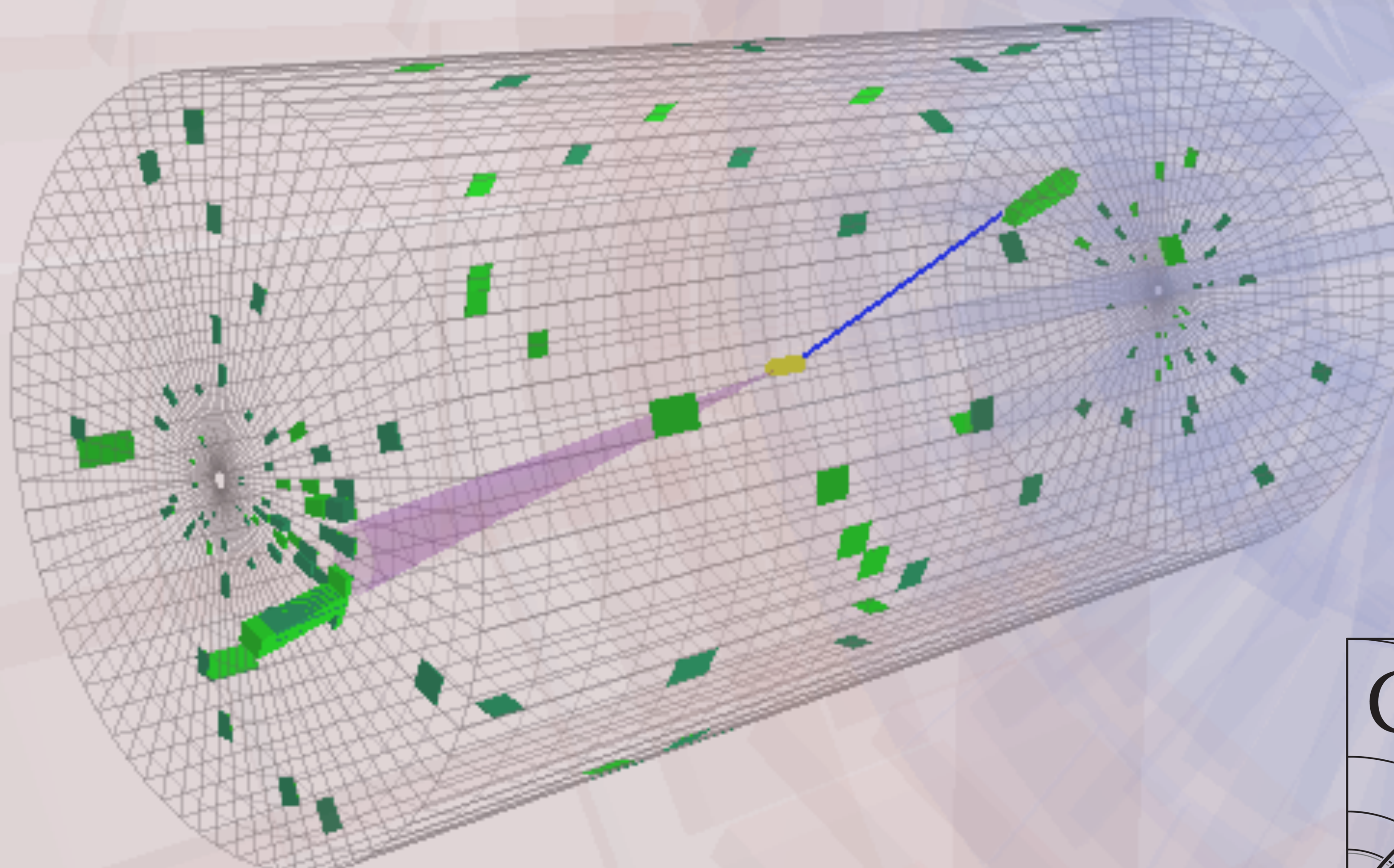
Search for Diboson Resonances with CMS and Pixel Barrel Detector Calibration and Upgrade

Jennifer Ngadiuba



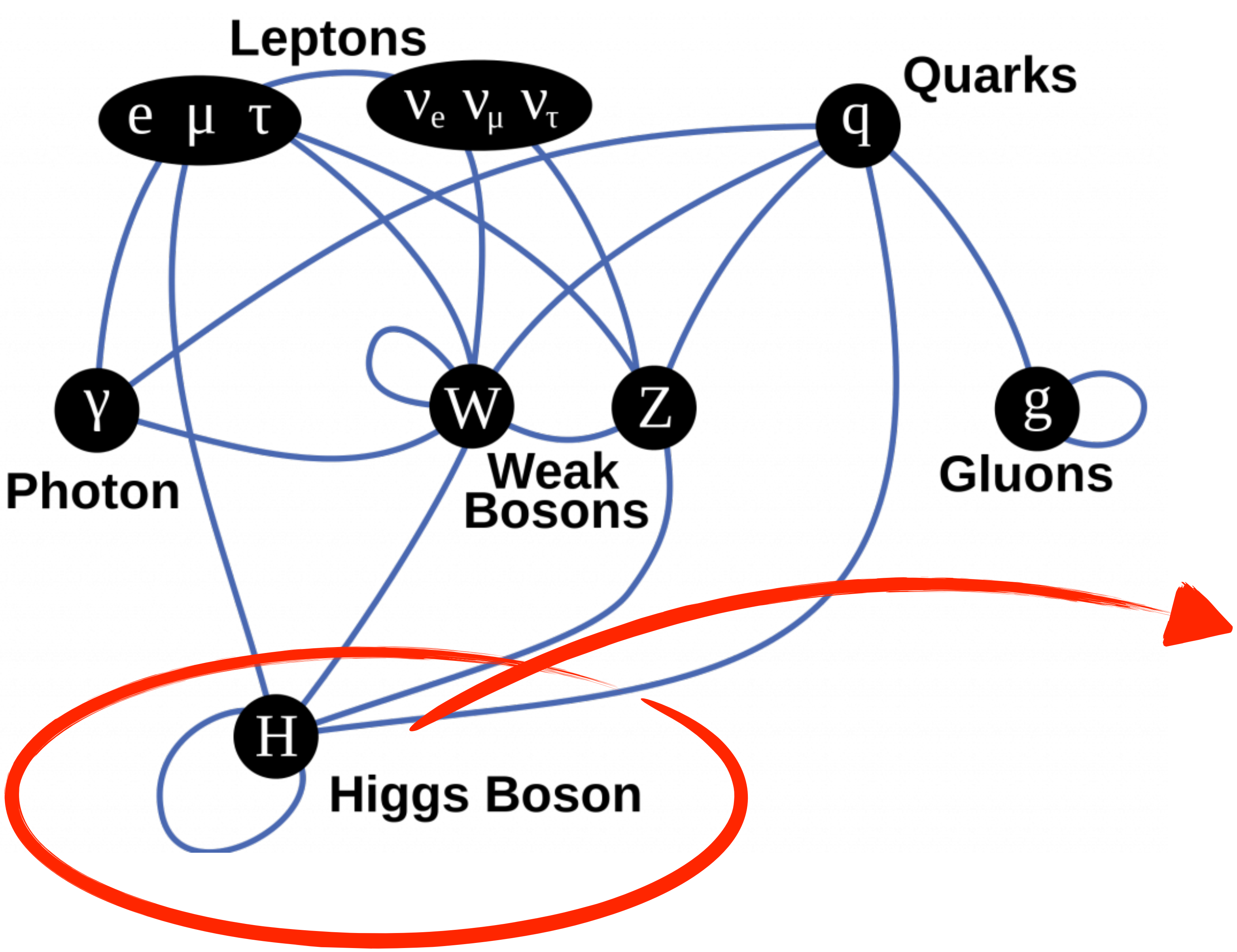
Promotionskommission:
Prof. Benjamin Kilminster
Prof. Florencia Canelli
Dr. Andreas Hinzmann
Dr. Lea Caminada

Ph.D. defense
6th April 2017
University of Zurich

Universität Zürich[UZH]
Physik-Institut

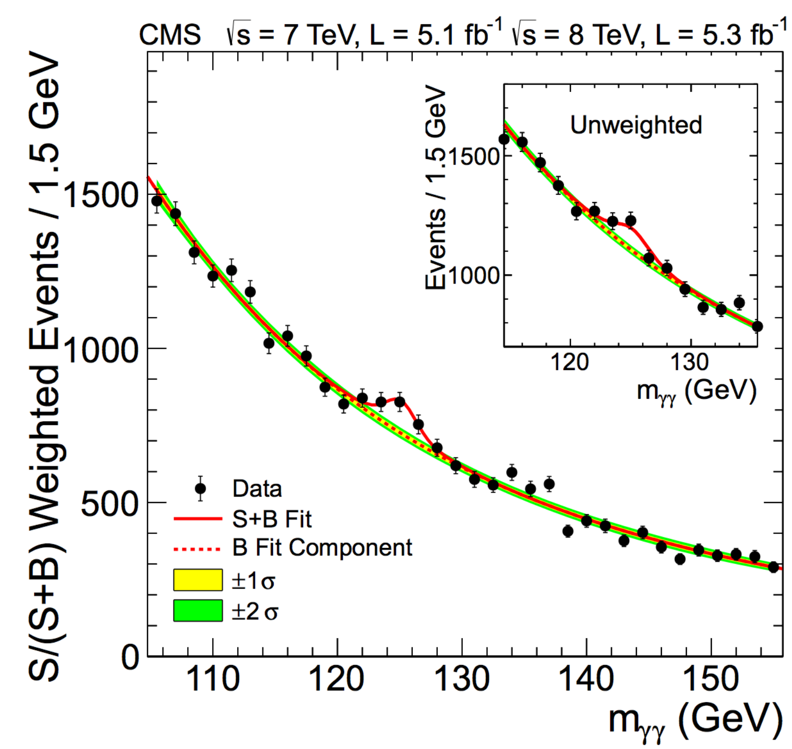
Our understanding of nature

The standard model of particle physics



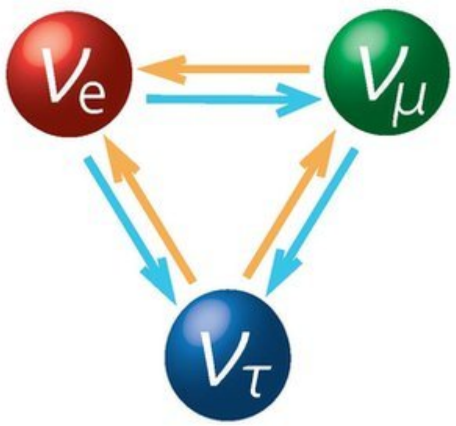
Last confirmation is the discovery of the Higgs boson at the Large Hadron Collider in 2012

Measured mass ≃ 125 GeV

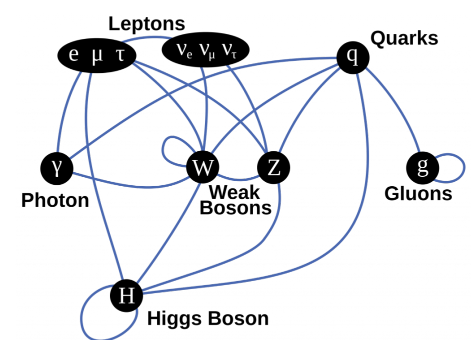


Need for beyond standard model

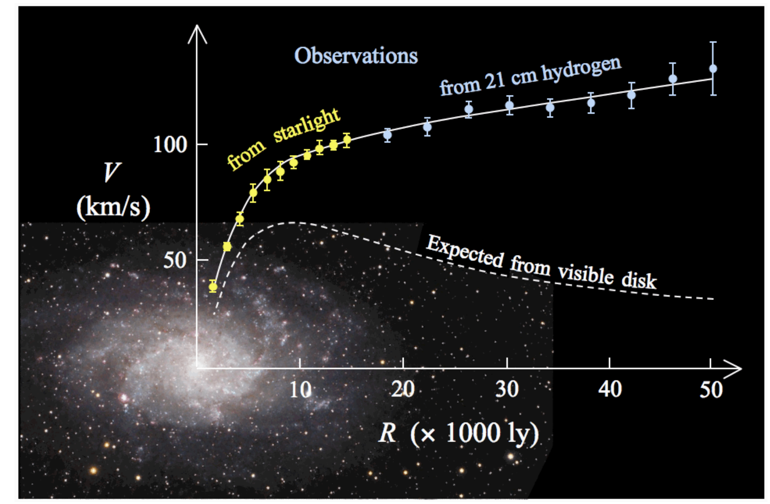
Neutrino masses



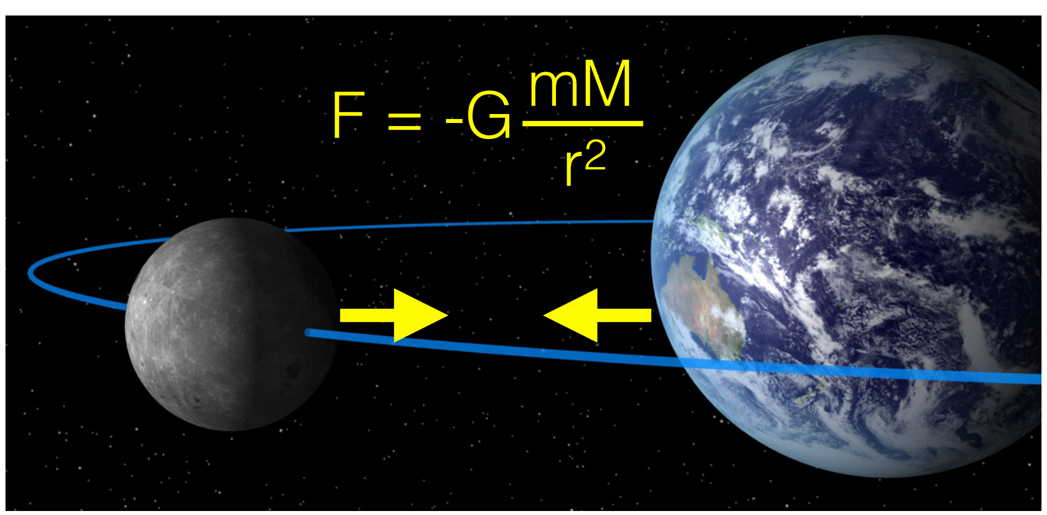
Standard Model =
our understanding of nature



Explains only 5% of the energy content of the Universe
No SM candidate for dark matter



Gravitational force not included in the theory



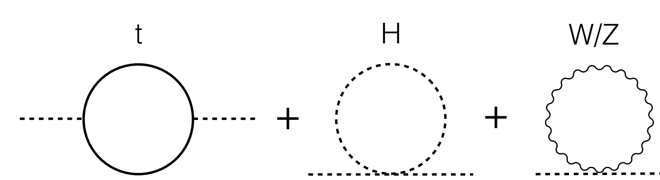
Hierarchy problem:

why gravitational force 10^{24} times weaker than the electroweak? ⇒ "unnatural"

Higgs mass

quantum corrections $\propto m^2_{Planck} = 10^{38}$ GeV

$(125 \text{ GeV})^2 = m_H^2 -$



tree-level mass
fundamental parameter
of the theory

top quark loop

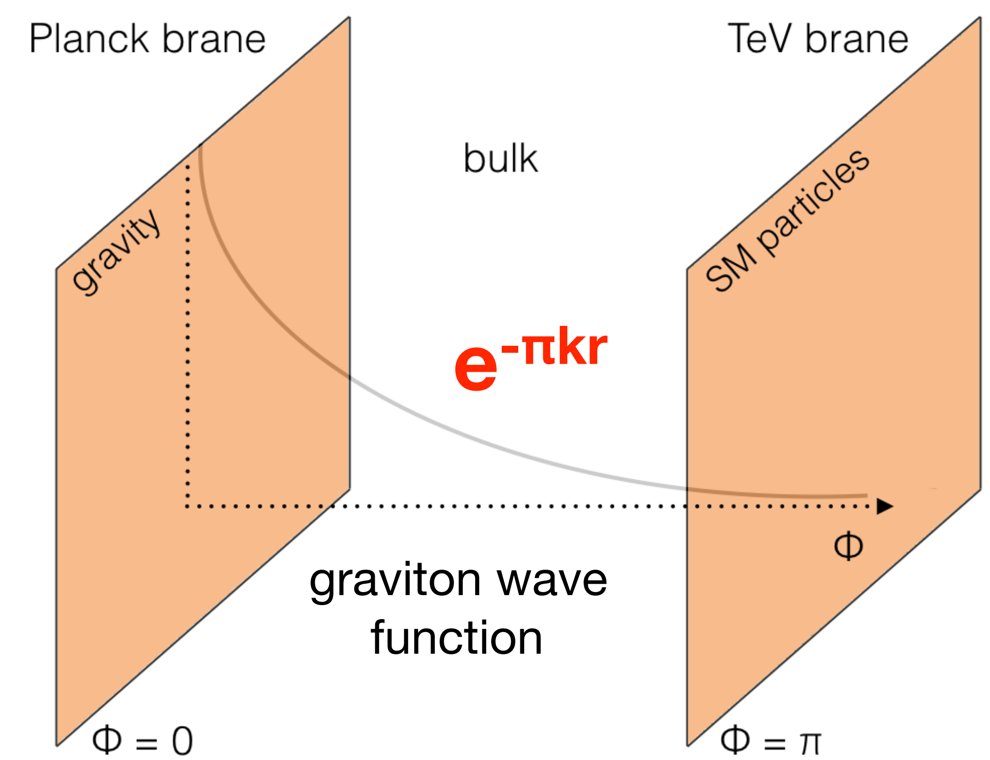
Higgs boson loop

gauge boson loop

New “natural” theories

Warped extra dimensions

Randall-Sundrum RS1 model:
PRL 83 (1999) 3370)



- We live in a warped 5-dimensional universe
- Gravity propagates in the extra dimension
- Predict a new **spin-2 graviton with m_G ~ TeV**

Extension: bulk graviton scenario

PRD 76 (2007) 036006)

- Allow SM fields to propagate in the extra dimension
- Dominant branching ratios of the graviton to a pair of SM bosons (WW,ZZ,HH)

$G \to \gamma\gamma$
$G \to qq/gg$
$G \to \ell\ell$
} suppressed decays

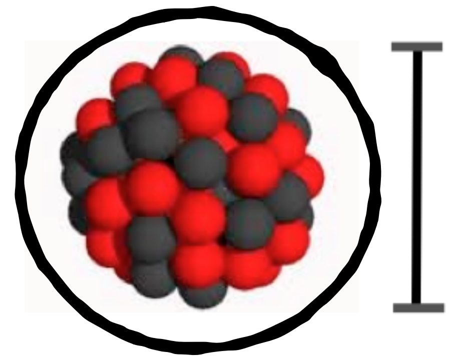
$G \to t\bar{t}$
$G \to HH$
$G \to WW/ZZ$
} enhanced decays

New “natural” theories

Composite Higgs models [R. Contino, et al: JHEP 10 (2011) 81]

- The Higgs boson is a composite state of a **new strong dynamics at a scale Λ ≈ O(TeV)**
- New composite states predicted:
  - the Higgs boson and the vector bosons
  - **new spin-1 resonances** decaying mainly to H, W and Z

