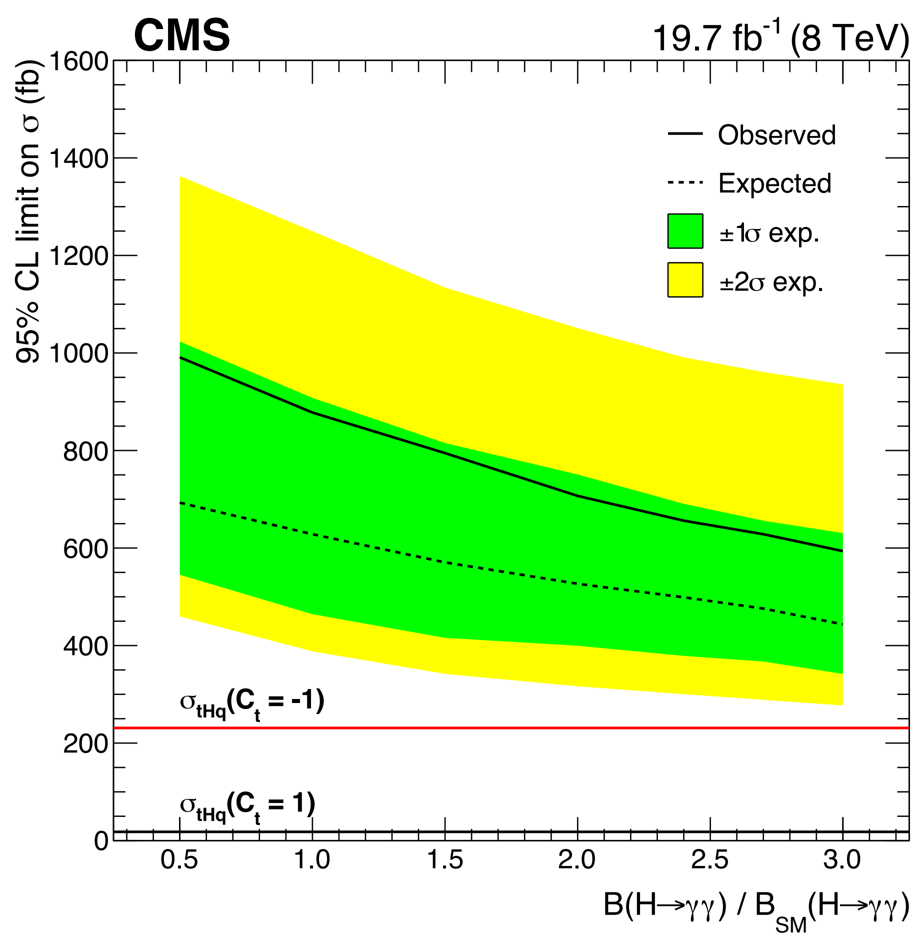


CMS: optimise for tHq (H→γγ, H→b, H→WW)

