Search for the dimuon Higgs decay

Adrian Perieanu
on behalf of CMS Collaboration

SUSY 2017 - Mumbai

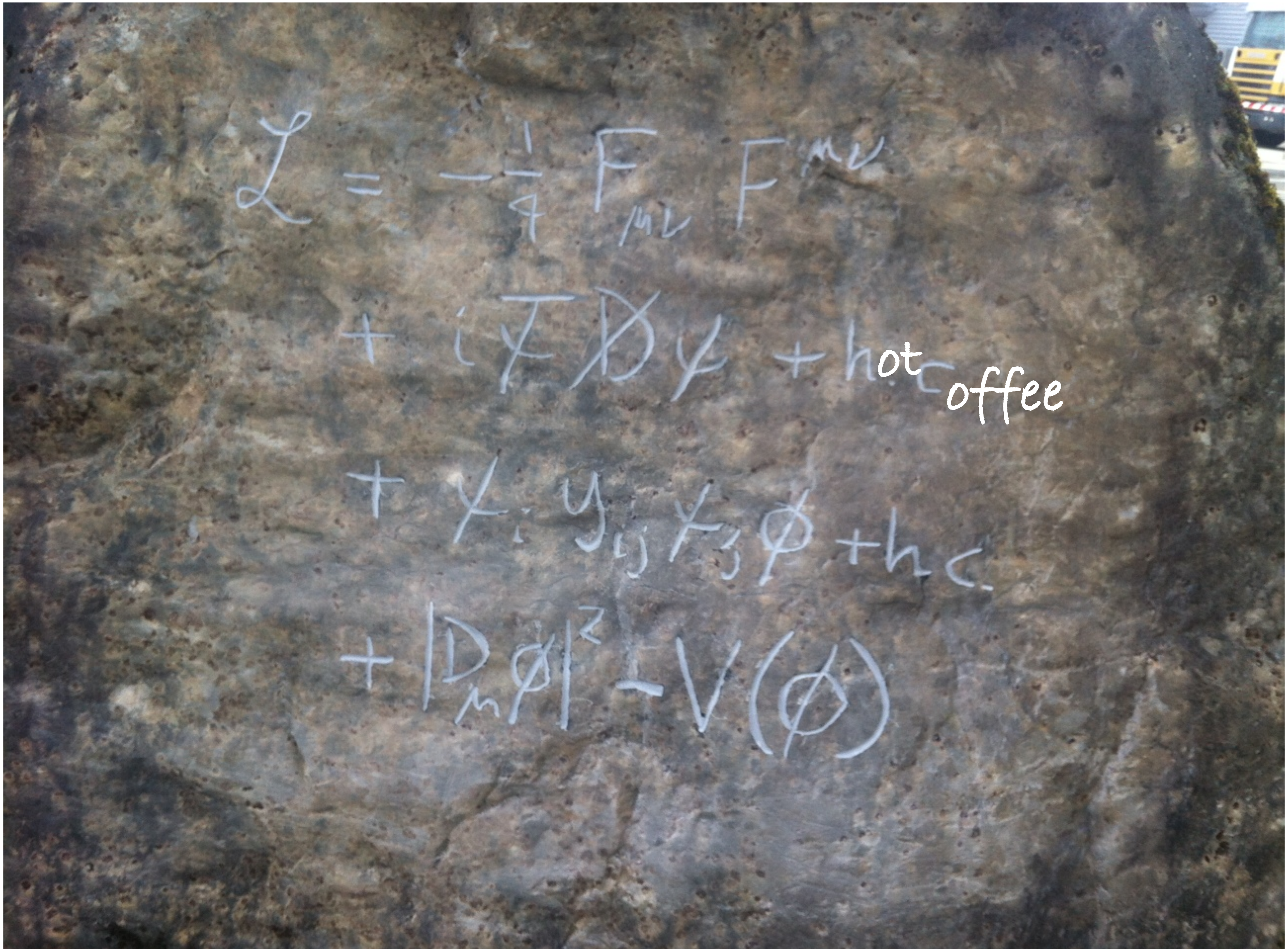
11th December 2017

Bandra-Worli Sea Link

overview

* why the Higgs dimuon channel?
* CMS & particle reconstruction
* Higgs dimuon search strategy
* where are we now? where do we go from here?

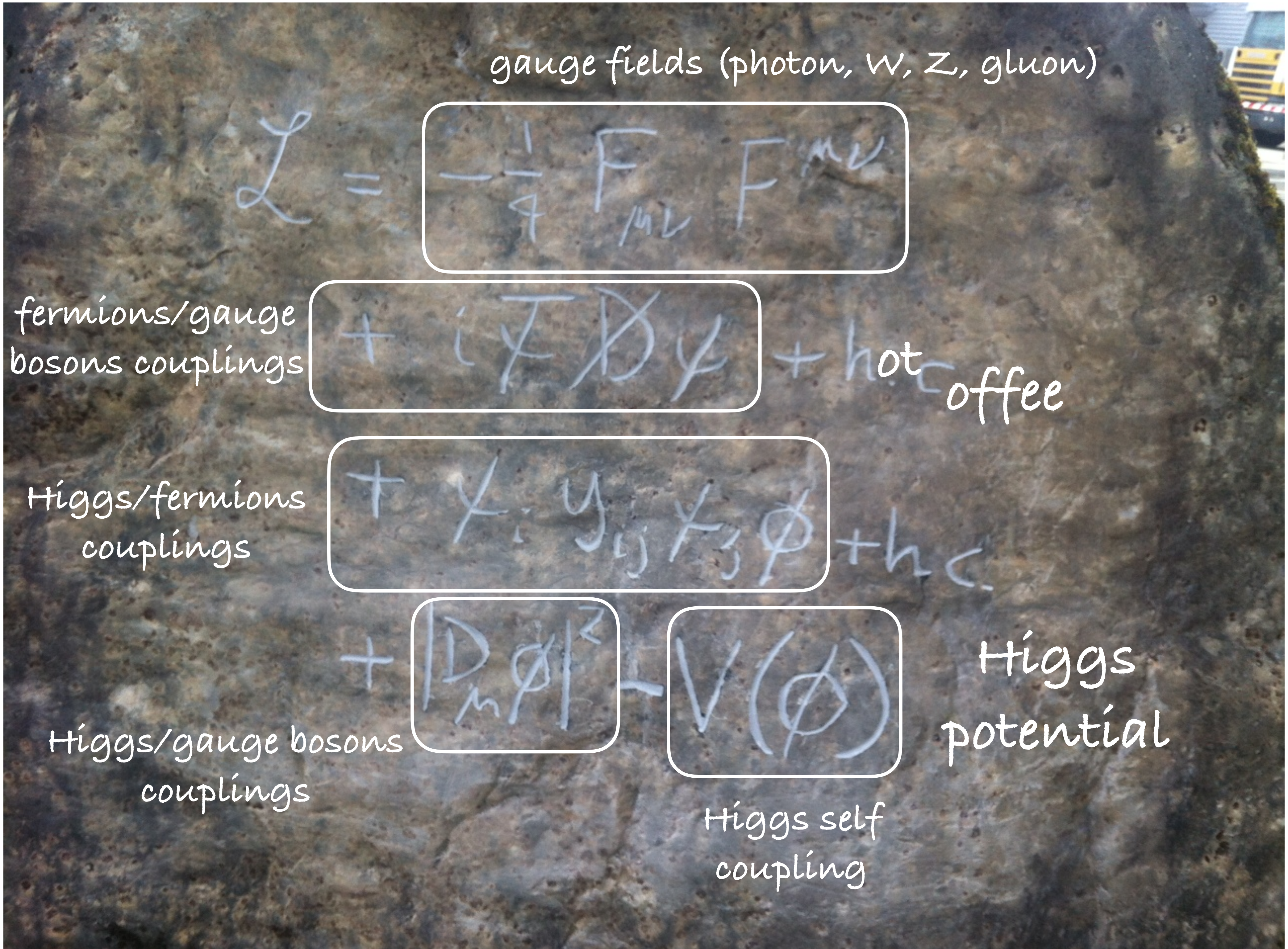
Higgs and its field



close to CERN Control Centre

by now everything is cast in "stone"
another type of evolution, from electrons back to…

Higgs and its field



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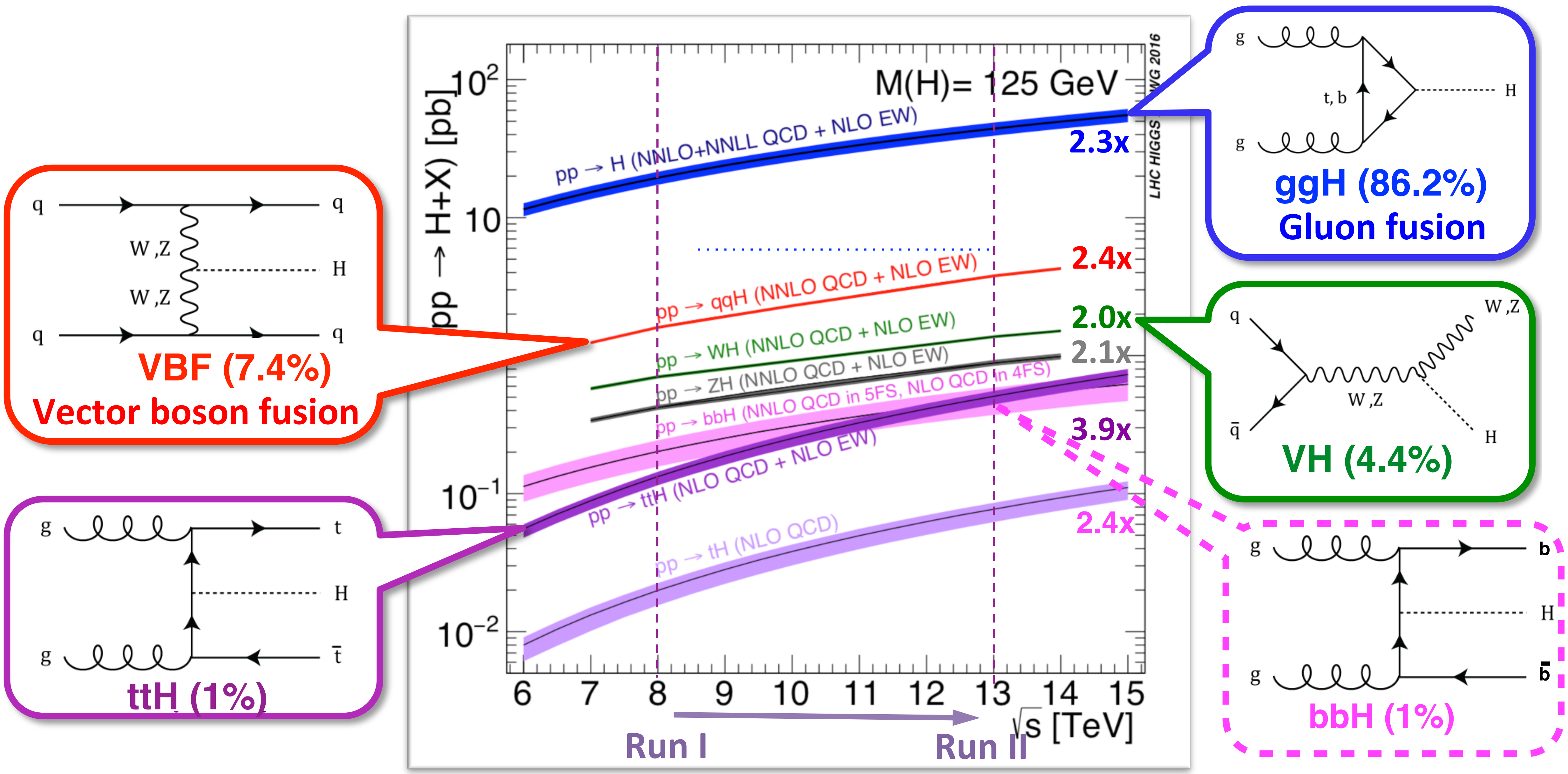
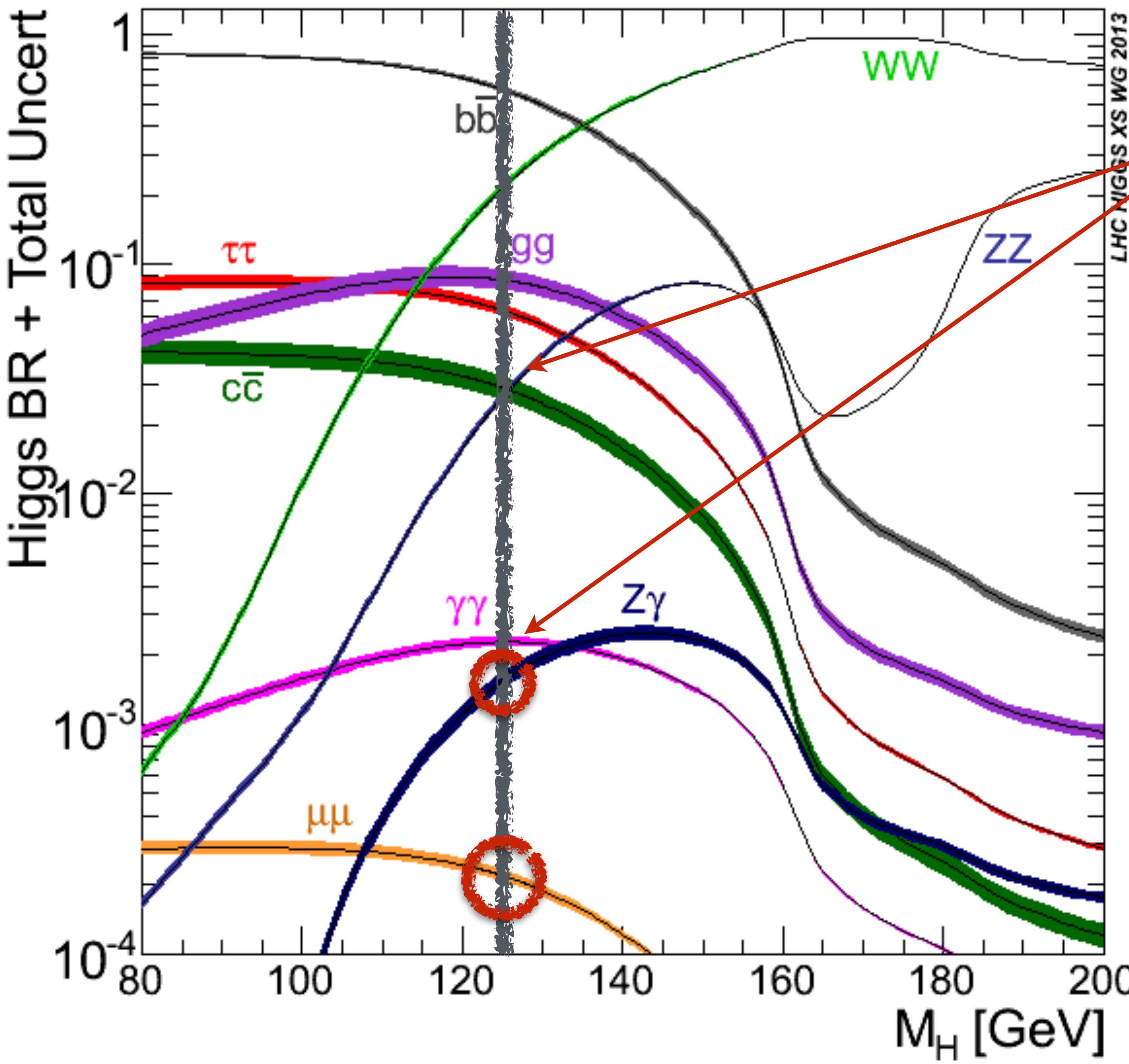
Higgs production at LHC from 8 to 13 TeV