Higgs boson

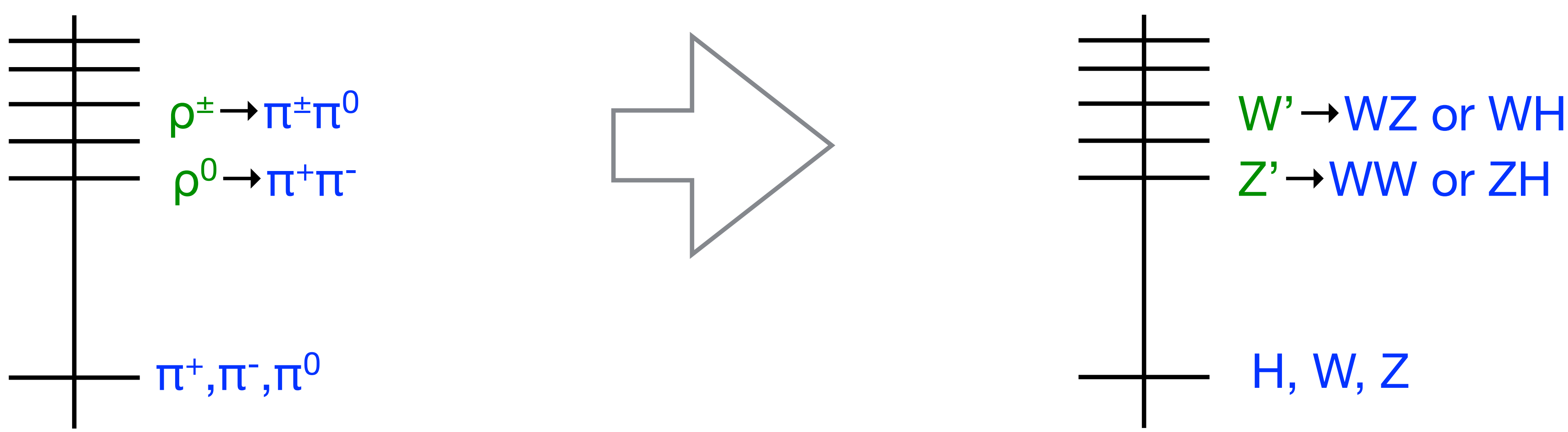


$$\sim \frac{1}{\mathrm{TeV}} = 10^{-18}\,\mathrm{m}$$

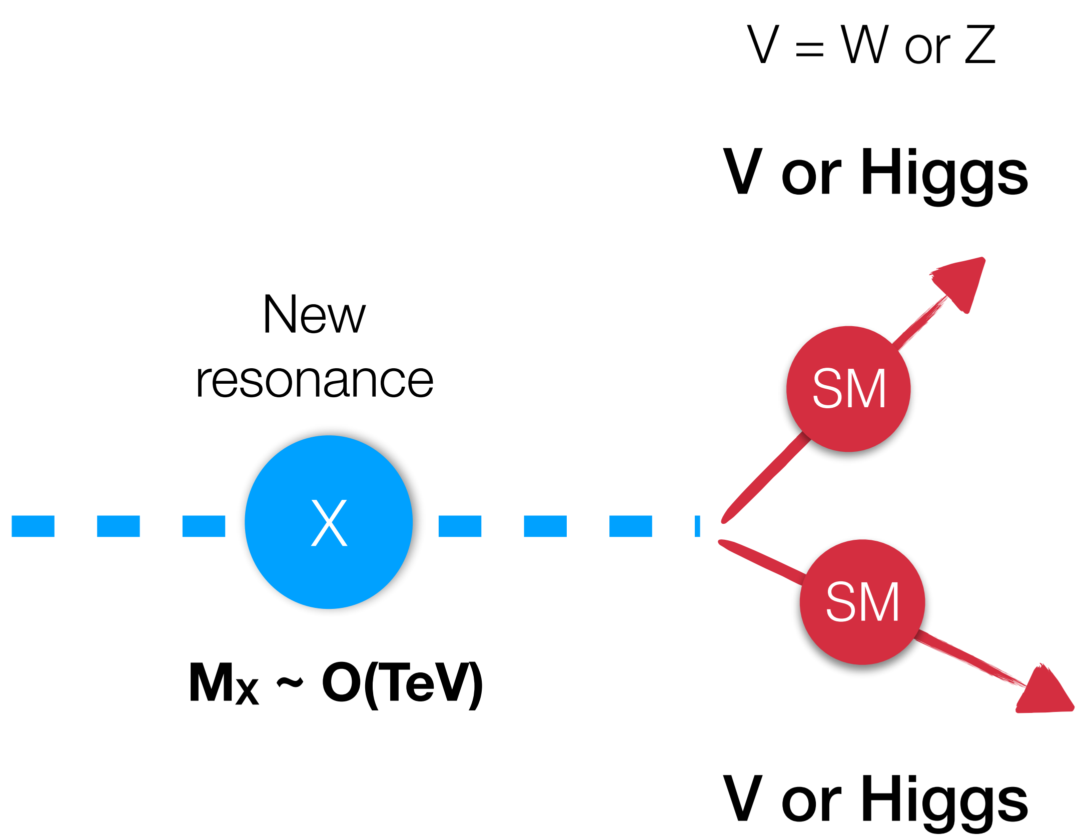
A naive example: QCD

new strong sector

π and ρ are composite states of quarks

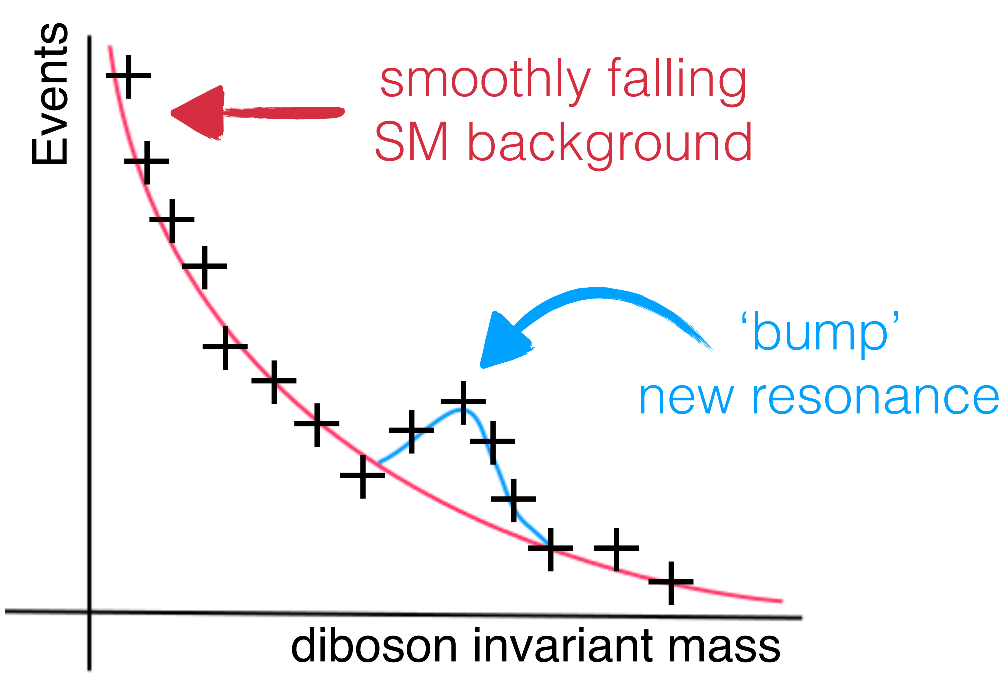


Search for X→diboson

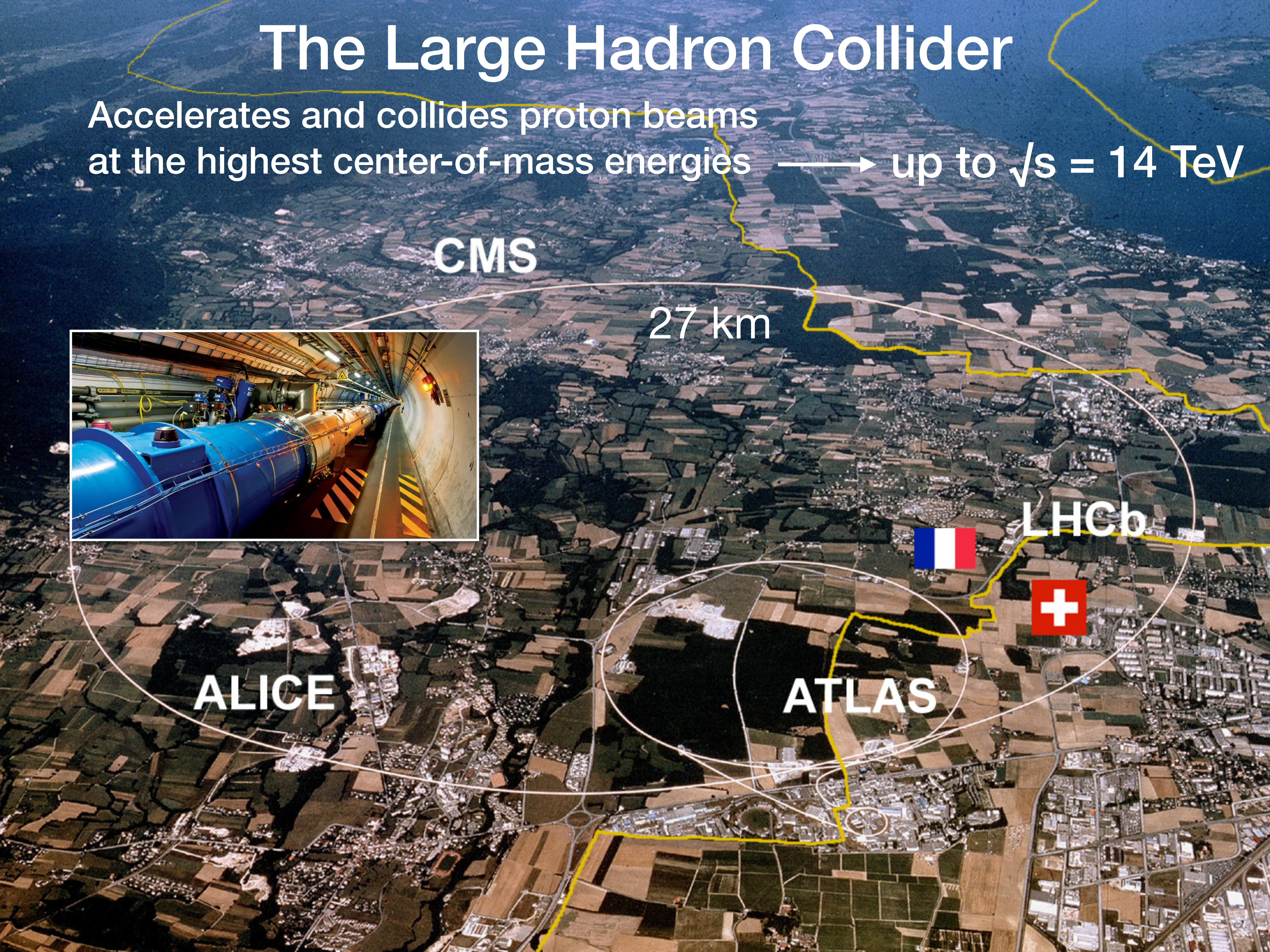


New "natural" theories are highly predictive

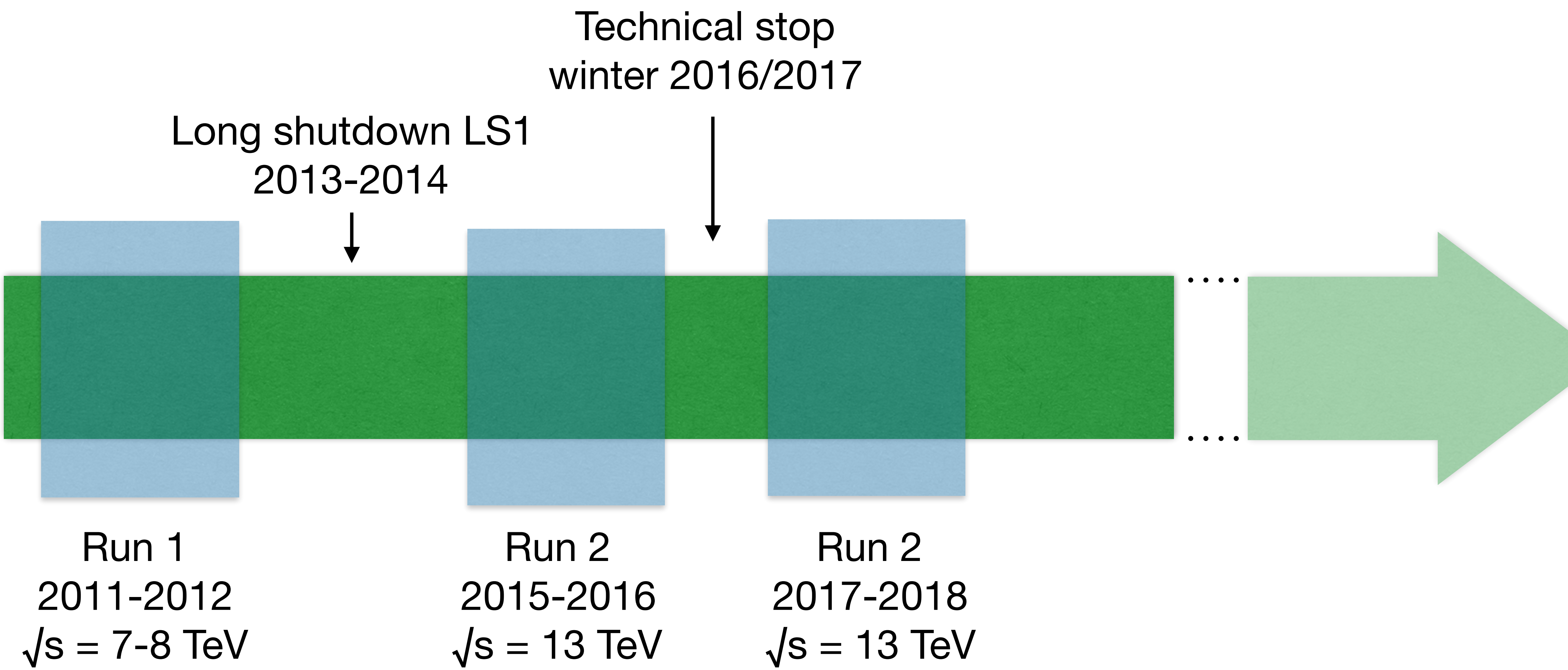
- Theoretical scenarios with **enhanced branching ratios** for X → diboson
- Clear experimental signature in the detector
  - known properties and decay kinematics



⇒ *direct verification of new beyond standard model theories*


The Large Hadron Collider
Accelerates and collides proton beams
at the highest center-of-mass energies
up to √s = 14 TeV
CMS
27 km
LHCb
ALICE
ATLAS

The Large Hadron Collider

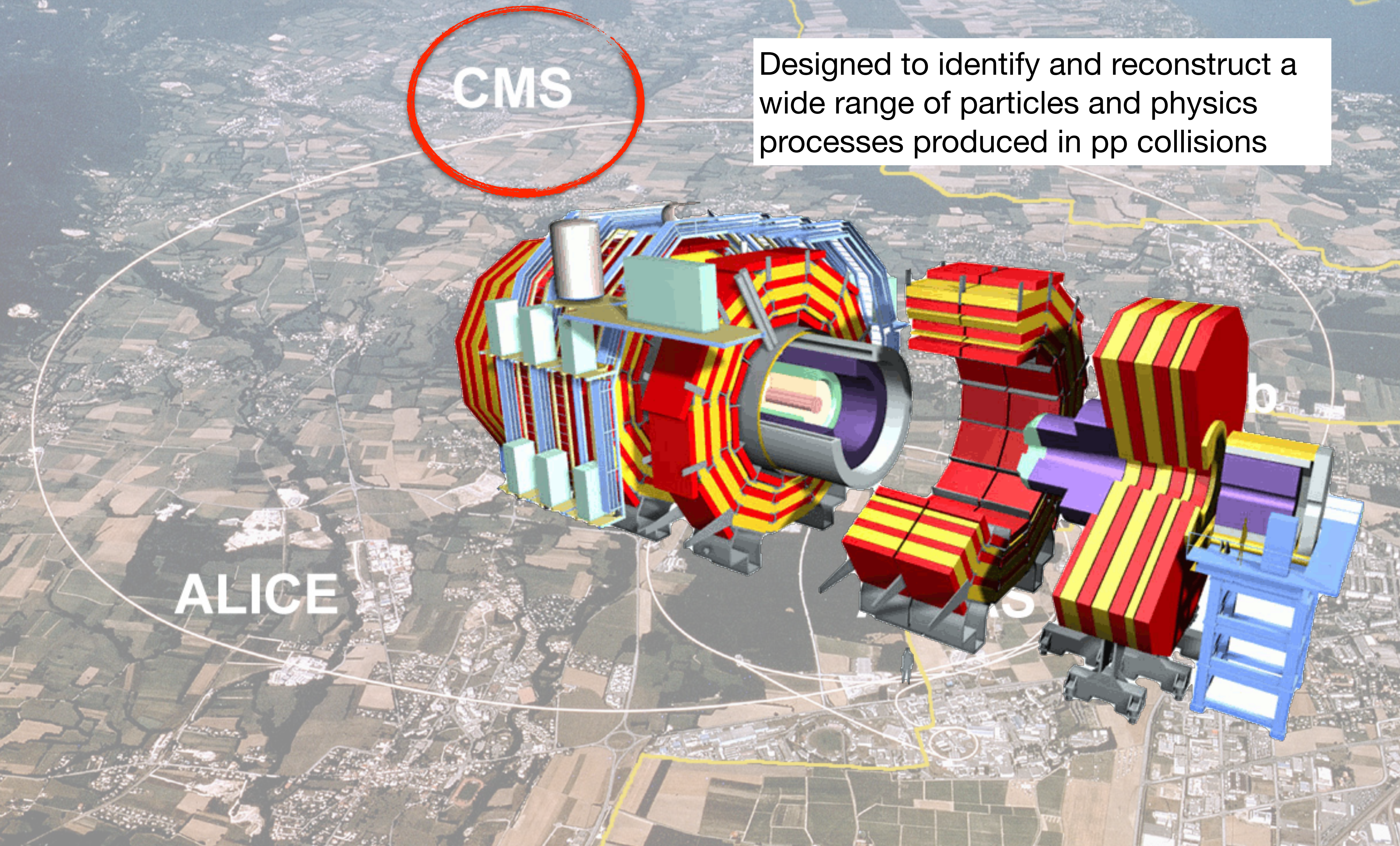


Higgs discovery

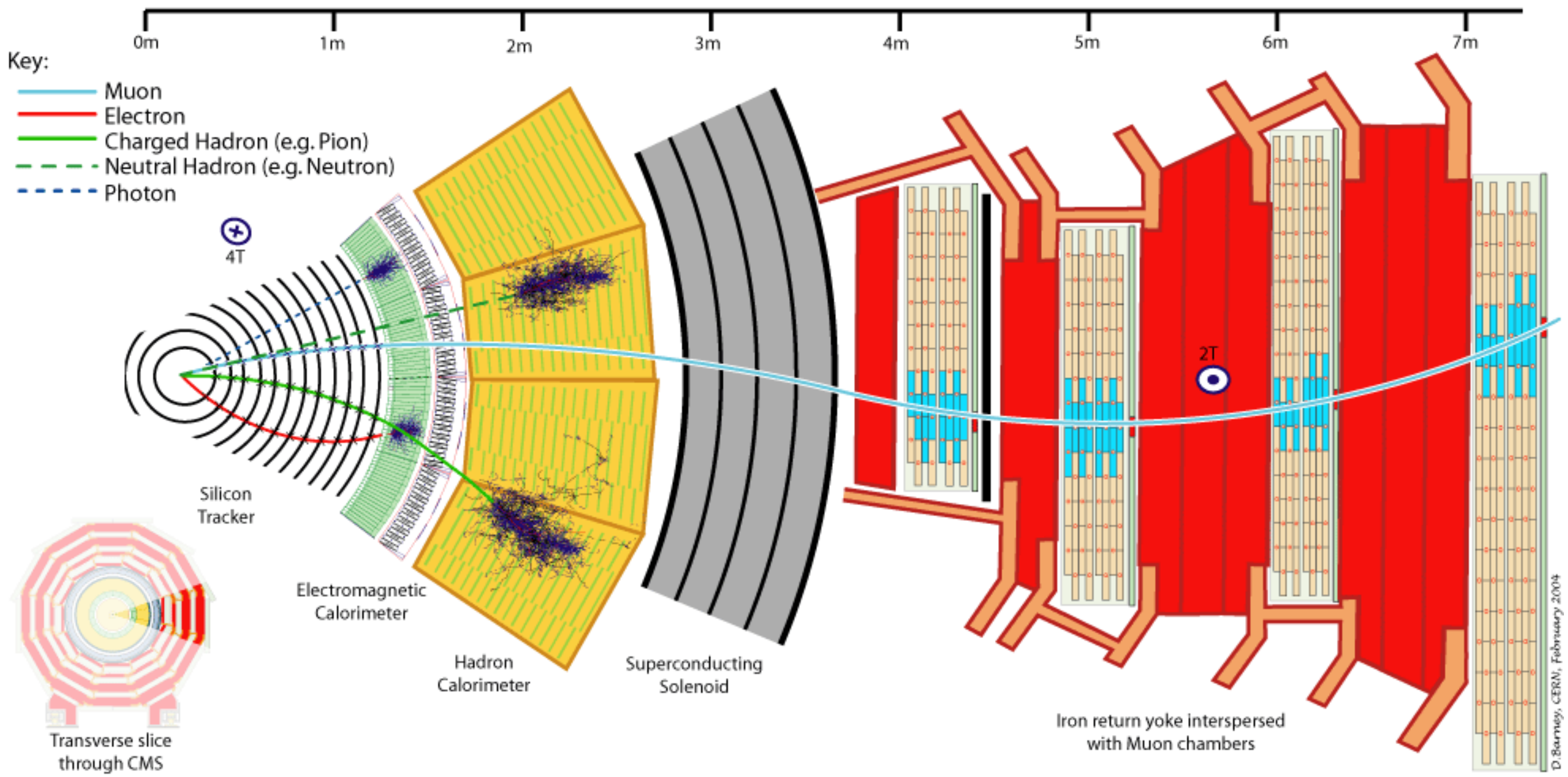
The detector: Compact Muon Solenoid

LHC interaction point 5 (P5)

Designed to identify and reconstruct a wide range of particles and physics processes produced in pp collisions



The CMS detector



Superconducting magnet generates a 3.8 T magnetic field

Mixture of sub-detectors to identify different kind of particles and measure their momenta and energy

Trigger system to select interesting events by reducing the rate of $O(10^5)$ ⇒ allow for data storage

Collected data sets used in this work:

LHC period	$\sqrt{s}$	Integrated luminosity
Run 1 (2012)	8 TeV	19.7 fb^{-1}
Run 2 (2015)	13 TeV	2.3 fb^{-1}