ATLAS: inclusive t(t)+H search



ATLAS, PLB 740 (2015) 222

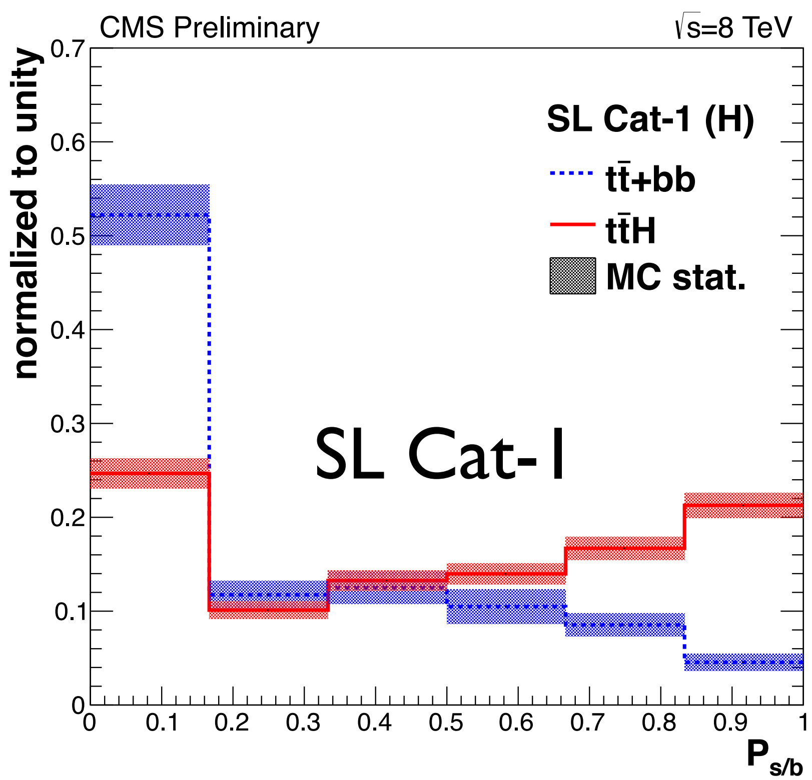


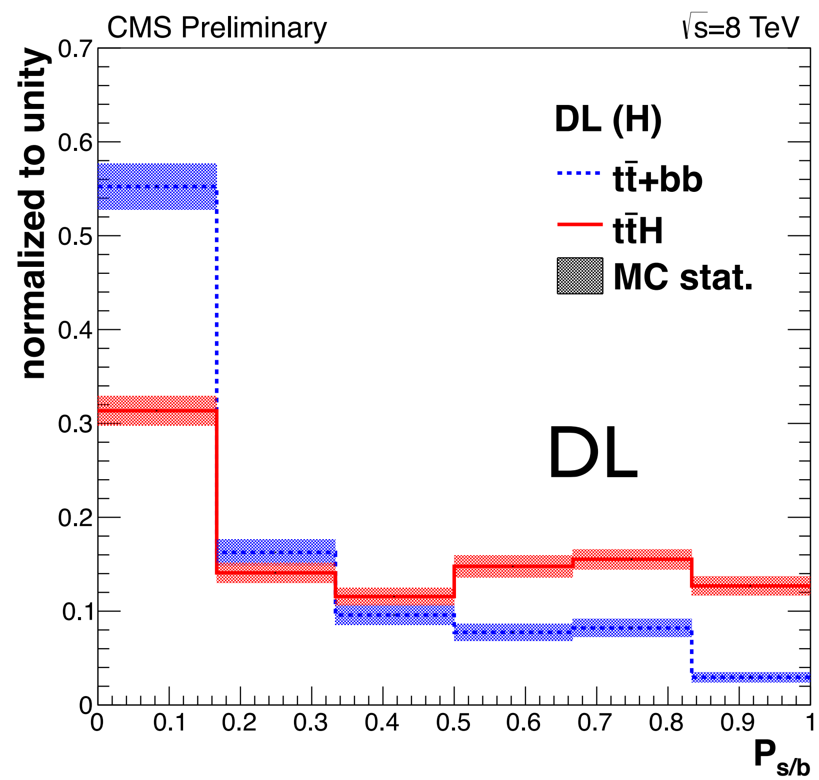
CMS, arXiv:1509.08159, *submitted to JHEP*

ttH→bb with Matrix Element Method

single-lepton			di-lepton
“SL Cat-1”	“SL Cat-3”	“SL Cat-2”	“DL”
$tt \rightarrow b\ell\nu\ bqq$	$tt \rightarrow b\ell\nu\ bqq$	$tt \rightarrow b\ell\nu\ bqq + g$	$tt \rightarrow b\ell\nu\ b\ell\nu$
all quarks reconstructed (+ *gluon(s)*)	all quarks *but one W-quark* reconstructed	all quarks *but one W-quark* reconstructed + ≥ *1 gluon(s)*	all quarks reconstructed