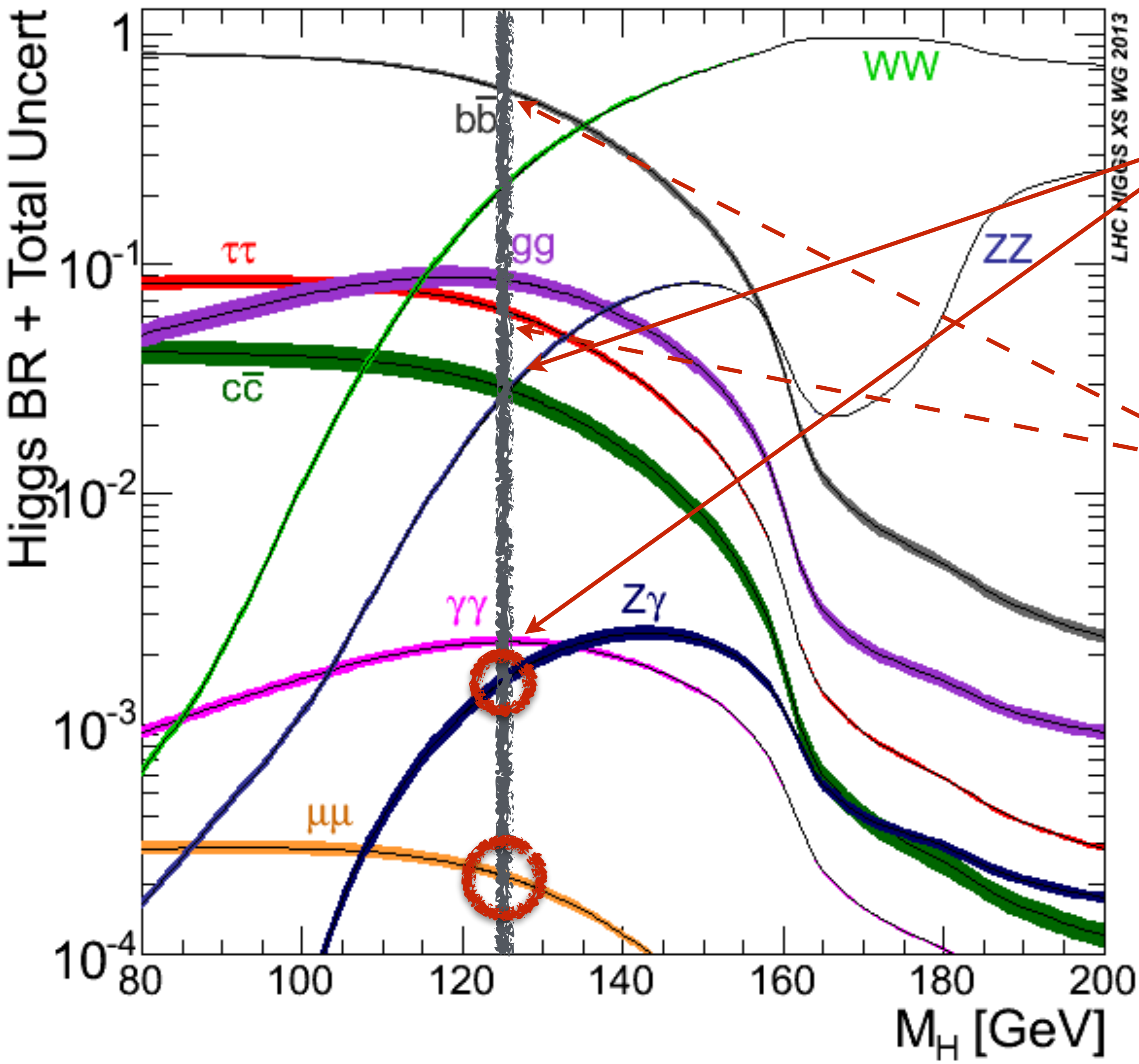
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt13TeV

Higgs decays
— overview —



* gauge bosons:
- high mass resolution and good S/B ratio
- - γγ and ZZ*
- worse mass resolution
- - WW*
- low S/B ratio
- - Zγ

Higgs decays
— overview —



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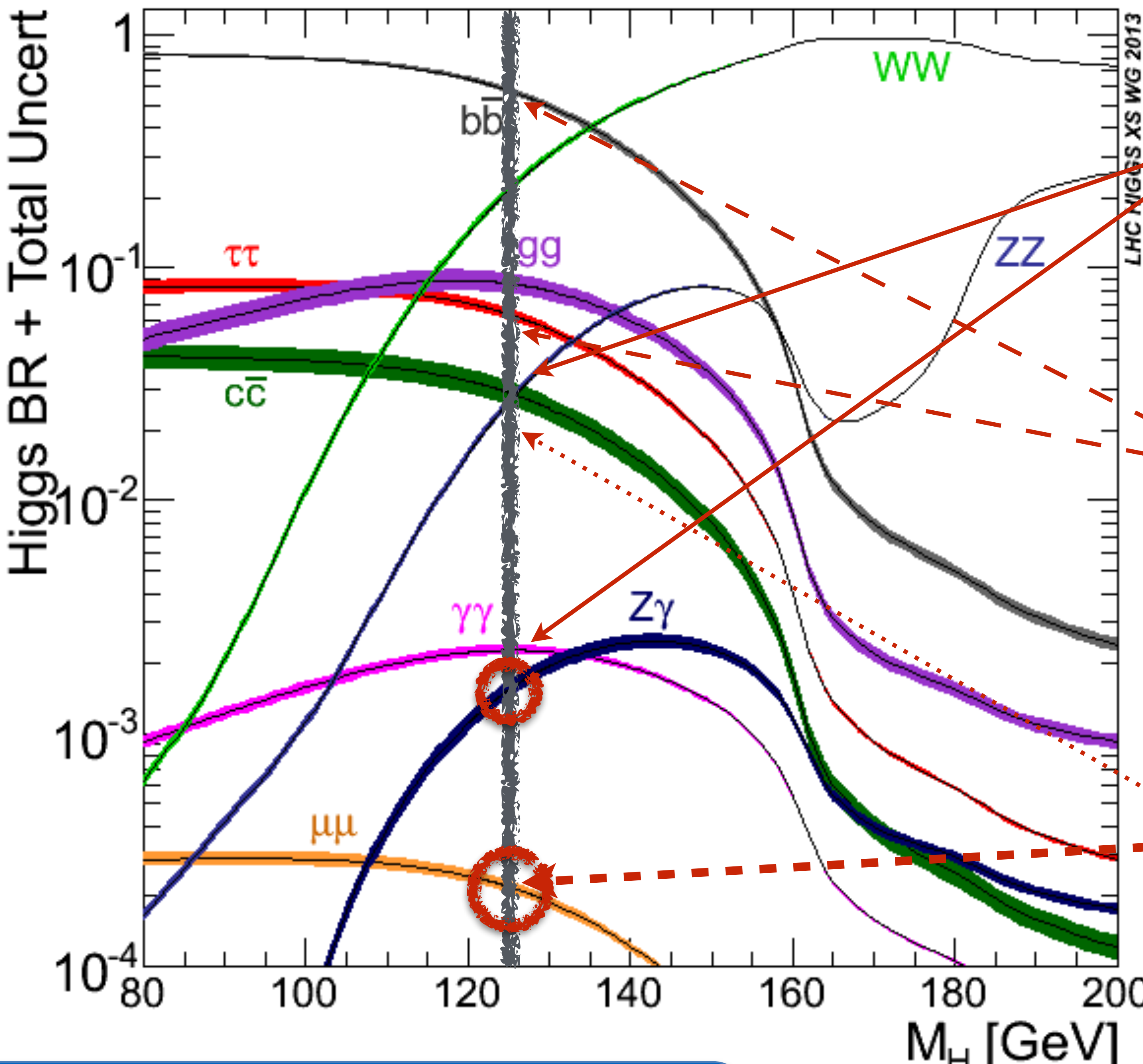
*** 3rd generation:**
- high yield
- low S/B ratio
- low mass resolution
- - $\tau\tau$ and bb

Higgs decays
— overview —



*** gauge bosons:**
- **high mass resolution and good S/B ratio**
- **- γγ and ZZ***
- **worse mass resolution**
- **- WW***
- **low S/B ratio**
- **- Zγ**

*** 3rd generation:**
- **high yield**
- **low S/B ratio**
- **low mass resolution**
- **- ττ and bb**

*** 2nd generation:**
- **good mass resolution**
- **low S/B ratio**
- **- μμ**
- **poor S/B ratio**
- **- cc**

*** H →μμ branching fraction: 2.18 x 10^{-4}**

Higgs boson in numbers after

H^0 — $J = 0$

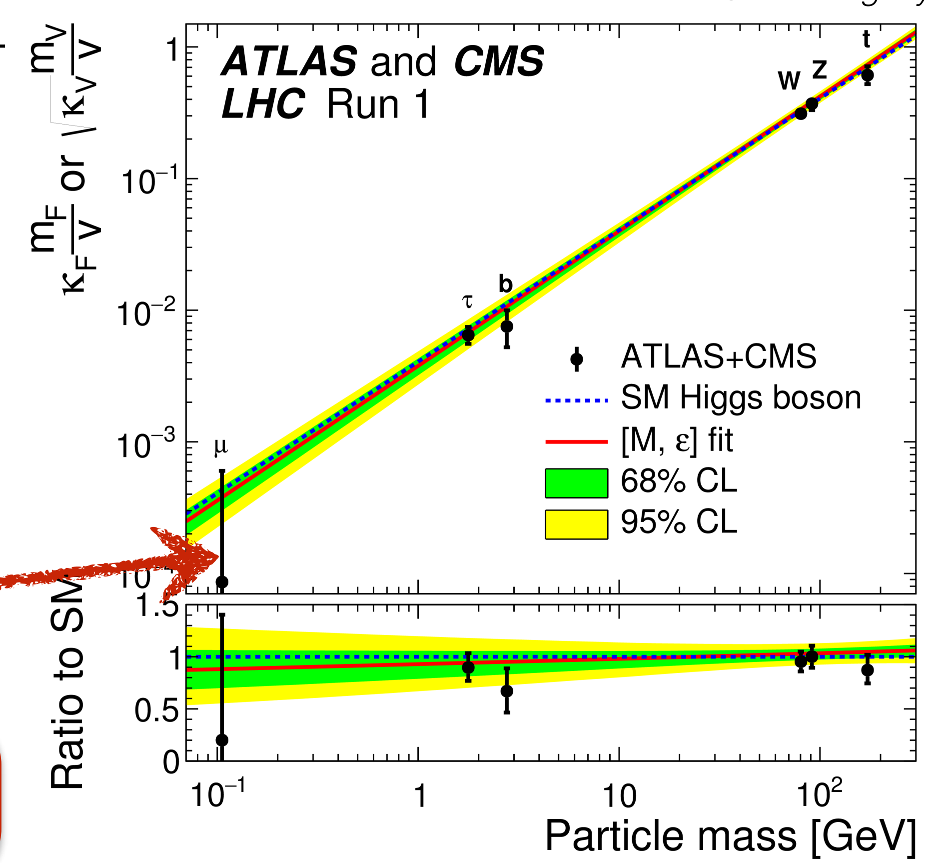
Mass $m = 125.09 \pm 0.24$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States = 1.10 ± 0.11
$WW^* = 1.08^{+0.18}_{-0.16}$
$ZZ^* = 1.29^{+0.26}_{-0.23}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.82 \pm 0.30$ (S = 1.1)
$\mu^+\mu^- = 0.1 \pm 2.5$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 9.5$, CL = 95%
$t\bar{t}H^0$ Production = $2.3^{+0.7}_{-0.6}$

the LHC Run I legacy …

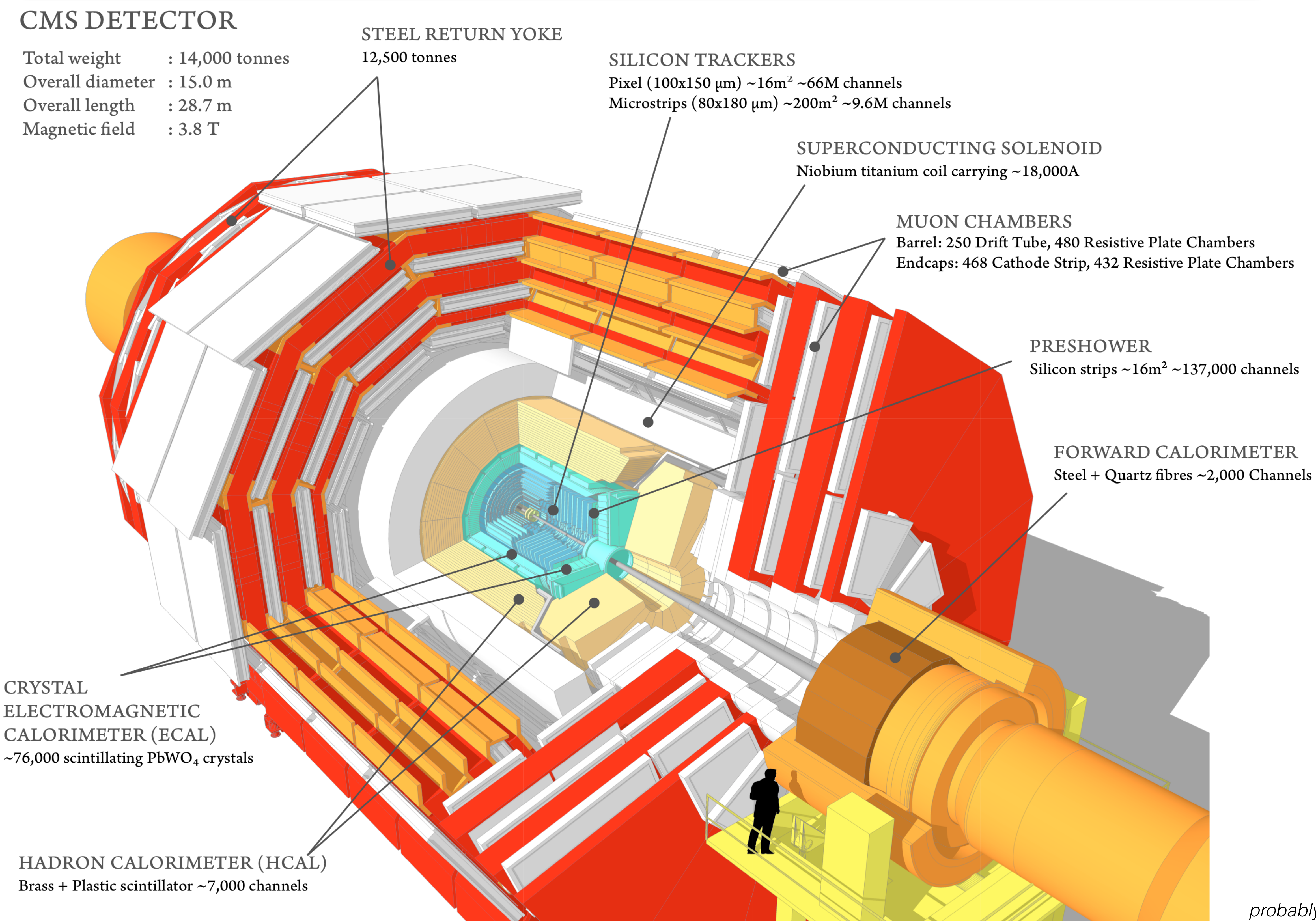


*** very large uncertainties on dimuon signal strength and Higgs-muon coupling**

CMS detector

a theory is a beautiful thing,
a detector is a brilliant idea,
to test a theory with a detector …

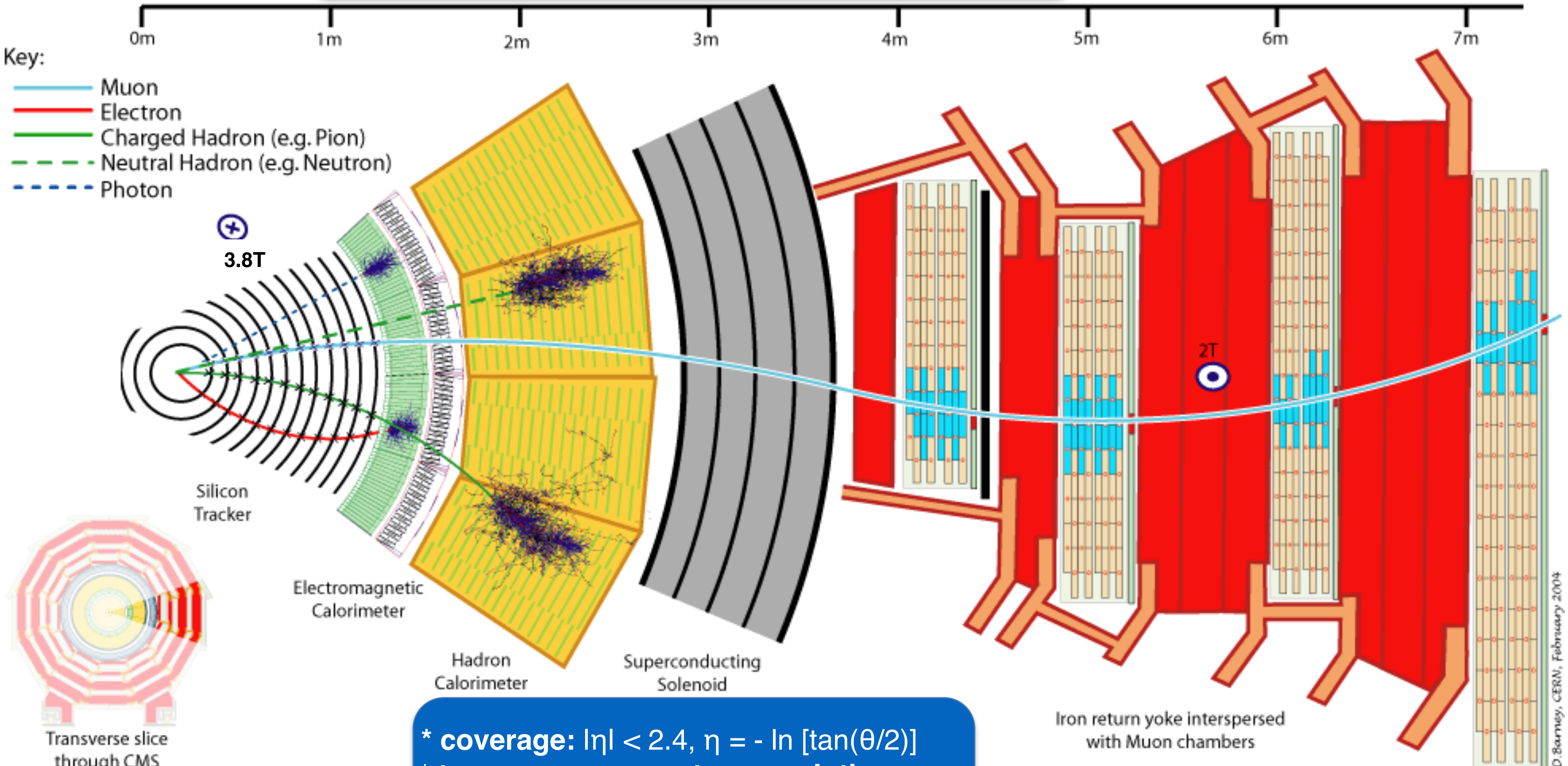
C(ompact) M(uon) S(olenoid)



probably, the best detector in the world

CMS: particle flow reconstruction

*** Muons in CMS:**
track segment reconstructed in the muon chambers is matched with the track in silicon tracker (global muon)



