

Higgs to beauty quarks

First observation of the big missing piece

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BNL
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U.S. DEPARTMENT OF
ENERGY

Office of Science



Outline

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

The Higgs boson

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

- **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, $\sim 25 \text{ fb}^{-1}$ delivered in **Run-1** at 7 and 8 TeV

On average $\sim 10\text{-}20$ p-p interactions per bunch crossing (**pileup**)

2015-2018, $\sim 150 \text{ fb}^{-1}$ delivered in **Run-2** at 13 TeV

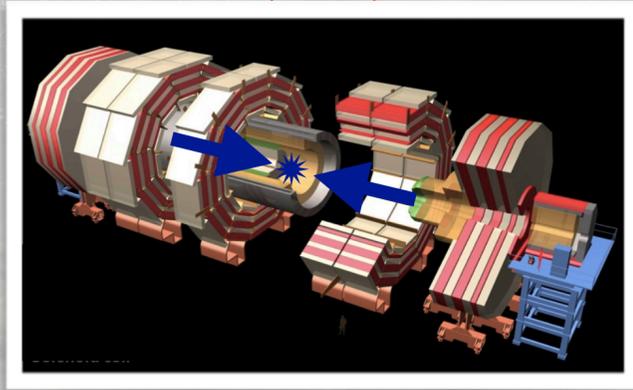
the last big jump in energy for a while, on average $\sim 30\text{-}40$ pileup



ATLAS



CMS



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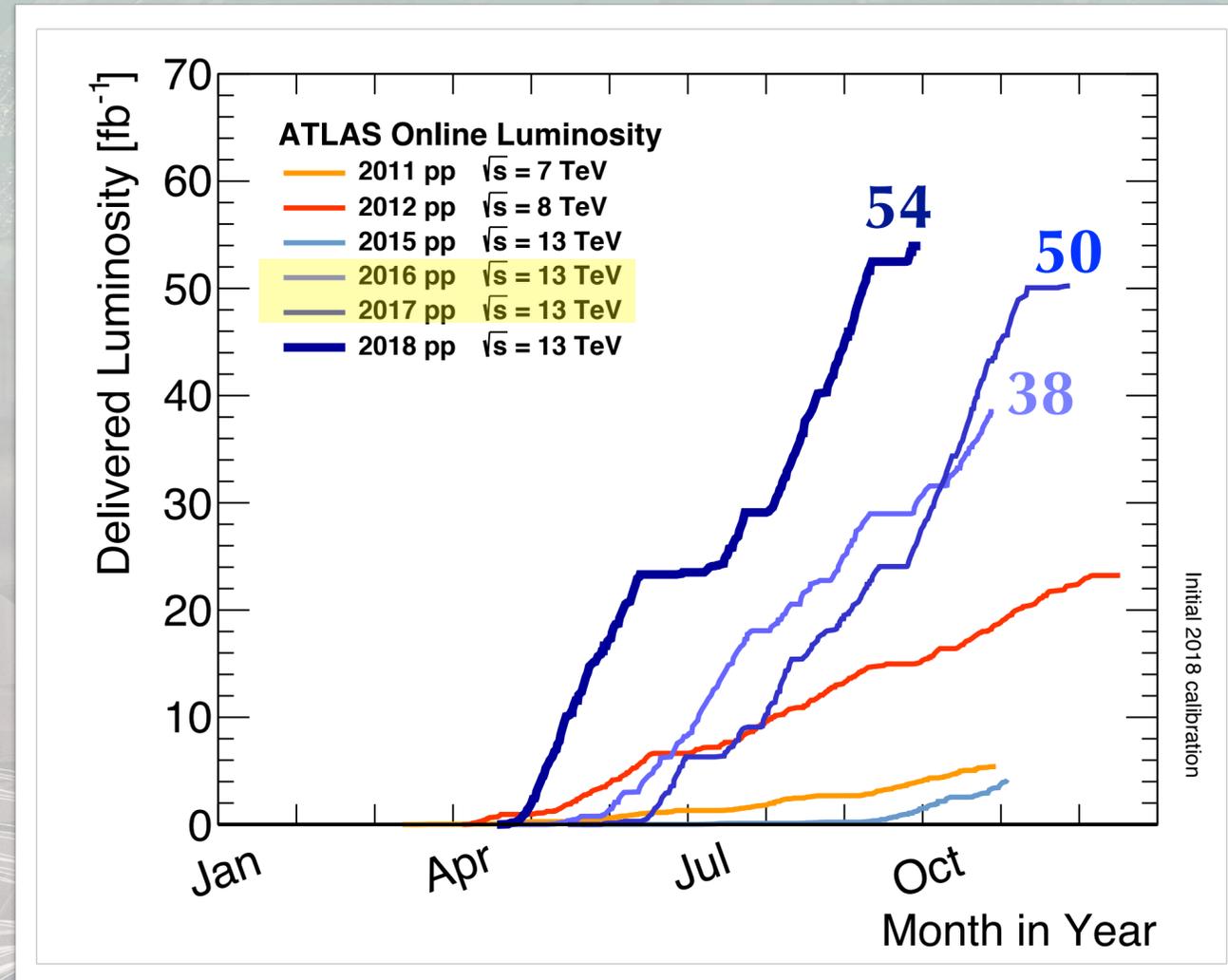
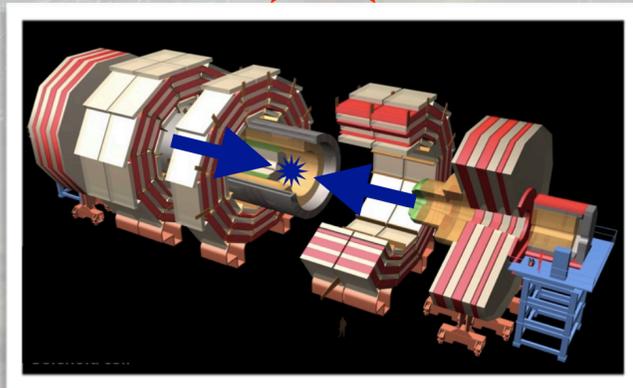
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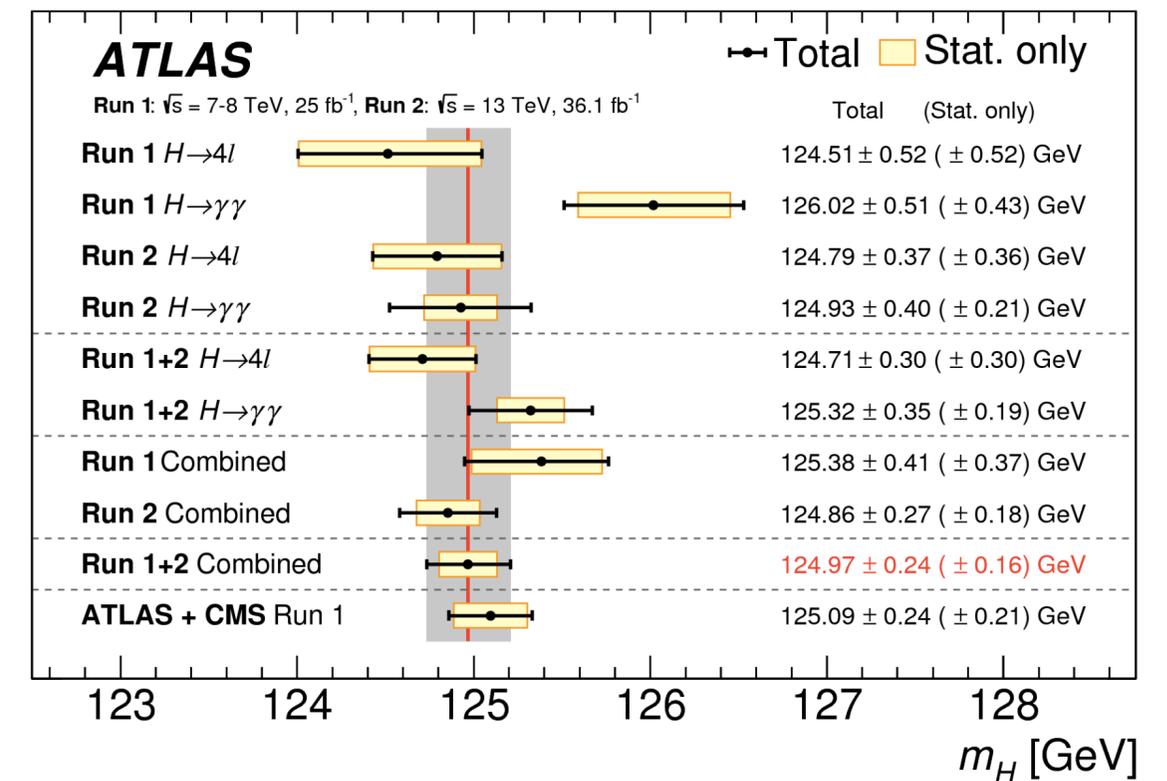
*A factor 10x more data
that at the time of the
Higgs discovery*

Is it a *SM* Higgs boson?

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

Is it a SM Higgs boson?

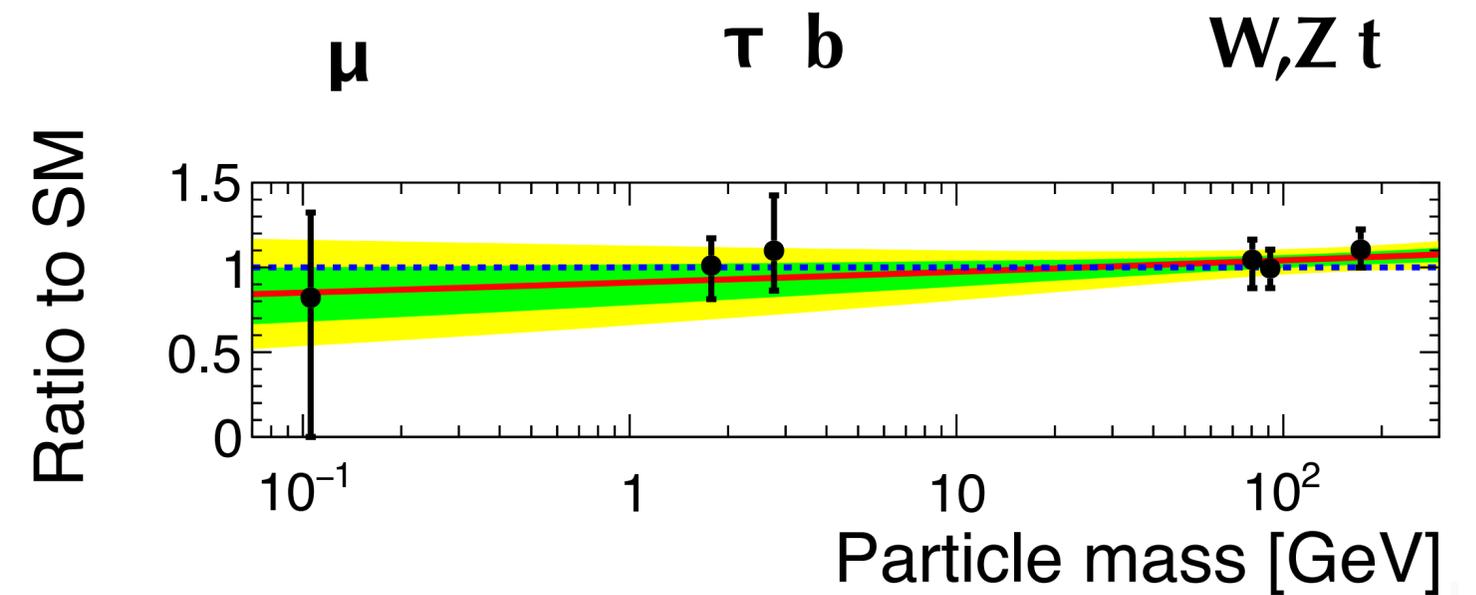
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CMS $H \rightarrow ZZ \rightarrow 4l$
 $m_H = 125.26 \pm 0.20$ (stat.) ± 0.08 (sys.) GeV

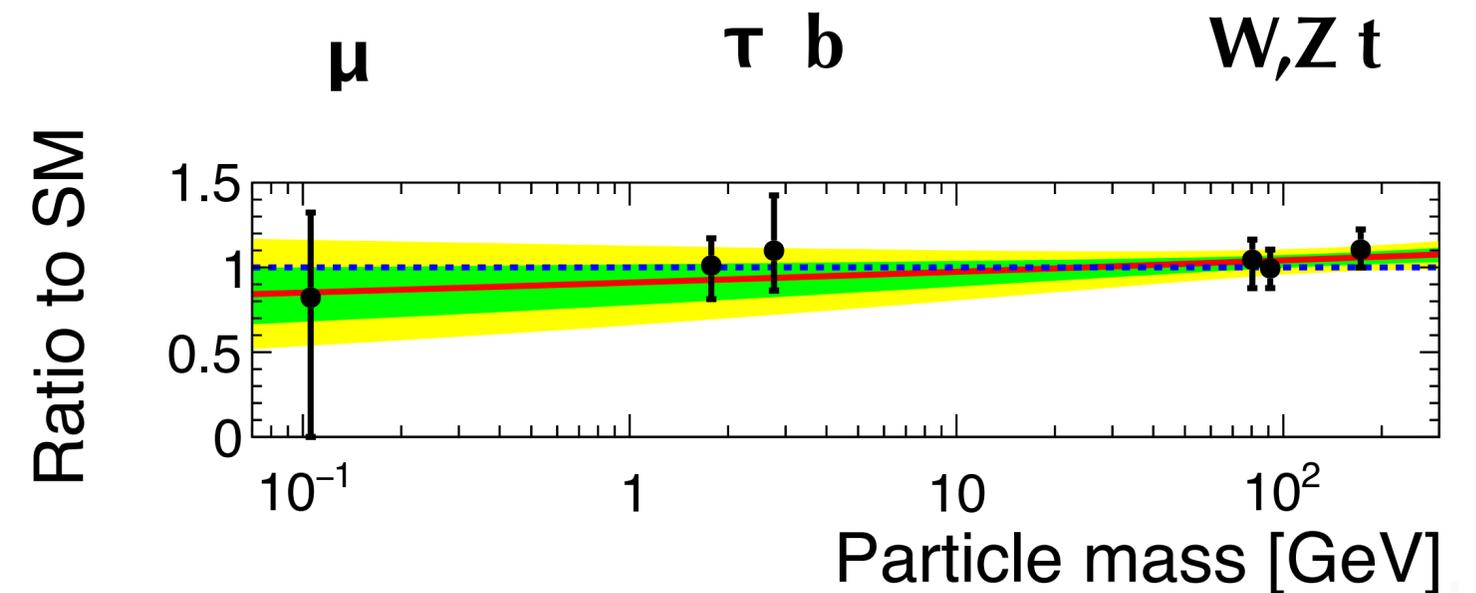
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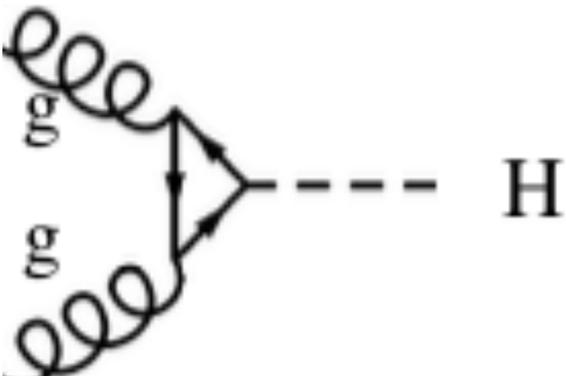
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***Couplings to W and Z established in Run-1 and to τ -leptons in Run-2
Missing direct test of the coupling of the Higgs boson to quarks...***

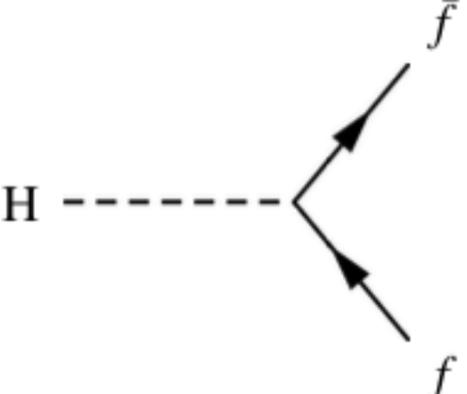
Couplings to Quarks

Indirect

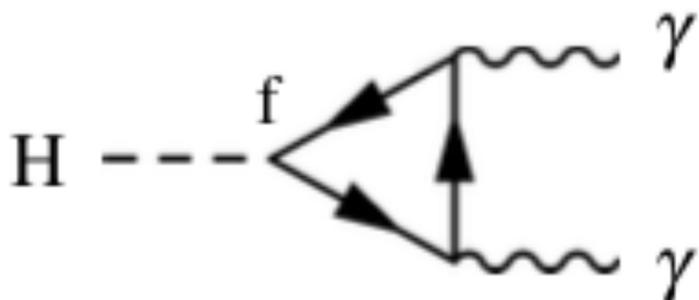


Gluon fusion

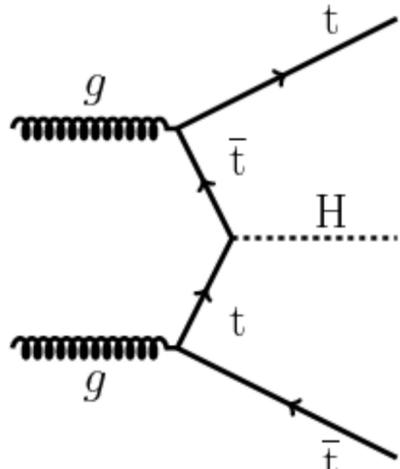
Direct



$H \rightarrow b\bar{b}$



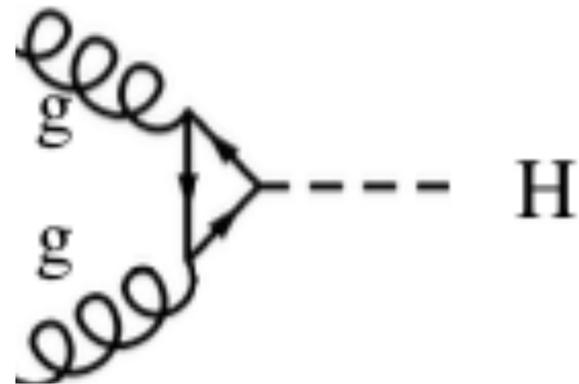
$H \rightarrow \gamma\gamma$



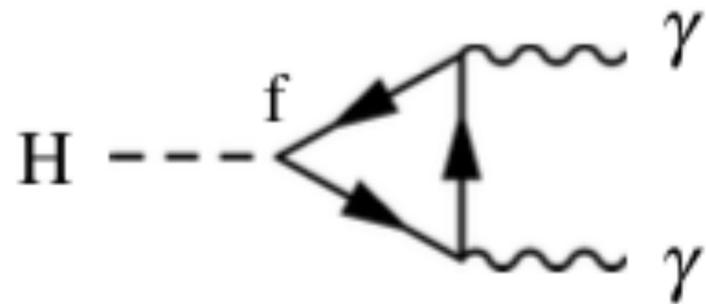
$t\bar{t}H$

Couplings to Quarks

Indirect

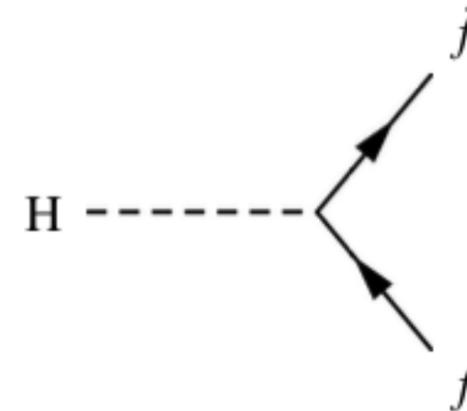


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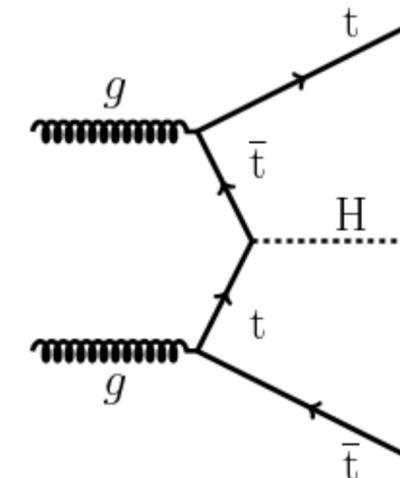


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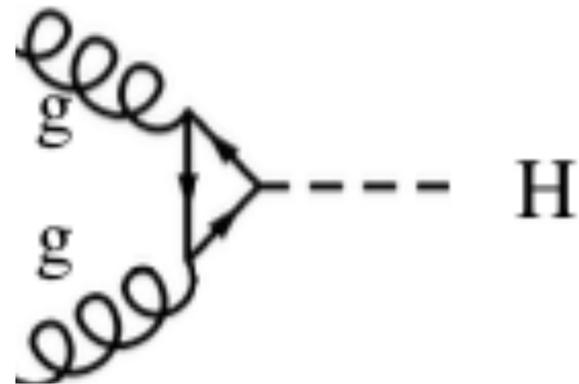


$t\bar{t}H$

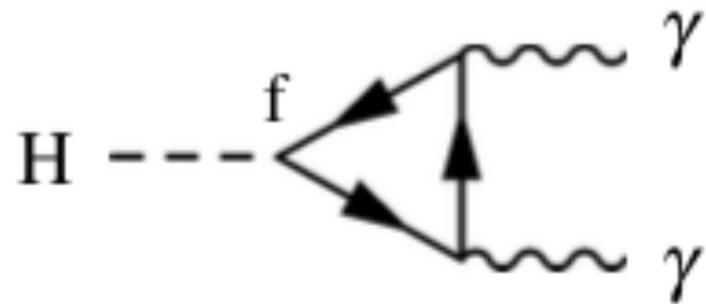
We have just observed the $t\bar{t}H$ process
CMS Run 1+2 (25+36/fb): 5.2σ (4.2σ exp.)
ATLAS Run 1+2 (25+80/fb): 6.3σ (5.1σ exp.)

Couplings to Quarks

Indirect

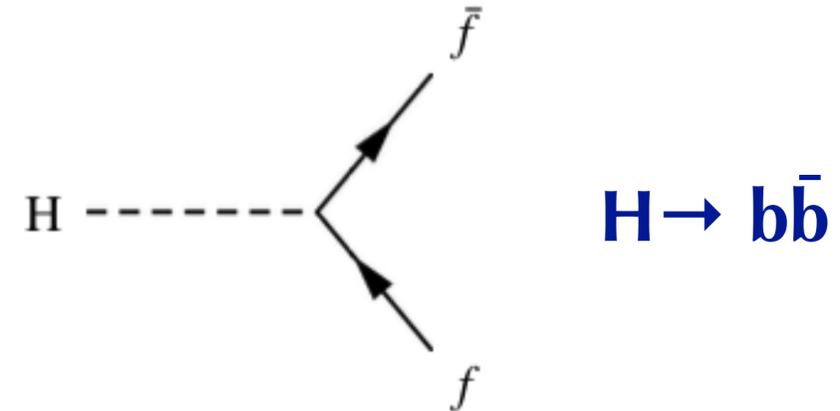


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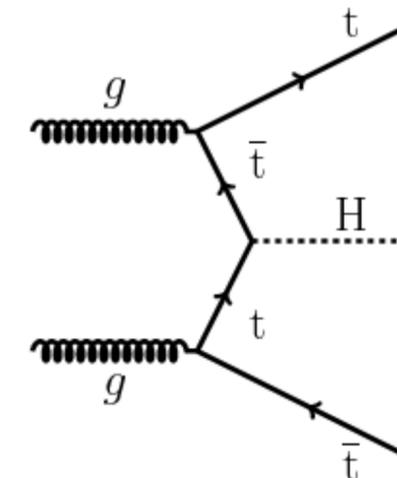
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Direct



$H \rightarrow b\bar{b}$

NEW



$t\bar{t}H$

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

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“ uncertainty of $\pm 5\%$ on the shape of the $Wb\bar{b}$ background in the $H \rightarrow b\bar{b}$ signal region. In conclusion, the extraction of a signal from $H \rightarrow b\bar{b}$ decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions for the b -tagging performance and calibration of the shape and magnitude of the various background sources from the data itself. ”

— SNOWMASS-2001-P111

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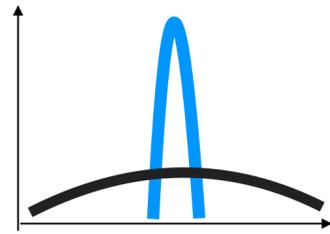
— SNOWMASS-2001-P111

“ $H \rightarrow b\bar{b}$, which has the largest branching ratio in this mass range. Due to the huge backgrounds from QCD jet production in this decay mode, only the associated production modes have sensitivity. It has been demonstrated that the discovery potential for a Standard Model Higgs boson in the WH production mode at the LHC is marginal.^{68,97,98} It is limited by large backgrounds from $Wb\bar{b}$, ”

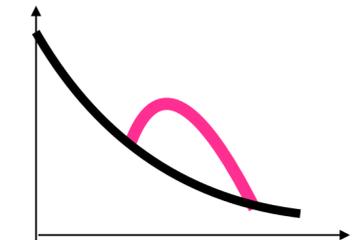
— Int. J. Mod. Phys. A 20:2523-2602, 2005

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

Comparison with one of the discovery channels



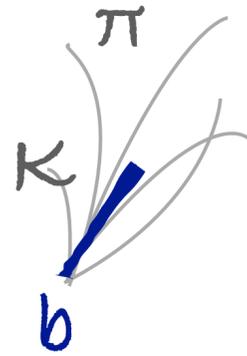
	$H \rightarrow 4\ell$	$H \rightarrow b\bar{b}$
Branching Ratio	0.03%	58%
mass resolution	1%	10%
S/B	2	0.05



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

- good **b-quark identification** performance
- best possible **resolution on $m(b\bar{b})$**
- to exploit all possible information from the event to **improve S/B**

b-quark Identification



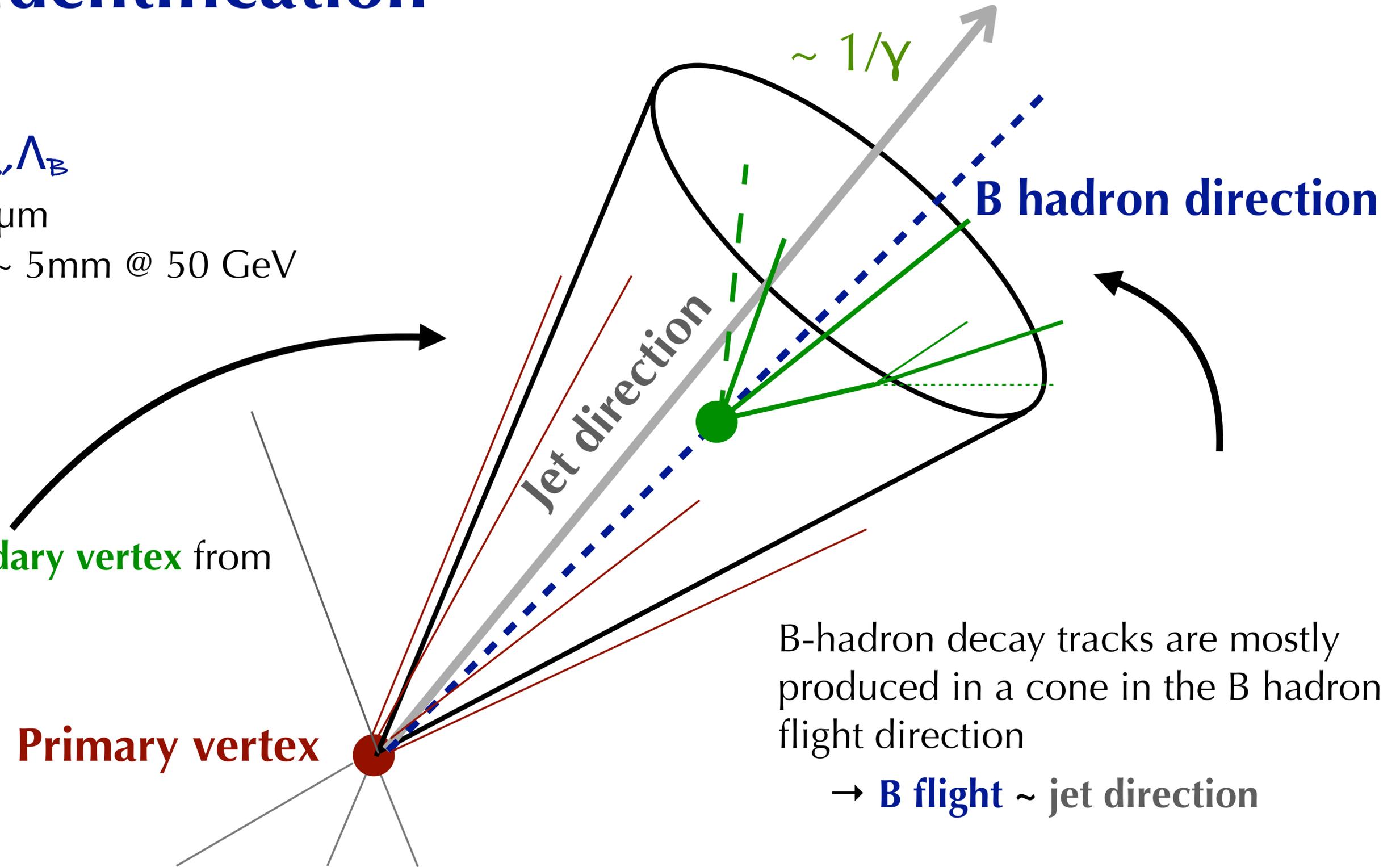
π
 $B^-, \bar{B}^0, \bar{B}_s, \Lambda_B$

$c\tau \sim 500 \mu\text{m}$

$\rightarrow \beta\gamma c\tau \sim 5\text{mm} @ 50 \text{ GeV}$

Reconstruct **secondary vertex** from B hadron decay

Primary vertex



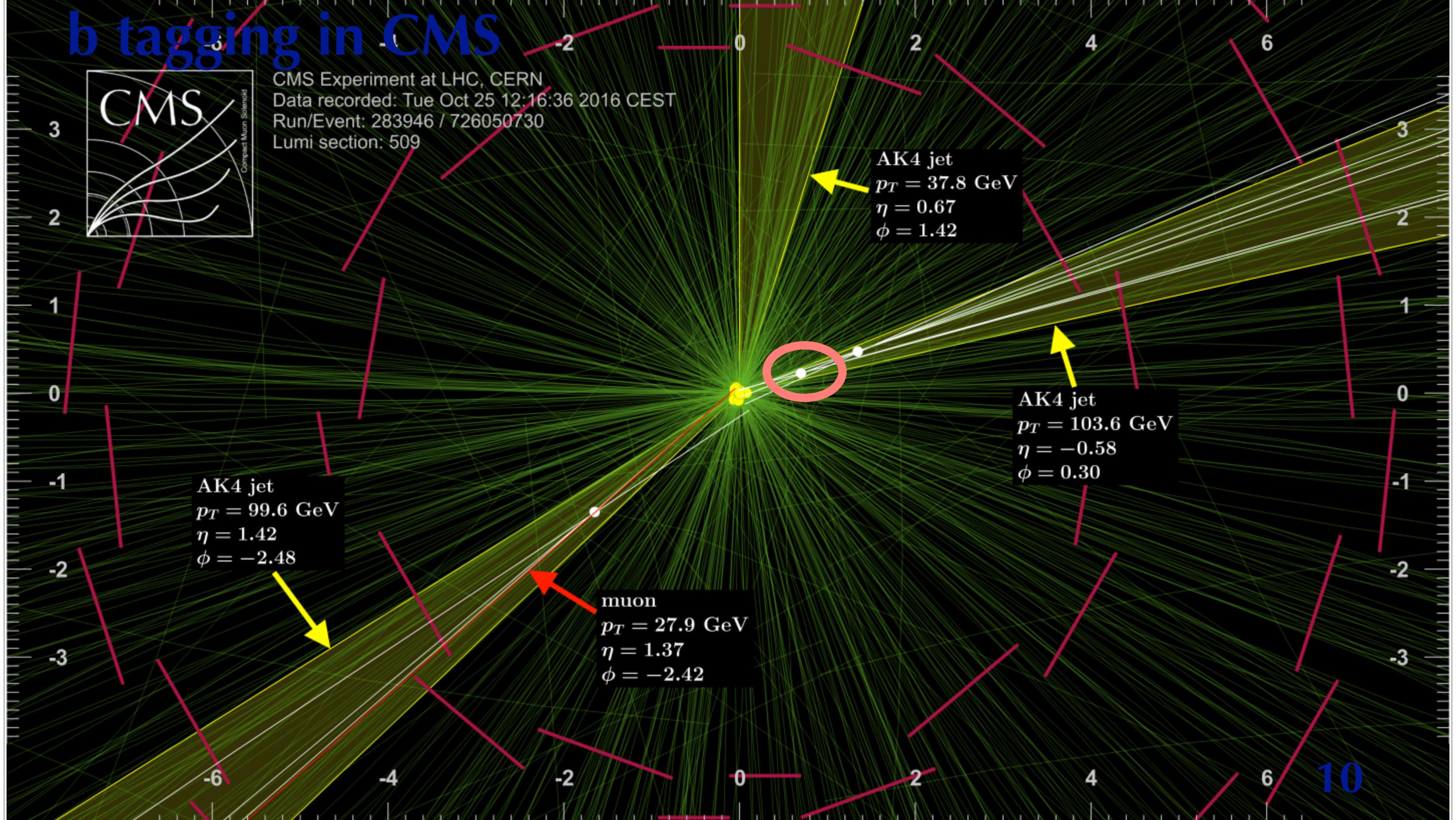
B-hadron decay tracks are mostly produced in a cone in the B hadron flight direction

\rightarrow **B flight** \sim jet direction

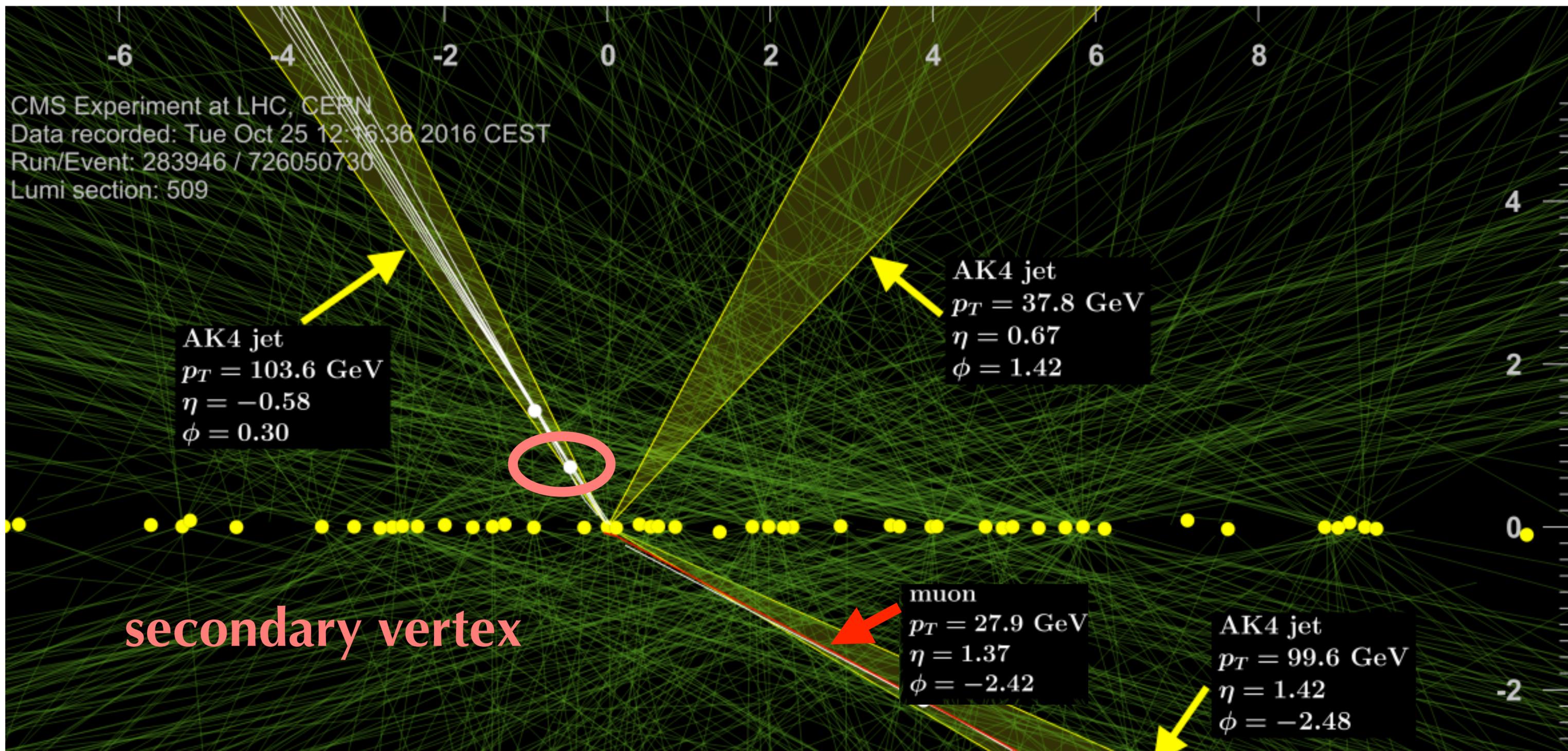
b tagging in CMS



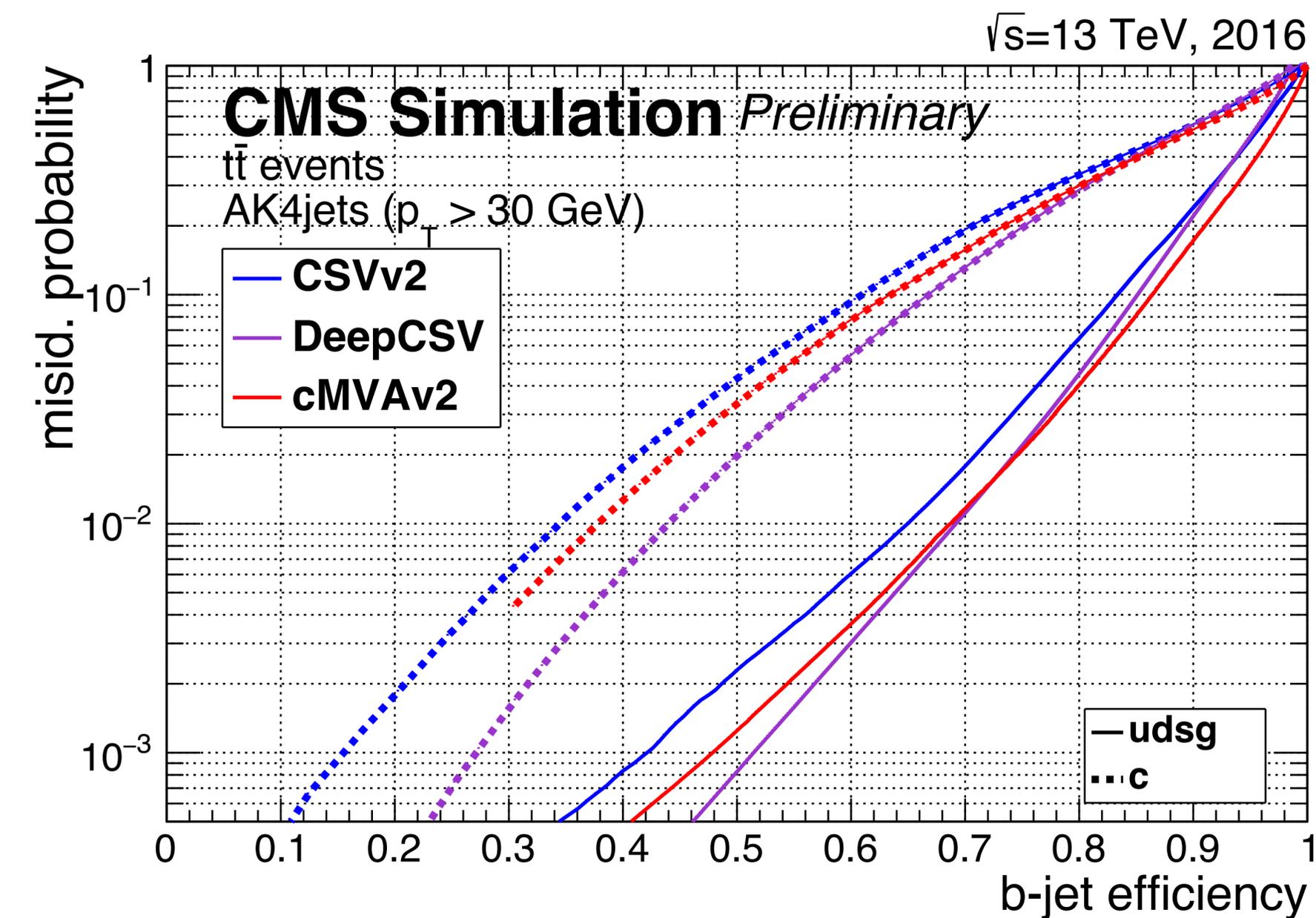
CMS Experiment at LHC, CERN
Data recorded: Tue Oct 25 12:16:36 2016 CEST
Run/Event: 283946 / 726050730
Lumi section: 509



b tagging in CMS



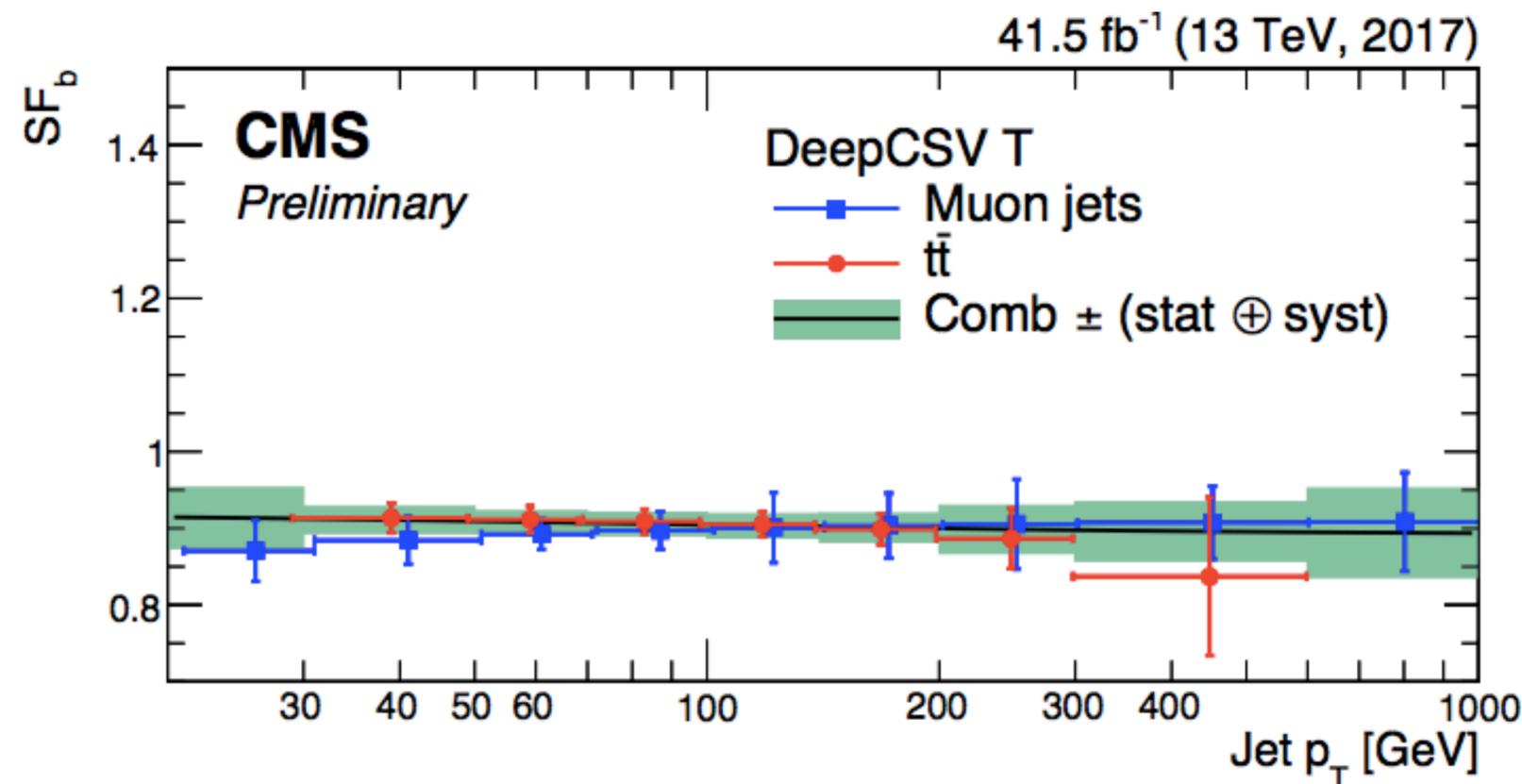
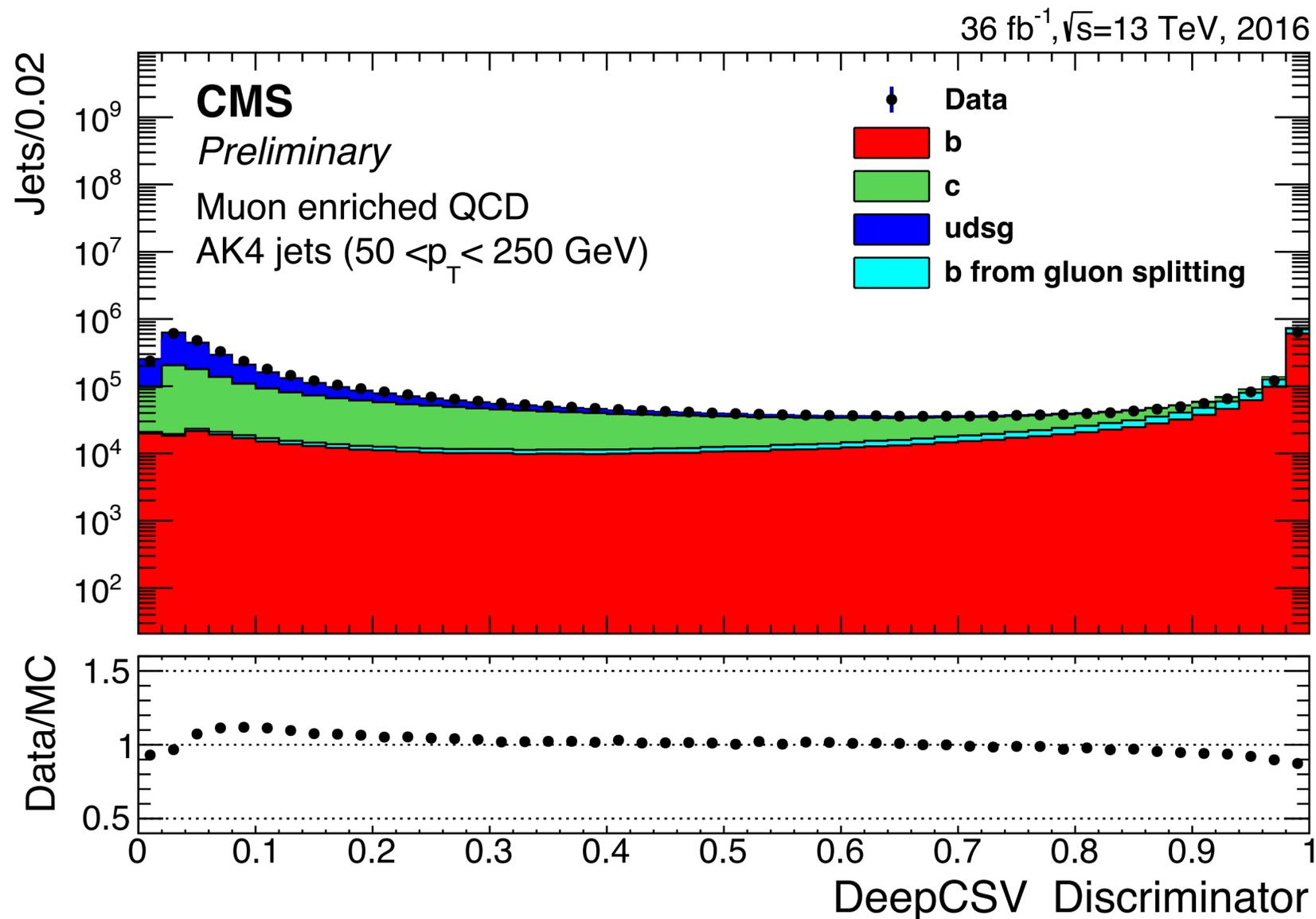
b tagging in CMS



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

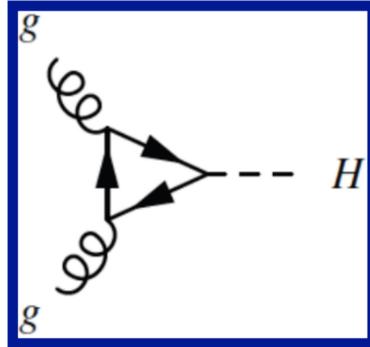
- **impact parameter** significance of charged-particle tracks
- the presence of a **lepton** in the jet and its properties
- the presence and properties of reconstructed **secondary vertices**

Performance in data

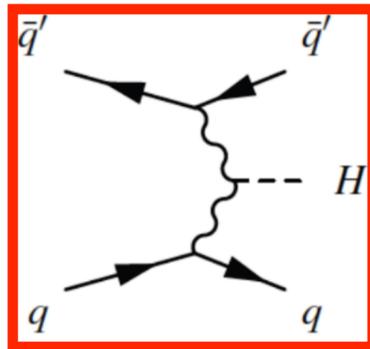


Agreement between data and simulation at 5% level

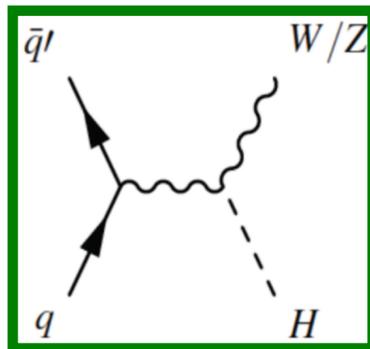
$H(b\bar{b})$ at the LHC



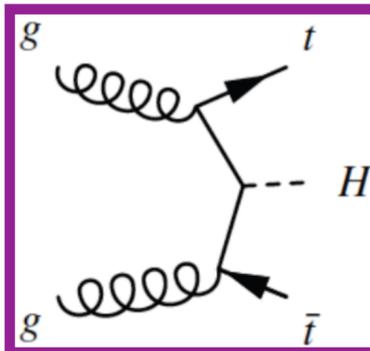
Gluon Fusion (87%)



Vector-Boson Fusion (7%)

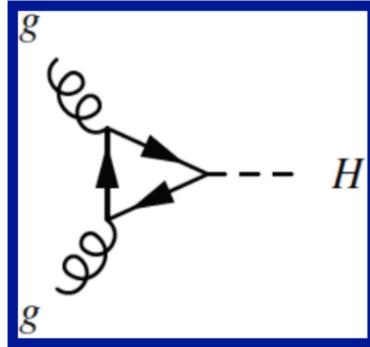


Higgs-strahlung (4%)



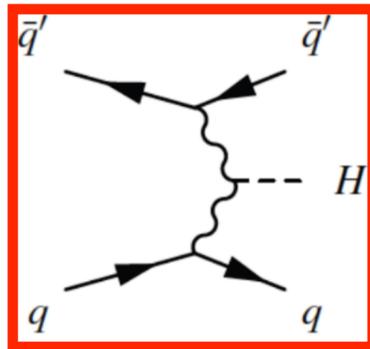
Top Fusion ttH (1%)

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

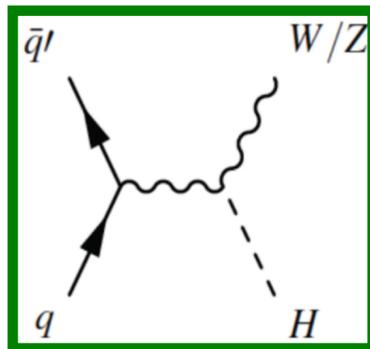


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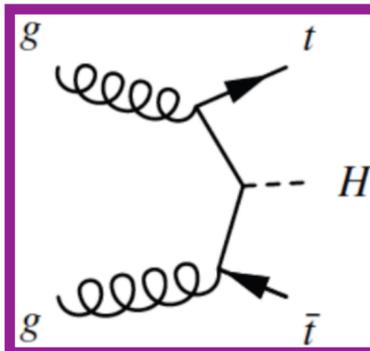
Overwhelming (10^7 larger) background of b-quark production due to strong interactions



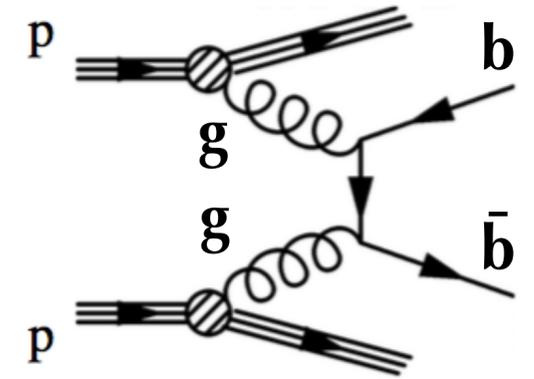
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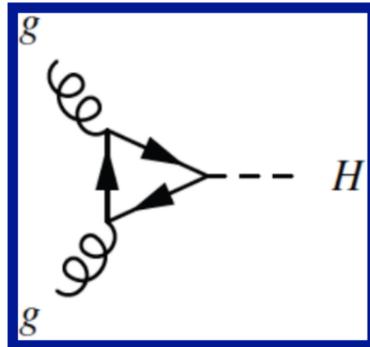
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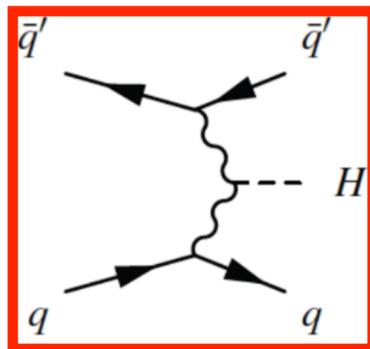


H($b\bar{b}$) at the LHC



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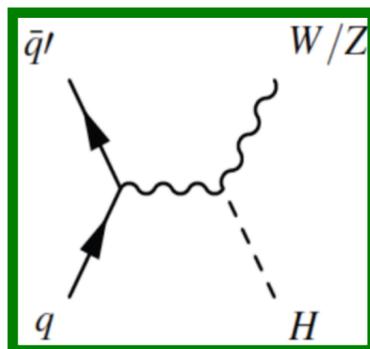
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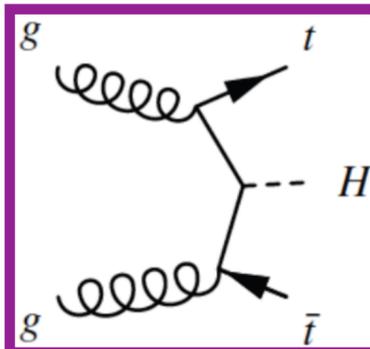
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Very large background but a very distinctive topology

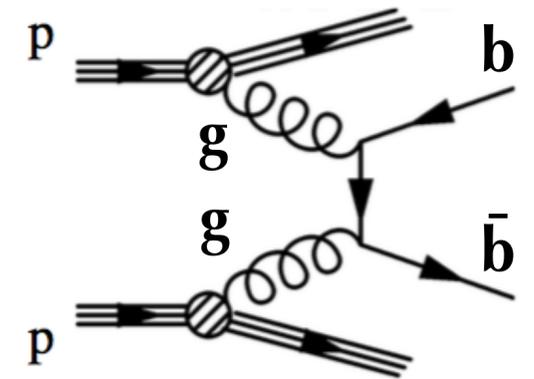
ISR photon to enhance S/B [Nucl. Phys. B 781, 64 (2007), ATLAS-Arxiv:1807.08639 sub to PRD]



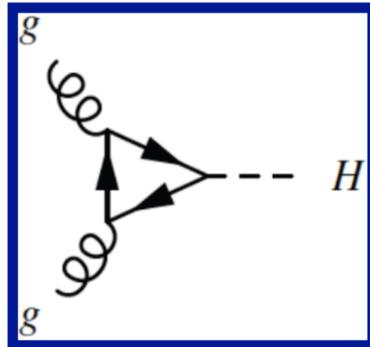
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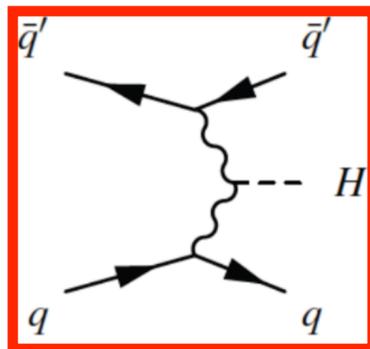