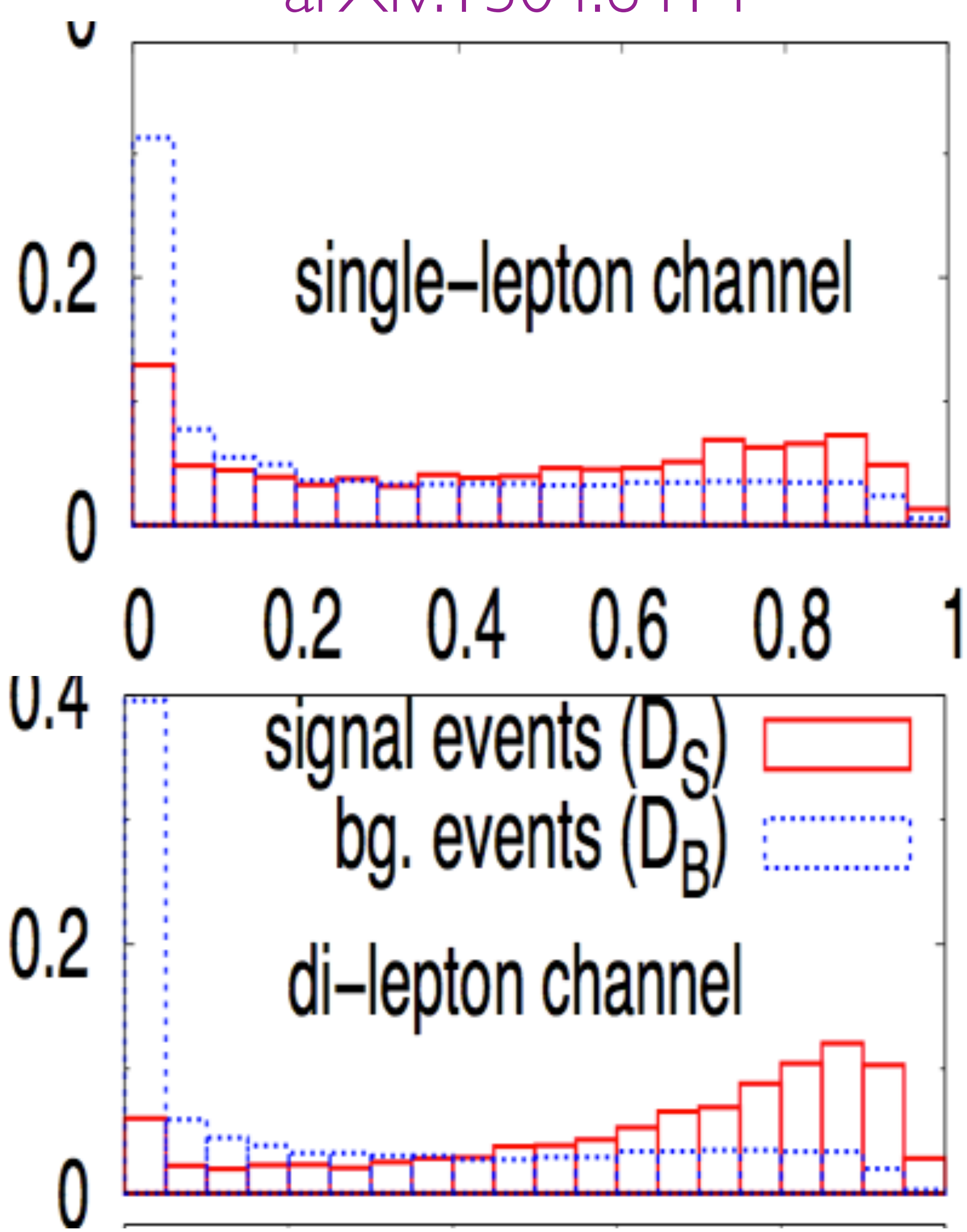
$P_{s/b}$=
ratio of ttH(bb)/tt+bb
probability densities