*** coverage:** $|\eta| < 2.4$, $\eta = -\ln[\tan(\theta/2)]$
*** transverse momentum resolution**:
$\sigma_{pT}/pT \approx 0.015\%\ pT \oplus 0.5\%$

Higgs dimuon search strategy

when this slide was first time shown in CMS people start laughing

Higgs: $\mu\mu$ channel targeting 2 x σ/σ_{SM}

CMS-PAS-HIG-17-019

goals

* exploit high mass resolution

* overcome the main dimuon background contributions from Drell-Yan and tt

* enhance signal over background (at maximum)

ingredients

* muon momentum corrections

* Higgs production process specific categories

* optimise the event categories using Boosted Decision Trees

but we kept cool and going…

so, let's mix the ingredients

* muon momentum corrections

* optimise the event categories using Boosted Decision Trees

* topological and Higgs production process specific categories

in Run I we said that we target 5 x σ/σ_{SM},
people said: be happy if you get 10 x σ/σ_{SM},
at the end of Run 1 we reached 6.5 x σ/σ_{SM}

now in Run II we said that we target 2 x σ/σ_{SM},
people did not say anything anymore…

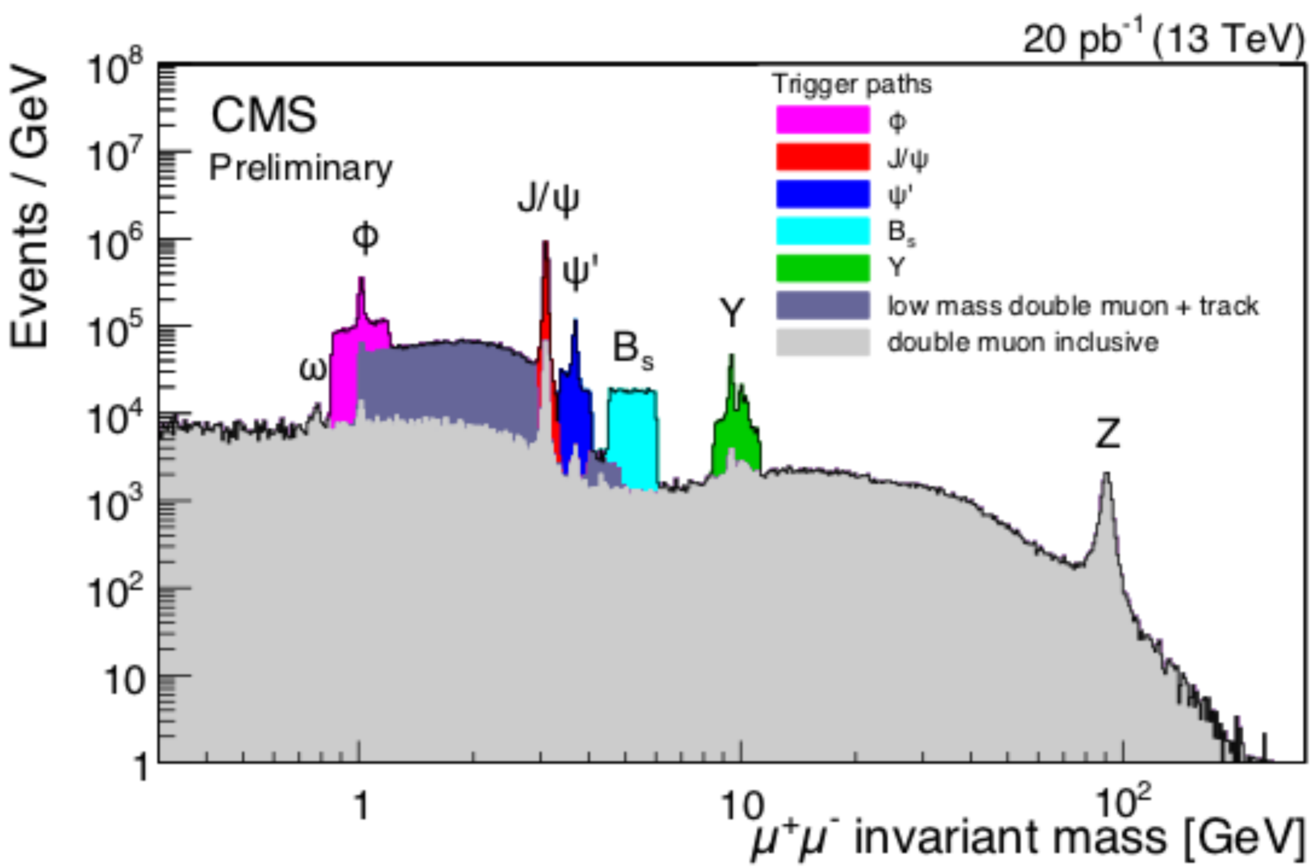
μ: momentum corrections

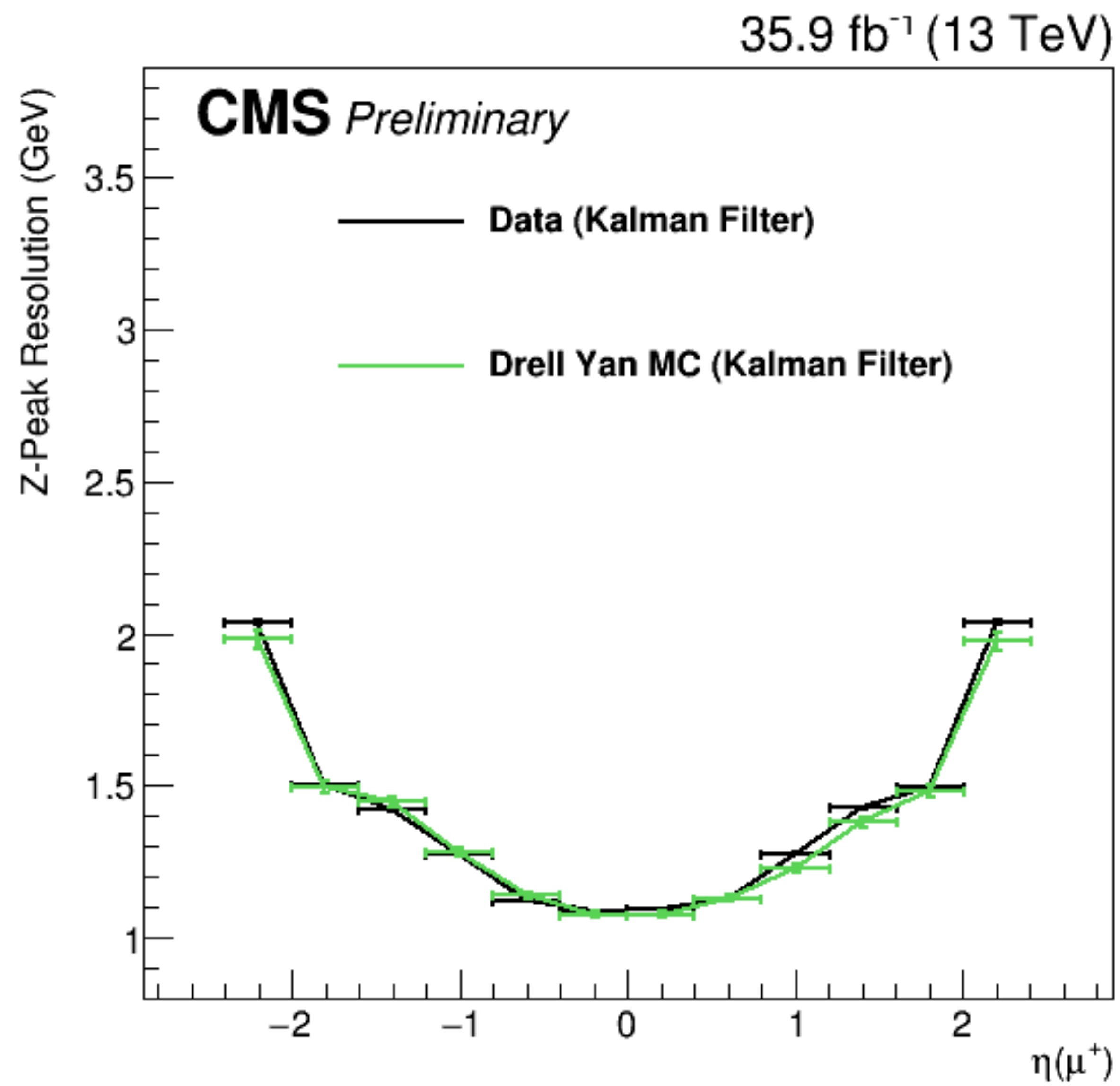
there is a reason why we are called CMS…

*** Kalman Filter [1] Corrections**

- derived from J/Ψ and Z boson at the pole mass
- extrapolated to Higgs mass

- previously used for precision measurements of the Higgs boson mass [2] in 13 TeV pp collisions





[1] NIM A 262 (1987) 444
[2] JHEP 11 (2017) 047

a small step for the muons, a big step for the Higgs boson

physics objects and event selection

physics objects:

*** muons**
- global reconstructed muons
- $p_T > 20$ GeV and $|\eta| < 2.4$
- ID working point: medium (98% efficiency)
- isolated

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- input: particle flow candidates (except the selected muons)
- reconstructed with the anti-k_T algorithm (d=0.4)
- corrected against multiple interactions in the same bunch crossing (pileup)
- $p_T > 30$ GeV and $|\eta| < 4.7$
- applied b-tag identification for jets with $|\eta| < 2.4$ at 65% efficiency and 1% mis-tagging rate

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event selection:

*** online**
- isolated single muon trigger with $p_T > 24$ GeV

*** offline**
- 2 opposite charged muons
- at least one muon matched with the trigger and $p_T > 26$ GeV

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*** MC pileup re-weighting**
*** data/MC scale factors for muons reconstruction and trigger efficiency, and b-tagging**

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this is what took most of the time,
a good wine needs its time

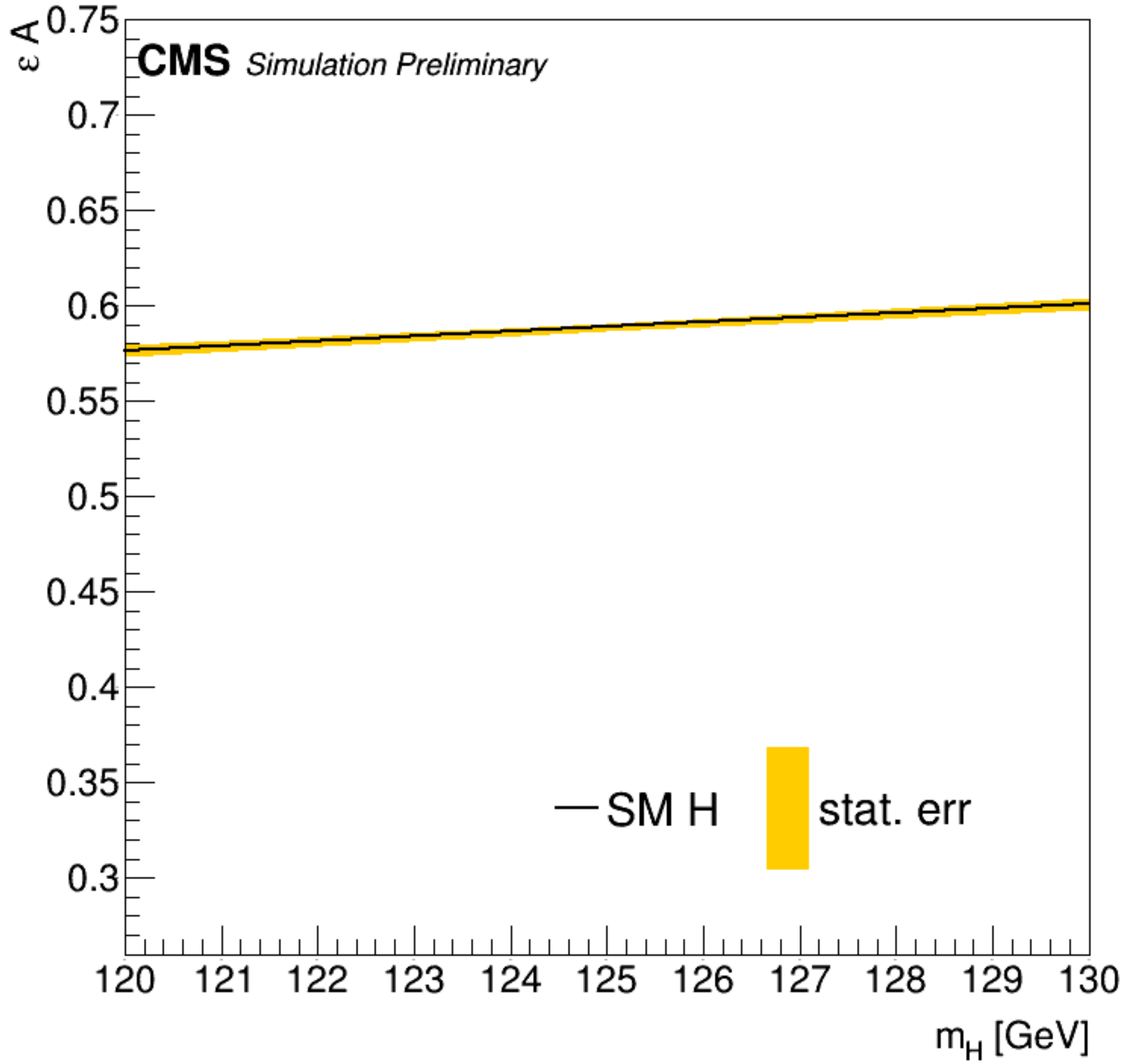
events

* total number of expected signal events:

- ggH = 380.4 events
- VBF = 29.6 events
- WH = 10.7 events
- ZH = 6.9 events
- ttH = 3.9 events