H(bb̄) at the LHC



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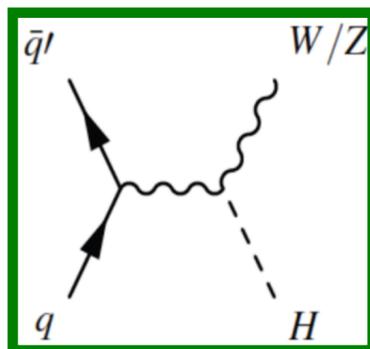
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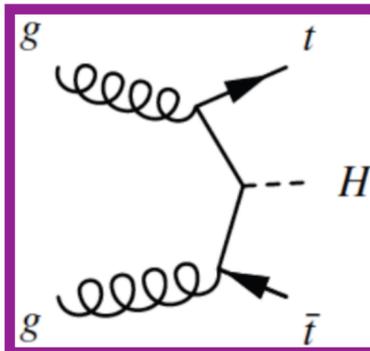
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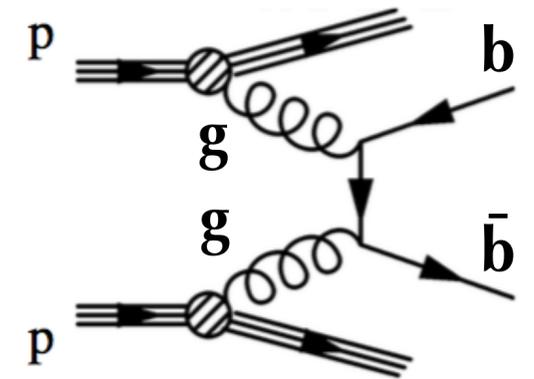


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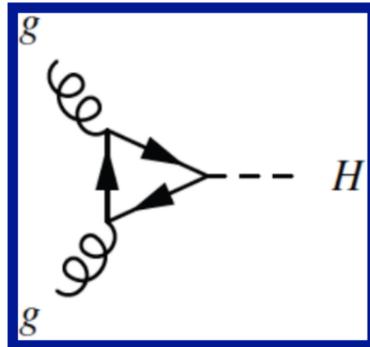
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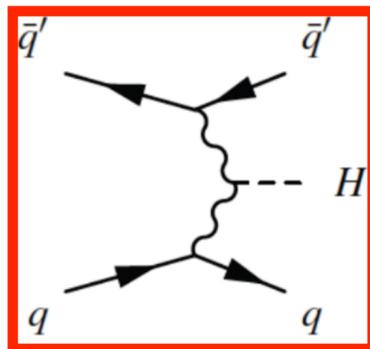


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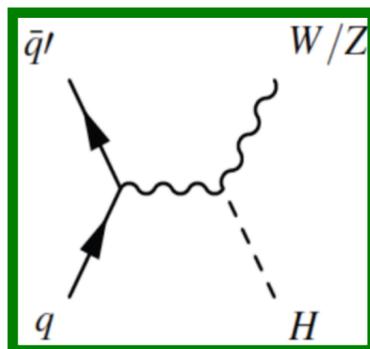
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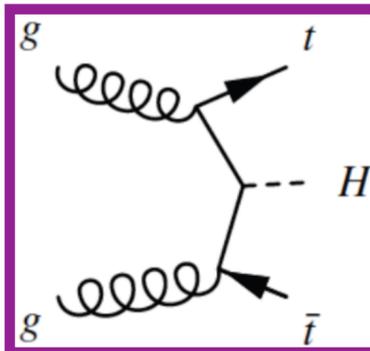
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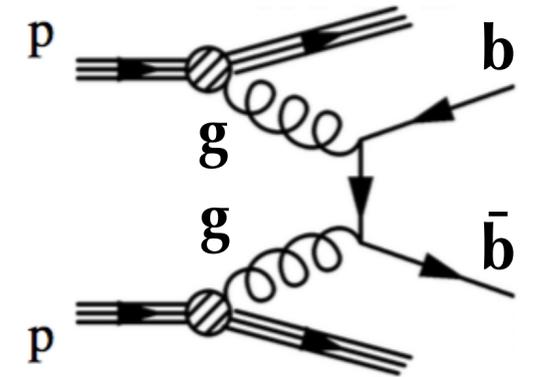
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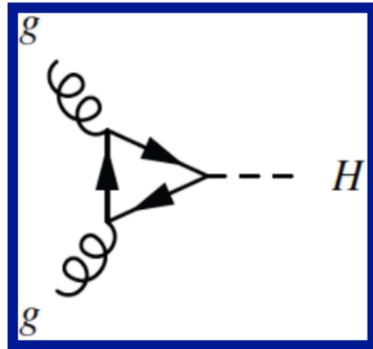


Top Fusion ttH (1%)

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

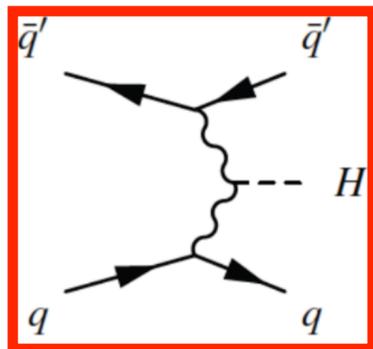


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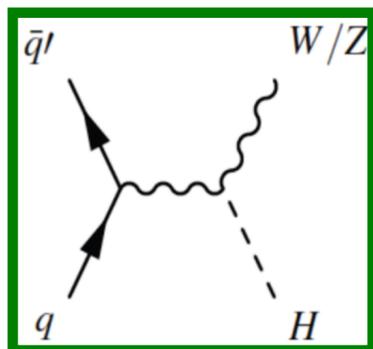
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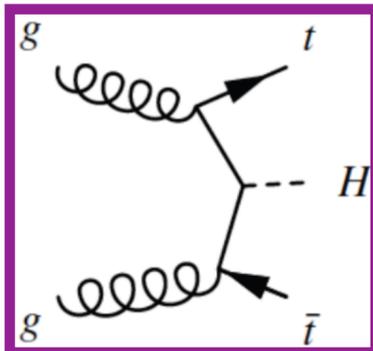
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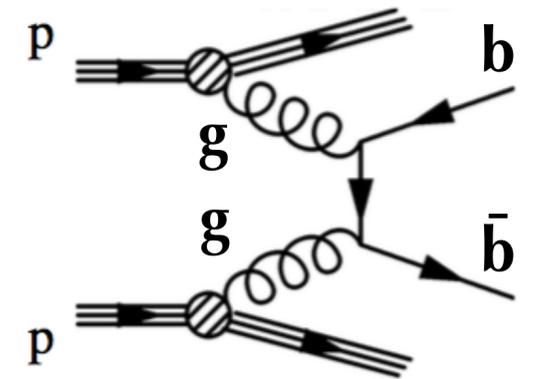
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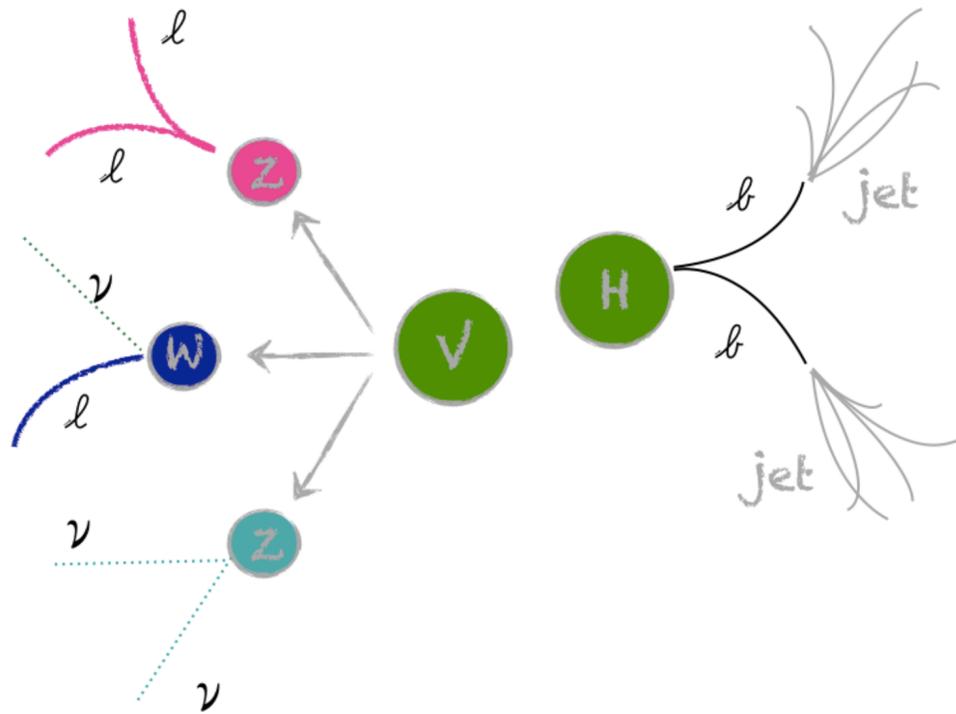
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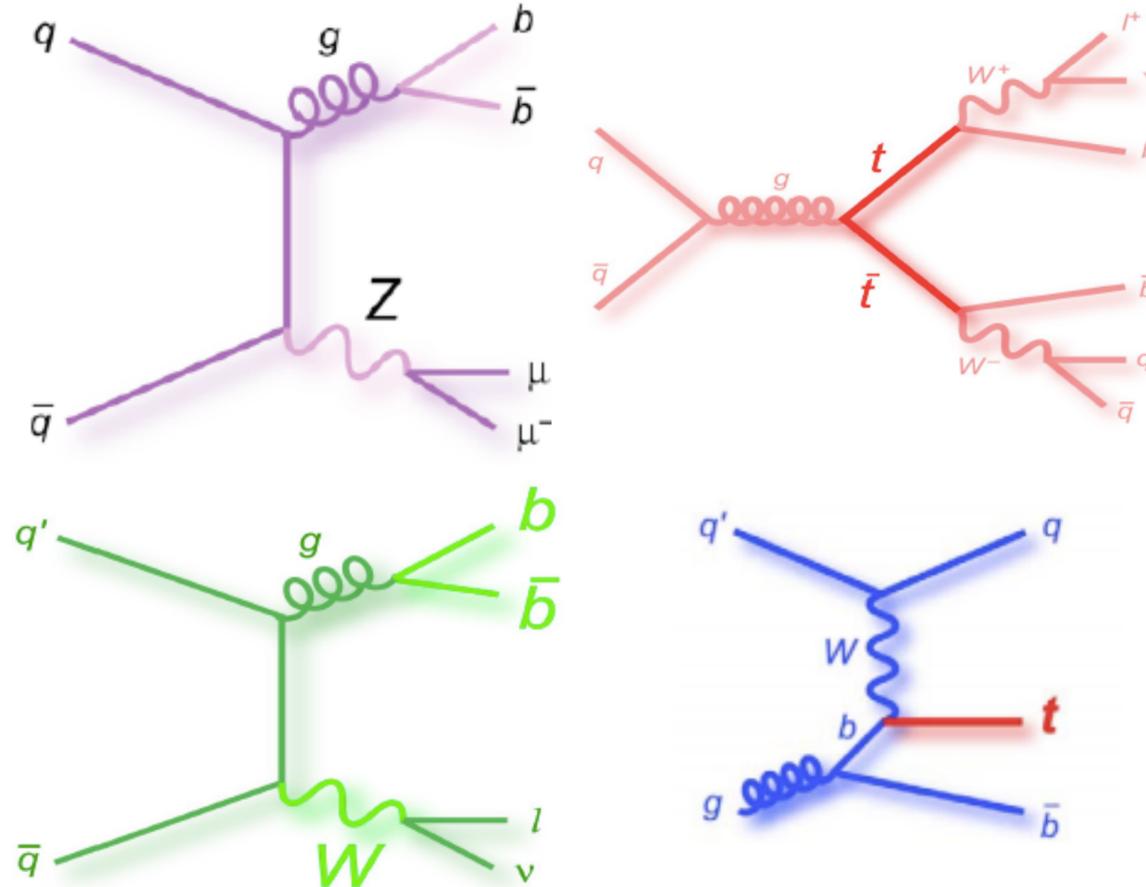
Most sensitive
S/B worse than in Run-1

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

signal



irreducible backgrounds



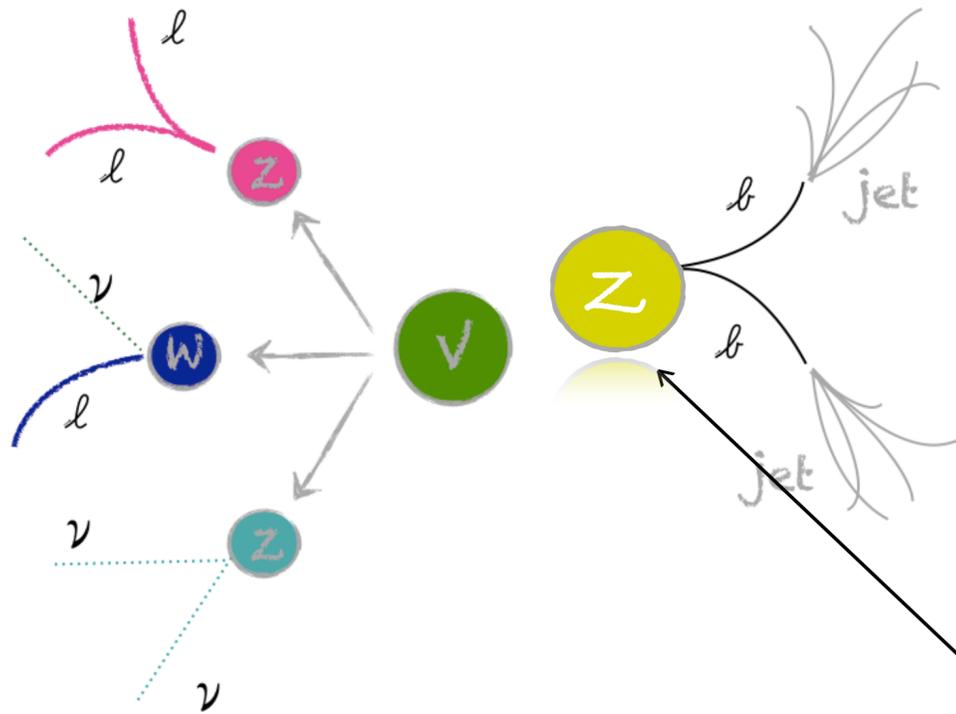
normalization from
data, shapes from MC

0-lepton (MET)

1-lepton [e, μ]

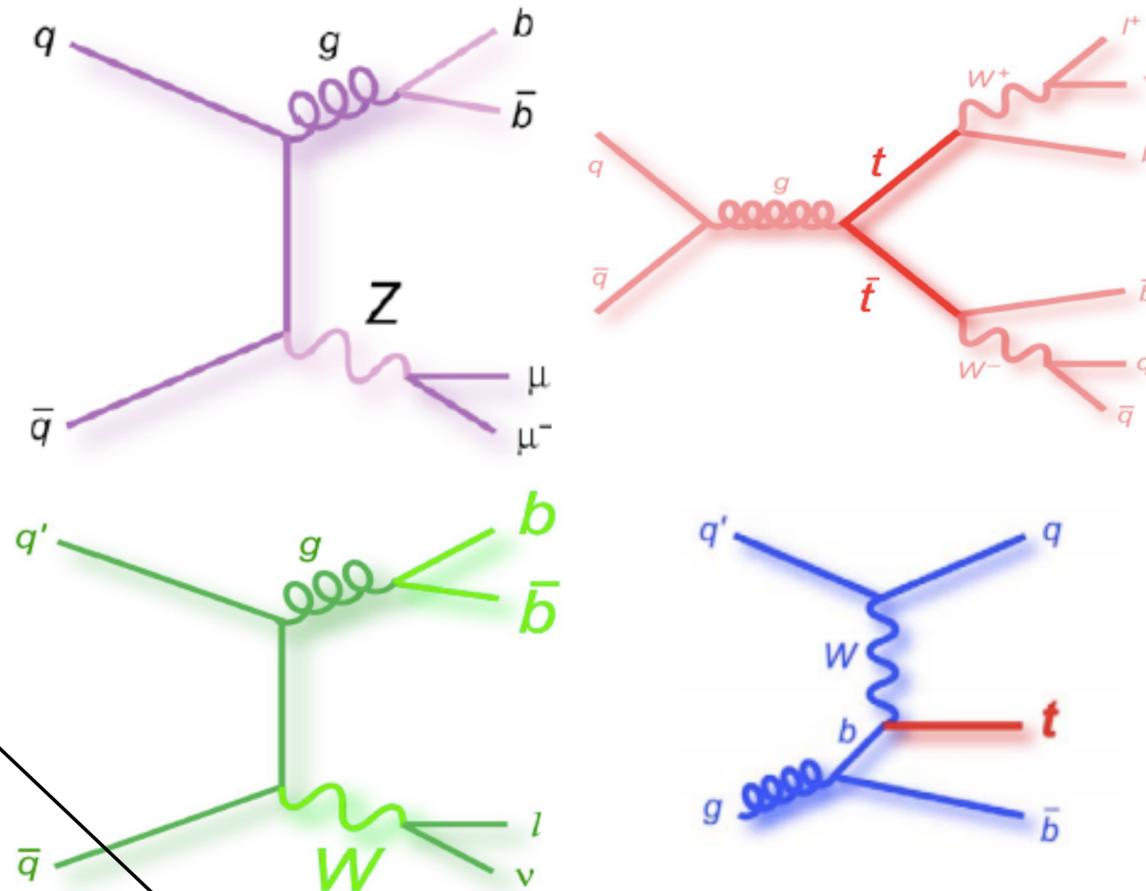
2-OSSF leptons [ee, $\mu\mu$]

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



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

irreducible backgrounds



and diboson, of course

normalization from data, shapes from MC

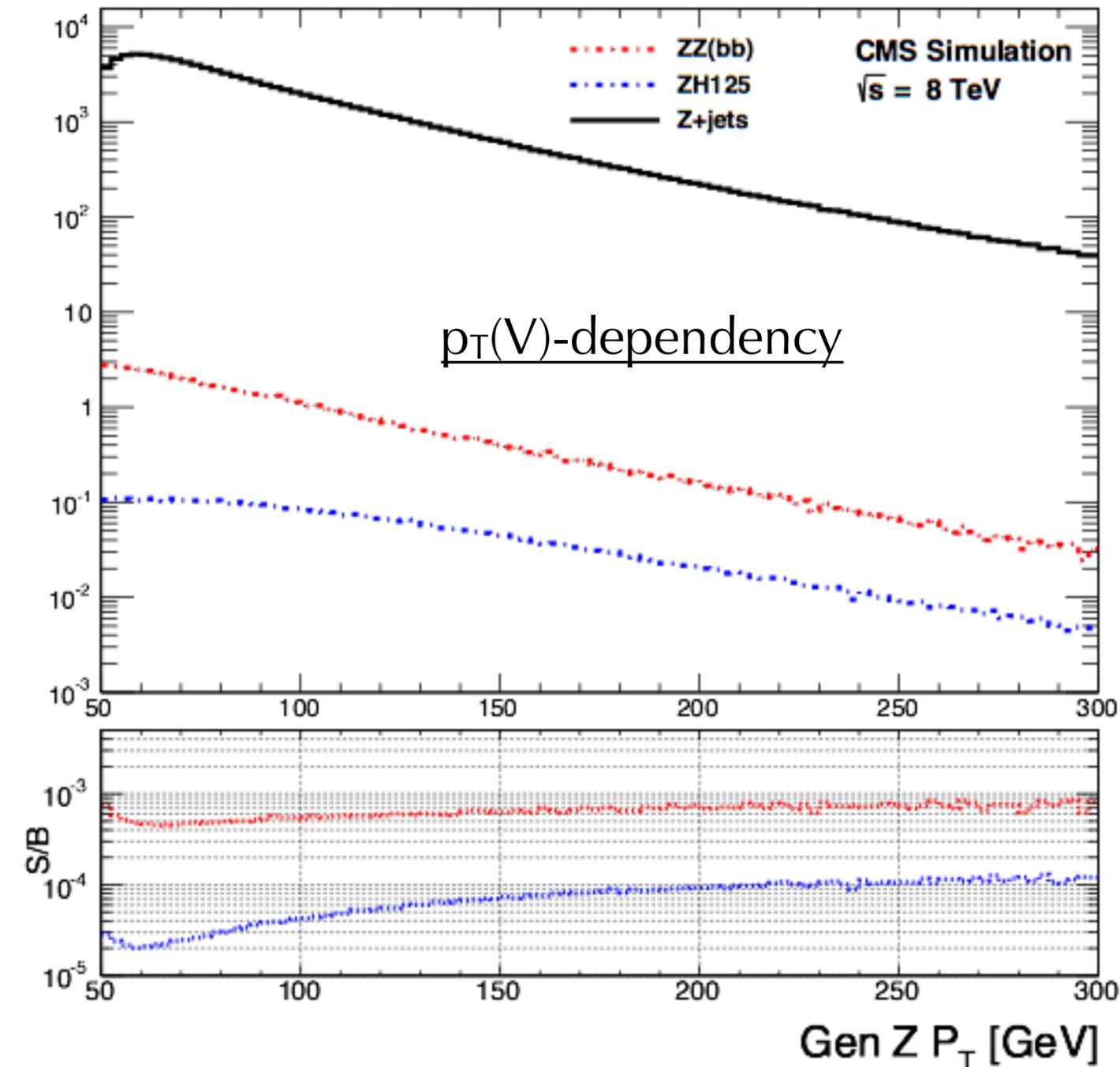
Used to validate the analysis strategy

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)



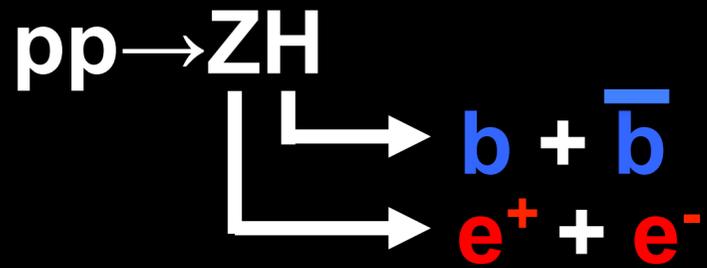


b-jet

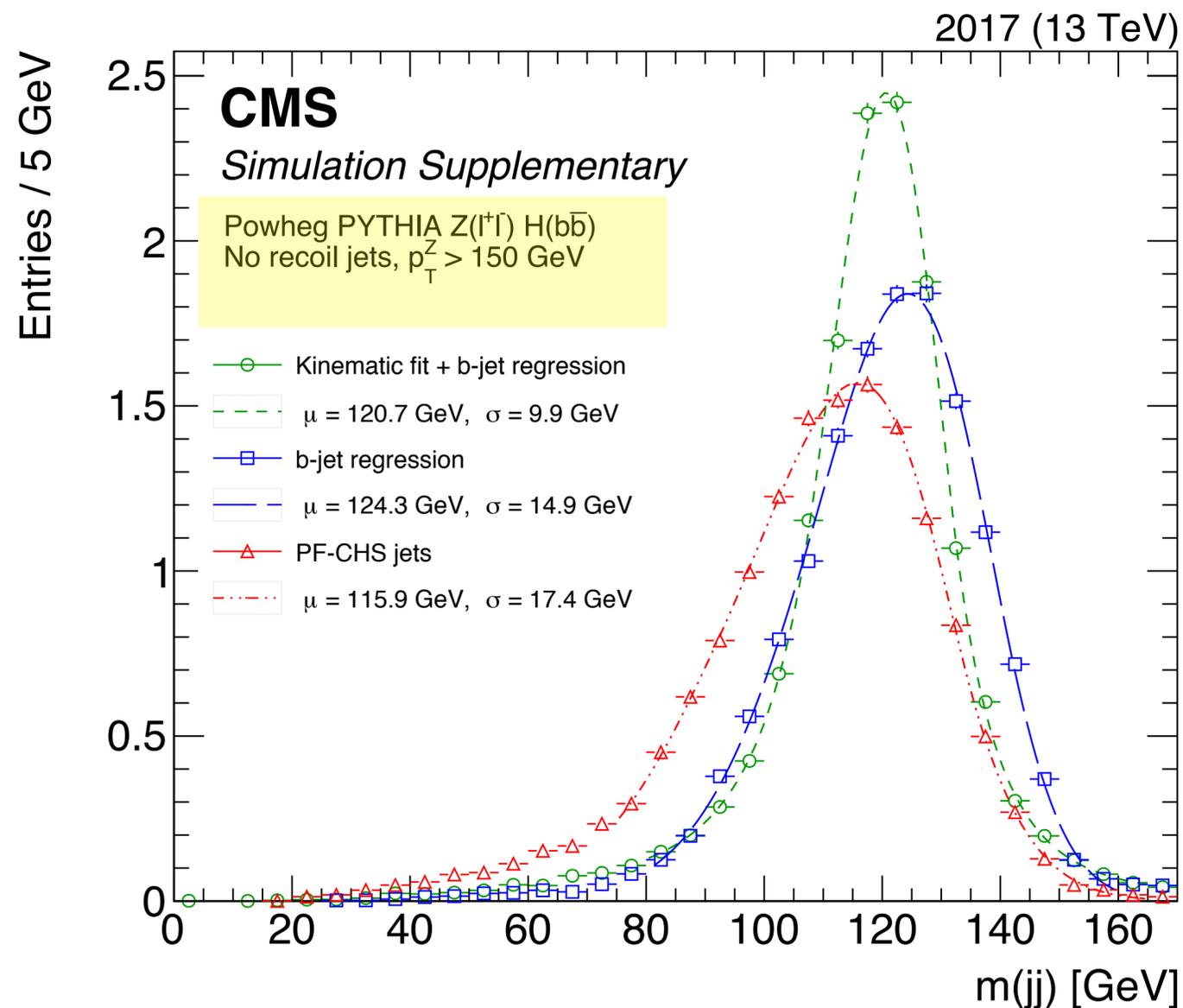
b-jet

electron

positron



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



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

$$\text{BR } 35\% \quad b \rightarrow l + \textcircled{v} + X$$

Derived from simulated $t\bar{t}$ 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

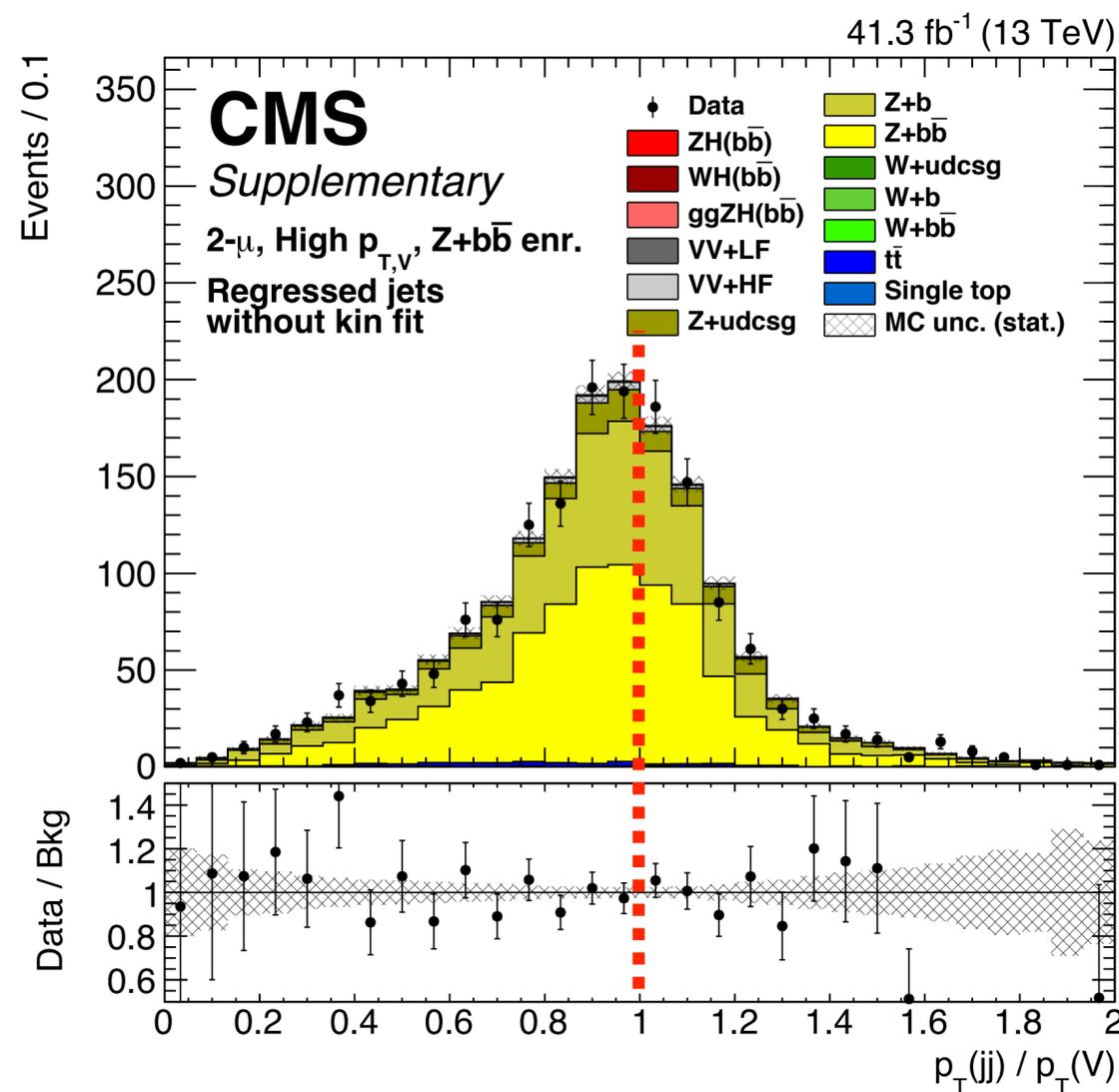
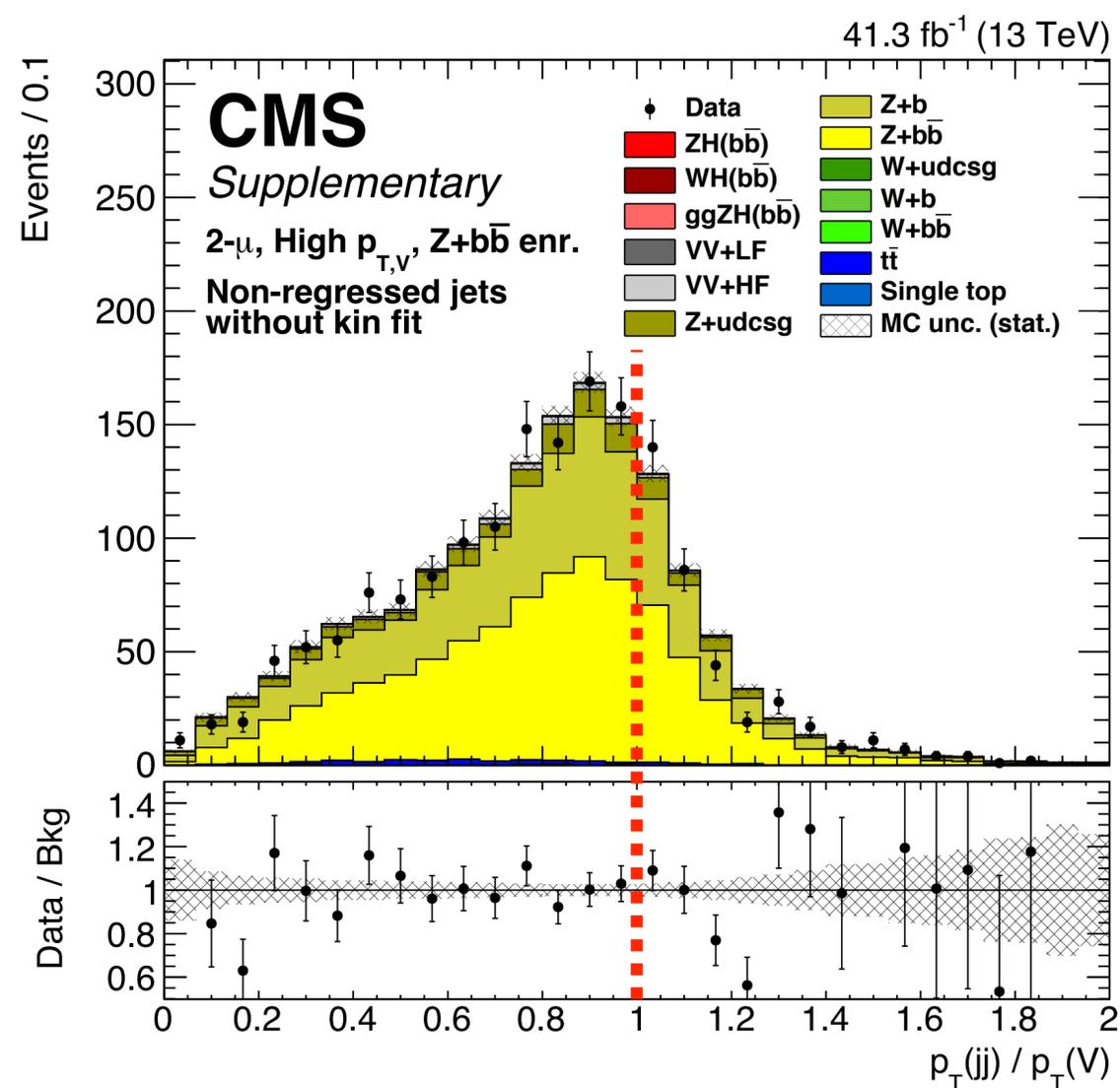
Balance in **Z(ll)+b-jet** data

Monitor regression performance in data

Extract JER data/MC correction for b-jets (~10%)

Dijet balance in Z(ll)+bb̄ data

$$p_{T\text{balance}} = \frac{p_T(jj)}{p_T(ll)}$$

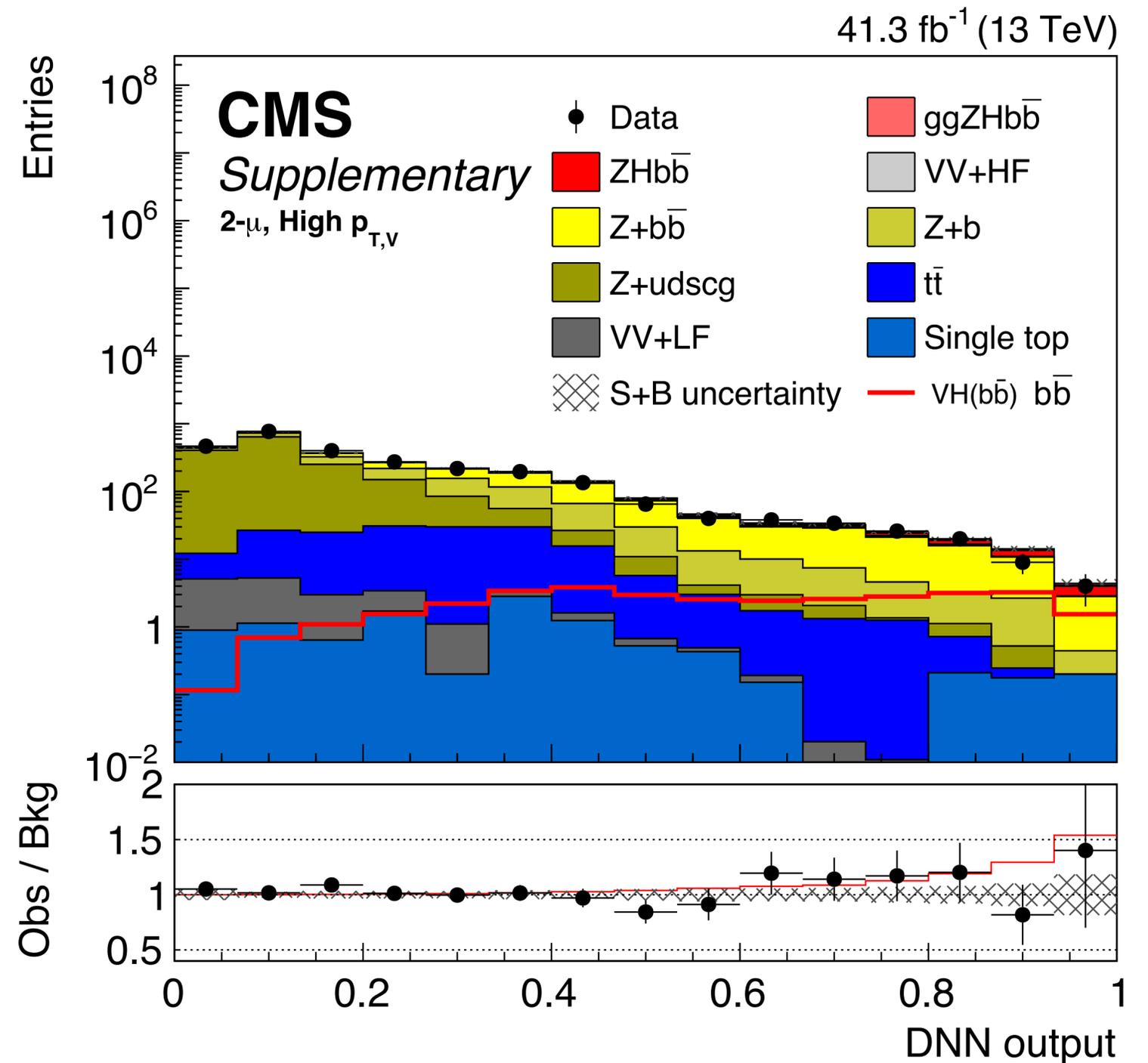


Machine learning for S vs. B

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

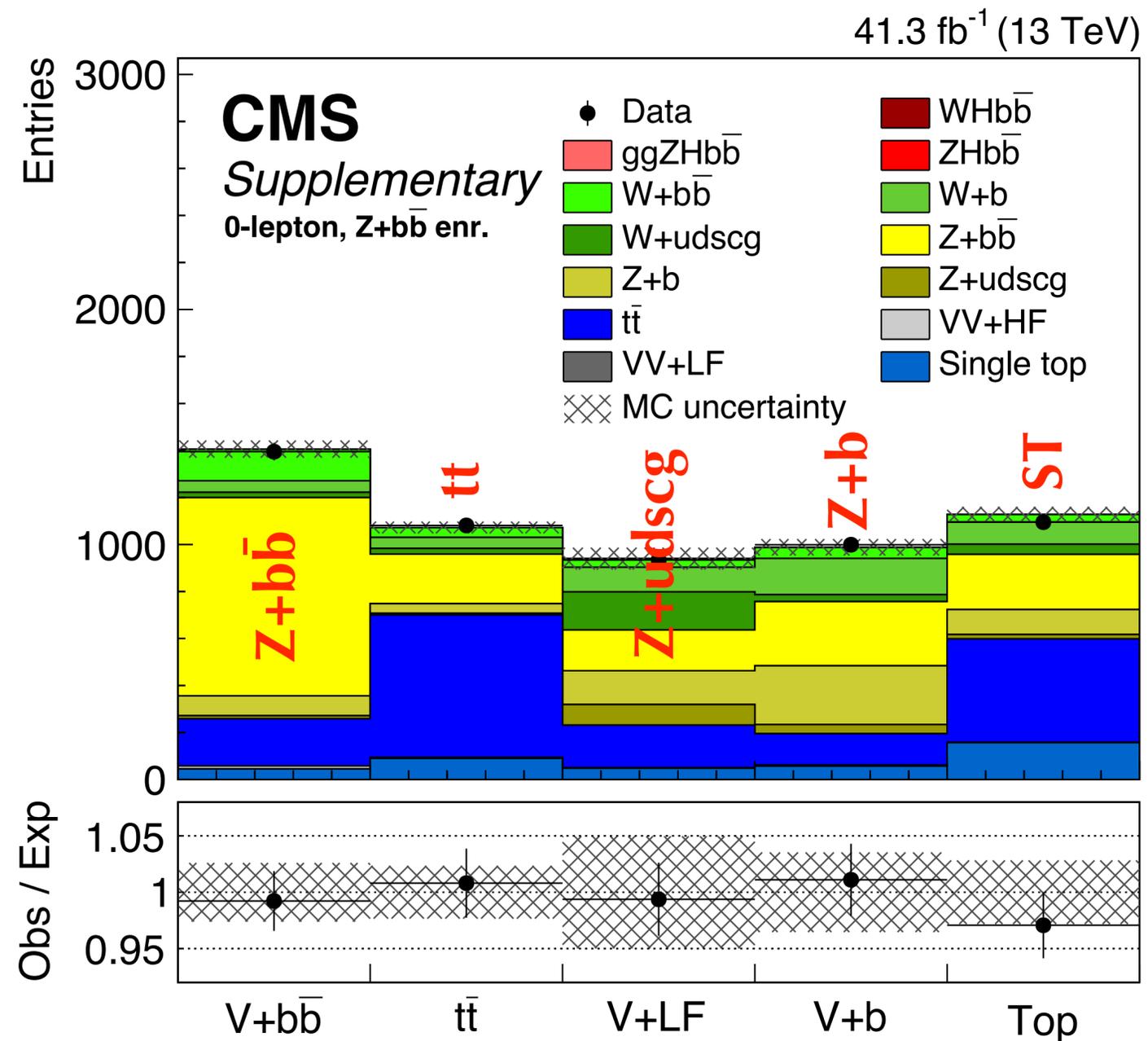
Combined into a DNN

$m(b\bar{b})$, $\Delta\eta(b\bar{b})$ 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 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
MC 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

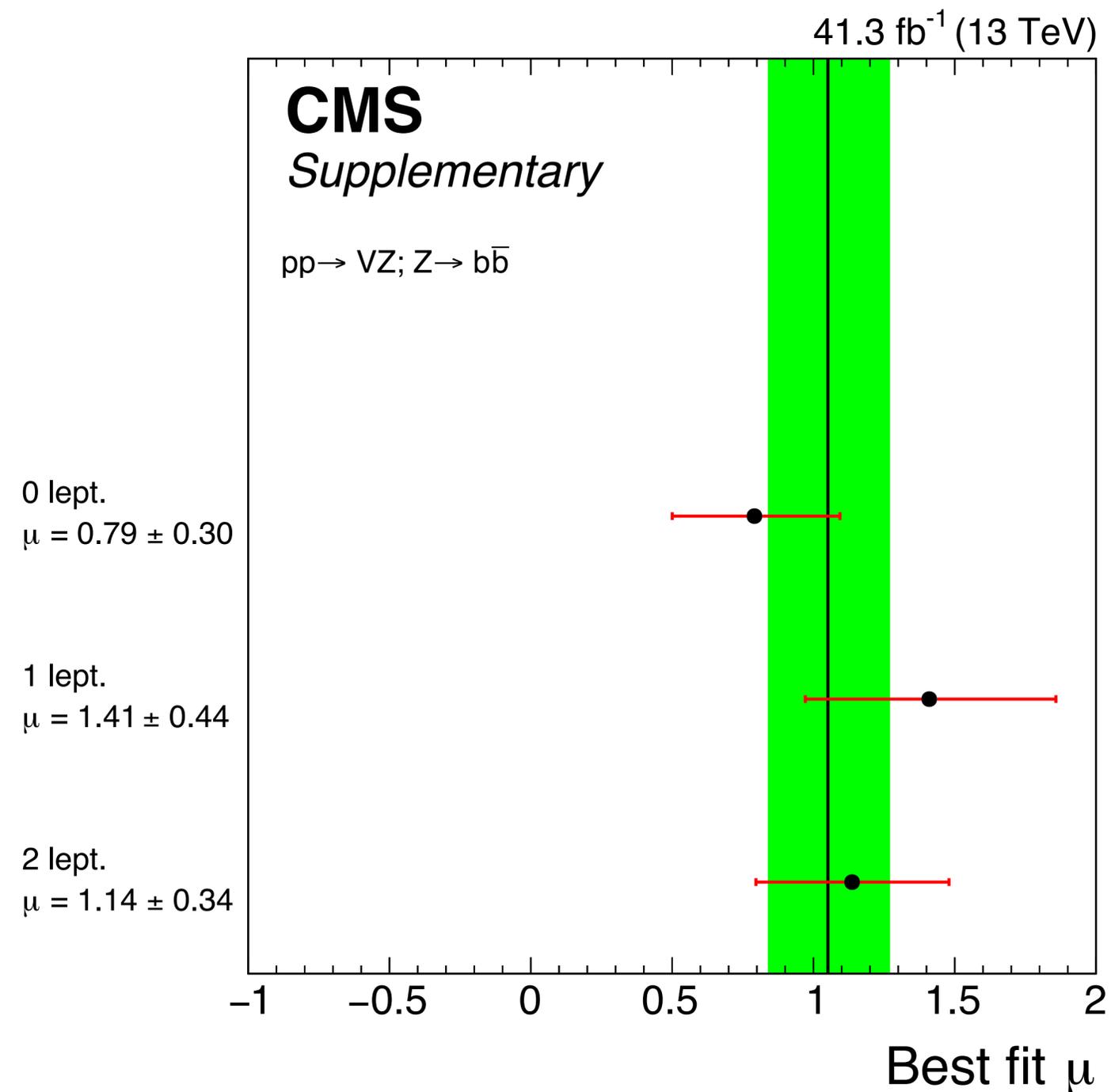
- Re-derive DNN in signal regions to discriminate $VZ(b\bar{b})$ signal
 - same input variables
 - $H(b\bar{b})$ treated as background - assuming SM cross section

Consistent with SM expectations

Run-2 2017

5.2 (5.0) σ

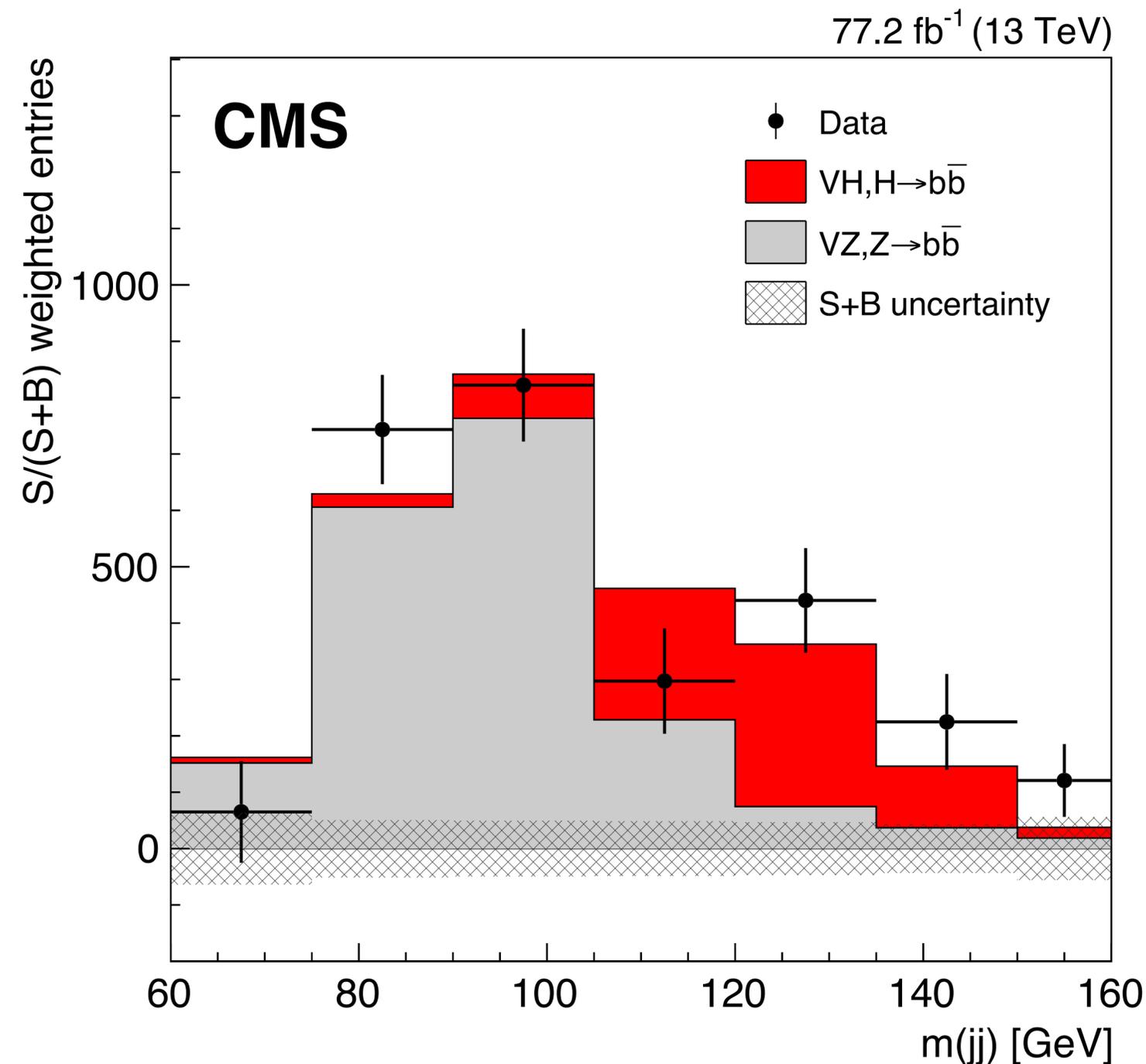
$$\mu = 1.05^{+0.22}_{-0.21}$$



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.