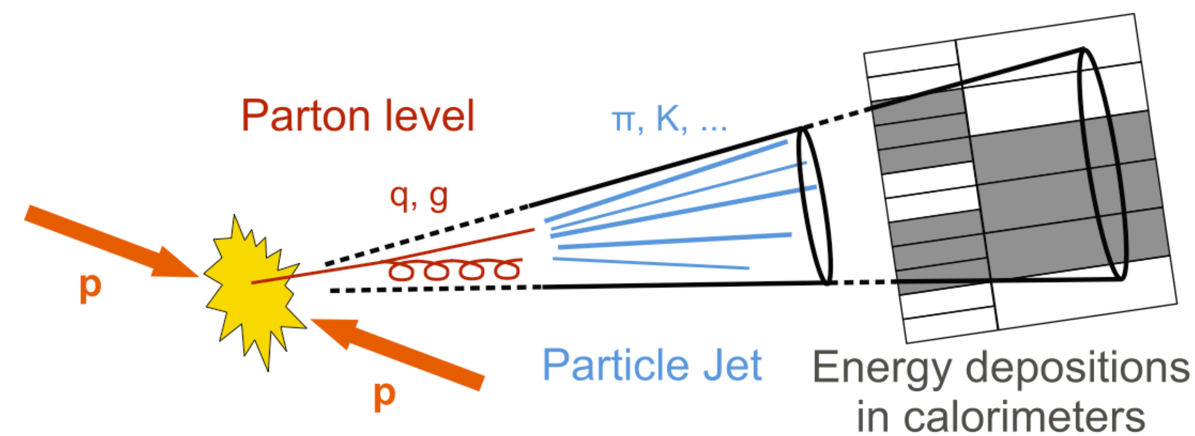
Particle reconstruction

Silicon Tracker → tracks and vertices
ECAL → electrons and photons
HCAL → charged and neutral hadrons
Muon system → muons

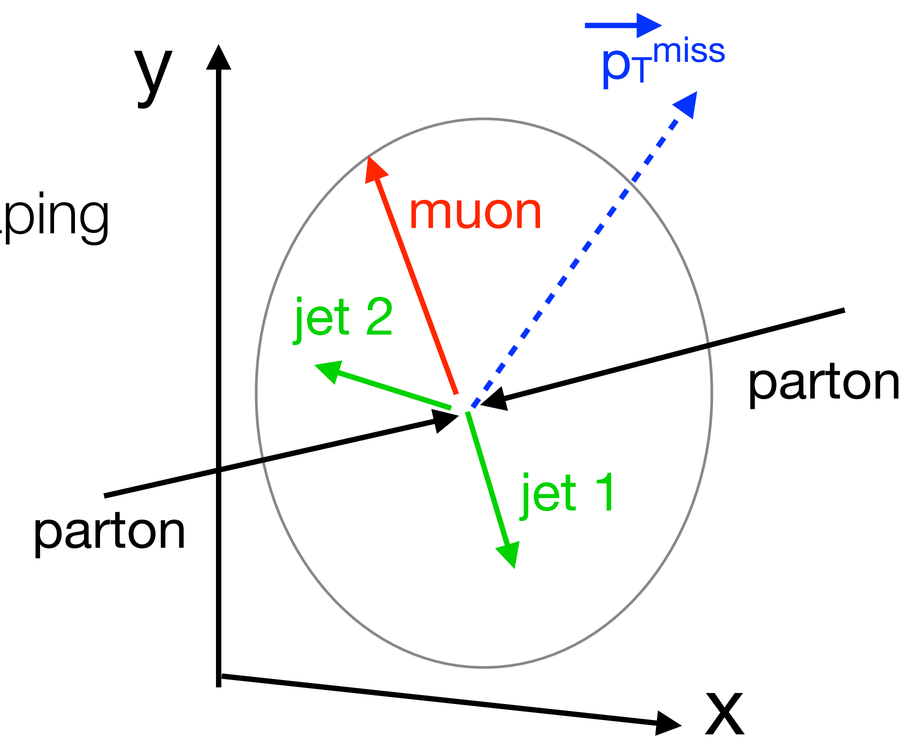
Particle-flow algorithm:
build all particles combining information from all sub-detectors

⇒ improves HCAL resolution with tracker

Jet reconstruction:
- cluster ensemble of PF candidates produced in the hadronization of the original parton
- apply calibrations to correct for pileup and detector effects



Neutrino reconstruction:
- CMS designed with large hermetic geometrical coverage → only escaping particle is the neutrino
- reconstructed by imbalance of the momenta of all visible particles



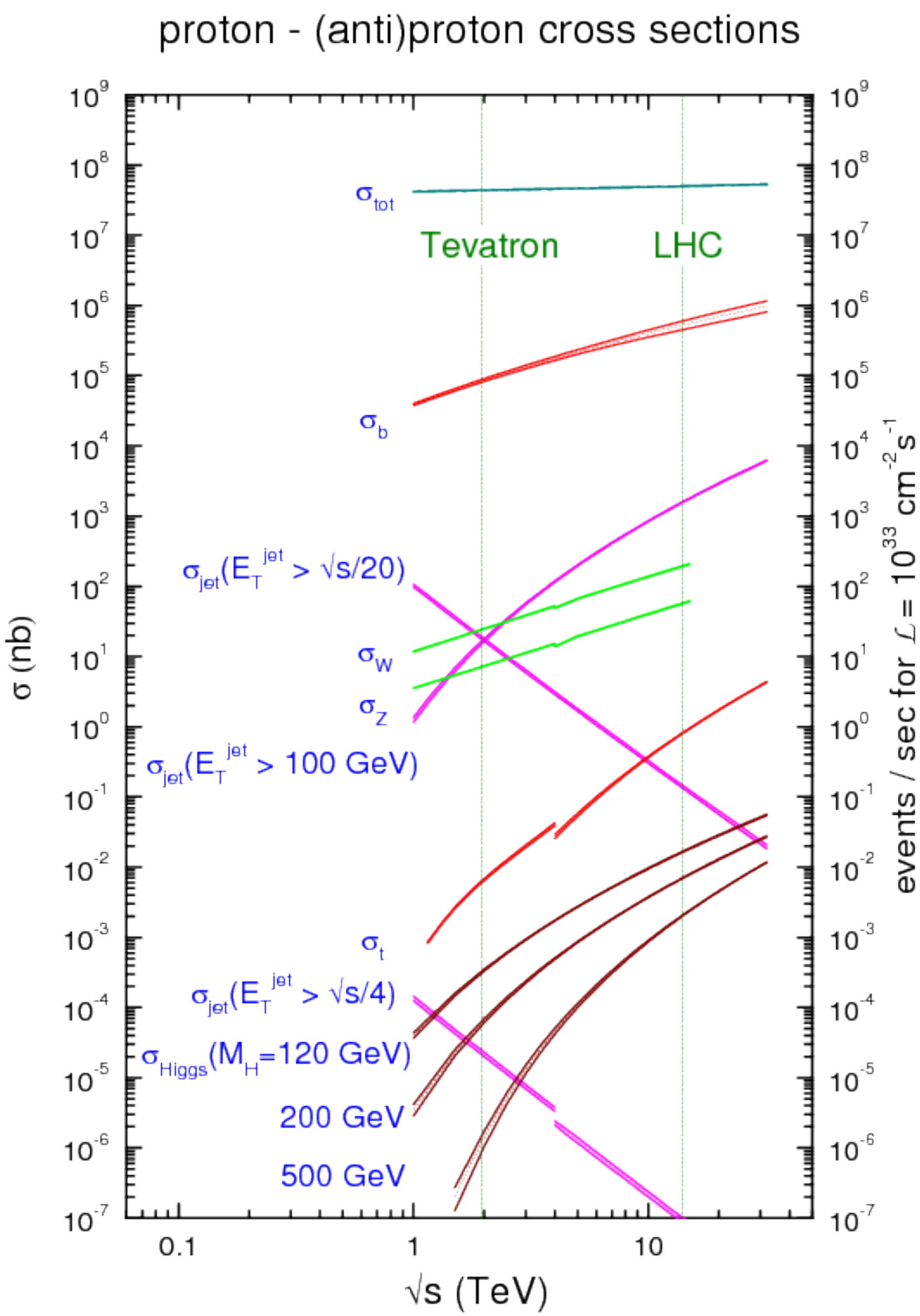
$$\vec{p}_{\mathrm{T}}(\nu) = \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_{i=1}^{N} \vec{p}_{\mathrm{T},i}$$

$$||\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}|| = E_{\mathrm{T}}^{\mathrm{miss}}$$

= missing transverse energy

Physics at the LHC

Main standard model processes produced in pp collisions



cross sections for √s = 13 TeV

QCD multijet: production of quarks and gluons ⇒ *jets* — $\sigma_{jet} \approx 10^6$ pb

Production of W and Z bosons — $\sigma_W \approx 2\text{x}10^5$ pb, $\sigma_Z \approx 6\text{x}10^4$ pb

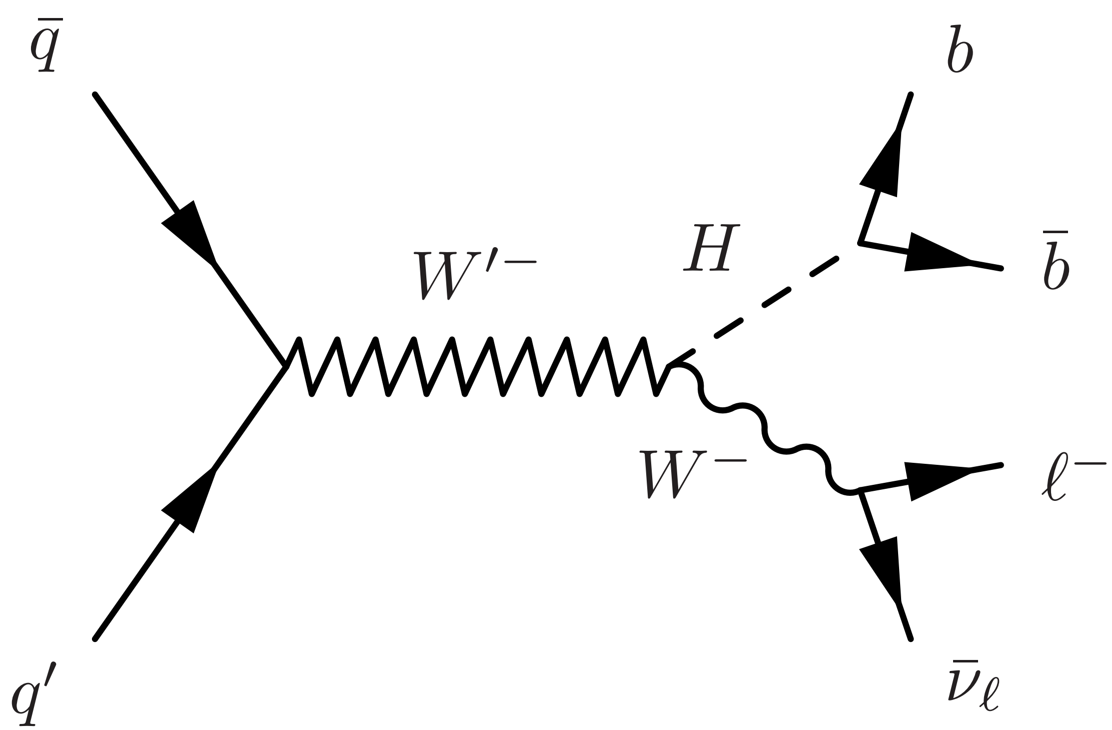
Production of top quarks — $\sigma_{top} \approx 10^3$ pb

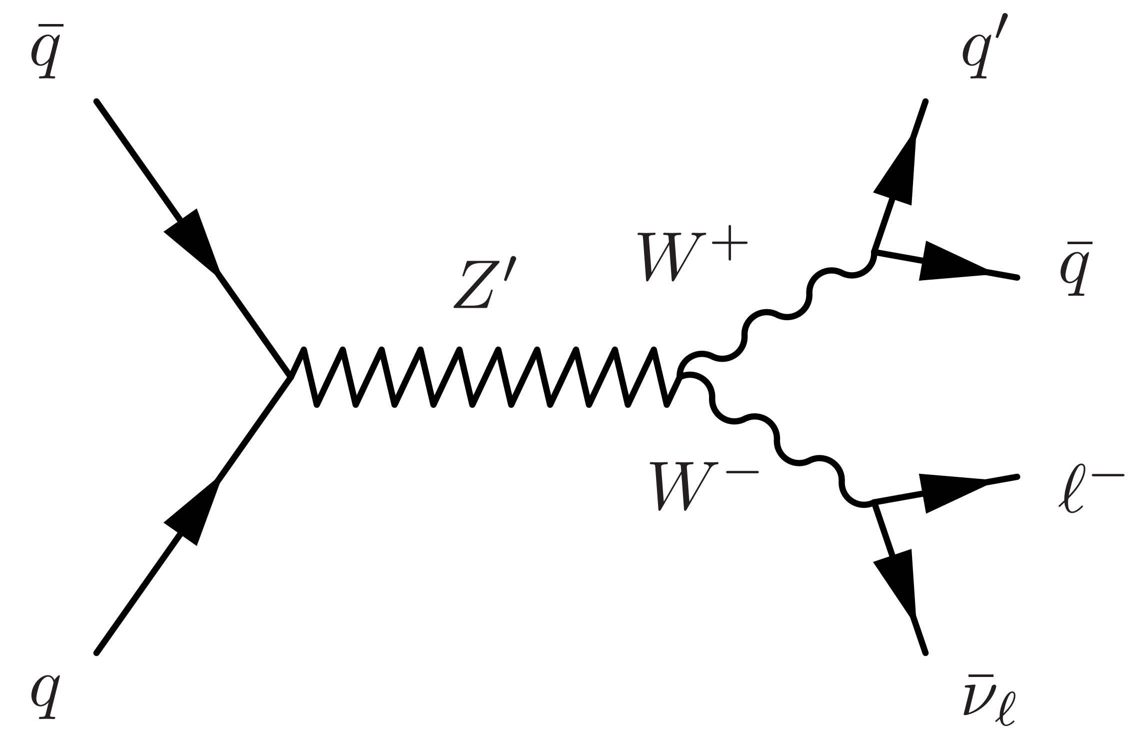
Typical production cross section for a W′ resonance with mass = 2 TeV

$\sigma_{W'} \approx 10^{-2}$ pb !

Lepton+jet final states

Provide high sensitivity for X→diboson signals





Lepton+jet final states

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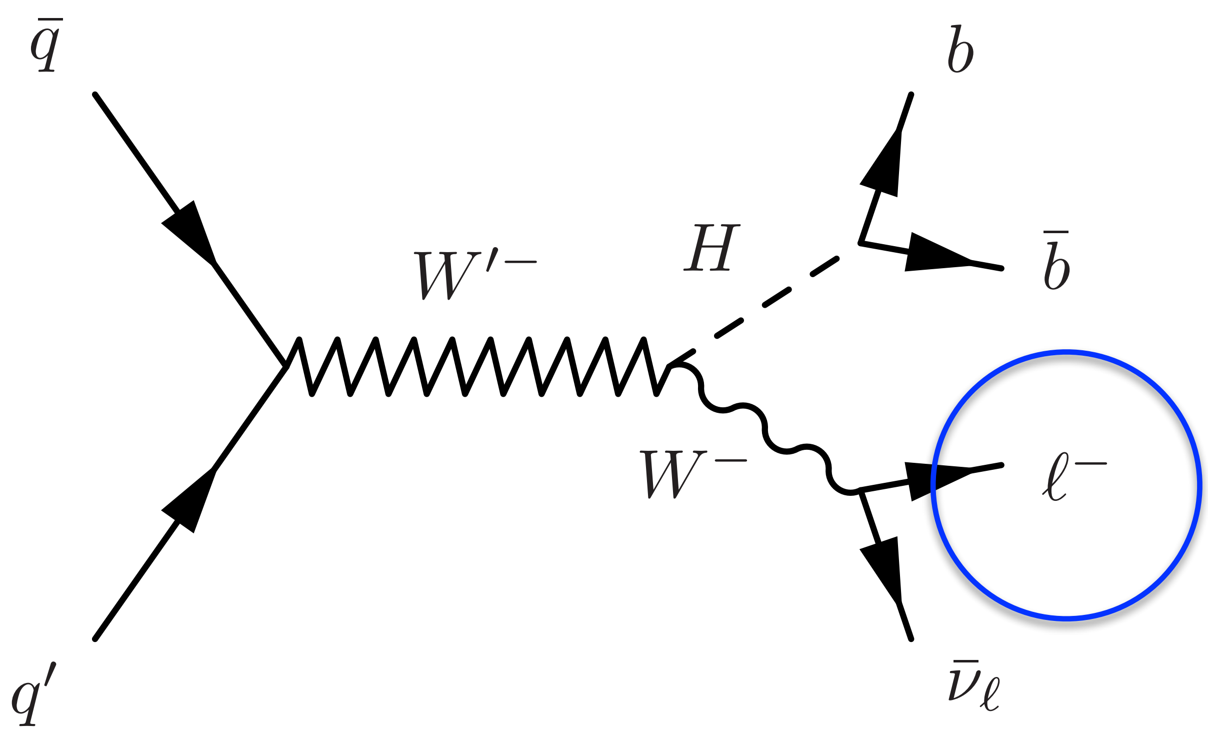
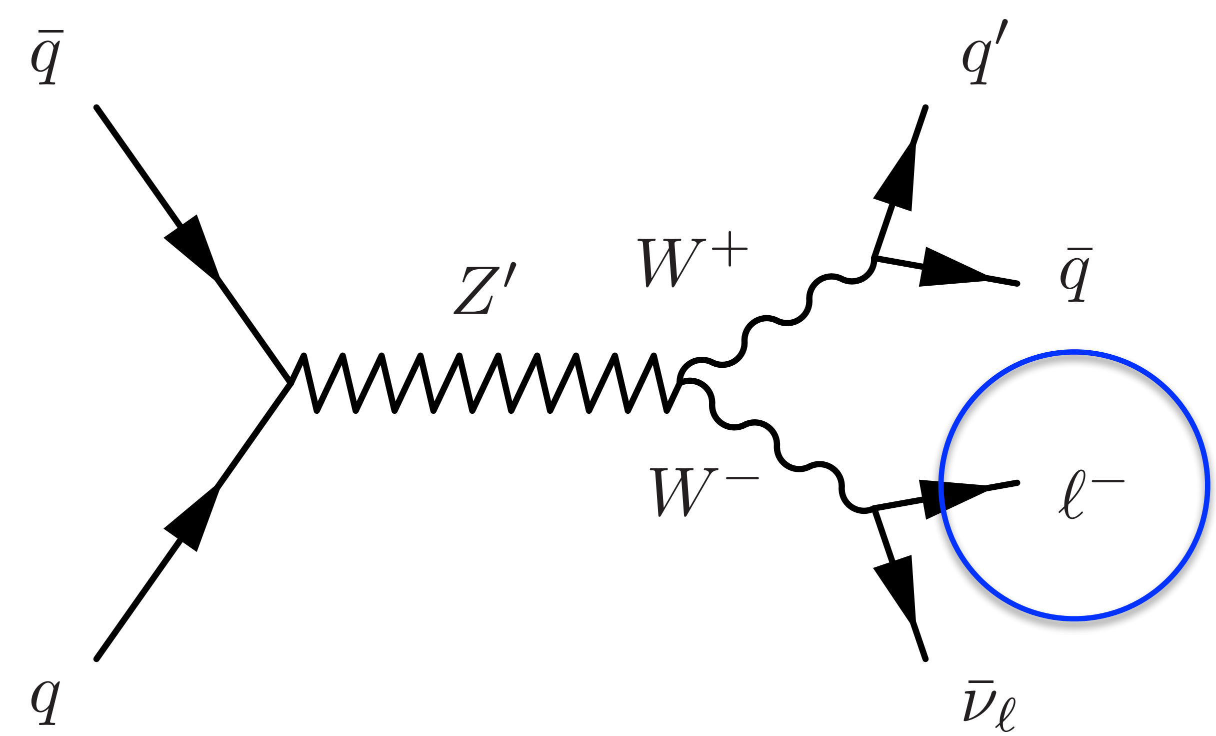
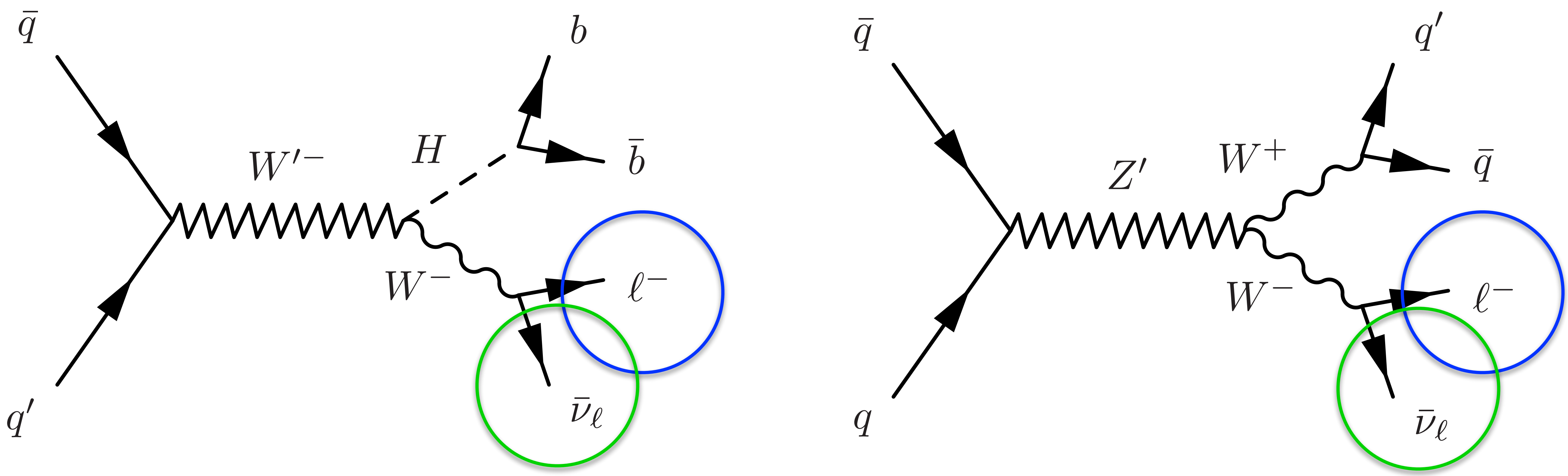