* efficiency* acceptance: ~ 57%

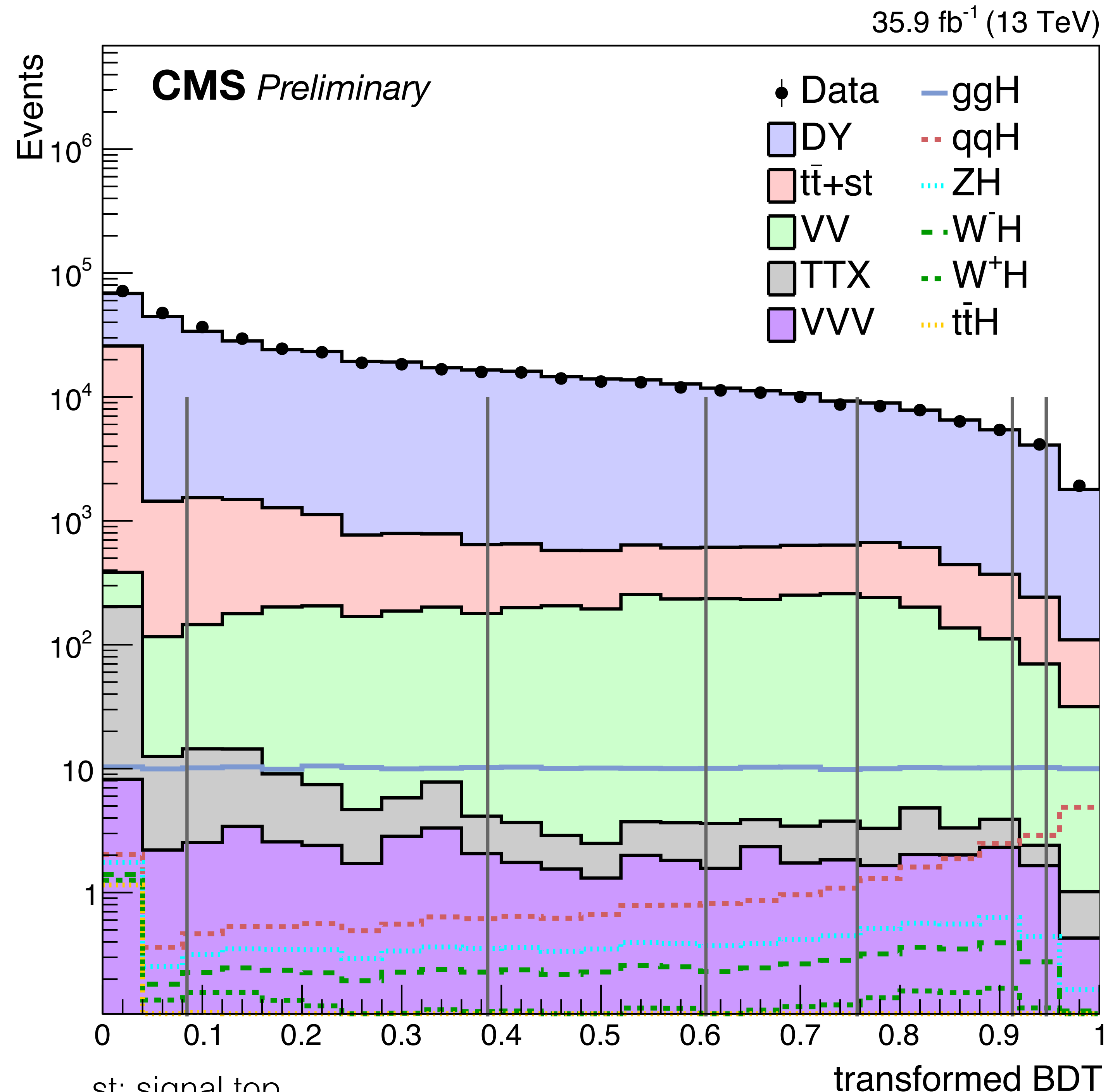
* total number of background events: ~13000/GeV @ 125 GeV



the difference between netto and brutto: don't forget about efficiency and acceptance

optimisation

*** Boosted Decision Tree:**
maximise separation between signal and background events



st: signal top
V: W, Z
TTX: $t\bar{t}$ V

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*** Boosted Decision Tree:**
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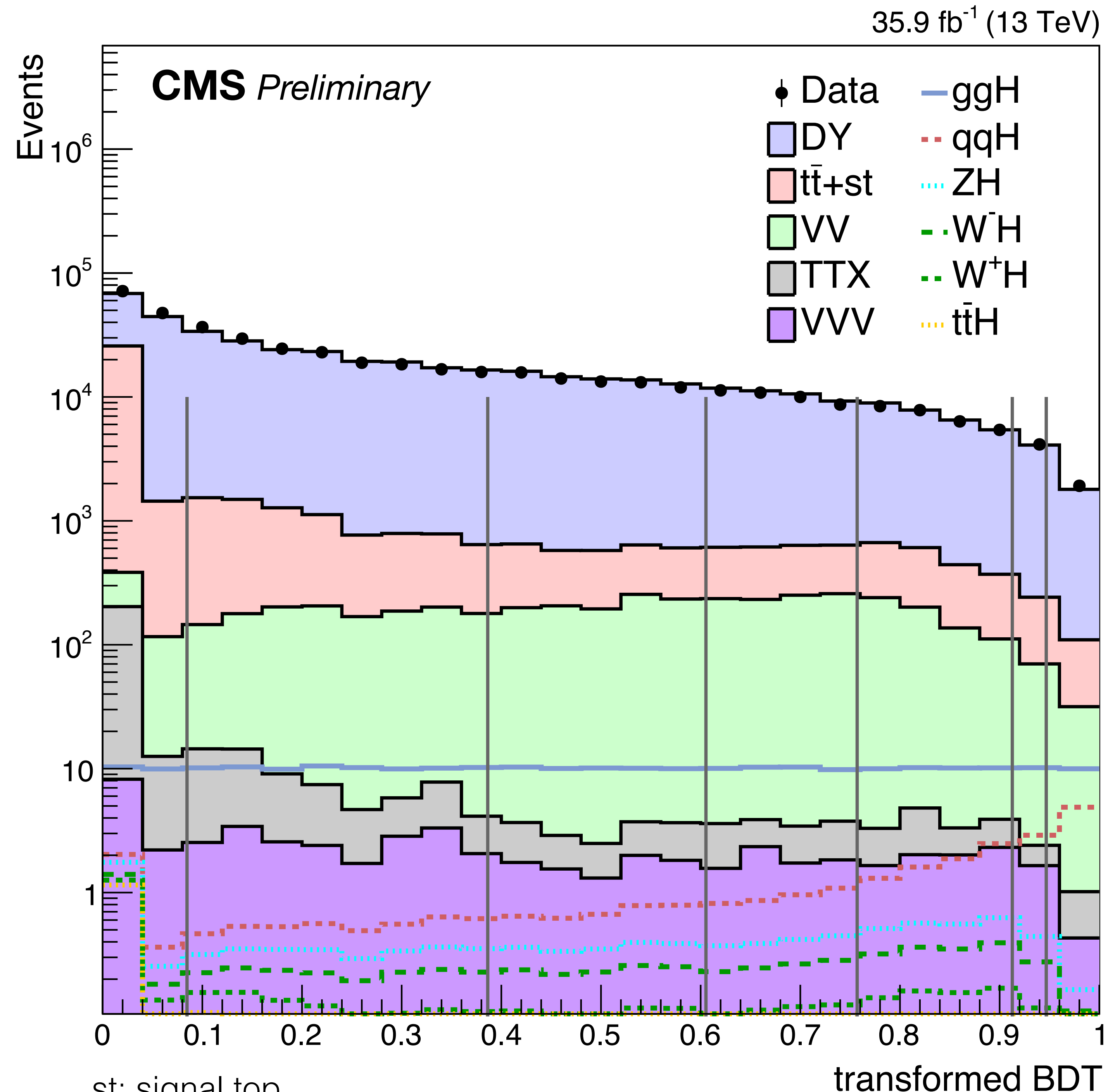
*** input variables:**
- p_T and η of the dimuon system
- $|\delta\eta|$ and $|\delta\phi|$ between the muons
- η values of the two highest - p_T jets
- invariant mass of the two highest–mass dijet pairs
- $|\delta\eta|$ between the jets in the two highest mass pairs
- number of jets with $|\eta| < 2.4$ and $|\eta| > 2.4$
- number of b-tagged jets
- missing energy in transverse plane



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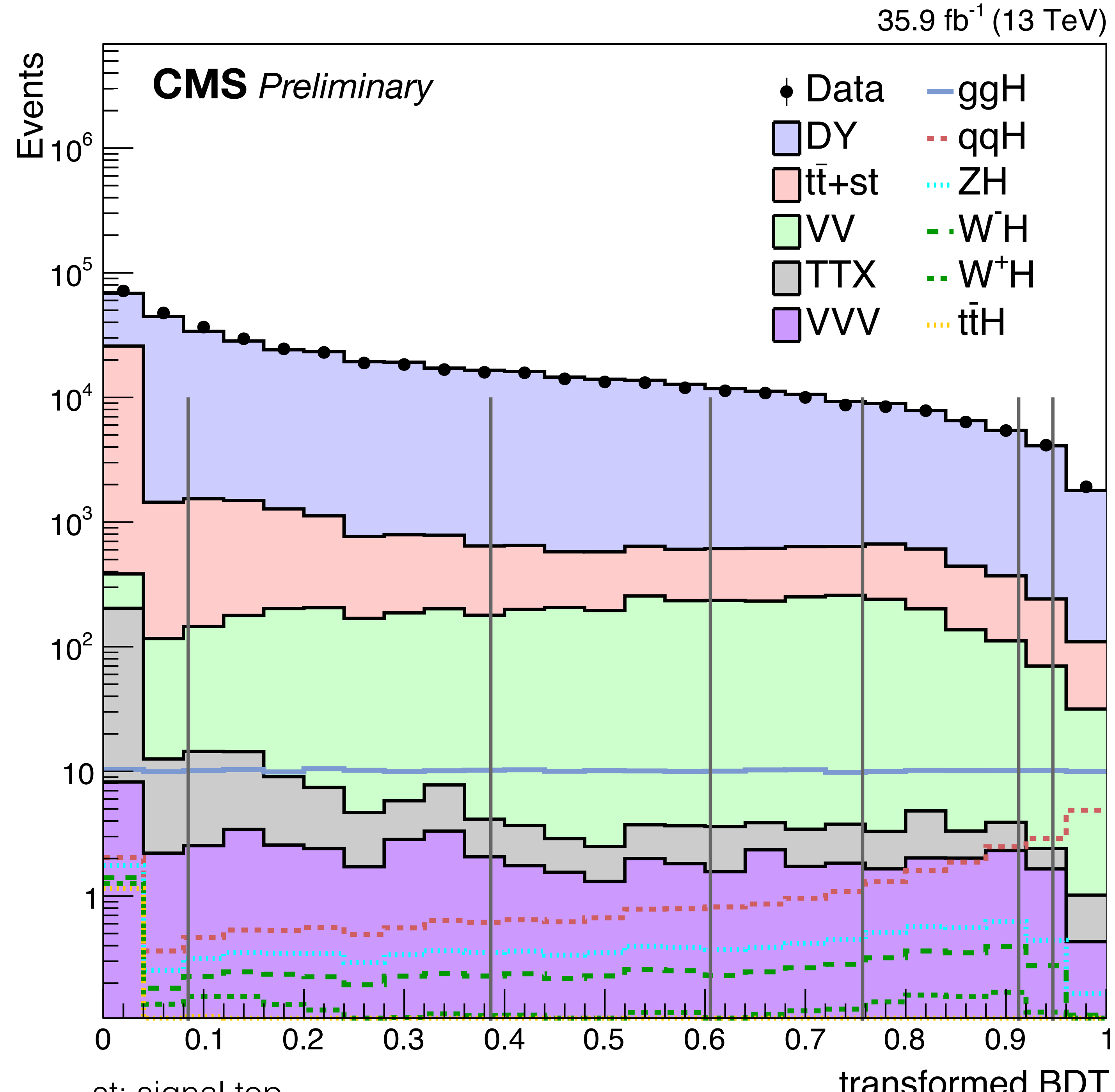
*** BDT output:**
for event categories we used the transformed BDT response: uniform signal expectation



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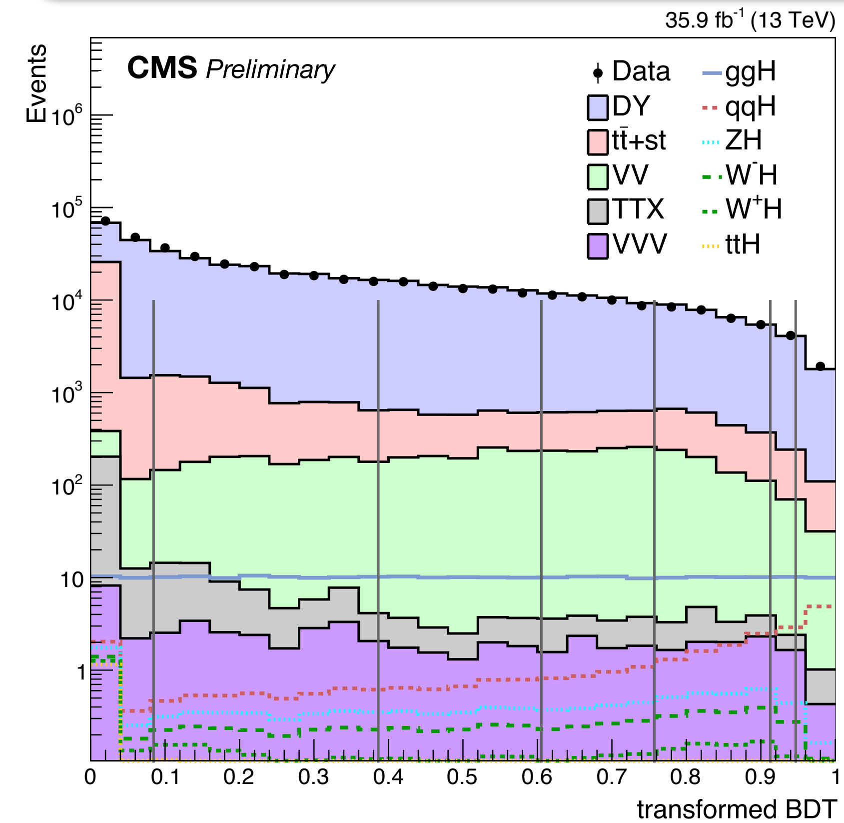
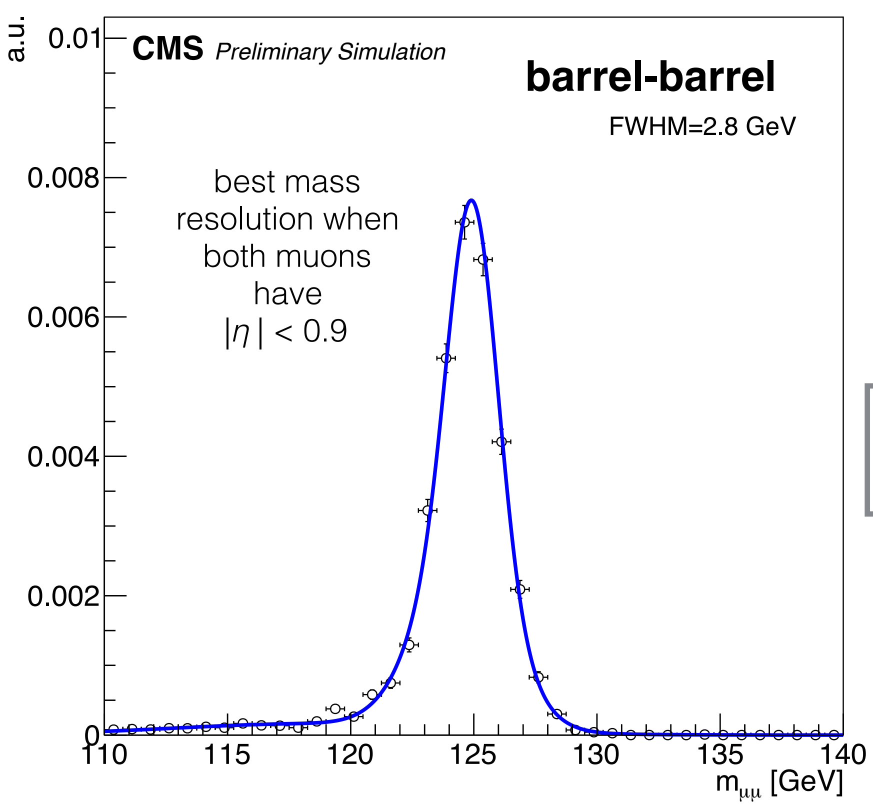
in case you didn't notice
the machines took over … since a while

auto-categoriser





input

input

* iterative process
* maximize gain

SIG^2=signal^2/background

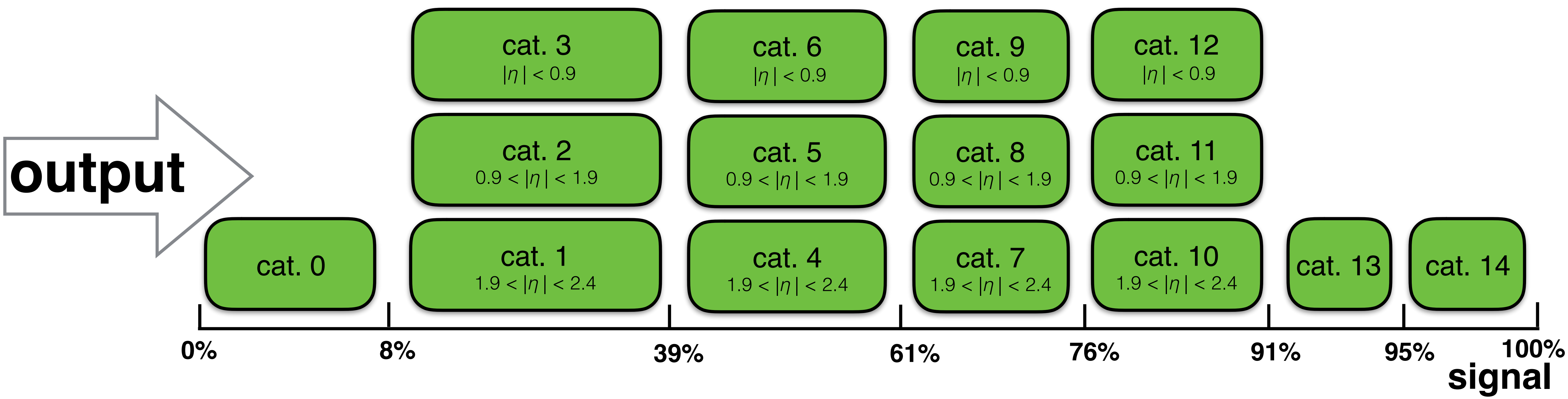
* step1: estimate SIG^2 for all events

* step2:
- split events according to max $|\eta|$ of the 2 muons
- categories: New1 & New2
- check gain