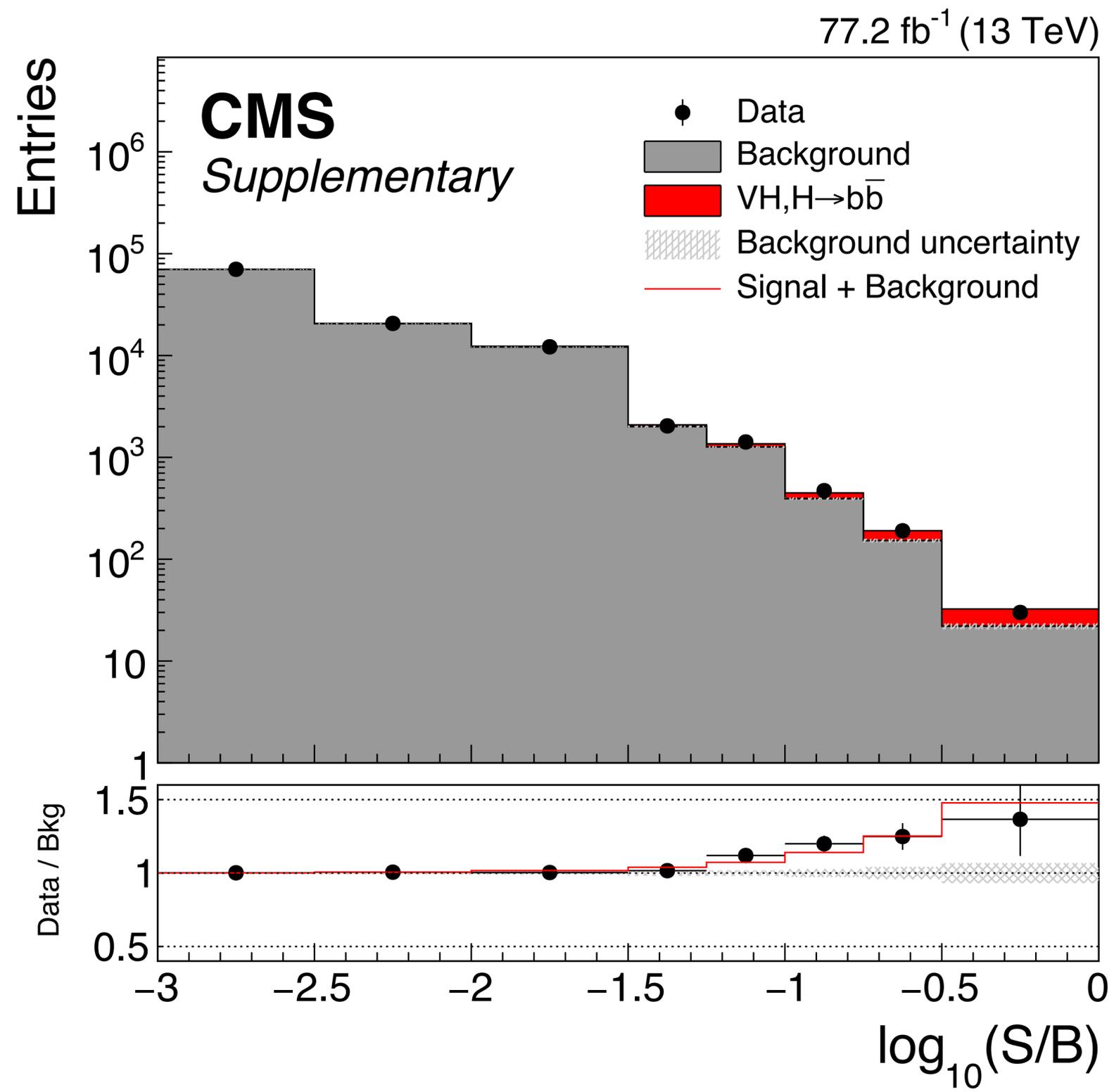
Run-2 2016+2017
2.7 (3.0) σ
 $\mu = 0.91^{+0.35}_{-0.34}$



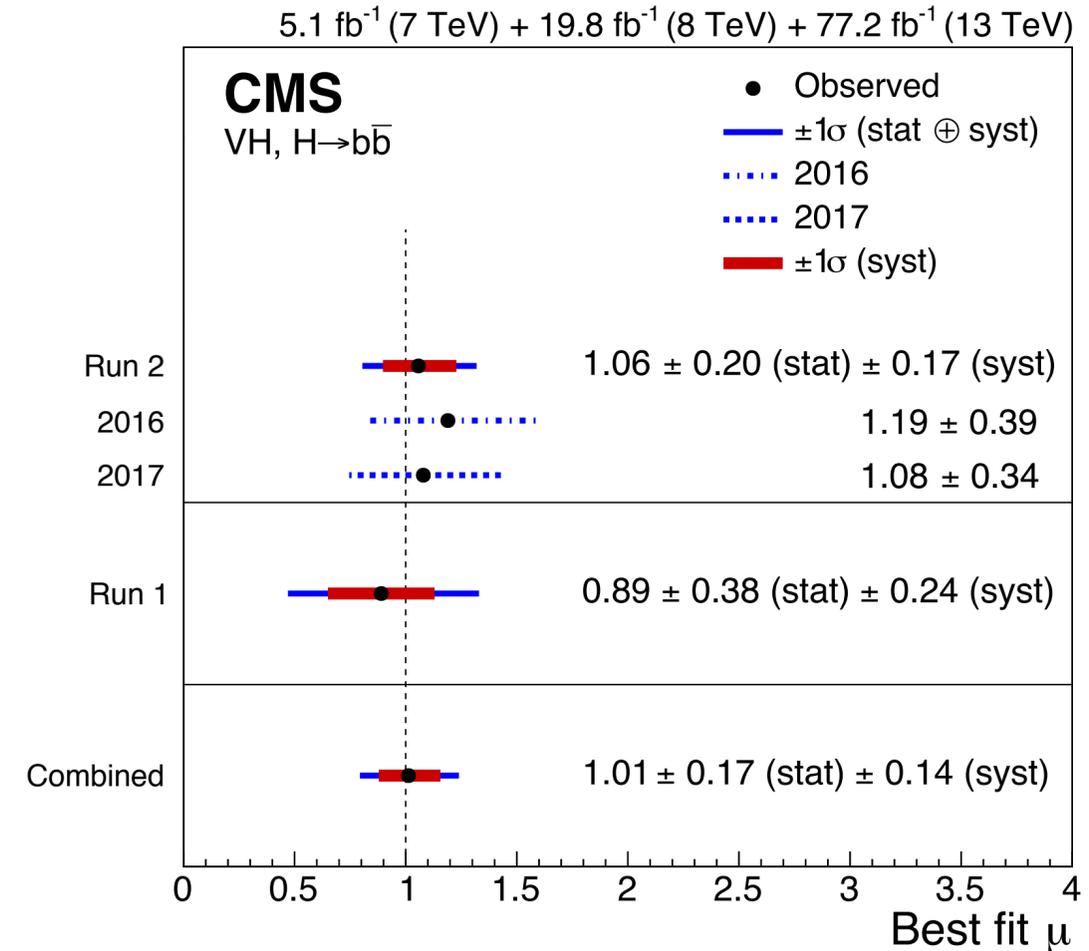
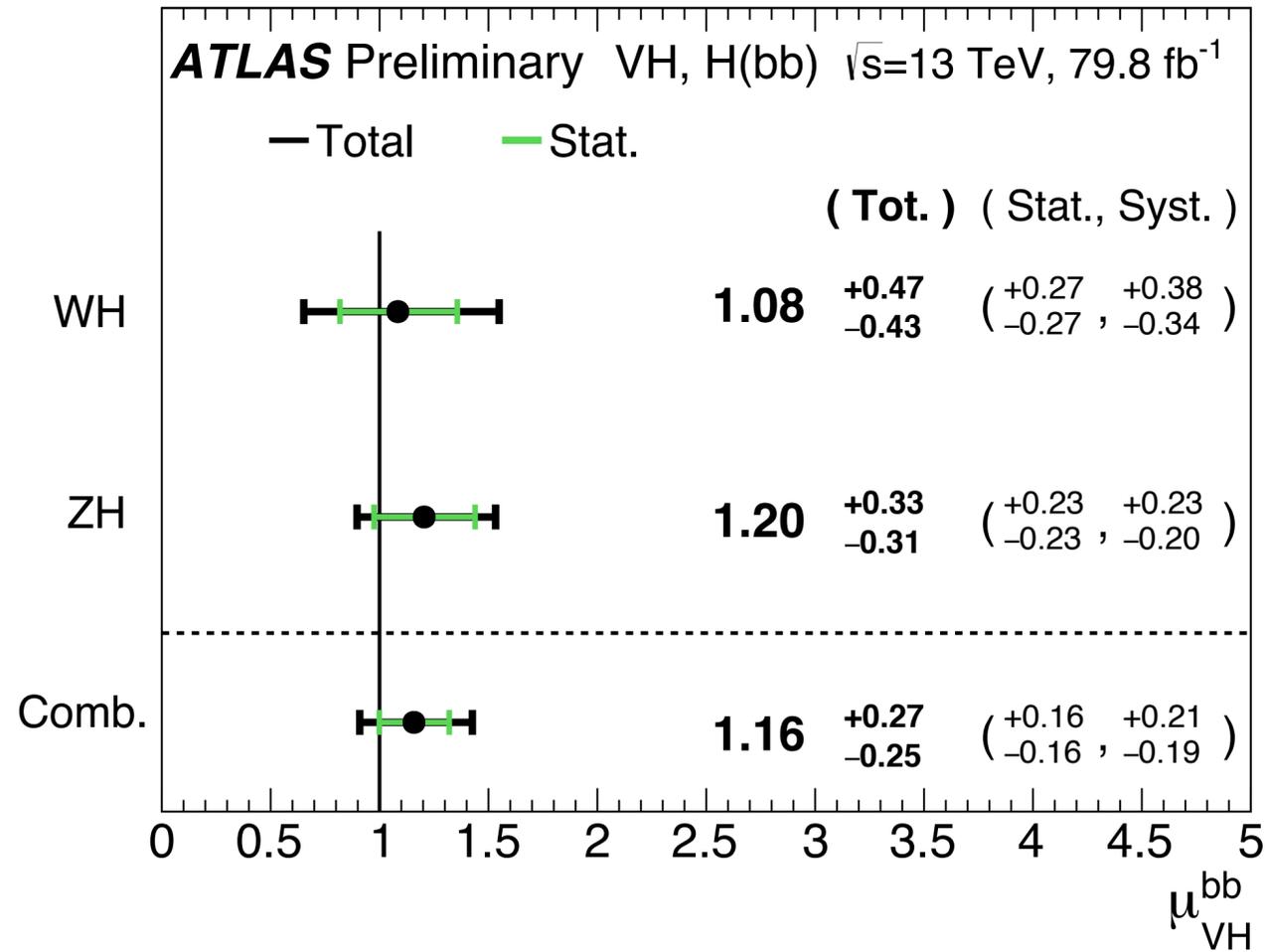
VH(b \bar{b}) Results

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

Run 2 2016+2017
4.8 (4.5) σ
 $\mu = 1.06^{+0.26}_{-0.25}$



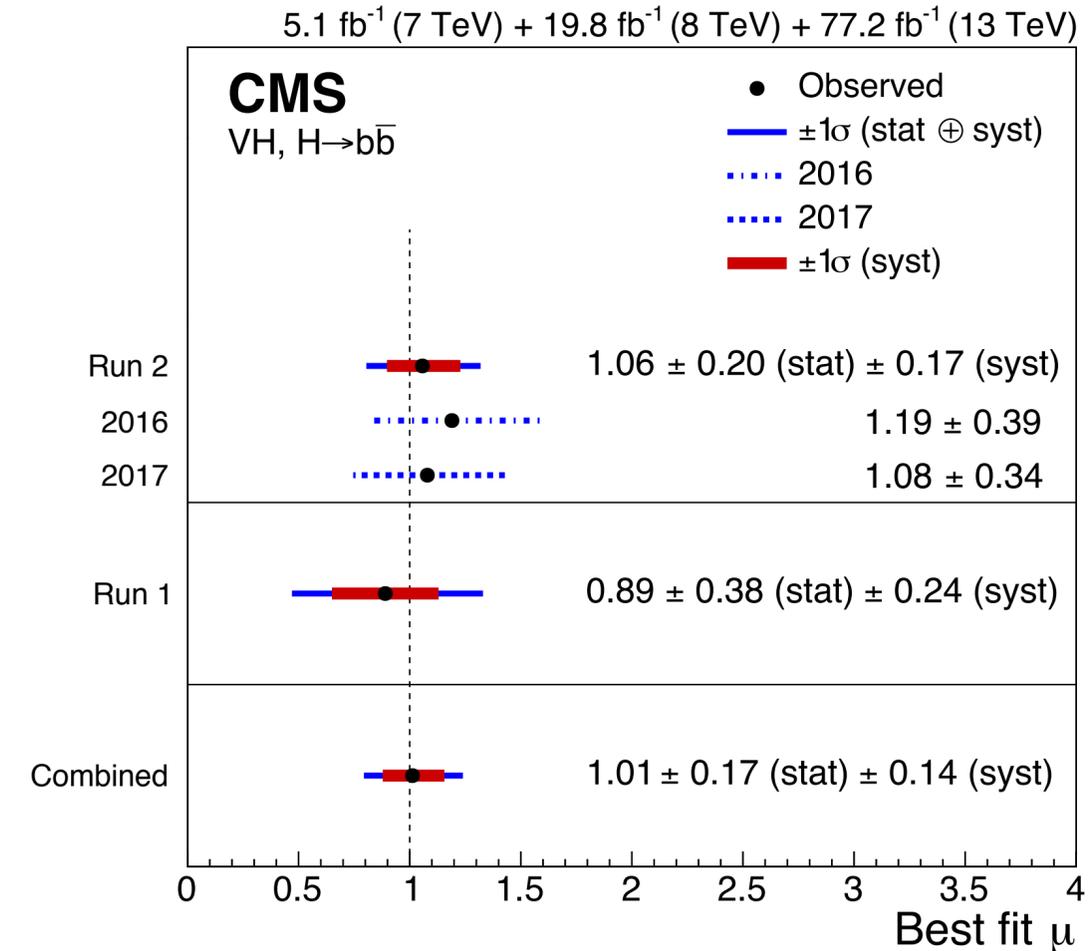
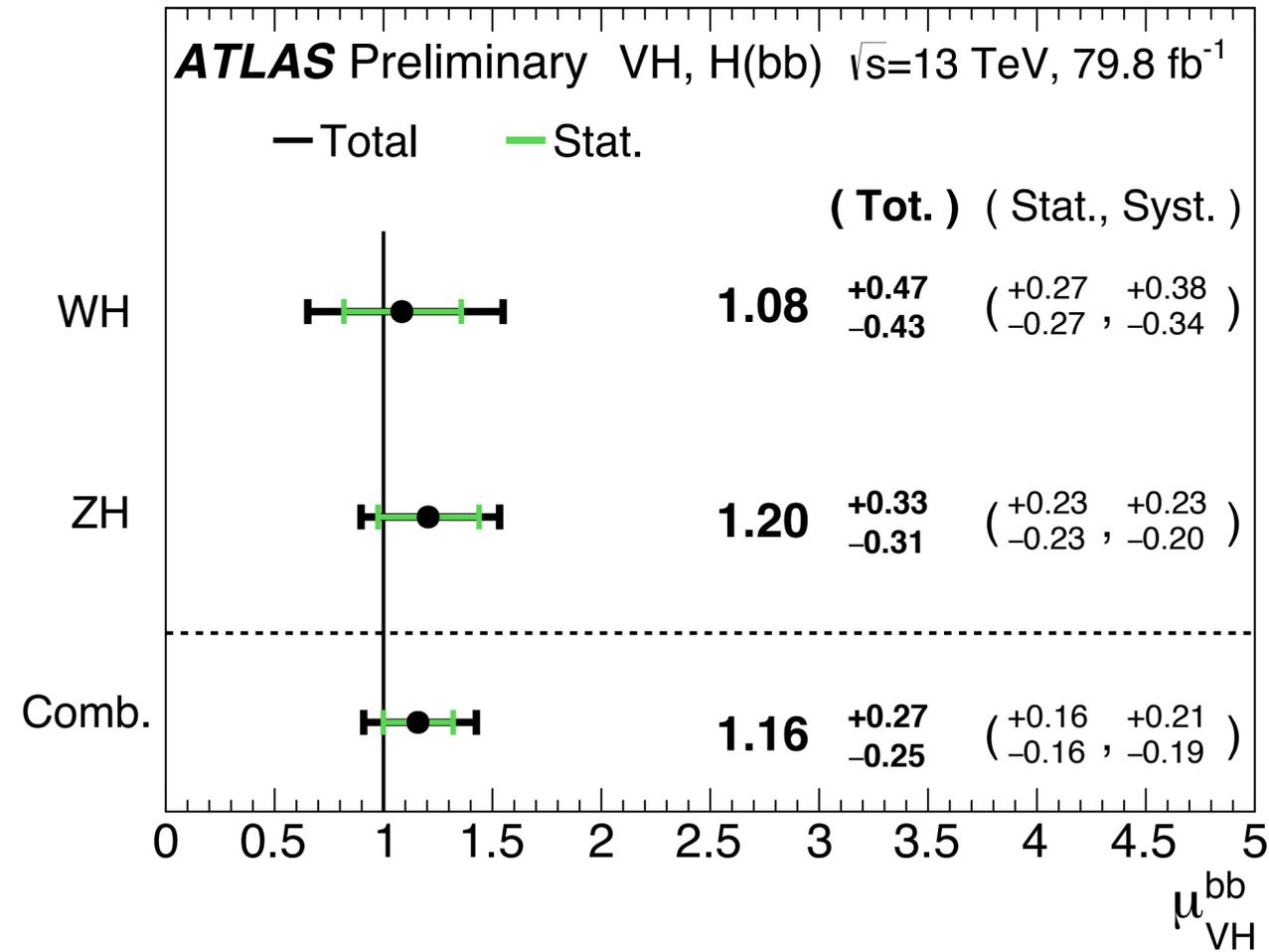
State of the art of $VH(b\bar{b})$ at LHC



CMS Run 1+2: 4.8 σ (4.9 σ exp.)

ATLAS Run 1+2: 4.9 σ (5.1 σ exp.)

State of the art of $VH(bb)$ at LHC



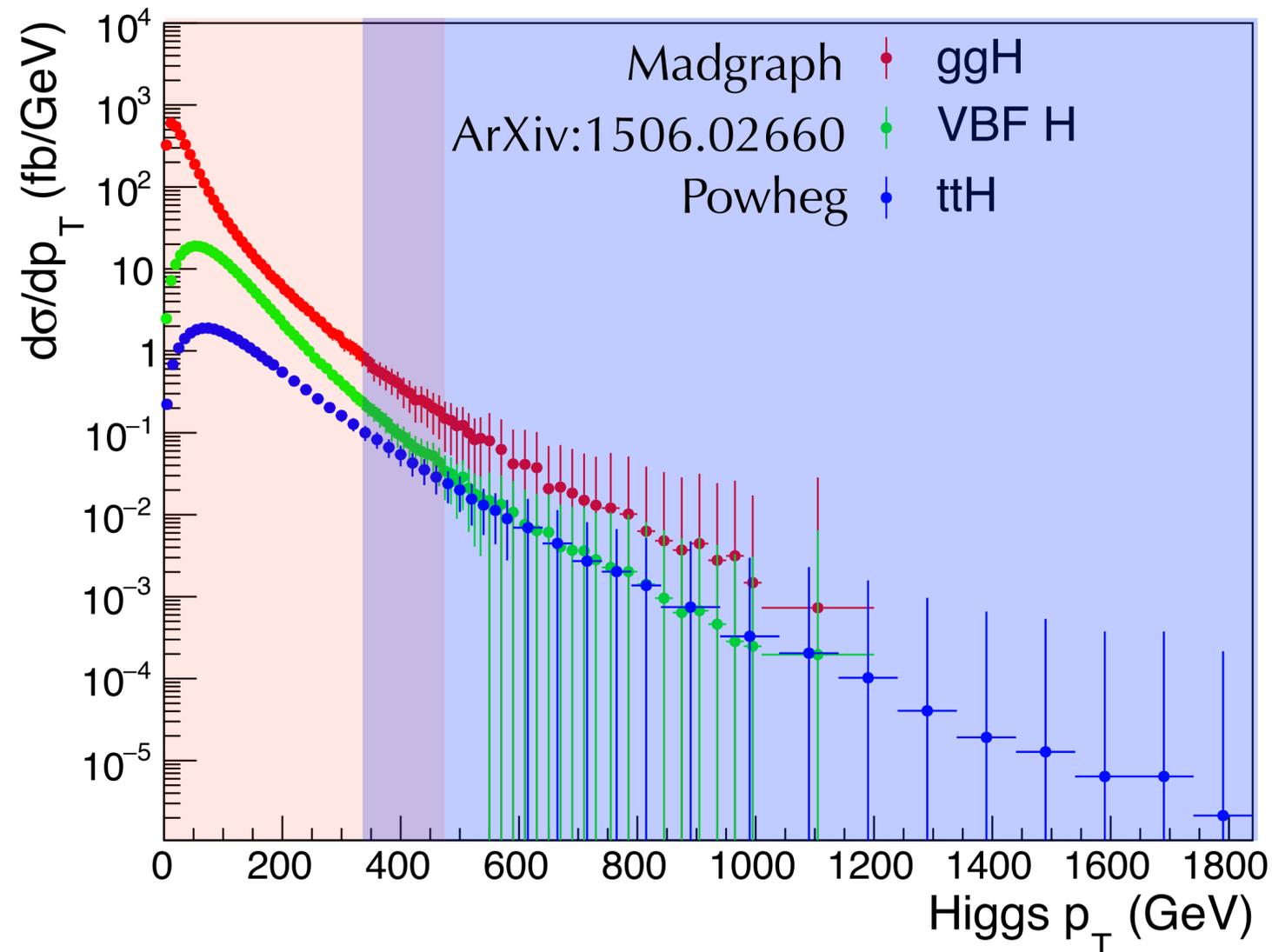
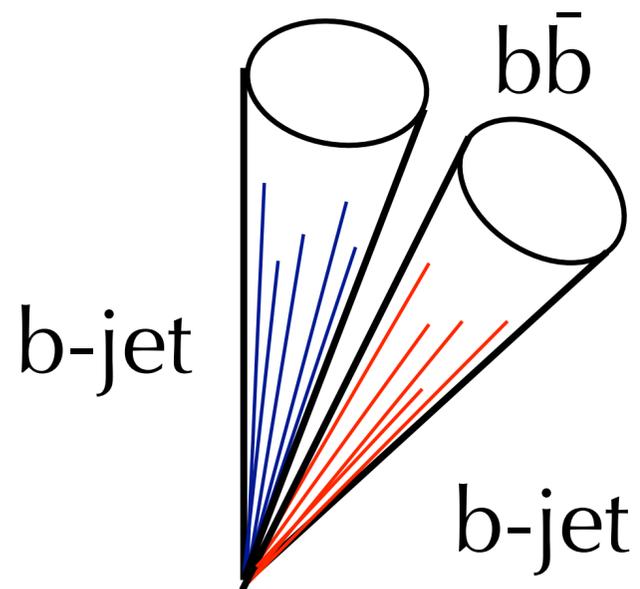
More information to be combined from the other production modes

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

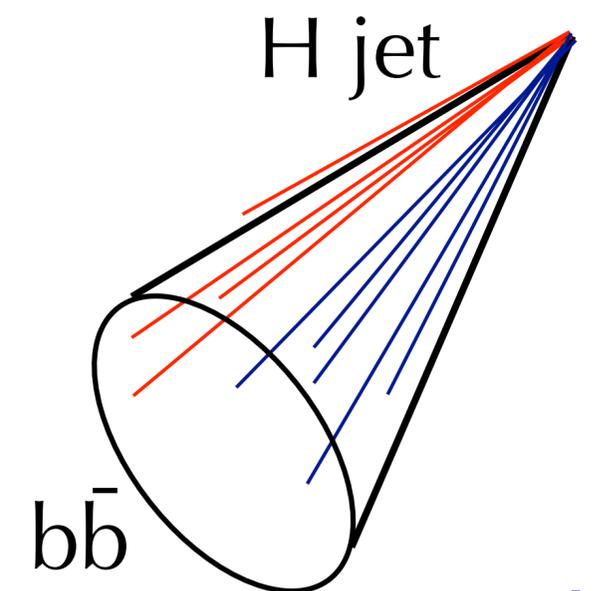
In the **gluon fusion** channel the sensitivity increases by looking at **very high momentum Higgs bosons**

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

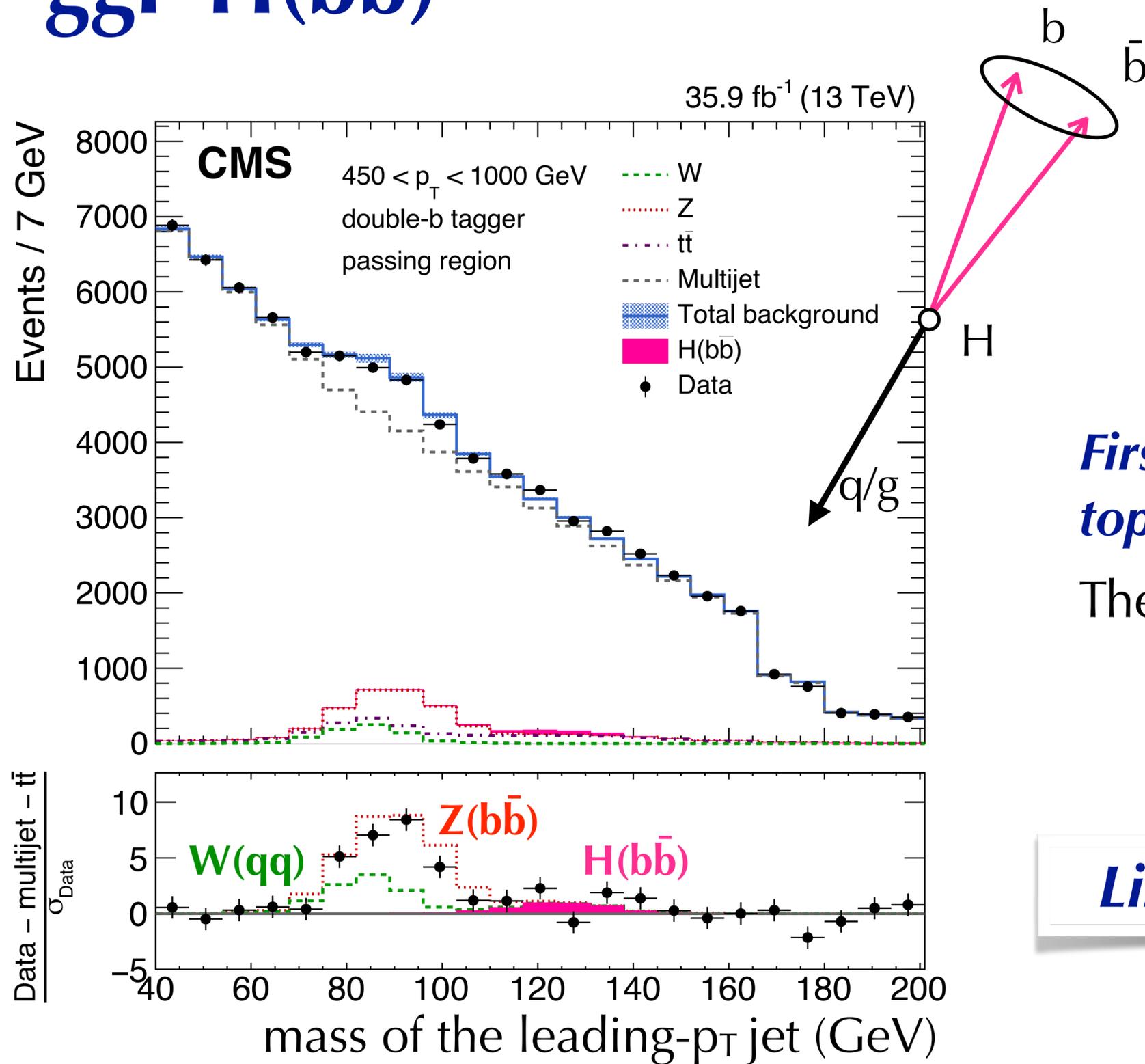
two-separate b-jets
($R = 0.4$)



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



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



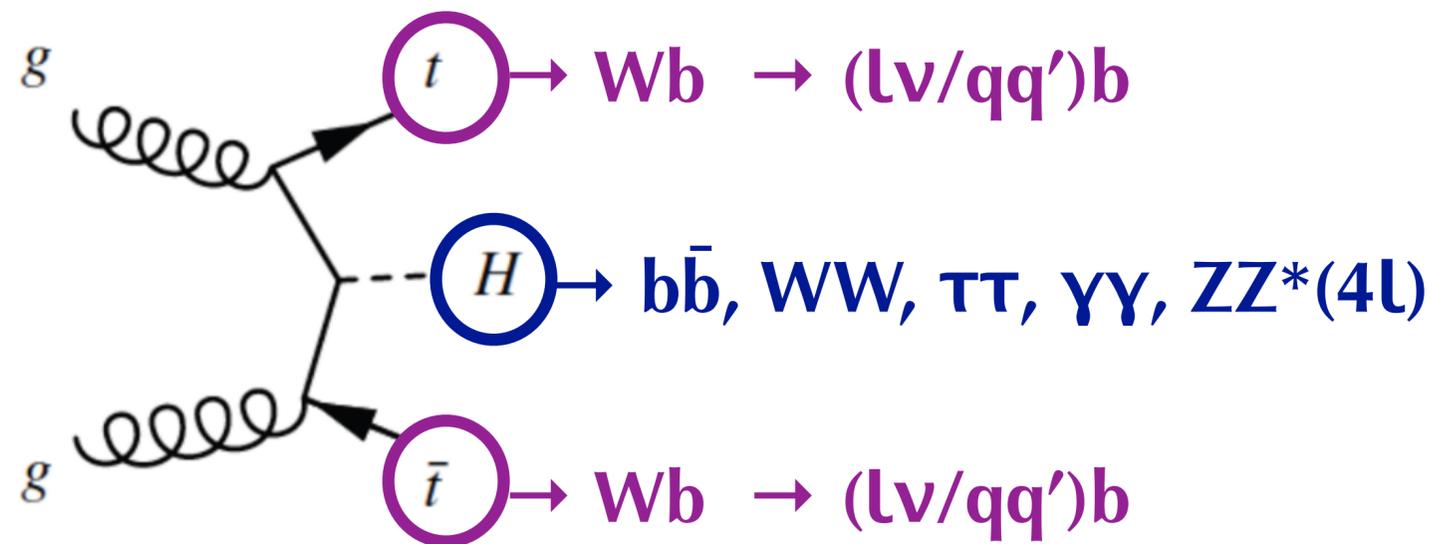
First Observation of the $Z(b\bar{b})$ in the one-jet topology 5.1 (5.8) σ

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

Limited by the statistical uncertainties

ttH production mode

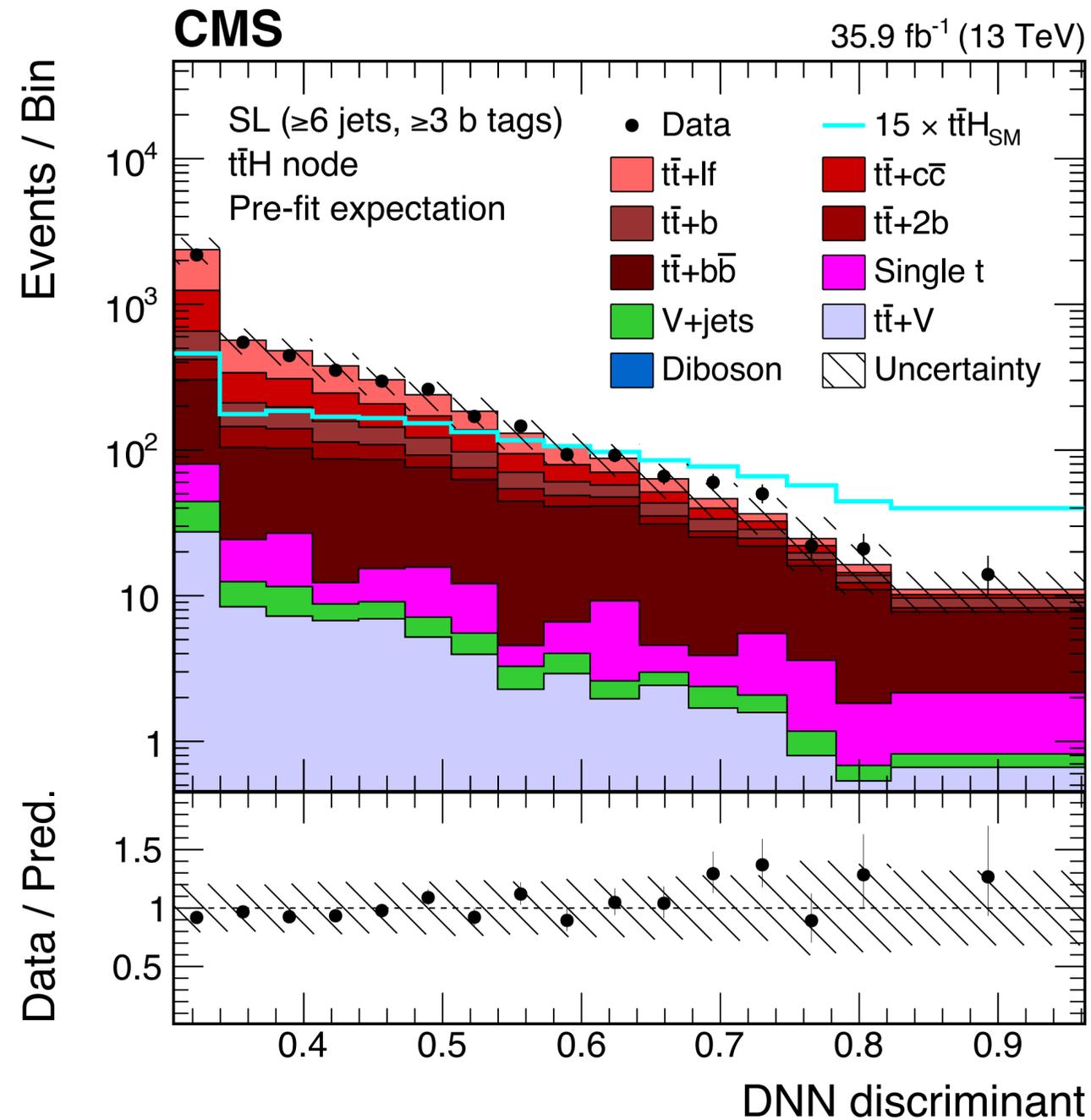
- **Best direct probe of the top-Higgs Yukawa coupling** ($y_t \sim 1$)
 - Challenges: $\sigma_{ttH} \sim 0.5$ pb, $\sigma_{tt} \sim 830$ pb at 13 TeV
 - Irreducible backgrounds from $tt+X$ ($X = b\bar{b}, W, Z$)
 - Large combinatorics of leptons and jets from top quark decays
- **Exploiting multiple final state**, depending on the top and Higgs decay channel



Depending on the H decay
Smaller BR vs. better S/B

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

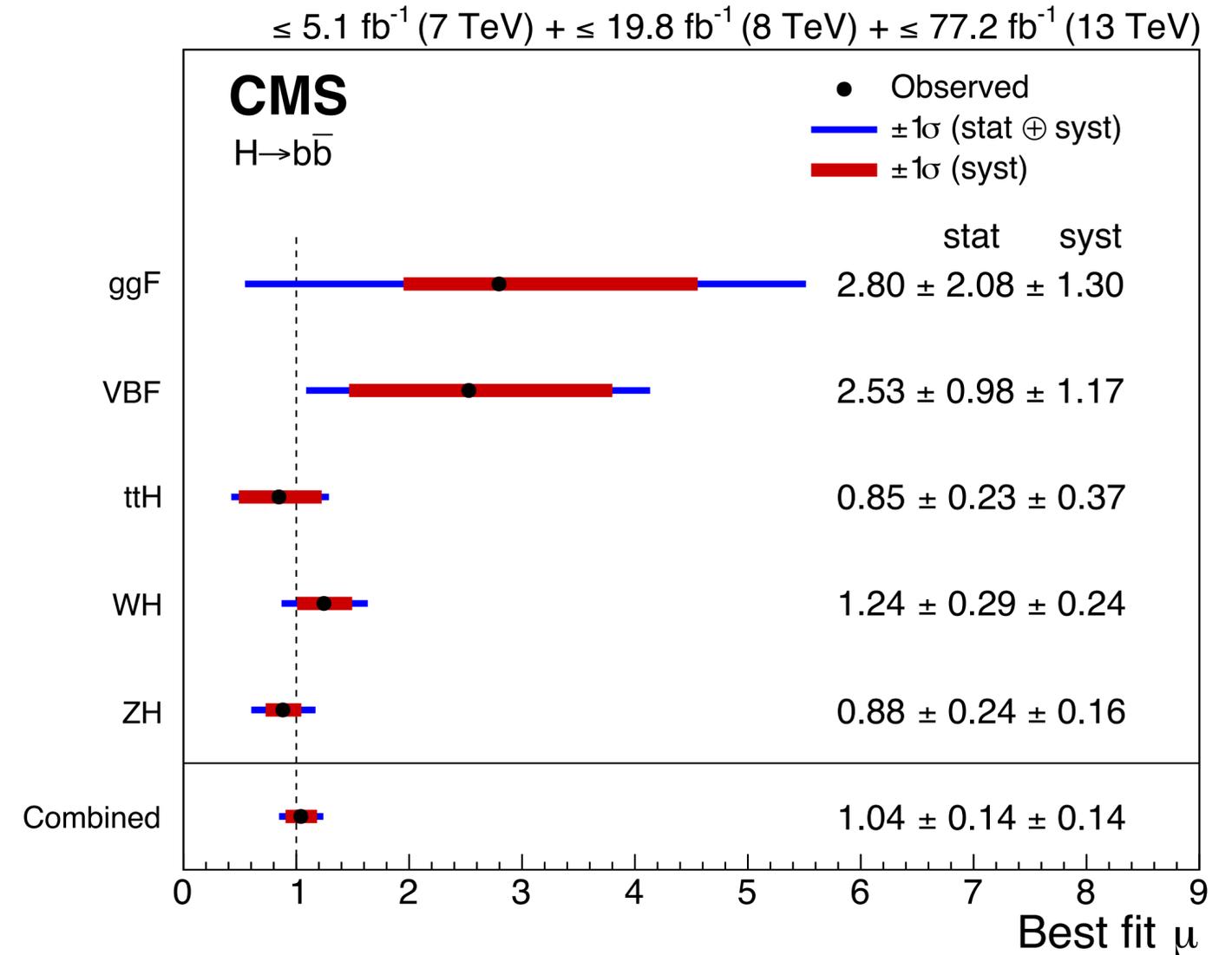
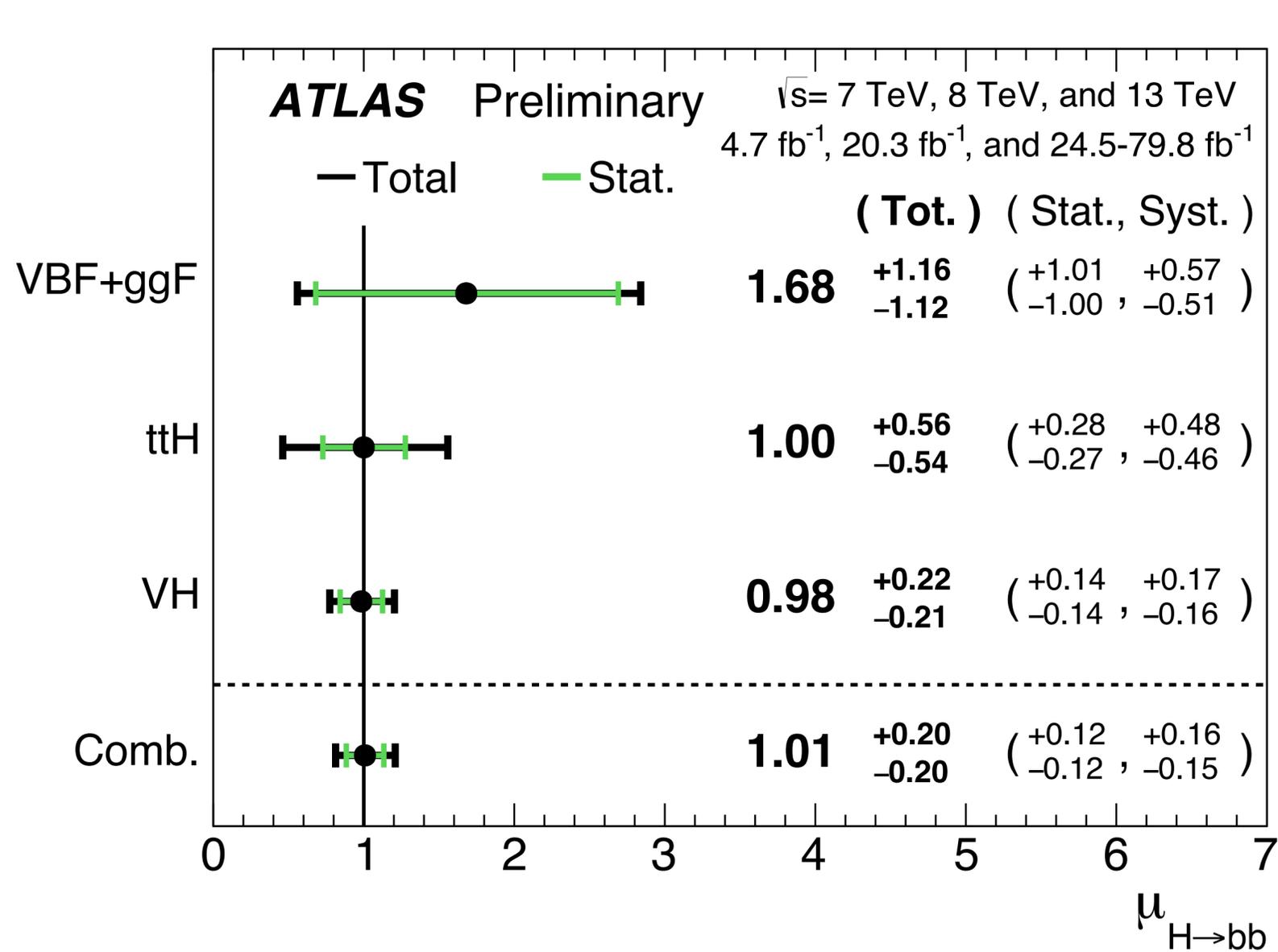
ttH(bb) searches



$tt \rightarrow l+jets \quad H \rightarrow b\bar{b}$

- Large combinatorics in the event reconstruction
- Dominant **tt+bb** 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**

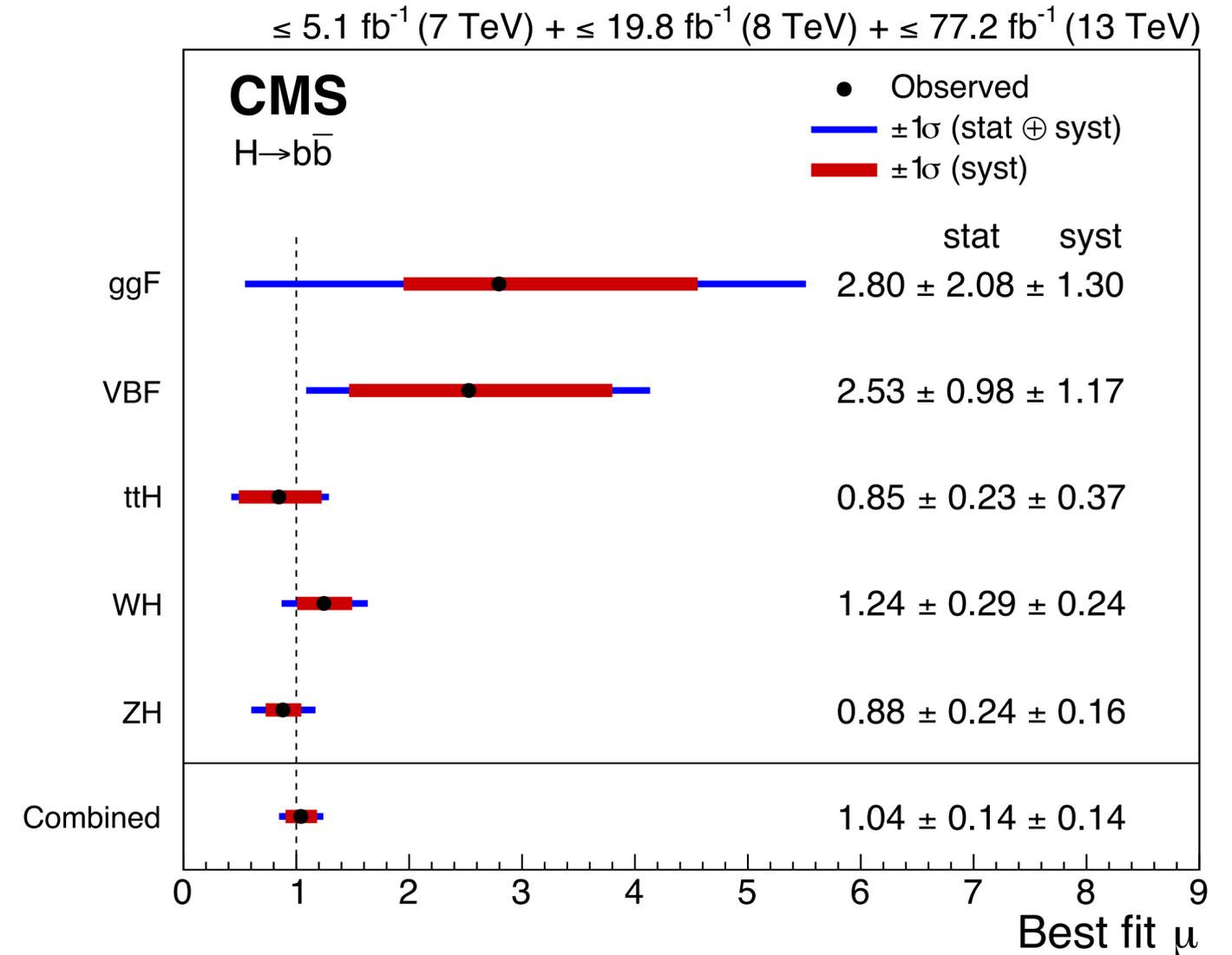
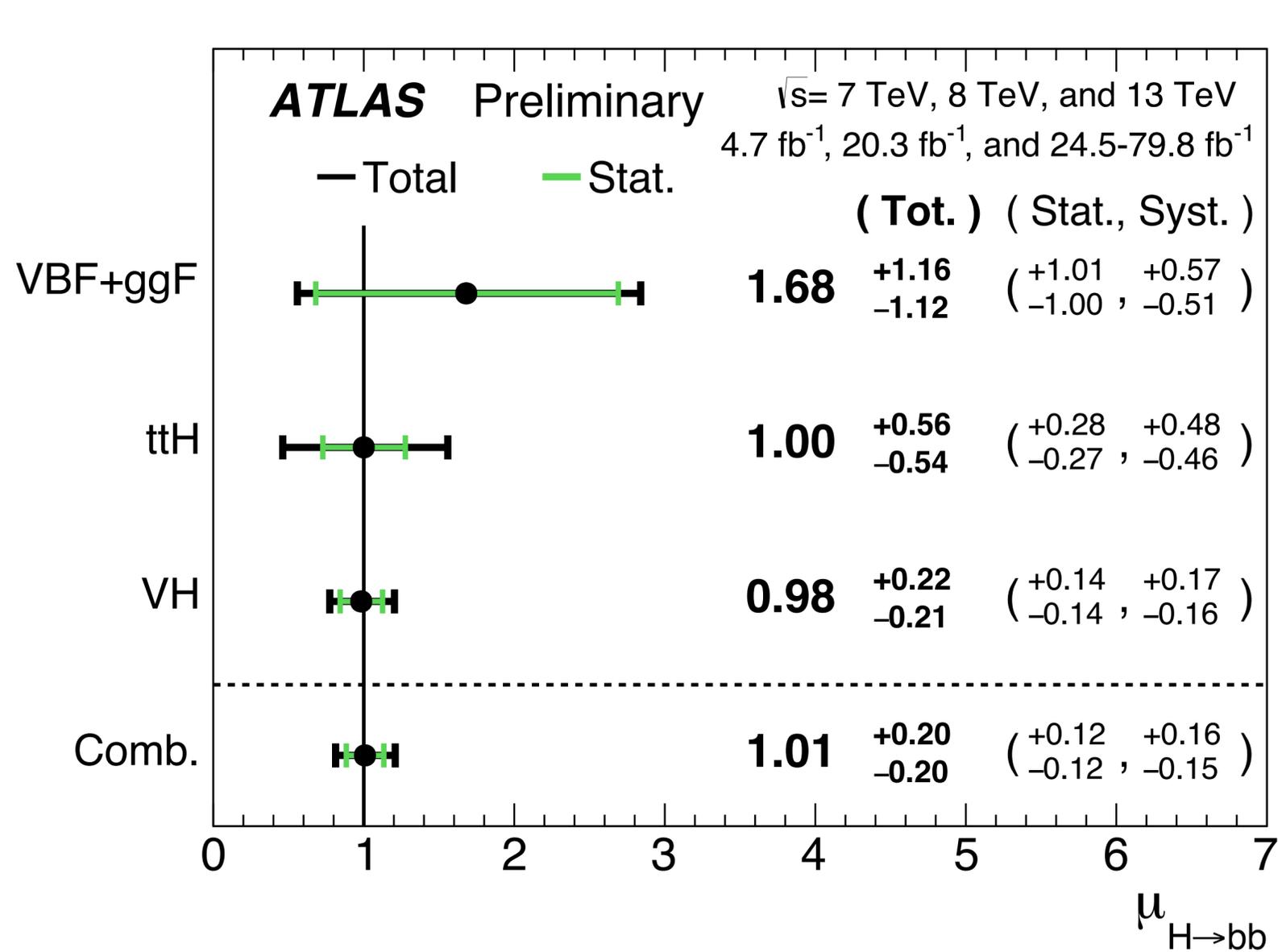
H(bb̄) observation



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

H(bb̄) 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

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

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 $\Lambda \sim 2.5 \text{ TeV}$

Higgs couplings: precision & kinematic

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Assuming new physics at some scale Λ

Testing multi-TeV scale with **sub-percent level measurements**

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

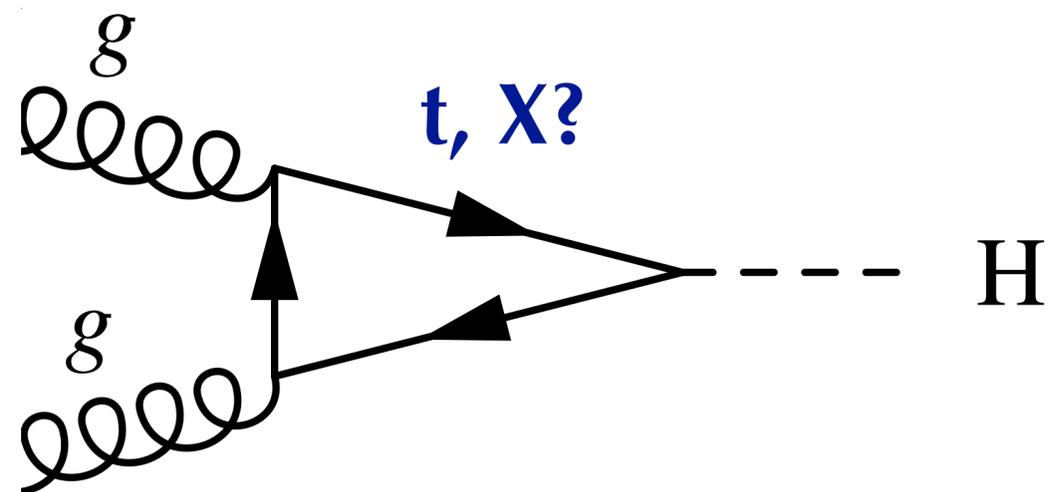
1% effect on coupling for $\Lambda \sim 2.5$ TeV

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

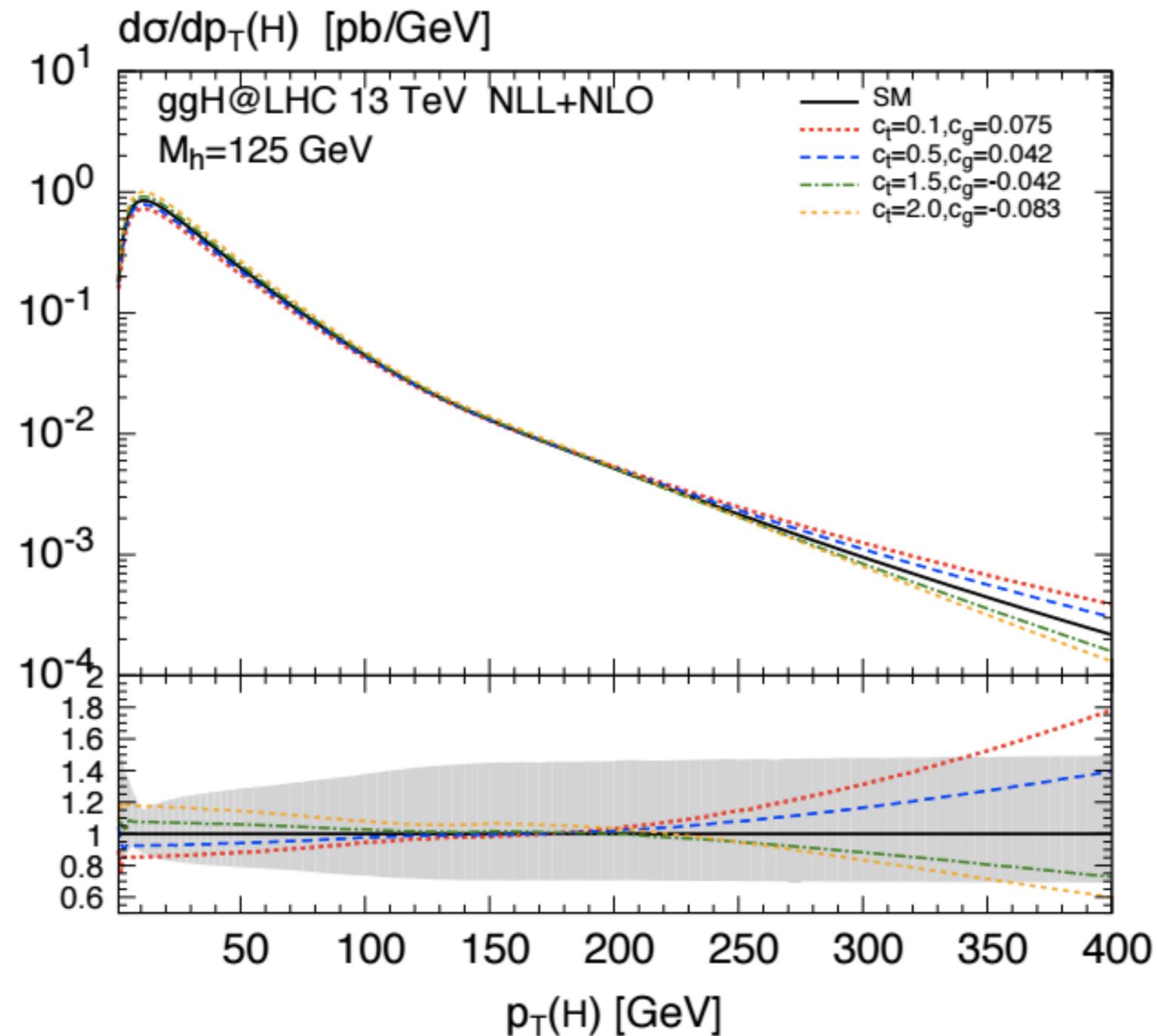
$$\delta\mathcal{O}_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

15% effect on $\delta\mathcal{O}_Q$ for $\Lambda \sim 2.5$ TeV

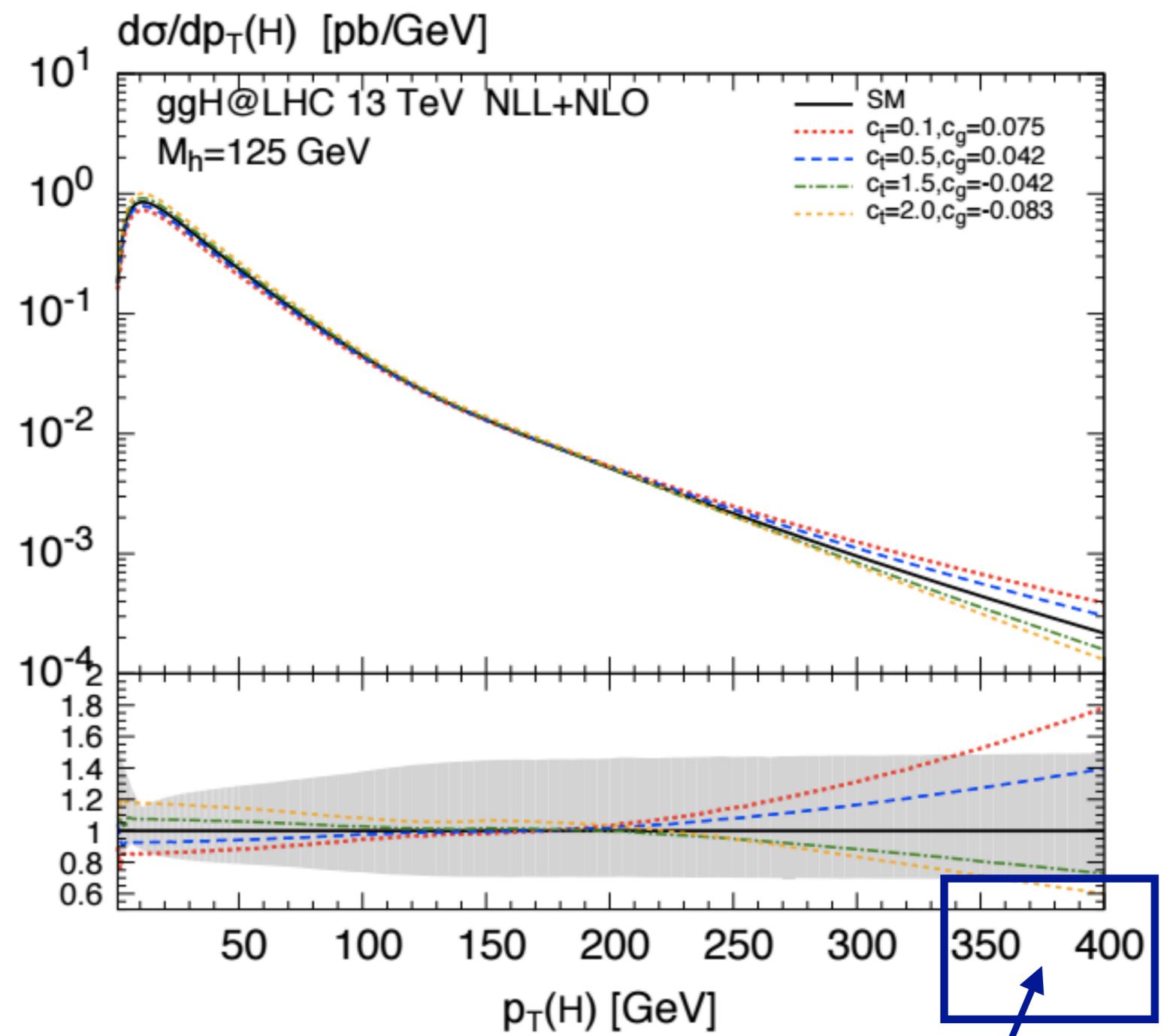
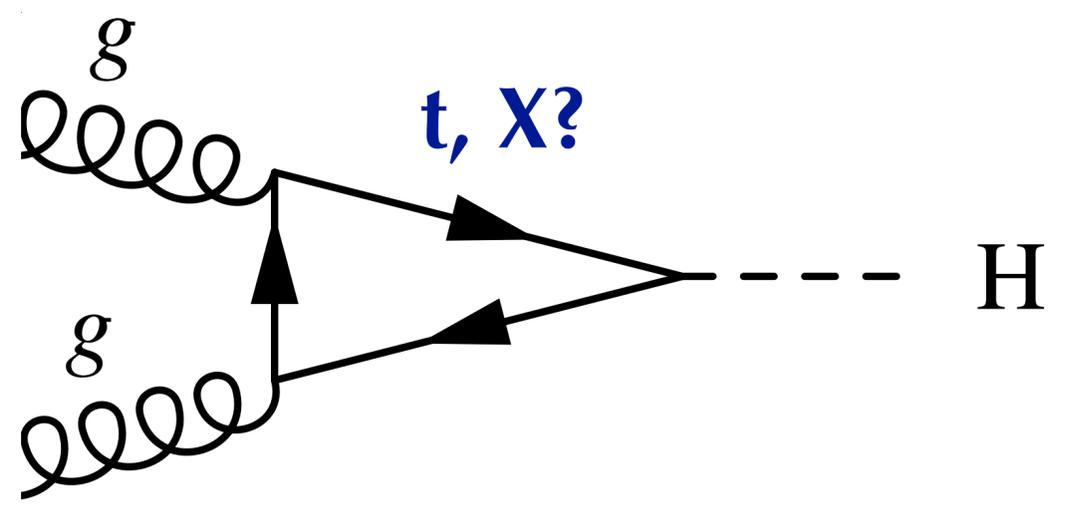
Higgs at high p_T



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

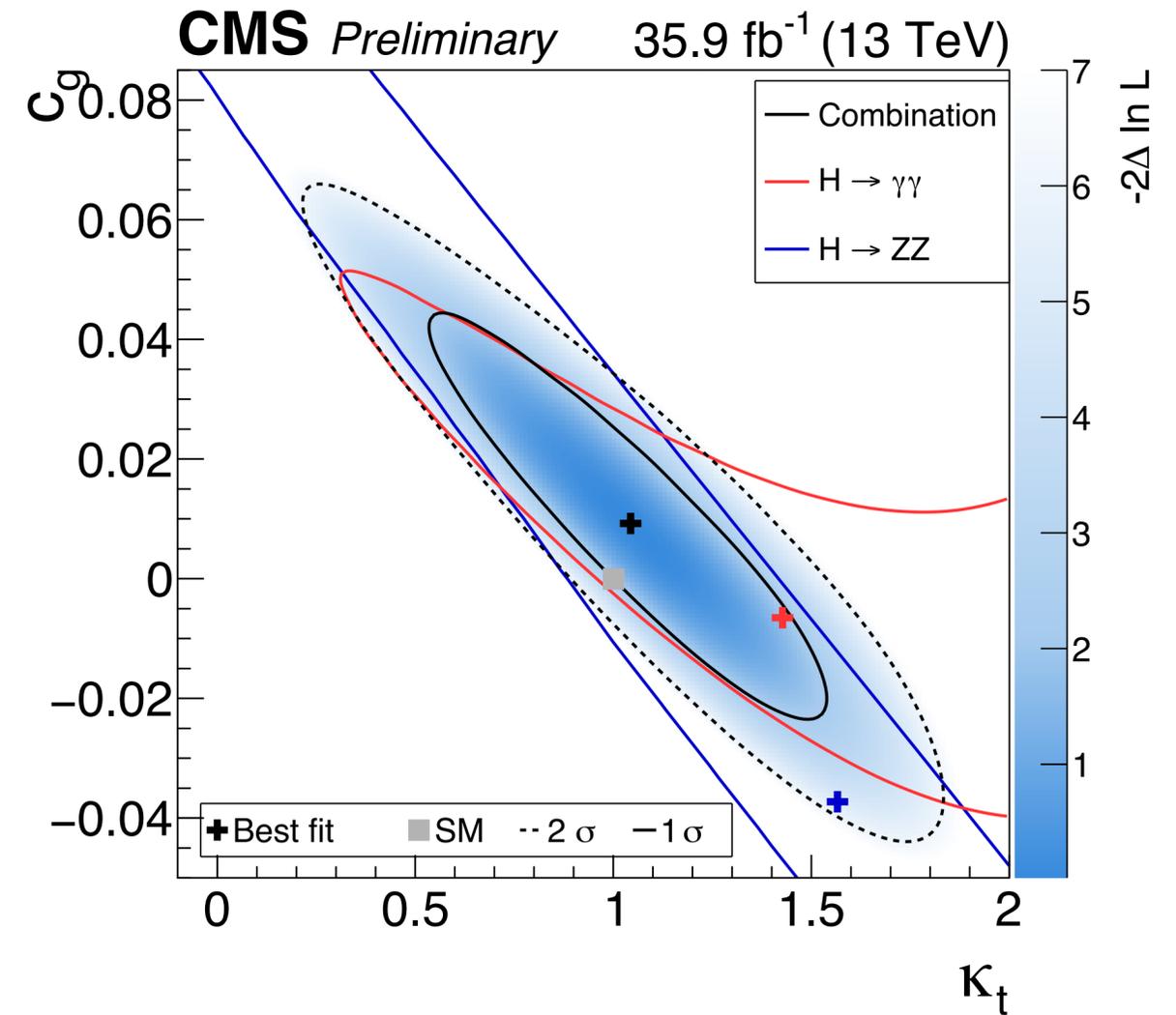
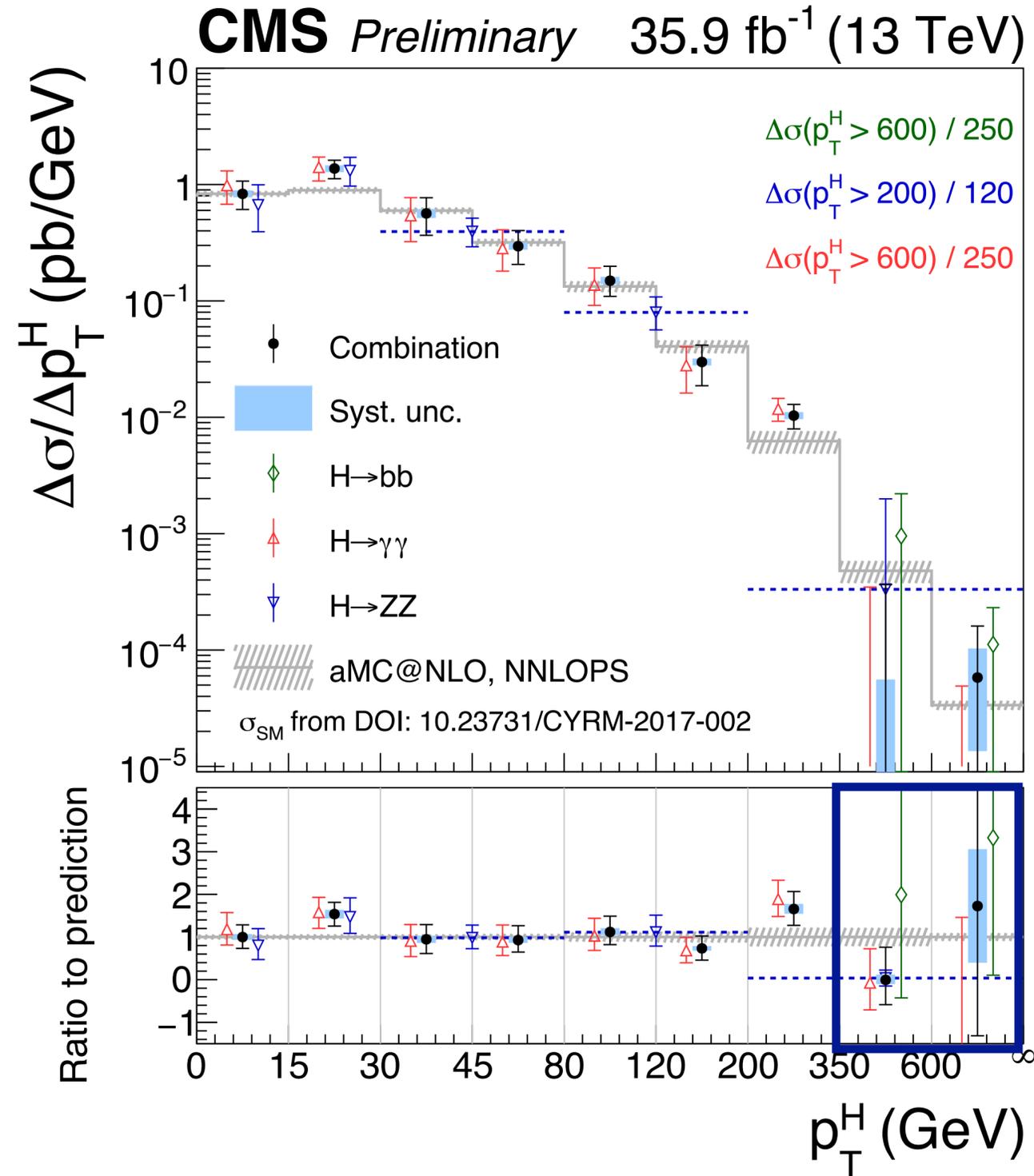


