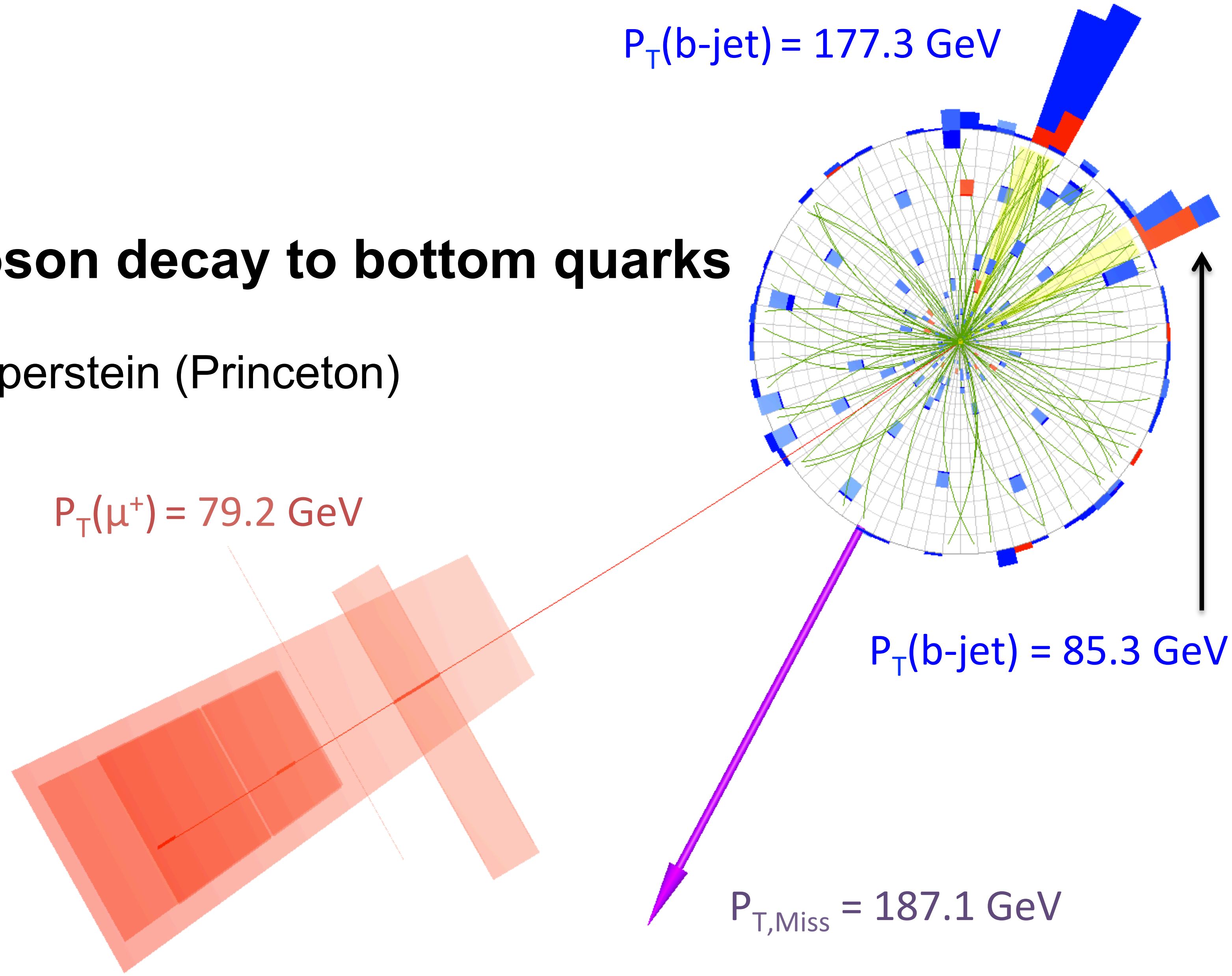
Observation of Higgs boson decay to bottom quarks

Stephane Cooperstein (Princeton)



CMS Experiment at LHC, CERN
Data recorded: Wed Oct 18 03:06:39 2017 CDT
Run/Event: 305208 / 457843574
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Phys. Rev. Lett. 121, 121801

Outline

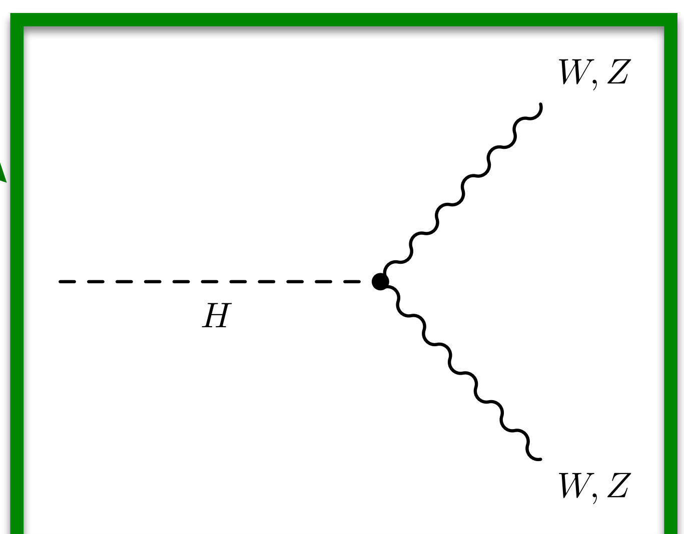
- Higgs boson at the LHC
- $H \rightarrow b\bar{b}$ analysis overview
- Observation of $H \rightarrow b\bar{b}$
- Future prospects

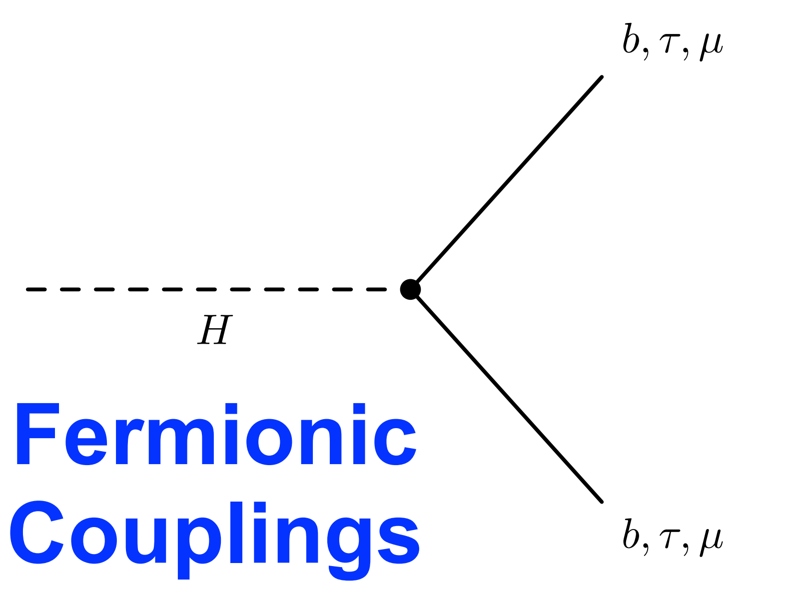
Higgs in the Standard Model

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

- In the Standard Model, Higgs mechanism provides mass to bosons and fermions.
- Two types of tree-level couplings.

Bosonic Couplings





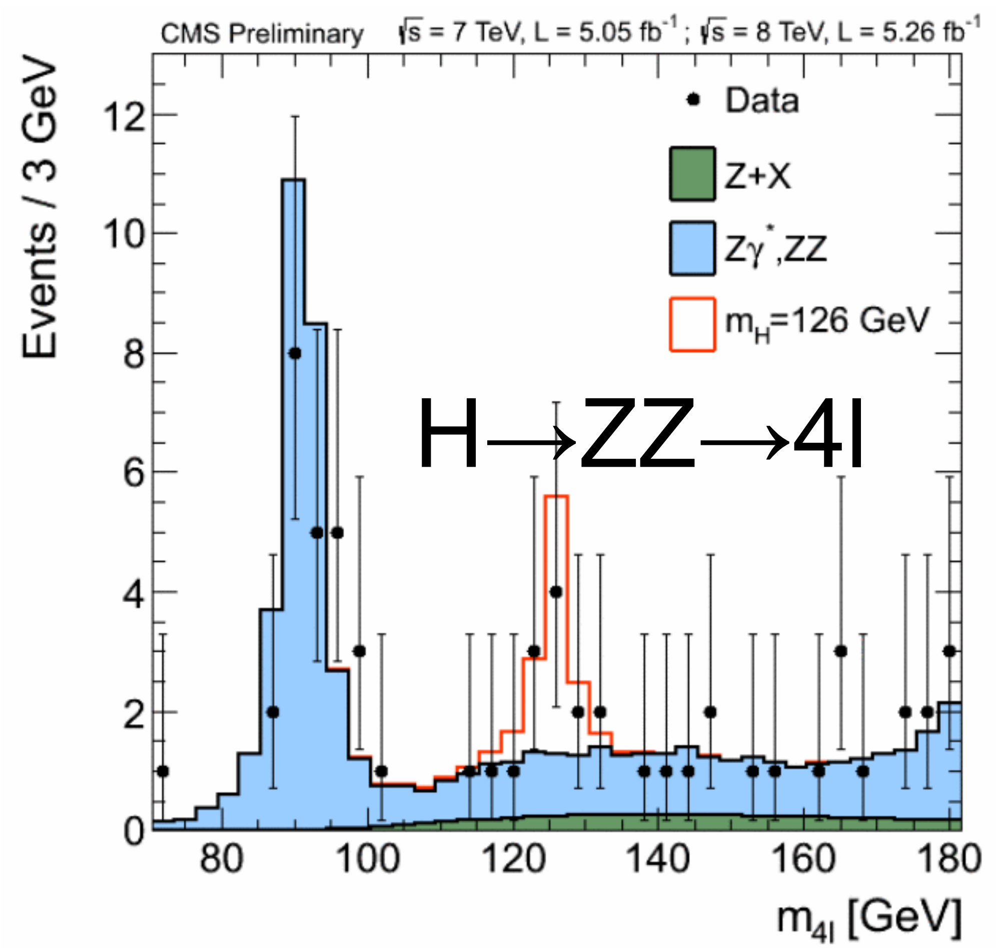
Fermionic Couplings

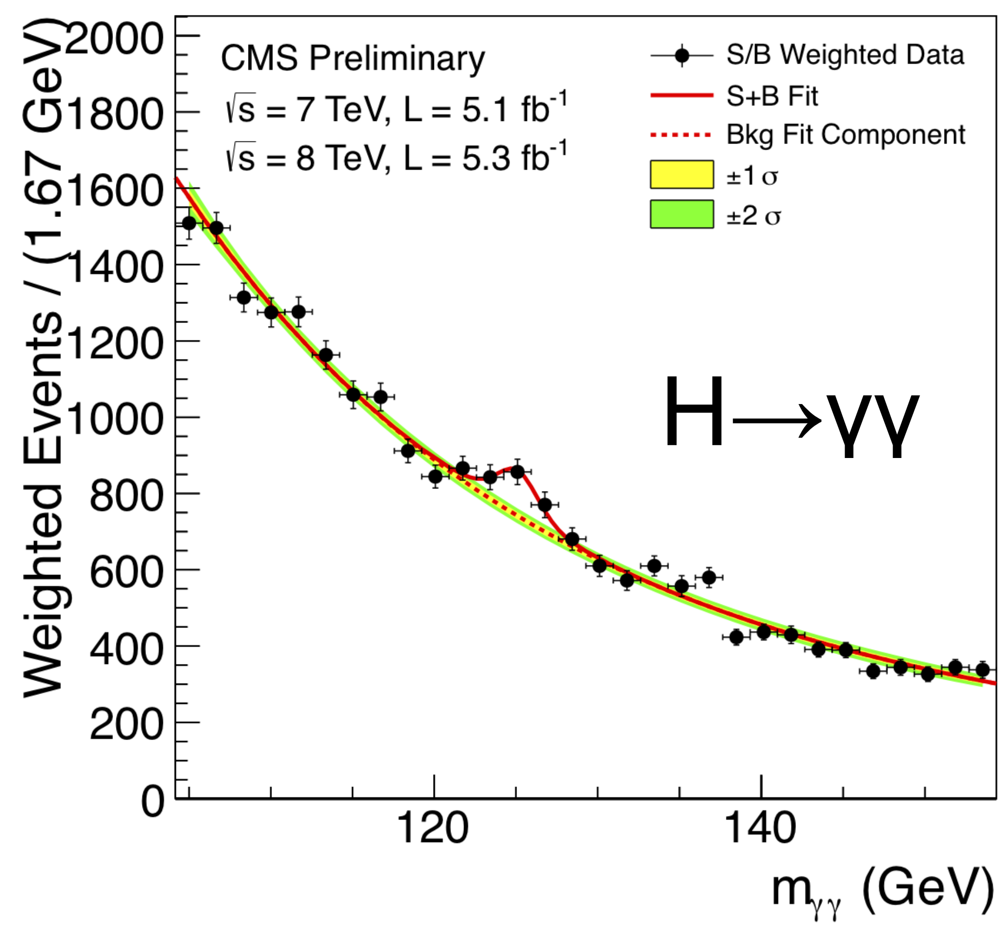
LHC Program primary goal: discover Higgs!

Photograph: Maximilien Brice © 2008 CERN

Higgs Discovery (2012)

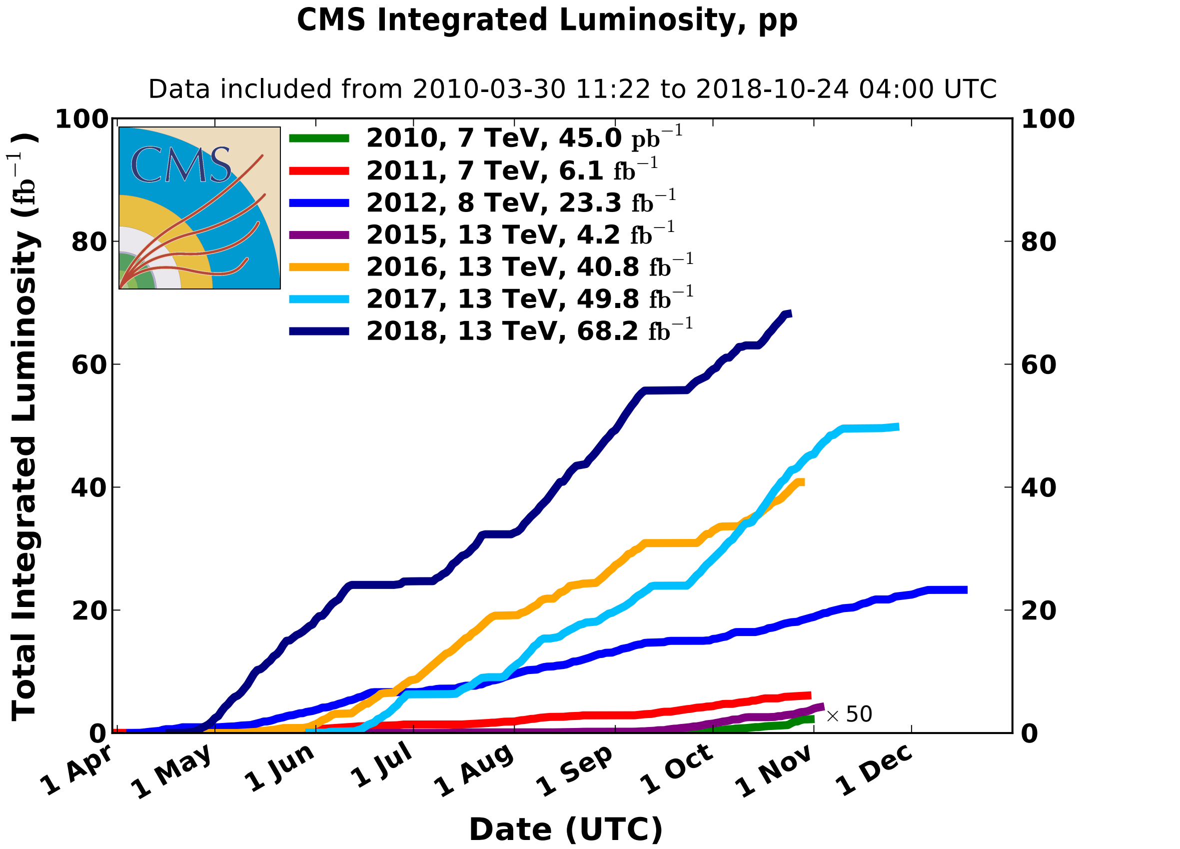
- Observation of new boson with mass 125 GeV by both ATLAS and CMS experiments.
- Relied primarily on H→ZZ and H→γγ decay channels.

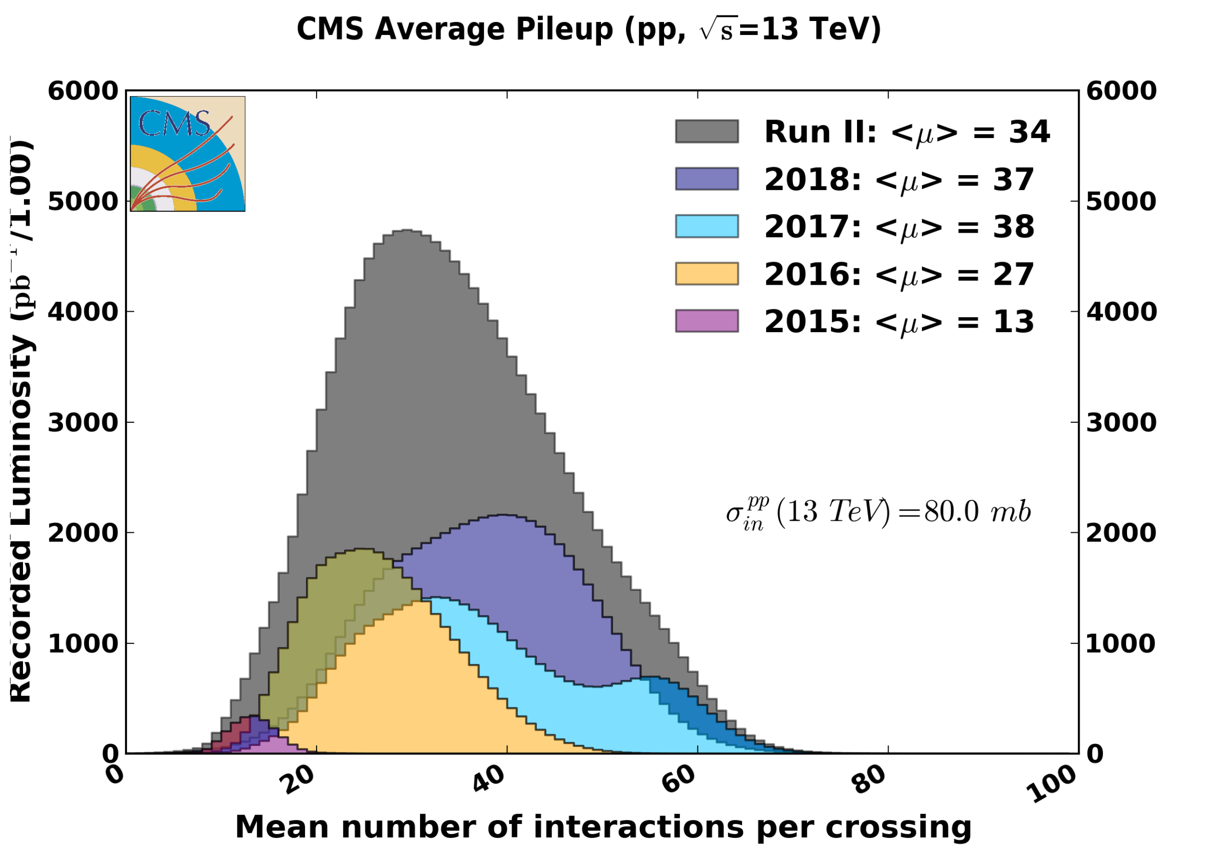




LHC Performance

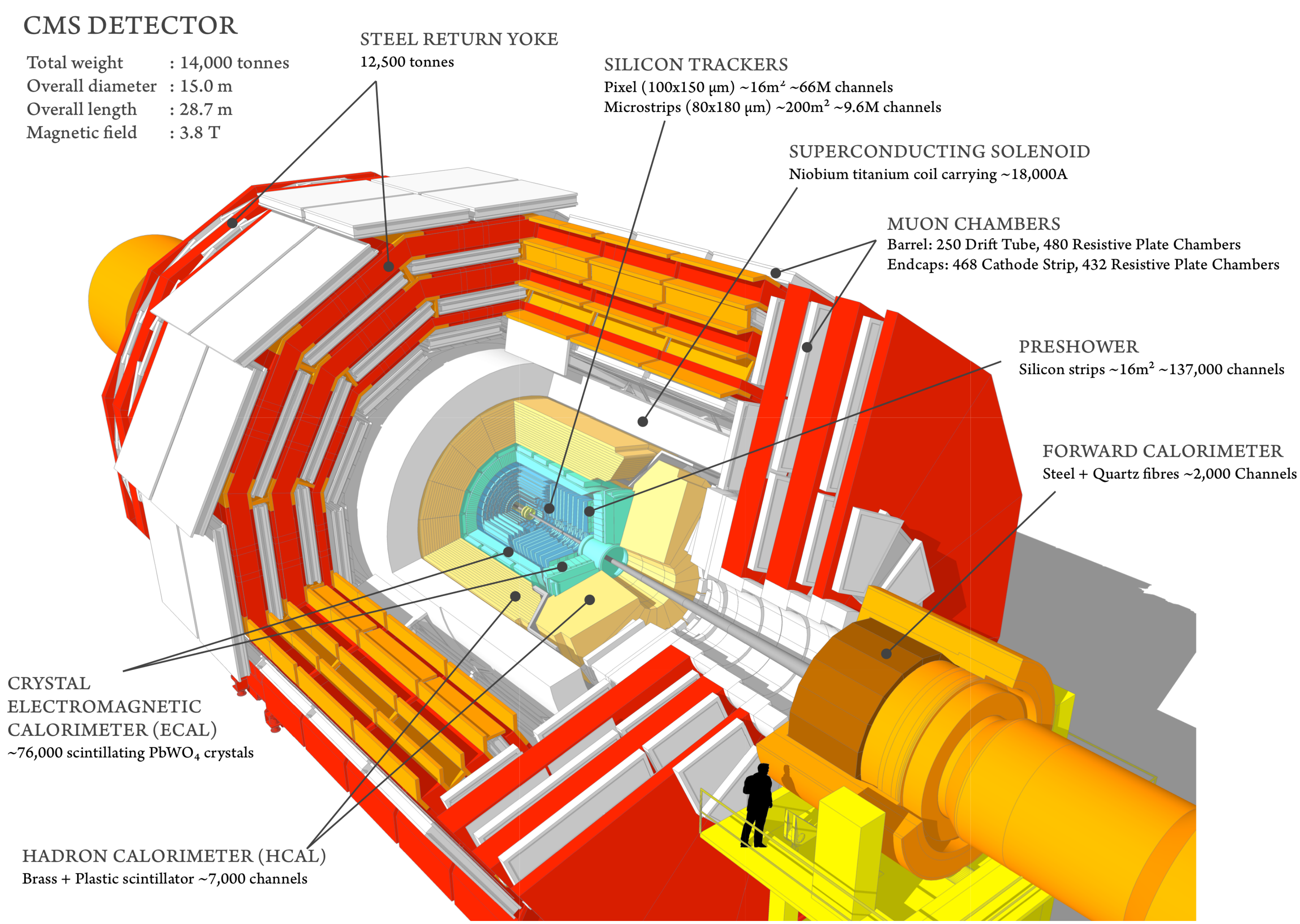
- 6 fb^{-1} of $\sqrt{s}$ = 7 TeV proton-proton collision data delivered by LHC in 2011 and 23 fb^{-1} at $\sqrt{s}$ = 8 TeV in 2012.
- 159 fb^{-1} at $\sqrt{s}$ = 13 TeV from LHC Run 2 (2015-2018).
- This seminar focuses on analysis of 42 fb^{-1} certified data collected by the CMS experiment in 2017.
- With excellent LHC performance comes challenge of high rates and number of simultaneous interactions (pile-up).





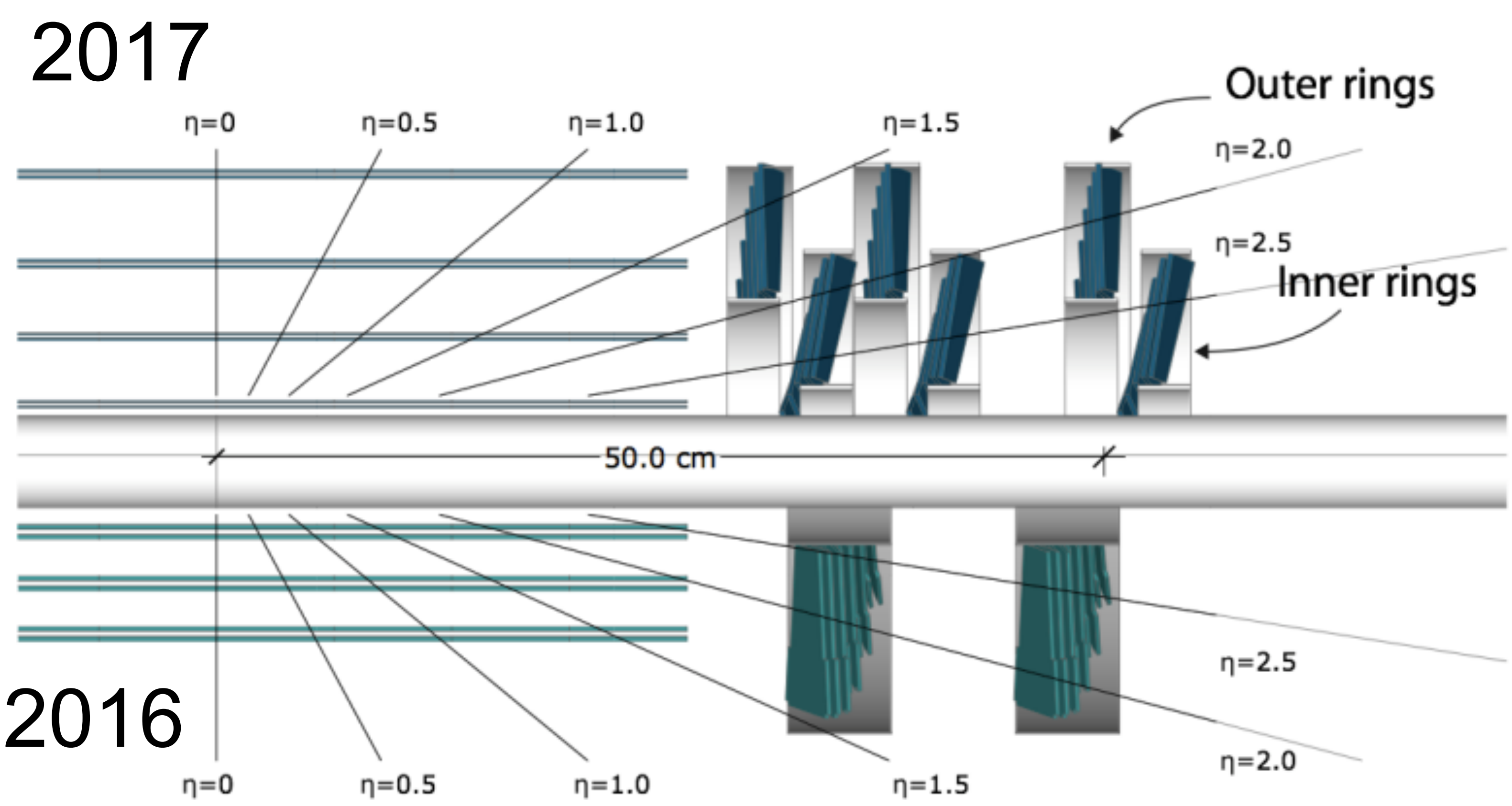
CMS Detector

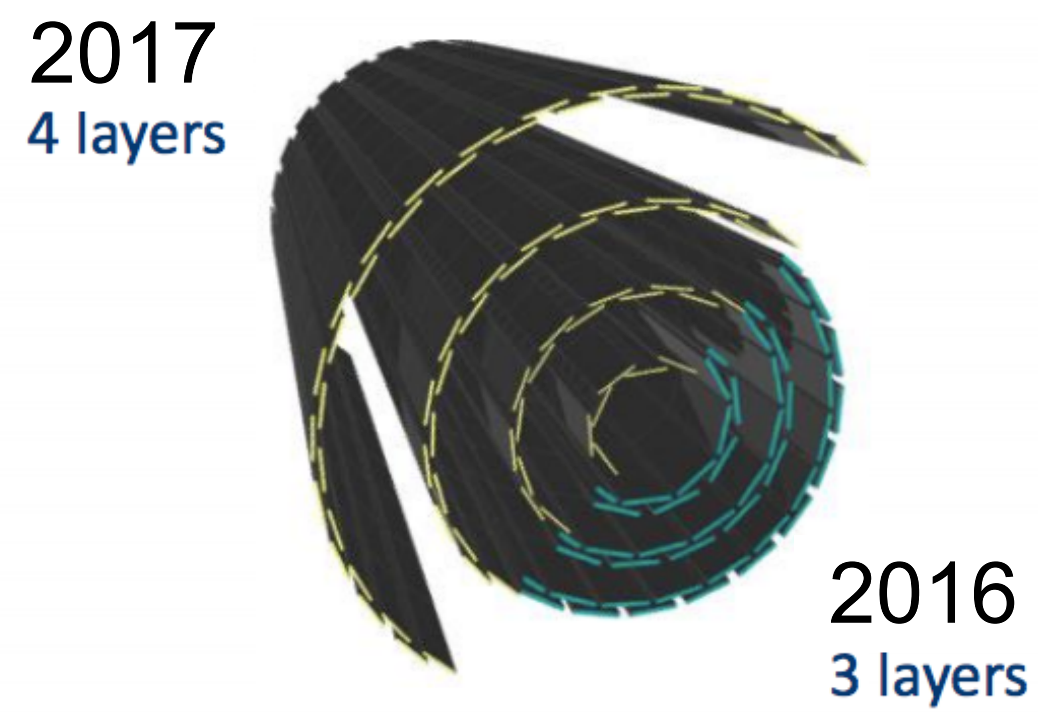
- 3.8T **superconducting solenoidal magnet** with 6m diameter.
- **Tracker System**: silicon strip+ pixel system which reconstructs the trajectories of charged particles.
- **Electromagnetic calorimeter** (ECAL): scintillator made from lead tungstate crystals sensitive to energy deposits from electrons and photons.
- **Hadronic calorimeter** (HCAL): brass scintillator sensitive to energy deposits from hadrons, mainly pions and kaons.
- Gas ionization chambers for **muon detection**.



CMS Pixel Detector Phase 1 Upgrade

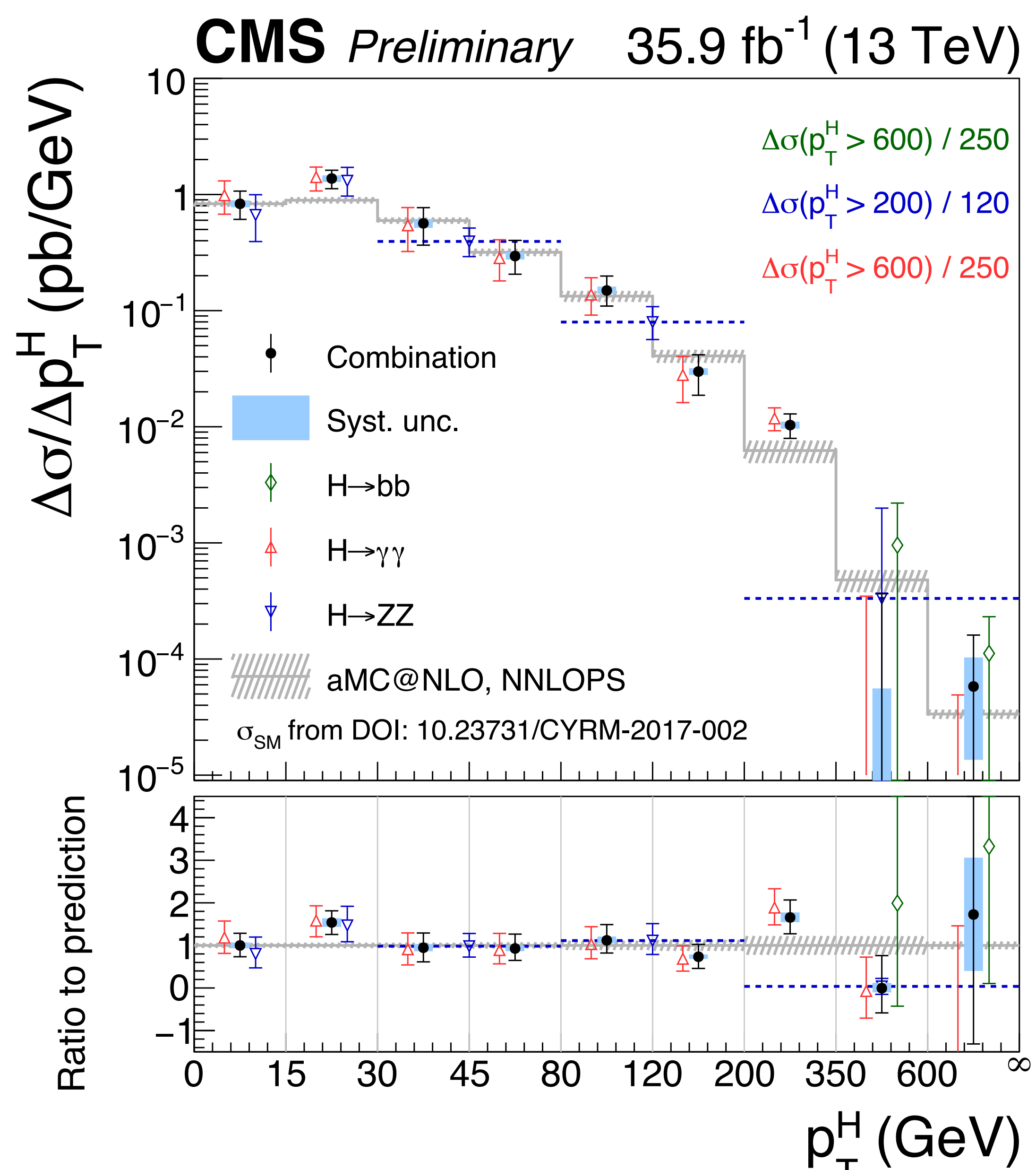
- Pixel detector upgraded for 2017 data taking.
- Additional layer with first tracking measurement closer to beam pipe.
- Improvements in tracking efficiency, vertex resolution, and b-tagging efficiency.



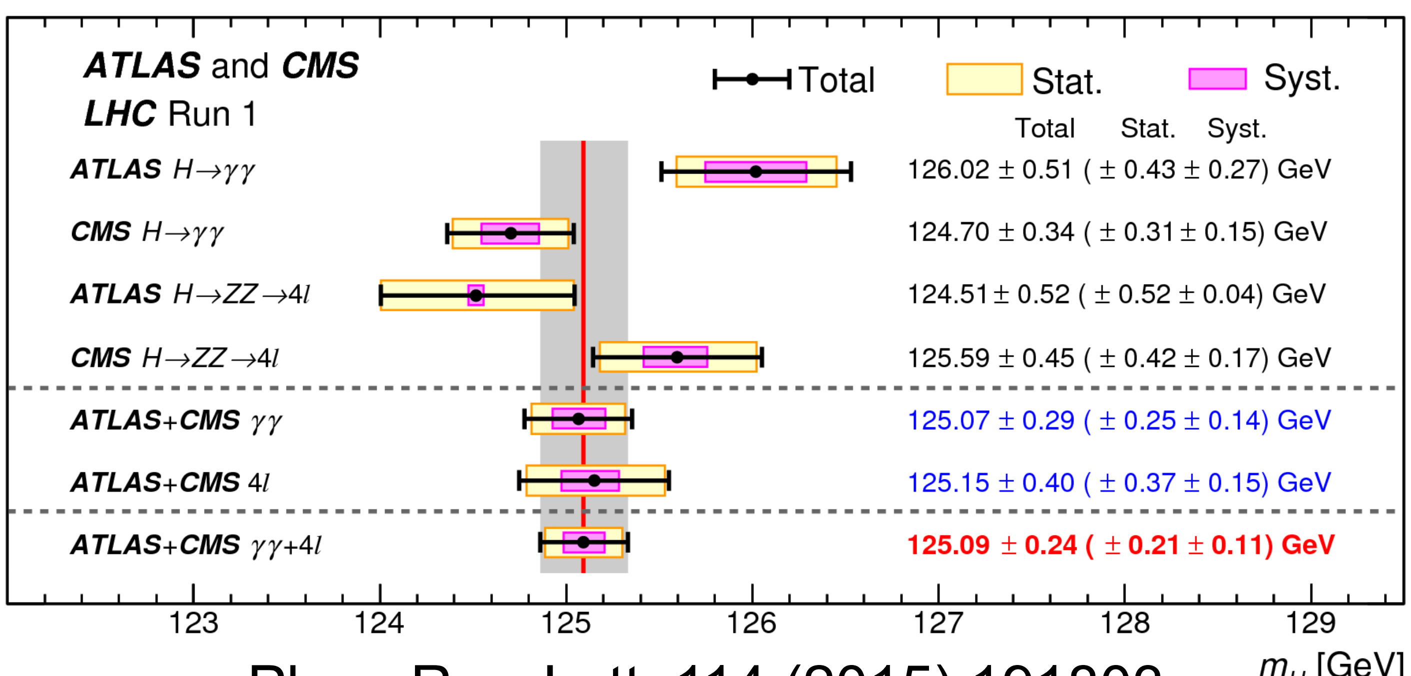


- Higgs precision measurement era:
  - mass measured to nearly per-mille, differential/fiducial σ, spin/CP (all consistent so far with SM Higgs boson).
  - rely primarily on H→γγ and H→ZZ decays.

- Measuring Yukawa couplings is experimentally more difficult but equally important in validating standard model description of Higgs sector.



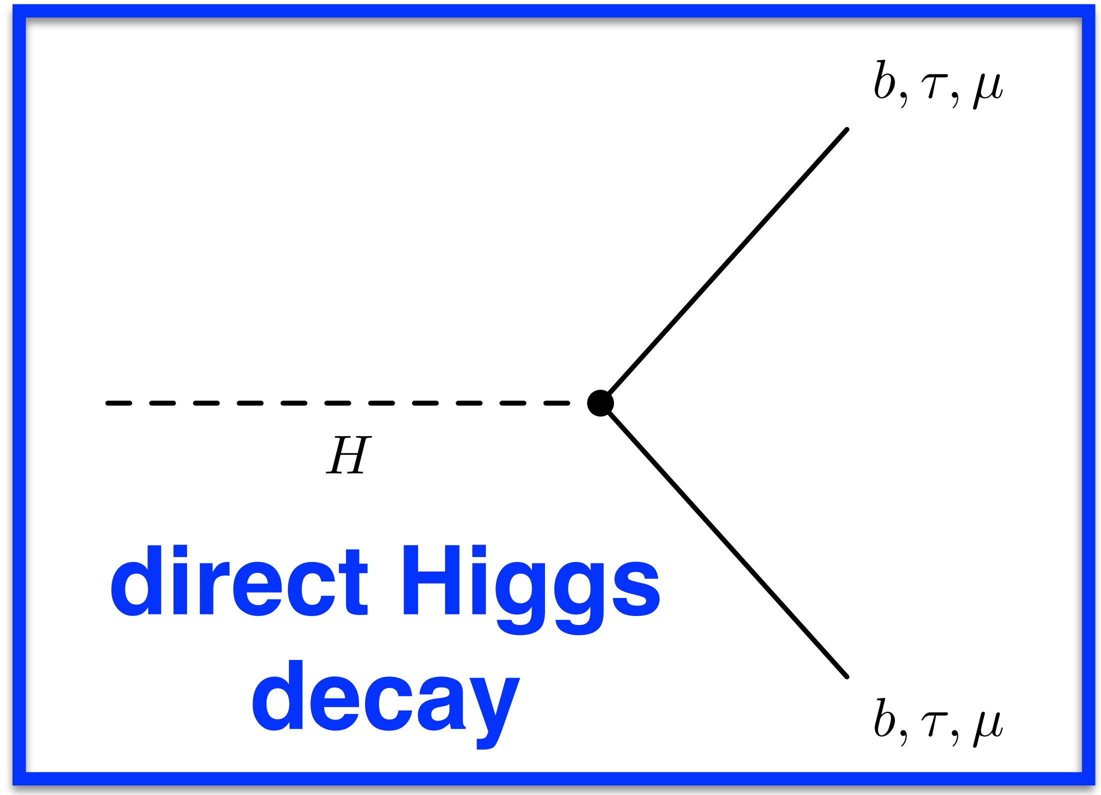
CMS-HIG-17-031
Submitted to Eur. Phys. J. C



Phys. Rev. Lett. 114 (2015) 191803

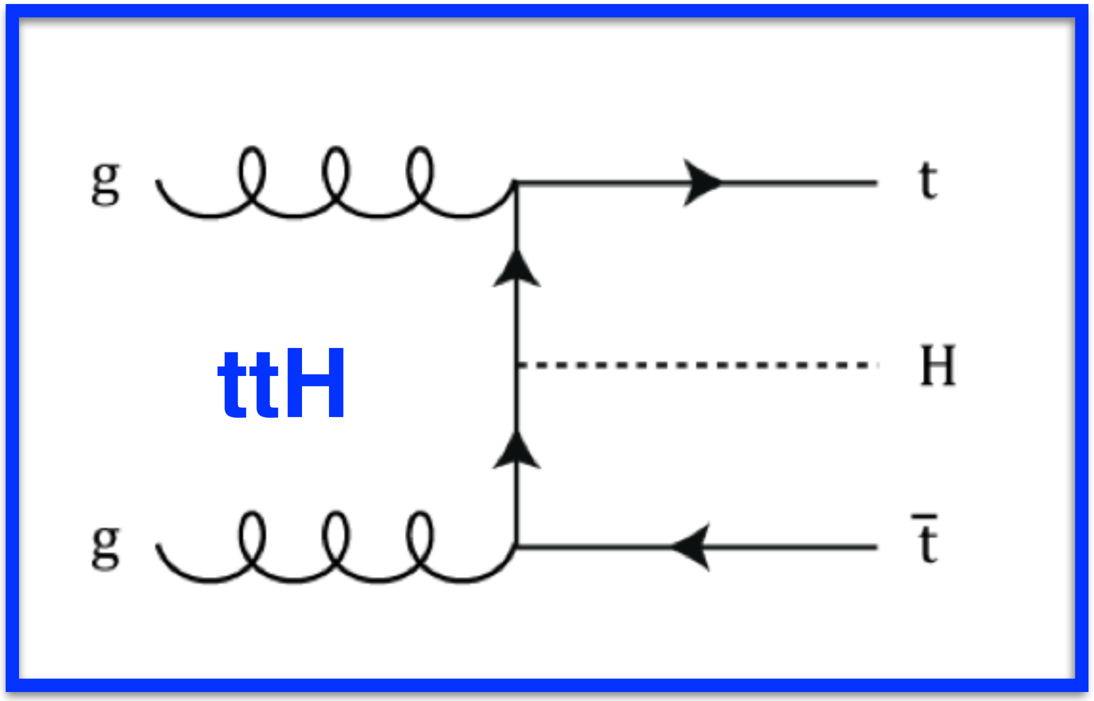
We can extract **Yukawa coupling directly from Higgs decays to fermions**:

- **$H \rightarrow b\bar{b}$:** (BR = 58%, large background)
- **$H \rightarrow \tau^+\tau^-$:** (BR = 6% but cleaner signature)
- **$H \rightarrow \mu^+\mu^-$:** (BR = 0.02%)

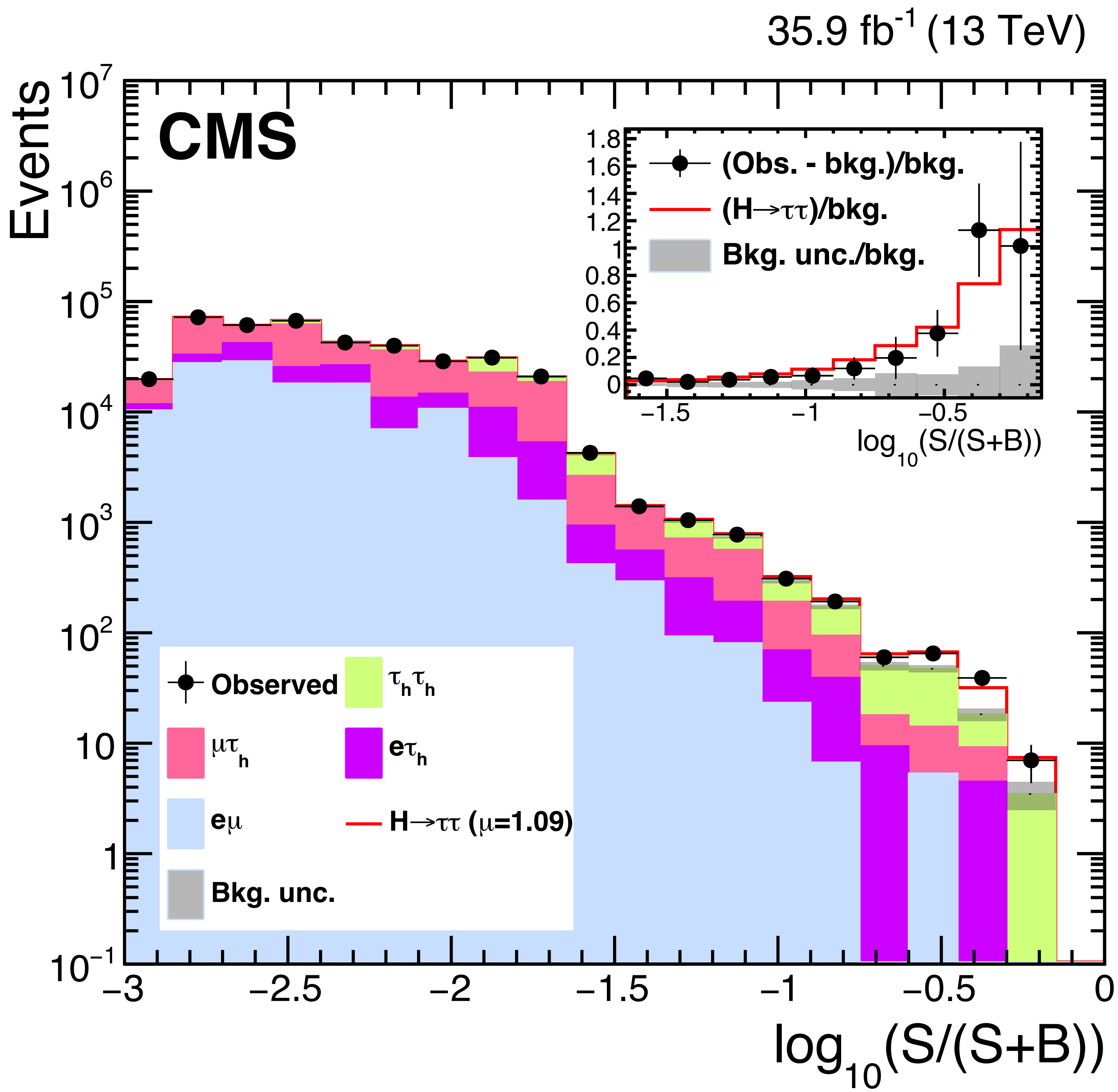


We can also **directly probe Y_t by measuring the ttH** production cross section.

- Combine ttH measurement among various Higgs decay modes.



- Higgs fermionic decay channel with best combination of selection efficiency and background rejection.
- Primary challenges: mass resolution, trigger.
- **First direct experimental observation of a Yukawa coupling:**
  - With 7+8 TeV data by combining ATLAS + CMS measurements.
  - Single experiment observations with 13 TeV data.



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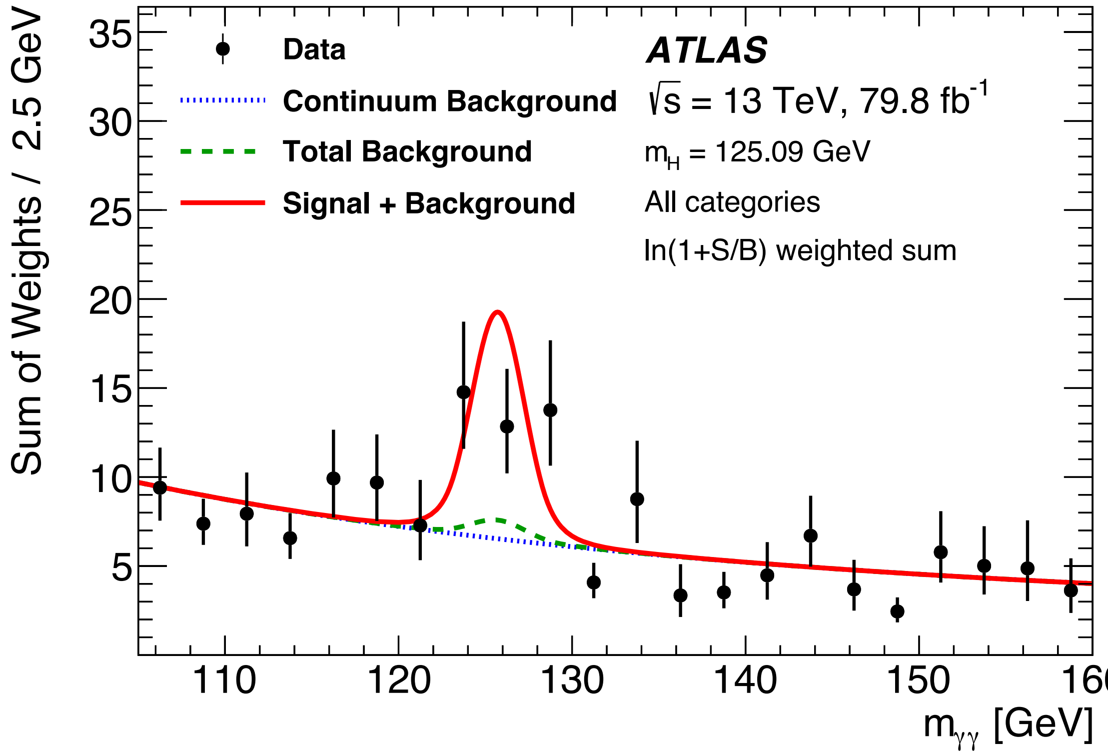
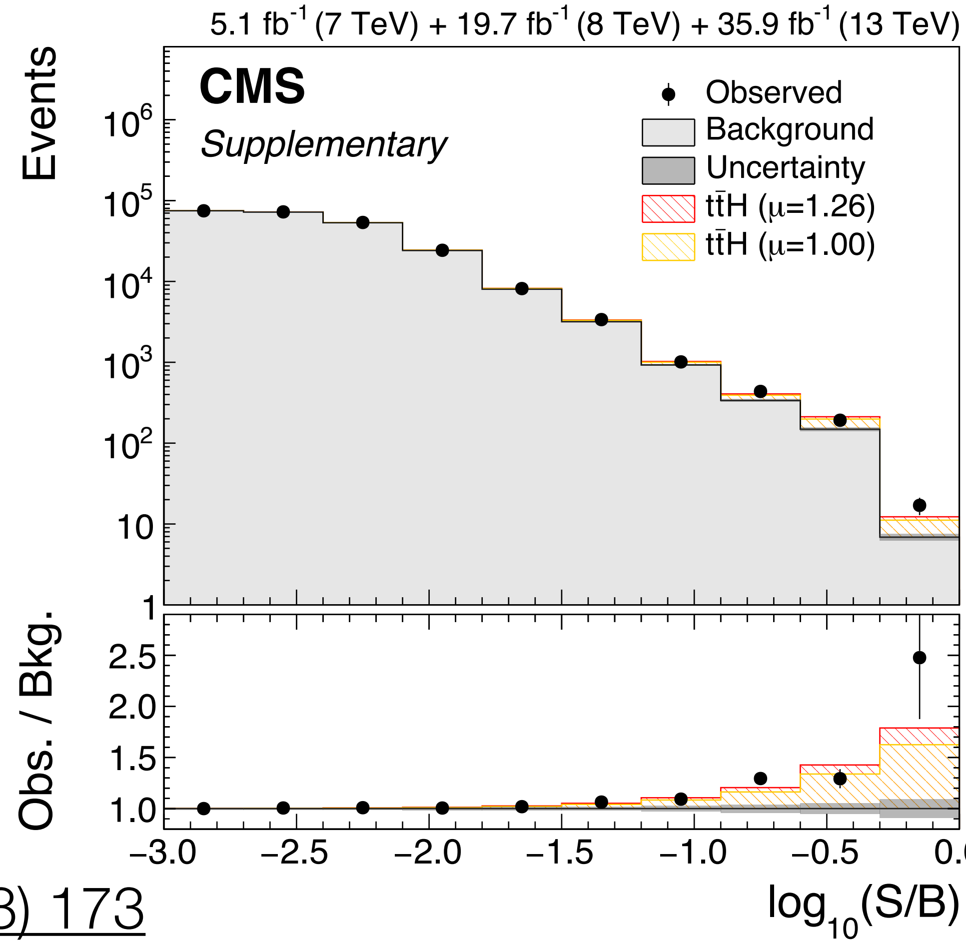
ttH Observation

- Observation of ttH production by both ATLAS and CMS experiments this year.
- Combination of multiple Higgs decay channels ($b\bar{b}$, WW*,ττ, γγ, ZZ*).
- Direct confirmation of Yukawa coupling to top quarks.