$GAIN = SIG^2_{New1} + SIG^2_{New2} - SIG^2_{Old}$

* step 3: if gain > 0 continue
…
* step n: if gain ~ 0 stop

event categories



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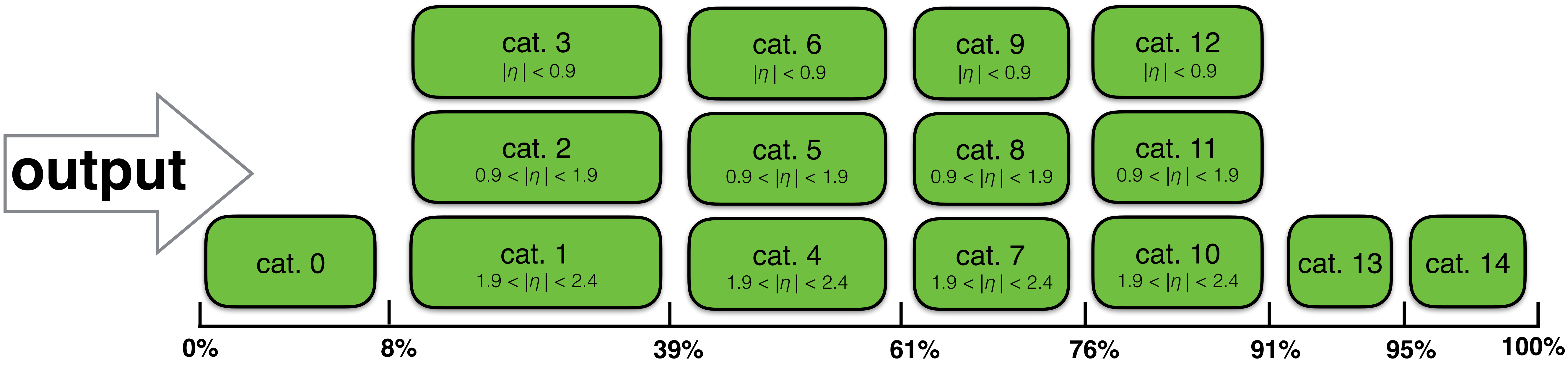

Index	transformed BDT	Max. muon $\|\eta\|$	ggH [%]	VBF [%]	WH [%]	ZH [%]	ttH [%]	Signal	Bkg./GeV @125GeV	FWHM [GeV]	Bkg. functional fit form	$S/\sqrt{B}$ @ FWHM
0	0 – 8%	$\|\eta\| < 2.4$	4.9	1.3	3.3	6.3	31.9	21.2	3150.5	4.2	mBW $\cdot B_{deg4}$	0.12
1	8 – 39%	$1.9 < \|\eta\| < 2.4$	5.6	1.7	3.9	3.5	1.3	22.3	1327.5	7.3	mBW $\cdot B_{deg4}$	0.16
2	8 – 39%	$0.9 < \|\eta\| < 1.9$	10.3	2.8	6.5	6.4	5.2	41.1	2222.2	4.1	mBW $\cdot B_{deg4}$	0.29
3	8 – 39%	$\|\eta\| < 0.9$	3.2	0.8	1.9	2.1	3.5	12.7	775.9	2.9	mBW $\cdot B_{deg4}$	0.17
4	39 – 61%	$1.9 < \|\eta\| < 2.4$	2.9	1.7	2.7	2.7	0.3	11.8	435.0	7.0	mBW $\cdot B_{deg4}$	0.14
5	39 – 61%	$0.9 < \|\eta\| < 1.9$	7.2	3.3	6.1	5.2	1.3	29.2	955.9	4.1	mBW $\cdot B_{deg4}$	0.31
6	39 – 61%	$\|\eta\| < 0.9$	3.6	1.1	2.6	2.2	0.9	14.5	479.3	2.8	mBW $\cdot B_{deg4}$	0.26
7	61 – 76%	$1.9 < \|\eta\| < 2.4$	1.2	1.5	1.8	1.7	0.2	5.2	146.6	7.6	mBW $\cdot B_{deg4}$	0.11
8	61 – 76%	$0.9 < \|\eta\| < 1.9$	4.8	3.6	4.5	4.4	0.7	20.3	514.3	4.2	mBW $\cdot B_{deg4}$	0.29
9	61 – 76%	$\|\eta\| < 0.9$	3.2	1.6	2.3	2.1	0.6	13.1	319.7	3.0	mBW	0.28
10	76 – 91%	$1.9 < \|\eta\| < 2.4$	1.2	3.1	2.2	2.1	0.2	5.8	102.4	7.2	Sum Exp(n=2)	0.14
11	76 – 91%	$0.9 < \|\eta\| < 1.9$	4.4	8.7	6.2	6.0	1.1	20.3	363.3	4.2	mBW	0.34
12	76 – 91%	$\|\eta\| < 0.9$	3.1	4.0	3.8	3.6	0.9	13.7	230.0	3.2	mBW $\cdot B_{deg4}$	0.34
13	91 – 95%	$\|\eta\| < 2.4$	1.7	6.4	2.5	2.6	0.5	8.6	95.5	4.0	mBW	0.28
14	95 – 100%	$\|\eta\| < 2.4$	2.0	19.4	1.5	1.4	0.7	13.7	82.4	4.2	mBW	0.47
overall			59.1	61.1	51.8	52.3	49.2	253.3	12 961.5	3.9		

event categories

* FWHM: full width at half maximum
* Bkg./GeV @ 125 GeV: total number of background events
* mBW, B_{deg4}, Sum Exp: fit functions used to estimated background with data

* most sensitive categories: 12 & 14

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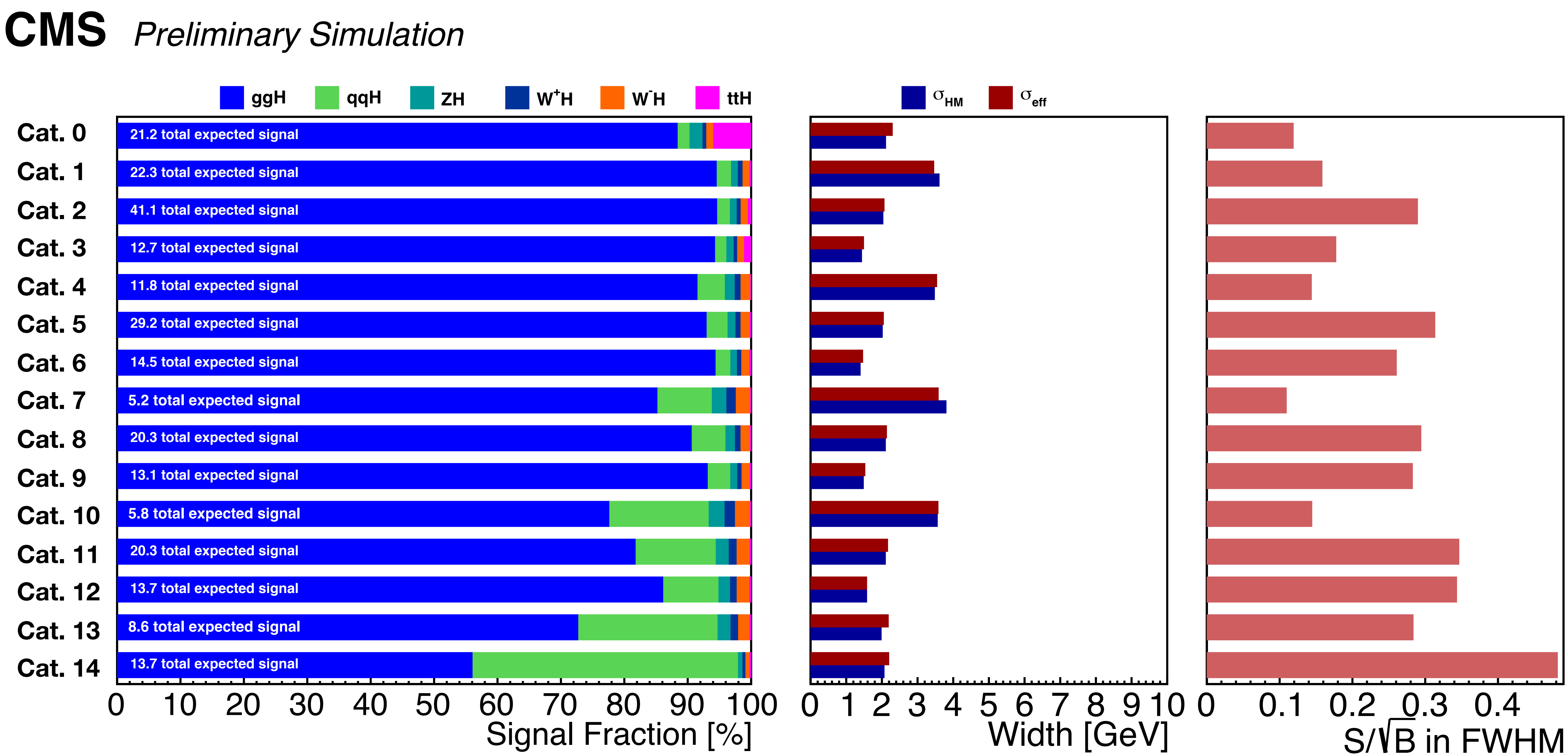
event categories: signal composition



so this is how nature could look like, pretty colourful

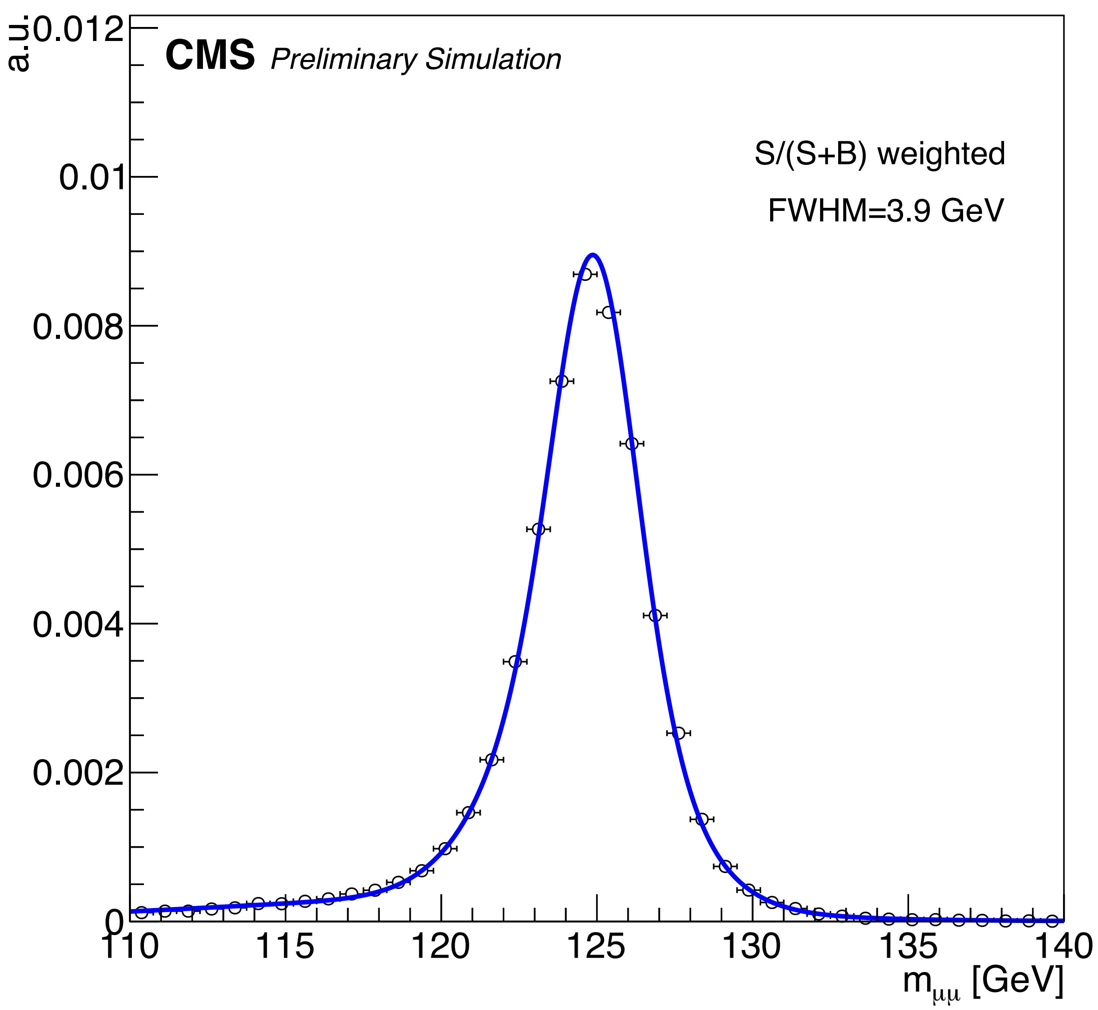
signal and background modelling

*** signal:**

- a sum of up to three Gaussian functions
- good description of the distributions including the tails

*** background:**

- functional form chosen separately for each category
- choice: based on minimising the possible bias in the fitted signal yield



$$\text{Bernsteins } (B_{deg\ n}) : B(x) = \sum_{i=0}^{n} \alpha_i \left[\binom{n}{i} x^i (1-x)^{n-i} \right]$$

$$\text{Sum of exponentials (Sum Exp)} : B(x) = \sum_{i=1}^{n} \beta_i e^{\alpha_i x}$$