Higgs at high p_T



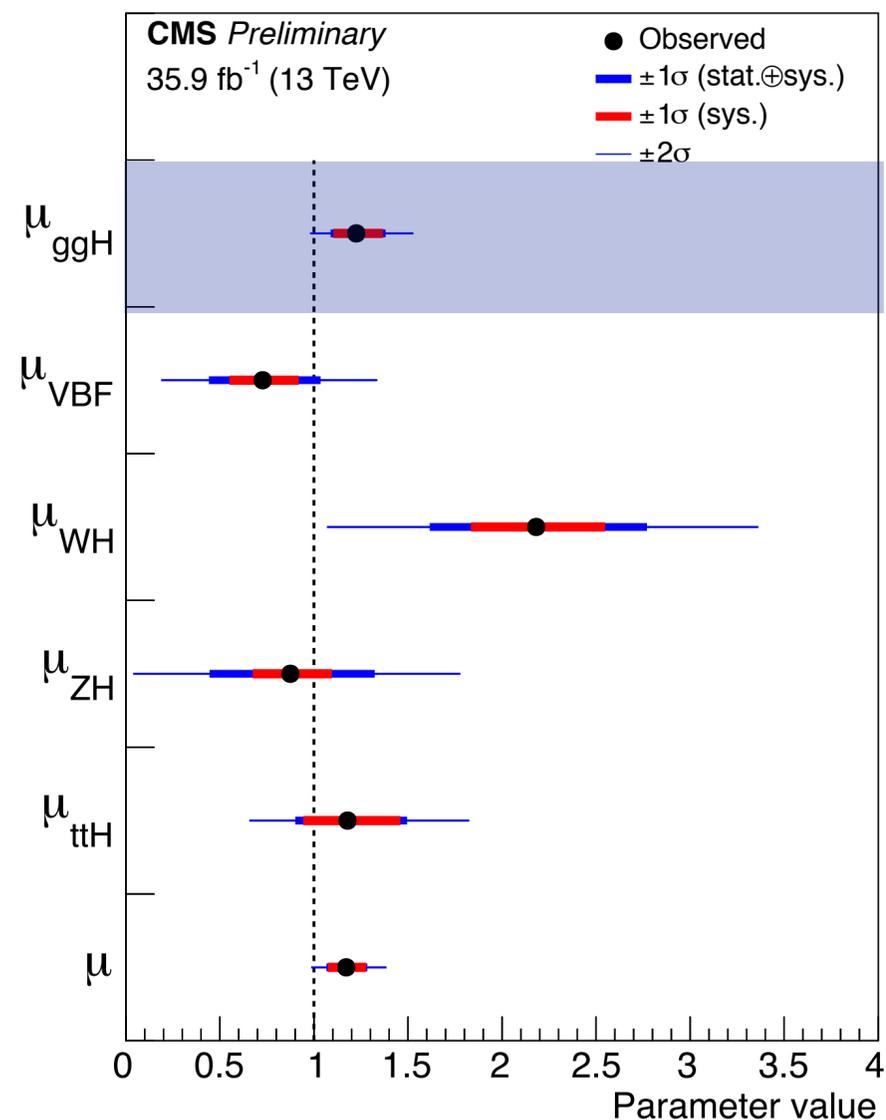
ggF H(bb) starts here

Probing ggF vs. H p_T

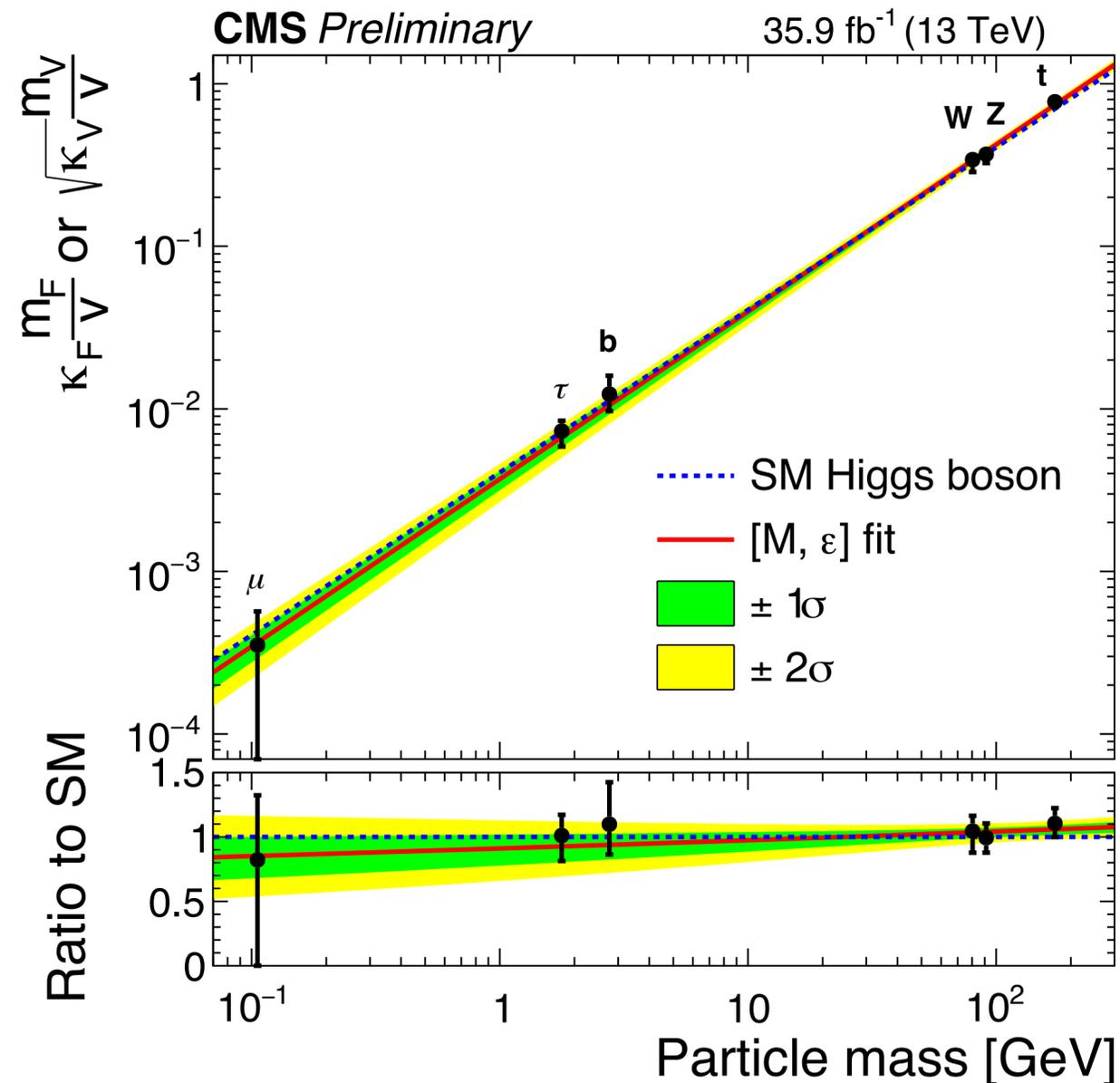


H(bb̄) improves constraints to new physics by 30%

Run1+2, Higgs boson summary



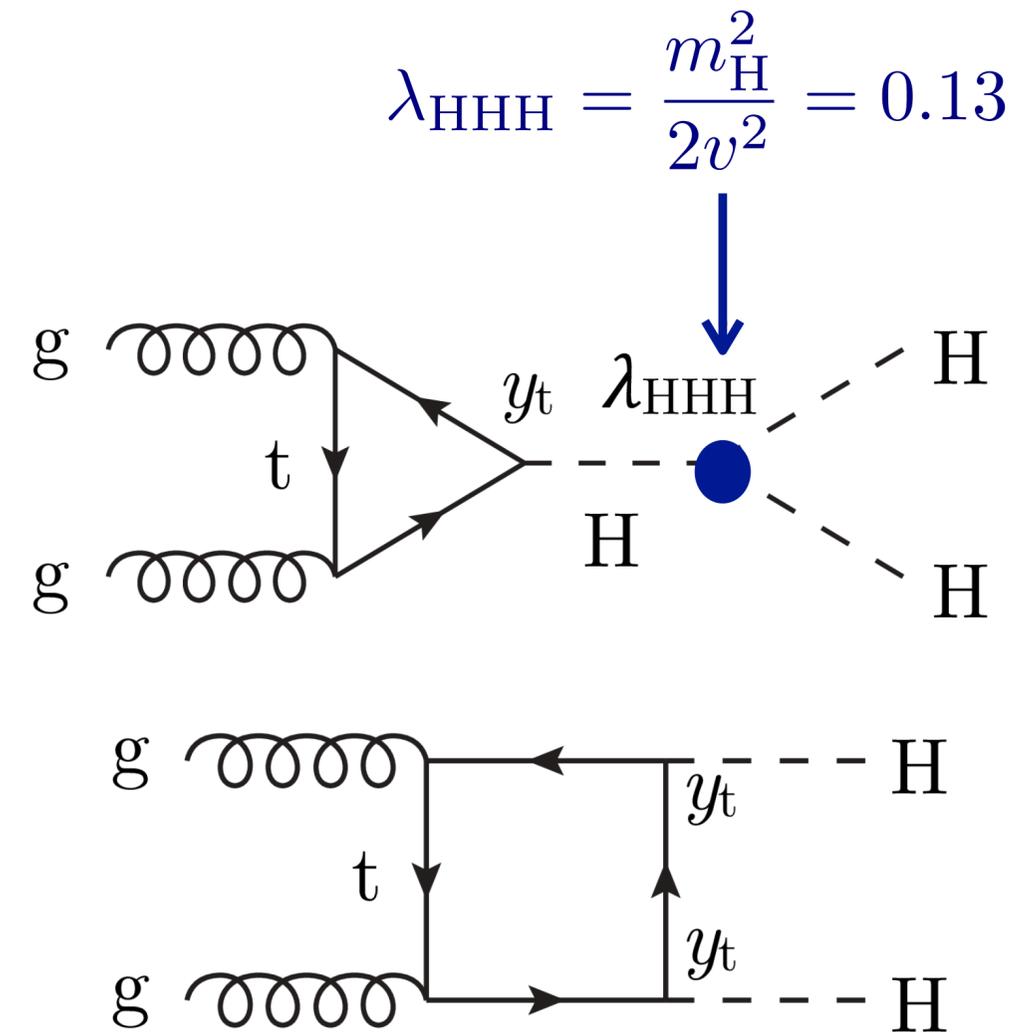
~10%



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)

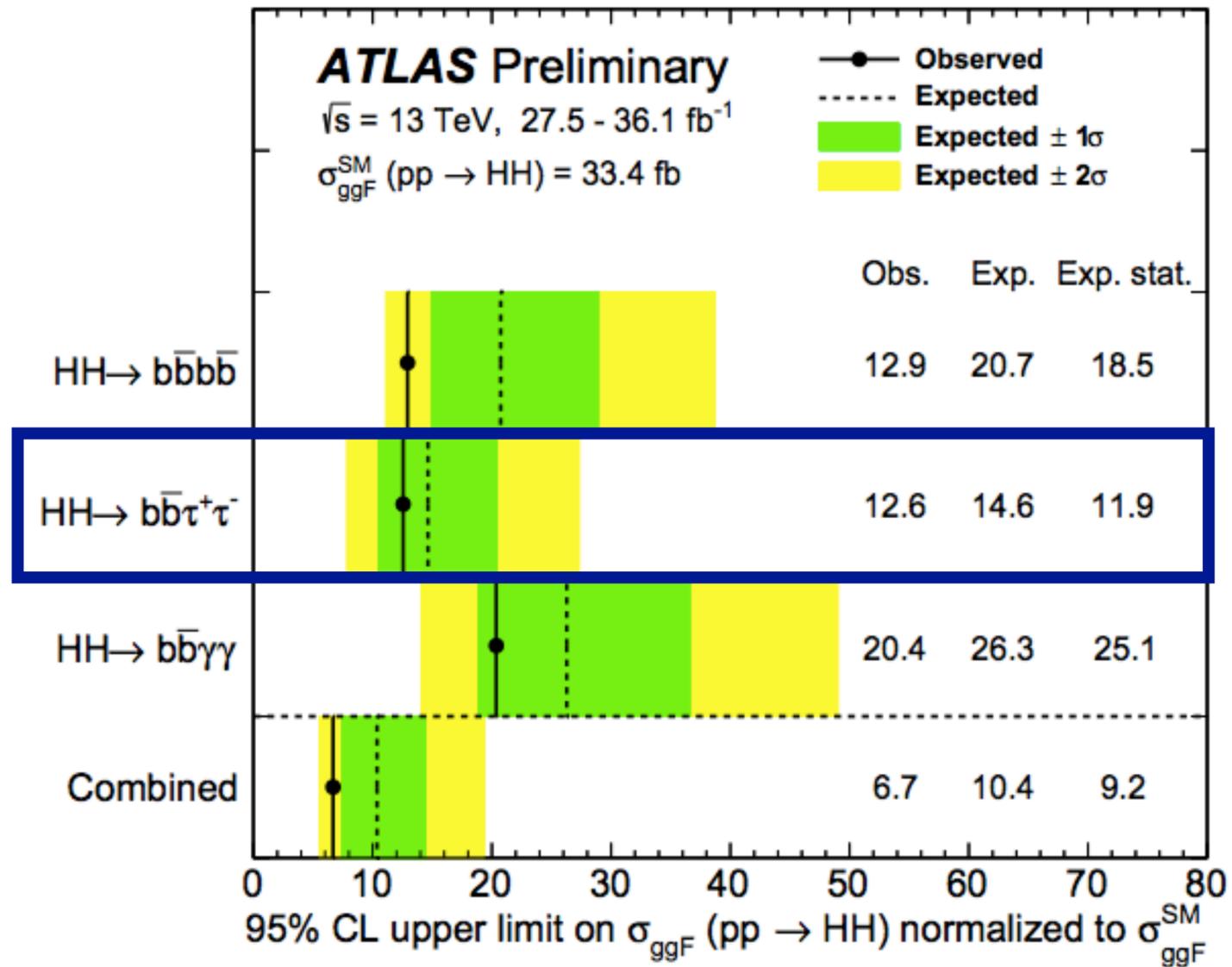
Is it a SM Higgs boson?

- 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)
20% precision on λ_{HHH} needed to probe BSM modifications

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 10 x SM

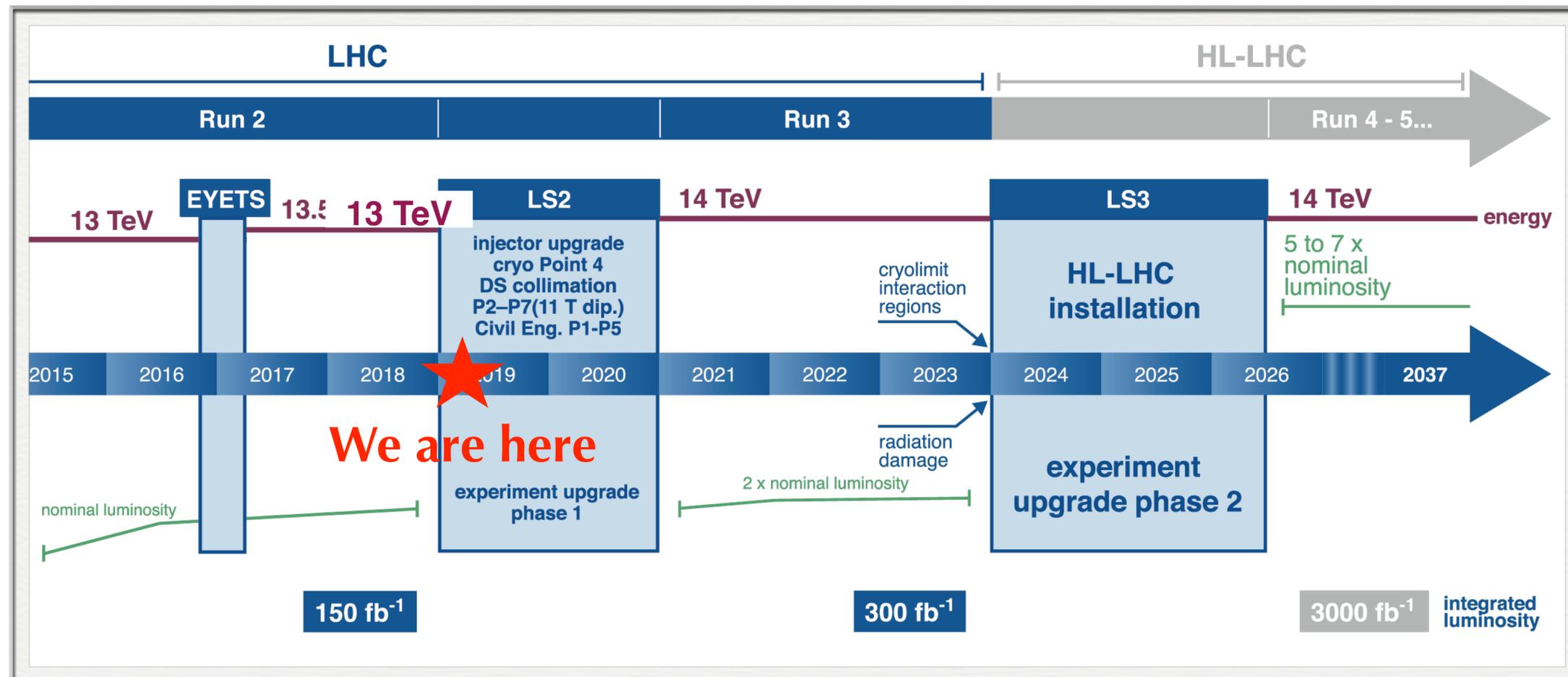
Conclusions

- Many **new** updates with **Run-2 dataset** ($\sim 80 \text{ fb}^{-1}$)
 - 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 $10 \times \text{SM}$

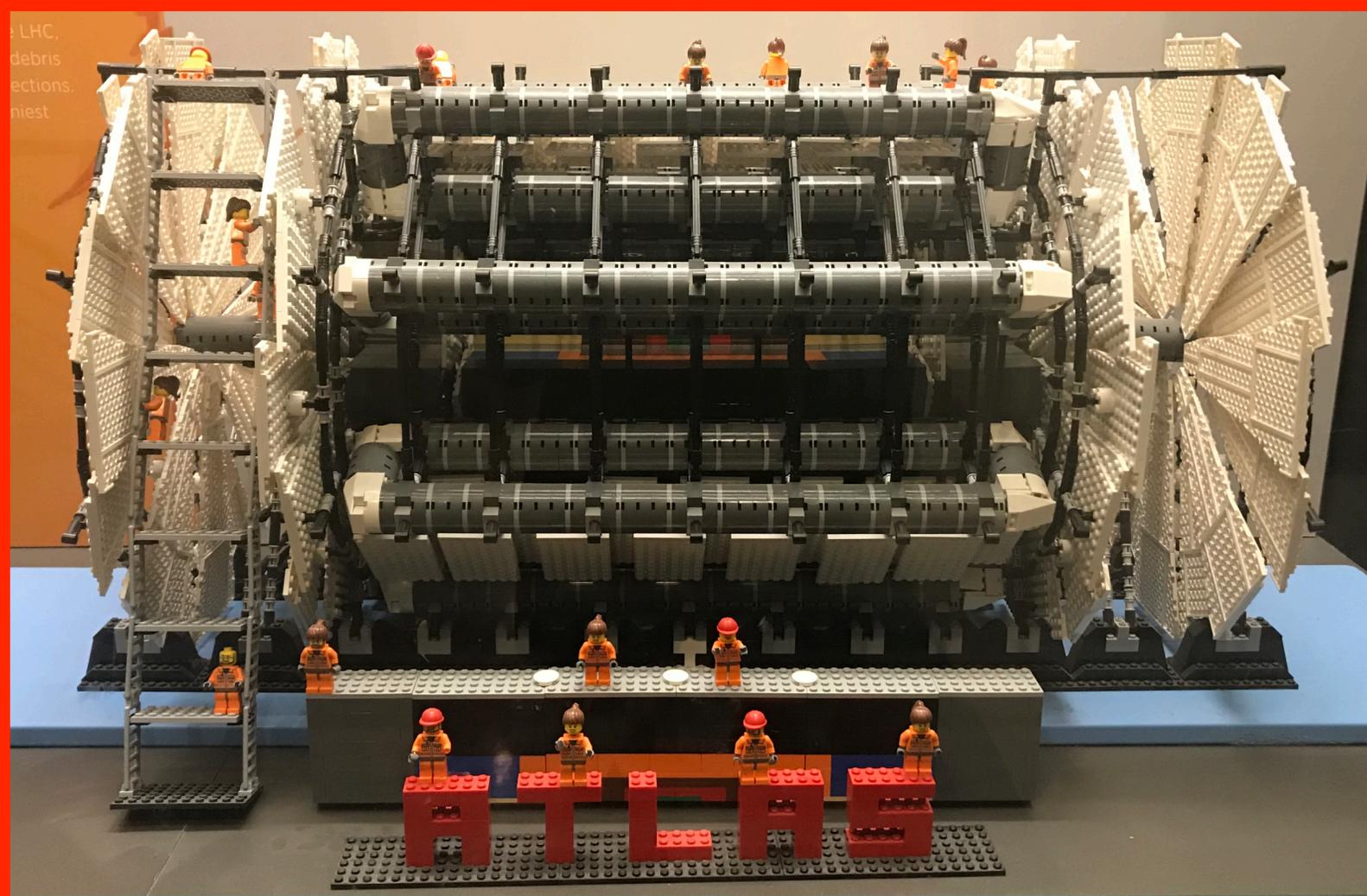
Outlook

HL-LHC will enable:

- precision measurements of H properties (couplings, self-couplings,...)
- to probe the existence of very rare new physics processes



Only analyzed <3% of the final LHC luminosity ...Just the beginning



thank you!

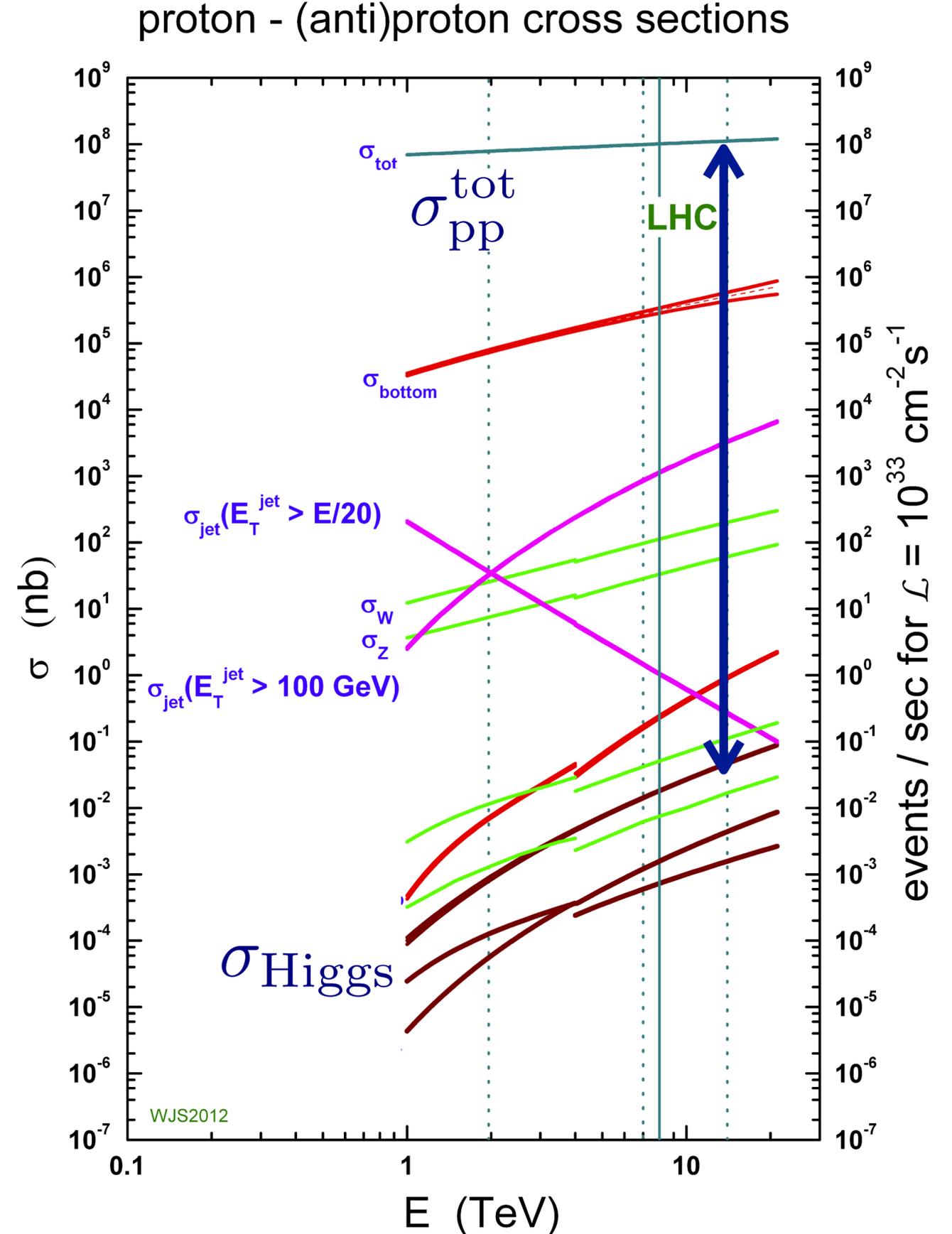
Cross section

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

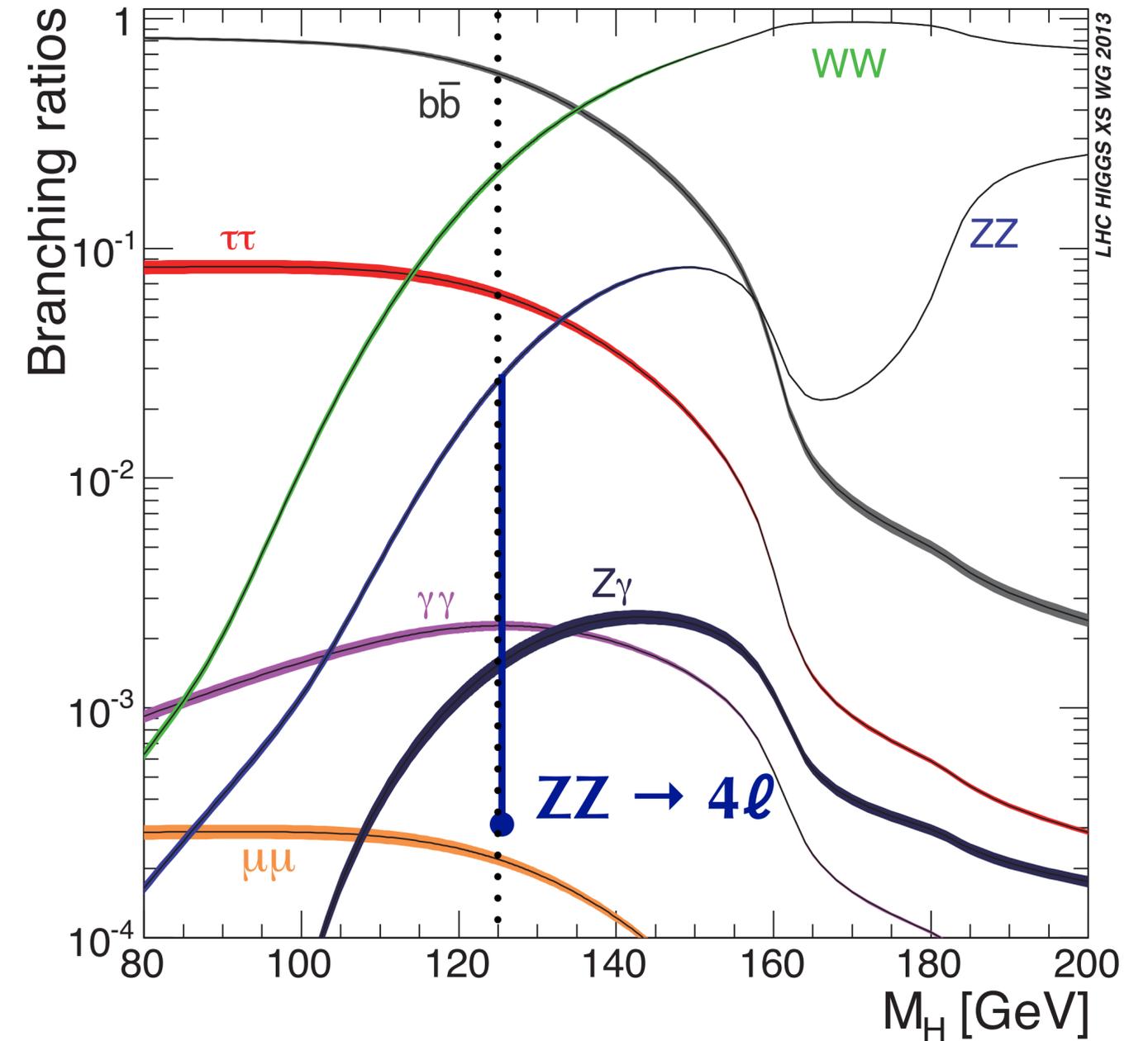
Only in one out of every one billion collisions a Higgs boson is produced

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

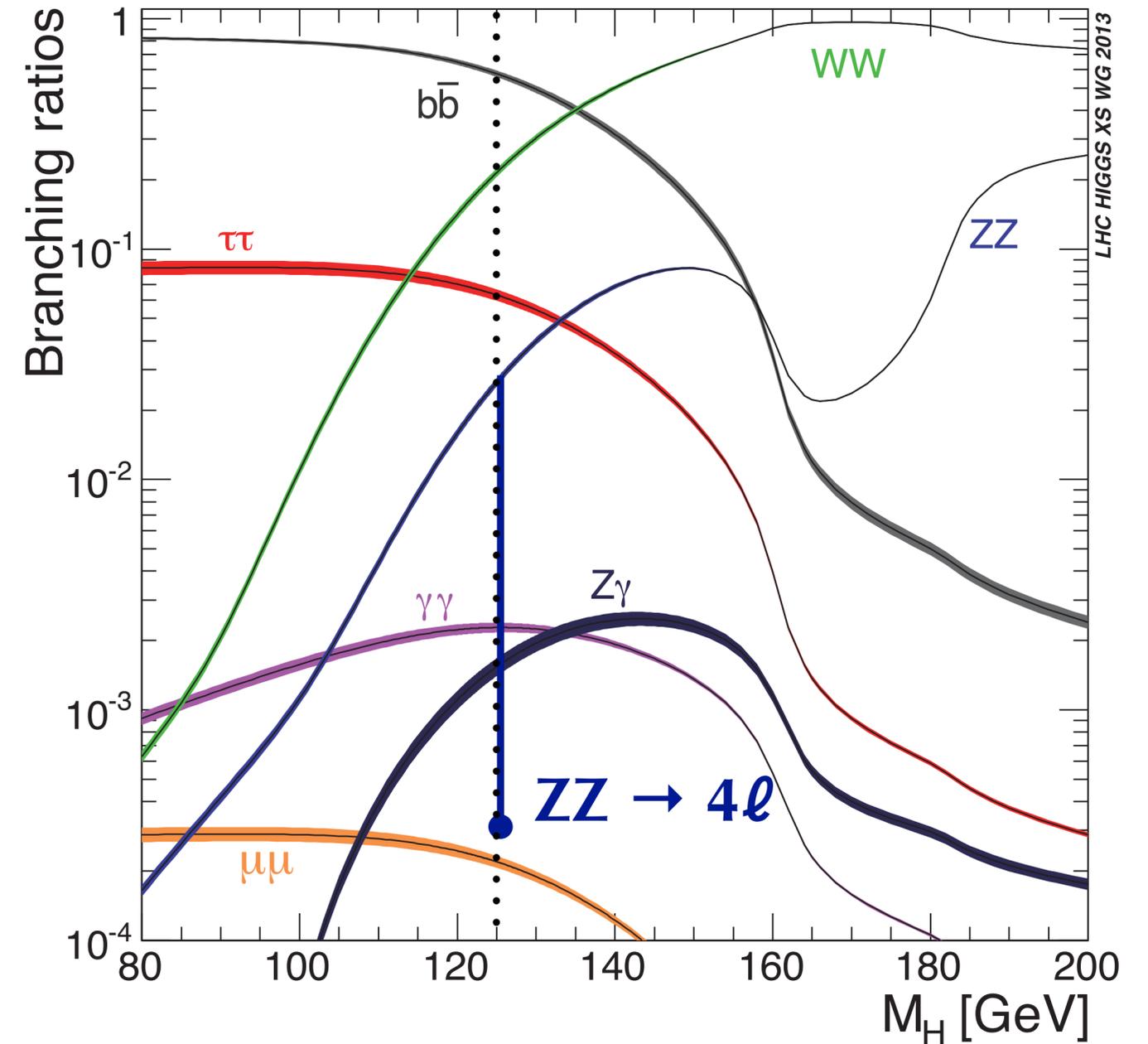
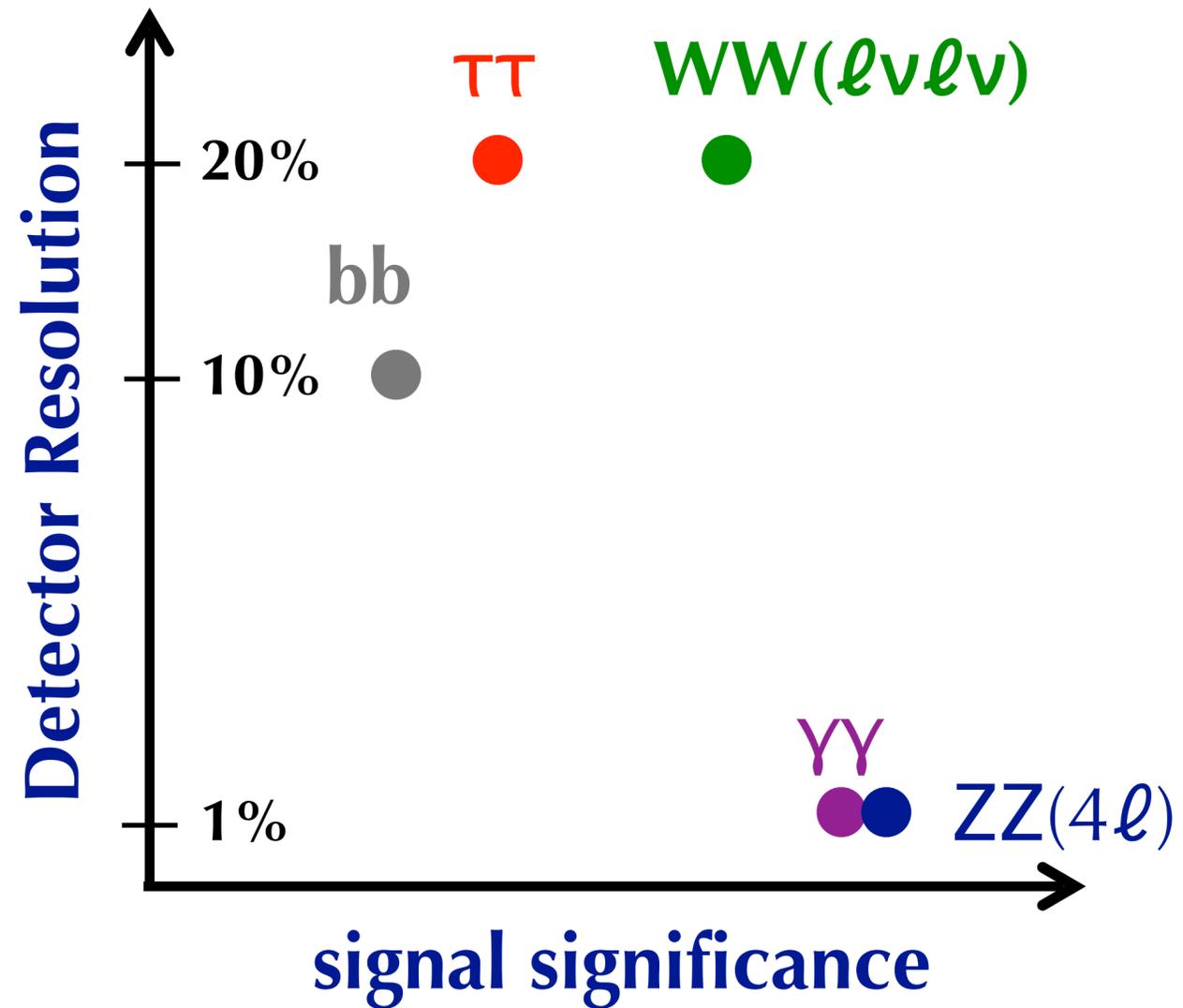
Storage and computing are limited



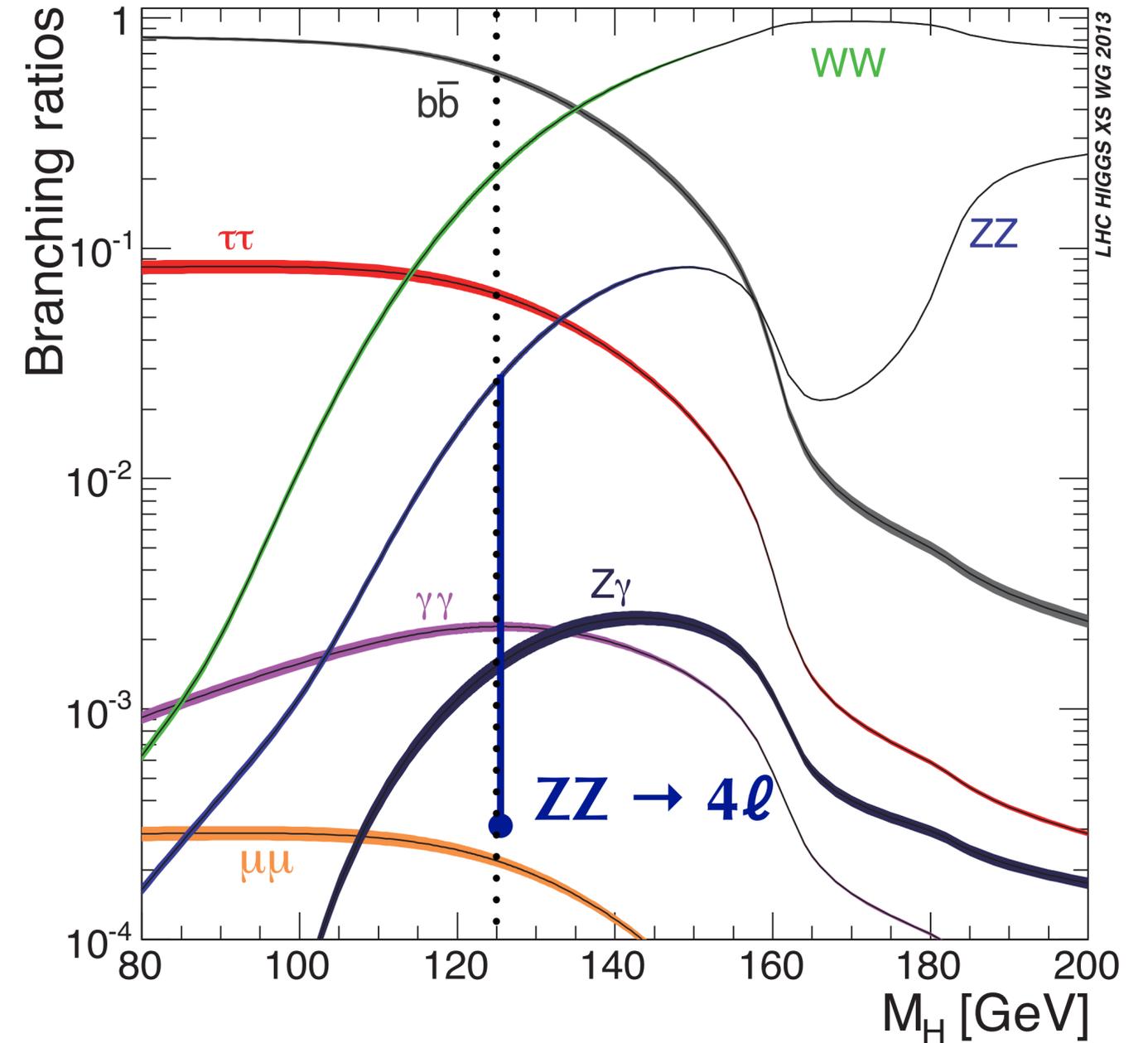
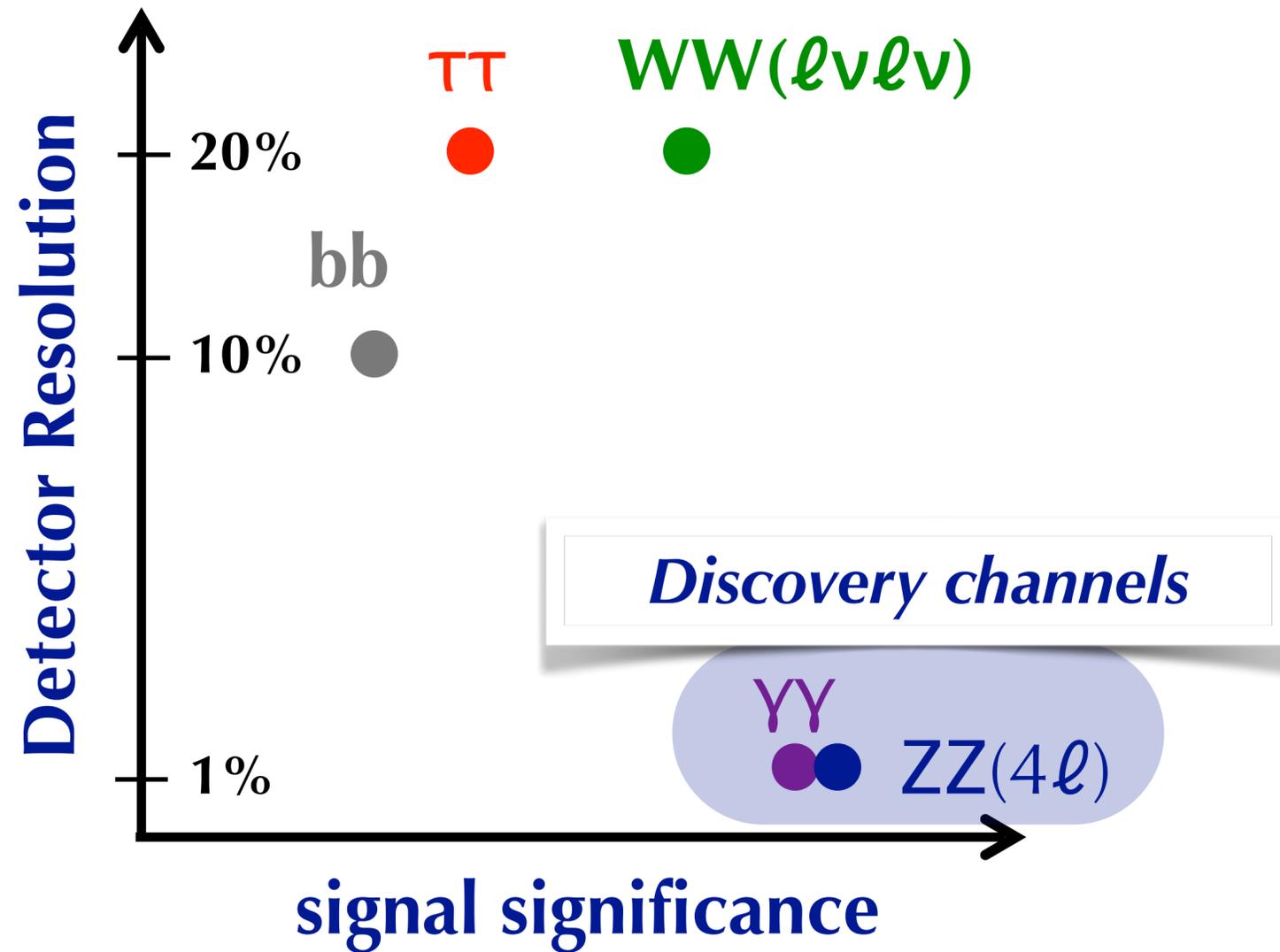
How does it Decay ($m_H = 125$ GeV) ?



How does it Decay ($m_H = 125 \text{ GeV}$) ?



How does it Decay ($m_H = 125 \text{ GeV}$) ?

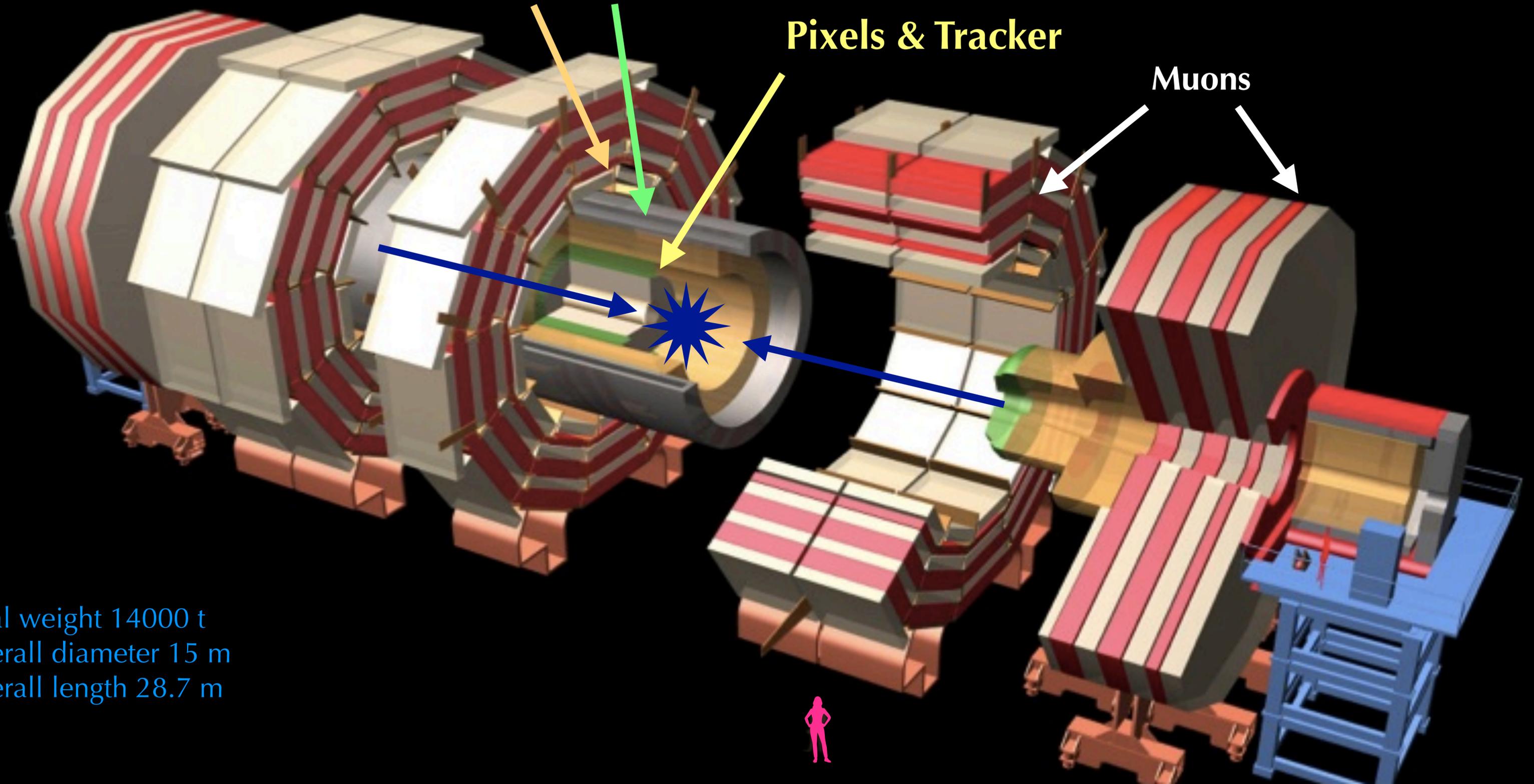


The Compact Muon Solenoid (CMS) experiment

HCAL ECAL

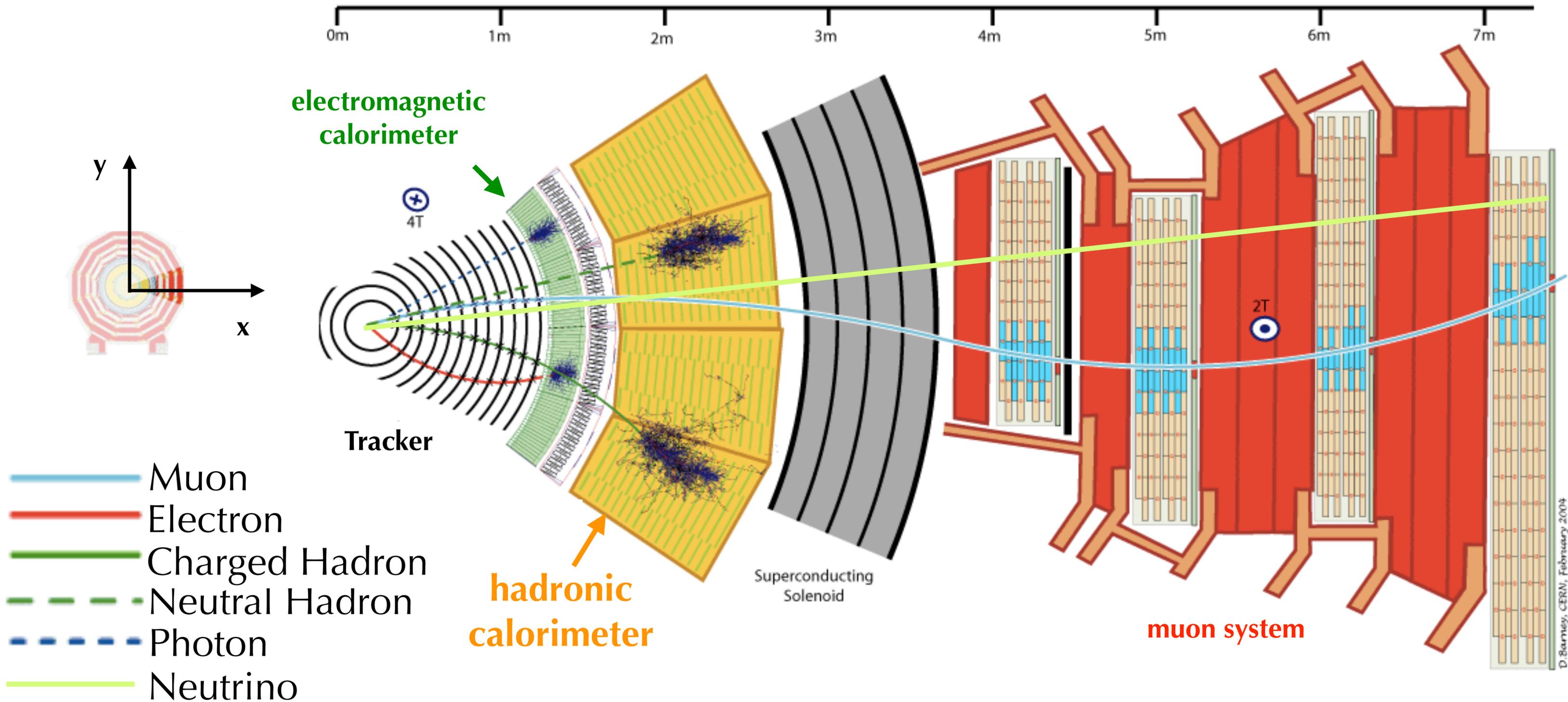
Pixels & Tracker

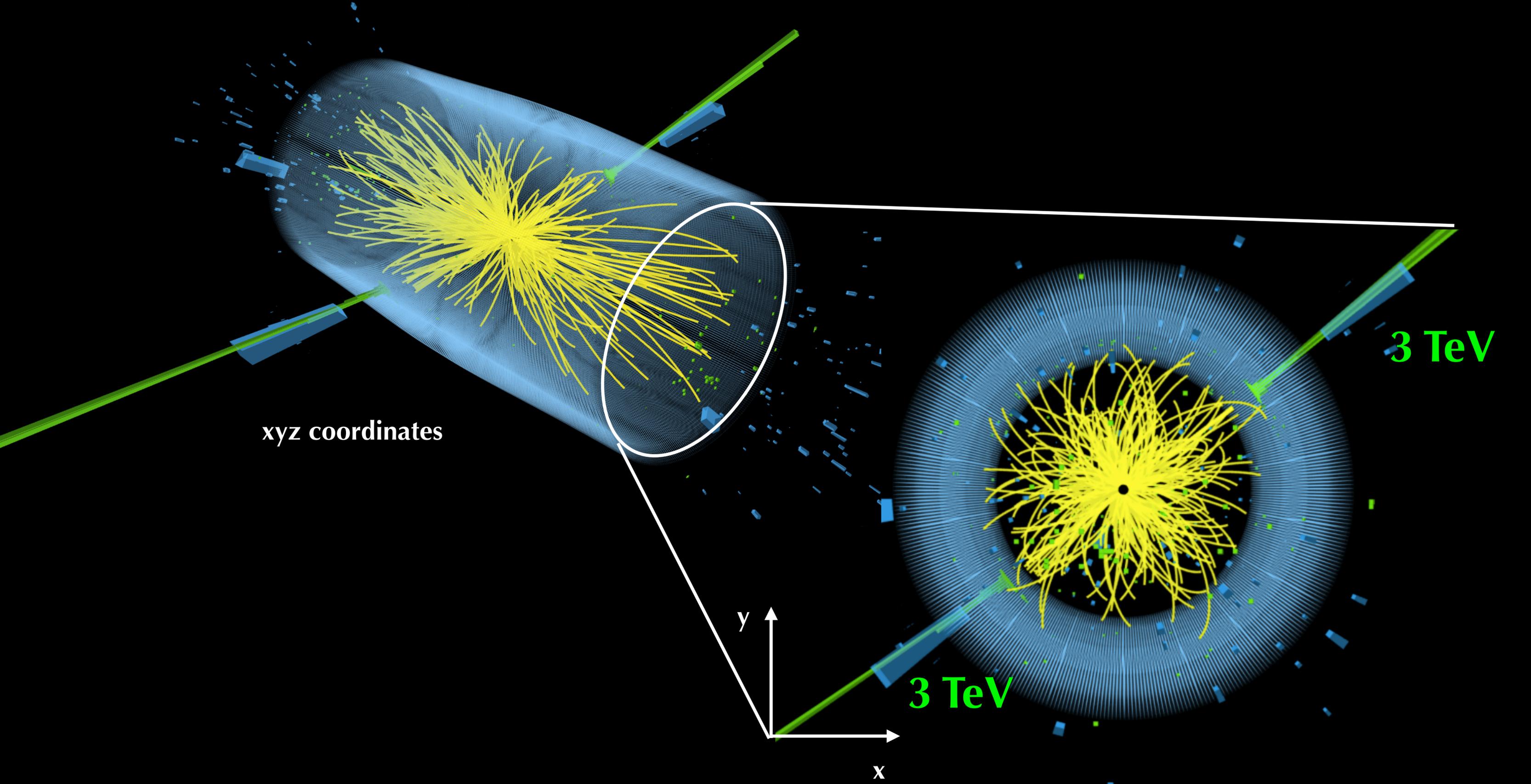
Muons

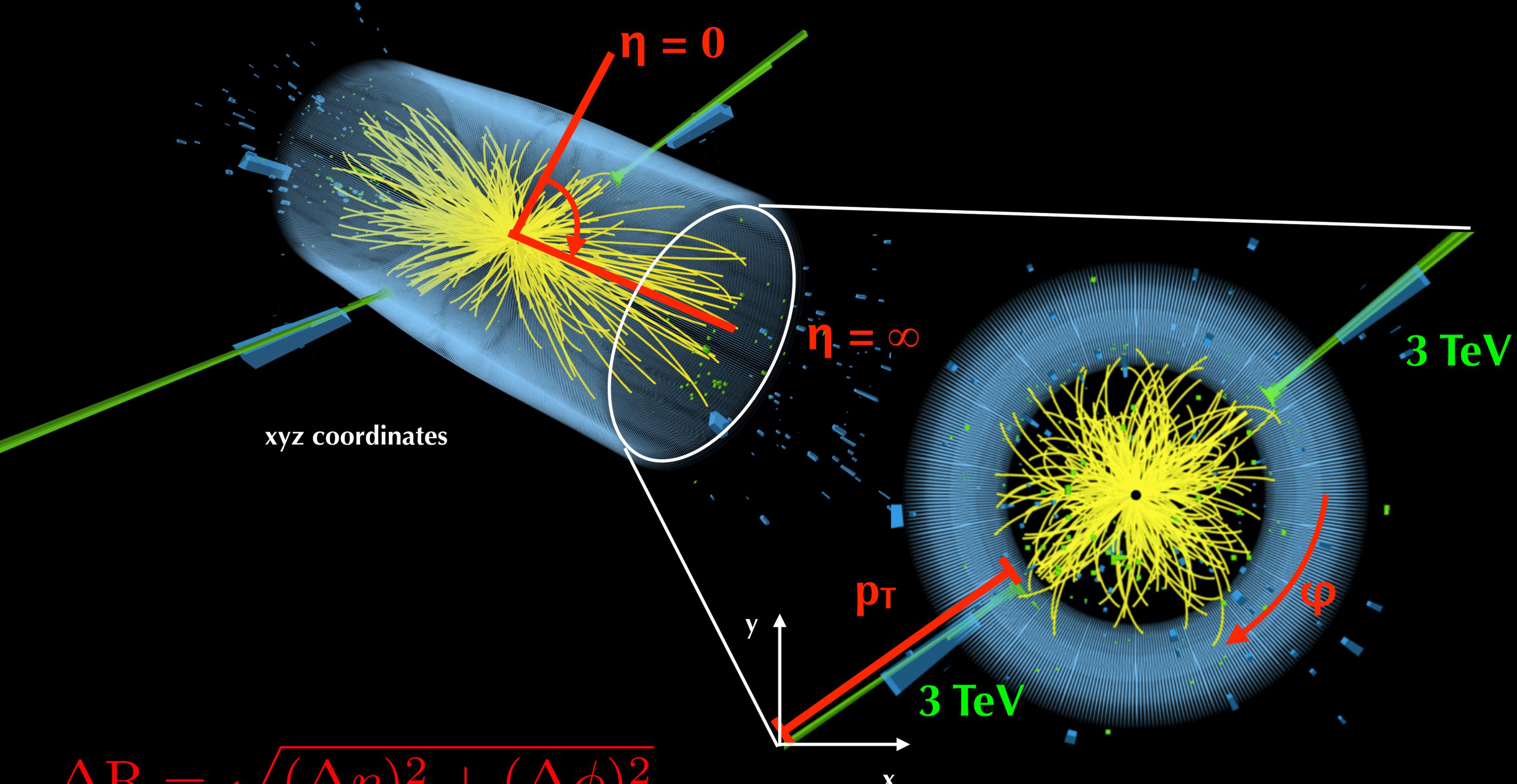


Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m

From the detector to physics objects

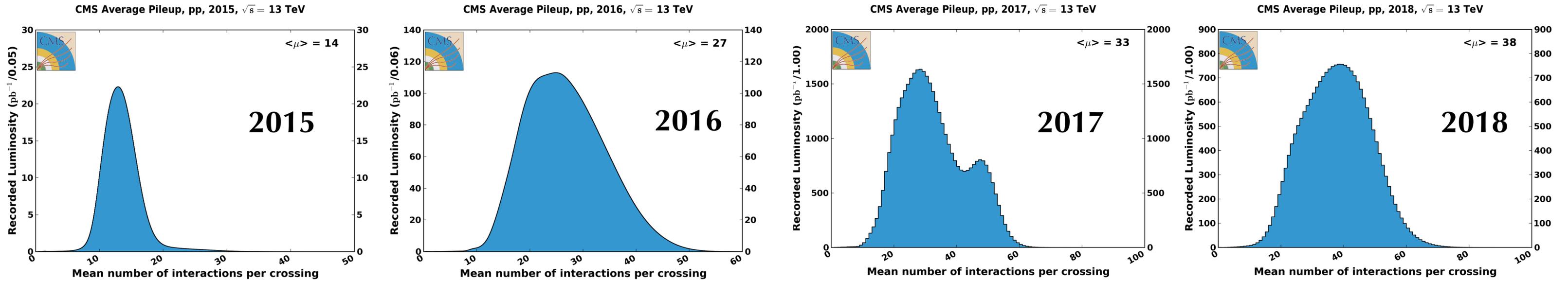






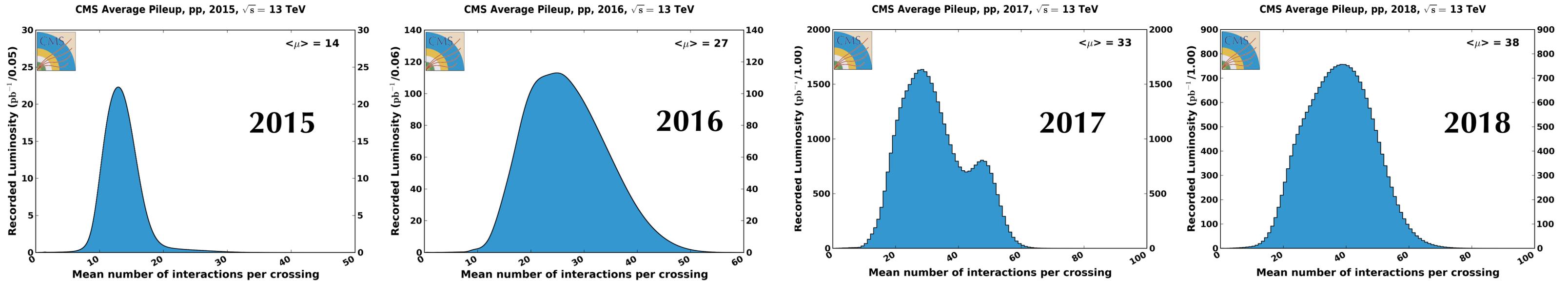
$$\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$$

