Higgs to beauty quarks
First observation of the big missing piece

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SLAC Seminar
August, 14 2018

Outline

I. Higgs boson at LHC
II. Experimental **techniques** to identify H to $b\bar{b}$
III. First observation of **H to $b\bar{b}$**
IV. Future perspectives
V. Conclusions

The Higgs boson

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - \underbrace{V(\phi)}_{-\mu^2\phi^2 + \lambda\phi^4}$$

- **Precision measurements** of the Higgs boson properties will provide a crucial test of the Standard Model
- It represents a **potential window to physics Beyond** the Standard Model
    - we know the SM is not a complete theory

The Large Hadron Collider

2010-2012, ~25fb^{-1} delivered in **Run-1** at 7 and **8 TeV**

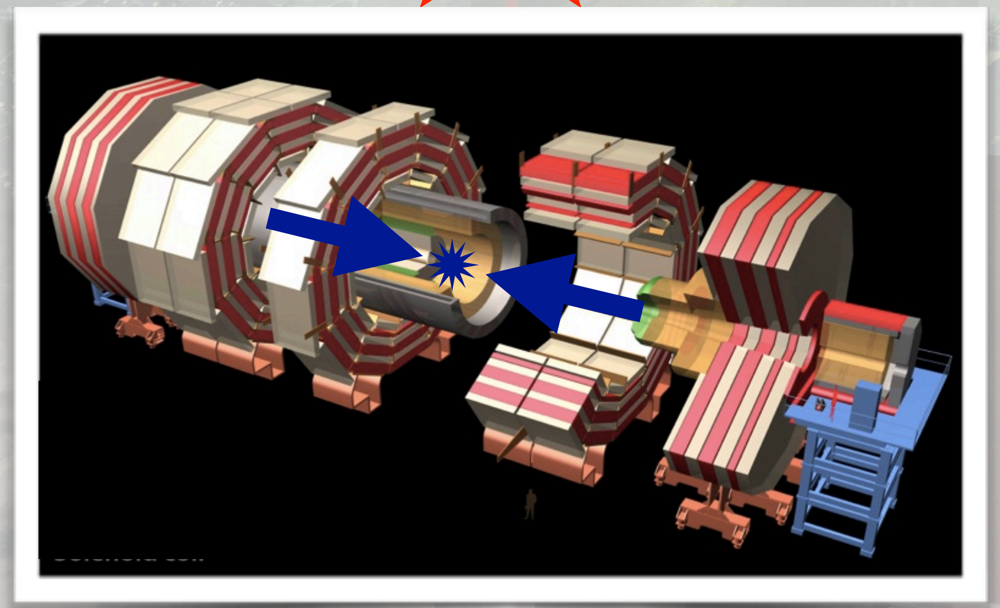
On average ~**10-20** p-p interactions per bunch crossing (**pileup**)

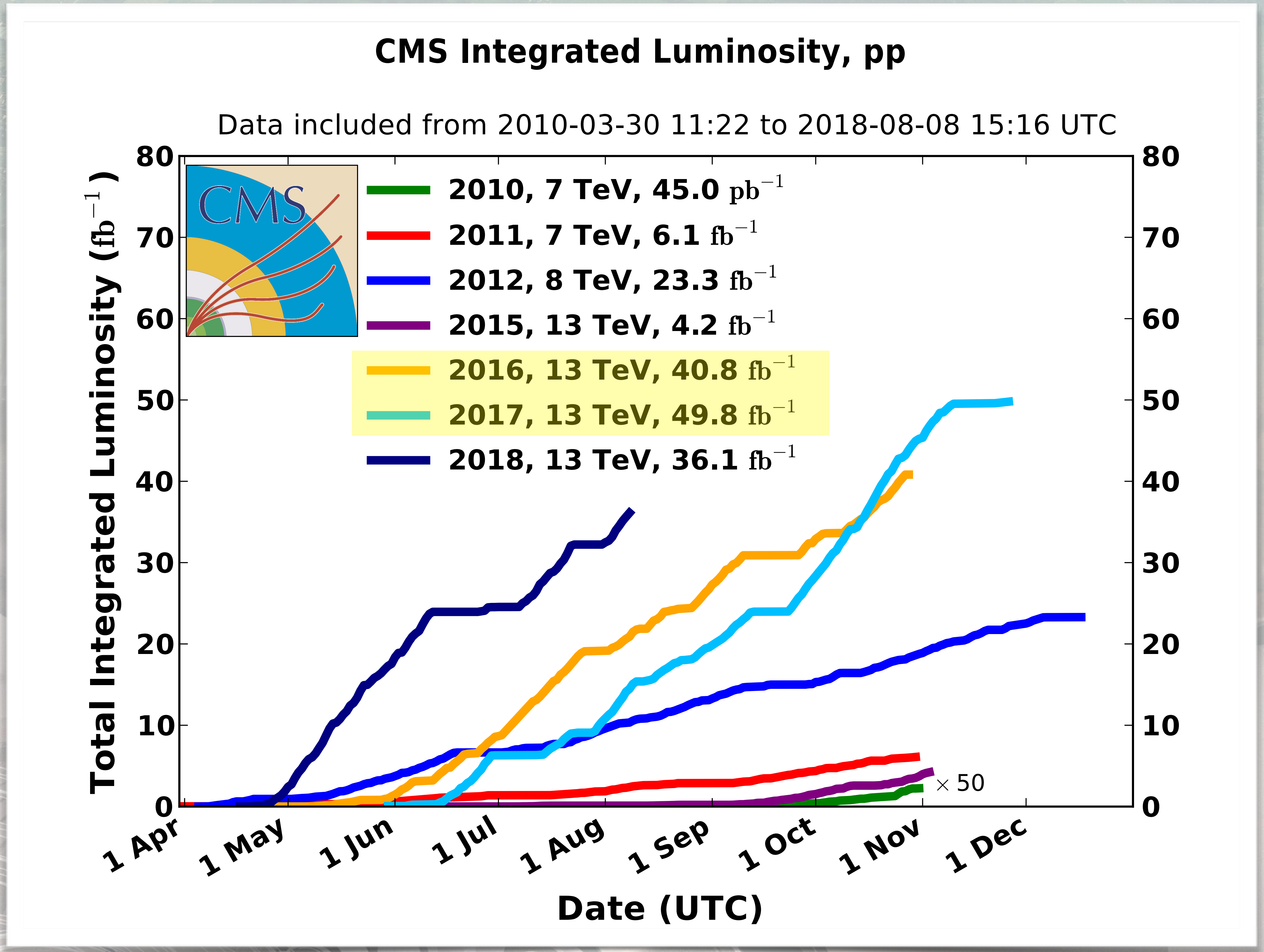
2015-2018, ~120 fb^{-1} delivered in **Run-2** at **13 TeV**

the last big jump in energy for a while, on average ~**30-40 pileup**

ATLAS

CMS





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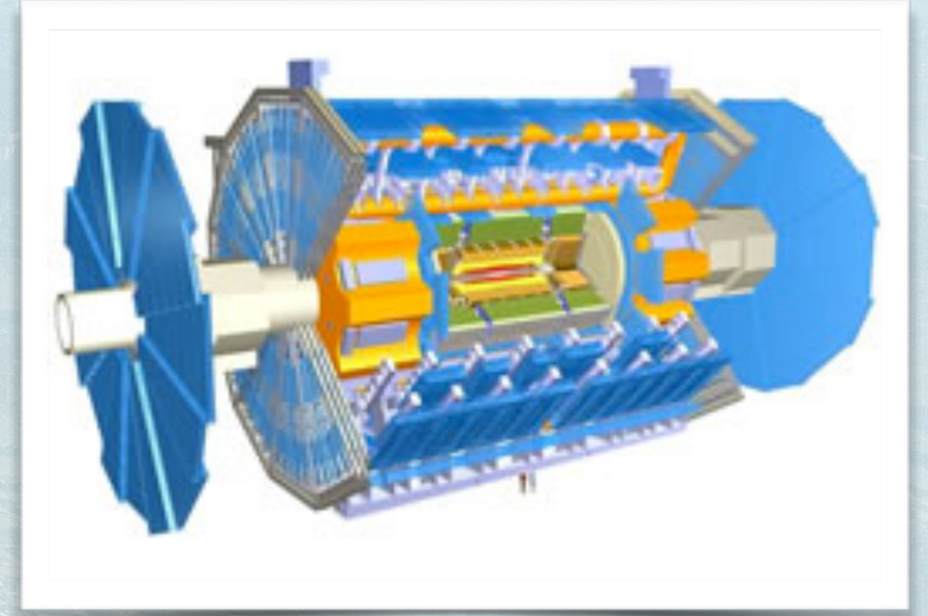

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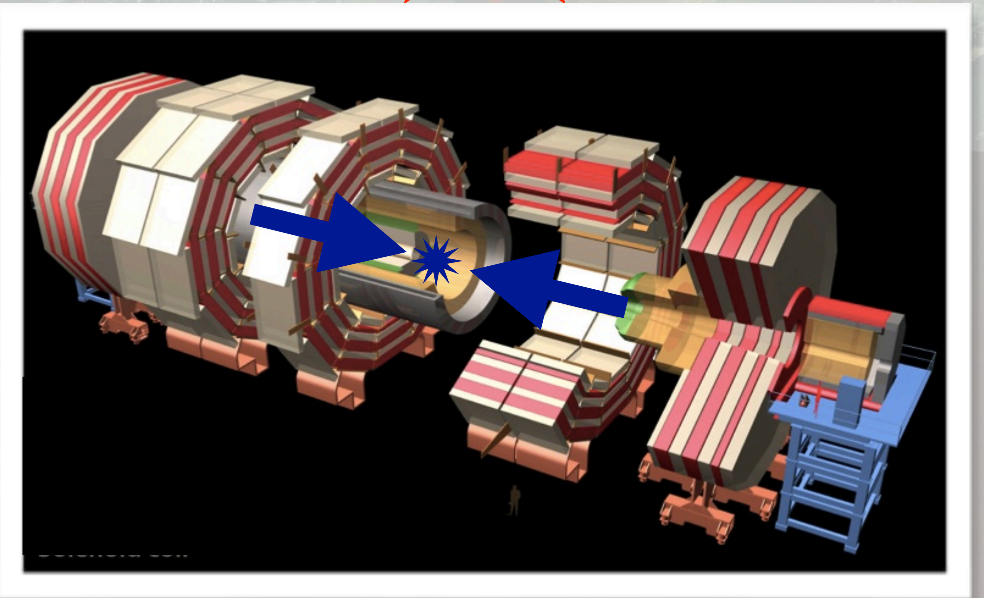

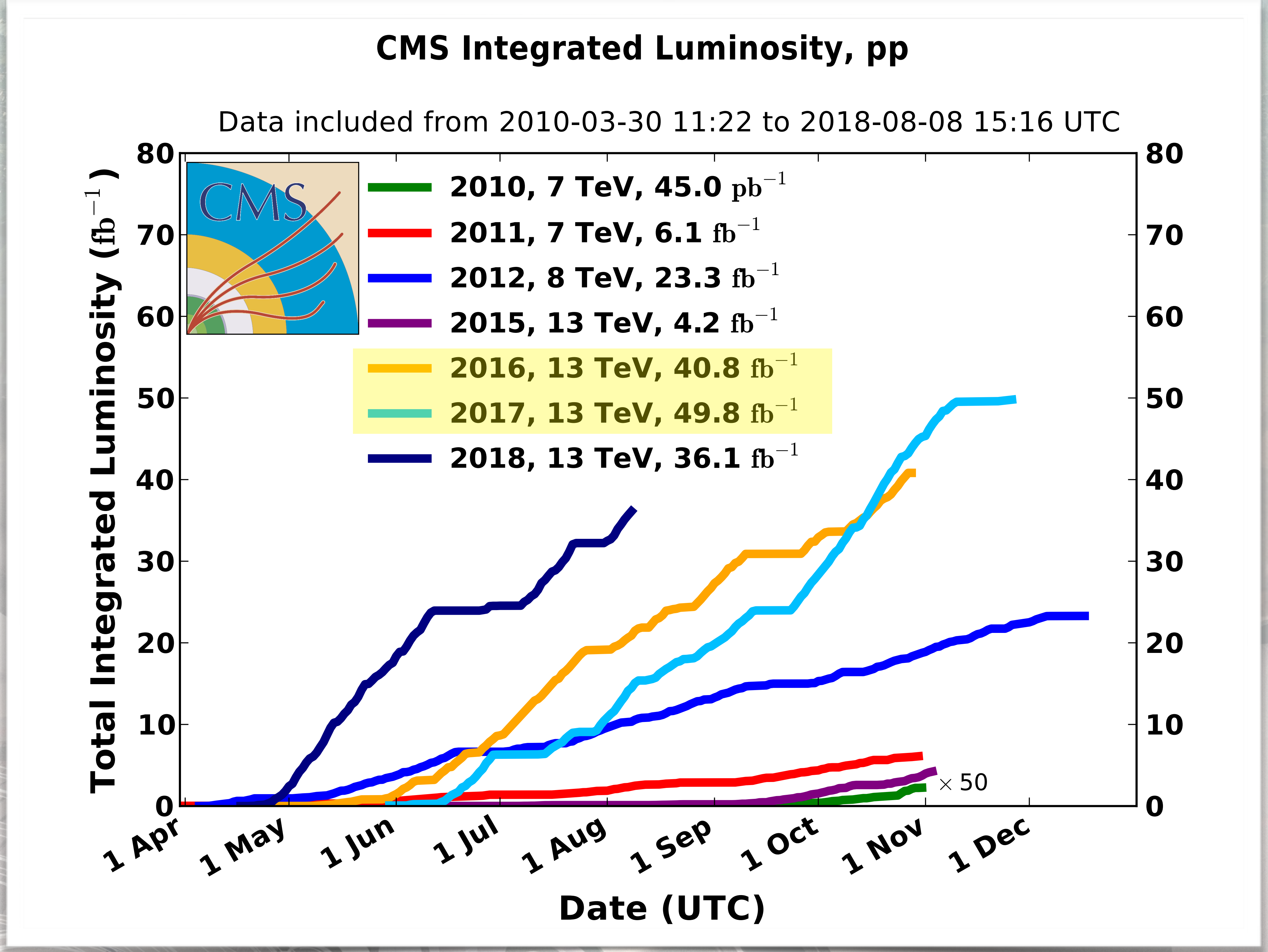

A factor 10x more data that at the time of the Higgs discovery

ATLAS-ArXiv:1806.00242, sub PLB
CMS-JHEP 11 (2017) 047
CMS-HIG-17-031

Is it a SM Higgs boson?

- Mass
- Spin-parity
- The couplings to fermions and bosons
- Width
- Study the self-coupling
- Any non-SM property?

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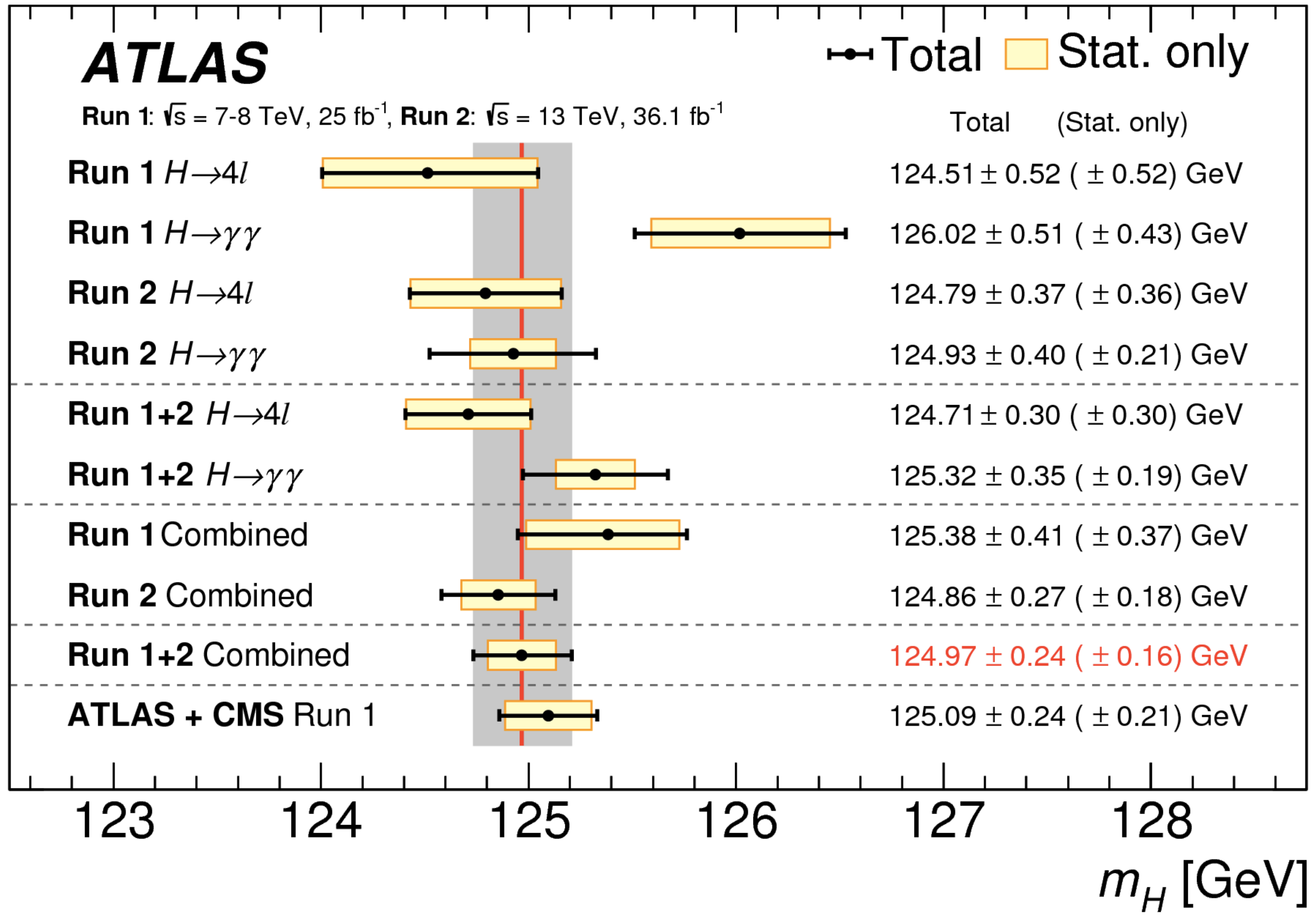

CMS $H \to ZZ \to 4l$

$$m_H = 125.26 \pm 0.20\ (\text{stat.}) \pm 0.08\ (\text{sys.})\ \text{GeV}$$

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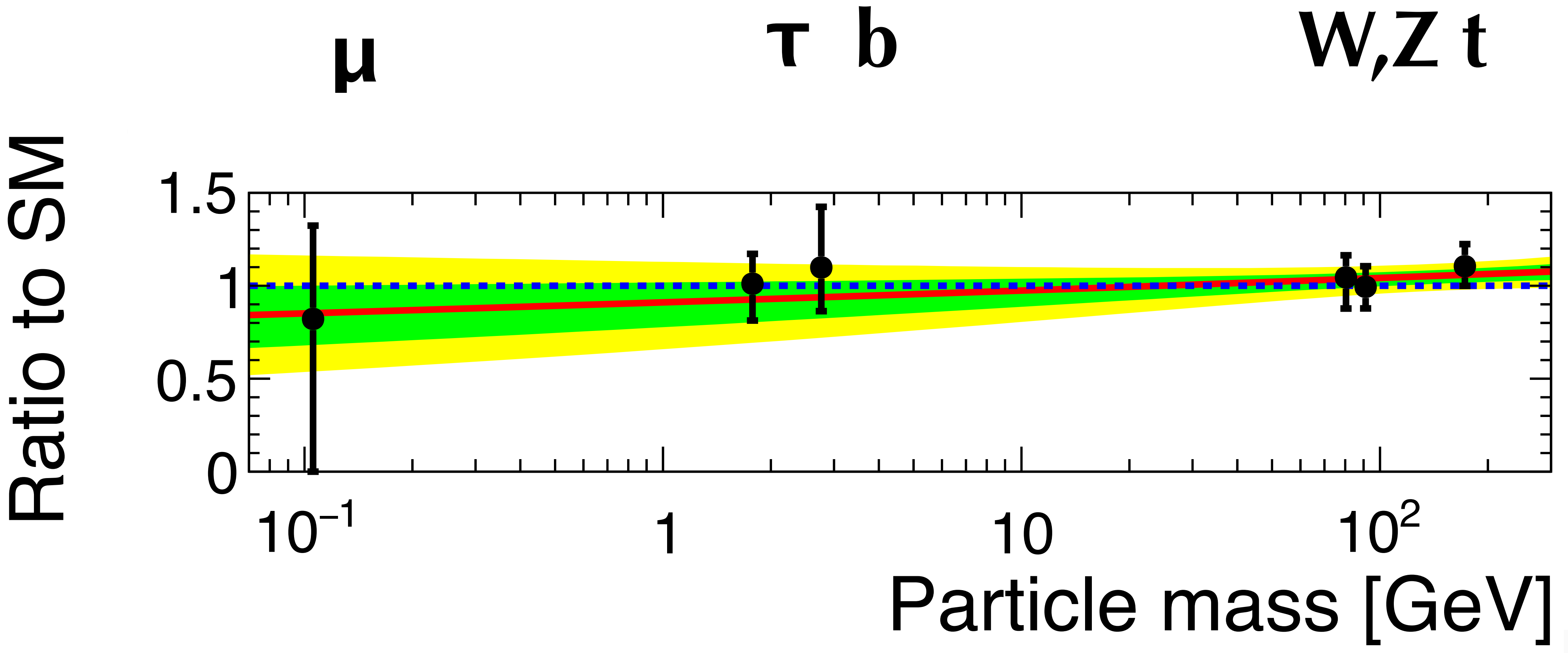

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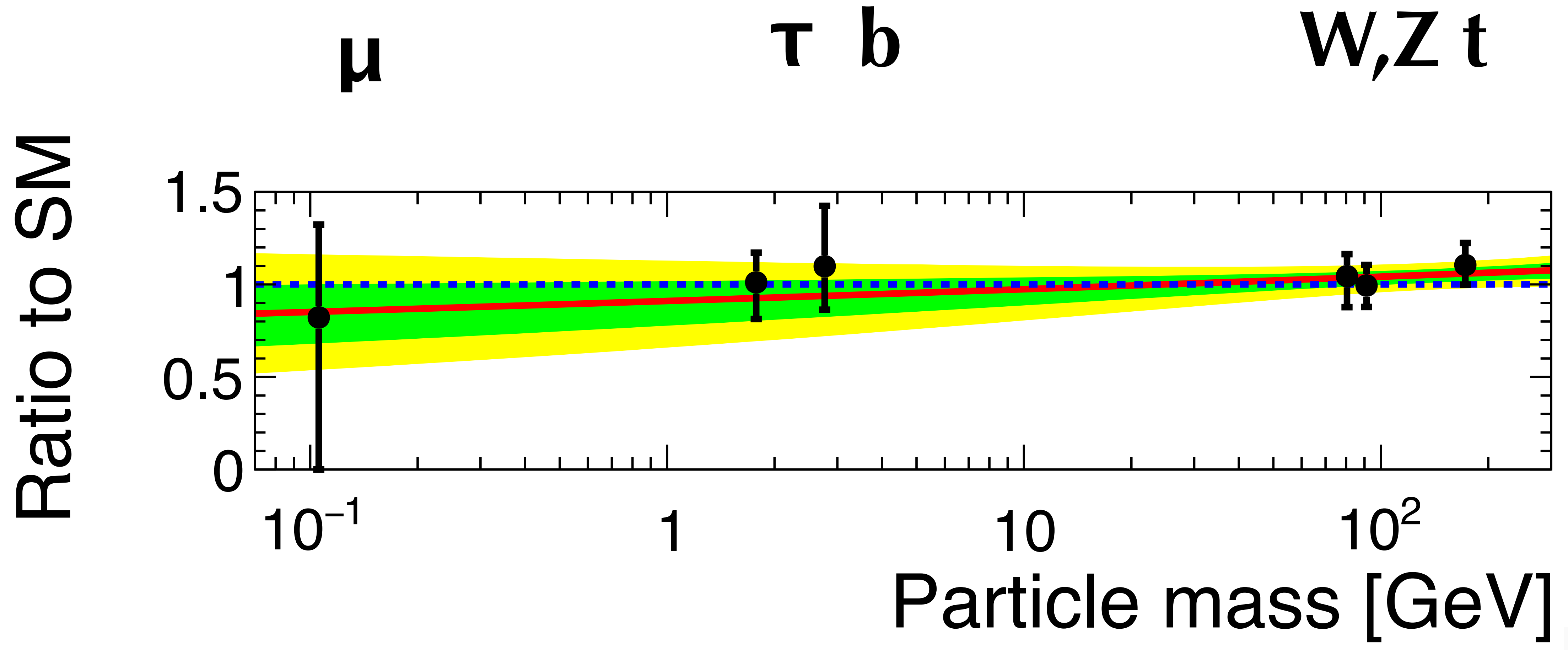
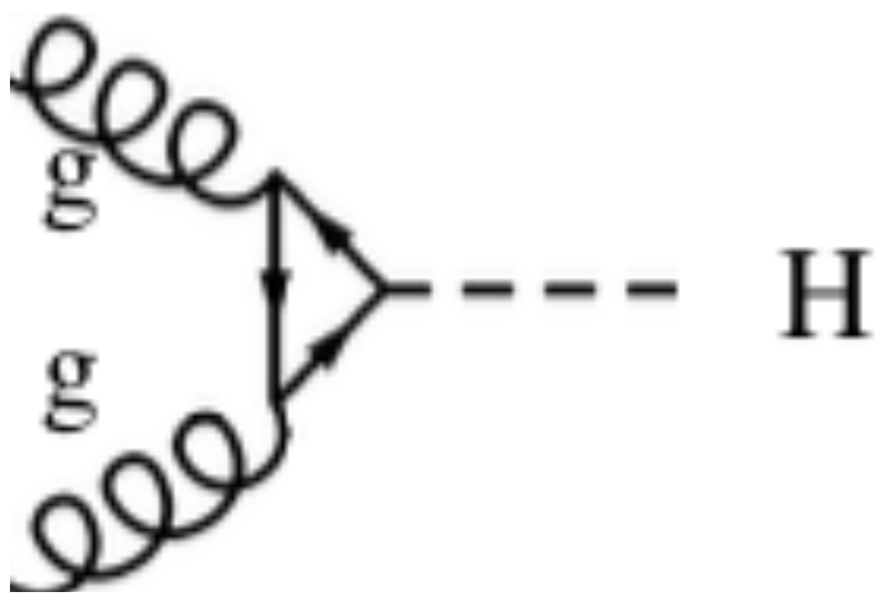


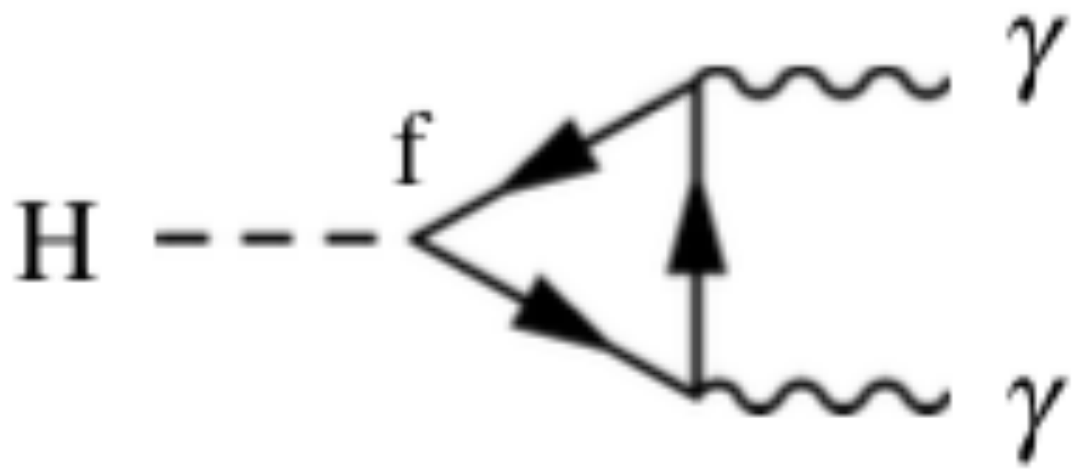
Couplings to W and Z established in Run-1 and to τ-leptons in Run-2
Missing direct test of the coupling of the Higgs boson to quarks…

Couplings to Quarks

Indirect

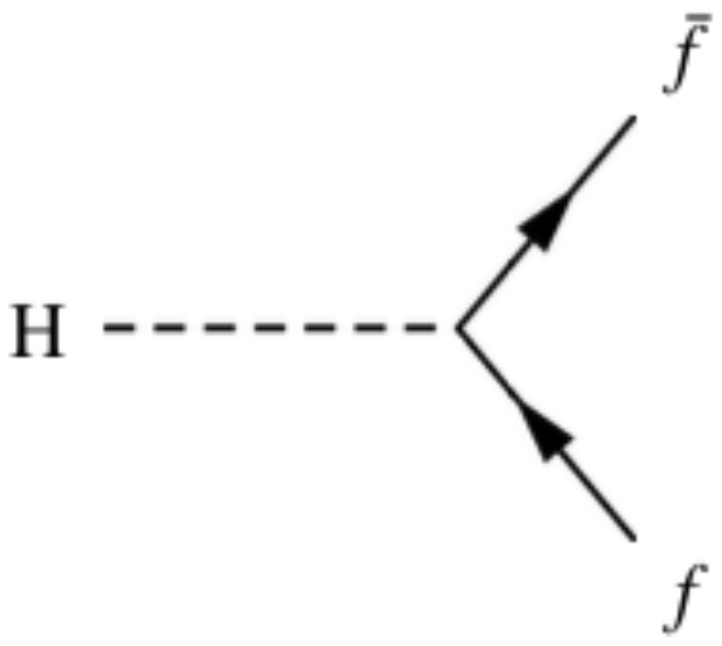


Gluon fusion

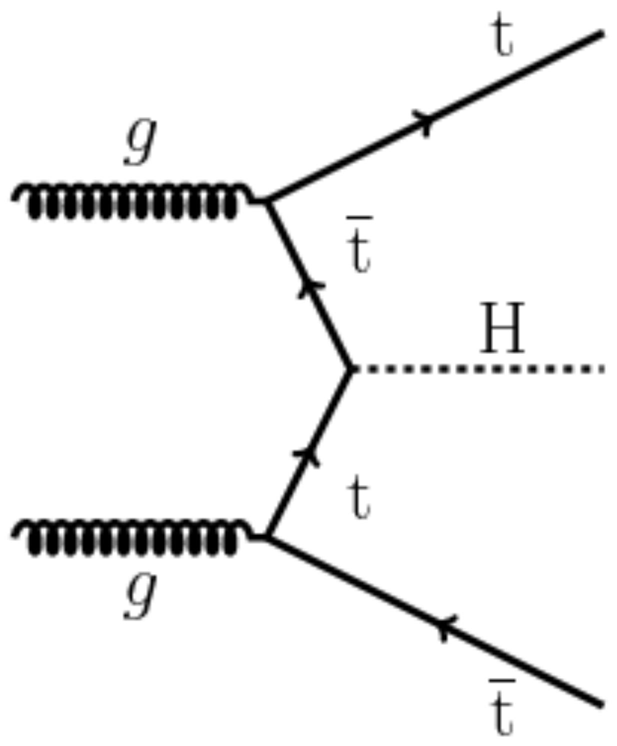


H→γγ

Direct



H→ b$\bar{b}$



ttH

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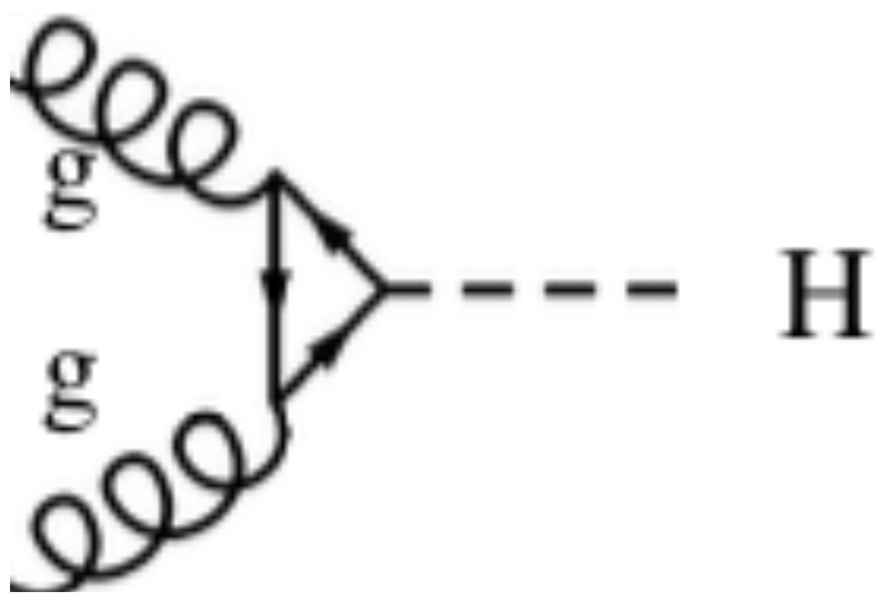

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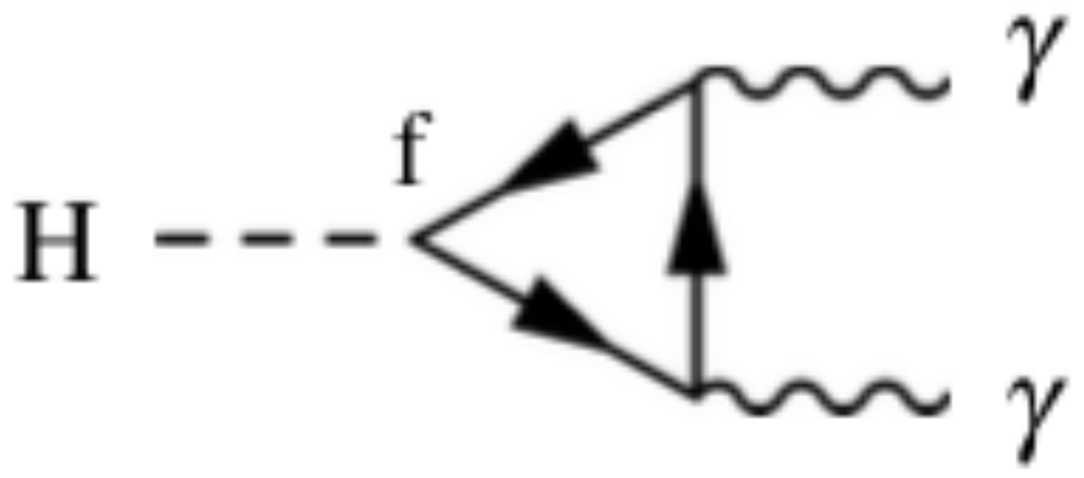

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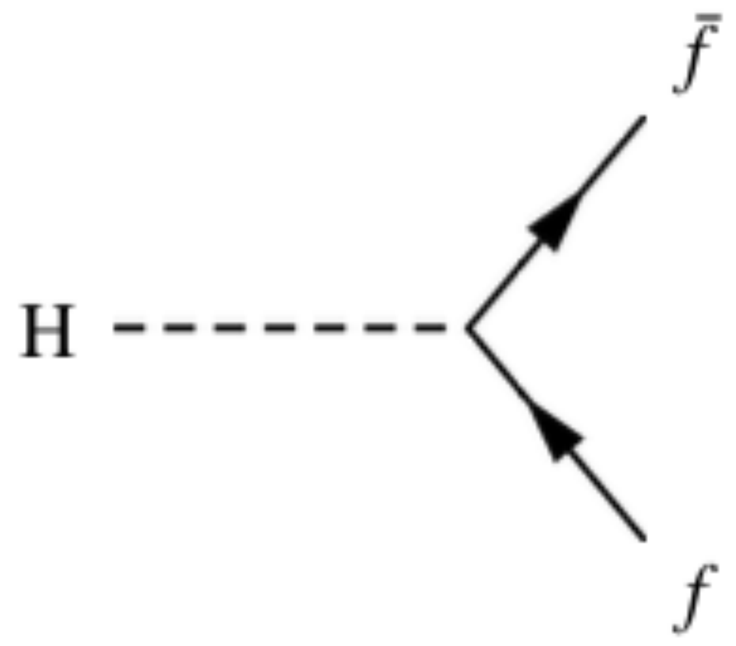

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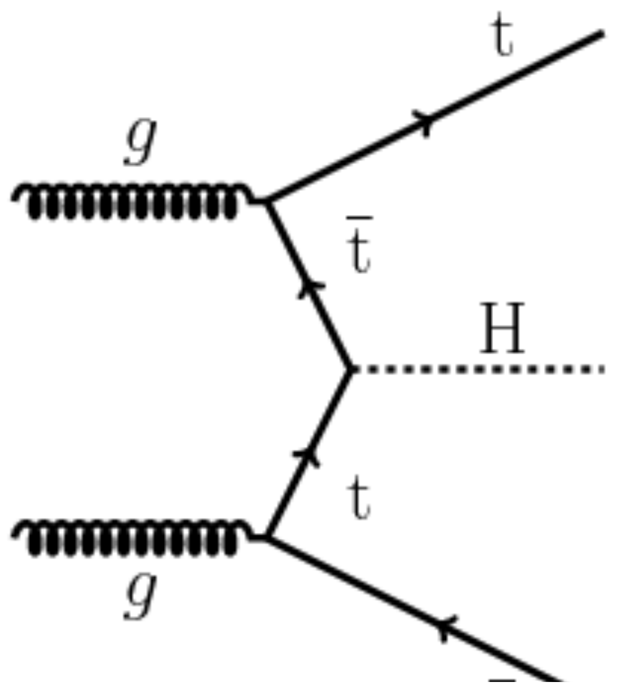

ttH

We have just observed the ttH process
CMS** Run 1+2 (25+36/fb): **5.2σ (4.2σ exp.)
ATLAS** Run 1+2 (25+80/fb): **6.3σ (5.1σ exp.)

Couplings to Quarks

NEW

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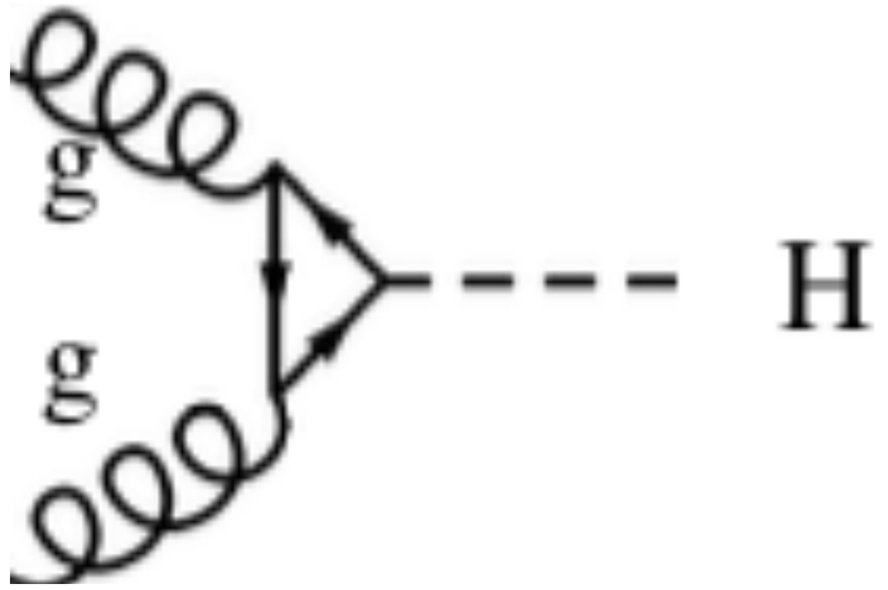

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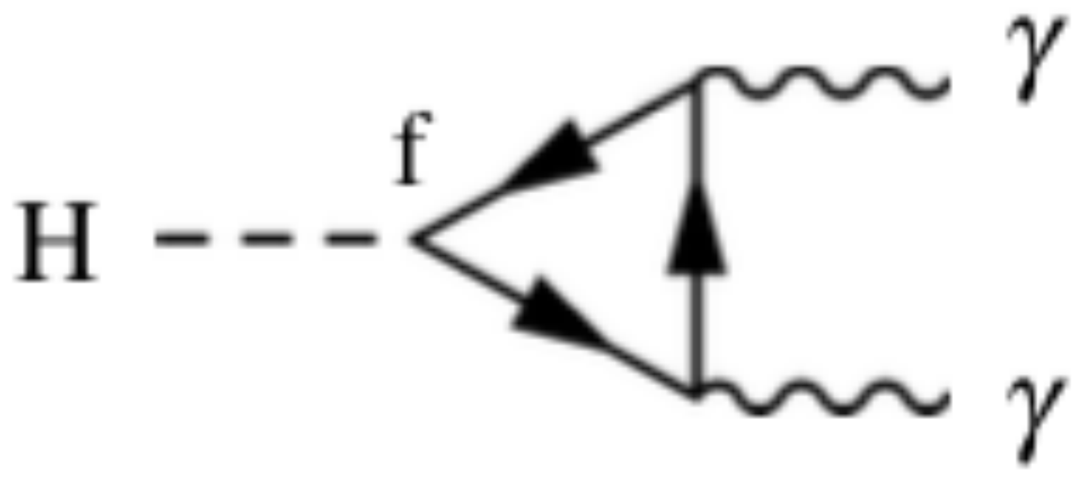

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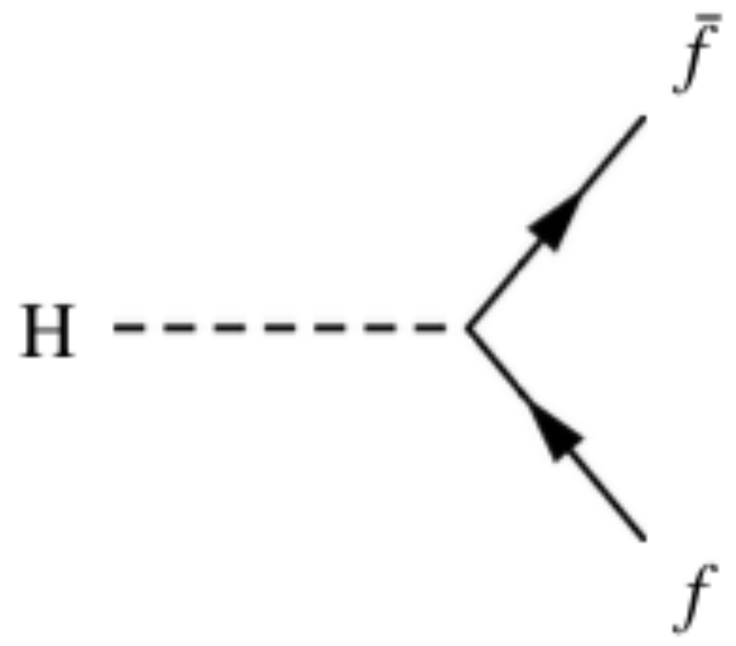

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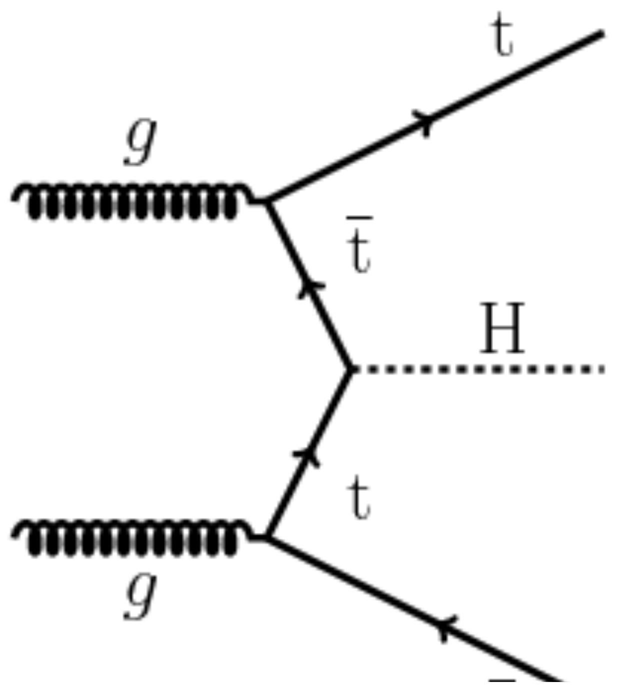

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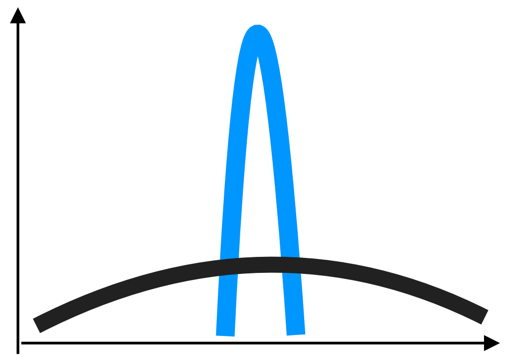
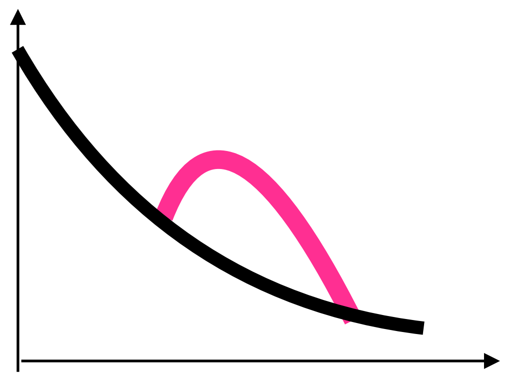
ATLAS-PHYS-PUB-2017-013
CMS-JINST 13 (2018) P05011

Challenges of the H($b\bar{b}$) mode at the LHC

Comparison with one of the discovery channels



	$H \to 4\ell$	$H \to b\bar{b}$
Branching Ratio	0.03%	58%
mass resolution	1%	10%
S/B	2	0.05



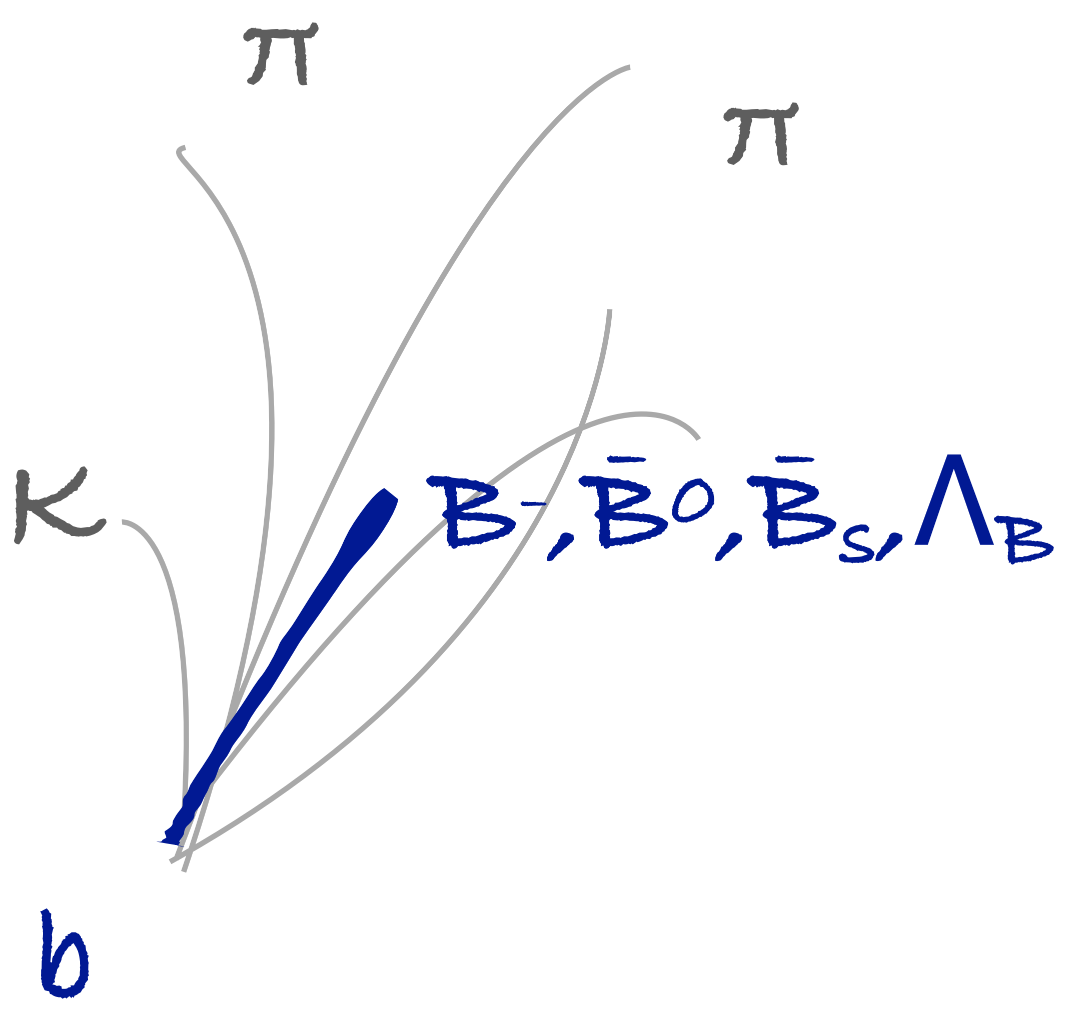
H($b\bar{b}$) searches need:

- good **b-jets identification** performance: 70% efficiency at 0.3-1% q/g mistag probability
- best possible **resolution on m($b\bar{b}$)**
- to exploit all possible information from the event to **improve S/B**

heavy flavor identification

b-tagging algorithms combine with a **multivariate approach** the information from:

- **impact parameter** significance of charged-particle tracks
- the presence of a **lepton** in the jet and its properties
- the presence and properties of reconstructed **secondary vertices**



b tagging in CMS

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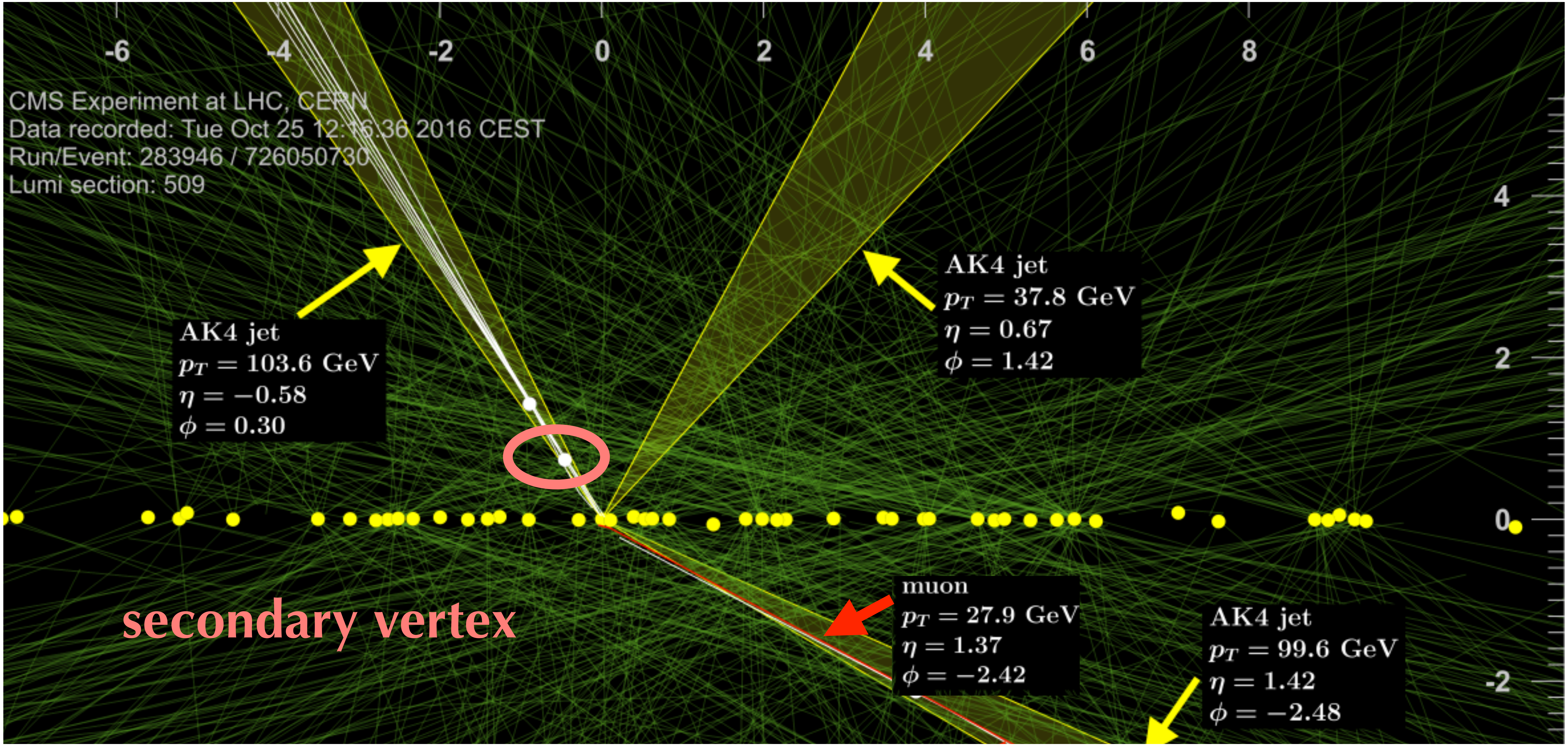

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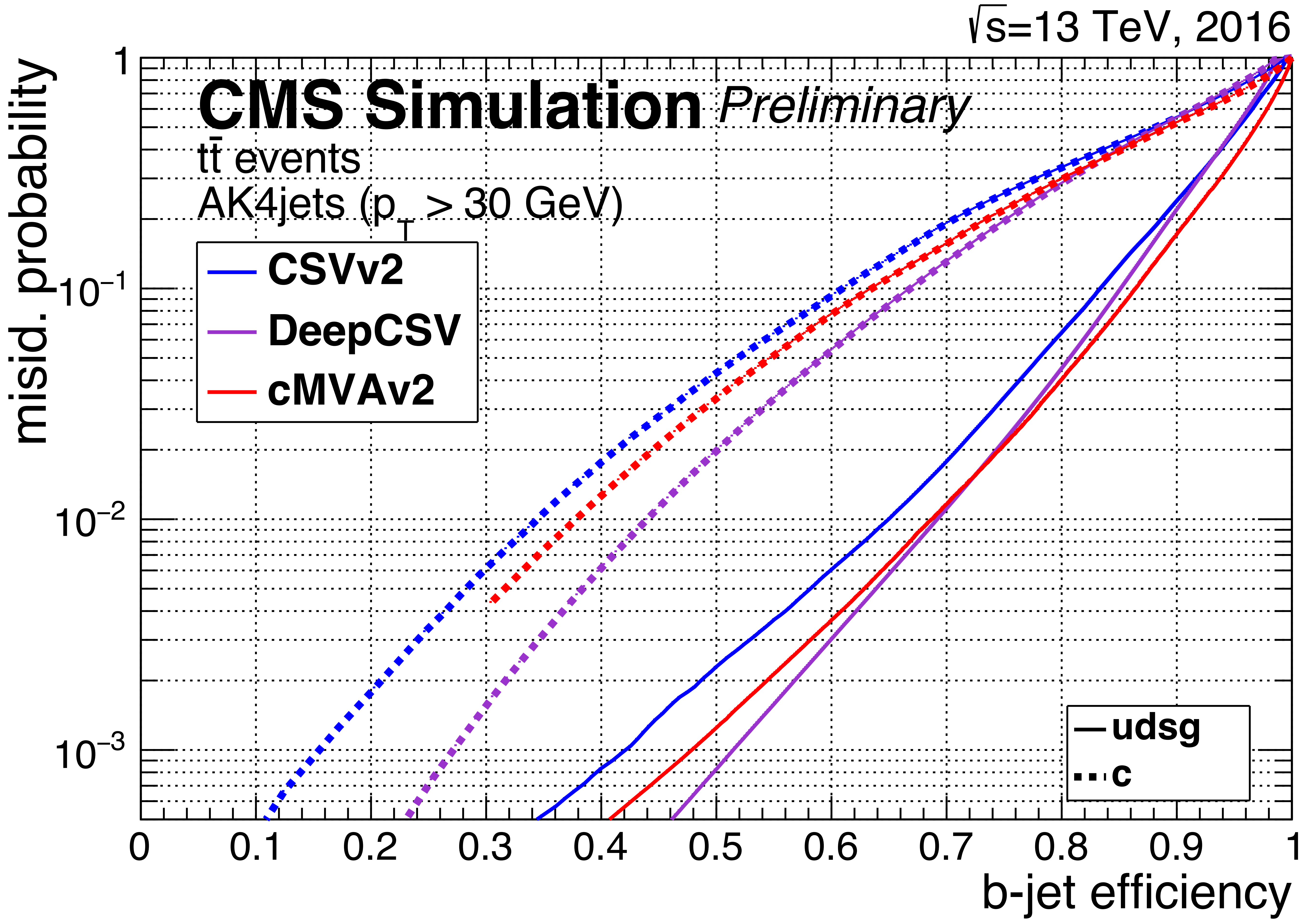
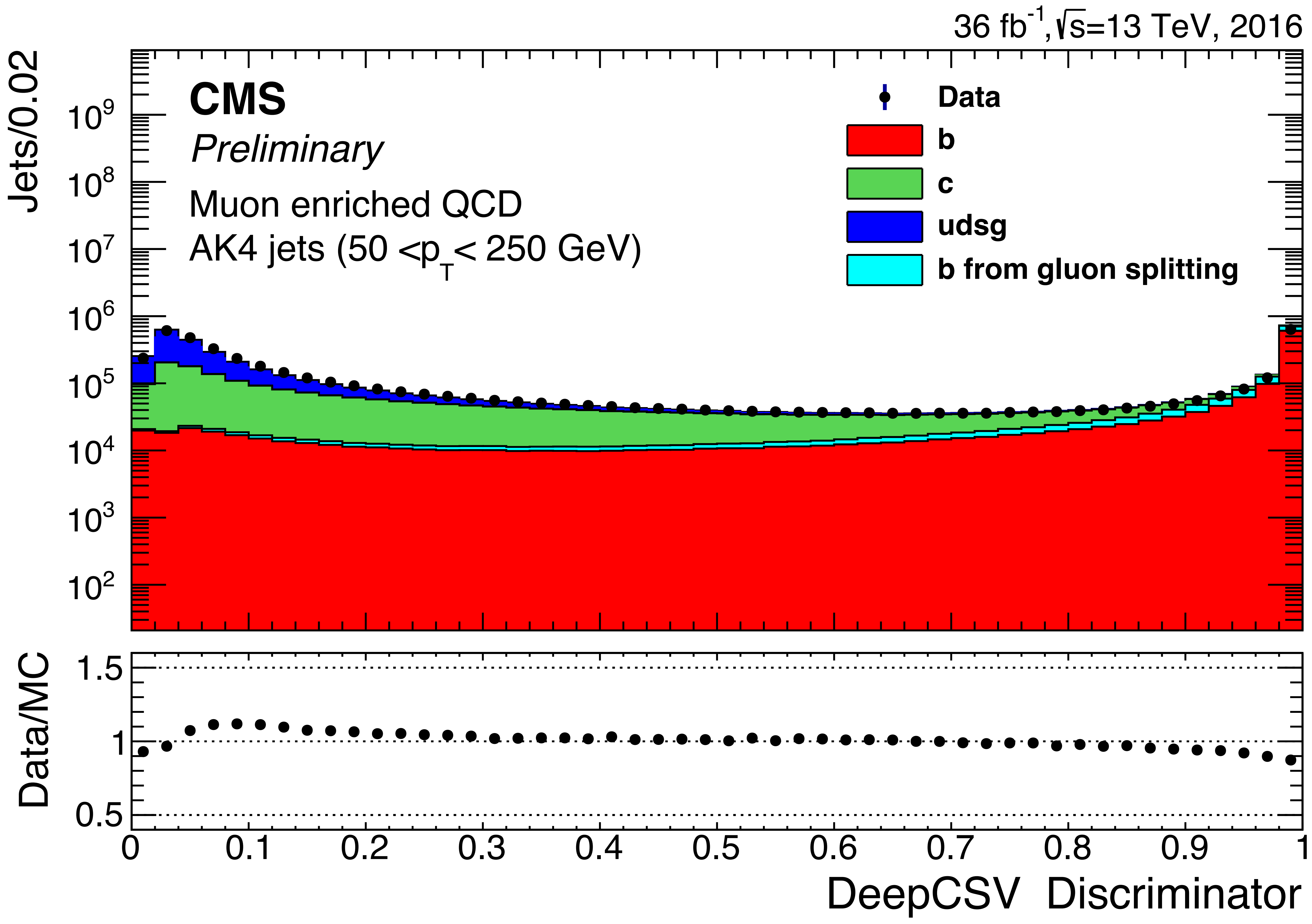
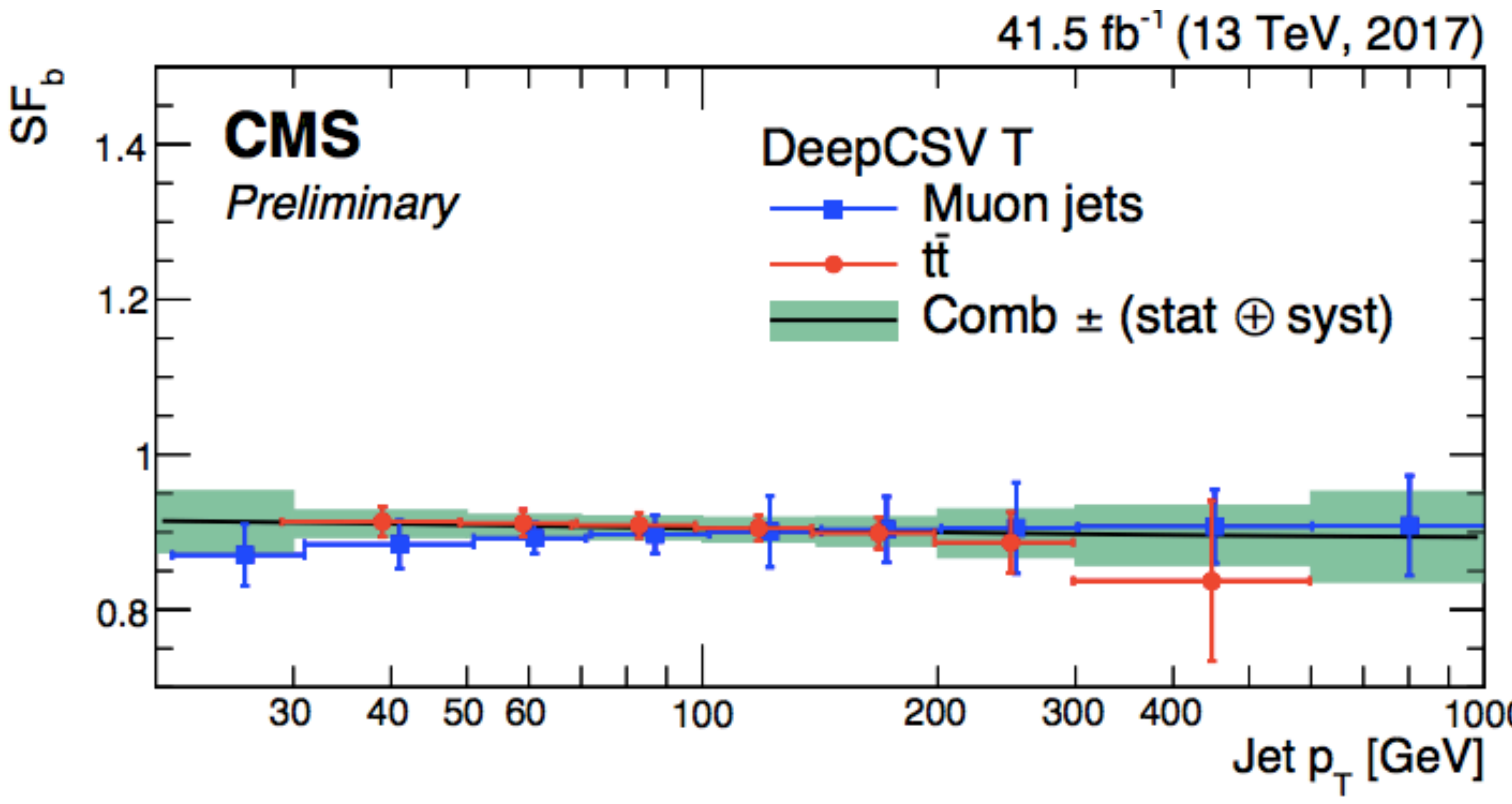


CSV Displaced vertices/tracks
CMVA Displaced vertices/tracks and non-isolated leptons
DeepCSV same as for CSV but more tracks
Dense Network (5 Hidden layers, 100 nodes)
Multiclass classifier: b, b$\bar{b}$, c, udsg