The presence of the lepton (electron or muon) highly suppresses QCD multijet background

Lepton+jet final states

Provide high sensitivity for X→diboson signals



The presence of the lepton (electron or muon) highly suppresses QCD multijet background

One neutrino in the event → access only p_T ☹

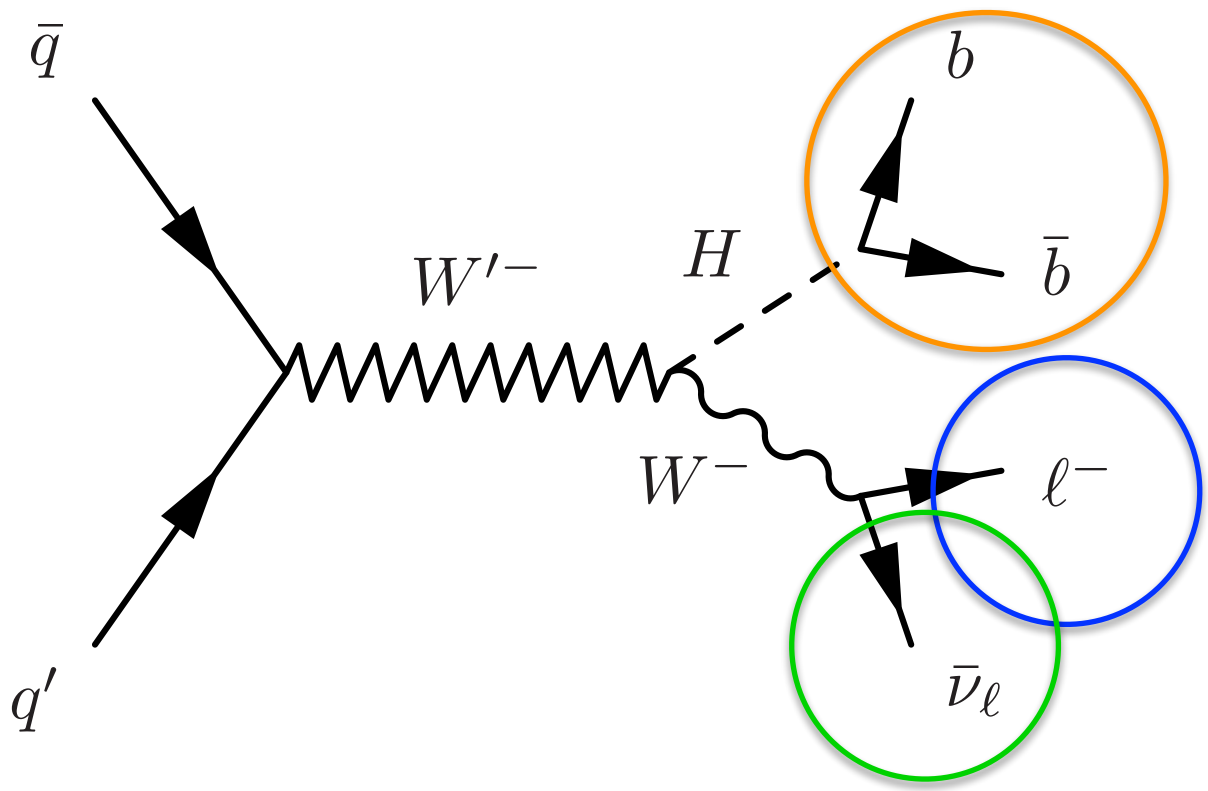
Then estimate its p_Z by imposing W mass constrain ☺ and reconstruct the entire resonance mass!

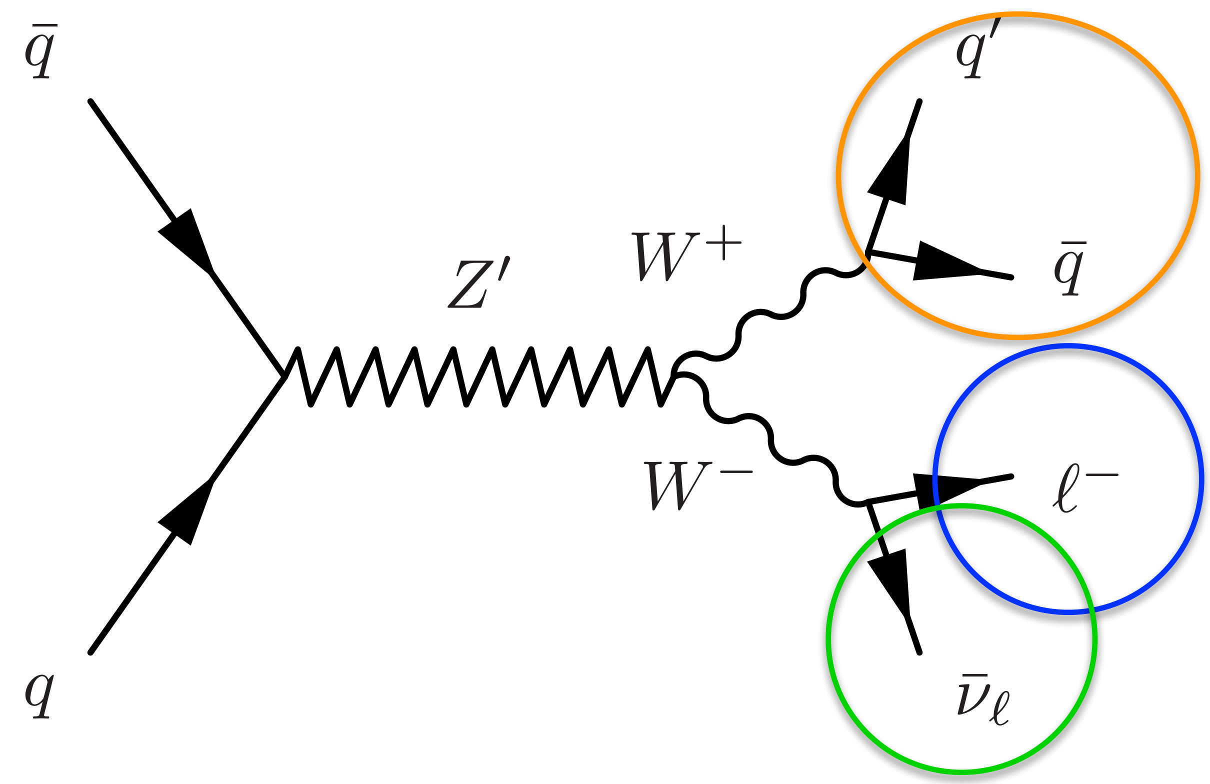
$$M_W^2 = (E_\mu + \sqrt{\mathbf{E}_T^{\mathrm{miss}\,2} + P_{z,\nu}^2})^2 - (\mathbf{P}_{T,\mu} + \mathbf{E}_T^{\mathrm{miss}})^2 - (P_{z,\mu} + P_{z,\nu})^2 = (80.4)^2$$

Lepton+jet final states

Provide high sensitivity for X→diboson signals

High branching ratios of W/Z→qq (70%) and H→bb (60%) ⇒ maximize signal cross sections





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Lepton+jet final states

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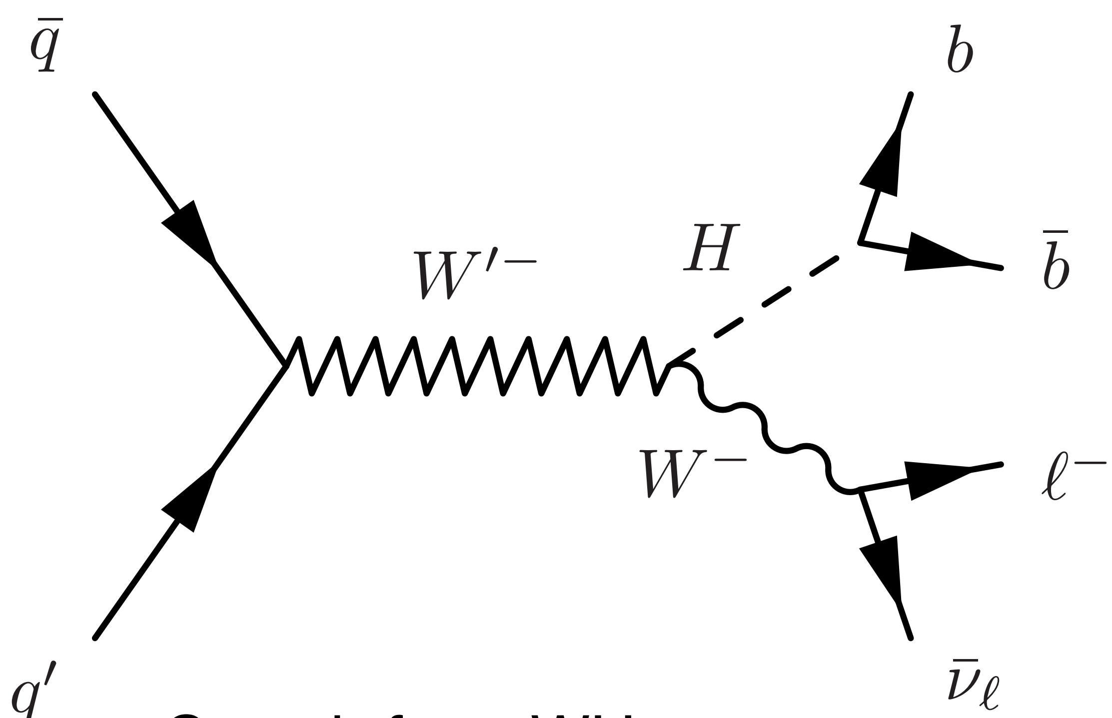


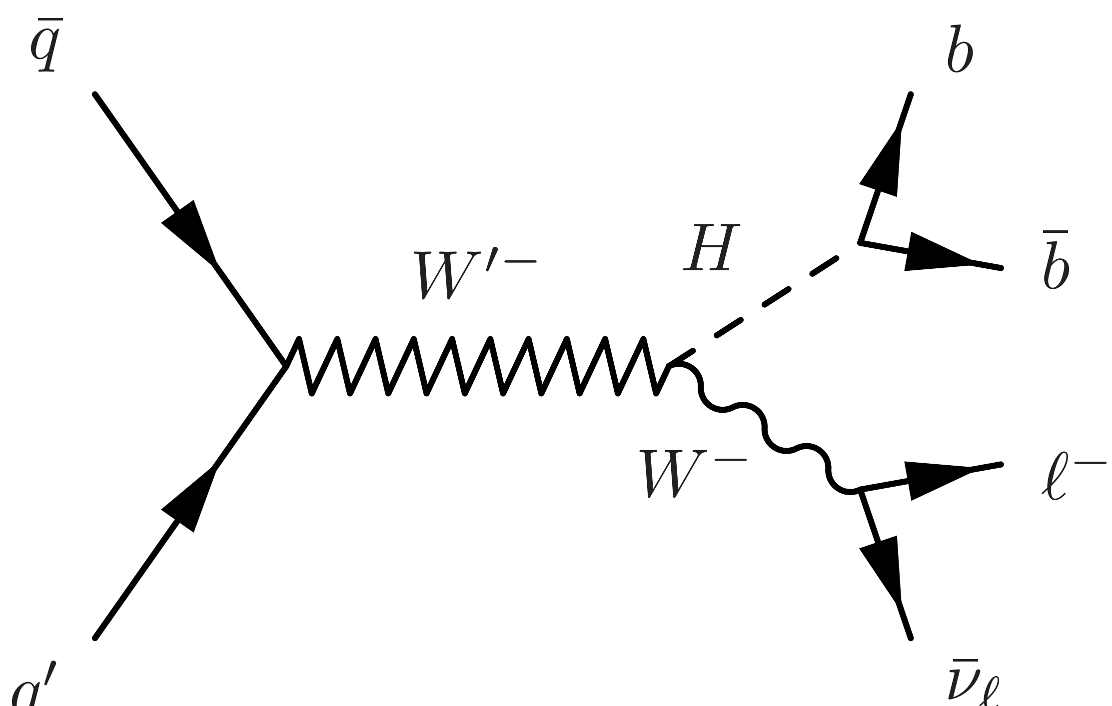
Search for a WH resonance
in the $\ell\nu b\bar{b}$ decay channel
with $\sqrt{s}$ = 8 TeV data

EPJC 76 (2016) 237

Possible only after discovery
of the Higgs boson!

Lepton+jet final states

Provide high sensitivity for X→diboson signals



Search for a WH resonance
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with $\sqrt{s}$ = 8 TeV data

[EPJC 76 (2016) 237]

Possible only after discovery
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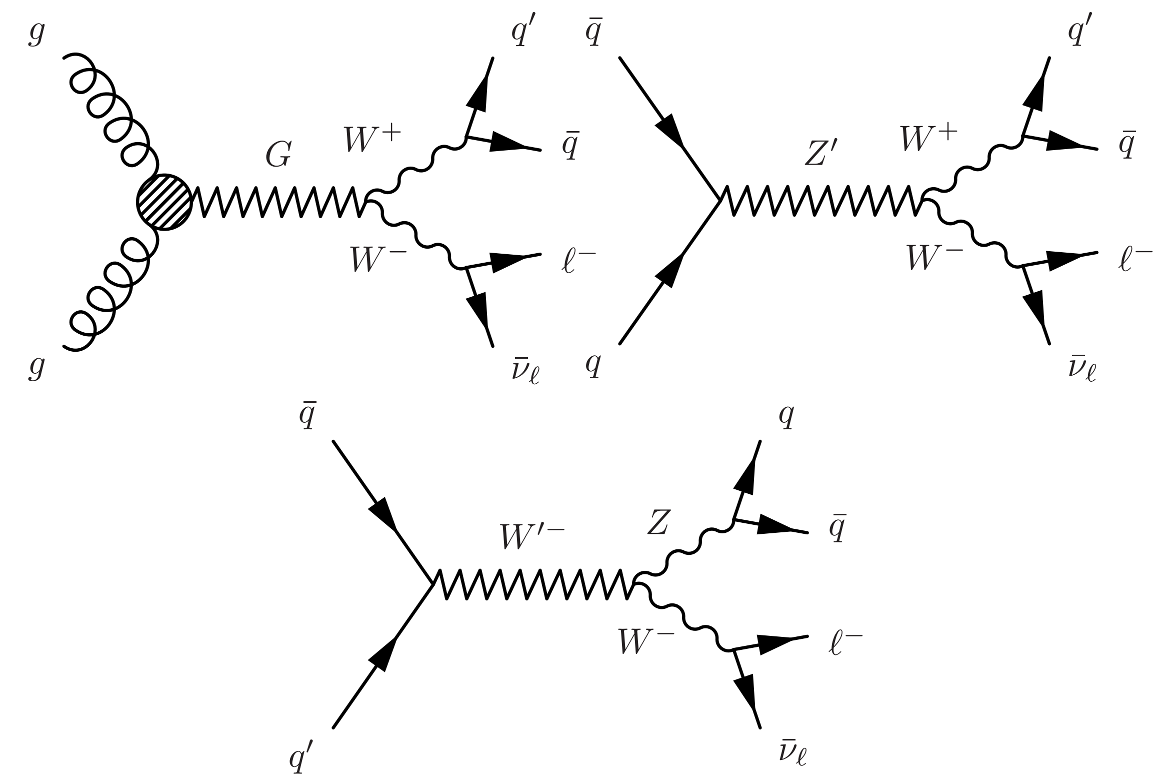


Search for a WW or WZ resonance
in the $\ell\nu q\bar{q}$ decay channel
with $\sqrt{s}$ = 13 TeV data

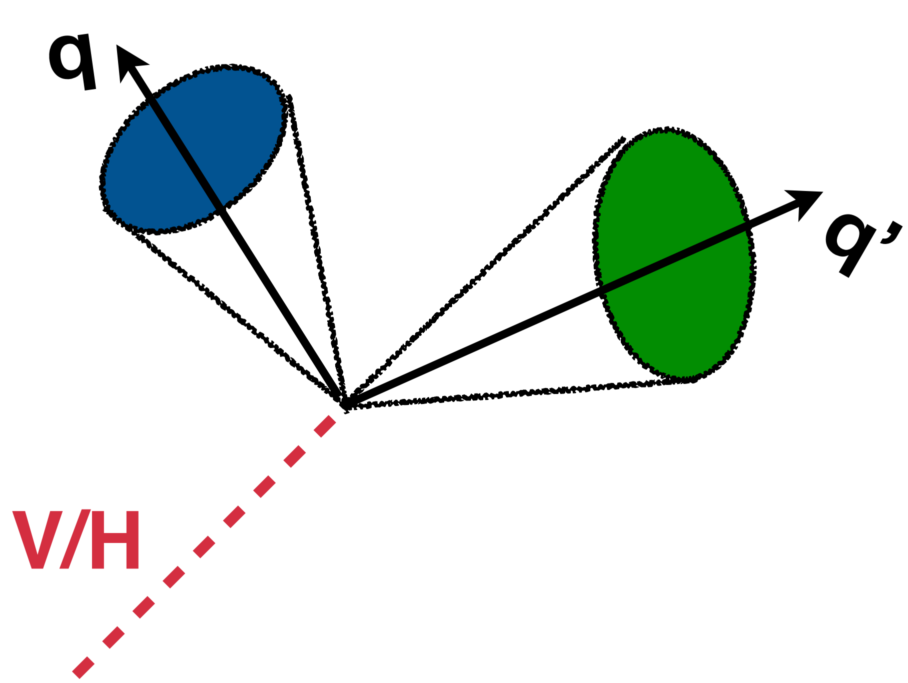
[eprint: arxiv.1612.09159]

[Submitted to JHEP]

Challenge: reconstruct boosted jets

- For heavy resonances (M_X ~ O(TeV)) bosons get high Lorentz-boost ⇒ p_T > 200 GeV
- The hadrons from $V \rightarrow q\bar{q}/H \rightarrow b\bar{b}$ boson are very collimated and merge into a single jet of large cone radius
- Use dedicated techniques to resolve substructure inside the jet