Pileup @LHC



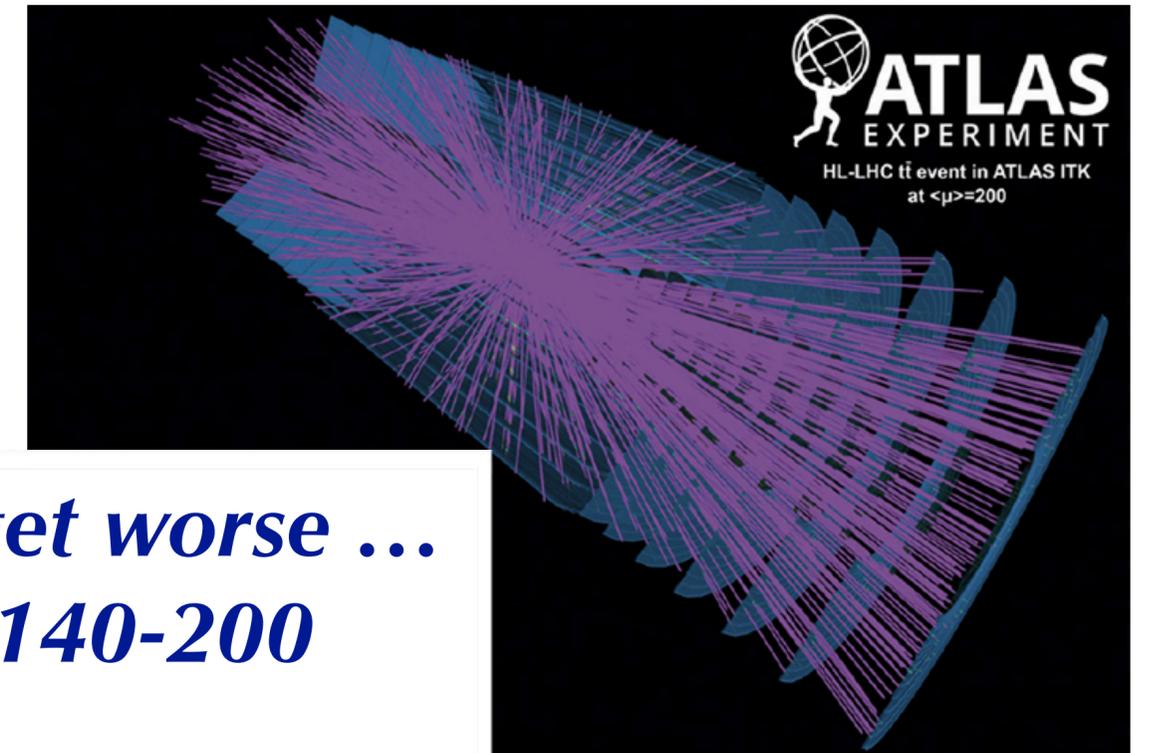
LHC during 2015-2018 on average ~15-40 pp interactions per bunch crossing

Pileup @LHC

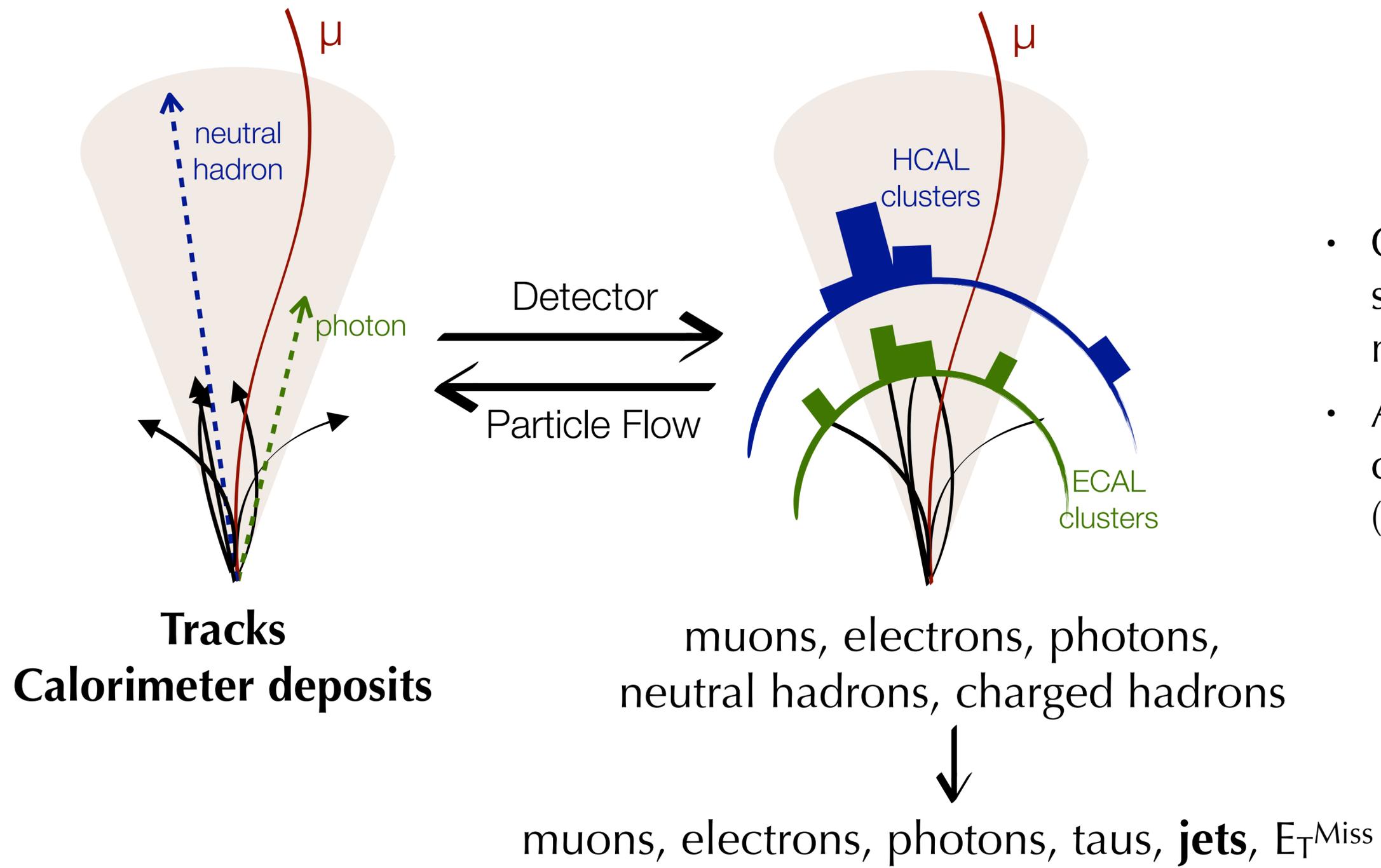


LHC during 2015-2018 on average ~15-40 pp interactions per bunch crossing

*it will only get worse ...
HL-LHC 140-200*

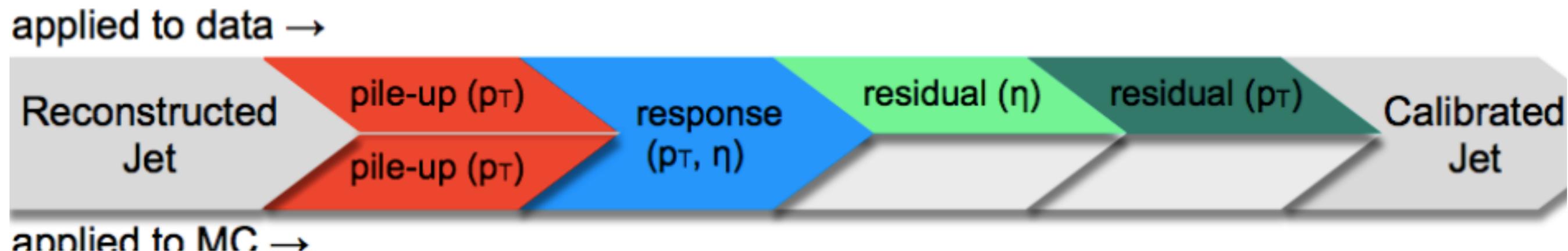


Physics objects in CMS



- 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

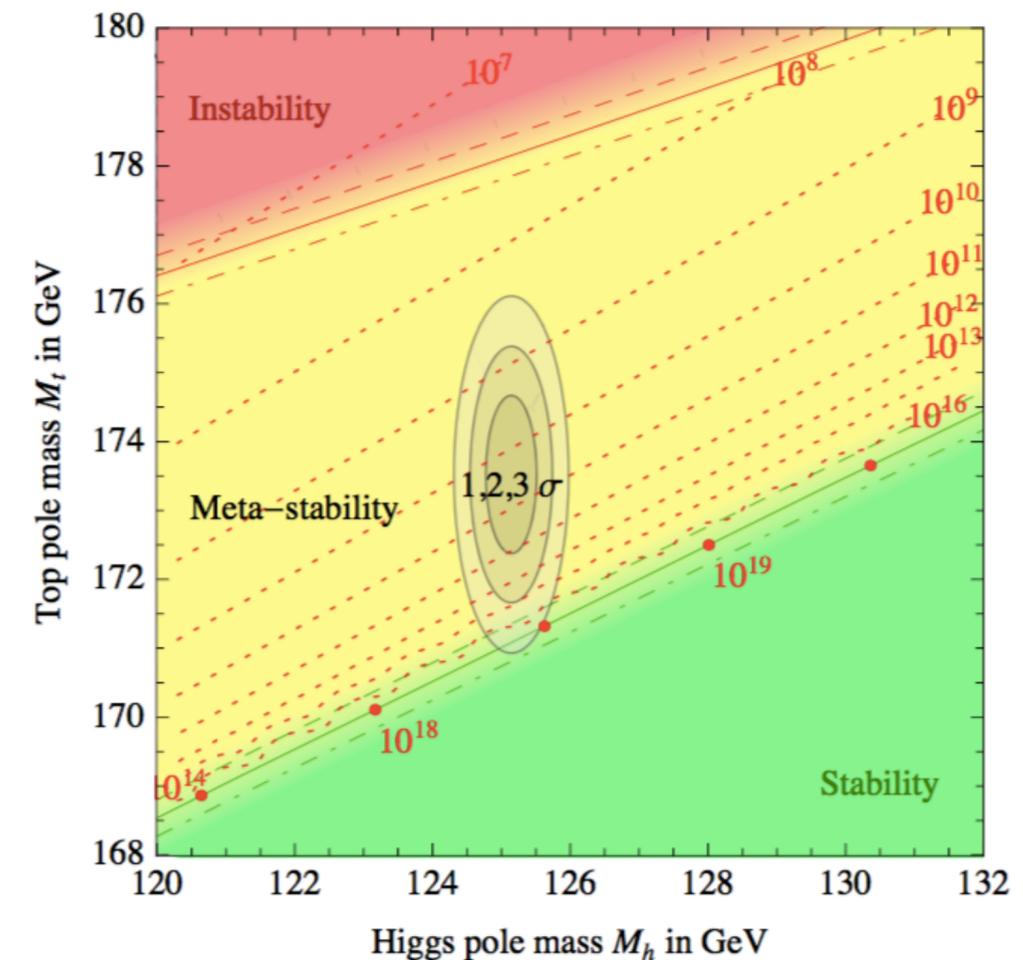
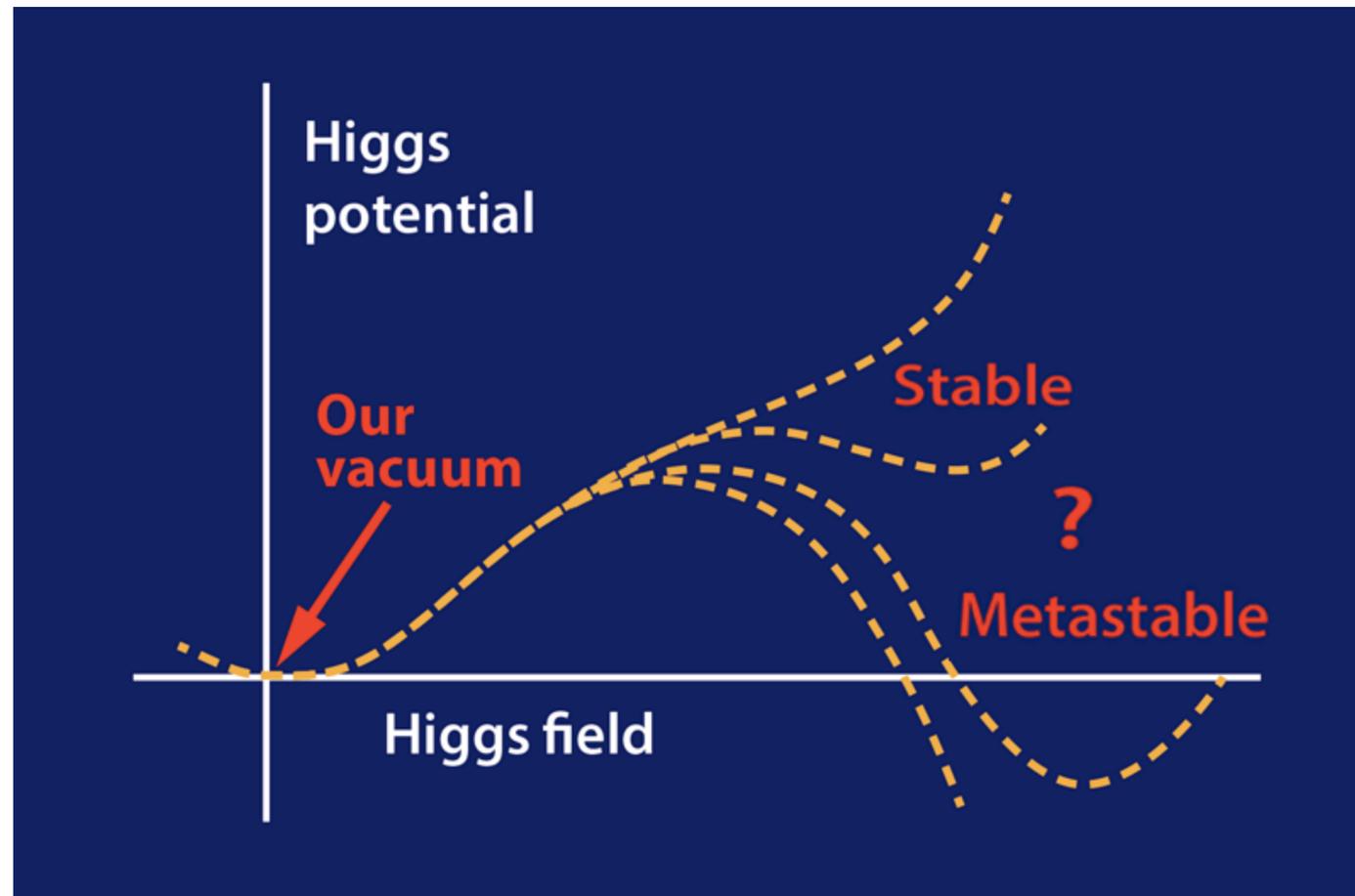


- Jet Calibration aims to give absolute energy measurement, correcting for all detector effects
- Multiple levels of corrections:
 - offset for pile-up and electronic noise
 - detector calibration and reconstruction efficiency
 - Data vs MC relative residual corrections for η
 - Data vs MC absolute residual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

Higgs vacuum

If SM \sim 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

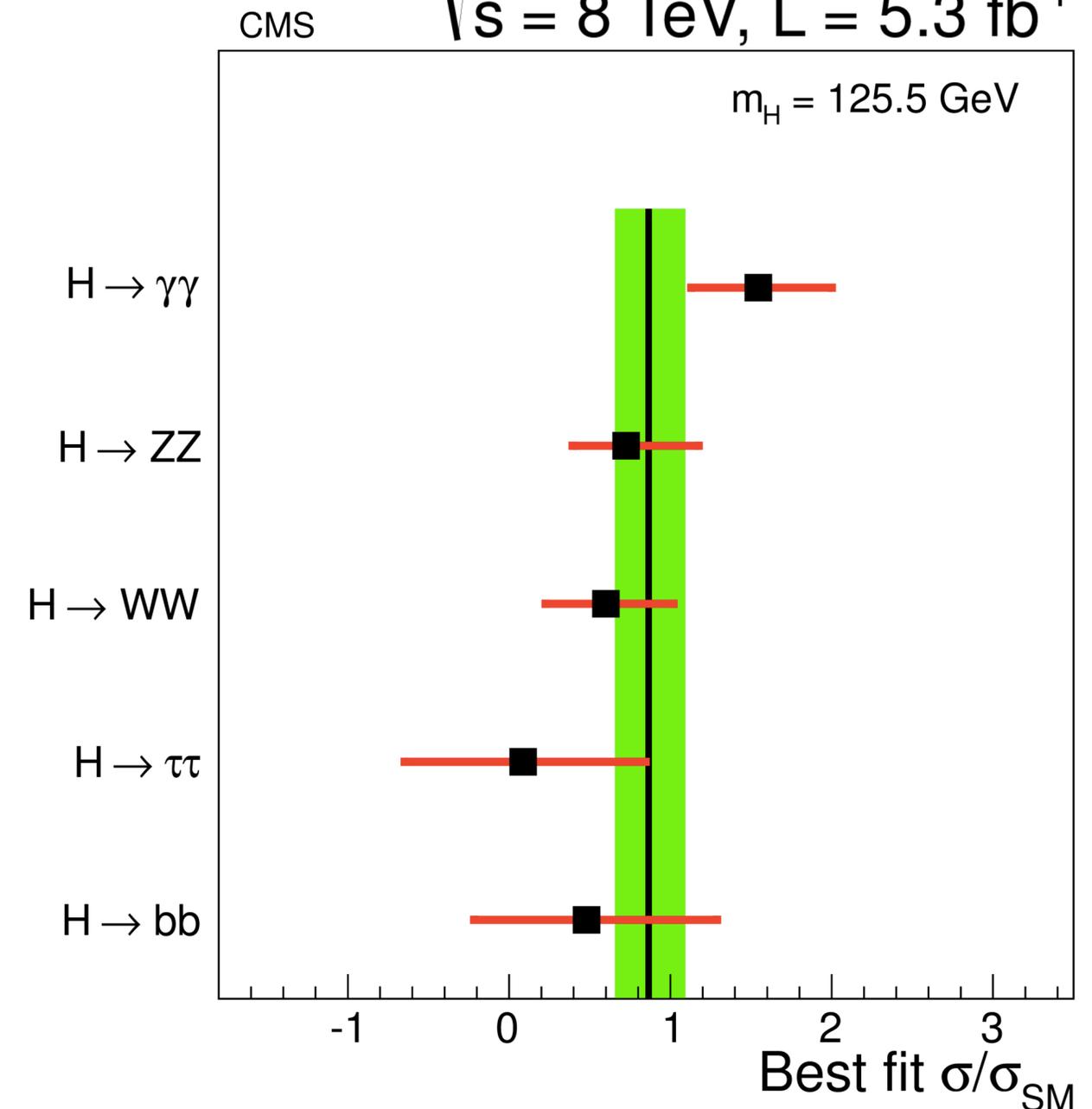
- **5.0 σ combining $\gamma\gamma$ and ZZ alone**

- **best mass resolution**

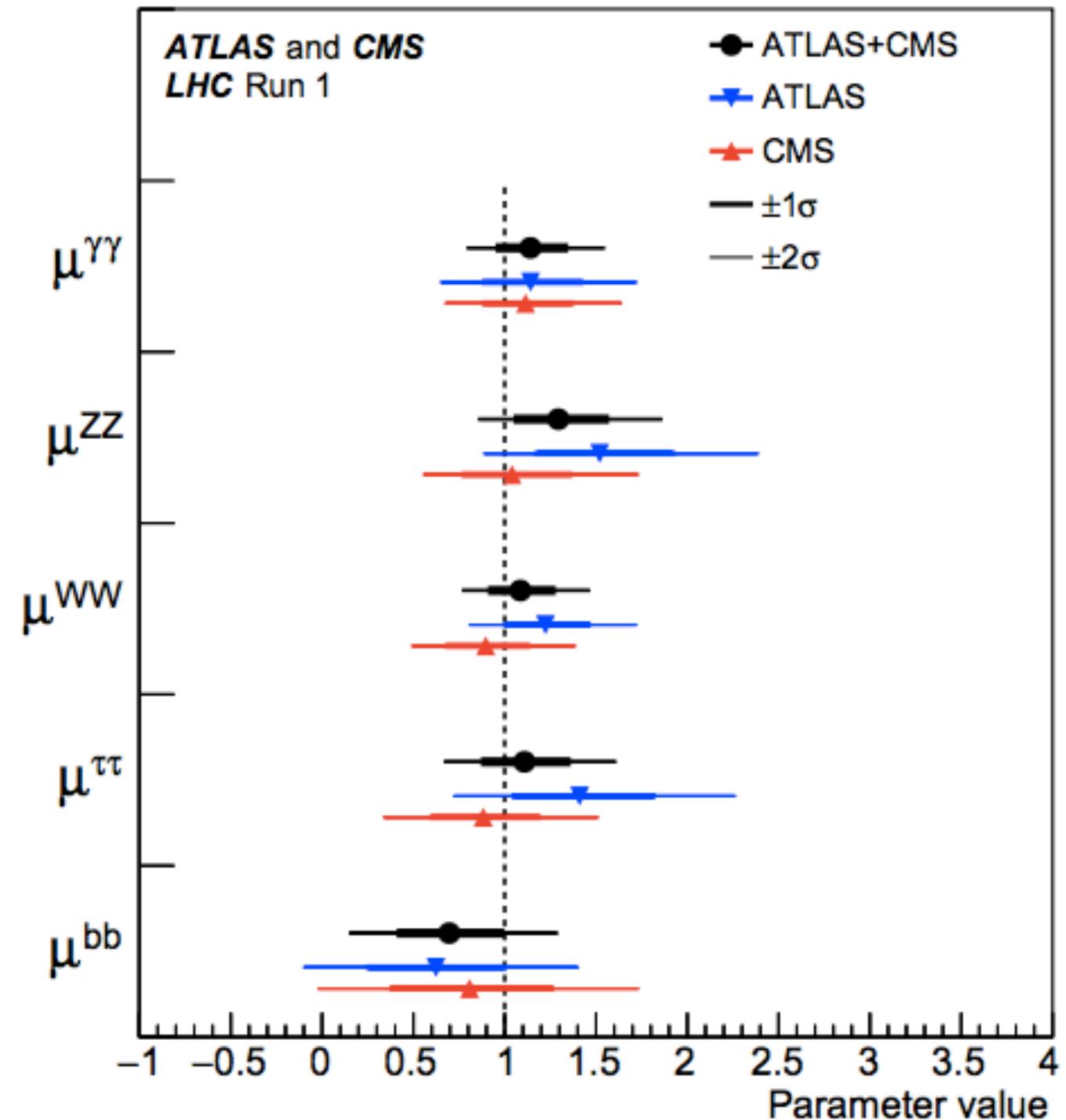
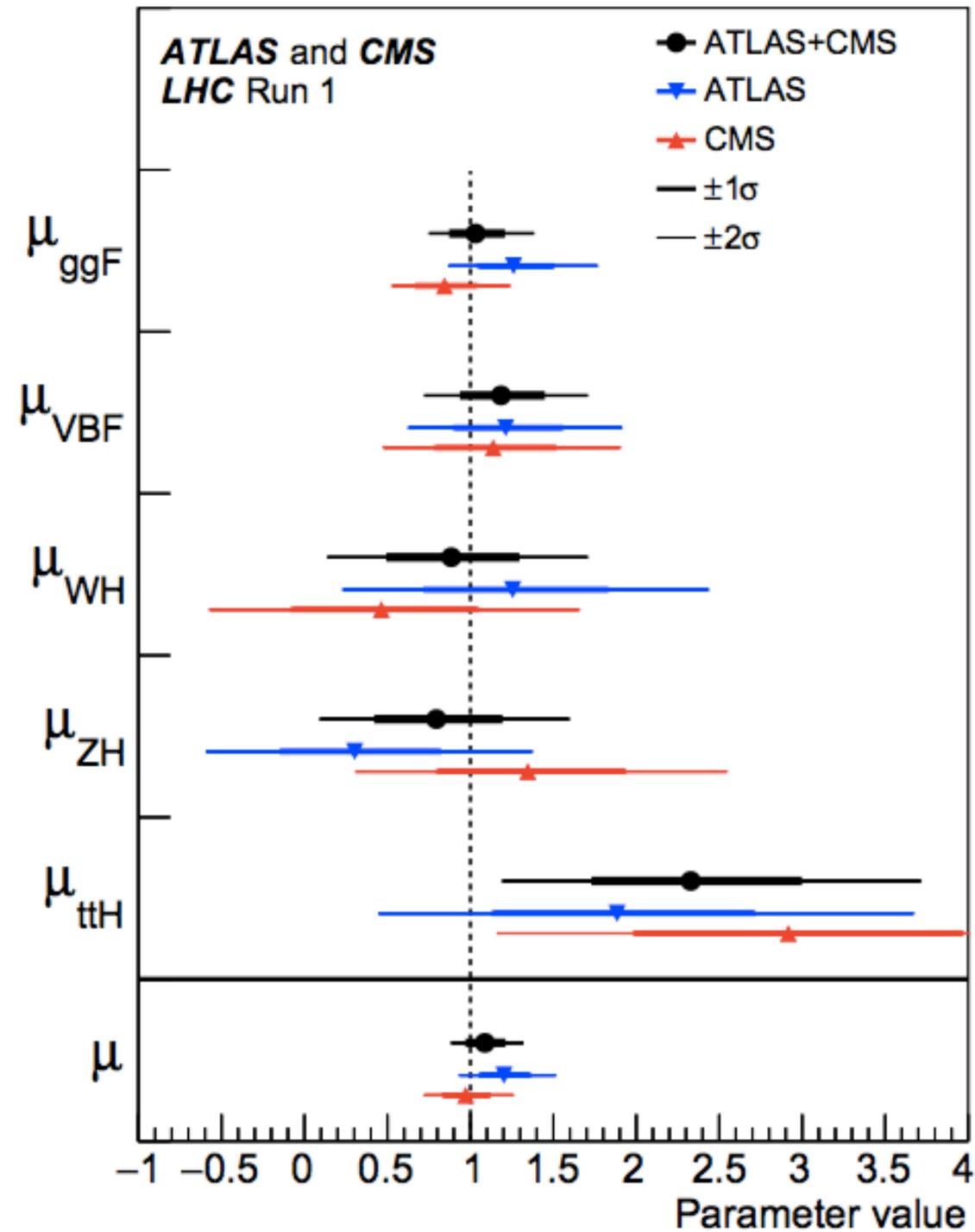
- thanks to the huge amount of LHC data we could exploit the lowest BR decay modes

$$\sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1}$$

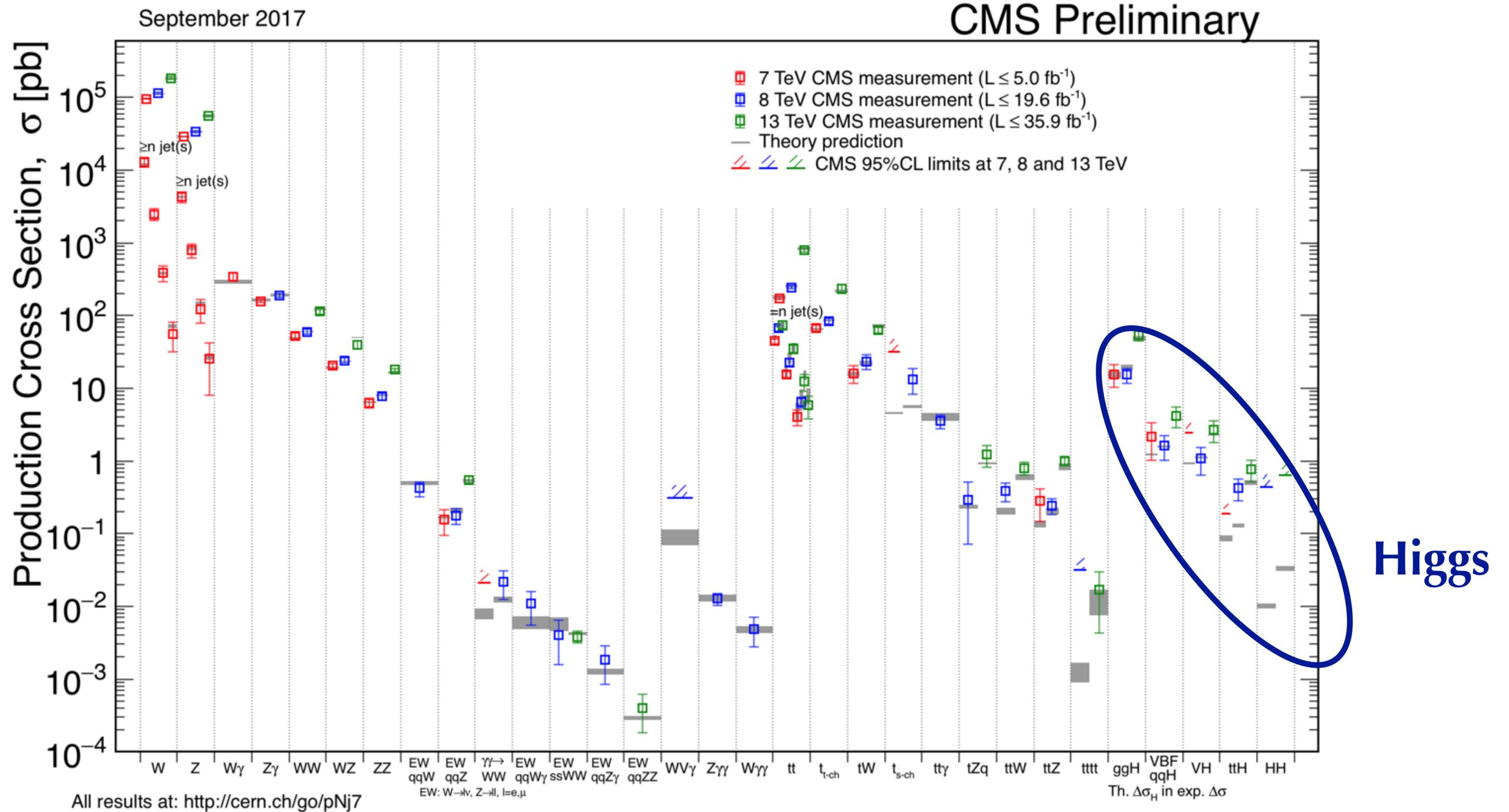
$$\sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1}$$



Higgs at LHC, Run 1 Legacy

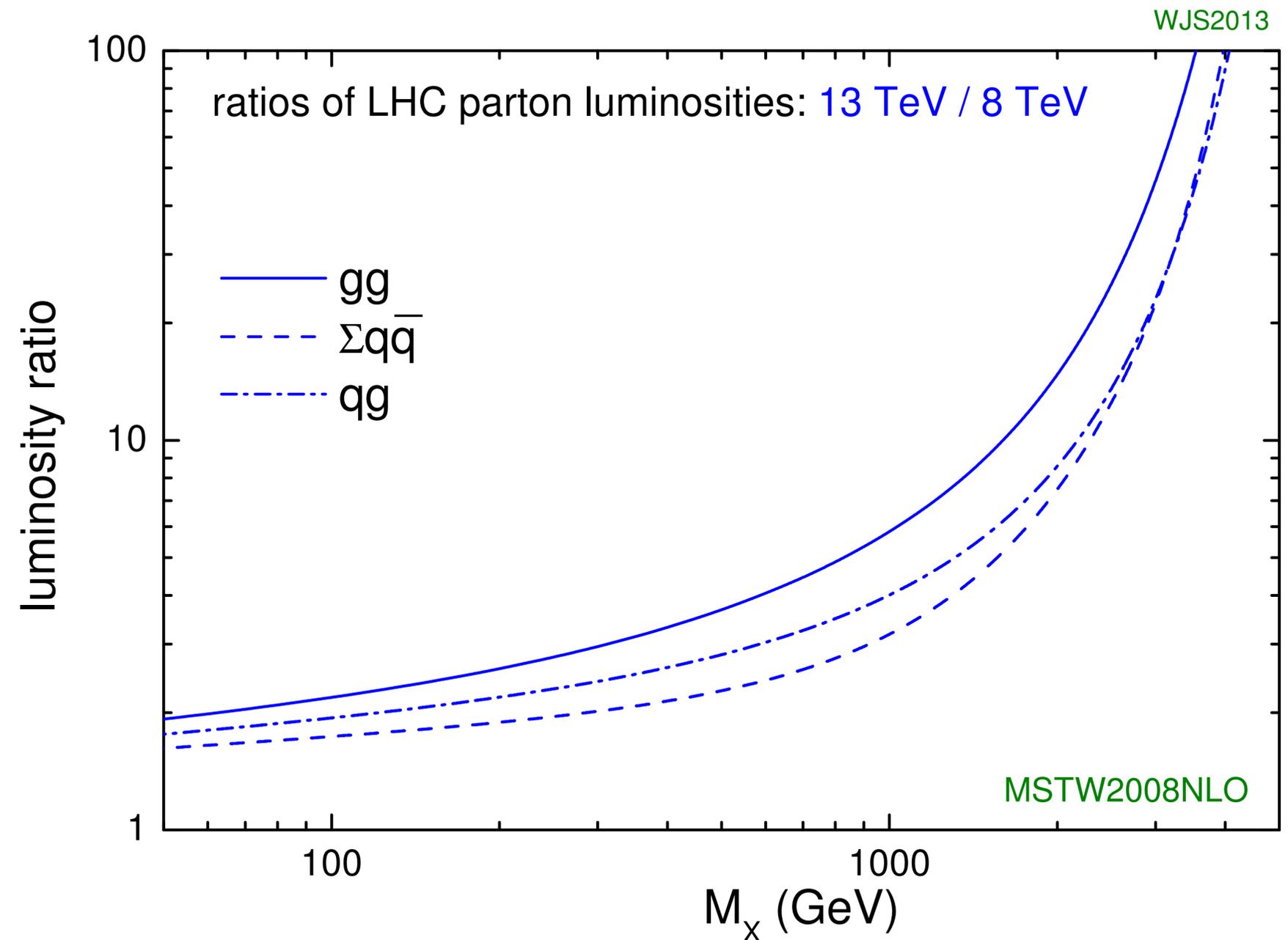


Our understanding of the Standard Model



From Run I to Run II

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



How well do we need to measure Higgs couplings?

- To be sensitive to a deviation δ , the measurement needs a precision of at least $\delta/3$
- How large are potential deviations from BSM physics?
 - Typical effect on coupling from heavy state Λ or new physics at scale Λ

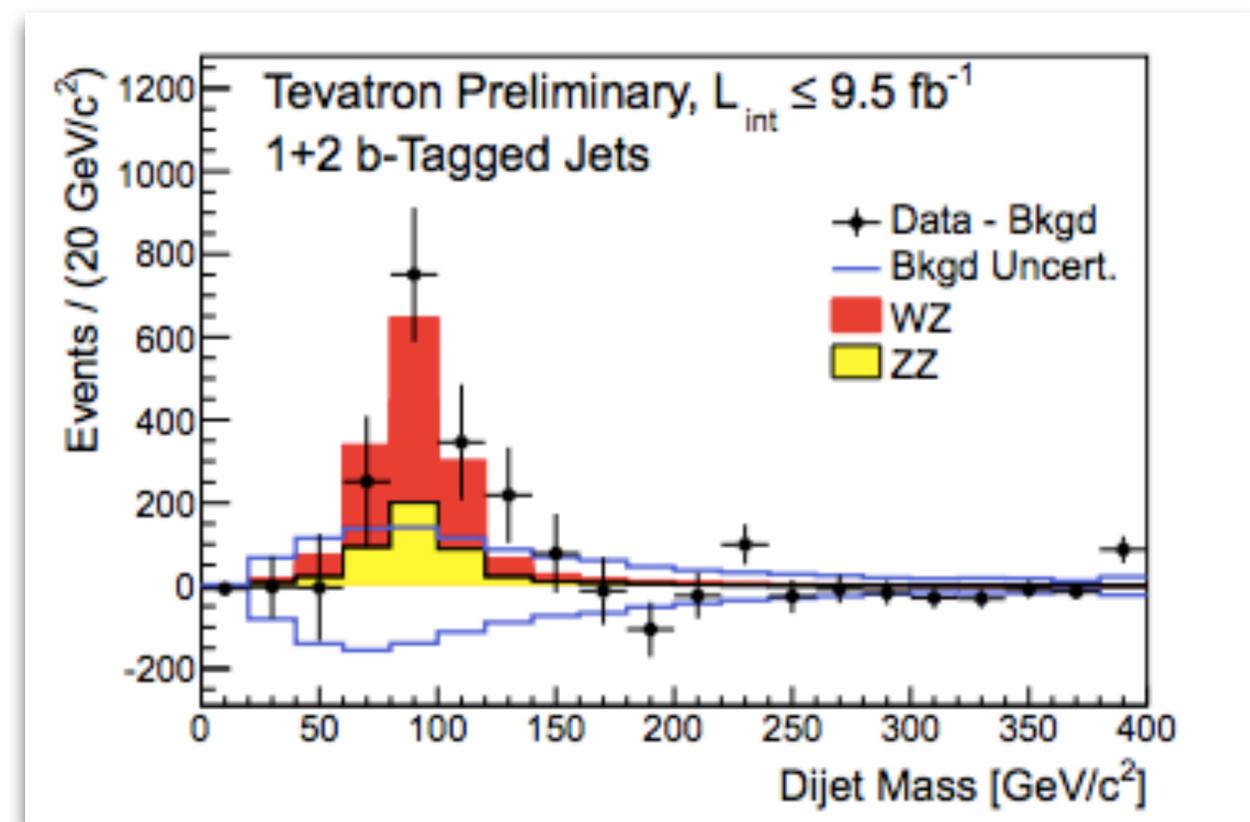
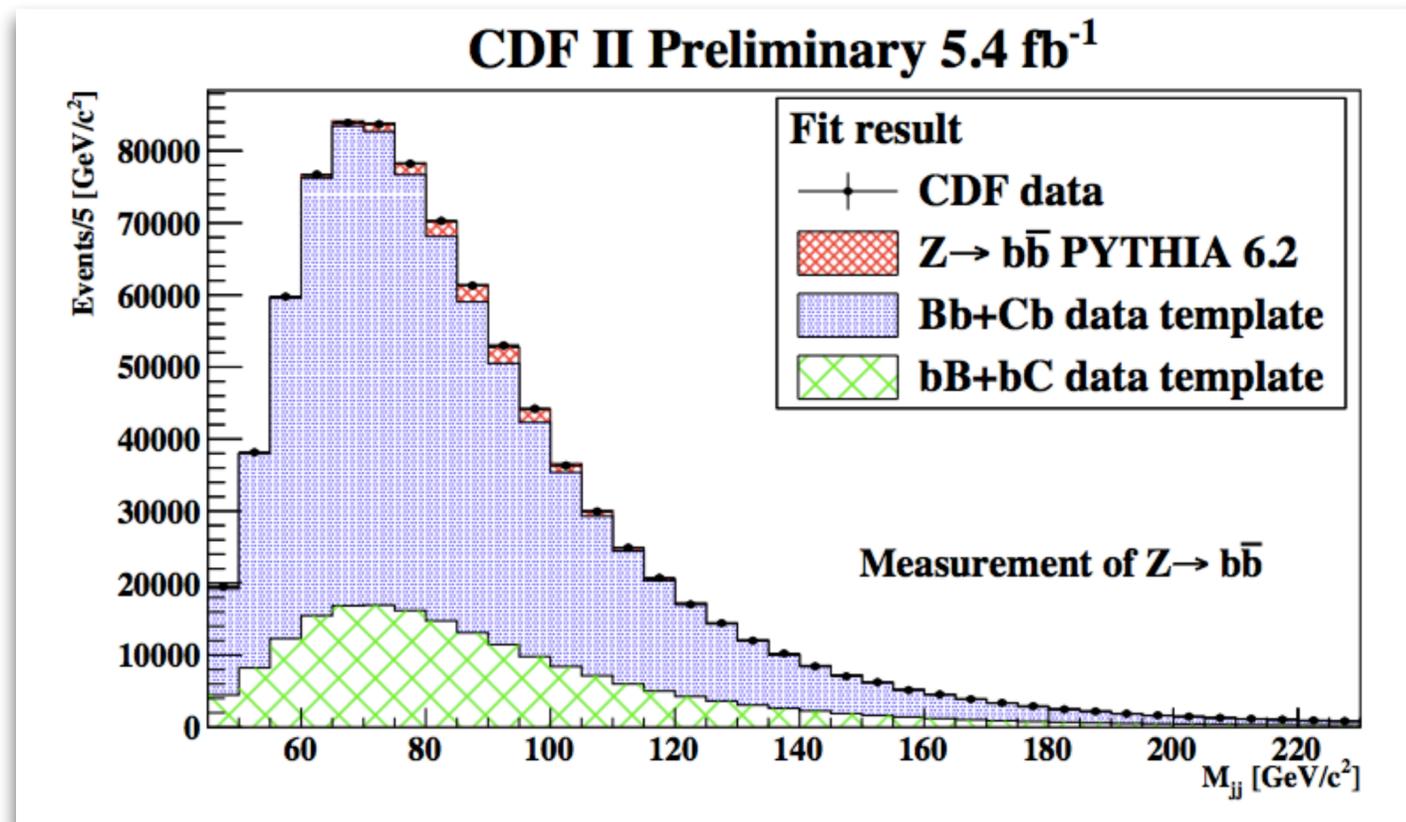
$$\delta = \left(\frac{v}{\Lambda}\right)^2 \quad \text{6\% effect on coupling for } \Lambda \sim 1 \text{ TeV}$$

Testing multi-TeV scale with sub-percent level measurements

- **There is no strict limit to the precision needed** [[arXiv:1310.8361](#)]
- Experimental precision must be accompanied by **theoretical precision program**
 - ideally: $\Delta_{\text{th}} \ll \Delta_{\text{exp}}$ and **current theoretical precision is O(1%)**
 - main sources of uncertainty come from the parametric dependences on α_s , m_b , and m_c [[arXiv:1404.0319](#)]

Z(b \bar{b}) measurements

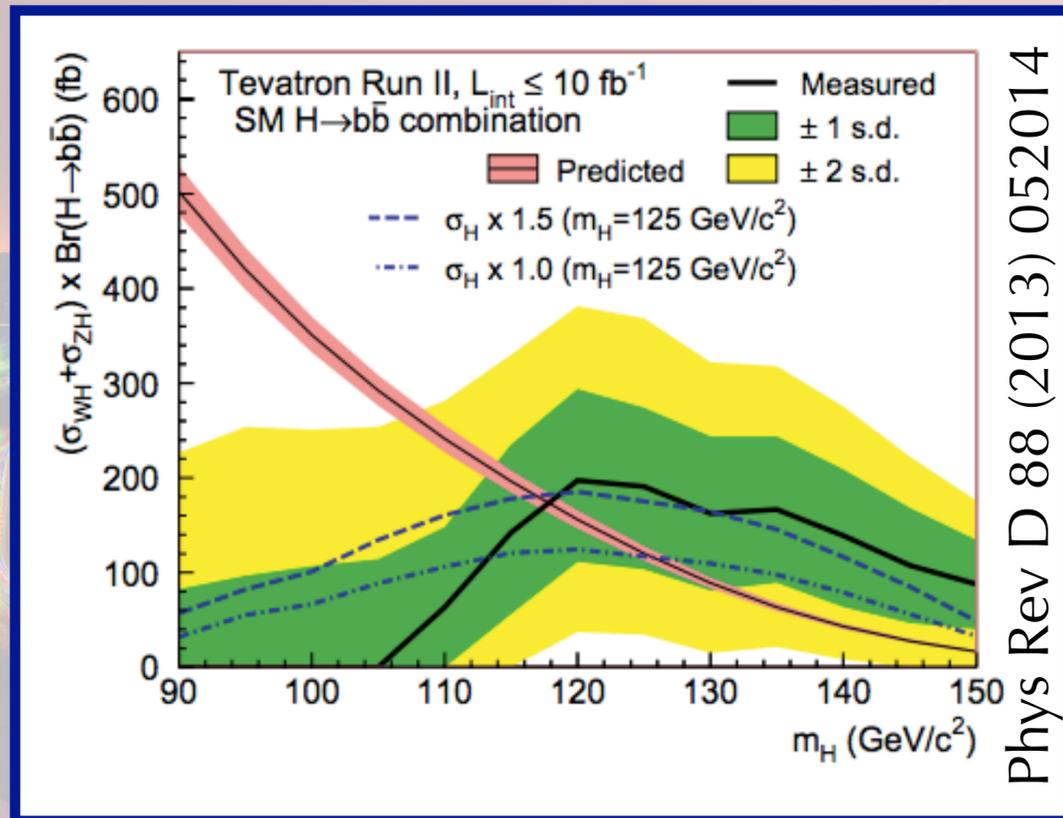
- **ATLAS** Z(b \bar{b})+ jets cross section measurement at 8 TeV Phys. Lett. B 738 (2014)
- **CDF** Z(b \bar{b})+ jets cross section measurement CDF-11228
- **Tevatron**: 4.6 σ evidence for VZ(b \bar{b}) at hadron collider Phys. Rev. Lett. 109 (2012)
- **CMS**: First VZ(b \bar{b}) 6 σ observation at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