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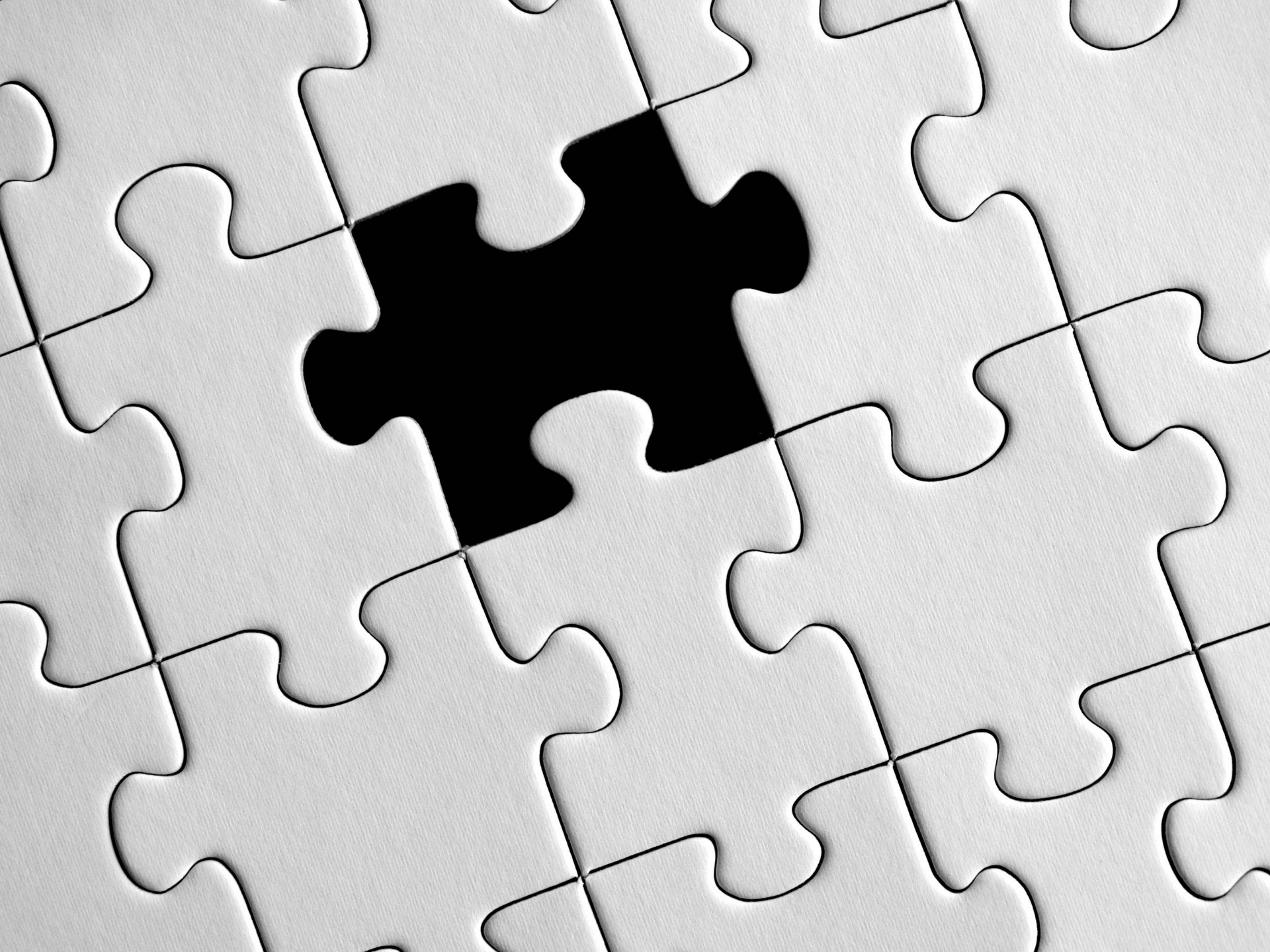
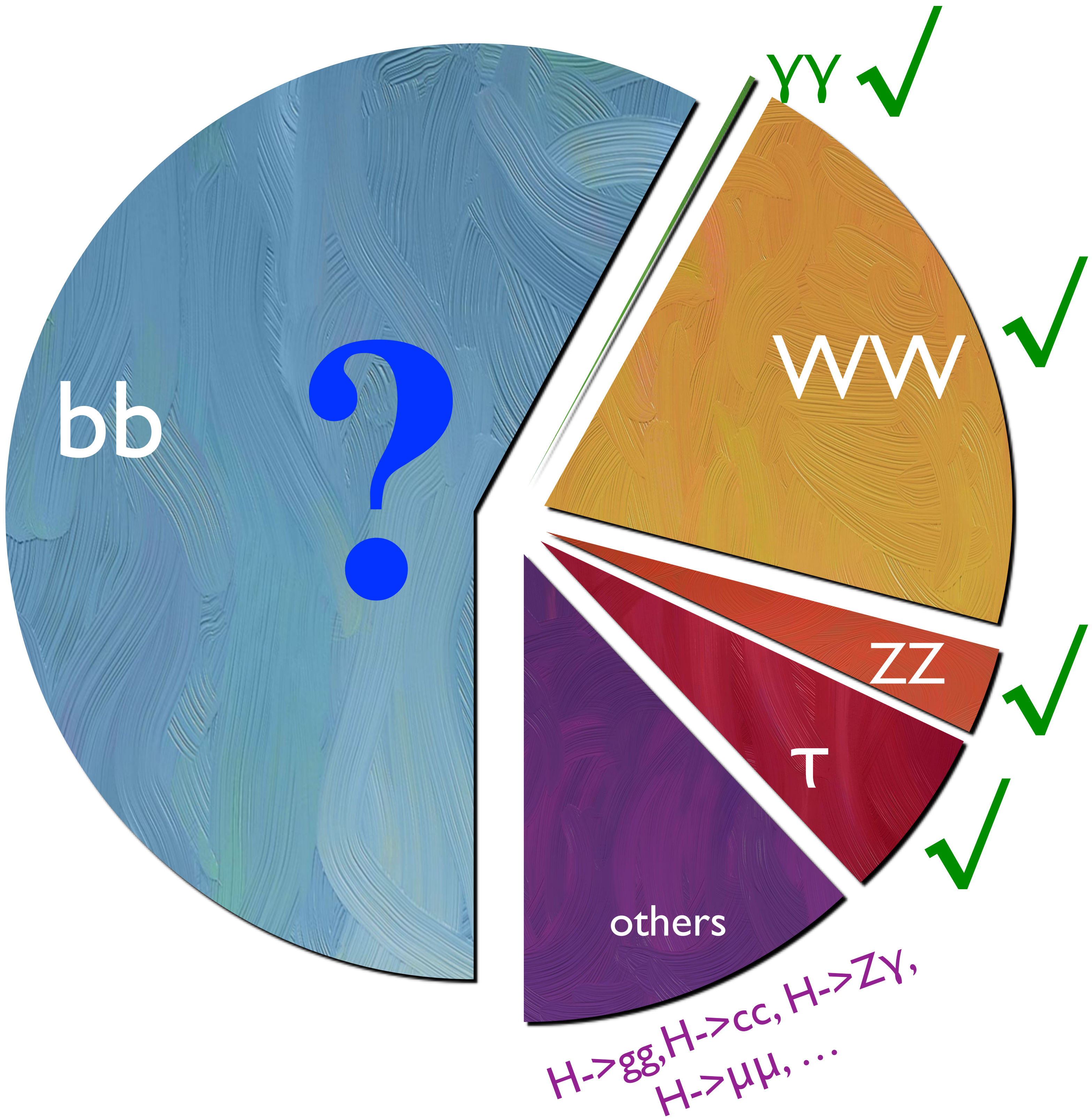


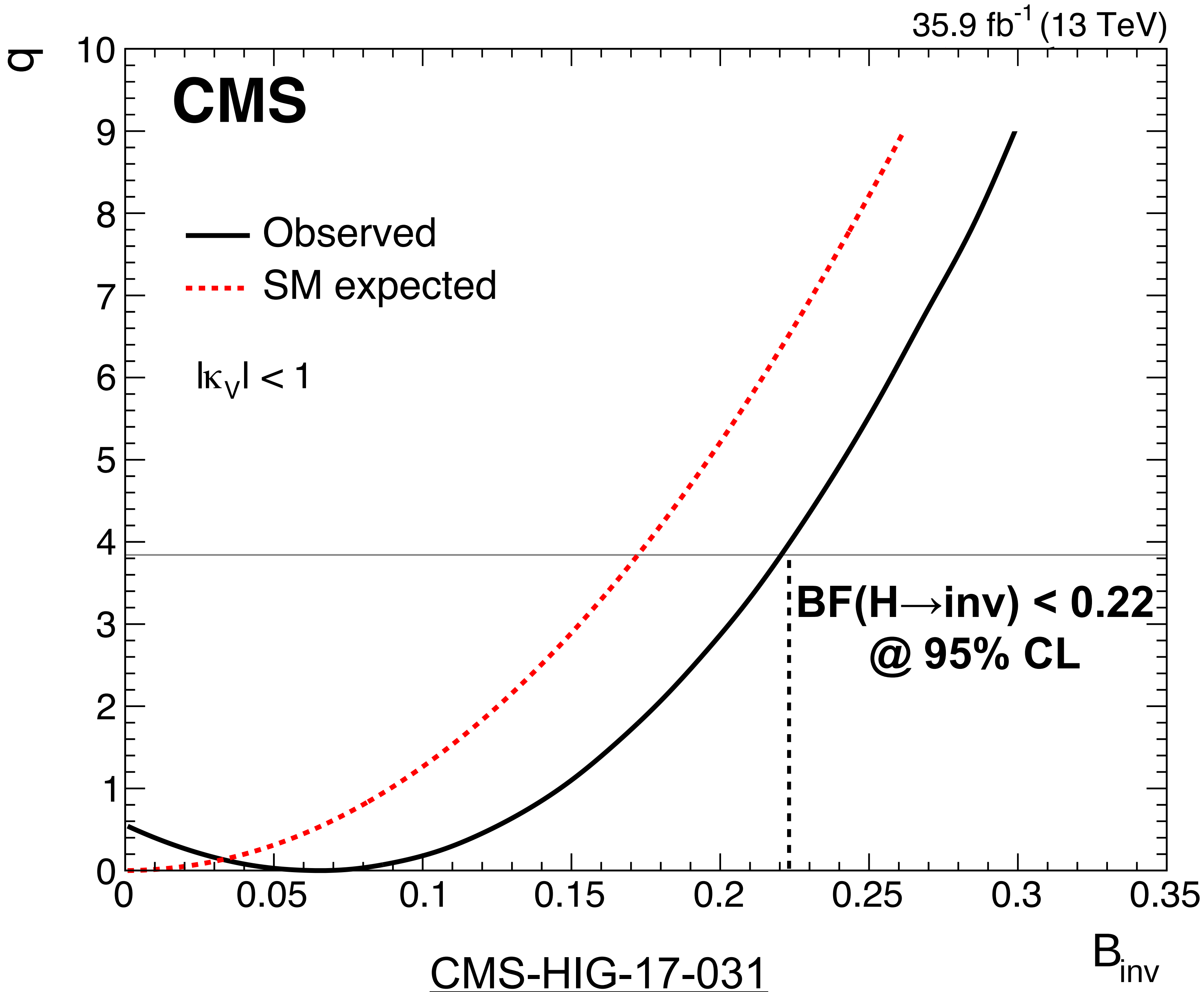
- More than half (58%) of Higgs bosons produced at the LHC decay to $b\bar{b}$!
- Unique final state to measure Higgs boson coupling to down-type quarks.
- Last third generation Yukawa coupling yet to be observed.

Observed:



Limit on BF(H→invisible)

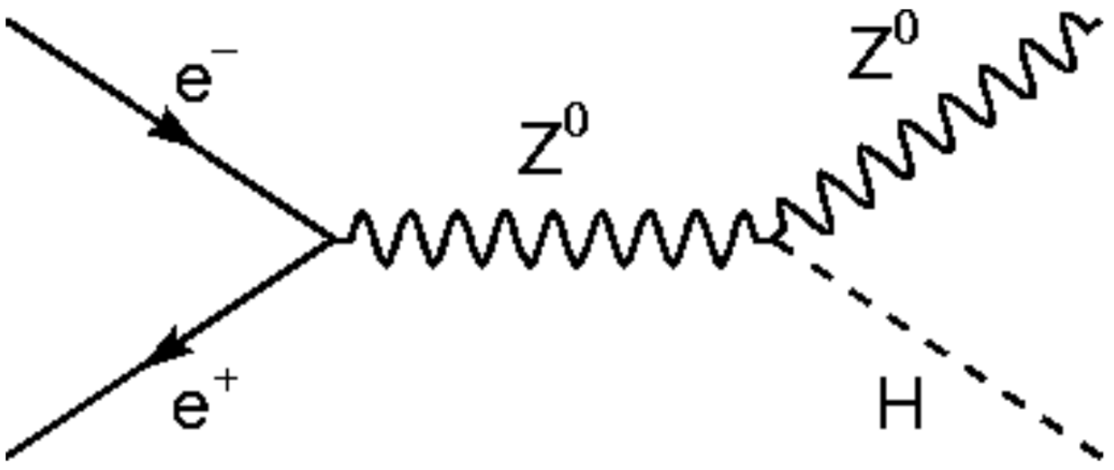
- Large uncertainty on BF($H \to b\bar{b}$) leaves room for BSM decays, even if all other channels are precisely measured!

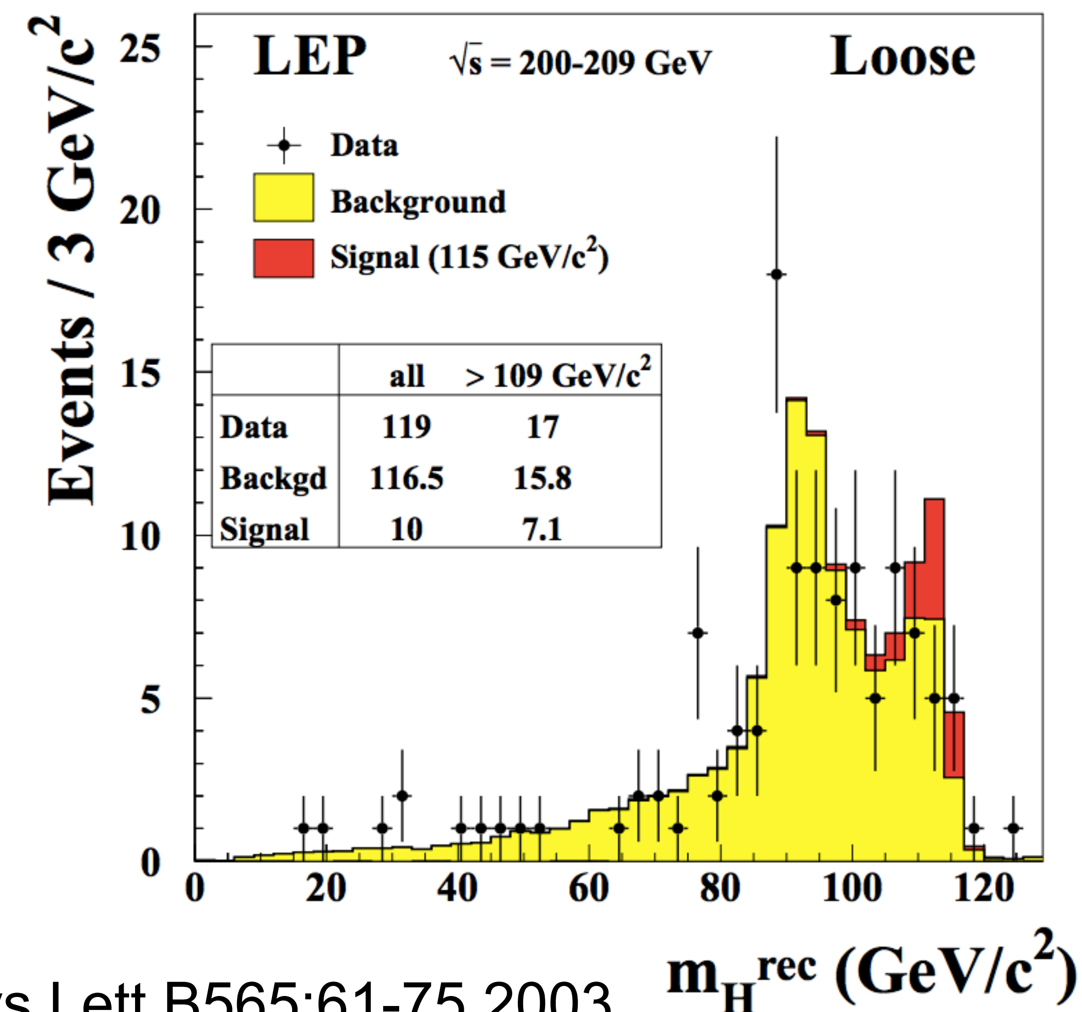


CMS-HIG-17-031
Submitted to Eur. Phys. J. C

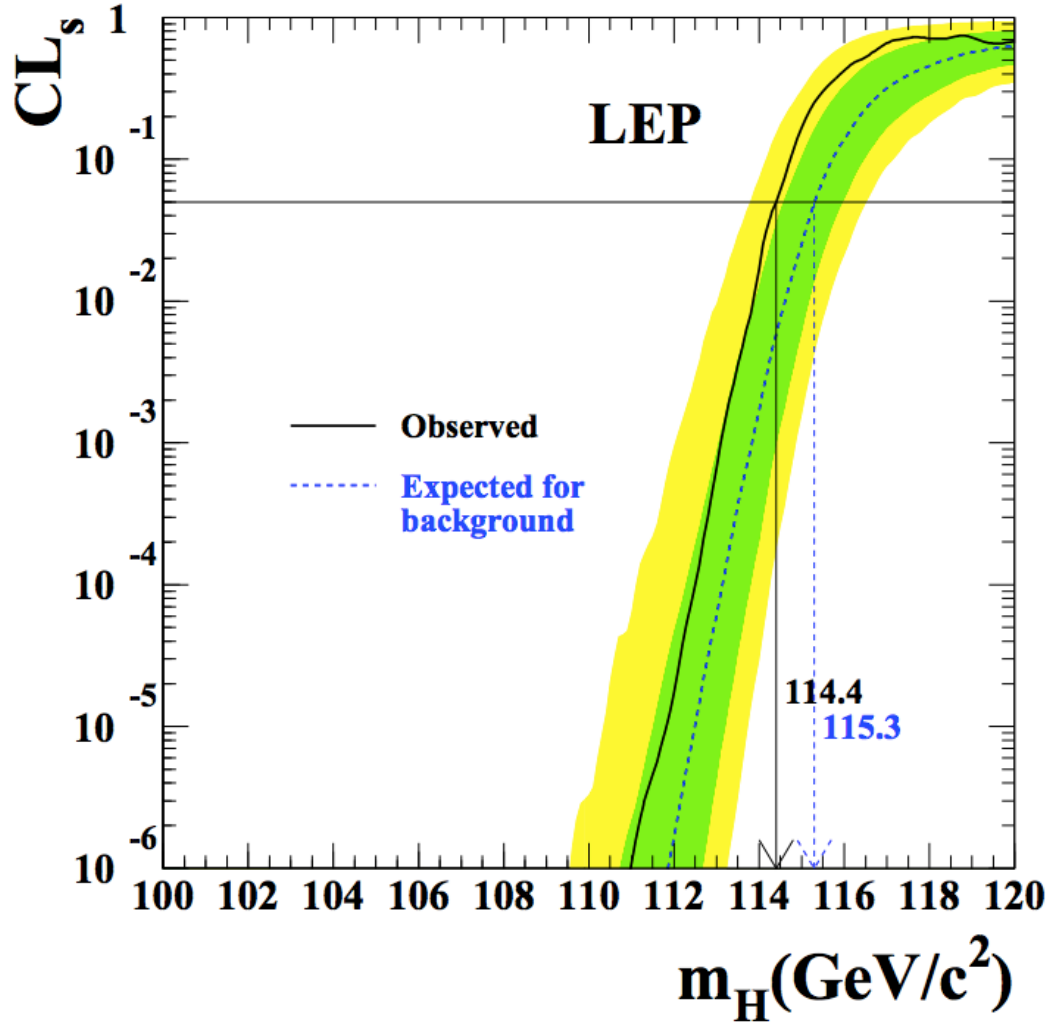
H→$b\bar{b}$ Legacy: LEP

- VH, H→$b\bar{b}$ dominant search channel at LEP.
- m_H > 114.4 GeV at 95% confidence level.





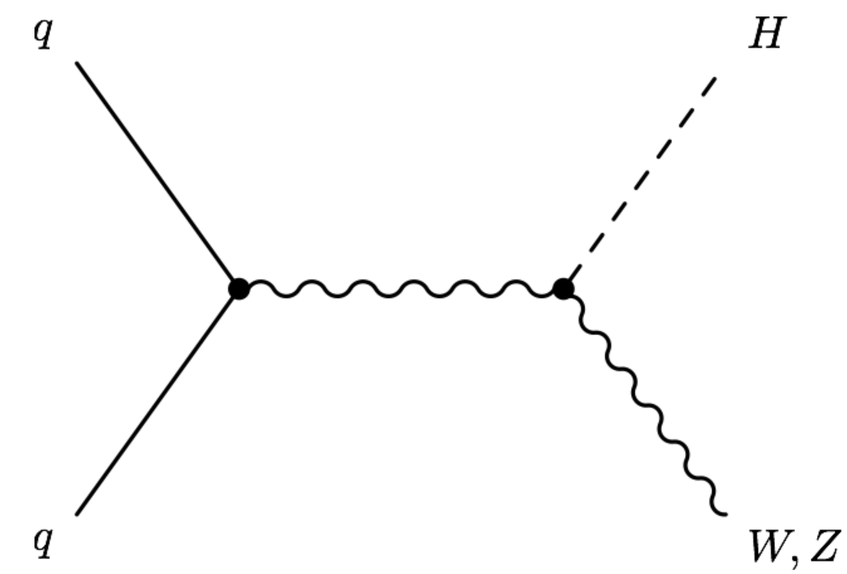
	all	> 109 GeV/c²
Data	119	17
Backgd	116.5	15.8
Signal	10	7.1

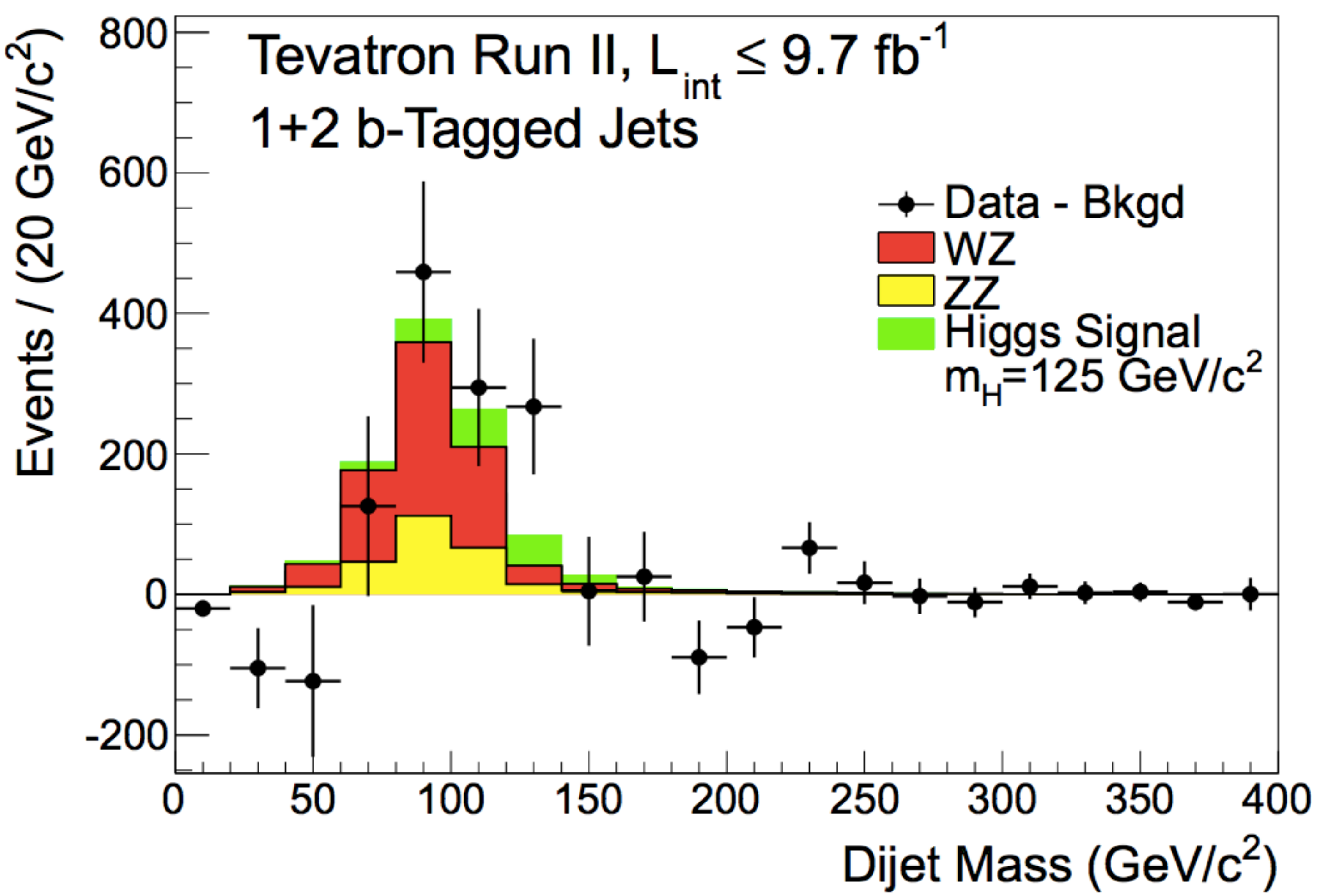


Phys.Lett.B565:61-75,2003

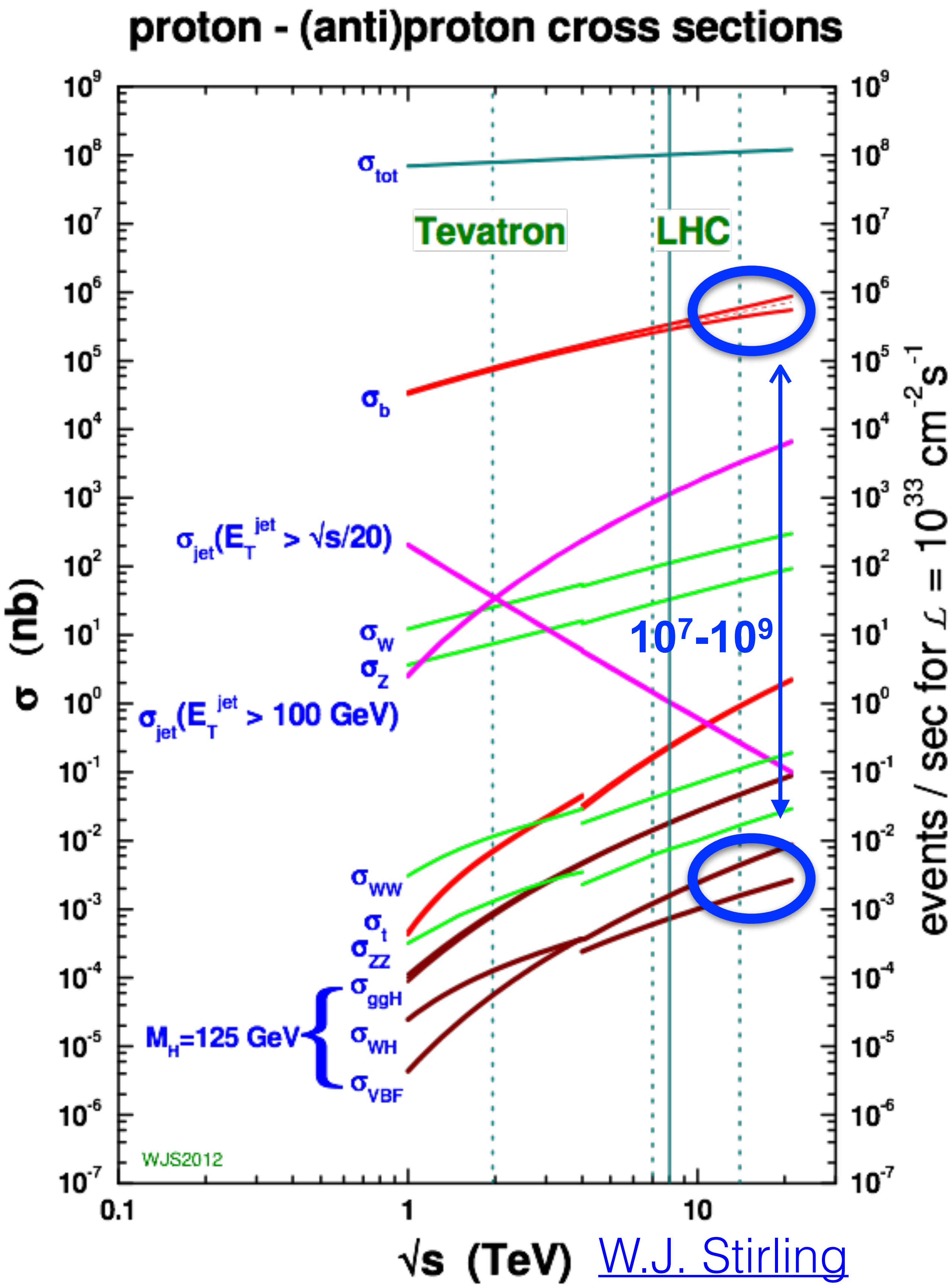
- VH, $H \to b\bar{b}$ most sensitive channel at Tevatron for low mass Higgs.

- CDF + D0 combination:
  - Local significance of 3.3σ @ m_H=135 GeV, global significance of 3.1σ after look elsewhere effect.
  - 2.8σ @ m_H = 125 GeV (1.5σ expected)





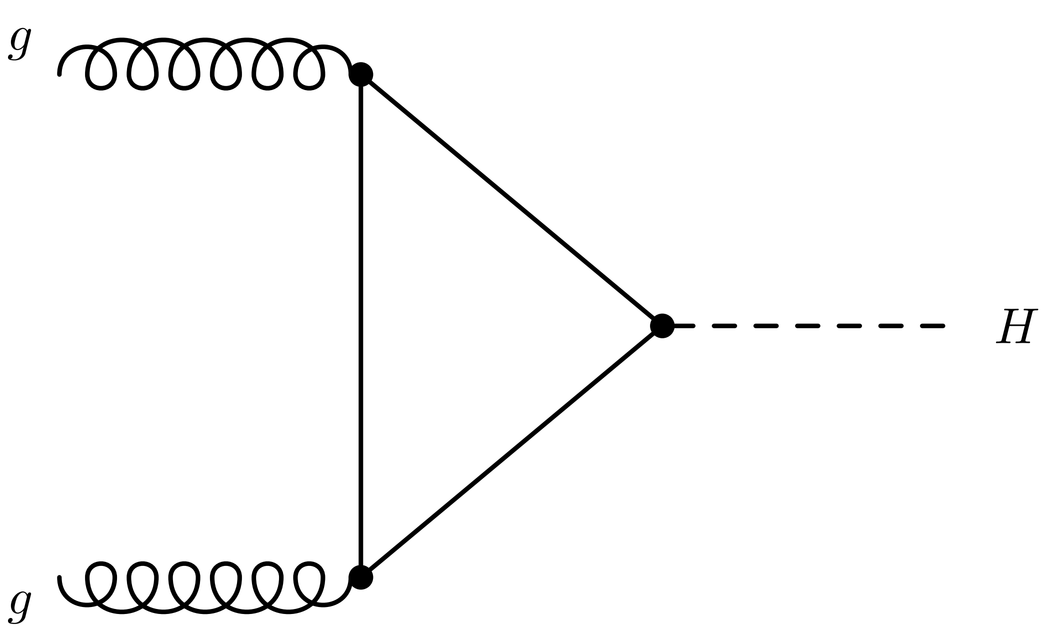
Phys. Rev. Lett. 109, 071804 (2012)



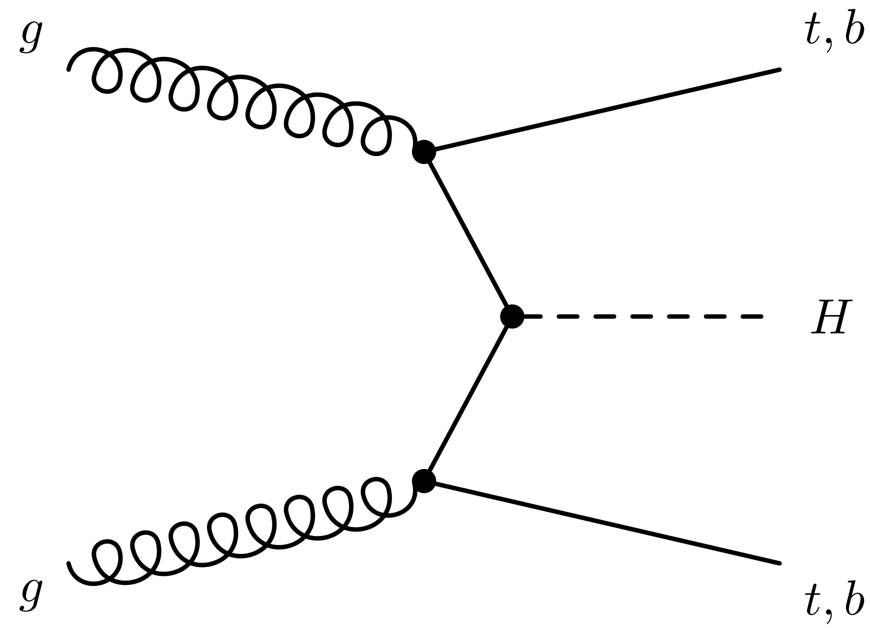
W.J. Stirling

- Events with b-jets produced abundantly at LHC.
- Experimental resolution on M_H order of magnitude worse than Higgs discovery channels.
- Requiring only two resolved b-jets and searching for M(b$\bar{b}$) peak extremely difficult at LHC.
  - Recently CMS was the first to try do so by requiring p_T(H) > 450 GeV and using jet substructure [PhysRevLett.120.071802].

Higgs Production at the LHC

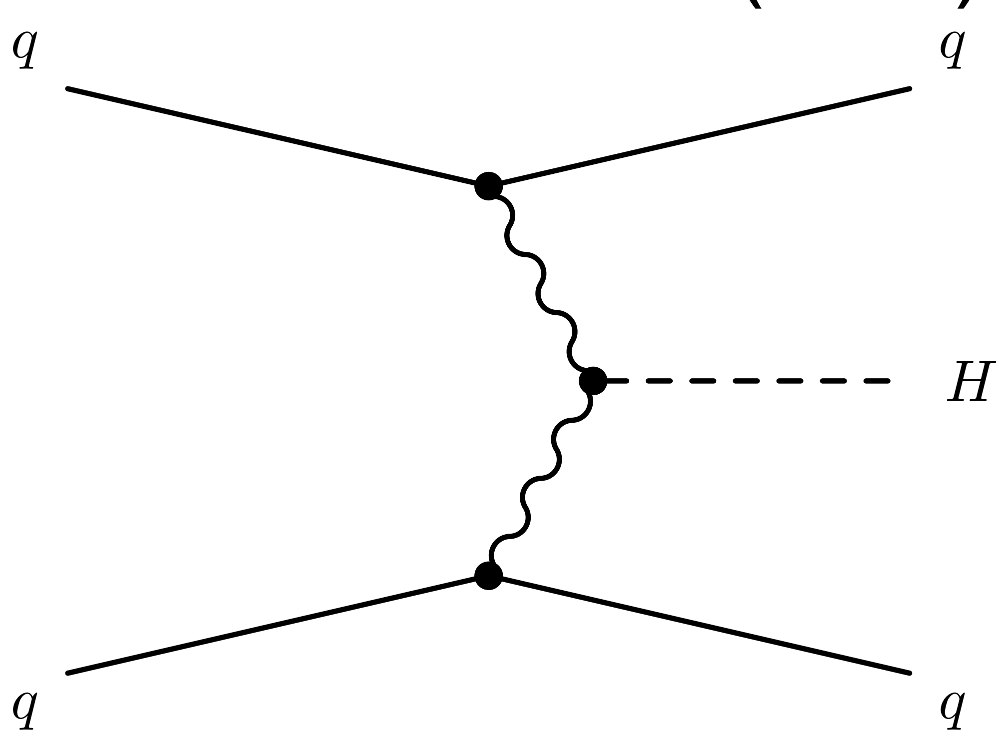


Gluon fusion (ggH): 87%

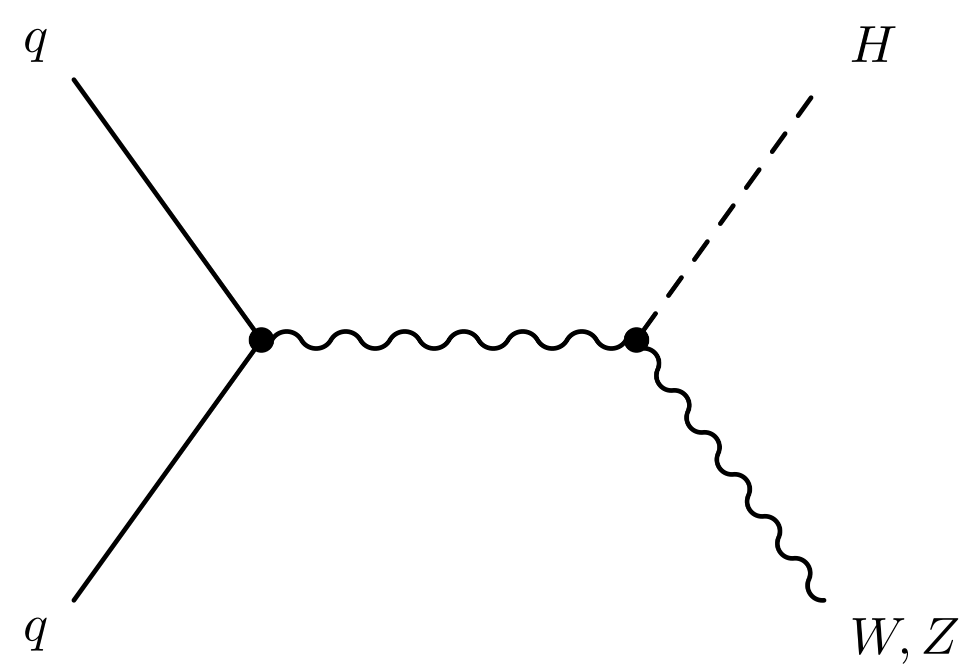


ttH: 1%

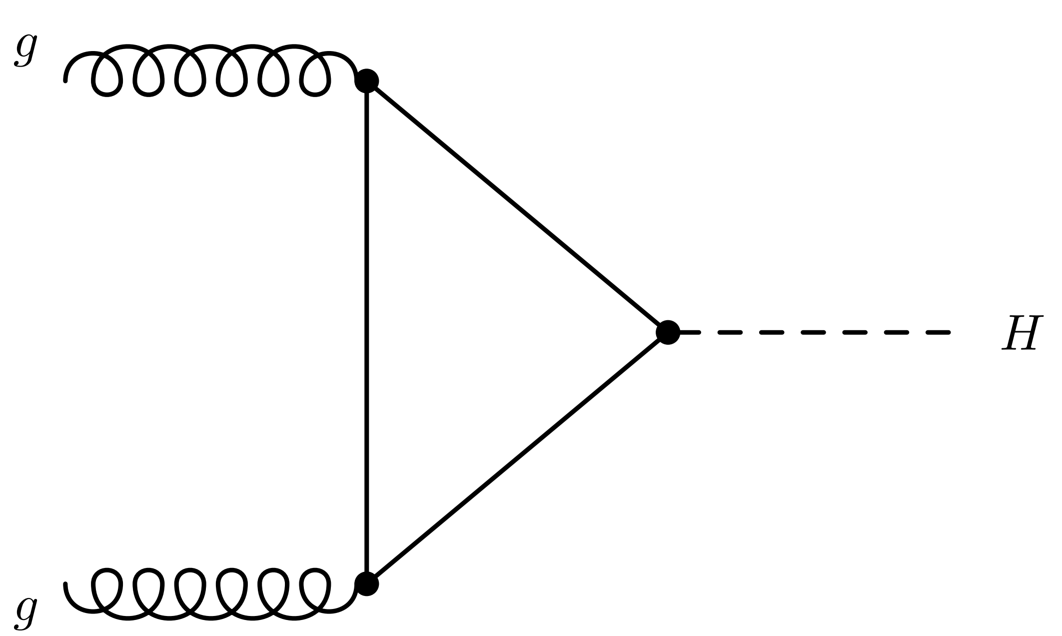
Vector boson fusion (VBF): 7%



VH “Higgs-strahlung”: 4%



Higgs Production at the LHC



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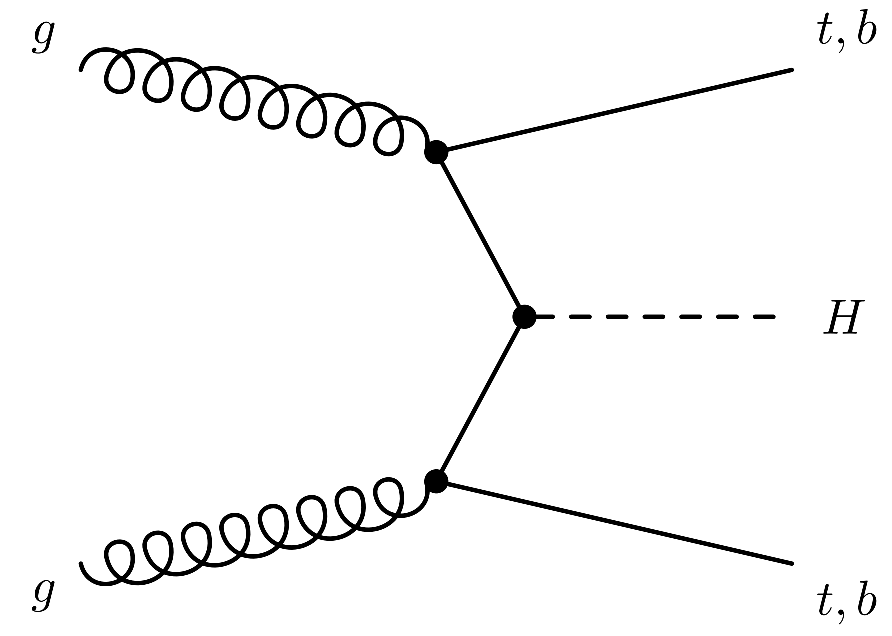

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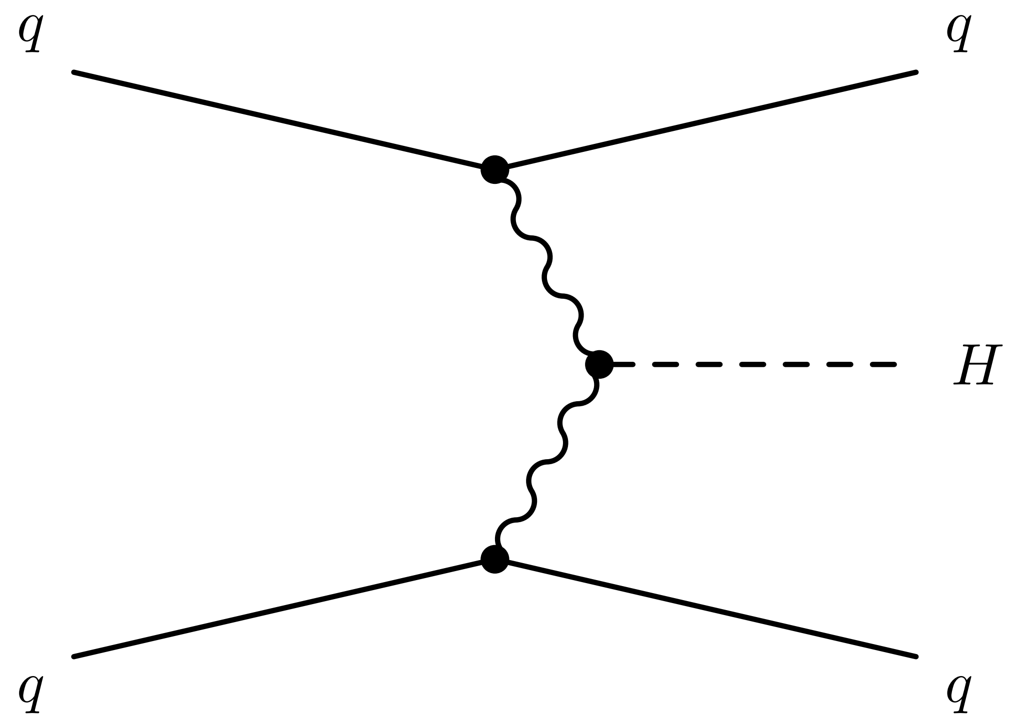
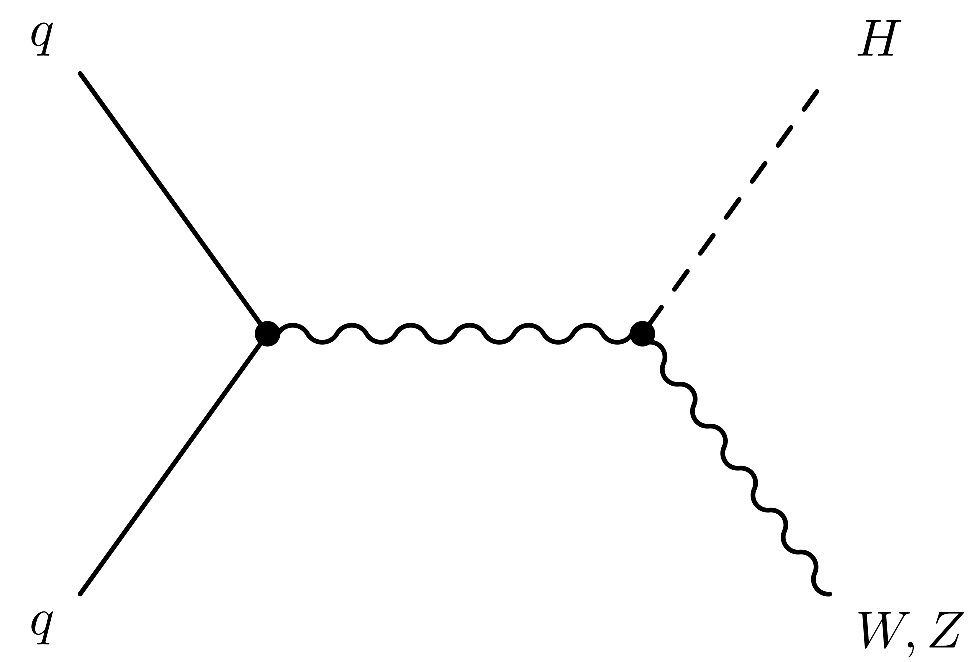
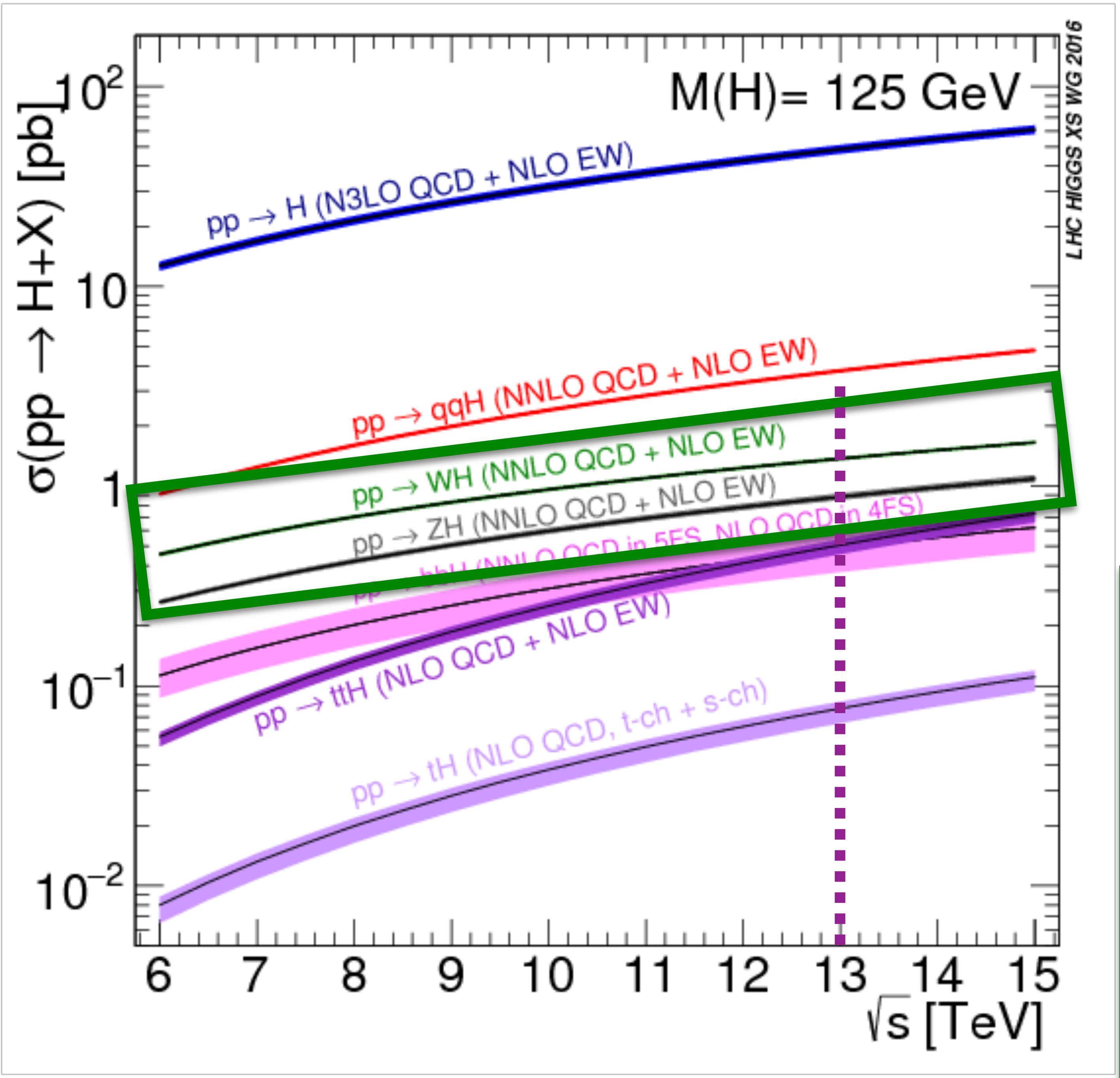


VH “Higgs-strahlung”: 4%

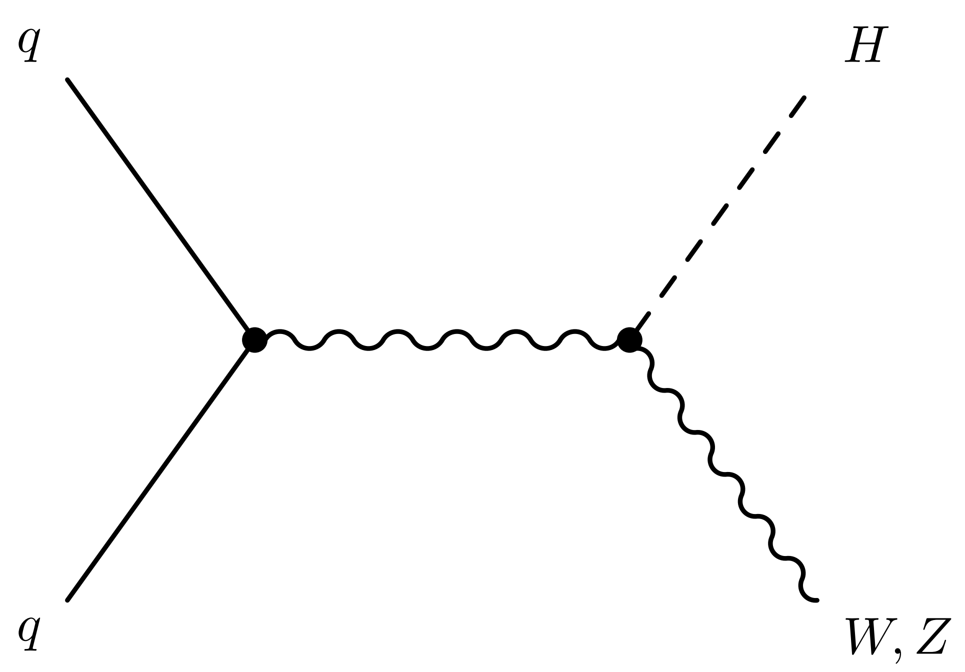


VH, H→b$\bar{b}$



- Leptonic V decay provides important handle on background and simple trigger strategy.
- **VH most sensitive search channel for H→b$\bar{b}$ at the LHC.**
- Note however that CMS also performs dedicated H→b$\bar{b}$ searches in the ttH, VBF, and ggH production modes.

VH "Higgs-strahlung": 4%



LHC Outlook

- Observation of $H \rightarrow b\bar{b}$ was not originally expected until much later in the LHC program.

"The WH channel will be very difficult…even under the most optimistic assumptions."

— SNOWMASS-2011-P111

"the discovery potential for… the WH production mode at the LHC is marginal… For $ZH \rightarrow llb\bar{b}$ a similar signal-to-background ratio is expected as for the WH channel."

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

"a Higgs-boson signal could be [observed for $\bar{t}tH(b\bar{b})$]… assuming an integrated luminosity of 300 fb^{-1}"

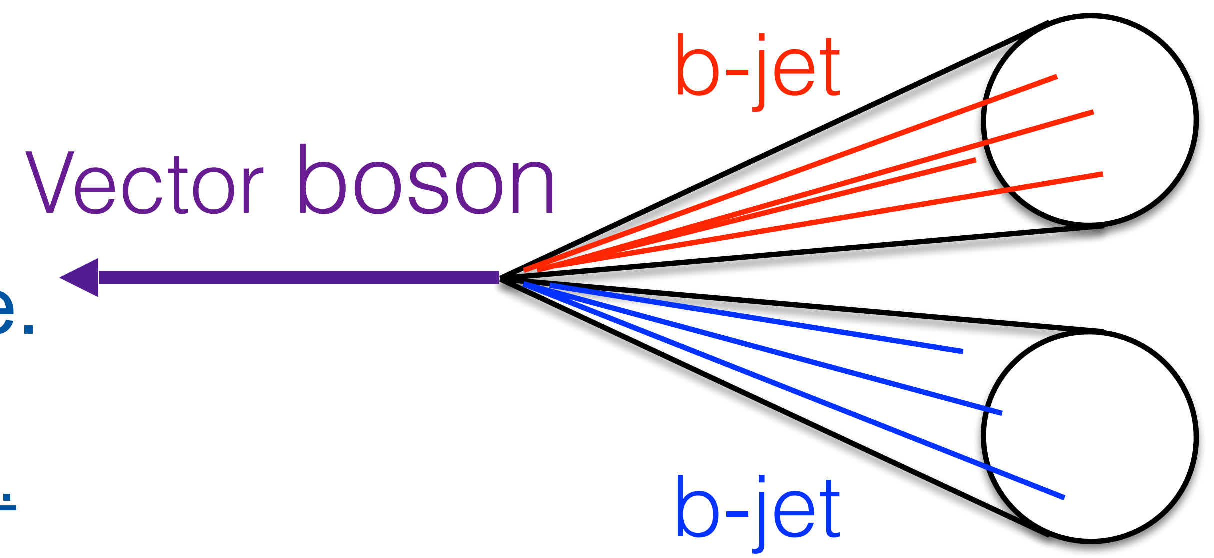
— ATLAS-TDR-15

"[ttH and WH] are definitely high-luminosity measurements."