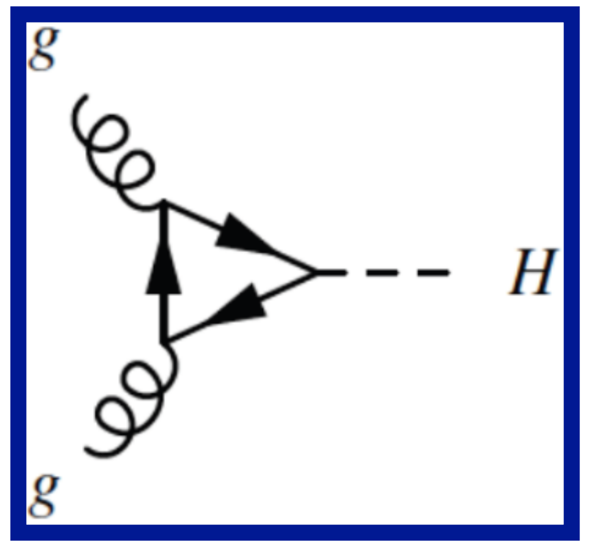
Performance in data



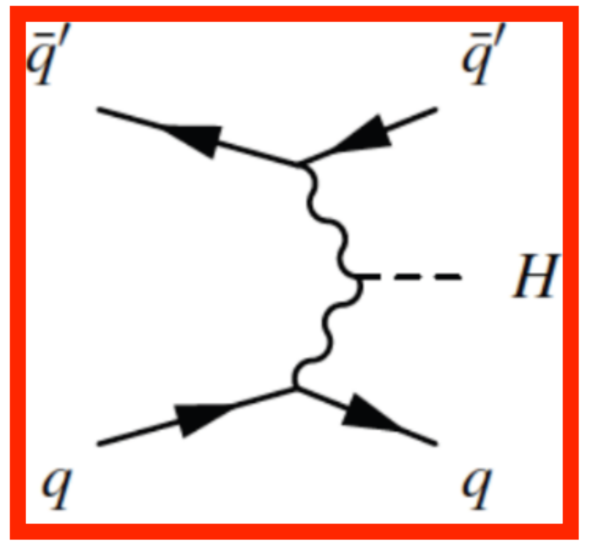


Agreement between data and simulation at 5% level

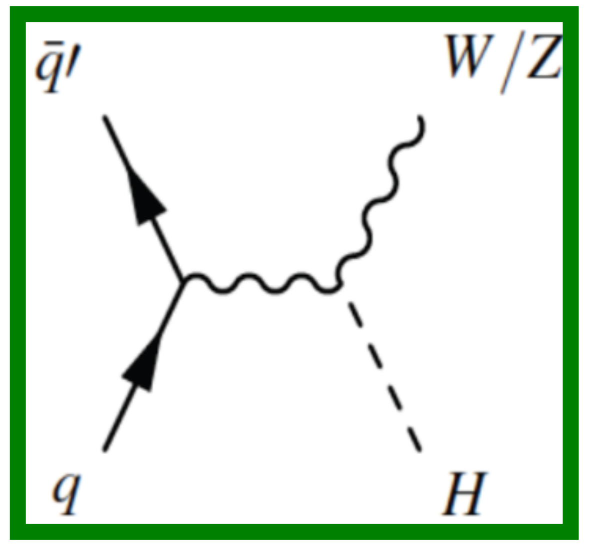
$H(b\bar{b})$ at the LHC



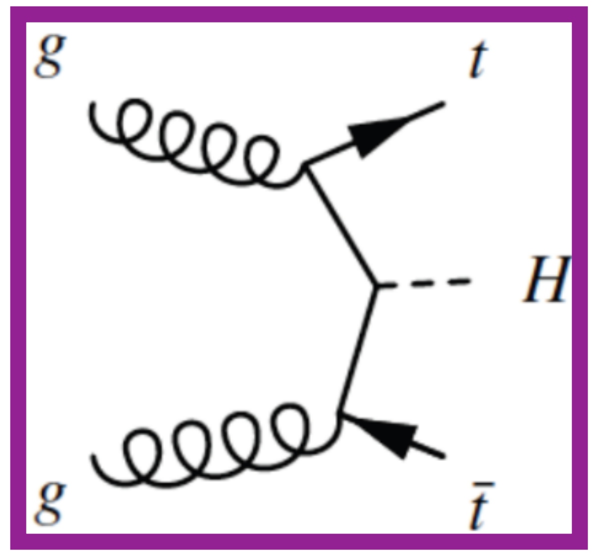
Gluon Fusion (87%)



Vector-Boson Fusion (7%)



Higgs-strahlung (4%)



Top Fusion ttH (1%)

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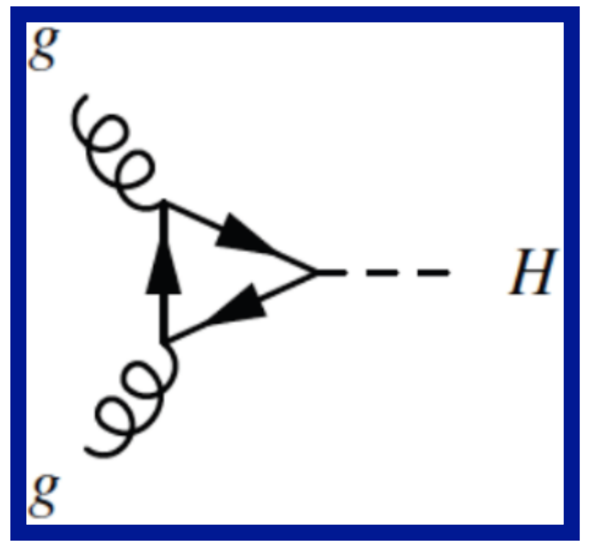

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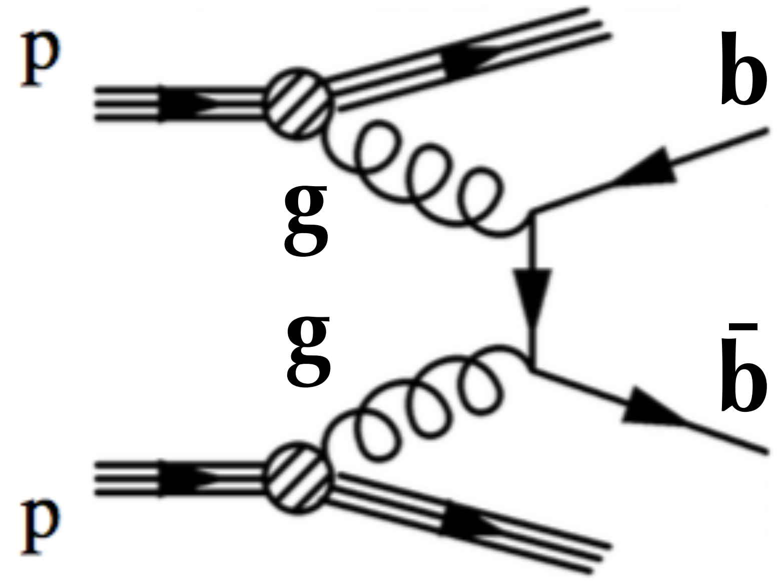

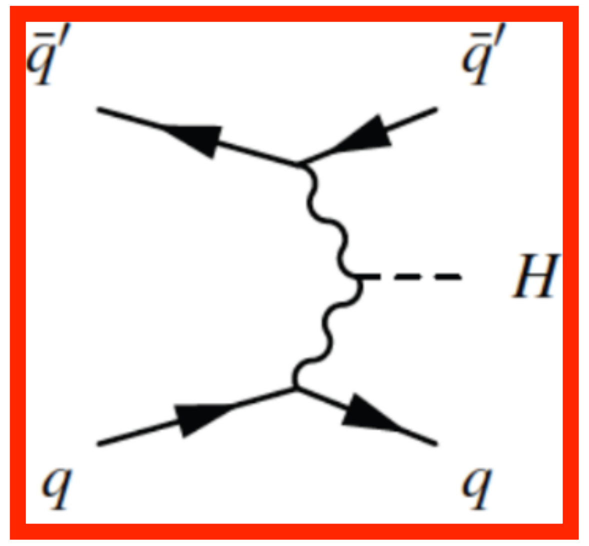

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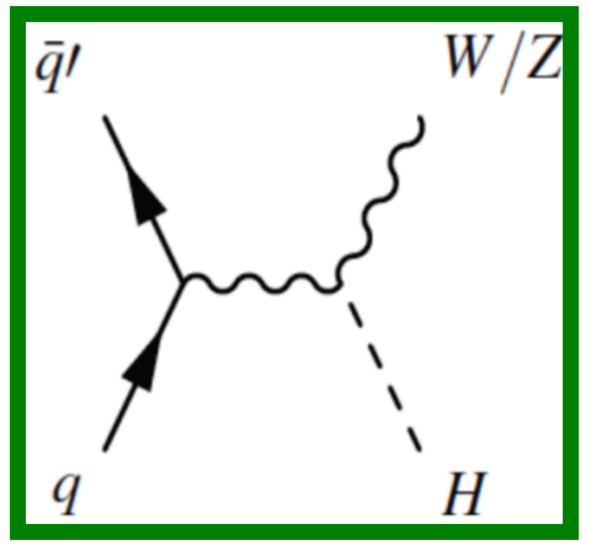

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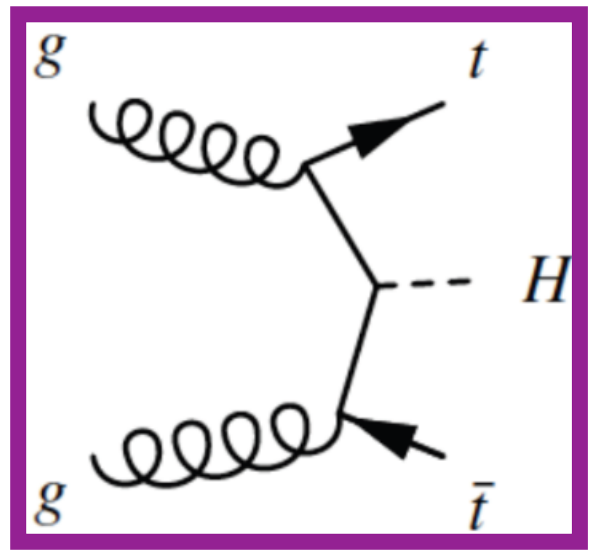

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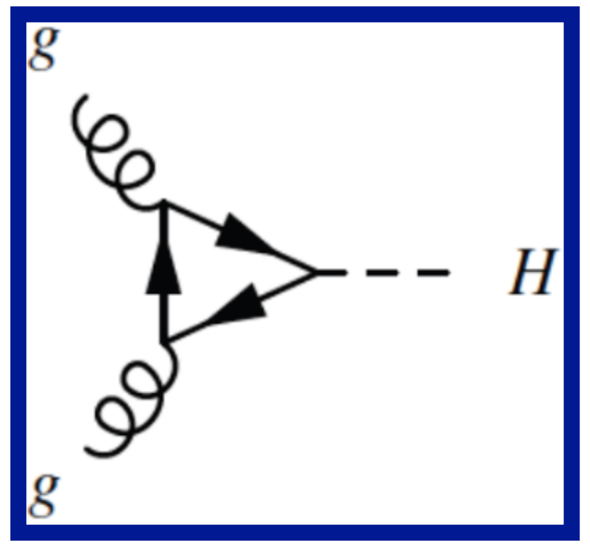

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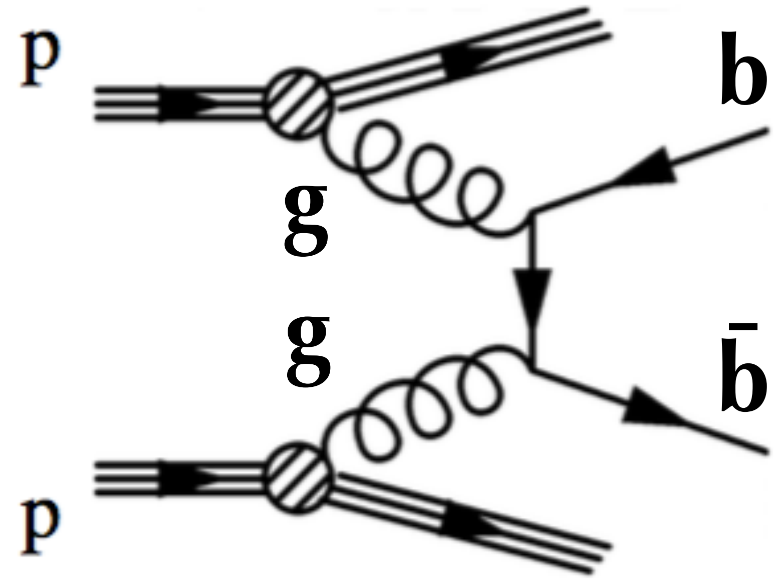

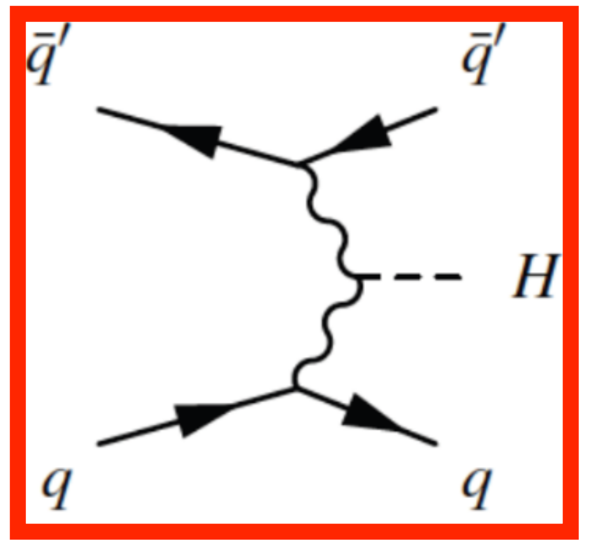

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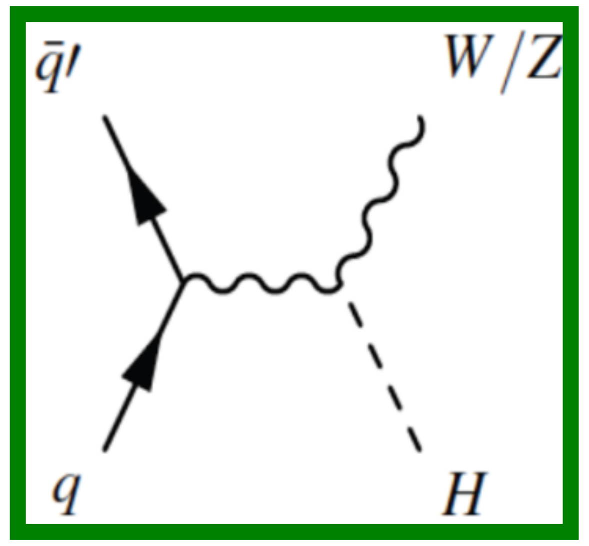

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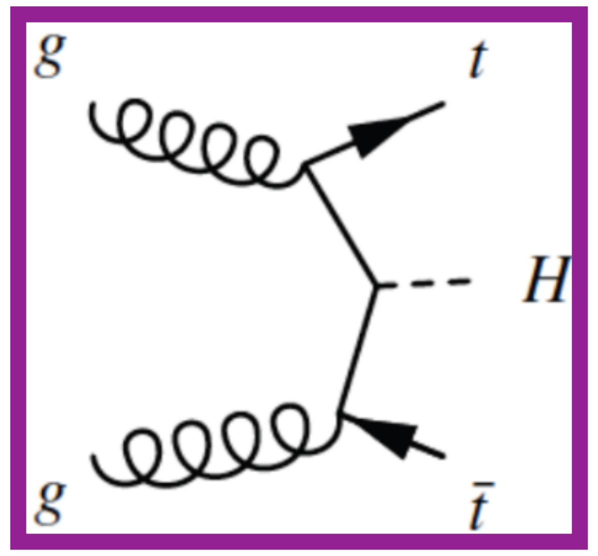

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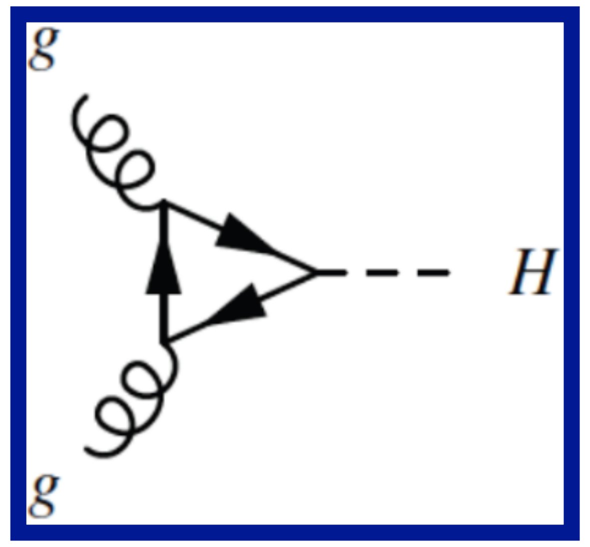

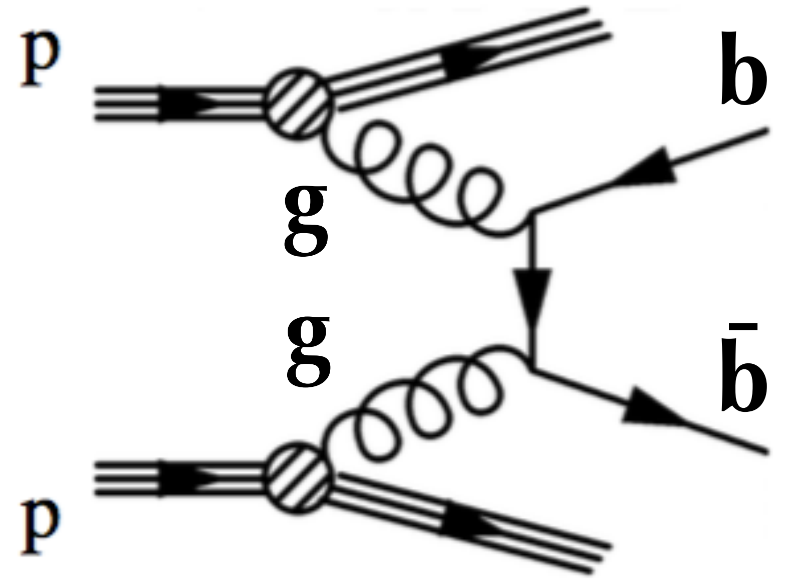

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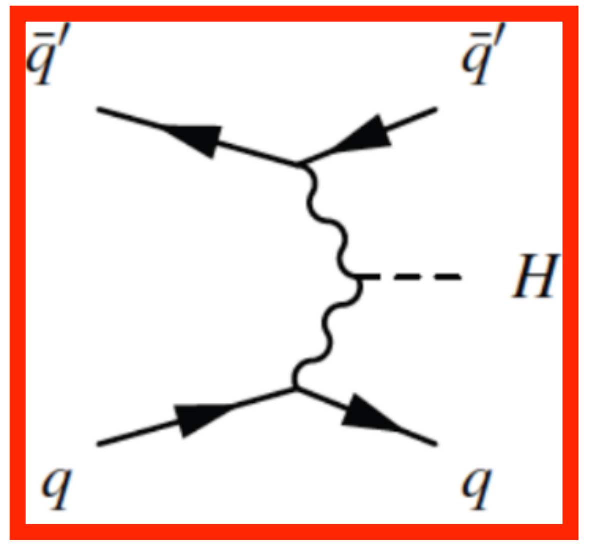

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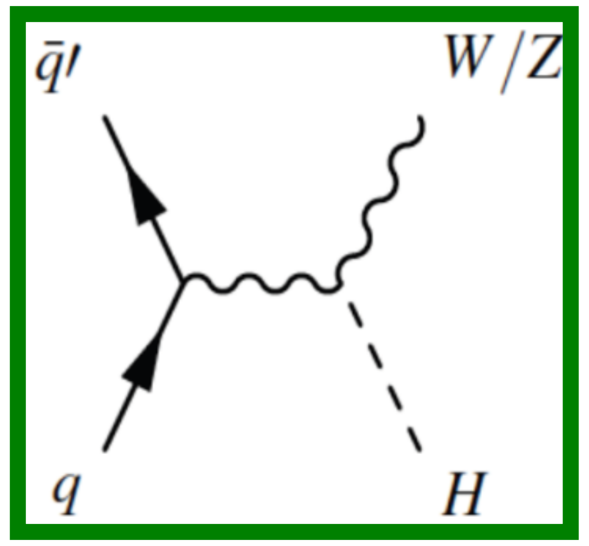

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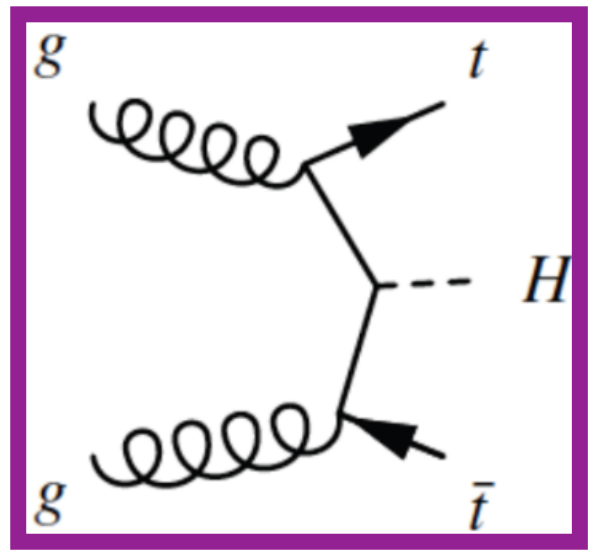

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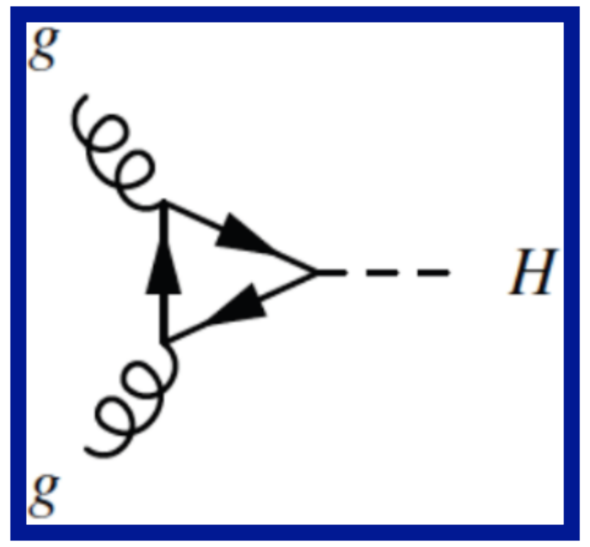

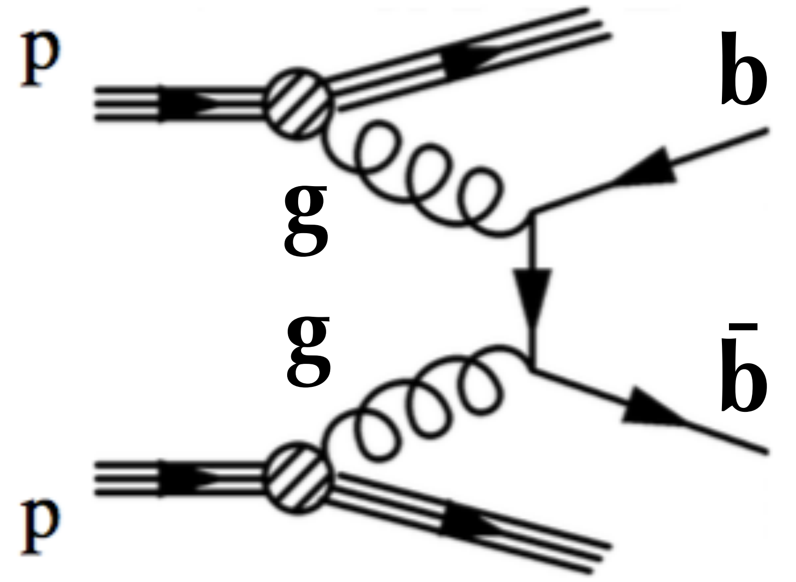

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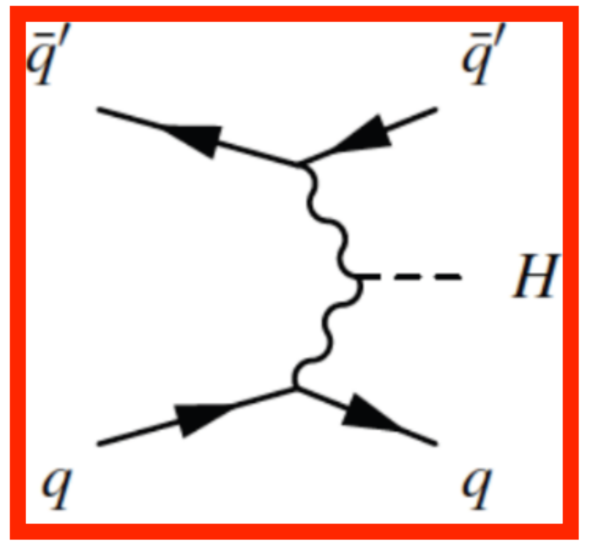

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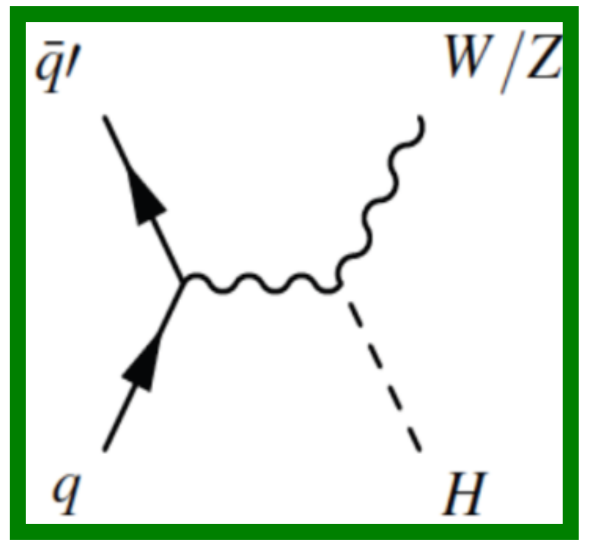

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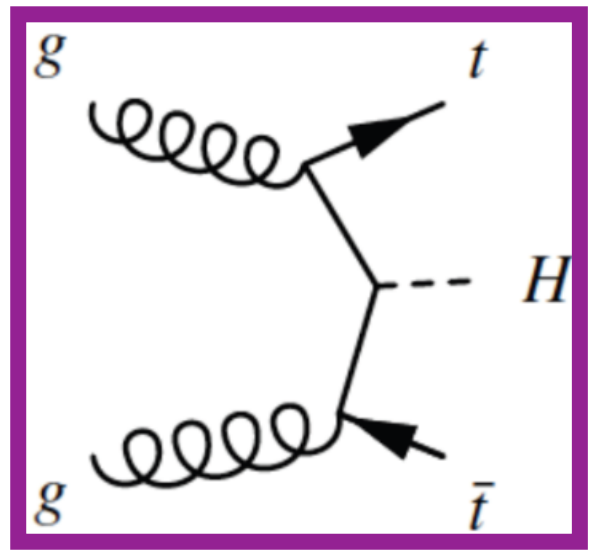

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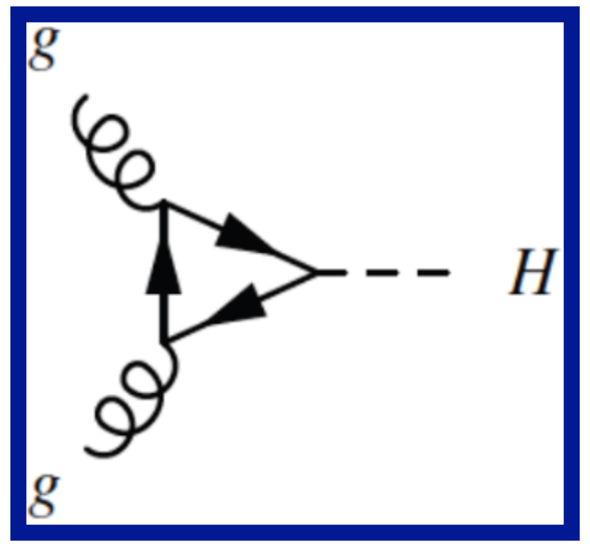
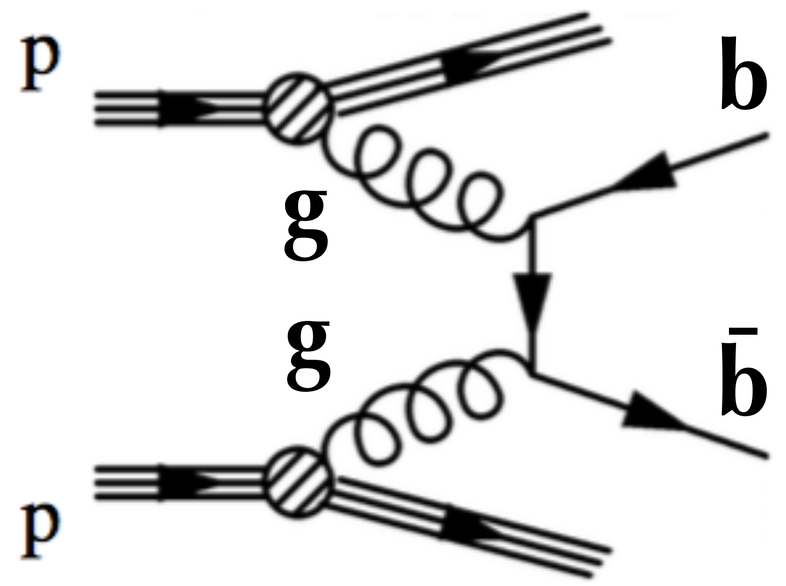
dominant backgrounds is $t\bar{t}$ + jets

H($b\bar{b}$) at the LHC





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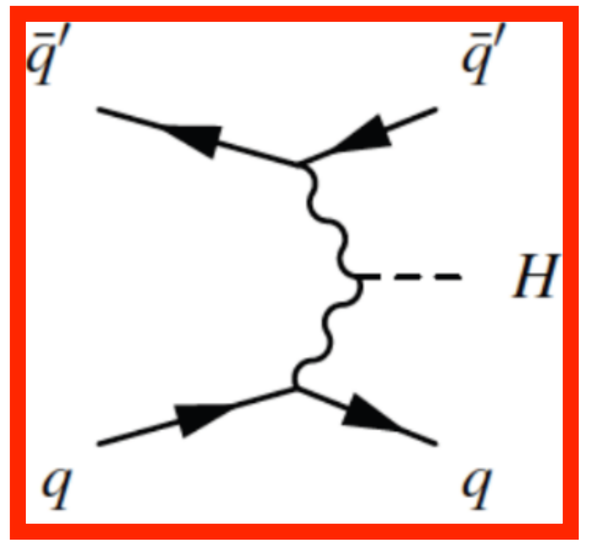

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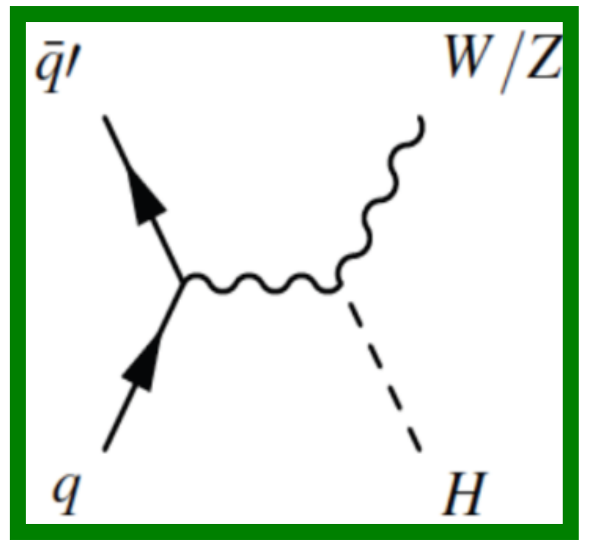

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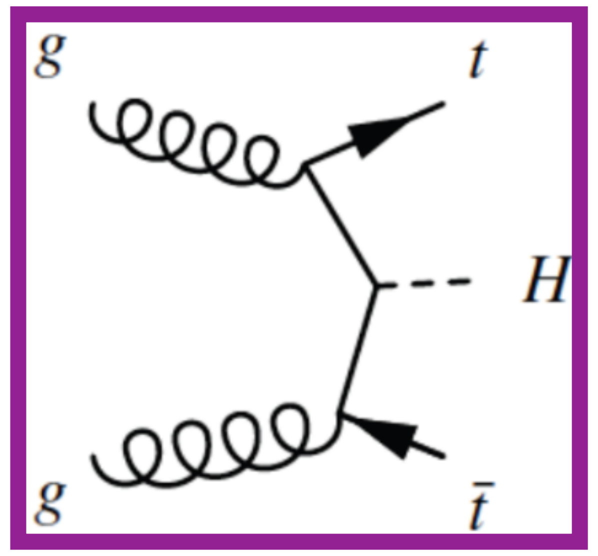
Most sensitive

S/B worse than in Run-1



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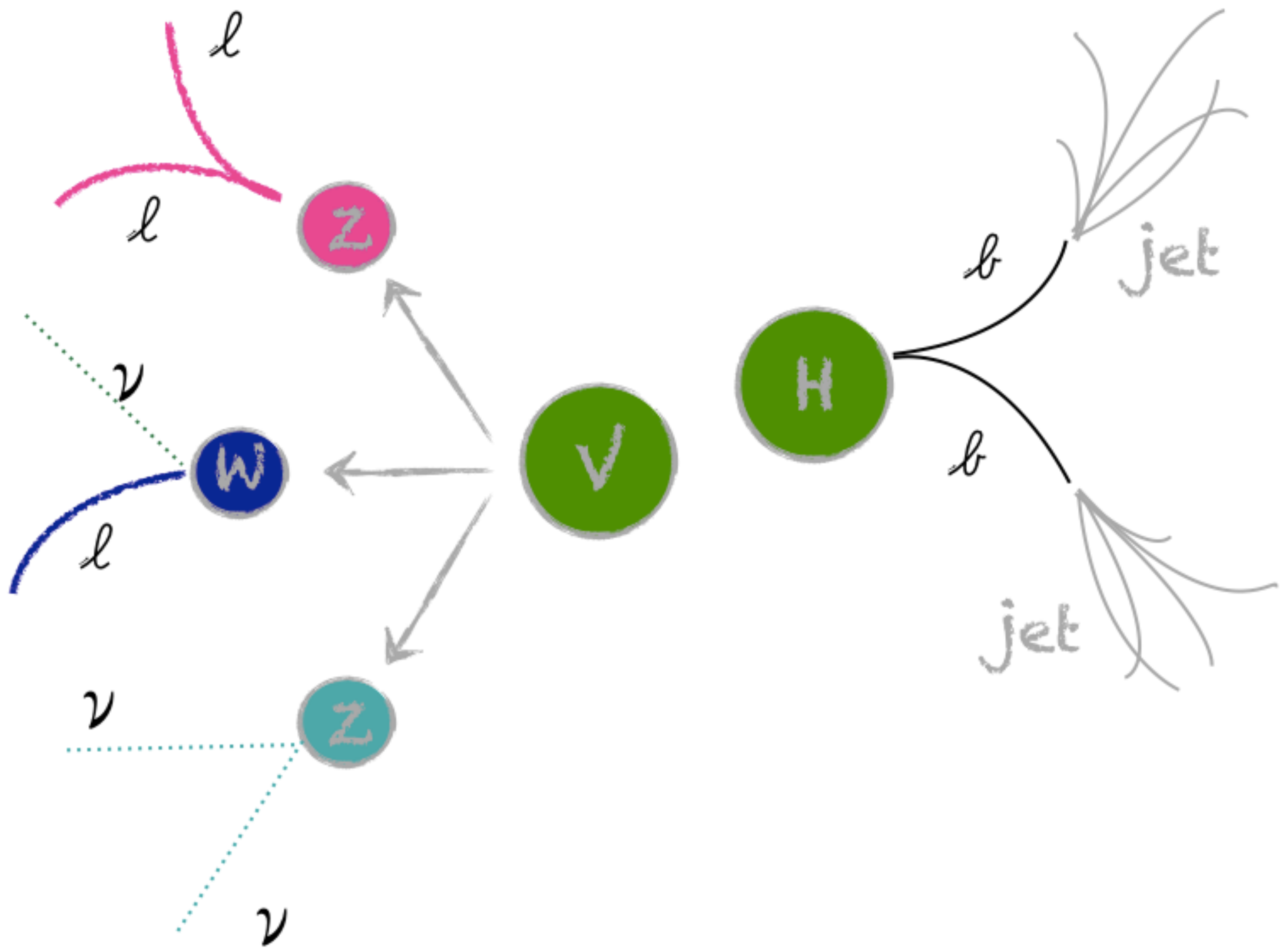
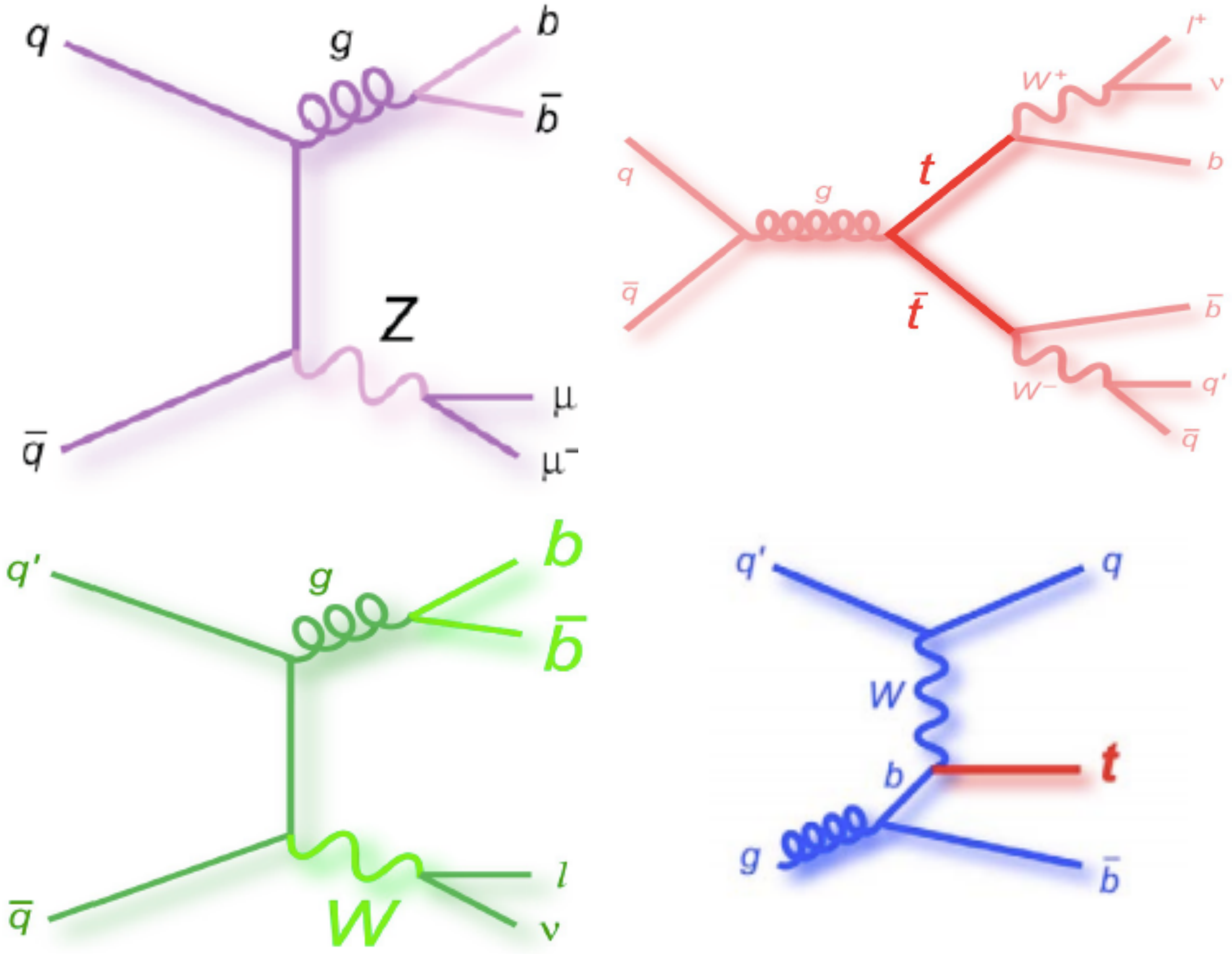
VH($b\bar{b}$) topology

signal



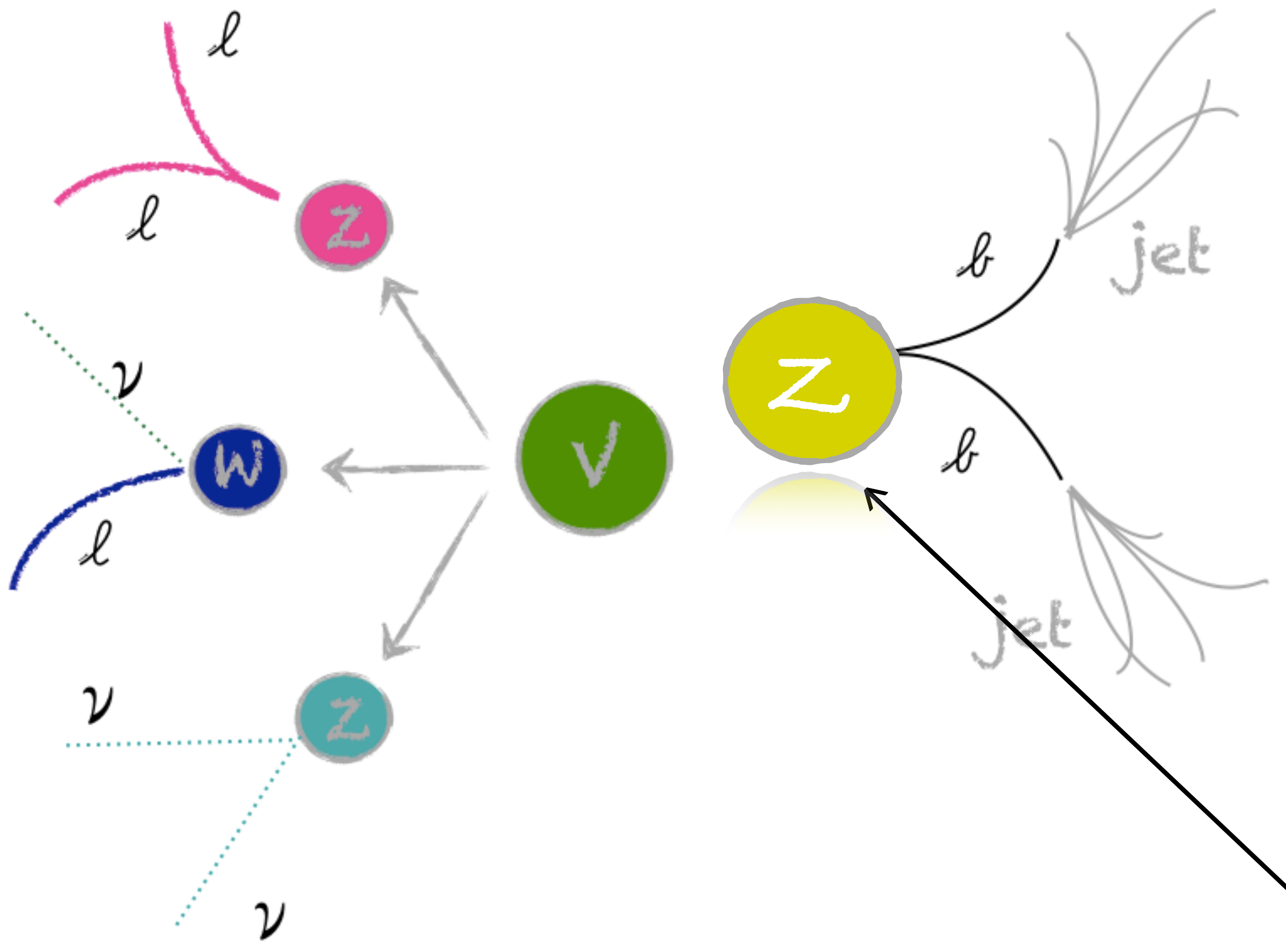
0-lepton (MET)
1-lepton [e,μ]
2-OSSF leptons [ee,μμ]

irreducible backgrounds



normalization from data, shapes from MC

VH($b\bar{b}$) topology



0-lepton (MET)
1-lepton [e,μ]
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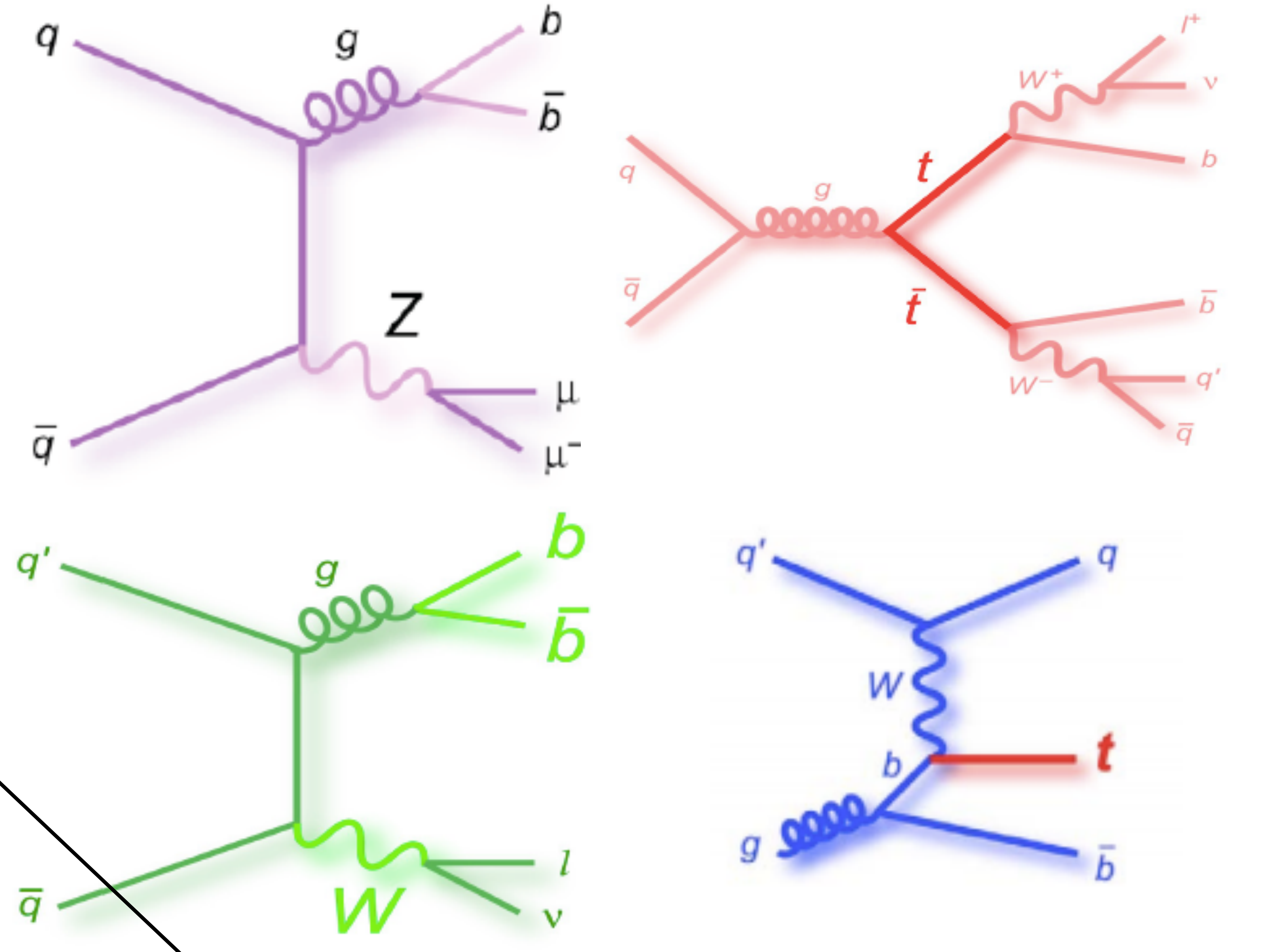


normalization from data, shapes from MC

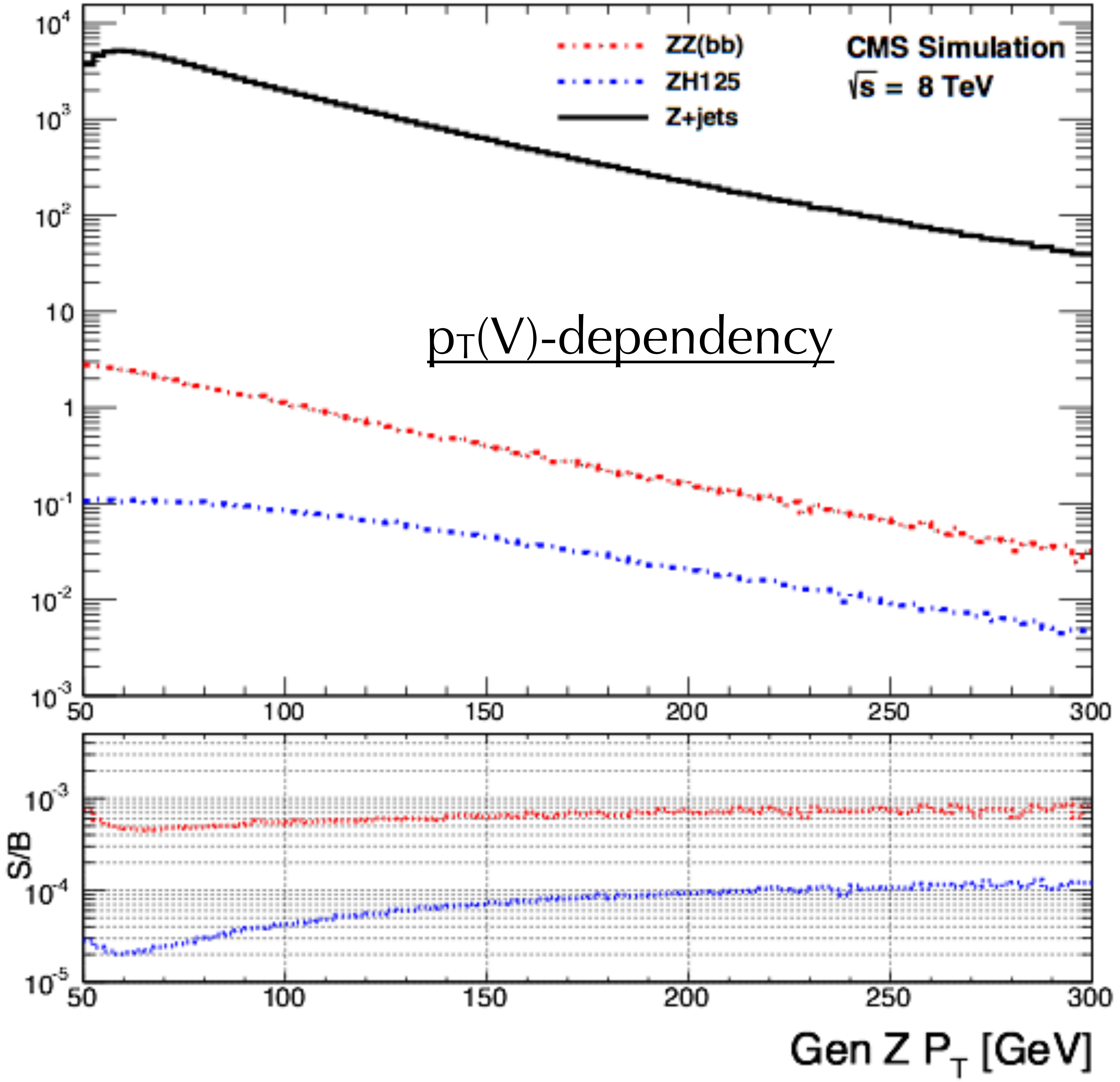
and diboson, of course

Used to validate the analysis strategy

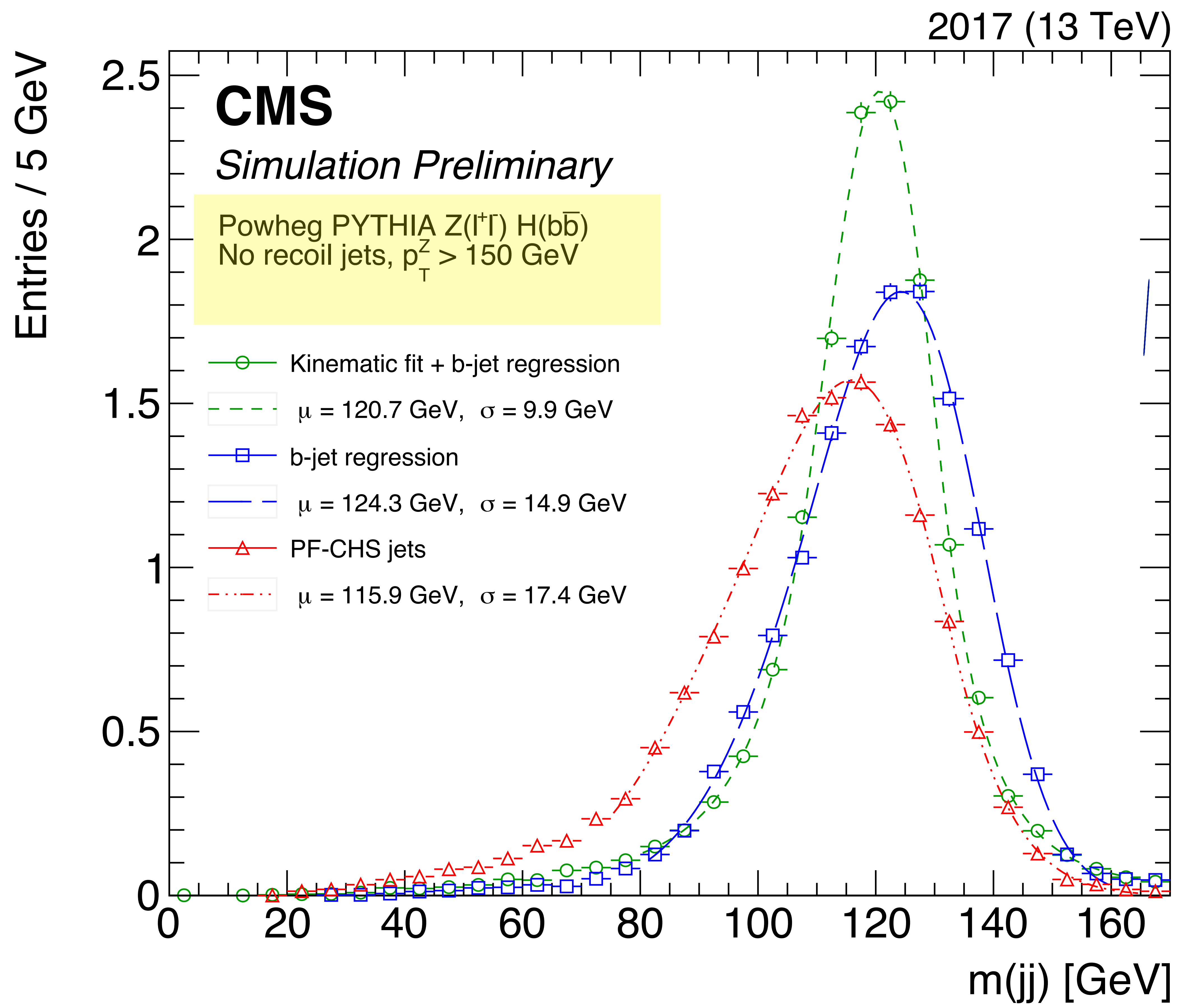
General Strategy

- Require W/Z to have large boost (~150 GeV)
  - multi-jet QCD background is highly suppressed
- Extract normalization for the dominant backgrounds from the data

  V+0b/1b/2b and top pair production
- b-jet energy specific corrections (**regression**)
- Multivariate analysis (DNN) to separate signal and background(s)



Dedicated corrections for $m_{b\bar{b}}$



DNN regression, a multidimensional calibration targeting the jet p_T at generator level

BR 35% $b \rightarrow l + \nu + X$

Derived from simulated tt events and exploiting:

- Jet kinematic and properties
- Secondary vertex and soft lepton information

Kinematic fit of the event exploits balance of well measured objects against b-jets (*2-lepton only*)

Improved mass resolution (10–13%) leads to 10% increase of the analysis sensitivity

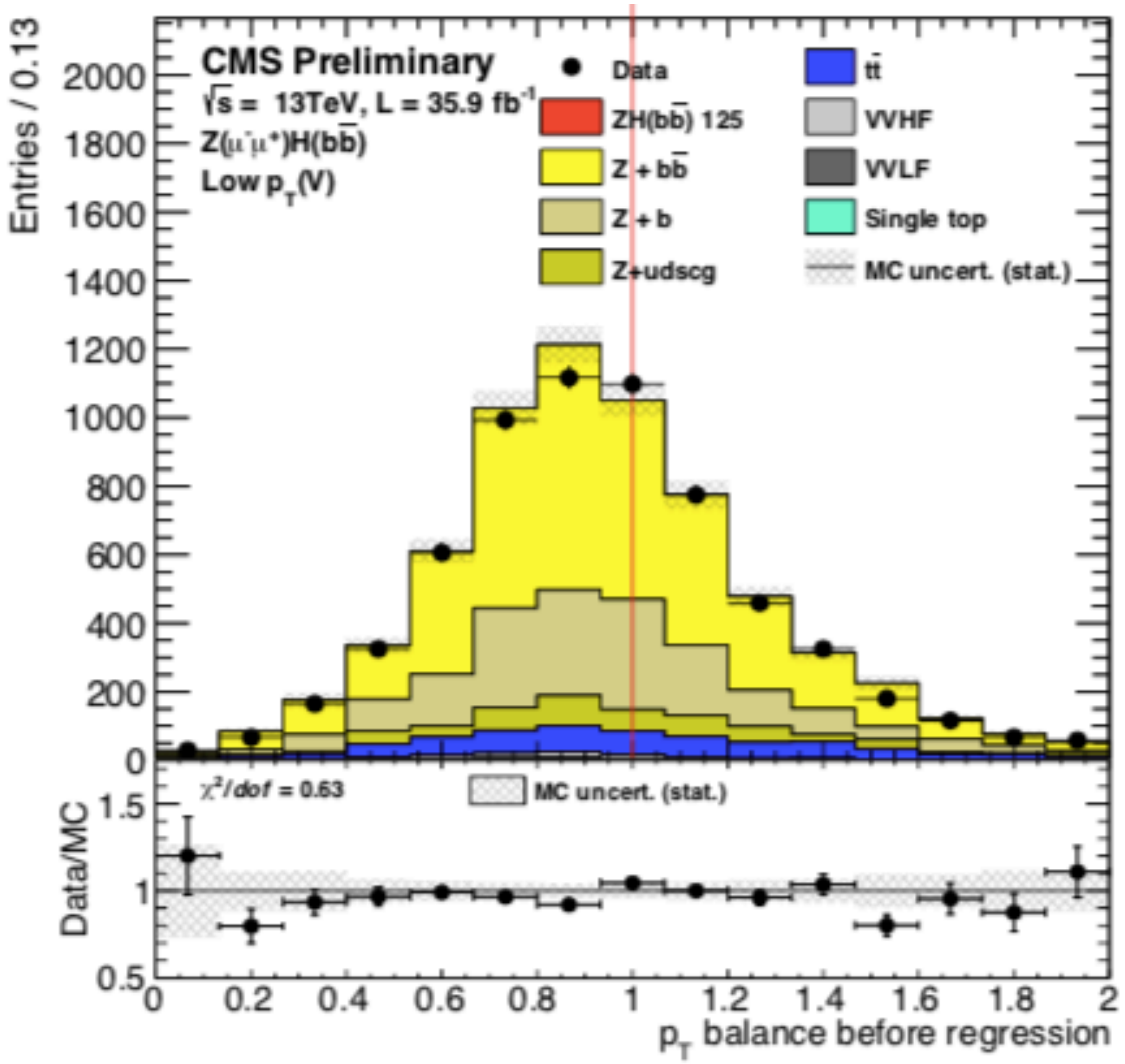
Validation in data

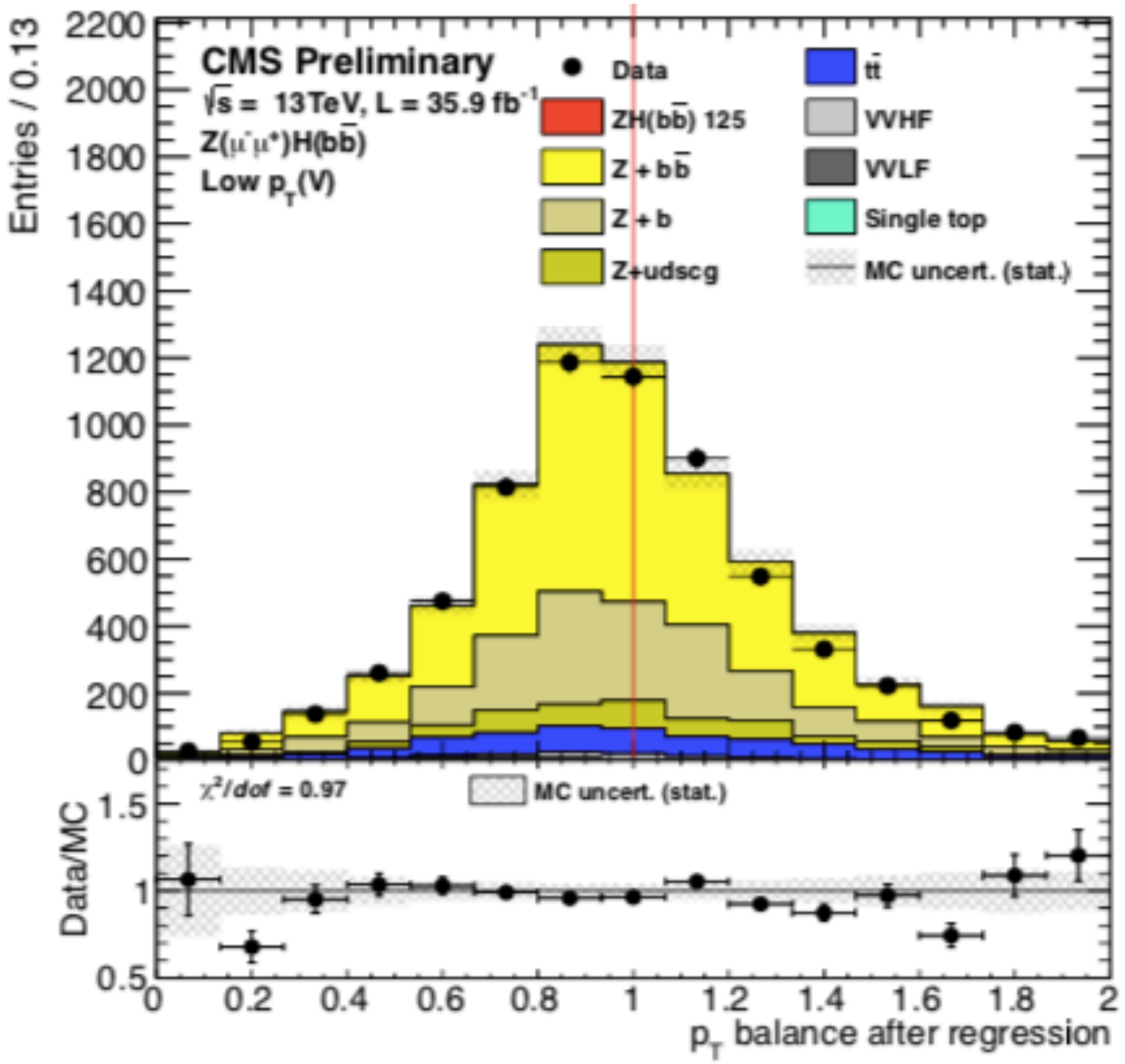
Balance in **Z(ll)+b-jet** data

- Monitor regression performance in data
- Extract JER data/MC correction for b-jets (~10%)

Dijet balance in Z(ll)+b$\bar{b}$ data

$$p_{T\,balance} = \frac{p_T(jj)}{p_T(\ell\ell)}$$



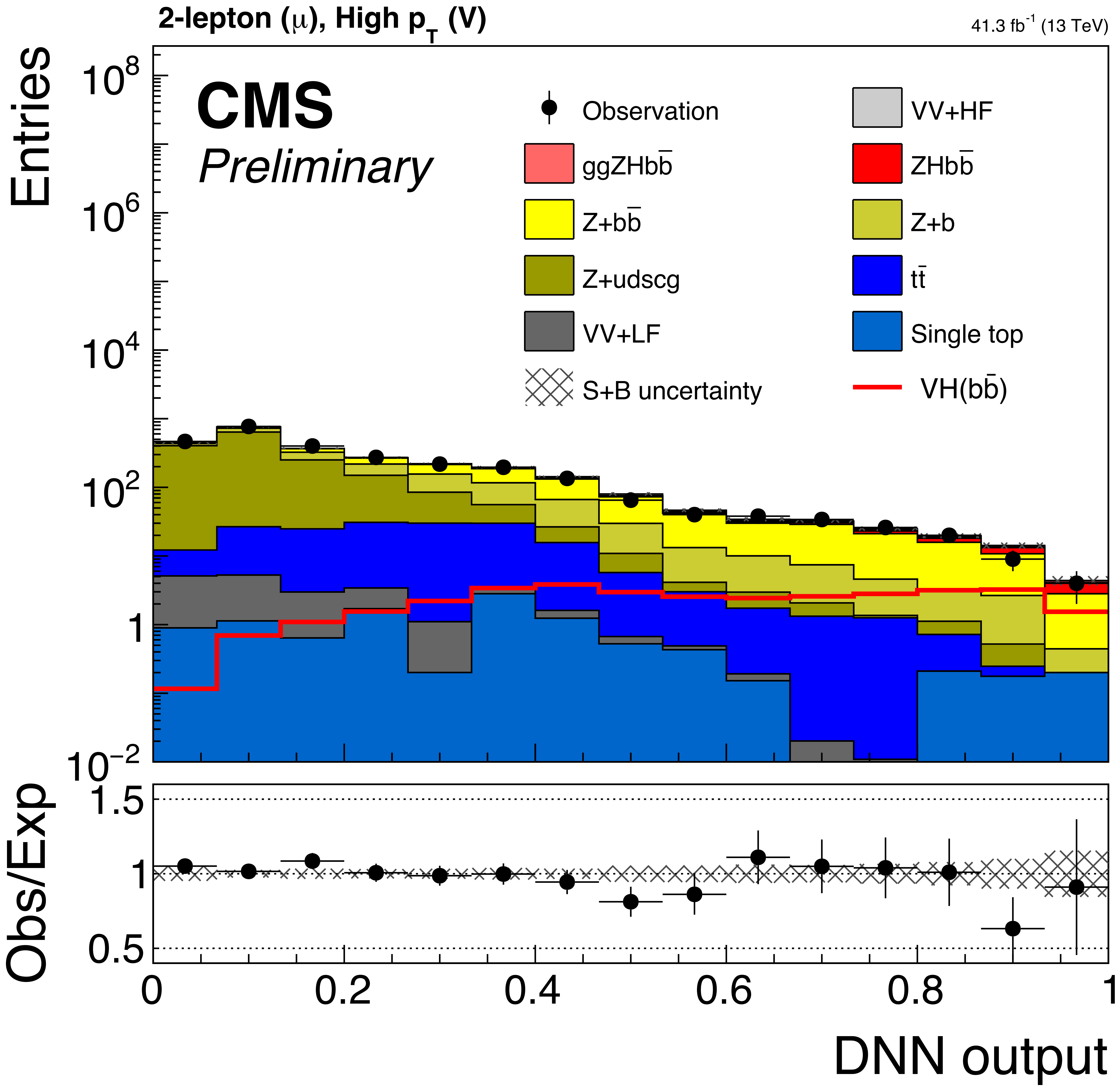


Machine learning for S vs. B

About 15 input variables describing the kinematics of the events are used depending on the regions