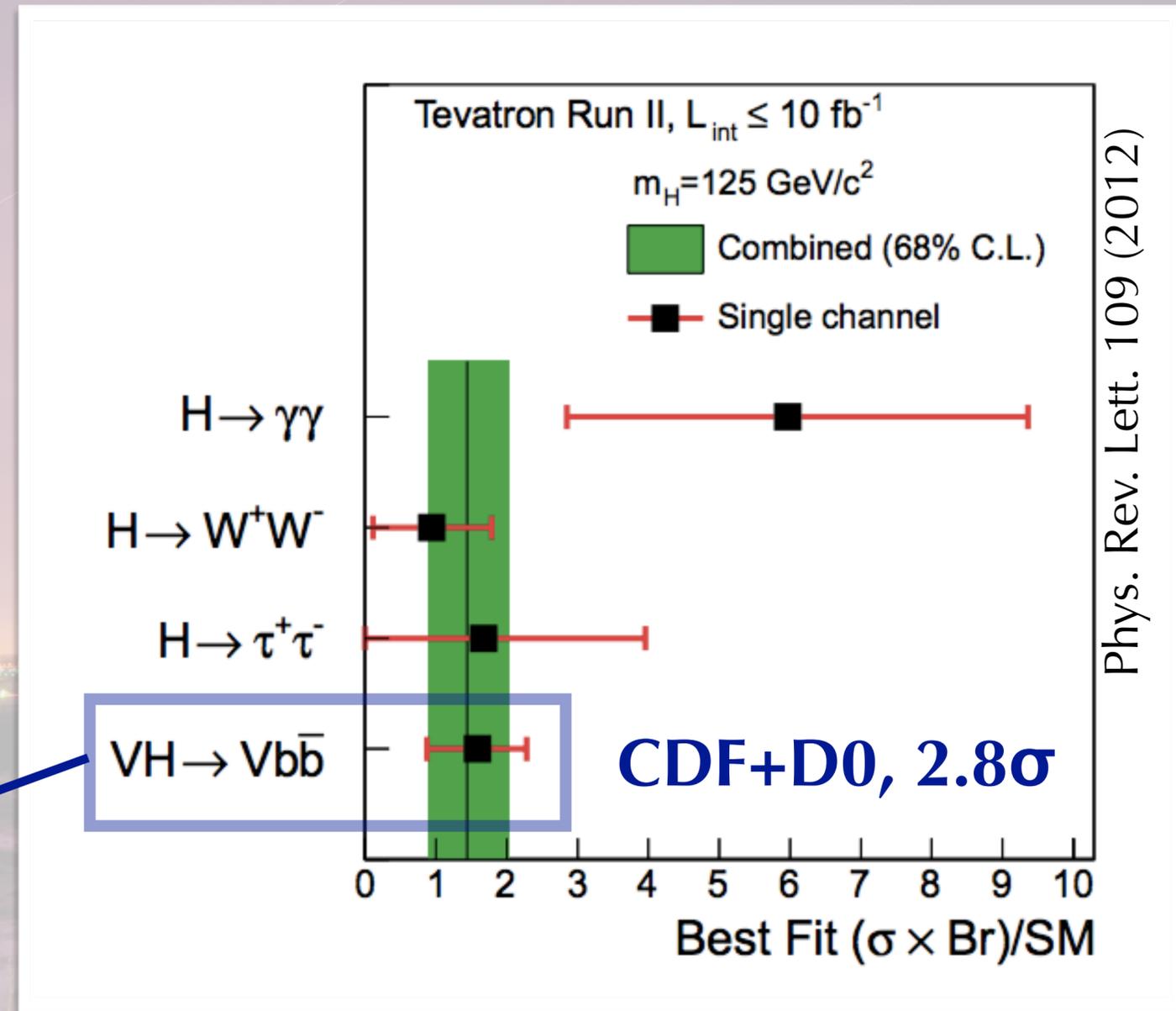
H(bb) at Tevatron

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

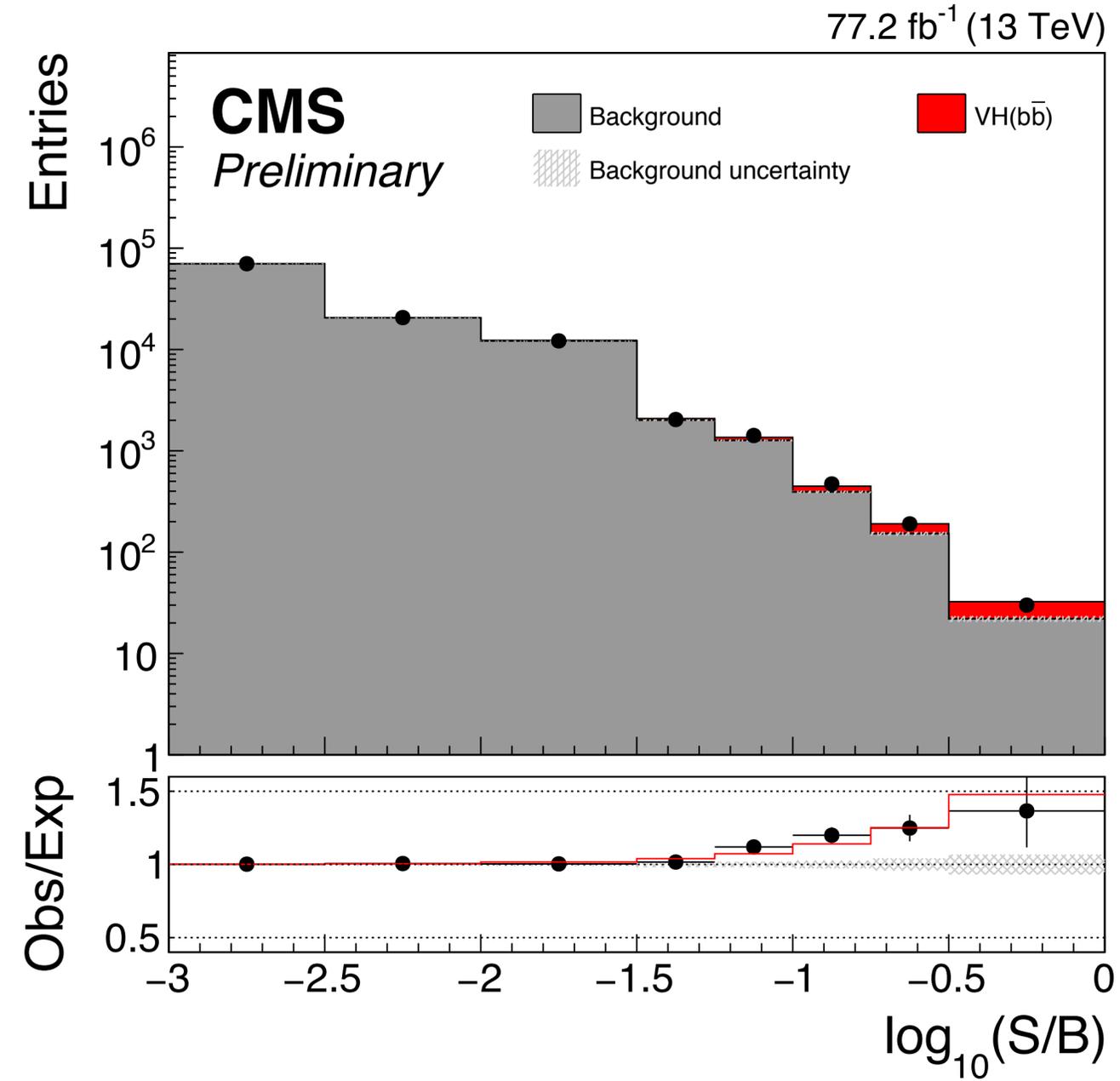
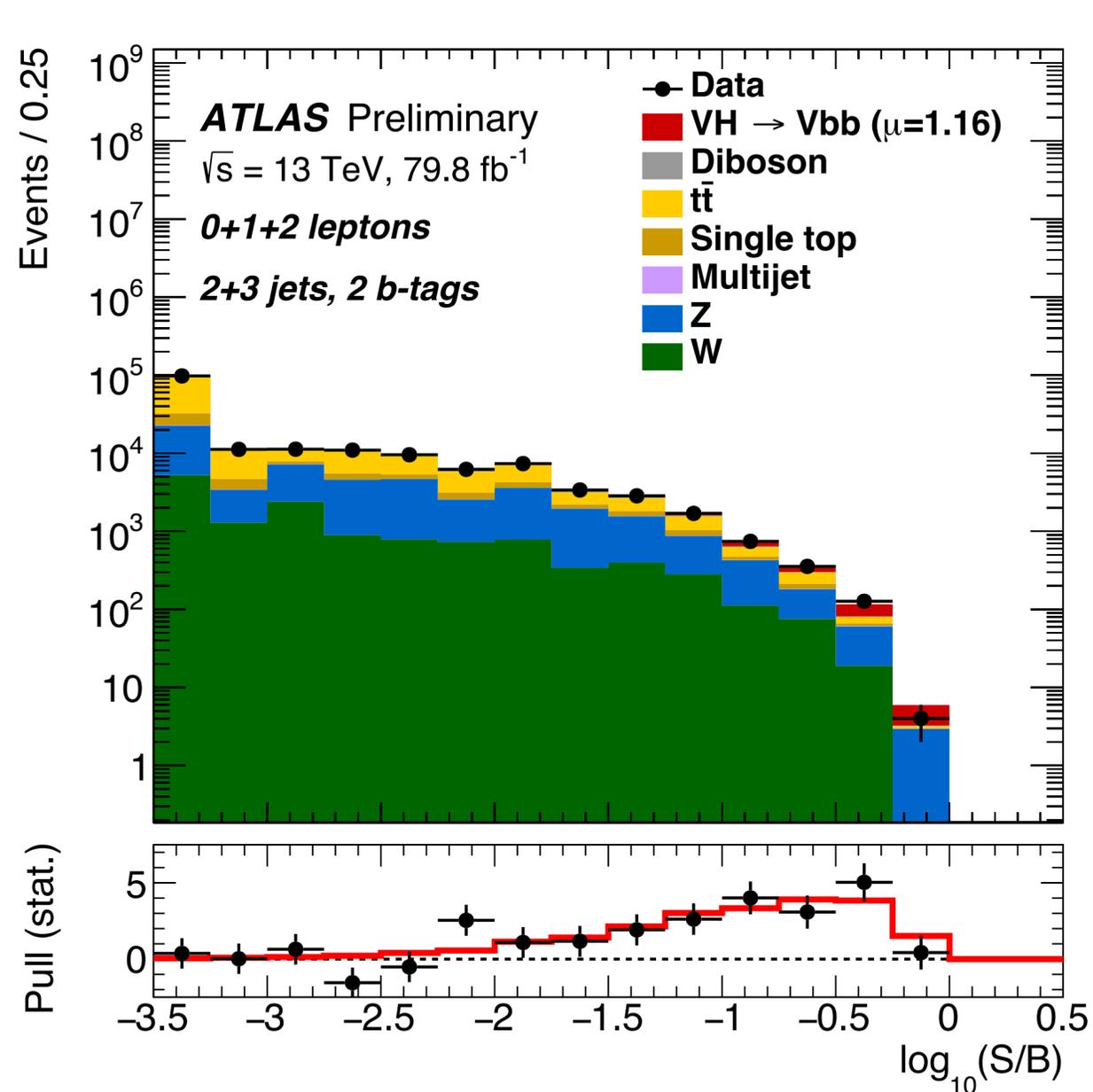
- 3.0σ at $m_H = 125$ GeV
- mainly from the $H \rightarrow b\bar{b}$



2.8 σ obs
(1.5 σ exp)

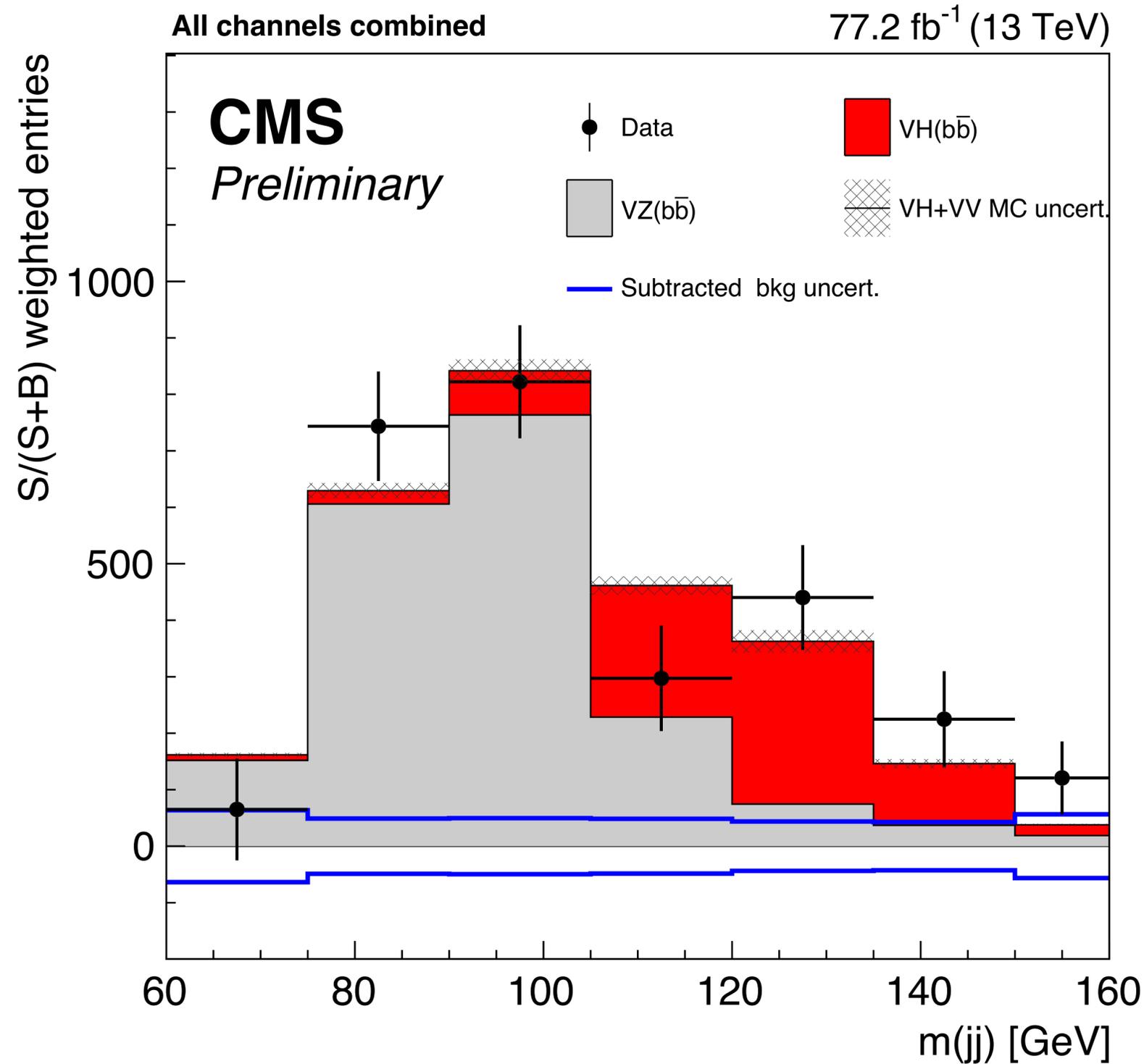
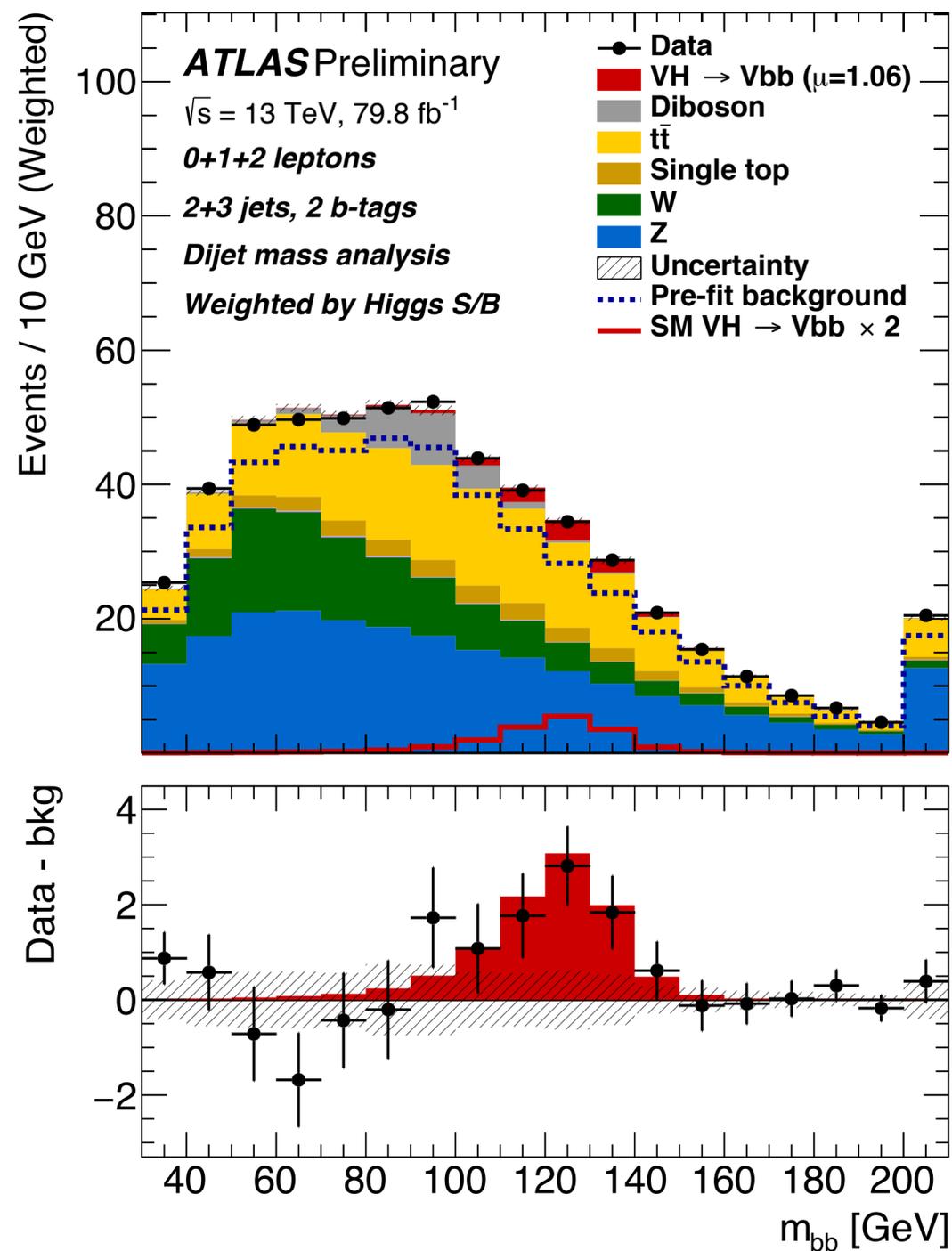


VH(bb) at LHC, machine learning



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

VH(bb) at LHC

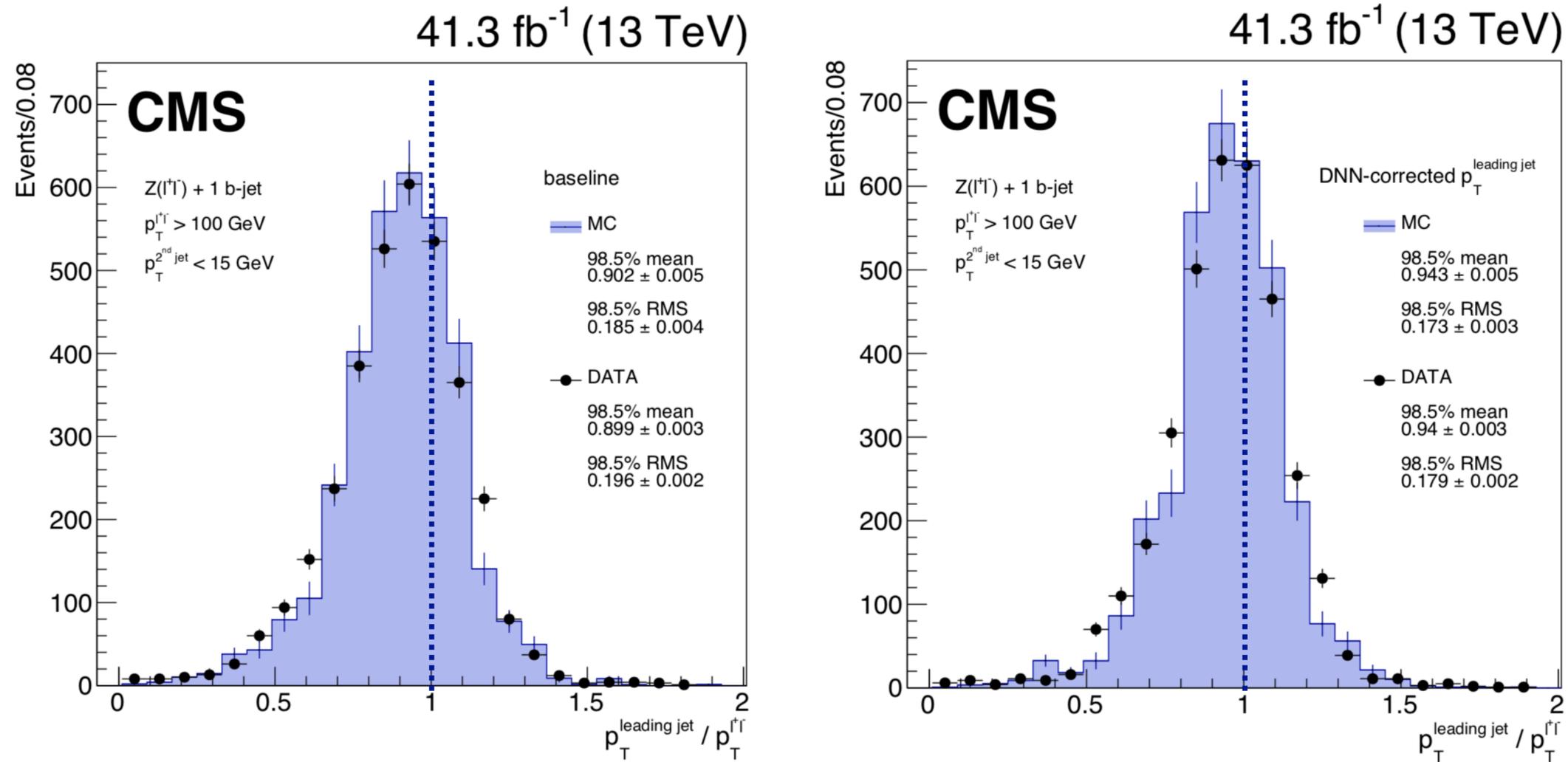


VH Event selection

Variable	Z($\nu\nu$)H	W($l\nu$)H	Z(ll)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	–
$M(jj)$	$[60 - 160]$	$[90 - 150]$	$[90 - 150]$
$btag_{max}$	$> \text{Tight}$	$> \text{Tight}$	$> \text{Loose}$
$btag_{min}$	$> \text{Loose}$	$> \text{Loose}$	$> \text{Loose}$
N_{aj}	–	< 2	–
N_{al}	$= 0$	$= 0$	–
E_T^{miss}	> 170	–	–
Anti-QCD	Yes	–	–
$\Delta\phi(V, H)(\text{rad})$	> 2.0	> 2.5	> 2.5
$\Delta\phi(\text{pfMET}, \text{trkMET})(\text{rad})$	< 0.5	–	–
$\Delta\phi(\text{pfMET}, \text{lep})(\text{rad})$	–	< 2.0	–
Tightened Lepton Iso.	–	$(0.06, 0.06)$	–

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

More on the JER extraction

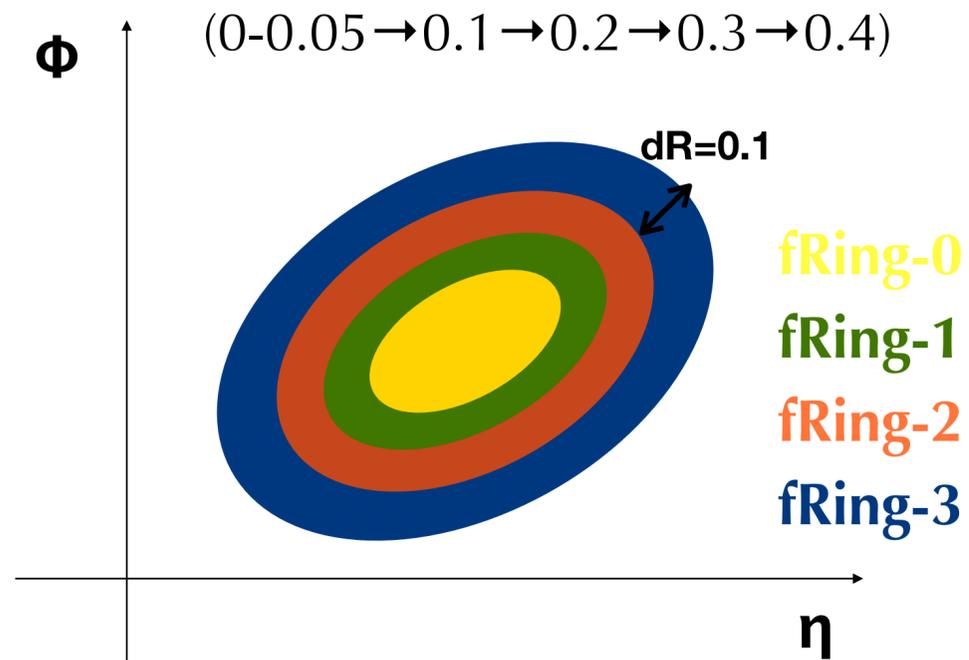


- The effect of the DNN-based corrections is to move the centroid of the distribution closer to unity and to reduce its width.
- The ratio between the jet resolution measured in data and simulated events is found to be (*) 1.1 ± 0.1 both before and after the application of the DNN-based corrections.

Inputs to the DNN regression

Common set of inputs for the b-jet energy regression

- Jet kinematic
- b-tagging
- Jet structure
- Pileup



Jet η

Jet p_T

Jet M_T

SecVtx Decay Length and significance

SecVtx #tracks associated to the vex

SecVtx Mass, p_T

Soft Lepton p_T^{Rel} to lepton and jet axis

Soft Lepton dR

Neutral hadron (EM/HE) energy fraction

Charged (EM/HE) energy fraction

N_{tot} , total number of jet constituents

p_T of the Leading Track

p_T^{Djet} energy variable $\frac{\sqrt{\sum_i p_{Ti}^2}}{\sum_i p_{Ti}}$

multiplicity of jet daughter $p_T > 0.3$ GeV

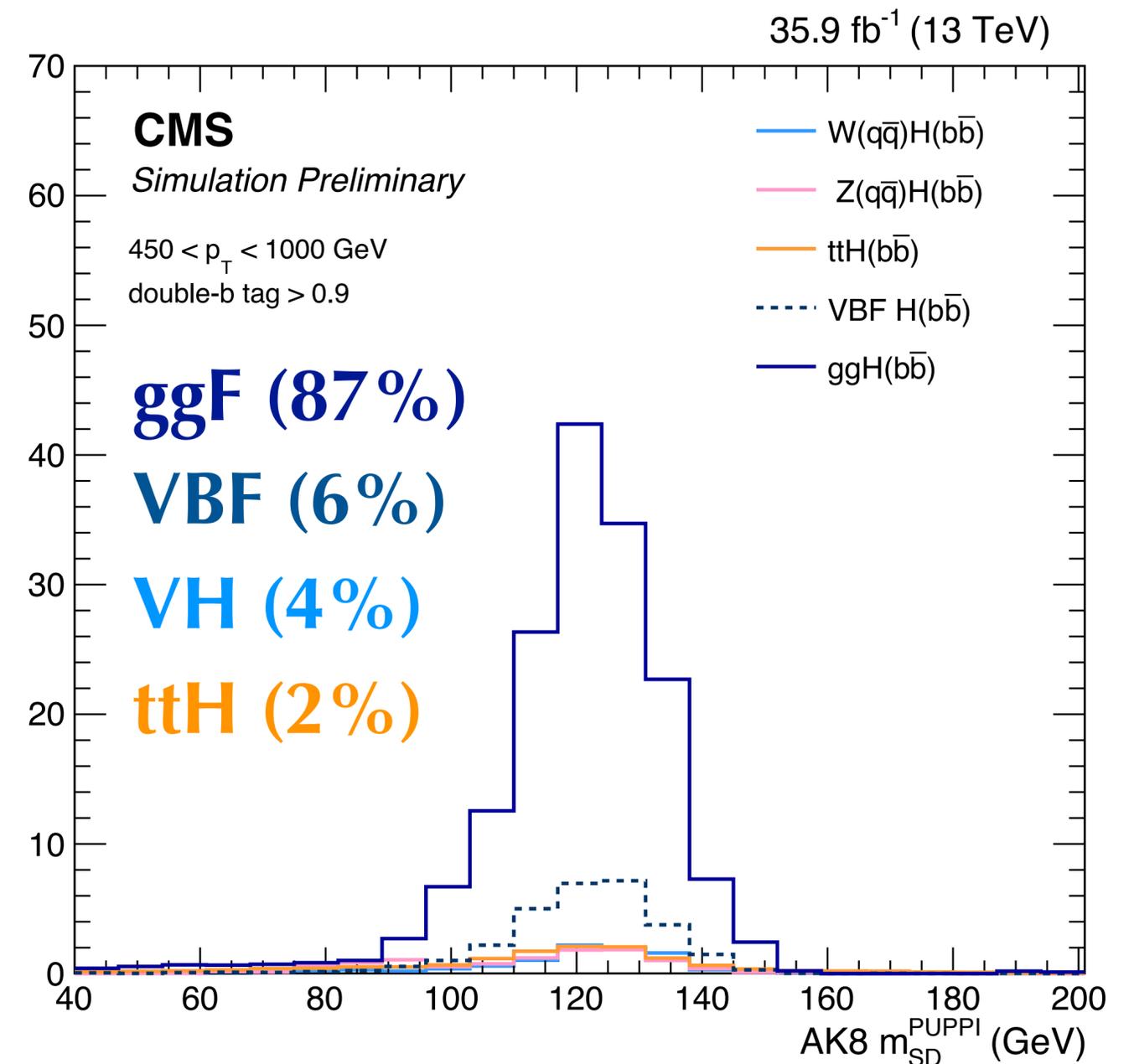
Jet energy (**rings**) fraction split by constituents and in rings of dR

Split by EM/Muon/Charged/Neutral

ρ : pile-up density of the event

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

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

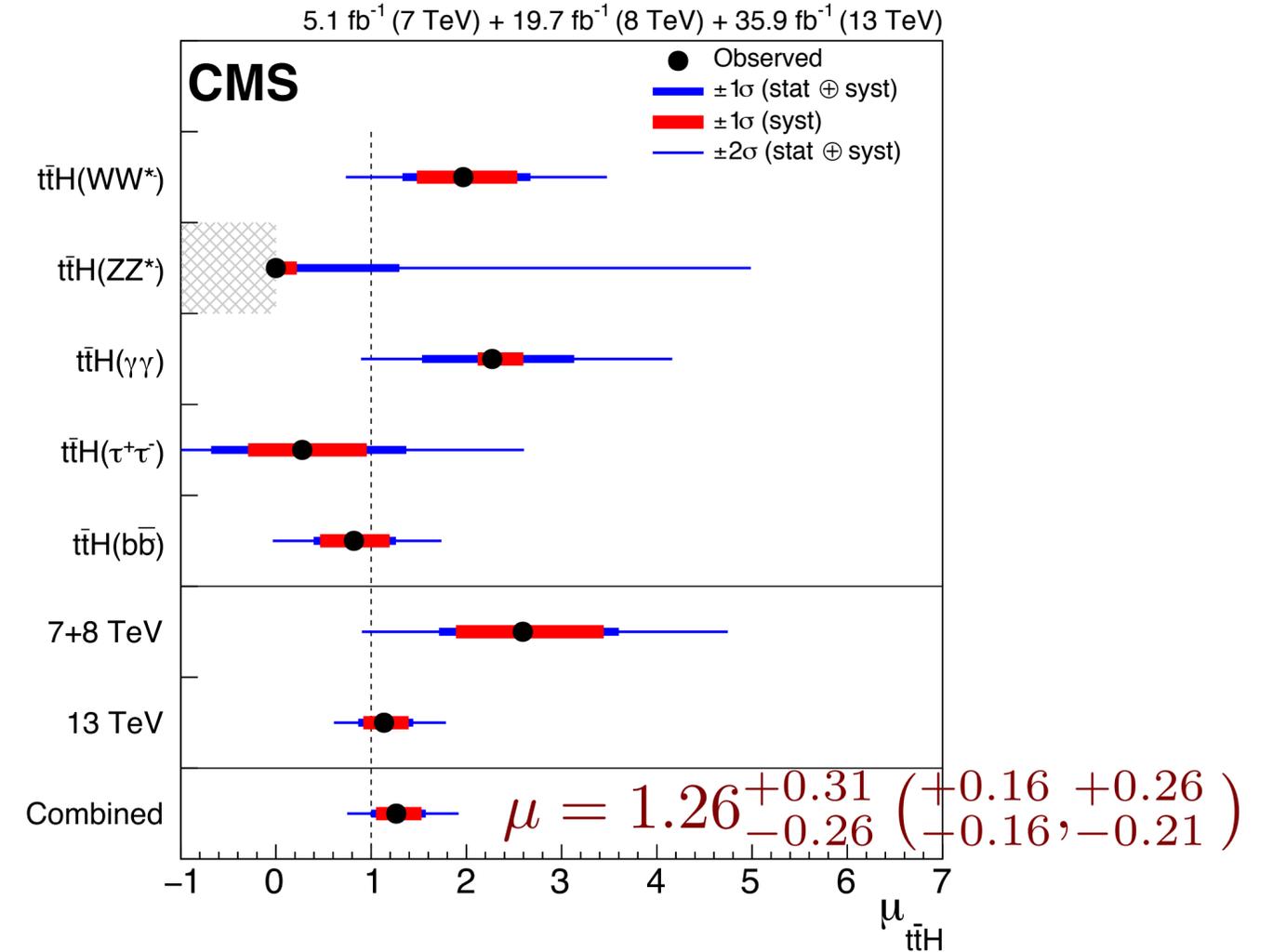
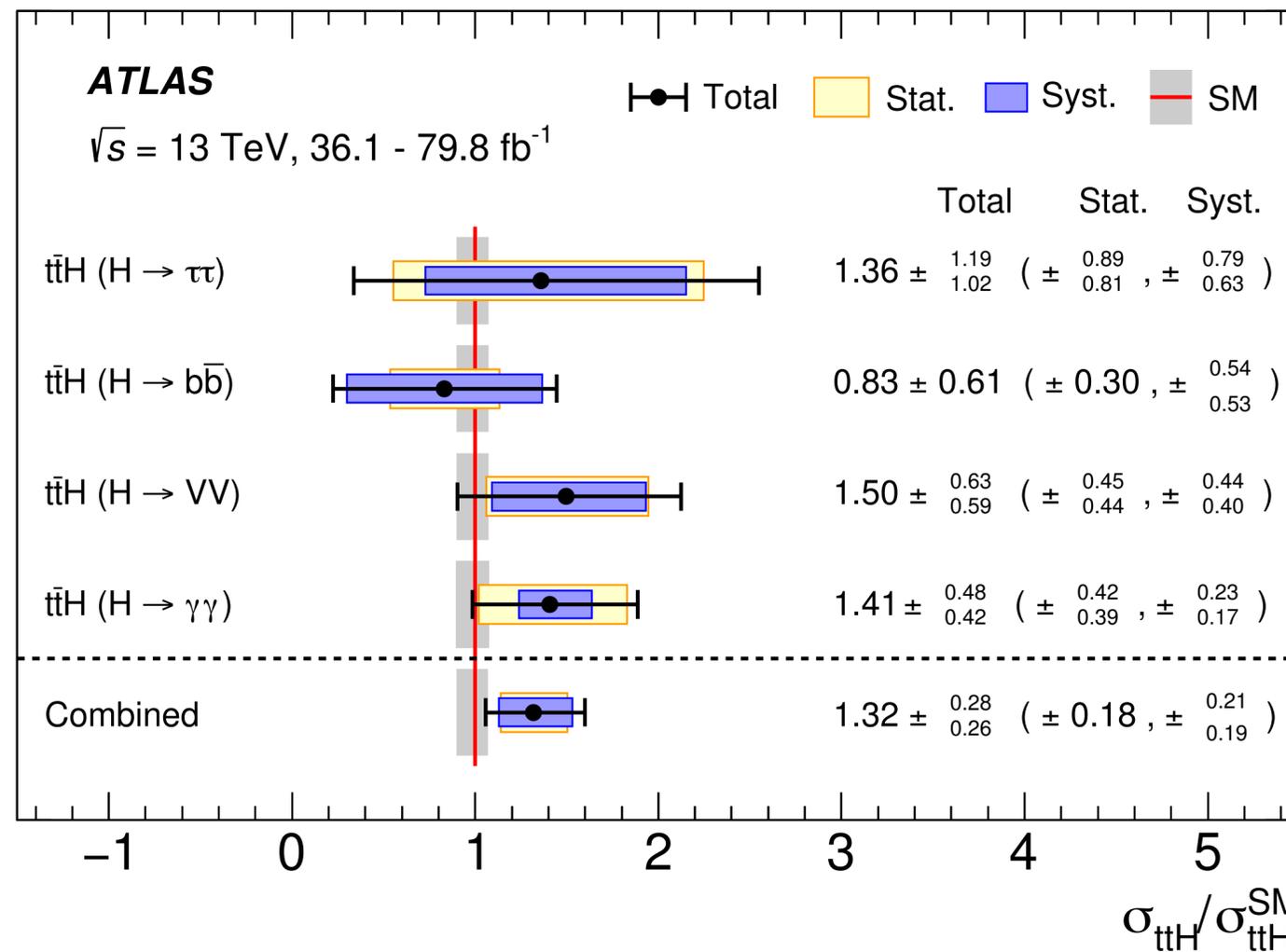


ggF $H(b\bar{b})$ Systematics Uncertainties

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%

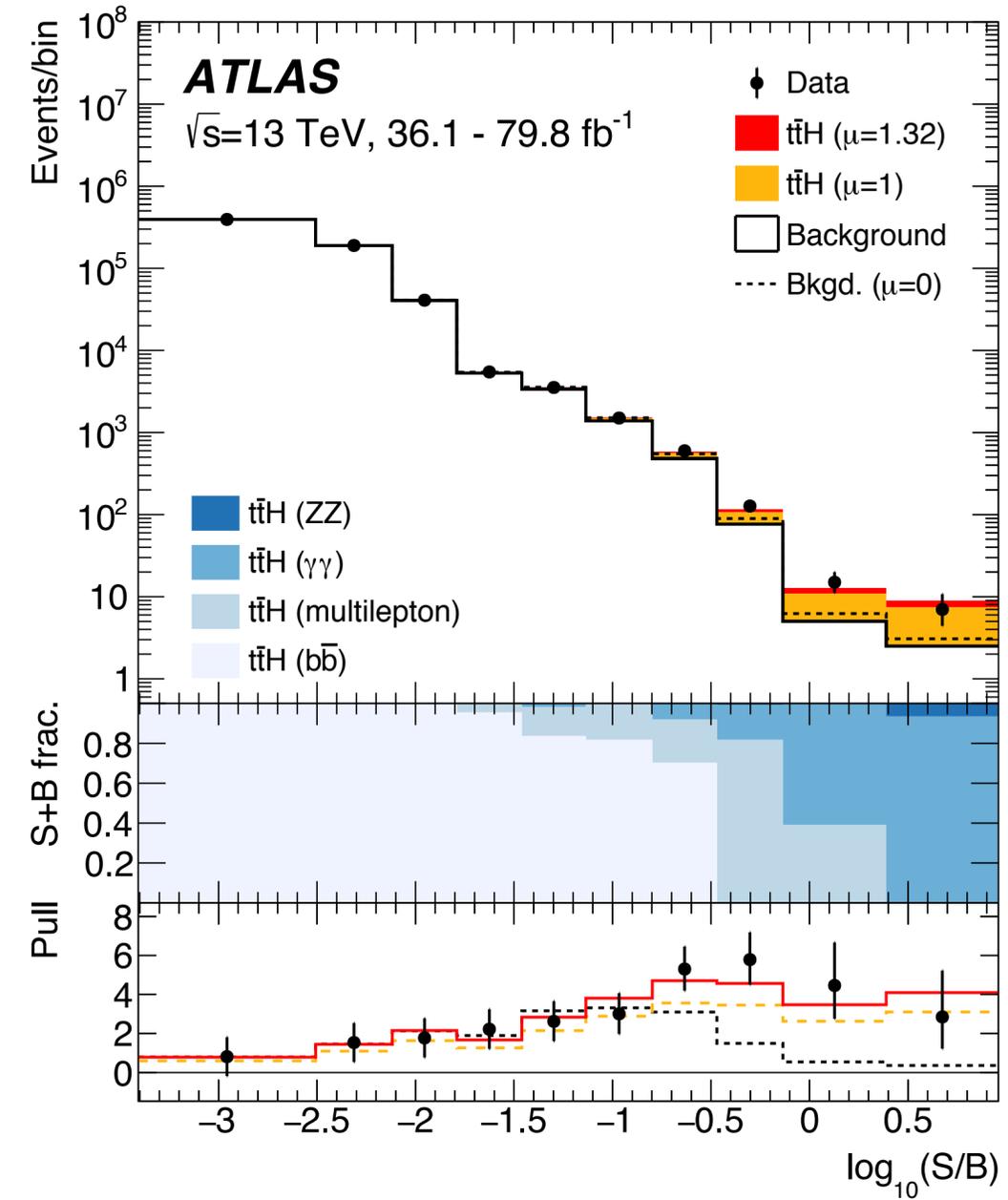
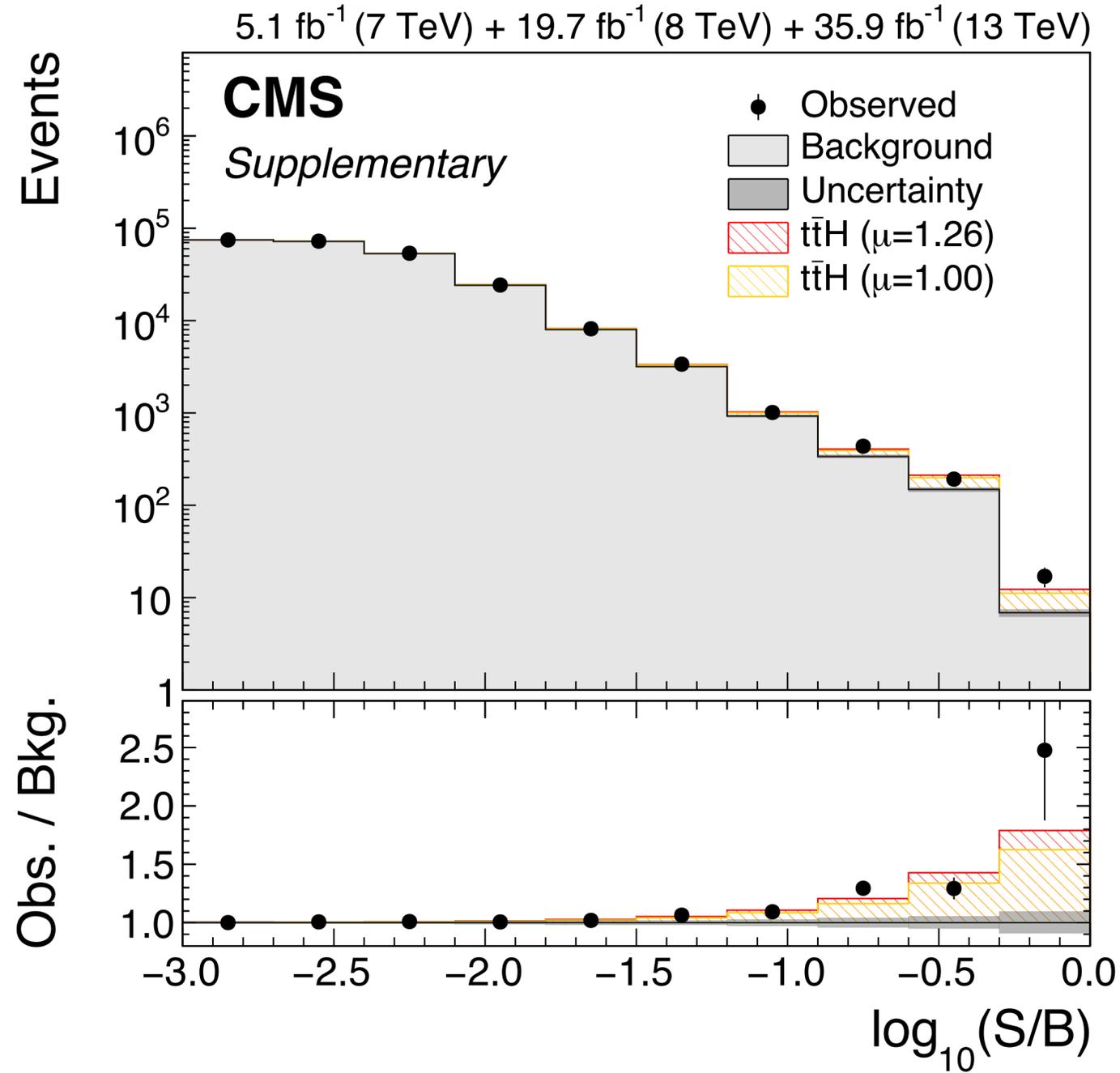
correlated among W, Z, and H

ttH observation

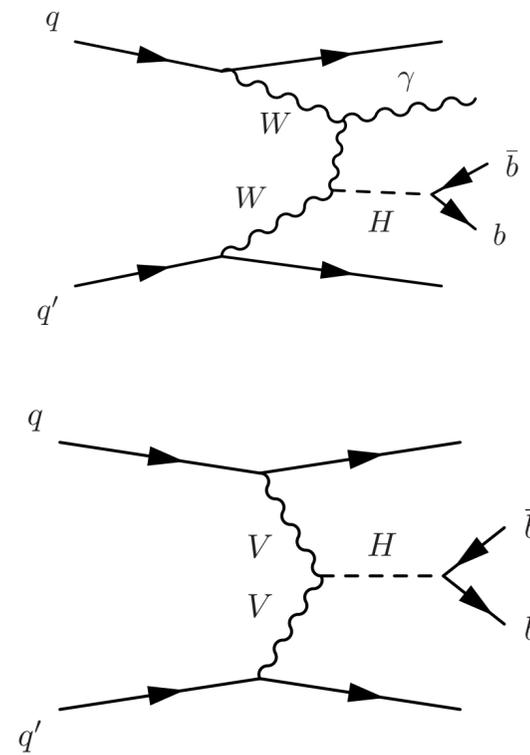
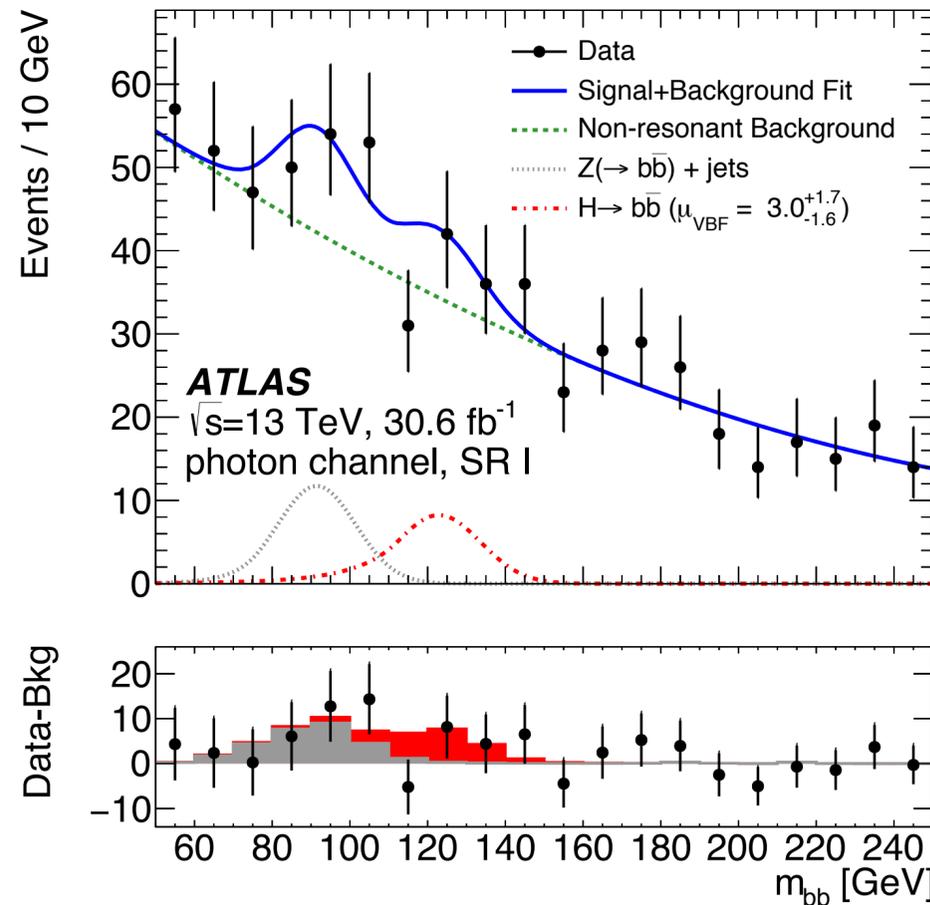


We have observed the ttH process
CMS Run 1+2 (25+36/fb): 5.2σ (4.2σ exp.)
ATLAS Run 1+2 (25+80/fb): 6.3σ (5.1σ exp.)

ttH observation

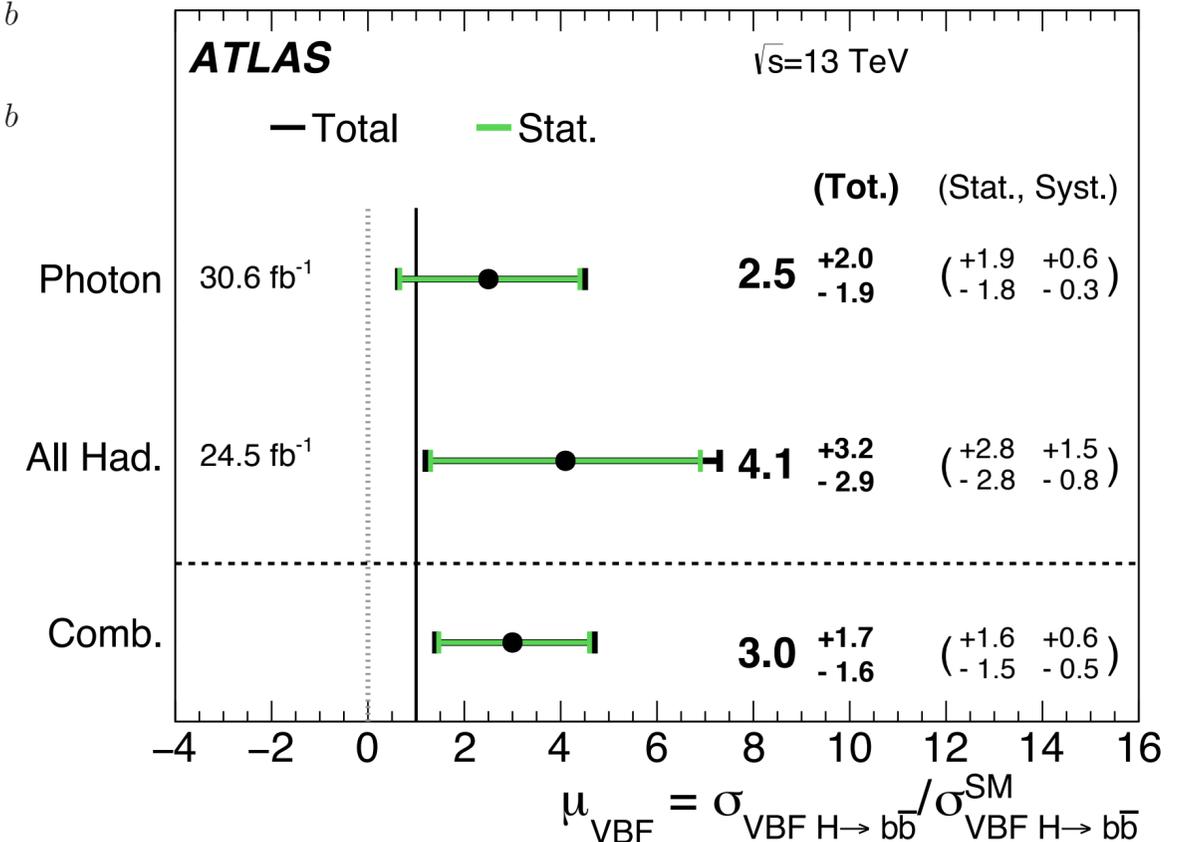


VBF $H(b\bar{b})$



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

ATLAS Run-2 (20-30/fb): $5.9 (3.0^{+1.3}_{-0.8}) \times \text{SM}$
CMS Run1+2 (2/fb): $3.4(2.3) \times \text{SM}, \mu = 1.3^{+1.2}_{-1.1}$



- * 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

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:

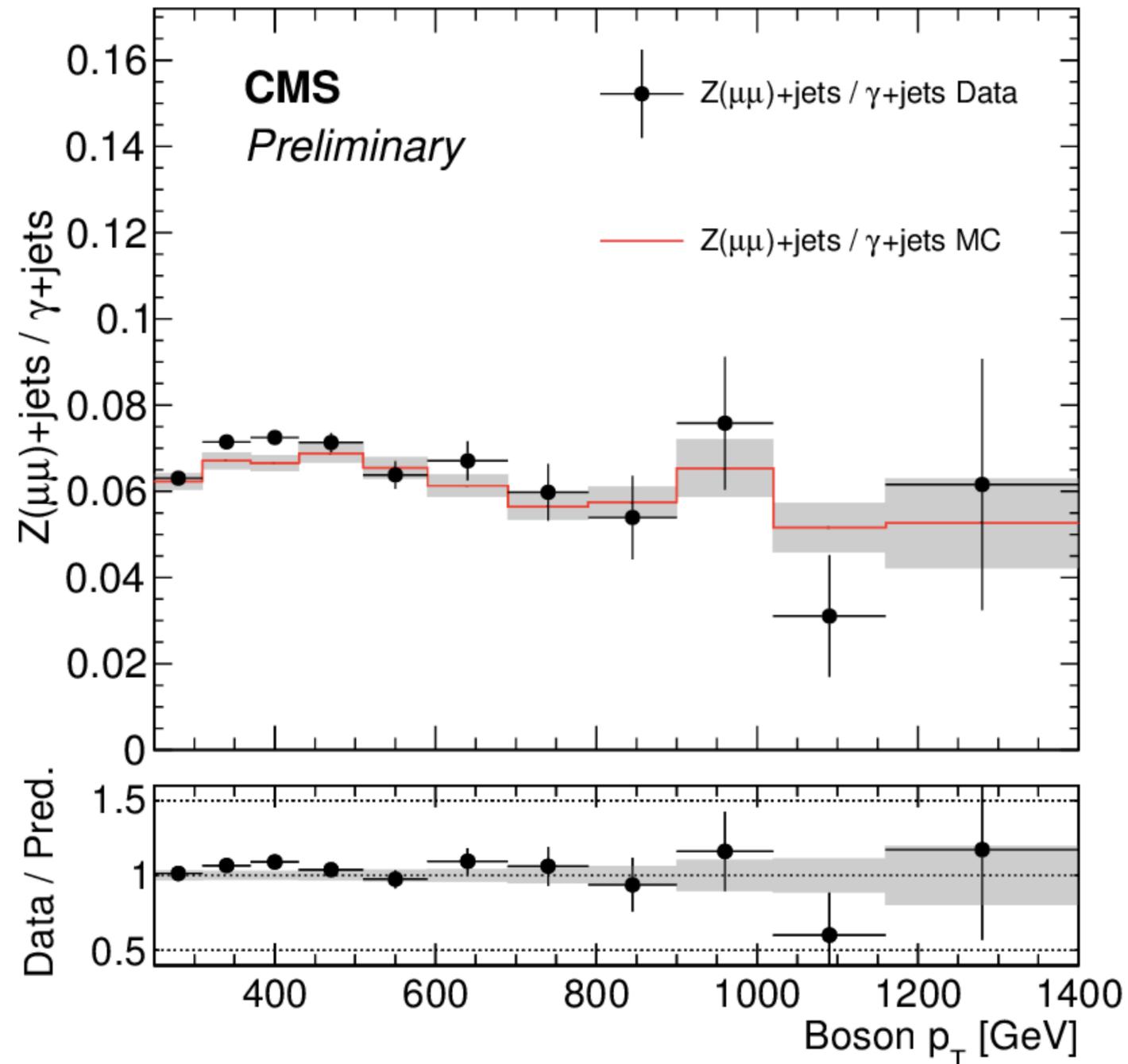
$$\sigma_Z = 849 +155/-155 \text{ (stat.) } +140/-205 \text{ (syst.) fb}$$

$$\sigma_H = 74 +48/-48 \text{ (stat.) } +10/-17 \text{ (syst.) fb}$$

Compatible with SM within uncertainties

W/Z+jets simulation

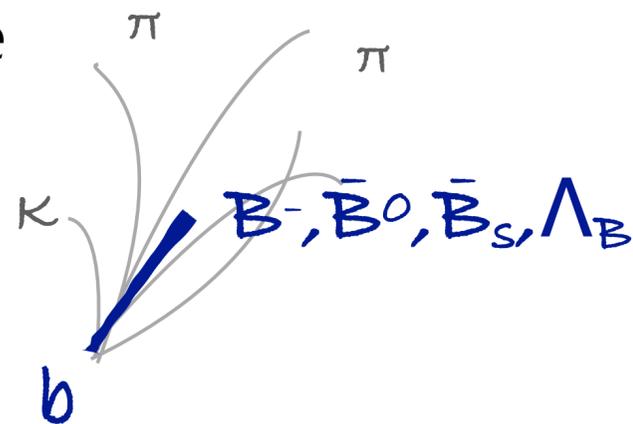
35.9 fb⁻¹ (13 TeV)