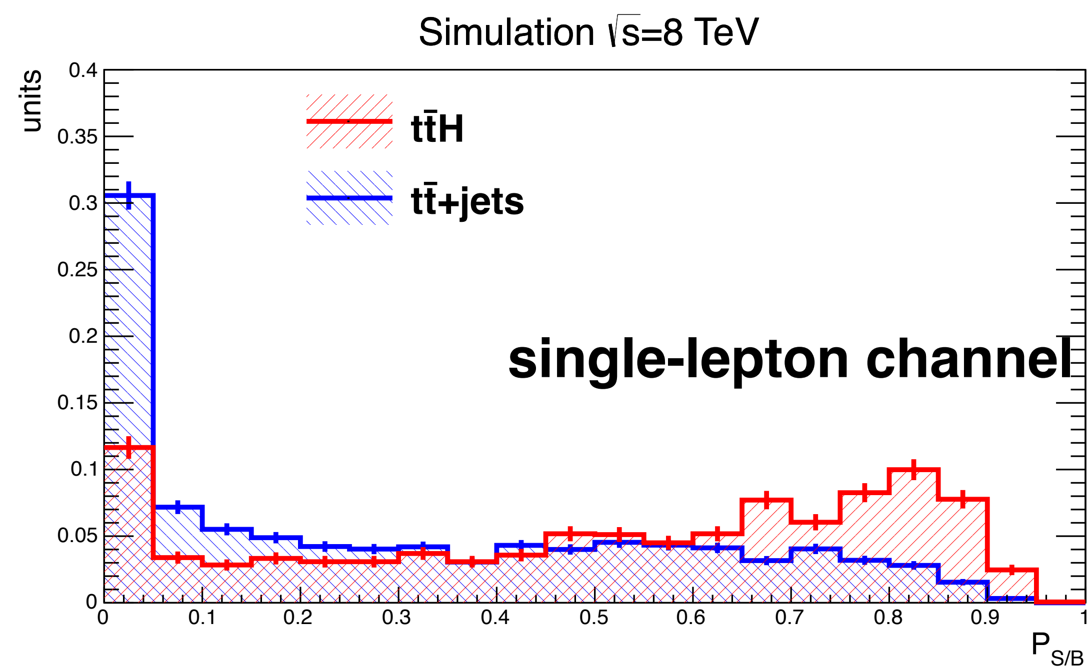


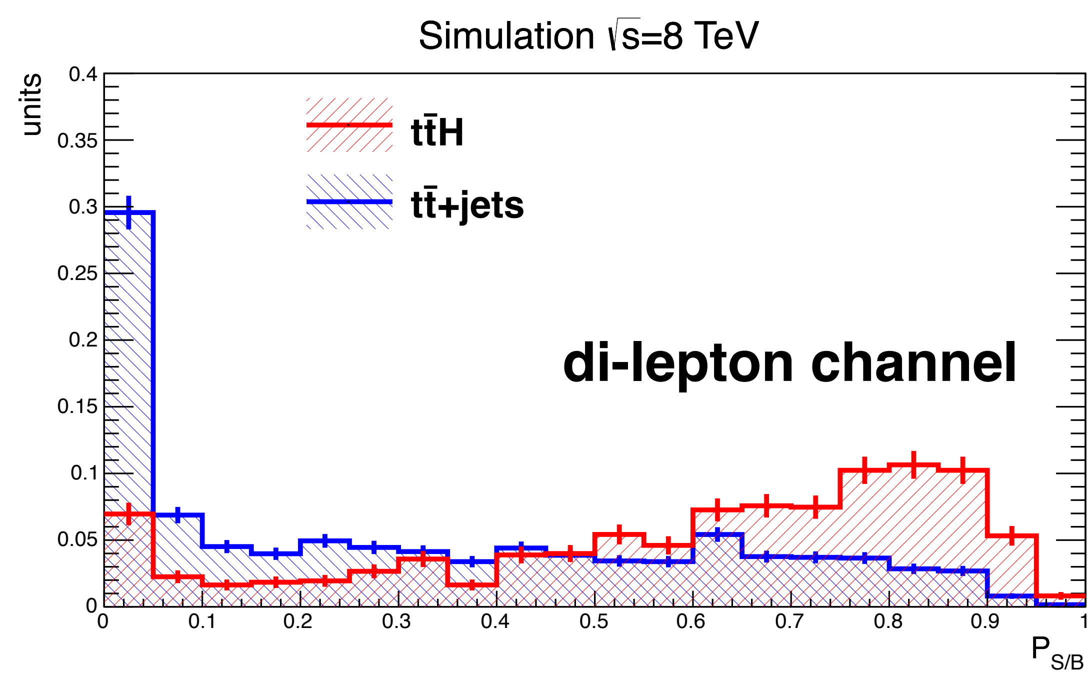


Comparing with MadWeight

arXiv:1304.6414

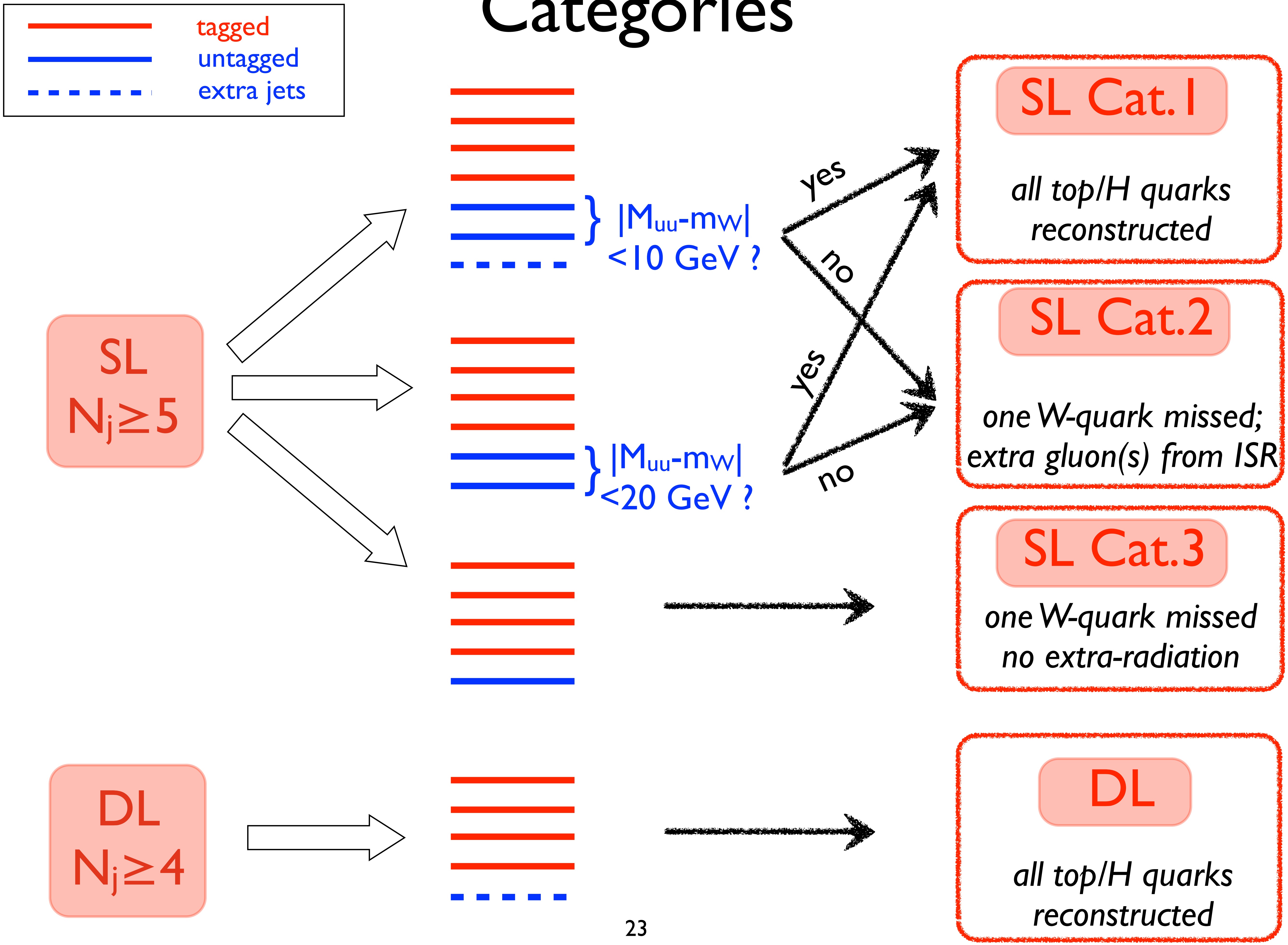






* looser *b*-tag cuts to enhance MC stat.

Categories



tagged
untagged
extra jets
SL
Nj≥5
DL
Nj≥4
} |Muu-mw| <10 GeV ?
} |Muu-mw| <20 GeV ?
yes
no
yes
no
SL Cat.1
all top/H quarks reconstructed
SL Cat.2
one W-quark missed; extra gluon(s) from ISR
SL Cat.3
one W-quark missed no extra-radiation
DL
all top/H quarks reconstructed

The likelihood ratio discriminant (LR)

- Take e.g. N_{jet}=6. Define an event-wise discriminant LR

× 6!/(4!2!)

$= P(\zeta_1, \zeta_2, \zeta_3, \zeta_4, \zeta_5, \zeta_6) +$
$P(\zeta_1, \zeta_2, \zeta_3, \zeta_4, \zeta_5, \zeta_6) +$
$P(\zeta_1, \zeta_2, \zeta_3, \zeta_4, \zeta_5, \zeta_6) +$
...

$$LR = \frac{\sum_i P(\zeta_1,\ldots,\zeta_6 \mid \{\mathbf{qqbbbb}\}_i)}{\sum_i P(\zeta_1,\ldots,\zeta_6 \mid \{\mathbf{qqbbbb}\}_i) + \sum_i P(\zeta_1,\ldots,\zeta_6 \mid \{\mathbf{qqqqbb}\}_i)}$$

The likelihood ratio discriminant (LR)