Low boost
large opening angle

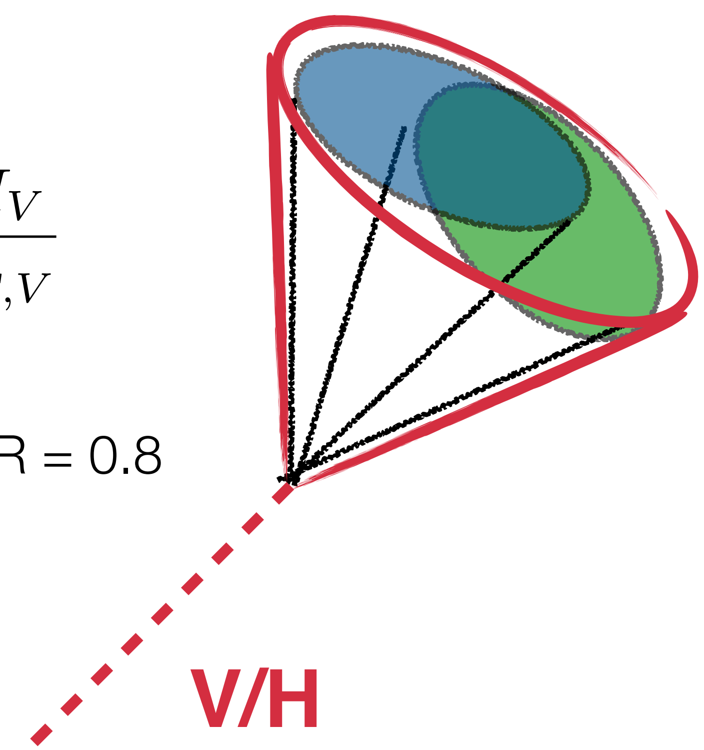


two jets with cone radius = 0.5

High p_T boson

$$\Delta R_{qq}^{min} \approx 2\frac{M_V}{p_{T,V}}$$

one jet with cone radius R = 0.8



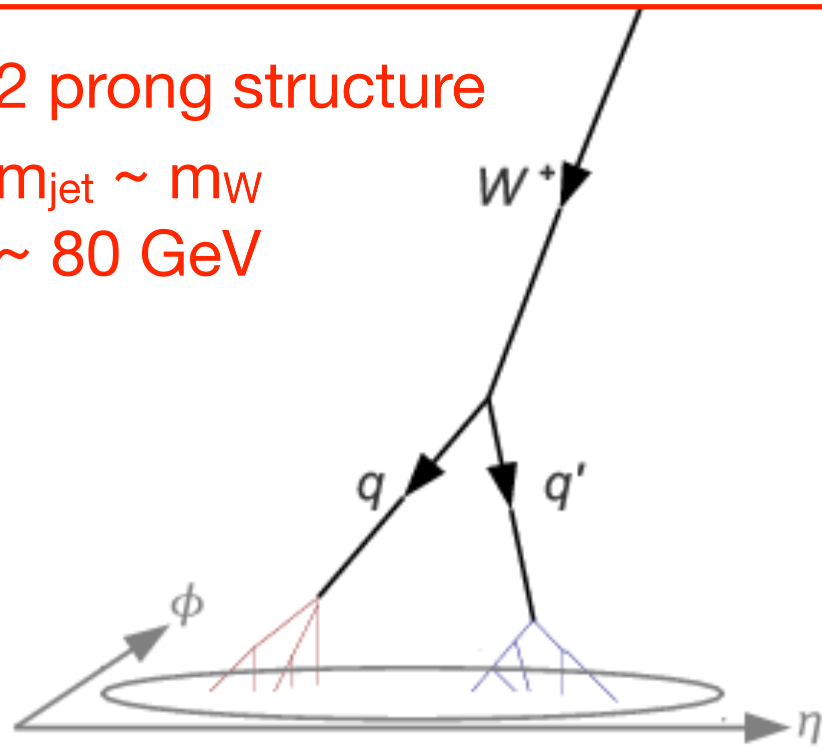
Resolving jet substructure

W-jet signal

2 prong structure

$m_{jet} \sim m_W$

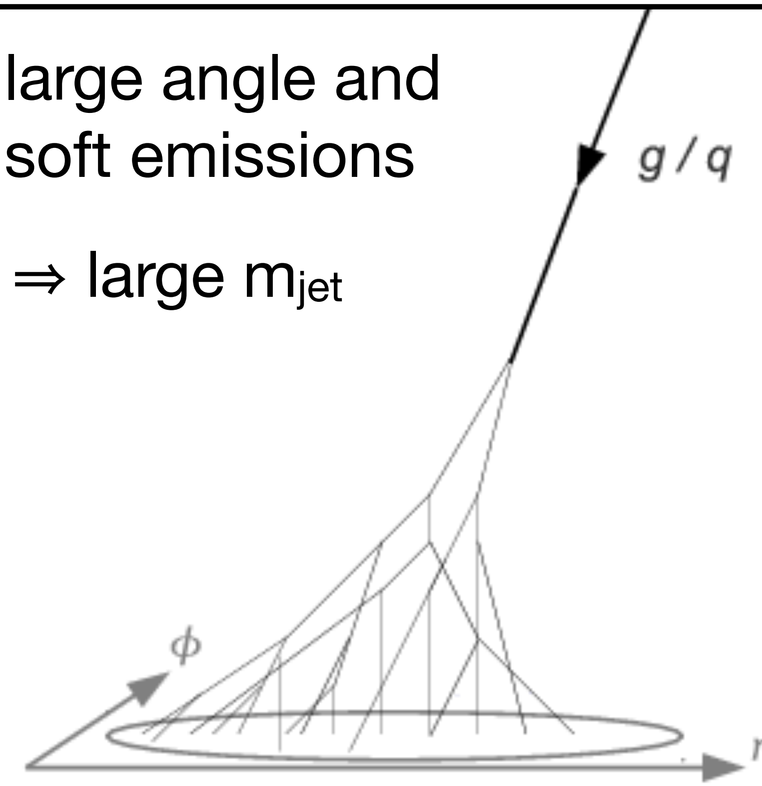
$\sim$ 80 GeV



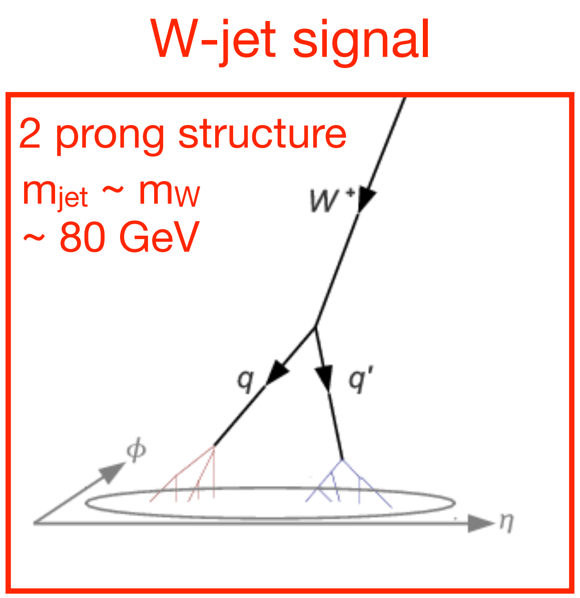
QCD jet background

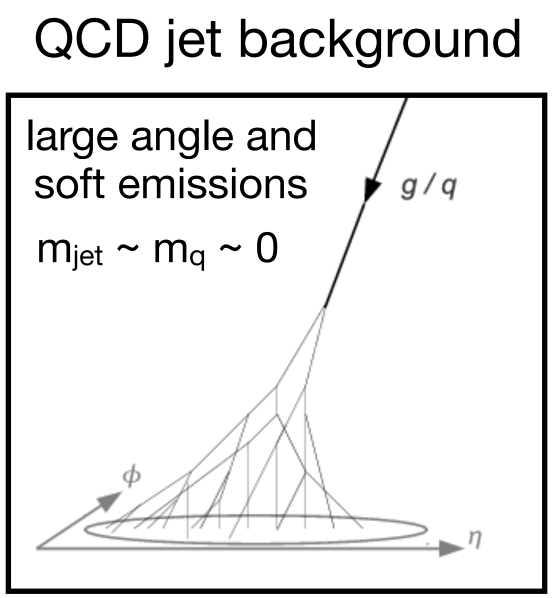
large angle and
soft emissions

$\Rightarrow$ large m_{jet}



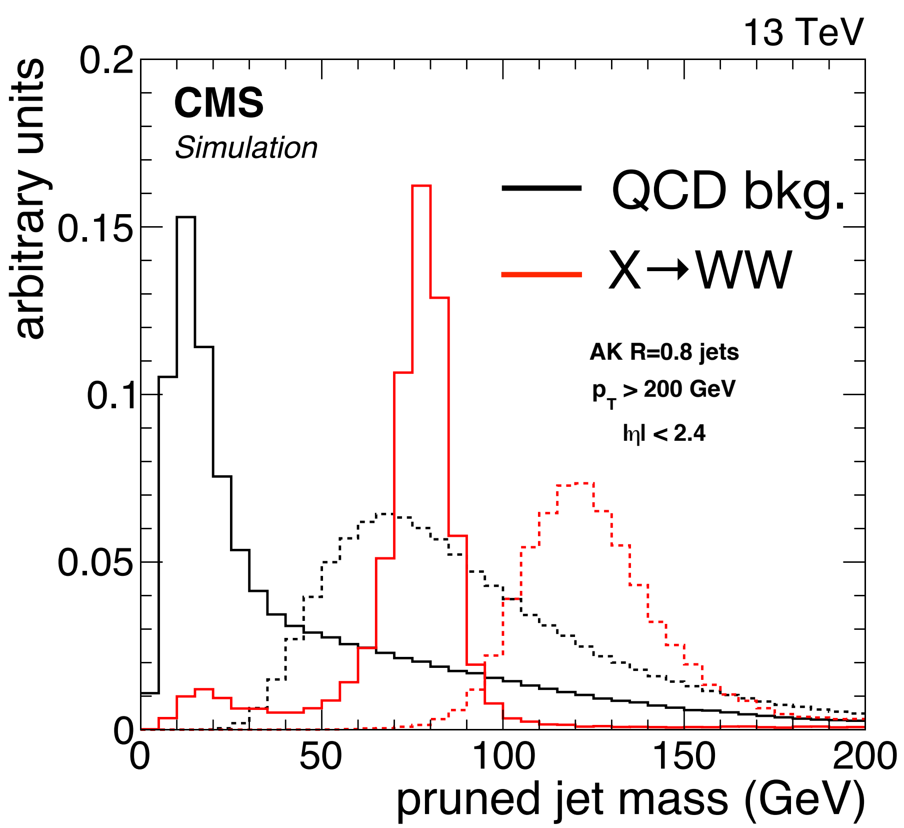
Resolving jet substructure





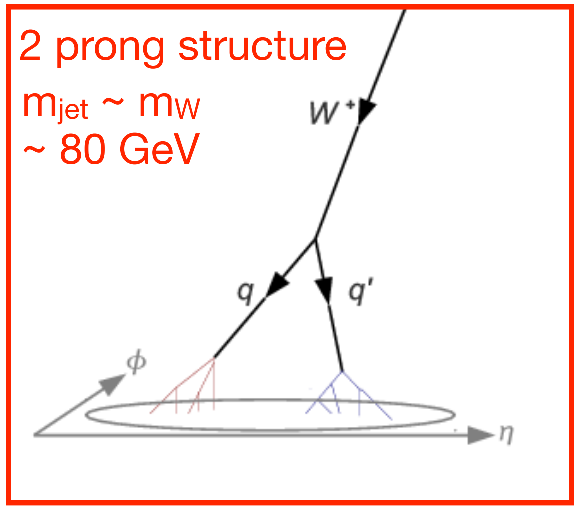
1) by filtering out large angle and soft emissions the mass of the QCD jet is pushed to zero! ⇒ **jet pruning**

pruned jet mass
= mass of the jet after pruning applied

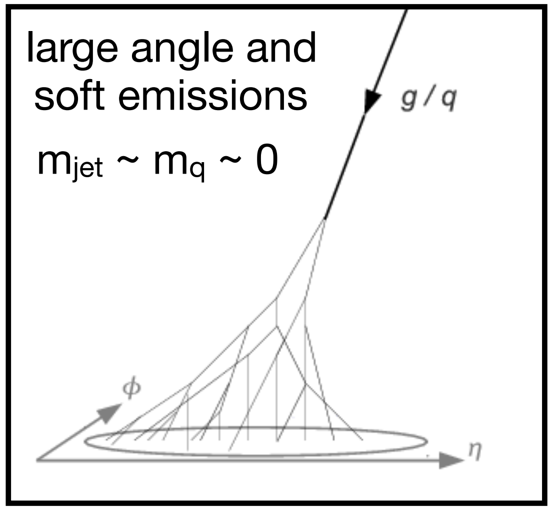


Resolving jet substructure

W-jet signal



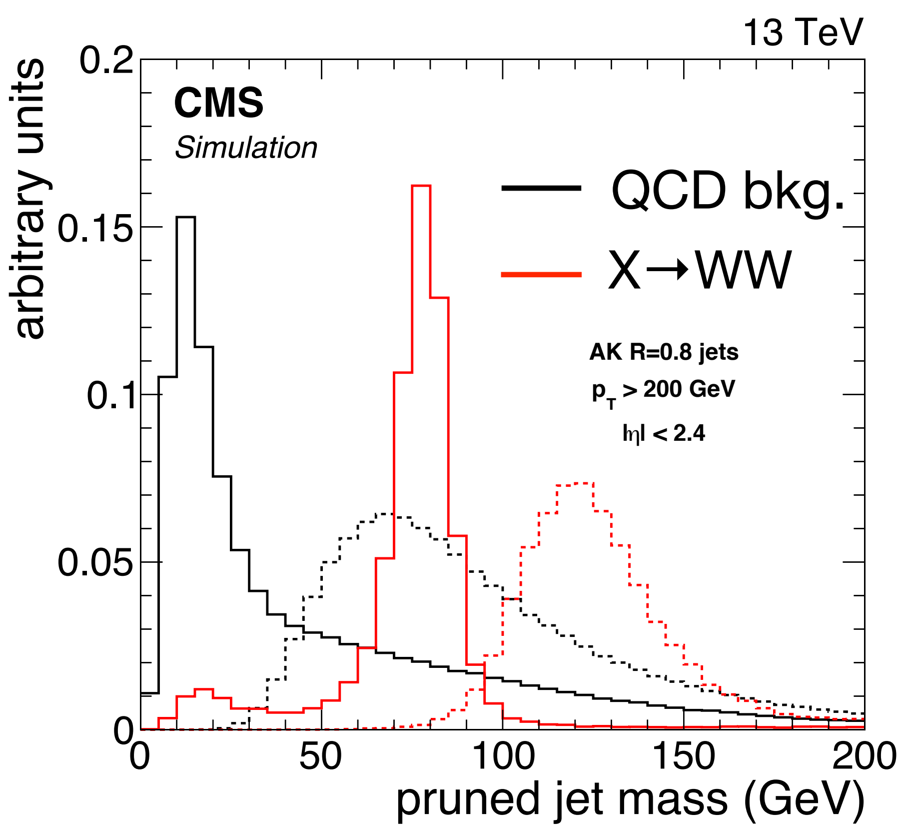
QCD jet background



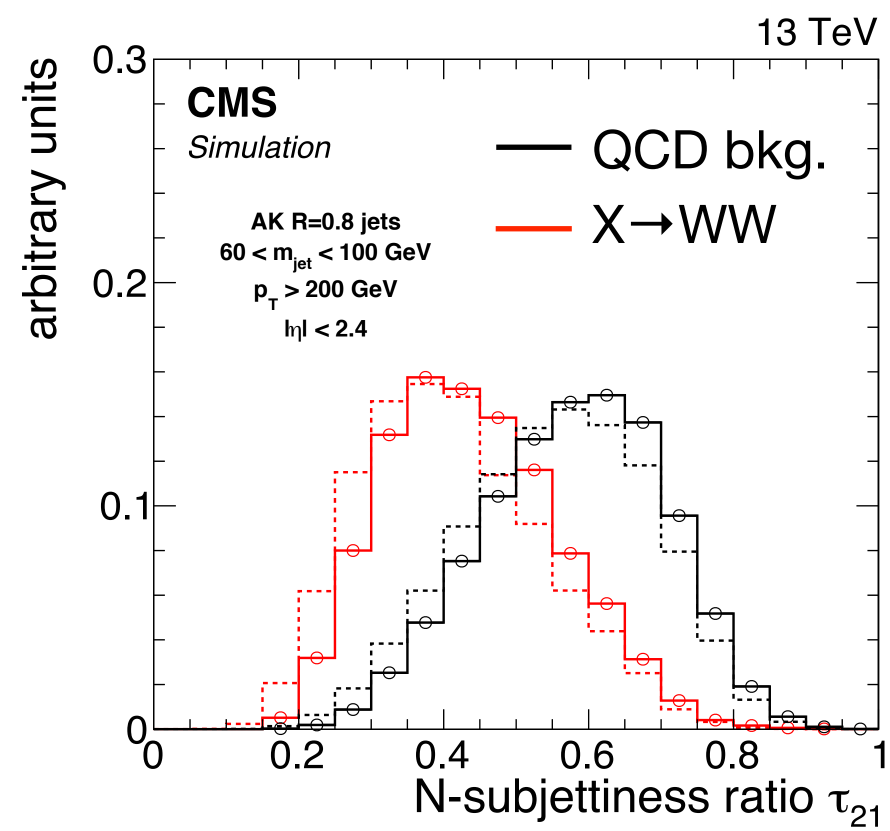
1) by filtering out large angle and soft emissions the mass of the QCD jet is pushed to zero! ⇒ **jet pruning**

2) decluster the jet in N subjets and evaluate compatibility with N subjets hypothesis ⇒ **N-subjettiness τ_N**

pruned jet mass
= mass of the jet after pruning applied



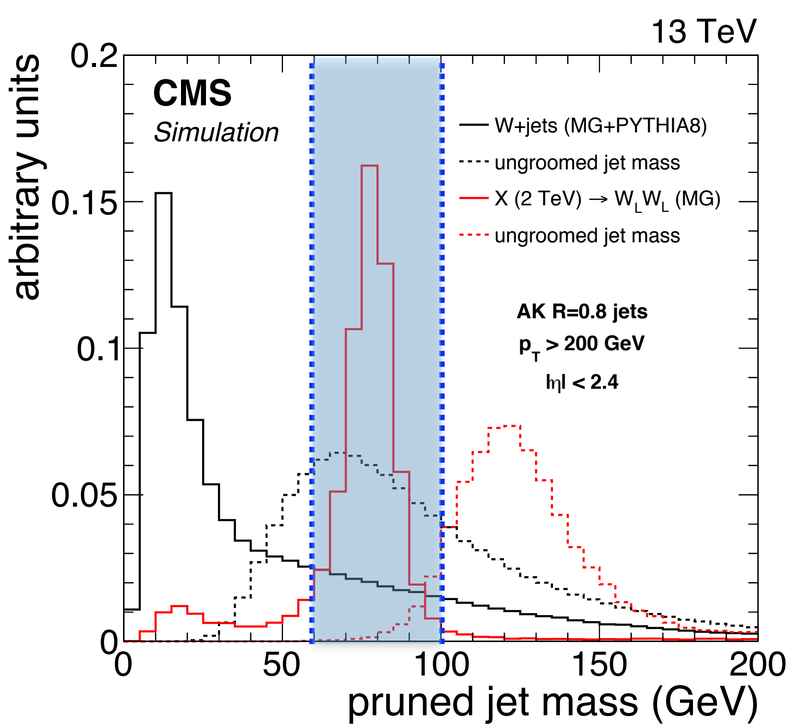
best discriminant: $\tau_{21} = \tau_2/\tau_1$

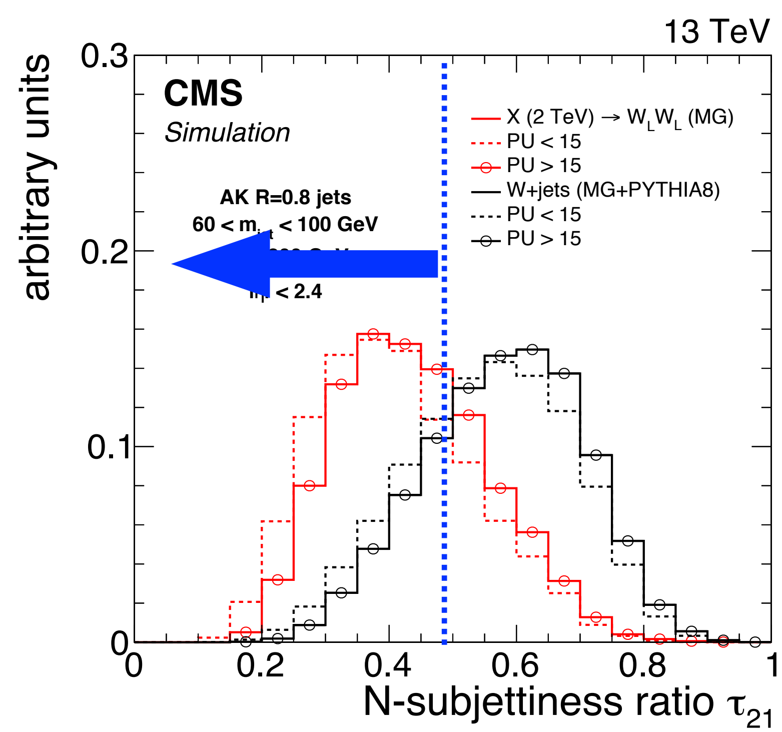


V-tagging for V→$q\bar{q}$

pruning + N-subjettiness τ_{21} V-tagging:

identification of V-jets



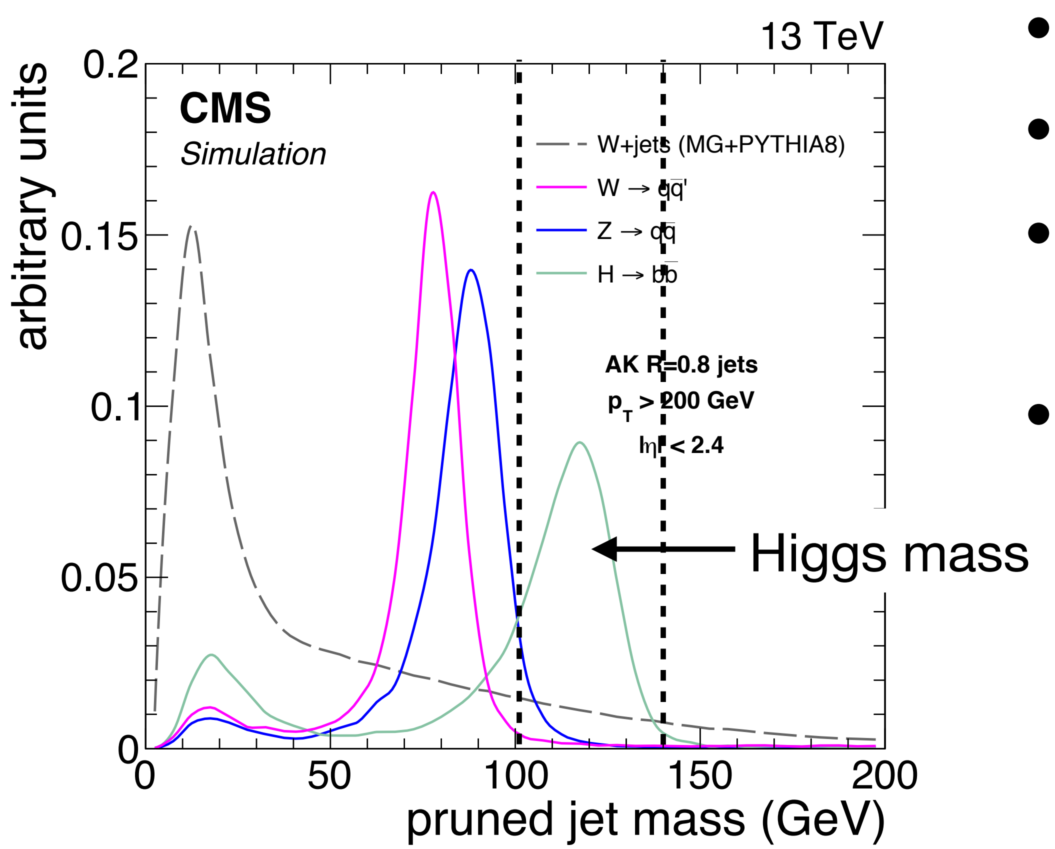


- large signal efficiencies (60-70%)
- small background rates (3-5%)

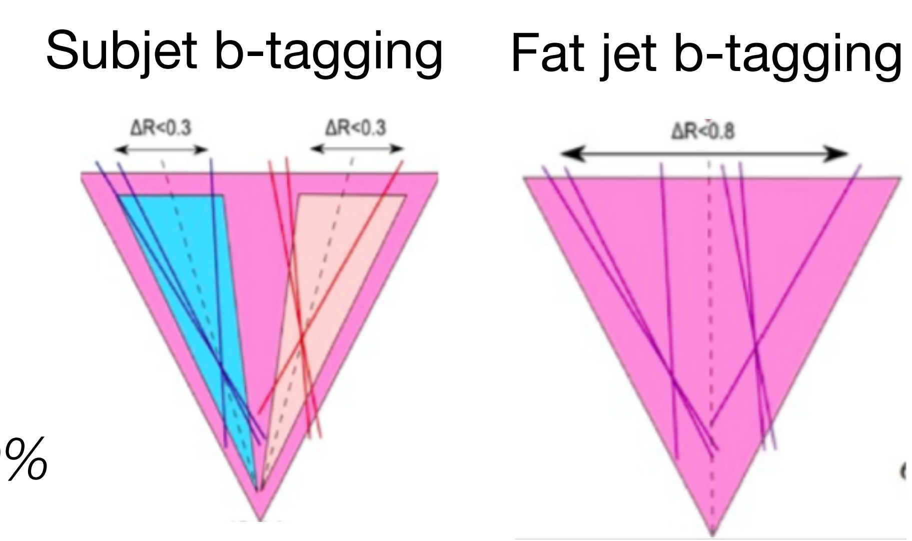
H-tagging for H→b$\bar{b}$

Higgs-jet mass + Boosted b-tagging

- Use same strategy as for V tagging but shift mass window to Higgs mass!