- 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



Measurable lifetime

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

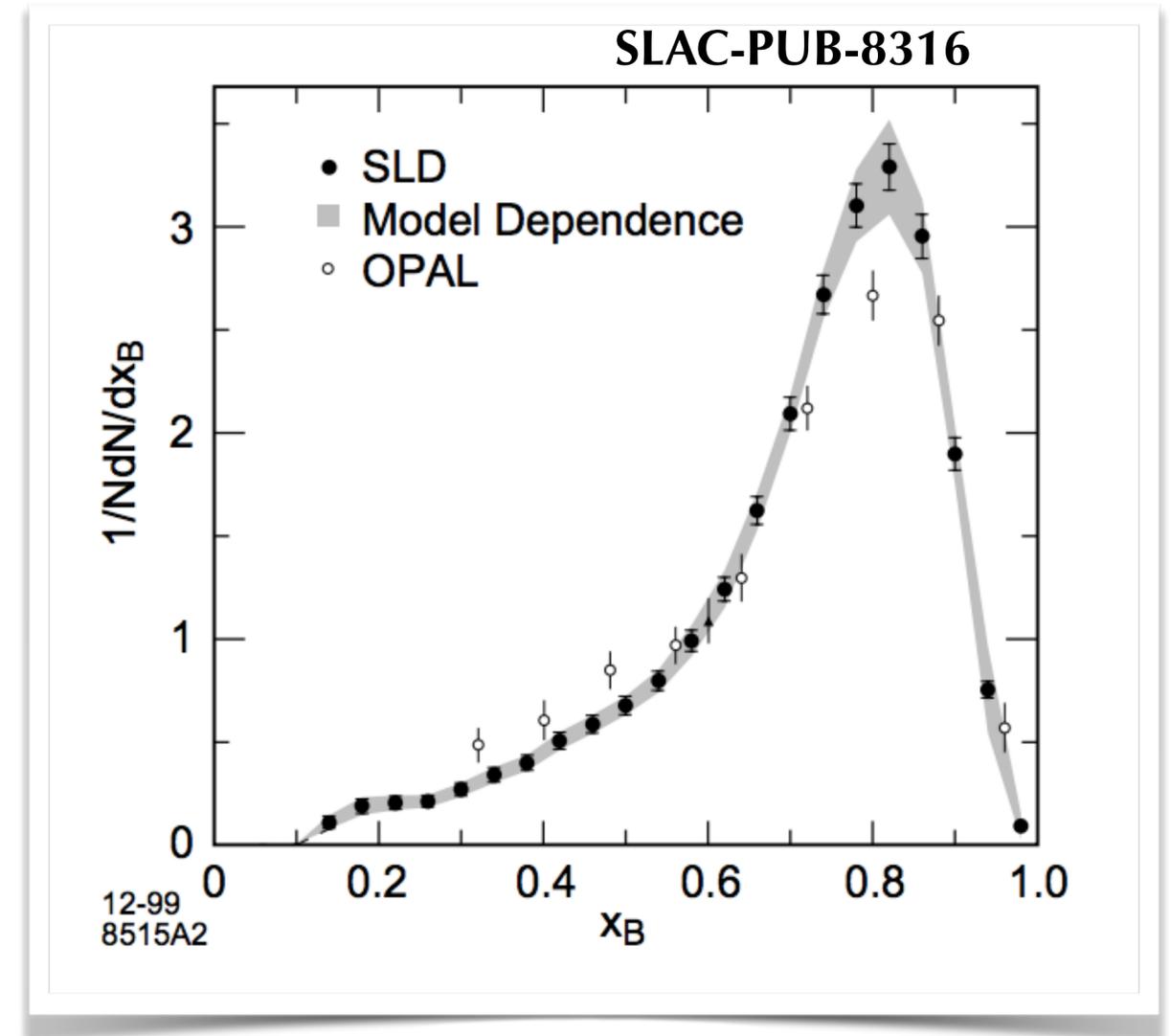
The **weak b-decay** often produces leptons

$$\text{BR: } B \rightarrow \ell + \nu + X \quad \sim 25\%$$

$$B \rightarrow D \rightarrow \ell + \nu + X' \quad \sim 20\%$$

tertiary vertex

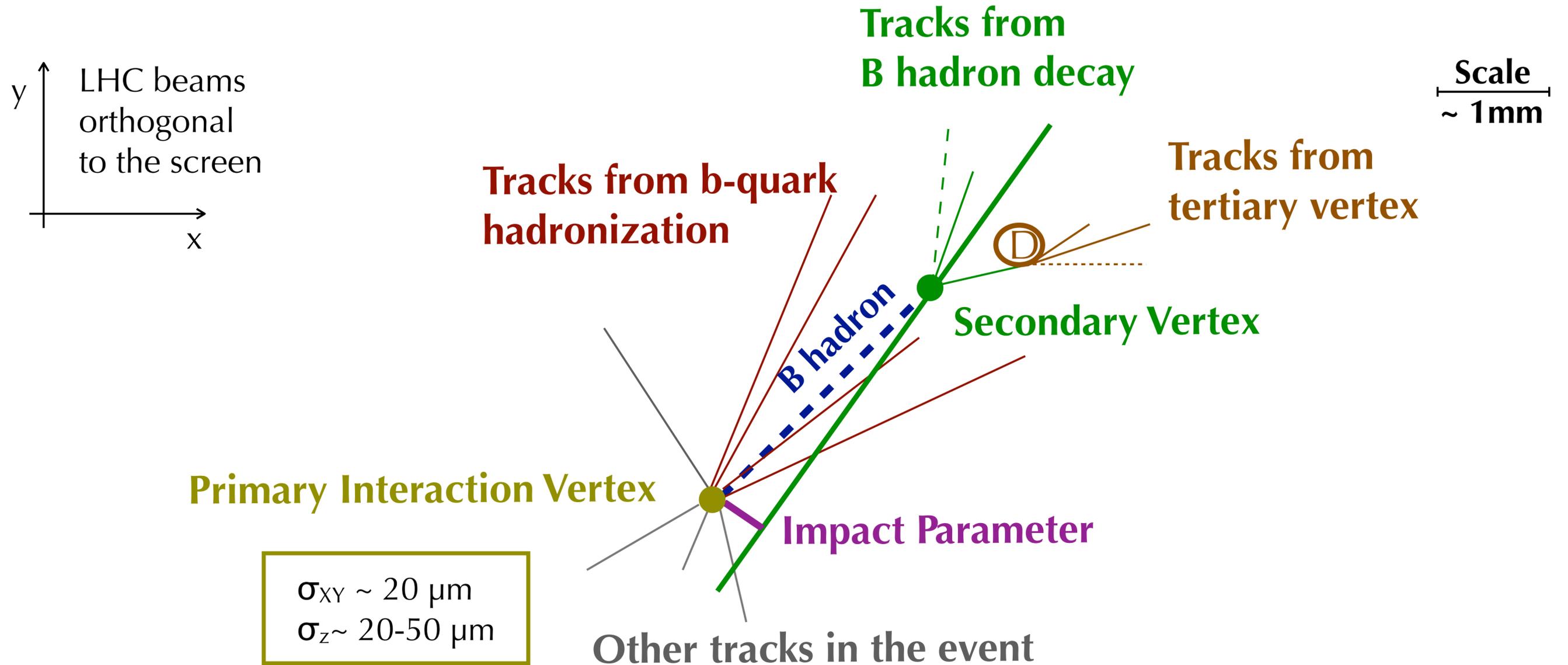
High momentum transferred to the B hadron



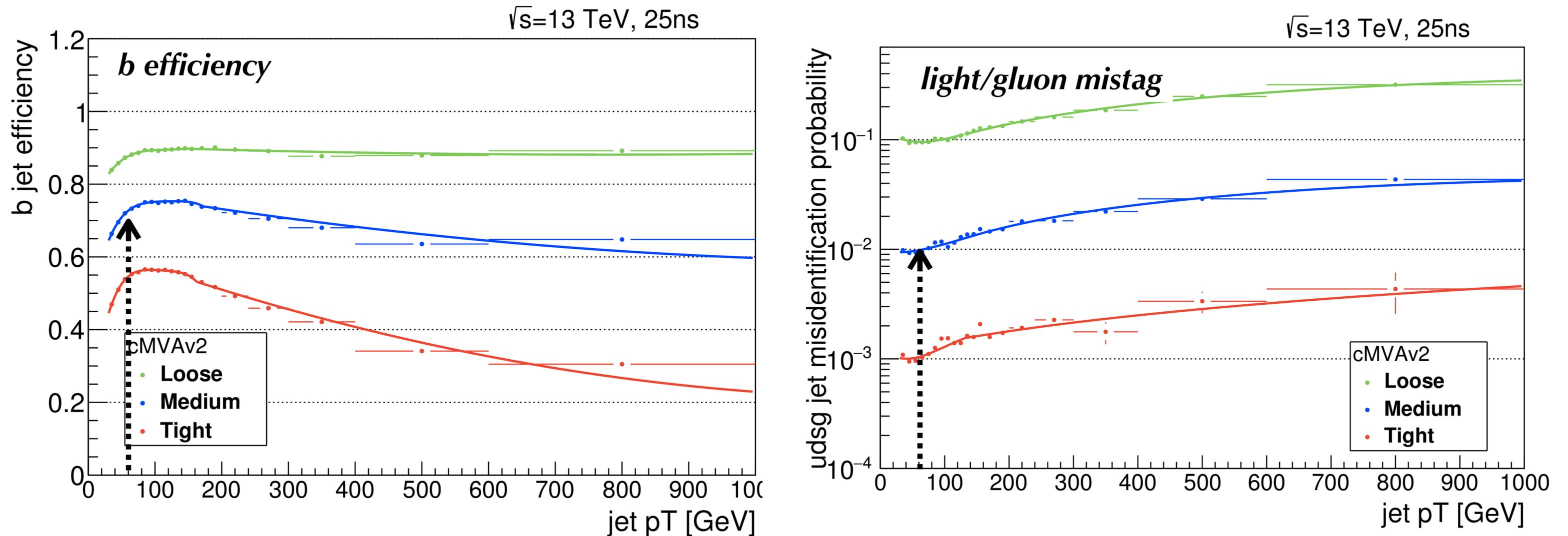
Fraction of the original b quark momentum carried by the B

$$\langle x_B \rangle \sim 0.7$$

The B tag picture

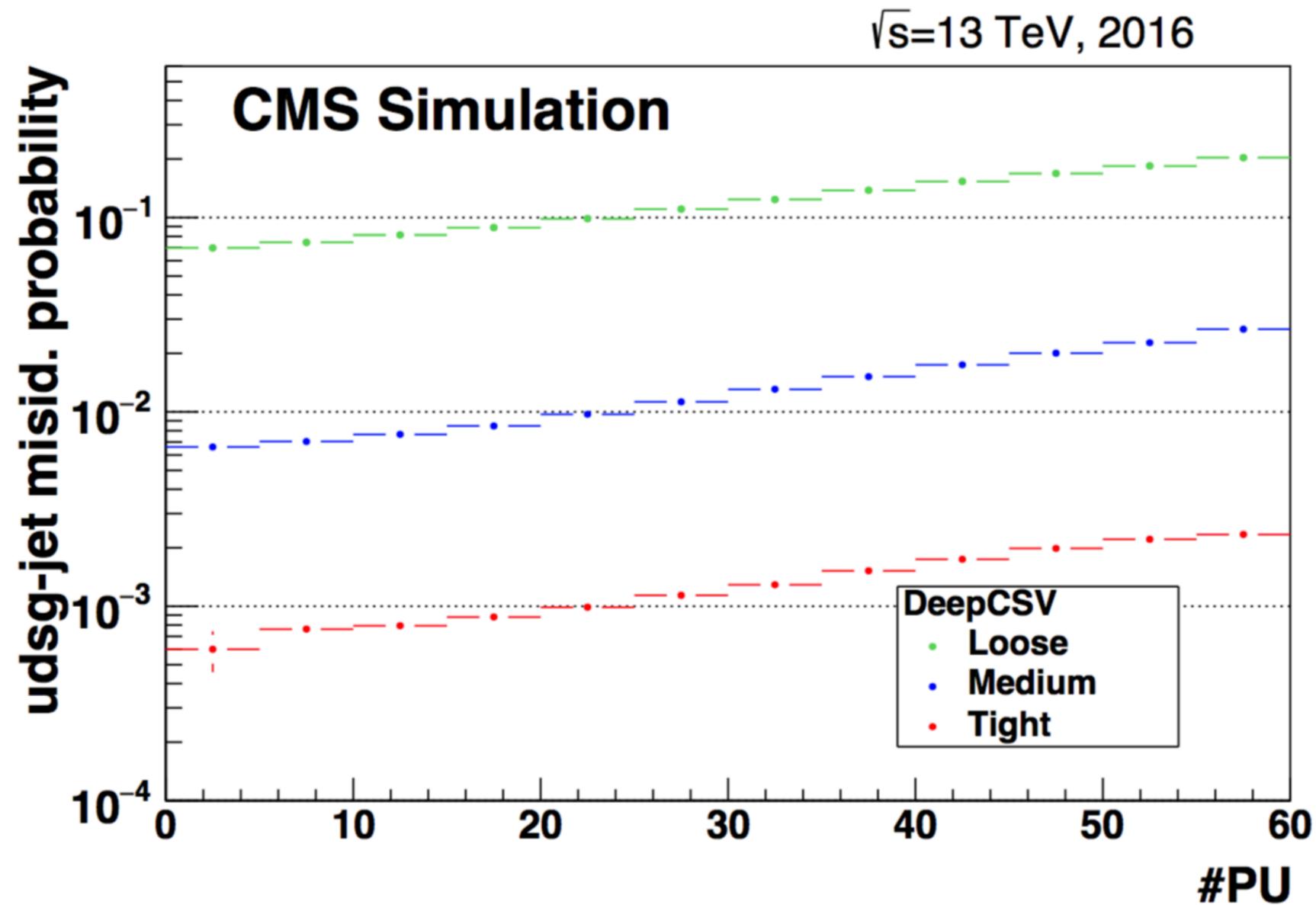


Performance of b-tagging in CMS

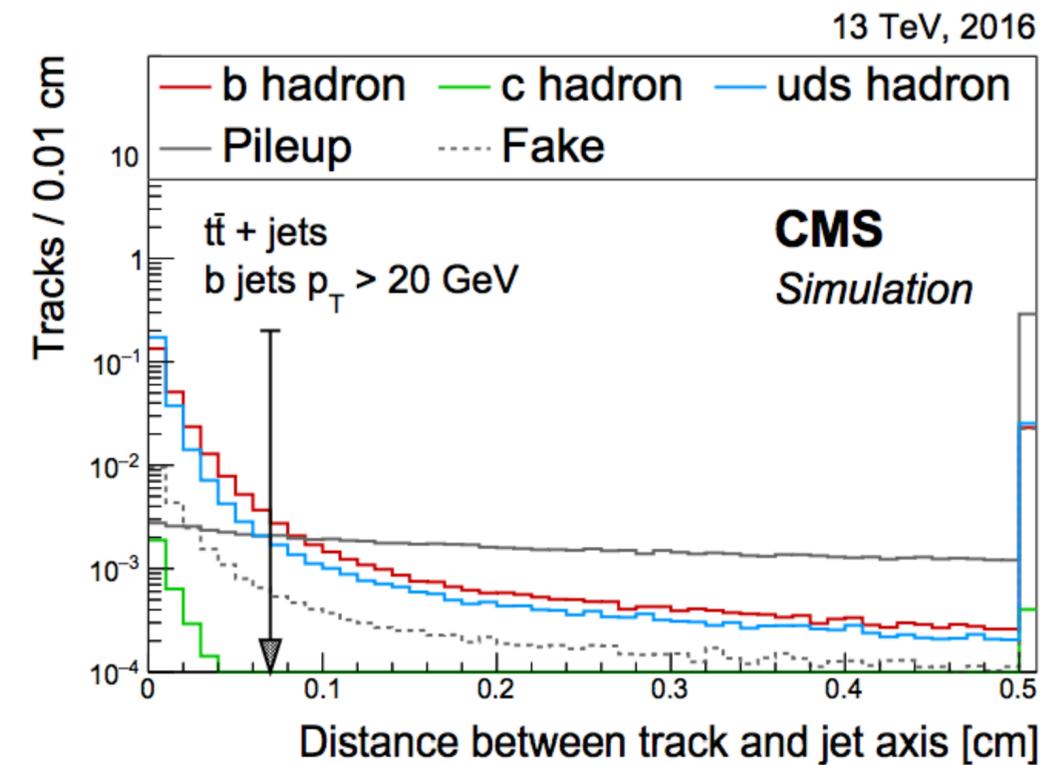


optimal working point for a **H to $b\bar{b}$ search** search has 70% b efficiency and 1% mistag probability

b-tagging vs. pileup



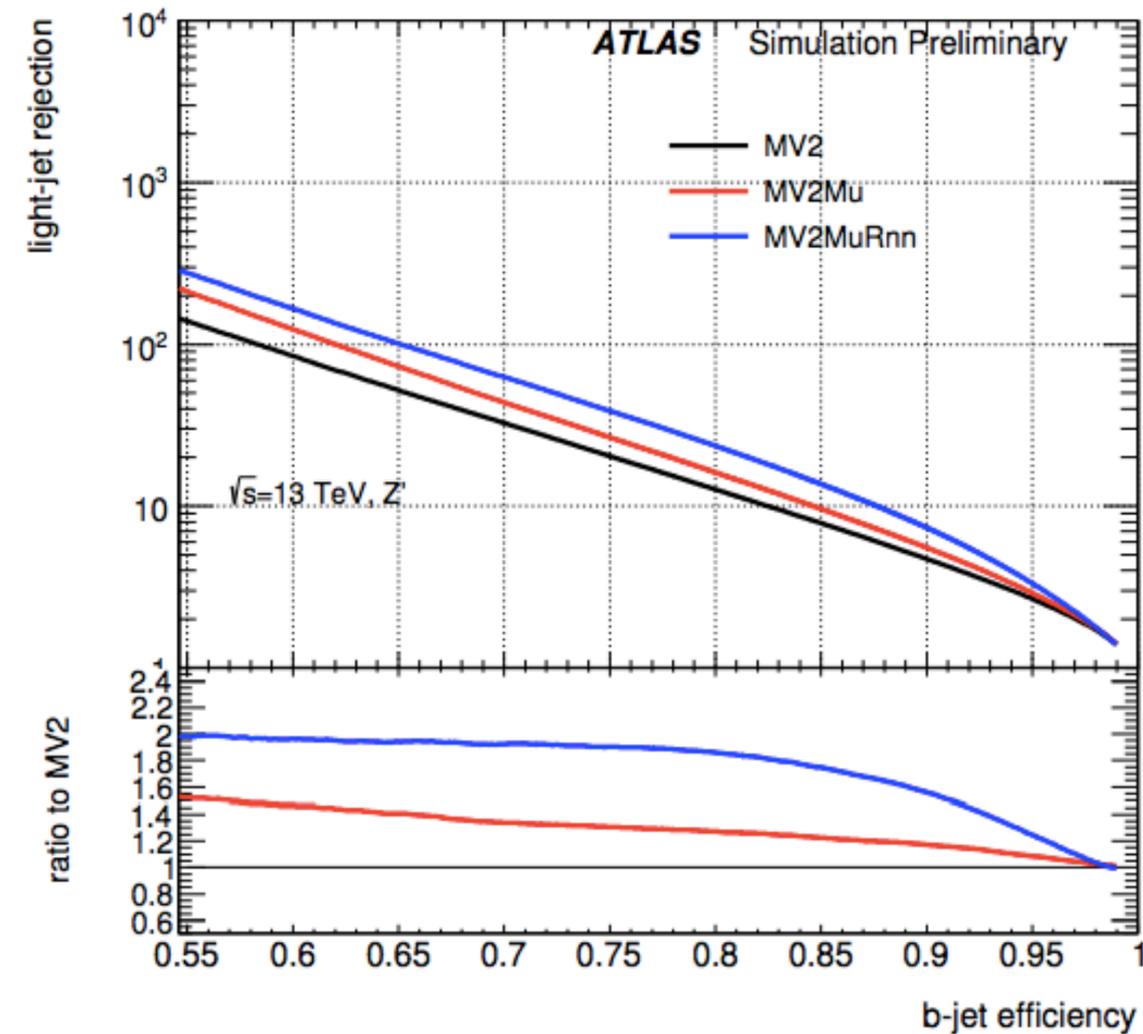
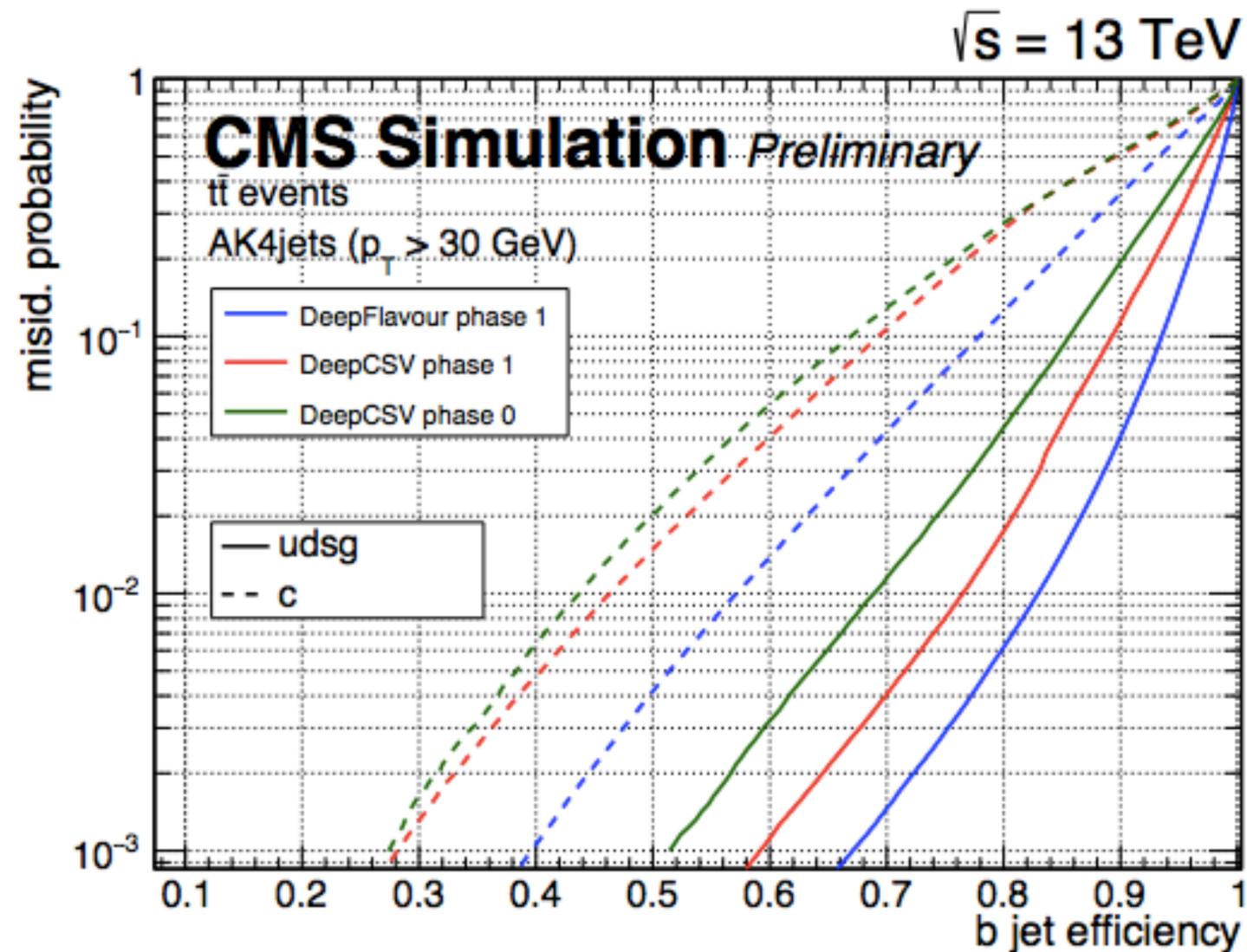
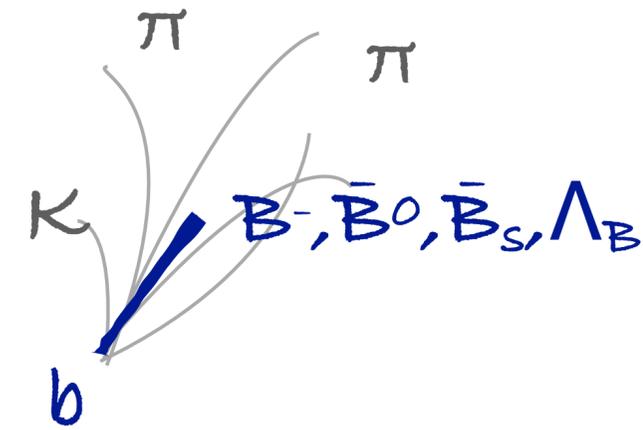
- transverse IP < 0.2 cm
- longitudinal IP < 17 cm
- distance between the track and the jet axis < 0.07 cm



heavy flavor identification

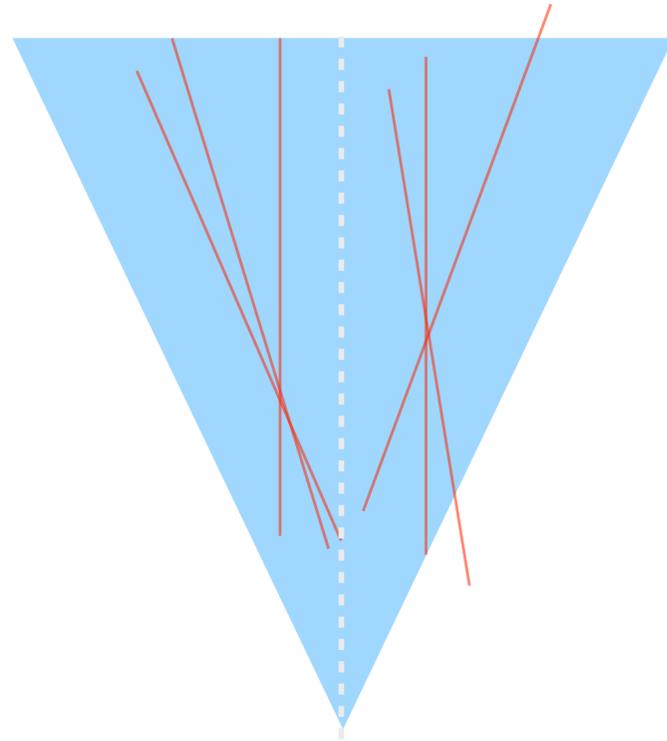
- CSVv2 (track,SV)
- DeepCSV (track, SV + more charged tracks)
- DeepFlavour (charged and neutral PF + SV)

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



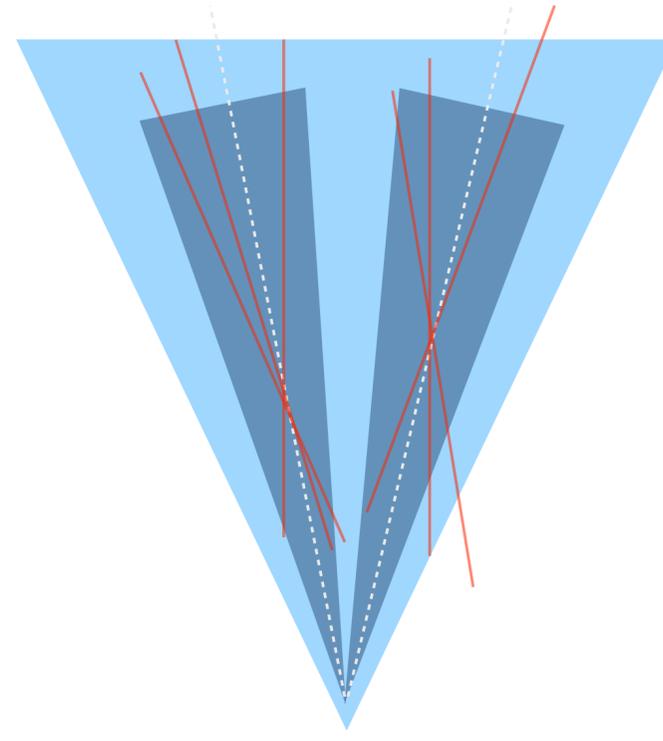
Multiple approaches

* τ -axes are *Nsubjettiness axis*



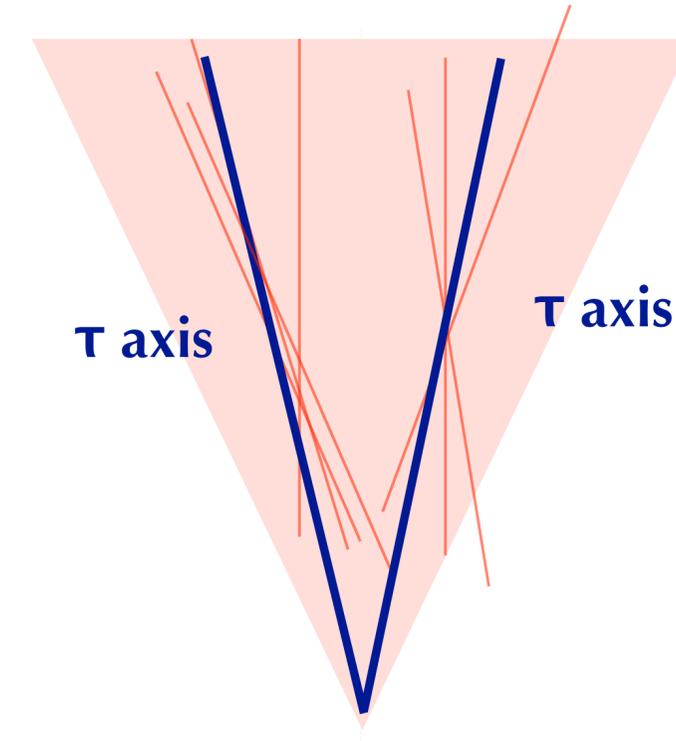
fat-jet b-tagging

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



sub-jet b-tagging

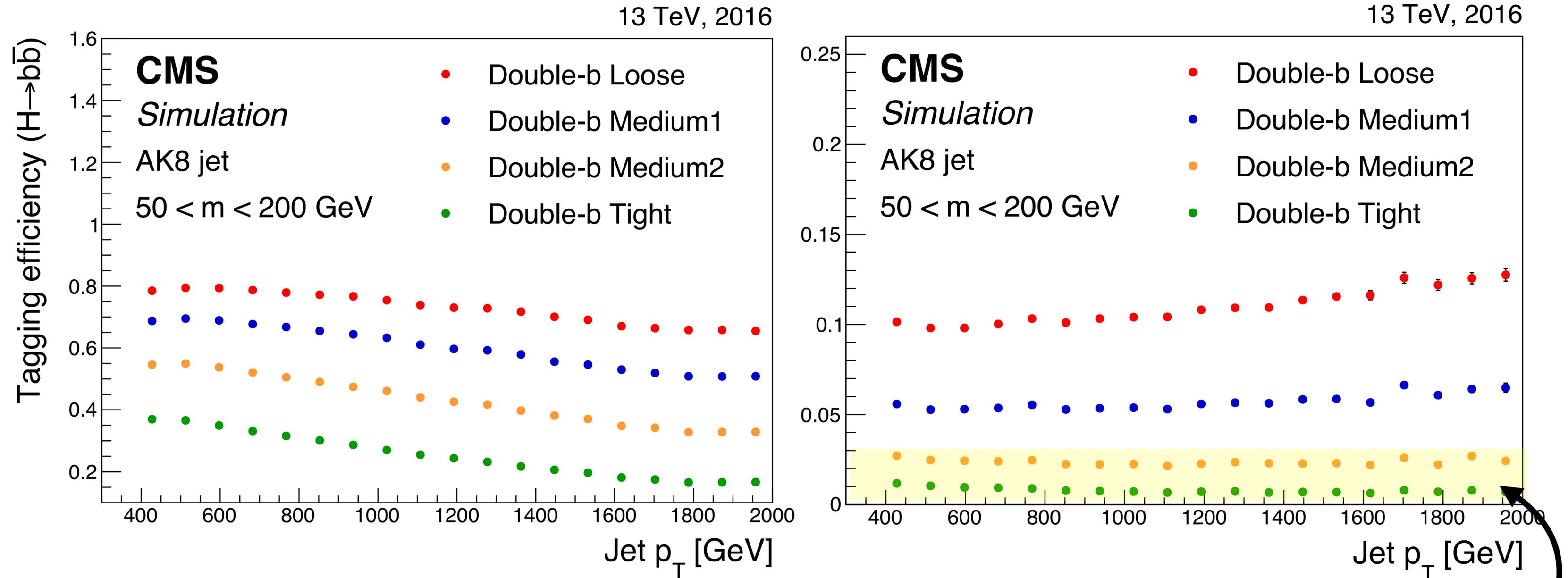
- Defines sub-jets
- Standard b-tagging algorithm applied to each subjet



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

Performance

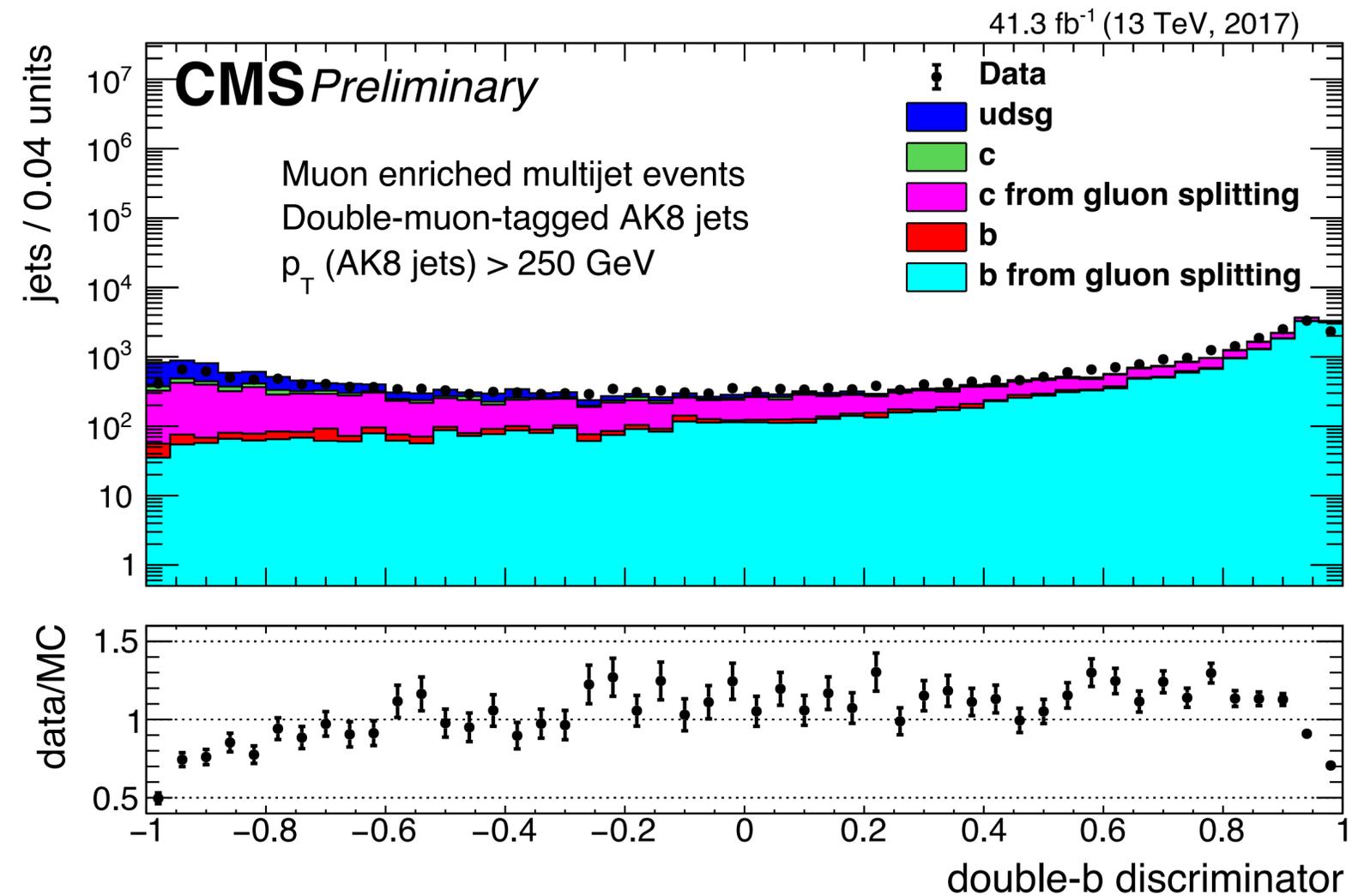
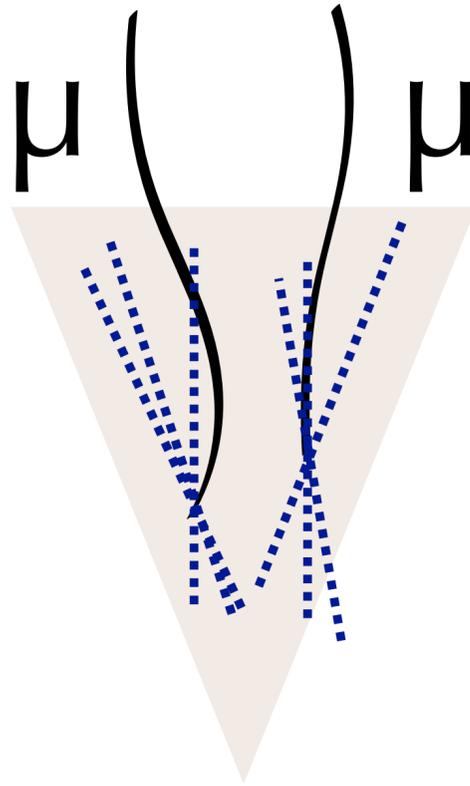


The mistag rate is approximately flat across the p_T range by design
Critical point for searches (background estimate)

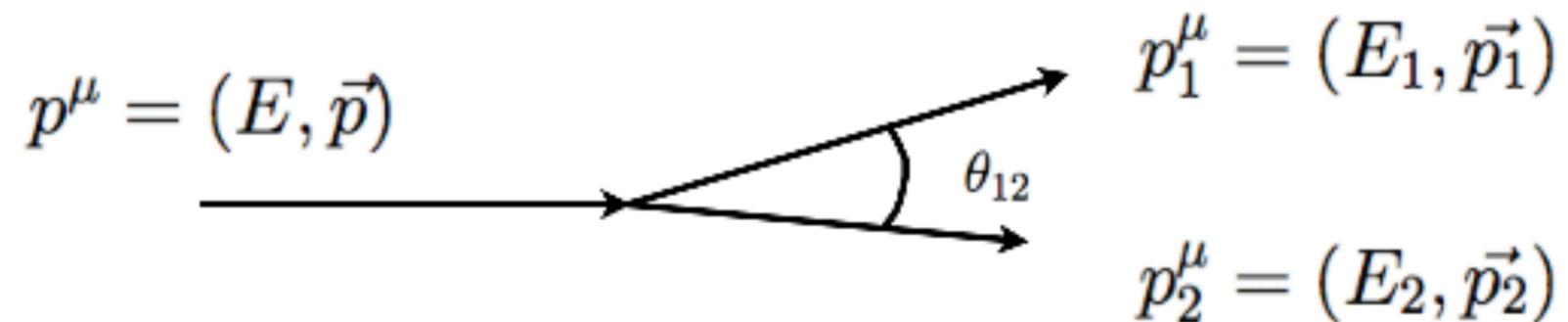
Calibration in data

Jet selection has been designed to ensure jets are signal-like

- High AK8 p_T jet ($p_T > 250$ GeV)
- **double-muon** tagged jets (muon $p_T > 7$ GeV)
- **mass cut** (>50 GeV)



Boost



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

$$\begin{aligned}
 p^\mu p_\mu &= (p_1 + p_2)^\mu (p_1 + p_2)_\mu \\
 m^2 &= (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2) \cdot (\vec{p}_1 + \vec{p}_2) \\
 m^2 &\approx 2E_1 E_2 (1 - \cos(\theta_{12}))
 \end{aligned}$$

If $E_1 = E_2$:

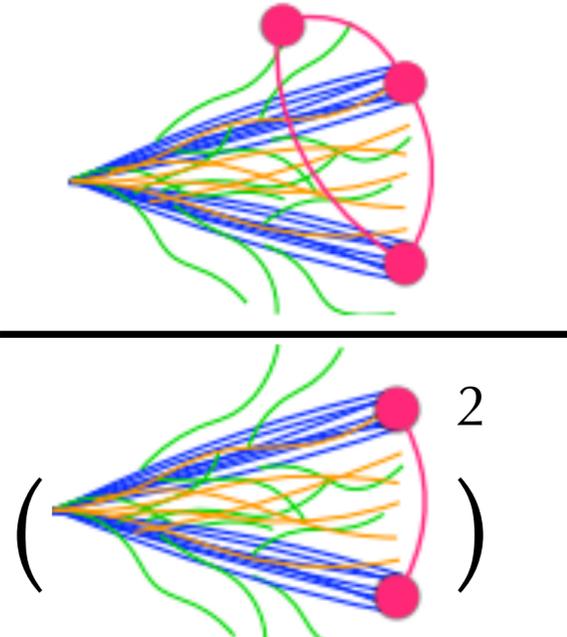
$$\begin{aligned}
 m^2 &\approx E^2 (1 - \cos(\theta_{12})) \\
 \cos(\theta_{12}) &\approx 1 - \frac{m^2}{E^2}
 \end{aligned}$$

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

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

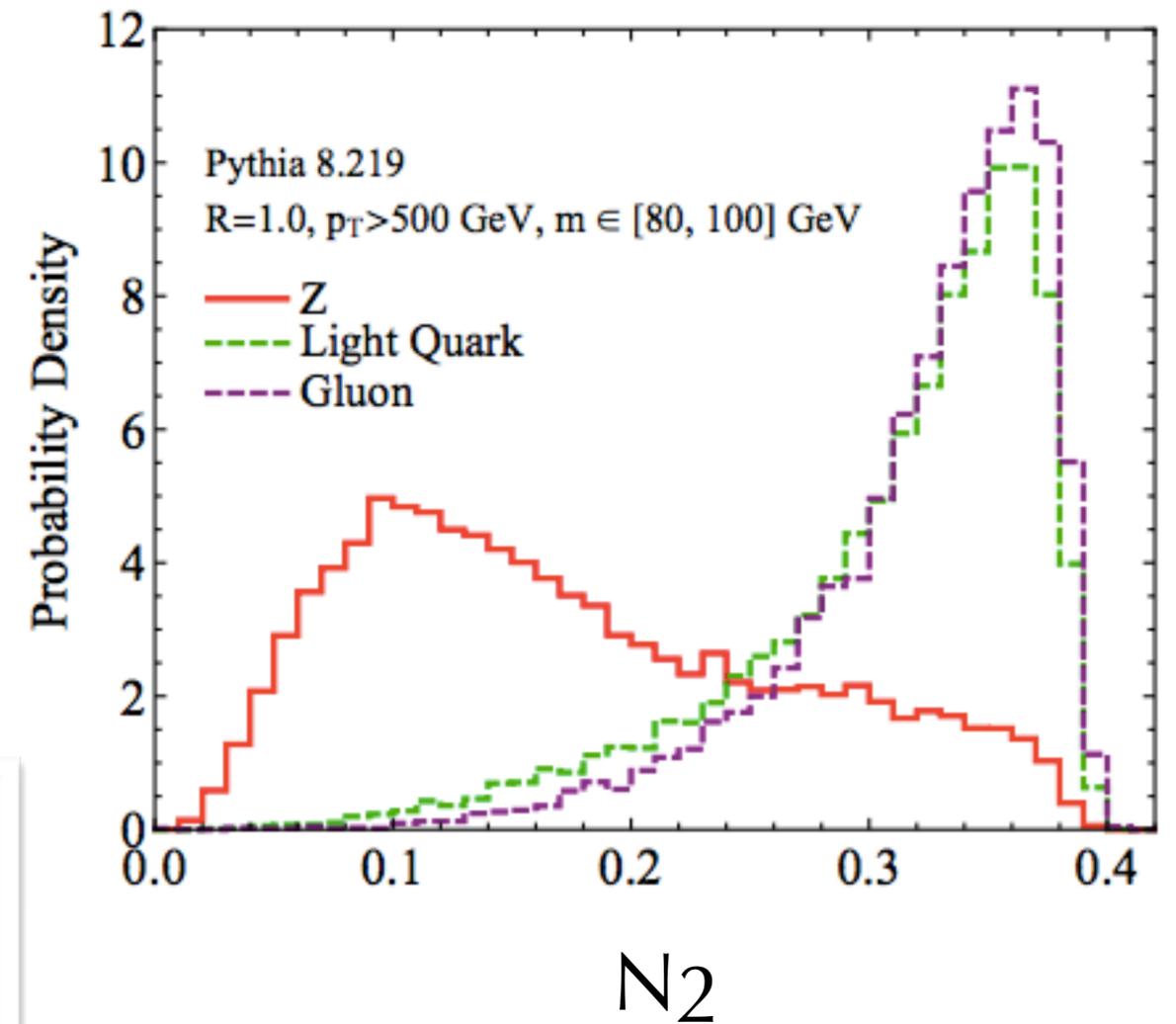
Jet Substructure

- 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 $e_3 < e_2$

$$N_2^\beta = \frac{2e_3^\beta}{(1e_2^\beta)^2} = \frac{\text{3-point}}{\left(\text{2-point}\right)^2}$$


$$1e_2^\beta = \sum_{1 \leq i < j \leq n_j} z_i z_j \Delta R_{ij}^\beta \quad z_i = \frac{p_{T_i}}{\sum_{j \in \text{jet}} p_{T_j}}$$

$$2e_3^\beta = \sum_{1 \leq i < j < k \leq n_j} z_i z_j z_k \min \left\{ \Delta R_{ij}^\beta \Delta R_{ik}^\beta, \Delta R_{ij}^\beta \Delta R_{jk}^\beta, \Delta R_{ik}^\beta \Delta R_{jk}^\beta \right\}$$



Jet mass

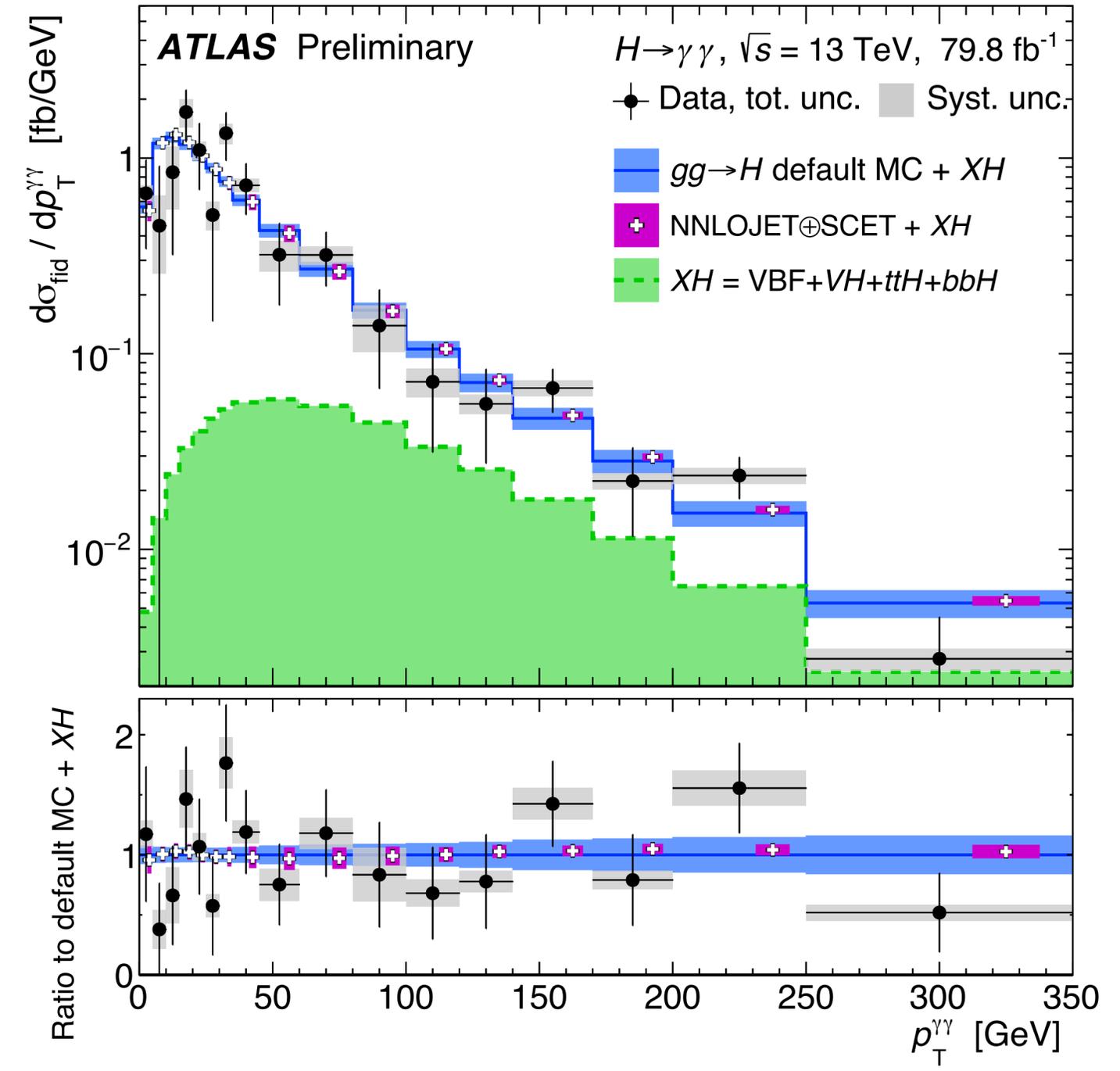
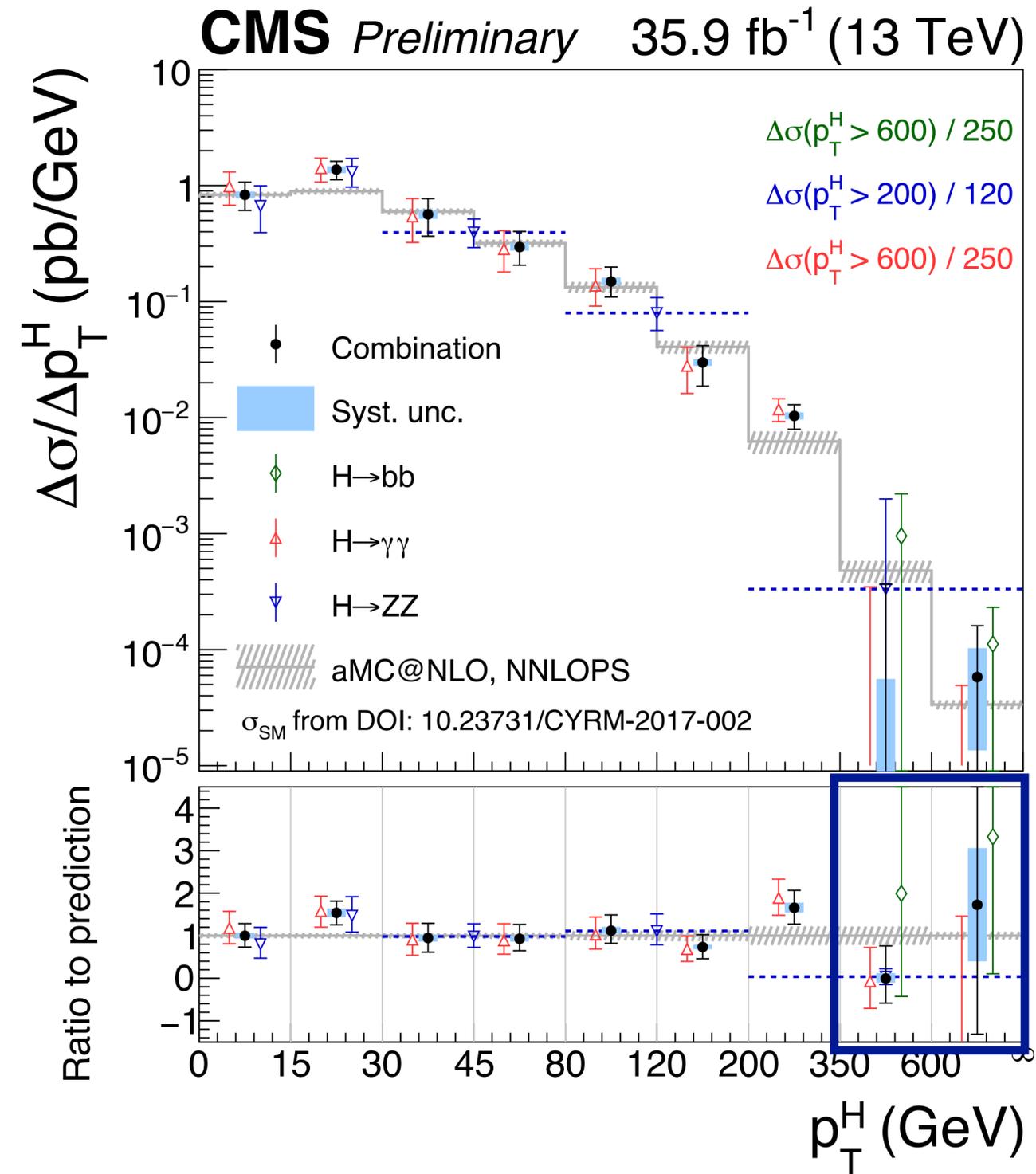
- Provides good separation between H-jets from q/g jets
- **Grooming** removes soft and wide-angle radiation



**soft drop/modified
mass soft drop**

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

Probing ggF vs. H p_T



di-Higgs in BSM

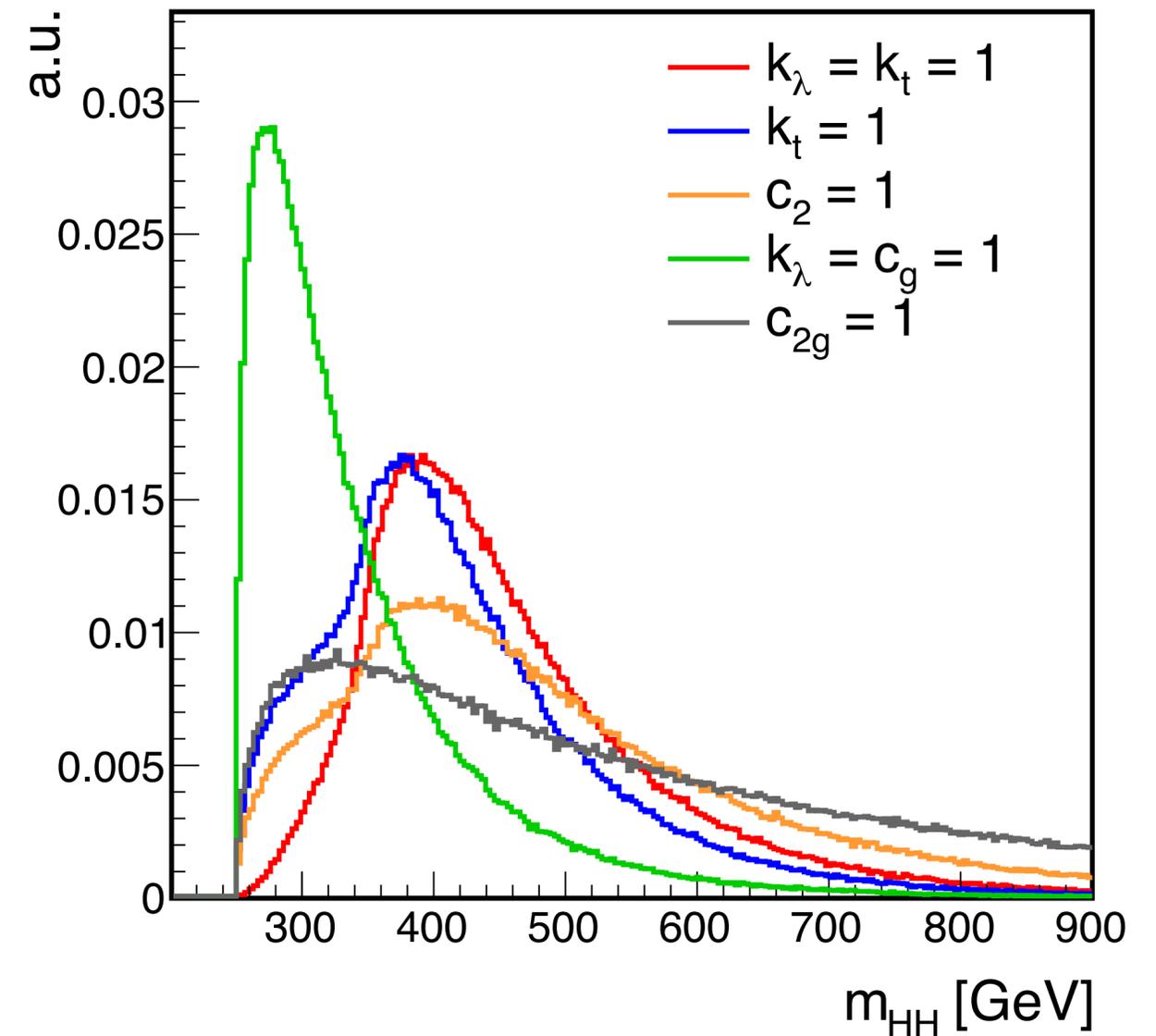
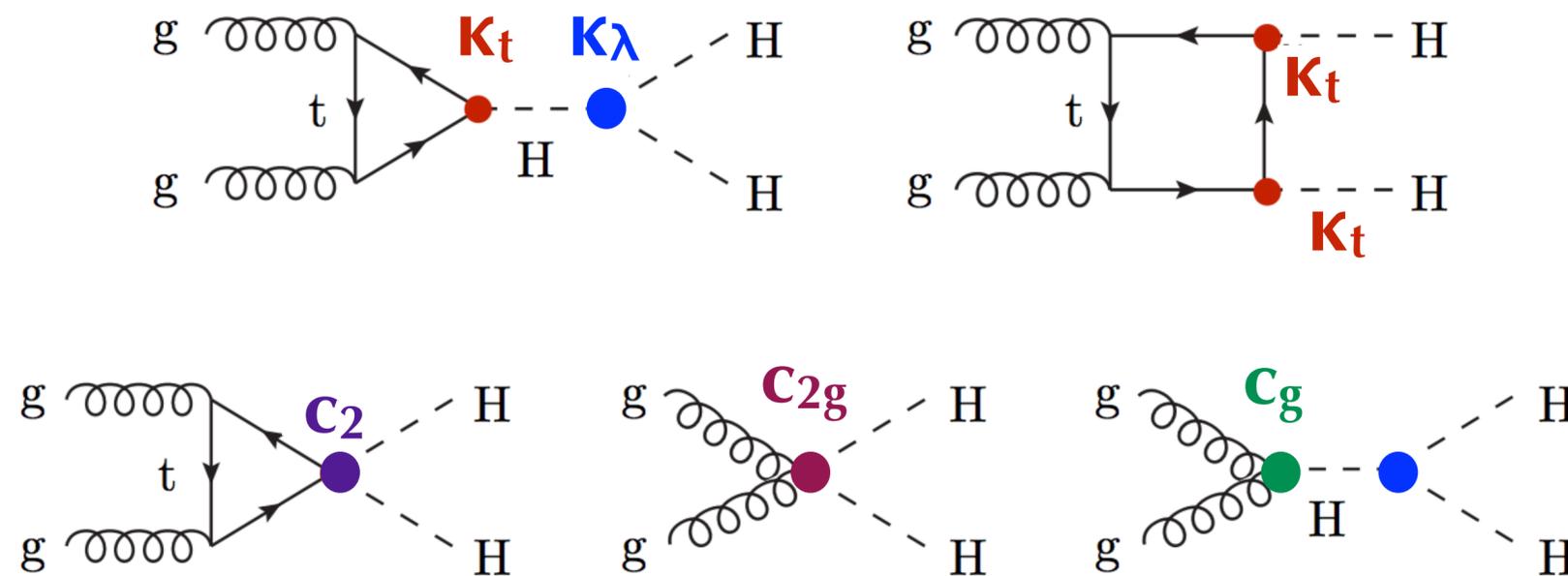
Anomalous Higgs boson couplings