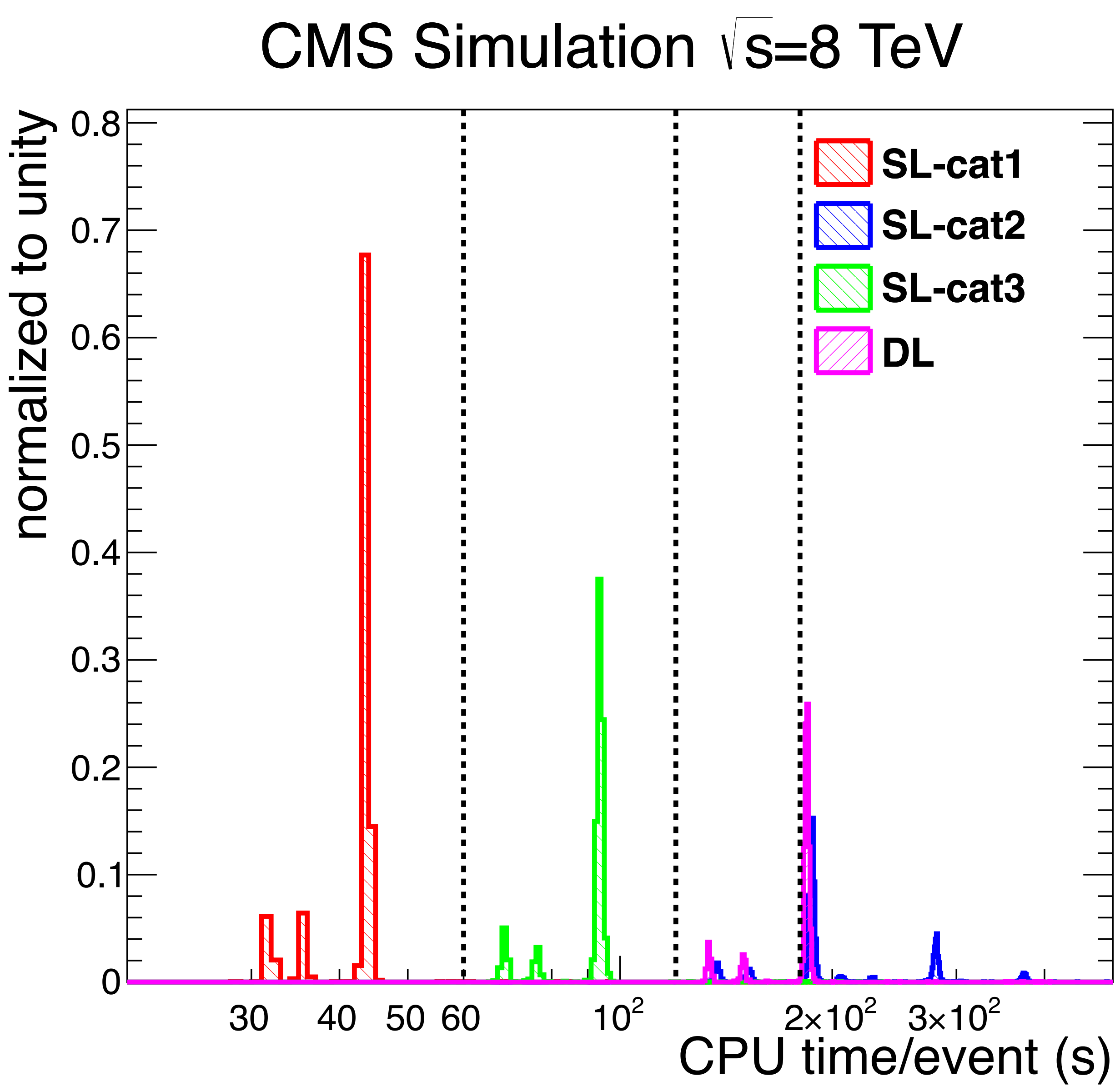
- Take e.g. N_{jet}=6. Define an event-wise discriminant LR

$$LR = \frac{\sum_i P(\zeta_1,\ldots,\zeta_6 \mid \{qqbbbb\}_i)}{\sum_i P(\zeta_1,\ldots,\zeta_6 \mid \{qqbbbb\}_i) + \sum_i P(\zeta_1,\ldots,\zeta_6 \mid \{qqqqbb\}_i)}$$

$$\begin{aligned} = \; & P(\zeta_1, \zeta_2, \zeta_3, \zeta_4, \zeta_5, \zeta_6) + \\ & P(\zeta_1, \zeta_2, \zeta_3, \zeta_4, \zeta_5, \zeta_6) + \\ & P(\zeta_1, \zeta_2, \zeta_3, \zeta_4, \zeta_5, \zeta_6) + \\ & \ldots \end{aligned}$$

$\times \; 6!/(4!2!)$

CPU time


CMS Simulation √s=8 TeV
normalized to unity
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
30
40
50
60
10^2
2×10^2
3×10^2
CPU time/event (s)
SL-cat1
SL-cat2
SL-cat3
DL