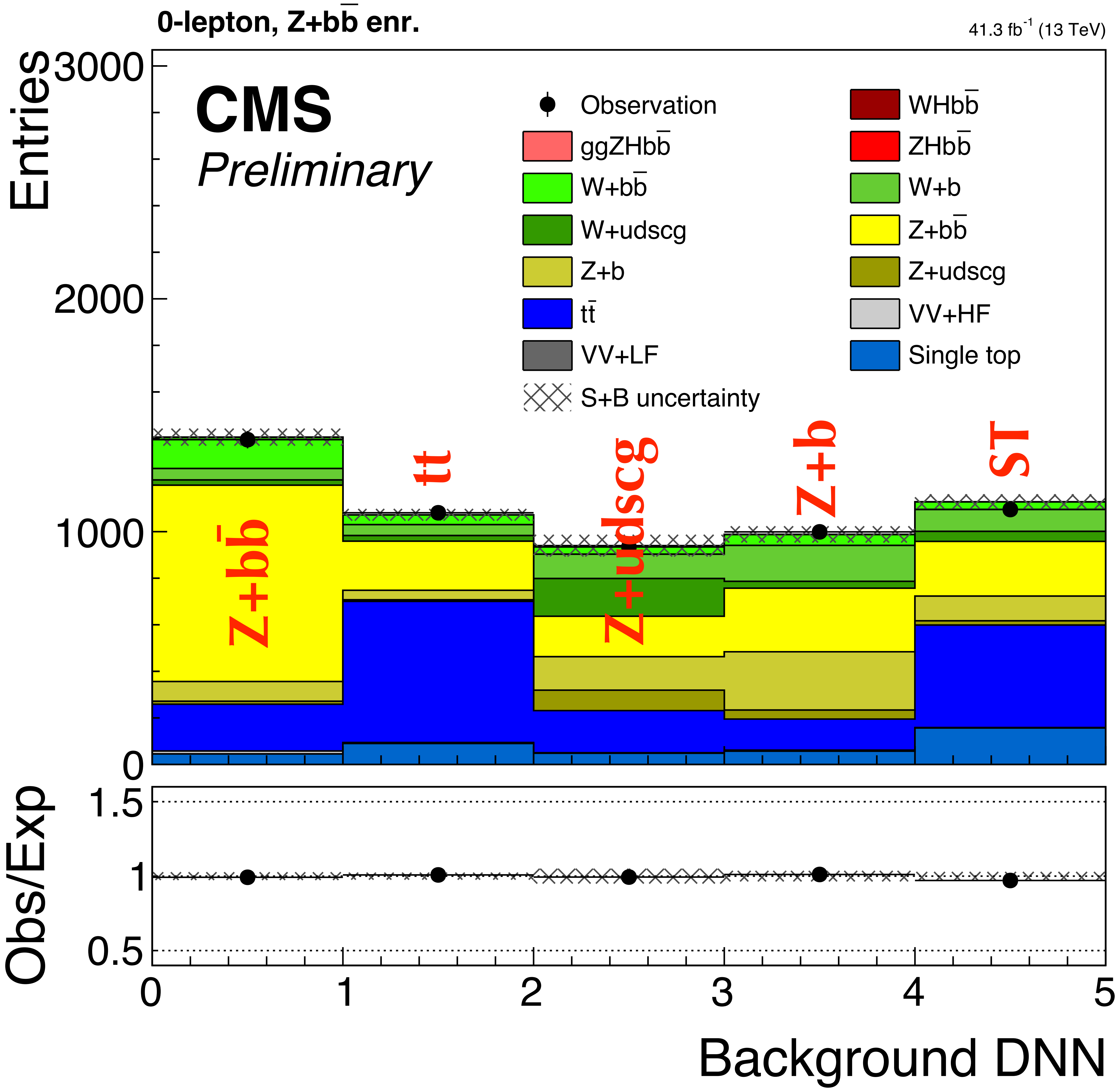
Combined into a DNN

$m(b\bar{b})$, $\Delta\eta(b\bar{b})$ and b-tagging are the most discriminant



Multi-Background discrimination

- **Leading systematic impact is uncertainty on normalization of V+1/2 b-jets**
- A multi-output DNN is used to differentiate among background components (*for 0-1 lepton channels*)
  - Using same inputs as S vs. B classifier
  - **5 probabilities** per event, one per background category



VH($b\bar{b}$) Systematic Uncertainties

Uncertainty source	$\Delta\mu$	
Statistical	**+0.26**	**−0.26**
Normalization of backgrounds	+0.12	−0.12
Experimental	**+0.16**	**−0.15**
b-tagging and efficiency and misid	+0.09	−0.08
V+jets modeling	+0.08	−0.07
Jet energy scale and resolution	+0.05	−0.05
Lepton identification	+0.02	−0.01
Luminosity	+0.03	−0.03
Other experimental uncertainties	+0.06	−0.05
Simulated sample size	**+0.12**	**−0.12**
Theory	**+0.11**	**−0.09**
Background modeling	+0.08	−0.08
Signal modeling	+0.07	−0.04
Total	**+0.35**	**−0.33**

- **Background normalizations** are derived from control regions in data with floating normalization
  - 15% uncertainty on VV and single top
- The many sources of uncertainty in the **jet energy scale correction** are decomposed into ~30 uncorrelated components
- Dedicated **jet energy resolution** estimate for b-jets after regression

Cross check 1/2 : diboson measurement

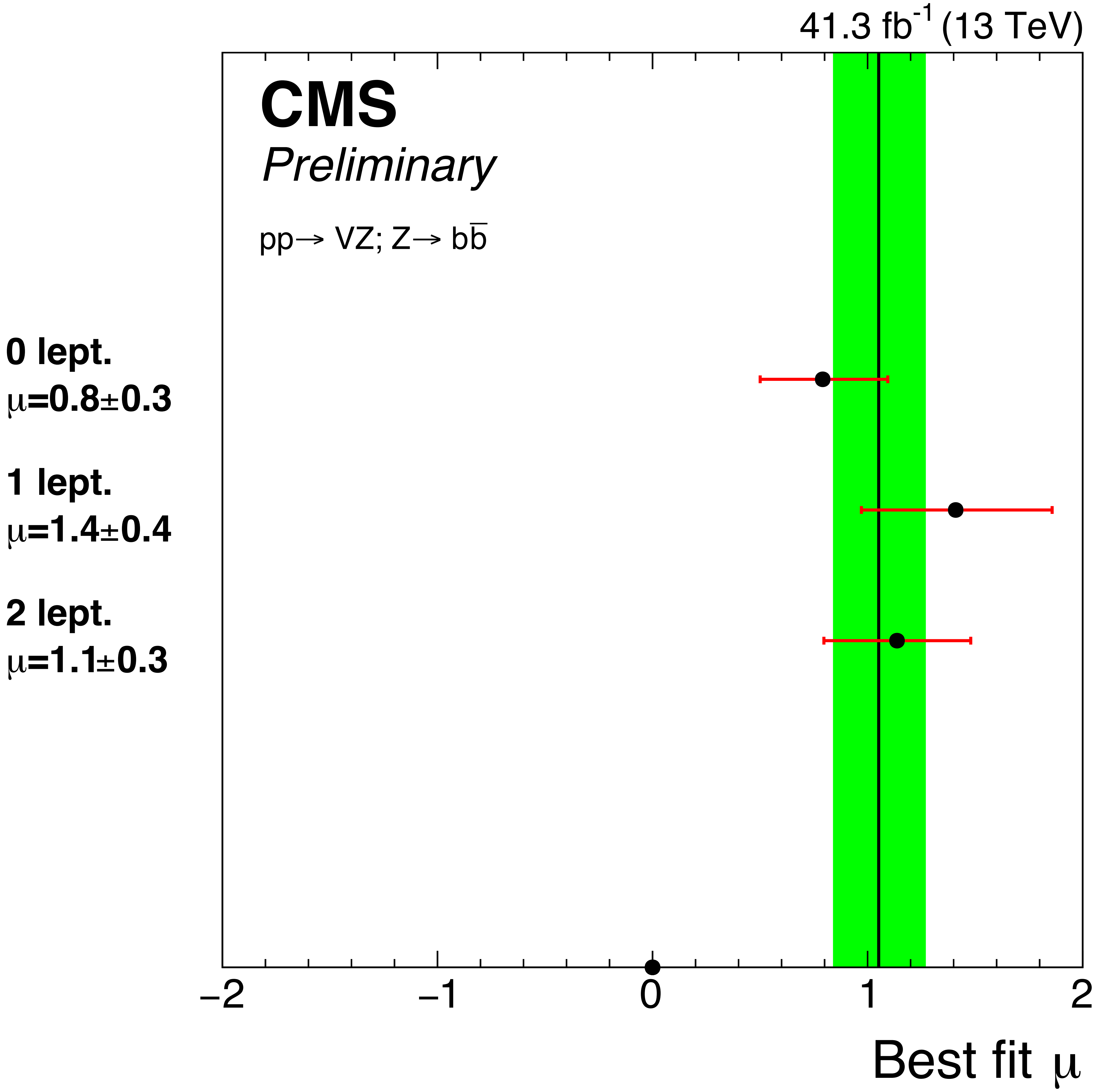
- Re-train DNN in signal regions to discriminate $VZ(b\bar{b})$ signal
  - same input variables
  - $H(b\bar{b})$ treated as background - assuming SM cross section

Consistent with SM expectations

Run-2 2017

5.2 (5.0) σ

$\mu = 1.05^{+0.22}_{-0.21}$



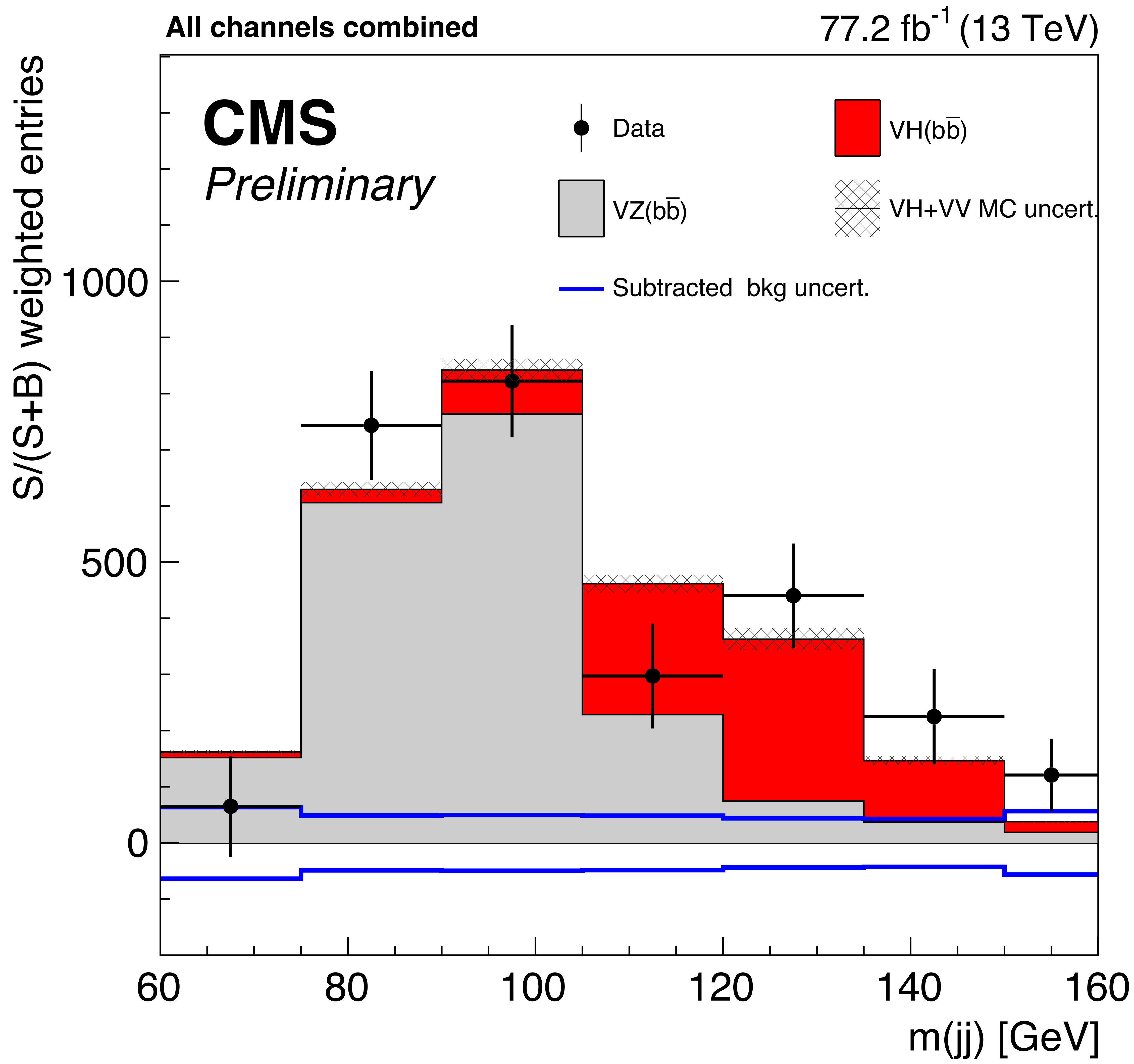
Cross check 1/2 : $m_{b\bar{b}}$ analysis

- Use the same DNN training but removing $m_{b\bar{b}}$ dependency
- Split each channel signal region into four categories based on **massless DNN** score.
- Fit $m_{b\bar{b}}$ simultaneously in all split signal regions as well as the usual control regions.

Run-2 2016+2017

2.7 (3.0) σ

$\mu = 0.91^{+0.35}_{-0.34}$



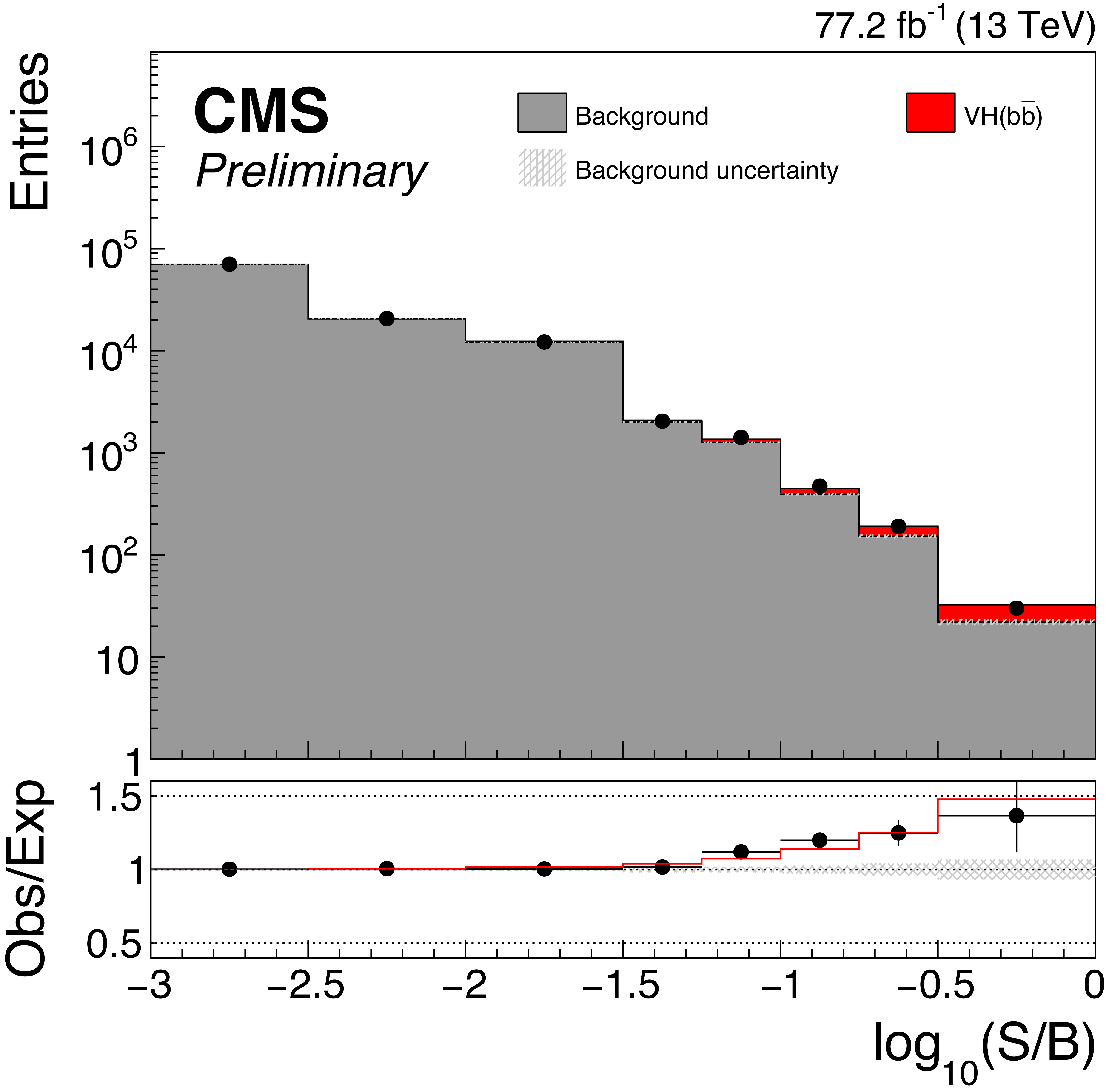
VH($b\bar{b}$) Results

In all signal regions a simultaneous fit to the **DNN output** to extract signal strength

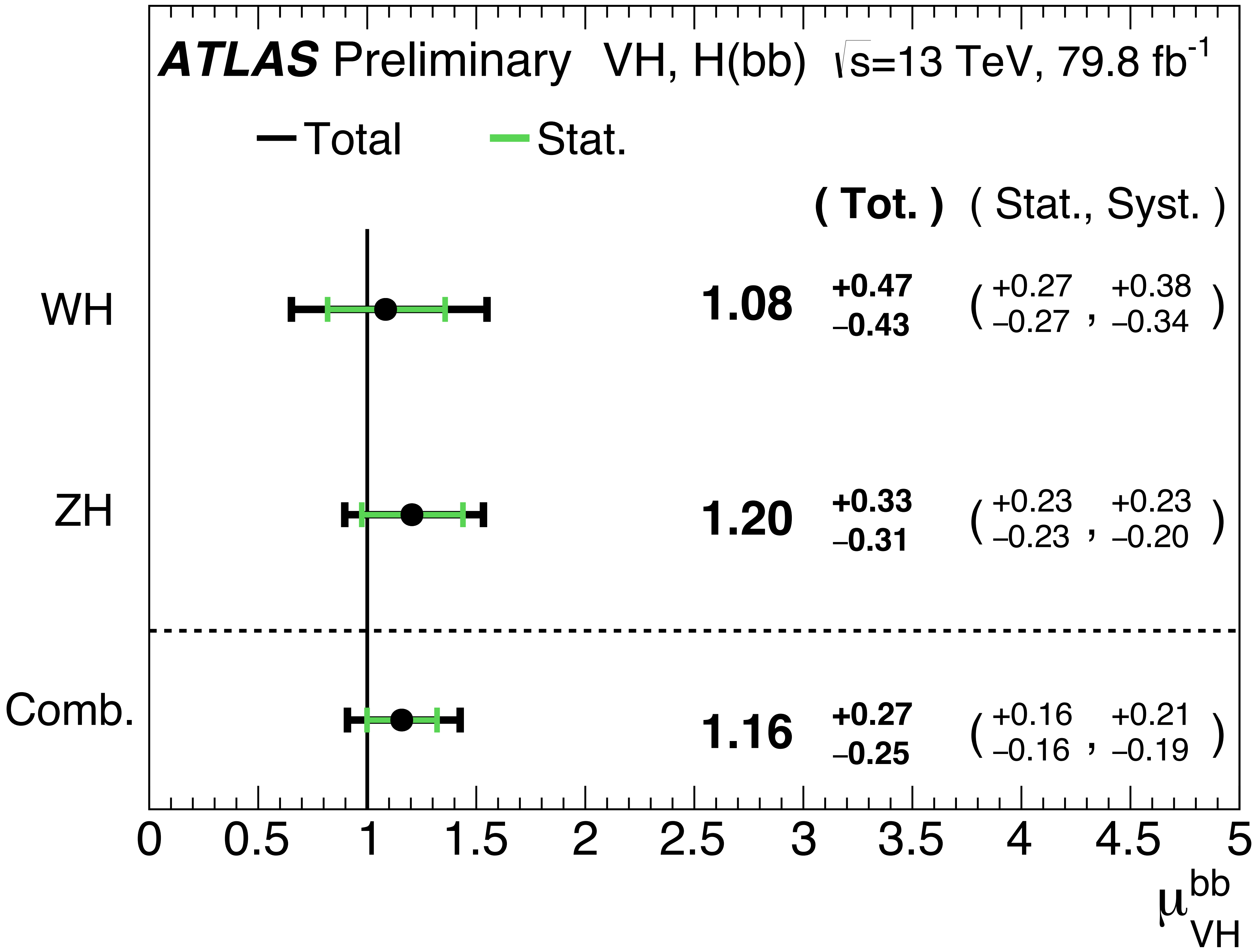
Run 2 2016+2017

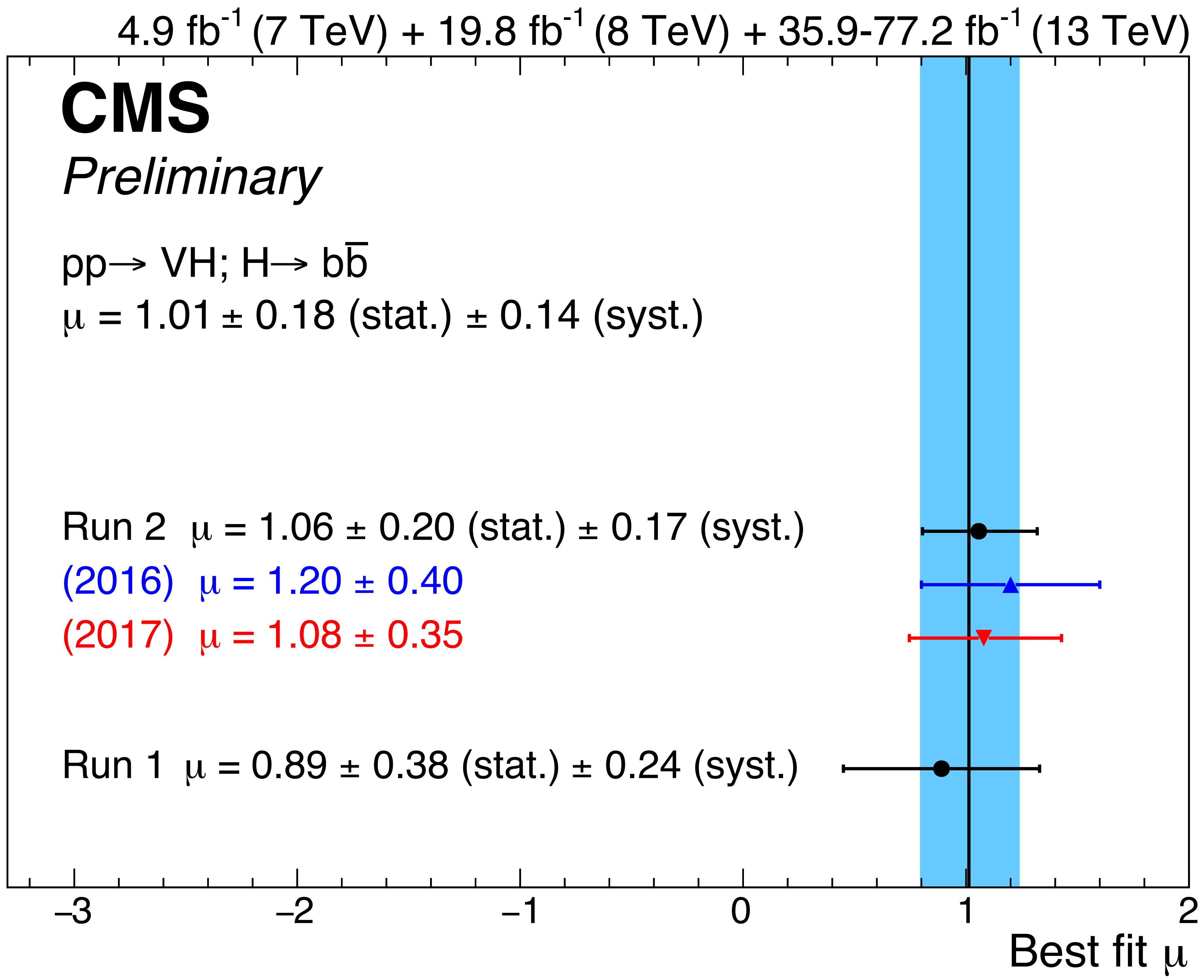
4.8 (4.5) σ

$\mu = 1.06^{+0.26}_{-0.25}$



State of the art of VH($b\bar{b}$) at LHC

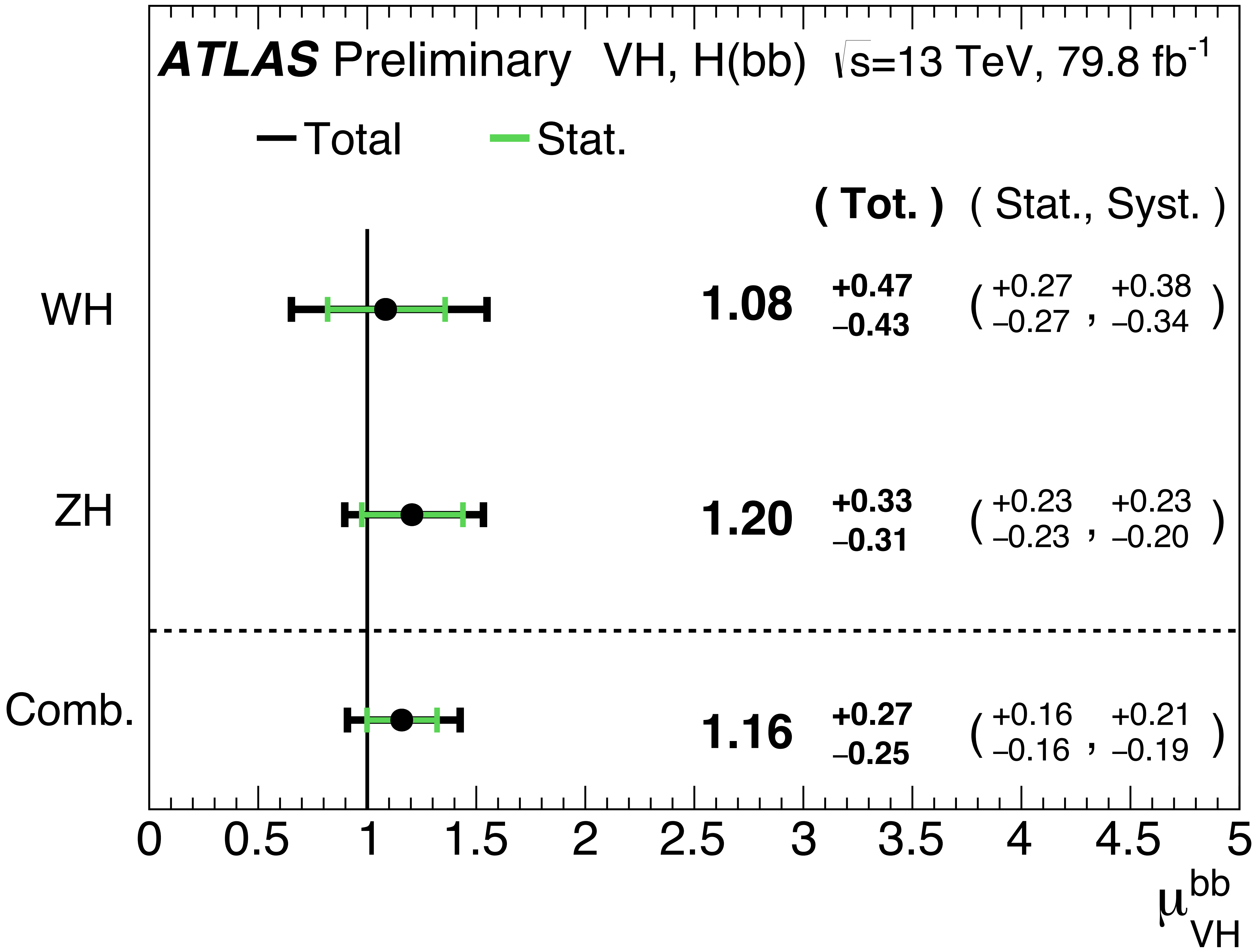


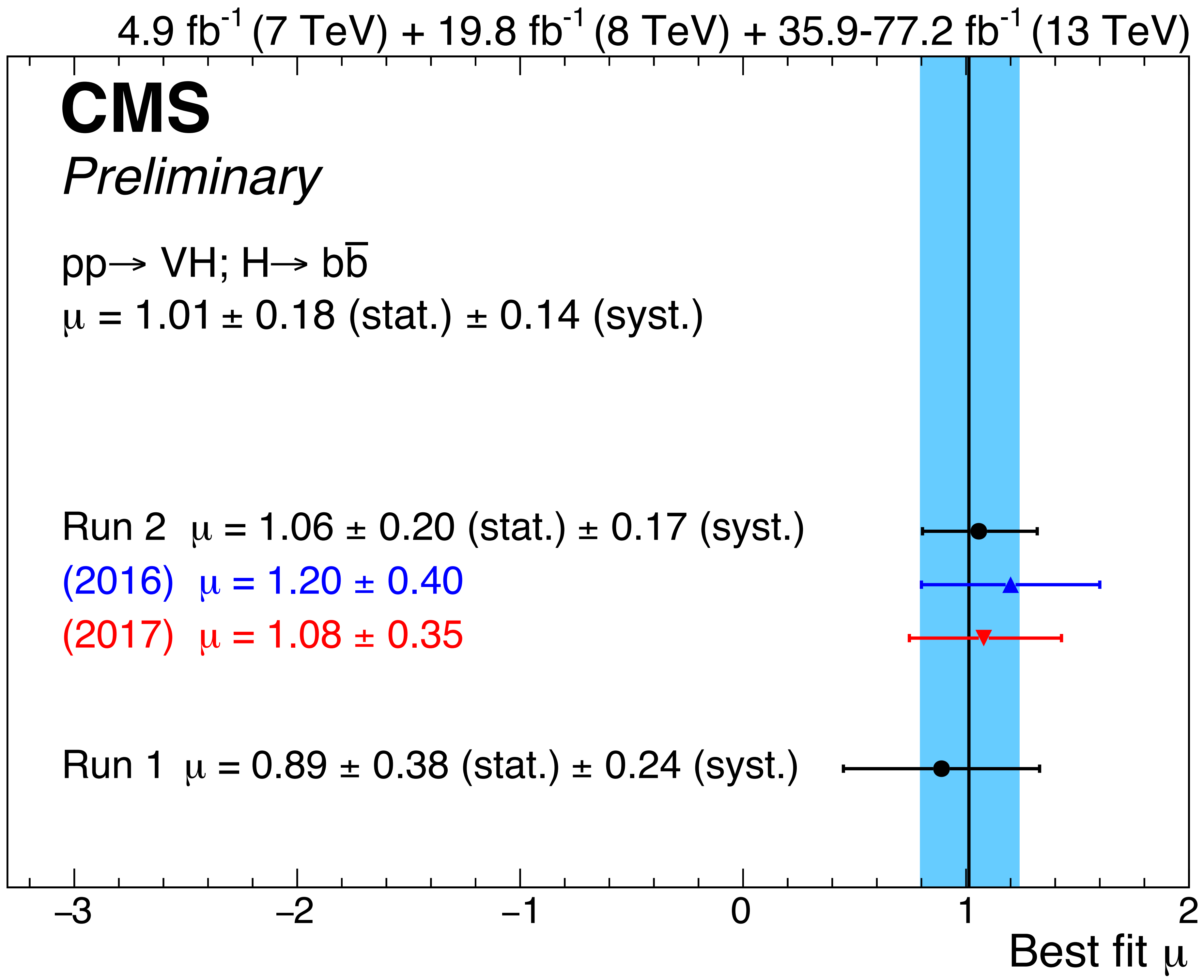


CMS** Run 1+2: **4.8 σ (4.9 σ exp.)

ATLAS** Run 1+2: **4.9 σ (5.1σ exp.)

State of the art of VH($b\bar{b}$) at LHC





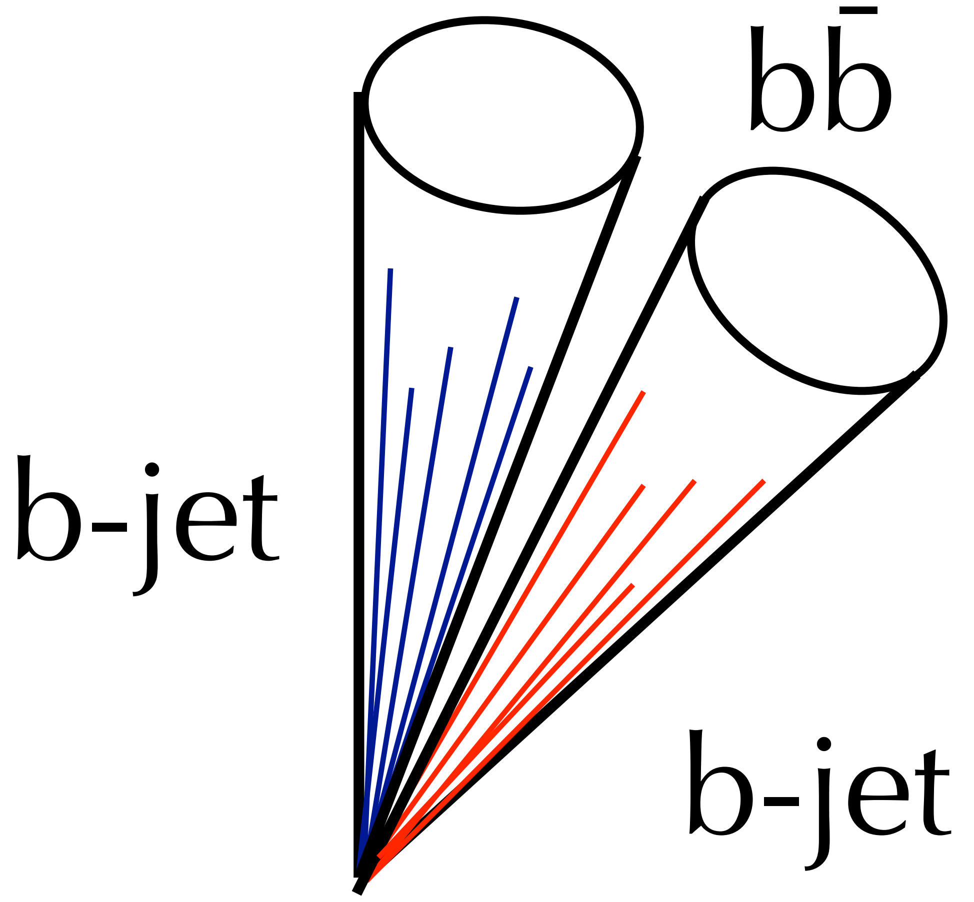
More information to be combined from the other production modes

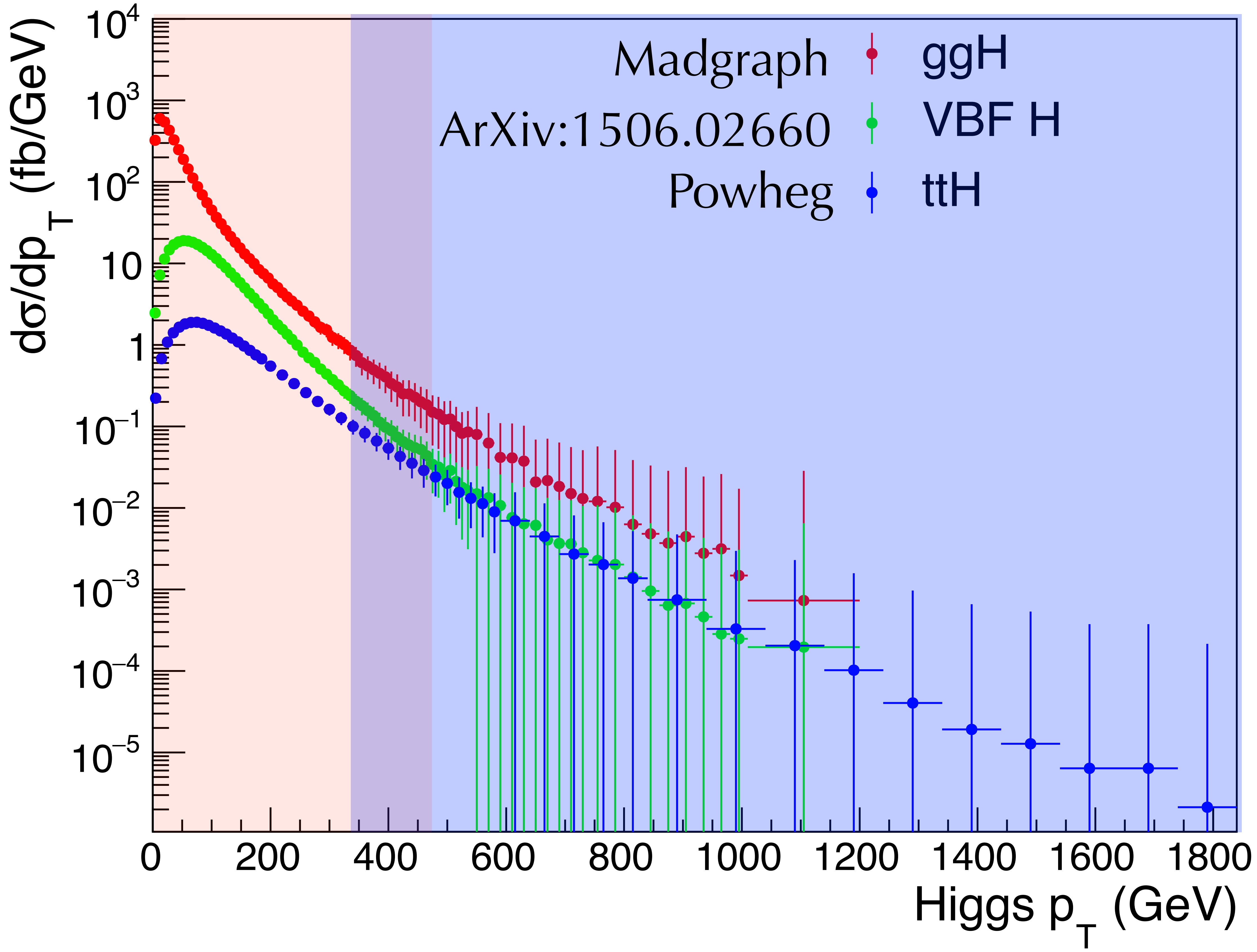
ggF H($b\bar{b}$)

In the **gluon fusion** channel the sensitivity increases by looking at **very high momentum Higgs bosons**

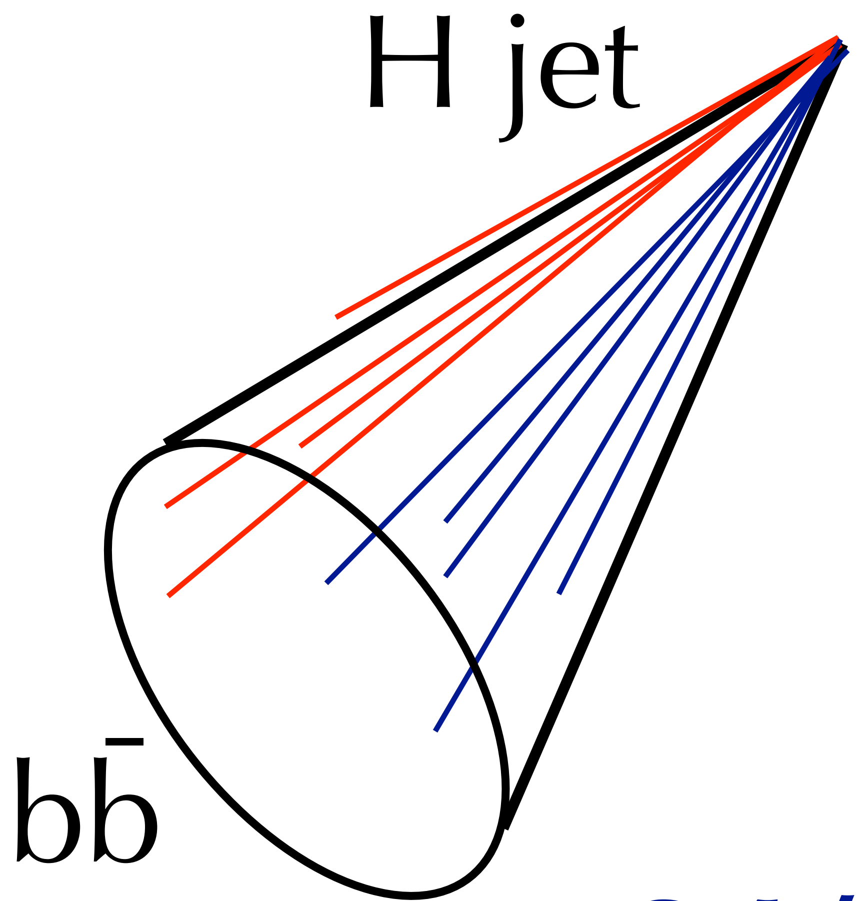
$dR(b\bar{b}) \sim 2m_H/p_T$

two-separate b-jets (R = 0.4)

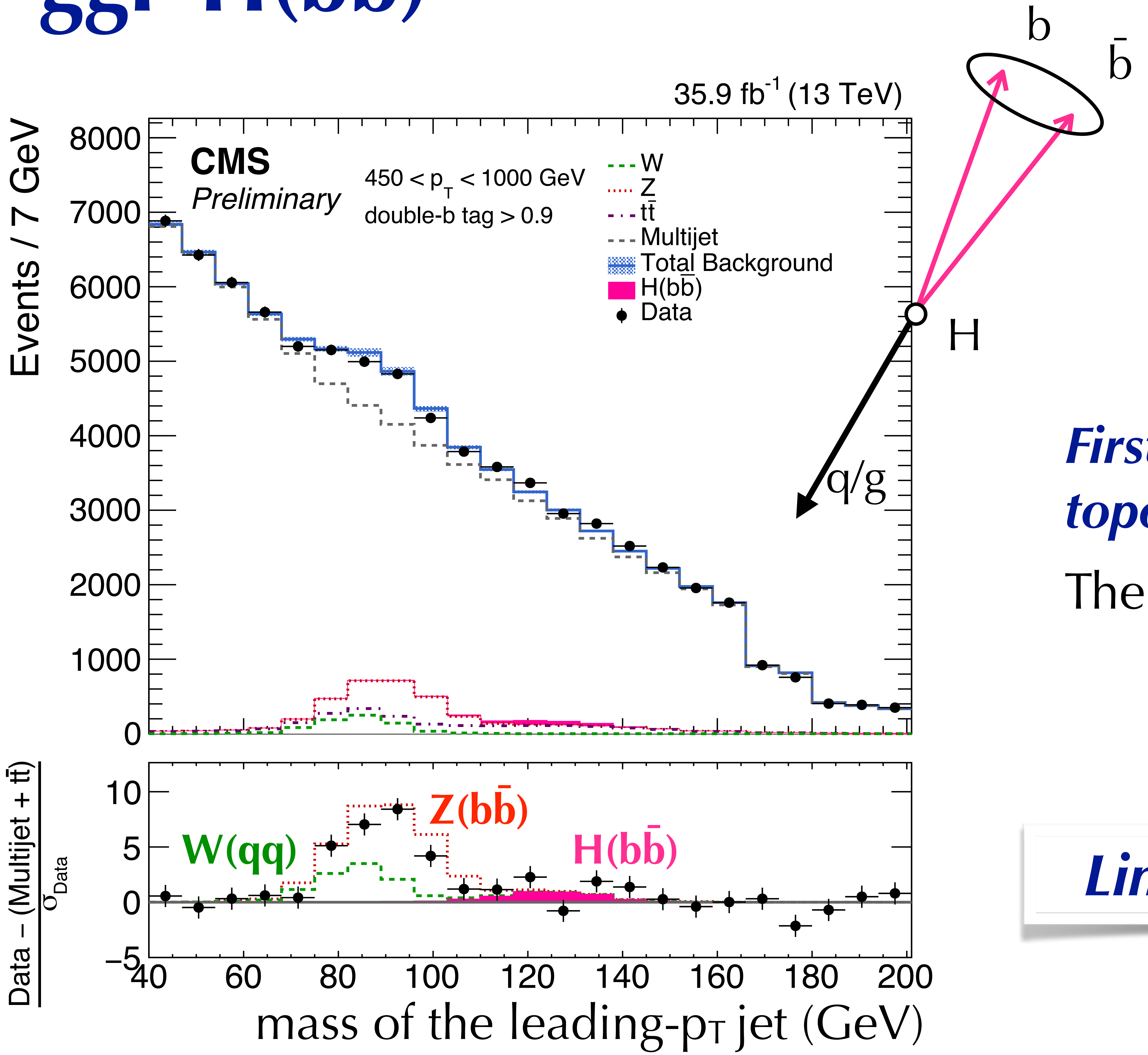




one single large-cone (fat) jet (R = 0.8)



ggF $H(b\bar{b})$



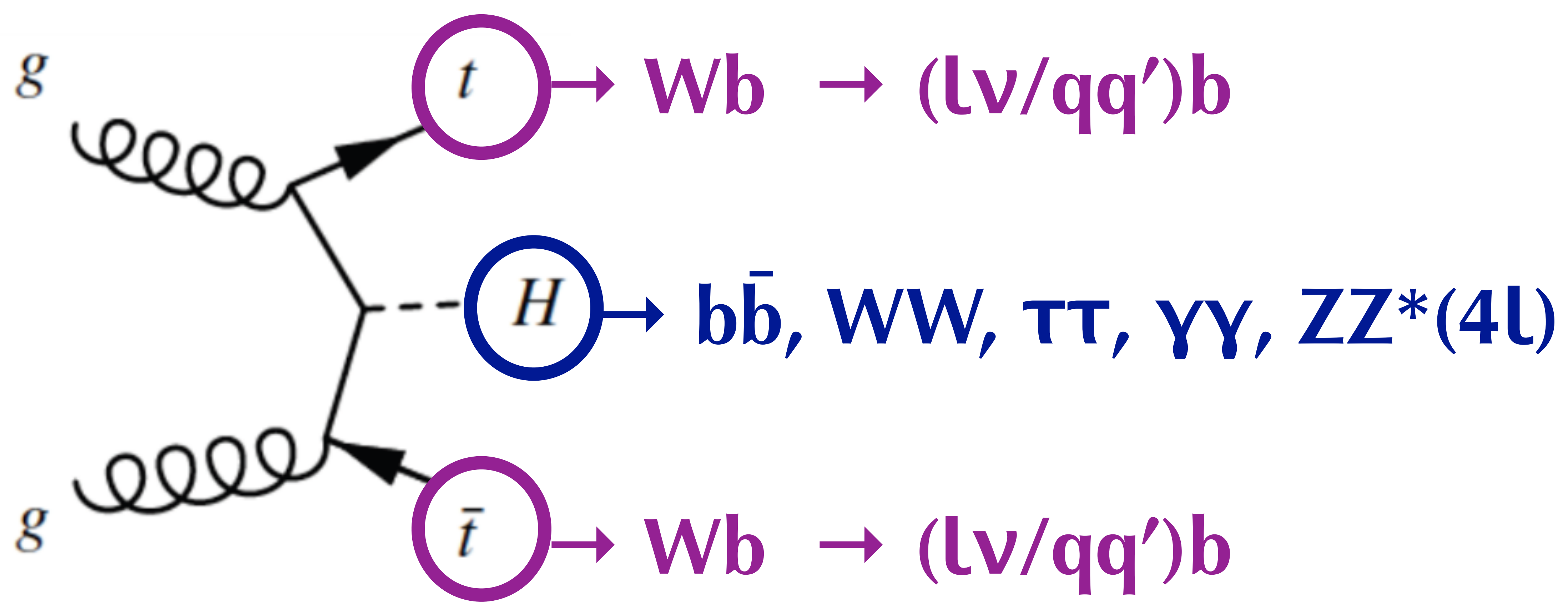
First Observation of the $Z(b\bar{b})$ in the one-jet topology 5.1 (5.8) σ

The observed significance is **1.5** (0.7) σ

Limited by the statistical uncertainties

ttH production mode

- **Best direct probe of the top-Higgs Yukawa coupling** (y_t ~1)
  - Challenges: σ_{ttH} ~ 0.5 pb, σ_{tt} ~ 830 pb at13 TeV
  - Irreducible backgrounds from tt+X (X = $b\bar{b}$, W, Z)
  - Large combinatorics of leptons and jets from top quark decays
- **Exploiting multiple final state**, depending on the top and Higgs decay channel



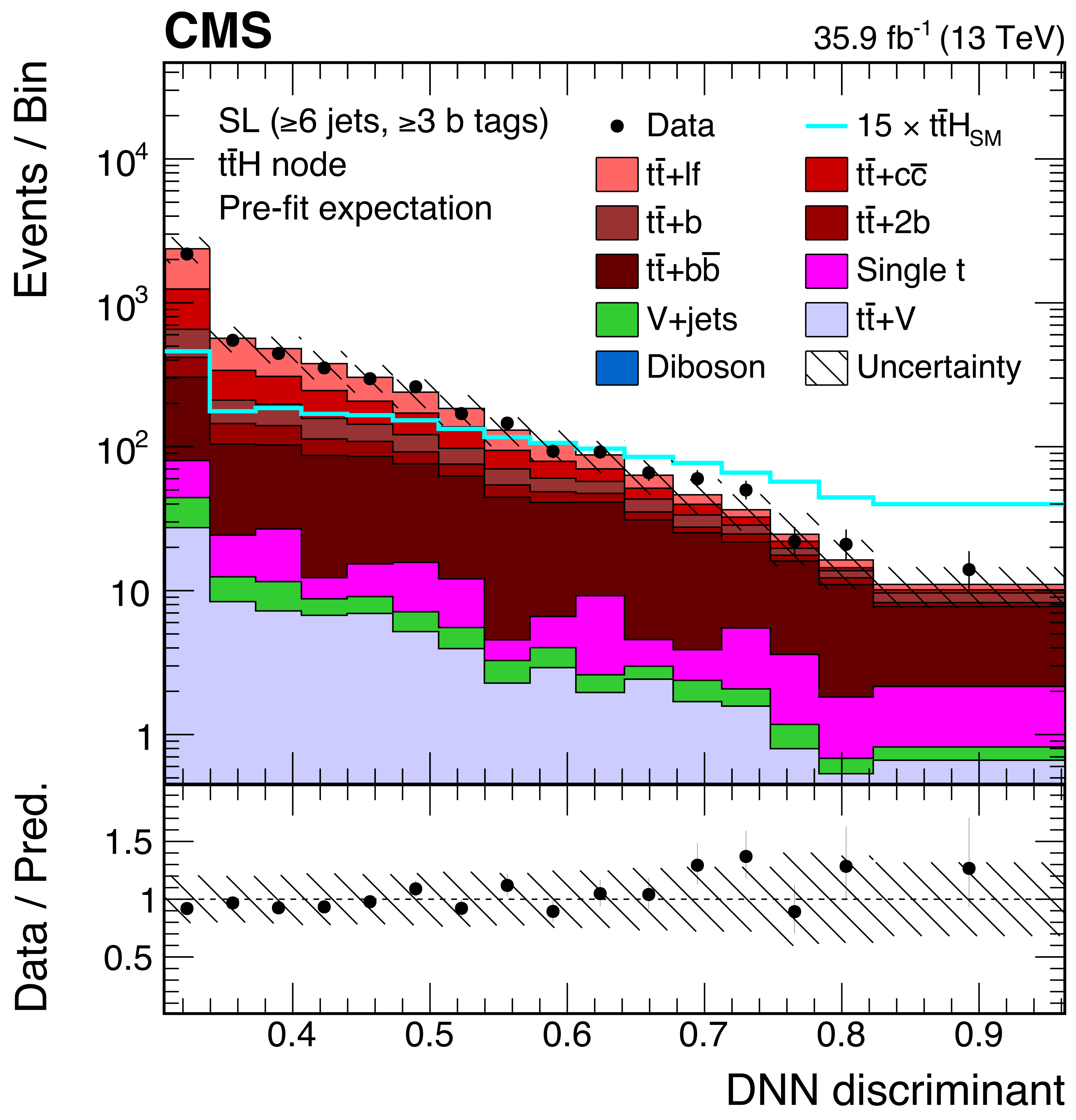
Depending on the H decay

Smaller BR vs. better S/B

	$b\bar{b}$	WW/ττ	γγ
rate	O(10^3)	O(50)	O(10)
S/B	~0.01	~0.1	~1

$t\bar{t}H(b\bar{b})$ searches

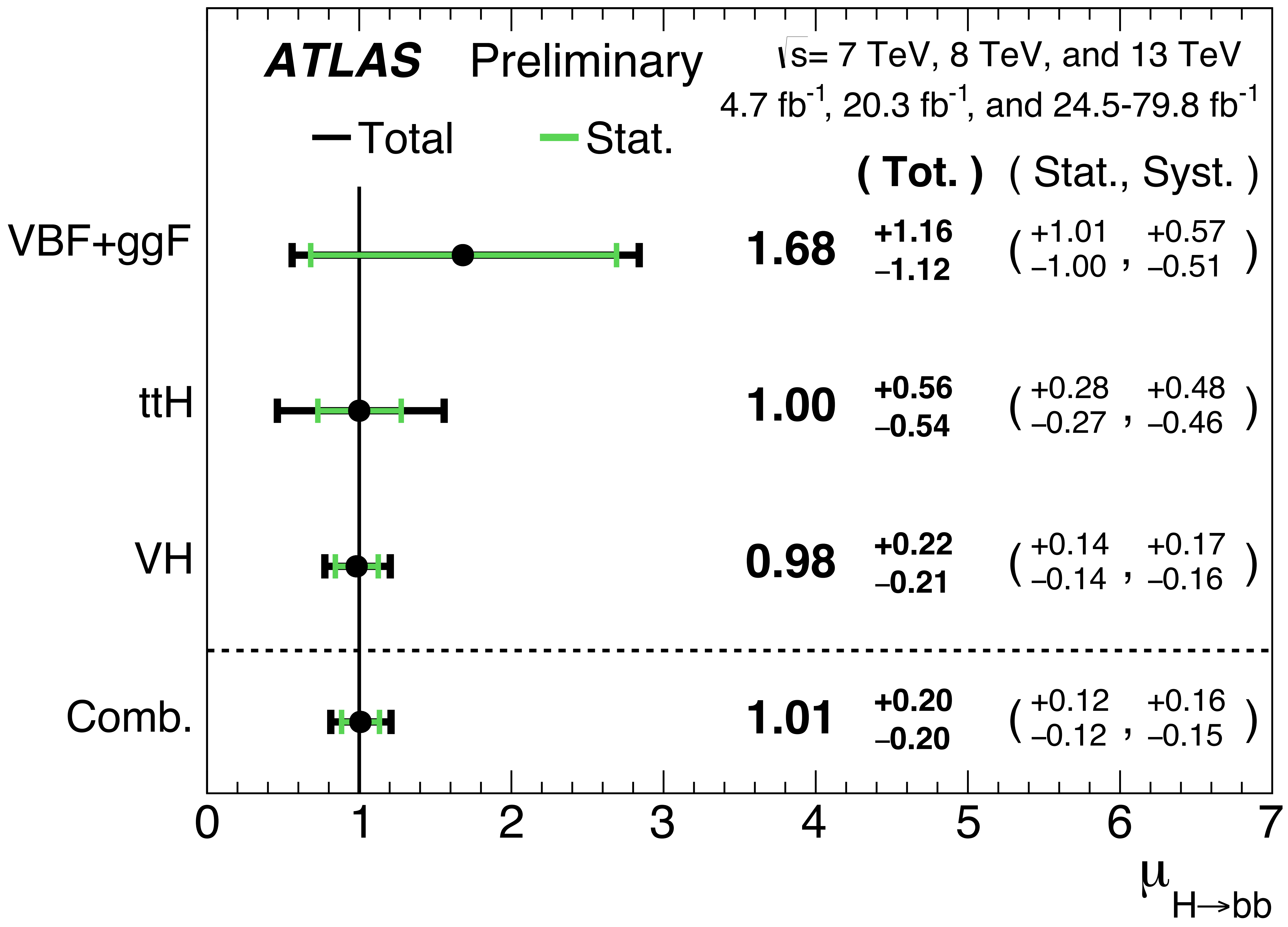
CMS-arXiv:1804.03682, sub. to JHEP

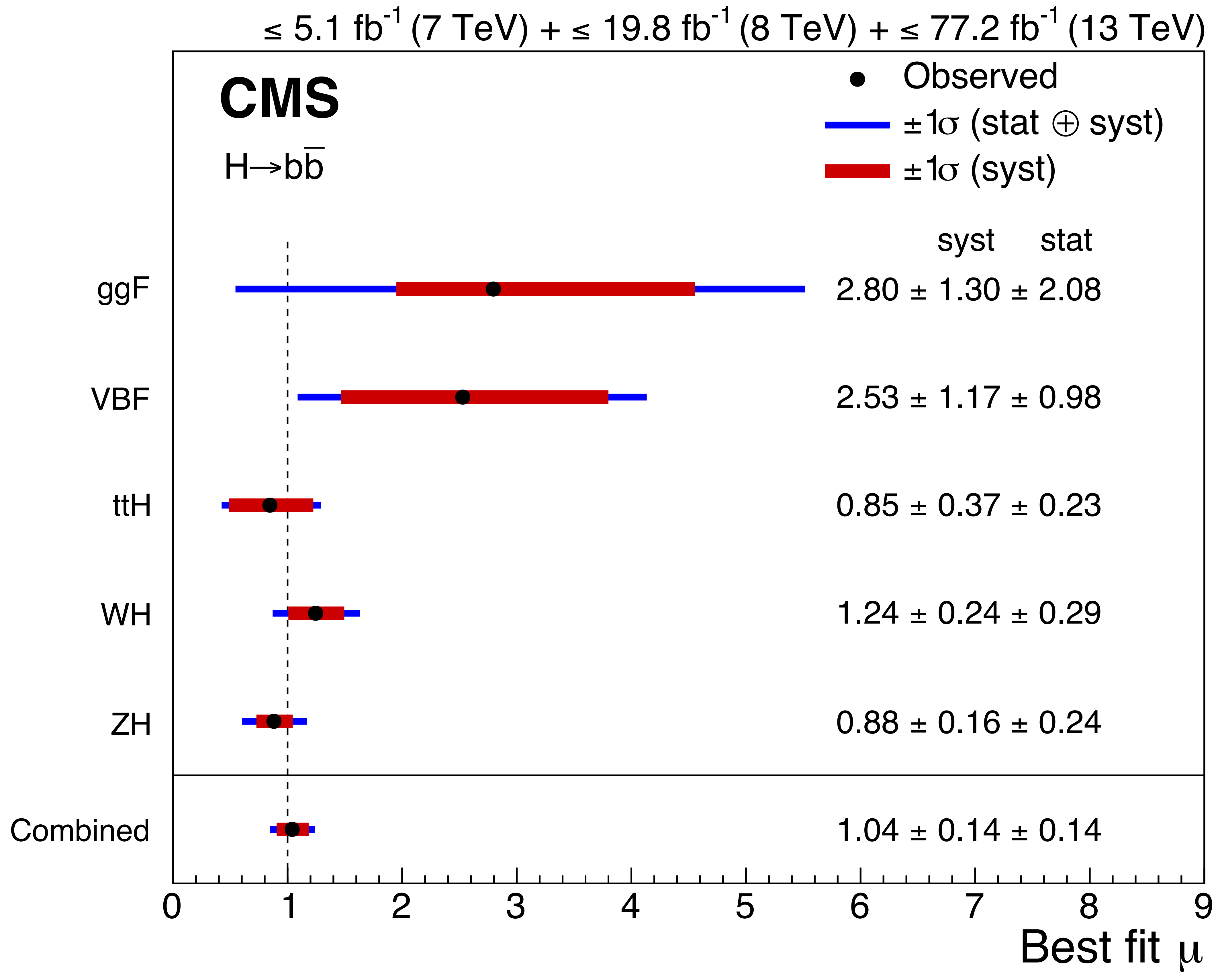


$t\bar{t}\rightarrow$ l+jets $H\rightarrow b\bar{b}$

- Large combinatorics in the event reconstruction
- Dominant tt+$b\bar{b}$ background O(10) pb with large associated theory uncertainty
- Combination of BDT, DNN and Matrix Element discriminants to extract the signal
- The observed significance is **1.6** (2.2) **σ**

$H(b\bar{b})$ observation





First observation of $H(b\bar{b})$ decay

CMS** Run 1+2: **5.6 (5.5) σ
ATLAS** Run 1+2: **5.4 (5.5) σ

Higgs couplings: precision & kinematic

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k$$

Assuming new physics at some scale Λ

Higgs couplings: precision & kinematic

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_k \mathcal{O}_k$$

Assuming new physics at some scale Λ

Testing multi-TeV scale with sub-percent level measurements

$$\delta\mathcal{O} \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

1% effect on coupling for Λ ~ 2.5 TeV

ArXiv:1310.8361

Higgs couplings: precision & kinematic

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_k \mathcal{O}_k$$

Assuming new physics at some scale Λ

Testing multi-TeV scale with sub-percent level measurements

$$\delta\mathcal{O} \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\rm TeV}{\Lambda}\right)^2$$