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

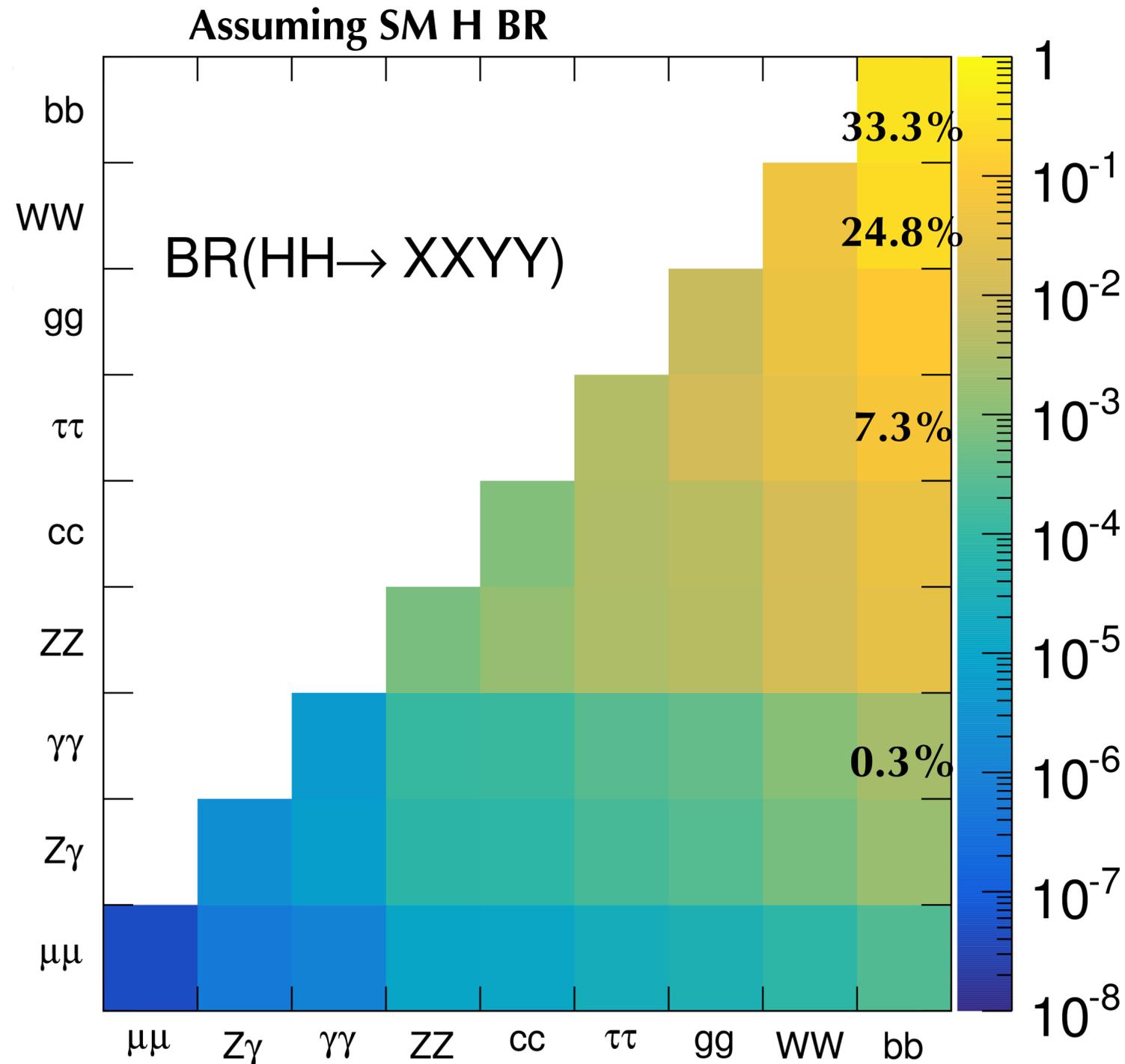
EFT approach parametrizes new physics (dim 6 operators)

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(bb)

highest BR: larger statistics

high b-tag efficiency and low fake rate

multi-light jets background is highly reduced

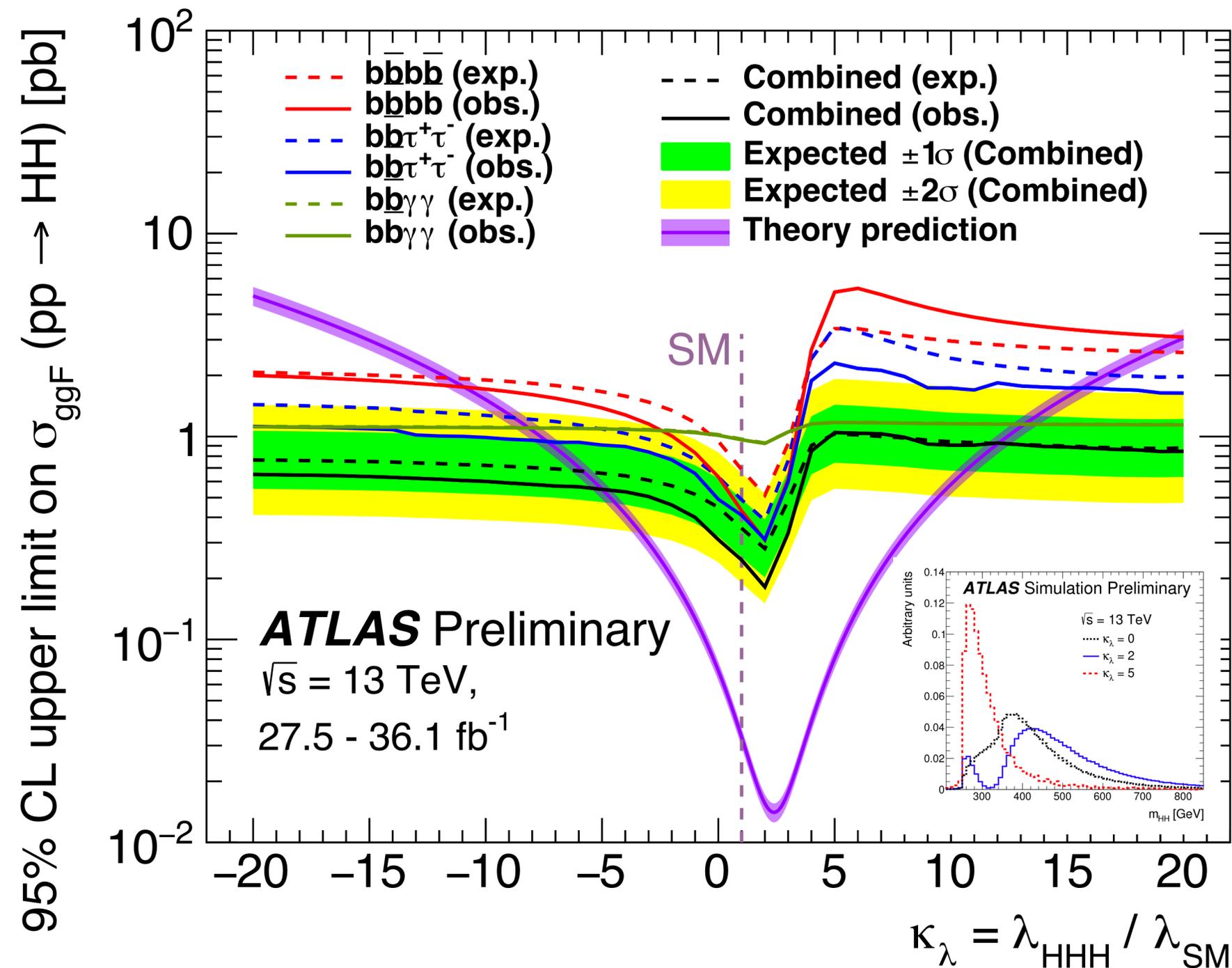
H(gamma-gamma)

simple topology

excellent mass resolution

Limited by small BR

Constraints on the self-coupling



HH combination constrains the trilinear coupling modifier $\kappa_\lambda = \lambda/\lambda_{\text{SM}}$

$\kappa_\lambda = \lambda/\lambda_{\text{SM}}$ in [-5.8, 12.1]

assuming SM top-H coupling

Projections for HL-LHC

Extrapolation from Run II to HL-LHC (3000 fb⁻¹)

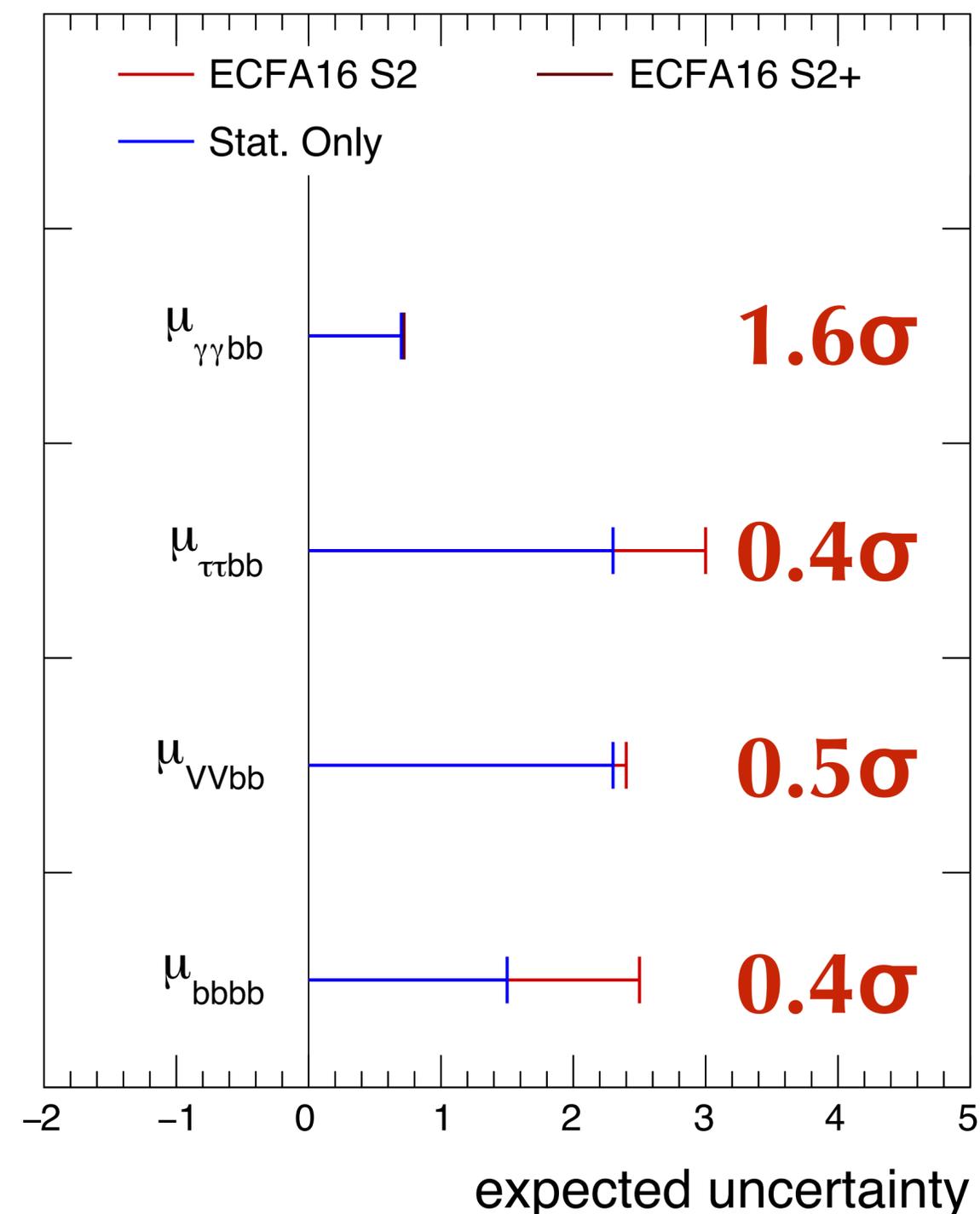
- based on 2015 data, about 2.3-2.7fb⁻¹
- *This is overly pessimistic*

HL-LHC projections and YR status - dedicated analysis

S.Gori

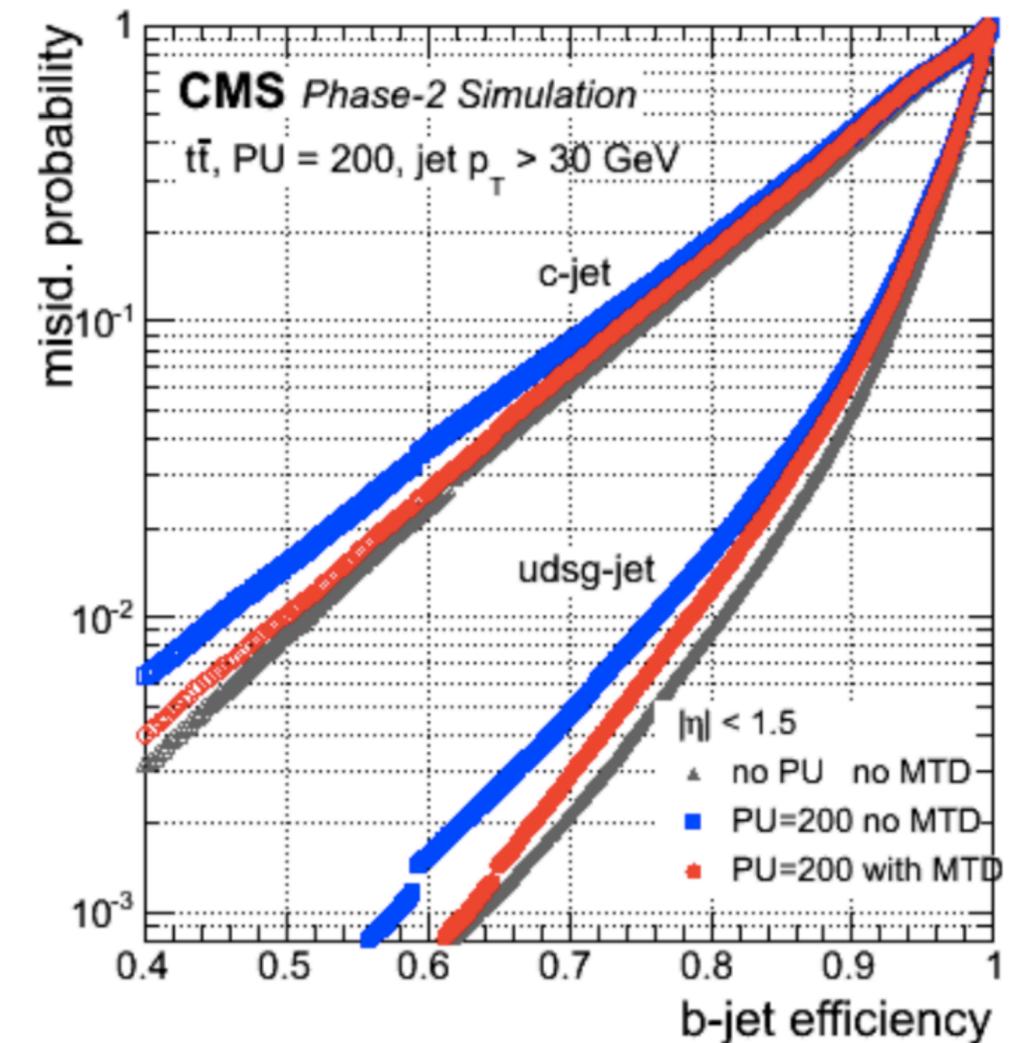
Channel	CMS	ATLAS
HH → bbbb	$Z(\sigma_{HH}(SM))=0.39 \sigma$ CMS PAS FTR-16-002	$-4.1 < \lambda_{HHH}/\lambda_{SM} < 8.7$ @95 % C.L. ATLAS-TDR-030
HH → bbττ	1.6 xSM CMS-TDR-019	0.6 σ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$ @95 % C.L. ATL-PHYS-PUB-2015-046
HH → bbγγ	1.43 σ CMS PAS FTR-16-002	1.5 σ $0.2 < \lambda_{HHH}/\lambda_{SM} < 6.9$ @95 % C.L. (stat only) ATLAS-TDR-030
HH → WWbb	0.45 σ CMS PAS FTR-16-002	
tt(HH → bbbb)		0.35 σ ATL-PHYS-PUB-2016-023

CMS Projection $\sqrt{s} = 13$ TeV SM gg → HH



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 $|\eta| = 4$
 - *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 (%)
$HH \rightarrow b\bar{b}\gamma\gamma$	22
$HH \rightarrow b\bar{b}b\bar{b}$	18

On going studies for HL-LHC (towards YR)

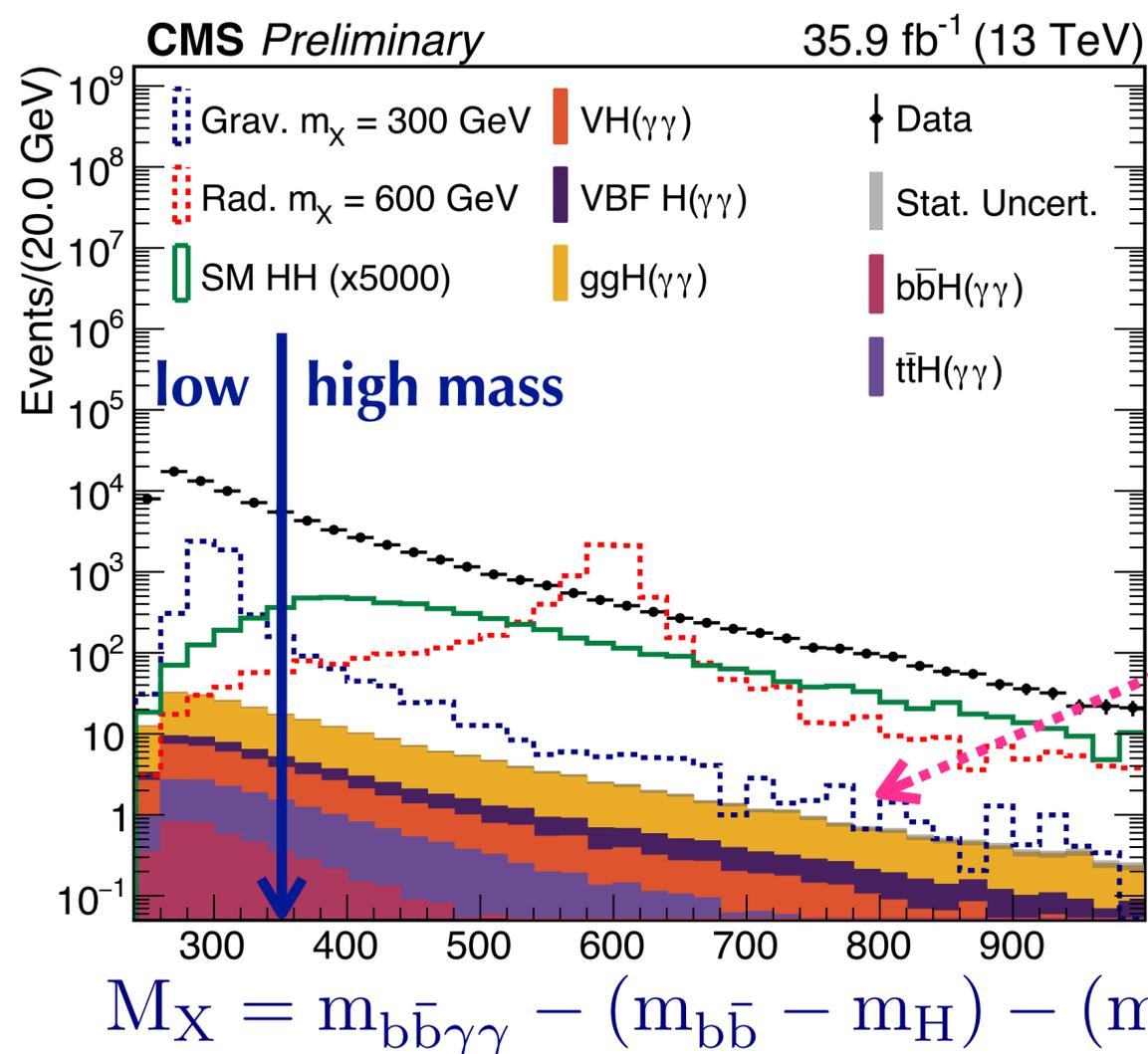
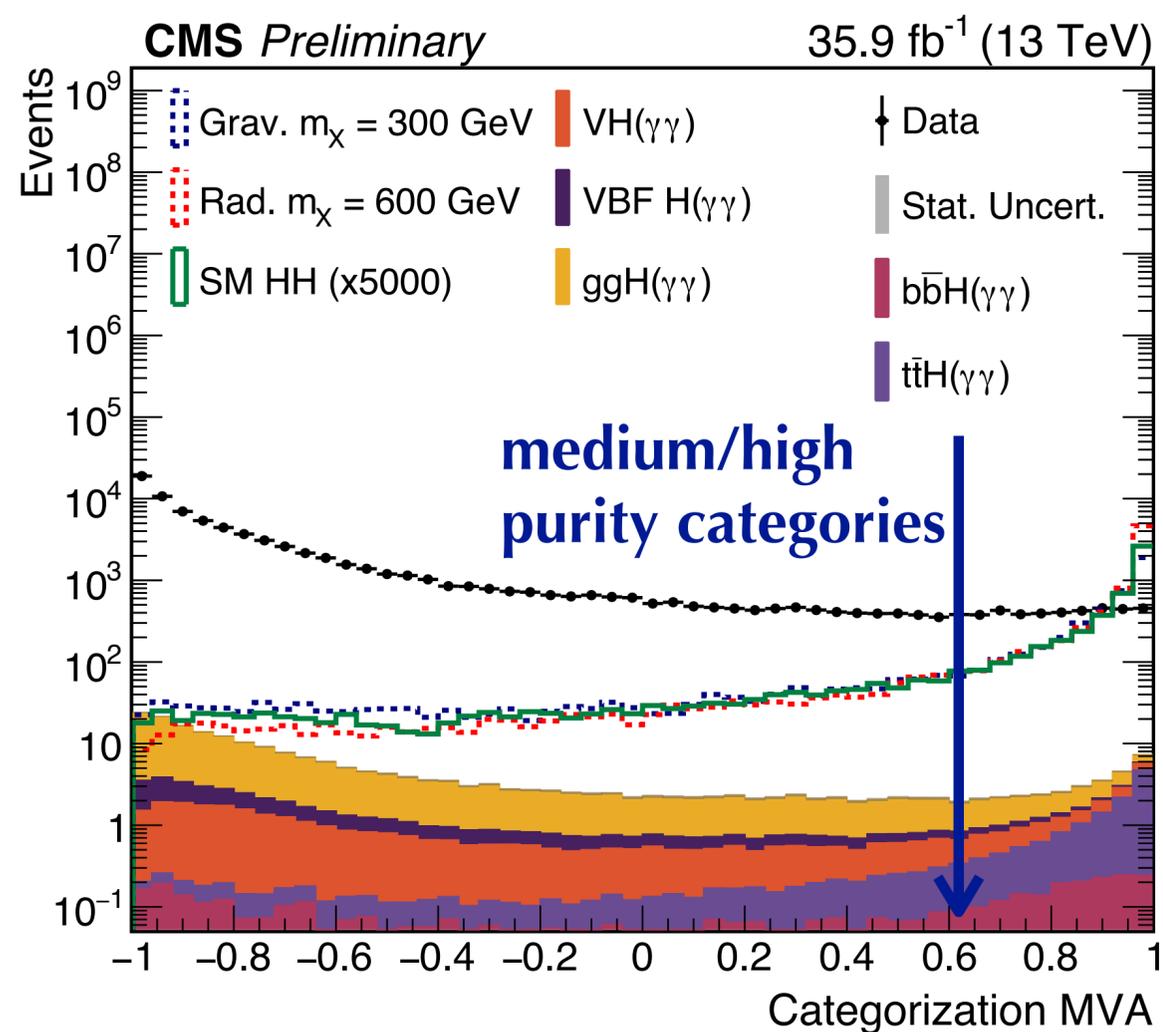
- **Dedicated analysis for Phase II** shows that SM HH production can be measured by CMS with approximately **50% precision** using 3000 fb^{-1}
 - $H(b\bar{b})H(b\bar{b})$ not included but a promising channel
- Studies based on **full-sim/Delphes** are on going:
 - $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}VV$, **$b\bar{b}\tau\tau$** , 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 $H(\gamma\gamma)$]
 - **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

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

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

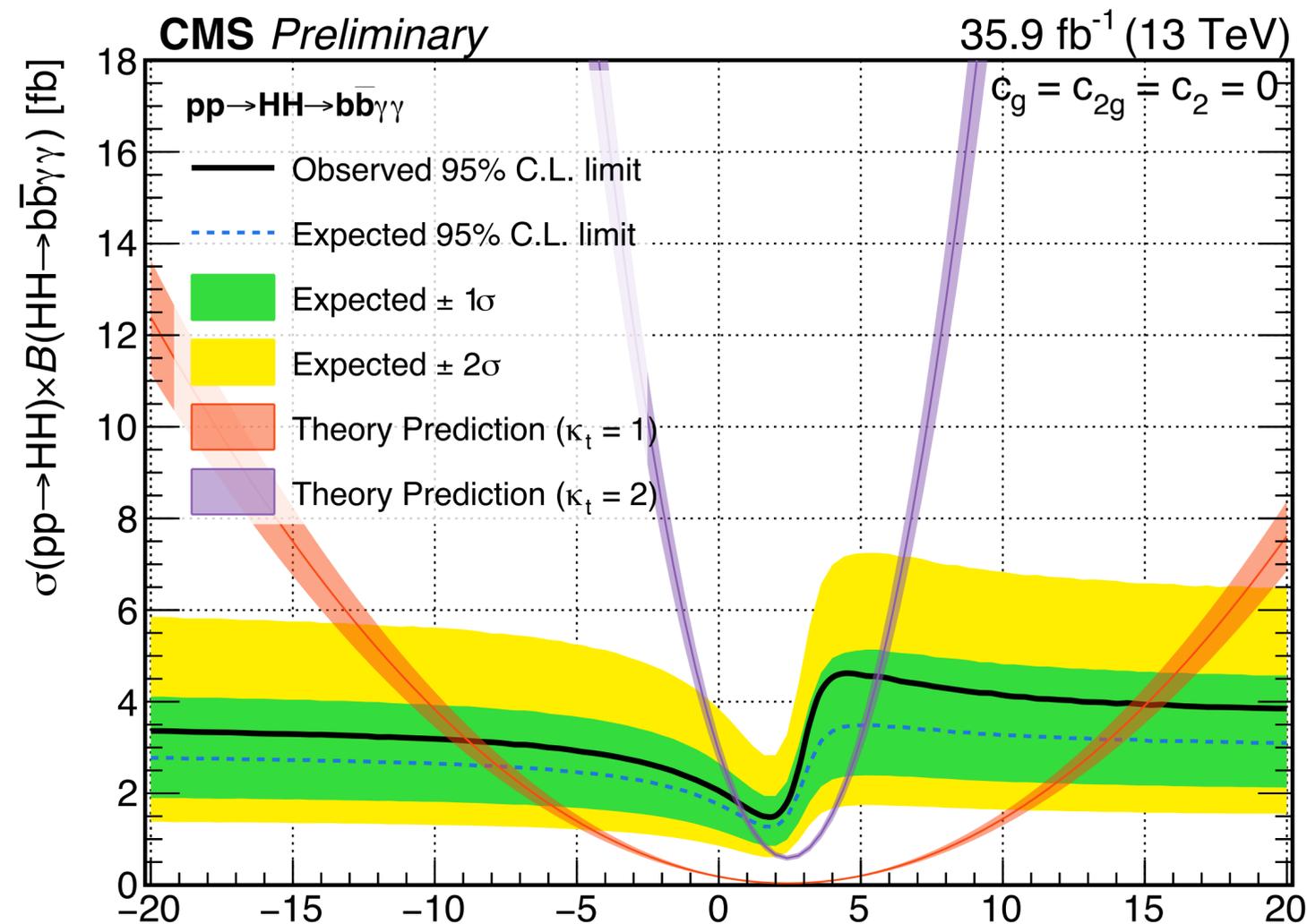


- photon+jets (prompt photons or jets misidentified as photon) **from data**
- **SM single Higgs** from simulation

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

- Likelihood fits simultaneous to $m(b\bar{b})$ and $m(\gamma\gamma)$
 - 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

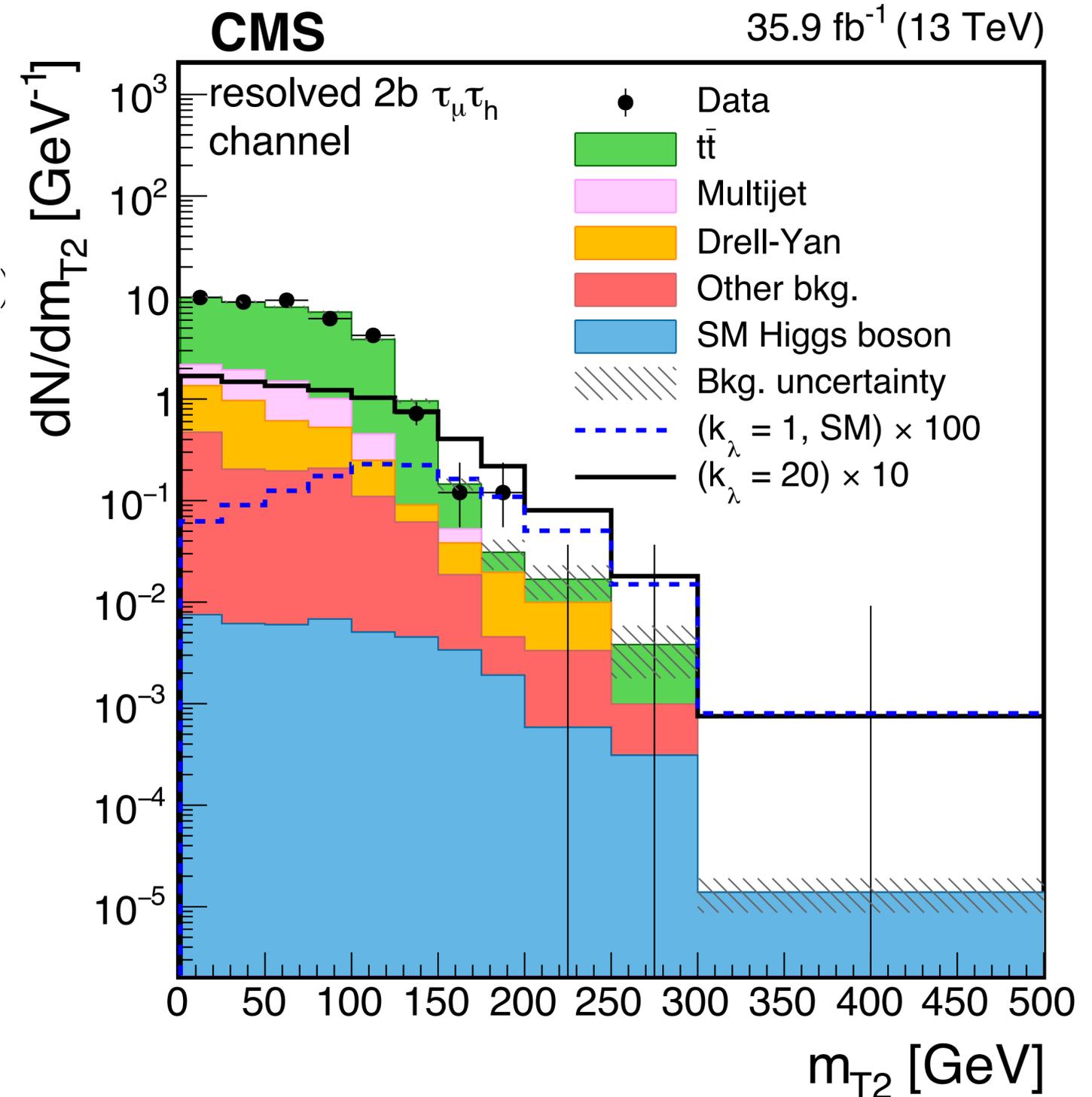
Sources of Systematical Uncertainties	Type	Value
General uncertainties		
Integrated luminosity	Normalization	2.5%
Photon related uncertainties		
Photon energy scale ($\frac{\Delta M(\gamma\gamma)}{M(\gamma\gamma)}$)	Shape	1.0%
Photon energy resolution ($\frac{\Delta\sigma_{\gamma\gamma}}{\sigma_{\gamma\gamma}}$)	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}_χ 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, $Z/\gamma^* + \text{jets}$ (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

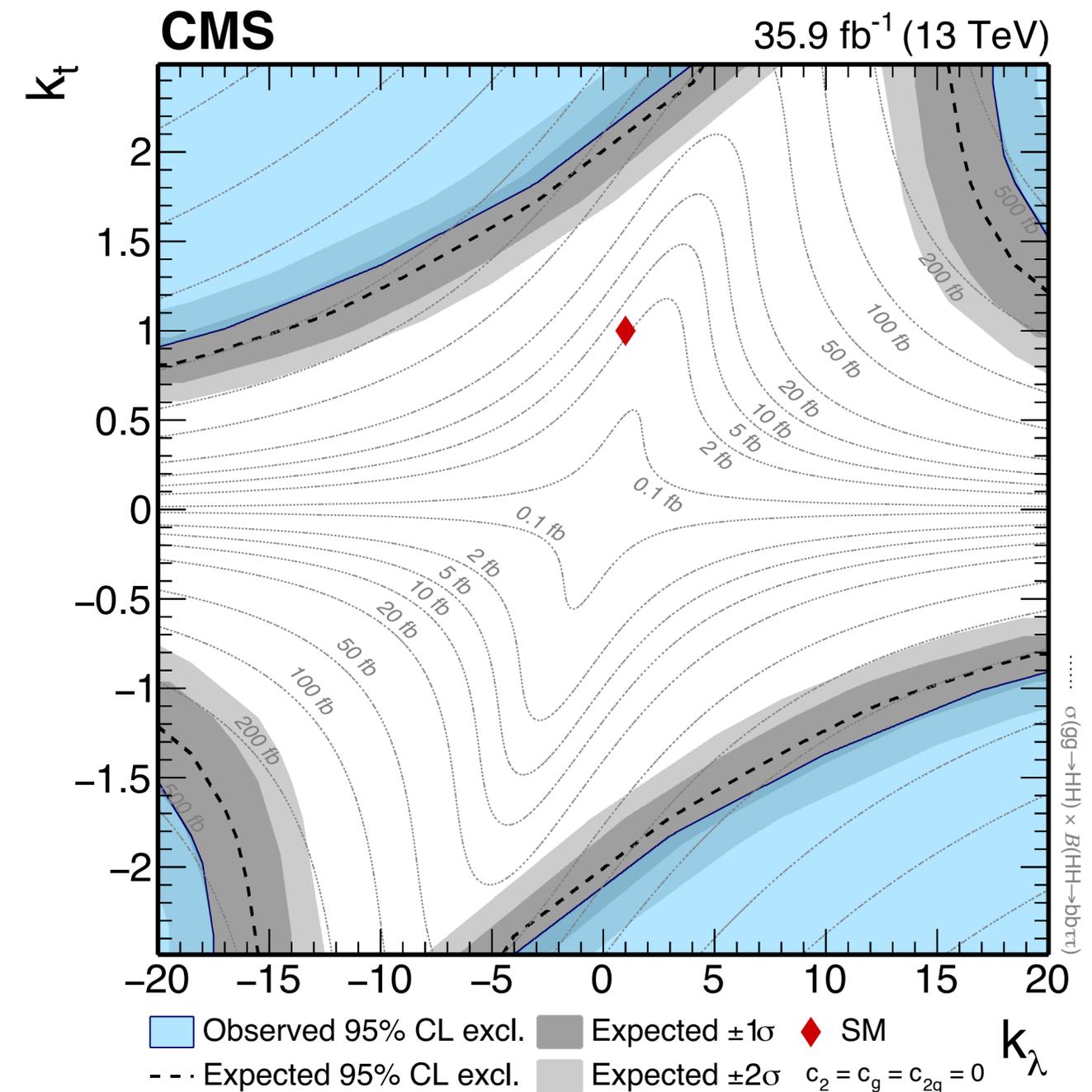
$$m_{T2} = \min_{p_{T1} + p_{T2} = p_T^{\tau\tau}} \{ \max(m_T, m'_T) \}$$



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

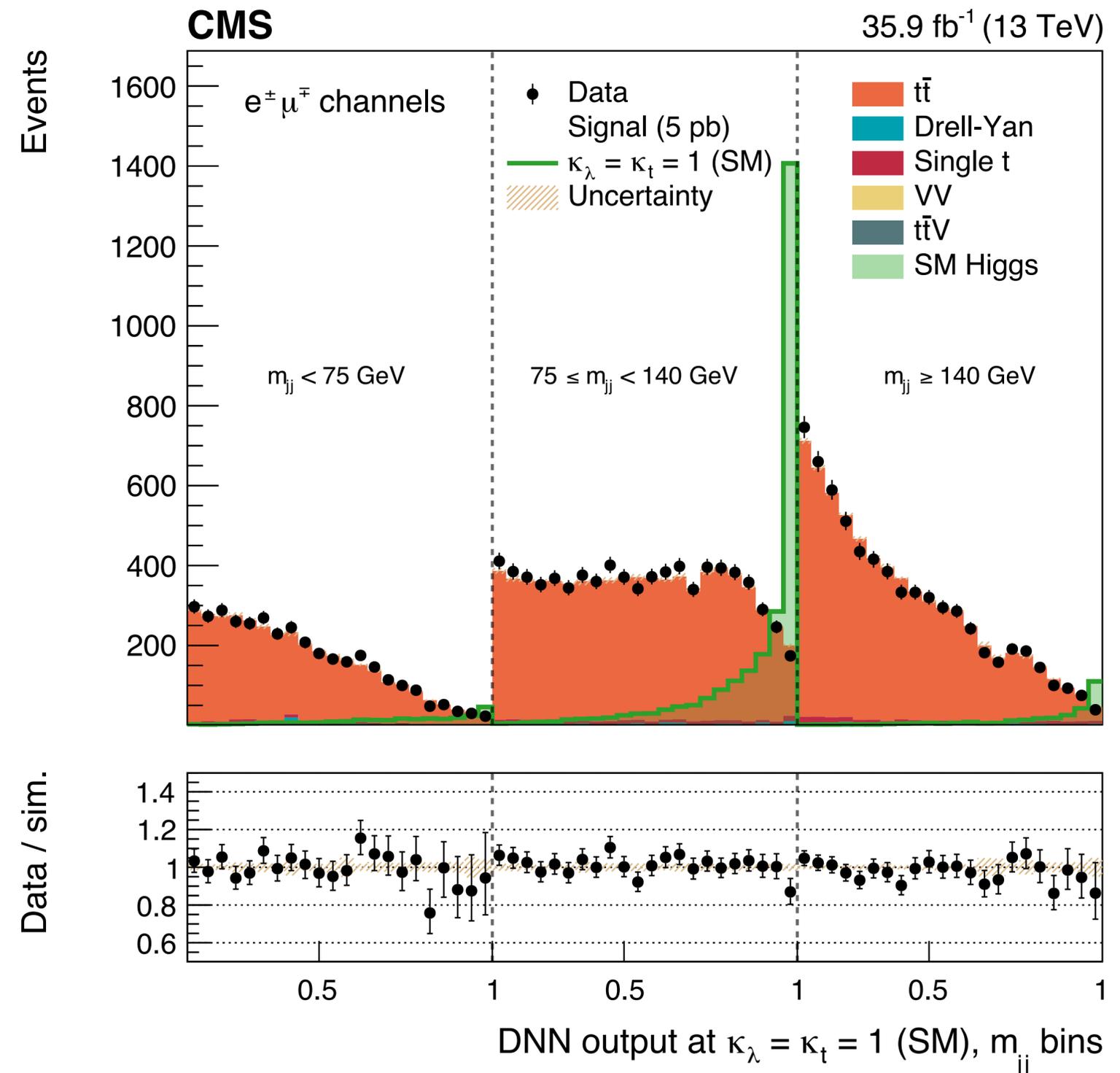
- The observed (expected) upper limit at 95% CL corresponds to about 30 (25) x SM
- Anomalous k_λ and k_t couplings tested

Systematic uncertainty	Value	Processes
Luminosity	2.5%	all but multijet, $Z/\gamma^* \rightarrow ll$
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, $Z/\gamma^* \rightarrow ll$
$Z/\gamma^* \rightarrow ll$ SF uncertainty	0.1–2.5%	$Z/\gamma^* \rightarrow ll$
Multijet normalization	5–30%	multijet
Scale unc.	+4.3% / -6.0%	signals
Theory unc.	5.9%	signals



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

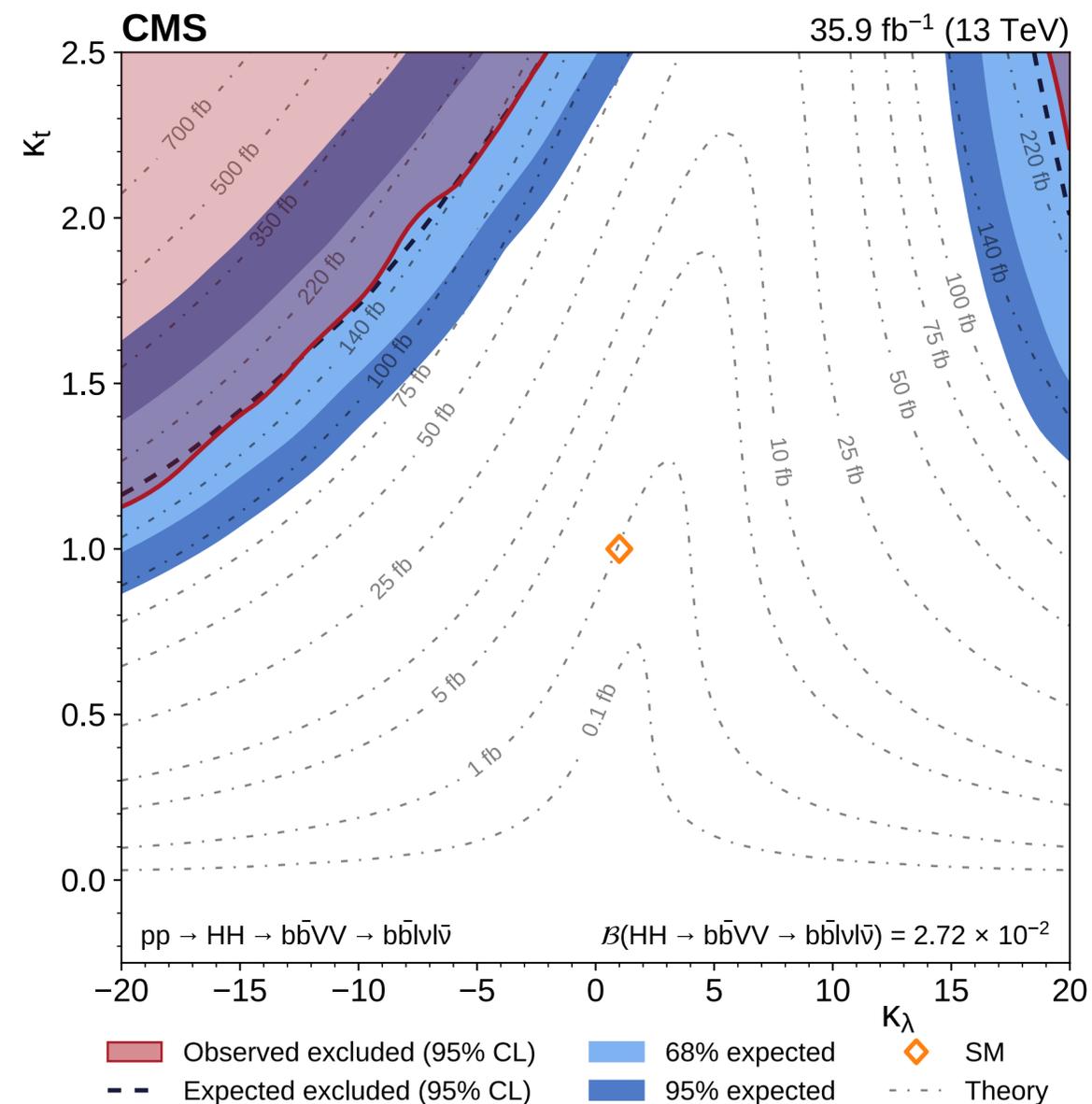
- 2 opposite sign leptons (ee , $\mu\mu$ and $e\mu+\mu e$) and 2 b-jets
- **Backgrounds:**
 - top (from MC)
 - Z+jets (from 0 b-jets data)
- **DNN** based on the event kinematic to separate signal and top background
 - Parametrized DNN as function of κ_λ and κ_t
- m_{jj} and **DNN** classifier used to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



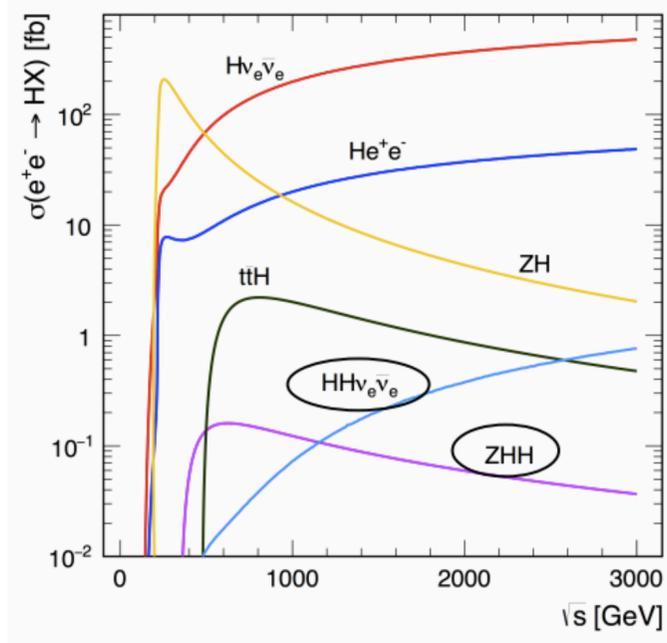
$H(VV^* \rightarrow l\nu l\nu)H(b\bar{b})$

- 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 K_λ and K_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	$m_\chi = 400$ GeV
μ_R and μ_F scales	24.2%	4.6–4.7%
Simulated sample size	<0.1%	<0.1%



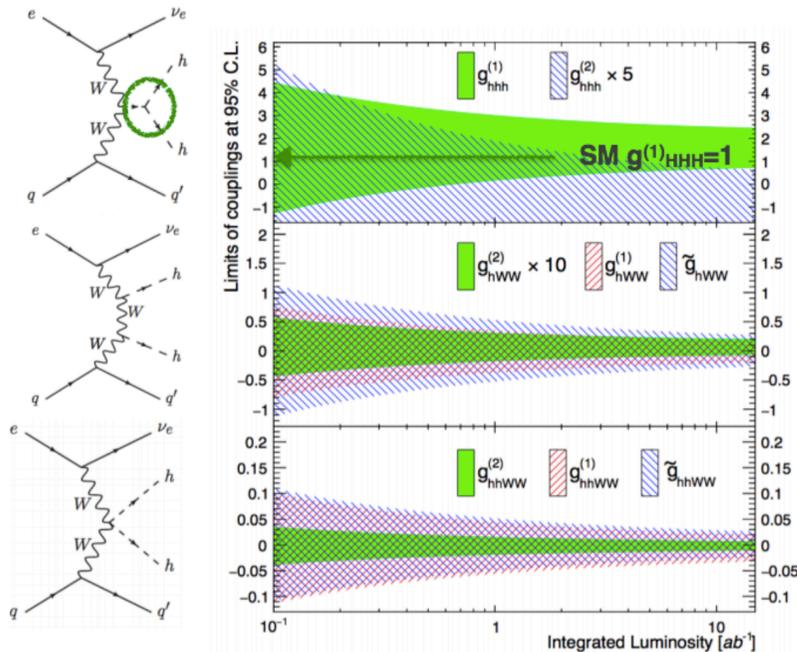
Beyond HL-LHC



Linear collider

Both **CLIC** and **ILC** allow to measure the Higgs-strahlung cross section and extract the total Higgs width in a model-independent manner

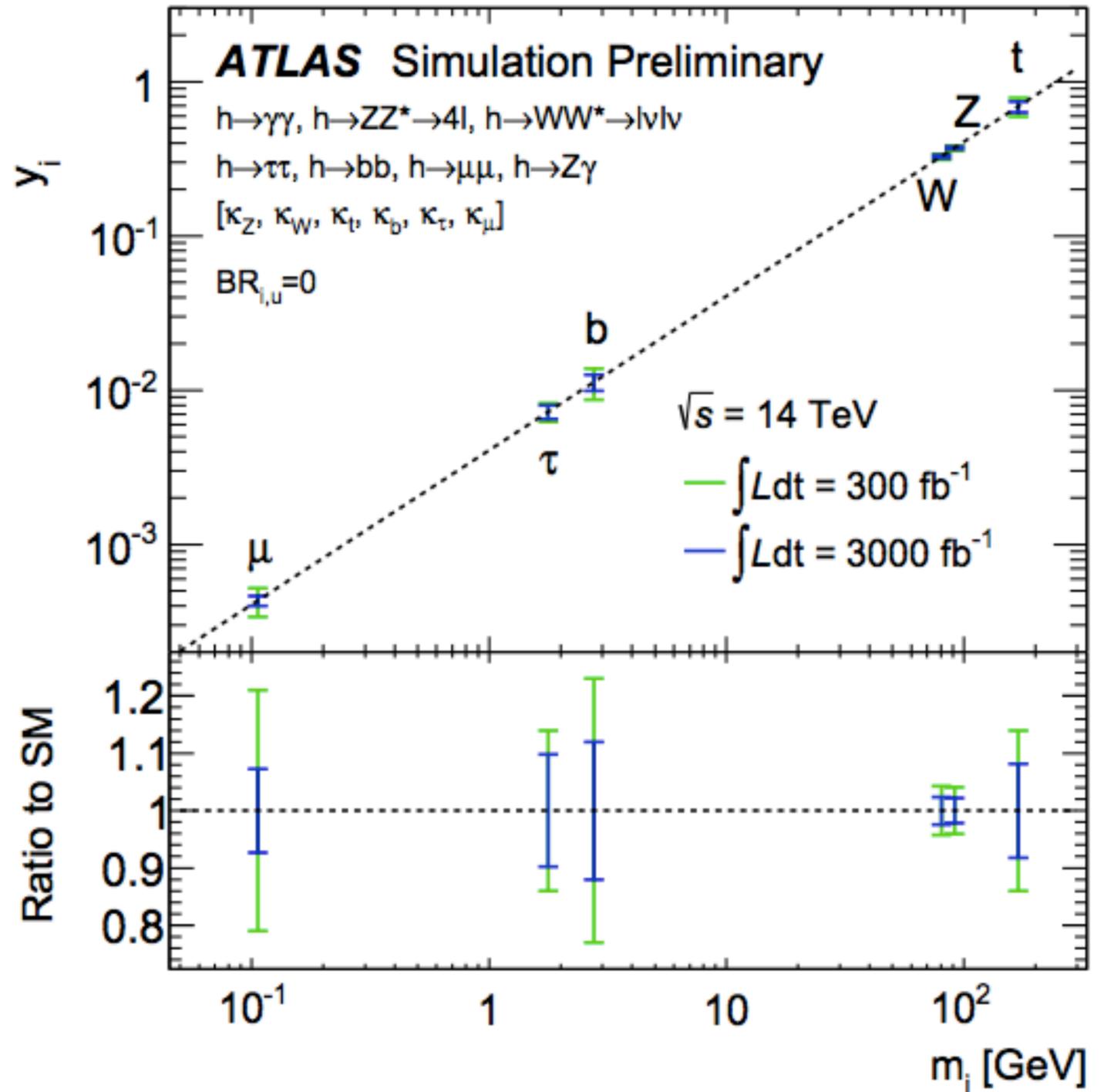
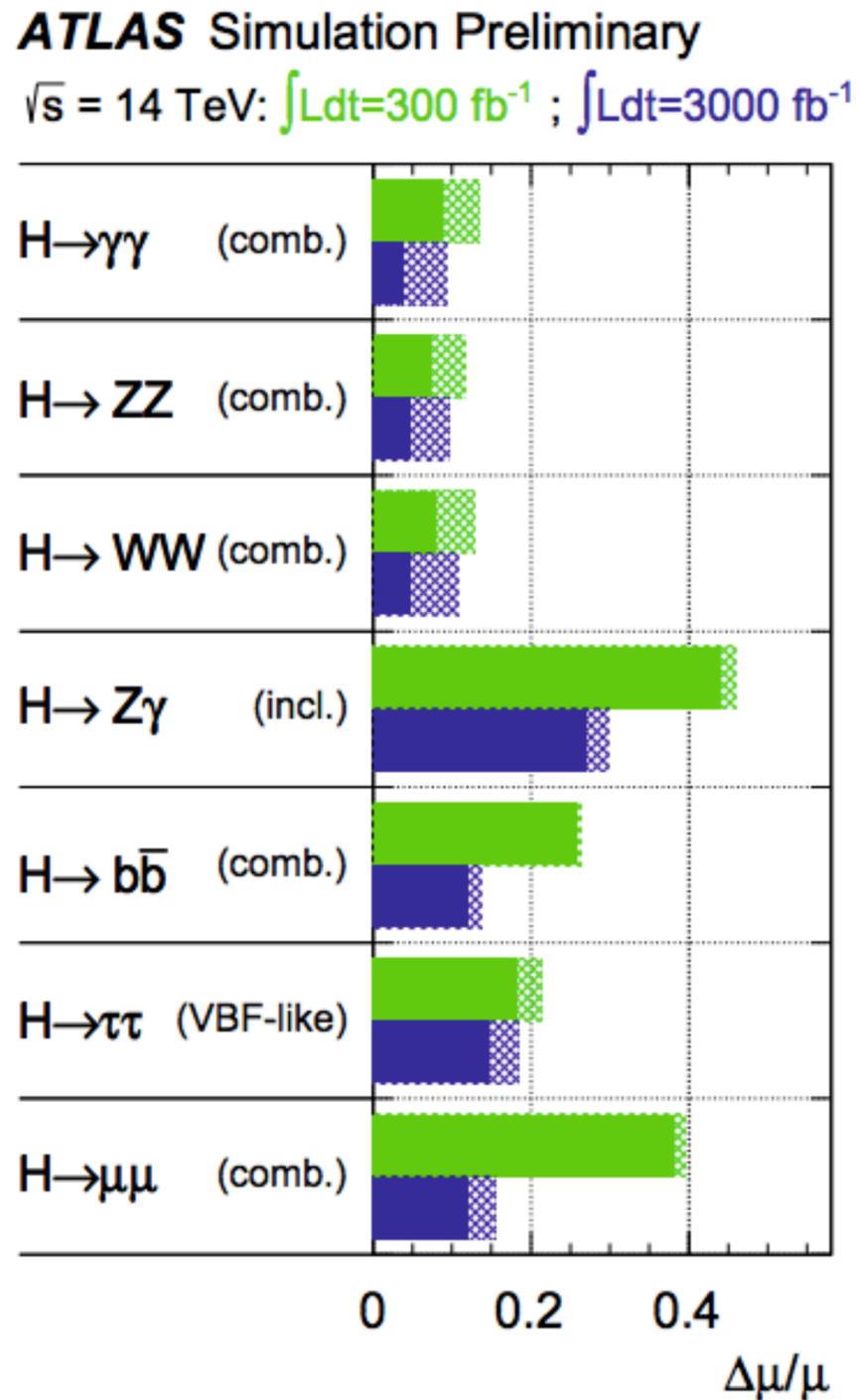
- at least 500 GeV to access to ttH and double Higgs production
- $\delta\lambda_{HHH} \sim 27\%$ @ ILC 500 GeV, 4/ab
- $\delta\lambda_{HHH} \sim 13\%$ @ CLIC 1.4 TeV, 2.5/ab + 3 TeV, 5/ab



Circular collider

- **FCC-hh**: σ (100 TeV) = $30 \times \sigma$ (14 TeV) and 7 x dataset HL-LHC
- $\delta\lambda_{HHH} \sim 5\%$ ($b\bar{b}\gamma\gamma$) / 10% ($b\bar{b}\tau\tau$) / 15% ($b\bar{b}ZZ4l$) / 30% ($b\bar{b}b\bar{b}$)
- **FCC-eh**: trilinear coupling study
- need 2 runs at $E(e^-) = 60$ and 120 GeV
- $\delta\lambda_{HHH} \sim 20\%$ in $j + 4b + MET$ (arXiv:1509.04016)

Projected sensitivity to Higgs couplings at HL-LHC



Projected sensitivity to Higgs couplings

arXiv:1506.05992

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 ($BR(\mu\mu)$, $BR(Z\gamma)$) measurements will be statistically limited at FCC-ee
- top Yukawa aiming at **1% precision**
- **Higgs self-coupling**