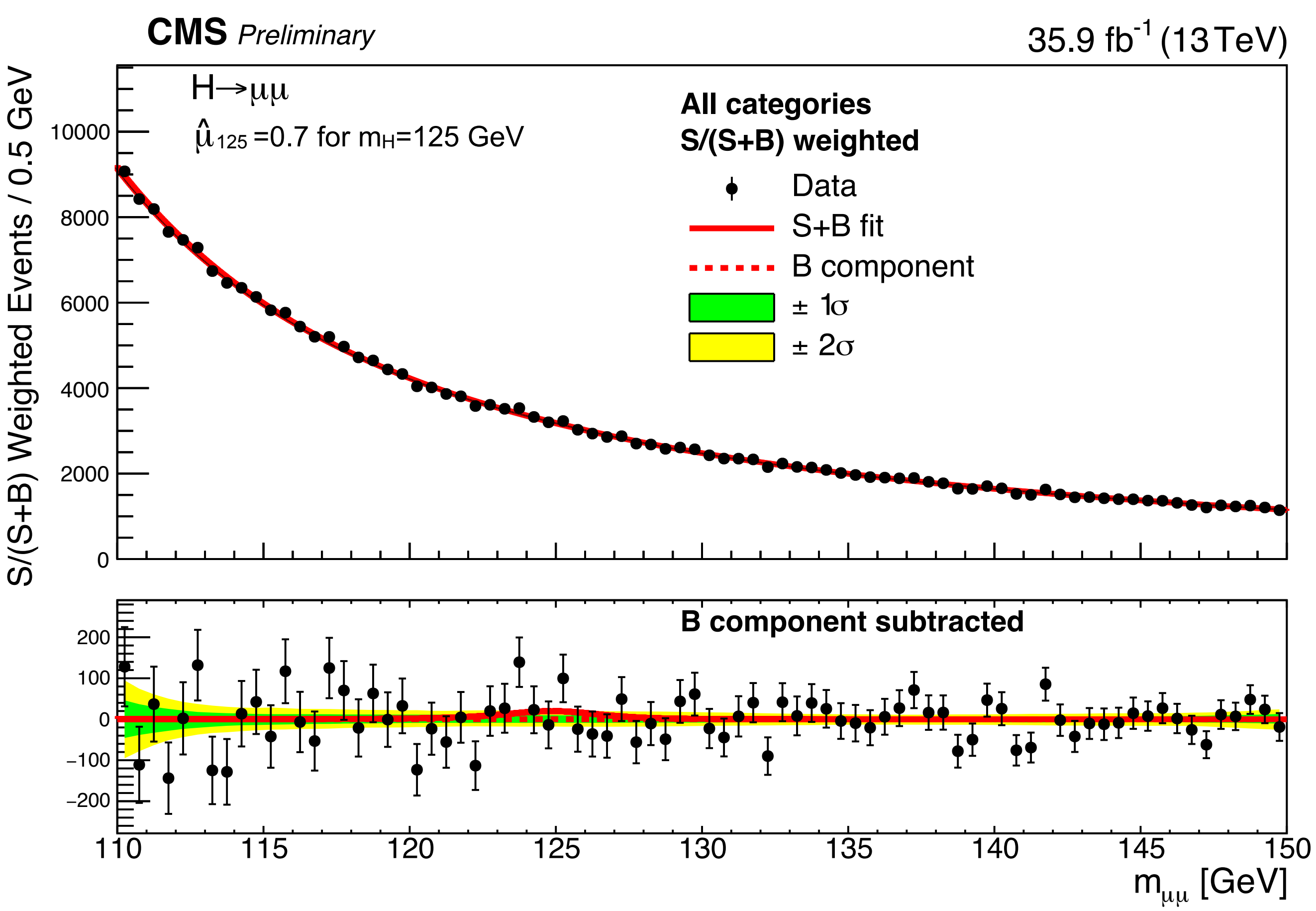
$$\text{Breit–Wigner} : B(x) = \frac{e^{ax}\sigma_z}{(x-\mu_z)^2 + (\frac{\sigma_z}{2})^2}$$

$$\text{Modified Breit–Wigner (mBW)} : B(x) = \frac{e^{a_2 x + a_3 x^2}}{(x-\mu_z)^{a_1} + (\frac{\sigma_z}{2})^{a_1}}$$

without models no chance to survive these days

Higgs: μμ channel targeting 2 x σ/σ_{SM}

* no significant signal was observed



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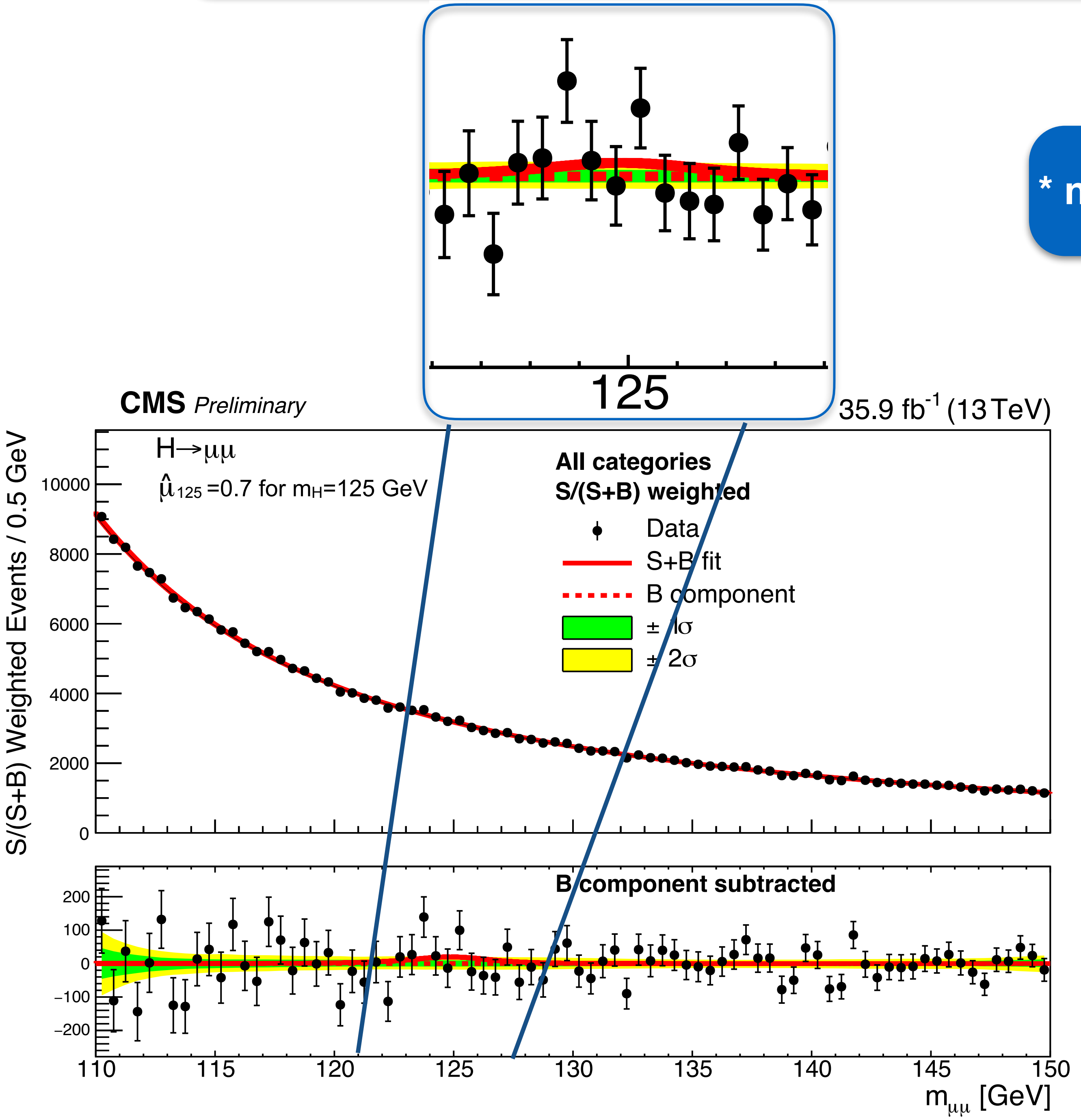

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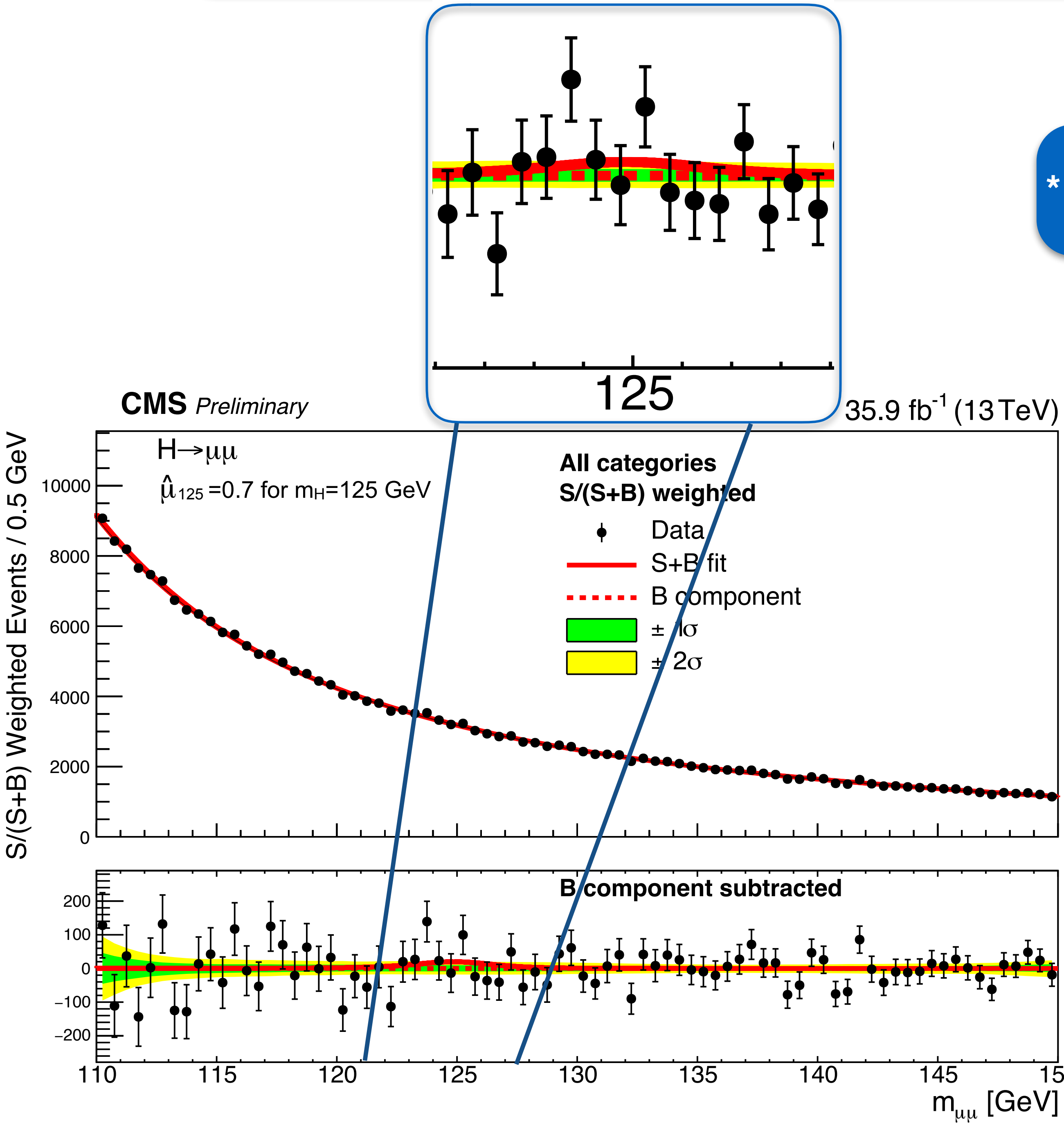
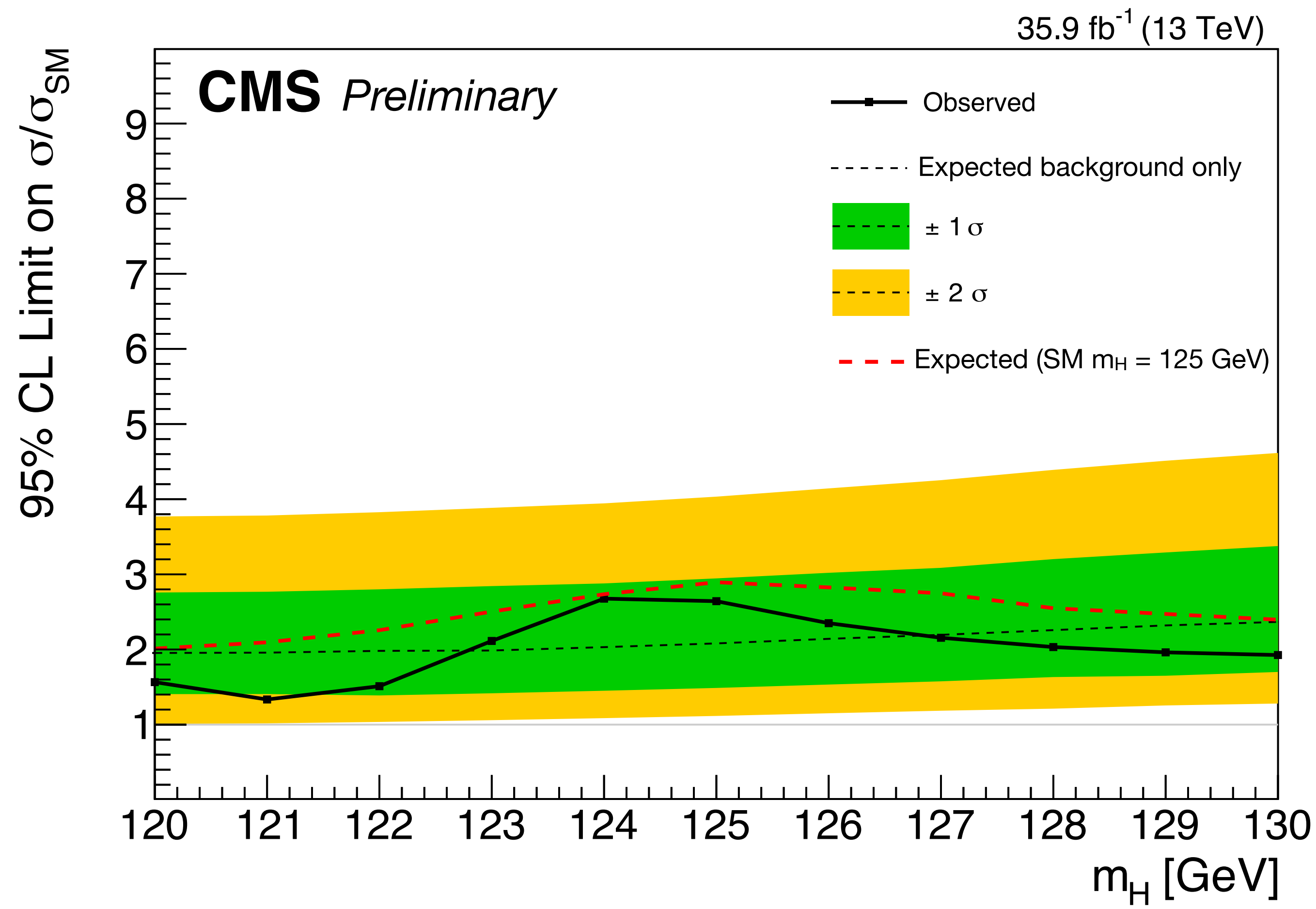