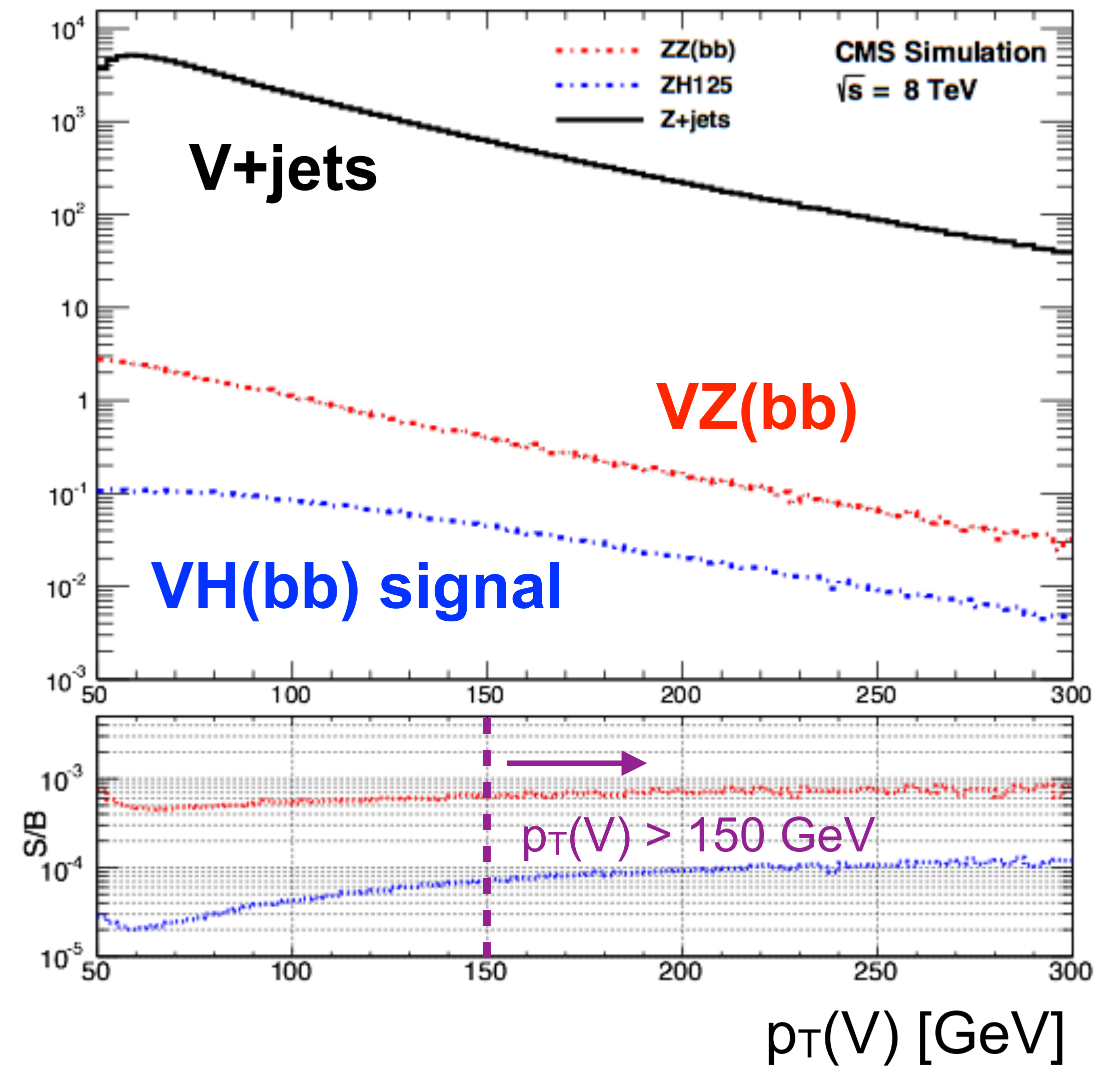
— CERN-PH-TH/2004-103

Boosted Vector Boson

- Signal to background ratio greatly enhanced by requiring that **vector boson is boosted and back-to-back with respect to Higgs** boson candidate.
  - First suggested by Butterworth, Davison, Rubin, and Salam in 2008:(Phys. Rev. Lett. 100 (2008) 242001).

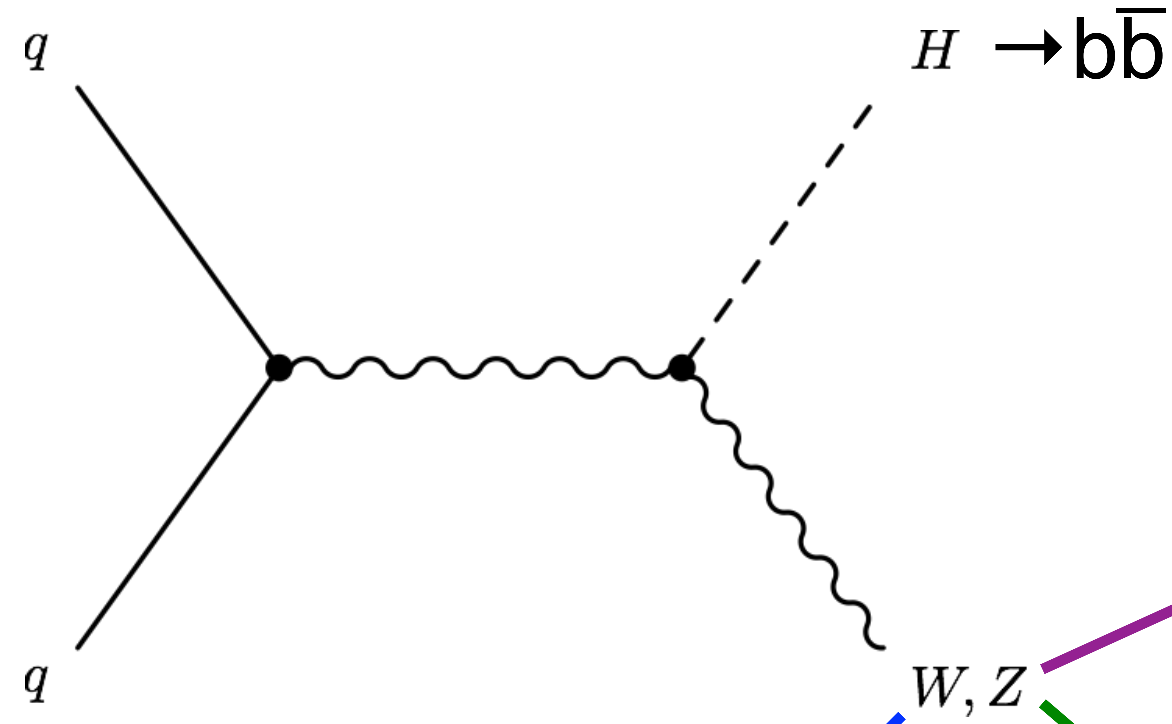


- ~5% total VH events with $p_T(V) > 200$ GeV but compensating advantages:
  - **Nearly eliminate QCD**, large reduction in V+jets and top backgrounds.
  - **Improved mass resolution**.
  - Makes **Z→νν channel accessible** (large missing E_T).



- **Key element making VH, H→b$\bar{b}$ search possible at the LHC.**

VH, $H\rightarrow b\bar{b}$ Categories



0-lepton: $Z\rightarrow\nu\nu$:

- Missing E_T > 170 GeV and no leptons.
- No more than one additional jet.
- Additional QCD rejection.

1-lepton: $W\rightarrow l\nu$:

- Exactly one electron or muon + missing E_T.
- $p_T(l\nu)$ > 150 GeV.
- No more than one additional jet.

2-lepton: $Z\rightarrow l^+l^-$:

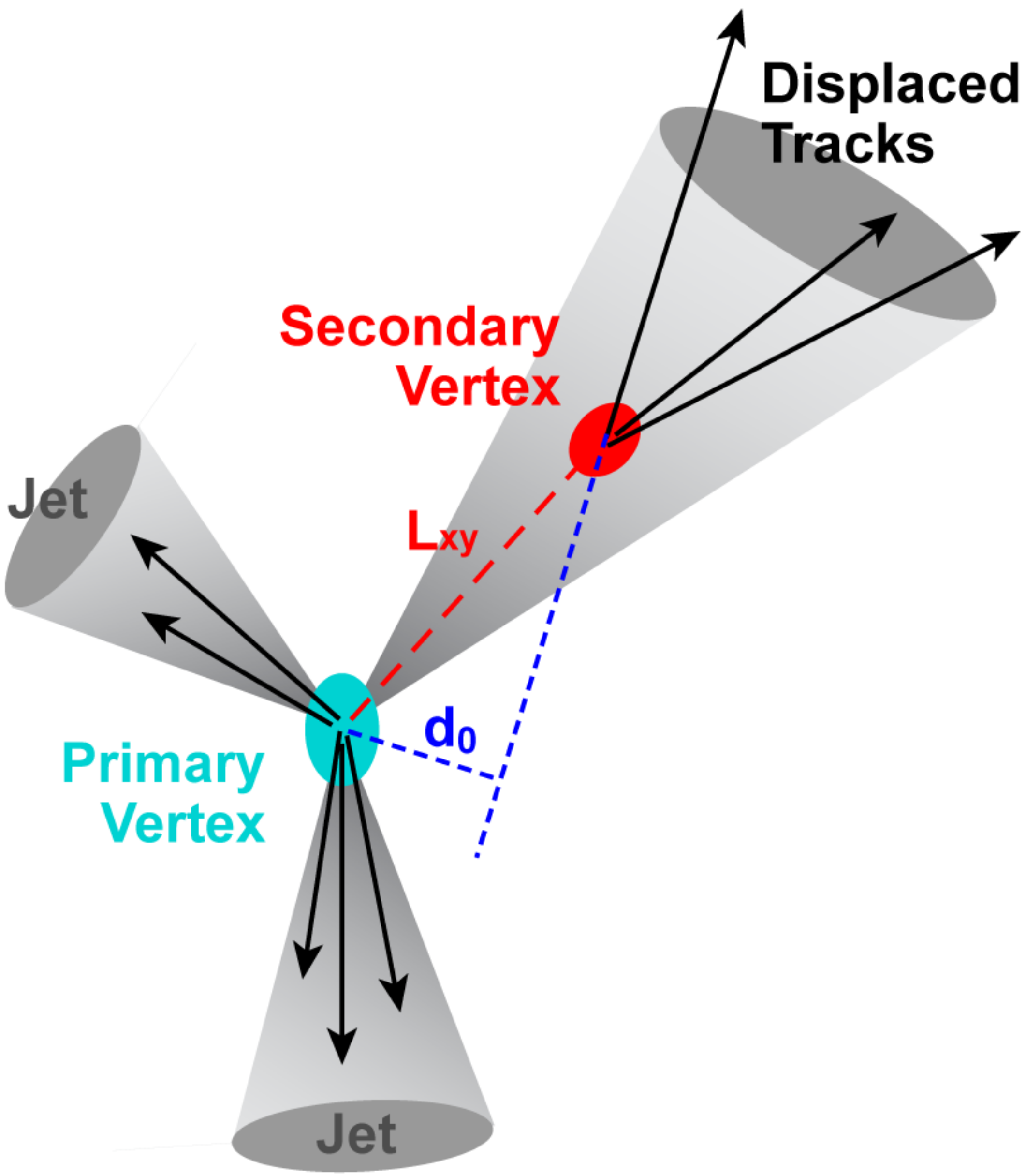
- Two opposite-sign electrons or muons.
- $|M_{ll} - M_{Z,PDG}| < 15$ GeV
- $p_T(ll)$ [50, 150] or > 150 GeV.

2017 VH, $H \rightarrow b\bar{b}$: Primary Improvements

- **Improved mass resolution via:**
  - Better **b-jet identification** (DeepCSV)
  - New and improved **b-jet energy regression**
  - **Kinematic fit in 2-lepton channel**
  - FSR jet recovery.

- Use of **deep neural network (DNN)** to:
  - **Discriminate signal from background**.
  - **Differentiate among background components** in critical 0- and 1-lepton V+heavy flavor control regions where V+(b)b purity is not possible.

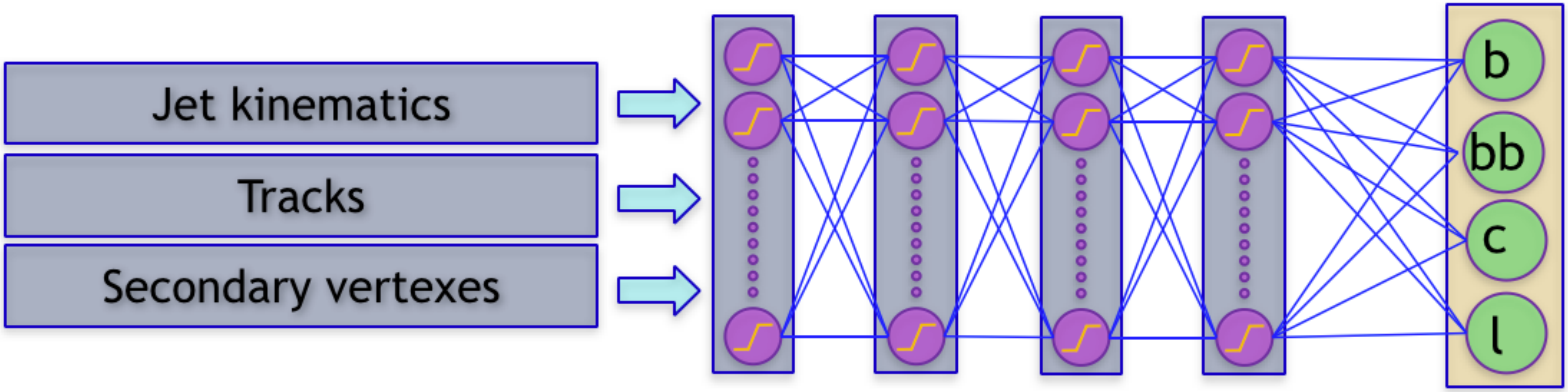
B-jet Identification



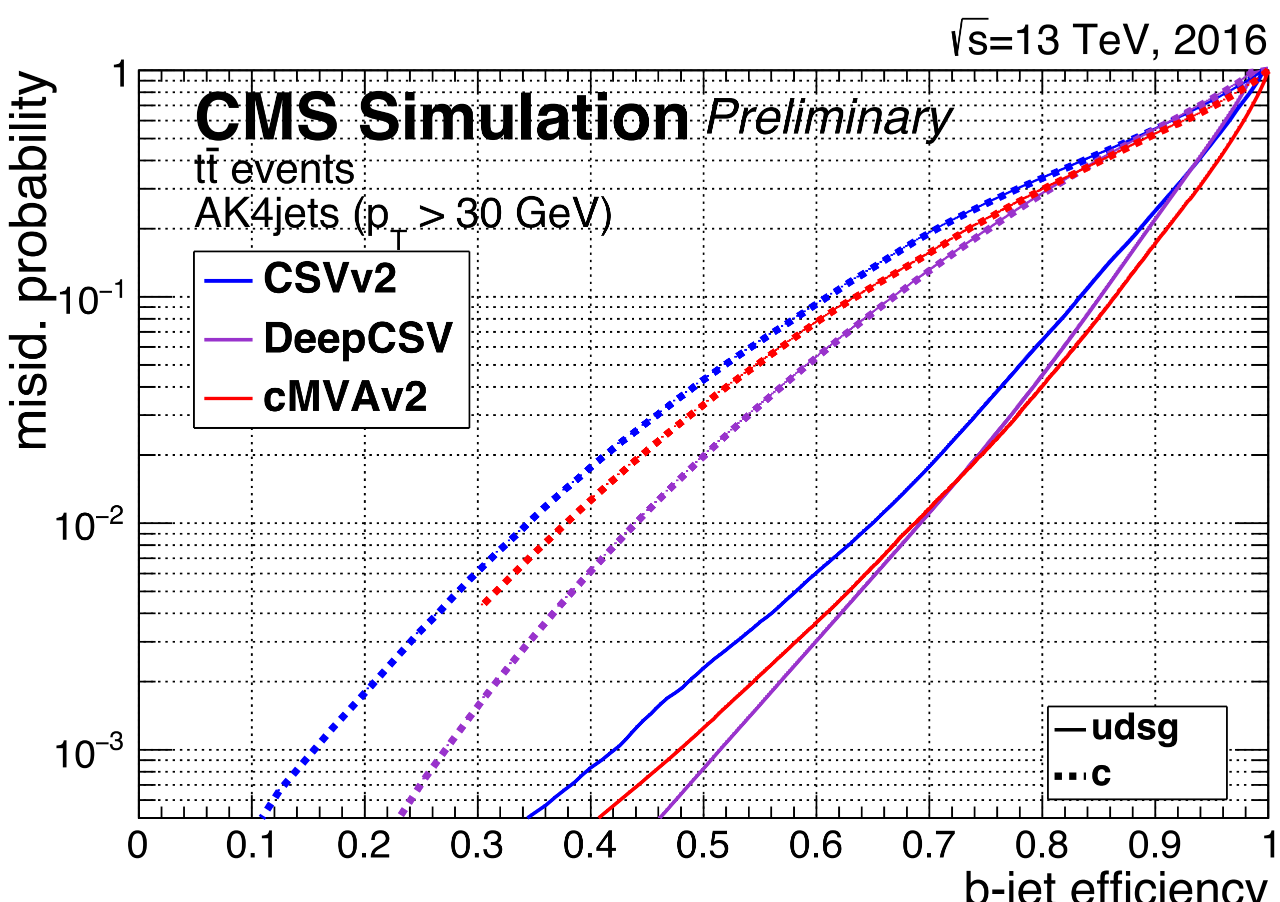
- Relatively long lifetime (1-1.5 ps) → displacements from few mm. to 1 cm.
- Larger mass and harder fragmentation compared to other quarks.
- MVA classifier to discriminate b-jets from udsg and c-jets.
  - Relies on secondary vertex information as well individual tracks.

B-tagging in CMS: DeepCSV

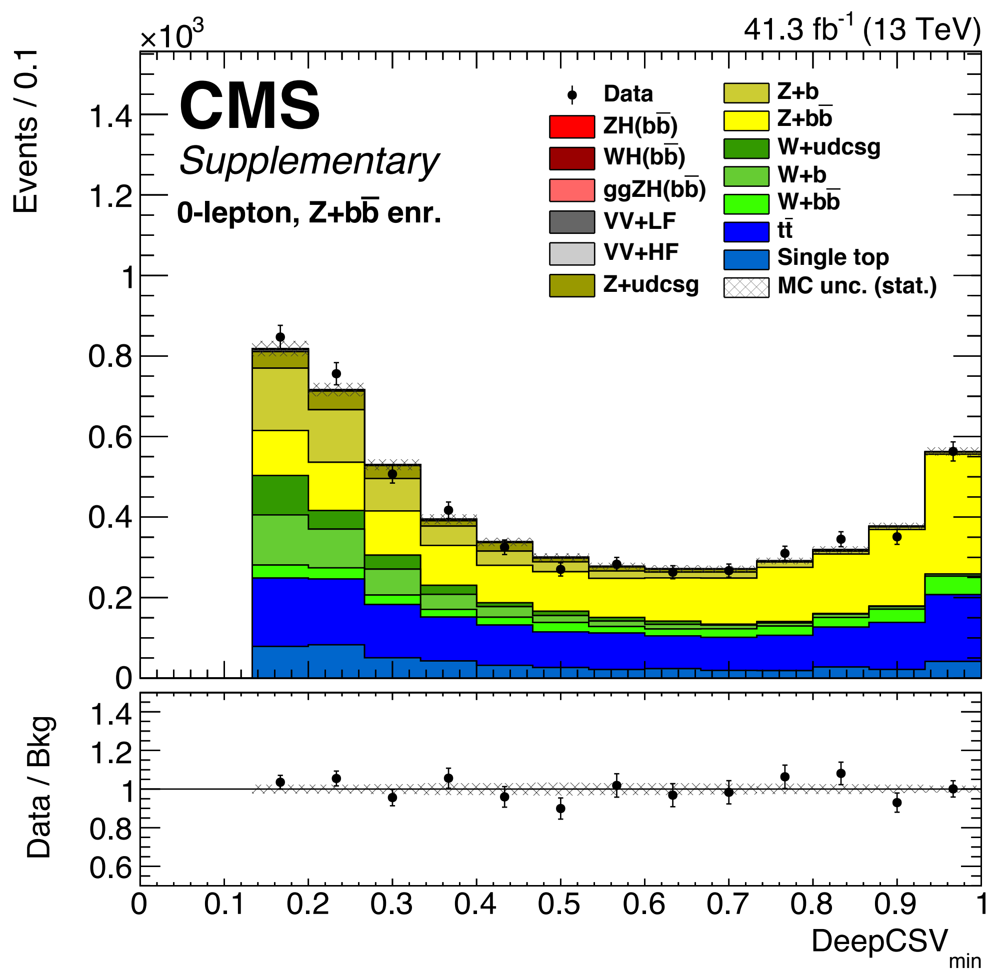
- **Deep neural network multi-classifier** (b, bb, c, cc, light).
  - Four hidden layers with a width of 100 nodes each.
  - Same track selection and input observables as previous boosted decision tree (BDT)-based tagger.



- O(10%) improvement in b-tagging efficiency in analysis phase space at same misidentification rate.
- Good agreement between data and simulation has been verified in all VH, H→b$\bar{b}$ analysis regions.



CMS-DP-2017-005



B-jet Energy Regression

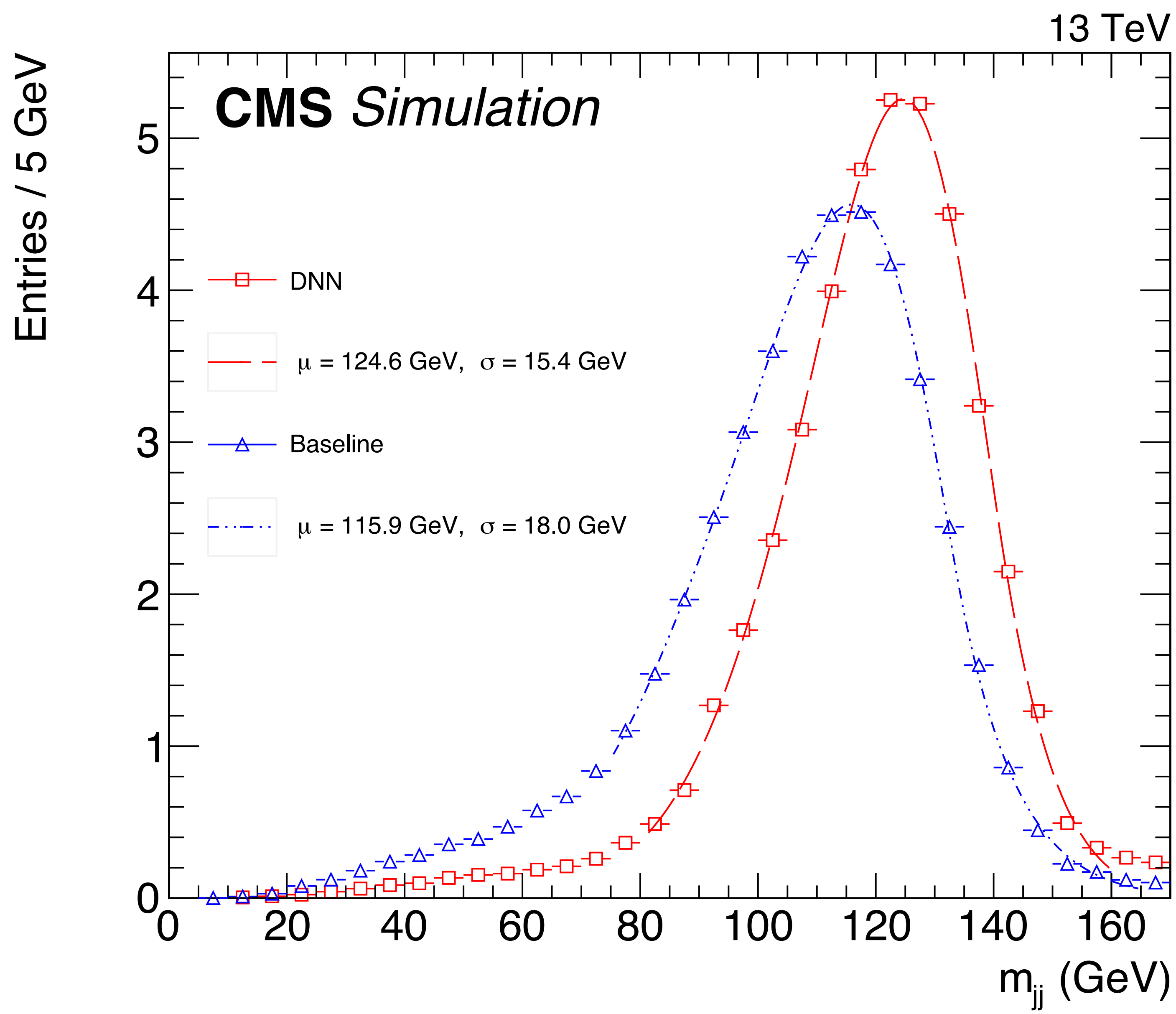
- Train **MVA regression to better reconstruct b-jet momentum**.
  - Primary effect: **correct for neutrino momentum** (semi-leptonic B hadron decays).
  - Secondary effect: overall calibration specially for b-jets.

- Regression improvements:
  - **switch from BDT to DNN**
  - **additional inputs** added to training:
    - jet shape: energy fractions in rings, energy spread (p_TD).

- **Relative resolution improved by O(20%).**
  - Significant improvement over previous BDT regression.

- Dedicated validation of jet resolution in data for regressed b-jets.

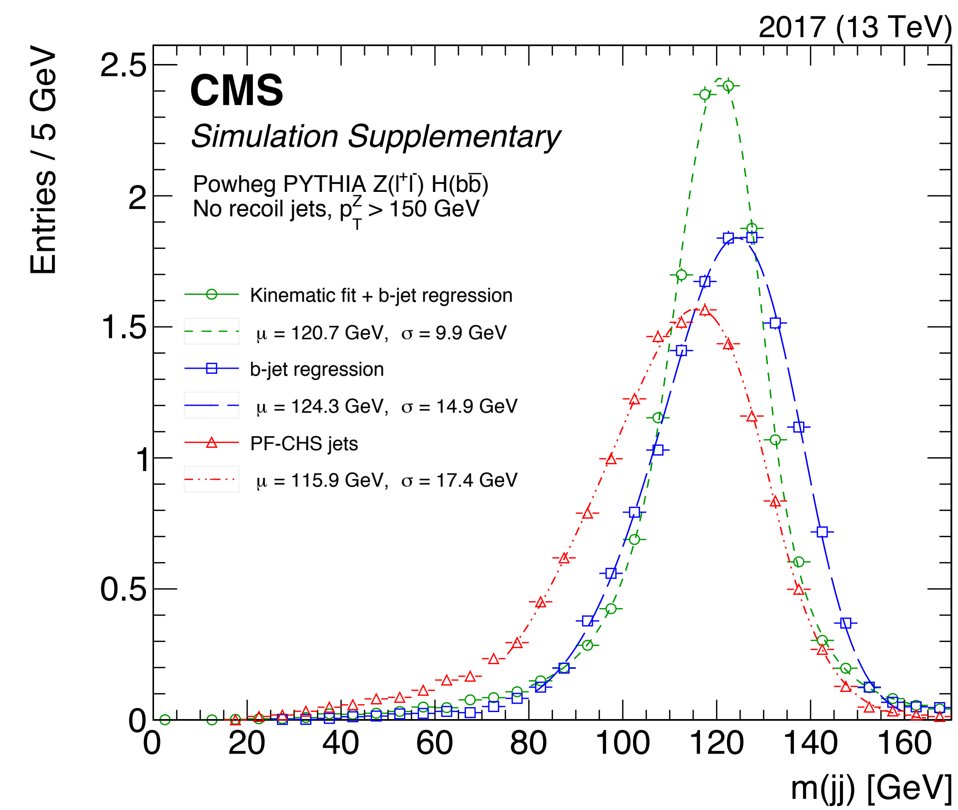
Z(ll)H($b\bar{b}$) signal $p_T(Z)$ > 150 GeV
(high-S/B analysis phase space)

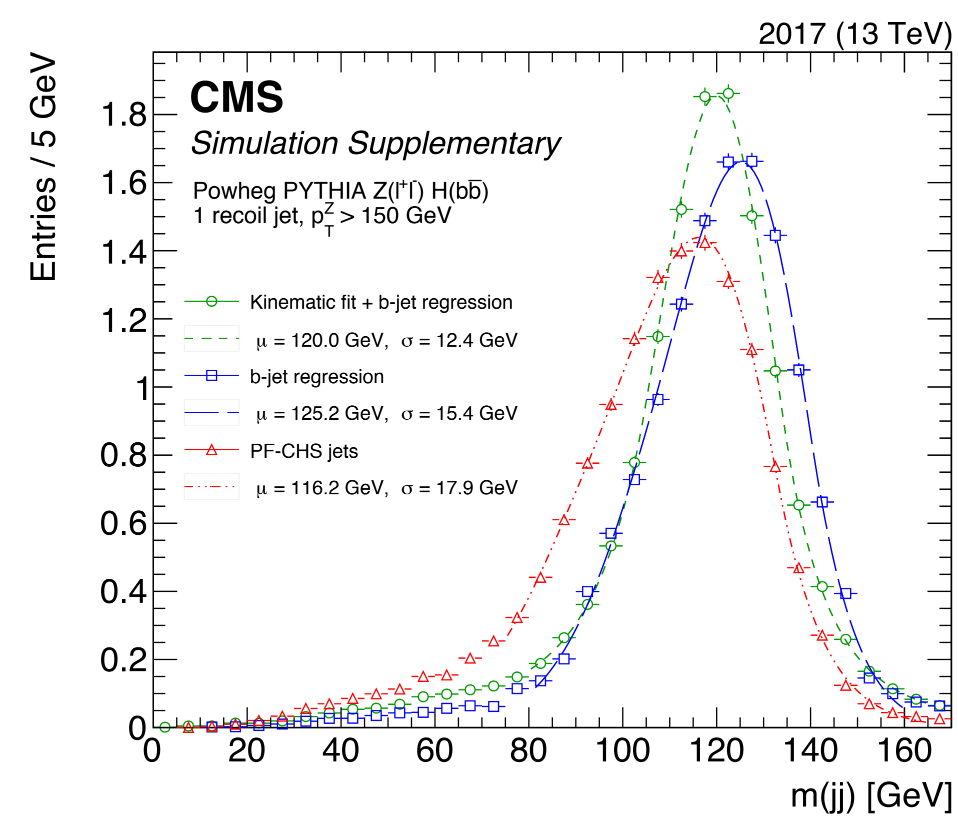


Z(ll)H($b\bar{b}$) Kinematic Fit

- In 2-lepton channel, further improve mass resolution by balancing ll+bb system.
  - No intrinsic missing energy for Z(ll)H($b\bar{b}$).
- Procedure:
  - Balance the ll+bb system in the (p_x,p_y) plane.
  - Fit lepton and jet p_T's varying within uncertainties.
  - Constrain dilepton system to Z mass.
- **Improvement of up to 36% on M($b\bar{b}$) resolution with respect to regression only in 2-lepton channel.**

# Recoil Jets	σ [GeV] Regression	σ [GeV] Kinematic Fit	Relative Improvement
0	14.3	9.2	36%
1	15.3	11.5	25%
> 1	15.7	12.8	13%



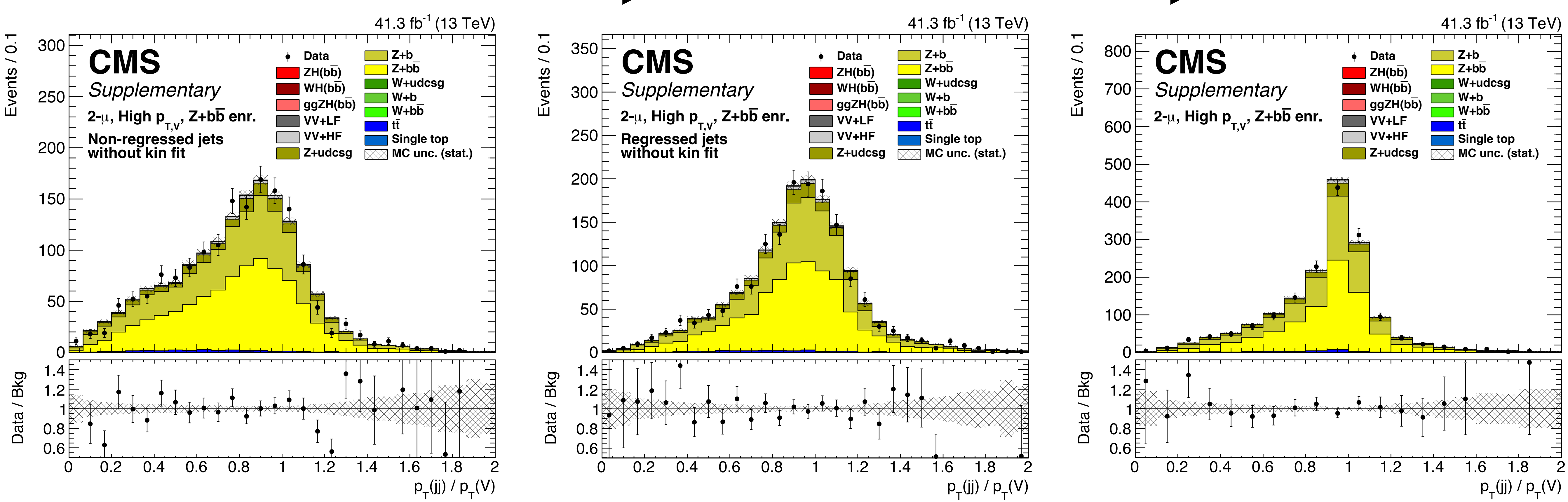


$M(b\bar{b})$ Resolution Improvement Validation

- $M(b\bar{b})$ resolution improvements do not sculpt backgrounds.
- Expected improvements from simulation match data.
- Improved $M(b\bar{b})$ resolution → better S/B and smaller uncertainty on signal strength.

B-jet Regression →

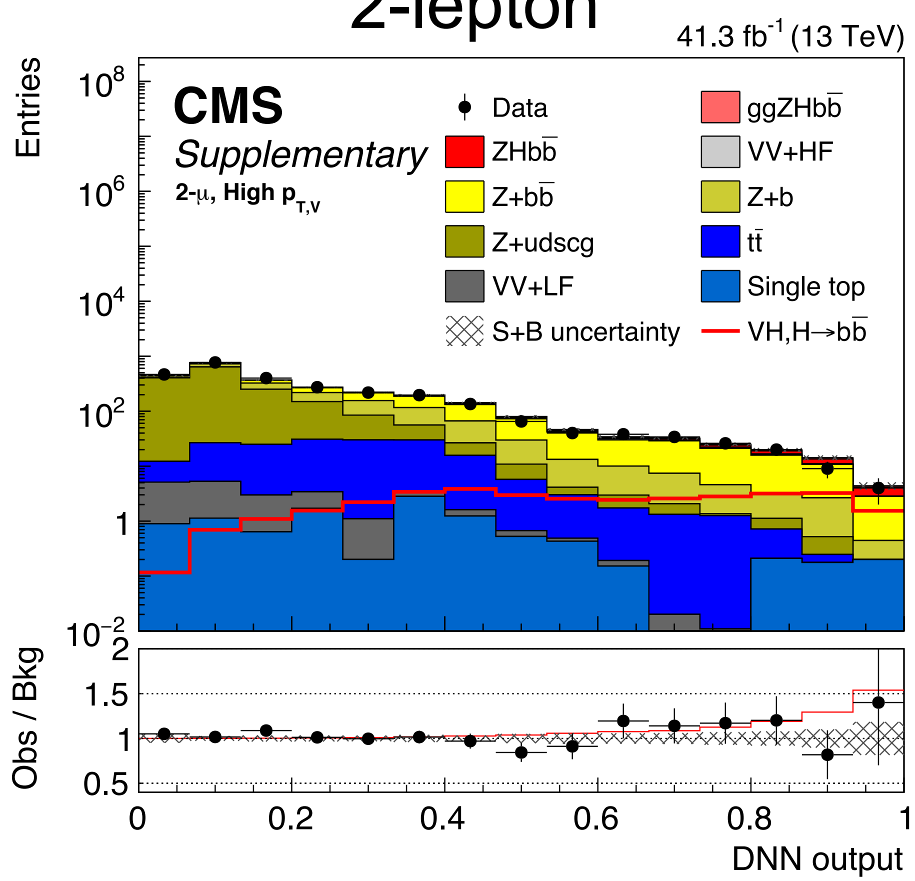
Kinematic Fit →



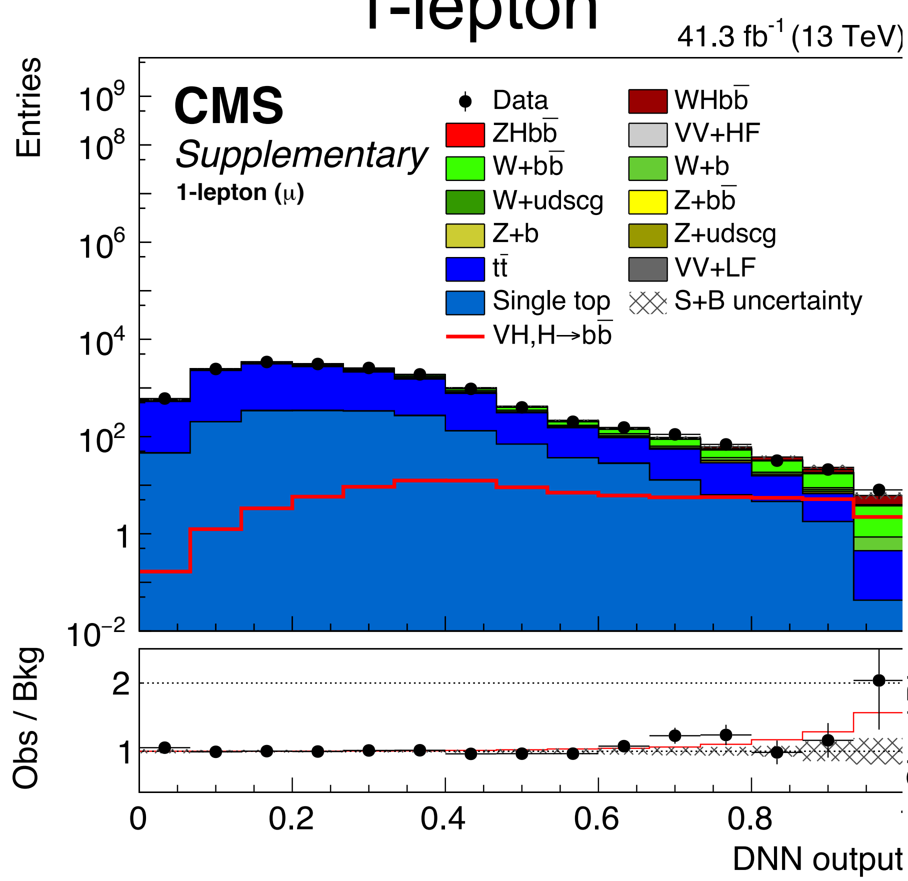
DNN as Final Discriminator

- **Use DNN to enhance separation between VH, $H\rightarrow b\bar{b}$ signal and backgrounds.**
- Primary input variables: $M(b\bar{b})$, $p_T(V)$, $p_T(b\bar{b})$, jet b-tagging.
- Trained separately in each channel to discriminate VH, $H\rightarrow b\bar{b}$ signal from the weighted sum of all backgrounds.
- **DNN output fit in all signal regions** simultaneously to extract signal strength.

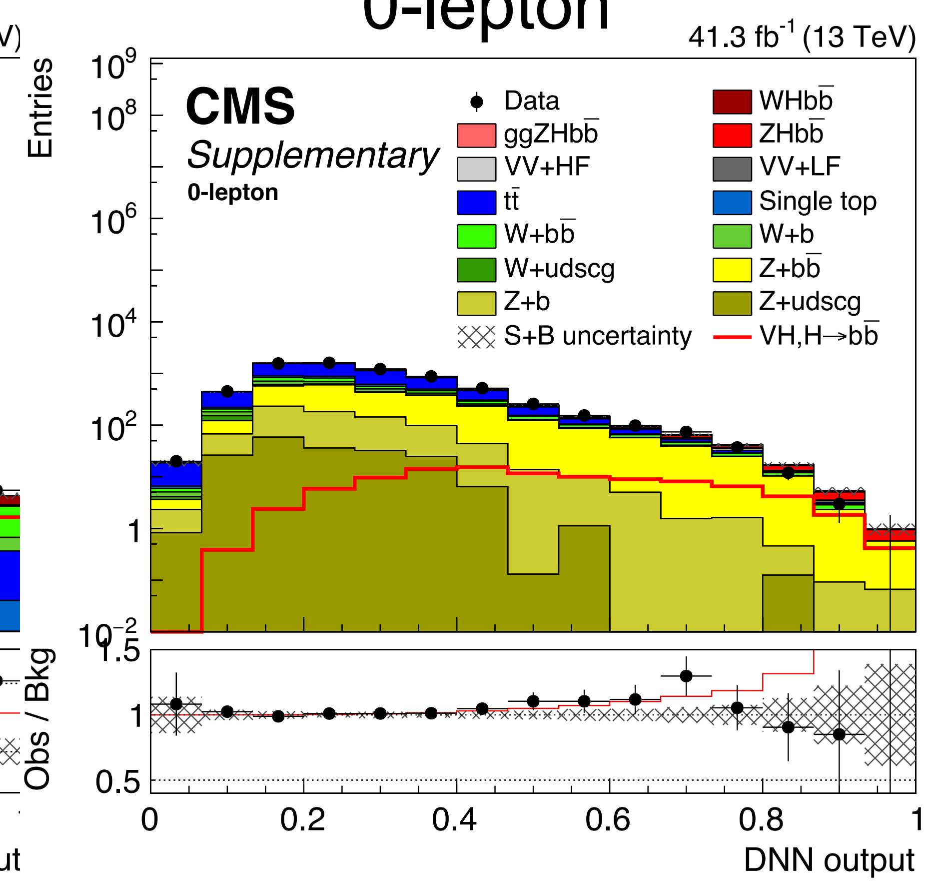
2-lepton



1-lepton



0-lepton



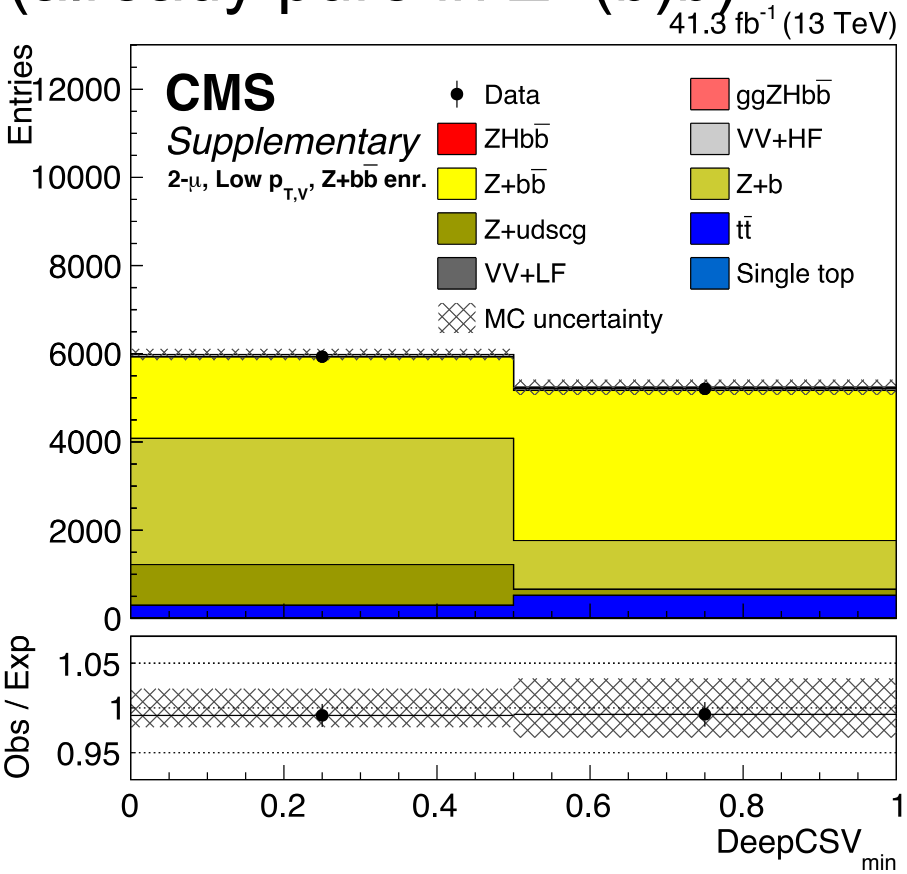
Background DNN Multi-classifier

- Leading systematic impact is uncertainty on normalization of V+(b)b.
  - Not possible to create a simple cut-based region very pure in V+(b)b for 0- and 1-lepton channels.

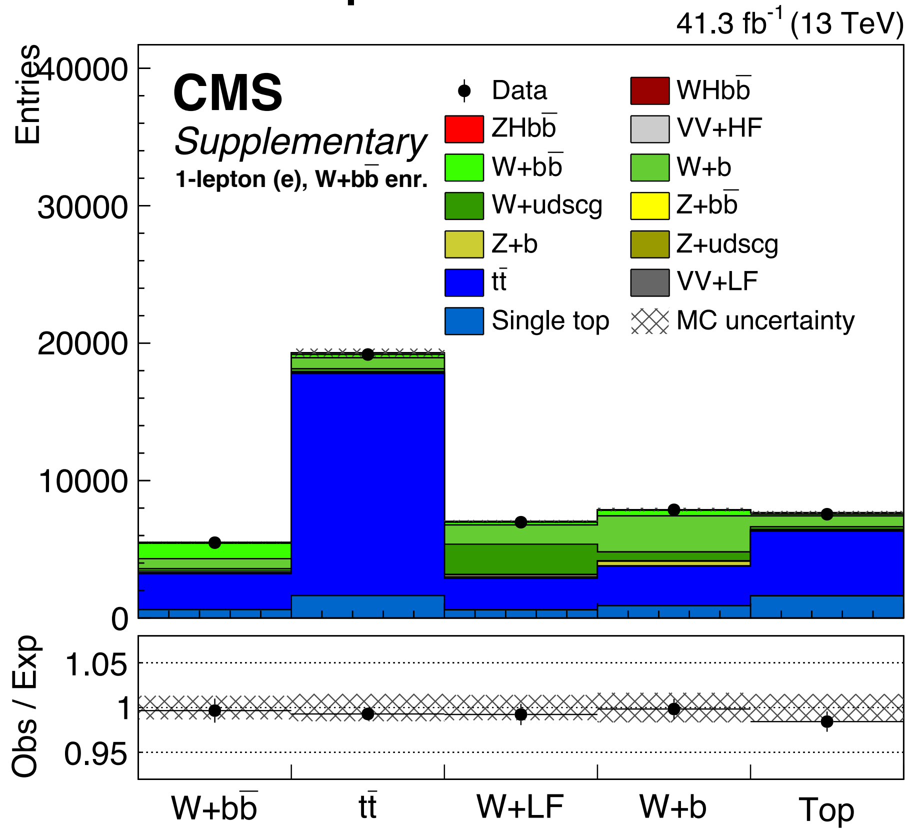
- Train a **DNN multi-classifier to distinguish among background components** using same inputs as DNN S vs. B classifier.

- Include in signal extraction simultaneous fit to constrain V+(b)b.

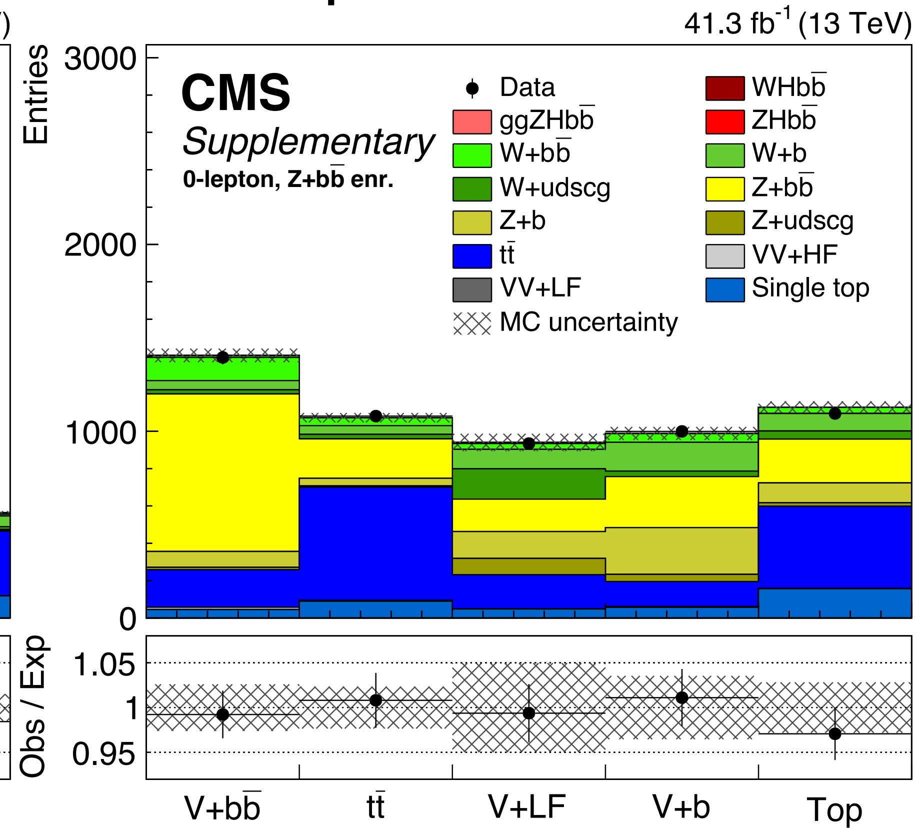
2-lepton
(already pure in Z+(b)b)



1-lepton: Multi-DNN



0-lepton: Multi-DNN



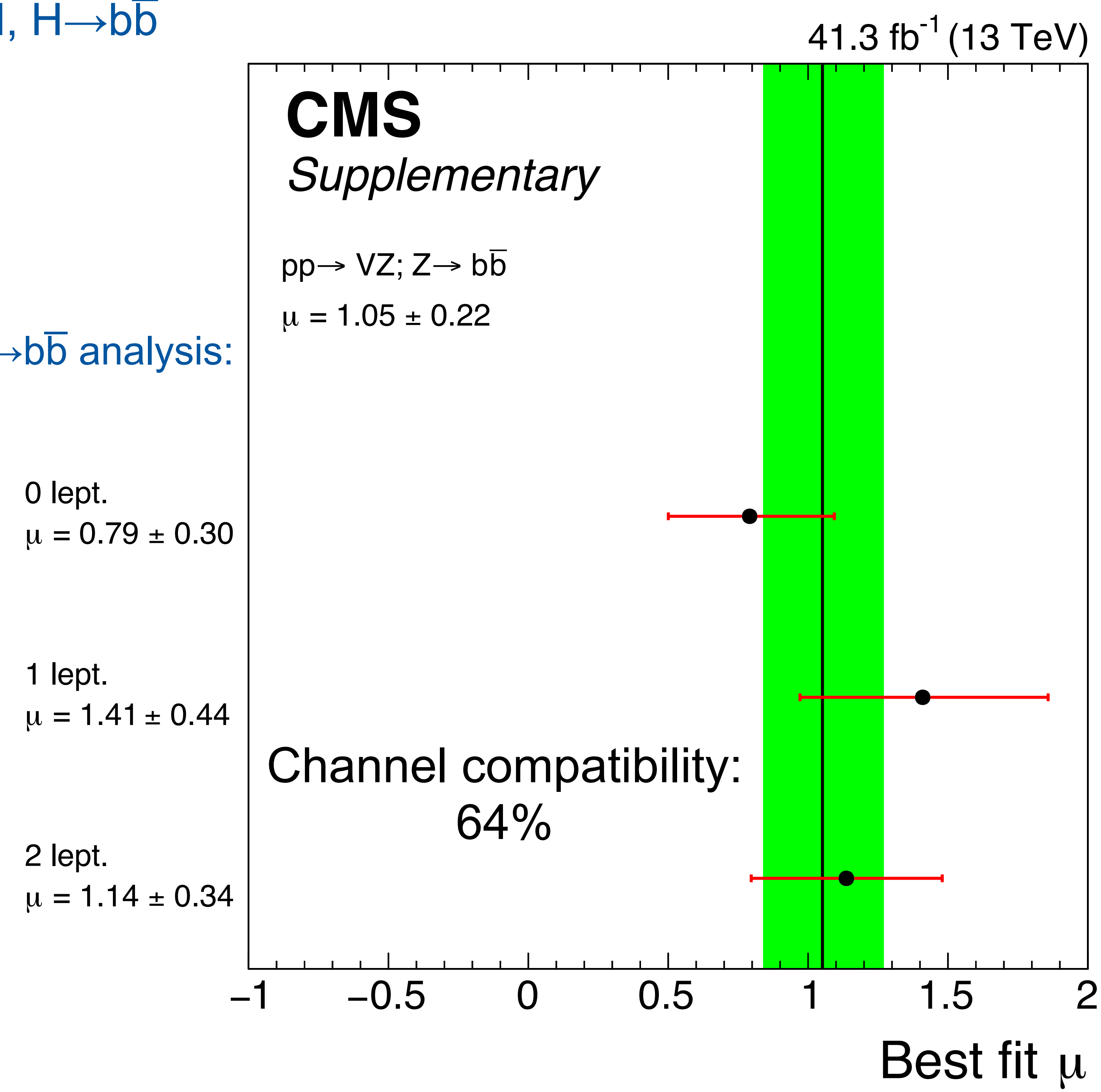
VZ, Z→b$\bar{b}$ Cross-check

- **Validate analysis strategy by extracting VZ, Z→b$\bar{b}$ signal with same techniques.**

- Same final state and similar kinematics as VH, H→b$\bar{b}$ signal.

- Minimal changes to analysis strategy:
  - **shift M(b$\bar{b}$) selection** to include Z(b$\bar{b}$).
  - **re-train DNN** to discriminate VZ, Z→b$\bar{b}$ "signal"
  - Otherwise everything is the same as the VH, H→b$\bar{b}$ analysis:
    - same DNN inputs, same fit strategy

Well consistent with SM expectation



Significance

5.0σ expected

5.2σ observed

Signal strength

μ = 1.05 ± 0.22

$\mu = (\sigma \times BR) / (\sigma \times BR)_{SM}$

2017 VH, $H \to b\bar{b}$ Result

- Standalone evidence for VH, $H \to b\bar{b}$ with 2017 dataset.