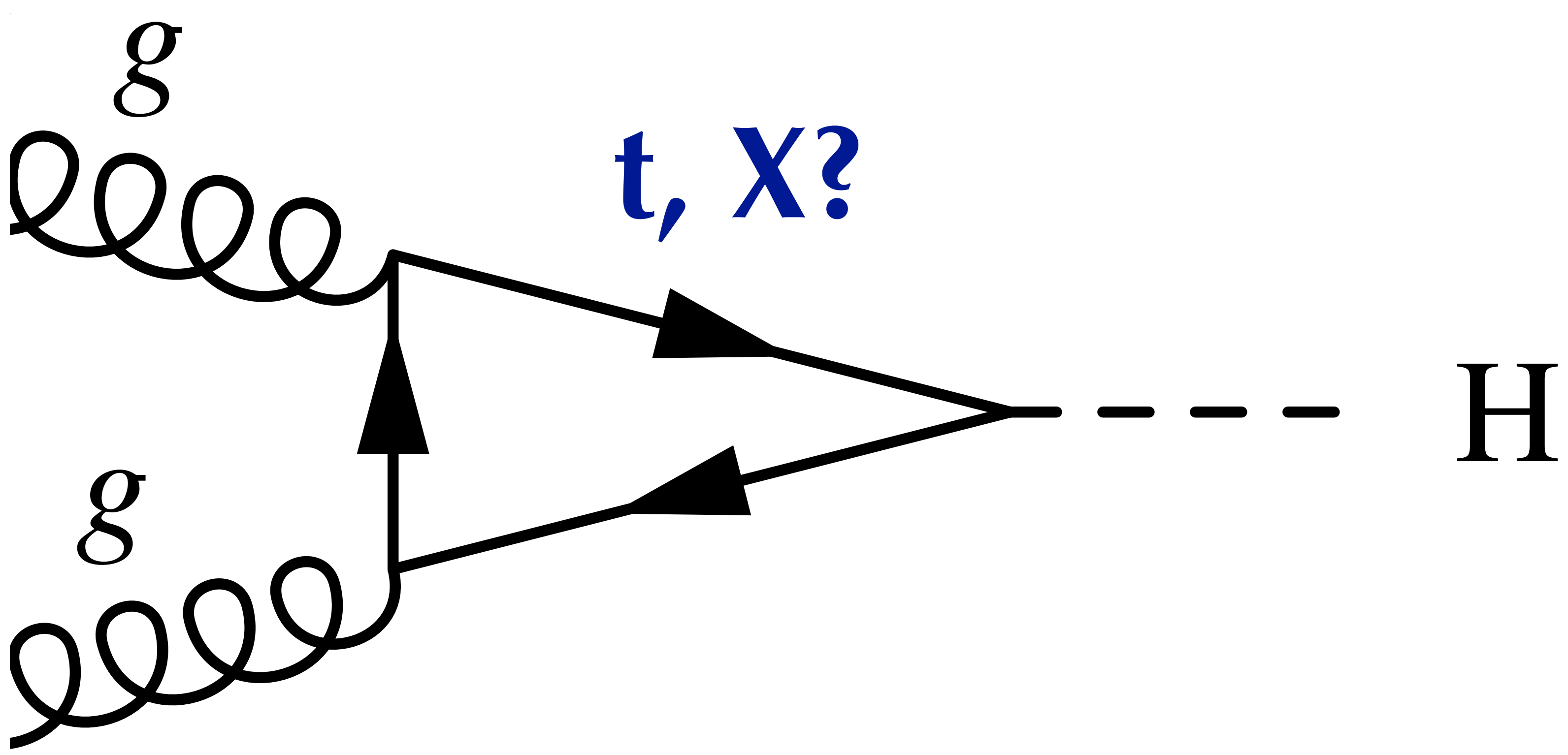
1% effect on coupling for Λ ~ 2.5 TeV

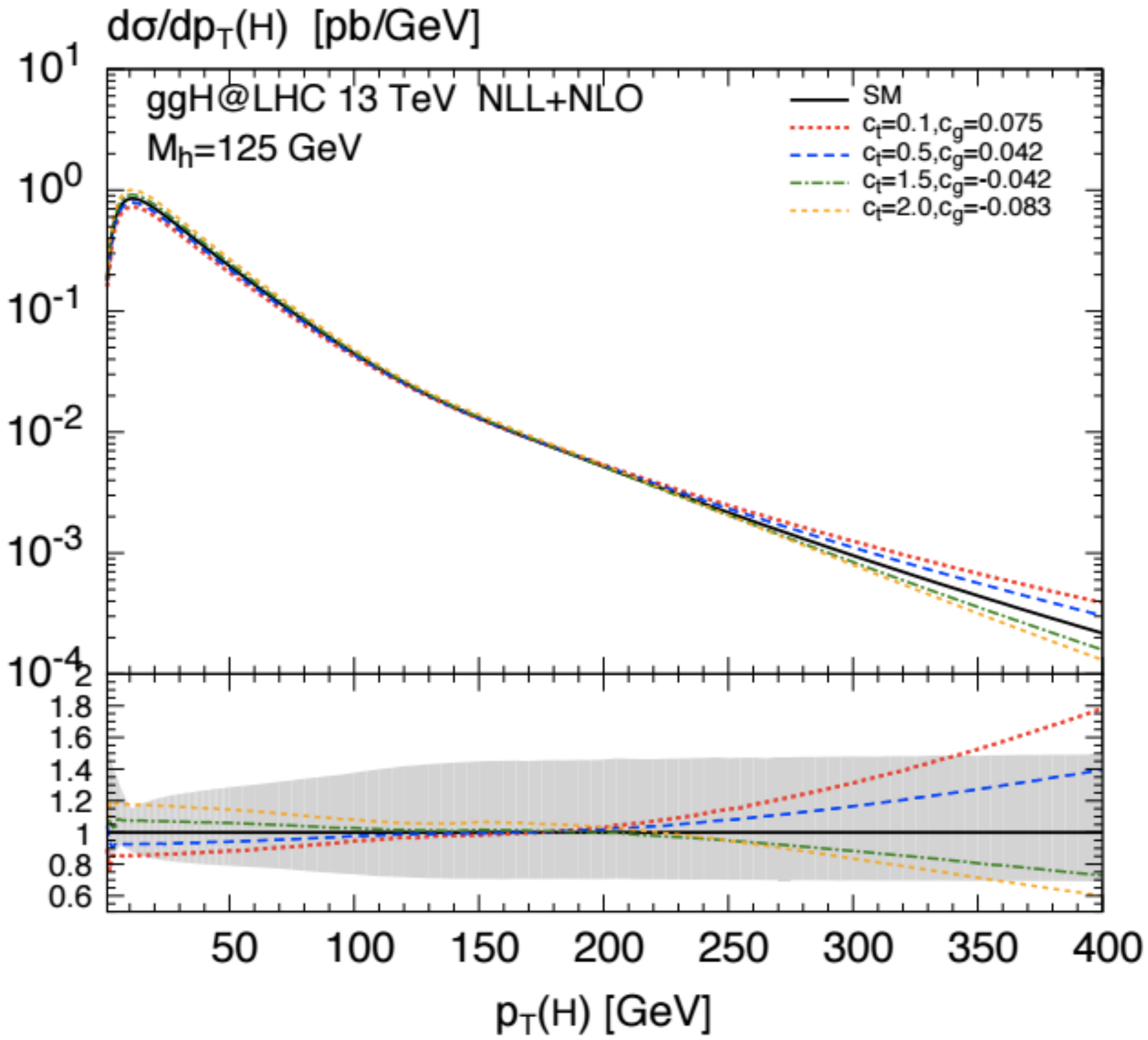
Measurements at large transferred momentum (Q) probe large Λ even if precision is low

$$\delta\mathcal{O}_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

15% effect on δO_Q for Λ ~ 2.5 TeV

Higgs at high p_T

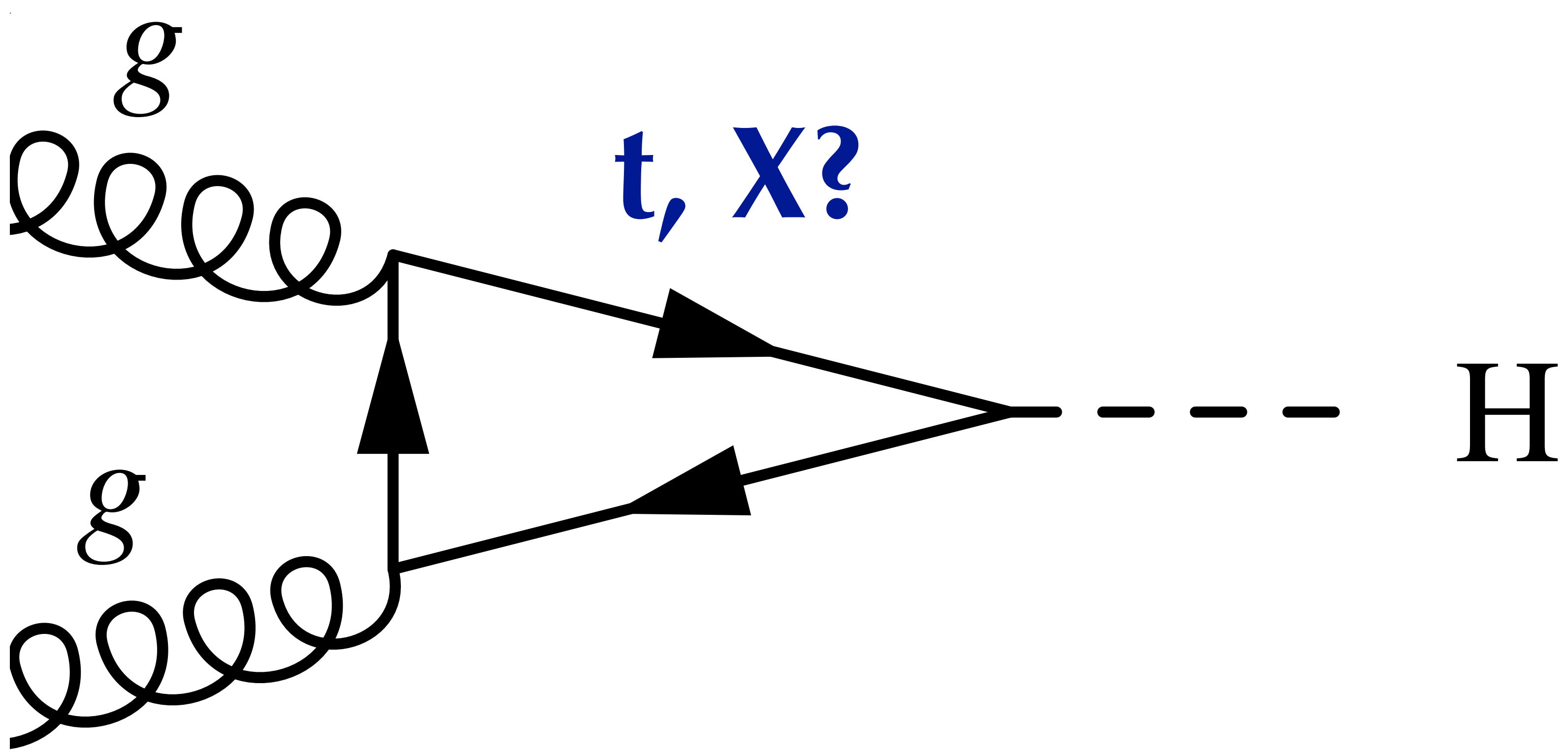


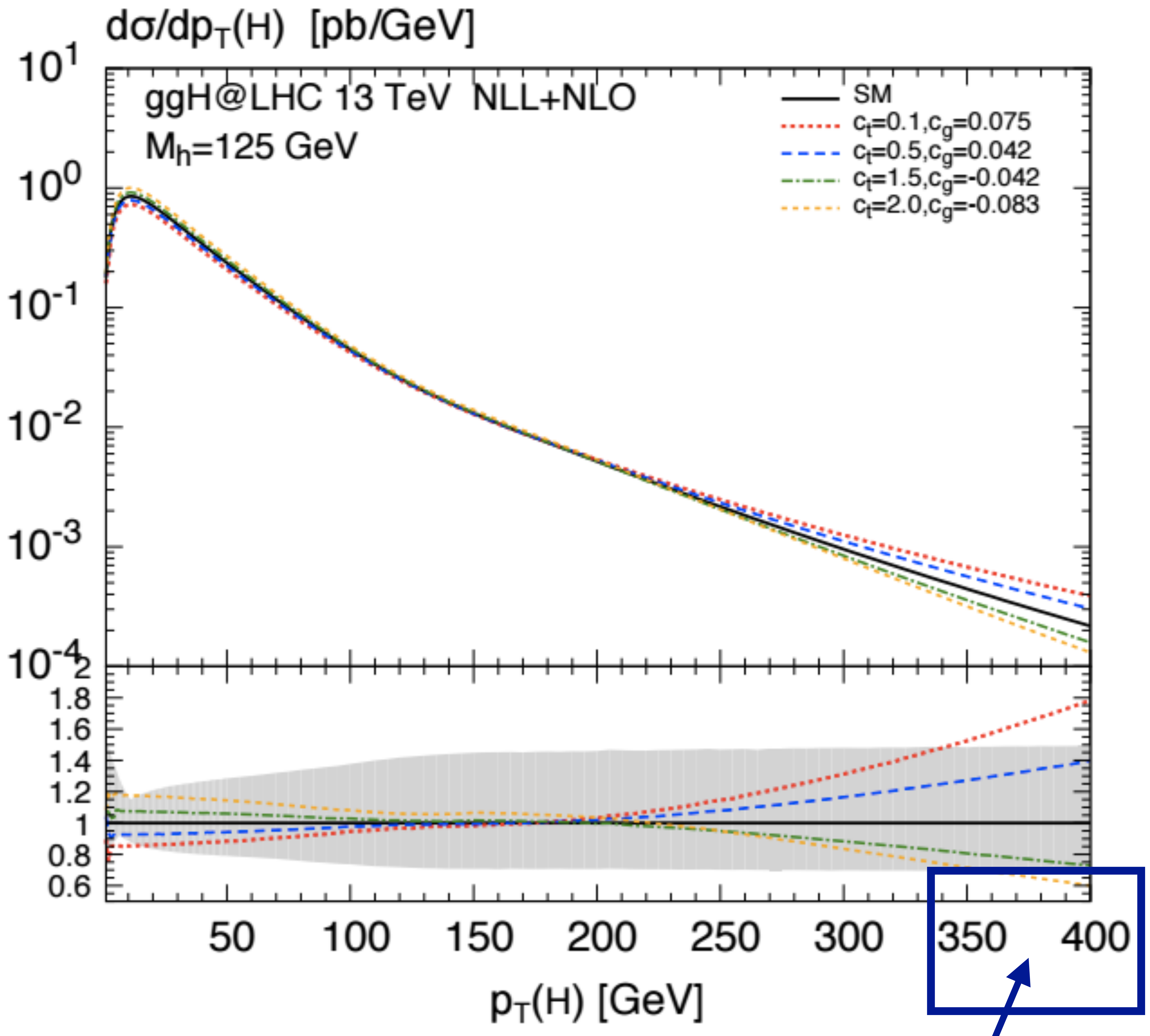


At high H p_T we can directly probe **modifications in top quark coupling**

Higgs at high p_T

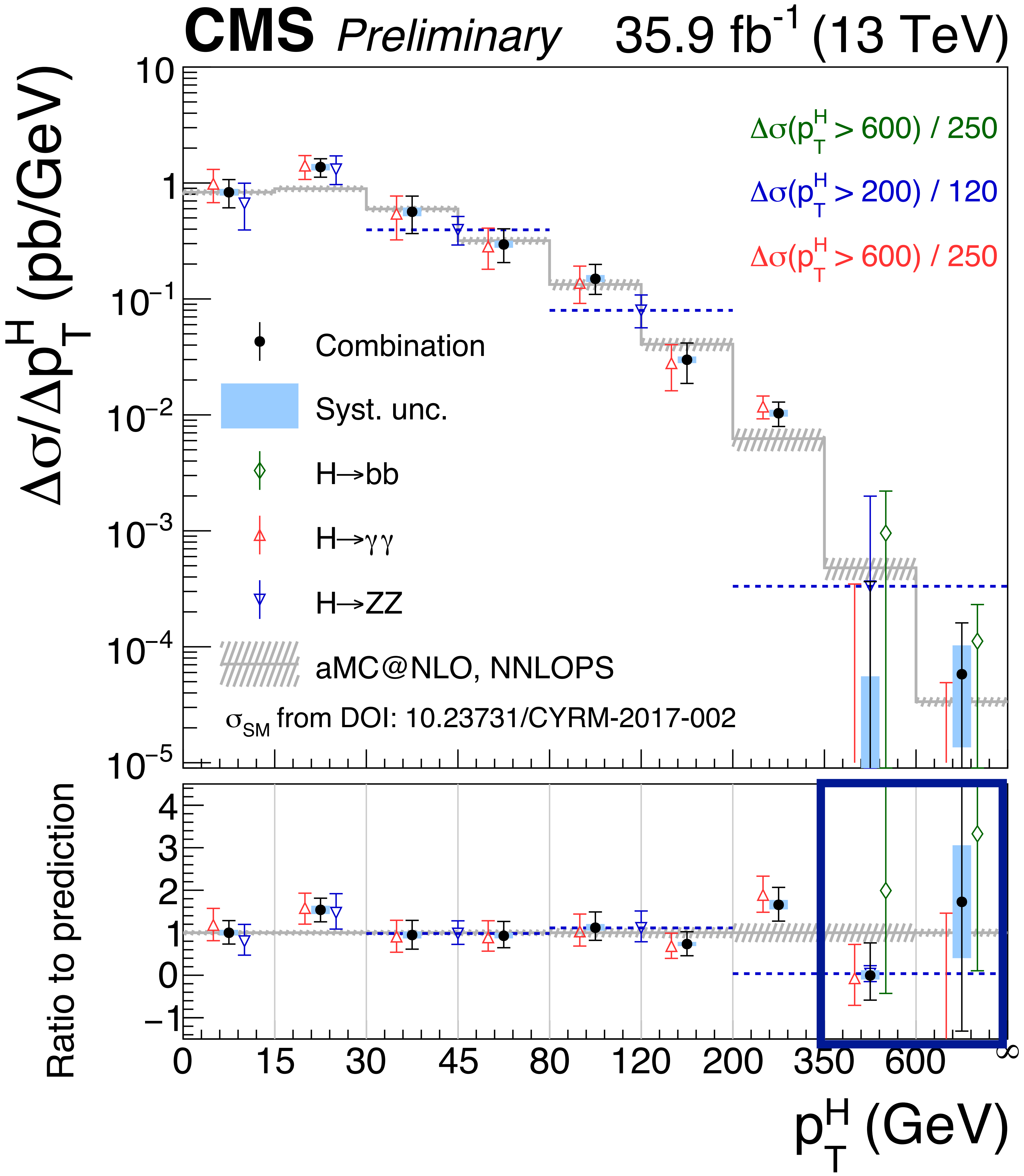
ArXiv:1612.00283
JHEP 10 (2016) 123

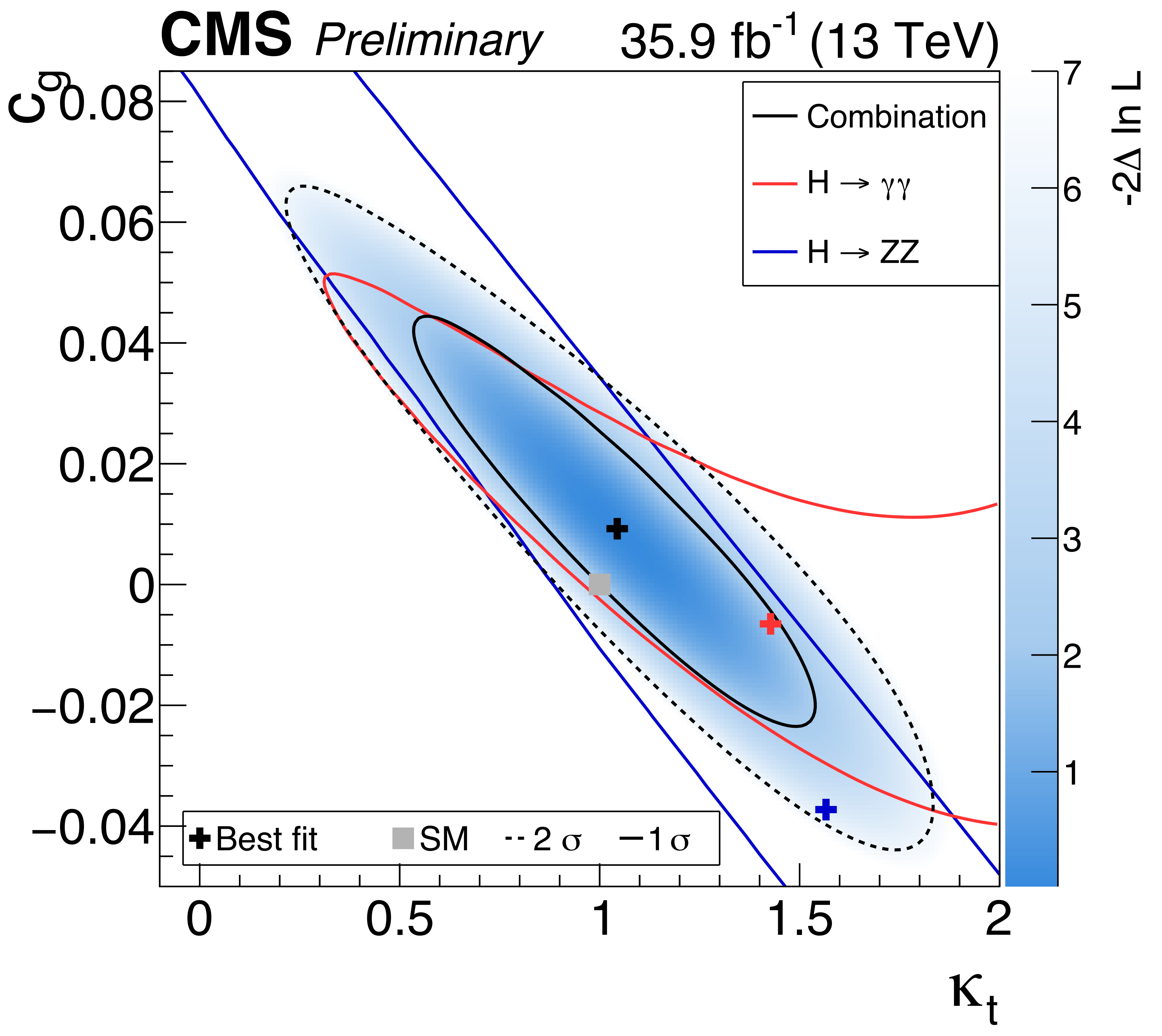




ggF $H(b\bar{b})$ starts here

Probing ggF vs. H p_T

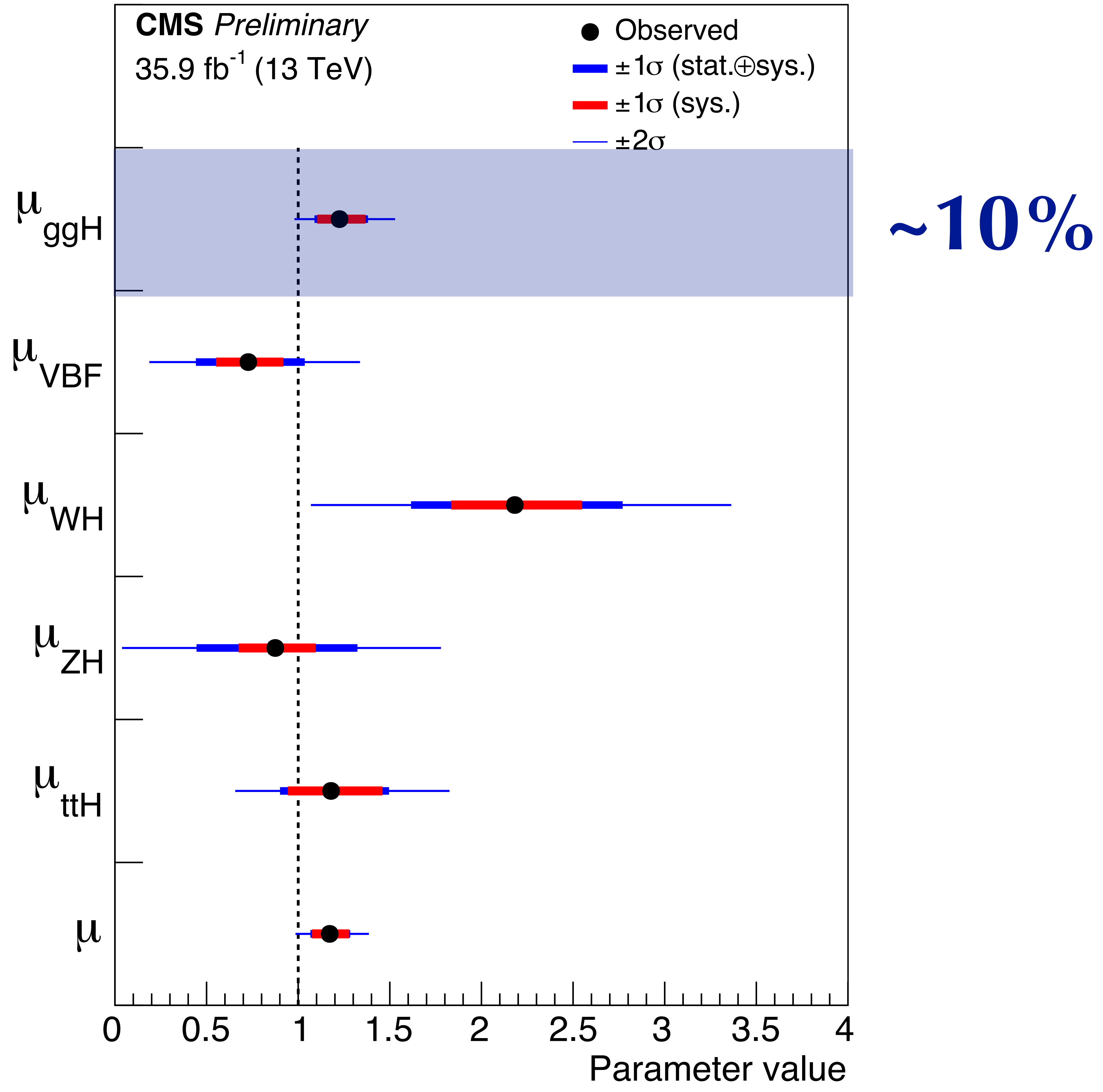


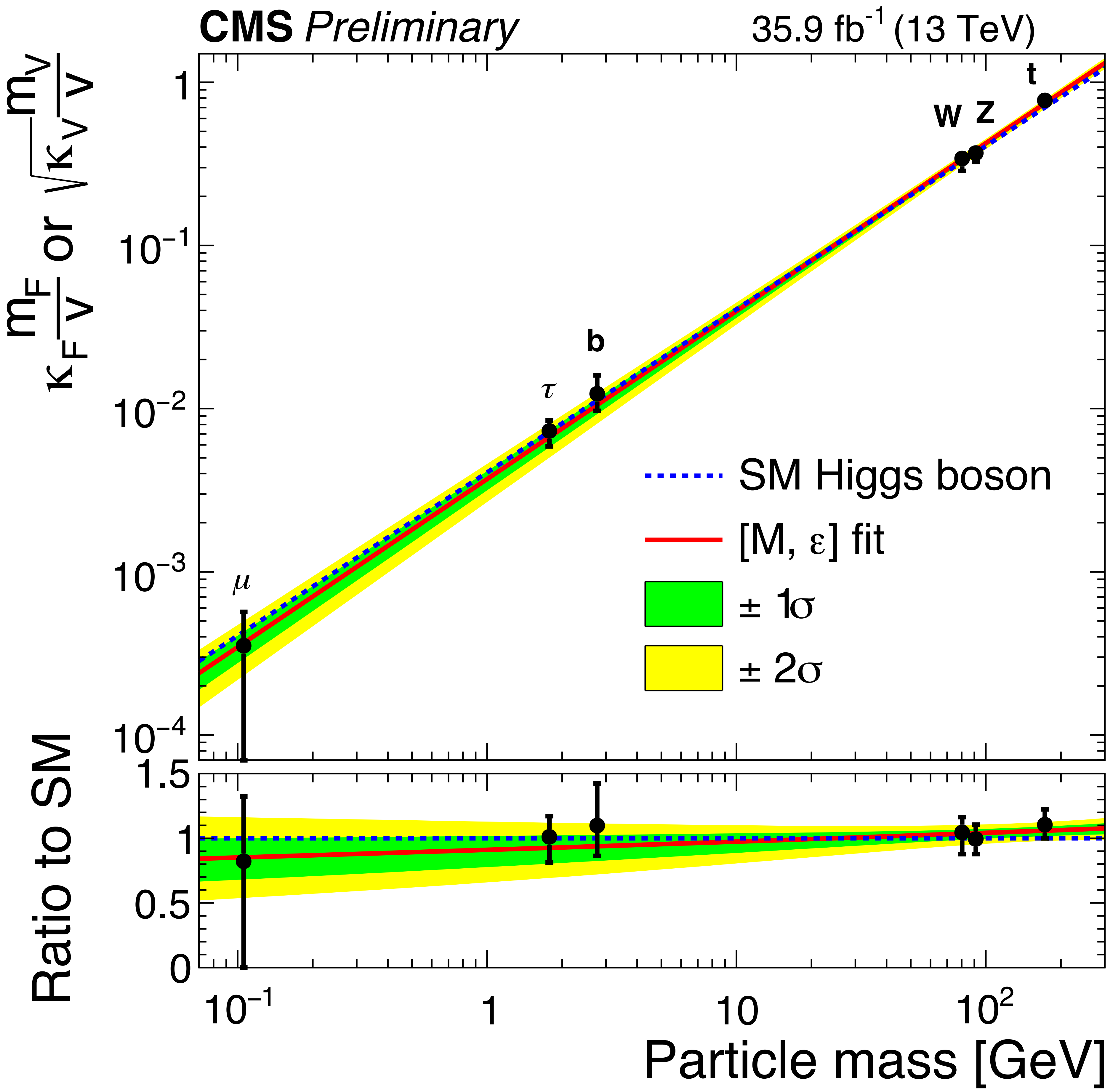


H(bb̄) improves constraints to new physics by 30%

CMS-PAS-HIG-17-031

Run1+2, Higgs boson summary



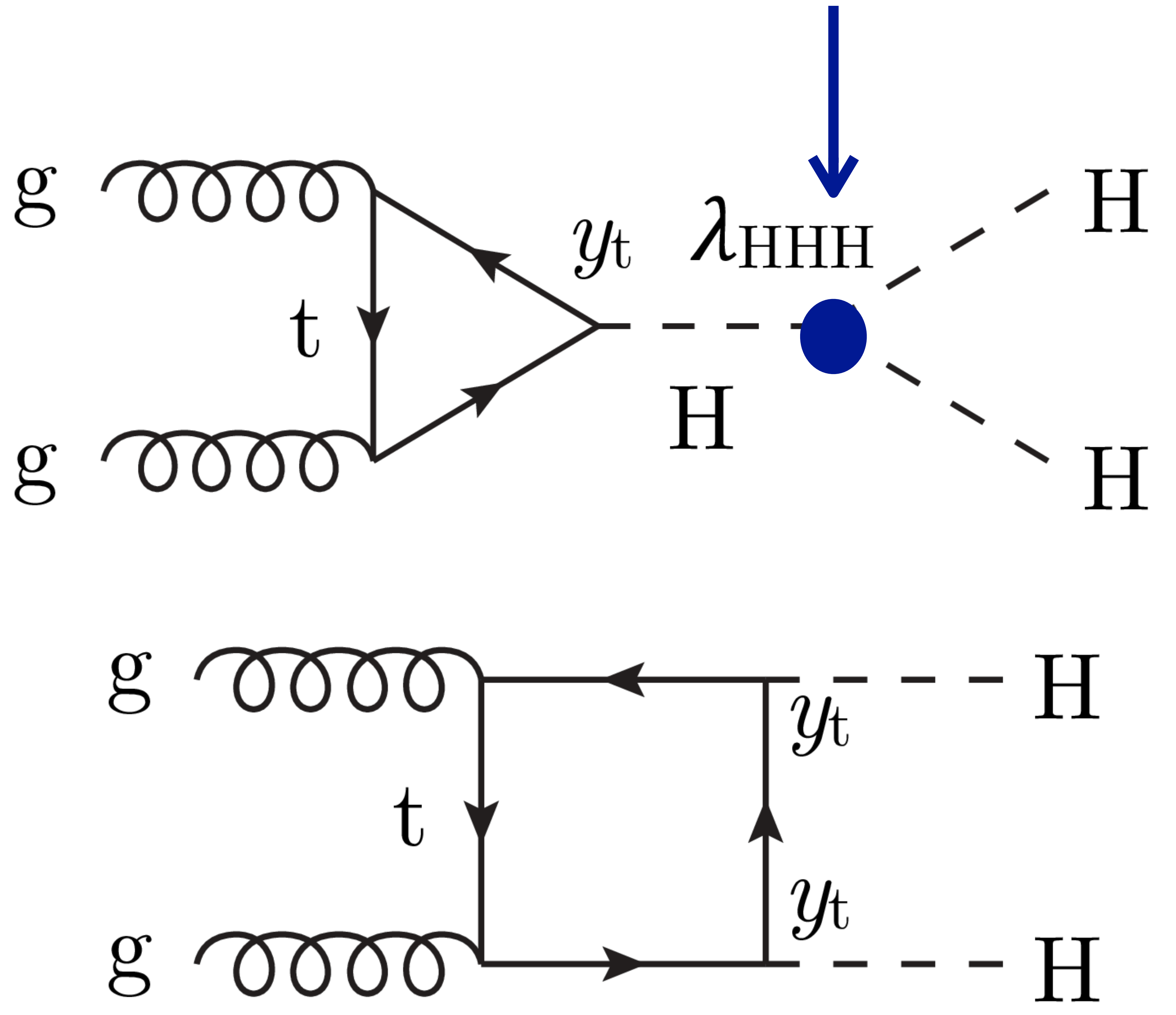


All main production modes (ggF, VBF, VH and ttH) have now been observed
First direct confirmation of coupling to all 3rd generation fermions (t/b-quarks and τ leptons)

Is it a SM Higgs boson?

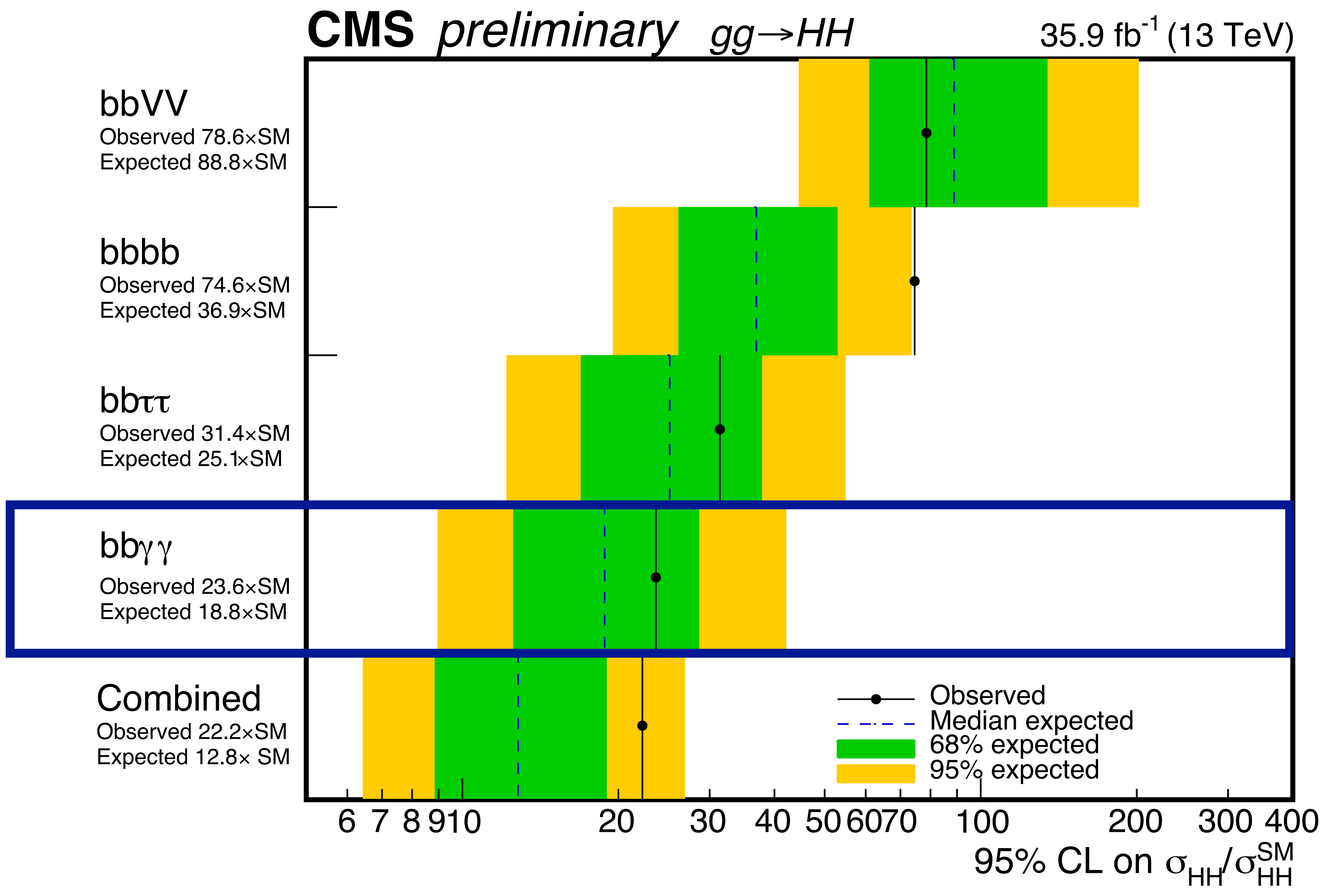
$$\lambda_{HHH} = \frac{m_H^2}{2v^2} = 0.13$$

- Mass
- Spin-parity
- Width
- The couplings to fermions and bosons
- Study the self-coupling
- Any non-SM property?



In the **SM HH has extremely small cross section** (33.5 fb at 13 TeV)
Modified in many BSM scenarios, better than 20% precision on λ_{HHH} needed

HH Run-2 results

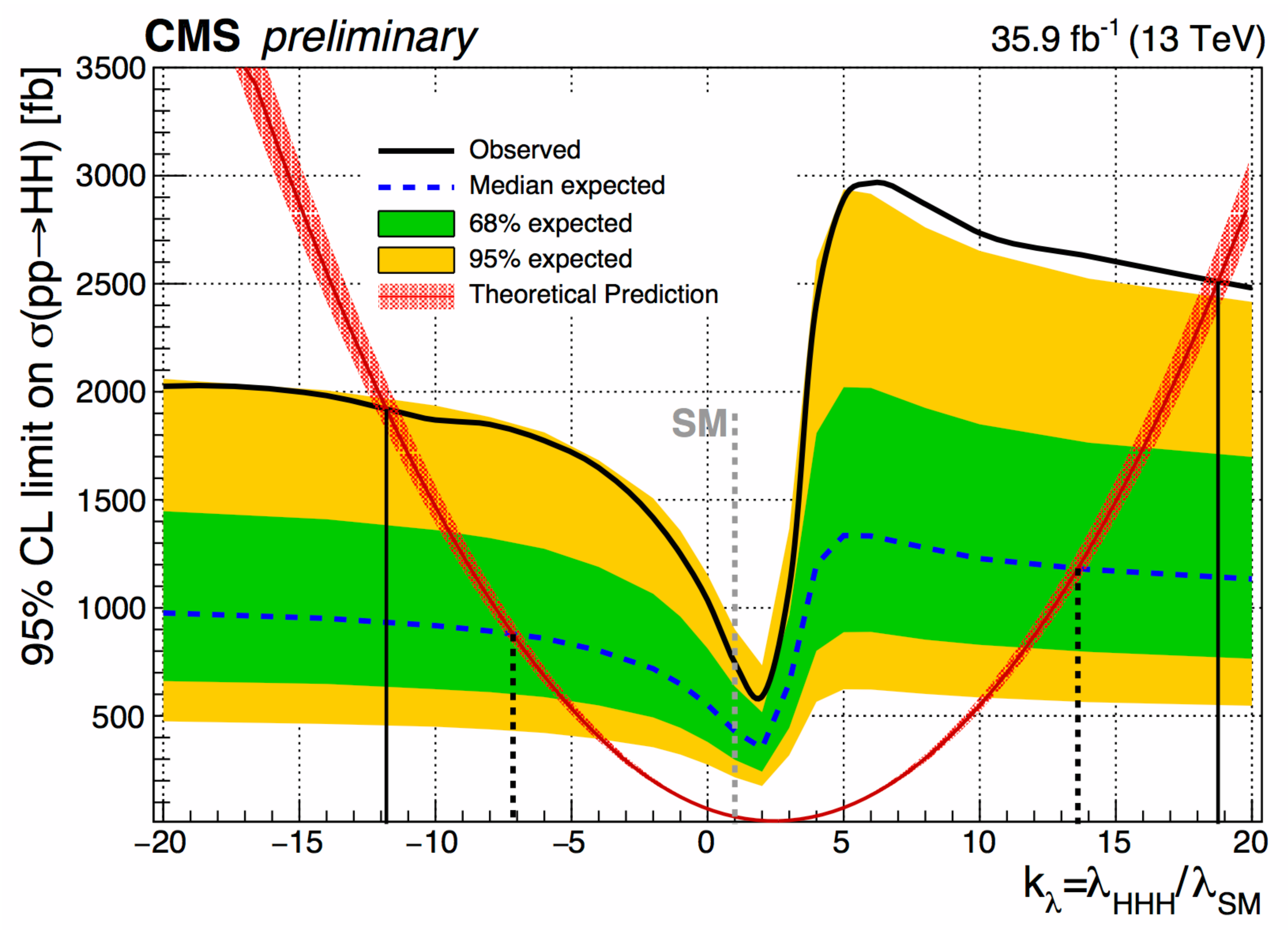


HH searches need:

- good **b-jets identification** efficiency
- best possible **resolution on $m_H/m_{b\bar{b}}$**
- exploit all possible information from the event to **improve S/B**

Similar sensitivity from several channels to SM HH production
SM production limits reach less than 20 x SM

Constraints on the self-coupling

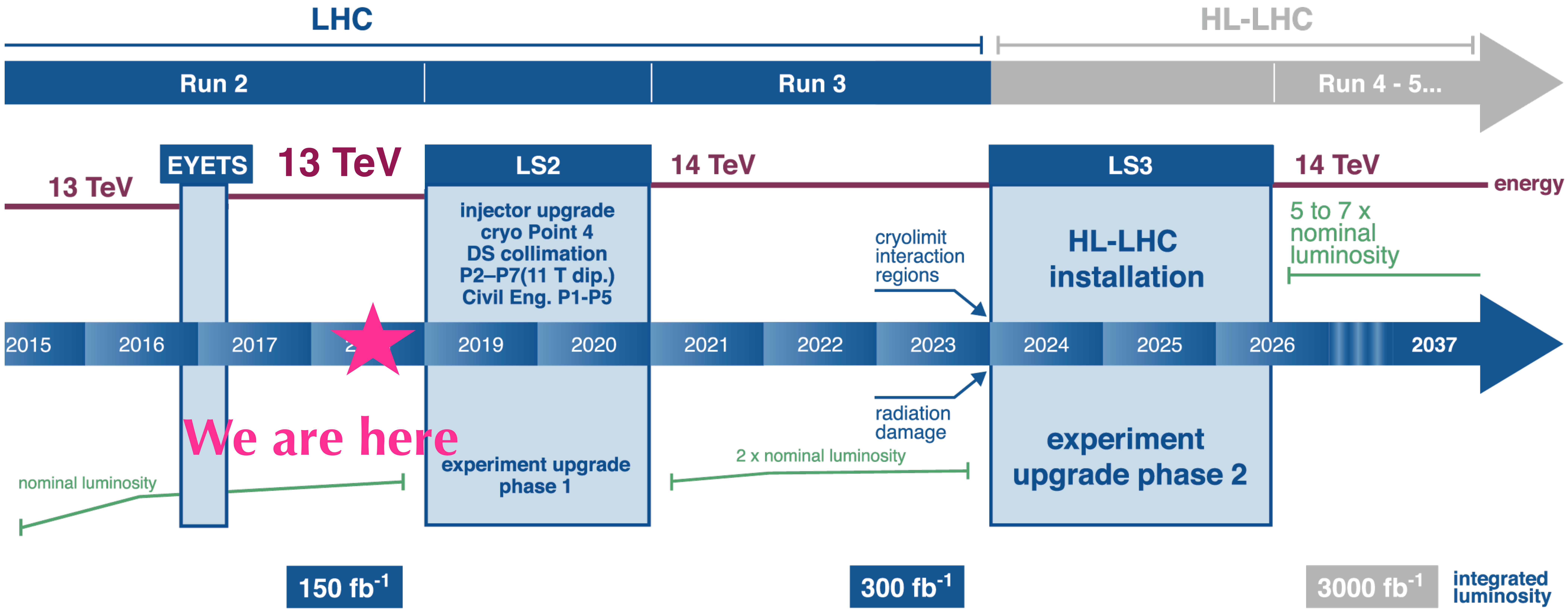


CMS HH combination constraints the trilinear coupling modifier $k_\lambda = \lambda/\lambda_{SM}$

$\kappa_\lambda \in$[-11.8, 18.8]

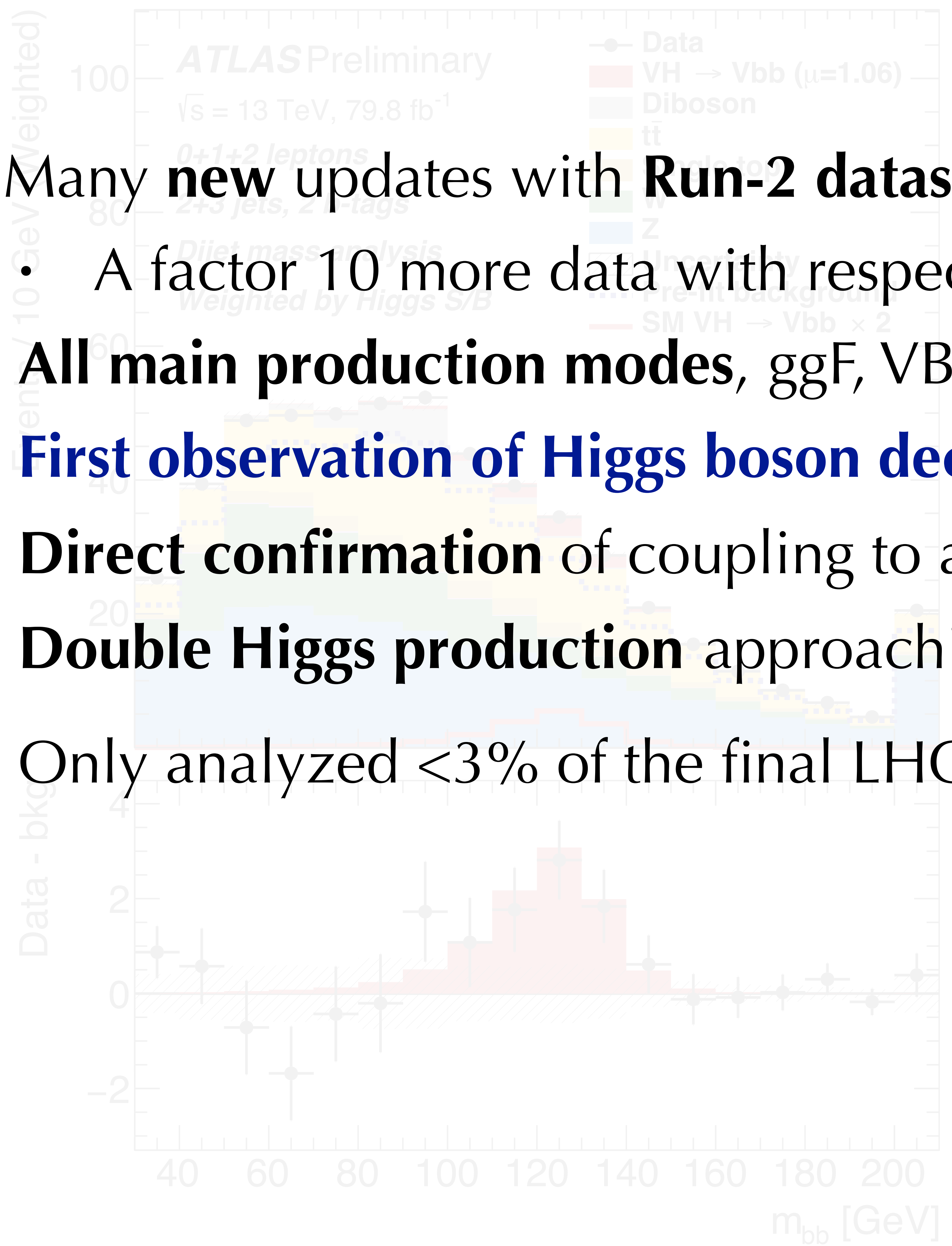
assuming SM top-H coupling

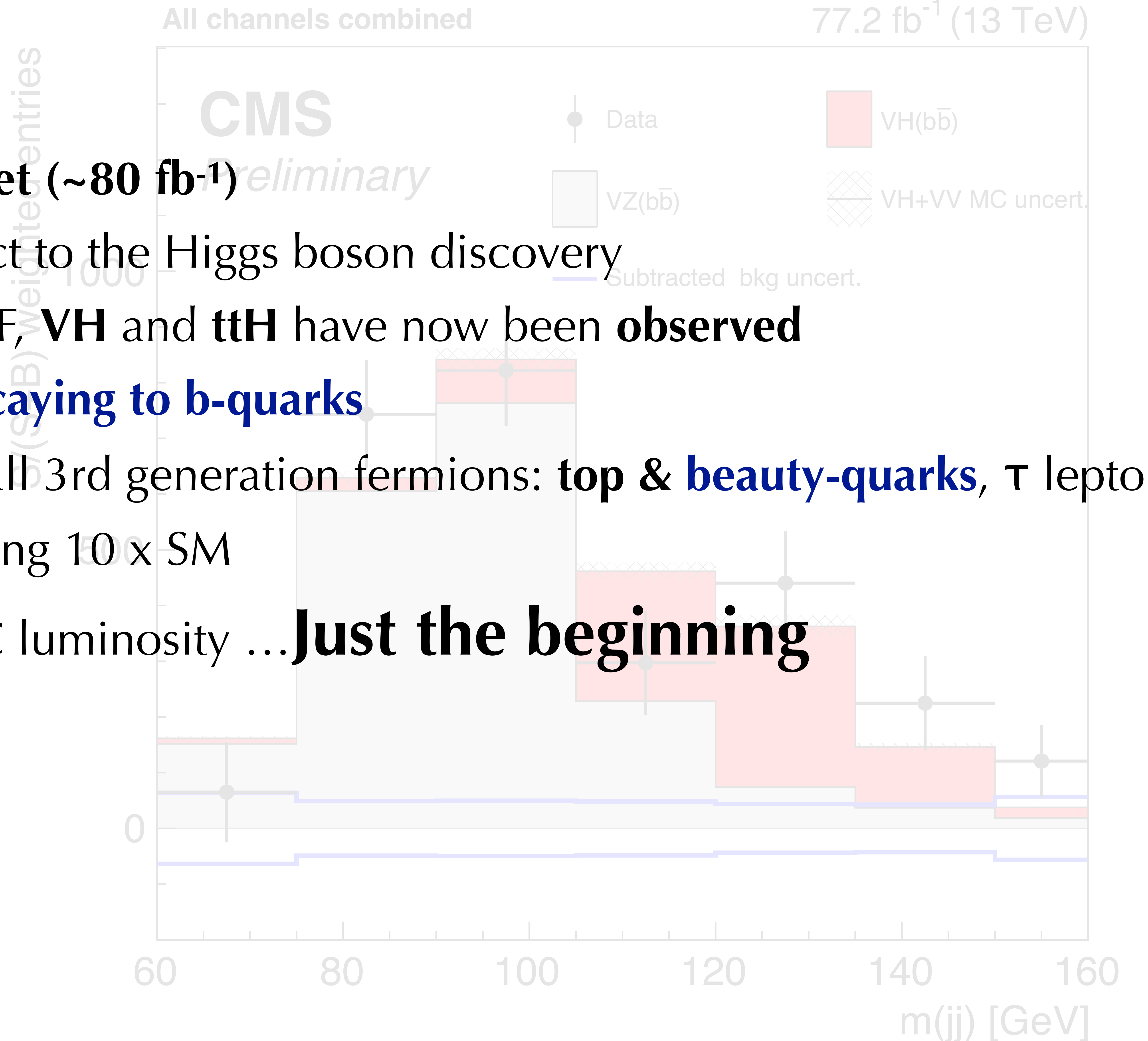
LHC → HL-LHC



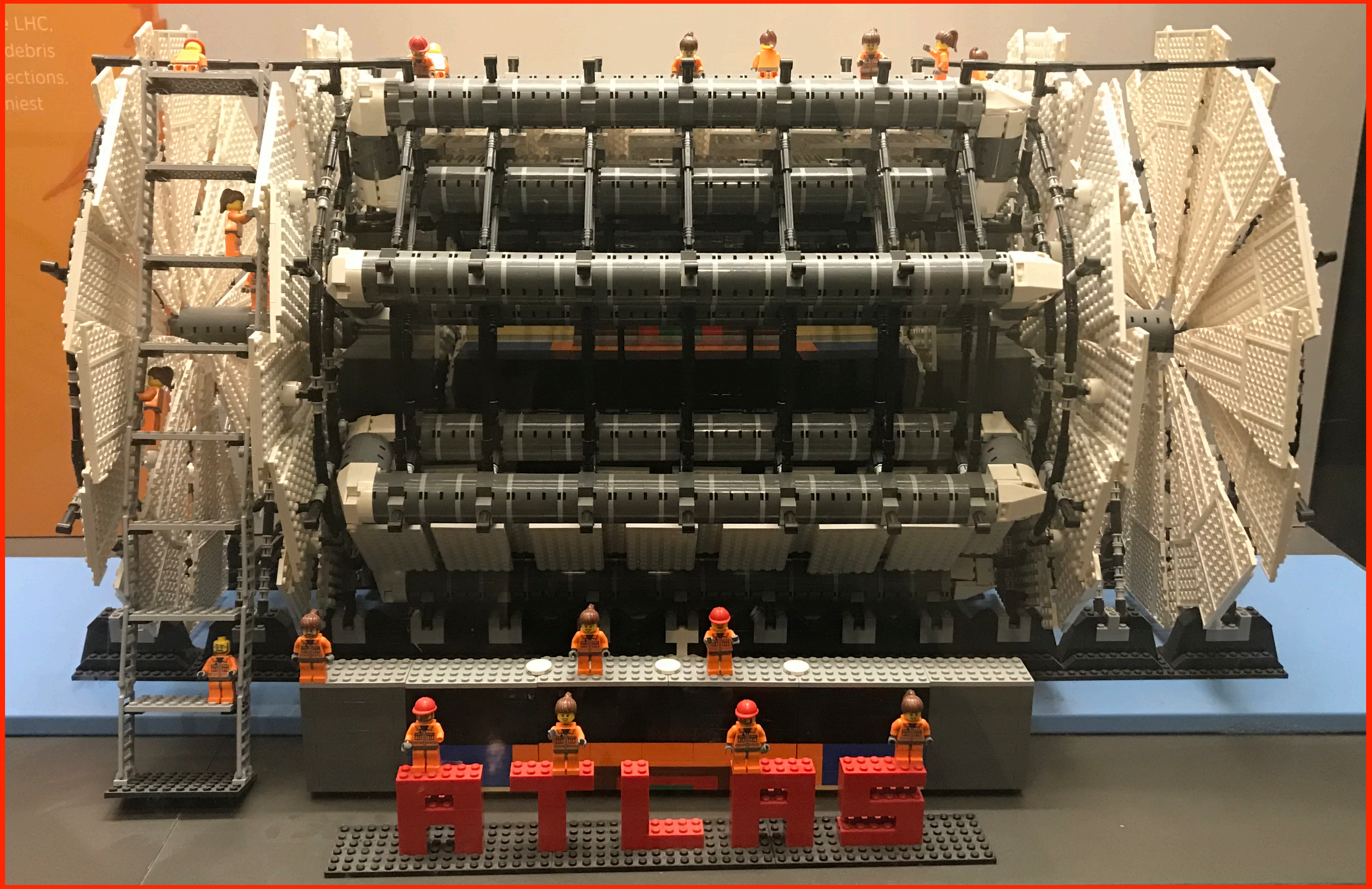
HL-LHC will enable precision measurements of H properties (couplings, self-couplings,…) and to probe the existence of very rare new physics processes

Conclusions





- Many **new** updates with **Run-2 dataset (~80 fb^{-1})**
  - A factor 10 more data with respect to the Higgs boson discovery
- **All main production modes**, ggF, VBF, **VH** and **ttH** have now been **observed**
- **First observation of Higgs boson decaying to b-quarks**
- **Direct confirmation** of coupling to all 3rd generation fermions: **top & beauty-quarks**, τ leptons
- **Double Higgs production** approaching 10 x SM
- Only analyzed <3% of the final LHC luminosity …**Just the beginning**



thank you!

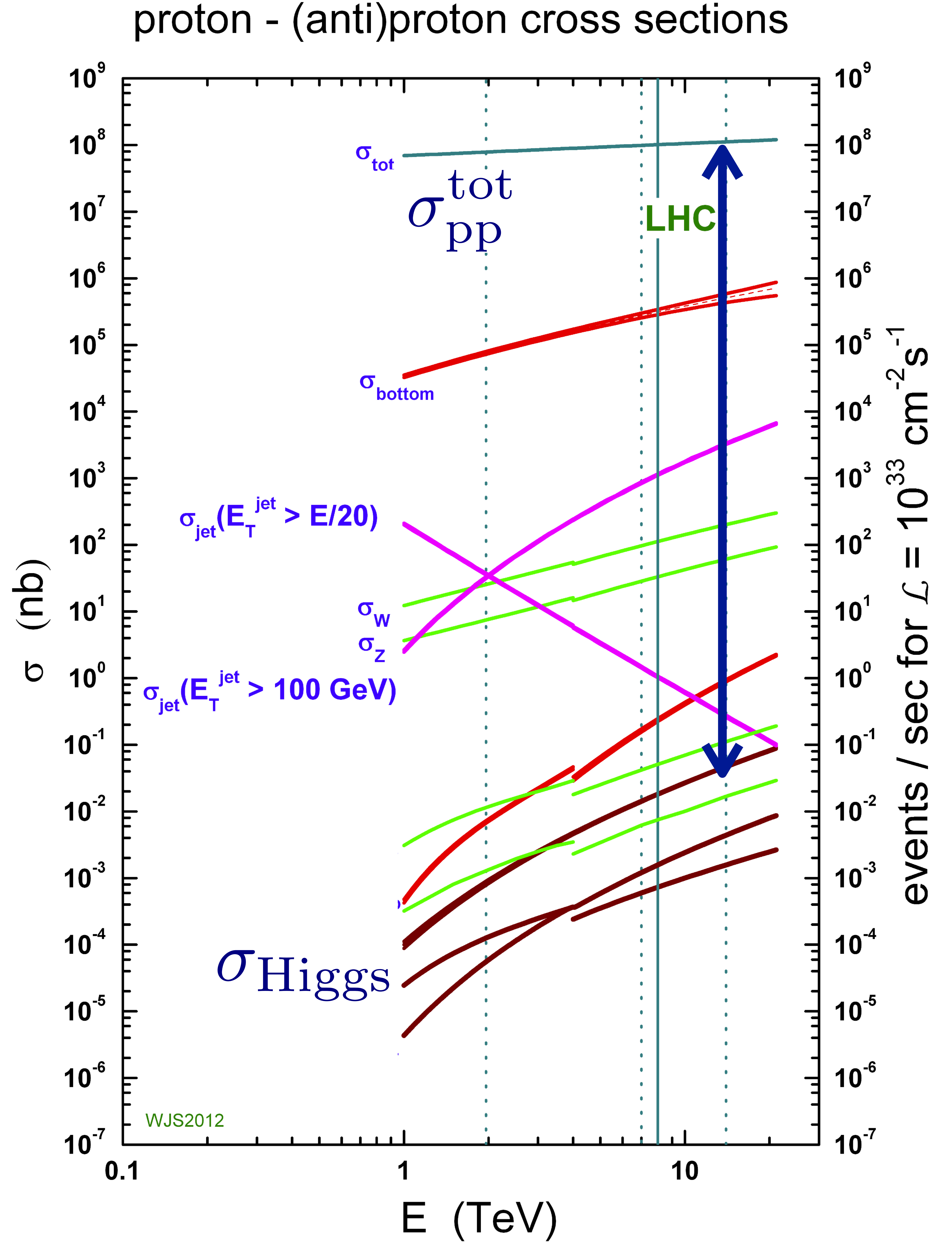
Cross section

- At the LHC in 2016 we had 7 x 10^8 pp inelastic interactions/sec

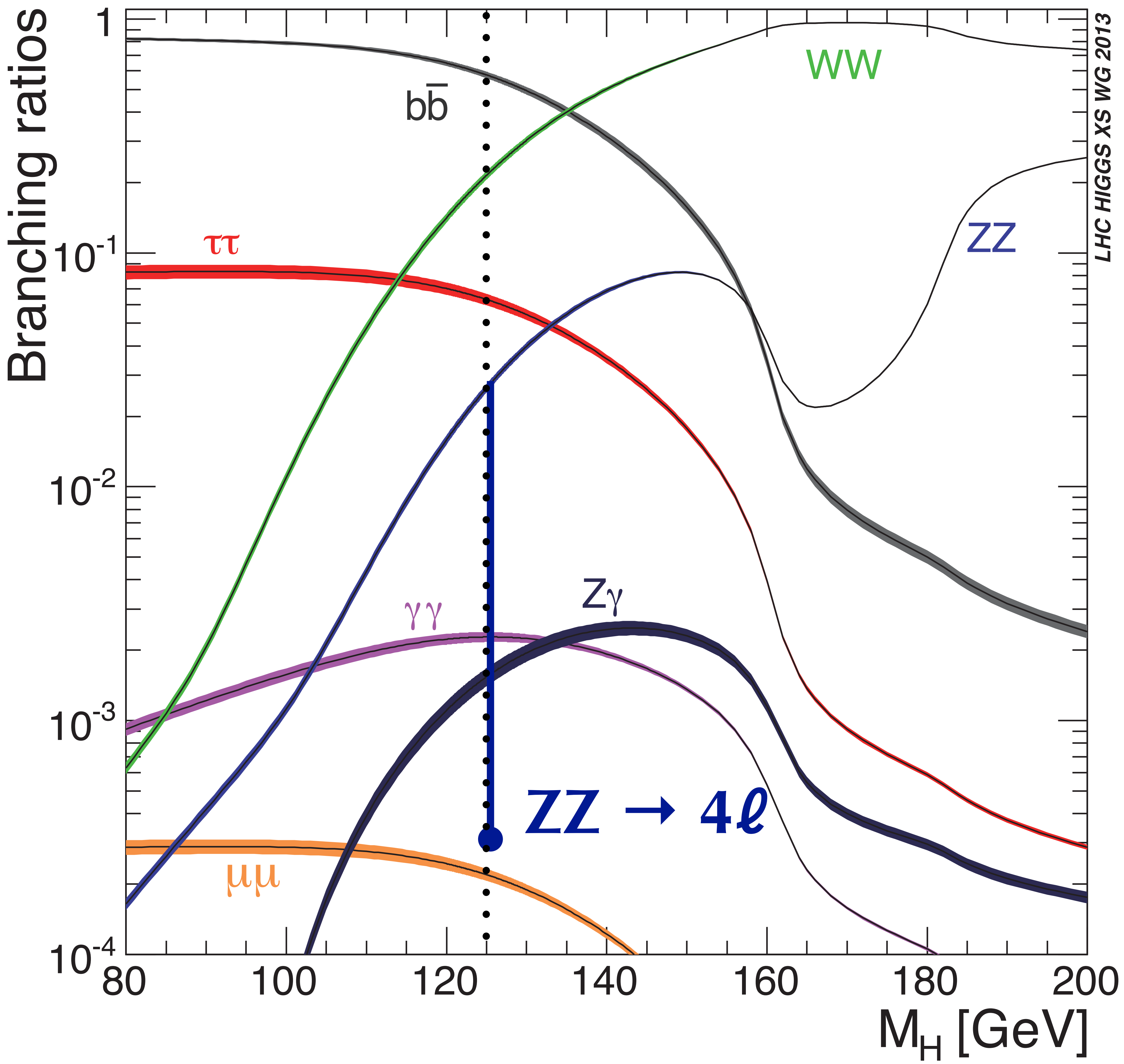
Only in one out of every one billion collisions a Higgs boson is produced

- We record a small selection of collisions (<0.01%)

  Storage and computing are limited



How does it Decay (m_H = 125 GeV) ?