* no significant signal was observed

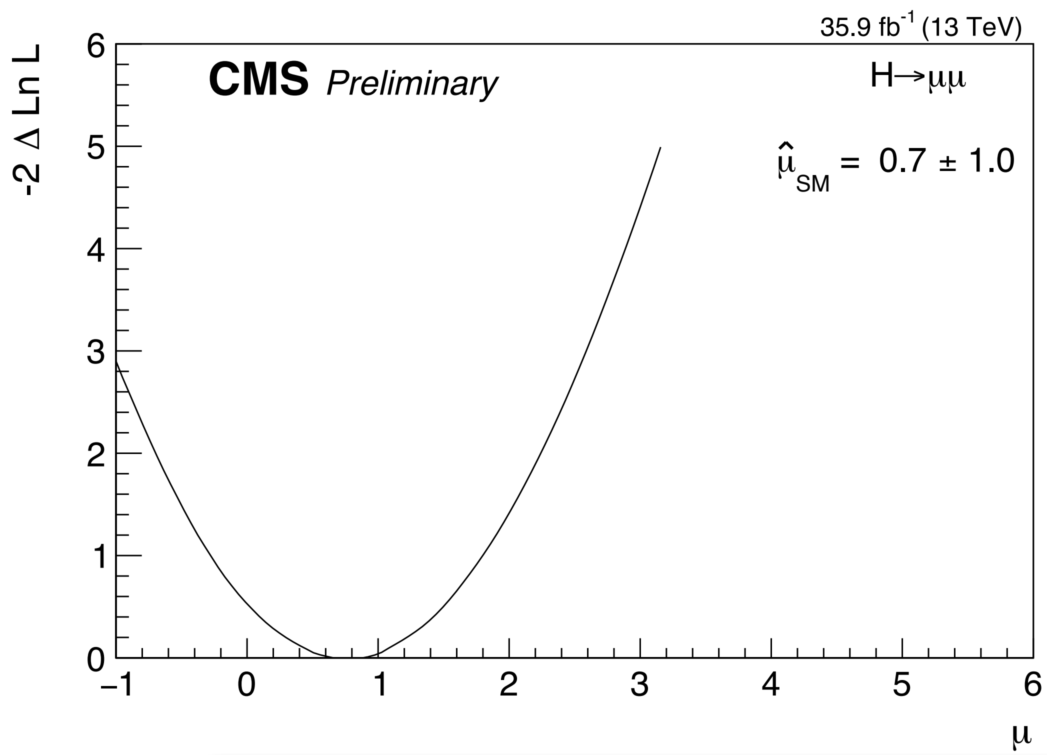


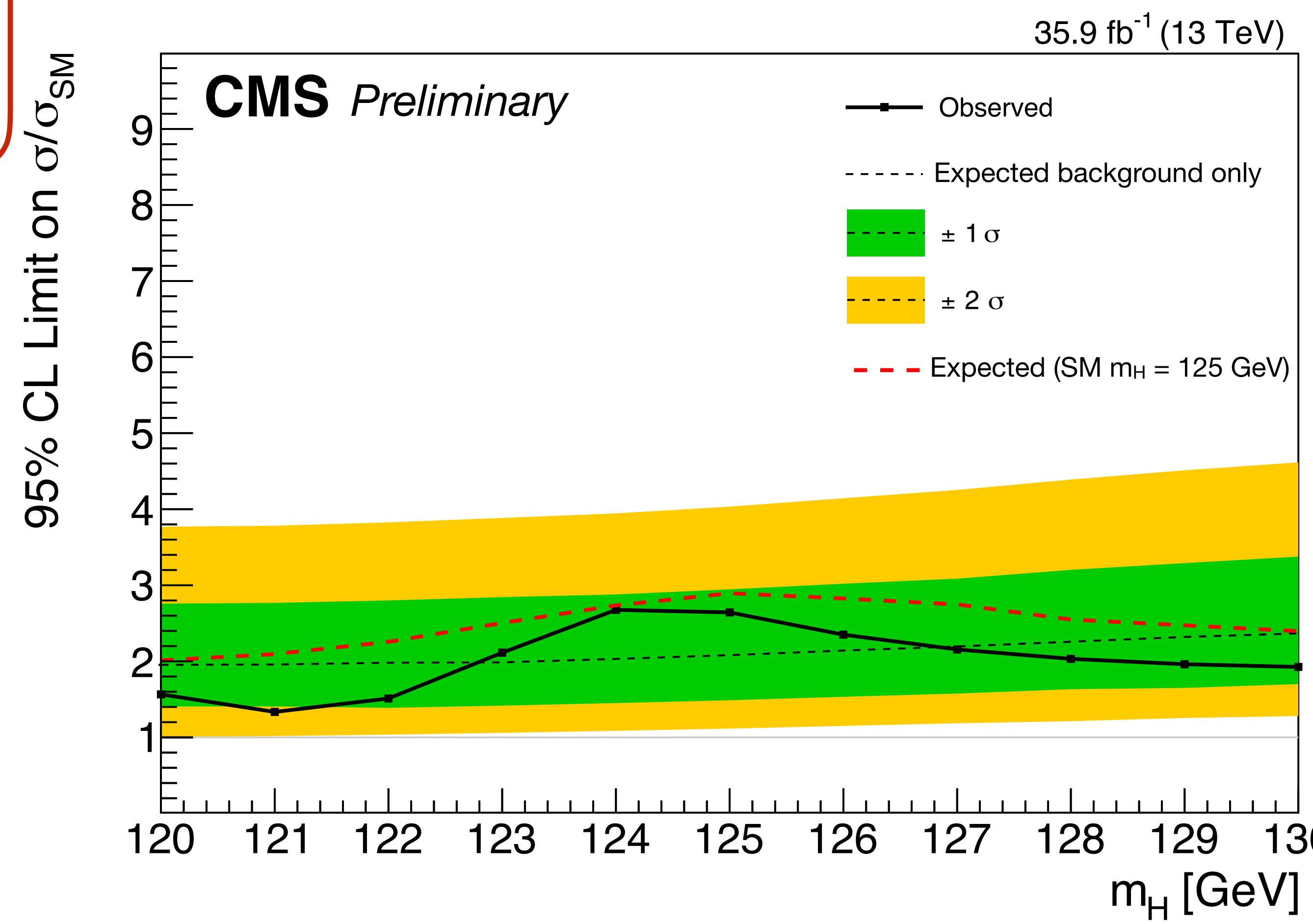
* 95% CL upper combined (expected) limit: 2.68 (2.08) for a Higgs mass of 125 GeV

Higgs: μμ channel targeting 2 x σ/σ_{SM}

m_H [GeV]	Expected Limits					Observed limit
	-2σ	-1σ	median	1σ	2σ	
120	1.01	1.41	1.95	2.76	3.77	1.57
121	1.02	1.41	1.96	2.77	3.78	1.33
122	1.04	1.39	1.98	2.80	3.83	1.51
123	1.06	1.42	1.99	2.84	3.89	2.11
124	1.09	1.45	2.03	2.88	3.94	2.68
125	1.12	1.49	2.08	2.95	4.03	2.64
126	1.15	1.53	2.14	3.02	4.14	2.35
127	1.19	1.58	2.19	3.09	4.25	2.16
128	1.21	1.63	2.26	3.20	4.39	2.03
129	1.26	1.65	2.32	3.29	4.51	1.96
130	1.28	1.70	2.37	3.38	4.62	1.93

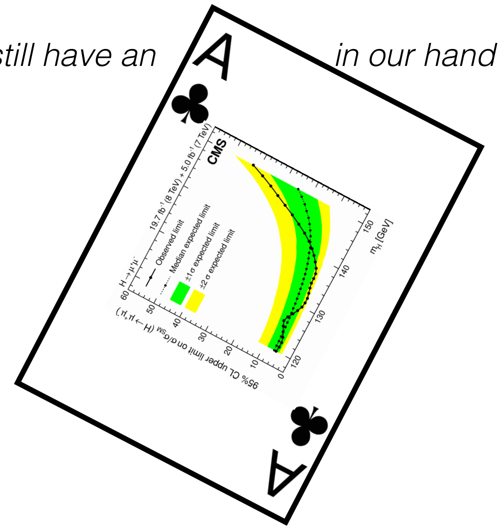
Run II (2016 @ 13 TeV)





*** best fit is obtained for a signal strength of 0.7 ± 1.0 at a Higgs mass of 125 GeV**

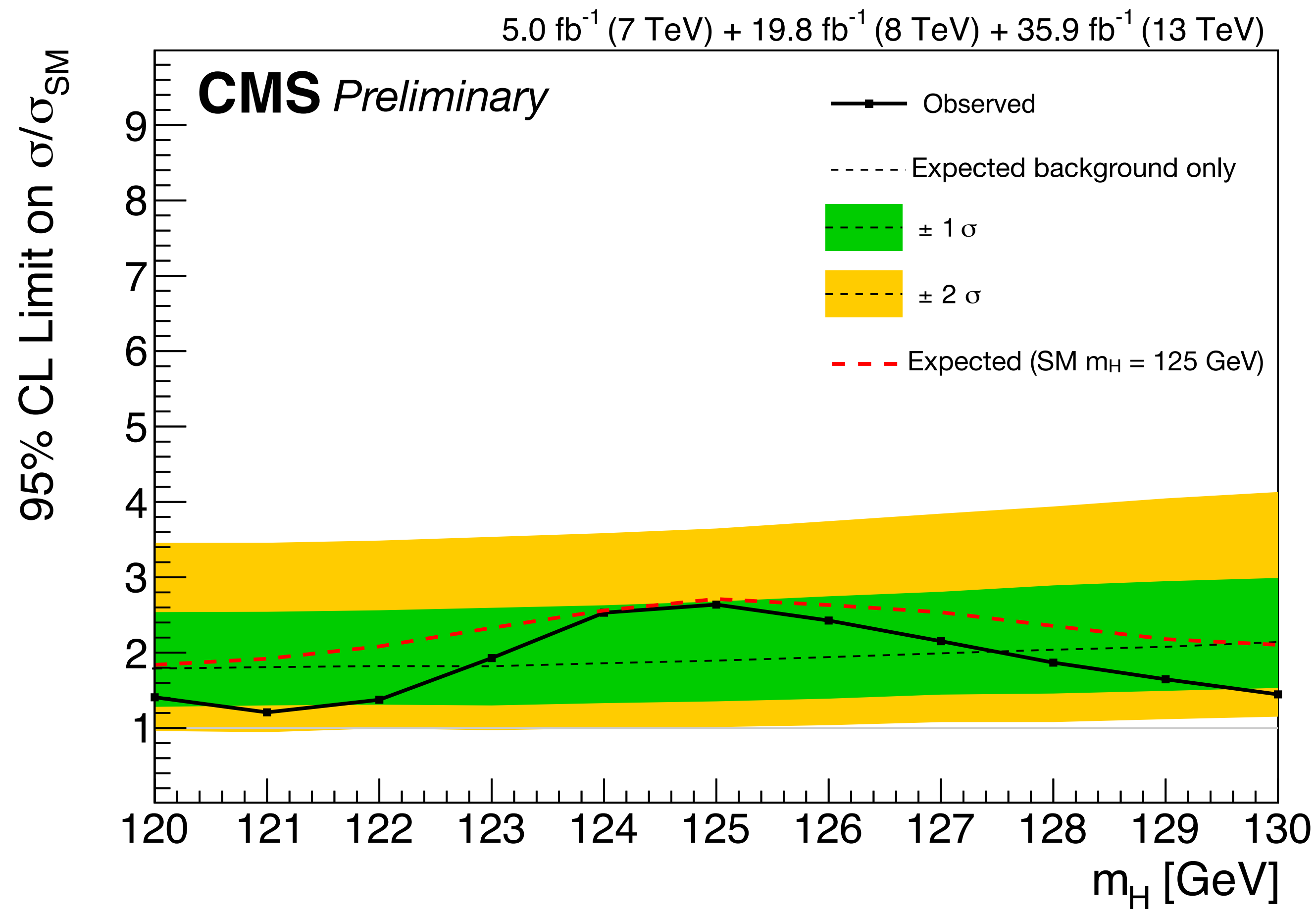
but this is not everything…

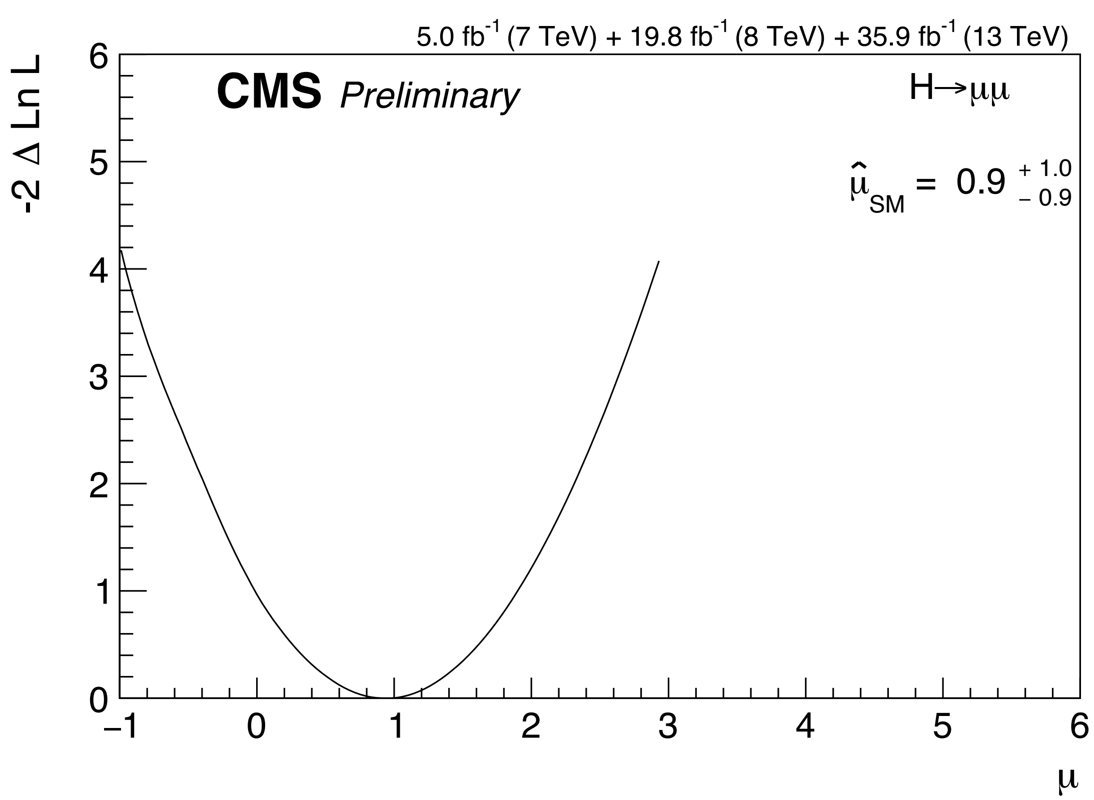
we still have an  *in our hand*

Higgs: μμ channel below 2 x σ/σ_{SM}

Run I & Run II

m_H [GeV]	Expected Limits					Observed limit
	-2σ	-1σ	median	1σ	2σ	
120	0.96	1.28	1.79	2.54	3.46	1.41
121	0.95	1.30	1.81	2.54	3.46	1.21
122	0.99	1.31	1.82	2.56	3.49	1.38
123	0.97	1.30	1.82	2.60	3.54	1.93
124	1.00	1.33	1.86	2.63	3.59	2.53
125	1.01	1.35	1.89	2.68	3.65	2.64
126	1.04	1.39	1.94	2.75	3.74	2.43
127	1.08	1.44	1.99	2.81	3.84	2.15
128	1.08	1.46	2.04	2.89	3.94	1.87
129	1.12	1.49	2.08	2.95	4.05	1.65
130	1.15	1.53	2.14	2.99	4.13	1.45





*** a milestone in the dimuon Higgs decay search for a mass of 125 GeV is achieved:**

- **combined (expected) σ/σ_{SM} : 2.68 (1.89)**
- **significance: 0.98**
- **signal strength: $0.9^{+1.0}/_{-0.9}$**
- **observed (expected) upper limit on branching fraction: 5.7 (5.1) x 10^{-4}**

where are we now? where do we go from here?

Higgs boson as of today

H^0 $J = 0$

Mass $m = 125.09 \pm 0.24$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

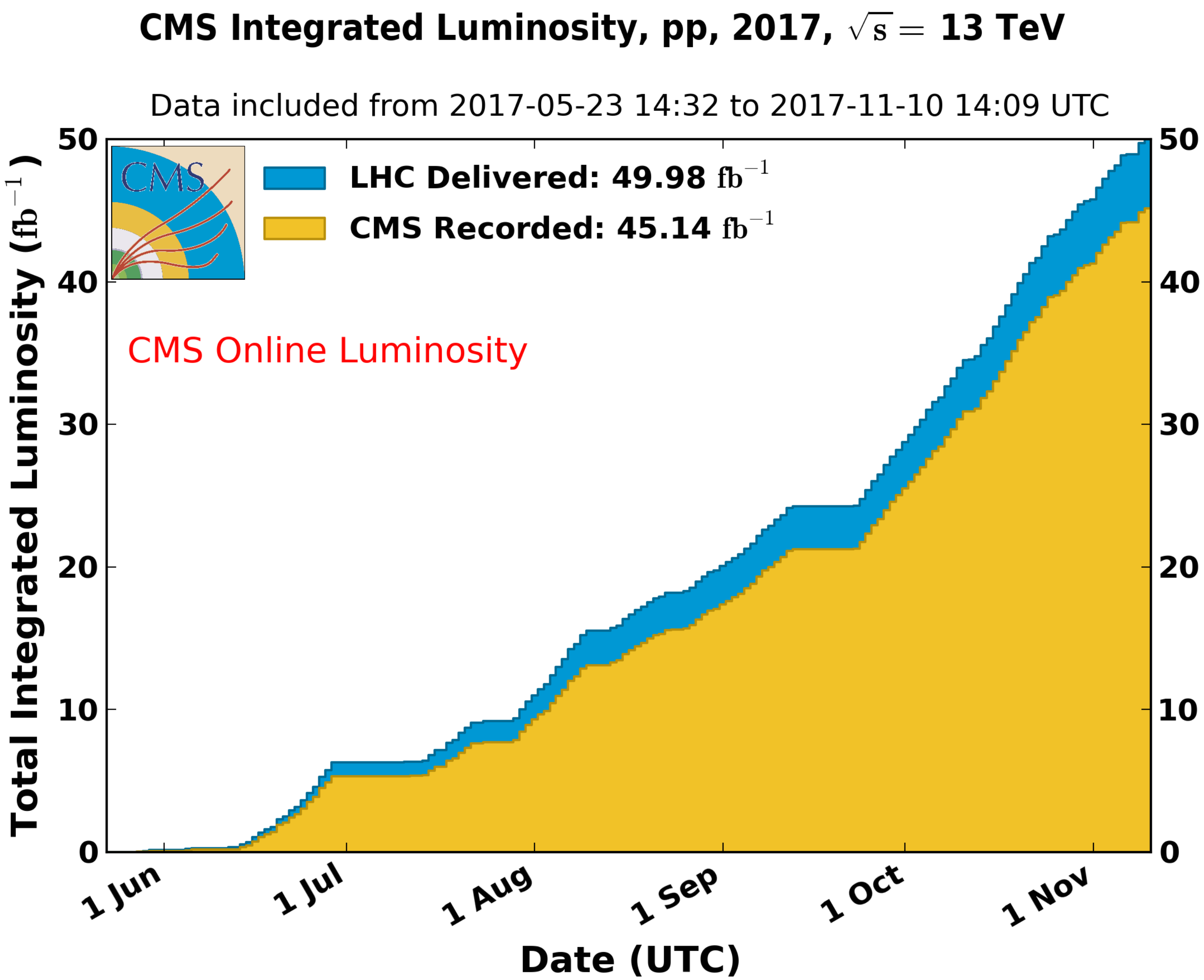
See Listings for the latest unpublished results.