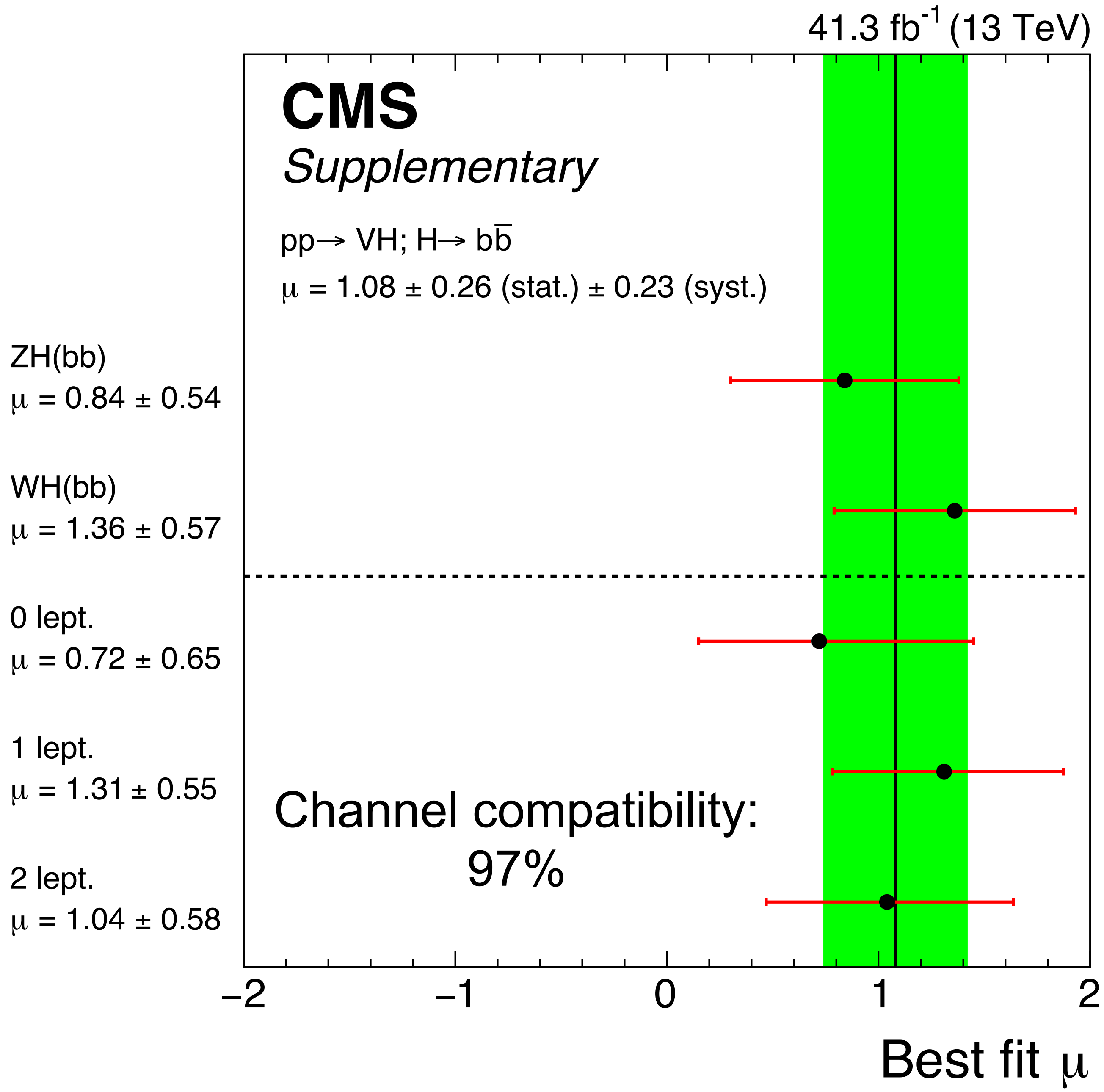
<u>Significance</u>

3.1σ expected

3.3σ observed

<u>Signal strength</u>

μ = 1.08 ± 0.34



$\mu = (\sigma \times BR) / (\sigma \times BR)_{SM}$

Systematic Uncertainties

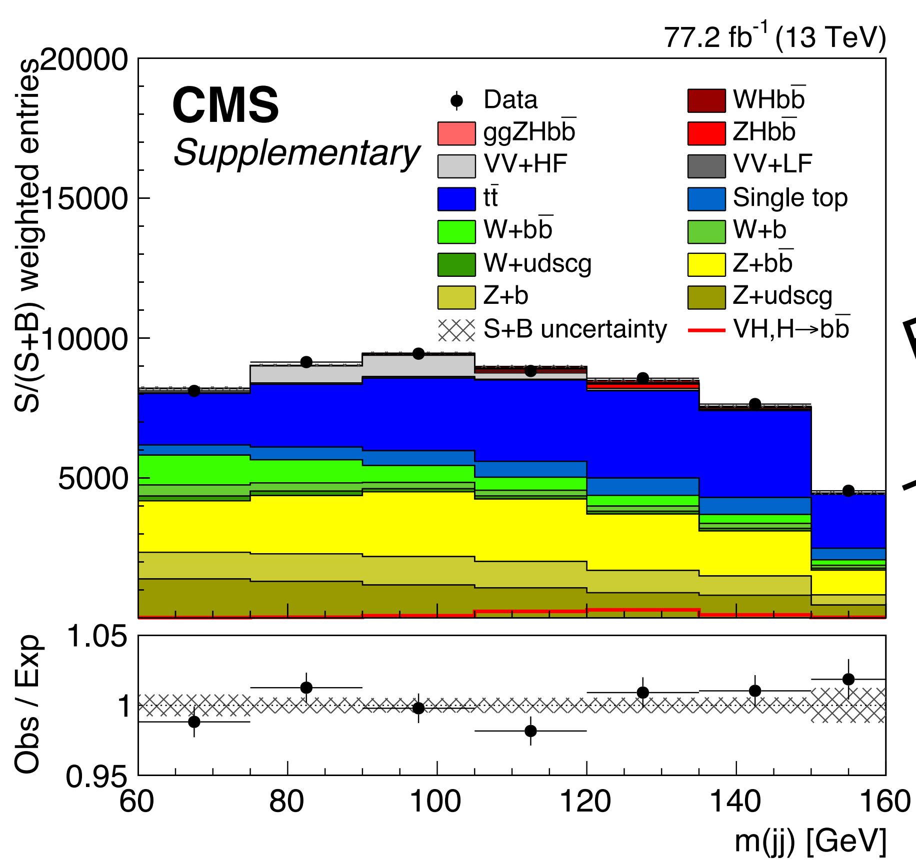
- Important statistical as well as systematic uncertainty component.
  - For 2017 analysis alone statistical uncertainty is still the largest contribution.
- Primary systematic uncertainties:
  - Background normalization and modelling
    - Impact reduced through use of background DNN multi-classifier.
  - B-tagging efficiency and misidentification rate
  - Limited statistical precision of simulated background events.
  - Primary theoretical uncertainties due to renormalization and factorization scales.

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

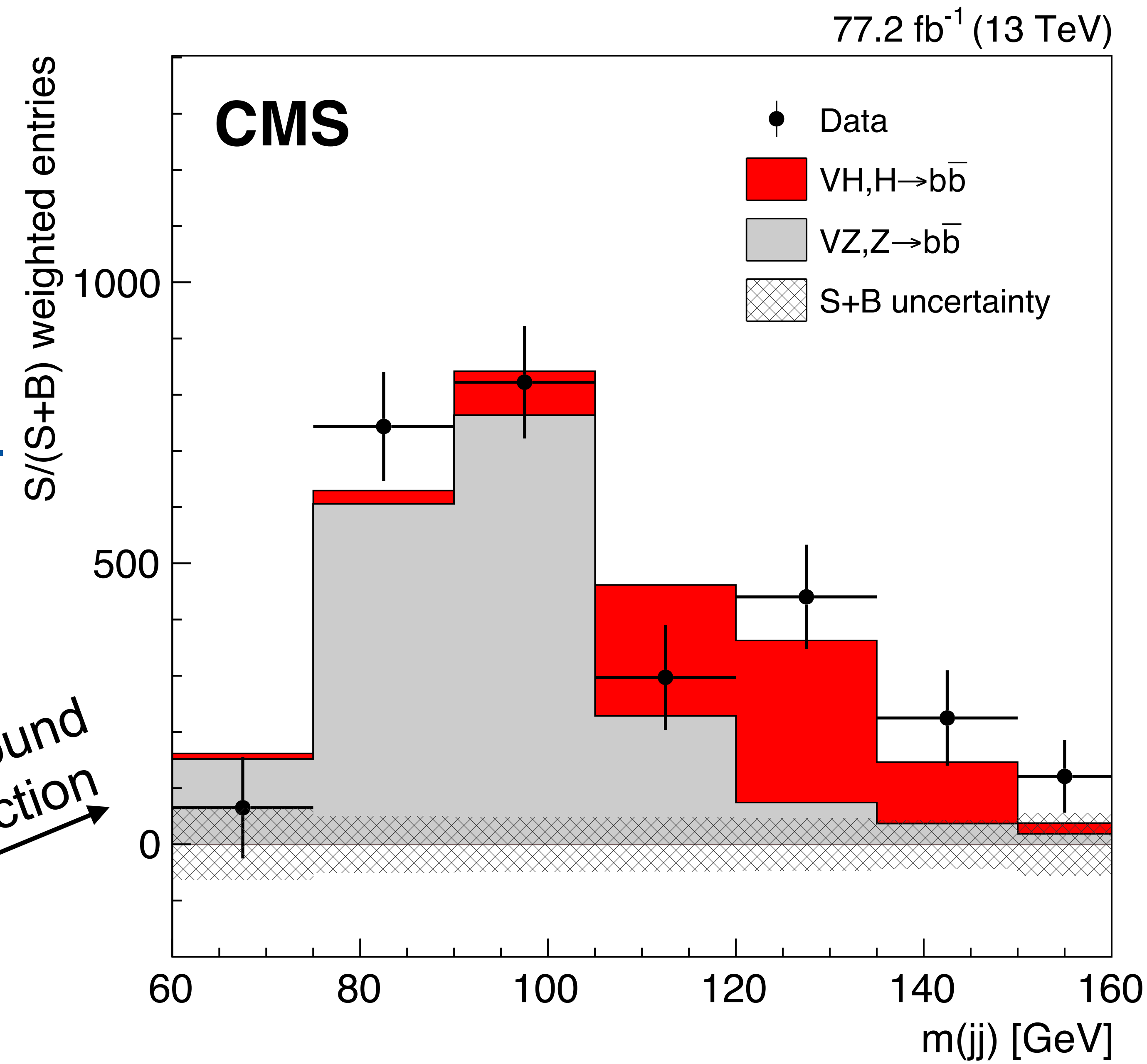
M(jj) Analysis: 2016 + 2017

- **Split each channel signal region into four categories based on mass-independent DNN score.**
- **Fit $M(b\bar{b})$ simultaneously in all split signal regions** as well as the usual control regions.
- Combined fit of 2016 and 2017 datasets.

Independent validation of observed signal



Background subtraction

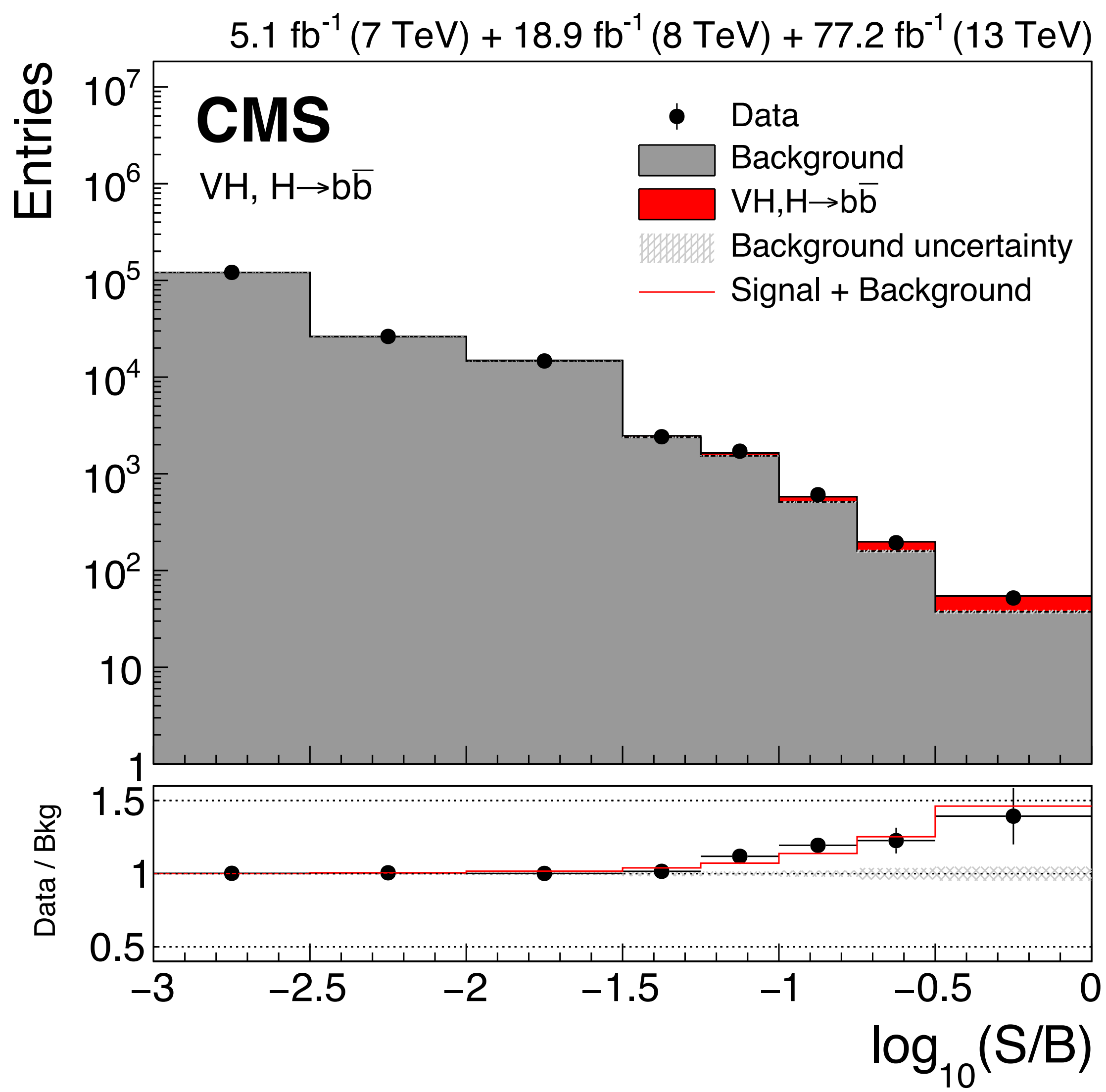


S/S+B-weighted combination of all signal regions

Combination of 7+8+13 TeV VH, H→b$\bar{b}$ results:

<u>23% precision on VH, H→b$\bar{b}$!</u>

Combine individual signal region DNN bins from all channels into a single distribution by merging events with the same S/B.



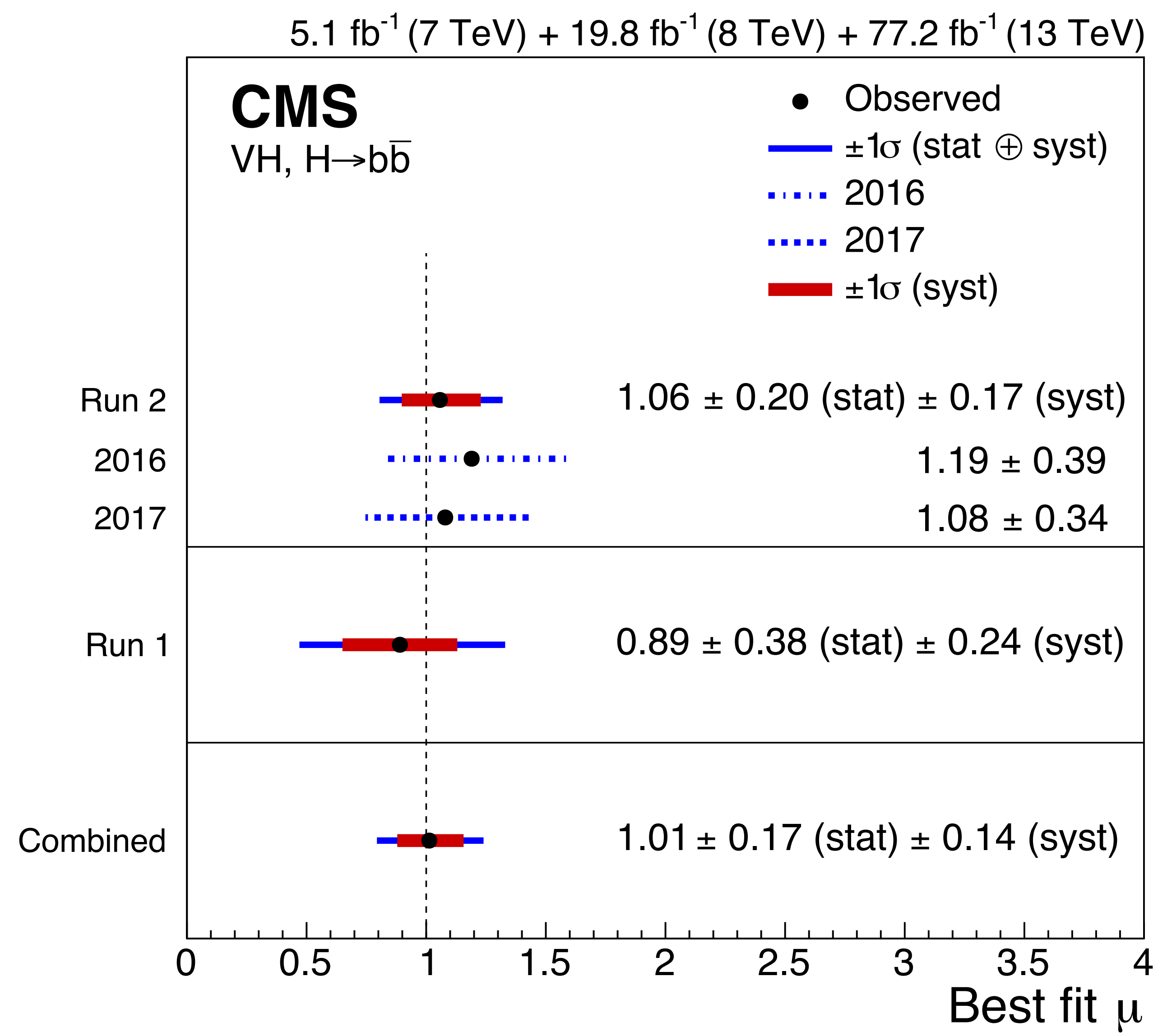
Significance

4.9σ expected

4.8σ observed

Signal strength

μ = 1.01 ± 0.23



$H \to b\bar{b}$ Combination

- Including all $H \to b\bar{b}$ published results from CMS (7+8+13 TeV).
  - Dedicated searches in ttH, VBF, and ggH (new for Run-2) production modes as well as VH (dominant contribution).
- Theory uncertainties correlated, most other uncertainty sources treated as uncorrelated.

Significance

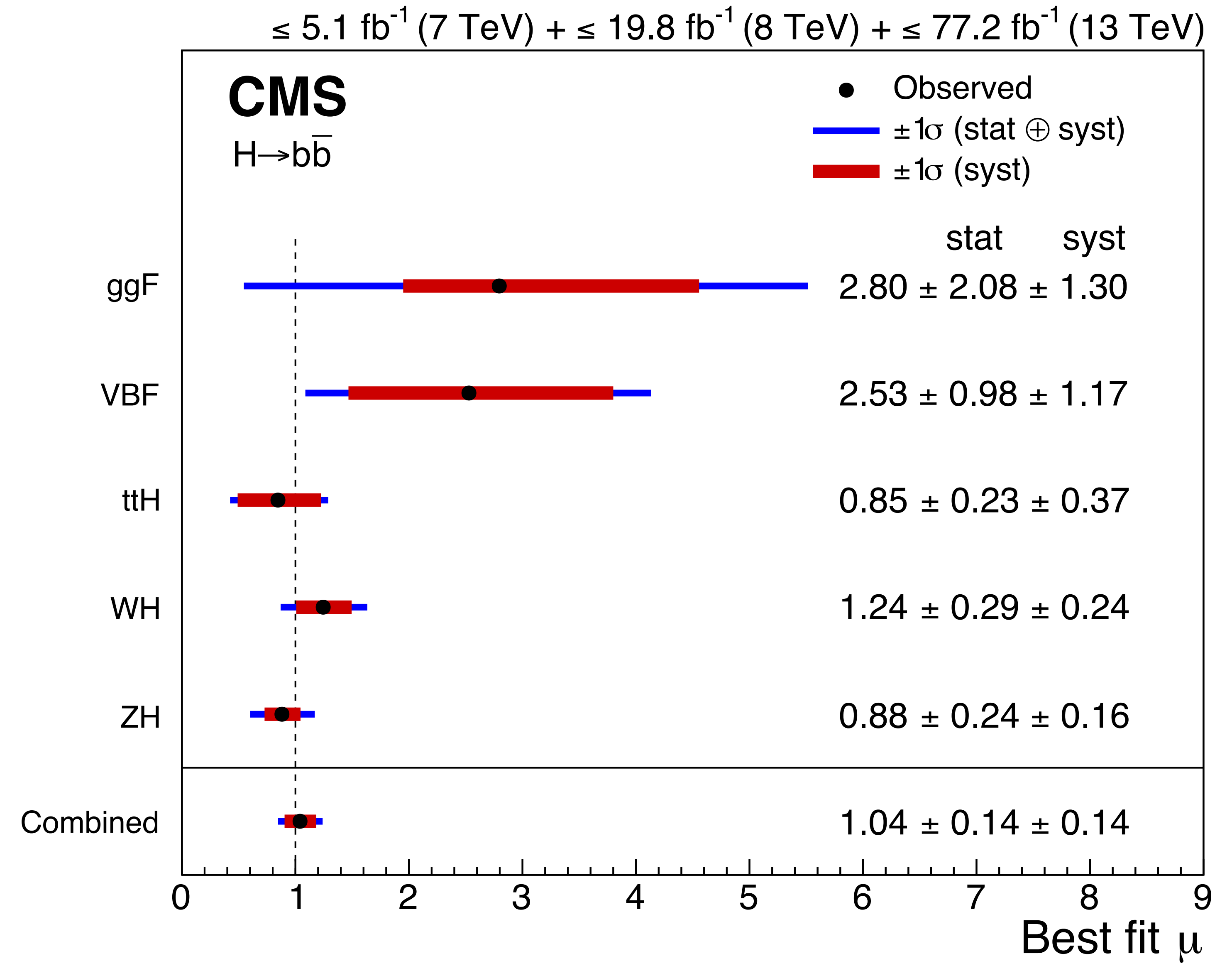
5.5σ expected

5.6σ observed

Signal strength

μ = 1.04 ± 0.20

Observation of $H \to b\bar{b}$ by the CMS collaboration!



Prospects

- **Differential VH measurements are now possible for the first time via $H\rightarrow b\bar{b}$**
  - VH measurements via other Higgs decay modes will be highly statistically limited until High Luminosity LHC (HL-LHC), scheduled to begin data taking in 2026.

- Minimizing the overall uncertainty on each Higgs coupling will also be important to maximize search potential for new physics.
  - **Can we achieve 10%-level or better precision on Higgs coupling to bottom quarks at the LHC?**

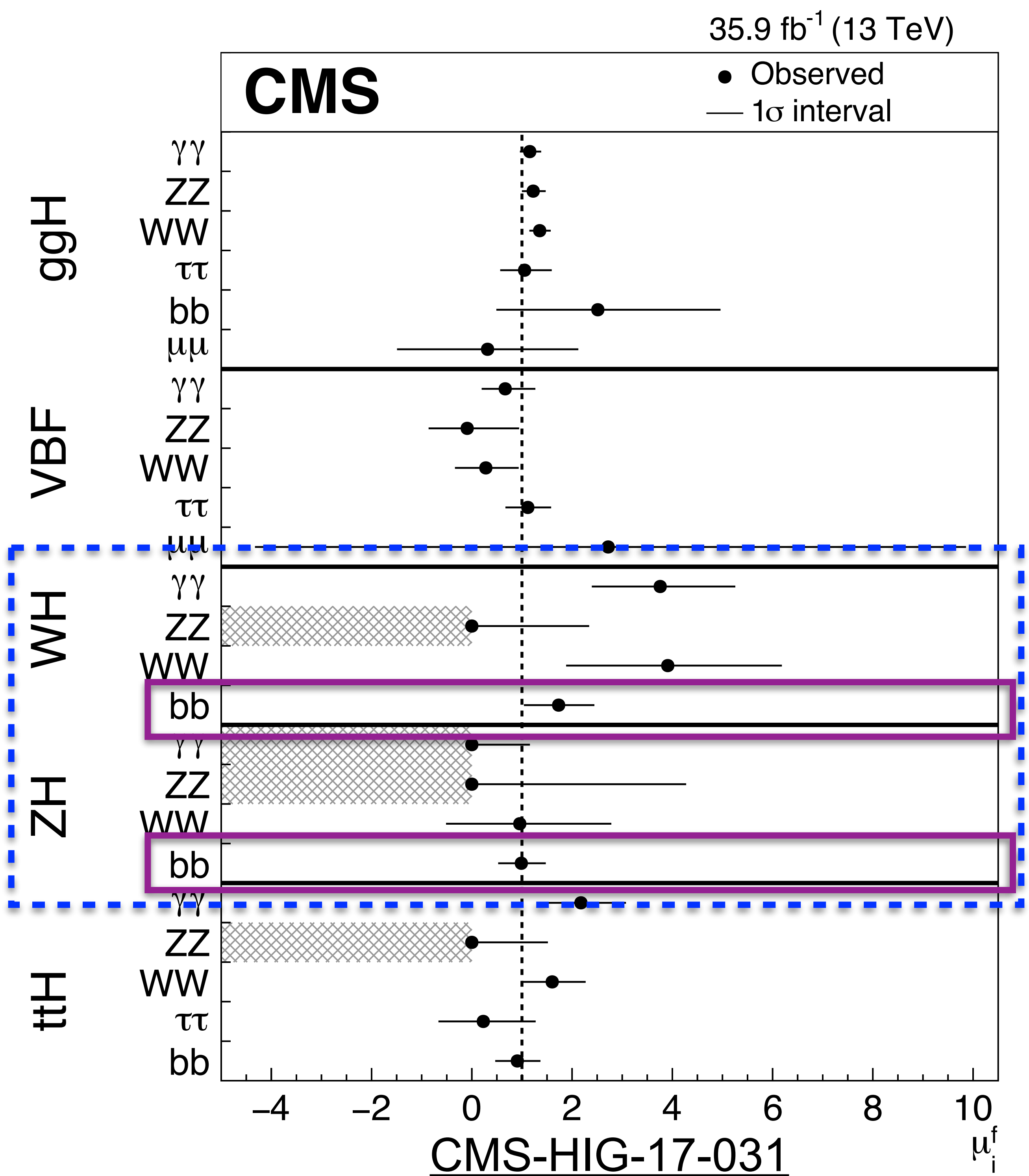
VH Precision Measurements

- **Complementary probe for new physics** effects.

- **Deviations from standard model** due to beyond the standard model Higgs couplings tend to be **more pronounced in high-energy tails of kinematic distributions**.

- H→b$\bar{b}$ analysis strategy at LHC already requires the Higgs candidate to have high-momentum to suppress background.
  - **H→b$\bar{b}$ analysis is well suited to make interesting differential VH measurements at high energy in the near future.**

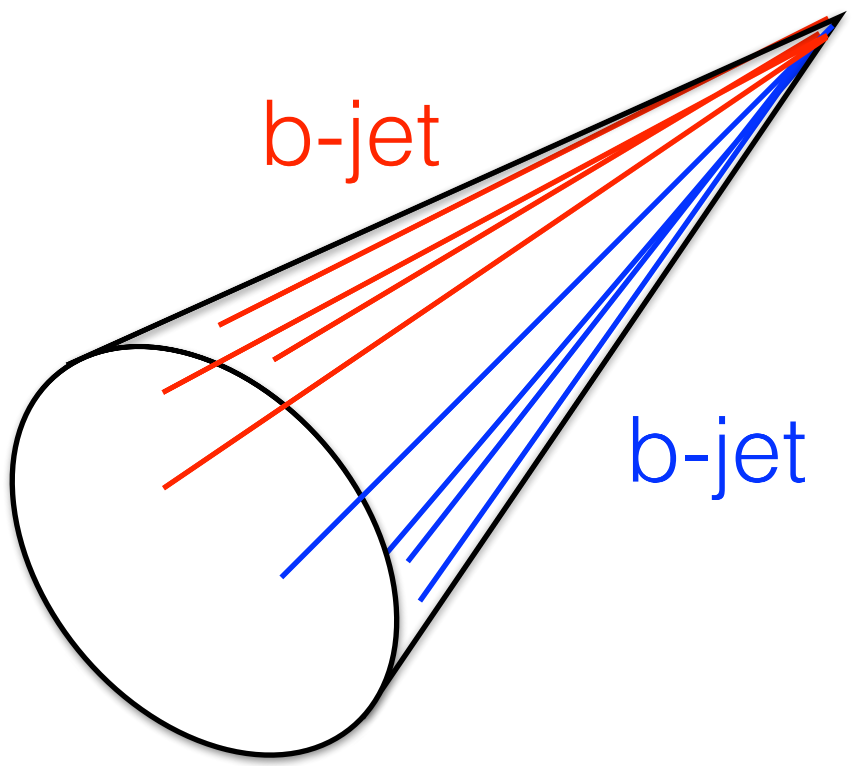
H→b$\bar{b}$ dominant probe of VH

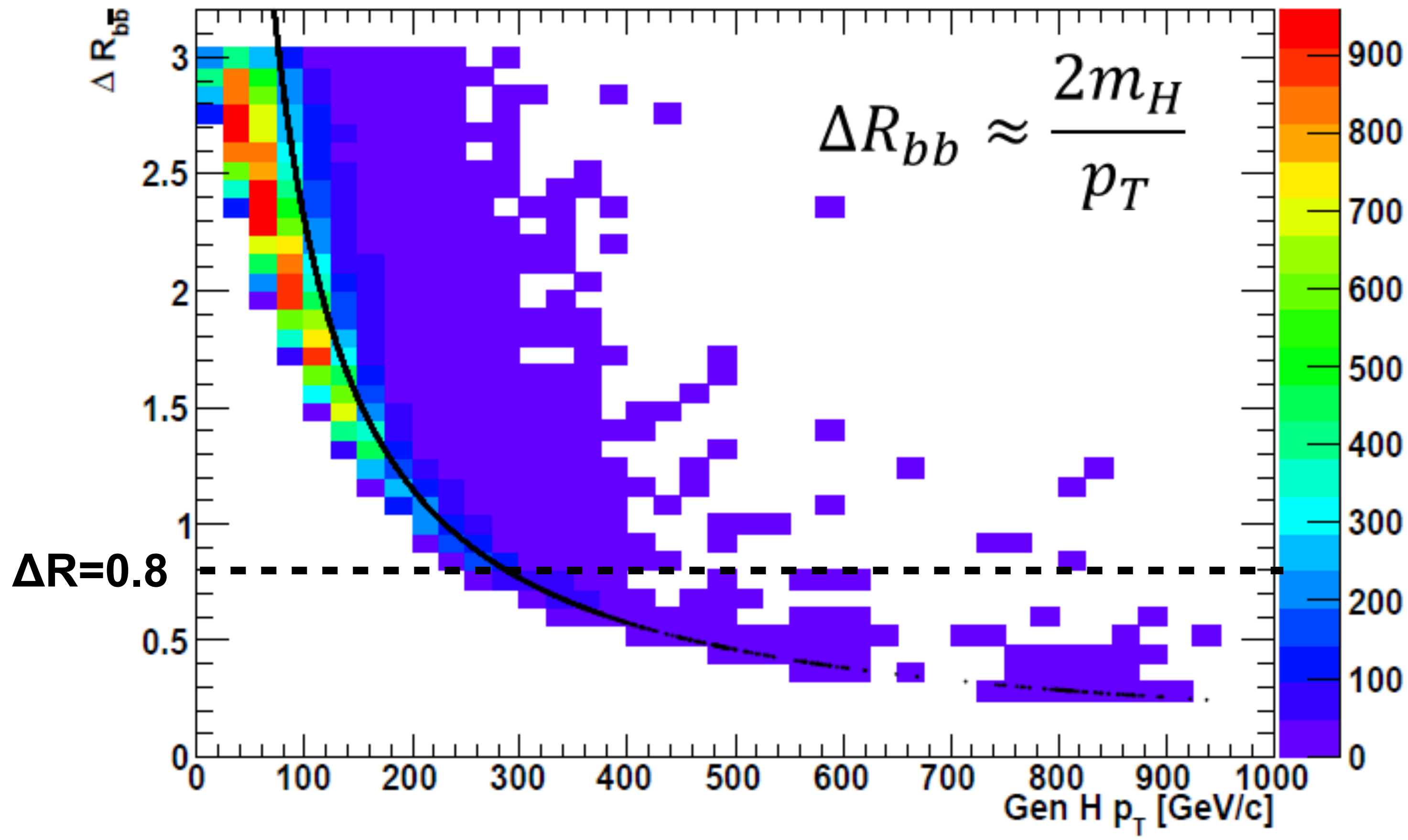


CMS-HIG-17-031

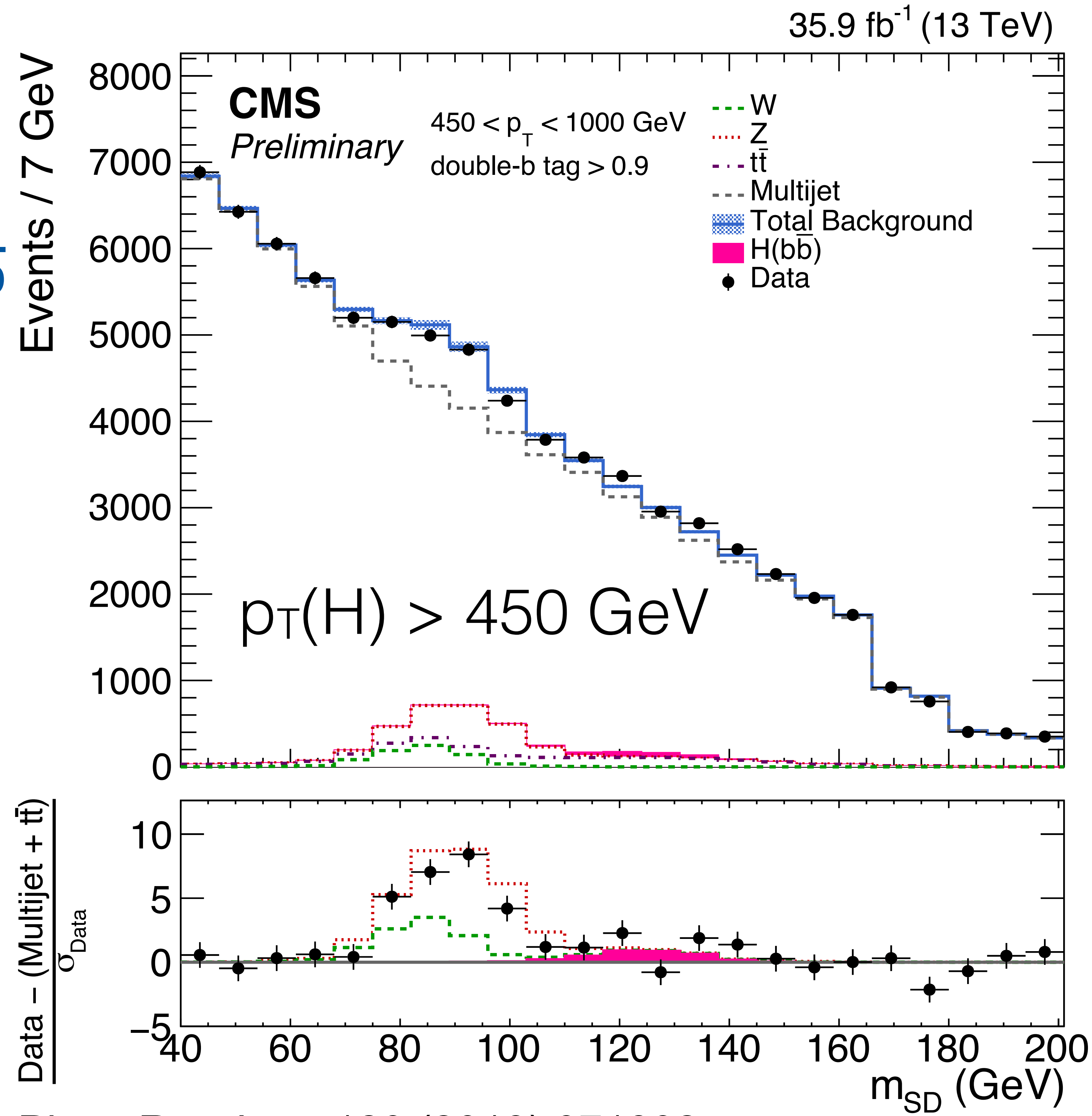
Submitted to Eur. Phys. J. C

- Angular separation between b-jets decreases with increasing Higgs boson momentum.
- Reconstruct **H→b$\bar{b}$ candidate as a single large-radius jet and use jet substructure techniques**.





- Trigger on high-p_T ISR jet.
- **First observation (5.1σ) of Z→b$\bar{b}$ in single merged jet topology.**
- Can **use the same techniques to improve VH differential measurement** in critical highest energy bins.

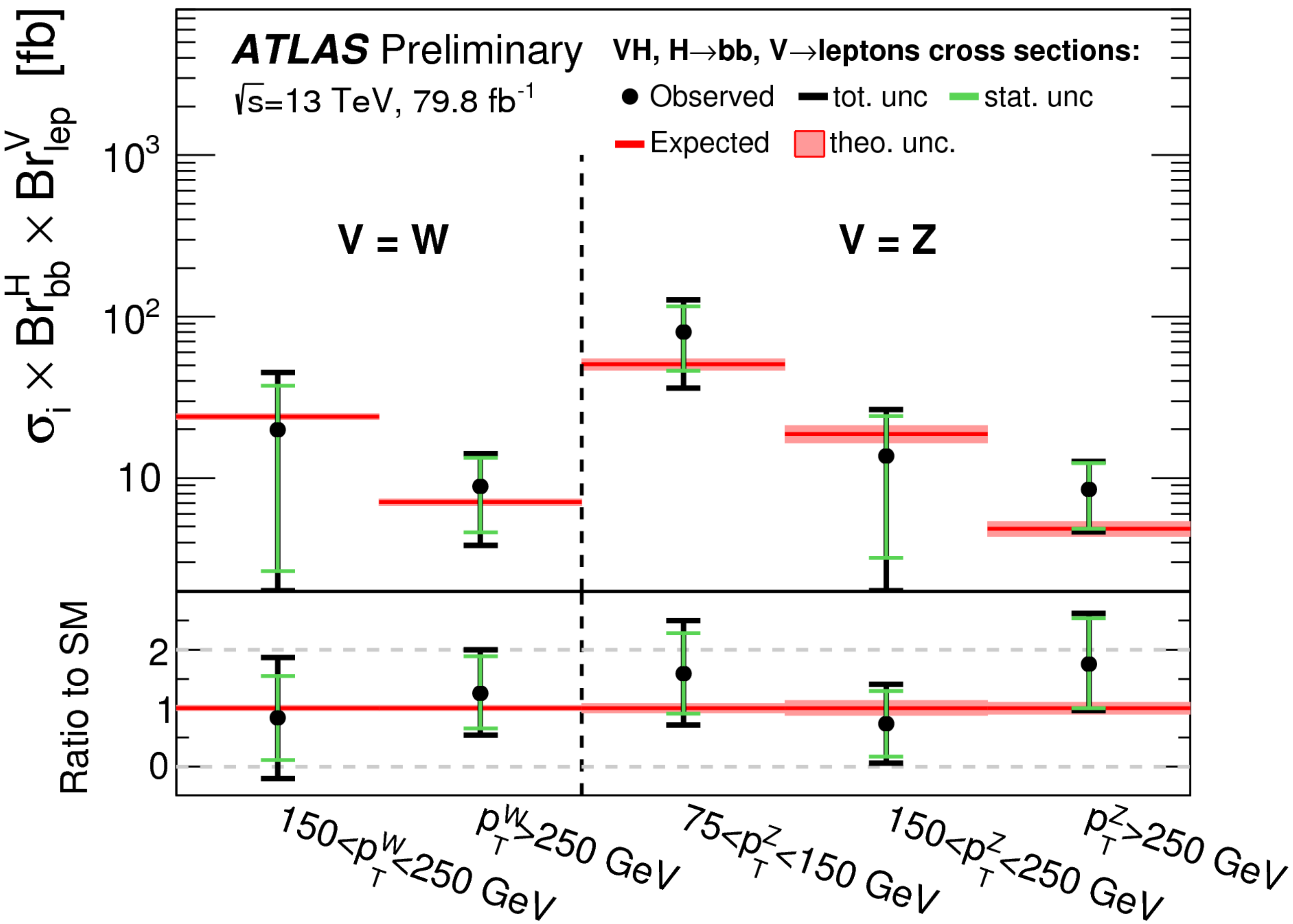


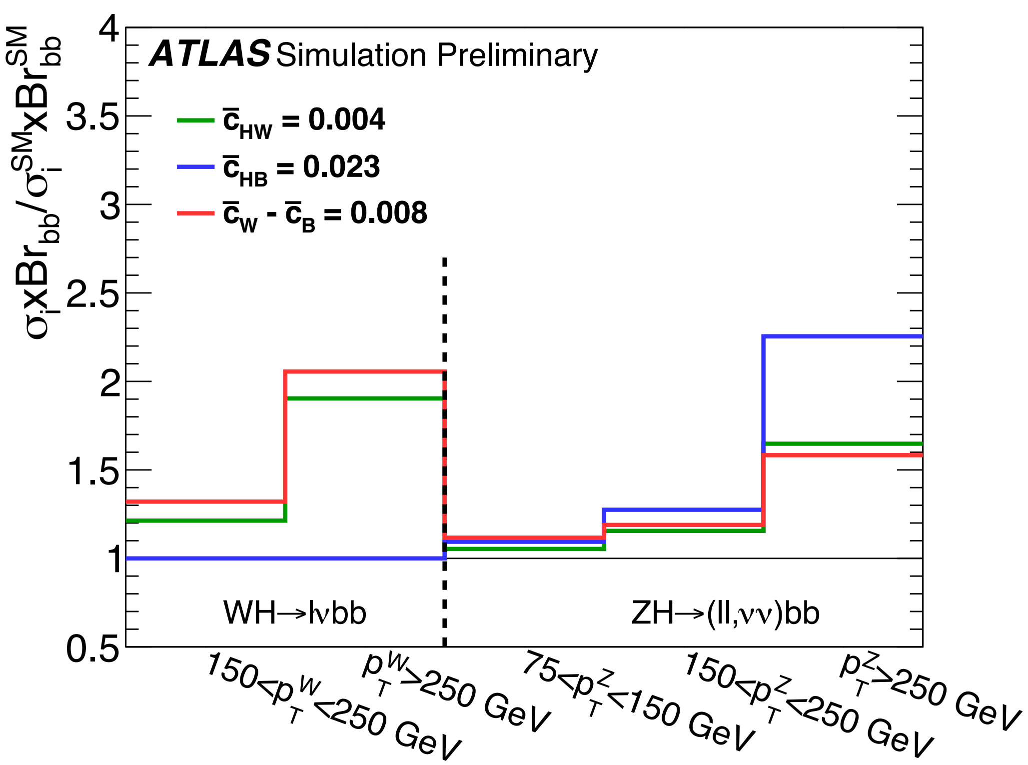
Phys. Rev. Lett. 120 (2018) 071802

First VH Differential Measurements from ATLAS

- First sensitive VH simplified template cross section measurements.
- First step in differential VH measurements.

NEW (this week)





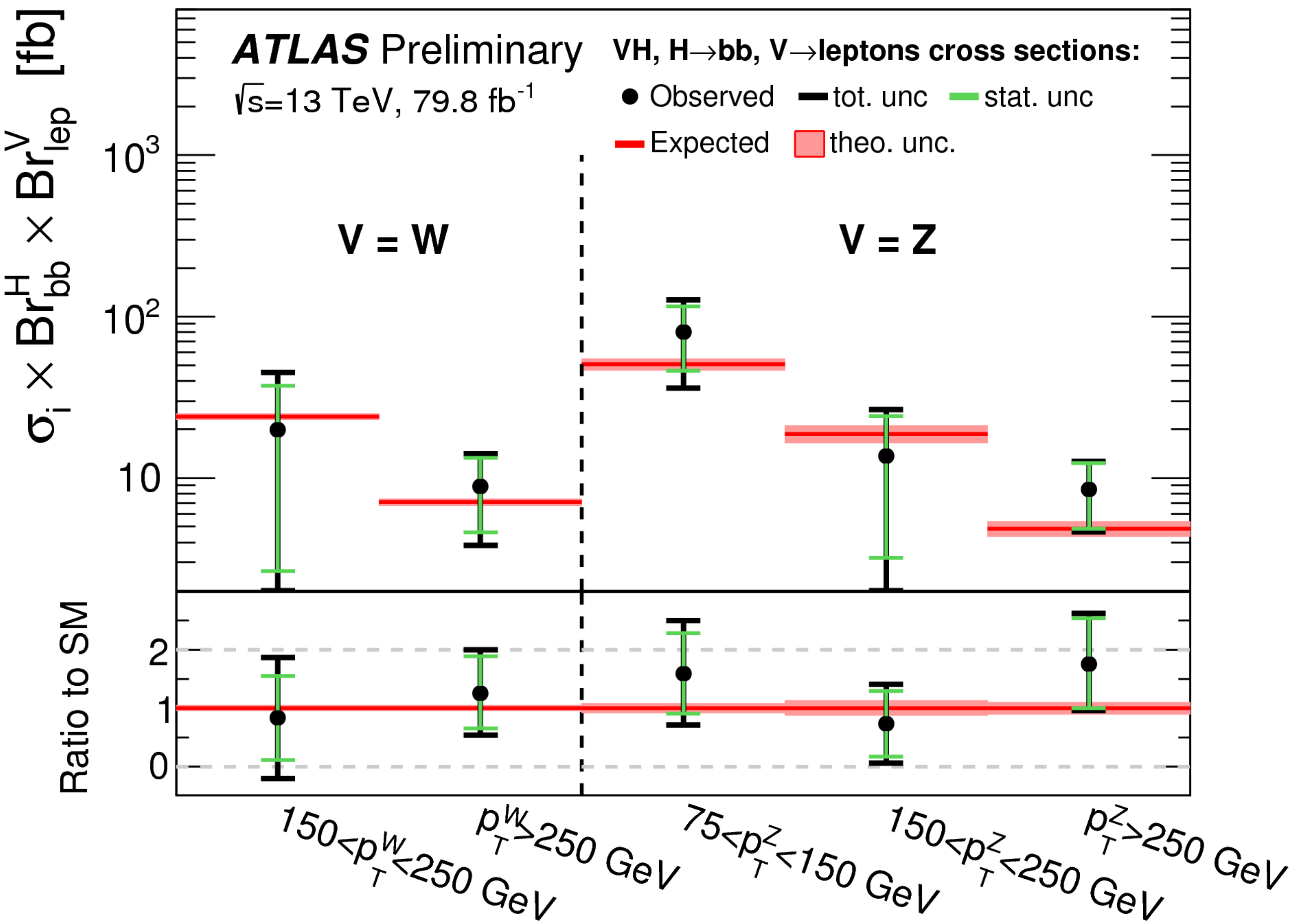
Parameter	Expected 95% CL intervals	Observed 95% CL intervals
$\bar{c}_{HW}$	$[-0.018, 0.004]$	$[-0.019, -0.010] \bigcup [-0.005, 0.006]$
$\bar{c}_{HB}$	$[-0.082, 0.023]$	$[-0.092, 0.029]$
$\bar{c}_W - \bar{c}_B$	$[-0.034, 0.080]$	$[-0.036, -0.024] \bigcup [-0.009, 0.010]$

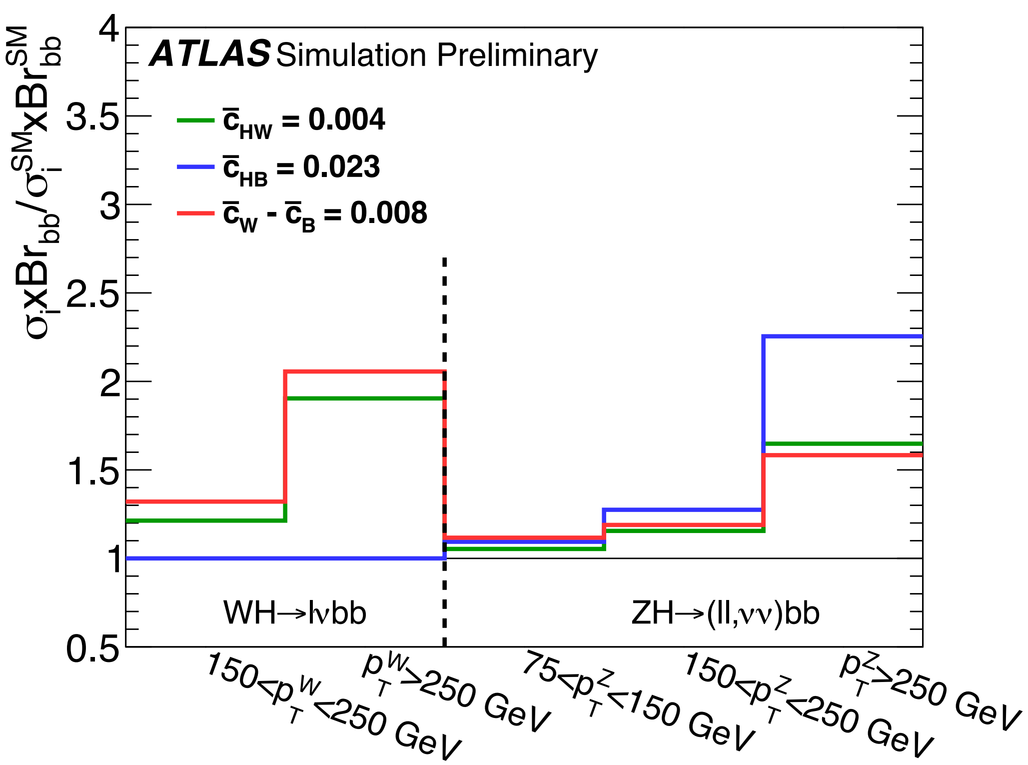
ATLAS-CONF-2018-053

First VH Differential Measurements from ATLAS

- **Next milestones:**
  - Enhance measurement precision in most interesting high-p_T(V) bins using **jet substructure (boosted H→b$\bar{b}$)**.
  - Include **2018 data** (nearly doubles 13 TeV statistics).
  - **Differential measurements of other observables** sensitive to BSM Higgs couplings:
    - M(VH)?