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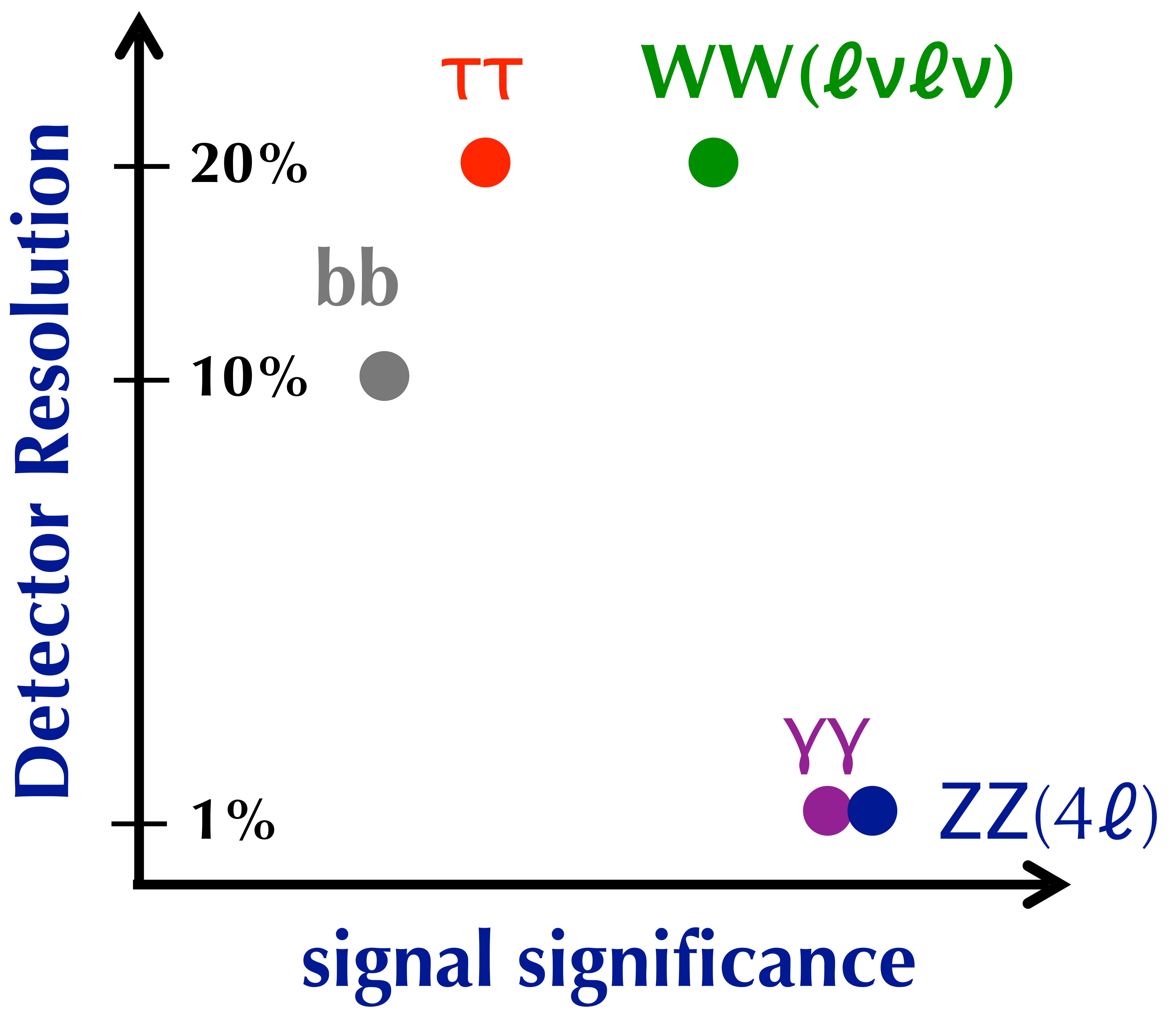

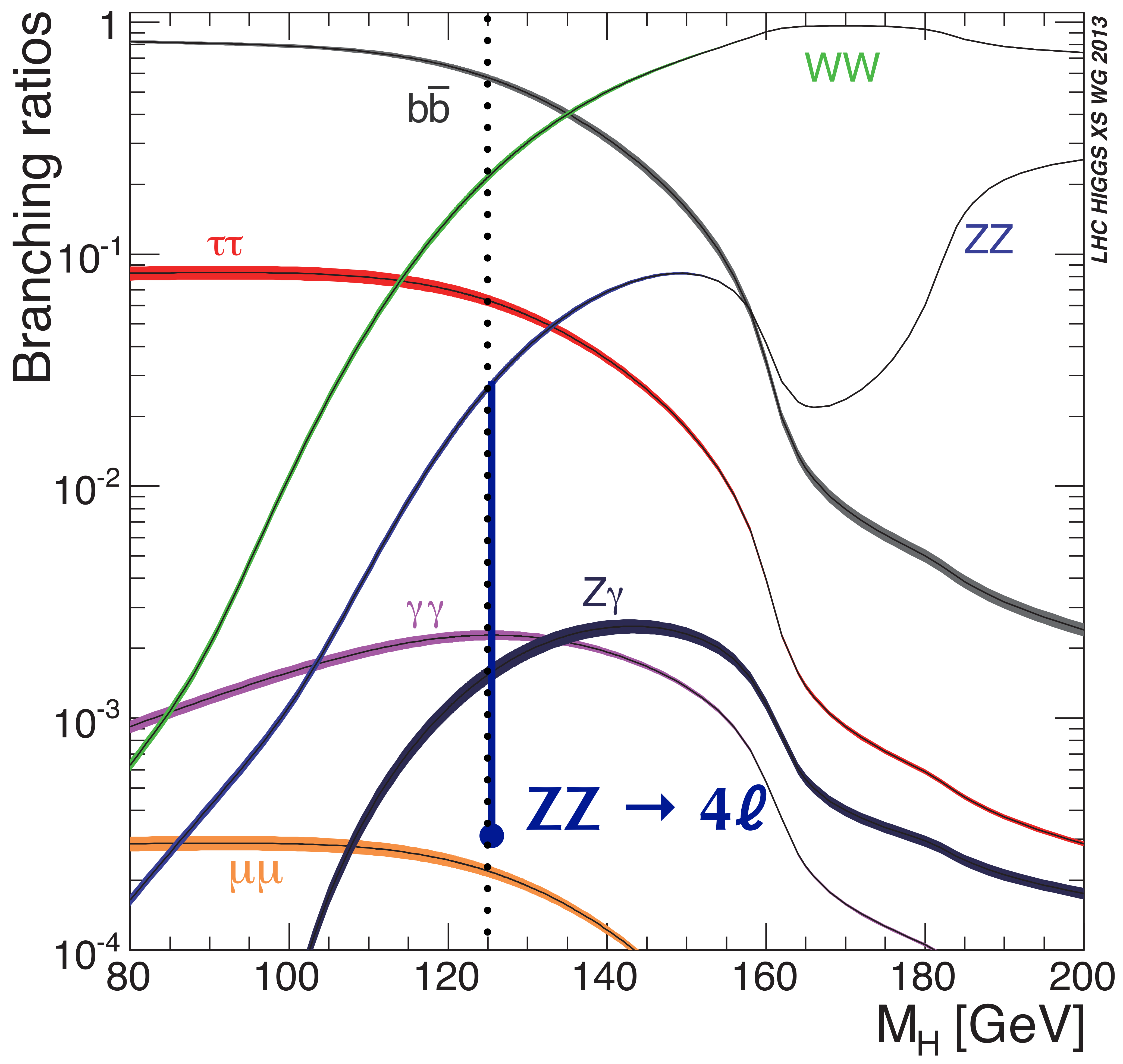

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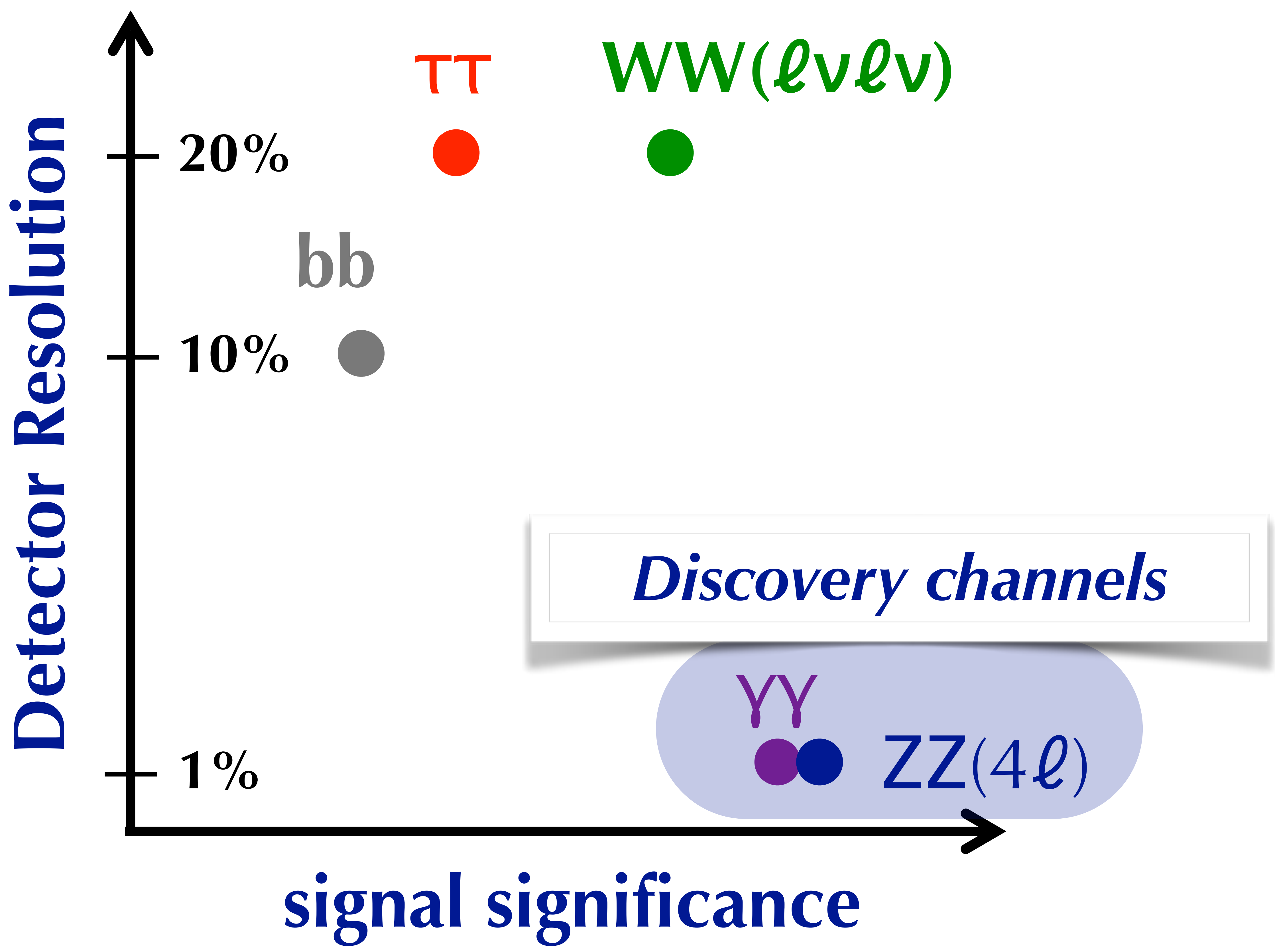
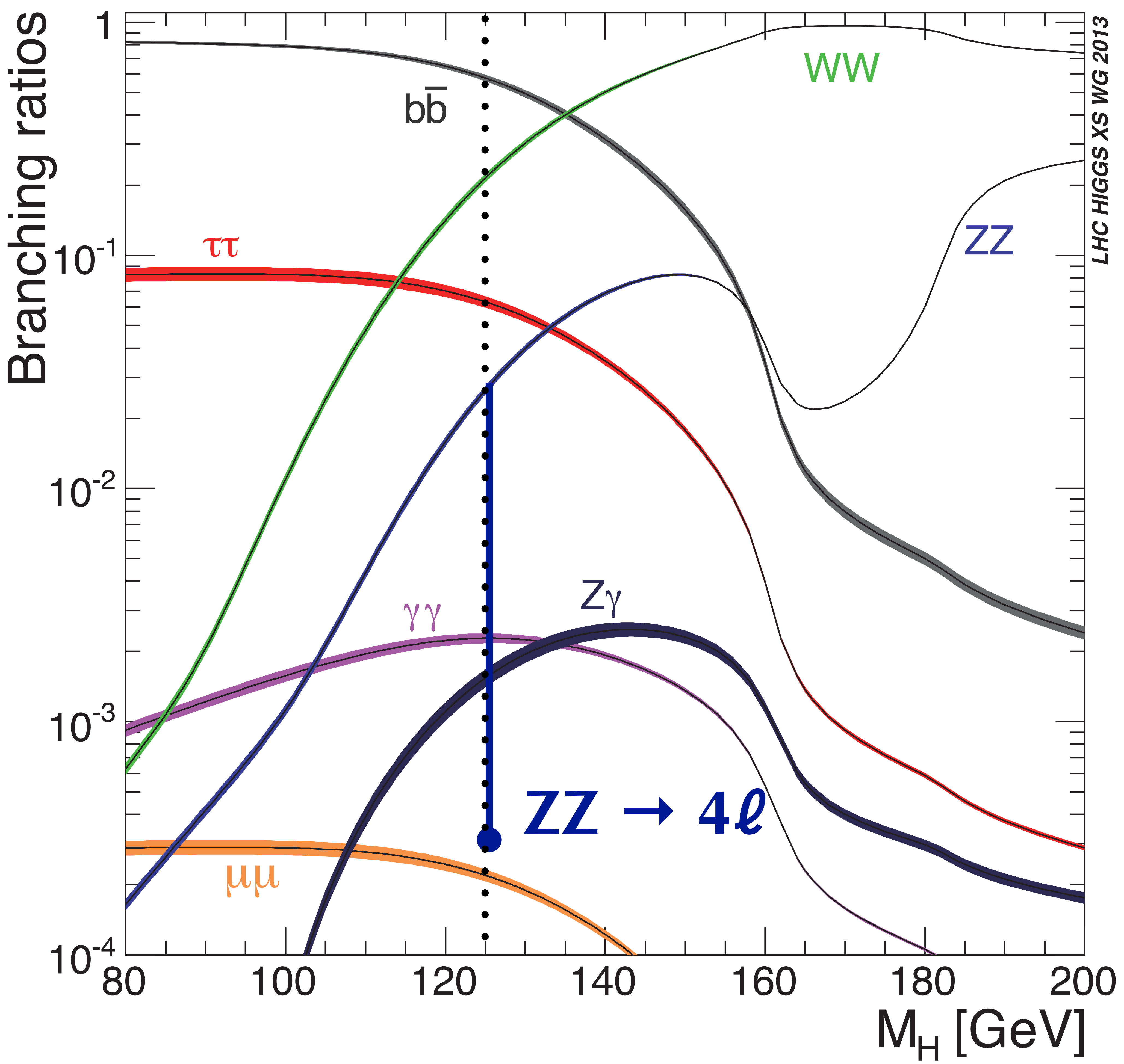
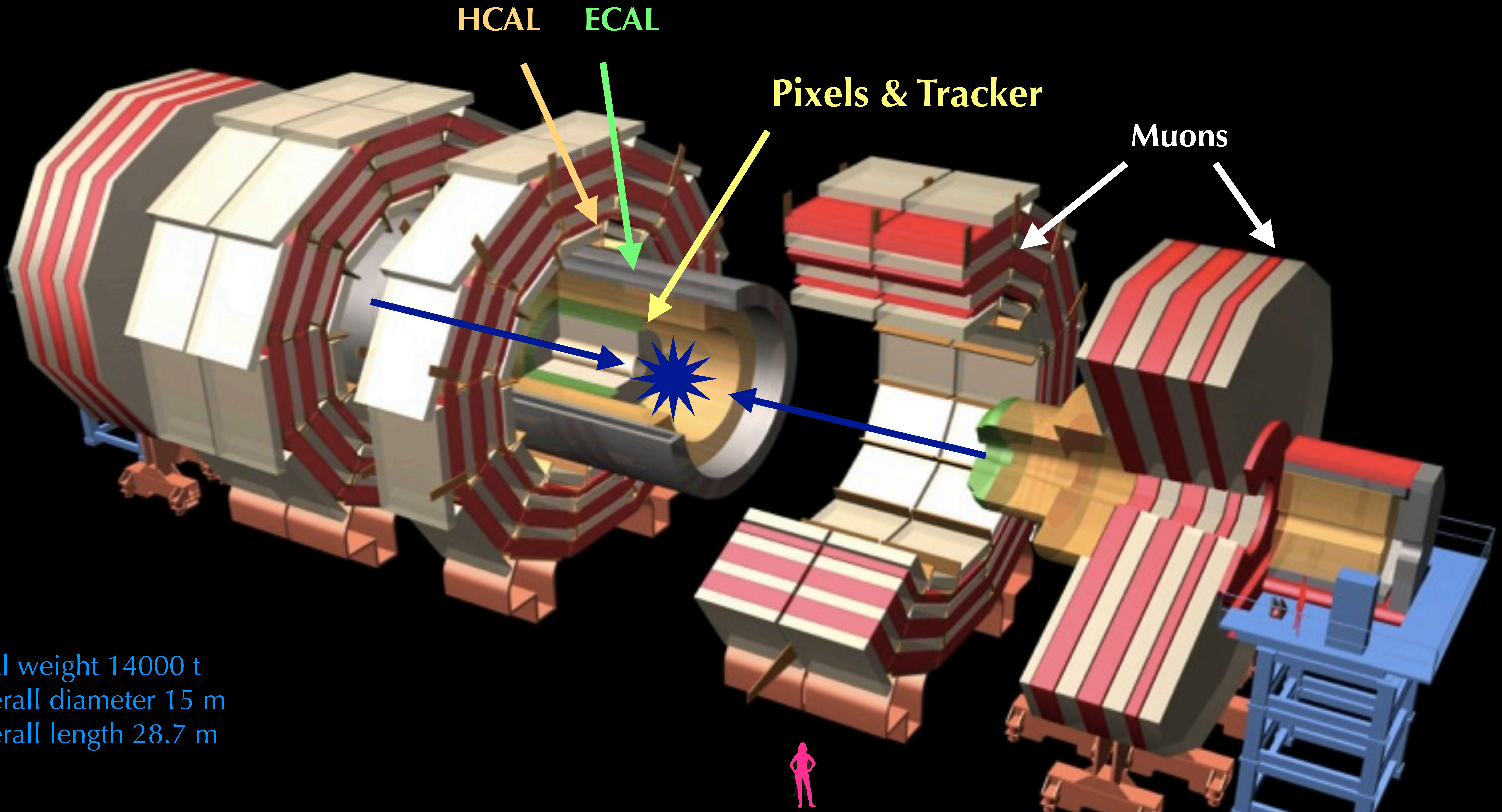




The Compact Muon Solenoid (CMS) experiment



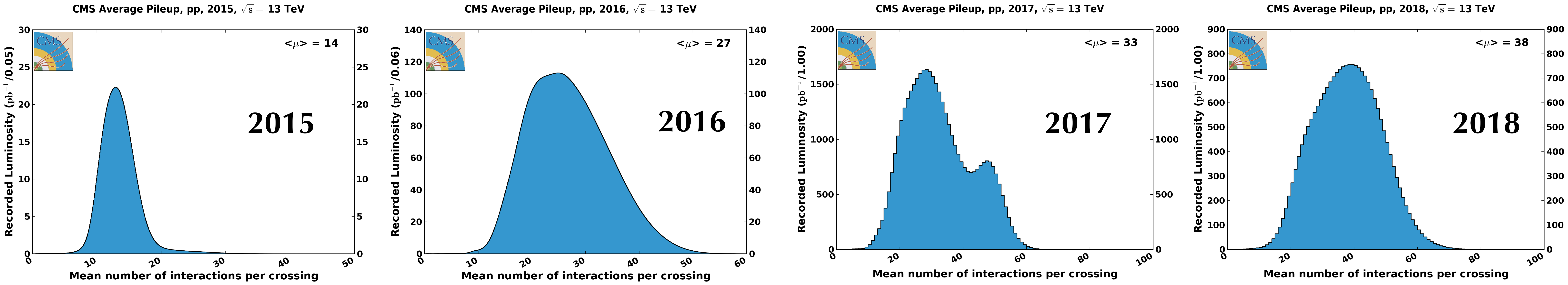
Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m

From the detector to physics objects


xyz coordinates
3 TeV
3 TeV
y
x

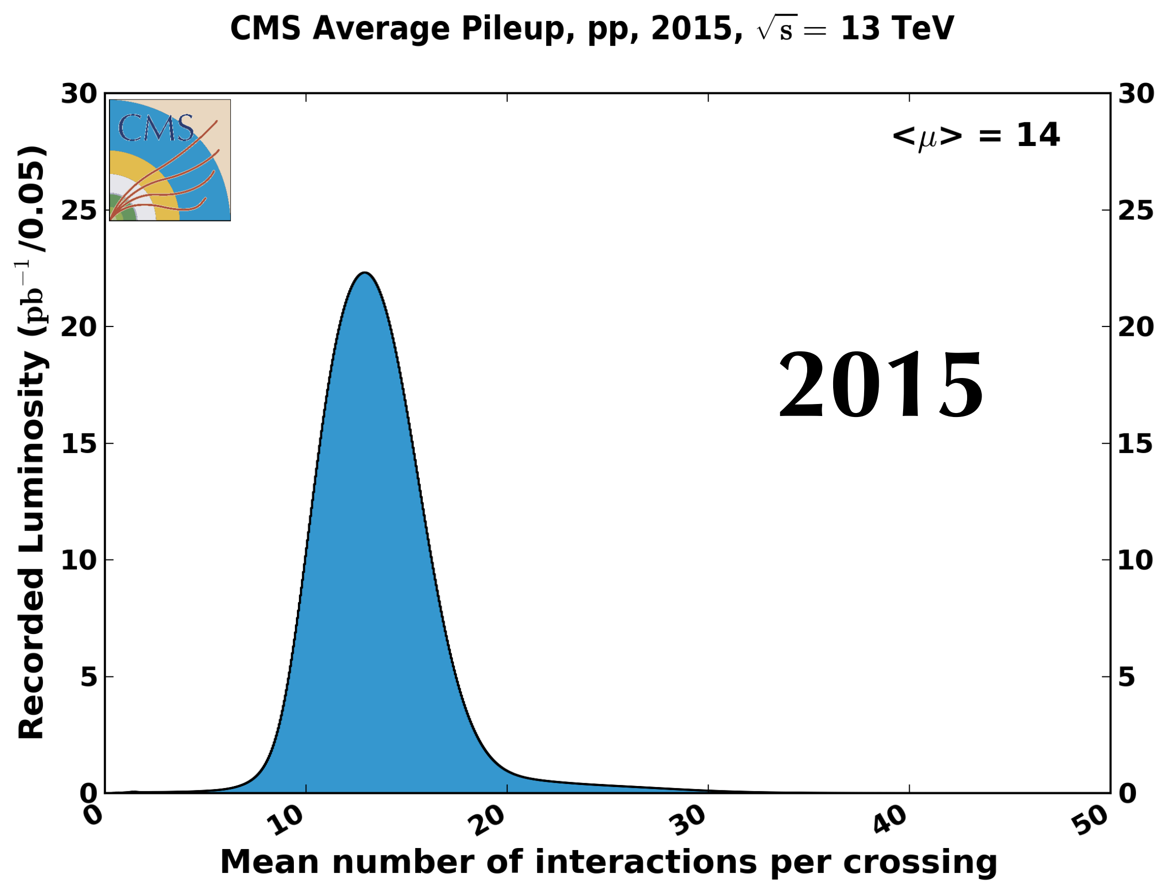
$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

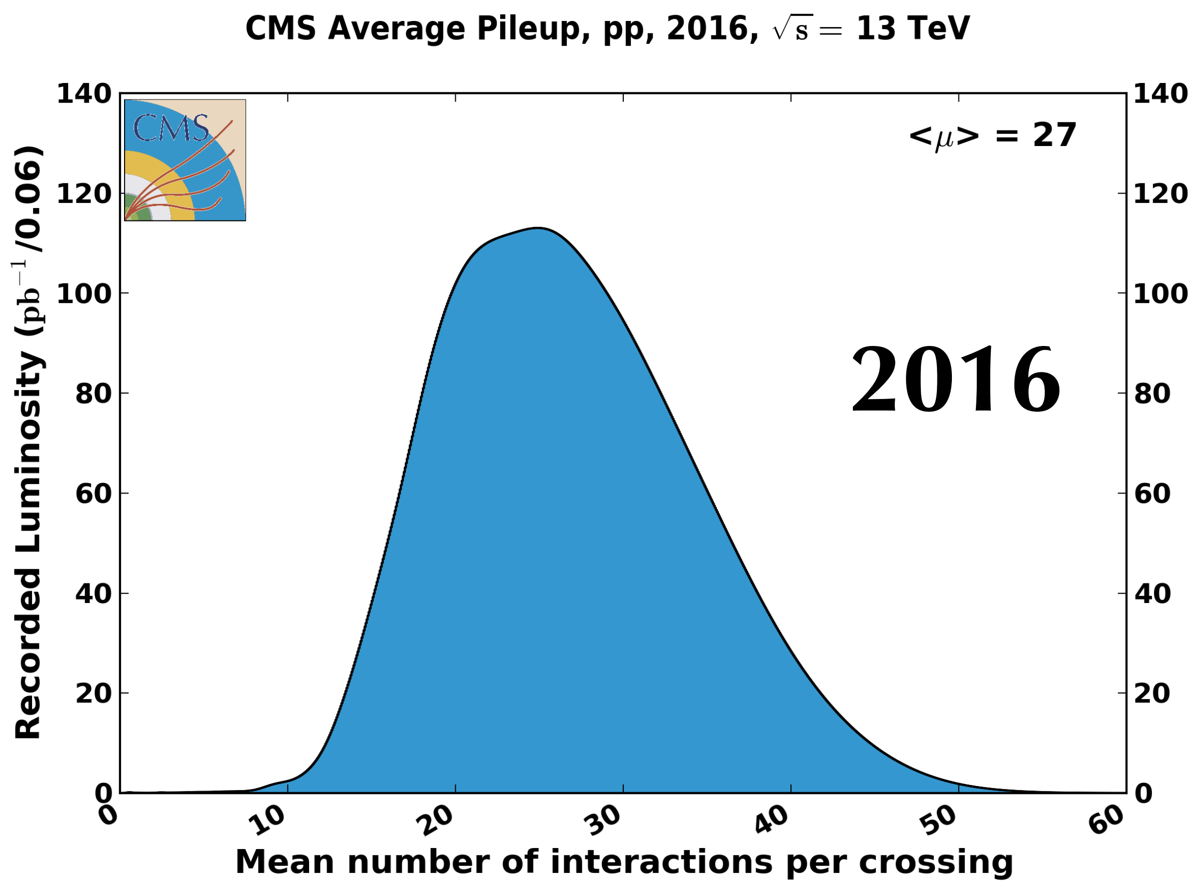
Pileup @LHC

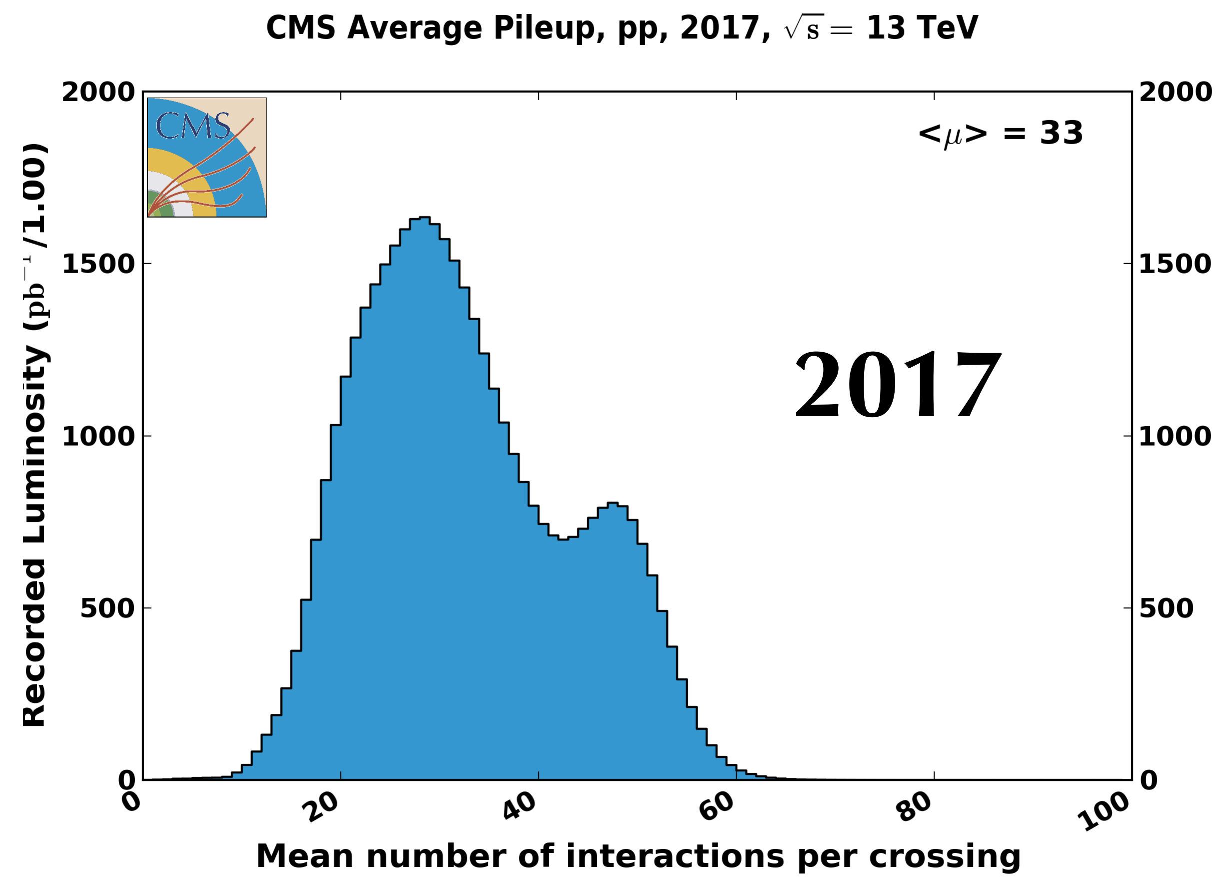


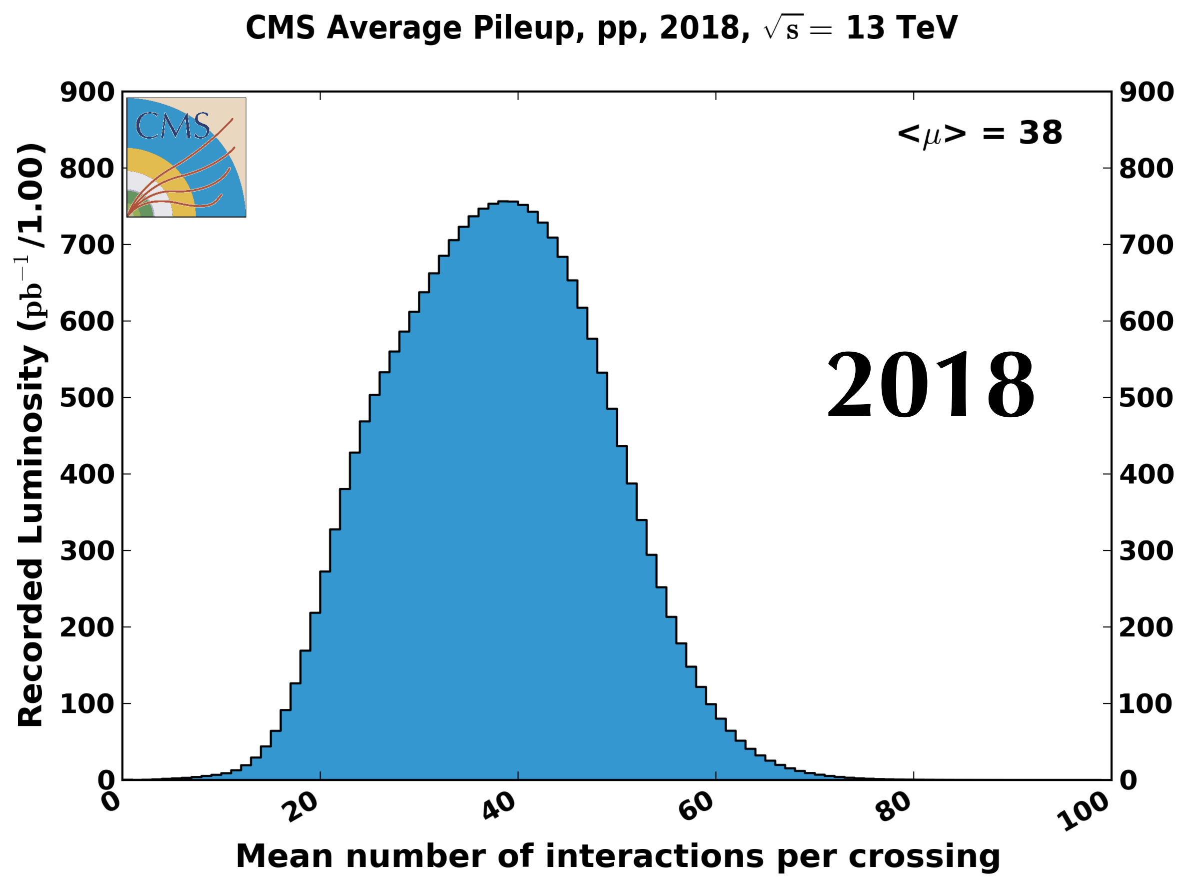
LHC during 2015-2018 on average ~15-40 pp interactions per bunch crossing

Pileup @LHC

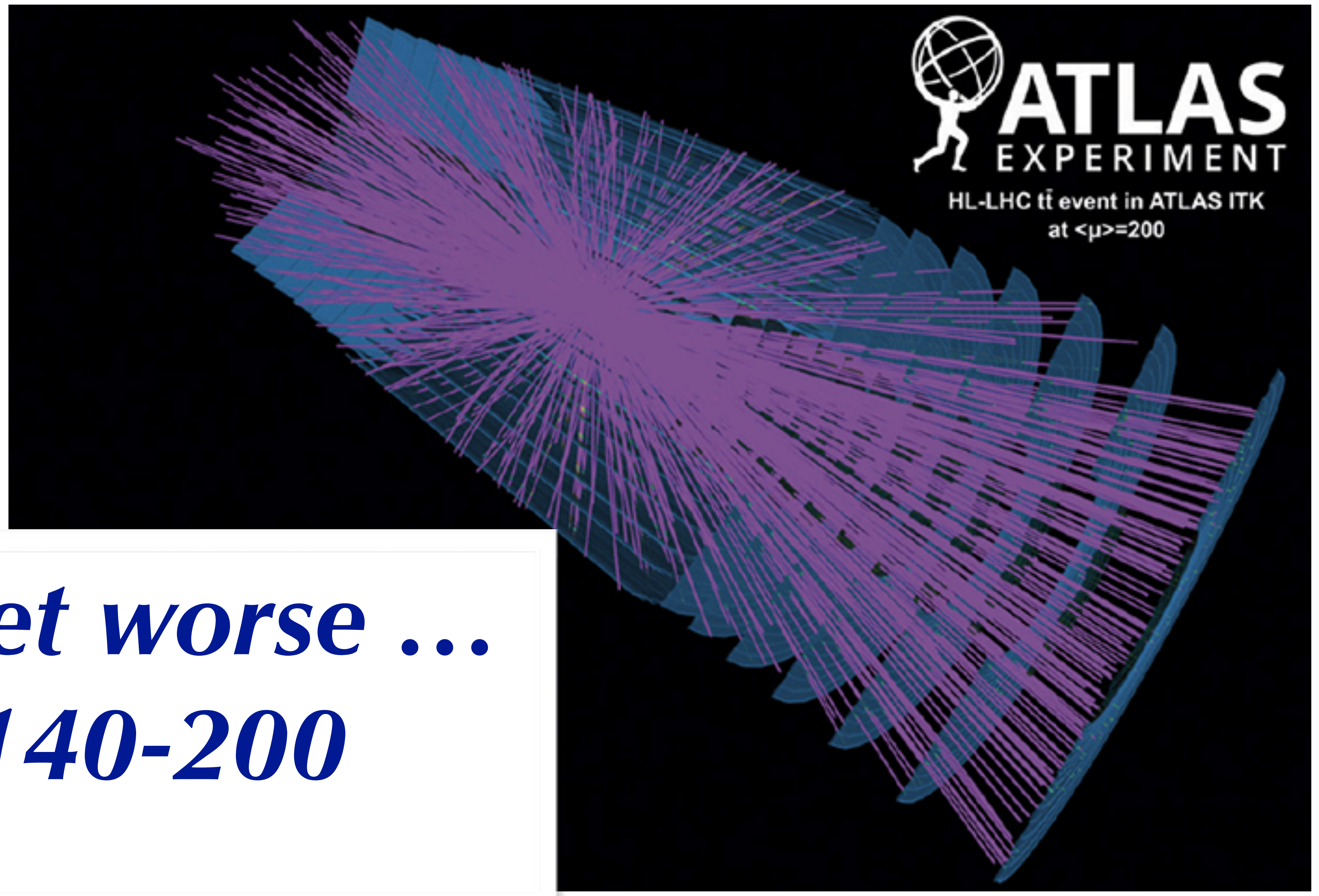






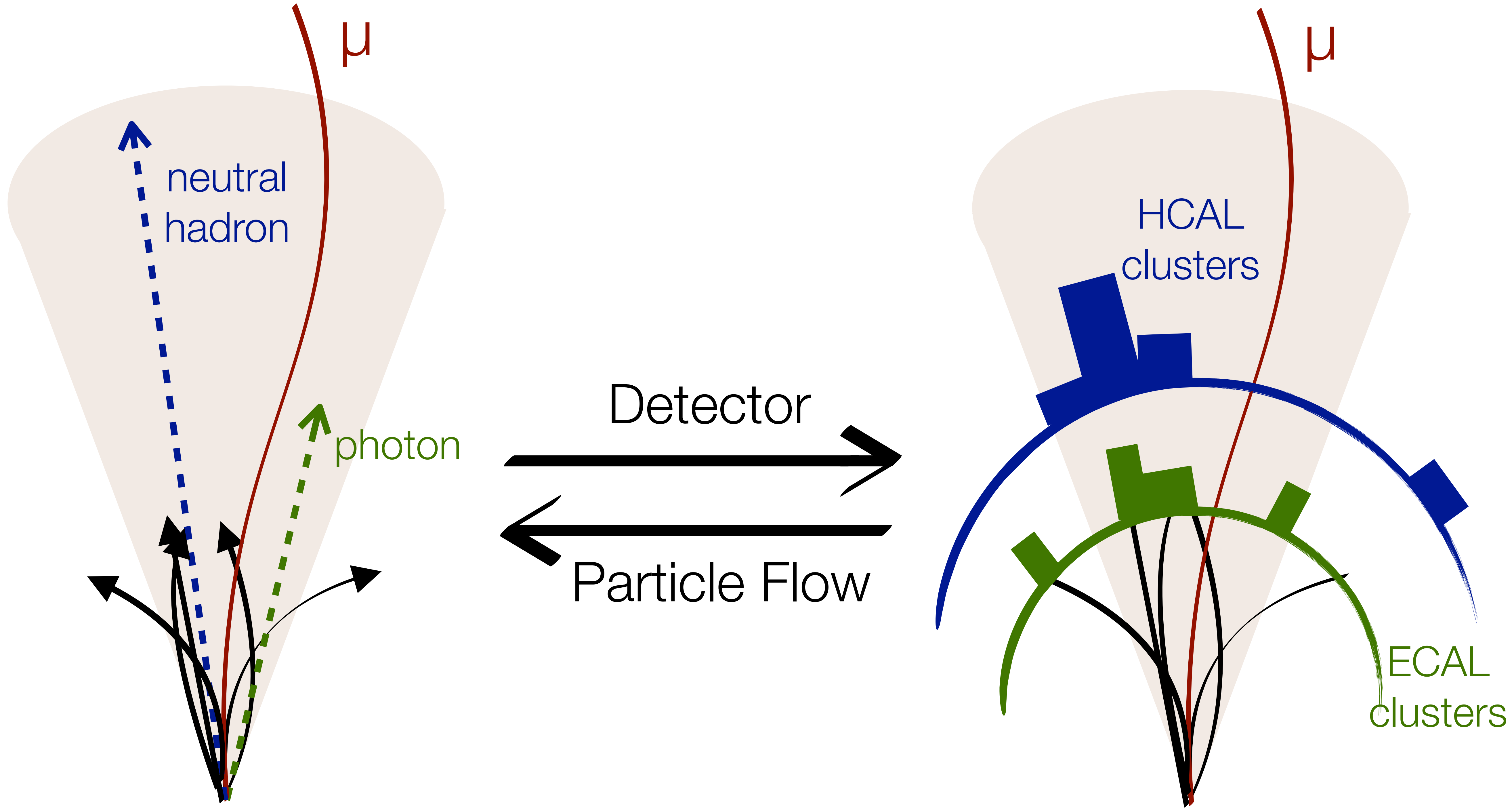


LHC during 2015-2018 on average ~15-40 pp interactions per bunch crossing



it will only get worse …
HL-LHC 140-200

Physics objects in CMS



Tracks
Calorimeter deposits

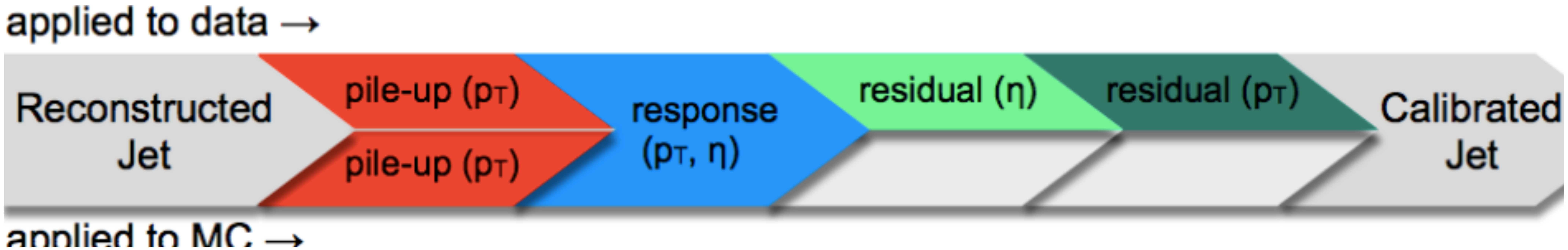
muons, electrons, photons,
neutral hadrons, charged hadrons

↓

muons, electrons, photons, taus, **jets**, E_T^{Miss}

- Quark and gluon ***fragment*** into stable particles resulting in narrow cone of hadrons, a ***jet***
- About 90% of the jet energy is carried by **charged hadrons** (**65%**) and **photons** (**25%**)

Jet Calibrations

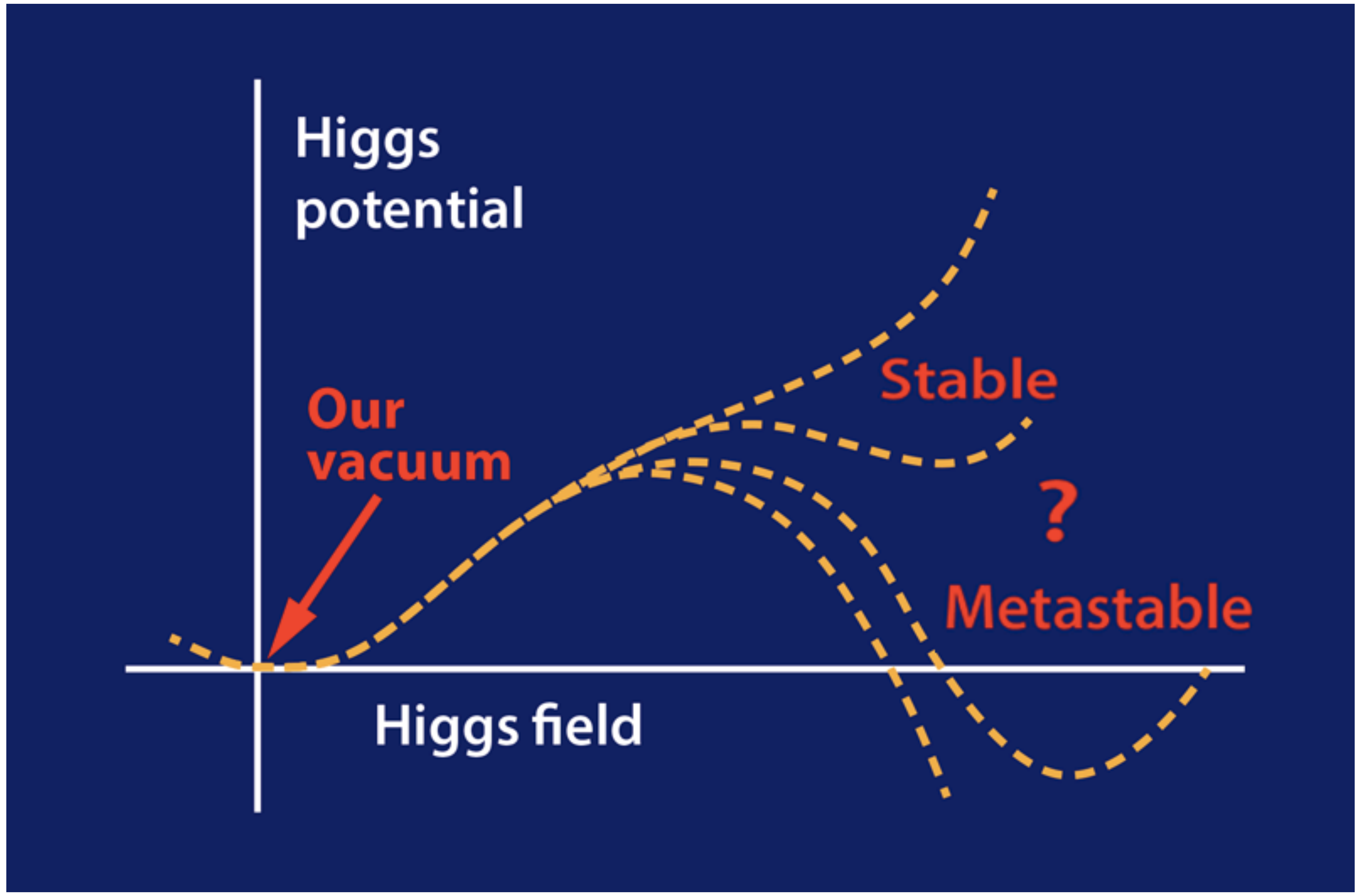


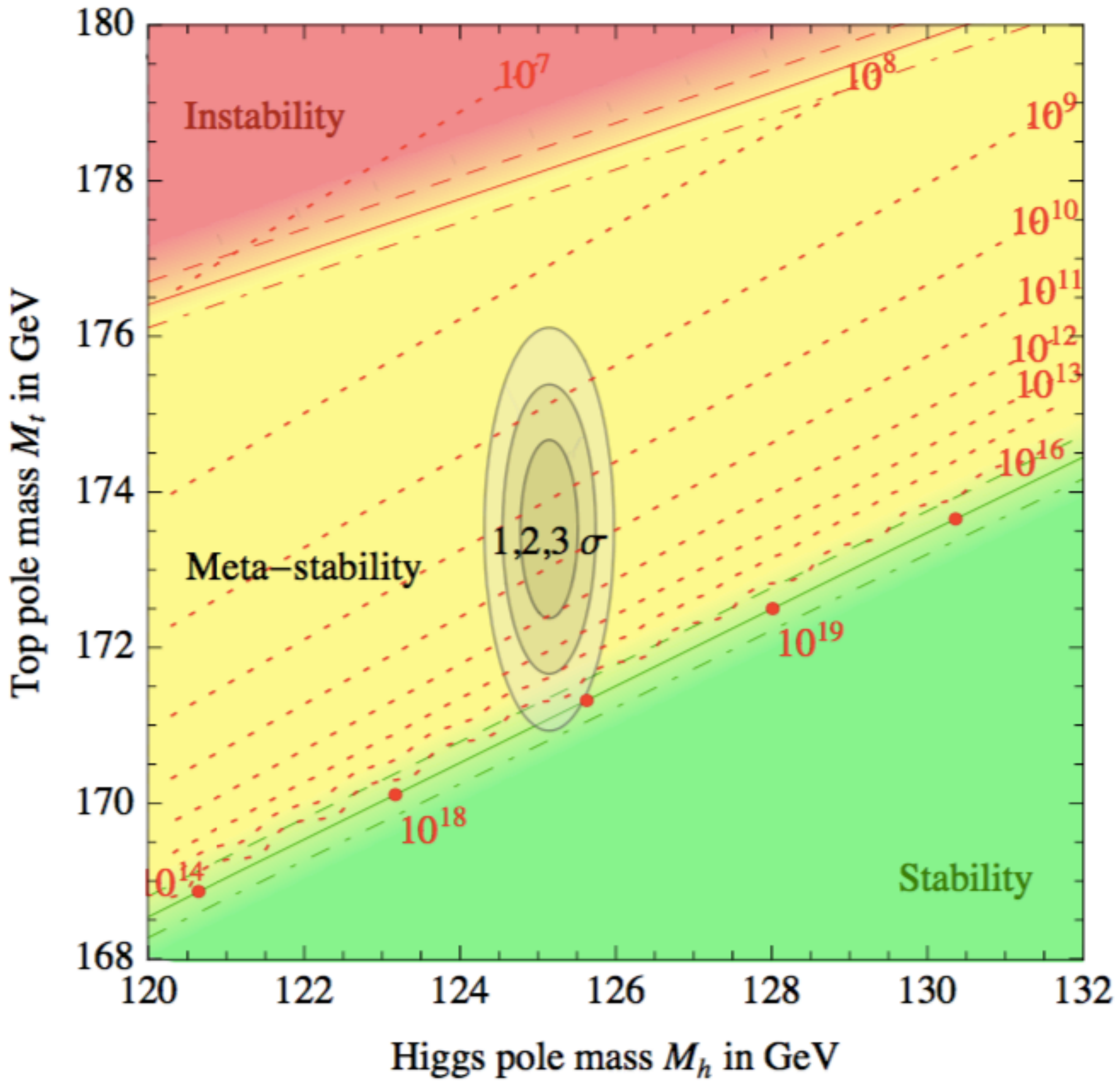
- Jet Calibration aims to give absolute energy measurement, correcting for all detector effects
- Multiple levels of corrections:
  - offset for pile-up and electronic noise
  - detector calibration and reconstruction efficiency
  - Data vs MC relative residual corrections for η
  - Data vs MC absolute residual corrections for p_T

Higgs vacuum

If SM ~ valid up to M_{Planck} then our vacuum metastable

- deeper implications?
  new particles and interactions could contribute to the scalar potential



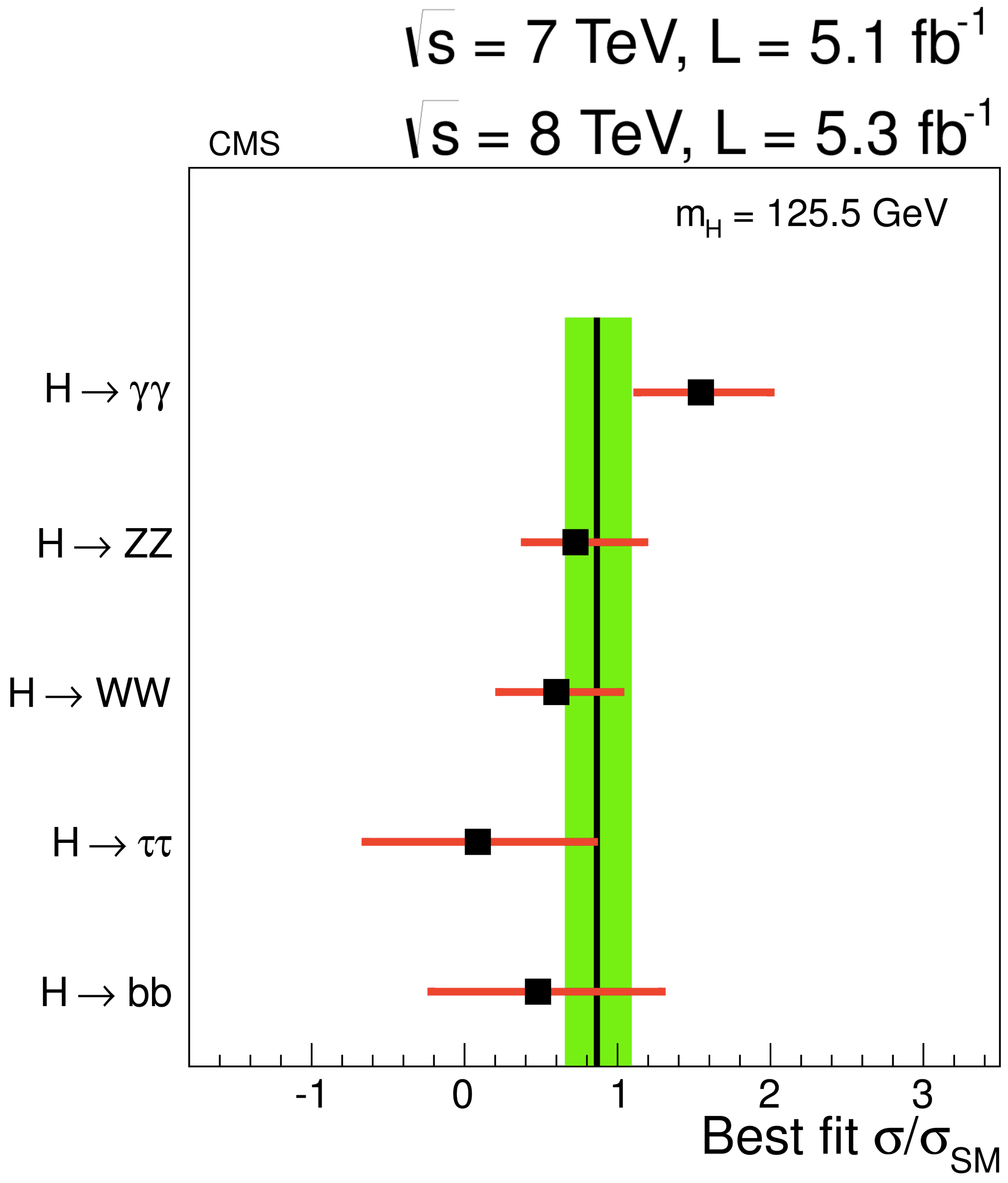


A more precise knowledge of the top-quark mass, the strong coupling constant …
will be needed to shed light on the issue

July 4th 2012, Higgs Boson discovery

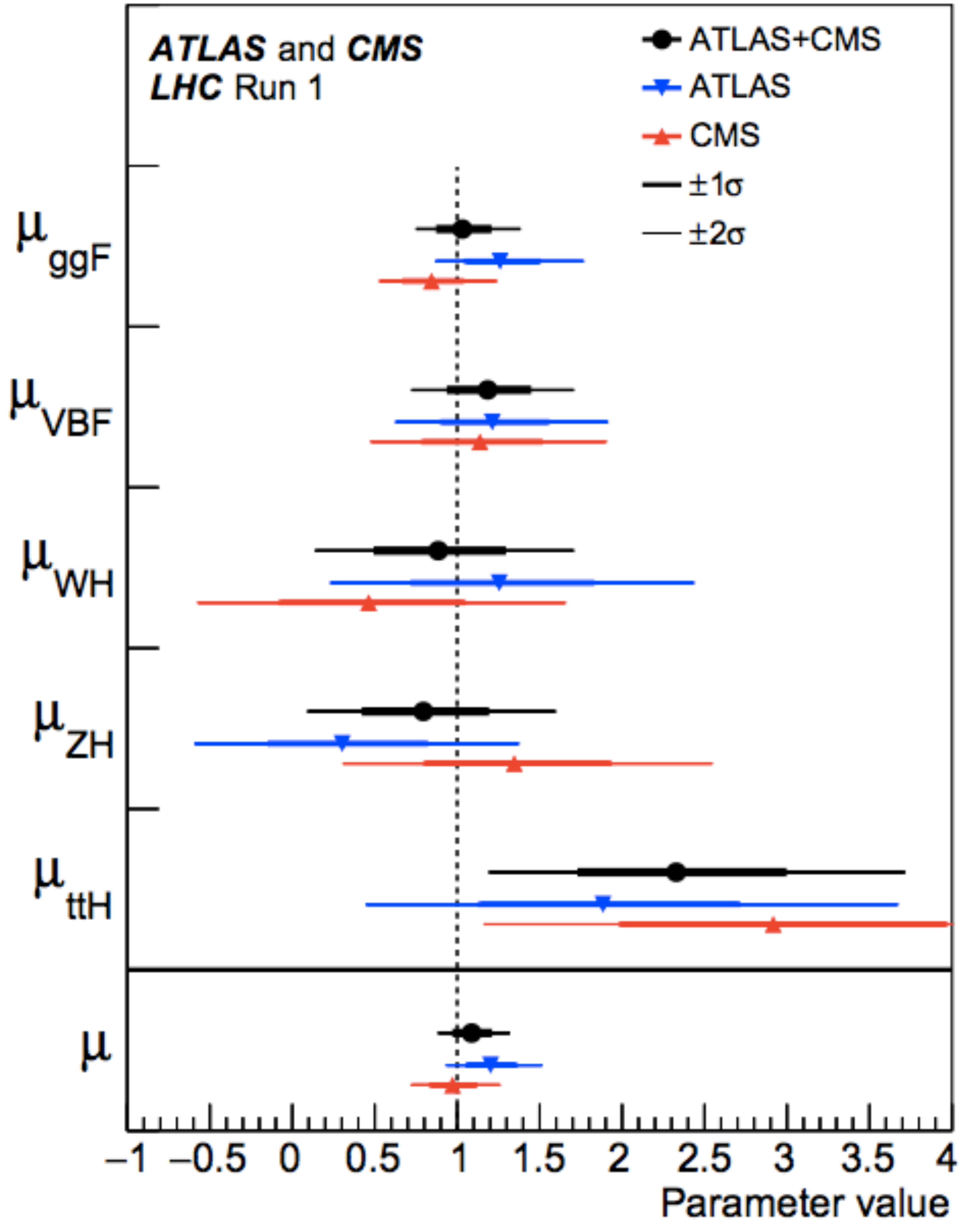
CMS and ATLAS reported independently the **first observation** of the Higgs boson

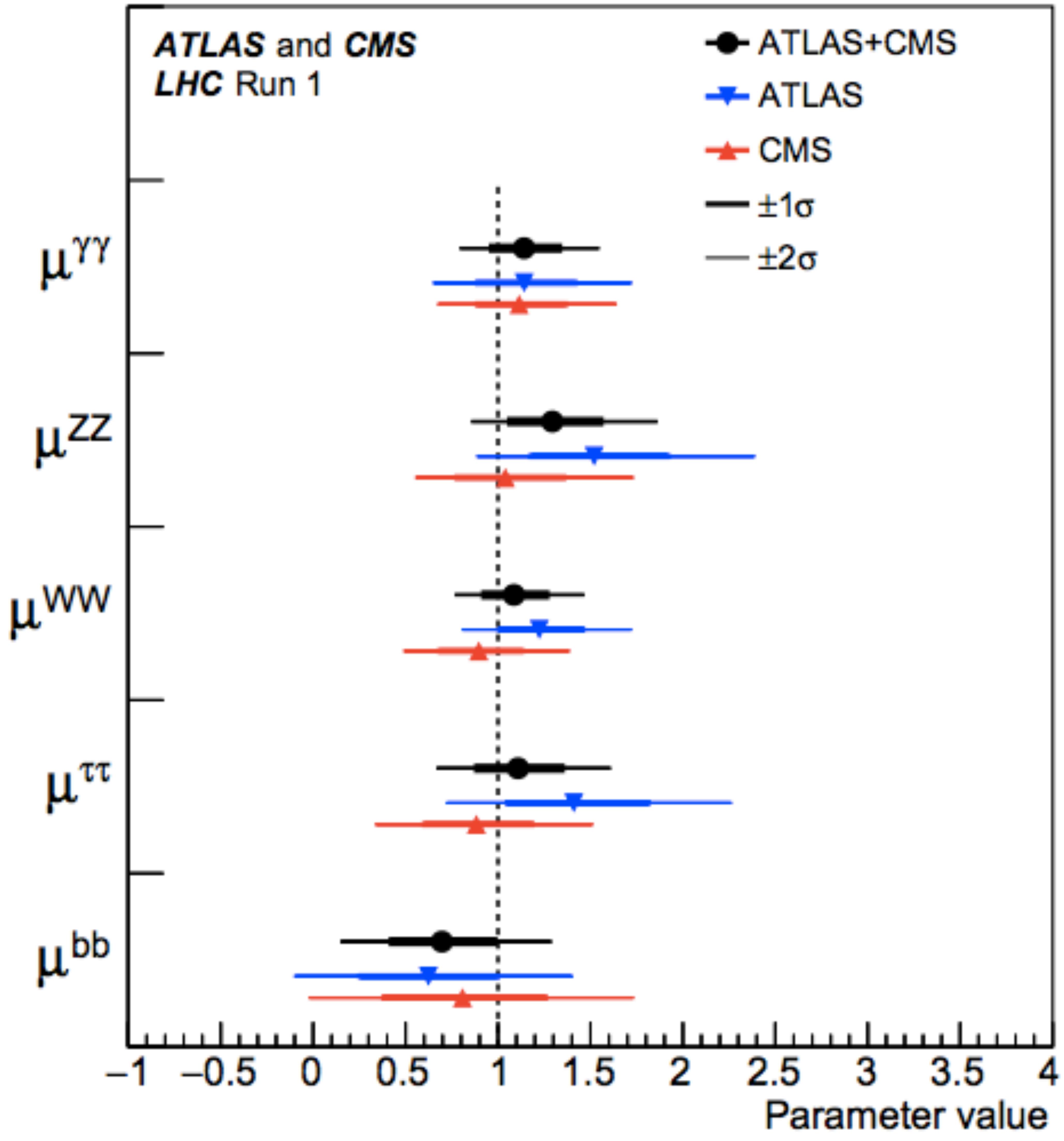
- **5.0σ combining γγ and ZZ alone**
  - **best mass resolution**
  - thanks to the huge amount of LHC data we could exploit the lowest BR decay modes



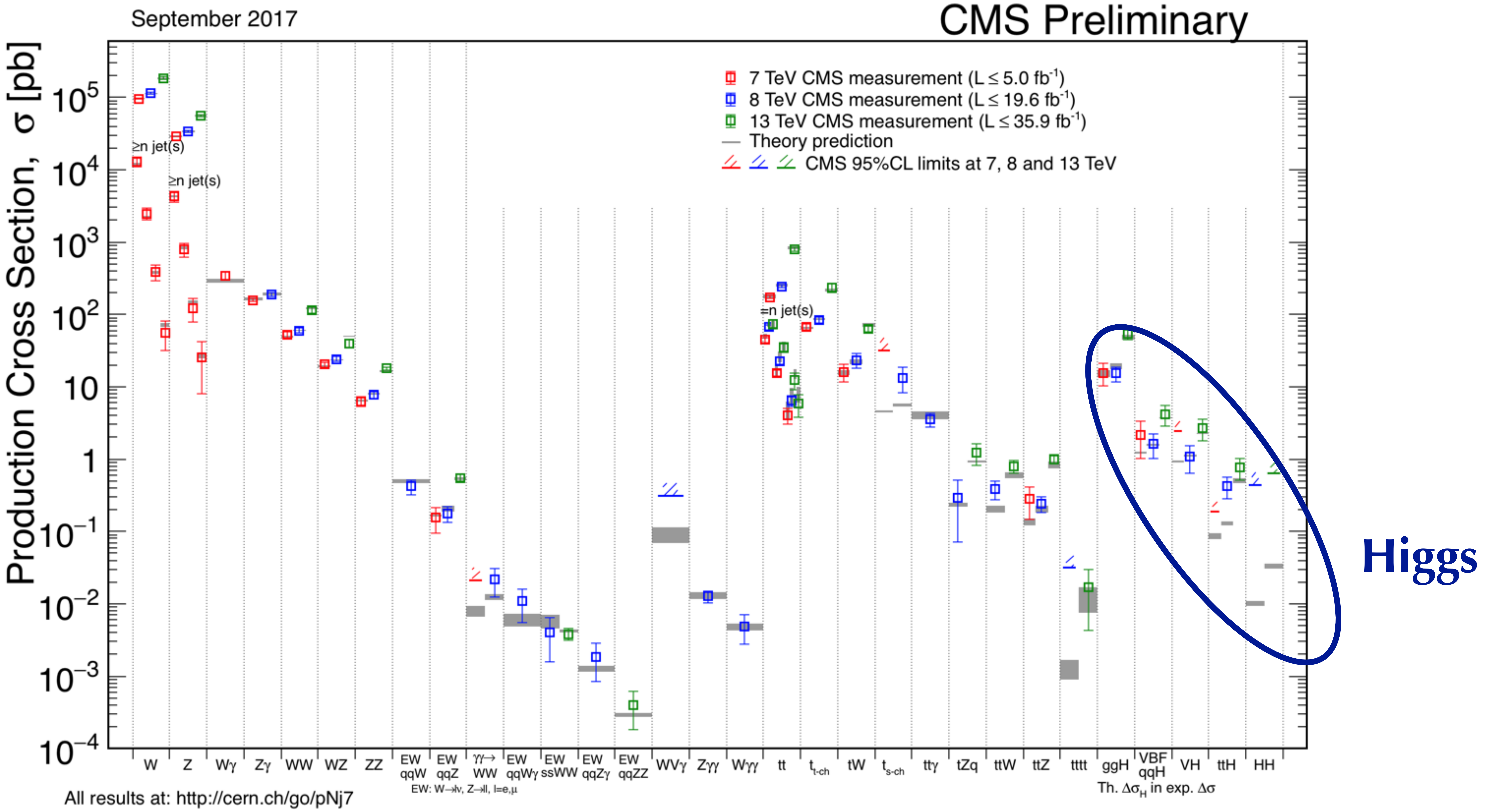
JHEP08(2016)045

Higgs at LHC, Run 1 Legacy



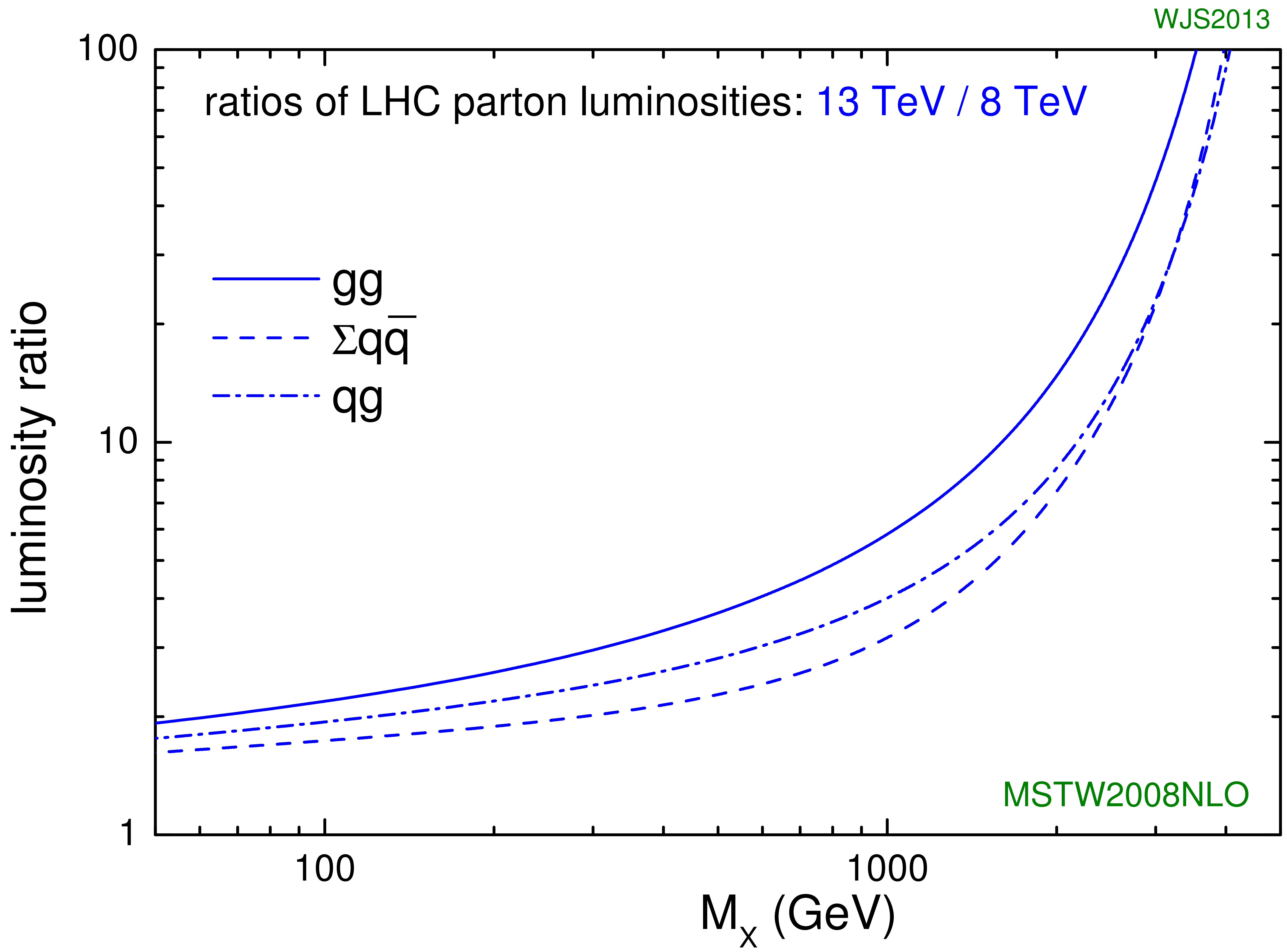


Our understanding of the Standard Model



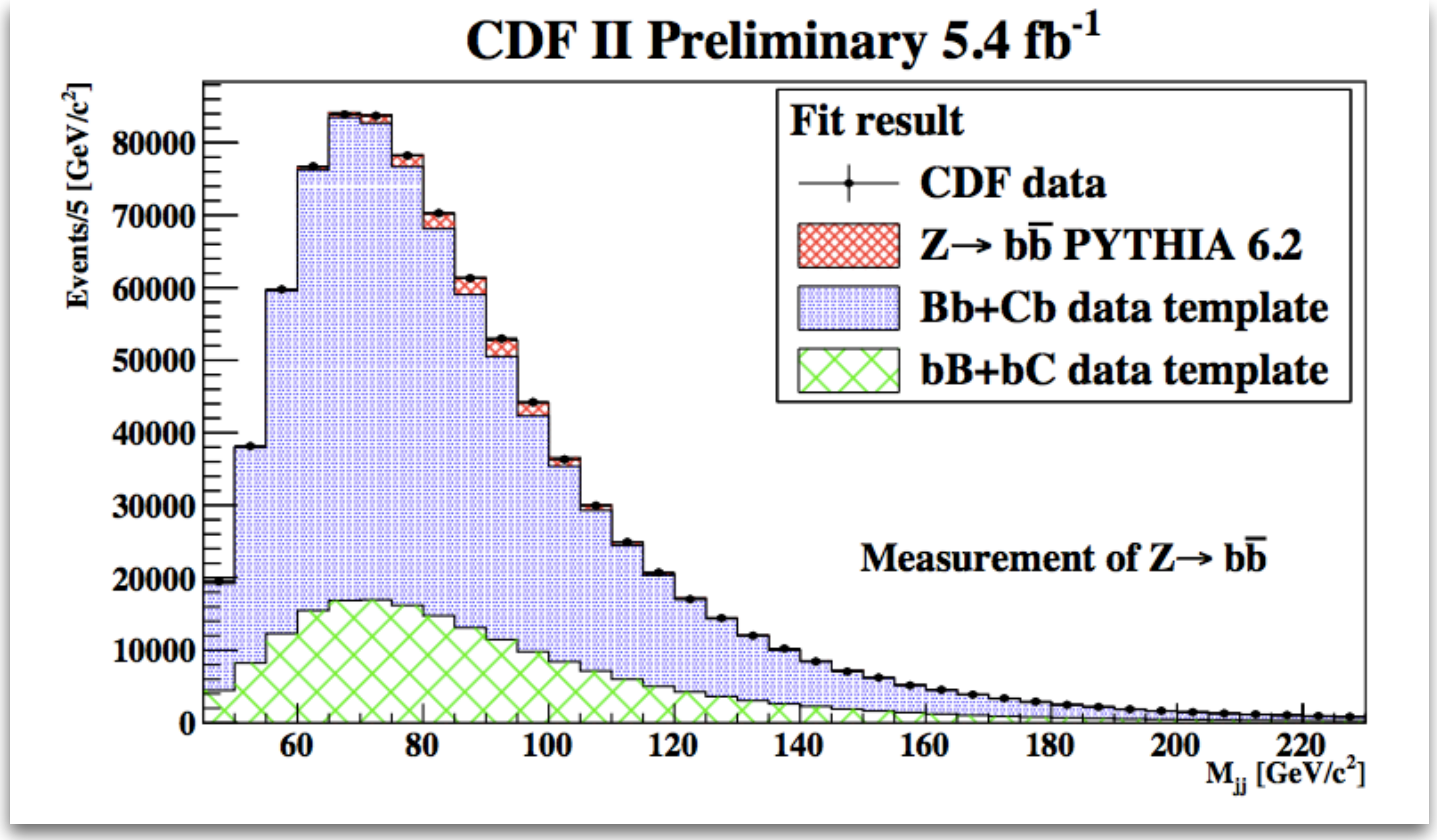
From Run I to Run II

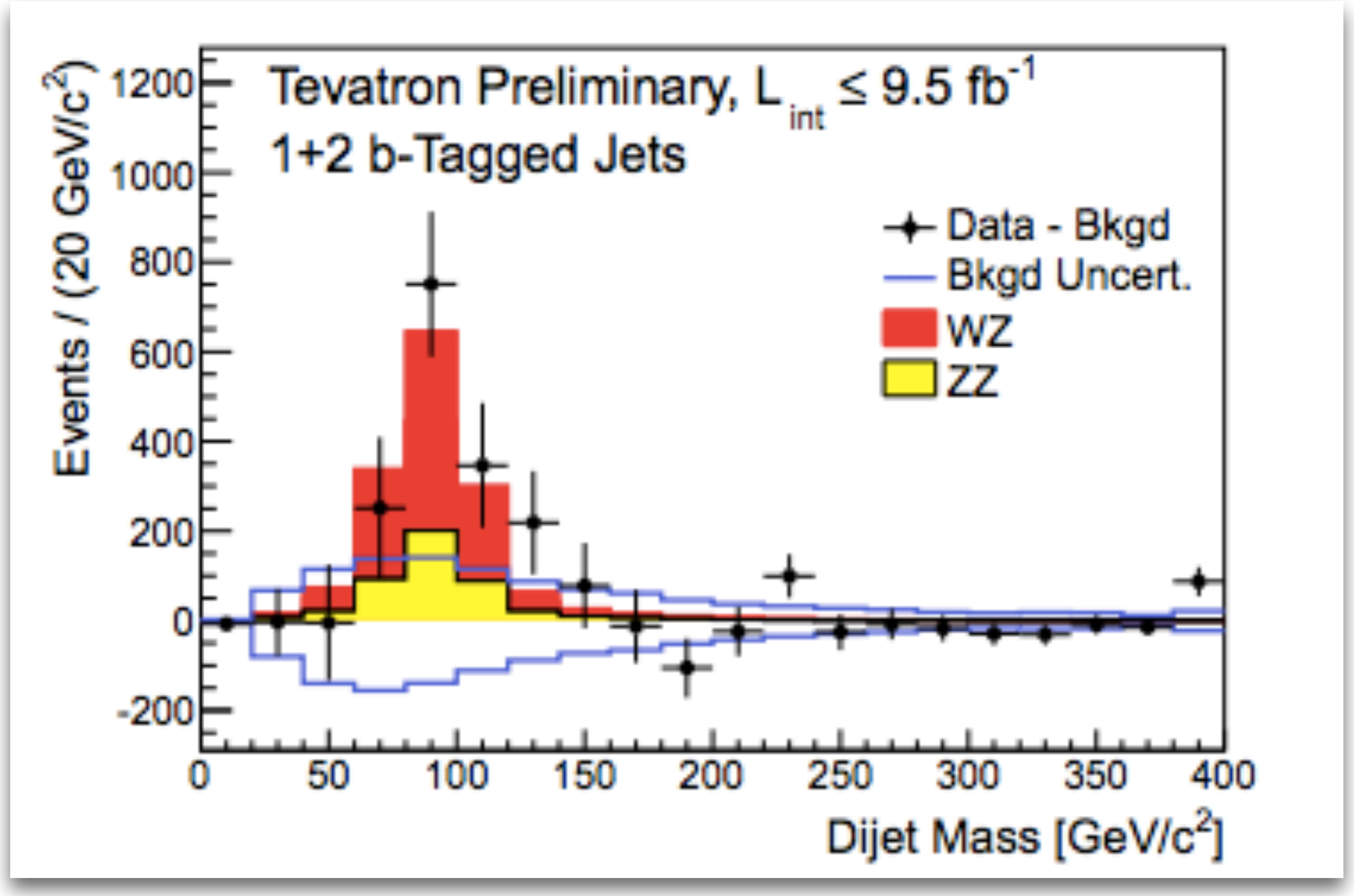
	√s =8 TeV	√s =13 TeV	13/8 TeV
ggH	19.4pb	44.1pb	2.27
VBF	1.6pb	3.8pb	2.38
VH	1.23	2.26 pb	1.84
ttH	133fb	507fb	3.81
tt	253pb	832pb	3.29