- Use CMS standard b-tagging algorithm (CSV): combined information from impact parameter, secondary vertex, track multiplicity, …
- fat jet b-tagging: apply b-tagging to the whole H-jet
- but we can do better … again jet substructure!
- the jet is split into 2 subjets by undoing the last iteration of the pruned jet clustering
- try to b-tag the subjets when not too close to each others



typical working points for jet p_T ~ 1 TeV:

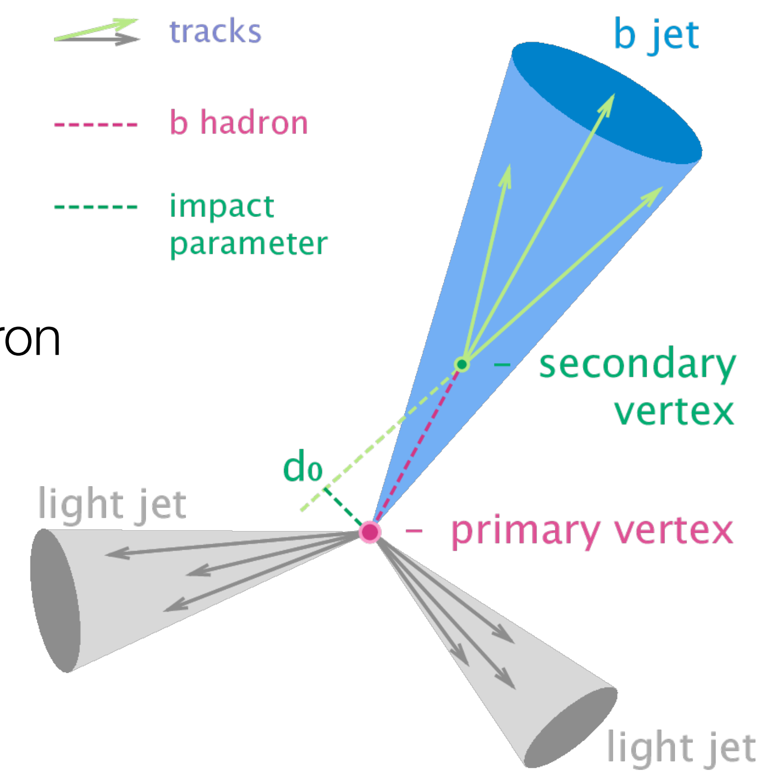
- *tagging efficiency ~ 40%*
- *mistagging rate < 1%*

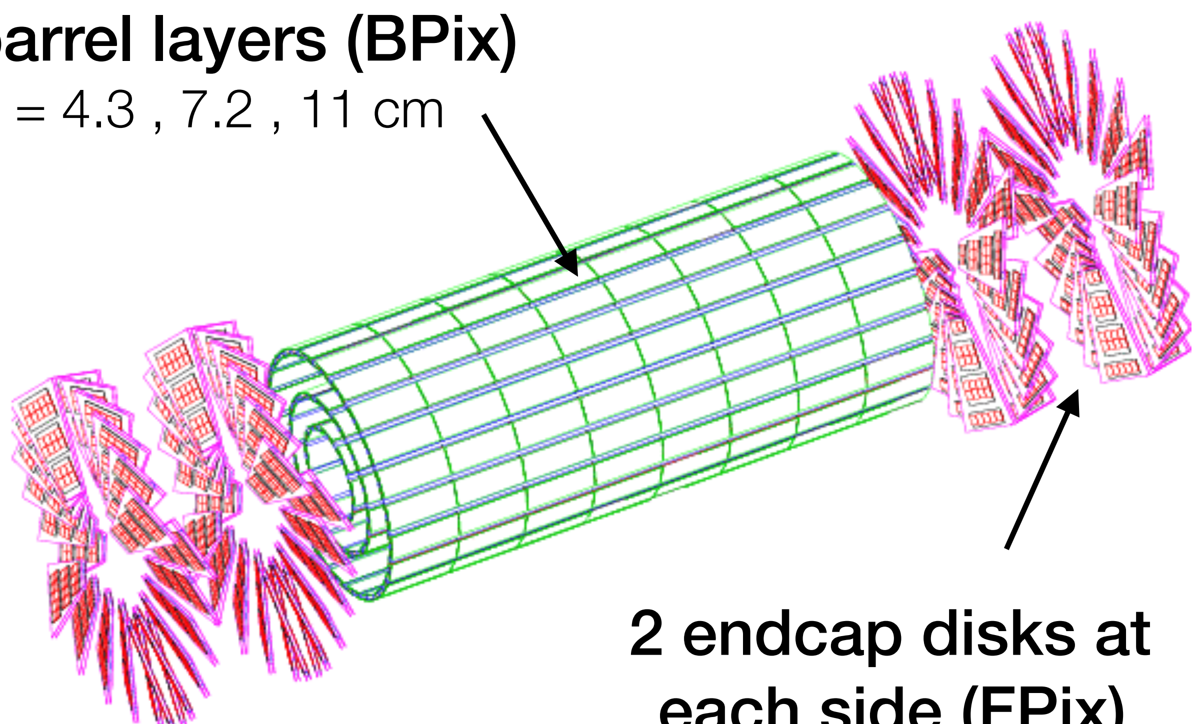
The CMS pixel detector

Key detector element for $H \rightarrow b\bar{b}$ identification

- Sensors technology:
  - n+ implants on n doped silicon bulk
  - pixel size : 100x150 μm^2

flight distance of B-hadron
with p_T = 50 GeV
is ~ 0.5 cm





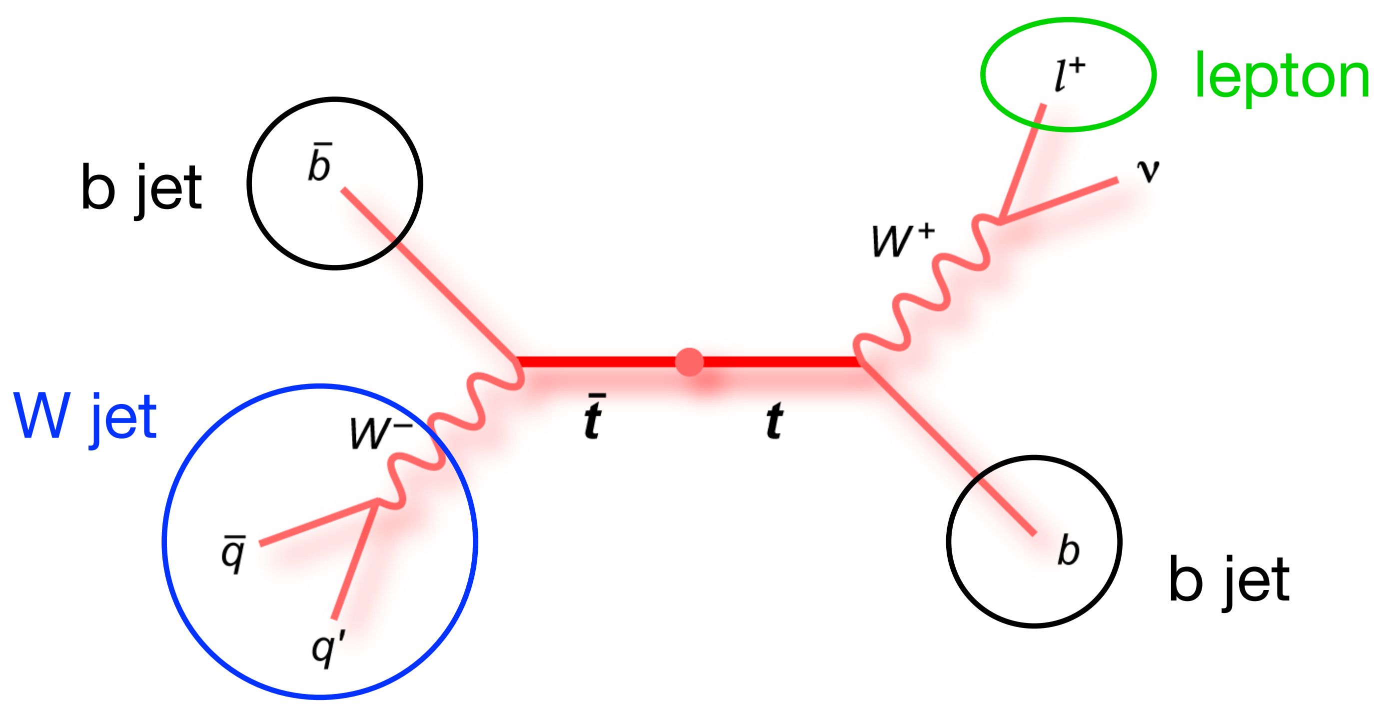
- Good hit resolution ~ 10-25 μm
- Good track impact parameter resolution and precise vertex reconstruction
  - efficient tagging of long-lived particles through secondary vertices
  - separation of primary vertex from pileup vertices

X→WV/WH: backgrounds

Main SM backgrounds with lepton+jet signature:

- W boson production in association with QCD jets (W+jets)
- top quarks pair production ($t\bar{t}$)
- single top quark production
- non-resonant diboson production (WW/WZ/ZZ)

largely reduced by V or H tagging selections



reduced by:

1) rejecting events with additional b-tagged jets outside the V/H jet cone

2) rejecting events with reconstructed top mass compatible with m_{top}

$X \to WV/WH$: backgrounds

Main SM backgrounds with lepton+jet signature:

- W boson production in association with QCD jets (W+jets)
- top quarks pair production ($t\bar{t}$)
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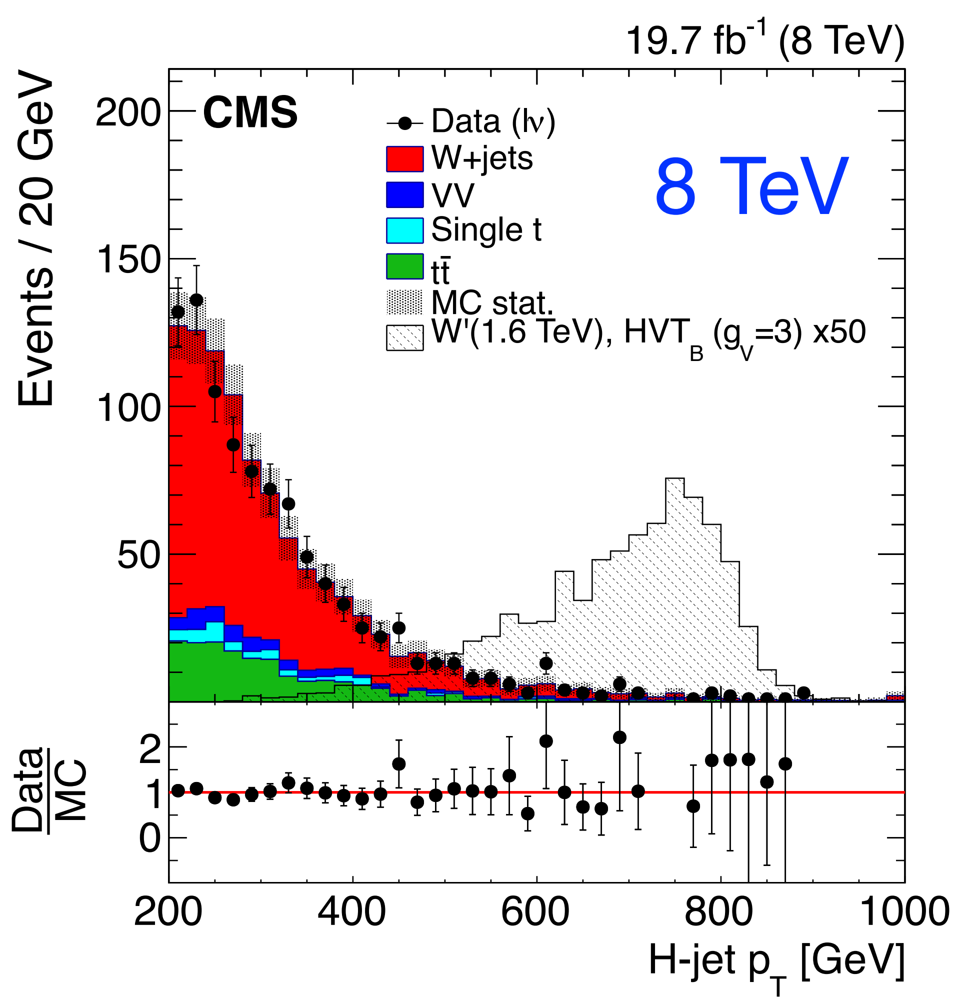
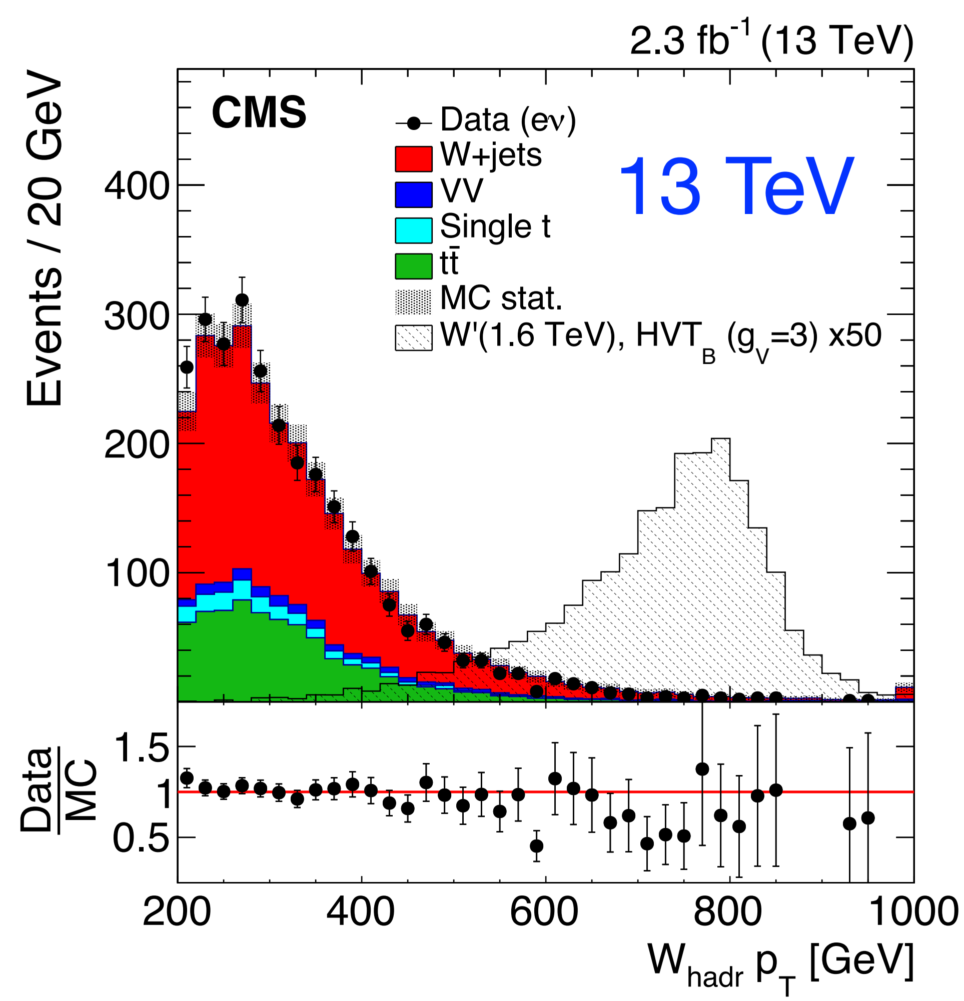
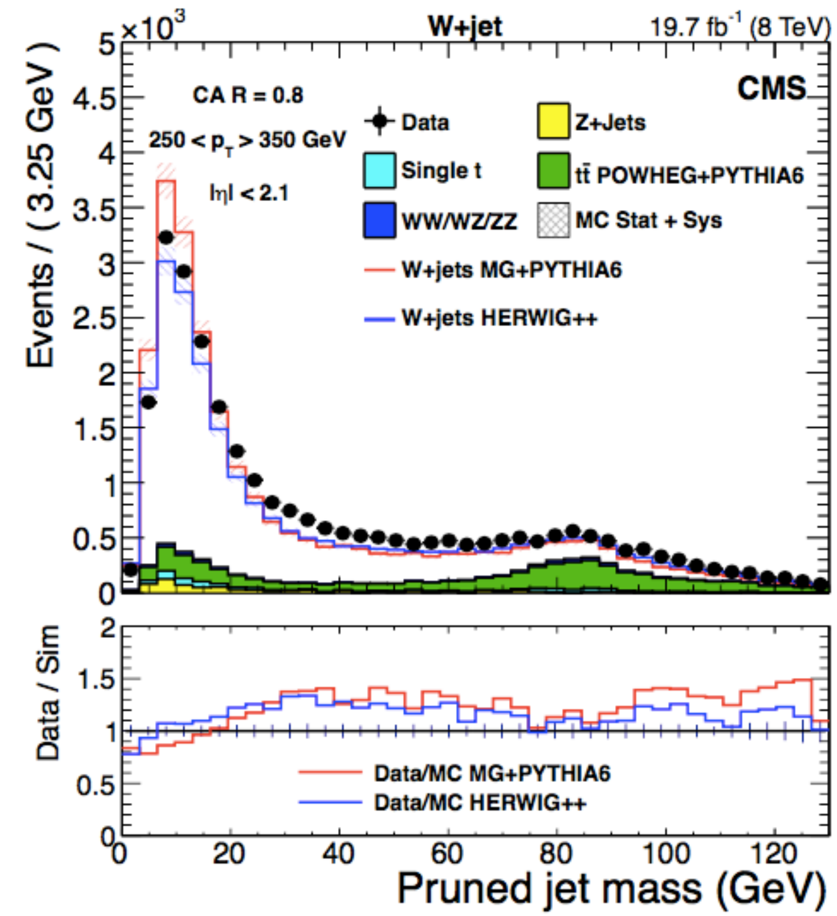
Distributions of the high-p_T H or V jet candidate





W+jets background estimation

W+jets background not correctly modelled in simulation: discrepancies in both distribution and normalization

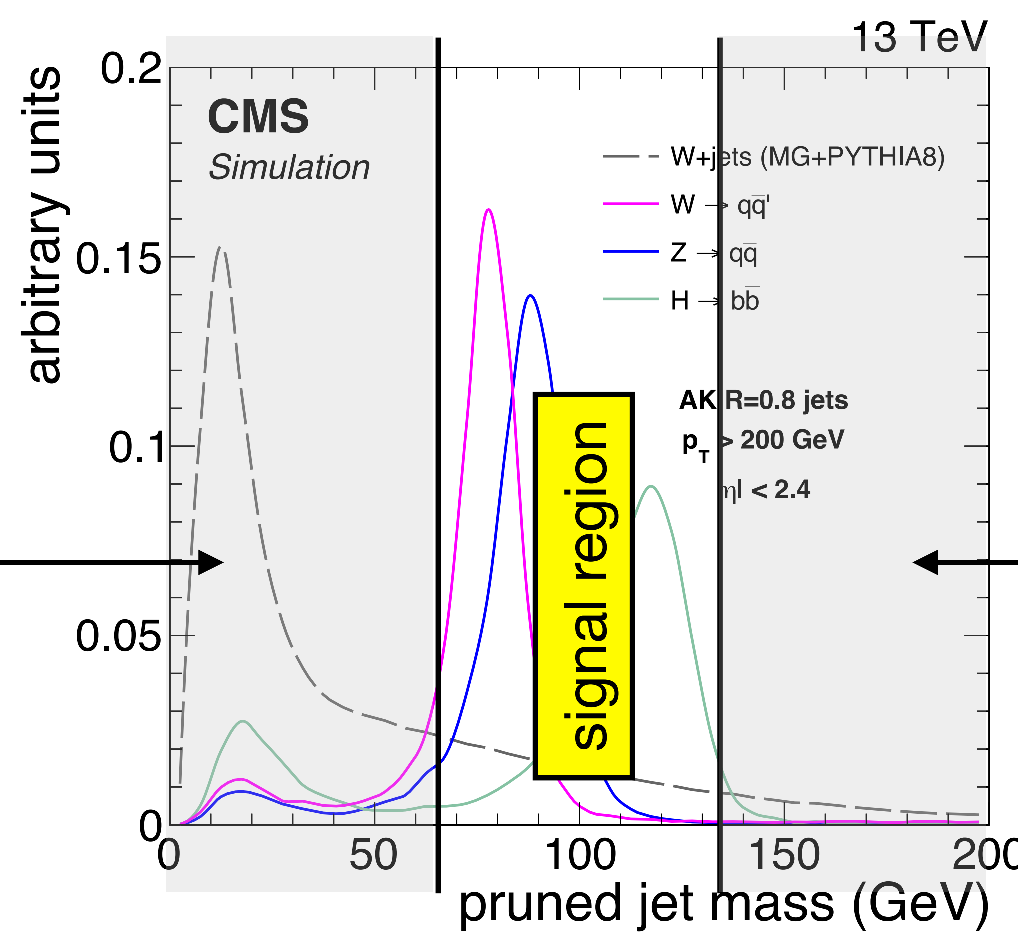


JHEP 12 (2014) 017

⇒ estimate this background from data in signal-free sidebands around the m_{jet} signal window

low mass sideband

populated by W+jets



high mass sideband

populated by W+jets

W+jets background estimation

⇒ estimate this background from data in signal-free sidebands around the m_{jet} signal window