NEW (this week)





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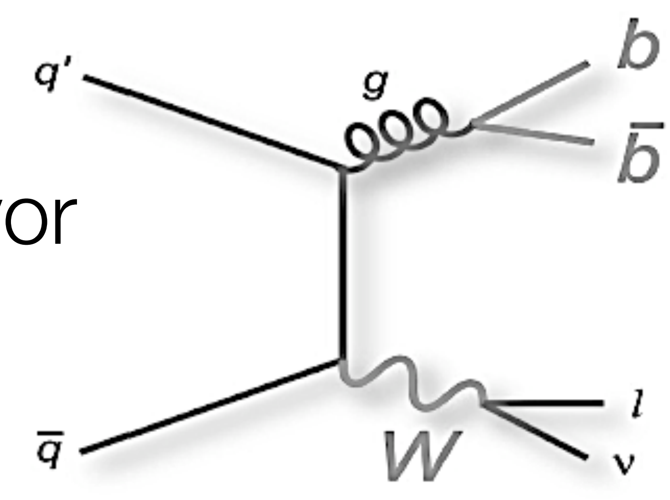
$\bar{c}_W - \bar{c}_B$	[−0.034, 0.080]	[−0.036,−0.024] ⋃ [−0.009, 0.010]

ATLAS-CONF-2018-053

Dedicated High-energy V+bb Measurement

- **$H \rightarrow b\bar{b}$ largest systematic uncertainty due to V+bb normalization.**
- V+bb norm. constrained in dedicated control region and extrapolated to signal region.
  - Similar strategy used by both ATLAS and CMS.
- With the large dataset now collected at $\sqrt{s}$=13 TeV **there is a clear opportunity to make dedicated V+bb measurements at high p_T(V).**
- The precision on this measurement will **likely be the limiting factor in measuring $H \rightarrow b\bar{b}$ for remainder of (HL-) LHC lifetime.**

V+heavy flavor (V+bb)



Uncertainty source	$\Delta\mu$	
Statistical	+0.26	−0.26
Normalization of backgrounds	+0.12	−0.12
Experimental	+0.16	−0.15
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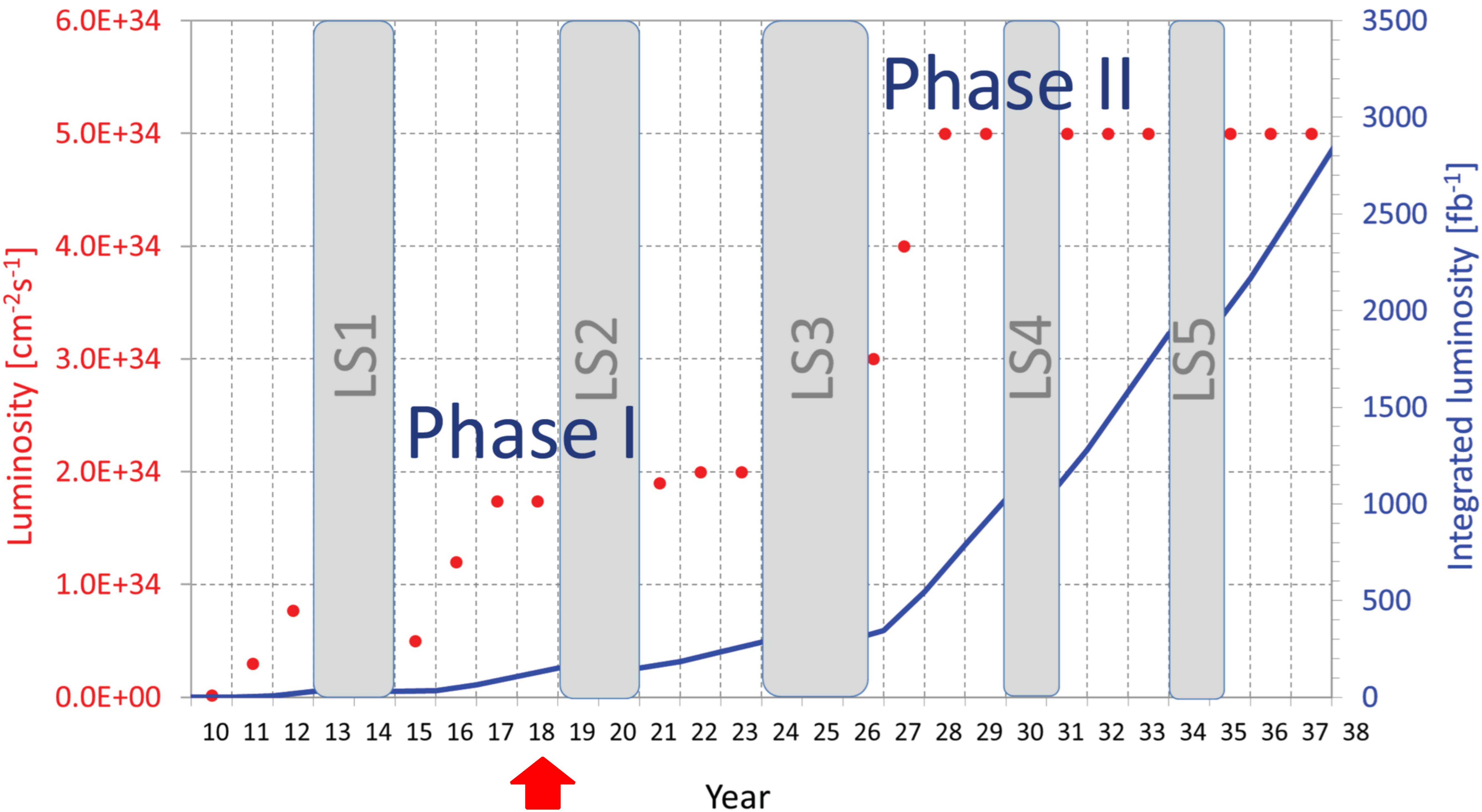
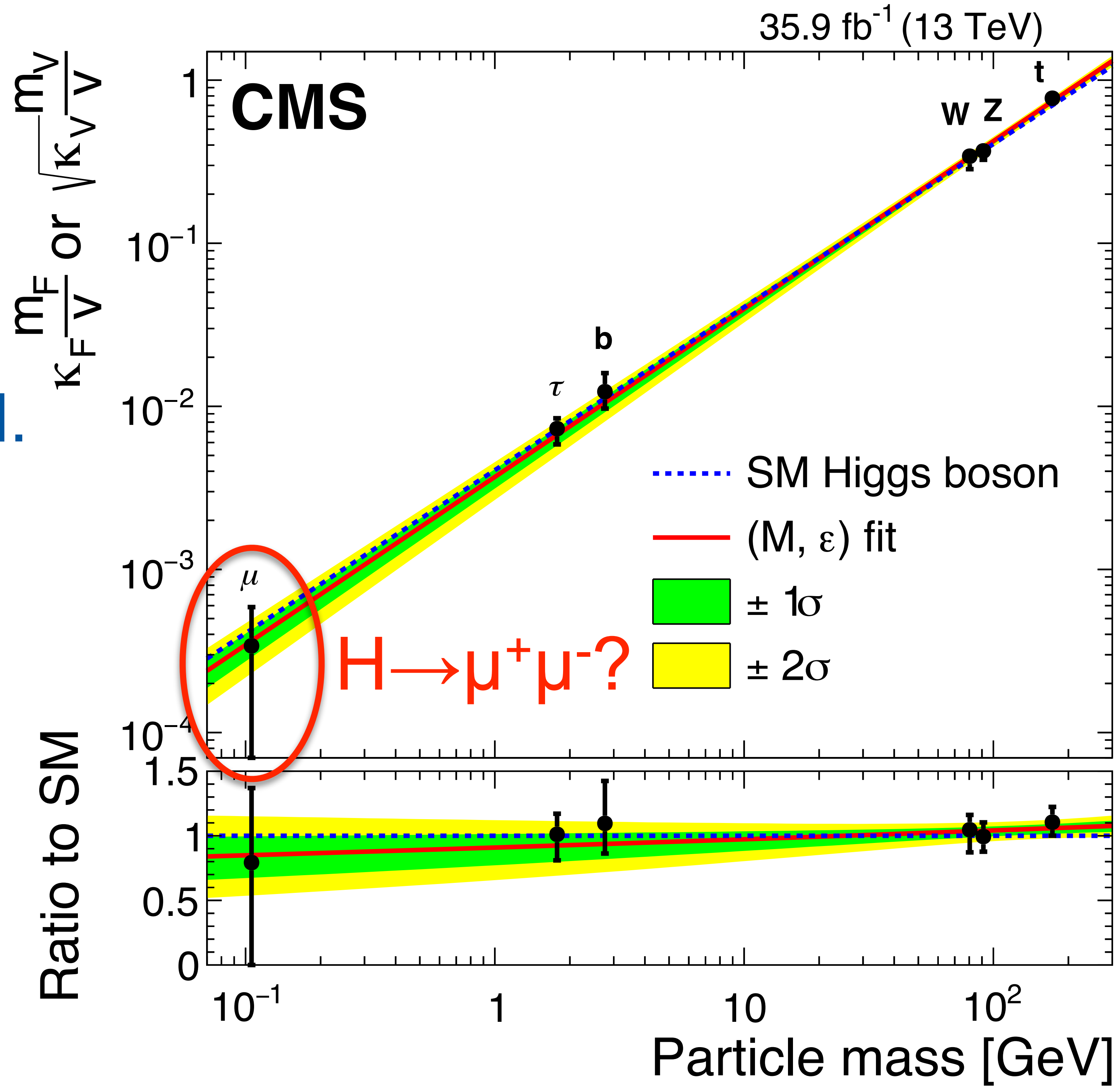
Other experimental uncertainties	+0.06	−0.05
MC sample size	+0.12	−0.12
Theory	+0.11	−0.09
Background modeling	+0.08	−0.08
Signal modeling	+0.07	−0.04
Total	+0.35	−0.33

(HL-) LHC Schedule



We are here (few % of final dataset)

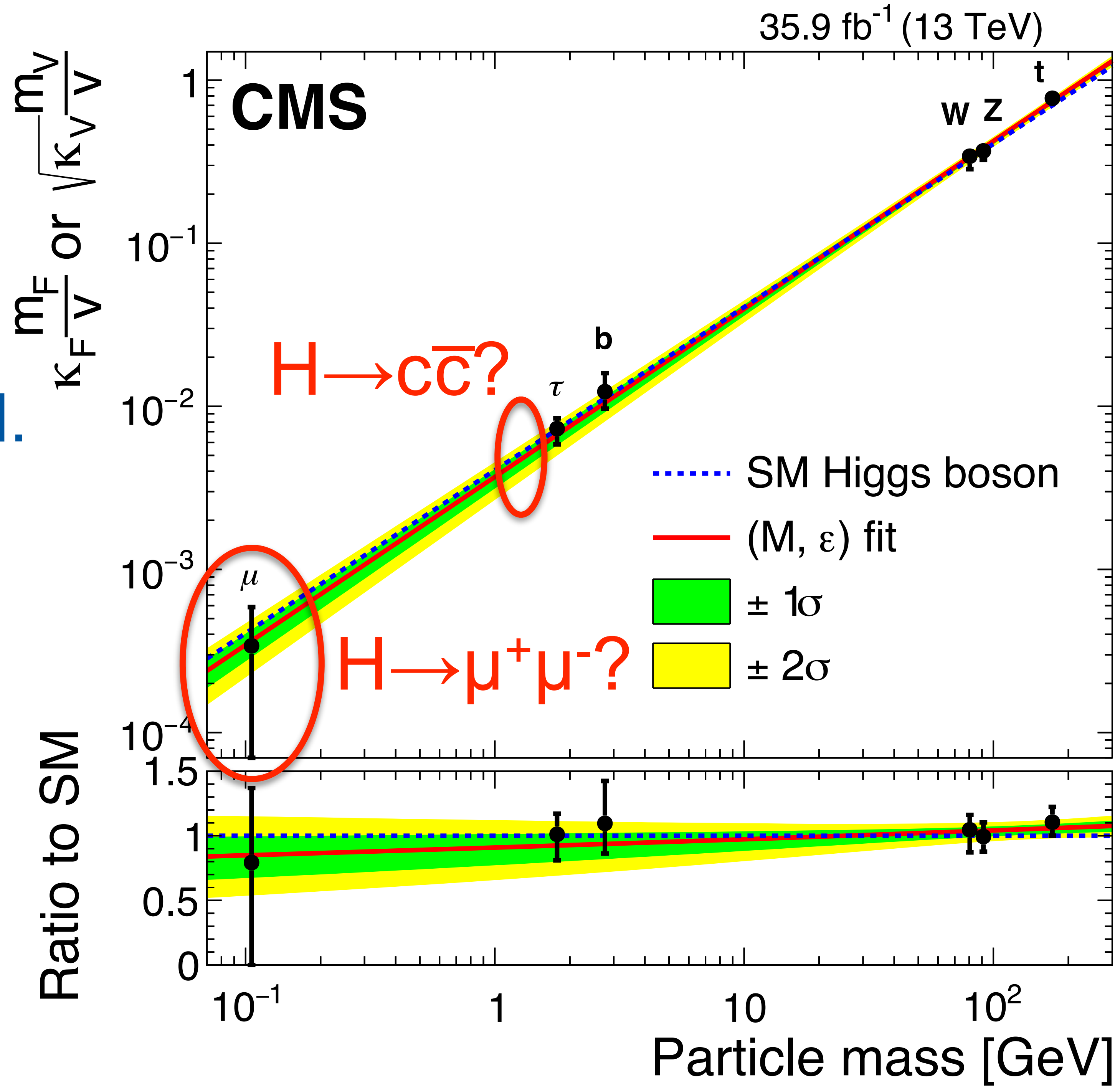
- Higgs Yukawa couplings to third generation fermions firmly and directly established.
- Second generation Yukawa couplings accessible during LHC lifetime?



CMS-HIG-17-031
Submitted to Eur. Phys. J. C

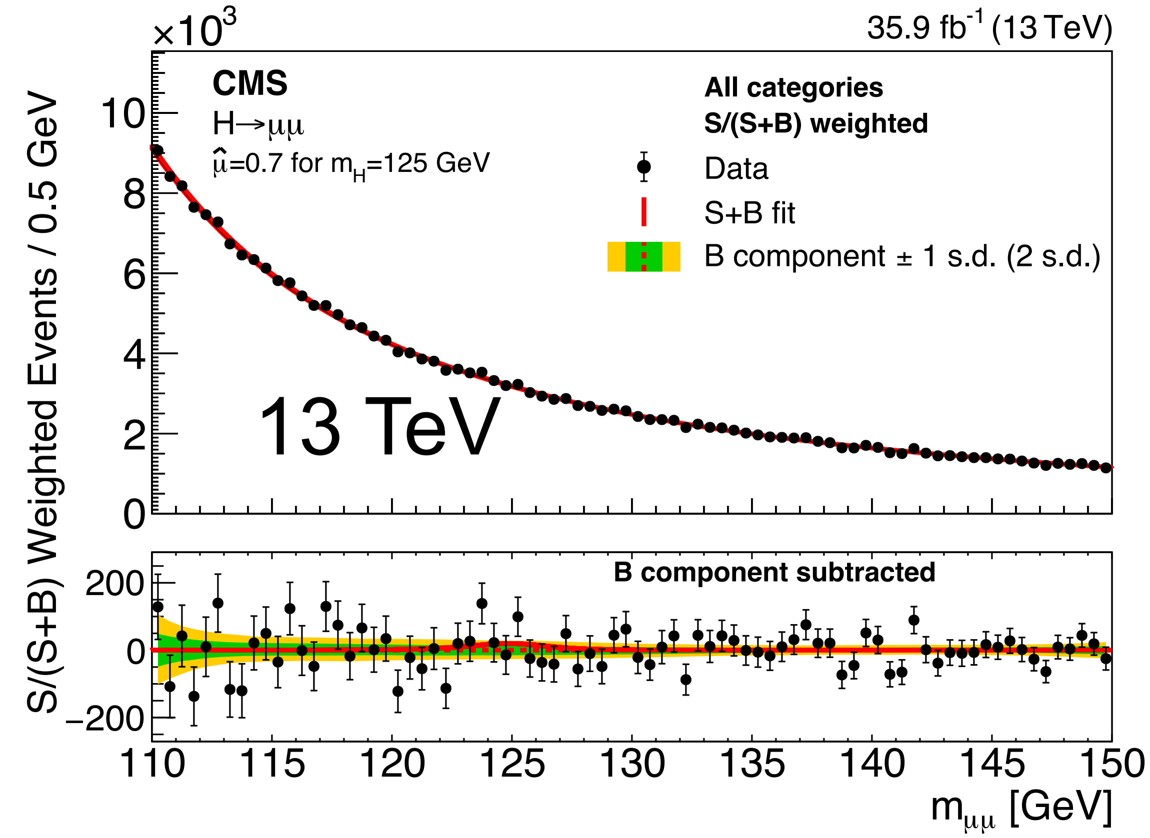
Second Generation Yukawa Couplings

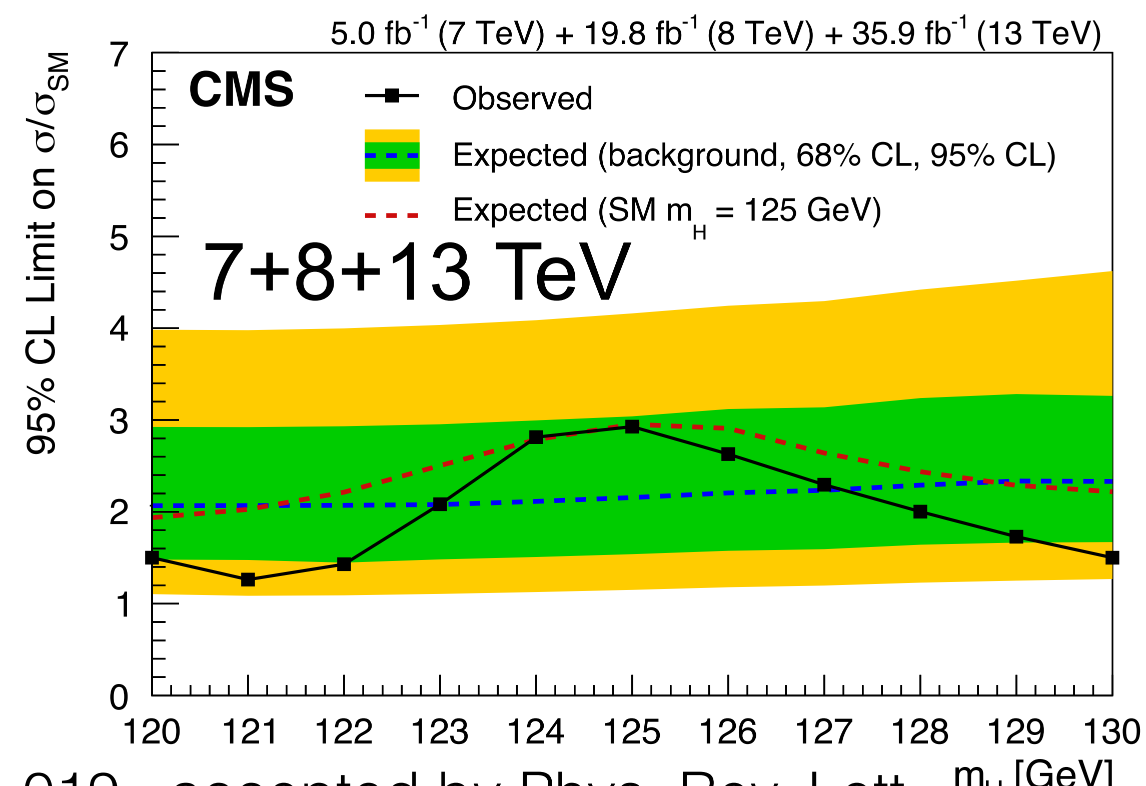
- Higgs Yukawa couplings to third generation fermions firmly and directly established.
- Second generation Yukawa couplings accessible during LHC lifetime?



CMS-HIG-17-031
Submitted to Eur. Phys. J. C

- Very rare decay: BR(H→μμ): ~0.022%
  - Clean experimental signature but large Z/γ*→μμ background.
- Categorize events by BDT score and fit $M_{\mu\mu}$.
- Observed (expected, no signal) 95% CL **upper limit on σxBR: 2.92 (2.16) times SM**.
  - significance: **0.9σ (1.0σ exp. with signal)**.
  - entirely statistics dominated.
- **Approaching sensitivity** to Higgs coupling **to second generation fermions**!
- **Evidence for H→μμ should be achievable with Run-3 data**, observation during HL-LHC.

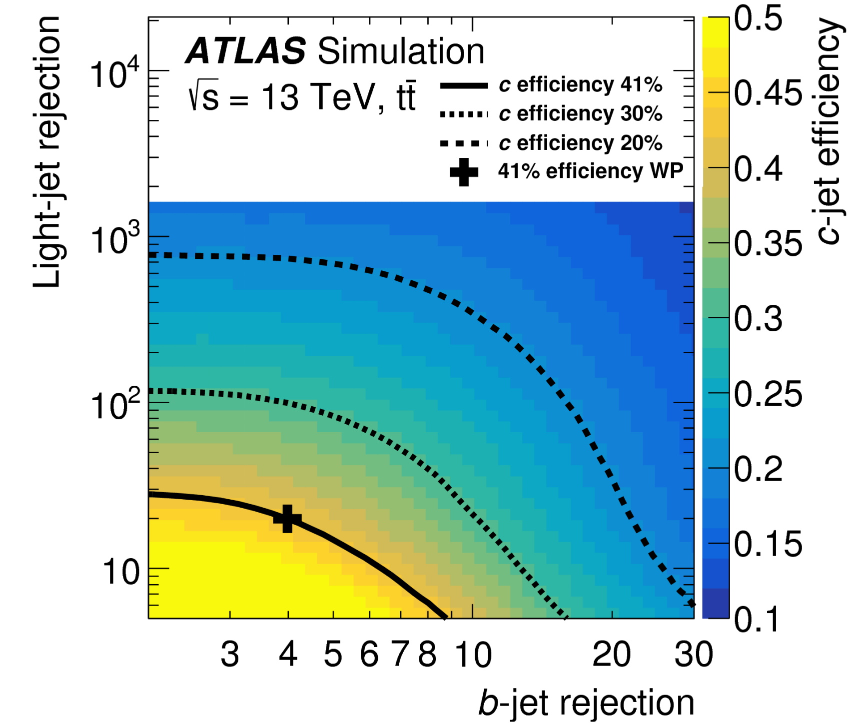


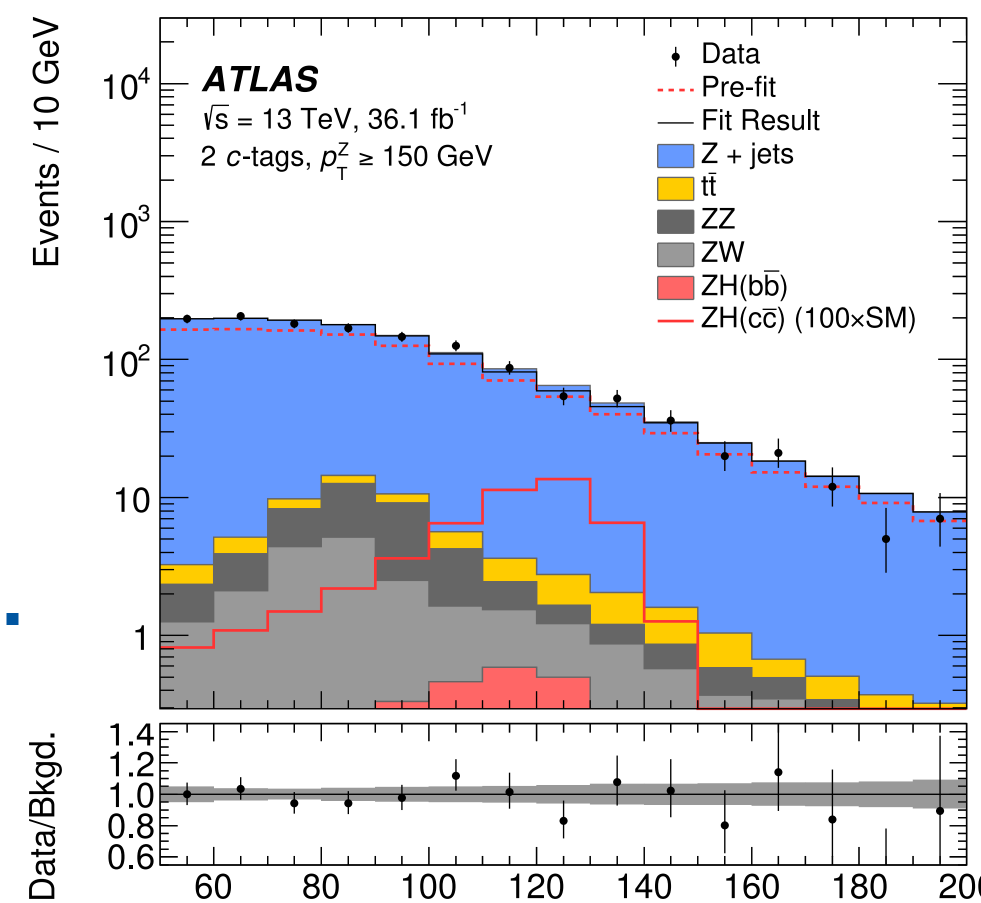


CMS-PAS-HIG-17-019, accepted by Phys. Rev. Lett.

H→c$\bar{c}$

- BR(H→c$\bar{c}$) = 2.7%
  - ~21 times less than BR(H→b$\bar{b}$).
- c-jets difficult to tag: generally intermediate properties between b-jets and udsg jets.
- First attempt by ATLAS with 2016 data via Z(ll)H(c$\bar{c}$) channel.
  - Upper limit on σ(VH)xBR(H→c$\bar{c}$): < 110 (150)xSM obs (exp).
- **Measurement of H→c$\bar{c}$ during LHC lifetime could be possible, but would require large improvements in c-tagging.**
  - Extensive work ongoing to improve resolved c-jet tagging and boosted cc-jet tagging.

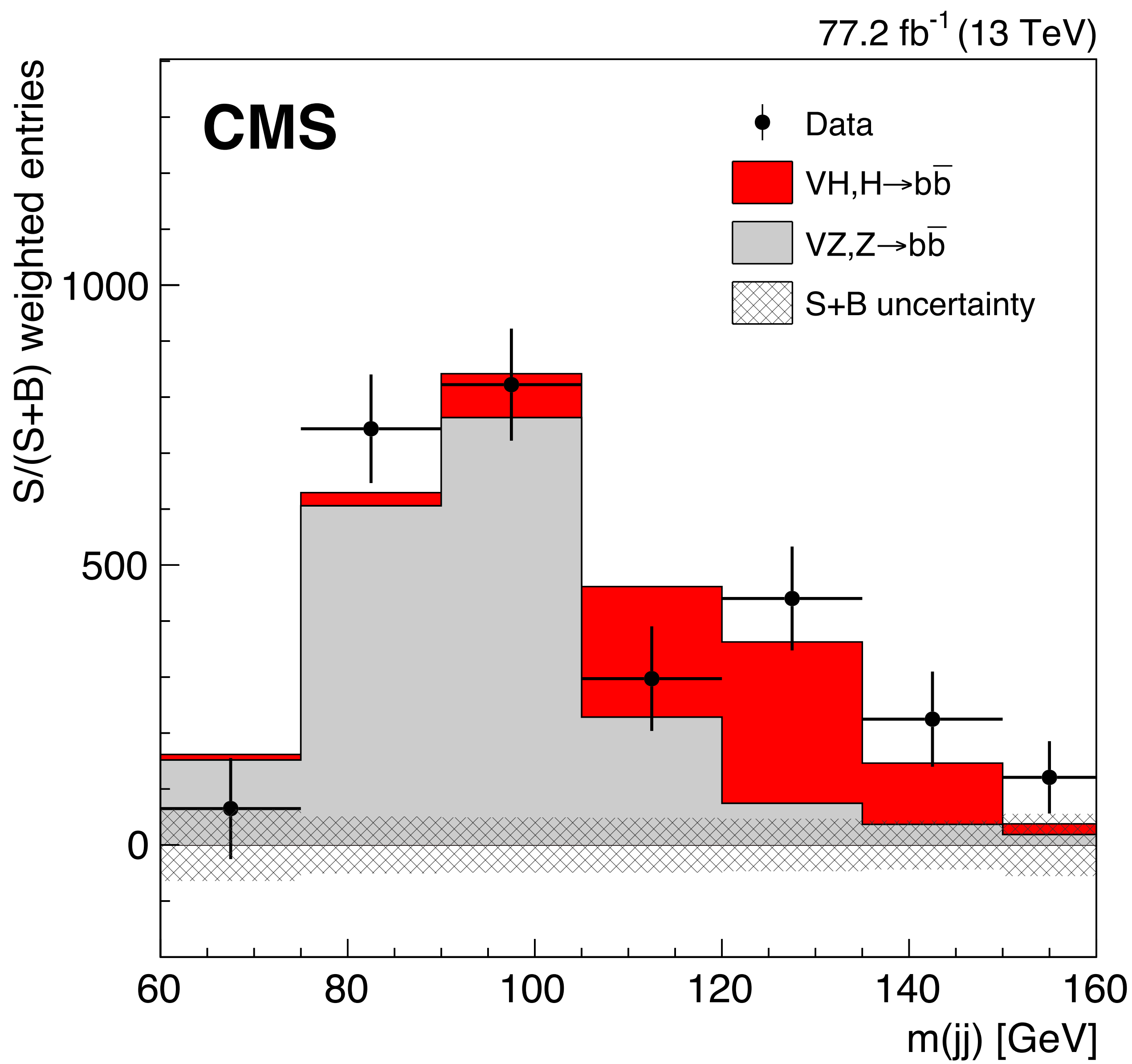




Phys. Rev. Lett. 120 (2018) 211802

Summary

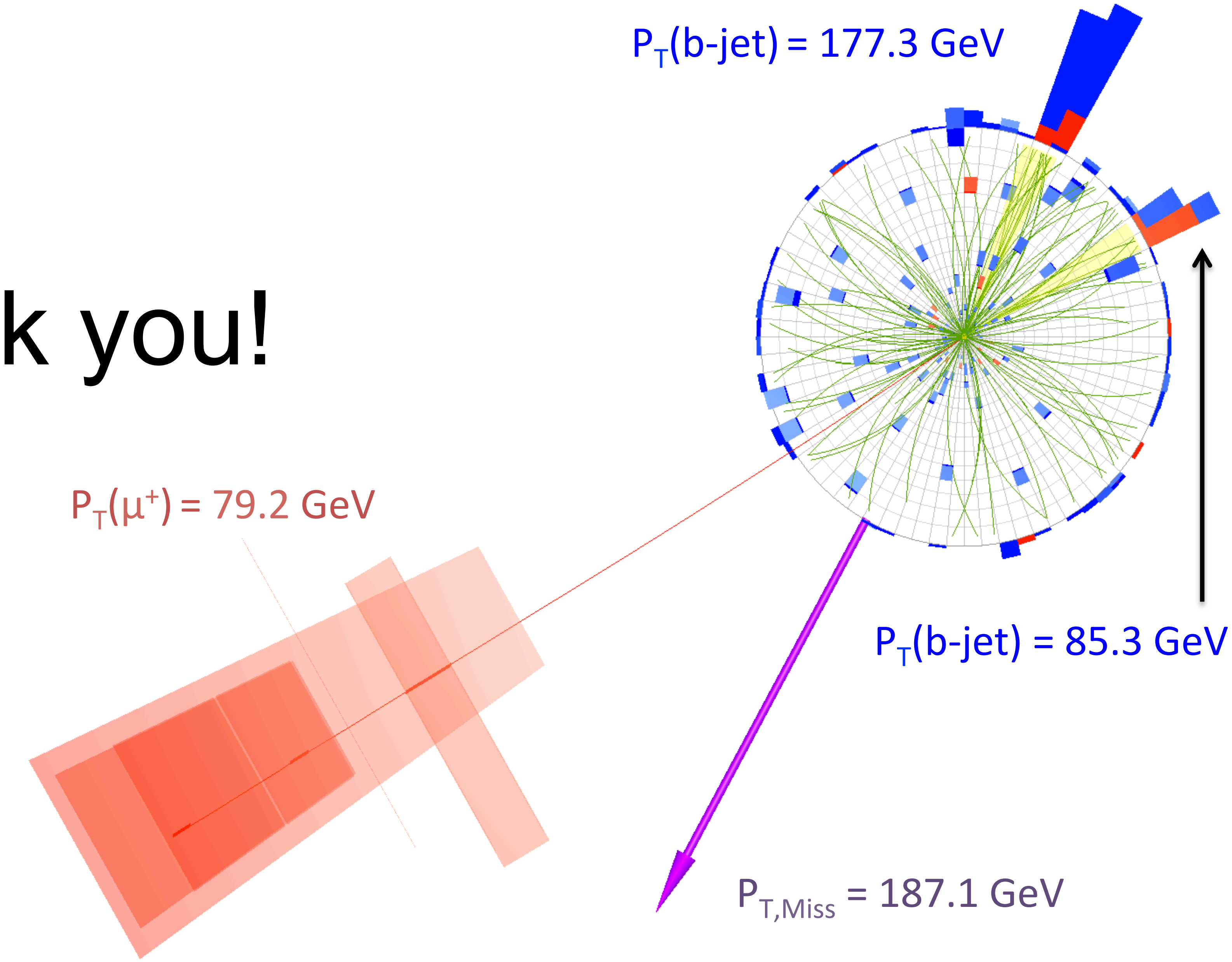
- Observation of Higgs boson decay to bottom quarks by the CMS collaboration.
  - **5.5σ** (5.6σ) observed (expected), **μ = 1.04 ± 0.20**



- Yukawa coupling to bottom quarks firmly and directly established.

- This observation is just the beginning of an era of H→bb precision measurements at the LHC.
  - Expect multiple interesting VH precision measurements in the near future.

Thank you!



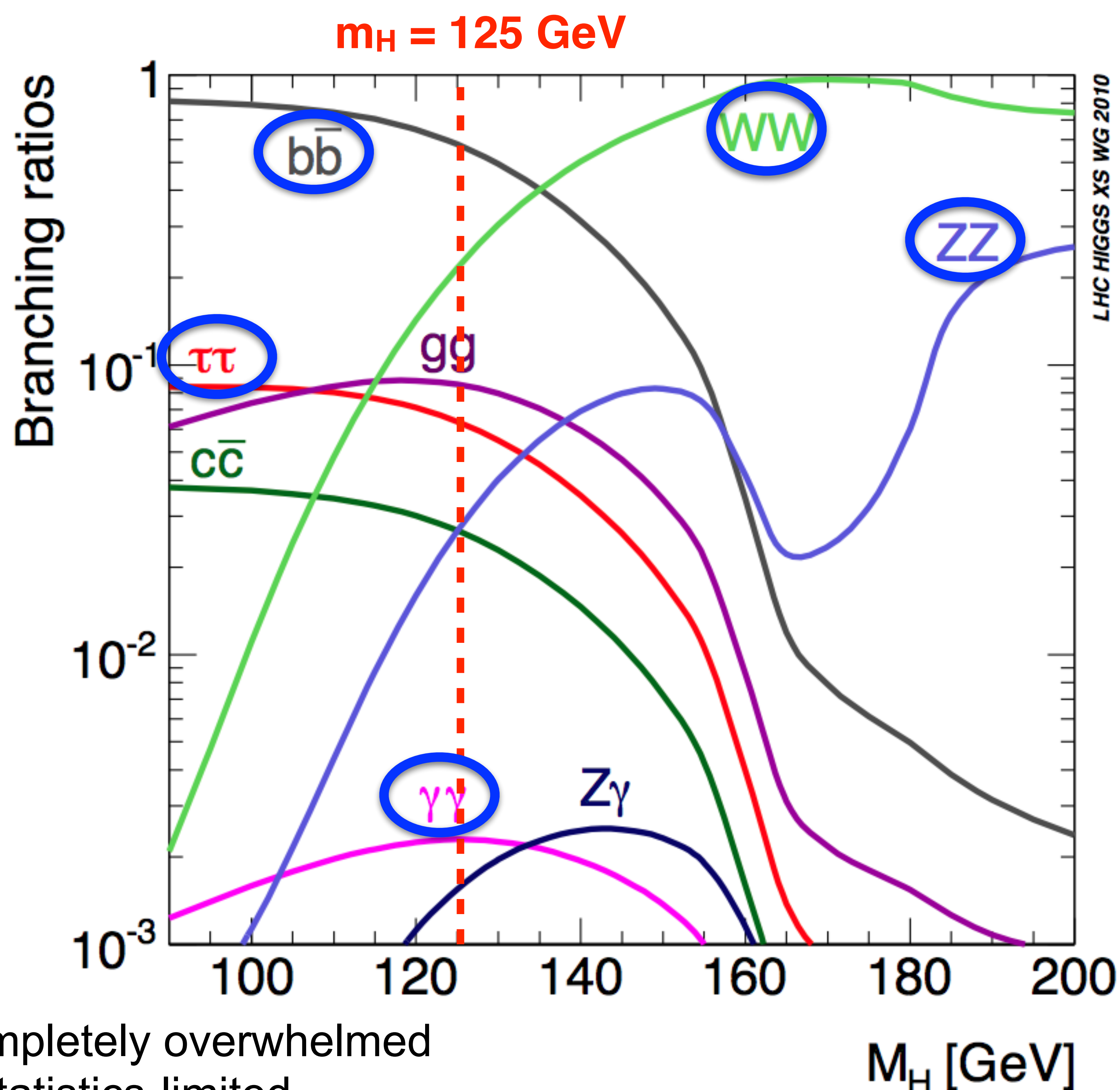
CMS Experiment at LHC, CERN
Data recorded: Wed Oct 18 03:06:39 2017 CDT
Run/Event: 305208 / 457843574
Lumi section: 286

Phys. Rev. Lett. 121, 121801

Additional Material

Where to measure the Higgs at the LHC

- At m_H ~ 125 GeV, many experimentally accessible final states at LHC.
- **H→γγ, H→ZZ:**
  - **Clean signature** and good control over background.
- **H→WW:**
  - Missing energy due to neutrinos from W→lν decays.
- **H→ττ:**
  - τ reconstruction more difficult and significant background.
- **H→$b\bar{b}$:**
  - Largest branching fraction but very difficult to control background.

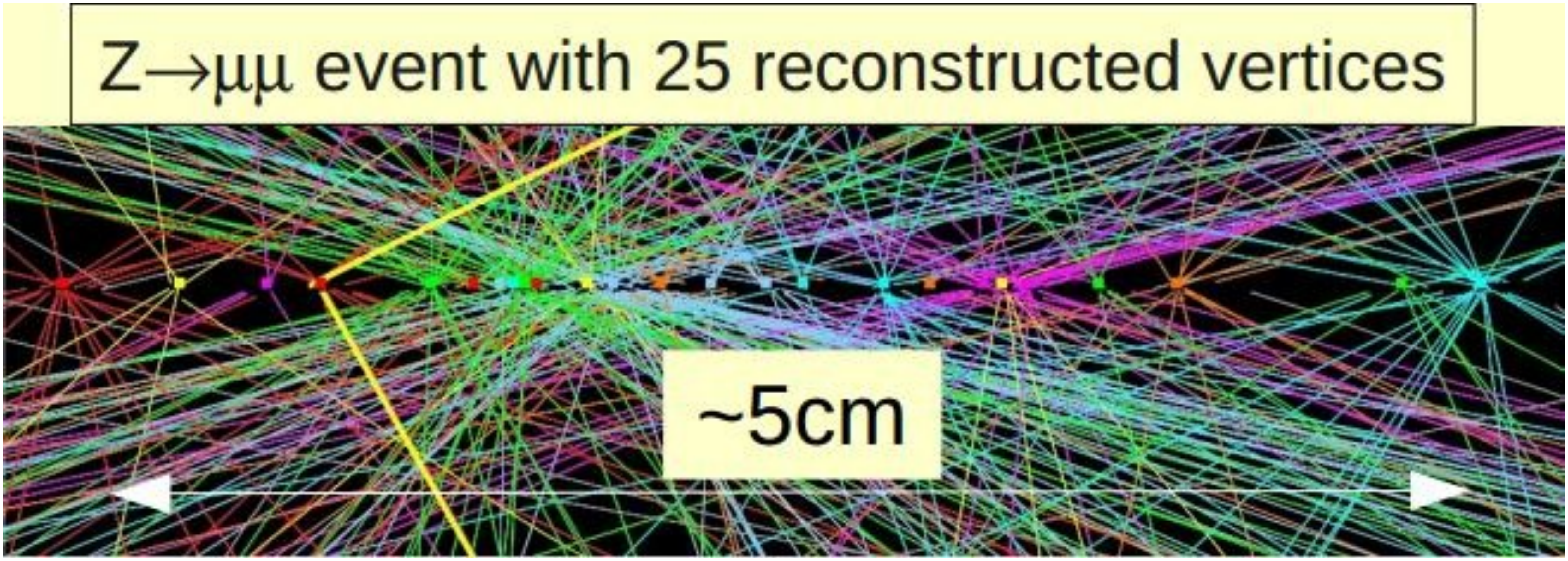


Remaining Higgs decays either completely overwhelmed by background or currently statistics-limited.

Pile-up

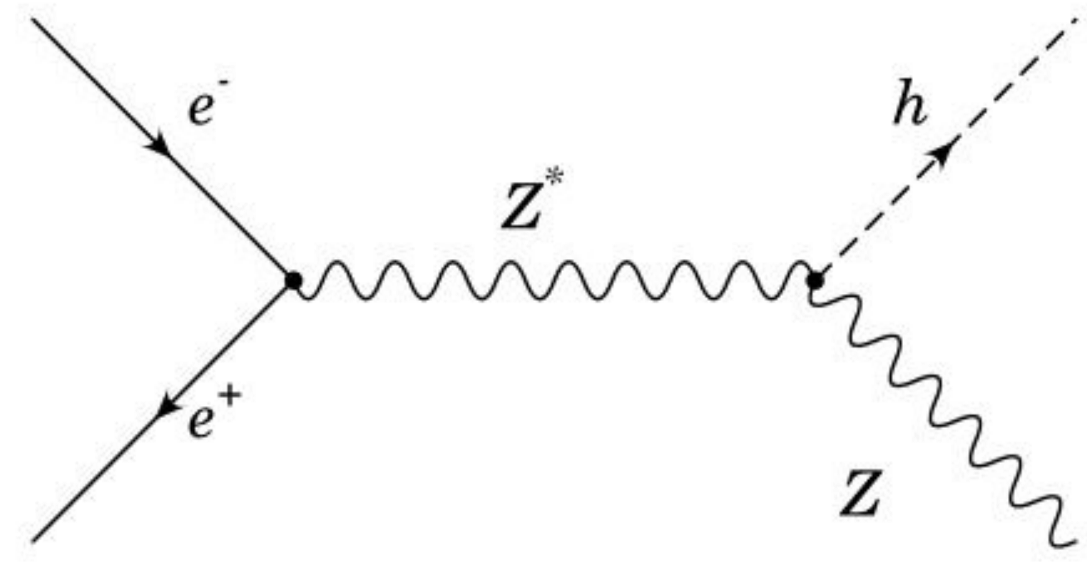
- In 2017, up to 70 interactions per bunch crossing!
  - 38 interactions per proton bunch crossing on average during 2017.

- Crucial to mitigate uncertainties due to pile-up:
  - Jet energy, E_T^{miss}, secondary vertex reconstruction for b-tagging all critical and sensitive to pile-up.



Previous Results: VH→$b\bar{b}$ (m_H = 125 GeV)

	signal strength	significance (exp)	significance (obs)
CDF+D0 [1]	$1.9^{+0.8}_{-0.7}$	1.5σ	2.8σ
ATLAS Run 1 [2]	$0.52^{+0.40}_{-0.37}$	2.6σ	1.4σ
CMS Run 1 [3]	$0.89^{+0.47}_{-0.44}$	2.5σ	2.1σ
ATLAS+CMS Run 1 [4]	$0.79^{+0.29}_{-0.27}$	3.7σ	2.6σ
ATLAS Run 2 [5]	$1.20^{+0.42}_{-0.36}$	3.0σ	3.5σ



- ZH "Higgs-strahlung" channel used at LEP to constrain m_H > 115 GeV.
- "Signal strength":
  - $\mu = (\sigma \times BR) / (\sigma \times BR)_{SM}$

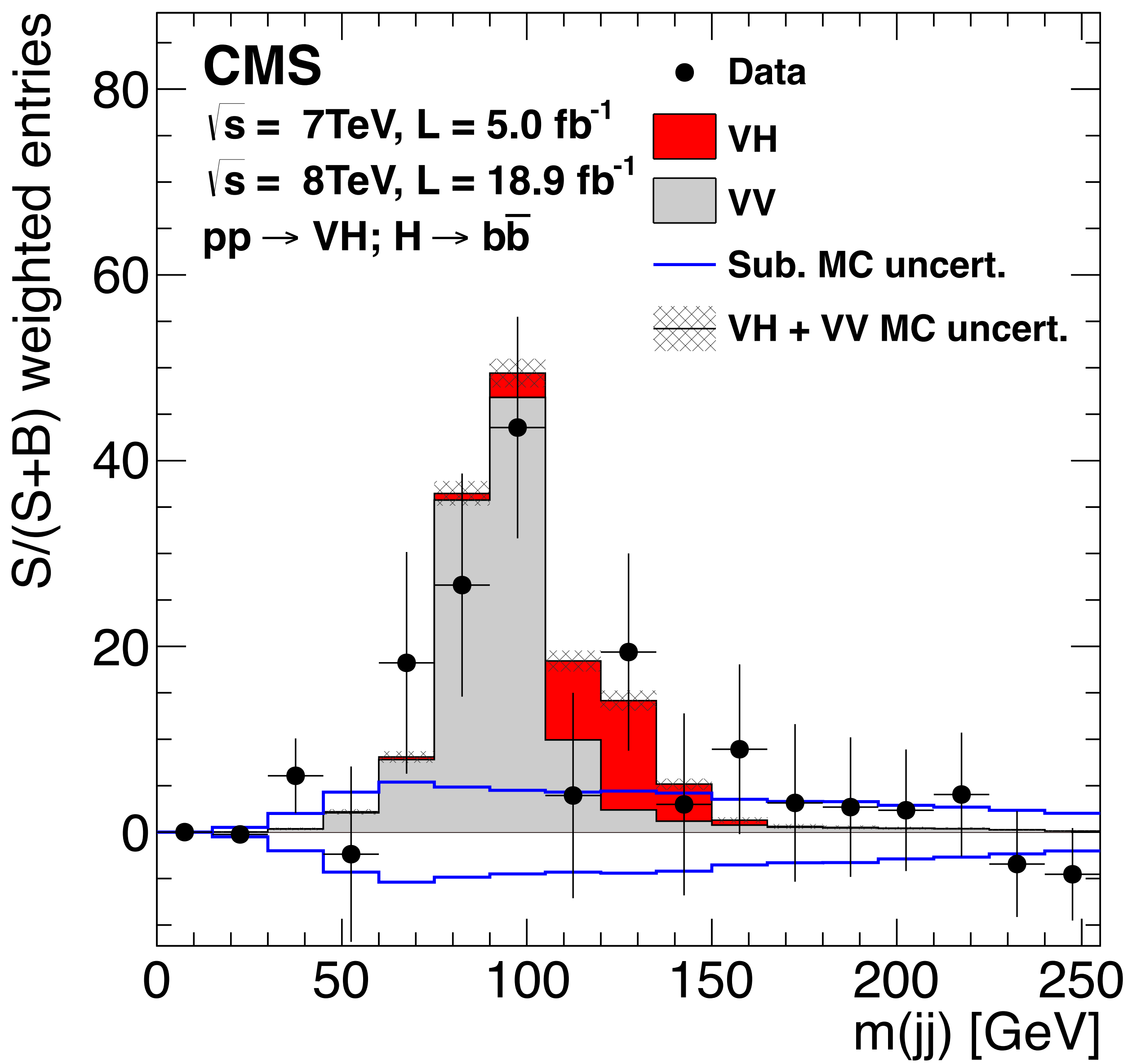
[1] Phys. Rev. Lett. 109 (2012) 071804
[2] Eur.Phys.J. C75(5), 212 (2015)
[3] JHEP08(2016)045
[4] JHEP01(2015)069
[5] arXiv:1708.03299, submitted to JHEP

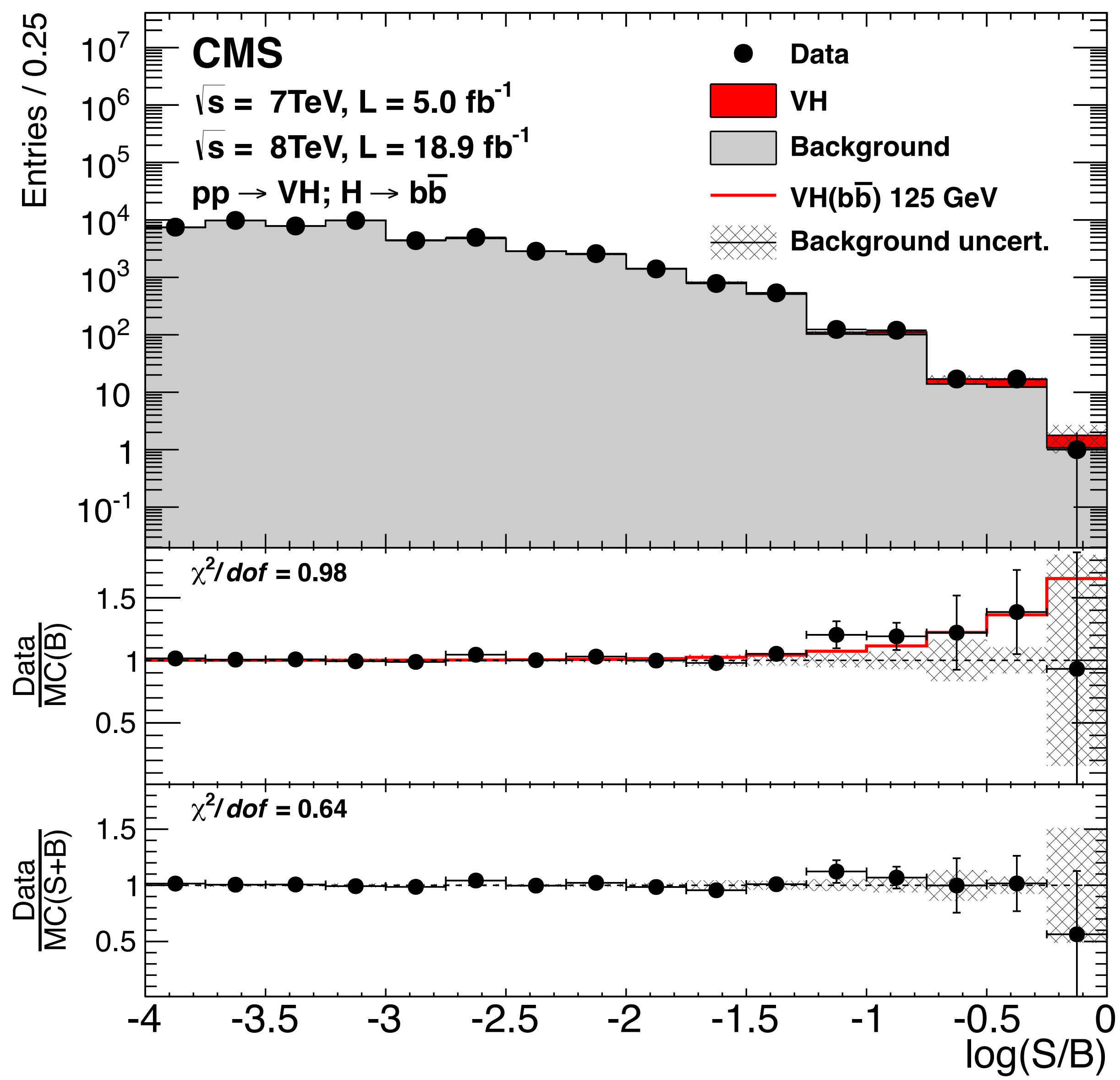
- 2.1σ excess over background-only expectation.

5 fb^{-1} (7 TeV) + 19 fb^{-1} (8 TeV)

- Signal strength: μ = 0.9 ± 0.5.

CMS-HIG-13-012

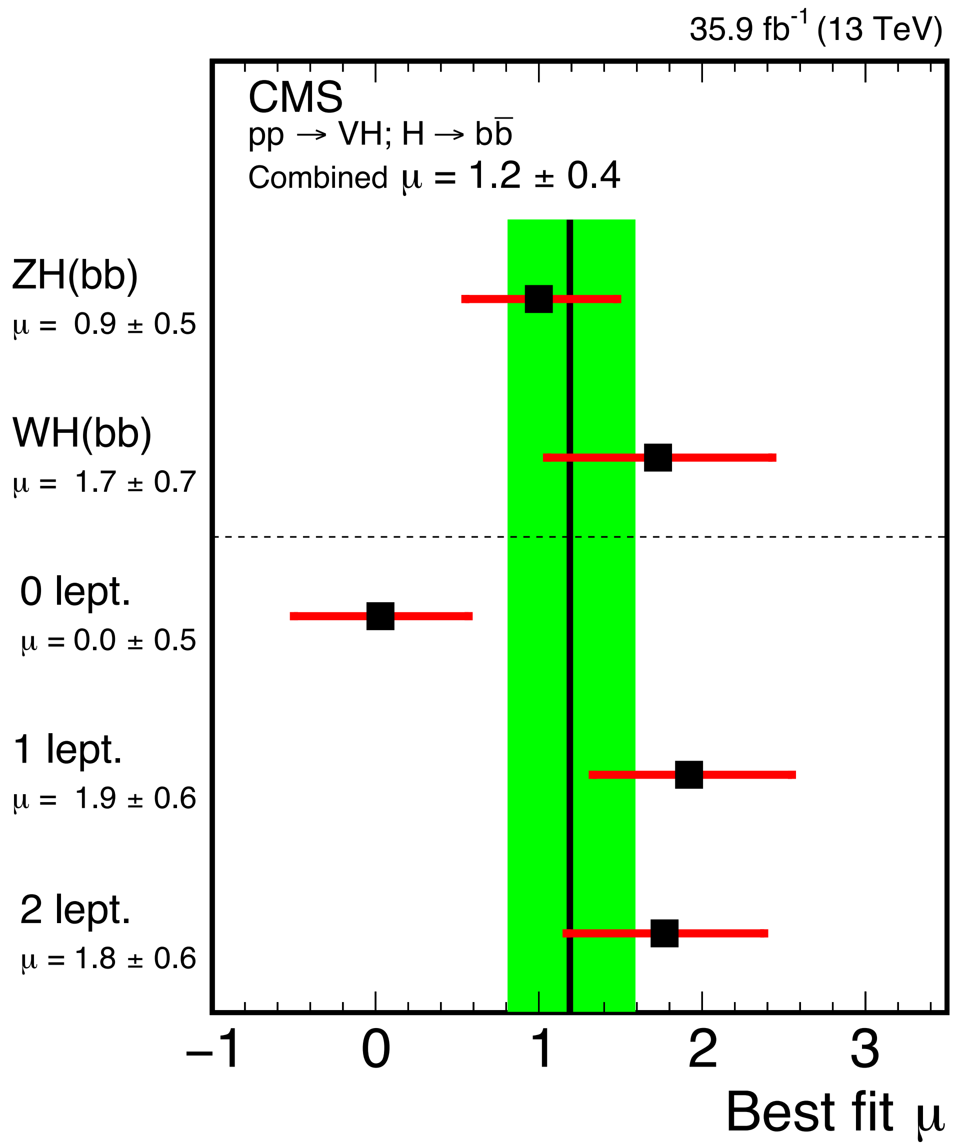


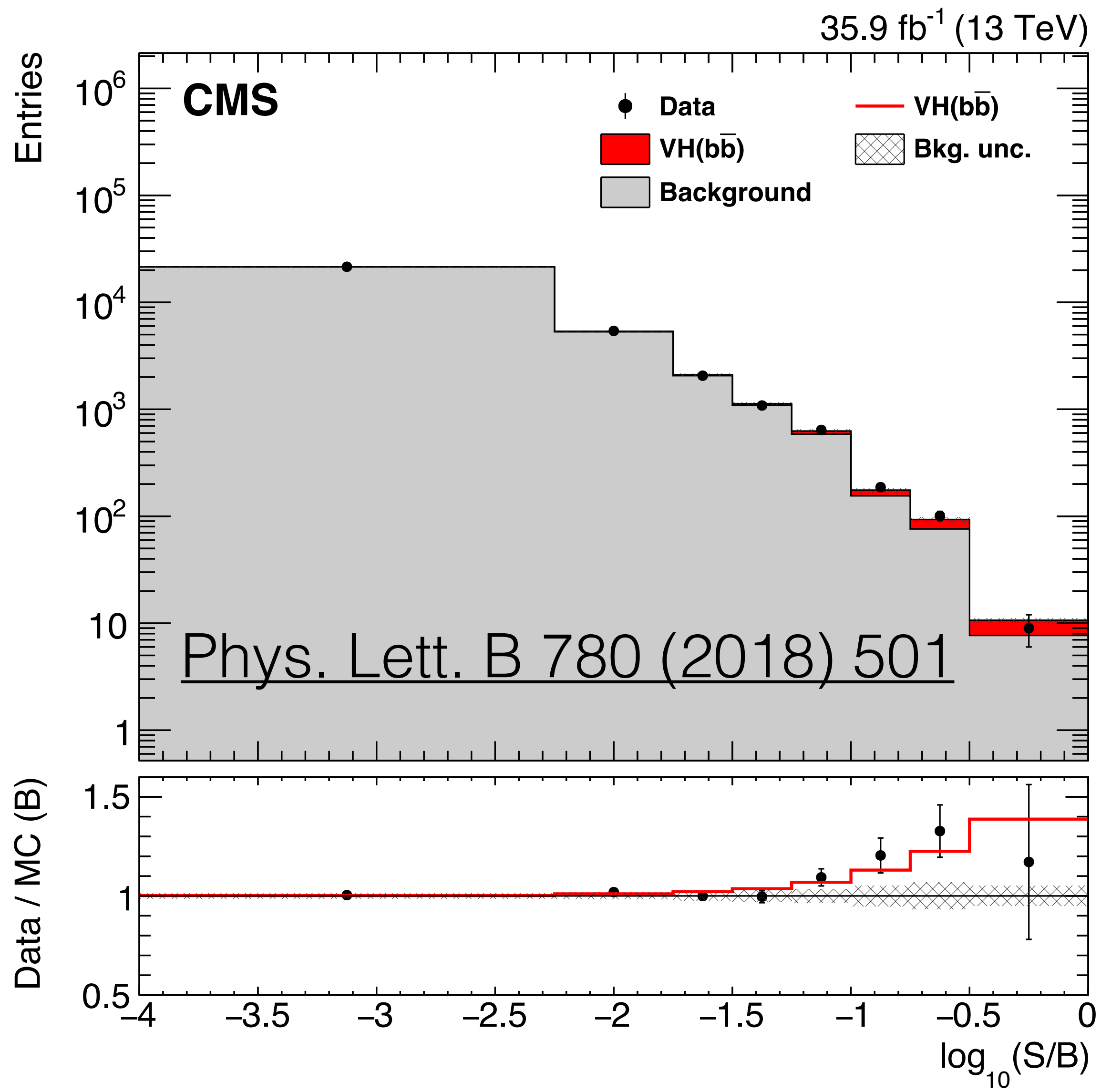


VH, H→$b\bar{b}$ Evidence Result with 36 fb^{-1} 2016 data

- Simultaneous fit of BDT distribution in Z(ll), Z(vv), and W(lv) channels.

$$\mu = 1.19^{+0.21}_{-0.20}(stat)^{+0.34}_{-0.32}(syst)$$



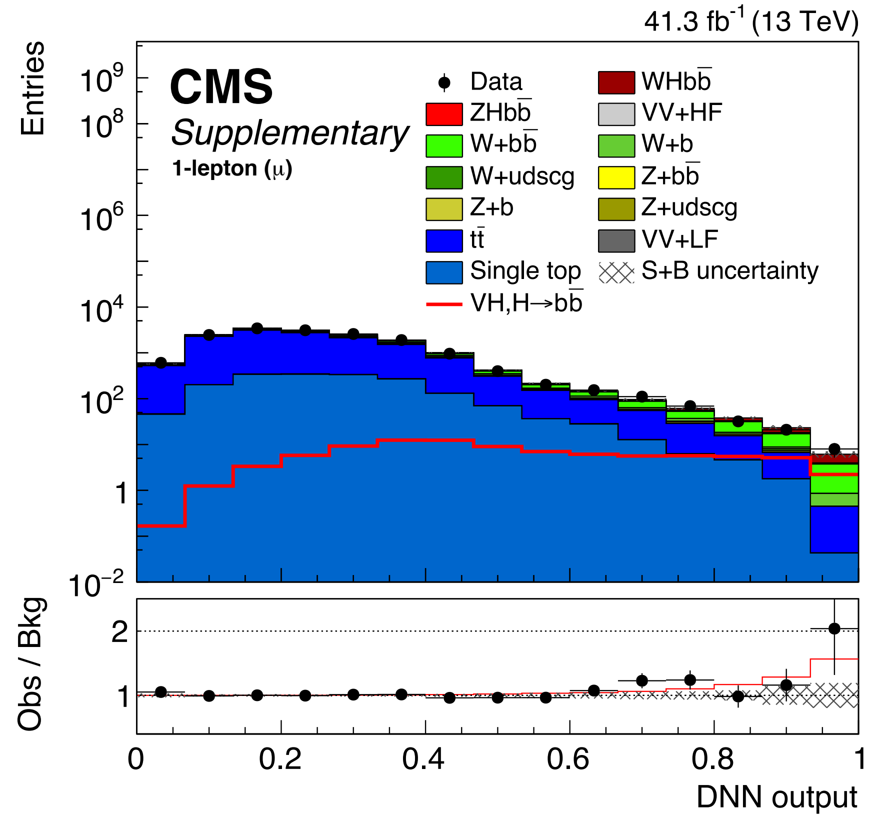


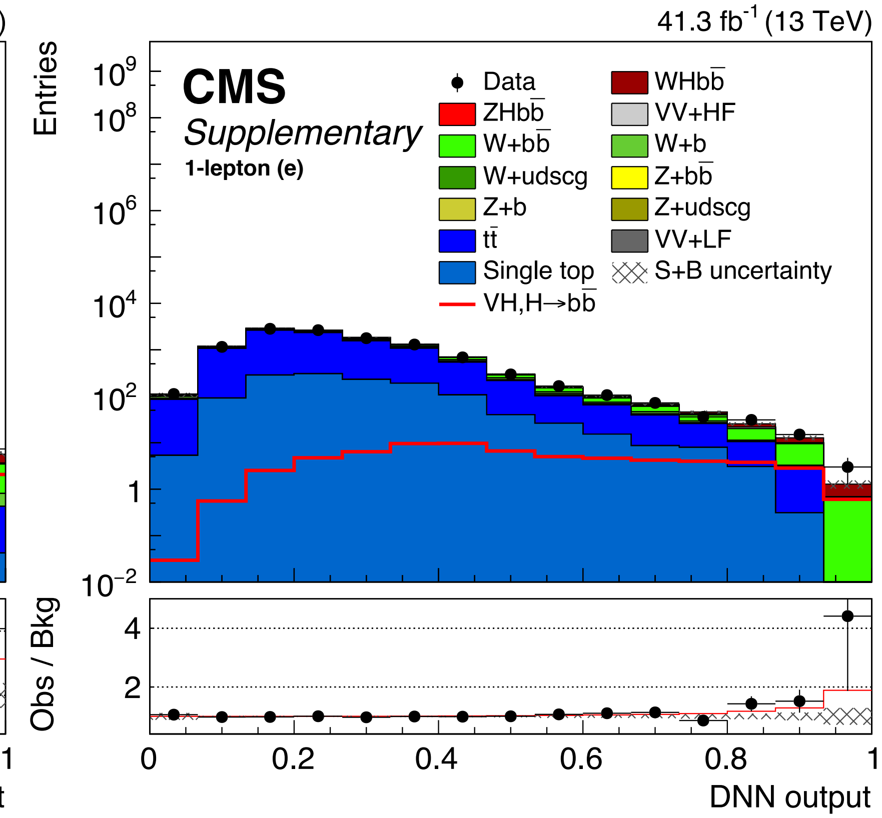
- **Evidence for H→$b\bar{b}$!**
  - 30% precision on signal strength (3.8σ) when combined with Run-1 result.