Z(b$\bar{b}$) measurements

- **ATLAS** Z(b$\bar{b}$)+ jets cross section measurement at 8 TeV Phys. Lett. B 738 (2014)
- **CDF** Z(b$\bar{b}$)+ jets cross section measurement CDF-11228
- **Tevatron**: 4.6σ evidence for VZ(b$\bar{b}$) at hadron collider Phys. Rev. Lett. 109 (2012)
- **CMS**: First VZ(b$\bar{b}$) 6σ observation at hadron collider Eur. Phys. J. C 74 (2014)

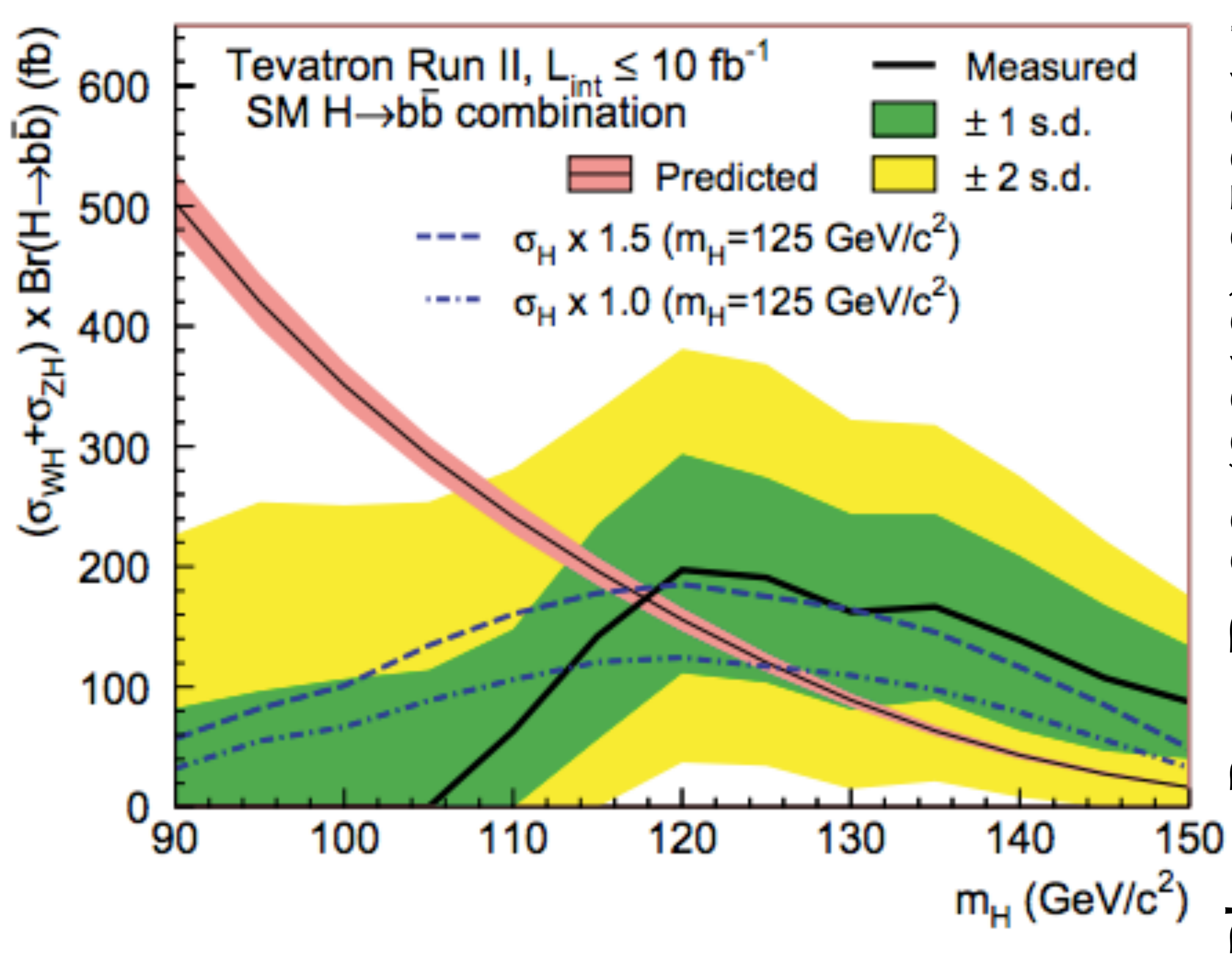




$H(b\bar{b})$ at Tevatron

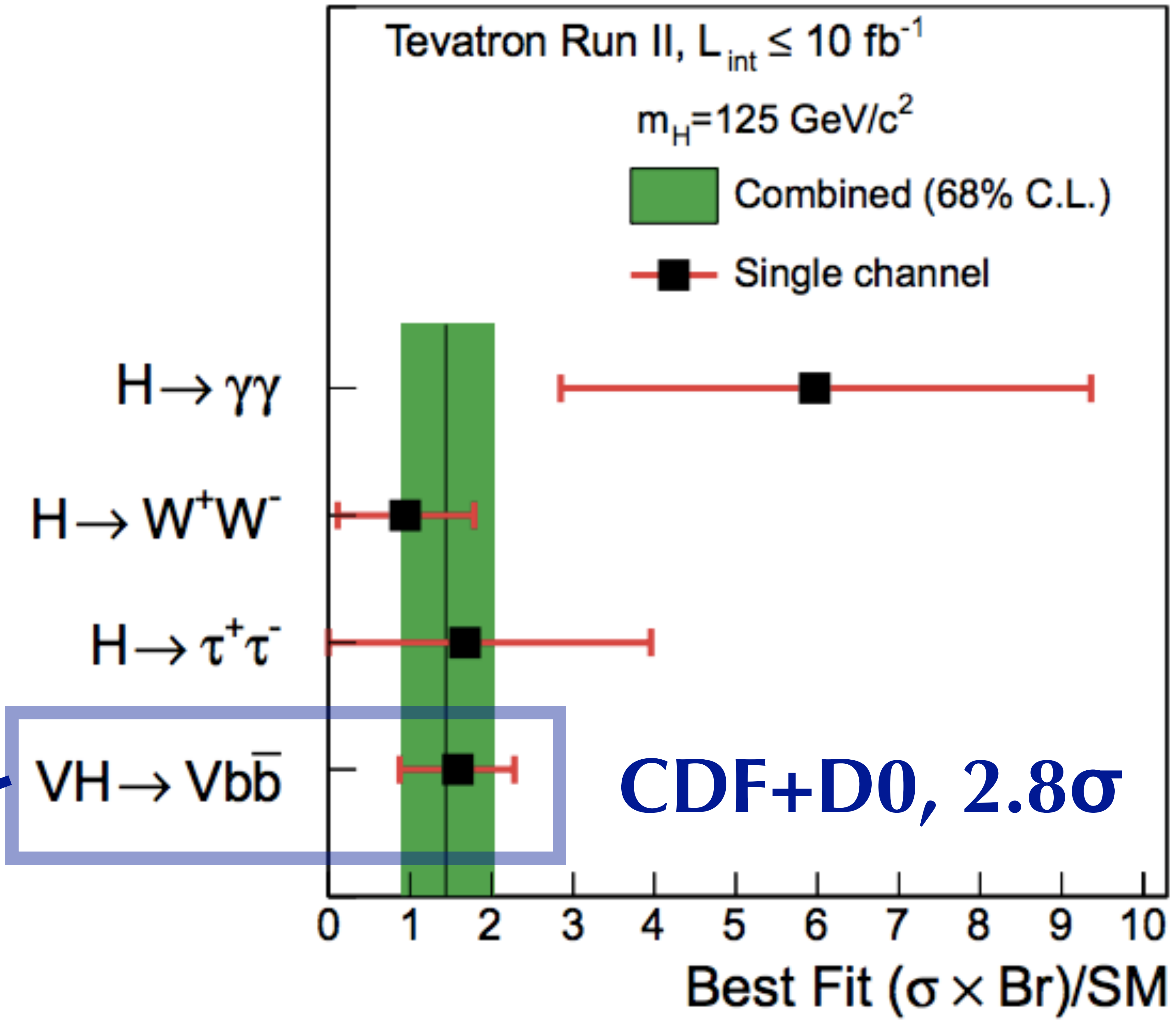
CDF and D0 combined results reported a broad excess in the mass range $115<m_H<140$ GeV

- 3.0 σ at m_H=125 GeV
- **mainly from the $H \to b\bar{b}$**



Phys Rev D 88 (2013) 052014

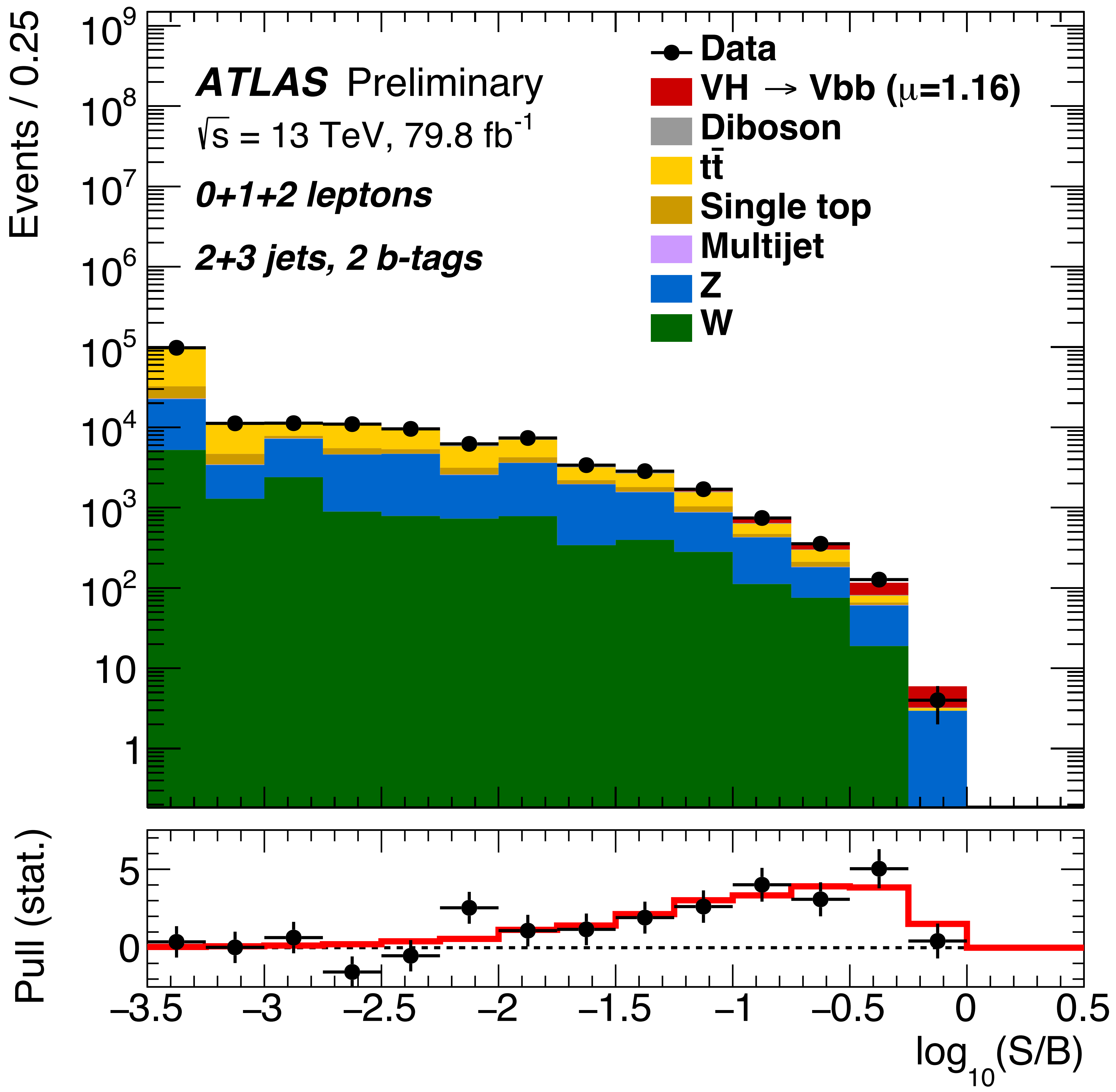
2.8 σ obs (1.5 σ exp)

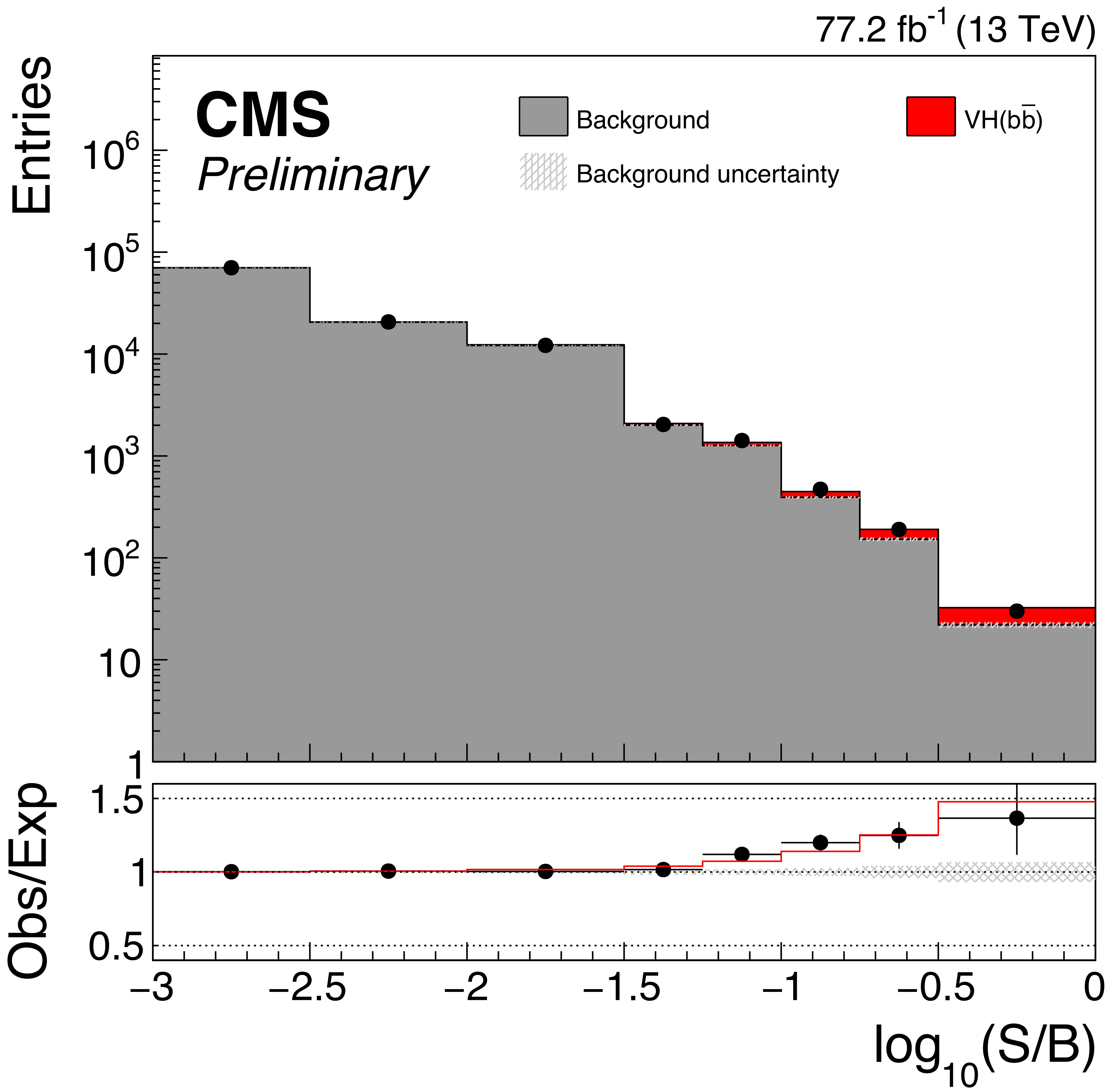


Phys. Rev. Lett. 109 (2012)

CDF+D0, 2.8σ

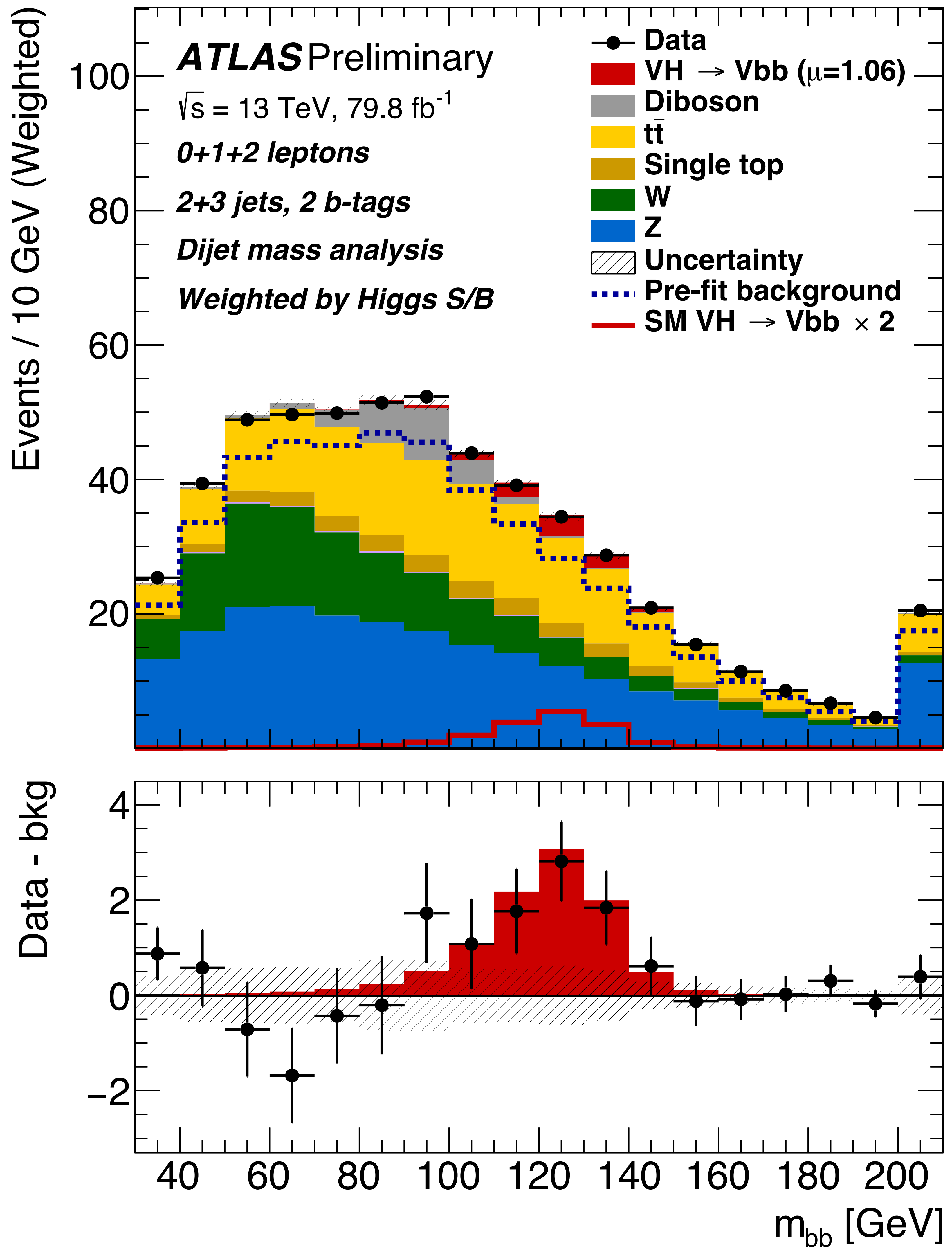
VH($b\bar{b}$) at LHC, machine learning

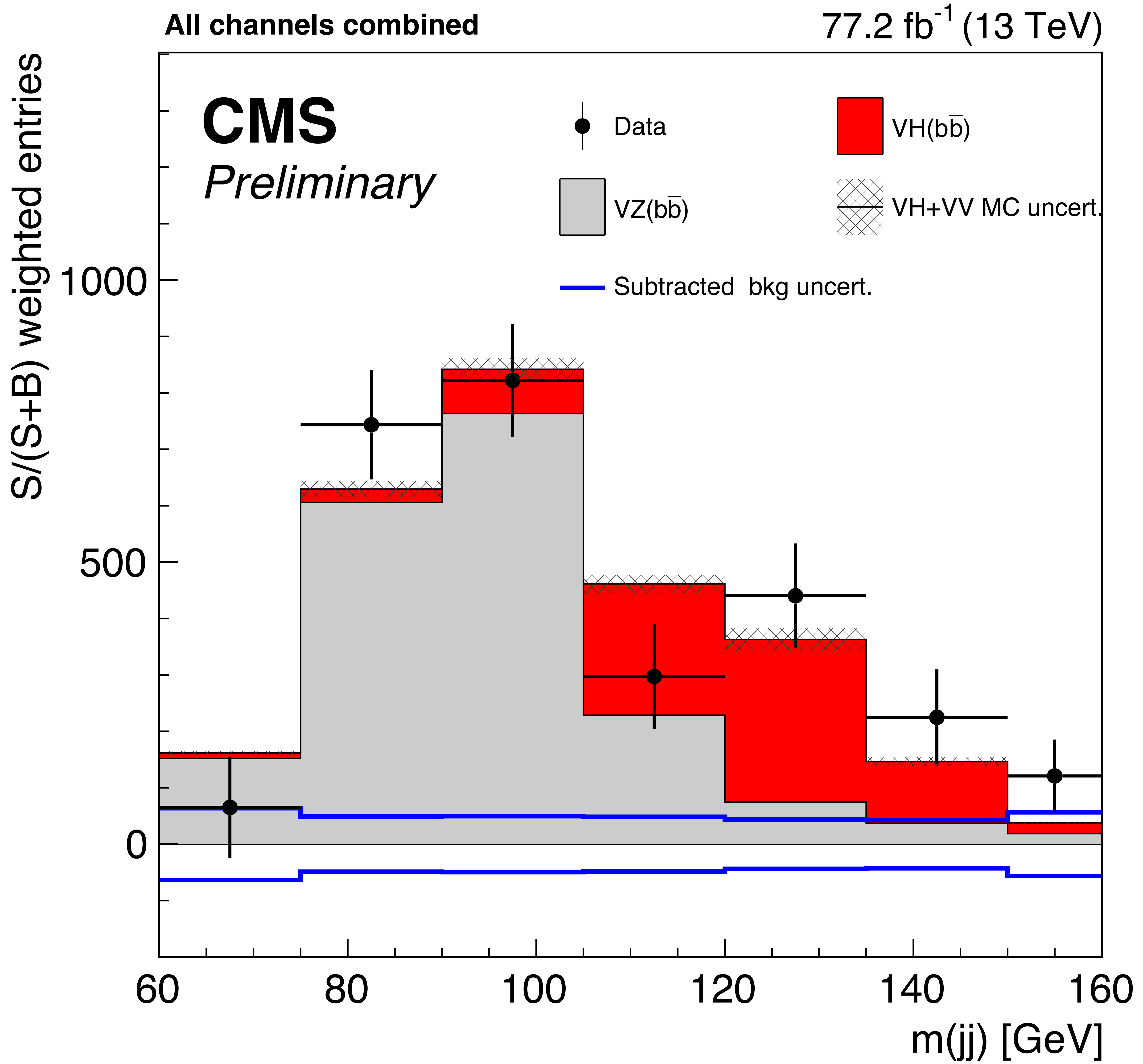




Main discriminant variables $m(b\bar{b})$, $p_T(V)$, $\Delta R(b\bar{b})$, b-tagging combined into a BDT or Deep Neural Network

VH($b\bar{b}$) at LHC





VH Event selection

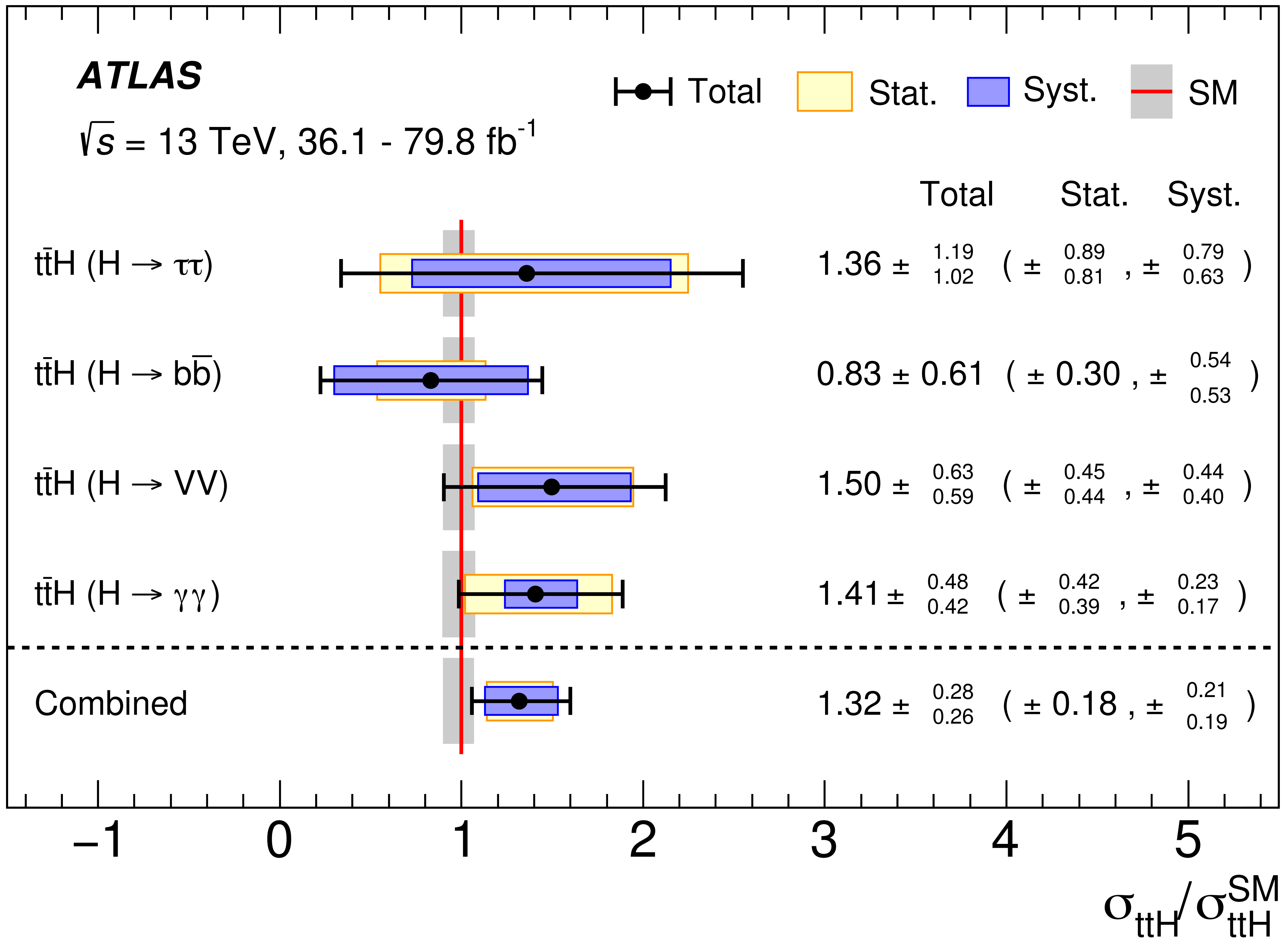
Variable	$Z(\nu\nu)H$	$W(\ell\nu)H$	$Z(\ell\ell)H$
$p_T(V)$	> 170	> 150 (**)	$[50-150], > 150$
$m_{\ell\ell}$	–	–	$[75-105]$
p_T^{ℓ}	–	$(> 25, > 30)$	> 20
$p_T(j_1)$	> 60	> 25	> 20
$p_T(j_2)$	> 35	> 25	> 20
$p_T(jj)$	> 120	> 100	–
$M(jj)$	$[60-160]$	$[90-150]$	$[90-150]$
$btag_{max}$	>Tight	>Tight	>Loose
$btag_{min}$	>Loose	>Loose	>Loose
N_{aj}	–	< 2	–
N_{al}	$= 0$	$= 0$	–
E_T^{miss}	> 170	–	–
Anti-QCD	Yes	–	–
$\Delta\phi(V,H)$(rad)	> 2.0	> 2.5	> 2.5
$\Delta\phi$(pfMET, trkMET)(rad)	< 0.5	–	–
$\Delta\phi$(pfMET, lep)(rad)	–	< 2.0	–
Tightened Lepton Iso.	–	(0.06, 0.06)	–

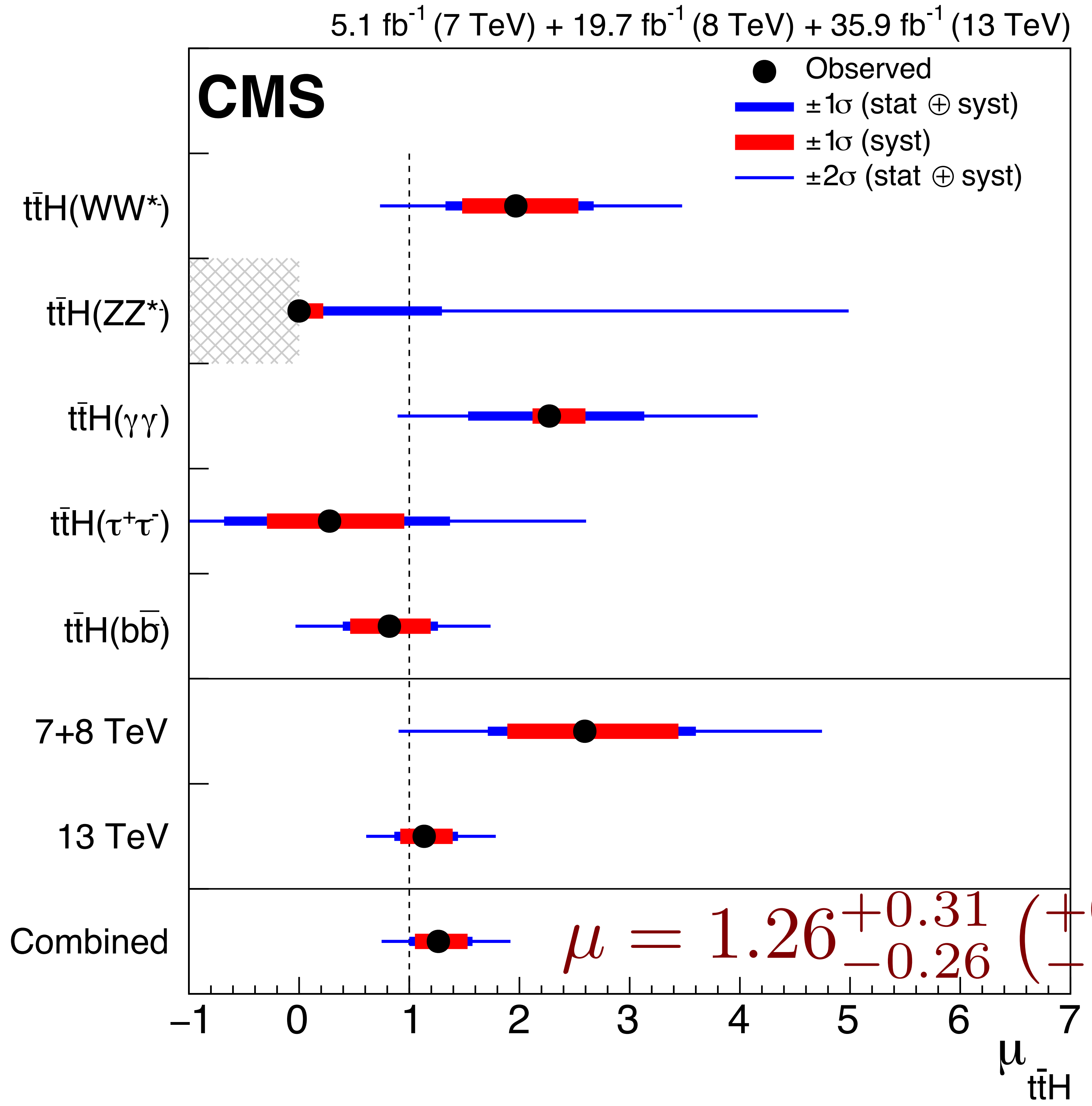
VH BDT/DNN inputs

Variable	Description	Channels
$M(\mathrm{jj})$	dijet invariant mass	All
$p_{\mathrm{T}}(\mathrm{jj})$	dijet transverse momentum	All
$p_{\mathrm{T}}(\mathrm{j}_1)$, $p_{\mathrm{T}}(\mathrm{j}_2)$	transverse momentum of each jet	0- and 2-lepton
$\Delta R(\mathrm{jj})$	distance in η–ϕ between jets	2-lepton
$\Delta\eta(\mathrm{jj})$	difference in η between jets	0- and 2-lepton
$\Delta\phi(\mathrm{jj})$	azimuthal angle between jets	0-lepton
$p_{\mathrm{T}}(\mathrm{V})$	vector boson transverse momentum	All
$\Delta\phi(\mathrm{V},\mathrm{jj})$	azimuthal angle between vector boson and dijet directions	All
$p_{\mathrm{T}}(\mathrm{jj})/p_{\mathrm{T}}(\mathrm{V})$	p_{T} ratio between dijet and vector boson	2-lepton
$M(\ell\ell)$	reconstructed Z boson mass	2-lepton
$\mathrm{CMVA}_{\mathrm{max}}$	value of CMVA discriminant for the jet with highest CMVA value	0- and 2-lepton
$\mathrm{CMVA}_{\mathrm{min}}$	value of CMVA discriminant for the jet with second highest CMVA value	All
$\mathrm{CMVA}_{\mathrm{add}}$	value of CMVA for the additional jet with highest CMVA value	0-lepton
$p_{\mathrm{T}}^{\mathrm{miss}}$	missing transverse momentum	1- and 2-lepton
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}},\mathrm{j})$	azimuthal angle between $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and closest jet ($p_{\mathrm{T}} > 30\,\mathrm{GeV}$)	0-lepton
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}},\ell)$	azimuthal angle between $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and lepton	1-lepton
m_{T}	mass of lepton $\vec{p}_{\mathrm{T}} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}}$	1-lepton
m_{top}	reconstructed top quark mass	1-lepton
N_{aj}	number of additional jets	1- and 2-lepton
$p_{\mathrm{T}}(\mathrm{add})$	transverse momentum of leading additional jet	0-lepton
SA5	number of soft-track jets with $p_{\mathrm{T}} > 5\,\mathrm{GeV}$	All

CMS-PRL 120 (2018) 231801
ATLAS-arXiv:1806.00425, sub. to PLB

ttH observation





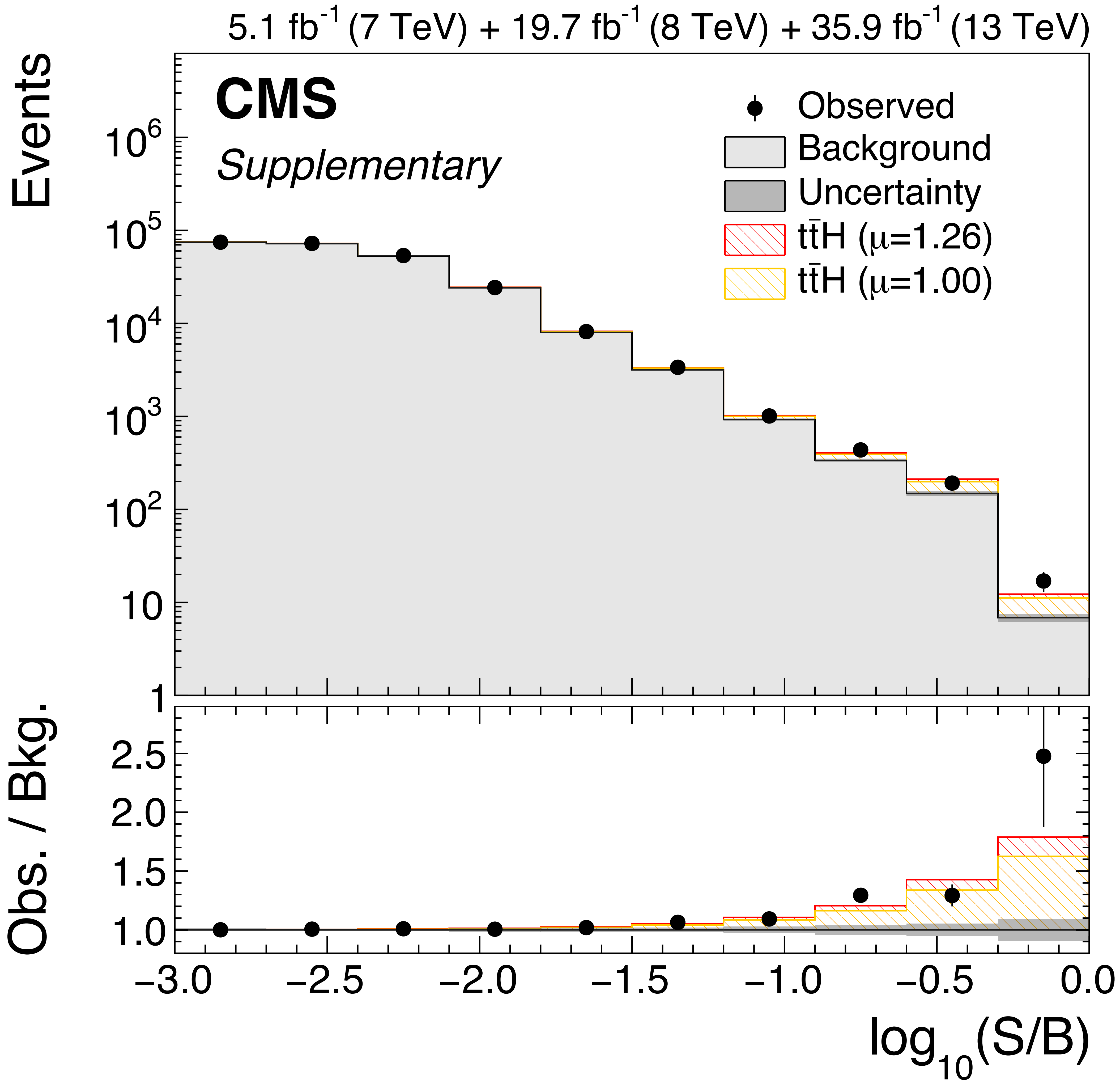
$$\mu = 1.26^{+0.31}_{-0.26} \left({}^{+0.16}_{-0.16}, {}^{+0.26}_{-0.21} \right)$$

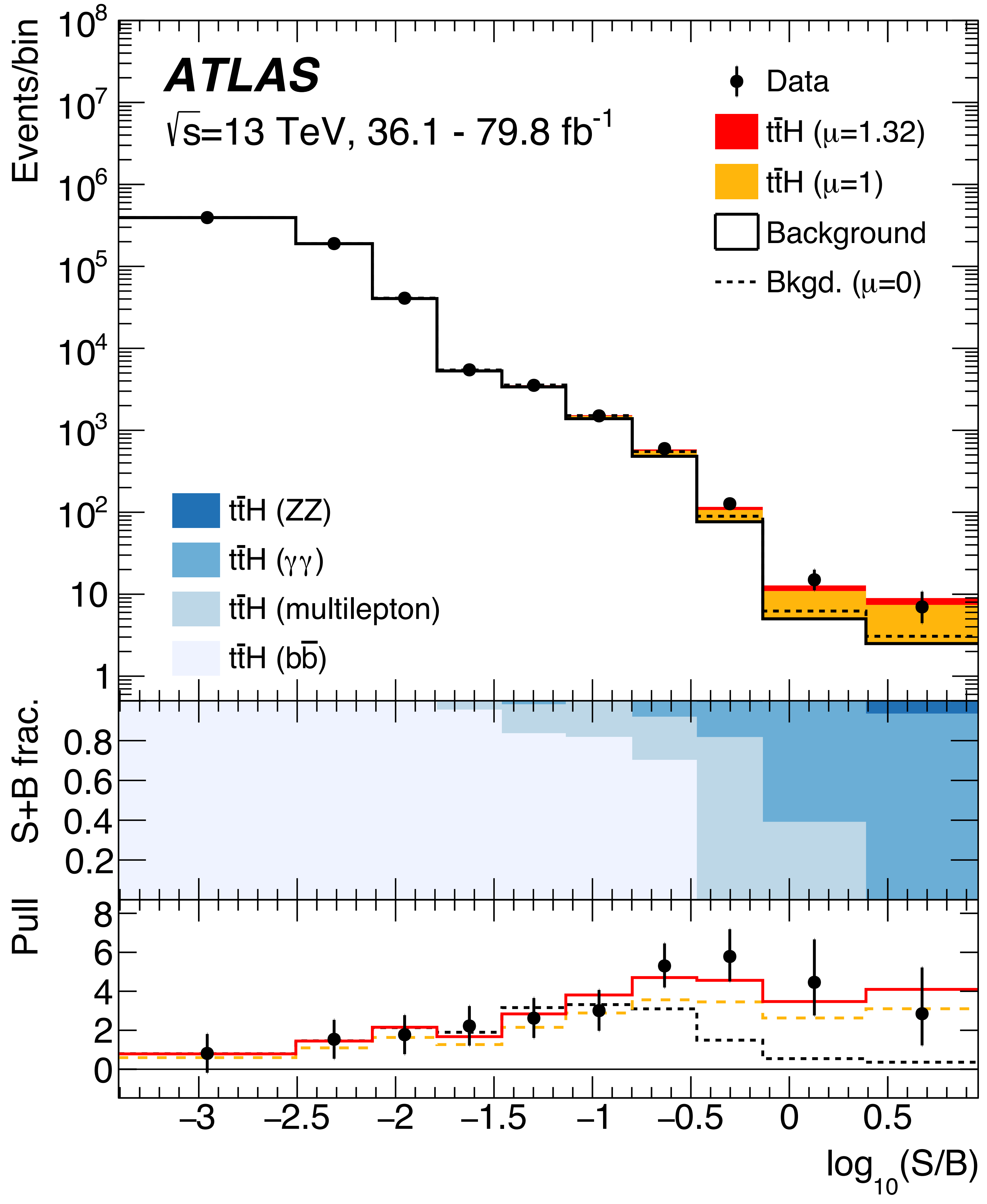
We have observed the ttH process

CMS** Run 1+2 (25+36/fb): **5.2σ (4.2σ exp.)

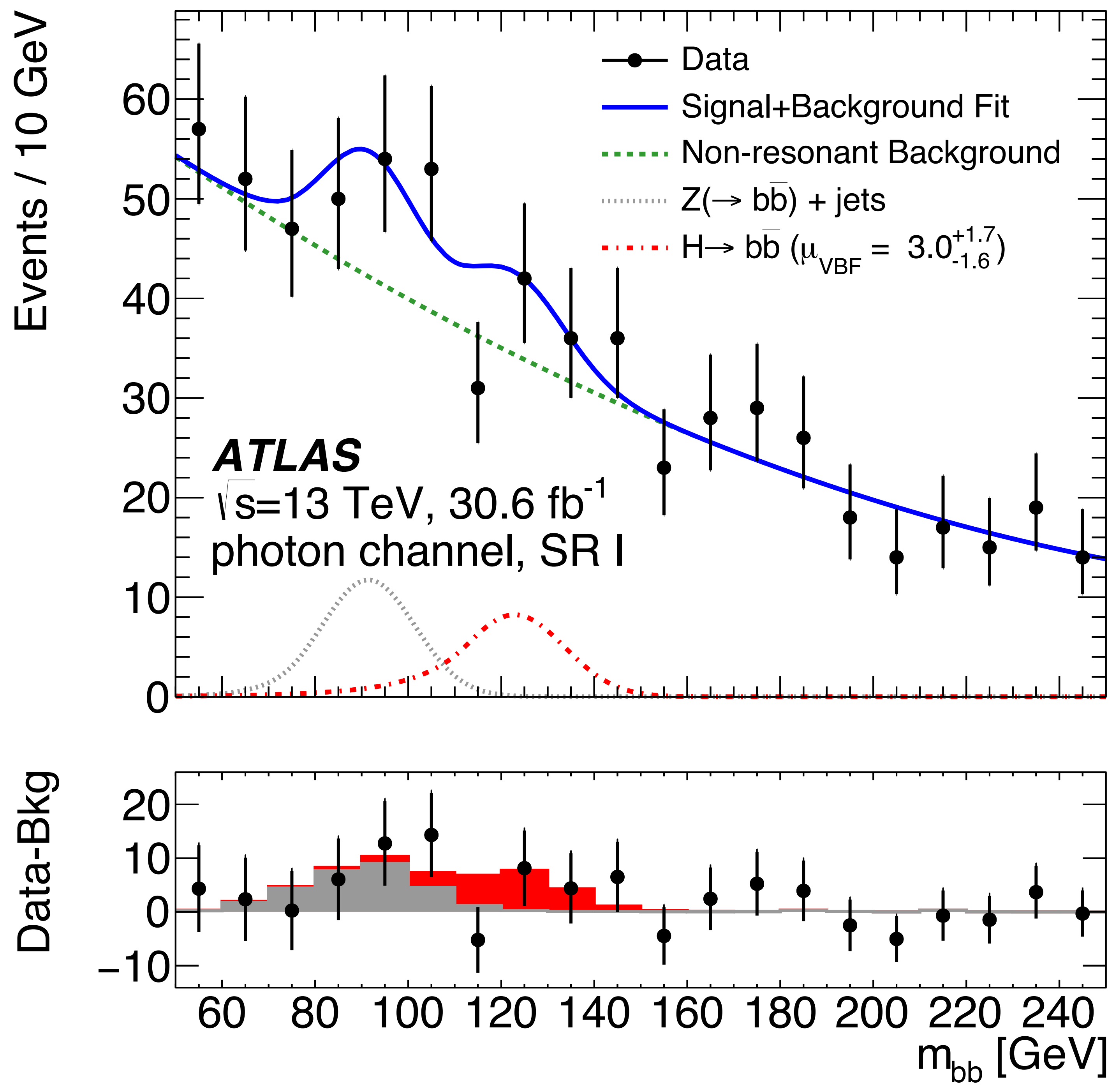
ATLAS** Run 1+2 (25+80/fb): **6.3σ (5.1σ exp.)

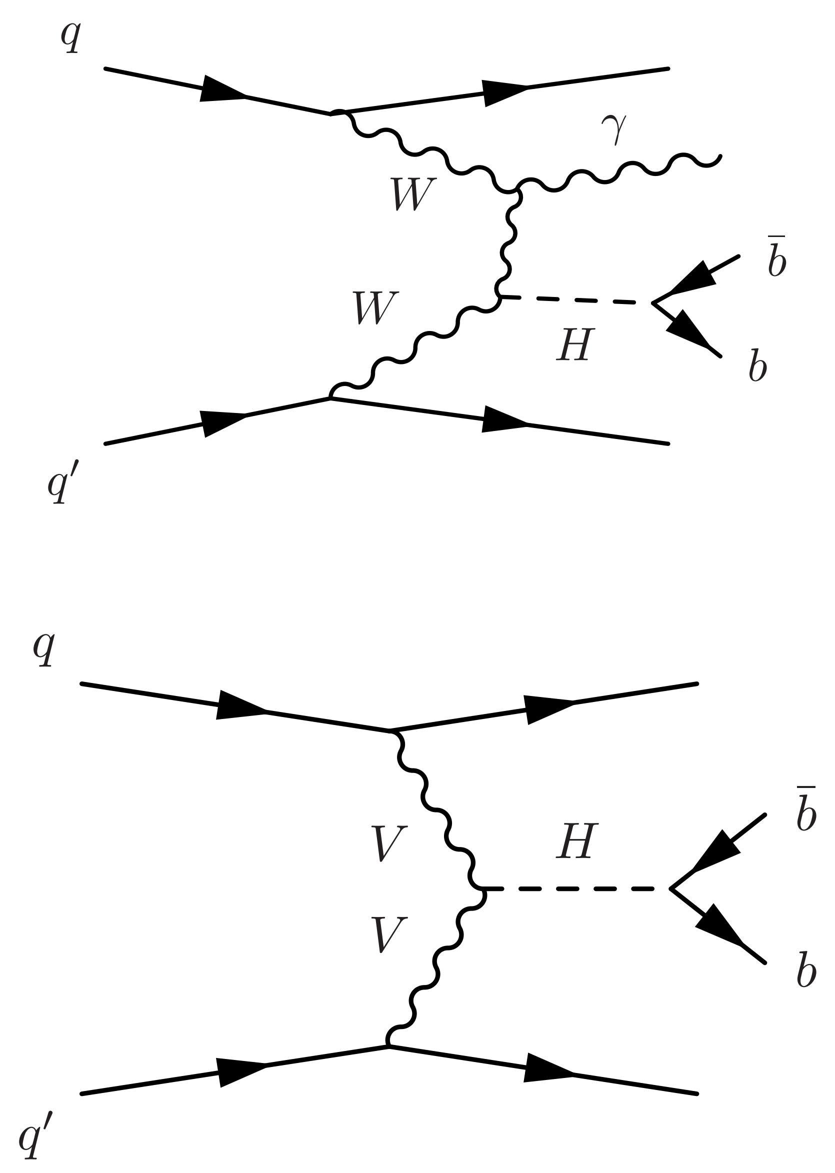
ttH observation





VBF H($b\bar{b}$)

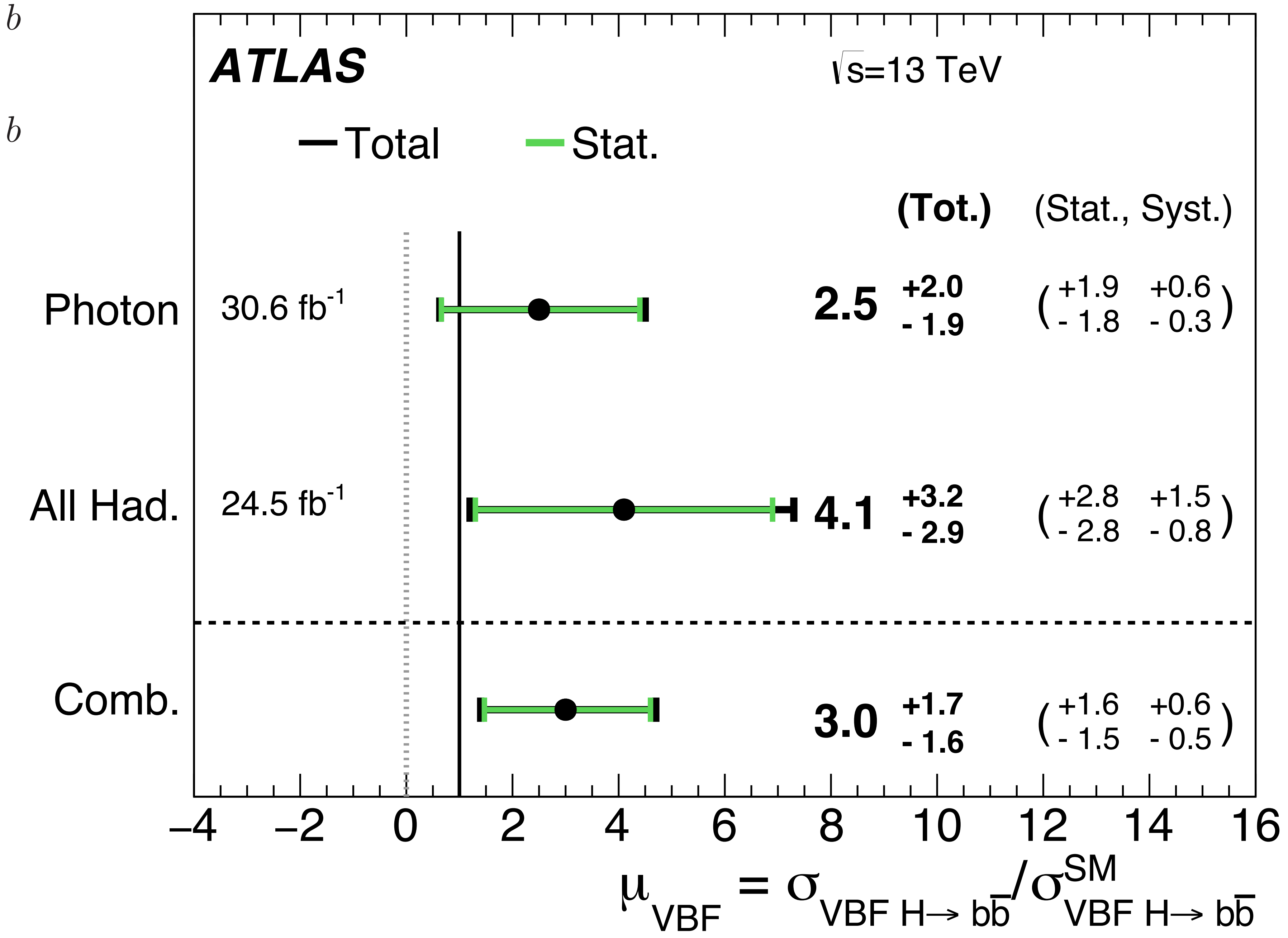




Observed (expected) 95% CL upper limit on the SM cross section

ATLAS Run-2 (20-30/fb): 5.9 ($3.0^{+1.3}_{-0.8}$)xSM

CMS Run1+2 (2/fb): 3.4(2.3)xSM, $\mu=1.3^{+1.2}_{-1.1}$

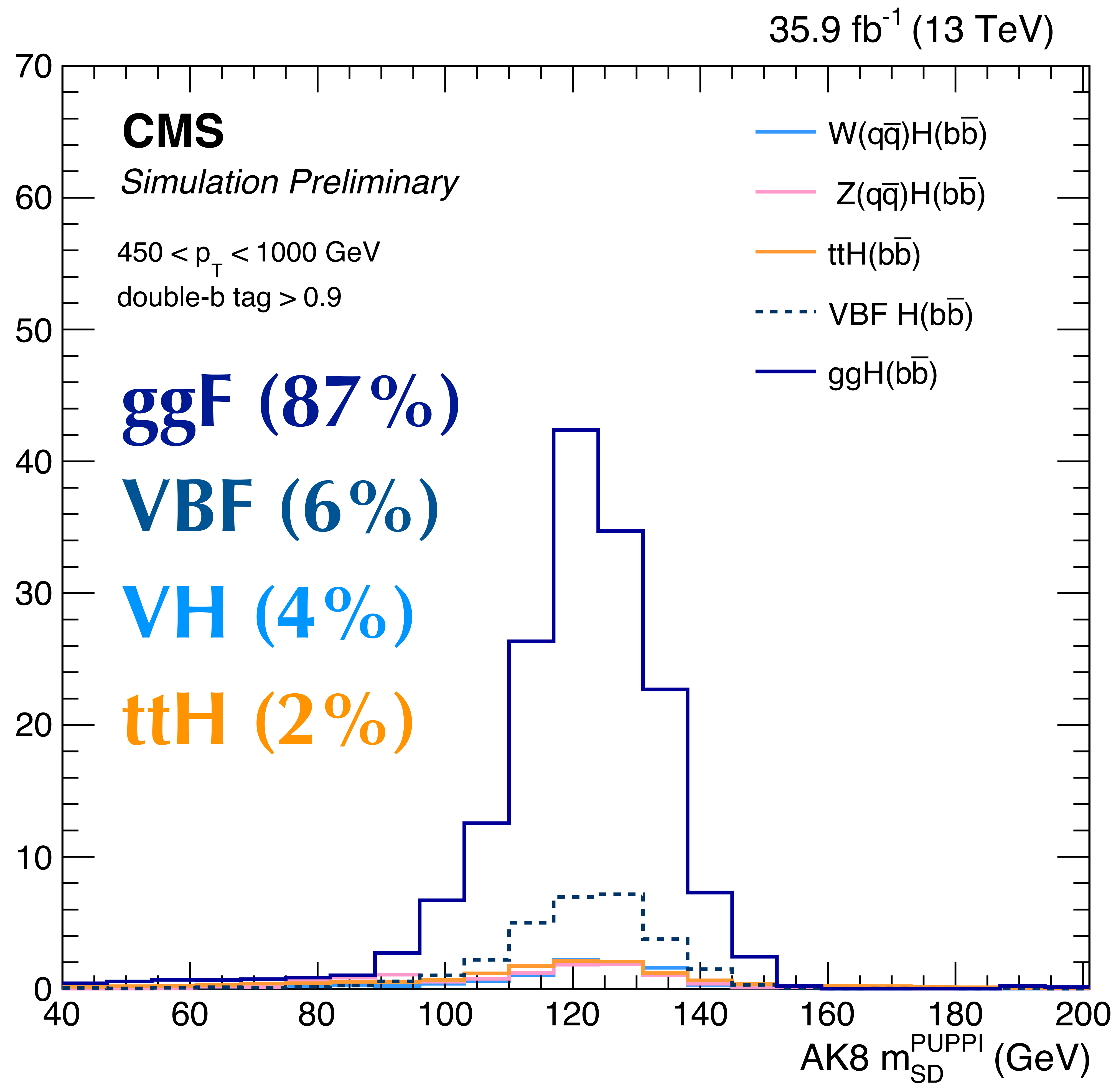


- Use **ISR photon to trigger events and enhance S/B**
- **BDT to categorize events in S/B bins**
- Fit the **m($b\bar{b}$) spectrum in each bin**
- Dominant uncertainty from limited number of data events
  → will benefit from more luminosity

Phys. Rev. Lett. 120 (2018) 071802

ggF H($b\bar{b}$)

- Dominant contribution in the signal region is the gluon fusion production mode
- **Mass resolution is about 9%**



Phys. Rev. Lett. 120 (2018) 071802

ggF H($b\bar{b}$) Systematics Uncertainties

Systematic uncertainty source	Type (shape or normalization)	Relative size (or description)
QCD transfer factor	both	profile $a_{k\ell}$ and QCD normalization
Luminosity	normalization	2.5%
V-tag ($N_2^{1,DDT}$) efficiency	normalization	4.3%
Muon veto efficiency	normalization	0.5%
Electron veto efficiency	normalization	0.5%
Trigger efficiency	normalization	4%
Muon ID efficiency	shape	up to 0.2%
Muon isolation efficiency	shape	up to 0.1%
Muon trigger efficiency	shape	up to 8%
$t\bar{t}$ normalization SF	normalization	from 1μ CR: 8%
$t\bar{t}$ double-b mis-tag SF	normalization	from 1μ CR: 15%
W/Z NLO QCD corrections	normalization	10%
W/Z NLO EWK corrections	normalization	15% – 35%
W/Z NLO EWK ratio decorrelation	normalization	5% – 15%
double-b tagging efficiency	normalization	4%
Jet energy scale	normalization	up to 10%
Jet energy resolution	normalization	up to 15%
Jet mass scale	shape	shift m_{SD} peak by $\pm 0.4\%$
Jet mass resolution	shape	smear m_{SD} distribution by $\pm 9\%$
Jet mass scale p_T	normalization	0.4%/100 GeV (p_T)
Monte Carlo statistics	normalization	-
H p_T correction (gluon fusion)	both	30%

correlated among W, Z, and H

ggF H($b\bar{b}$), Results

	H	H no p_T corrections	Z
Observed best fit	$\mu_H = 2.3^{+1.8}_{-1.6}$	$\mu'_H = 3.2^{+2.2}_{-2.0}$	$\mu_Z = 0.78^{+0.23}_{-0.19}$
Expected significance	0.7σ ($\mu_H = 1$)	0.5σ ($\mu'_H = 1$)	5.8σ ($\mu_Z = 1$)
Observed significance	1.5σ	1.6σ	5.1σ

- The measured cross sections for Z+jets and gluon fusion H to $b\bar{b}$ for jet p_T > 450 GeV are:

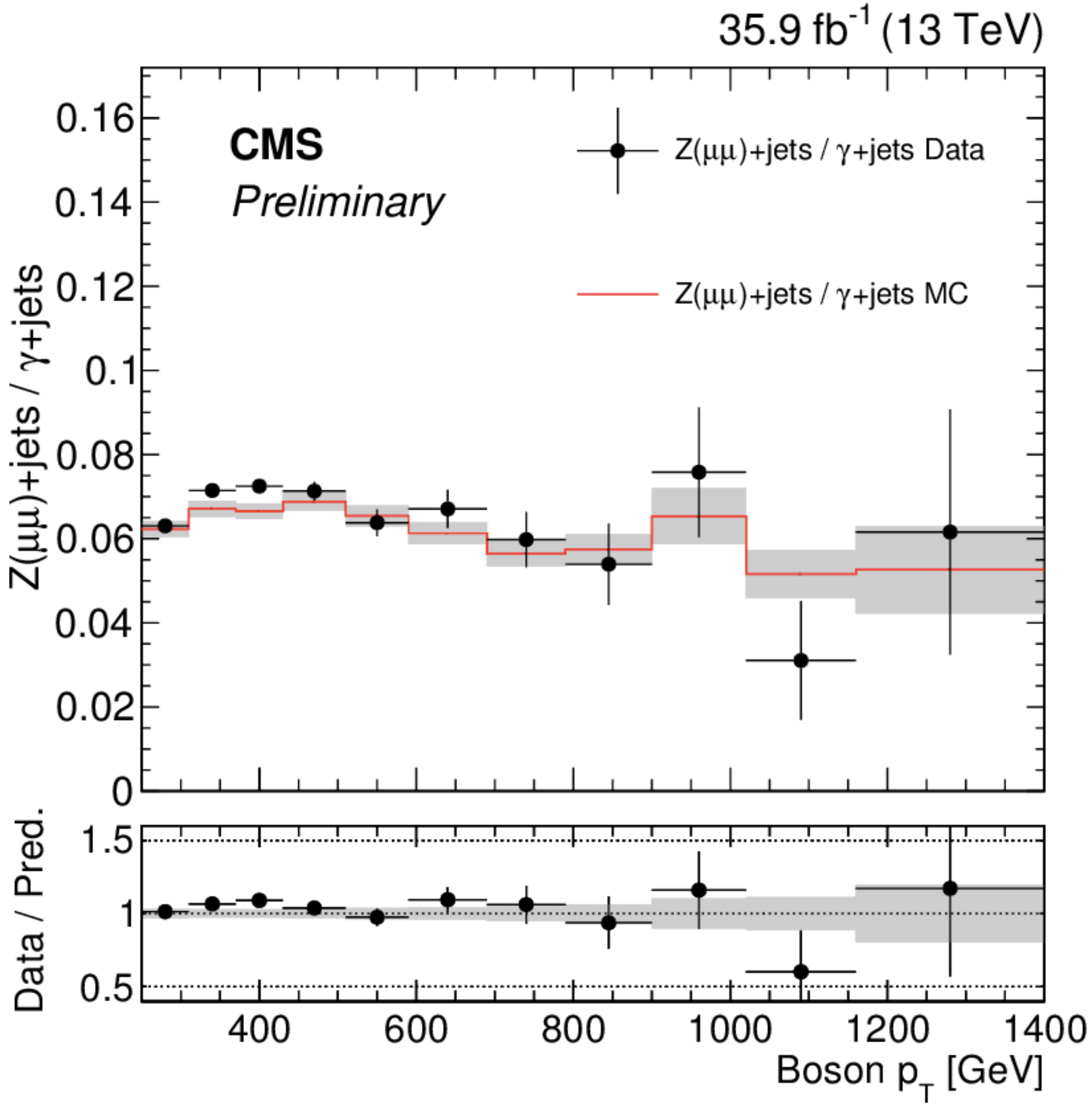
σ_Z = 849 +155/-155 (stat.) +140/-205 (syst.) fb