Combined Final States = 1.10 ± 0.11
$W W^* = 1.08^{+0.18}_{-0.16}$
$Z Z^* = 1.29^{+0.26}_{-0.23}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.82 \pm 0.30$ (S = 1.1)
$\mu^+\mu^-$ = ~~0.1 ± 2.5~~ ← $0.9^{+1.0}_{-0.9}$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 9.5$, CL = 95%
$t\bar{t}H^0$ Production = $2.3^{+0.7}_{-0.6}$

where do we go from here?

* LHC had yet another great year in 2017 (CMS best wishes for the next year)

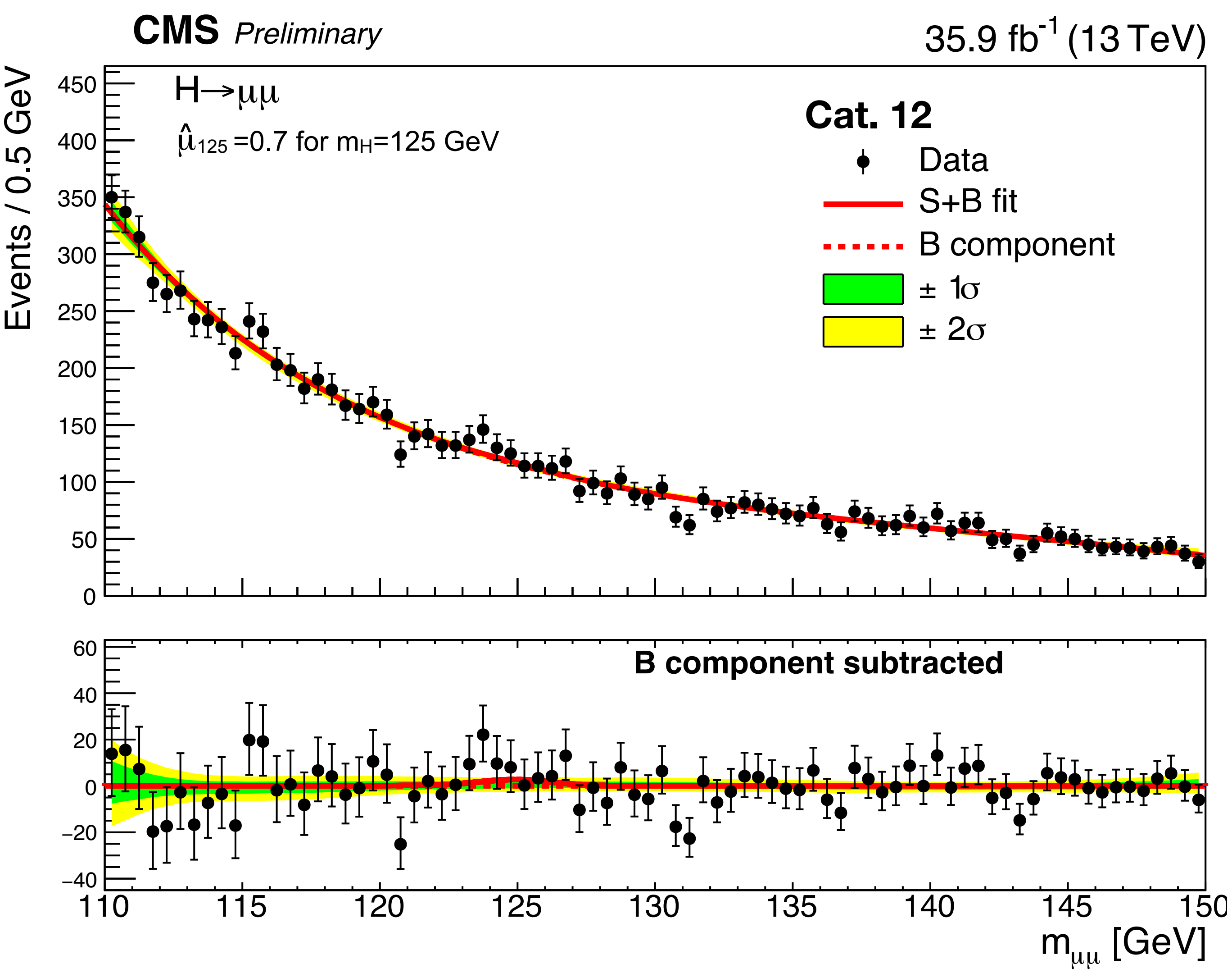
* we have the chance of doubling the 2016 statistics: a factor $\sqrt{2}$ improvement in sensitivity is within reach

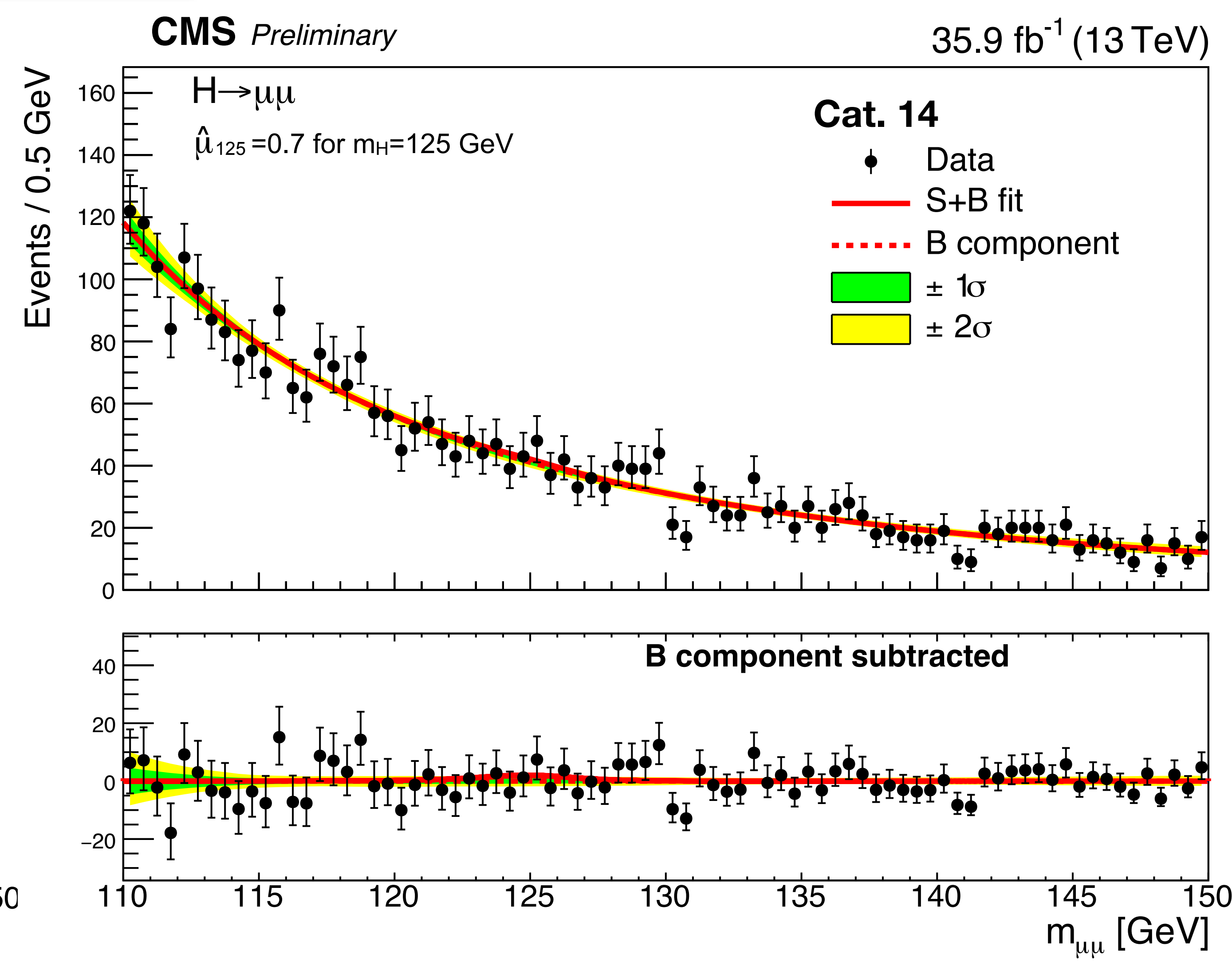


this is were the dimuon story takes a break today, it is time for questions…

dimuon mass spectrum

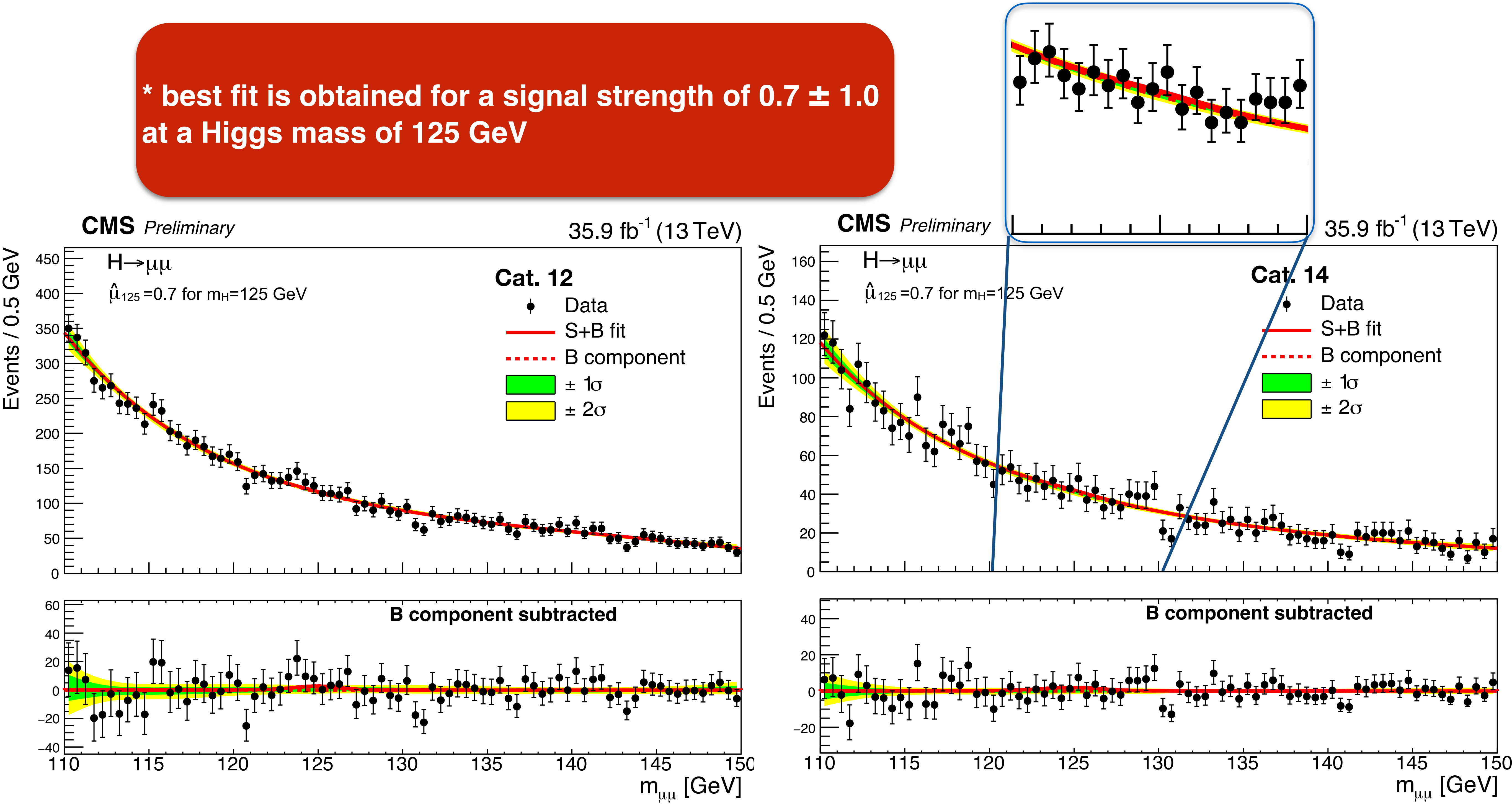
* best fit is obtained for a signal strength of 0.7 ± 1.0 at a Higgs mass of 125 GeV



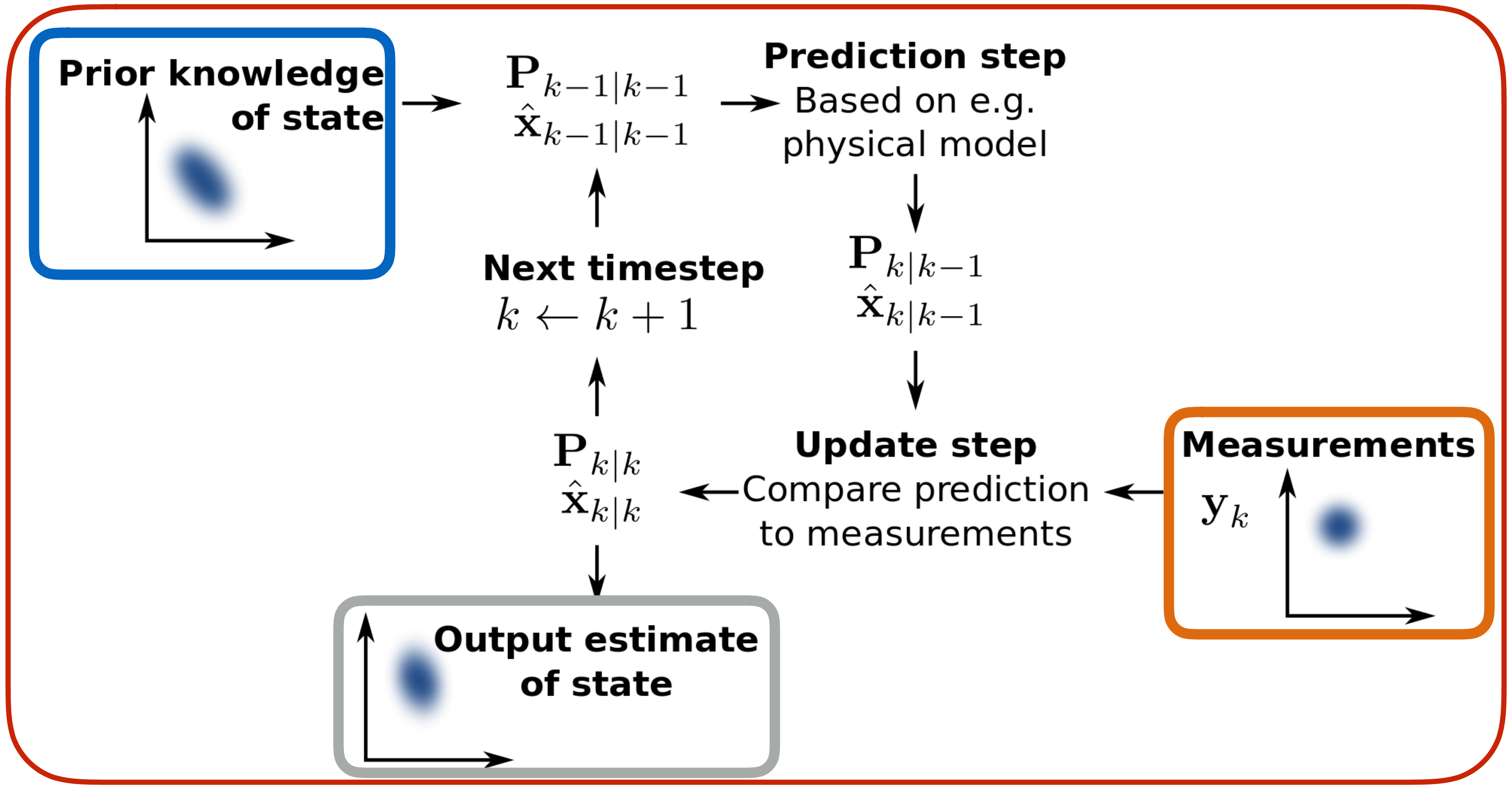


dimuon mass spectrum

*** best fit is obtained for a signal strength of 0.7 ± 1.0 at a Higgs mass of 125 GeV**



Kalman filter



* an iterative process

* can be used for:

- track reconstruction (not only in particle physics)

- momentum calibration