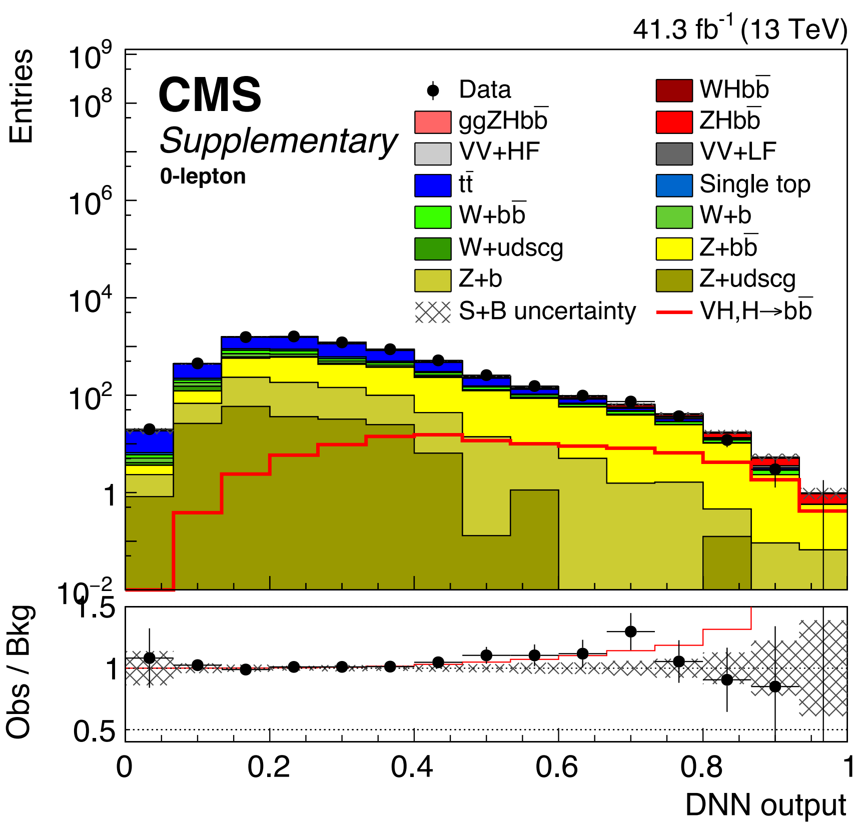
significance
2.8σ expected
3.3σ observed

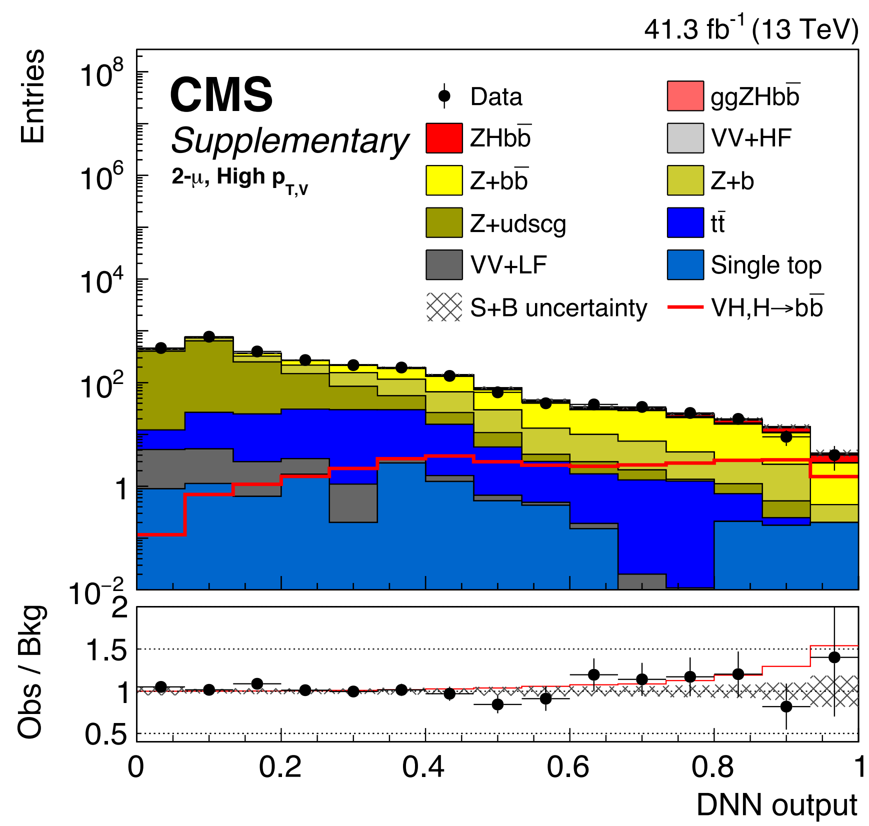
VH, H→b$\bar{b}$ Post-fit DNN

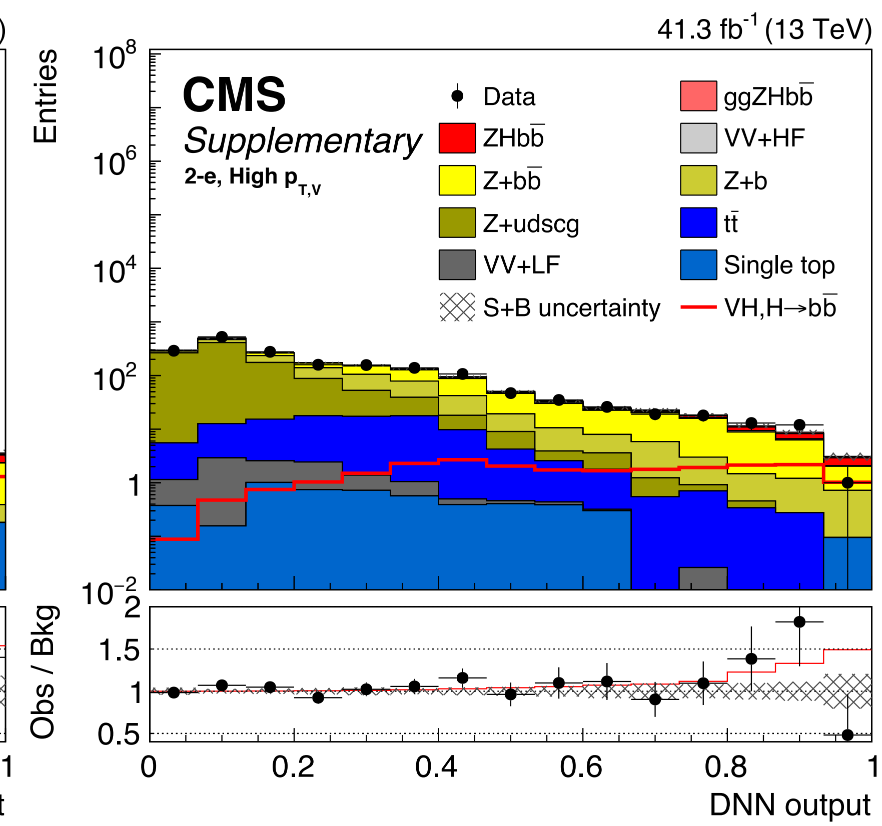
- Using result of combined fit over all channels (common signal strength).



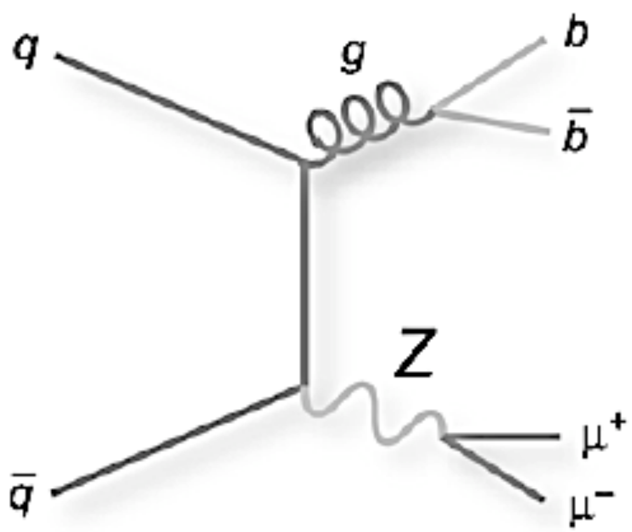






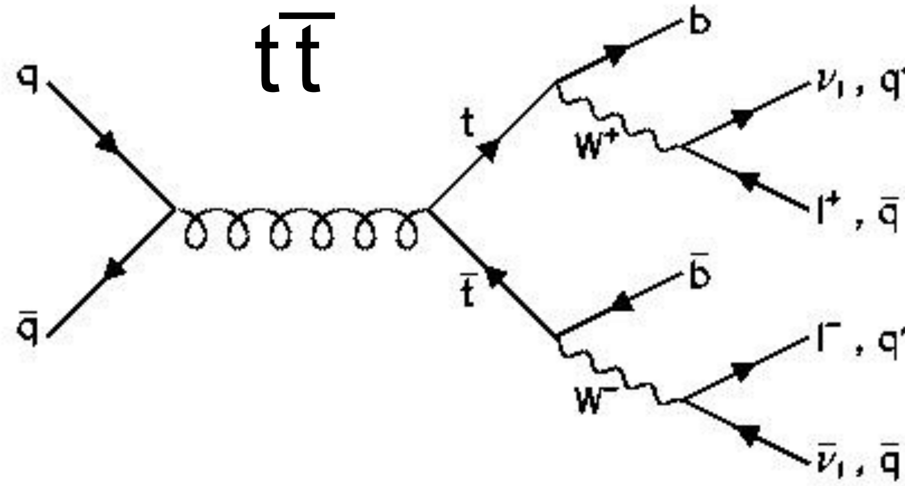


Backgrounds

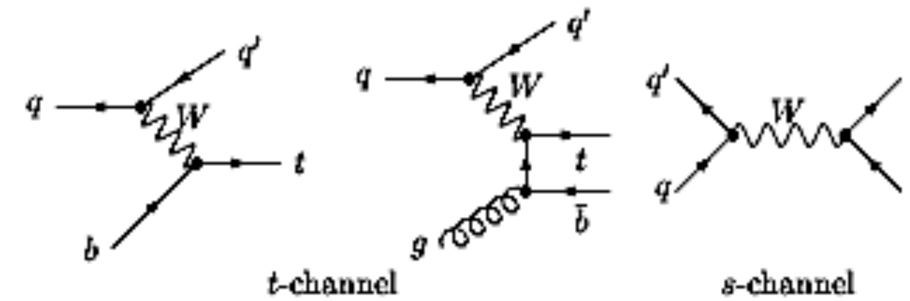


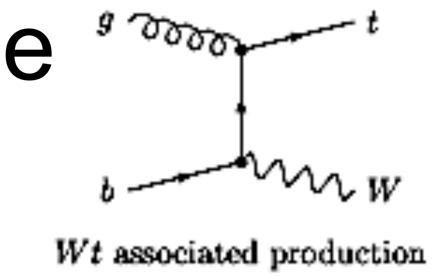
Z+jets

$t\bar{t}$

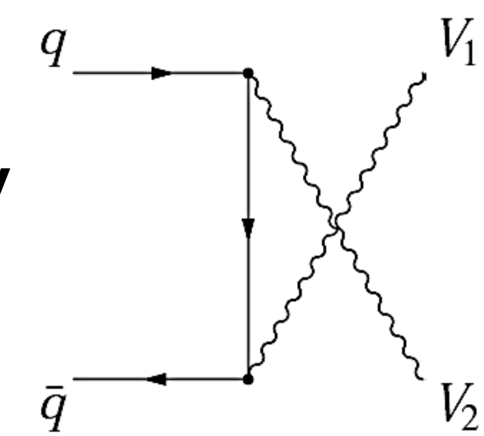


single top



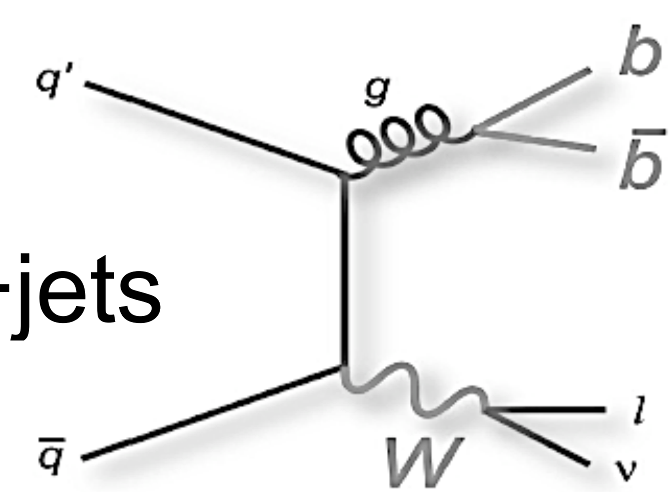


VV

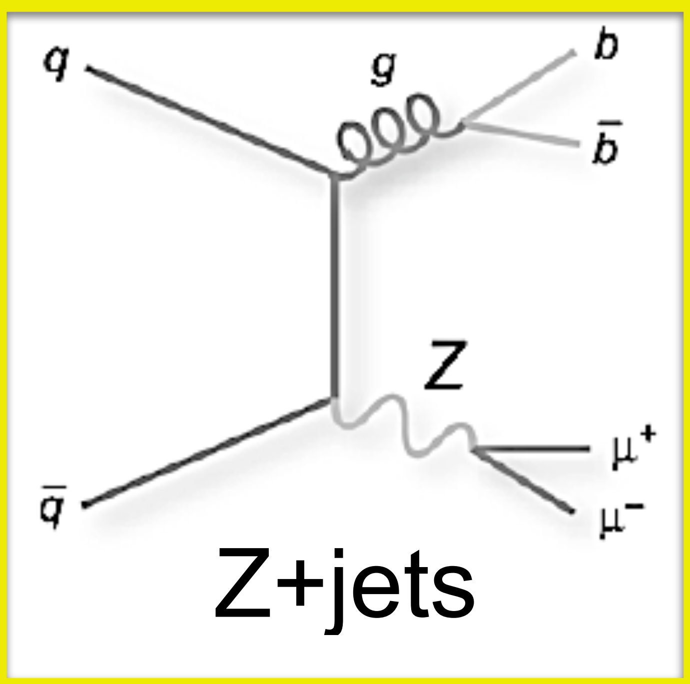


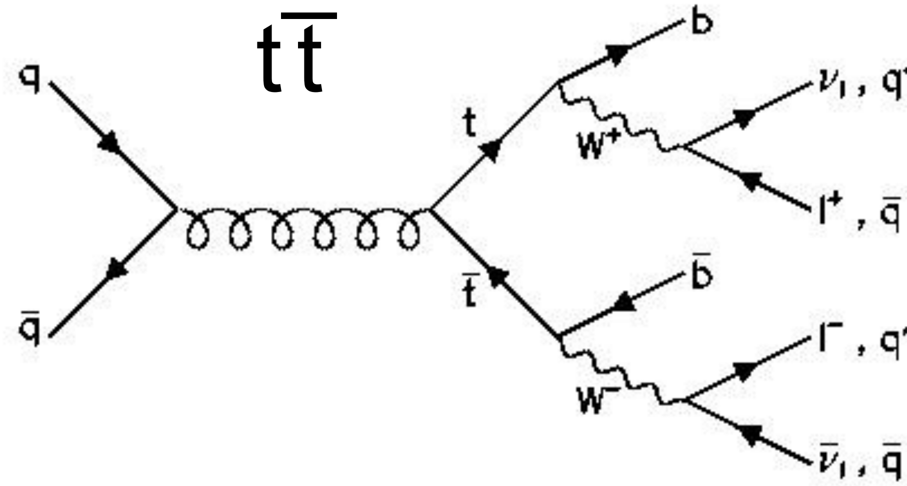
- Note that QCD $b\bar{b}$ production nearly negligible after boosted V selection.

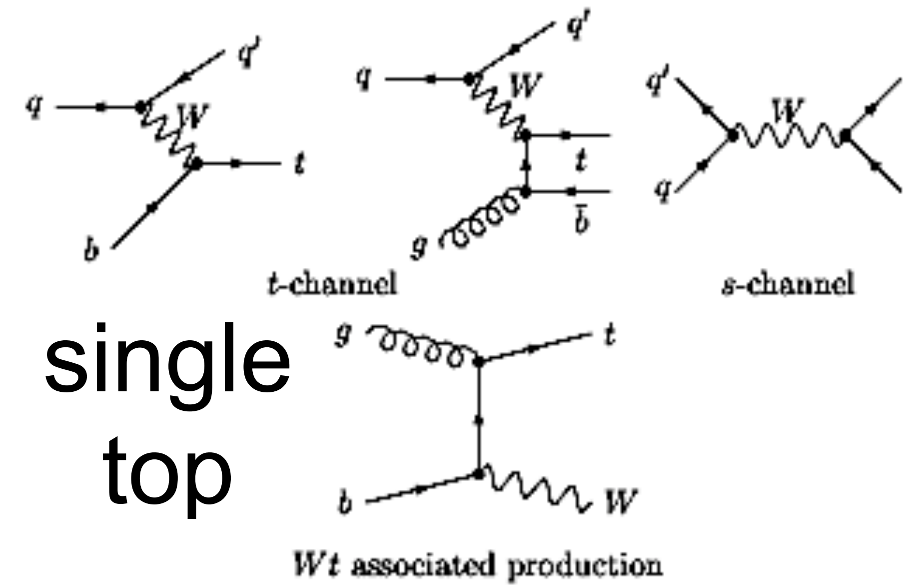
W+jets



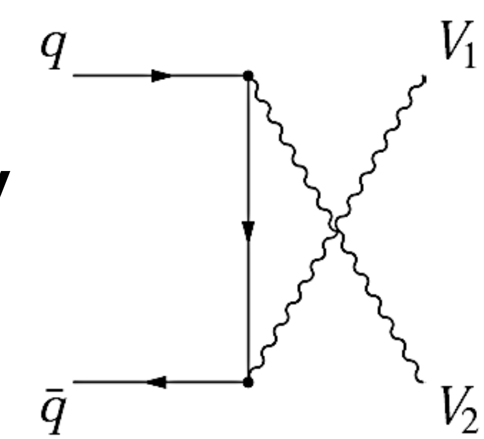
Backgrounds



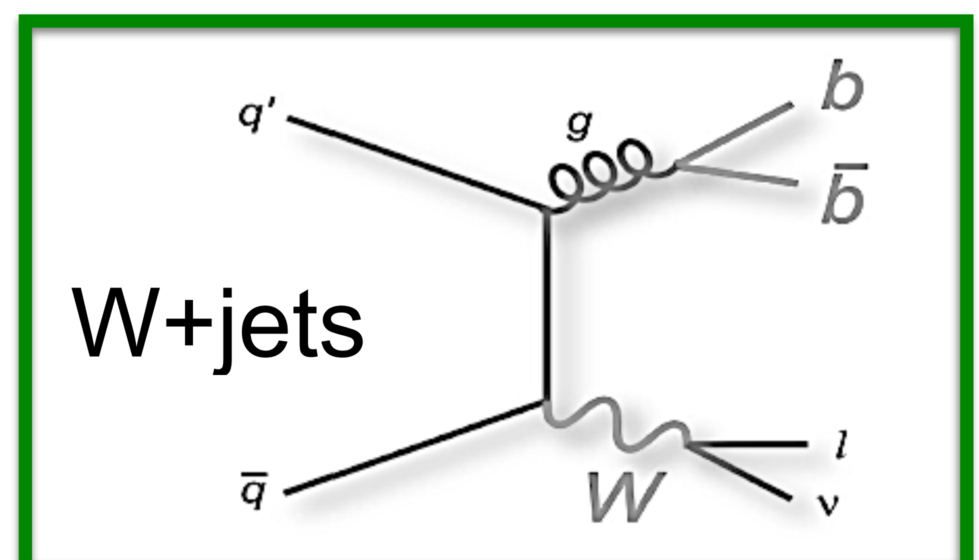




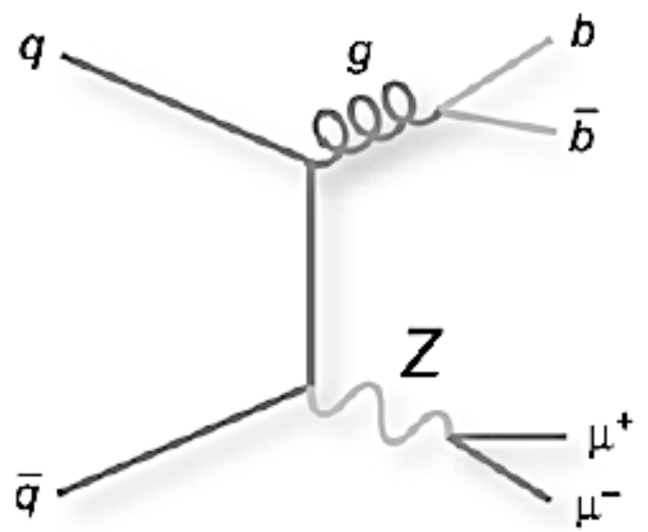
VV



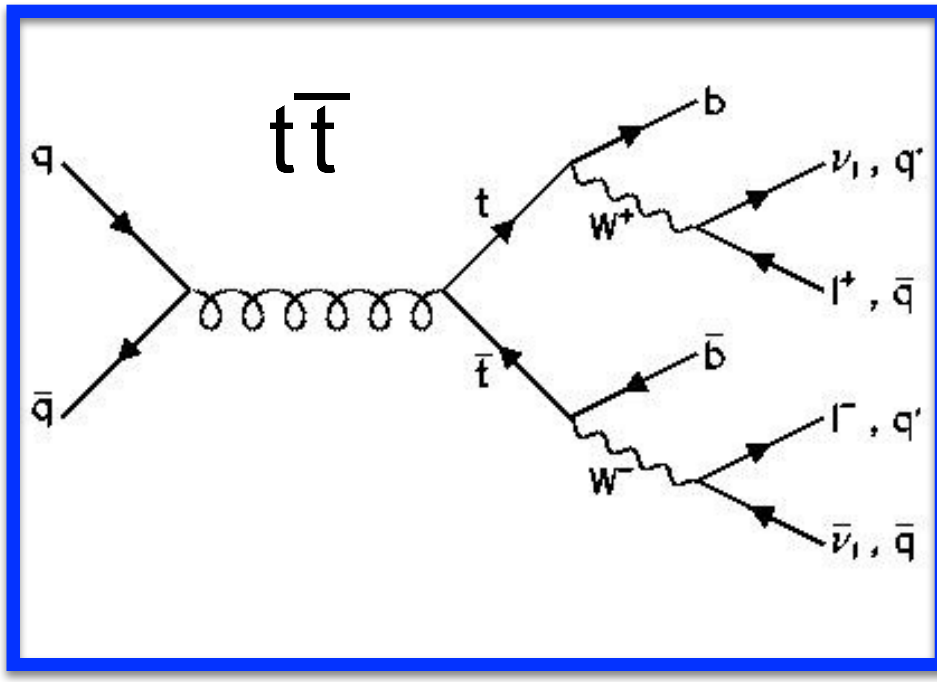
- **V+jets:**
  - In particular V+(b)b.
  - Reduced via boosted $p_T(V)$, $M(b\bar{b})$ selection.
  - Primary background in all channels.

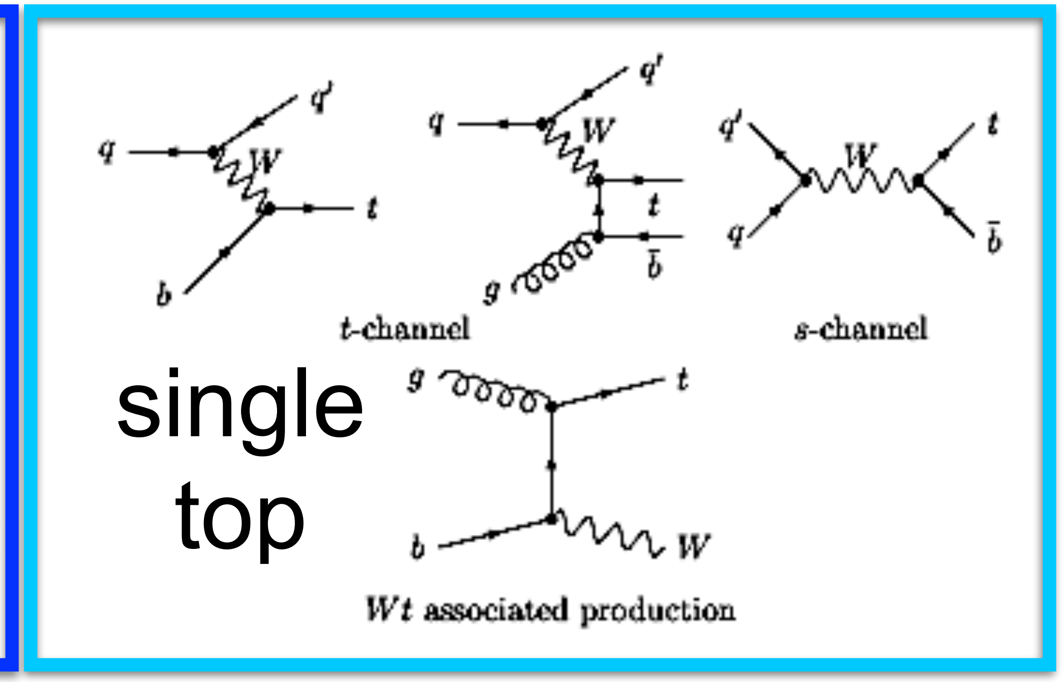


Backgrounds



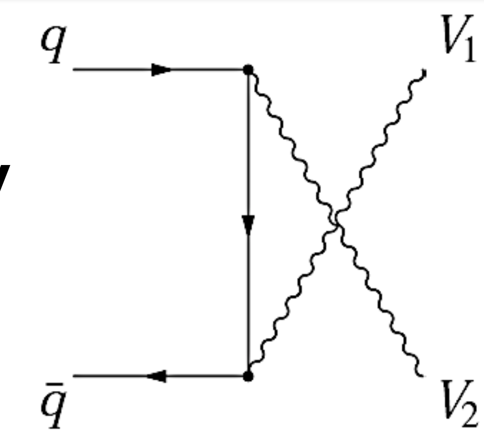
Z+jets



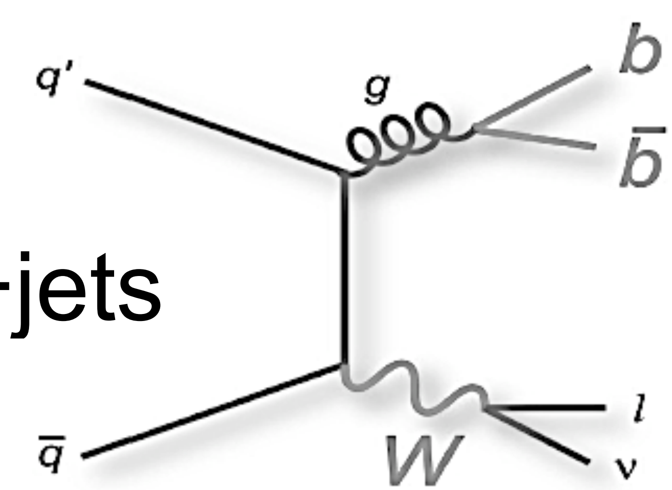


- **$t\bar{t}$, single top:**
  - Reduced via additional jet veto, M($b\bar{b}$) selection, H/V back-to-back requirements.
  - $t\bar{t}$ particularly significant in 1-lepton channel.

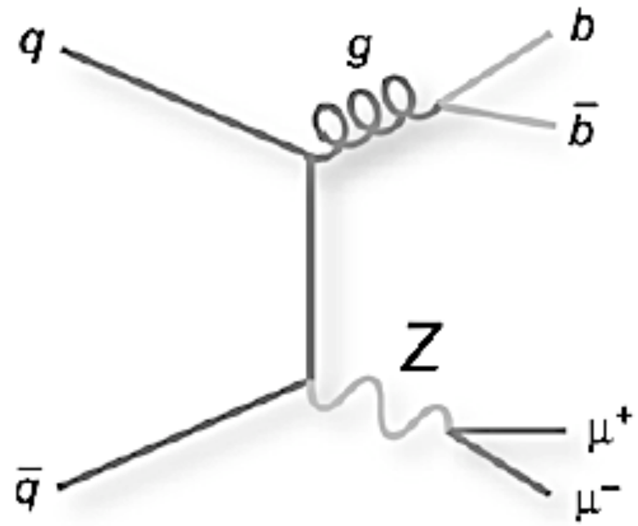
VV



W+jets

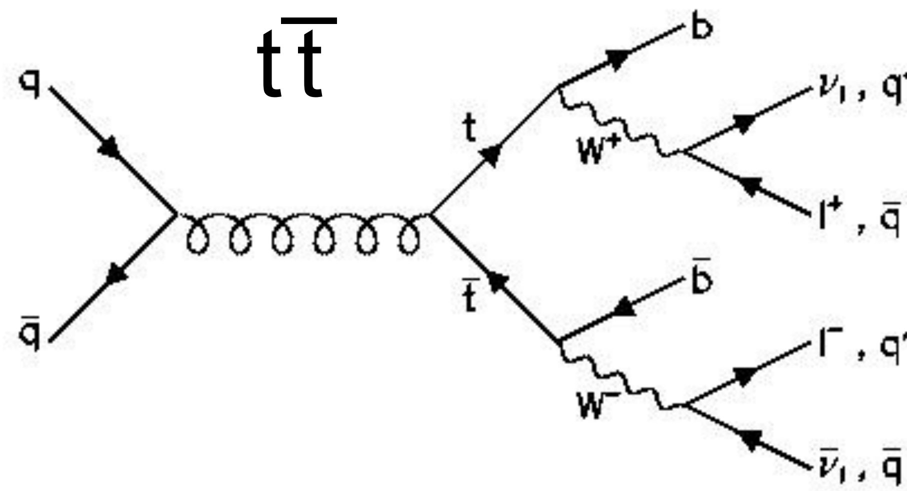


Backgrounds

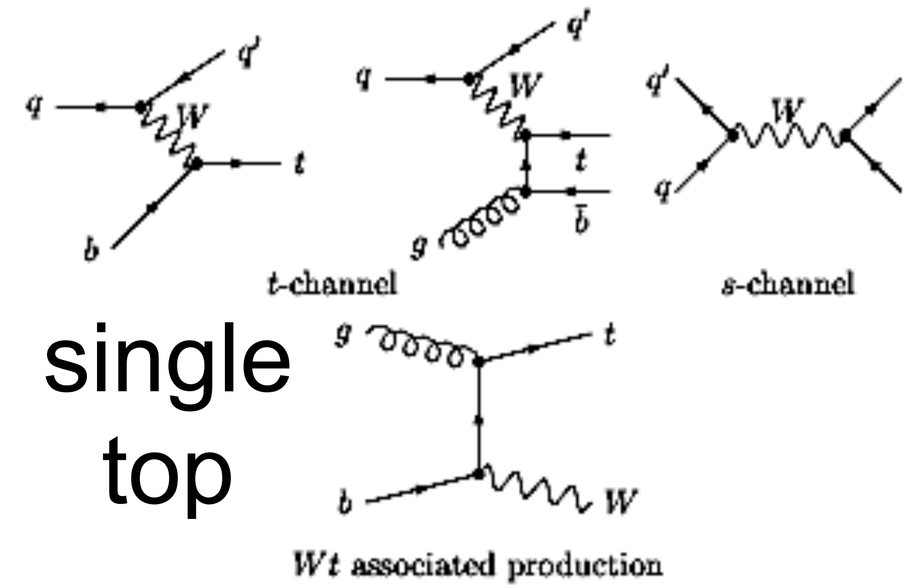


Z+jets

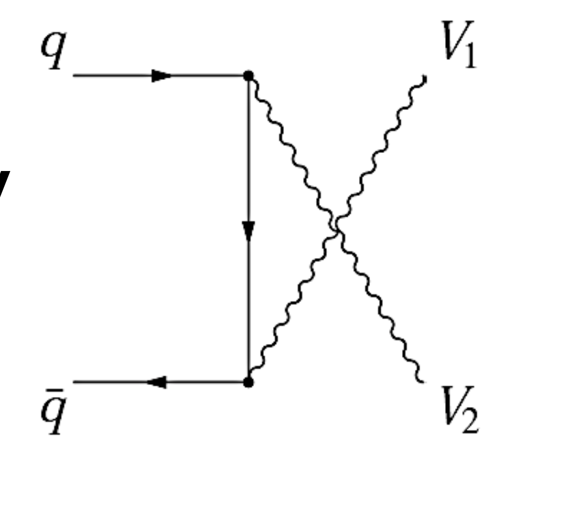
$t\bar{t}$



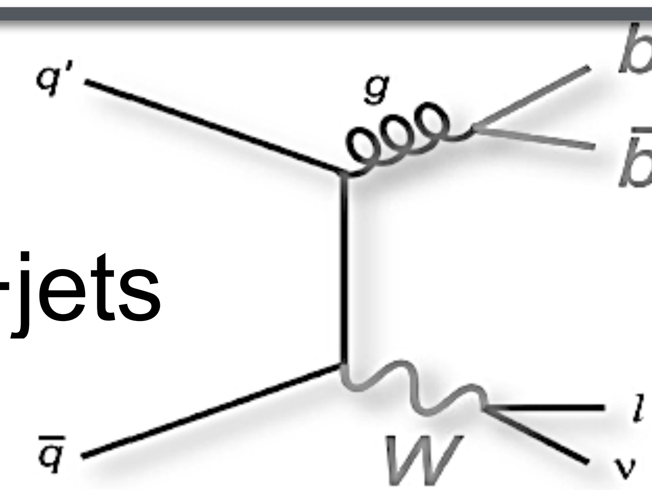
single top



VV



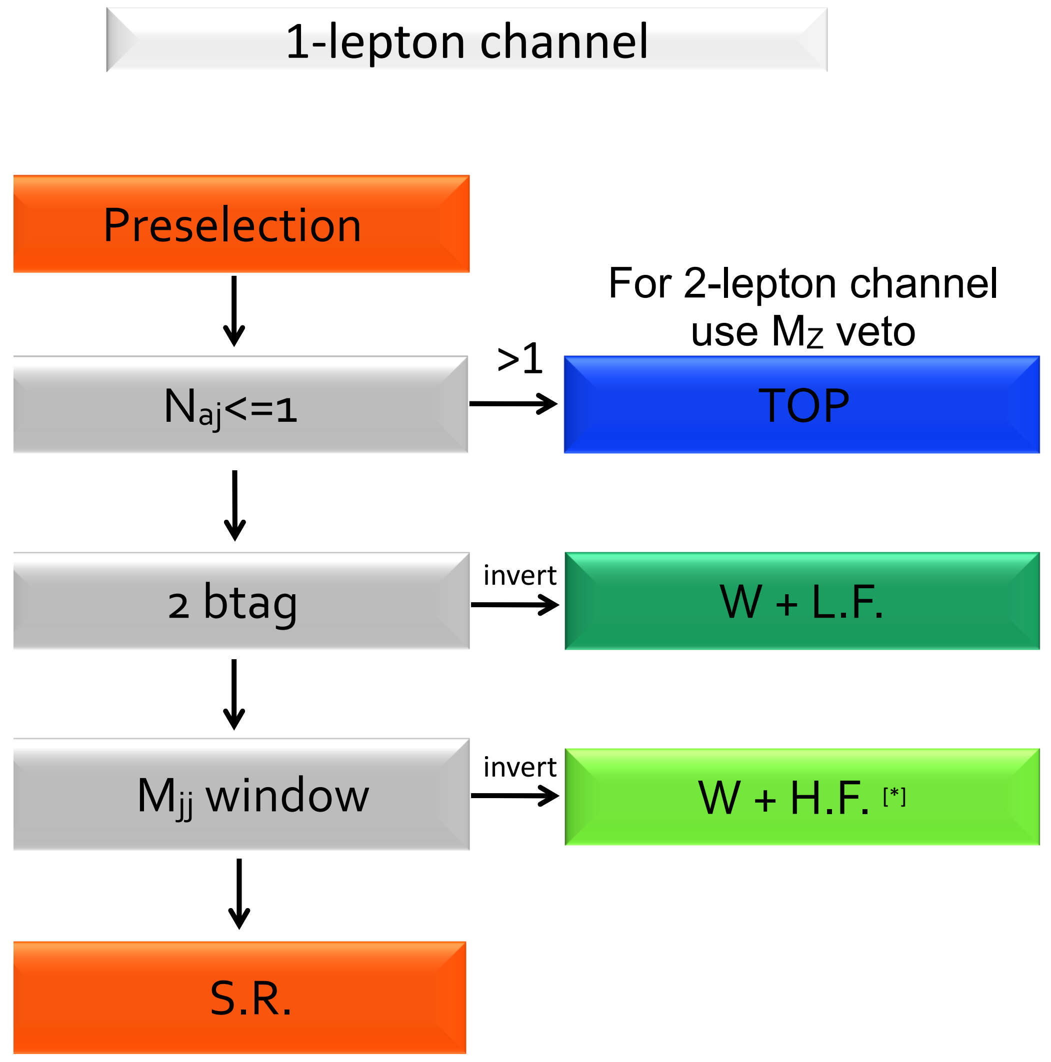
W+jets



- **VZ, Z→b$\bar{b}$ (diboson):**
  - p_T(V) spectrum harder than other backgrounds but softer than VH, H→b$\bar{b}$ signal.
  - Besides M(b$\bar{b}$), kinematics otherwise very similar to signal.
  - Can extract VZ, Z→b$\bar{b}$ signal to validate analysis procedure.

Event Selection/Categorization: Details

- Jet/lepton p_T cuts and b-tagging discriminator working points used optimized separately by channel.
- Define **control regions** to have selection **as similar as possible to signal region** but with a **selection inverted to eliminate signal and enhance purity in targeted background.**
- **Separate $t\bar{t}$, V+light flavor, and V+heavy flavor control regions per channel.**
- **Boosted vector boson:**
  - 2-lepton: two categories
    - 50 GeV < $p_T(Z)$ < 150 GeV, $p_T(Z)$ > 150 GeV
  - 1-lepton: $p_T(W)$ > 150 GeV
  - 0-lepton: $p_T(Z)$ > 170 GeV



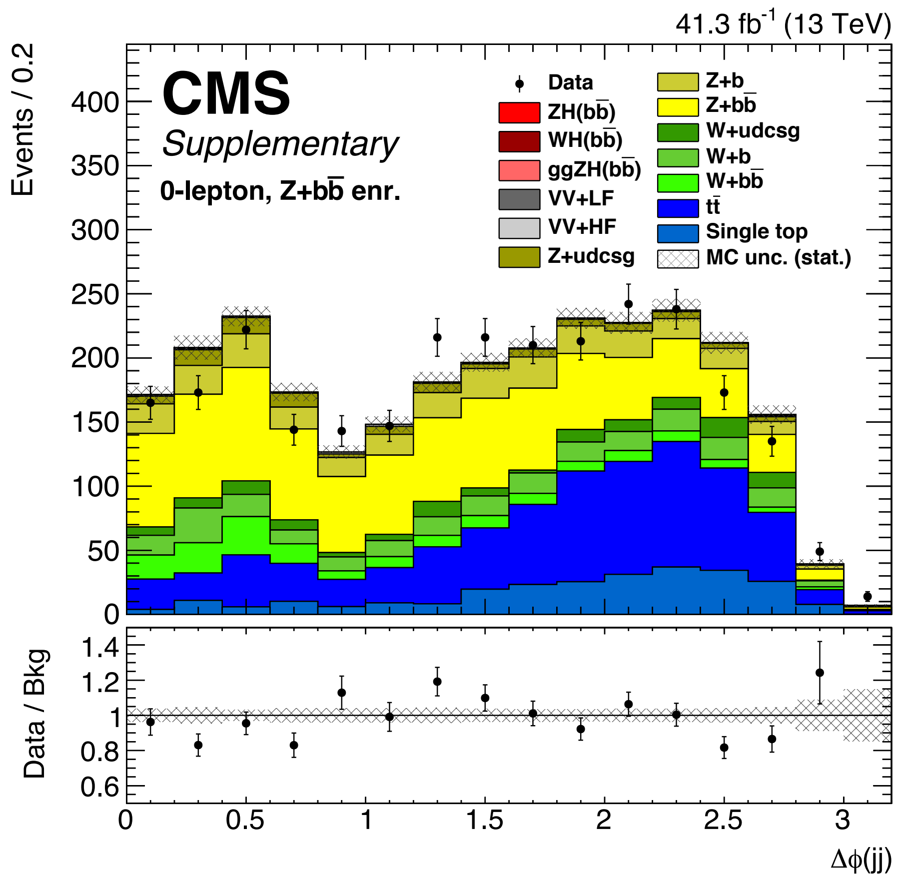
All analysis regions orthogonal

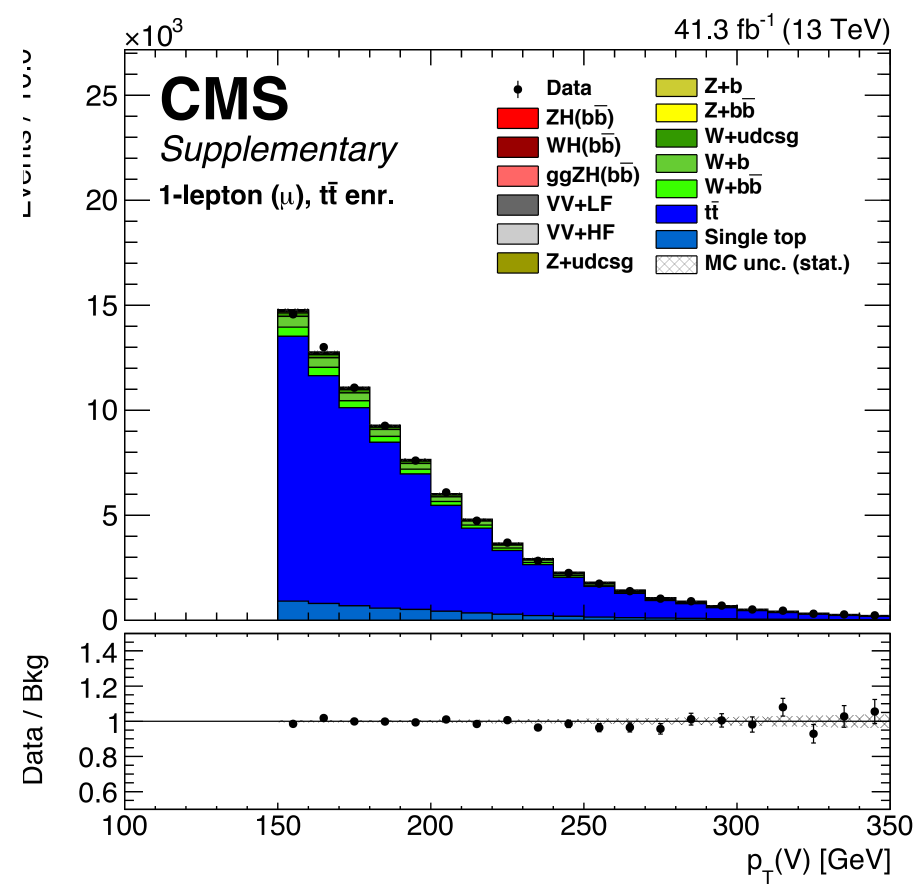
Control Regions

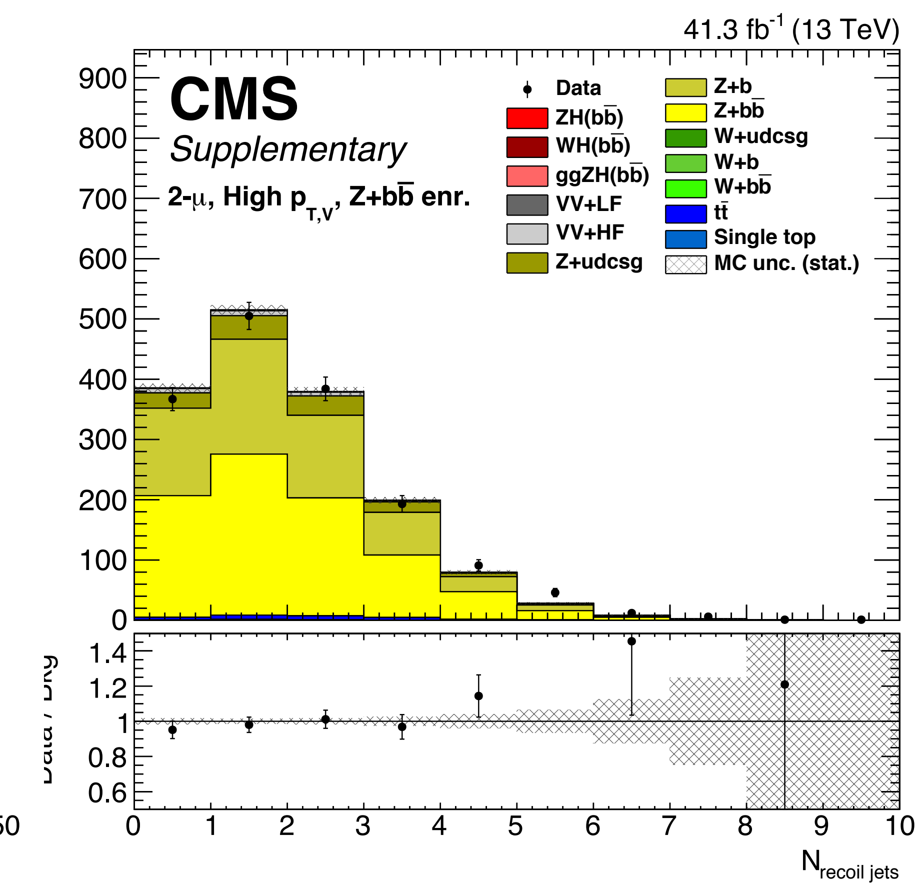
- Selections similar to signal region but with specific cut(s) inverted to target particular background.
  - Invert additional jet multiplicity selection for $t\bar{t}$, mass window veto for V+(b)b, etc.

- Validates background modelling and constrains background normalizations.

- 23 control regions in total.