σ_H = 74 +48/-48 (stat.) +10/-17 (syst.) fb

Compatible with SM within uncertainties

W/Z+jets simulation

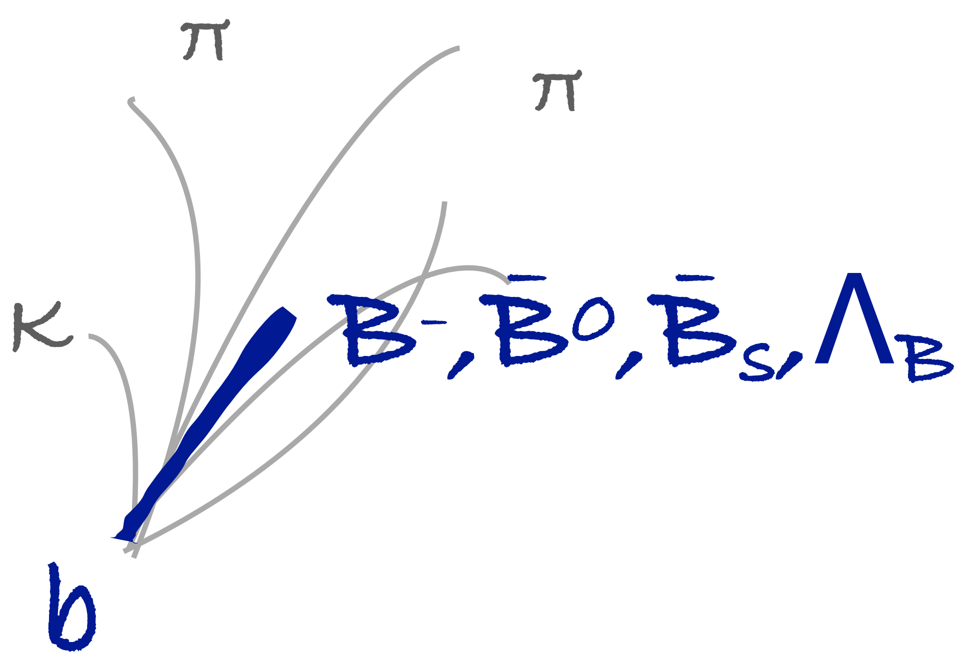
ArXiv:1705.04664
CMS-PAS-EXO-16-048

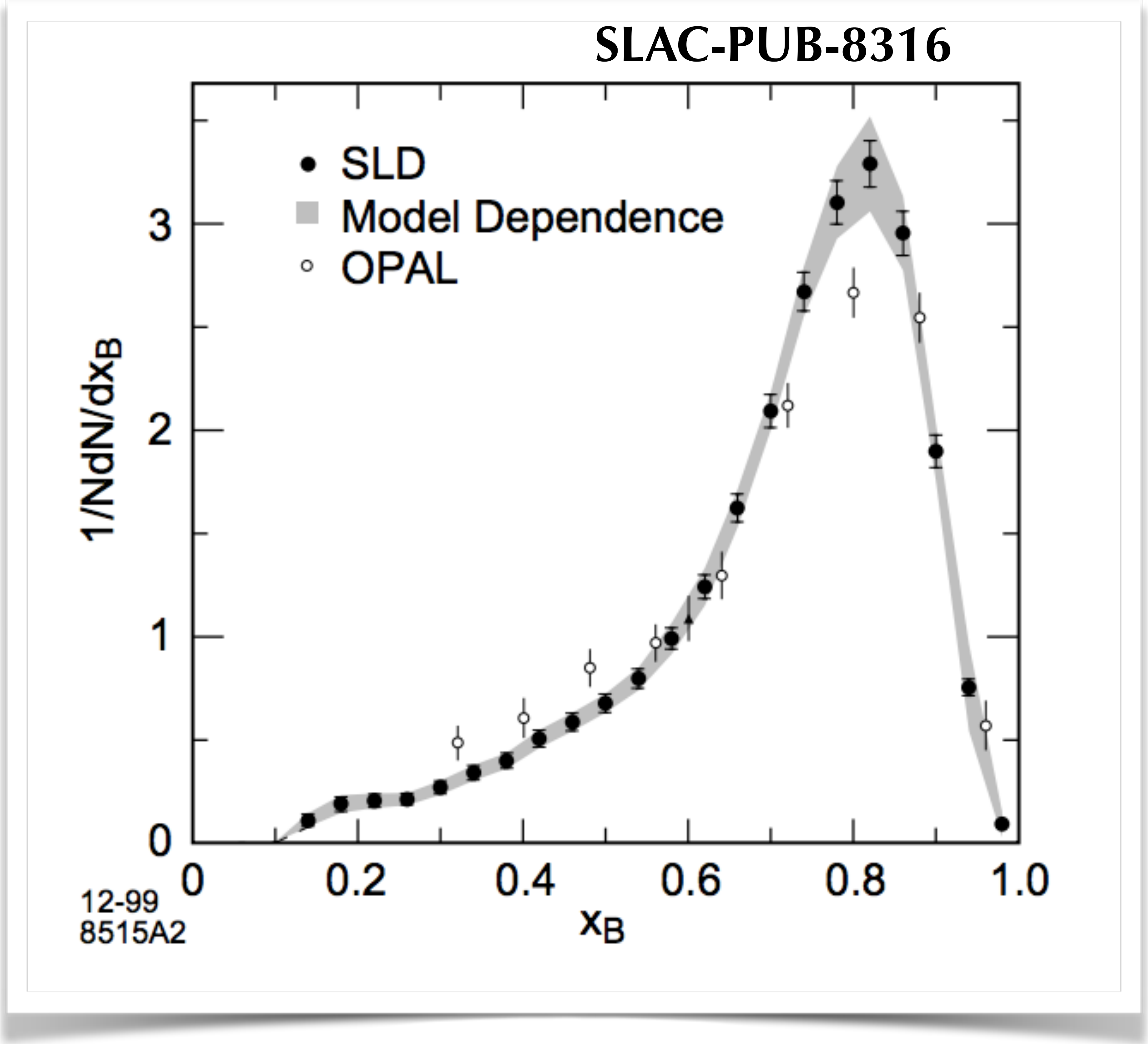


- LO simulations for the W/Z+jets are corrected using **p_T-dependent** :
  - **NLO QCD** k-factors
  - **NLO electroweak** k-factors
- Associated uncertainties are 10% (QCD) and 15-35% (EWK)

B properties useful for its tagging

b quarks hadronize





Fraction of the original b quark momentum carried by the B
$\langle x_B \rangle \sim 0.7$

Measurable lifetime

$c\tau \sim 500\ \mu m \rightarrow \beta\gamma c\tau \sim 5mm$ @ 50 GeV

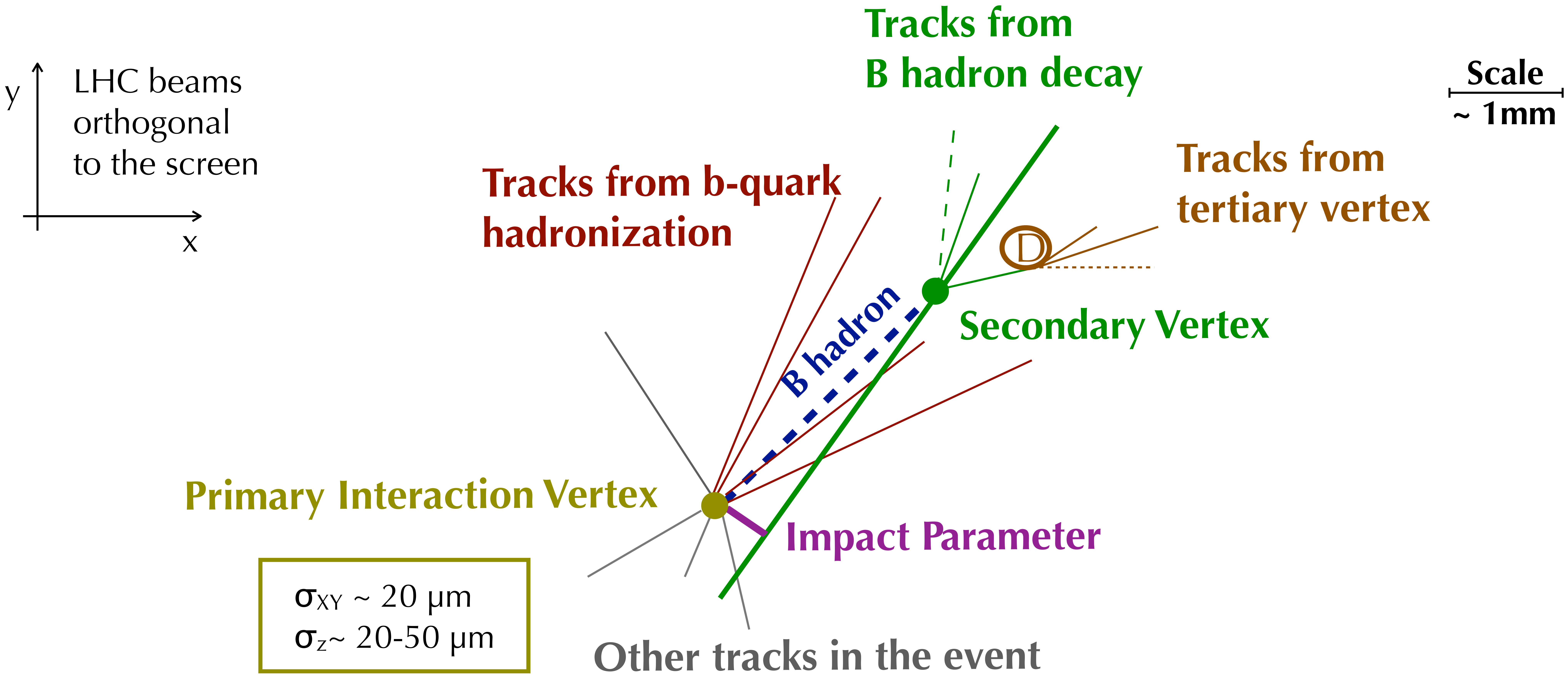
The **weak b-decay** often produces leptons

BR: $B \rightarrow l + \nu + X$ ~ 25%

$B \rightarrow D \rightarrow l + \nu + X'$ ~ 20% **tertiary vertex**

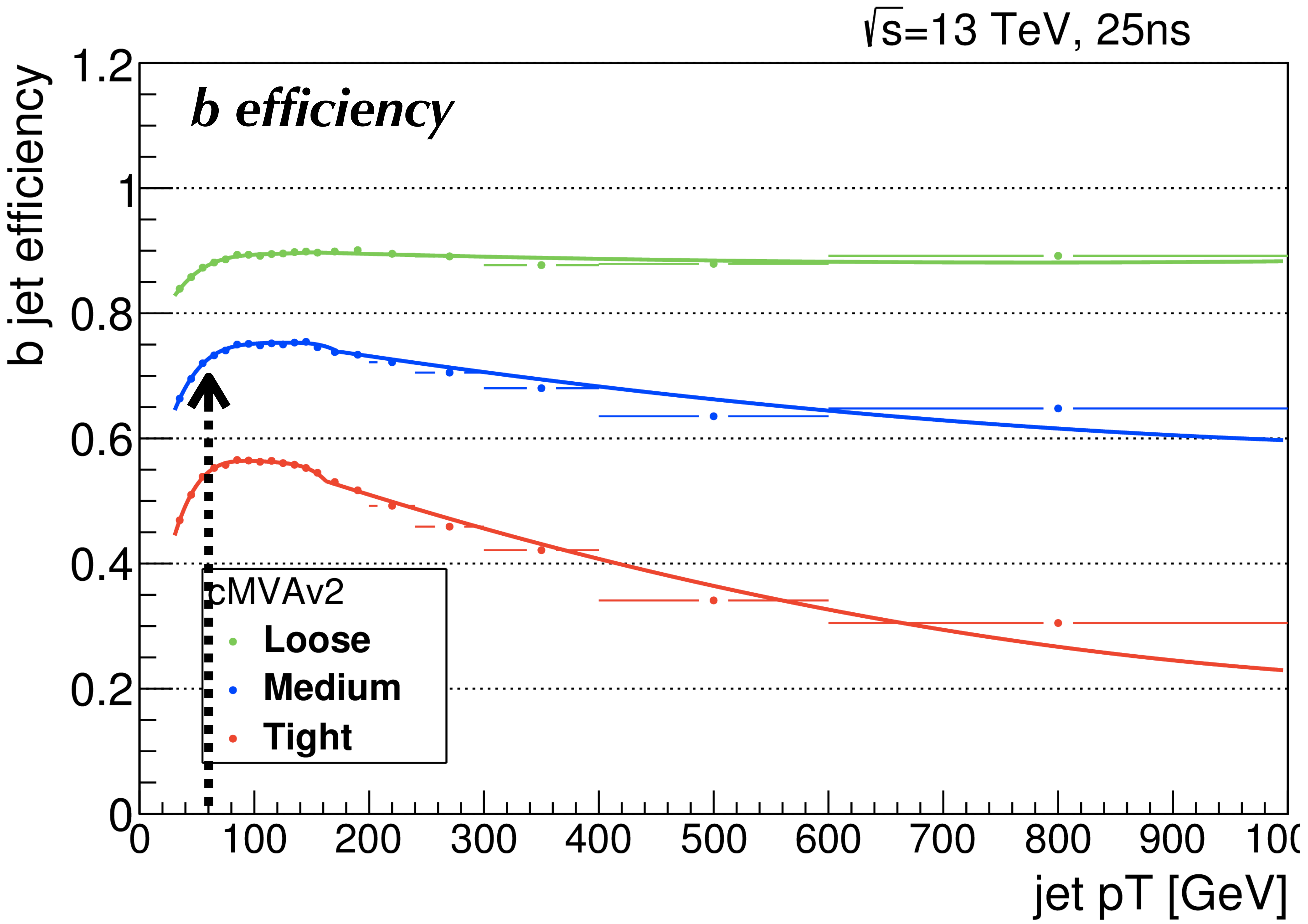
High momentum transferred to the B hadron

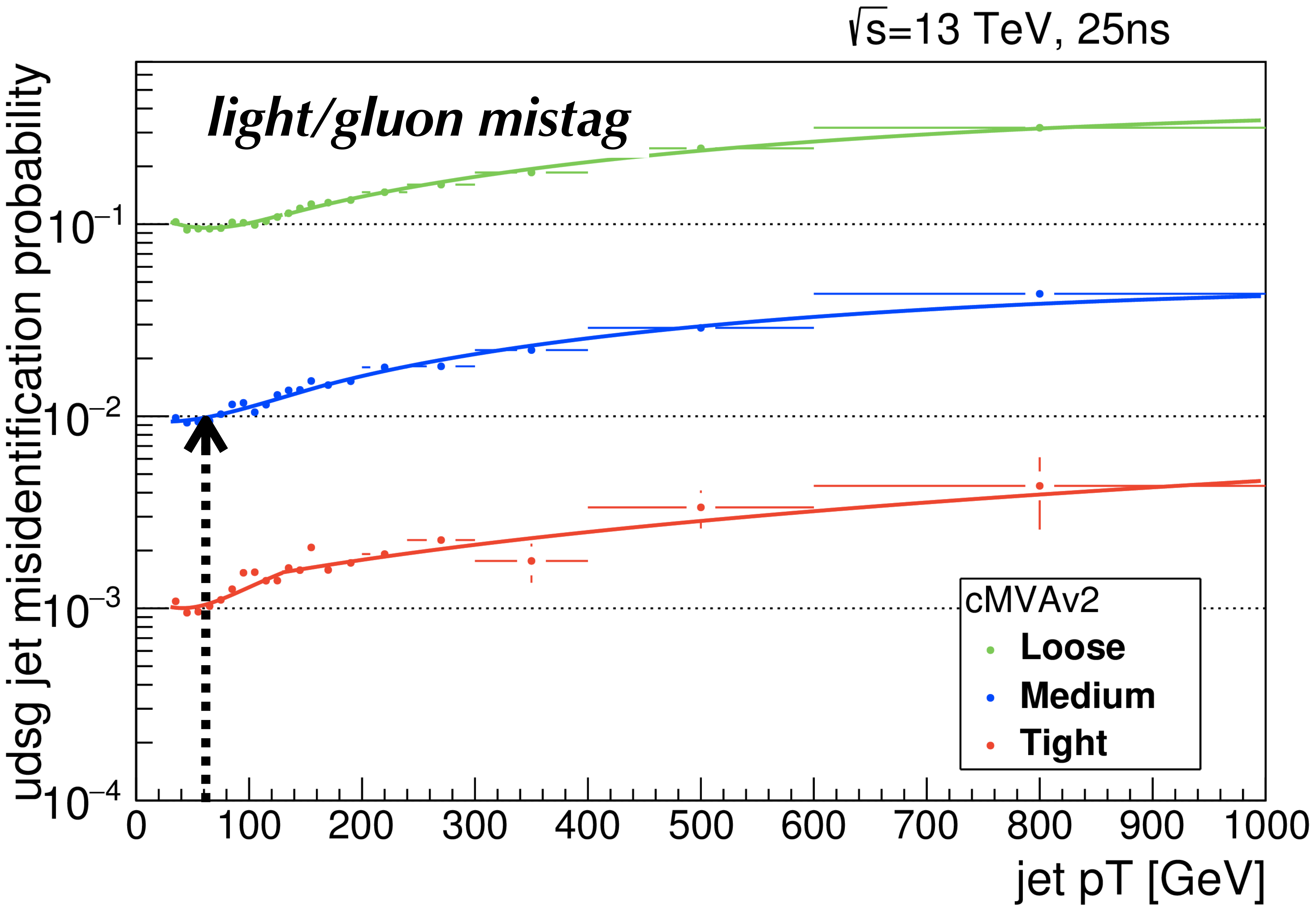
The B tag picture



arXiv:1712.07158

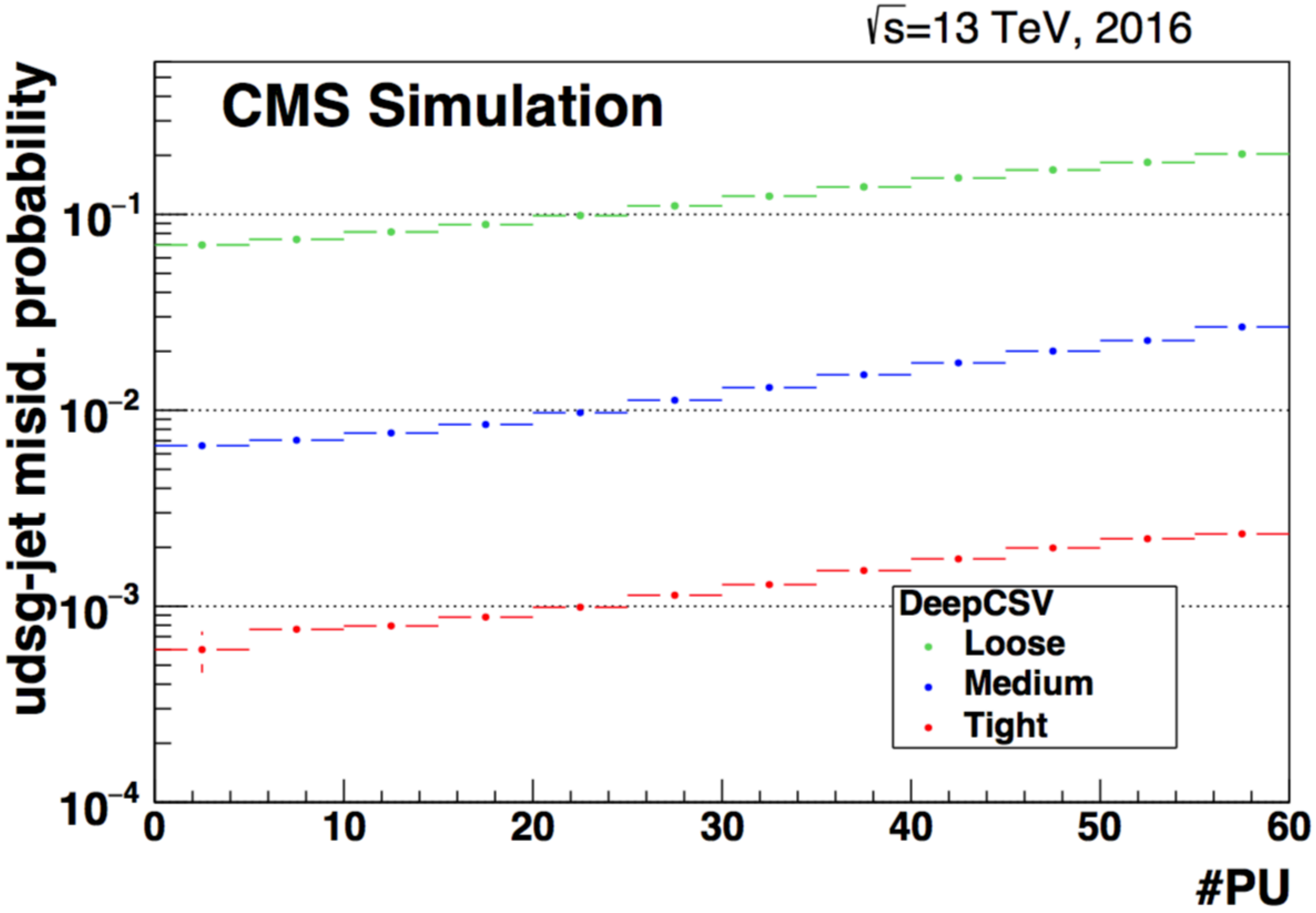
Performance of b-tagging in CMS



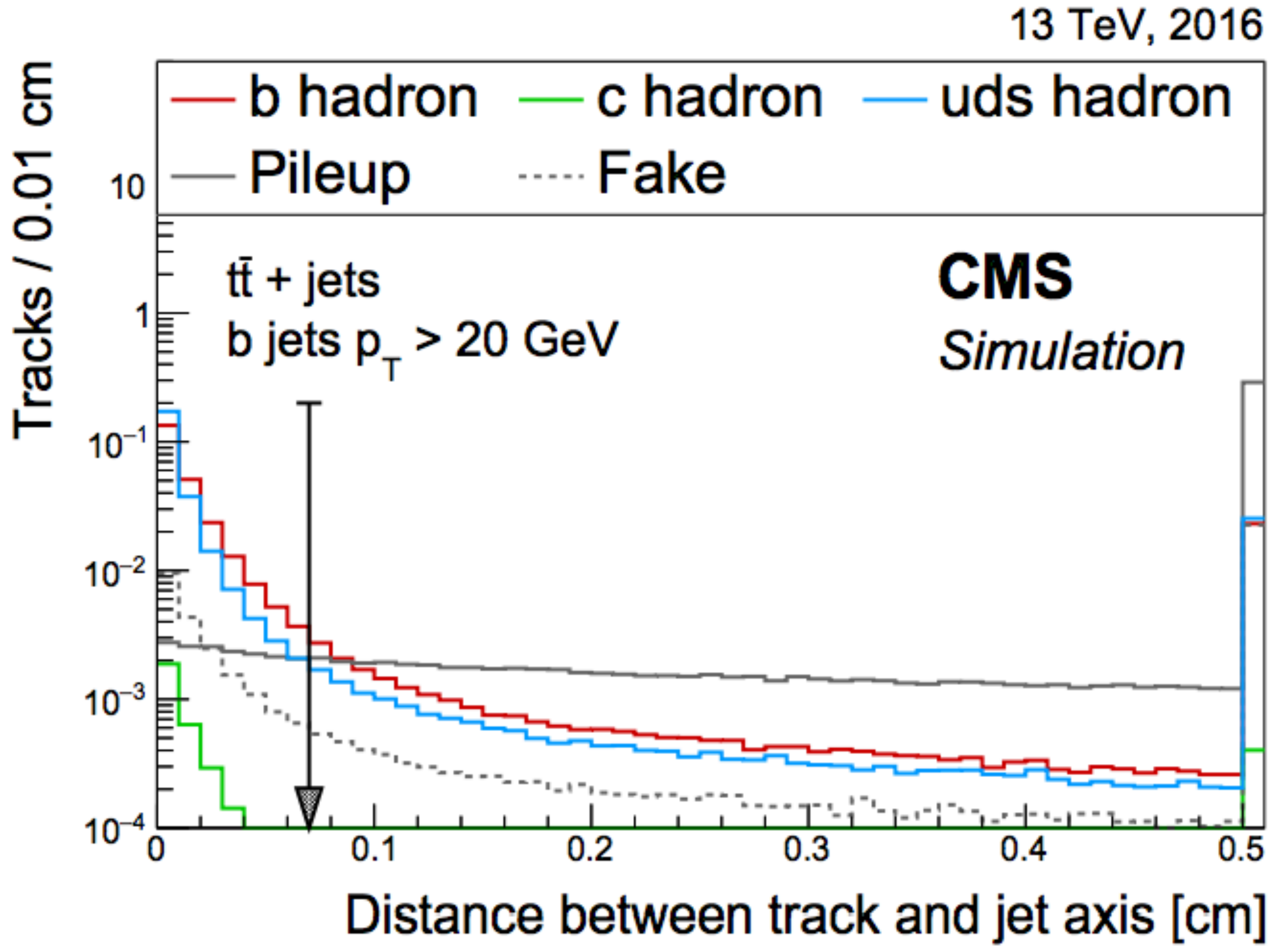


optimal working point for a **H to $b\bar{b}$ search** search has 70% b efficiency and 1% mistag probability

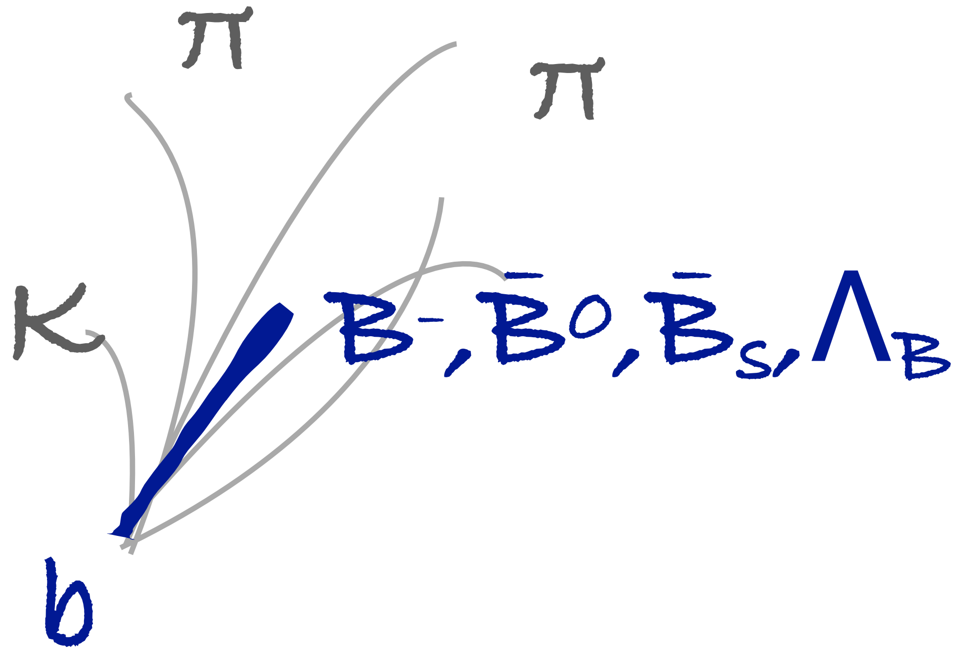
b-tagging vs. pileup



- transverse IP < 0.2 cm
- longitudinal IP < 17 cm
- distance between the track and the jet axis < 0.07 cm

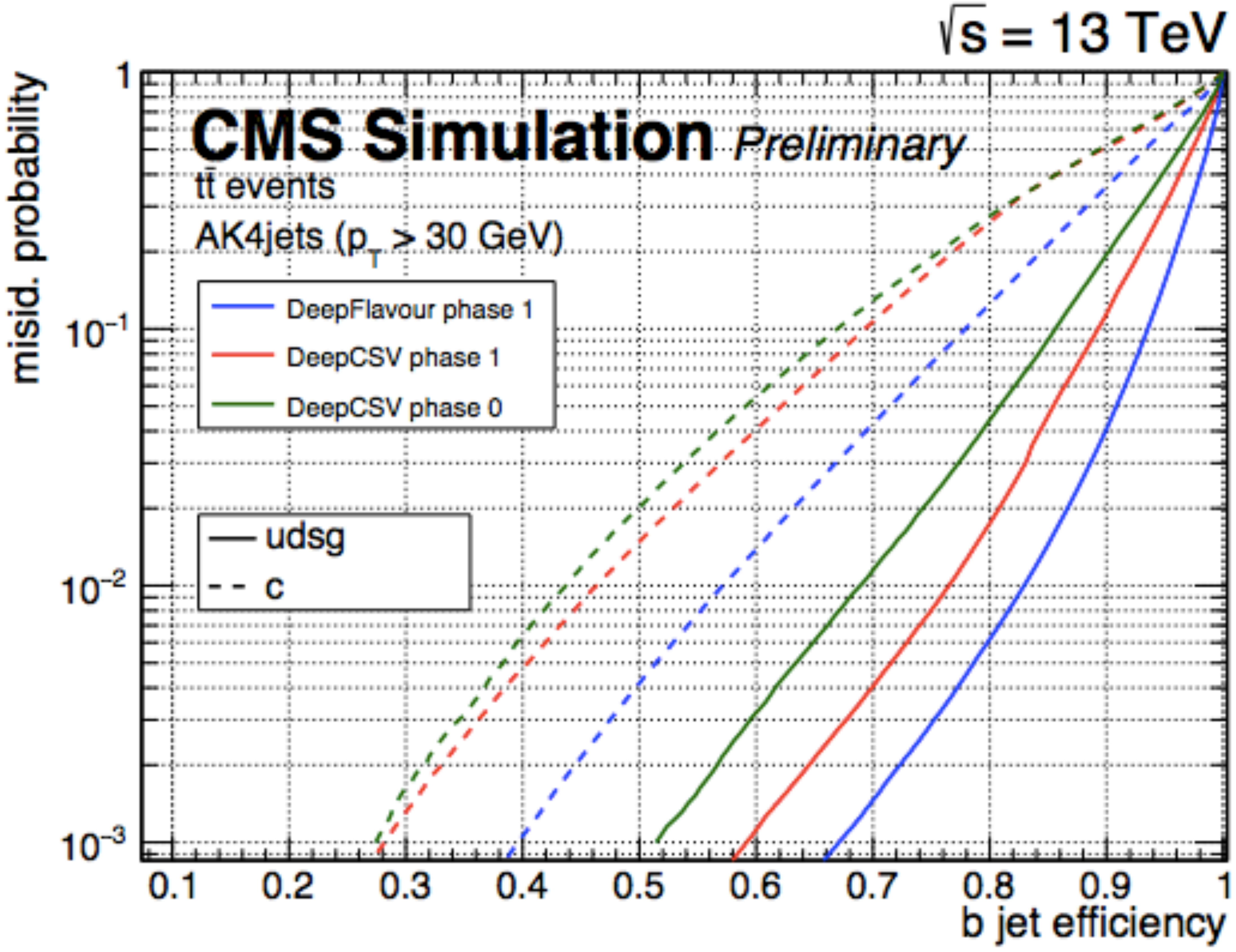


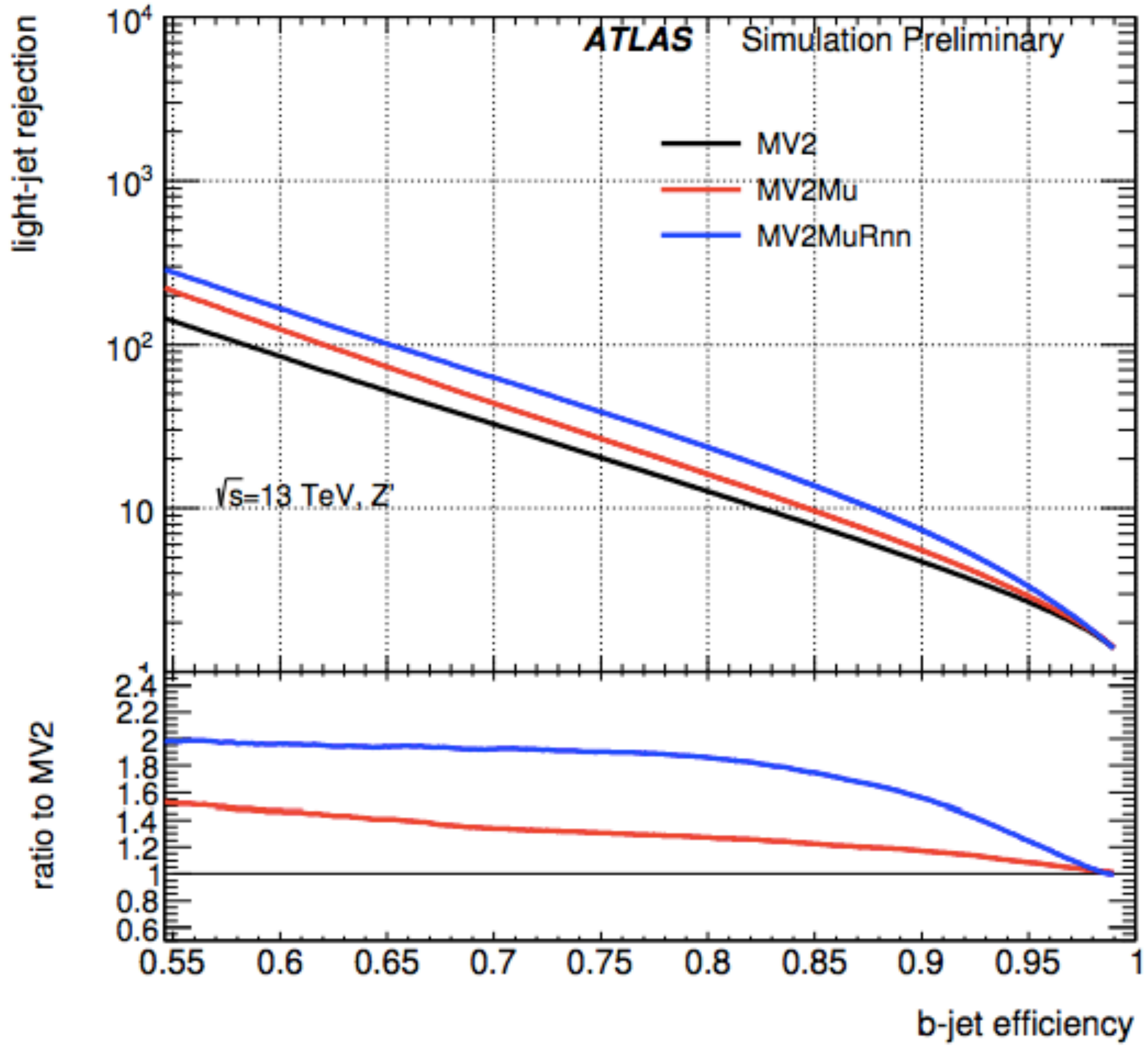
heavy flavor identification



CSVv2 (track,SV)
DeepCSV (track, SV + more charged tracks)
DeepFlavour (charged and neutral PF + SV)

MV2 (IP+SV)
MV2Mu (MV2+ soft muon)
MV2MuRnn (MV2Mu+track info)

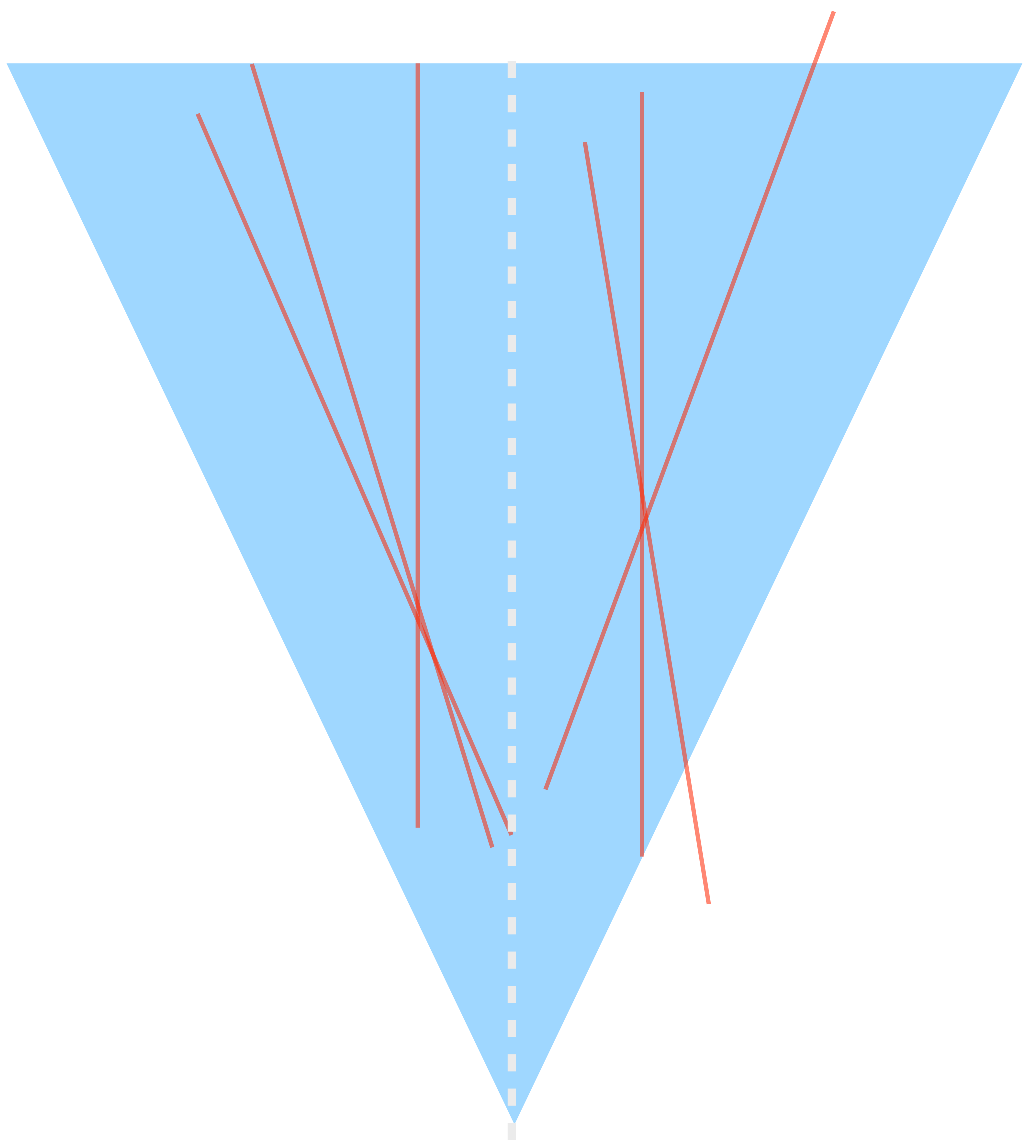


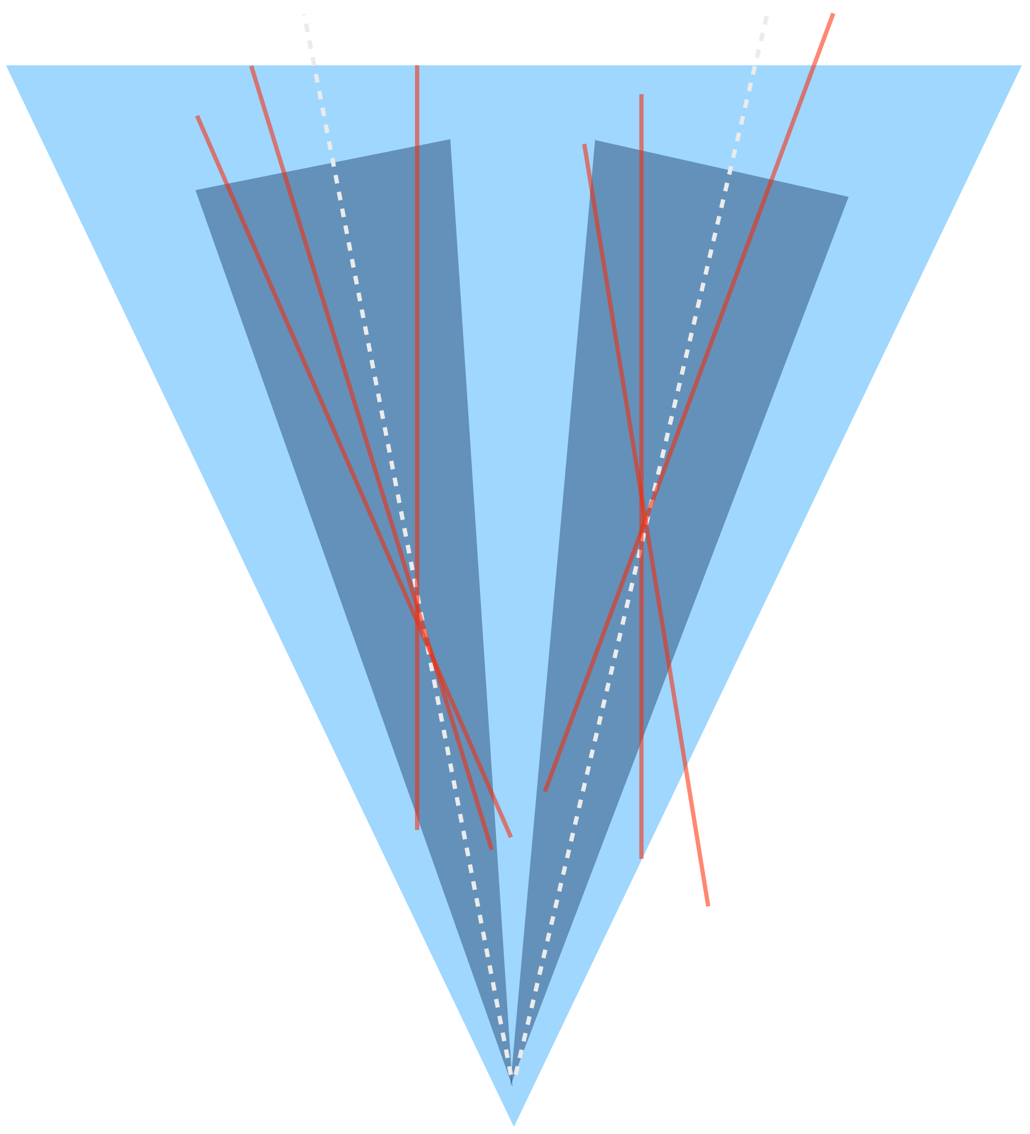


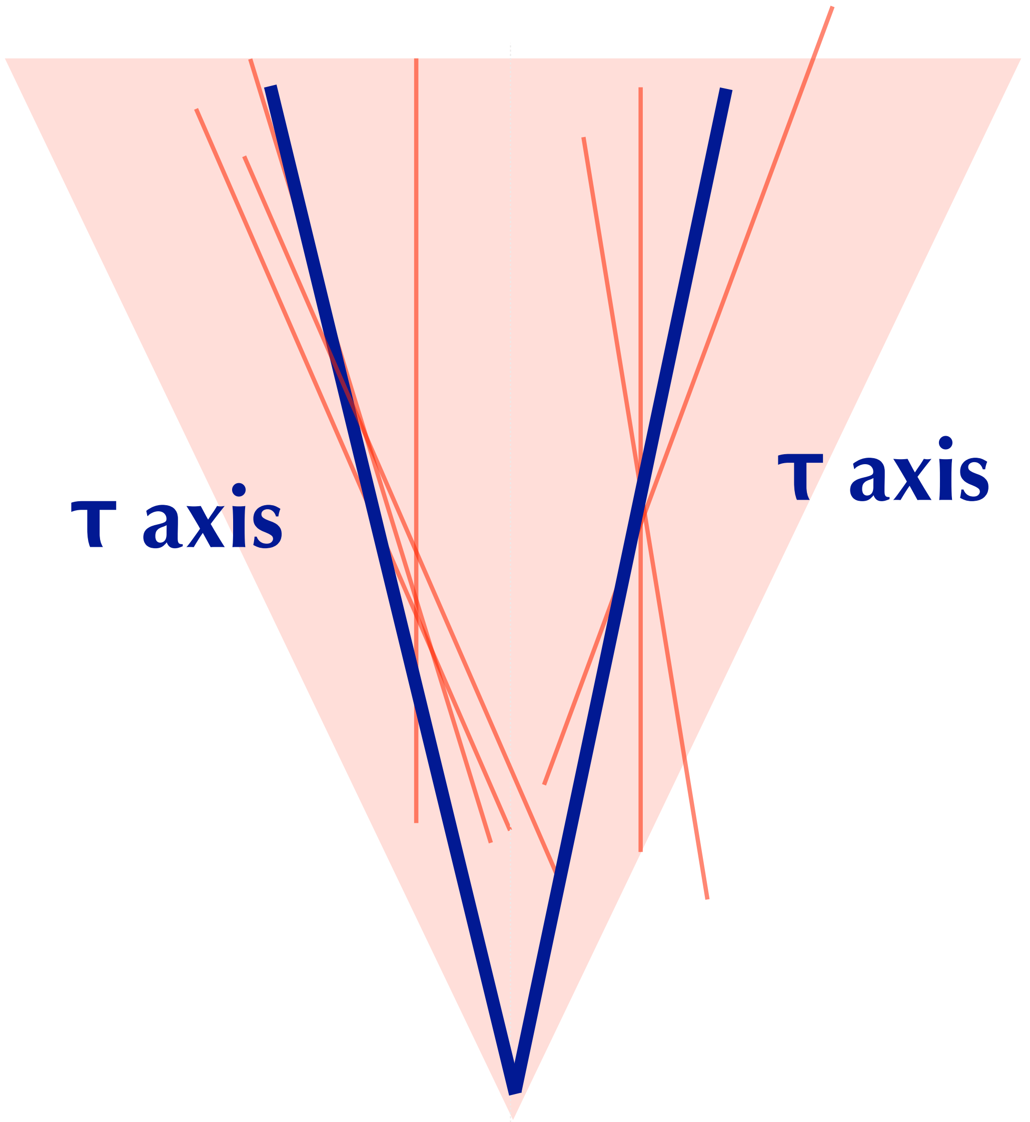
arXiv:1712.07158

Multiple approaches

**τ*-axes are Nsubjettiness axis*







fat-jet b-tagging

- Based on the standard b-tagging algorithm
- Not designed for tagging two b's in the same jet

sub-jet b-tagging

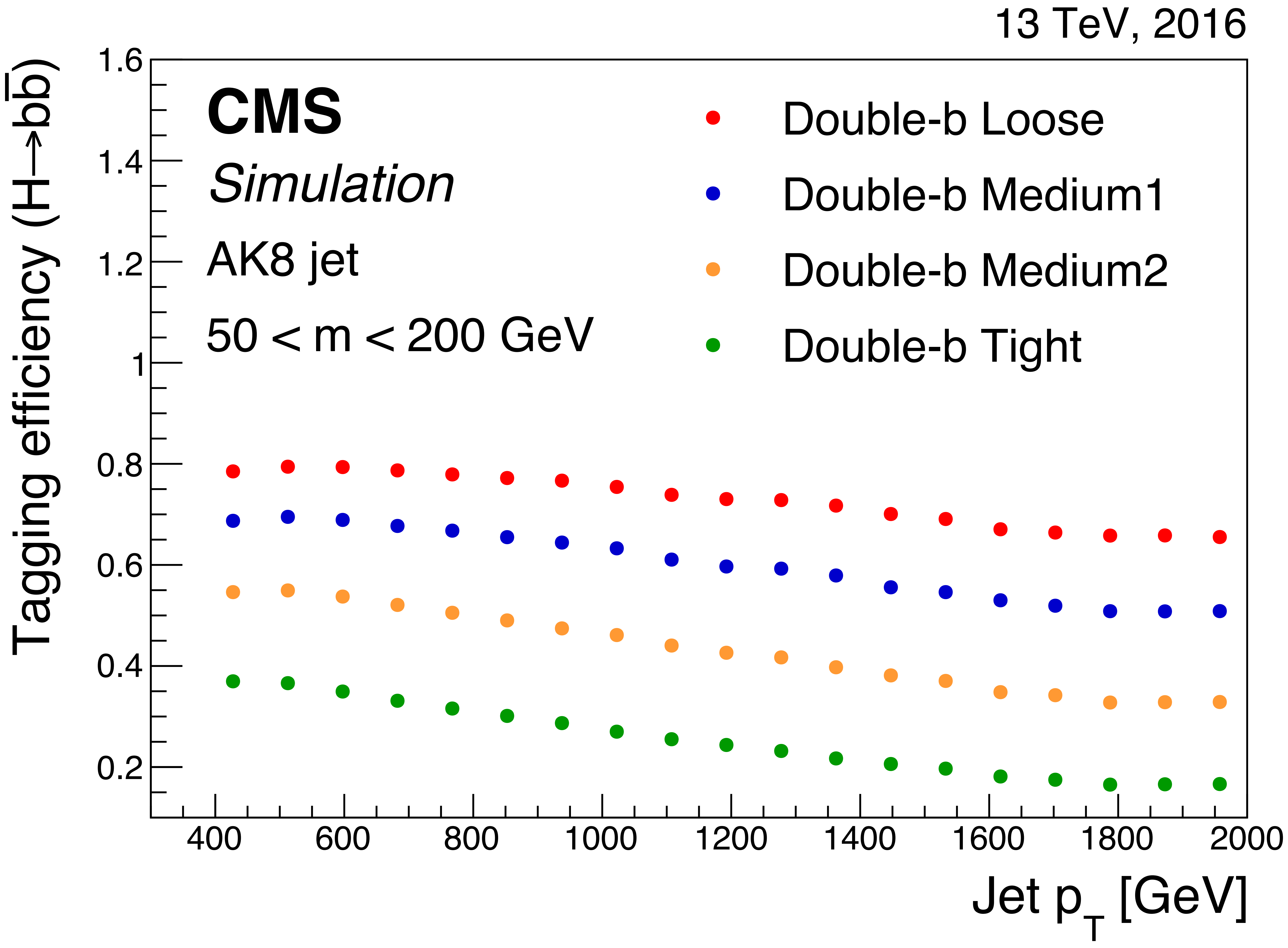
- Defines sub-jets
- Standard b-tagging algorithm applied to each subjet

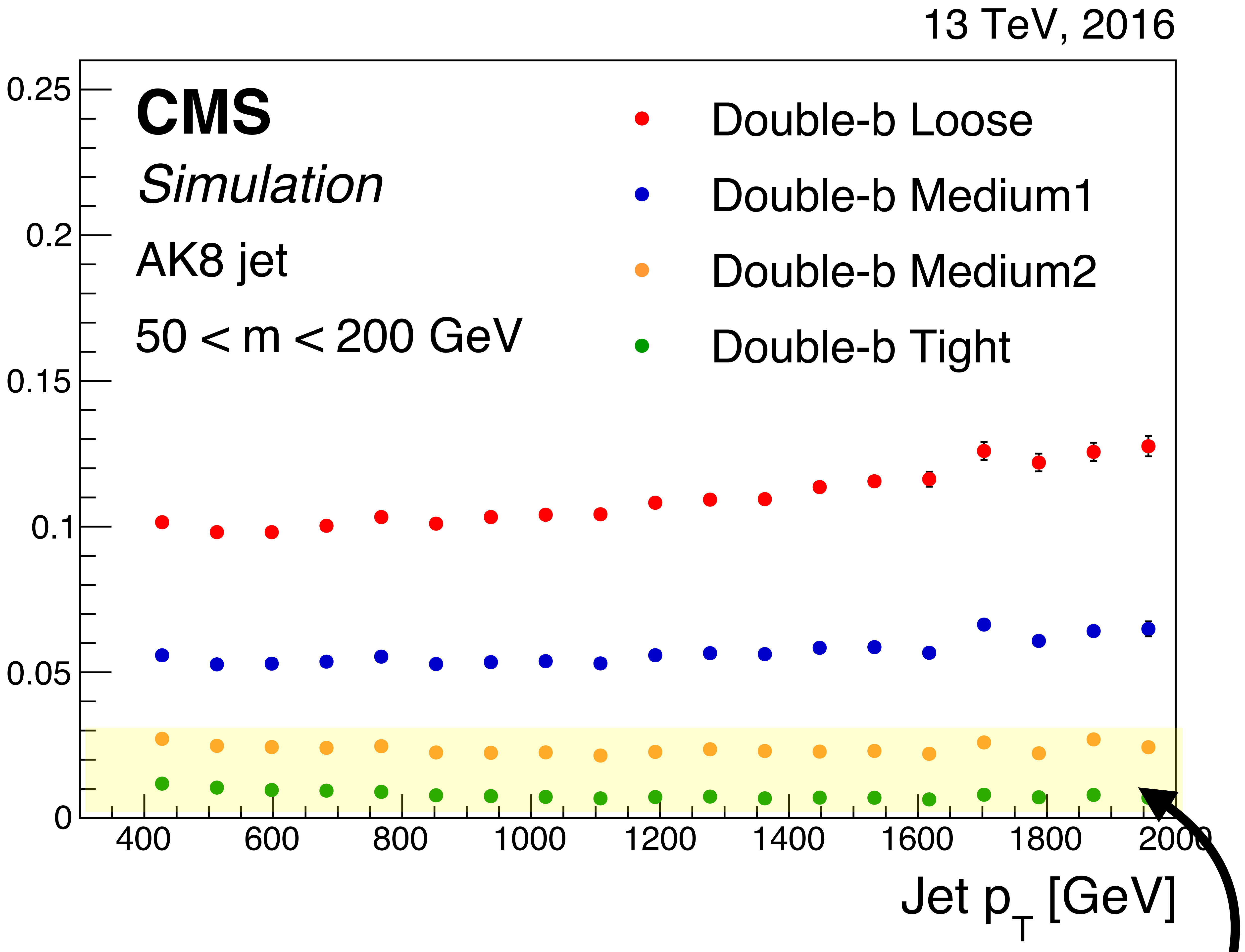
double-b tagger

- Identifies the two B hadron decay chains from b and $\bar{b}$ within the same fat jet.
- It does not define sub-jet but uses N-jettiness axes

arXiv:1712.07158

Performance



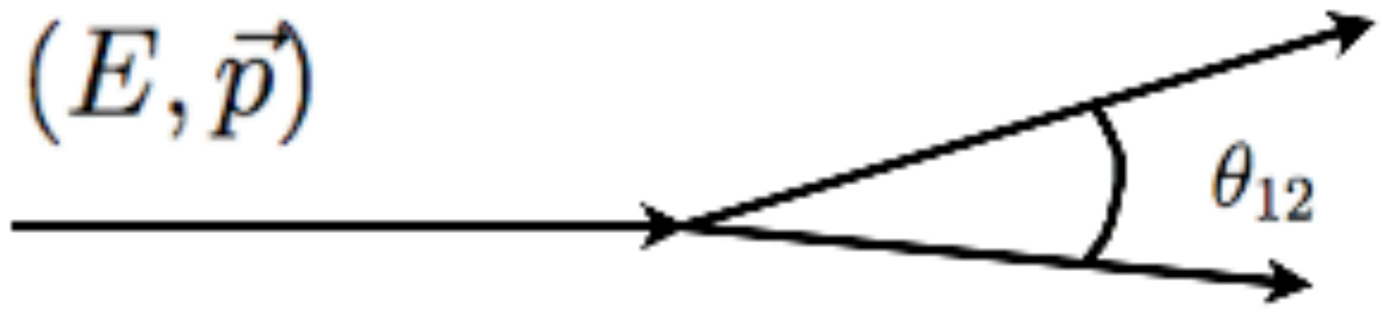


The mistag rate is approximately flat across the p_T range by design

Critical point for searches (background estimate)

Boost

$$p^\mu = (E, \vec{p})$$



$$p_1^\mu = (E_1, \vec{p_1})$$

$$p_2^\mu = (E_2, \vec{p_2})$$

$$\begin{aligned} p^\mu p_\mu &= (p_1 + p_2)^\mu (p_1 + p_2)_\mu \\ m^2 &= (E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2}) \cdot (\vec{p_1} + \vec{p_2}) \\ m^2 &\approx 2E_1 E_2 (1 - \cos(\theta_{12})) \end{aligned}$$

If E1=E2 :

$$\begin{aligned} m^2 &\approx E^2 (1 - \cos(\theta_{12})) \\ \cos(\theta_{12}) &\approx 1 - \frac{m^2}{E^2} \end{aligned}$$

$$\cos(\theta_{12}) \approx 1 - \theta_{12}^2 \approx 1 - \frac{m^2}{E^2}$$

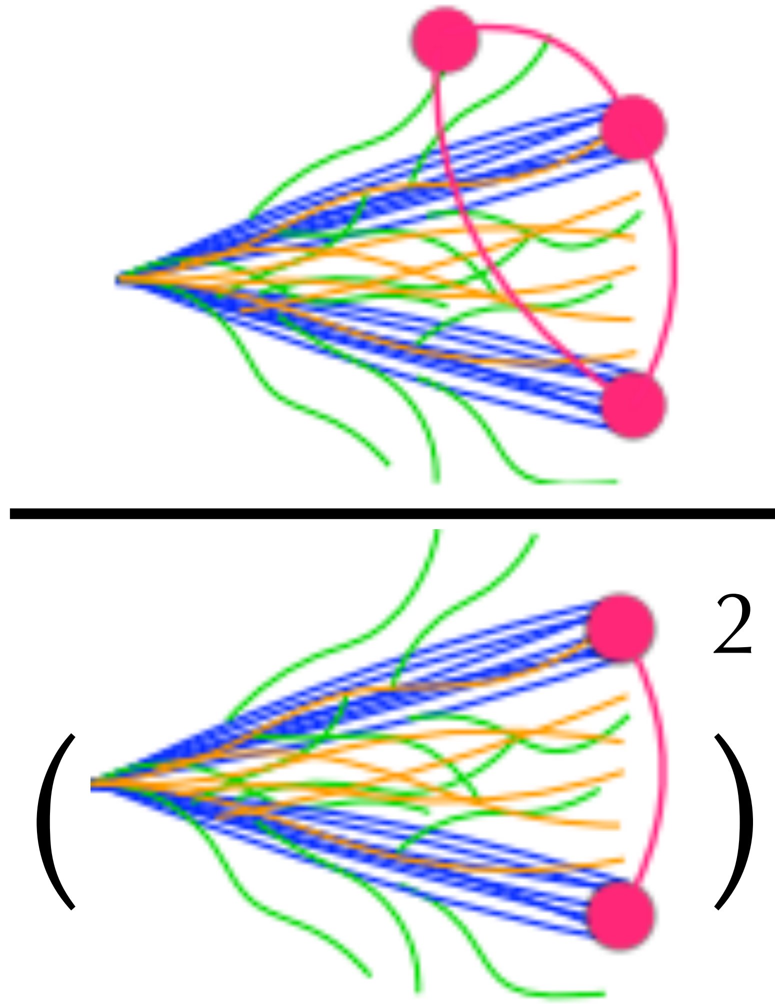
$$\theta \approx \frac{m}{E} = \frac{1}{\gamma}$$

larger is the *boost*, smaller is the angular separation between the two particles

Jet Substructure

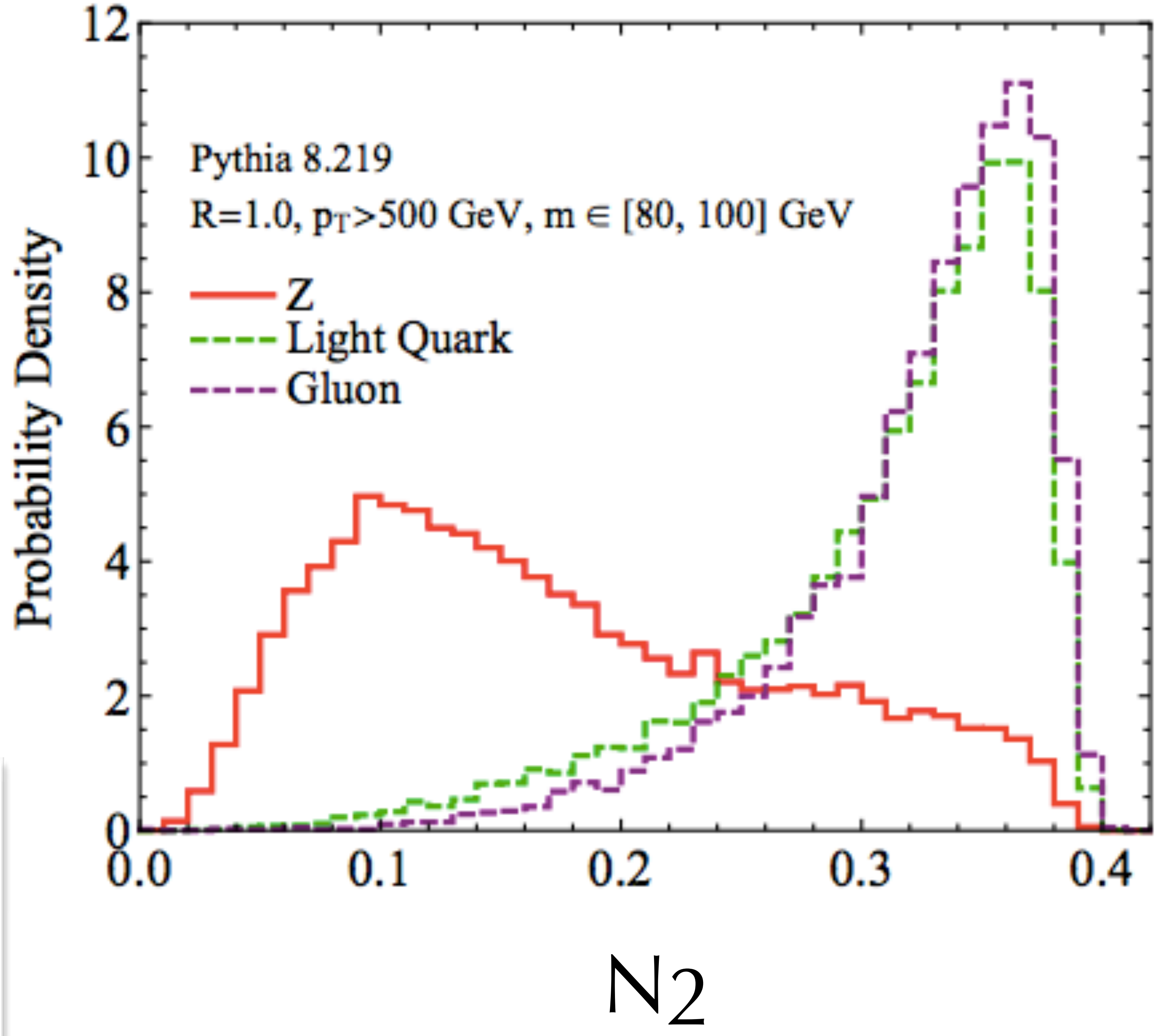
- Measures the degree to which a jet can be considered as composed of N prongs
- **Energy correlation functions** are sensitive to N-point correlations in a jet
  - A 2-pronged jet will have $e_3 < e_2$

$$N_2^\beta = \frac{{}_2e_3^\beta}{({}_1e_2^\beta)^2} =$$



3-point

2-point



$${}_1e_2^\beta = \sum_{1\leq i<j\leq n_j} z_i z_j \Delta R_{ij}^\beta \qquad z_i = \frac{p_{T_i}}{\sum_{j\in \text{jet}} p_{T_j}}$$

$${}_2e_3^\beta = \sum_{1\leq i<j<k\leq n_j} z_i z_j z_k \min\left\{\Delta R_{ij}^\beta \Delta R_{ik}^\beta, \Delta R_{ij}^\beta \Delta R_{jk}^\beta, \Delta R_{ik}^\beta \Delta R_{jk}^\beta\right\}$$

ArXiv:1307.0007
ArXiv:1402.2657

Jet mass

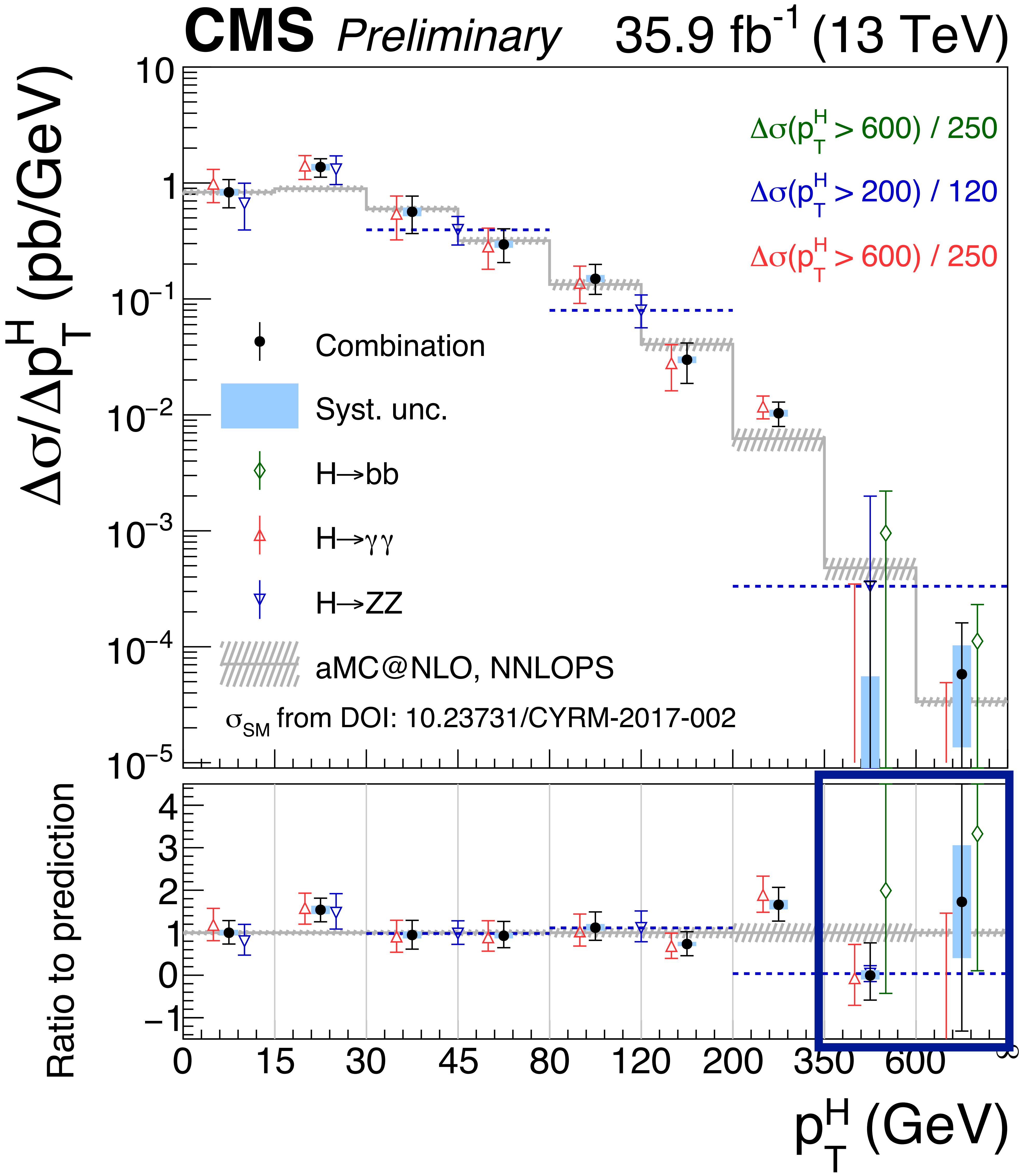
- Provides good separation between H-jets from q/g jets
- **Grooming** removes soft and wide-angle radiation

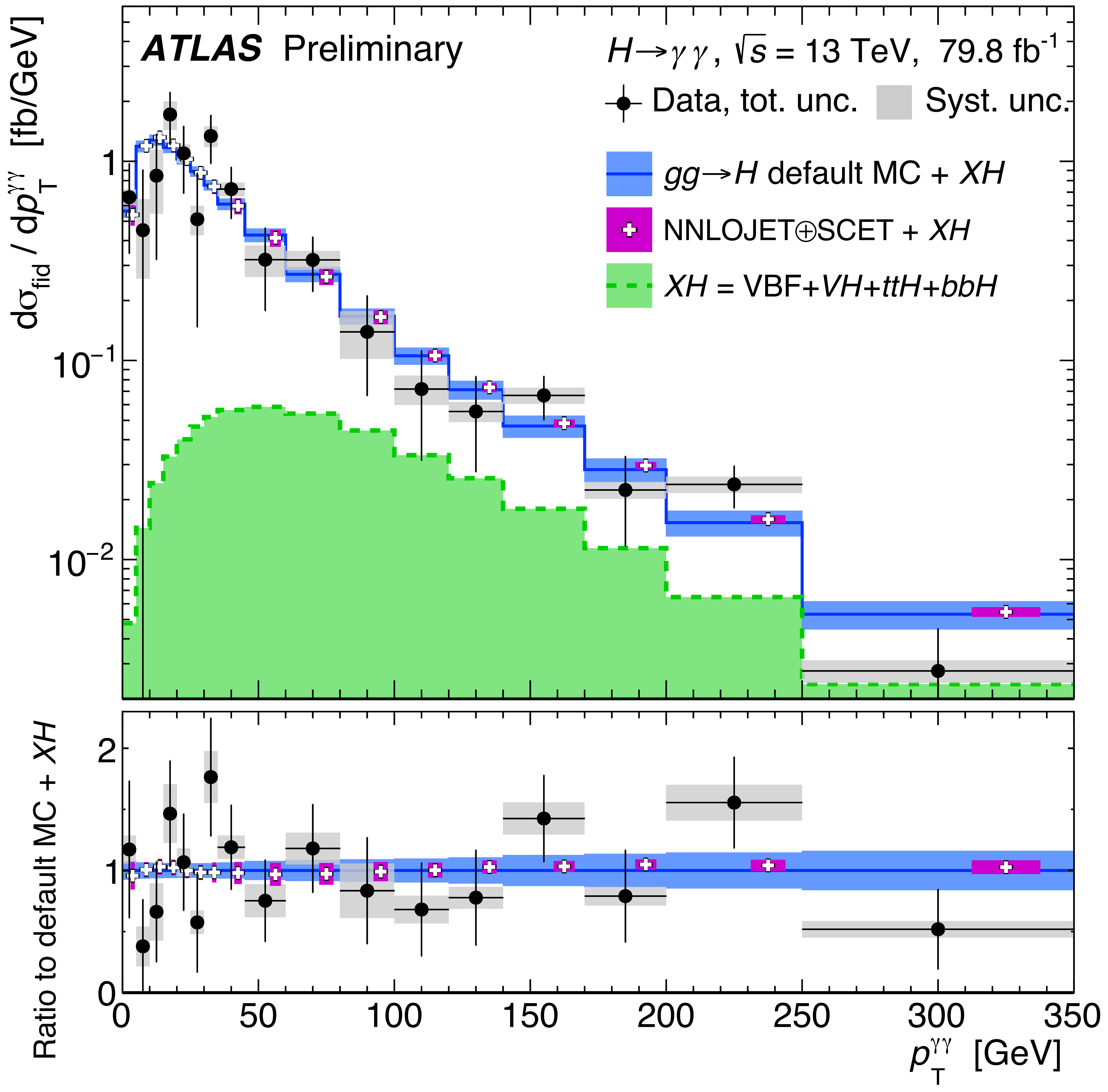
soft drop/modified mass soft drop

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\mathrm{cut}}$$

Probing ggF vs. H p_T

CMS-PAS-HIG-17-028
ATLAS-CONF-2018-028





di-Higgs in BSM

ArXiv:1610.07922
JHEP04(2016)126

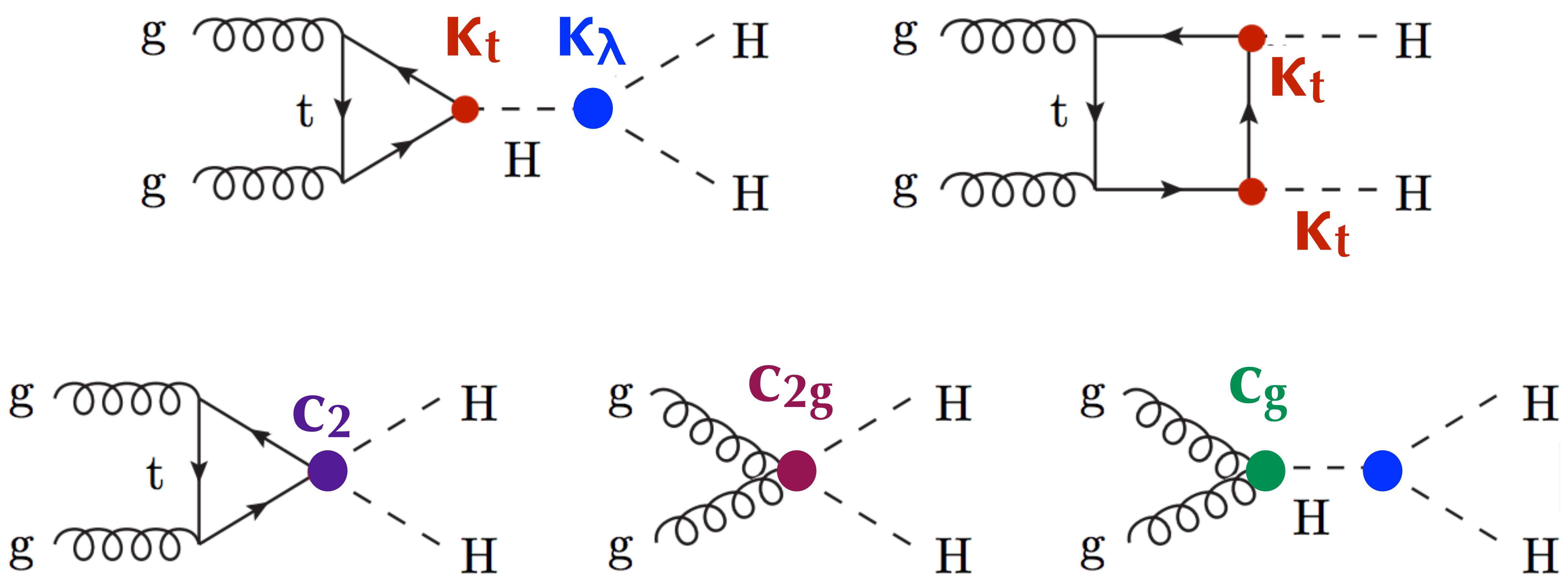
Anomalous Higgs boson couplings

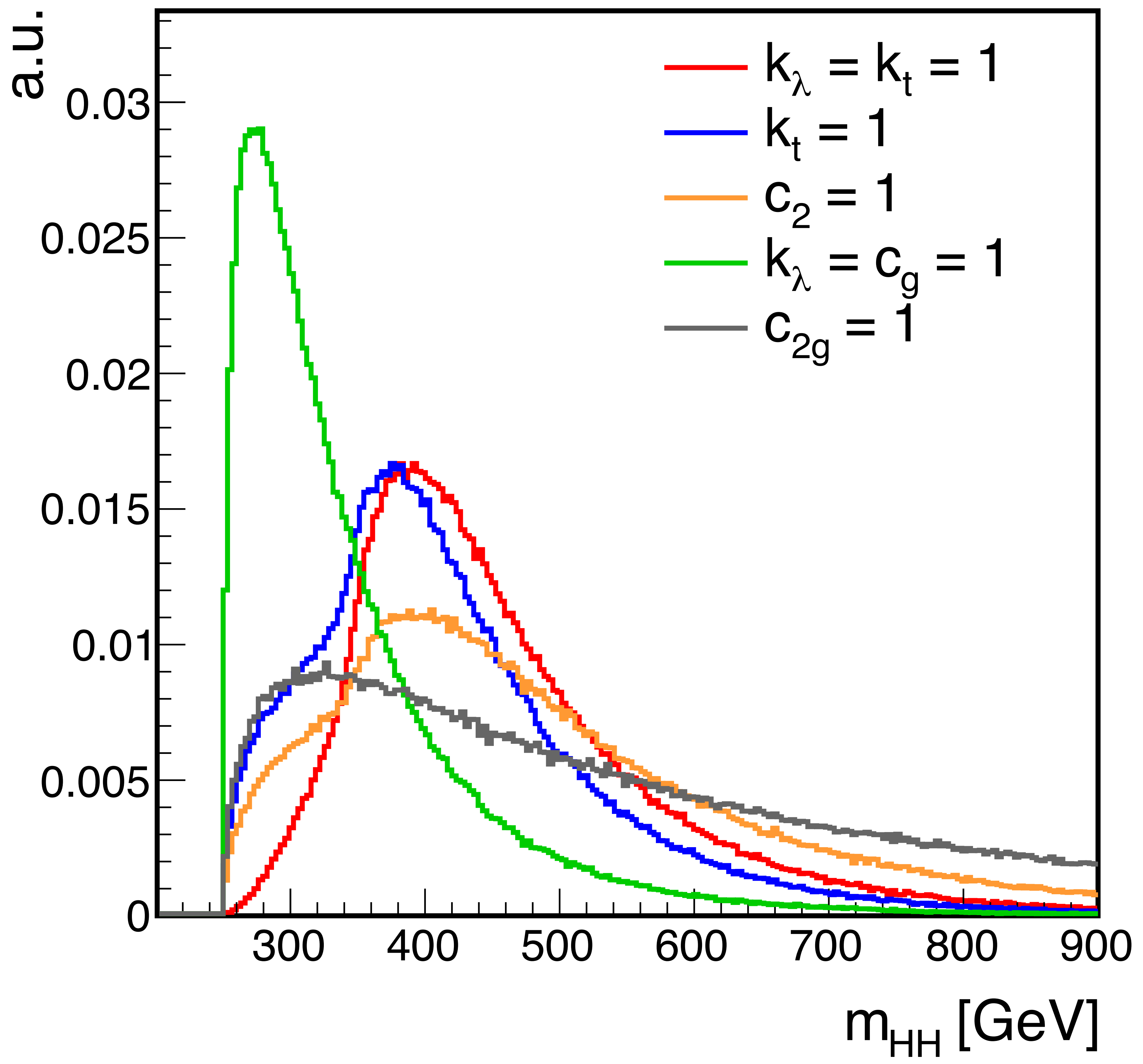
Strong effect on cross-section and m(hh) shape

EFT approach parametrizes new physics (dim 6 operators)

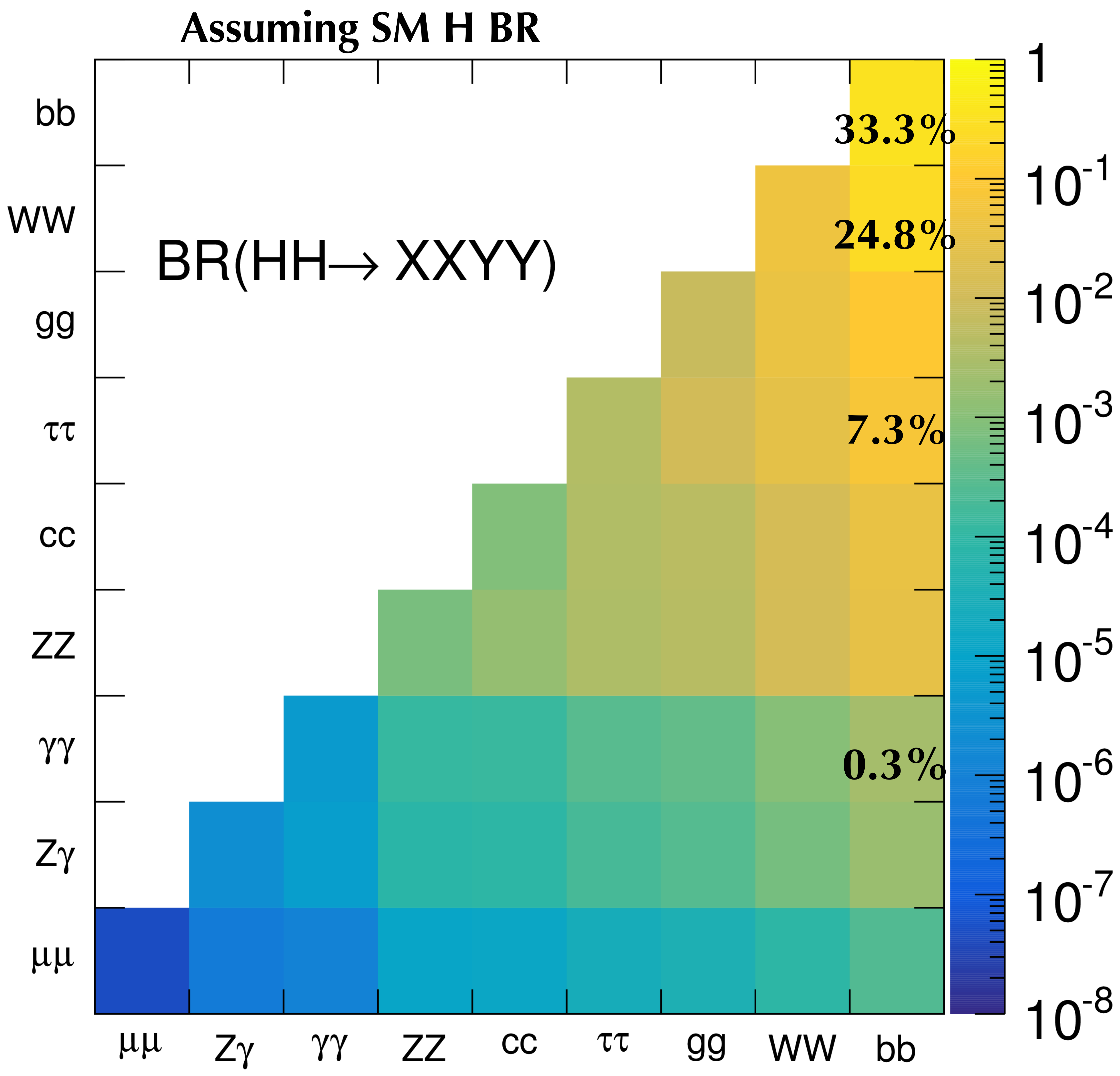
modifications to $\kappa_\lambda = \lambda/\lambda_{SM}$ and $\kappa_t = y_t/y_{t,SM}$

three new interactions: c_2, c_{2g}, c_g





HH, a variety of final states



Complementarity of the channels

$H(b\bar{b})$

highest BR: larger statistics

high b-tag efficiency and low fake rate

multi-light jets background is highly reduced

$H(\gamma\gamma)$

simple topology

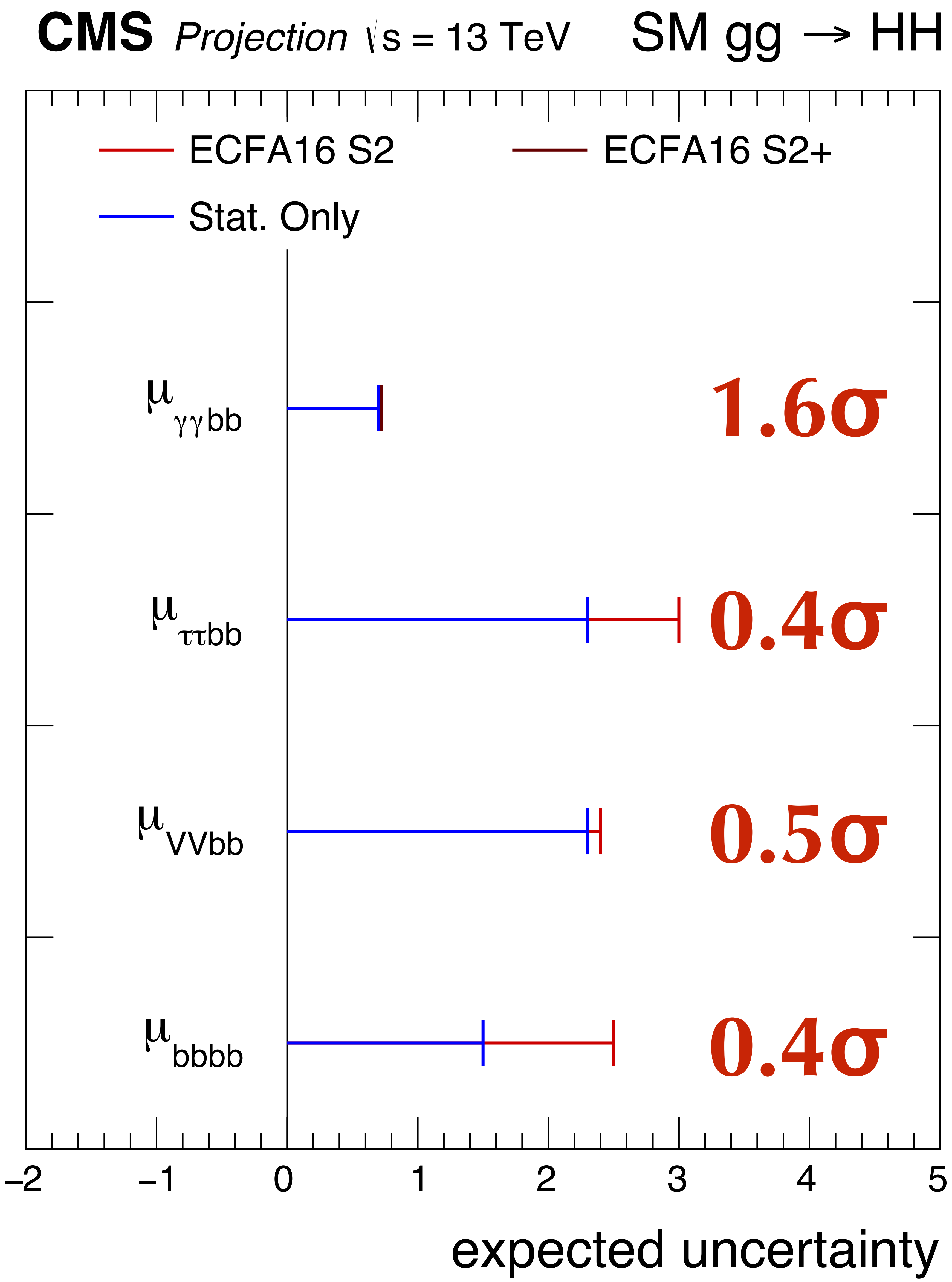
excellent mass resolution

Limited by small BR

Projections for HL-LHC

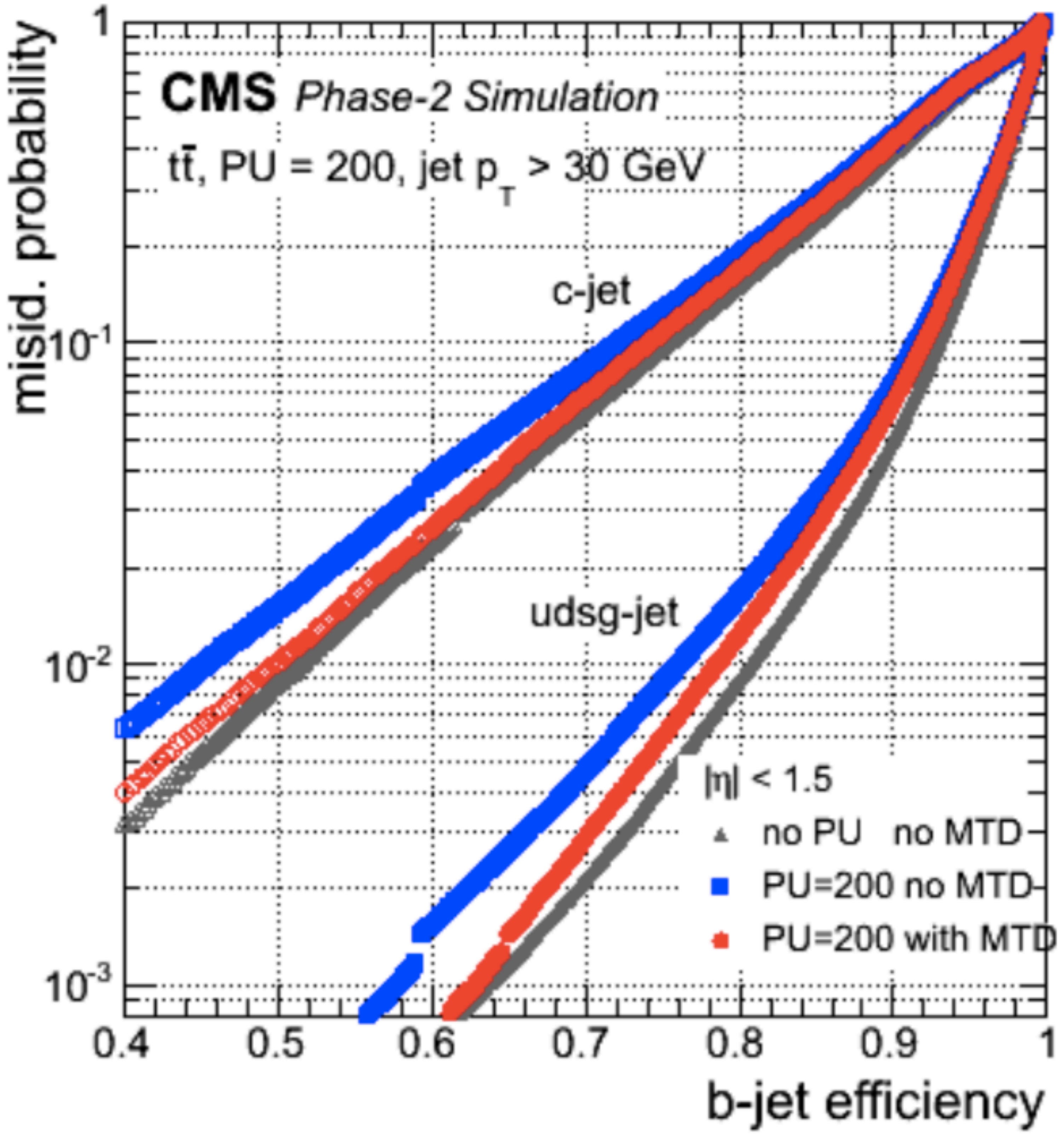
Extrapolation from Run II to HL-LHC (3000 fb^{-1})

- based on 2015 data, about 2.3-2.7fb^{-1}
- Different scenarios:
  - **No systematics**
  - **ECFA16 S2** reduced theory uncertainties and reduced systematics
  - **ECFA16 S2 +** including future detector performance



Considerations about HL-LHC

- ***SM HH discovery is challenging*** but analysis improvements thus far are faster than only luminosity gains
- We will have a **new tracker detector at HL-LHC…**
  - *10% improvement in signal acceptance* for H(b$\bar{b}$)H(b$\bar{b}$) from extended tracker acceptance up to |η| = 4
  - *10-15% increase for the VBF* process
  - b-tagging performance will benefit from a more granular detector
- We will have a **timing detector at HL-LHC…**
  - *~ 30% improvement in light-jet discrimination* by removing spurious tracks entering into secondary vertex reconstructing
  - *~20% increase in effective integrated luminosity for HH*
- **Better background discrimination** from selection optimization with the large dataset



Mip Timing Detector

Channel	Signal increase (%)
HH→ $bb\gamma\gamma$	22
HH→ $b\bar{b}b\bar{b}$	18

On going studies for HL-LHC (towards YR)

CMS-TDR-17-001
CMS-TDR-17-007
arXiv:1704.01953
arXiv:1709.08649

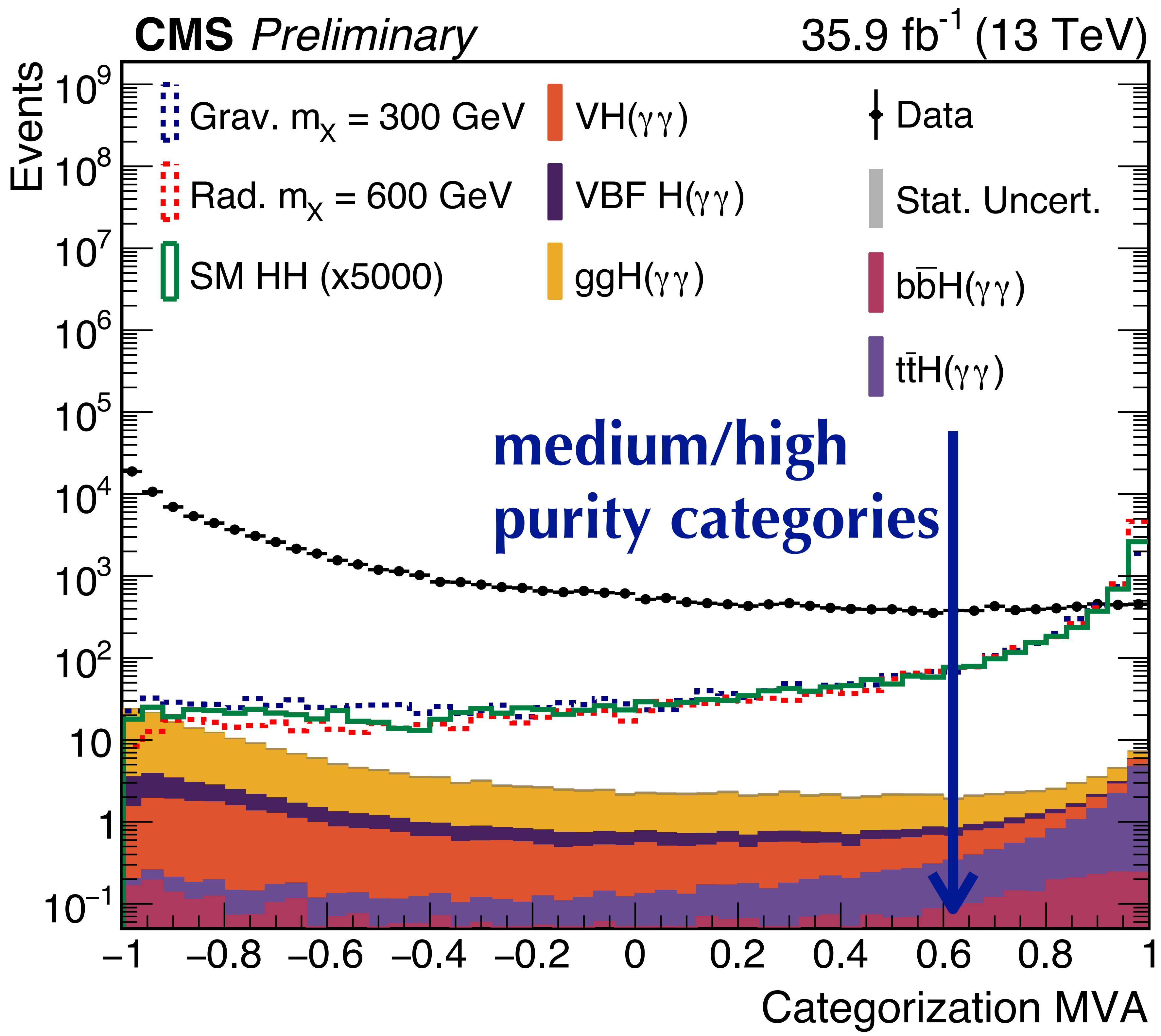
- ***Dedicated analysis for Phase II*** shows that SM HH production can be measured by CMS with approximately **50% precision** using 3000 fb^{-1}
  - $H(b\bar{b})H(b\bar{b})$ not included but a promising channel
- Studies based on **full-sim/Delphes** are on going:
  - $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}VV$, $\boldsymbol{b\bar{b}\tau\tau}$, and VBF for VVHH
- **Combination** of all channels
  - projections from CMS HH 13 TeV combination as reference
  - possible combination with ATLAS
- Possibility to constrain λ_{HHH} further from:
  - **single** H measurement [currently interest in $H(\gamma\gamma)$]
  - $\boldsymbol{m_{HH}}$ **differential information**

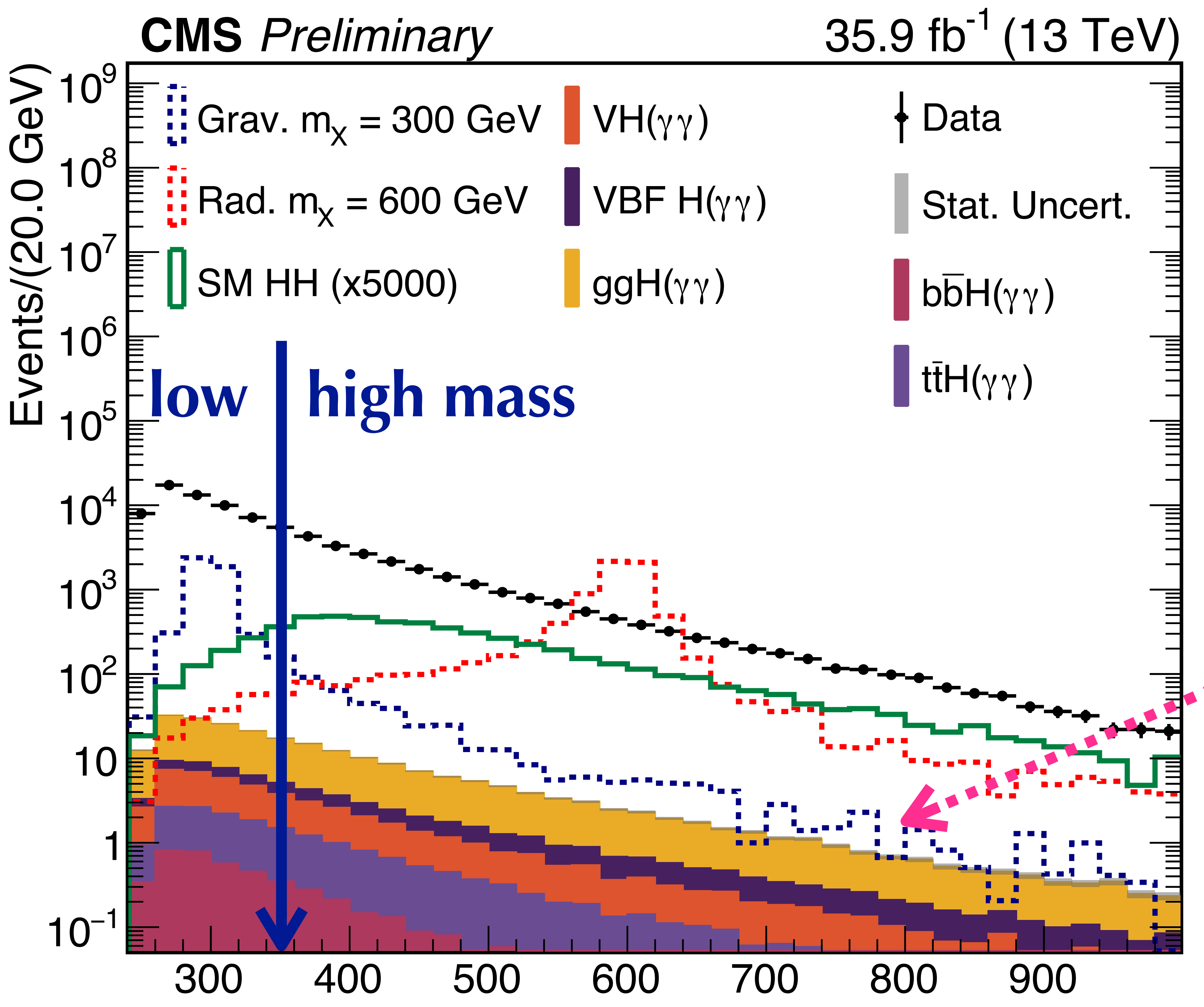
Category	σ_{HH}/σ_{SM}	$\sigma_{ggHH}/\sigma_{SM}$	σ_{VBF}/σ_{SM}
2b0j	1.8	3.0	72.6
VBF	3.9	5.4	86.6
Combined	1.6	2.8	52.2

$b\bar{b}\tau_h\tau_h$ ~ 1.5xSM
(2-3xSM from Run II projections)

$H(\gamma\gamma)H(b\bar{b})$

- 2 photons, $100 < m_{\gamma\gamma} < 180$ GeV
- 2 jets, $70 < m_{jj} < 190$ GeV
- b-jet energy regression to improve $m(b\bar{b})$ resolution
- **Mx** and **BDT (including angular correlations)** classifier used to categorize events





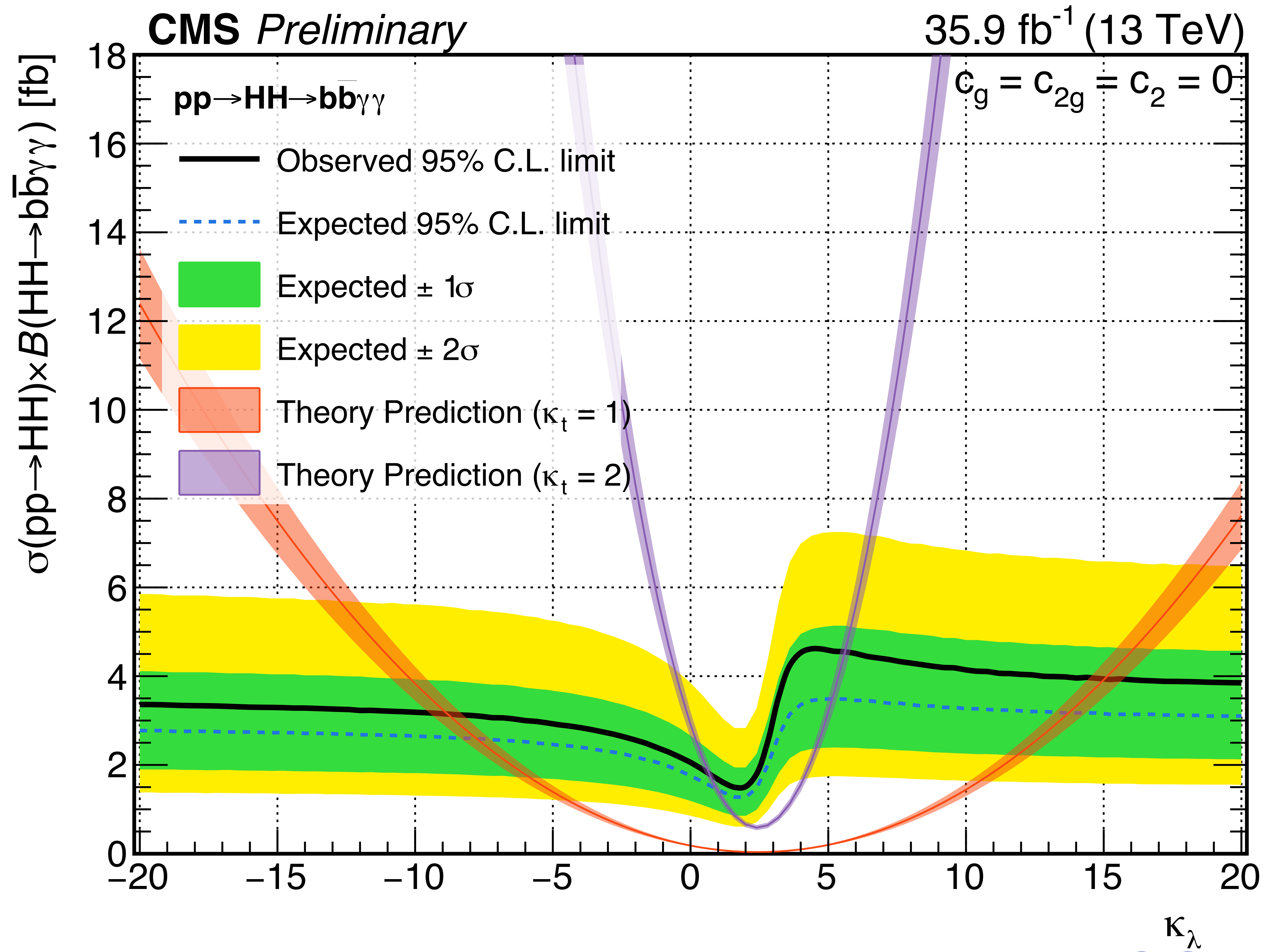
$$M_X = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - m_H) - (m_{\gamma\gamma} - m_H)$$

- photon+jets (prompt photons or jets misidentified as photon) **from data**
- **SM single Higgs** from simulation

H(γγ)H(b$\bar{b}$)

- Likelihood fits simultaneous to m(b$\bar{b}$) and m(γγ)
  - single Higgs background constrained as no resonant structure is expected in the m(b$\bar{b}$) distribution
- The observed (expected) upper limit at 95% CL corresponds to about **19 (16) x SM**
- Anomalous κ_λ coupling tested

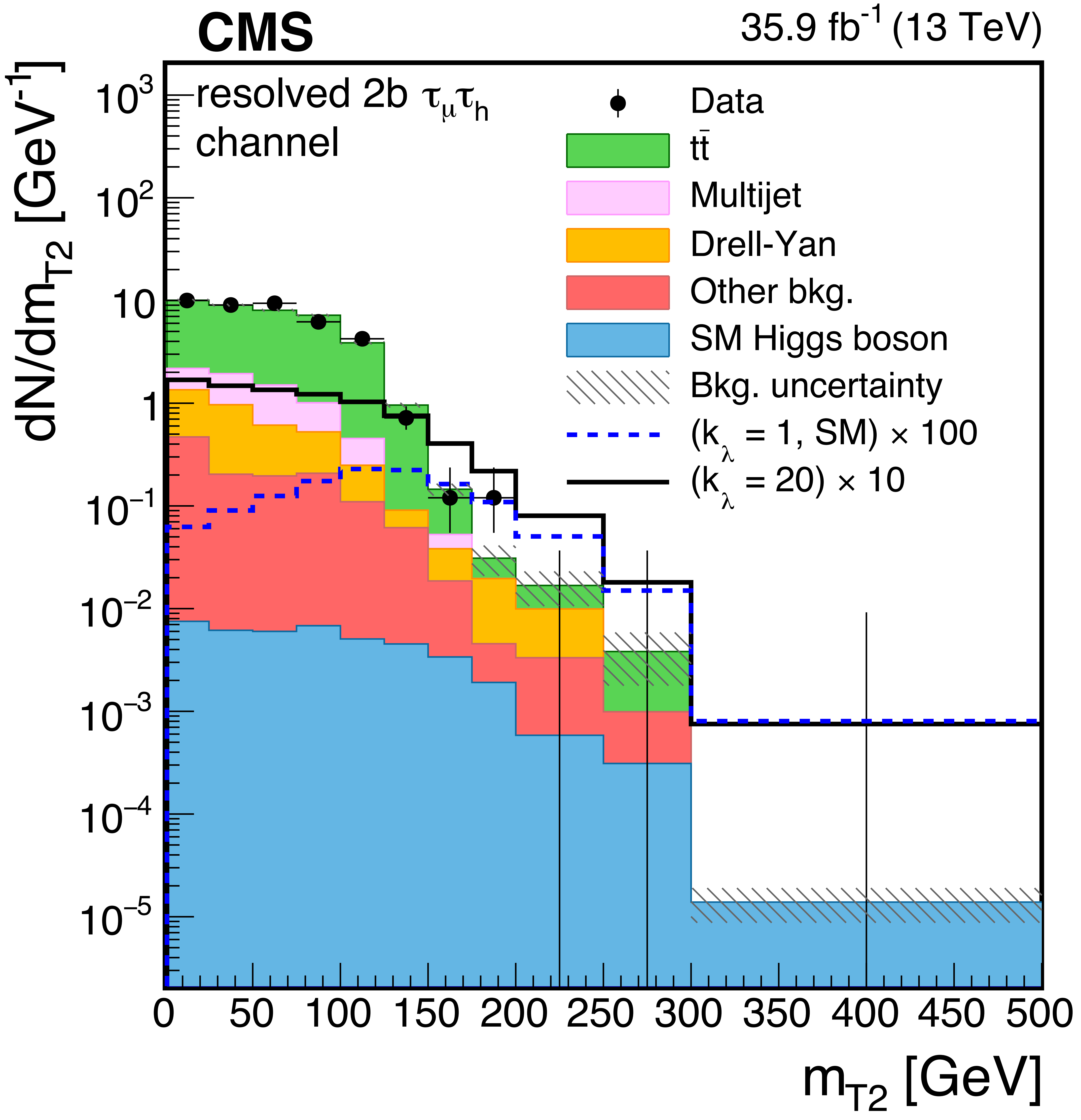
Sources of Systematical Uncertainties	Type	Value
General uncertainties		
Integrated luminosity	Normalization	2.5%
Photon related uncertainties		
Photon energy scale ($\frac{\Delta M(\gamma\gamma)}{M(\gamma\gamma)}$)	Shape	1.0%
Photon energy resolution ($\frac{\Delta\sigma_{\gamma\gamma}}{\sigma_{\gamma\gamma}}$)	Shape	1.0%
Diphoton selection (with trigger uncertainties and PES)	Normalization	2.0%
Photon Identification	Normalization	1.0%
Jet related uncertainties		
Jet energy scale ($\frac{\Delta M(jj)}{M(jj)}$)	Shape	1.0%
Jet energy resolution ($\frac{\Delta\sigma_{jj}}{\sigma_{jj}}$)	Shape	5.0%
Dijet selection (JES)	Normalization	0.5%
Nonresonant specific uncertainties		
$\tilde{M}_X$ Classification	Normalization	0.5%
Classification MVA (high purity)	Normalization	5%
Classification MVA (medium purity)	Normalization	2.0%



$H(\tau\tau)H(b\bar{b})$

- $\tau_h\tau_\mu+\tau_h\tau_e+\tau_h\tau_h$ (88%)
- 2 jets (resolved) or 1 large-R jet (boosted)
- Likelihood fit to estimate $m(\tau\tau)$ (despite the missing energy)
- $m(b\bar{b})$ and $m(\tau\tau)$ compatible with m_H
- Events are then categorized by number of b-tags
- **Main backgrounds**:
  - top, Z/γ^*+jets (from MC)
  - multijet (from data)
- **BDT** to reject top background in $\tau_h\tau_\mu+\tau_h\tau_e$
  - based on angular separation of leptons and visible mass
- **stranverse mass** (m_{T2}) used to extract the signal

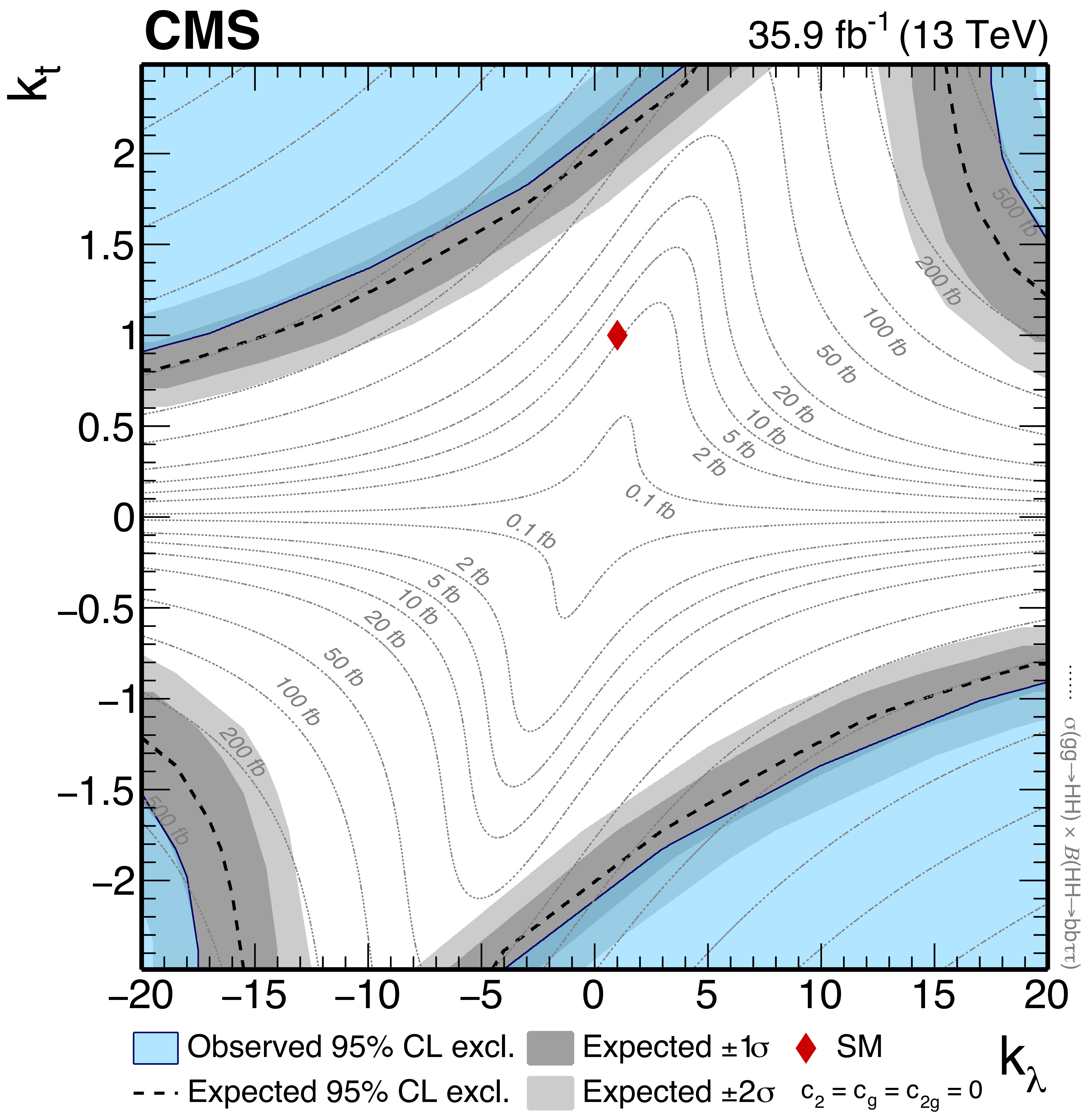
$$m_{T2} = \min_{p_{T1}+p_{T2}=p_T^{\tau\tau}} \{\max(m_T, m'_T)\}$$



$H(\tau\tau)H(b\bar{b})$

- The observed (expected) upper limit at 95% CL corresponds to about 30 (25) x SM
- Anomalous κ_λ and κ_t couplings tested

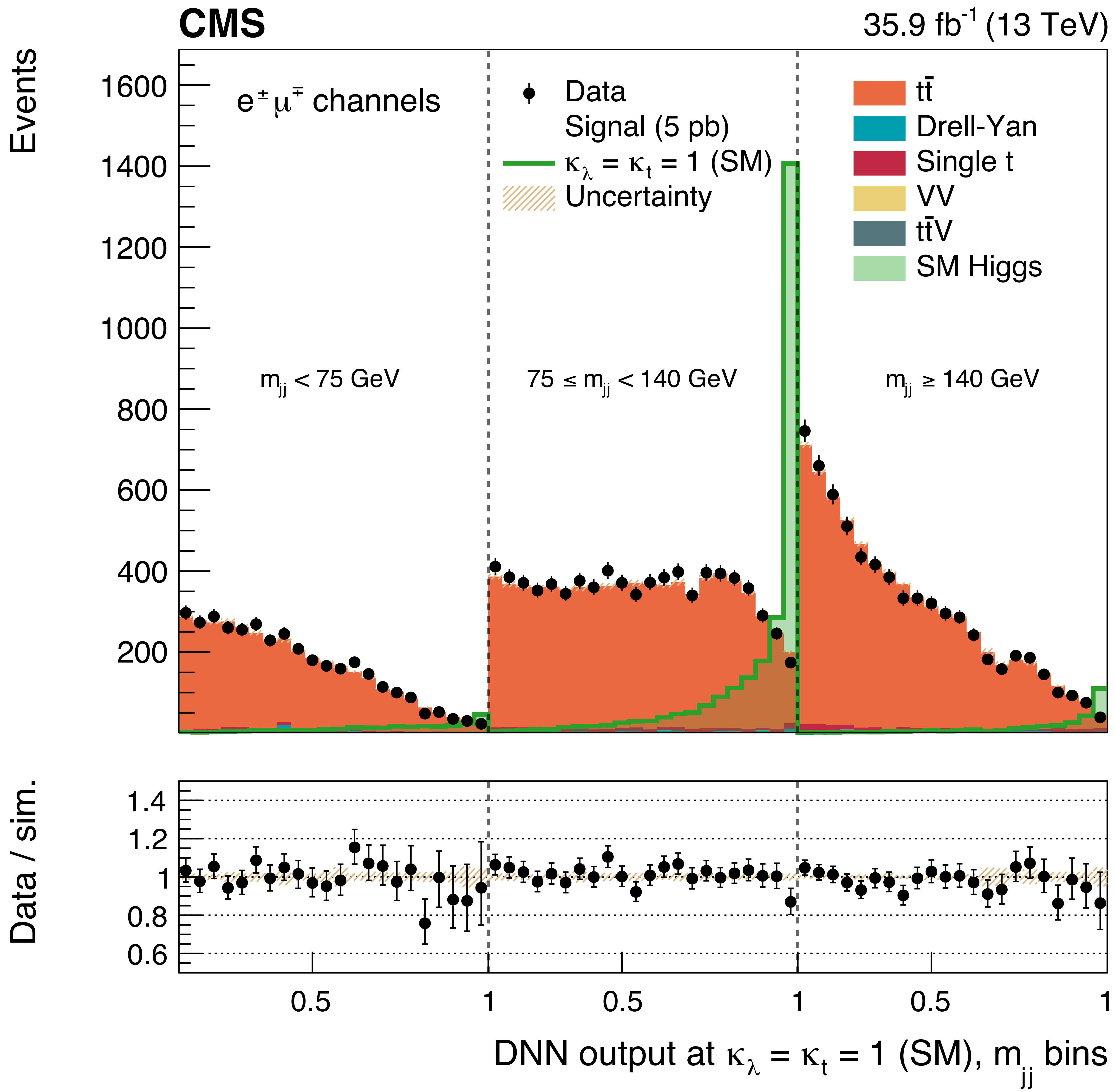
Systematic uncertainty	Value	Processes
Luminosity	2.5%	all but multijet, $Z/\gamma^* \to \ell\ell$
Lepton trigger and reconstruction	2–6%	all but multijet
τ energy scale	3–10%	all but multijet
Jet energy scale	2–4%	all but multijet
b tag efficiency	2–6%	all but multijet
Background cross section	1–10%	all but multijet, $Z/\gamma^* \to \ell\ell$
$Z/\gamma^* \to \ell\ell$ SF uncertainty	0.1–2.5%	$Z/\gamma^* \to \ell\ell$
Multijet normalization	5–30%	multijet
Scale unc.	+4.3%/−6.0%	signals
Theory unc.	5.9%	signals



JHEP 01 (2018) 054

$H(VV^* \rightarrow l\nu l\nu)H(b\bar{b})$

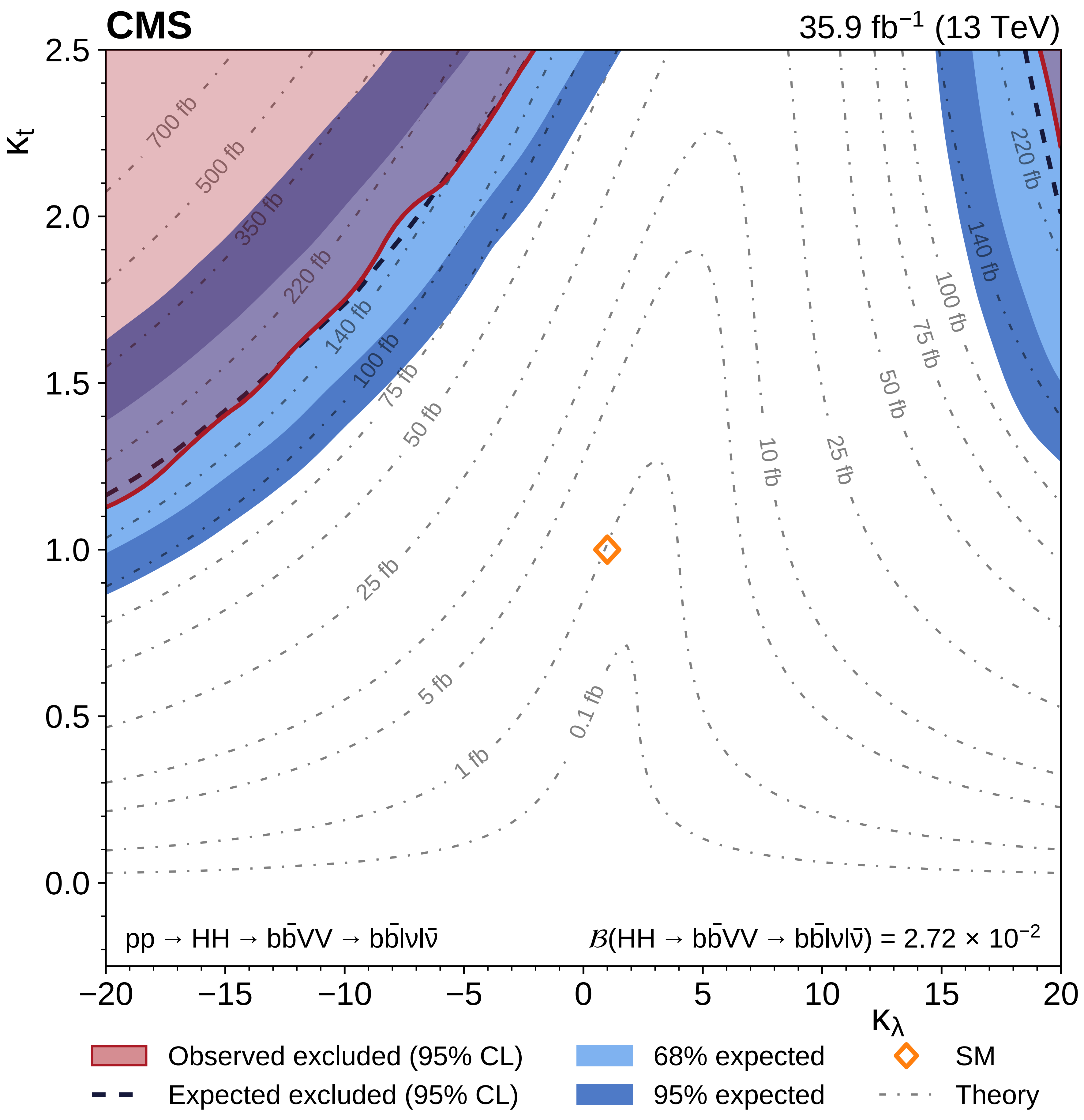
- 2 opposite sign leptons (ee, μμ and eμ+μe) and 2 b-jets
- **Backgrounds**:
  - top (from MC)
  - Z+jets (from 0 b-jets data)
- **DNN** based on the event kinematic to separate signal and top background
  - Parametrized DNN as function of κ_λ and κ_t
- $\mathbf{m_{jj}}$ and **DNN** classifier used to categorize events



$H(VV^* \to l\nu l\nu)H(b\bar{b})$

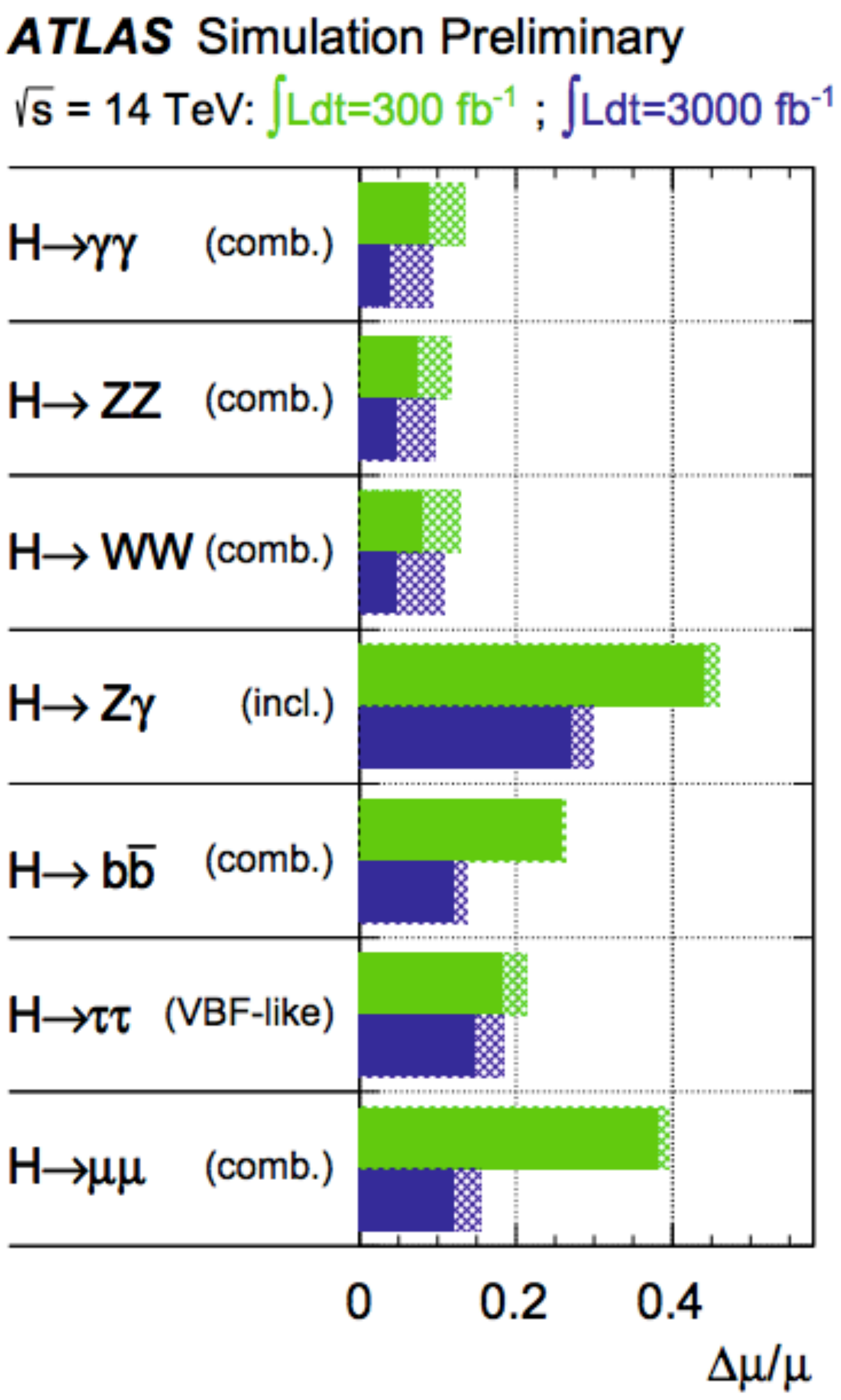
- The final DNN discriminant is used in three m($b\bar{b}$) regions
- The observed (expected) upper limit at 95% CL corresponds to about **79 (89) x SM**
- Anomalous κ_λ and κ_t couplings tested

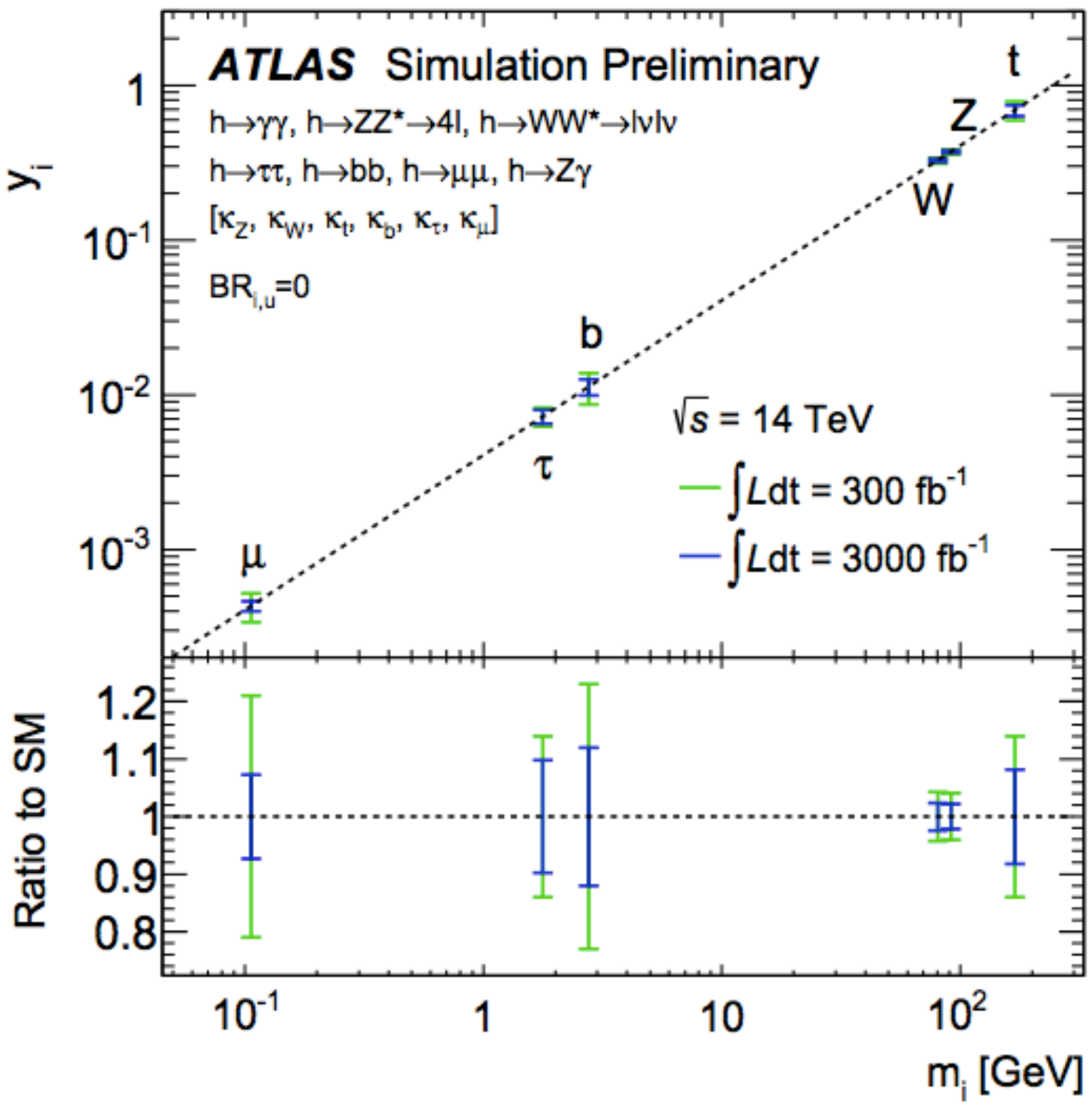
Source	Background yield variation	Signal yield variation
Electron identification and isolation	2.0–3.2%	1.9–2.9%
Jet b tagging (heavy-flavour jets)	2.5%	2.5–2.7%
Integrated luminosity	2.5%	2.5%
Trigger efficiency	0.5–1.4%	0.4–1.4%
Pileup	0.3–1.4%	0.3–1.5%
Muon identification	0.4–0.8%	0.4–0.7%
PDFs	0.6–0.7%	1.0–1.4%
Jet b tagging (light-flavour jets)	0.3%	0.3–0.4%
Muon isolation	0.2–0.3%	0.1–0.2%
Jet energy scale	<0.1–0.3%	0.7–1.0%
Jet energy resolution	0.1%	<0.1%
Affecting only $t\bar{t}$ (85.1–95.7% of the total bkg.)		
μ_R and μ_F scales	12.8–12.9%	
$t\bar{t}$ cross section	5.2%	
Simulated sample size	<0.1%	
Affecting only DY in $e^{\pm}\mu^{\mp}$ channel (0.9% of the total bkg.)		
μ_R and μ_F scales	24.6–24.7%	
Simulated sample size	7.7–11.6%	
DY cross section	4.9%	
Affecting only DY estimate from data in same-flavour events (7.1–10.7% of the total bkg.)		
Simulated sample size	18.8–19.0%	
Normalisation	5.0%	
Affecting only single top quark (2.5–2.9% of the total bkg.)		
Single t cross section	7.0%	
Simulated sample size	<0.1–1.0%	
μ_R and μ_F scales	<0.1–0.2%	
Affecting only signal	SM signal	m_X = 400 GeV
μ_R and μ_F scales	24.2%	4.6–4.7%
Simulated sample size	<0.1%	<0.1%



Projected sensitivity to Higgs couplings at HL-LHC

ATL-PHYS-PUB-2014-016





Projected sensitivity to Higgs couplings

in %	HL-LHC	FCC-ee 350 GeV
g_{HZ}	2-4	0.21
g_{HW}	2-5	0.43
g_{Hb}	5-7	0.64
g_{Hc}	-	1.04
g_{Hg}	3-5	1.18
$g_{H\tau}$	5-8	0.81
$g_{H\mu}$	5	8.79
$g_{H\gamma}$	2-5	2.12
Γ_H	5-8%	1.55

arXiv:1307.7135 arXiv:1308.6176

M. Klute, 2nd FCC Physics Workshop, Jan 16th, 2018

FCC-hh provides complementary measurements:

- rare decays (BR(μμ), BR(Zγ)) measurements will be statistically limited at FCC-ee
- top Yukawa aiming at **1% precision**
- **Higgs self-coupling**

arXiv:1506.05992