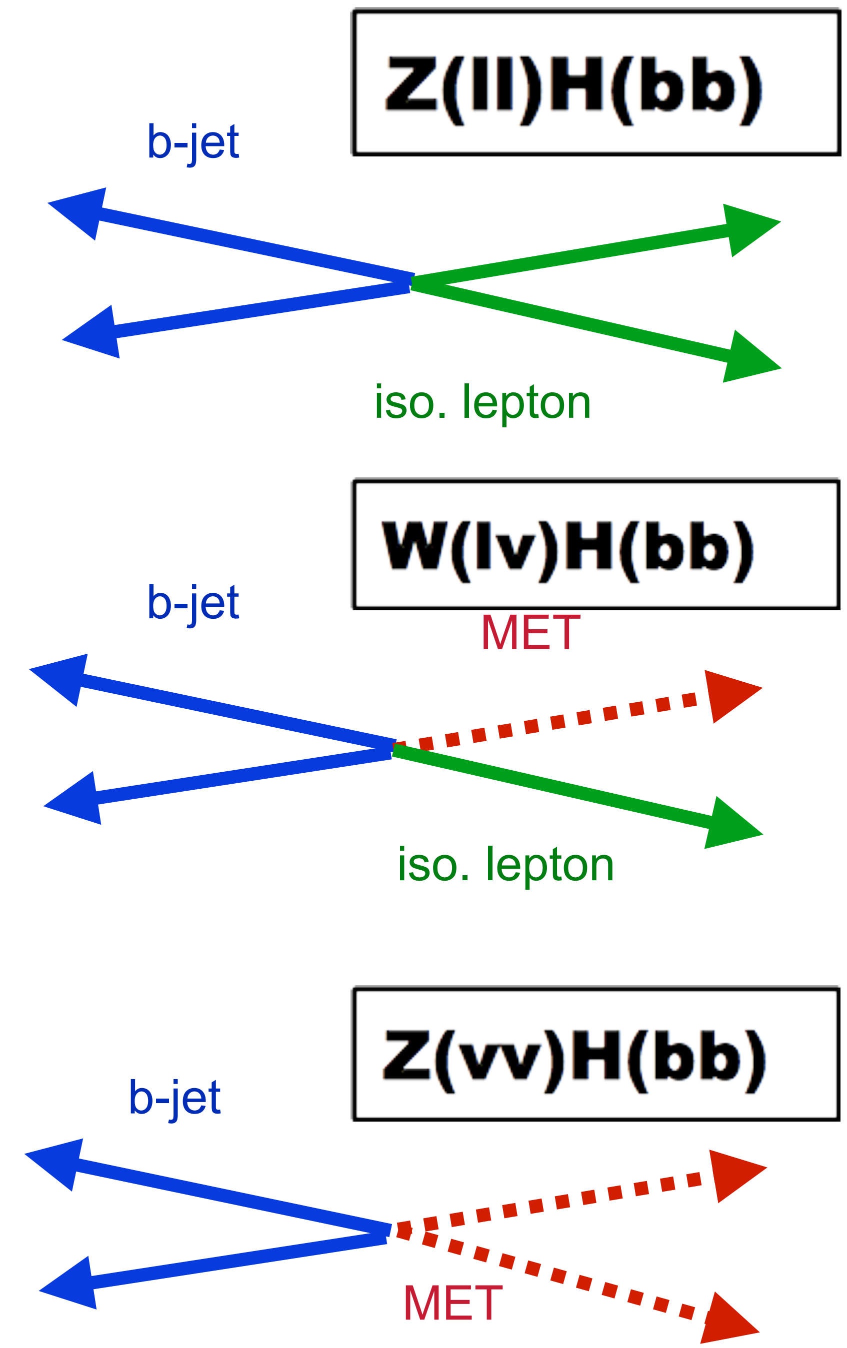


VH, $H \to b\bar{b}$ Combination Details

	Significance (σ)		
Data set	Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23

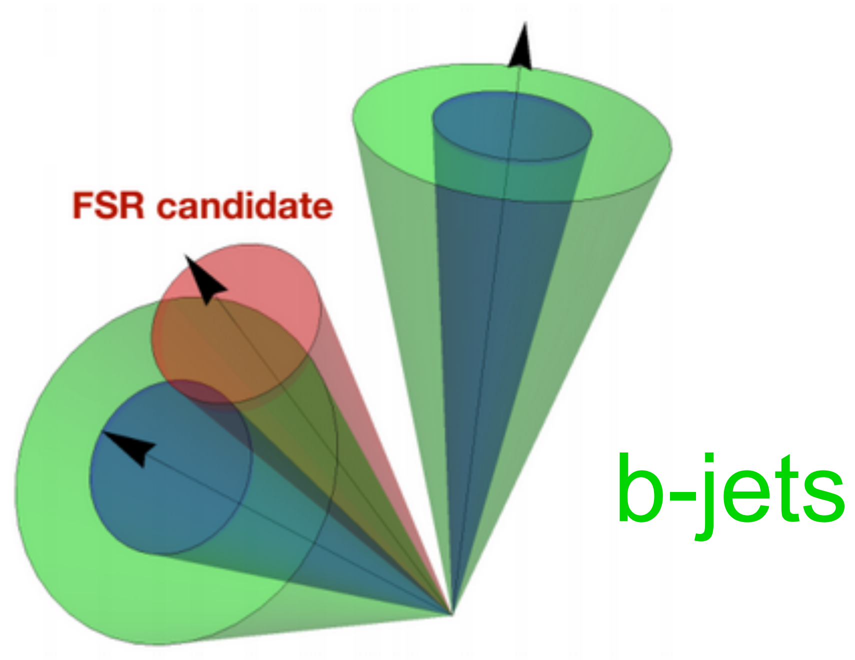
Analysis Strategy

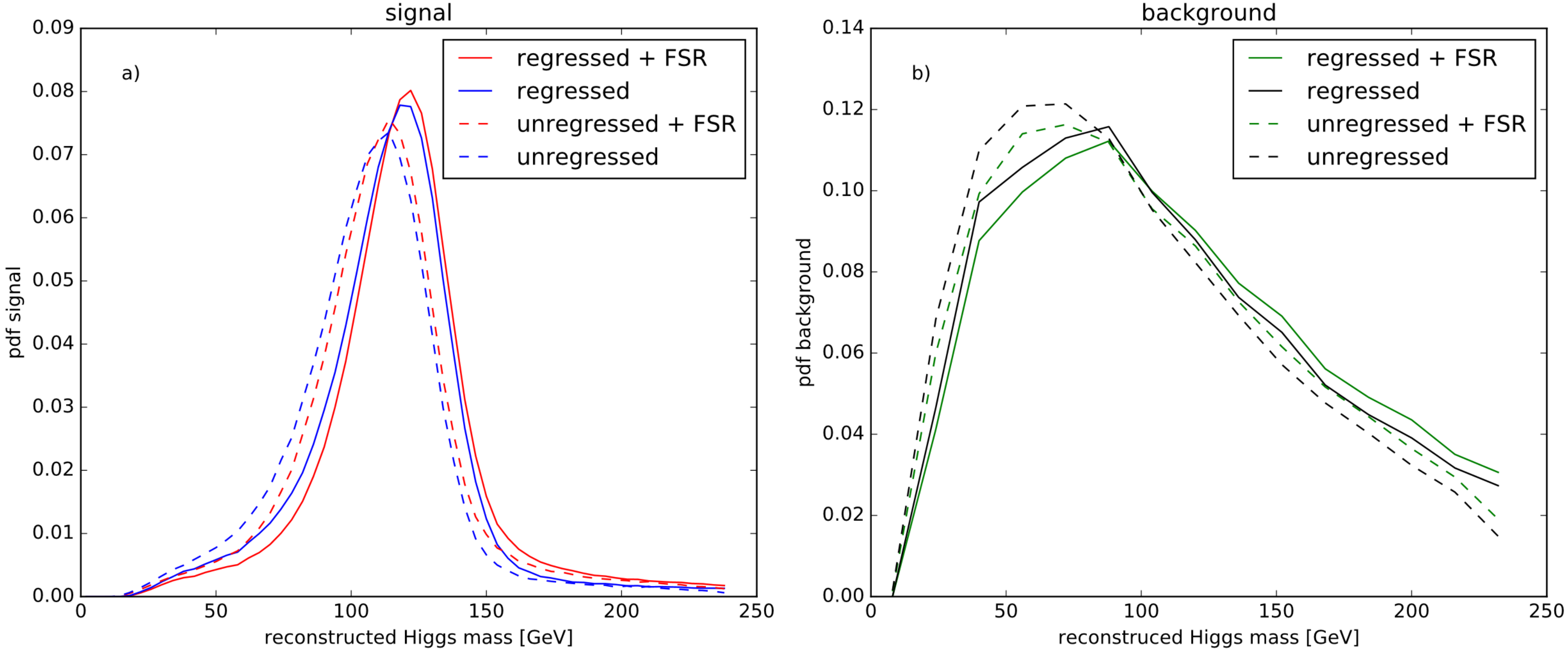
- Strategy similar to Run-1 and 2016:
  - **Boosted vector boson** back-to-back with respect to bb system.
  - **Separate categories** tagging **0, 1, or 2 leptons** in final state.
  - **Multivariate discriminants** trained separately in each channel to **differentiate signal from background**.
  - **Control regions**: enriched in primary backgrounds, used for validation as well as **control/constrain background normalization** and systematics.
  - Signal extracted via **simultaneous fit of all control regions and signal regions.**



FSR Recovery

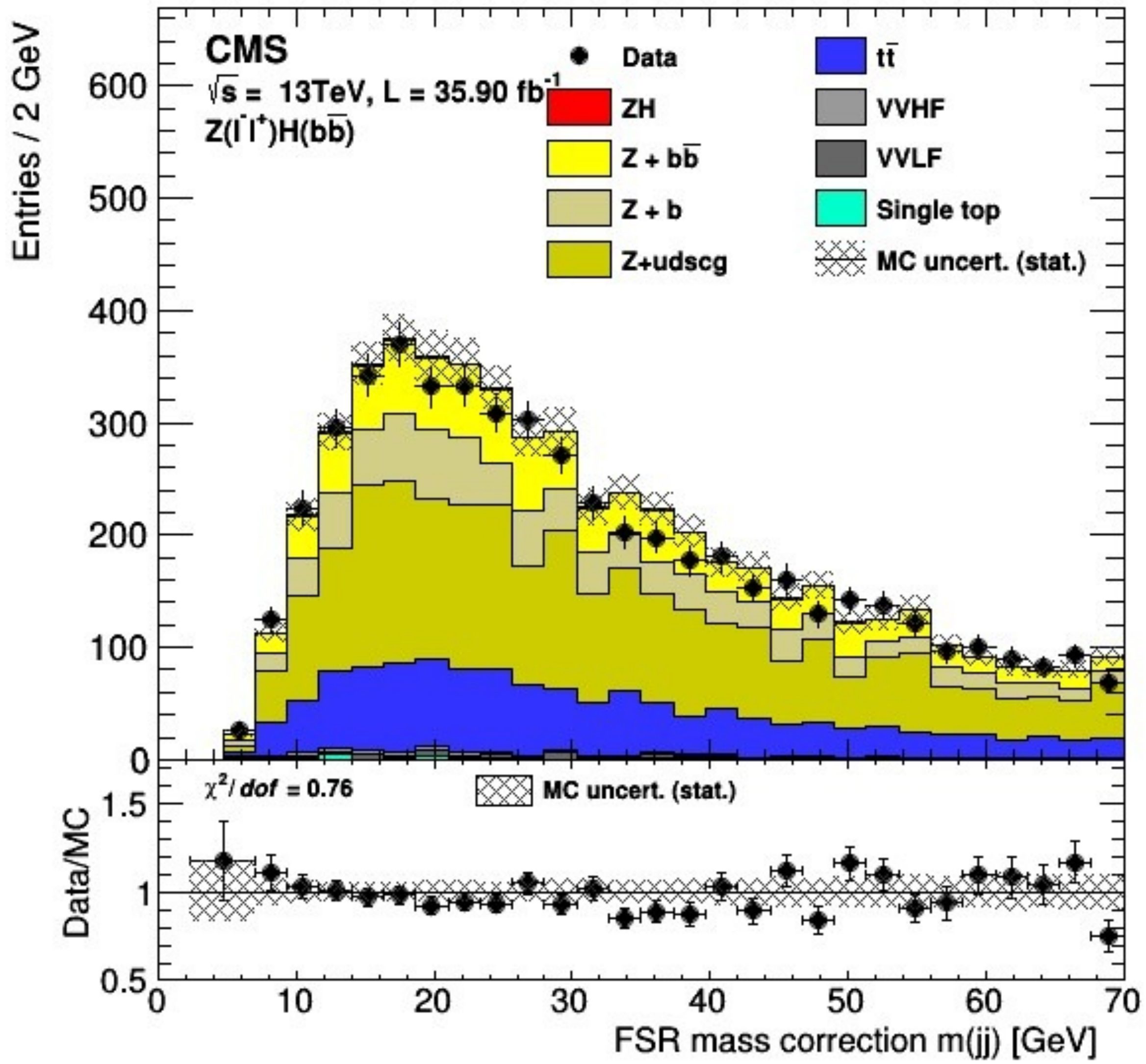
- FSR jets for signal are reconstructed as additional jets.
- Recover FSR jets within $\Delta R < 0.8$ of $H \rightarrow b\bar{b}$ candidate jets, with $p_T > 20$ GeV and $|\eta| < 3.0$.
- **Improves mass resolution for signal by a few percent without sculpting background shape.**

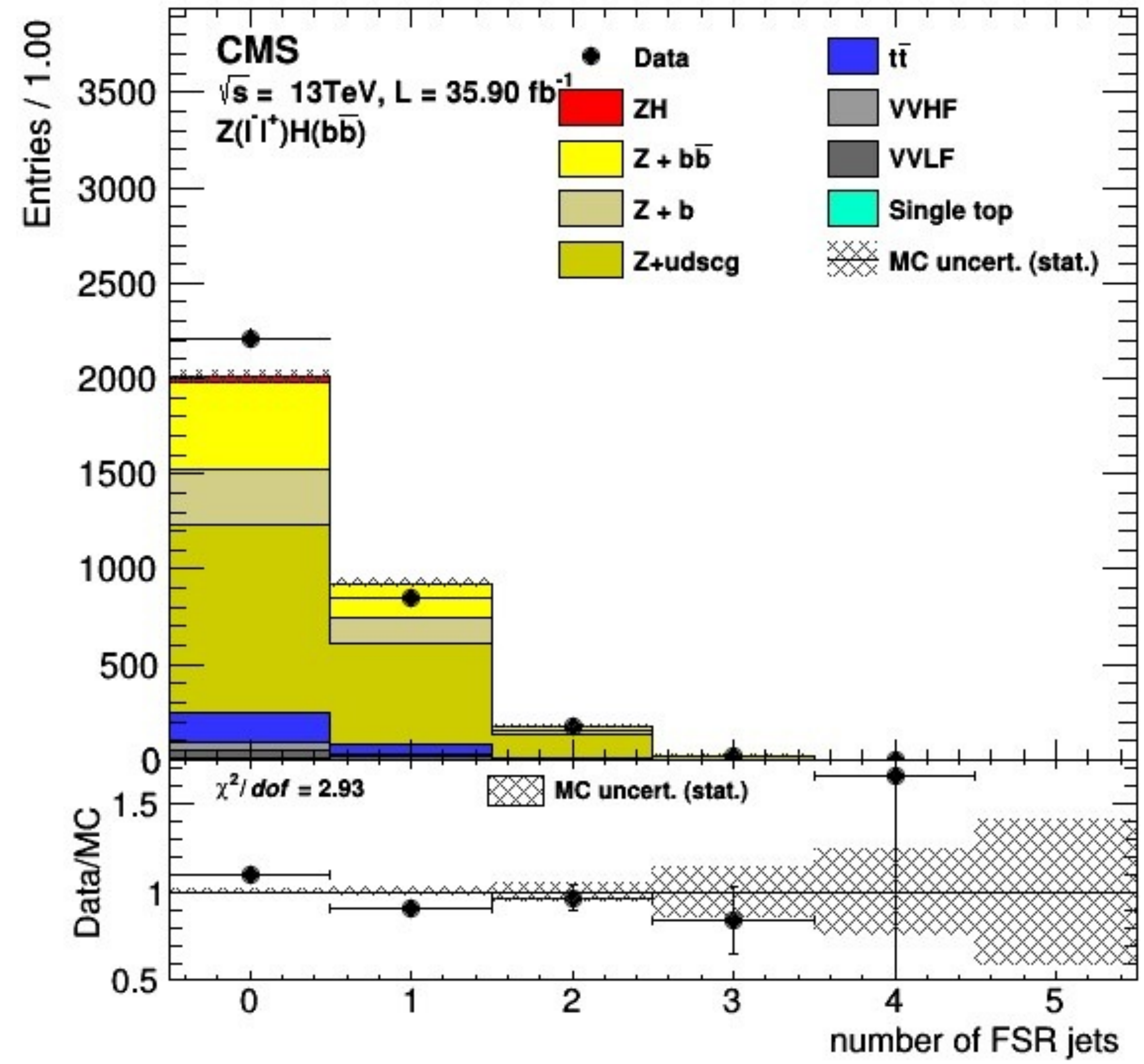




FSR Recovery Validation

- FSR variables validated in data and included in MVA discriminator training.
- Improvement in signal mass resolution of a few percent.



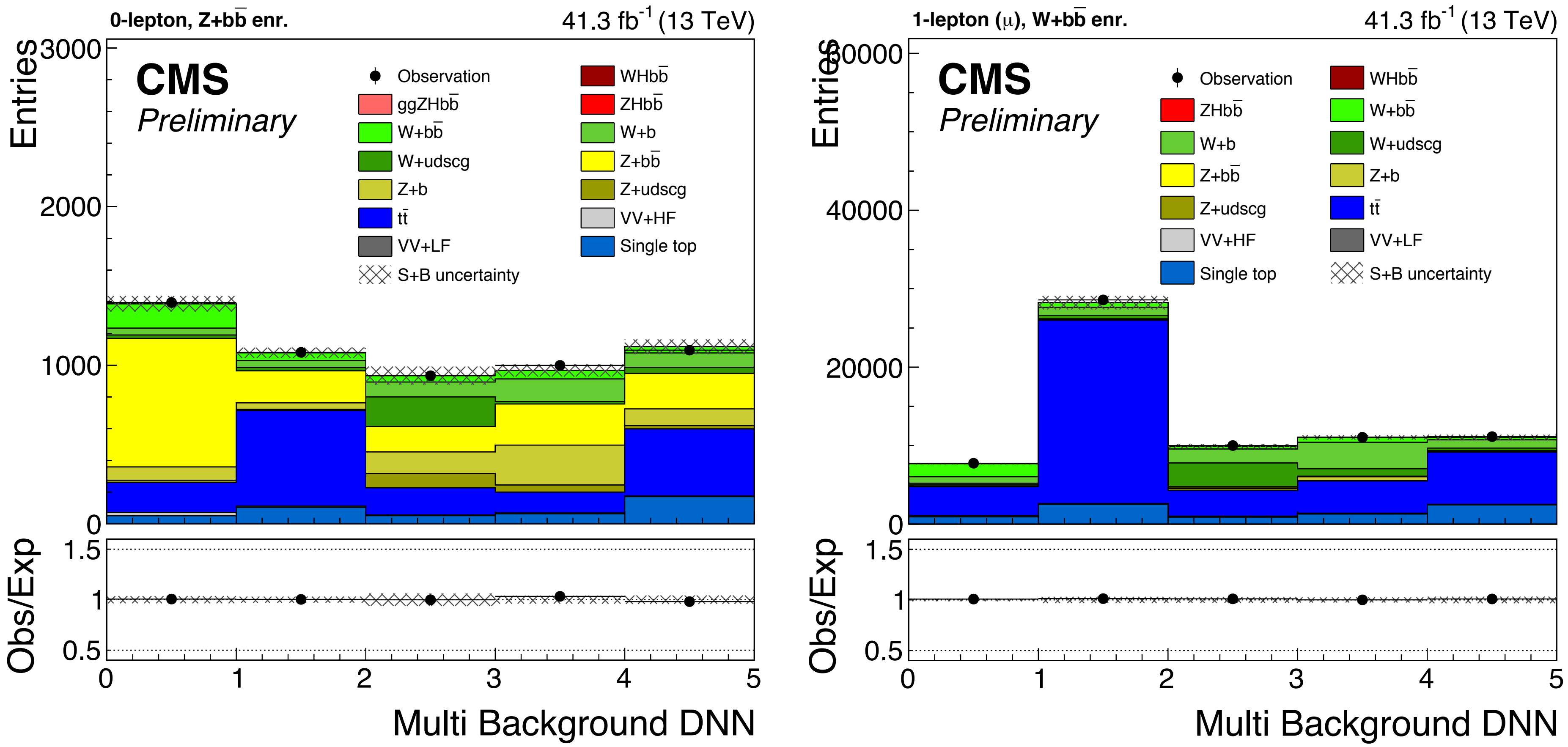


Fit Methodology: Details

- **Fit simultaneously all control regions and signal regions.**
- In **V+light flavor and $t\bar{t}$** control regions **fit only the normalization** (one-bin).
- **In V+heavy flavor** control regions:
  - **0-lepton and 1-lepton: fit 5-bin multi-output DNN**, one bin per category
  - In **2-lepton fit 2-bin** distribution of **sub-leading jet DeepCSV** score.
- **In signal regions fit the DNN** classifier output (15 bins).
- Allow **normalisations of $t\bar{t}$, V+udcsg, V+b, and V+bb** backgrounds to **float independently** in each channel.
  - The normalisations of these processes is constrained by the control regions targeting these processes.

Fitted Background Normalizations

- Note that 2017 samples use NNLO pdf
  - → cross sections generally ~15% higher than 2016
  - → scale factors 15% lower with respect to 2016.



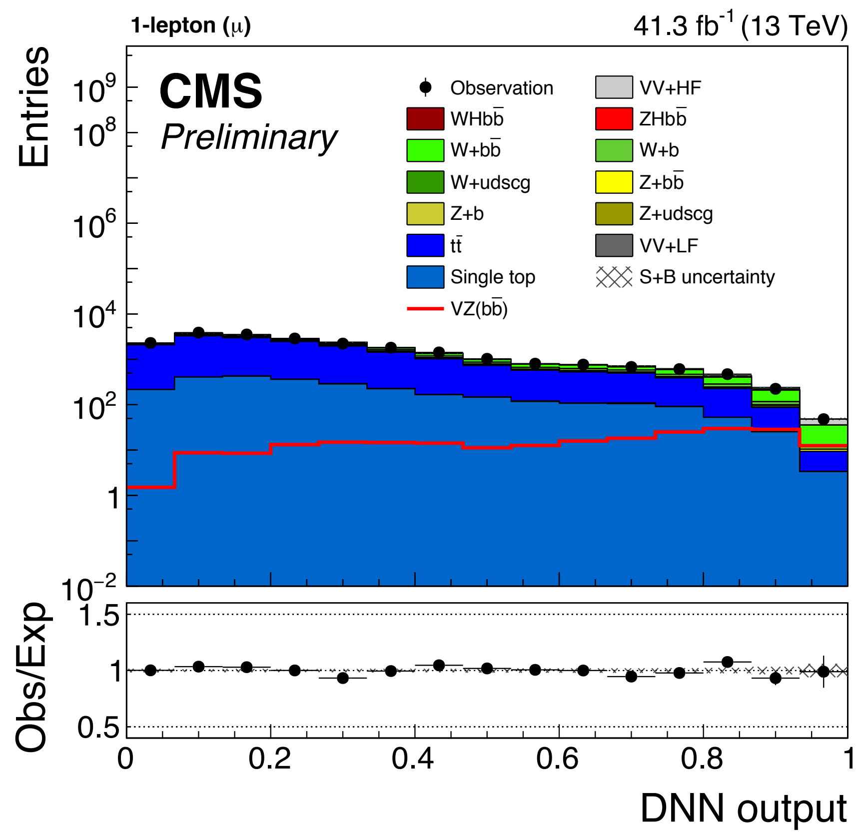
Process	$Z(\nu\nu)H$	$W(\ell\nu)H$	$Z(\ell\ell)H$ low-p_T	$Z(\ell\ell)H$ high-p_T
W + udscg	1.04 ± 0.07	1.04 ± 0.07	–	–
W + b	2.09 ± 0.16	2.09 ± 0.16	–	–
$W + b\bar{b}$	1.74 ± 0.21	1.74 ± 0.21	–	–
Z + udscg	0.95 ± 0.09	–	0.89 ± 0.06	0.81 ± 0.05
Z + b	1.02 ± 0.17	–	0.94 ± 0.12	1.17 ± 0.10
$Z + b\bar{b}$	1.20 ± 0.11	–	0.81 ± 0.07	0.88 ± 0.08
$t\bar{t}$	0.99 ± 0.07	0.93 ± 0.07	0.89 ± 0.07	0.91 ± 0.07

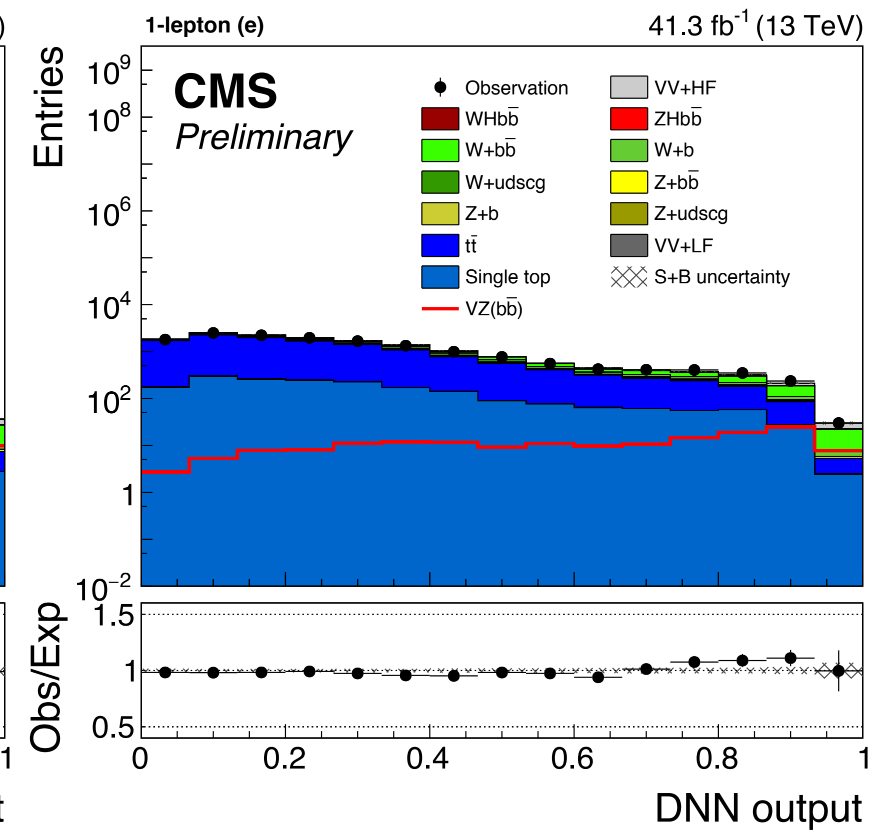
Systematic Uncertainties

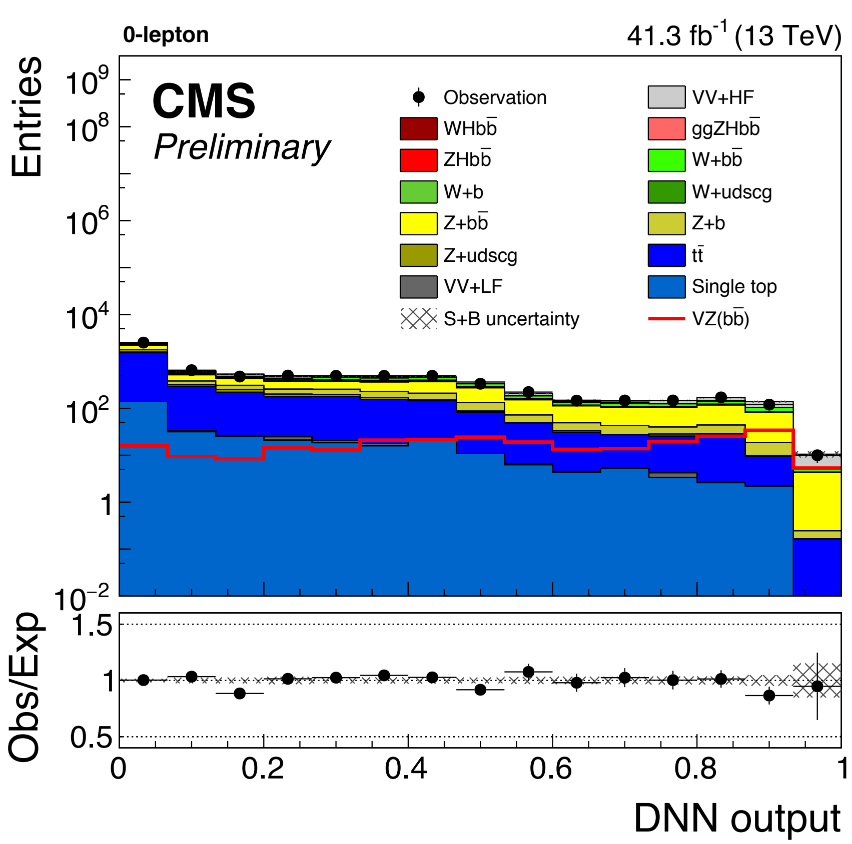
- **Jet energy scale:**
  - Split into 27 independent uncertainty sources.
- **Jet energy resolution:**
  - 10% uncertainty on regressed b-jets from dedicated study in VH, $H \rightarrow b\bar{b}$ analysis phase space.
    - **Uncorrelated for signal** to avoid any possible constraining, should cover any uncertainties from PS.
  - Standard JER uncertainty for additional jets.
- **B-tagging:**
  - Split into independent uncertainty sources (light flavour mistag, charm mistag, heavy flavor efficiency).
  - Further de-correlated based on jet p_T/η, as in 2016 analysis.
- **Background normalizations:**
  - Derived from fit to data for backgrounds with floating normalisation (V+udcsg, V+b, V+bb, tt)
  - 15% uncertainty on VV and single top cross section.
- **Monte Carlo statistics**
- QCD scale and pdf (acceptance as well as overall cross section).
- $\Delta\eta(jj)$ LO to NLO re-weighting:
  - Full correction taken as uncertainty.
- $p_T(W)$ linear re-weighting (1-lepton channel only)
  - Statistical uncertainty band from fit to derive corrections.
- Lepton efficiency, min-bias σ, luminosity,

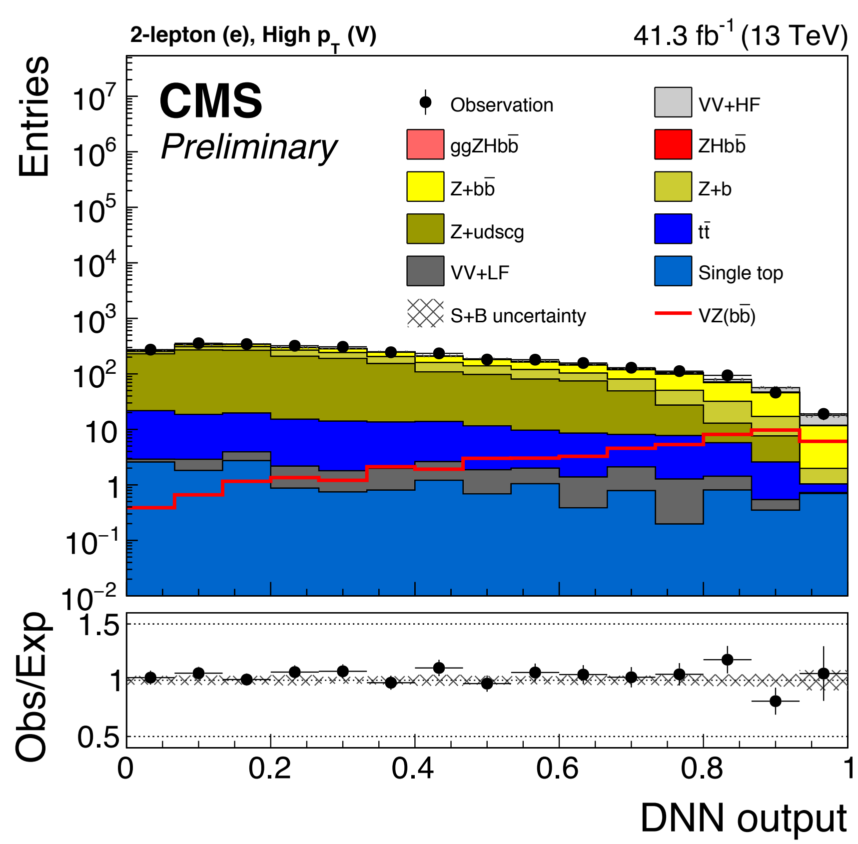
VZ, Z→b$\bar{b}$ Post-fit DNN

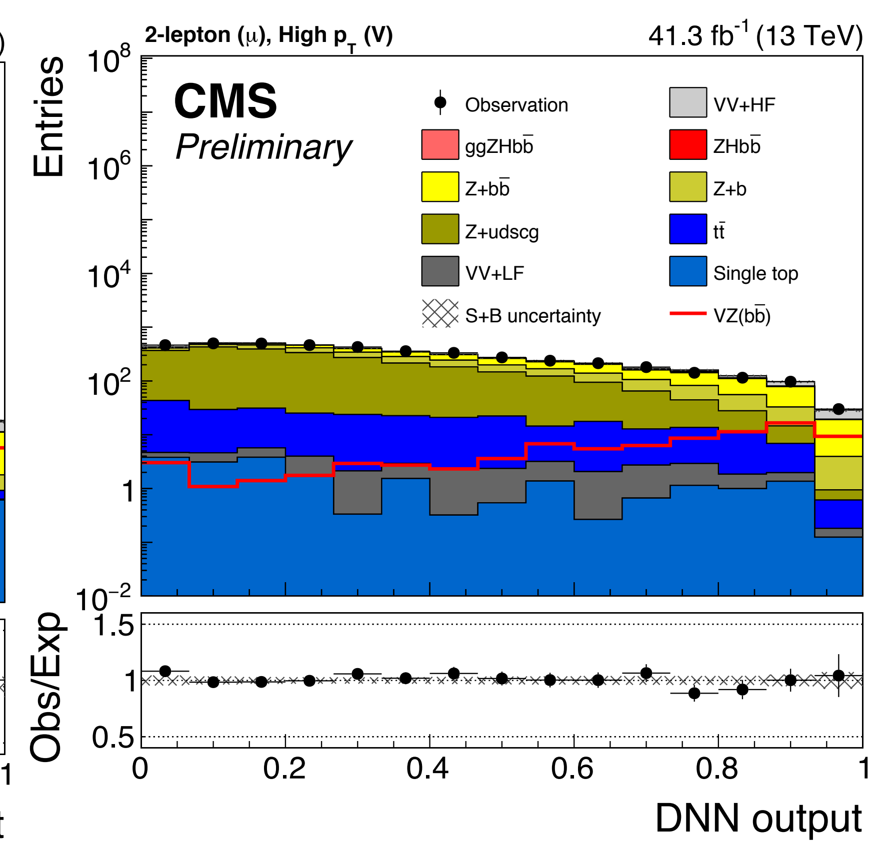
- Using result of combined fit over all channels (common signal strength).
- Good agreement between data and simulation throughout distributions.







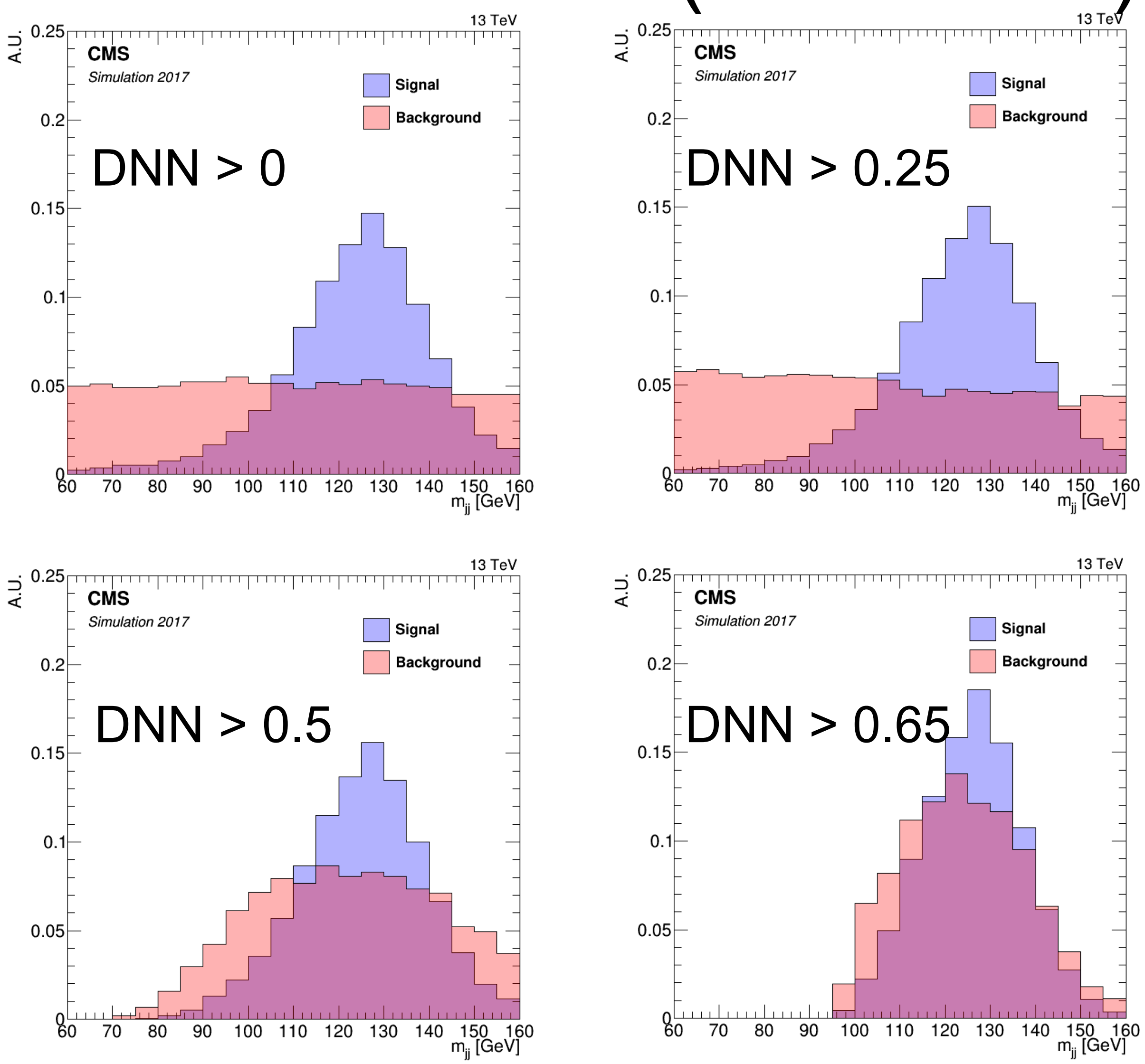




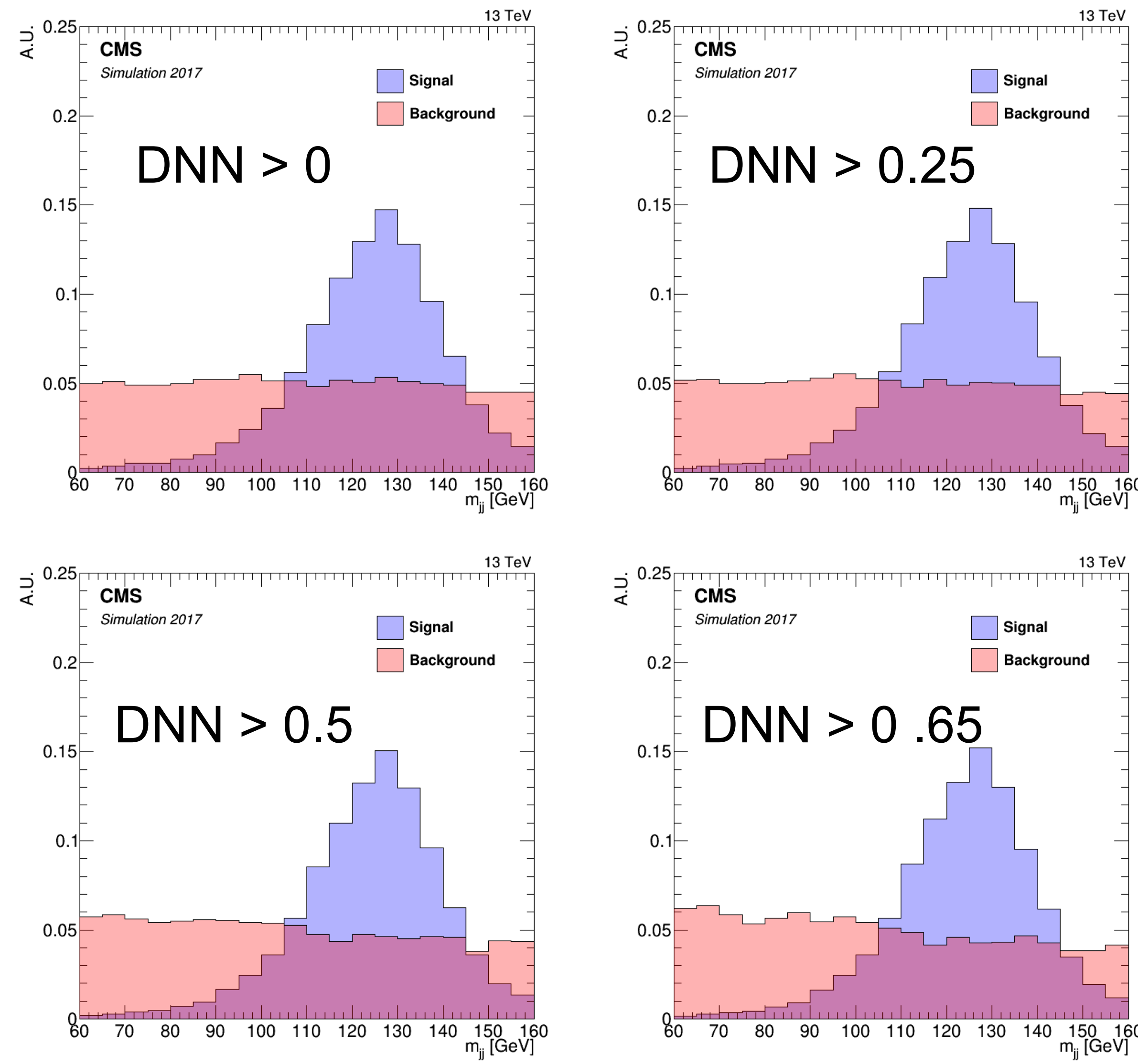
Massless DNN Evaluation

- **Categorizing events based on nominal analysis DNN would highly sculpt the M($b\bar{b}$)** distribution (left plots).
  - M($b\bar{b}$) is the most discriminating variable in the DNN training.
- Use the **same DNN training but fix M($b\bar{b}$)-correlated variables** to mean background values (right plots).
- Use widened mass window as in VZ($b\bar{b}$) cross-check analysis in order to accommodate Z($b\bar{b}$) and H($b\bar{b}$) peak.

Nominal DNN (with mass)



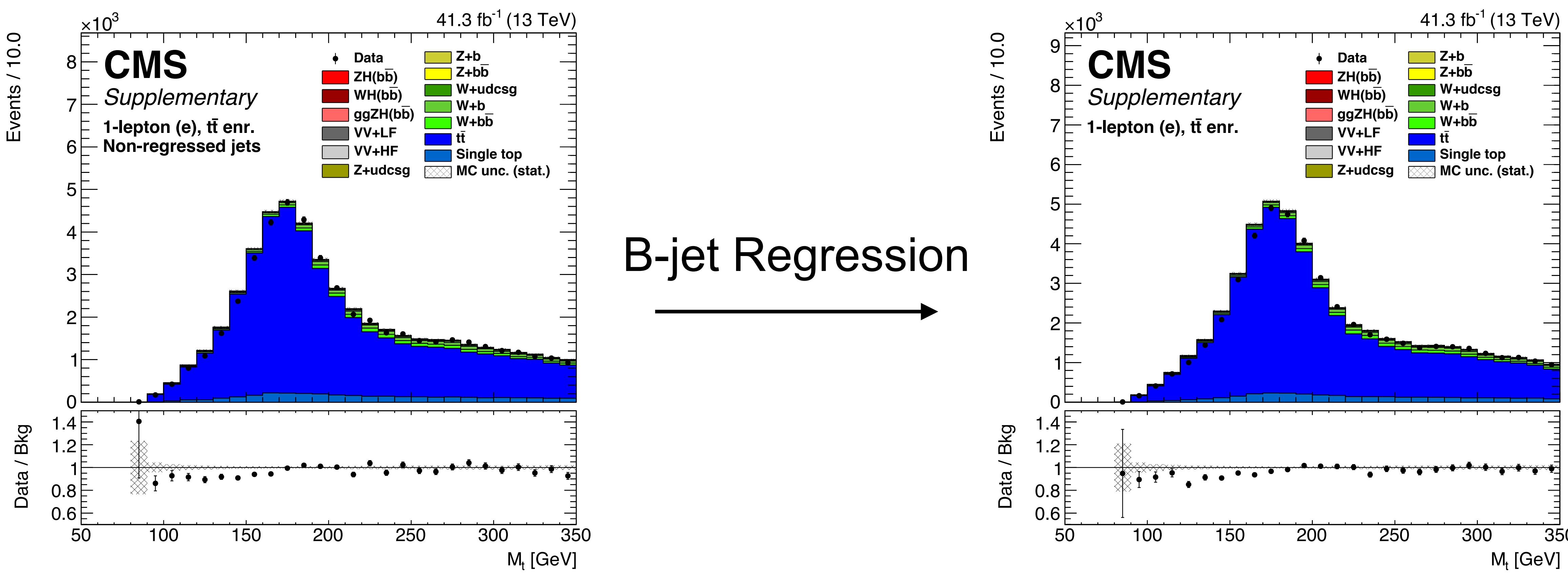
Massless DNN



M($b\bar{b}$) Resolution Improvement Validation

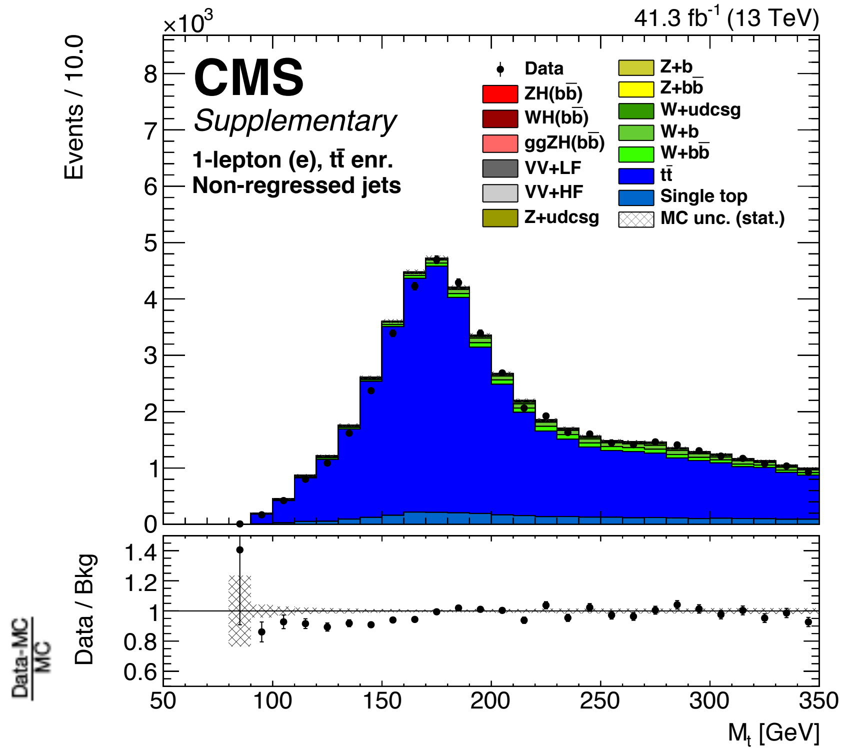
- M($b\bar{b}$) resolution improvements do not sculpt backgrounds.
- Expected improvements from simulation match data.
- Improved M($b\bar{b}$) resolution → better S/B and smaller uncertainty on signal strength.

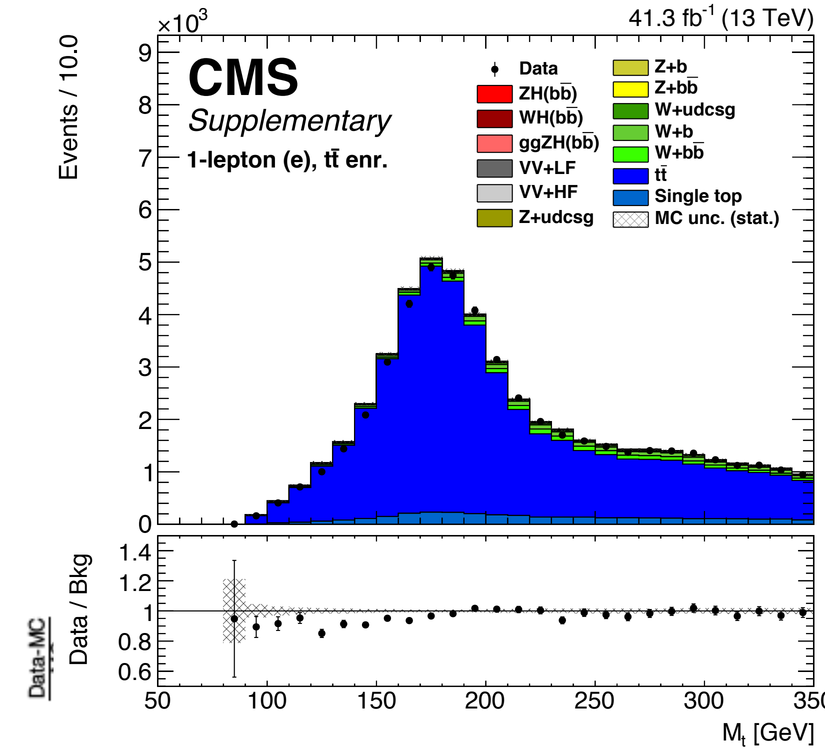
M_{top} before and after regression

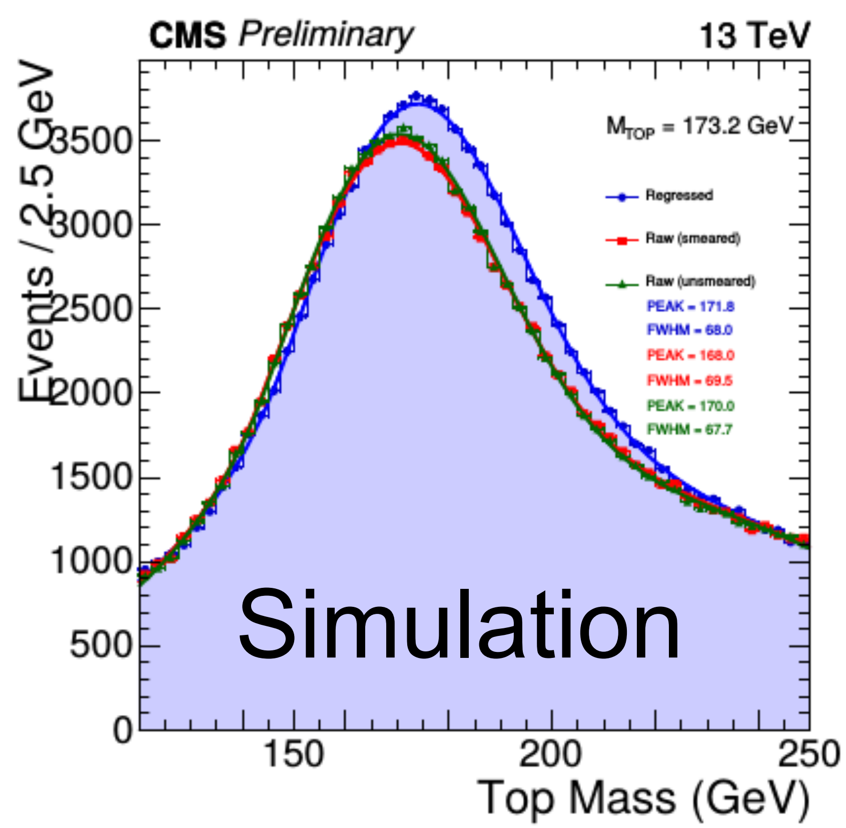


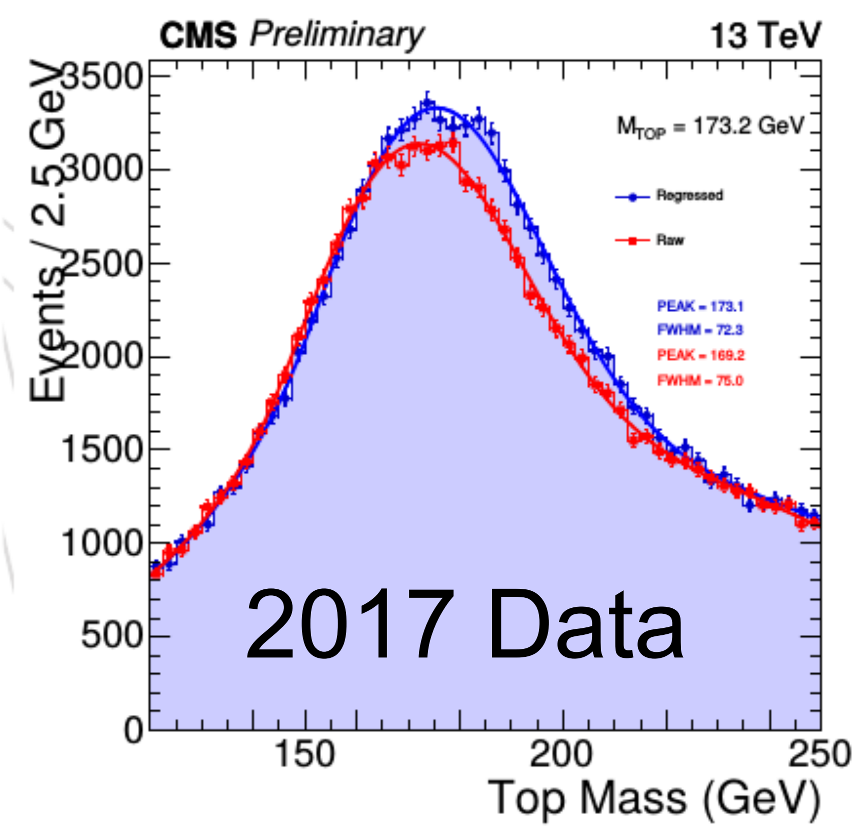
B-jet Energy Regression Validation: M_{top}

- Reconstruct full top four-vector by assuming W mass and solving analytically for neutrino p_Z.
- Clear improvement in M_{top} resolution that is consistent between simulation and data.



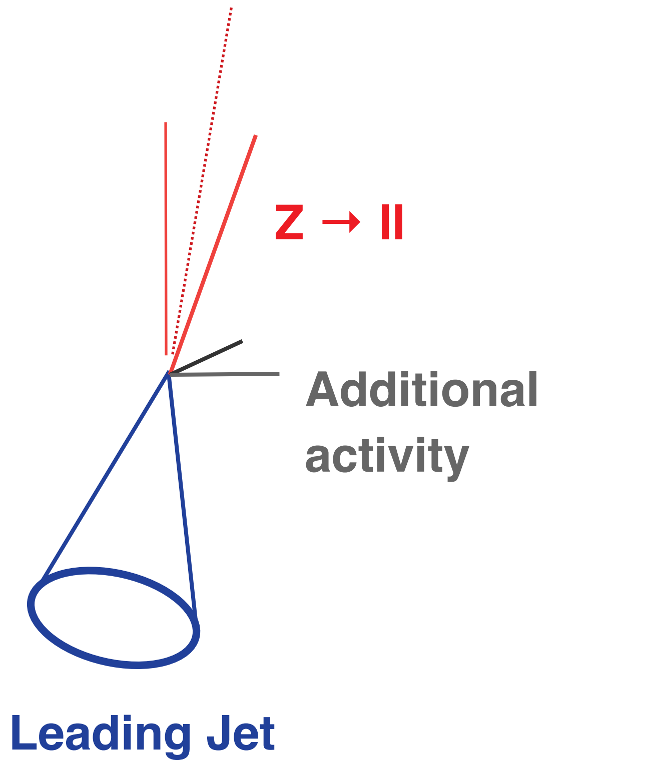


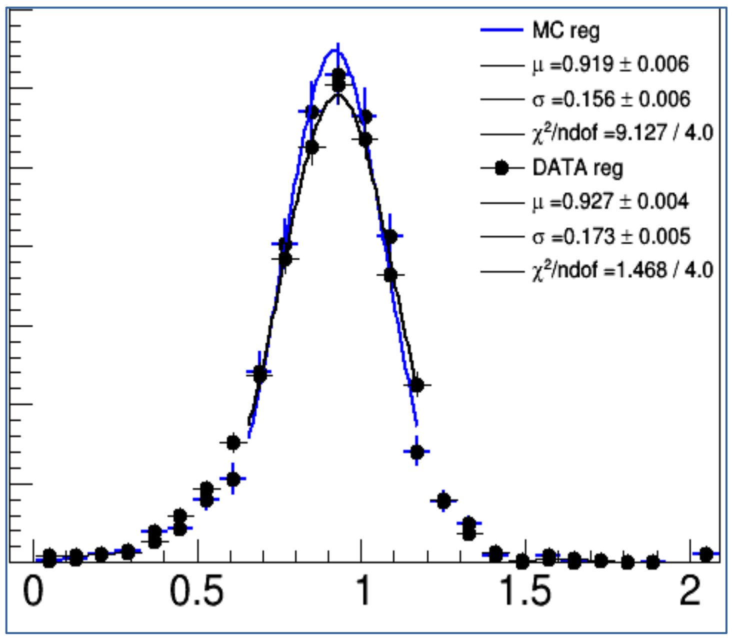




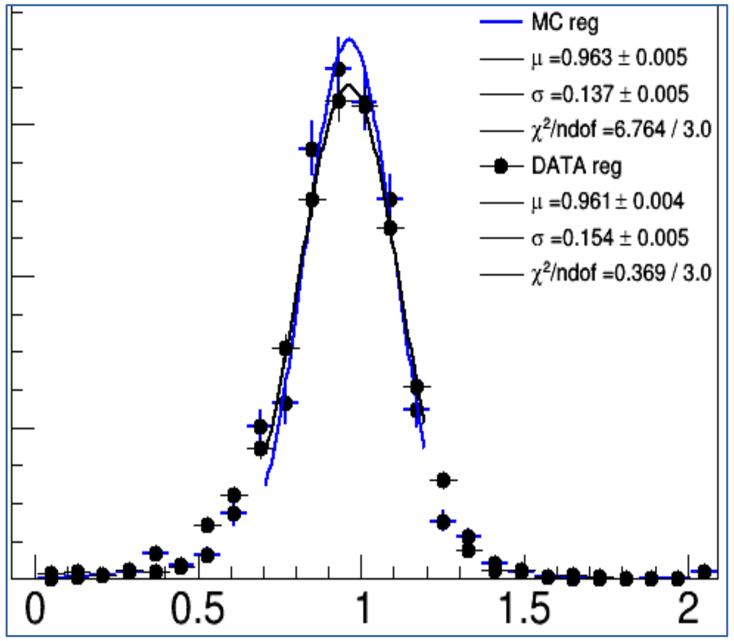
Regression in Data

- Performance on data evaluated with p_T balance in Z(ll) + b-jet topology.
  - JME recommendations:
    - Cut on additional activity ($\alpha = p_T$ 2nd jet / $p_T(Z) > 0.3$), bin in α
    - Leading jet collinear with Z: $\Delta\varphi(Z,jet1) > 2.8$
    - Leading jet p_T and η in fiducial region
    - Extrapolation in α
- Good agreement on scale between simulation and data.
- Resolution improvement in both data and simulation, however JER SF necessary.
- Extrapolation to "zero-activity" ($\alpha = 0$) to determine JER SF: 1.1 ± 0.1





Apply regression →



Performance in lowest activity bin (p_T 2nd jet <15 GeV)

Fiducial cuts $p_T(Z) > 100$ GeV, $|\eta| < 2.0$

σ_{Data} 0.173 → 0.154

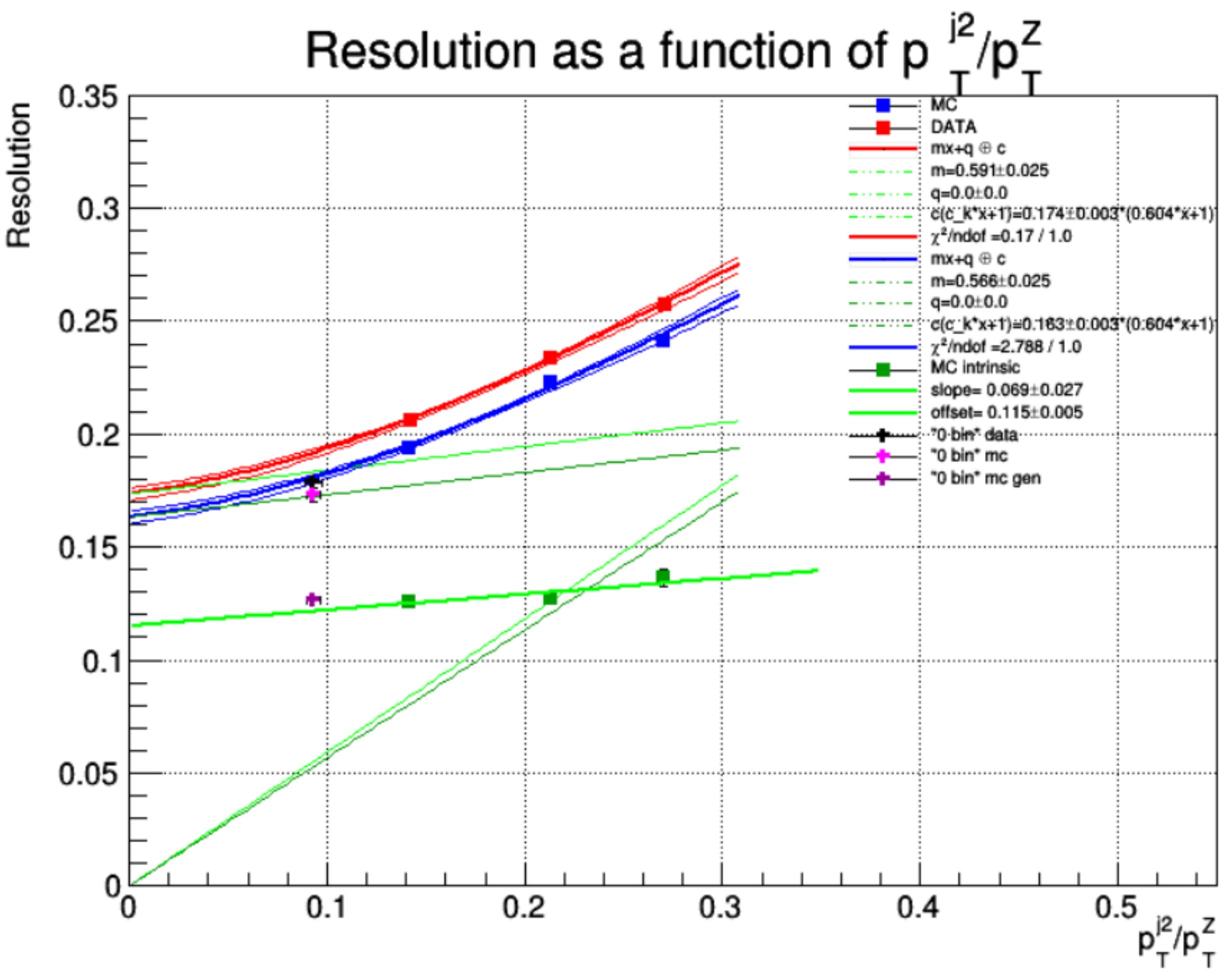
σ_{MC} 0.156 → 0.137

~11% pt resolution per jet
→ 20% on M(jj)

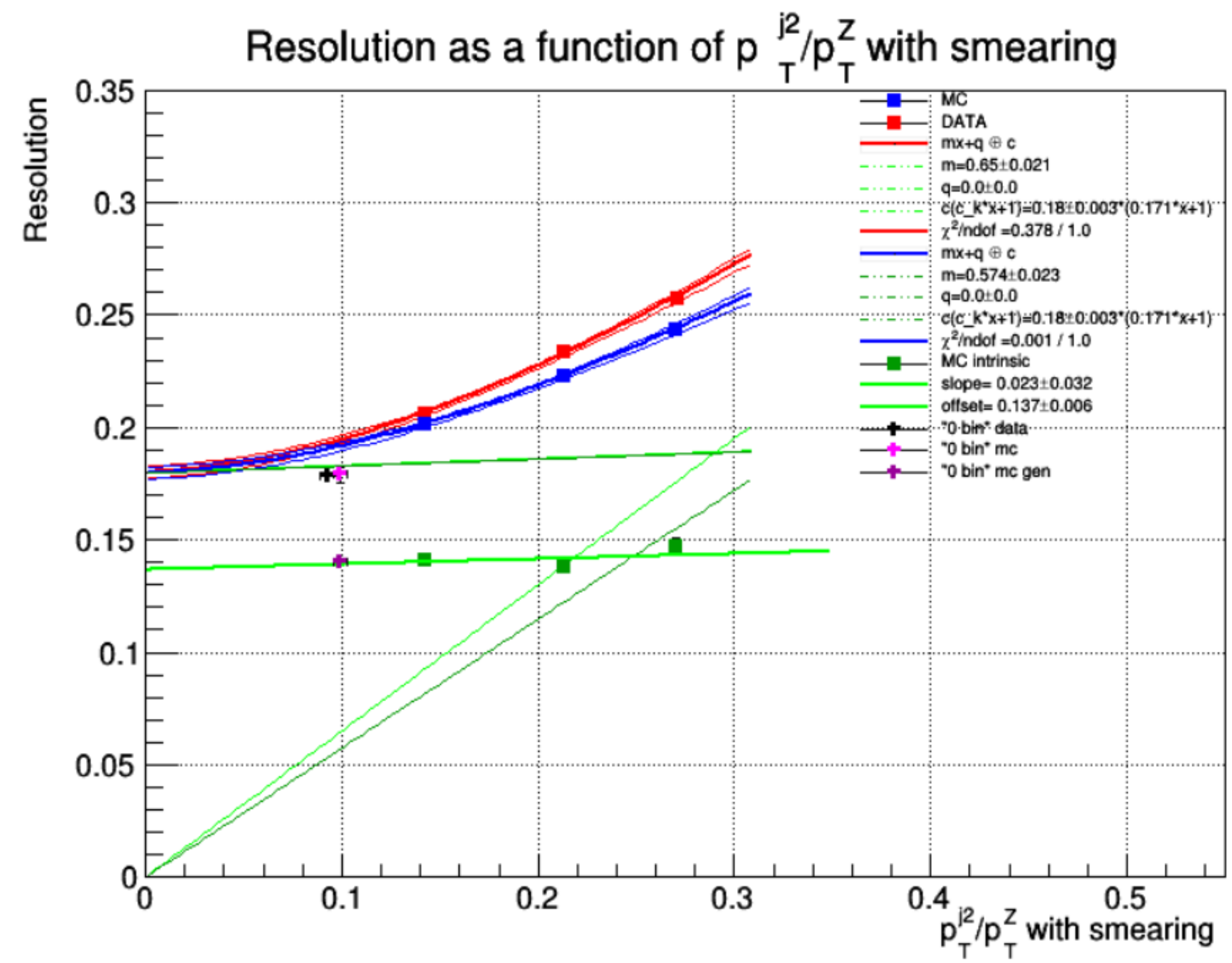
Regressed b-jet JER SF Extrapolation

- Extrapolation for JER SF measurement
- SF measured using b-jet p_T / $p_T(Z)$ balance binning in α (p_T 2^{nd} jet >15 GeV) + fiducial cuts $p_T(Z)$ > 100 GeV, |η|<2.0, with extrapolation to intrinsic resolution

→ JER SF for regressed b-jets: 1.1 ± 0.1



No JER smearing applied



All JER SF applied

Regressed b-jet JER SF: Closure Test

	$p_{T,j1}$ unregressed unsmeared, $p_{T,j2}$ unsmeared	$p_{T,j1}$ regressed unsmeared, $p_{T,j2}$ unsmeared	$p_{T,j1}$ regressed with 1.1 JER SF, $p_{T,j2}$ unsmeared	$p_{T,j1}$ regressed with 1.1 JER SF, $p_{T,j2}$ smeared
MC intrinsic				
m_0	0.067 ± 0.031	0.069 ± 0.027	0.066 ± 0.030	0.030 ± 0.032
q_0	0.132 ± 0.006	0.115 ± 0.005	0.128 ± 0.006	0.137 ± 0.006
MC reco				
m	0.563 ± 0.026	0.566 ± 0.025	0.551 ± 0.026	0.574 ± 0.023
q	0	0	0	0
c	0.172 ± 0.003	0.163 ± 0.003	0.172 ± 0.003	0.180 ± 0.003
Data				
m	0.586 ± 0.026	0.591 ± 0.025	0.603 ± 0.024	0.650 ± 0.021
q	0	0	0	0
c	0.184 ± 0.003	0.174 ± 0.003	0.175 ± 0.003	0.180 ± 0.003

Resolution improvement from regression

Extrapolation closure

H→$b\bar{b}$ Combination: Correlation Scheme

- Inherits from previous combinations:
  - Correlations between run 1 analyses already settled for run 1 coupling combination
  - Correlations between 2016 analyses were already settled for 2016 coupling combination
  - Correlations between run 1 & run 2 ttH and were already settled for ttH combination
- Features of correlations between run 1 VH and run 2, and VH 2016 - 2017 in table below
- Note: we update run 1 cross sections and uncertainties with the values from YR4

Jet energy scale	Between 2016 and 2017 we correlate some of the sources following JME recommendations
b-tagging	Not correlated between 2016-2017 and not correlated between VH and other channels due to different treatment
Signal theory	Inclusive QCD scale and pdf uncertainties correlated between run 1 and run 2. QCD scale acceptance uncertainties correlated between VH 2016 and 2017, pdf acceptance uncertainties not correlated
Background theory	Inclusive cross section uncertainties correlated between VH 2016 and 2017. QCD scale acceptance uncertainties correlated between VH 2016 & 2017, pdf acceptance uncertainties not correlated
Lumi	Uncorrelated between 2016 & 2017
JER	Correlated between 2016 & 2017 (note JER in 2017 split in ‘regular’ JER and regressed jet JER. The latter is not correlated with anything)
PU uncertainty	Correlated between 2016 and 2017

Event Selection (detailed)

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)	–

Control Region Selections (detailed)

0-lepton

Variable	$t\bar{t}$	$Z+$light	$Z+$bb
V Decay Category	$W(\ell\nu)$	$Z(\nu\nu)$	$Z(\nu\nu)$
$p_T(j_1)$	> 60	> 60	> 60
$p_T(j_2)$	> 35	> 35	> 35
$p_T(jj)$	> 120	> 120	> 120
E_T^{miss}	> 170	> 170	> 170
$\Delta\phi(V,H)$	> 2	> 2	> 2
N_{al}	≥ 1	$= 0$	$= 0$
N_{aj}	≥ 2	≤ 1	≤ 1
$M(jj)$	–	–	$\notin [60-160]$
$DeepCSV_{max}$	DeepCSVM	!DeepCSVM	DeepCSVT
$DeepCSV_{min}$	DeepCSVL	DeepCSVL	DeepCSVL
$\Delta\varphi(j, E_T^{miss})$	–	> 0.5	> 0.5
$\Delta\varphi(tkMET, E_T^{miss})$	–	< 0.5	< 0.5
$\min\Delta\varphi(j, E_T^{miss})$	$< \pi/2$	–	–

DRAFT

2-lepton

Variable	$t\bar{t}$	Z+LF	Z+HF
$p_T(j_1)$	> 20	> 20	> 20
$p_T(j_2)$	> 20	> 20	> 20
$p_T(V)$	$[50, 150], > 150$	$[50, 150], > 150$	$[50, 150], > 150$
$DeepCSV_{max}$	> DeepCSV Tight	< DeepCSV Loose	> DeepCSV Tight
$DeepCSV_{min}$	> DeepCSV Loose	< DeepCSV Loose	> DeepCSV Loose
E_T^{miss}	–	–	< 60
$\Delta\phi(V,H)$	–	> 2.5	> 2.5
$m_{\ell\ell}$	$\notin [0, 10], \notin [75, 120]$	$[75, 105]$	$[85, 97]$
$M(jj)$	–	$[90, 150]$	$\notin [90, 150]$

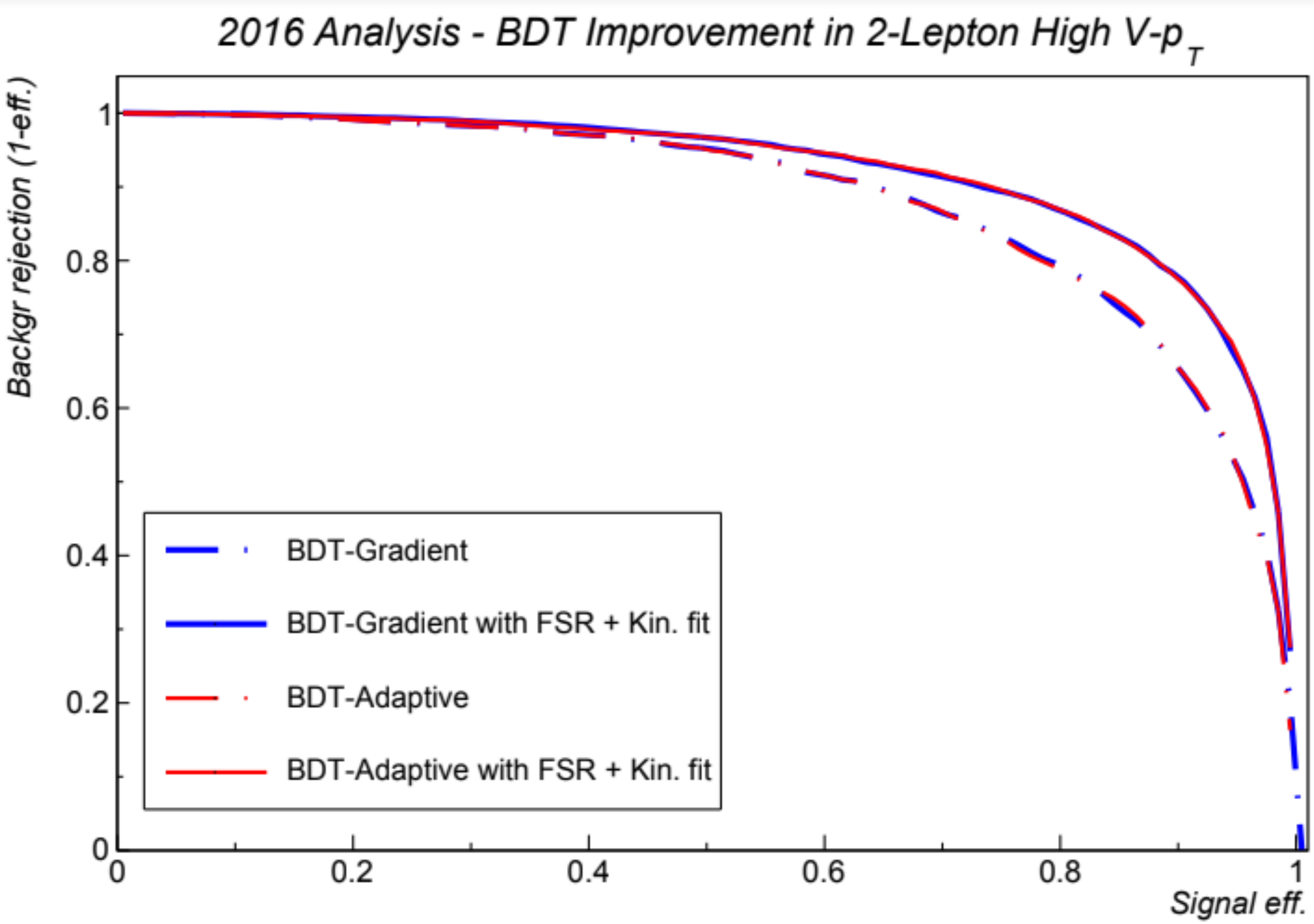
1-lepton

Variable	W+LF	$t\bar{t}$	W+HF
$p_T(j_1)$	> 25	> 25	> 25
$p_T(j_2)$	> 25	> 25	> 25
$p_T(jj)$	> 100	> 100	> 100
$p_T(V)$	> 100	> 100	> 100
$DeepCSV_{max}$	$[-0.5884 - 0.4432]$	> 0.9432	> 0.9432
N_{aj}	–	> 1	$= 0$
N_{al}	$= 0$	$= 0$	$= 0$
METsig	> 2.0	–	> 2.0
$\Delta\phi(pfMET, lep)$	< 2	< 2	< 2
$M(jj)$	< 250	< 250	< 250, veto $[90 - 150]$

DNN Variable Rankings

Rank	$W(\ell\nu)H$	$Z(\nu\nu)H$	$Z(\ell\ell)H$ low p_T	$Z(\ell\ell)H$ high p_T
1	$\lvert b-jets\ \Delta\eta \rvert$	$M(jj)$	$\mathrm{DeepCSV_{max}}$	$\mathrm{DeepCSV_{max}}$
2	$M(jj)$	$\mathrm{DeepCSV_{min}}$	$M(jj)$	$M(jj)$
3	$\mathrm{DeepCSV_{min}}$	$\Delta\varphi(jj)$	$\mathrm{DeepCSV_{min}}$	$\mathrm{DeepCSV_{min}}$
4	M_t	$\Delta\eta(jj)$	M_Z	$\Delta\eta(jj)$
5	SA5	$\mathrm{DeepCSV_{max}}$	$\Delta\eta(jj)$	M_Z
6	E_T^{miss}	SA5	$p_T(Z)$	E_T^{miss}
7	$\lvert\Delta\phi(V,H)\rvert$	Sub-leading b-jet	E_T^{miss}	Sub-leading b-jet
8	$\Delta\varphi(\mathrm{pfMET, lept.})$	$\Delta\phi(V,H)$	Sub-leading b-jet	Leading b-jet
9	p_T balance	Max $p_T(add.jet)$	$\Delta\phi(V,H)$	N_{aj}
10	$\Delta R(jj)$	$p_T(jj)$	Leading b-jet	$p_T(jj)$
11	$\mathrm{DeepCSV_{max}}$	$p_T(Z)$	SA5	SA5
12	$p_T(Z)$	Leading b-jet	$N_{recoil\,jets}$	$\Delta\phi(V,H)$
13	Leading b-jet	Max $\mathrm{DeepCSV_{add}}$	N_{aj}	$p_T(Z)$
14	Sub-leading b-jet	Min $\Delta\phi_{add}$	$p_T(jj)$	$\sigma(H_{mass})$
15	$p_T(jj)$	–	p_T balance	p_T balance
16	N_{aj}	–	$\sigma(H_{mass})$	$N_{recoil\,jets}$
17	$m_T(W)$	–	–	–

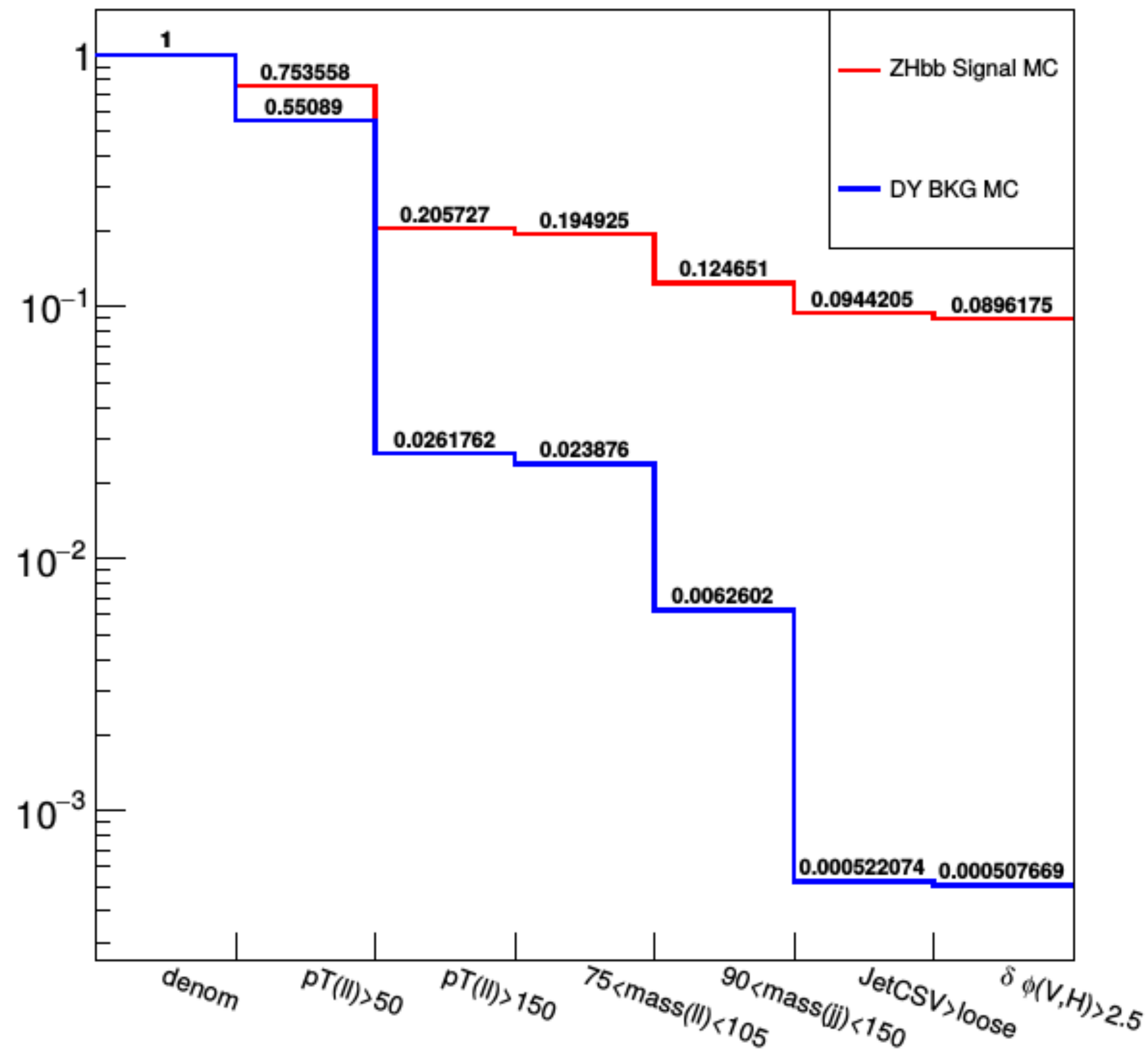
2-lepton Performance Improvement



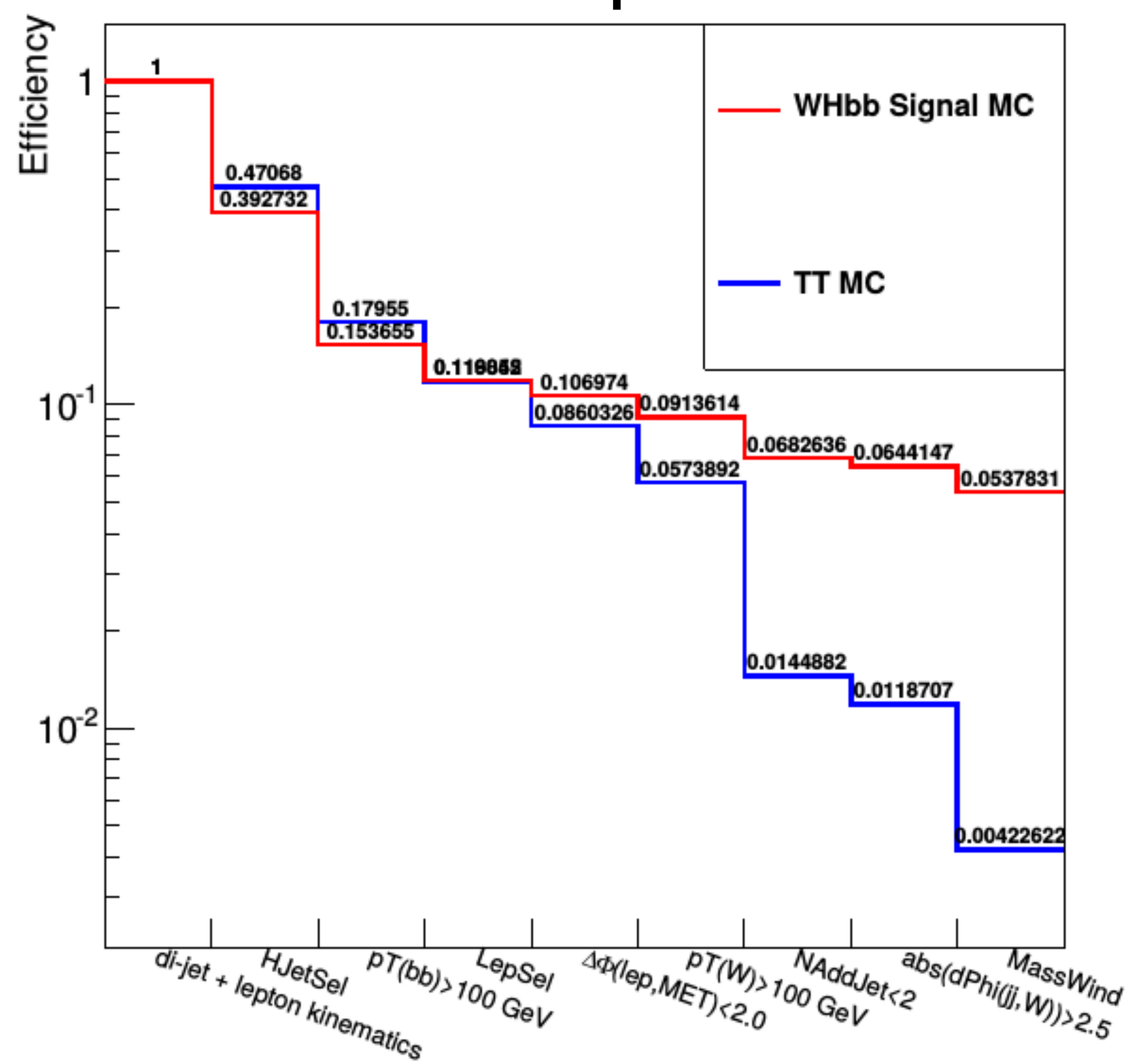
Significant improvement in signal vs. background discrimination in 2-lepton channel from kinematic fit + FSR

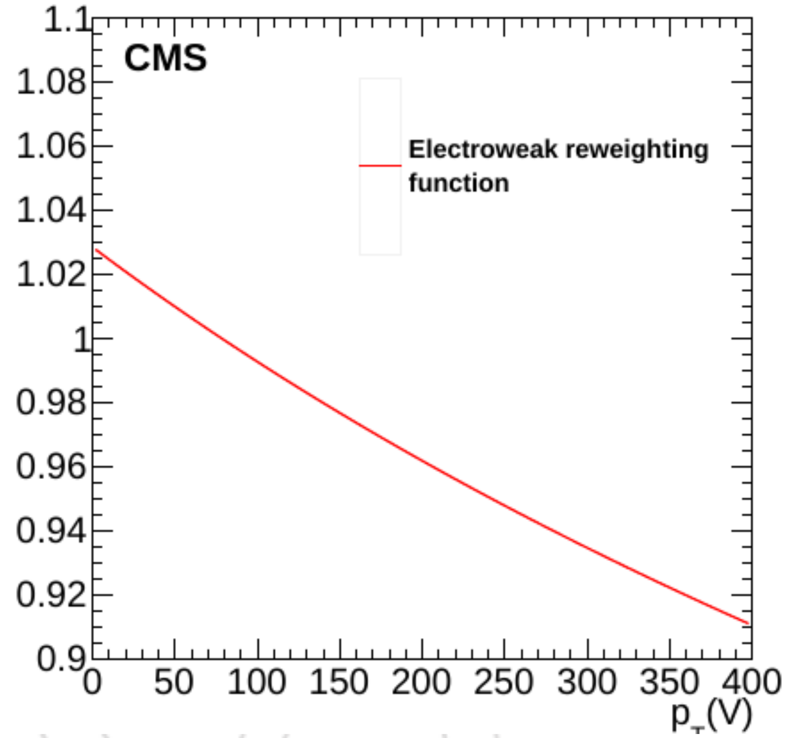
Cut-flow: 2-lepton and 1-lepton channels

2-lepton



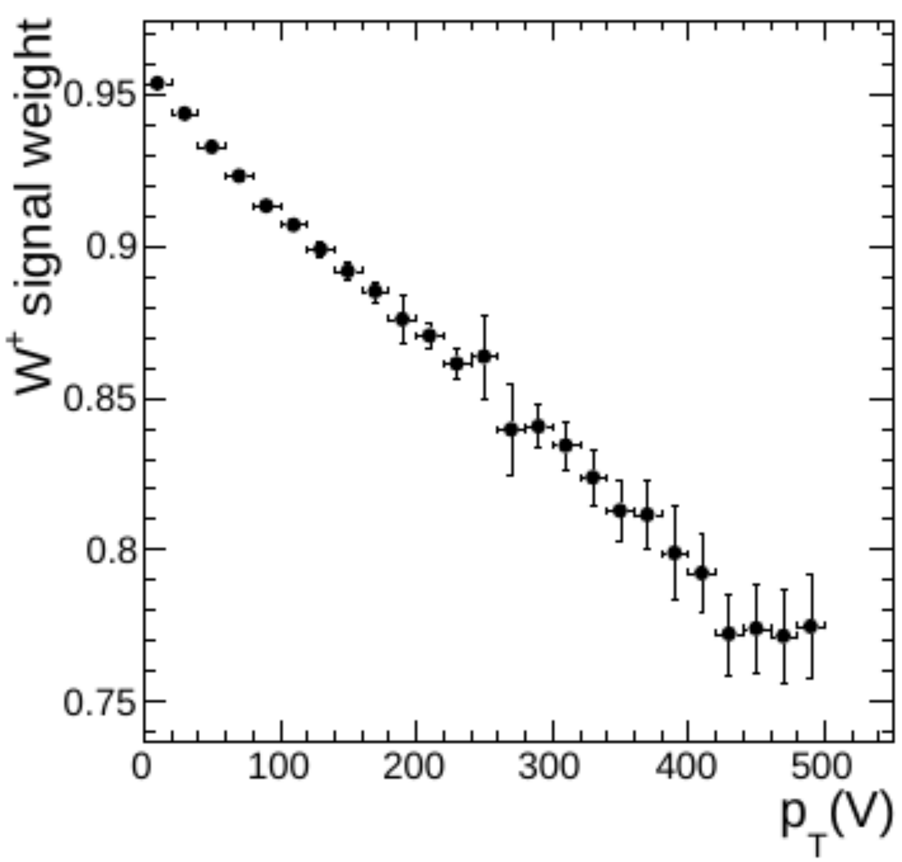
1-lepton

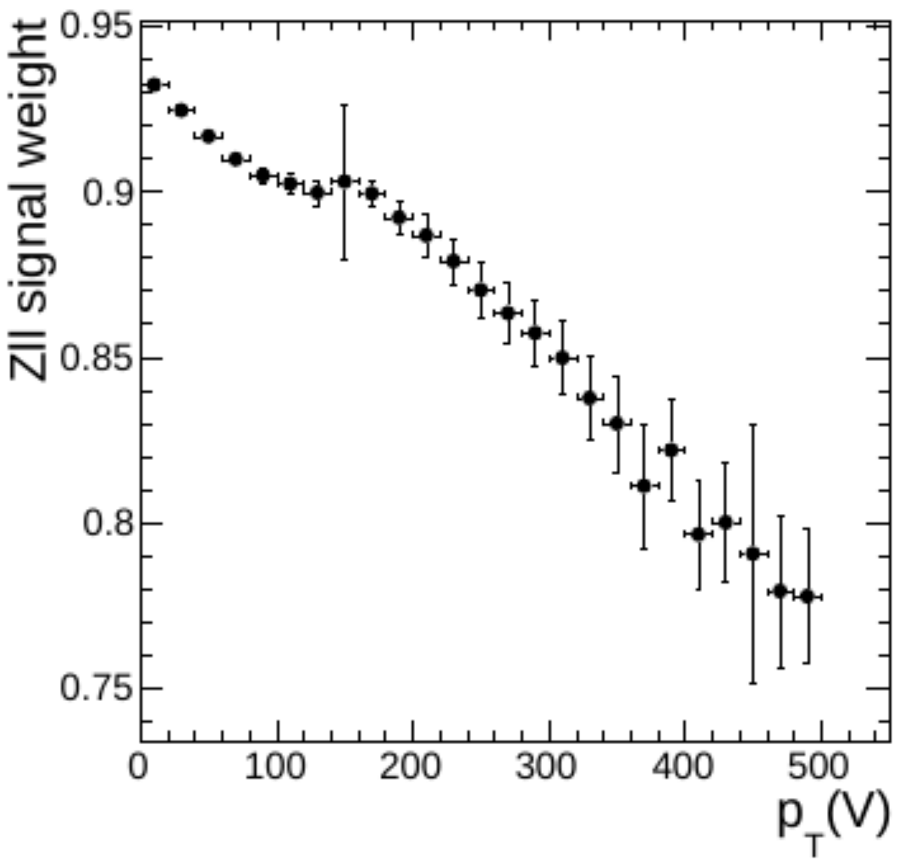




V+jets $p_T(V)$ correction:

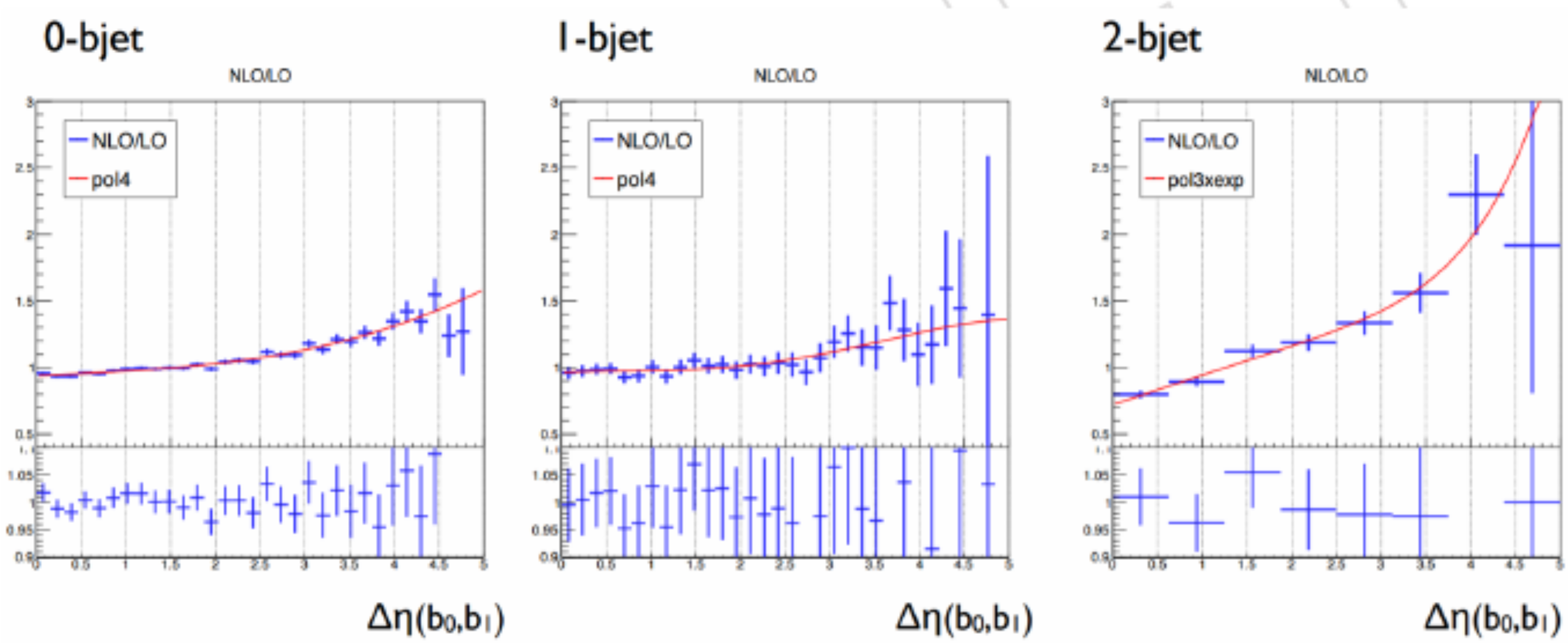
negative correction from higher order QCD and electroweak corrections to the vector boson production.





The signal Monte Carlo sample for qqVH is produced with POWHEG +MiNLO and then rescaled to NNLO QCD.
EWK correction applied

- LO to NLO corrections for V+jets as a function of Δη(jj)

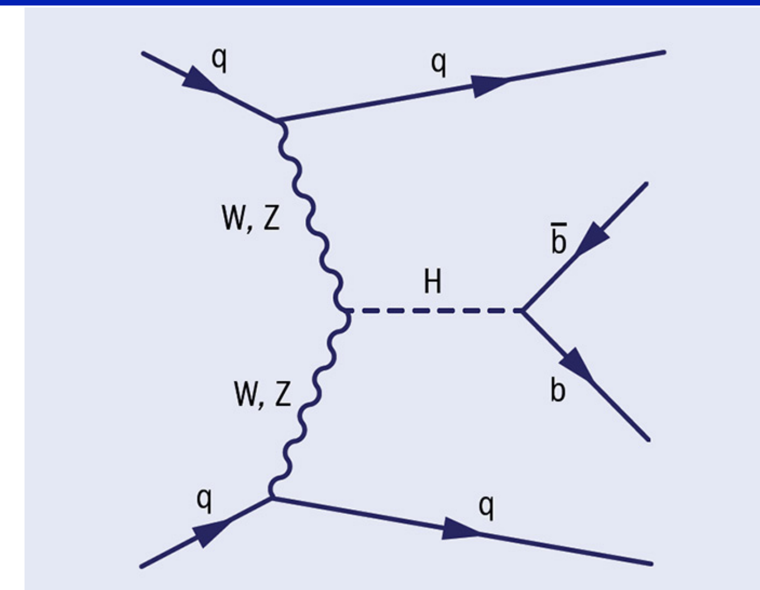


Linear correction for W and Top pT

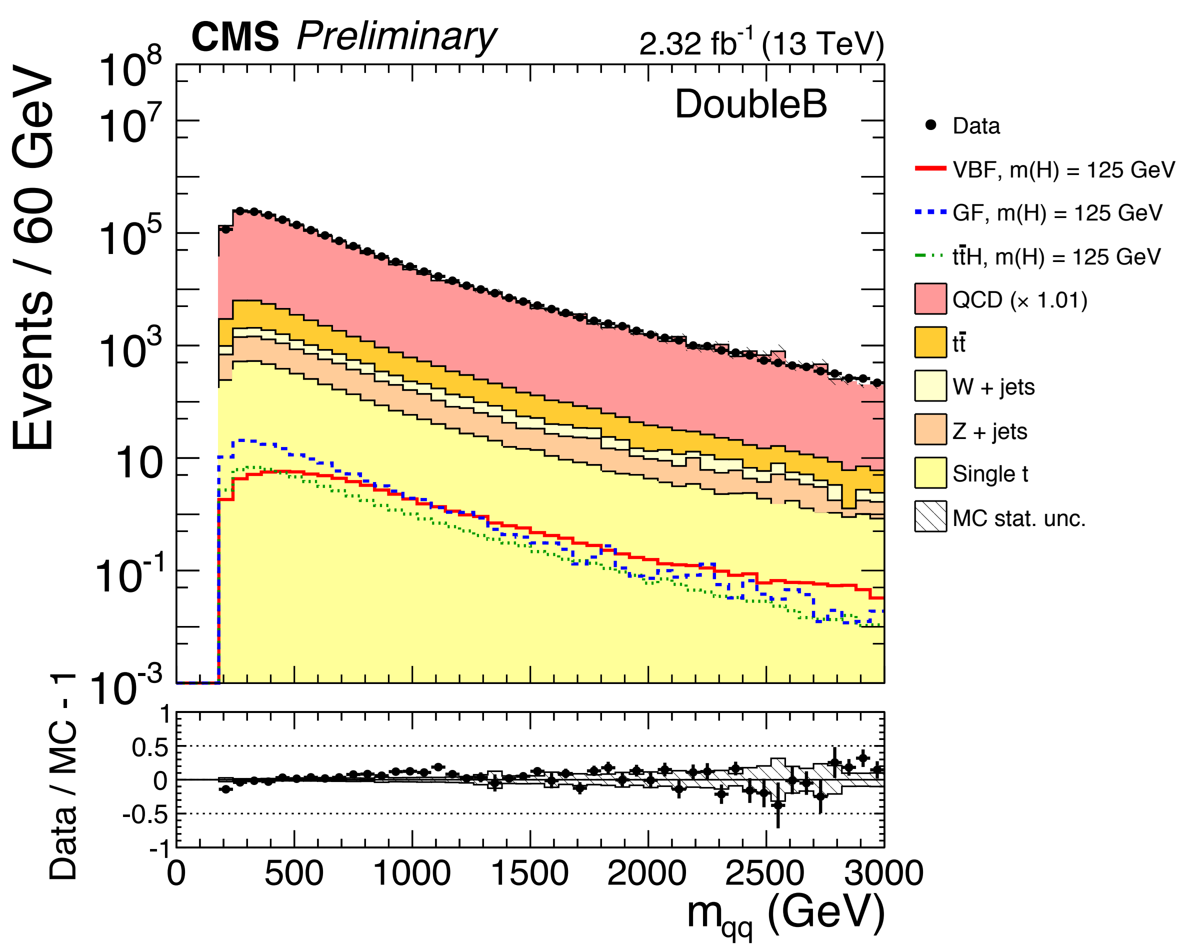
Process	$t\bar{t}$	W + udscg	$Wb\bar{b}$ + single top
Fitted Slope (/ GeV)	0.00061 ± 0.00008	0.00064 ± 0.00004	0.0016 ± 0.0001
Norm preserving constant	1.103	1.115	1.337

VBF H→b$\bar{b}$

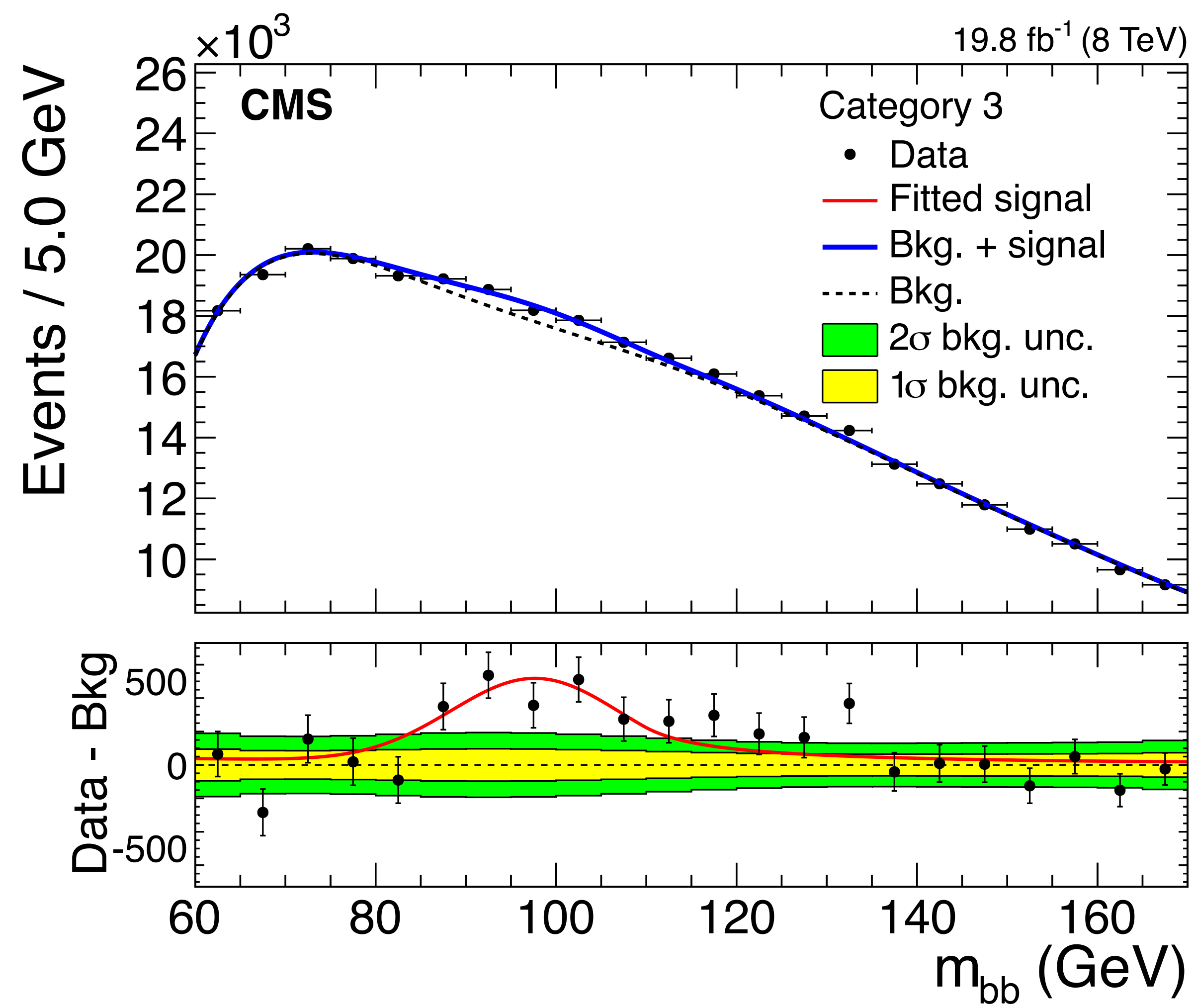
- All-jet final state dominated by QCD multi-jet background.
- Data-driven fits to M(b$\bar{b}$) on events categorized by MVA discriminant.
- Similar strategy could be possible for VH, H→b$\bar{b}$, especially as statistical precision of simulating becomes more and more limiting.



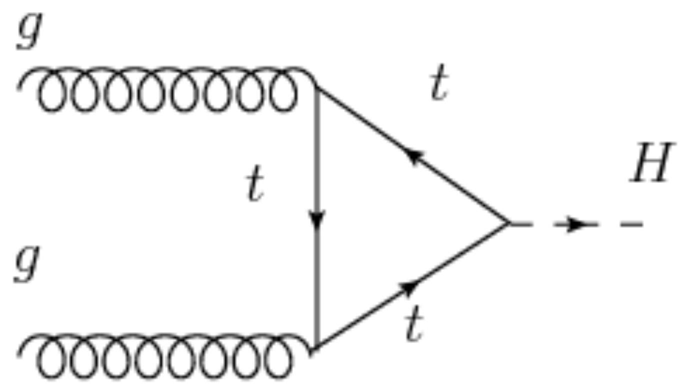
13 TeV (2015 preliminary)



8 TeV (3.6σ Z→b$\bar{b}$)



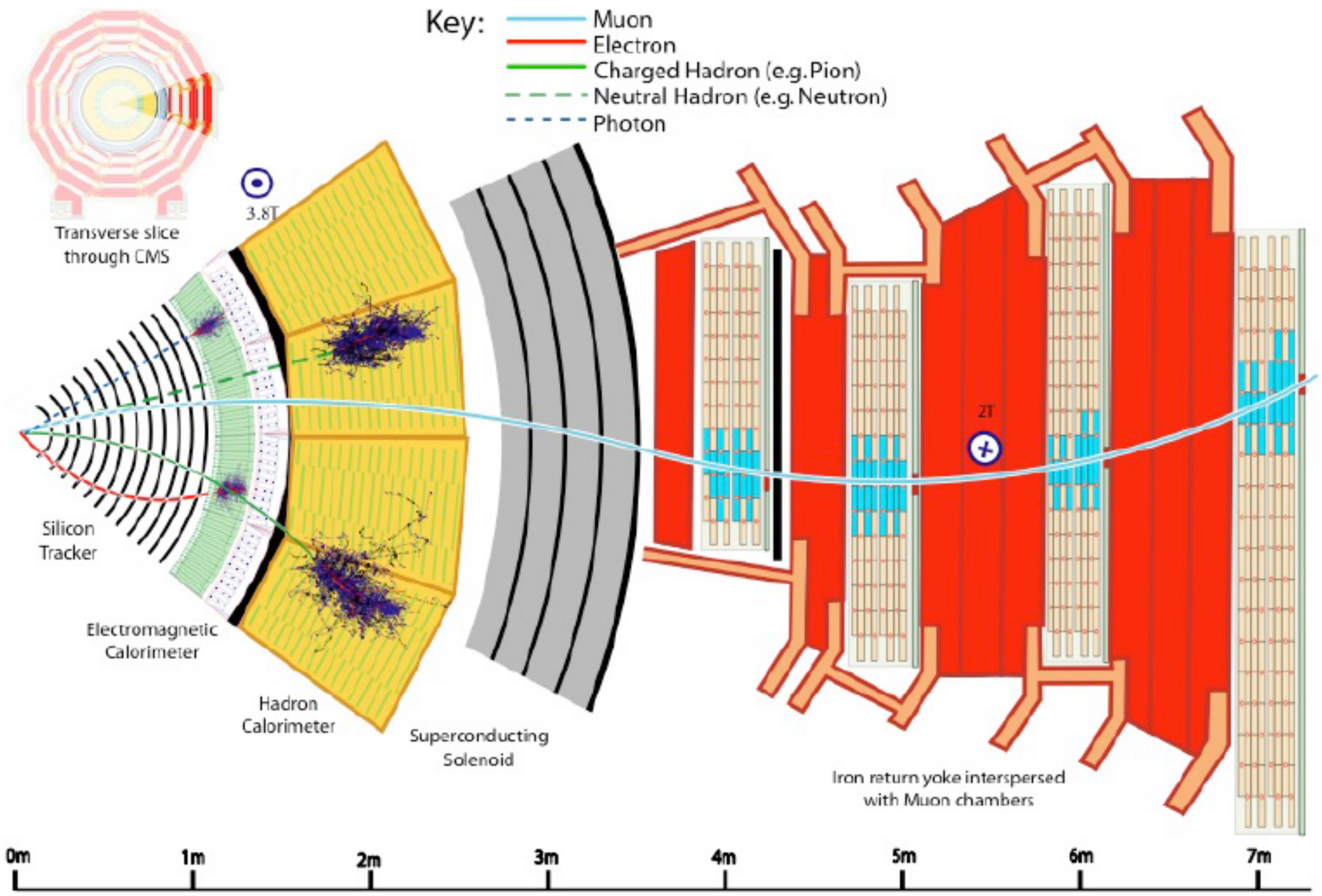
- Indirect probe (loop-induced):
  - gg→H



✓ Observed

- Direct probe (tree-level):
  - H→ττ (leptons) ✓ Observed
  - H→b$\bar{b}$ (down-type quarks) ✓ Observed
  - t$\bar{t}$H production (up-type quarks) ✓ Observed

- arXiv:1706.04965, accepted by JINST.
- Combine information from sub-detectors into global event description.

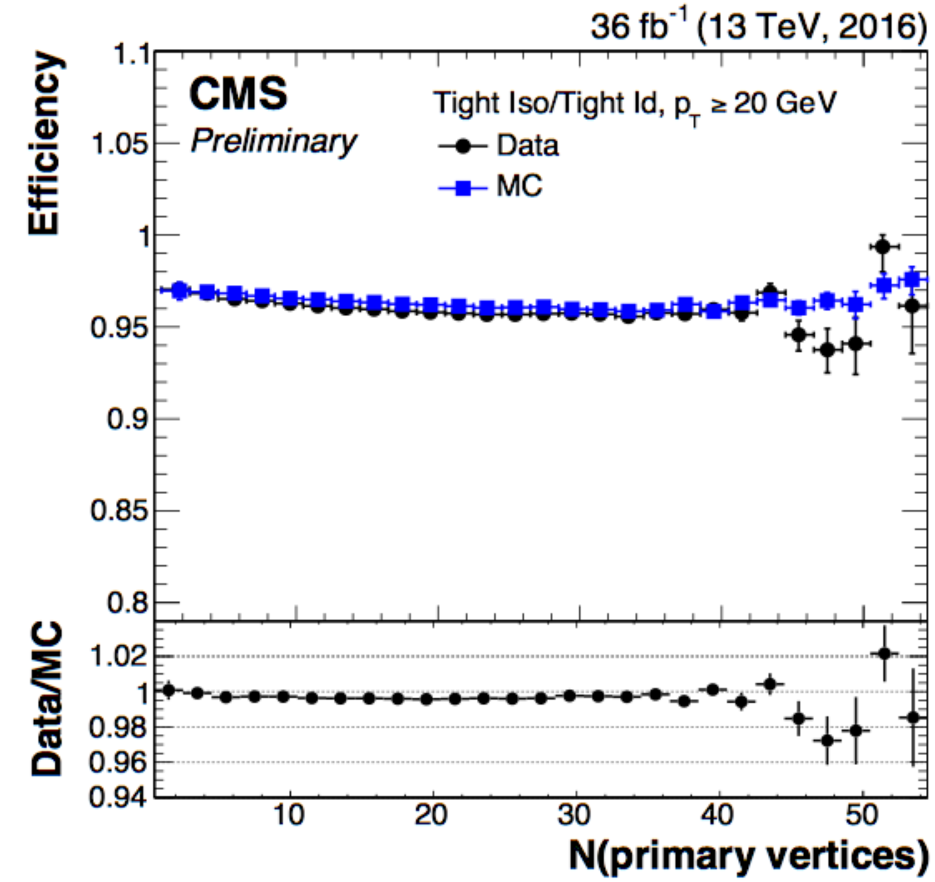


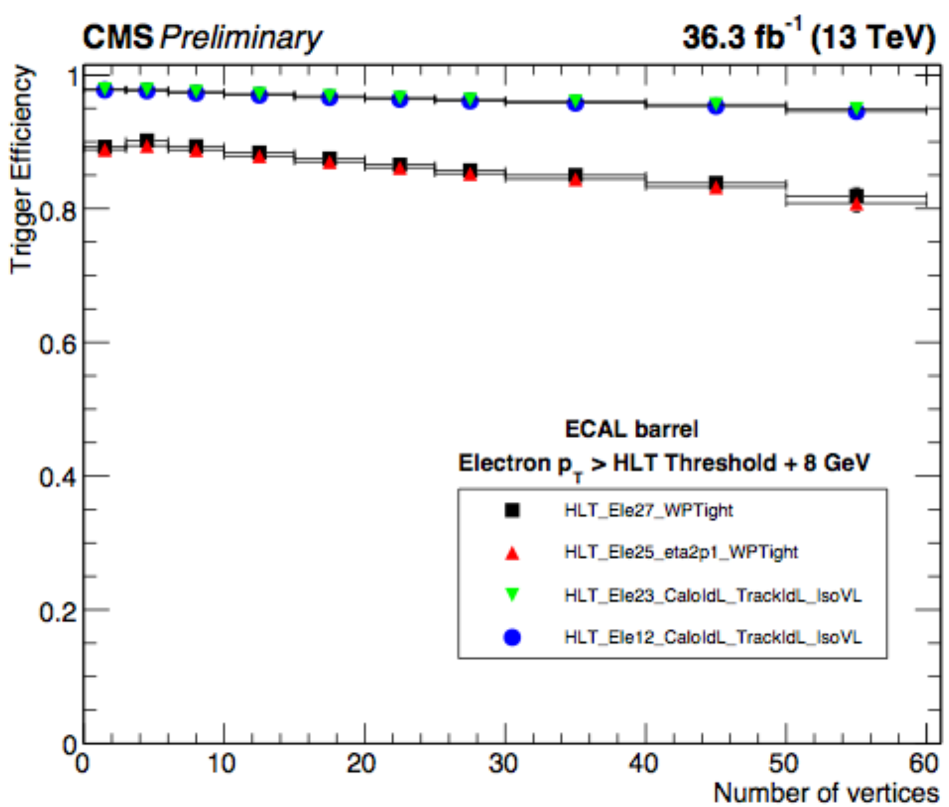
- Reconstruct all particles: electrons, muons, photons, charged/neutral hadrons.
- VH($b\bar{b}$) analysis depends critically on ability to efficiently reconstruct (b)-jets, E_T^{miss}, isolated leptons.
  - Relies on all particle flow objects except photons.

Lepton Reconstruction

- Detector-level selections to identify electrons and muons.
  - Cut-based for muons, MVA for electrons.
- Require minimal additional particle activity in cone around lepton.
  - Important to distinguish “real” leptons from jets.

CMS-DP-2017-007





CMS-DP-2017-004

Trigger and offline thresholds used in this analysis

	online [GeV]	offline [GeV]
1-μ	24	25
1-e	27	30
2-μ	17,8	20,20
2-e	23,12	25,20

Missing E_T Trigger

- E_T^{miss}: negative vectorial sum of all particle flow object p_T's.
- E_T^{miss} trigger nearly fully efficient with respect to offline selection for 0-lepton channel.