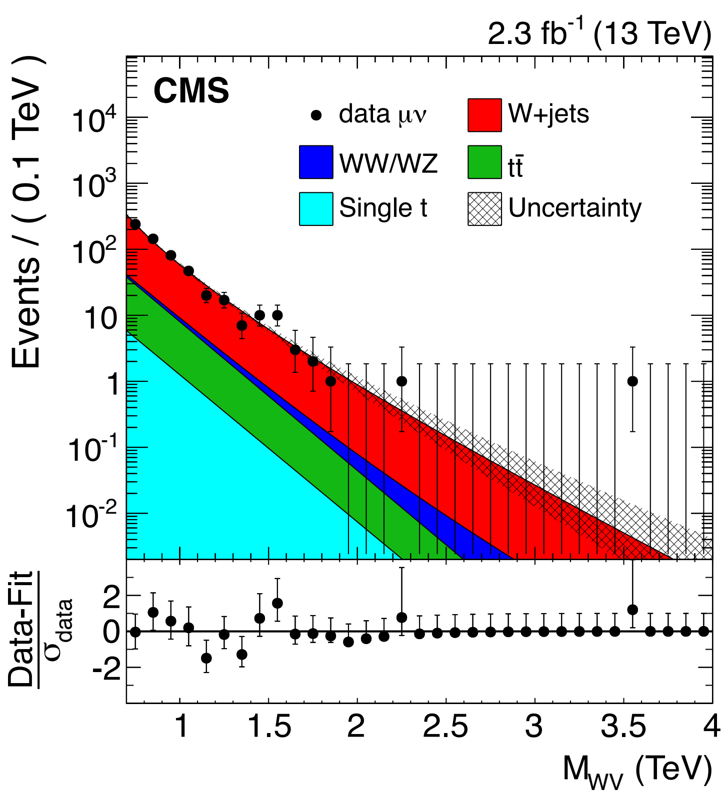
1) fit data in sideband

with exponentially falling function

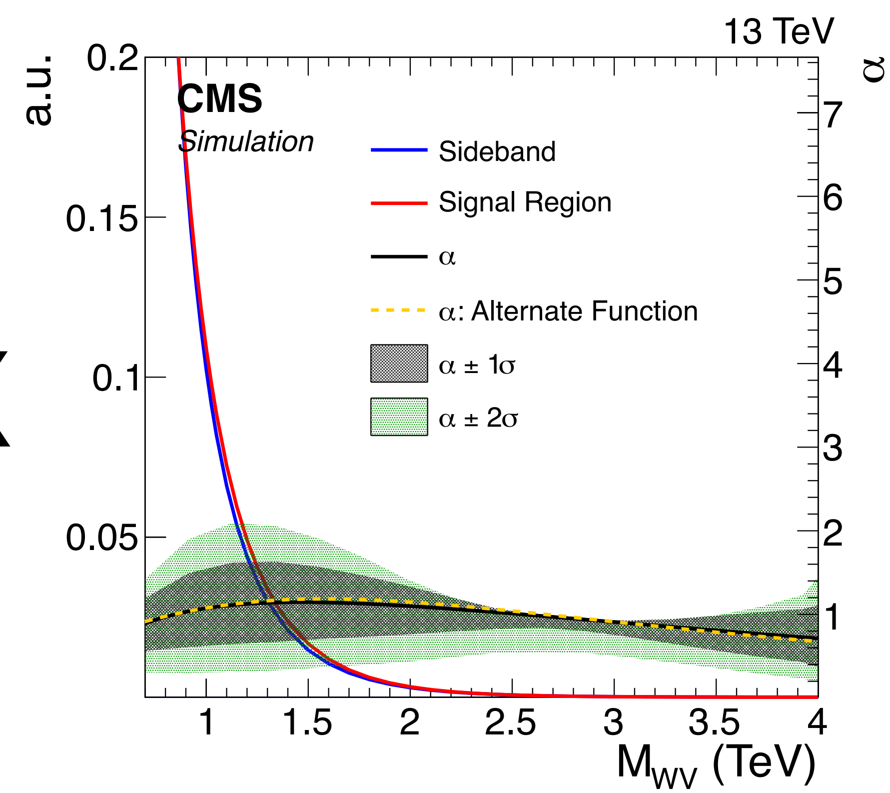
2) compute transfer function from simulation

$$\alpha_{MC} = \frac{F_{MC}\text{ (signal region)}}{F_{MC}\text{ (sideband)}}$$

3) predict background in the signal region



X



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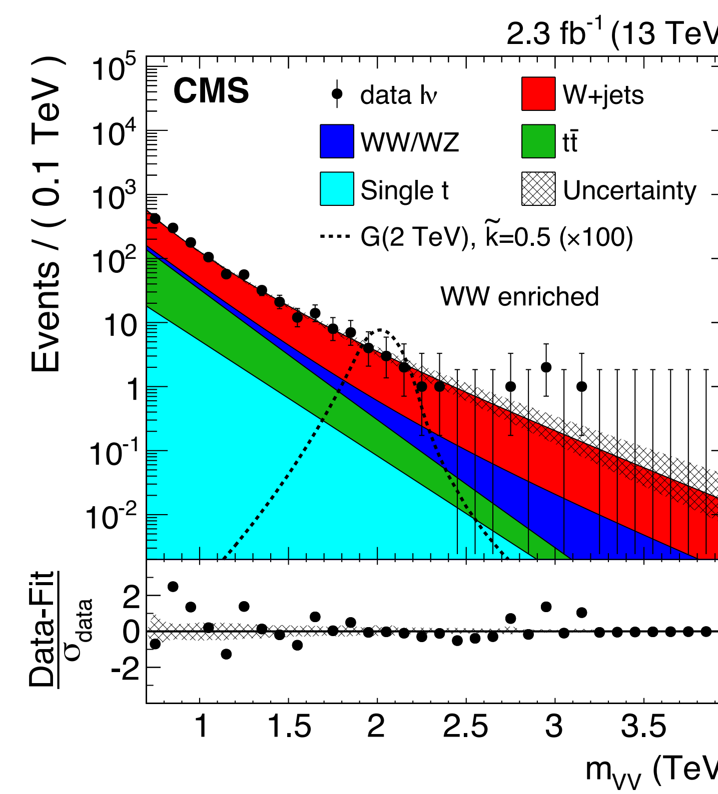
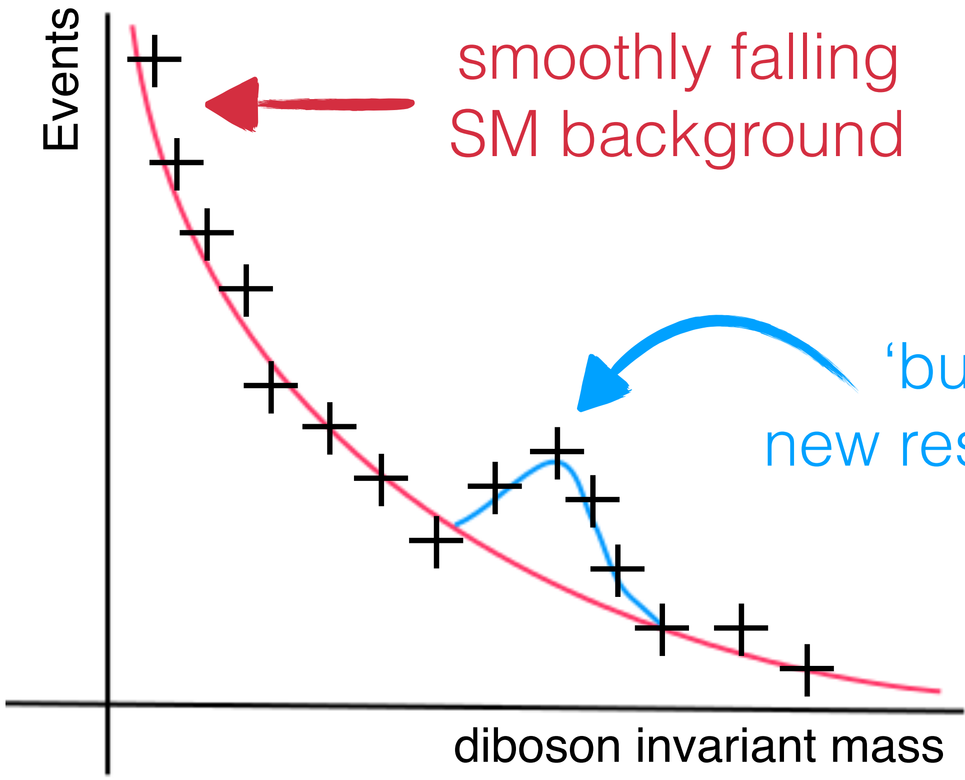


Top quark and non-resonant diboson backgrounds from simulation (corrected)

Signal description

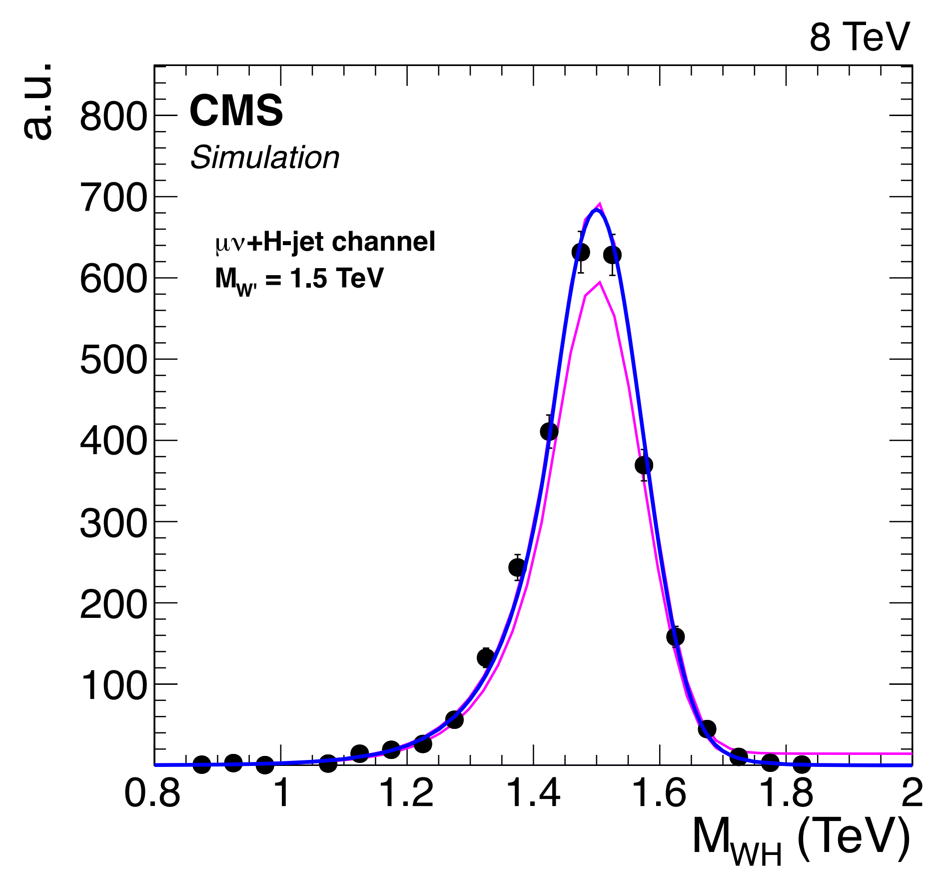


Resonance mass shape parametrized with Gaussian core + power law tails

Typical mass resolution (Gaussian core width)

4-7%

dominated by jet energy and E_T^{miss} resolution



- Search restricted to "narrow" resonances:

natural width < experimental resolution

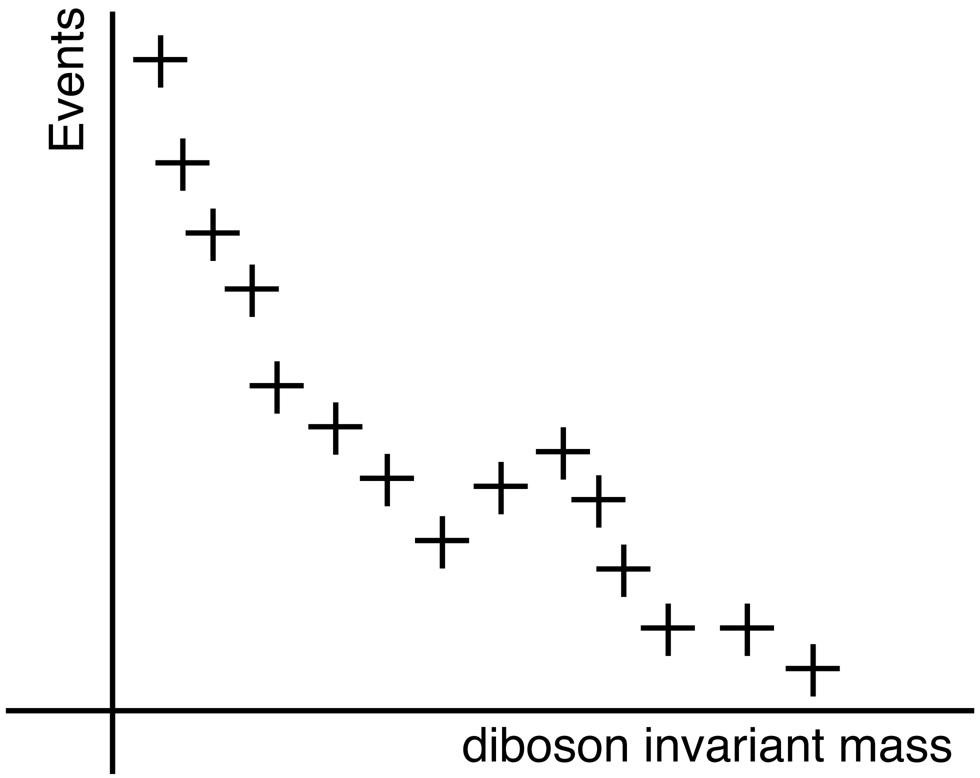
⇒ model-independent search:

restrict description of resonance mass to detector effects only

Interpreting the observation

Construct the likelihood from:

- observed WV/WH mass spectrum
- background prediction
- resonant signal shape



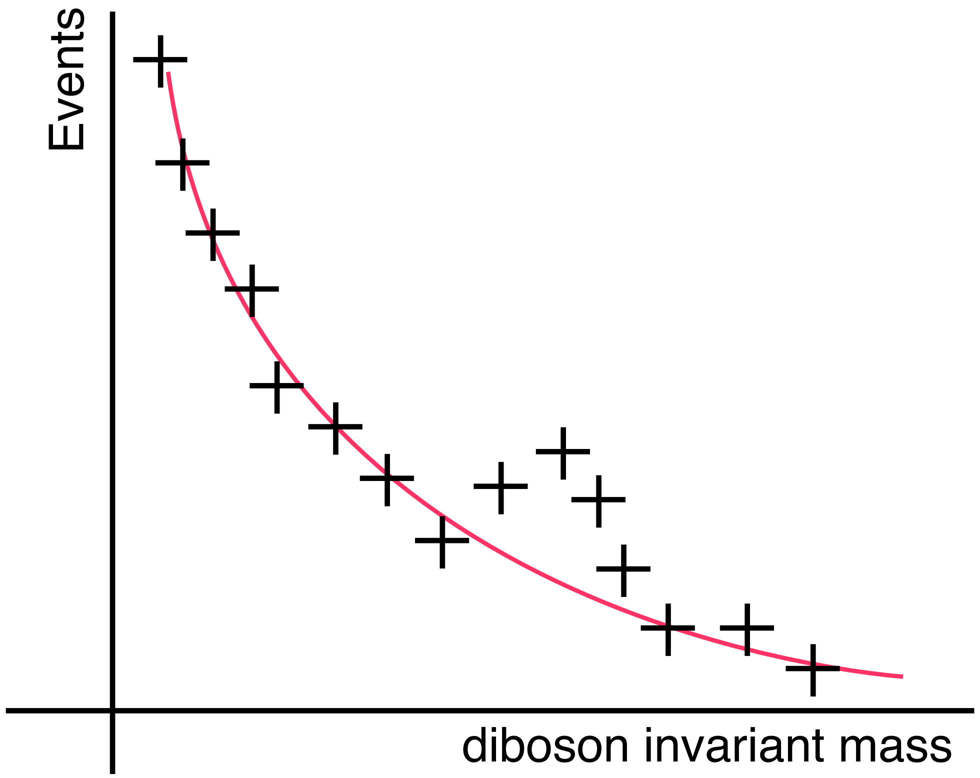
k = number of observed events

$$k^{-1}\prod_i(\mu S f_s(x_i) + B f_b(x_i))e^{-(\mu S+B)}$$

Interpreting the observation

Construct the likelihood from:

- observed WV/WH mass spectrum
- background prediction
- resonant signal shape



k = number of observed events

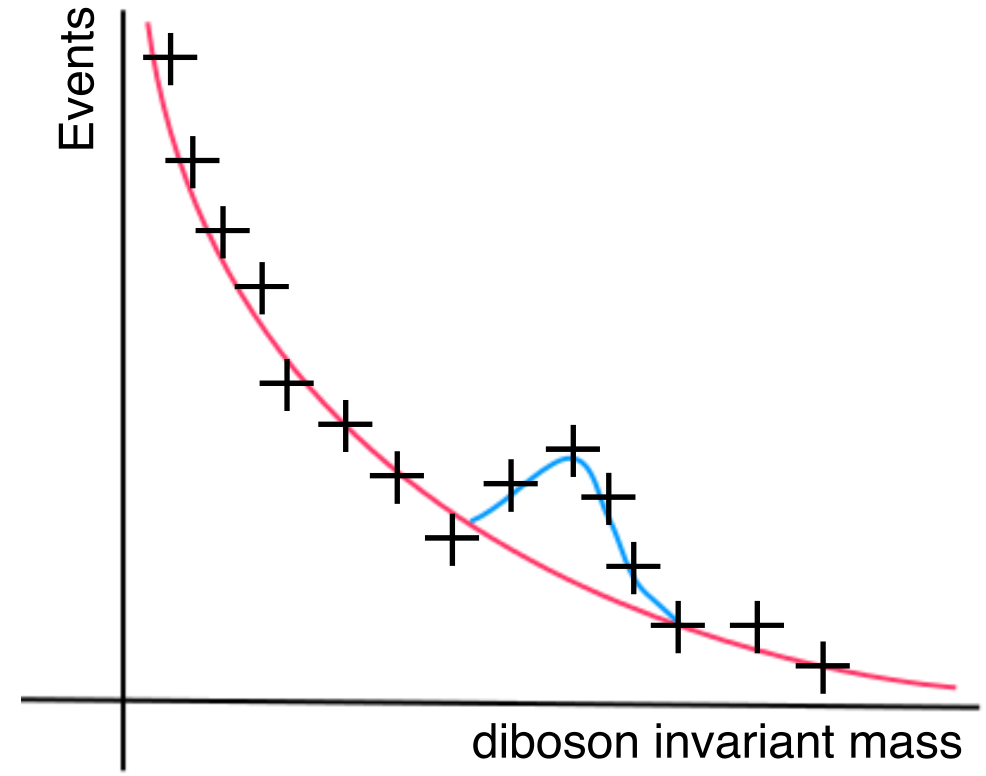
$$k^{-1}\prod_{i}(\mu S f_s(x_i) + B f_b(x_i))e^{-(\mu S+B)}$$

B = expected number of background events
$f_b(x)$ = probability density function of background

Interpreting the observation

Construct the likelihood from:

- observed WV/WH mass spectrum
- background prediction
- resonant signal shape



k = number of observed events

Poisson probability

$$k^{-1}\prod_i (\mu S f_s(x_i) + B f_b(x_i)) \boxed{e^{-(\mu S + B)}}$$

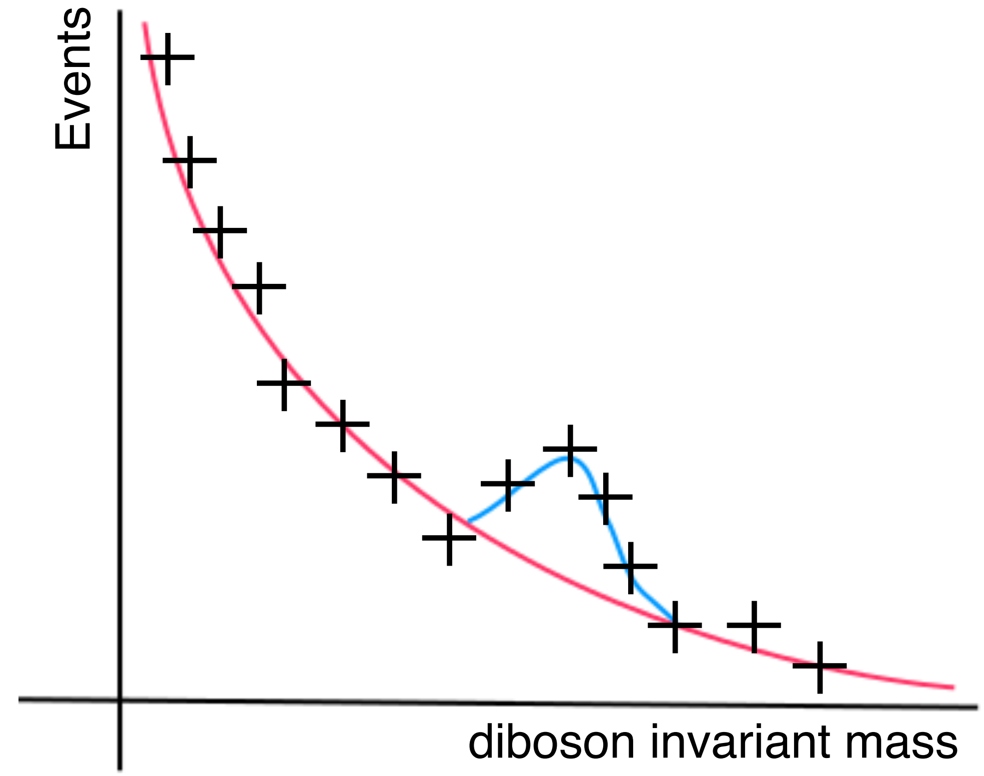
B = expected number of background events
$f_b(x)$ = probability density function of background

S = expected number of signal events
$f_s(x)$ = probability density function of signal

Interpreting the observation

Construct the likelihood from:

- observed WV/WH mass spectrum
- background prediction
- resonant signal shape



both shapes and normalizations are subject to multiple systematic uncertainties

- experimental and theoretical uncertainties (ex: V-tagging, jet calibrations, statistics of the data in sidebands, parton distribution functions, …)

⇒ introduce nuisance parameters θ in the likelihood

$$k^{-1}\prod_i(\mu S(\theta)f_s(x_i,\theta)+B(\theta)f_b(x_i,\theta))e^{-(\mu S(\theta)+B(\theta))}$$

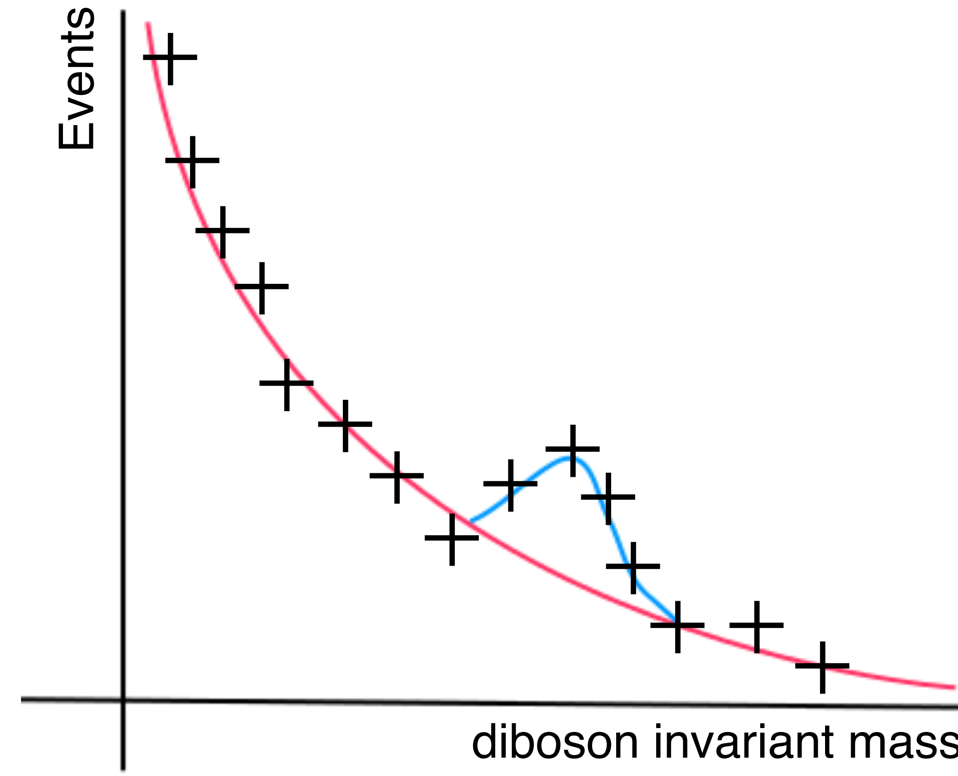
constrained through log-normal probability density function

Interpreting the observation

Construct the likelihood from:

- observed WV/WH mass spectrum
- background prediction
- resonant signal shape

+ nuisance parameters θ



Parameter of interest μ = signal strength
= scale factor on the hypothesized signal cross section σ_{th}

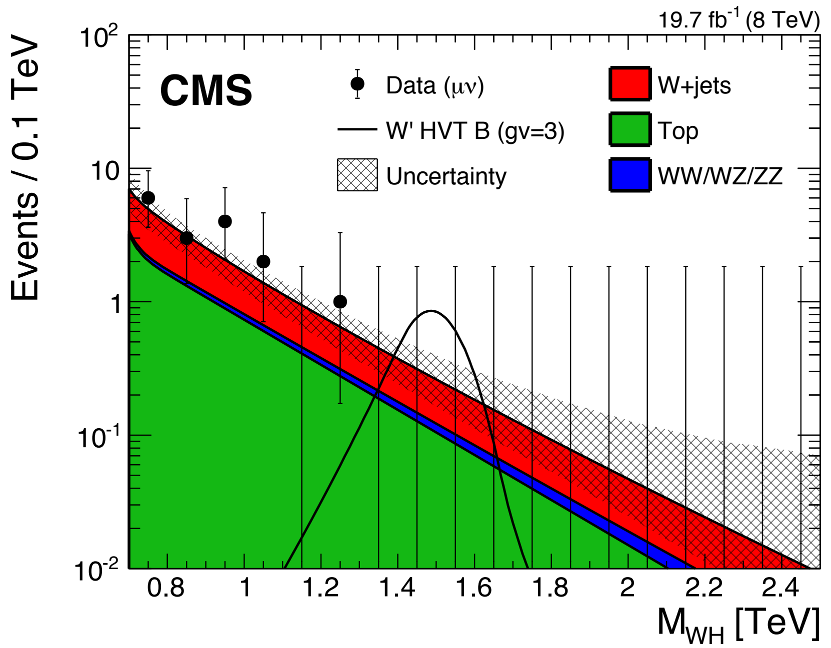
$$k^{-1}\prod_i(\mu S(\theta)f_s(x_i,\theta)+B(\theta)f_b(x_i,\theta))e^{-(\mu S(\theta)+B(\theta))}$$

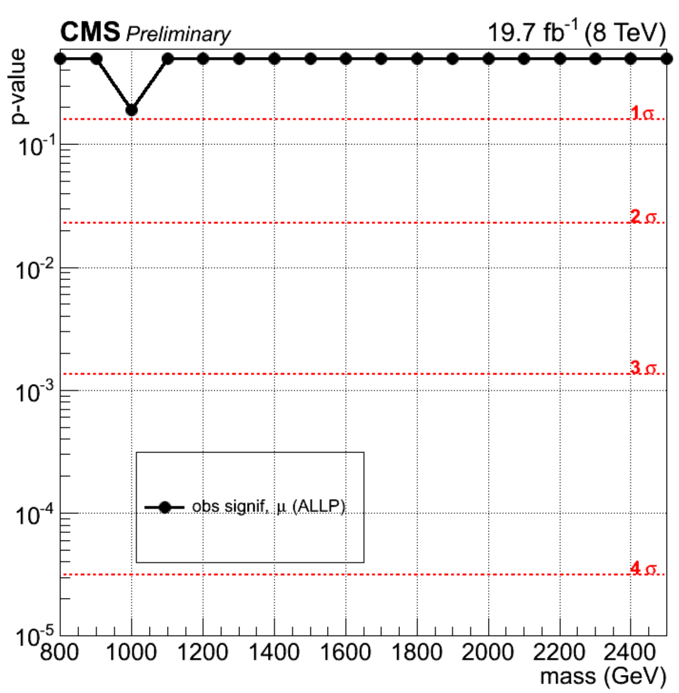
⇒ for each resonance mass hypothesis maximize the likelihood to obtain best fit of μ

⇒ calculate p-values and 95% CL upper limits with profile-likelihood ratio method

Results of the search for a WH→$\ell\nu b\bar{b}$ resonance

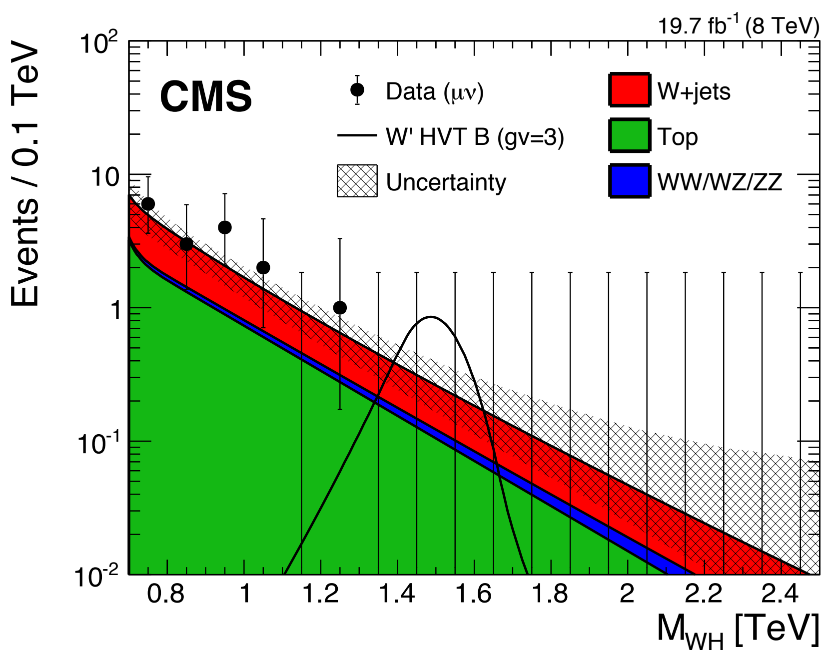
μν+H-jet



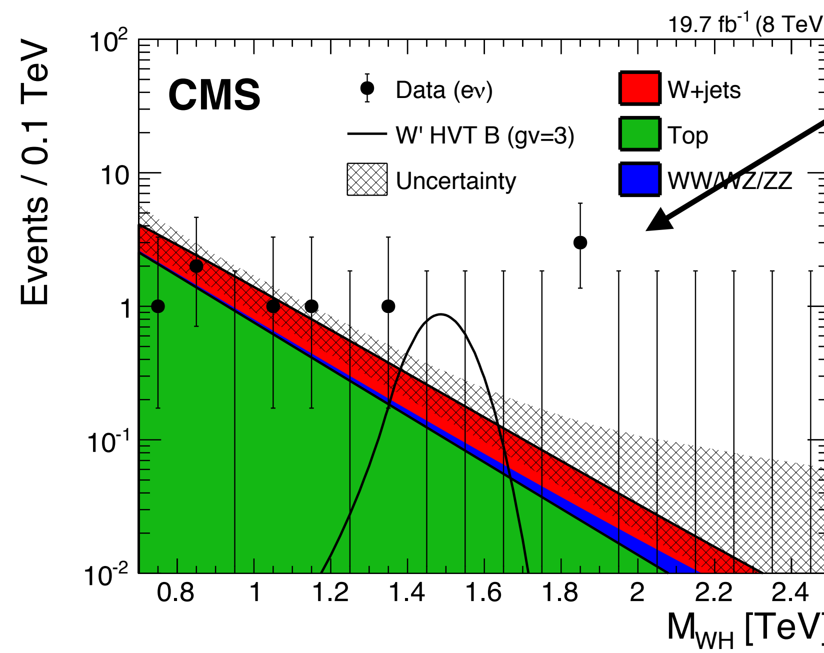


Results of the search for a $WH \to \ell \nu b\bar{b}$ resonance

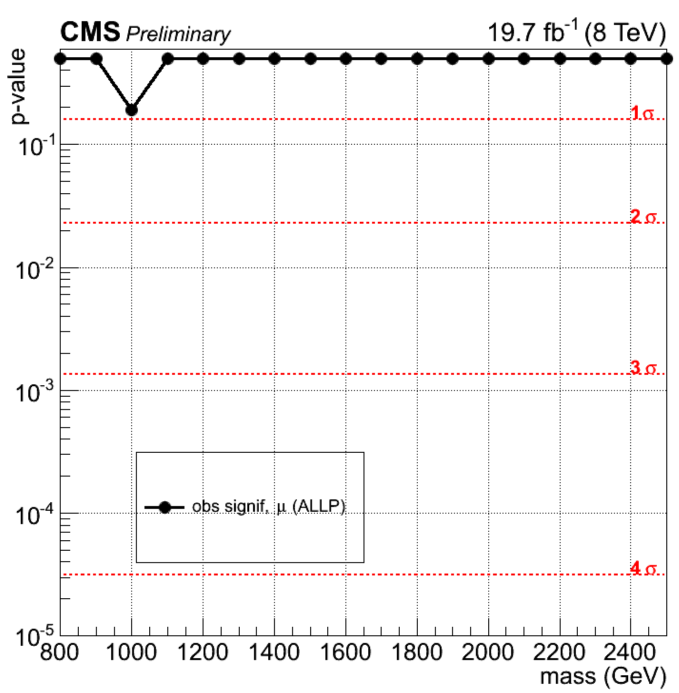
$\mu\nu$+H-jet

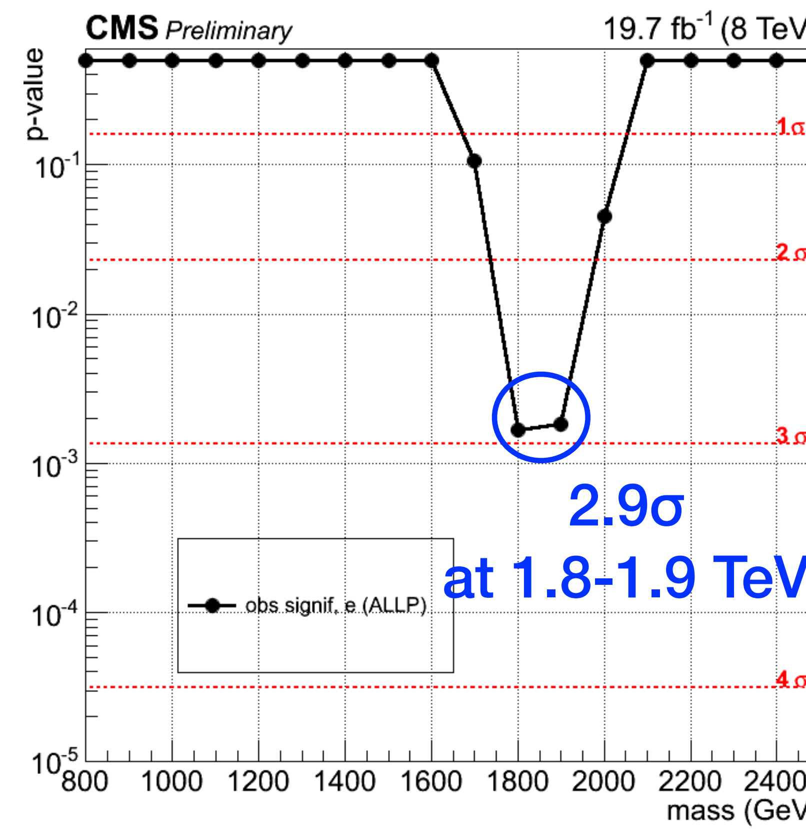


$e\nu$+H-jet



Deviation @ 1.8 TeV !



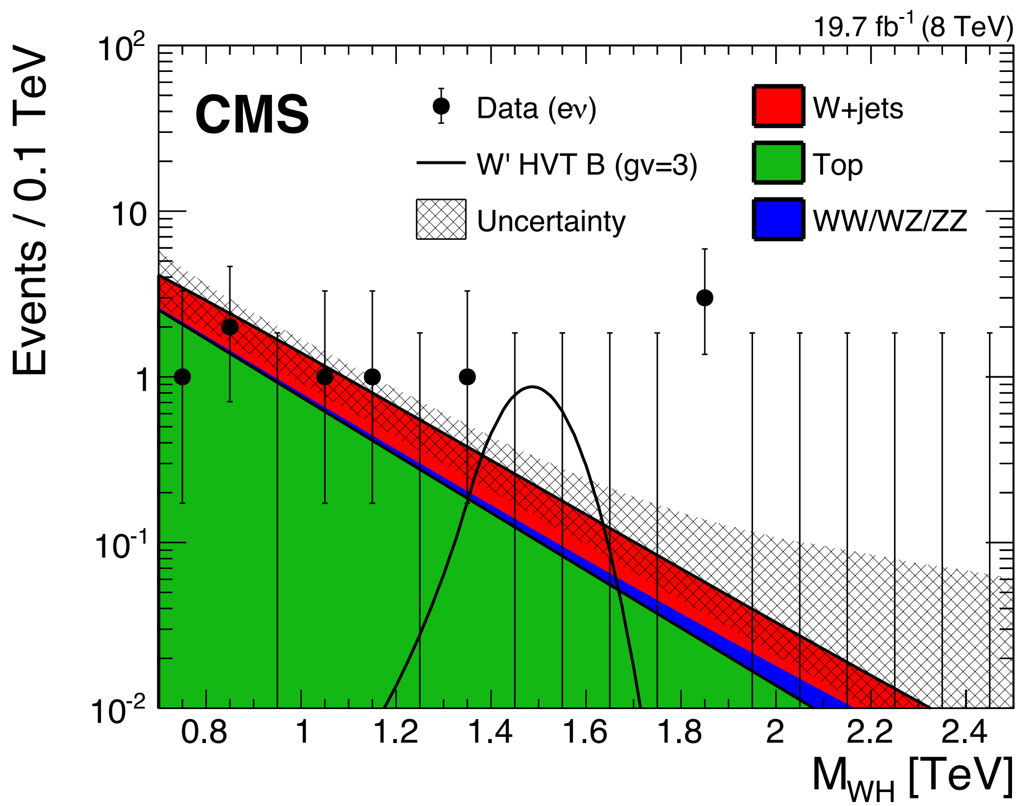


2.9σ at 1.8-1.9 TeV

Observations with $\sqrt{s}$ = 8 TeV data

Things got more exciting…

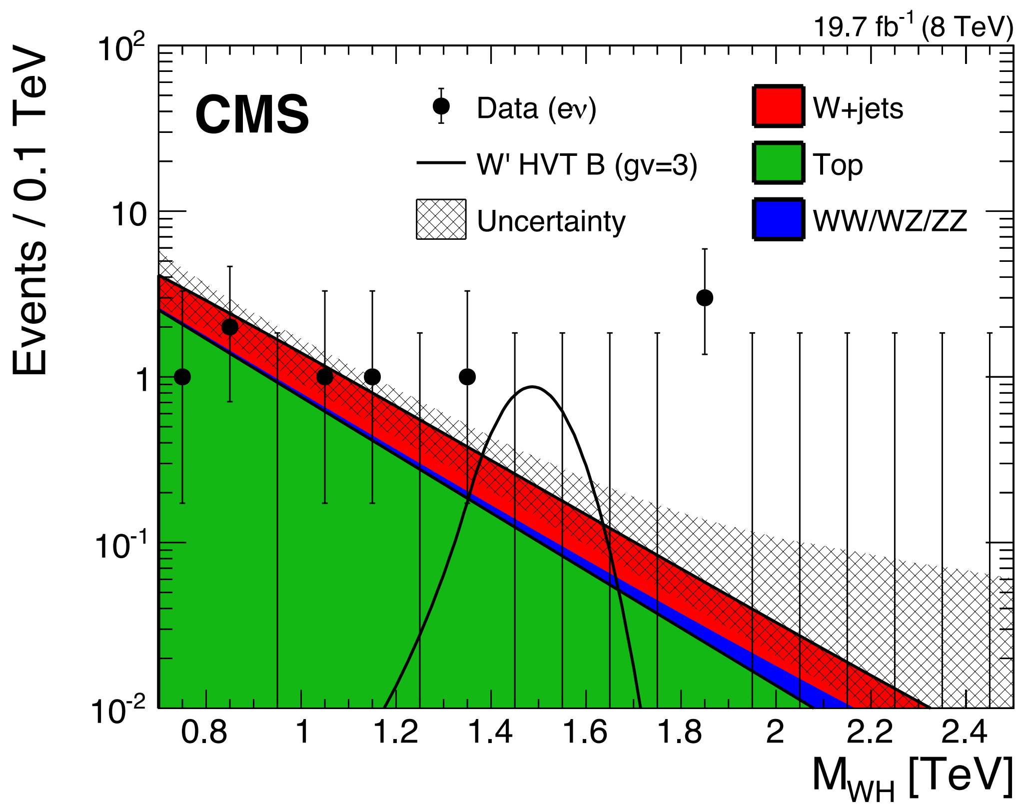
CMS: 2.9σ at 1.8 TeV



Observations with $\sqrt{s}$ = 8 TeV data

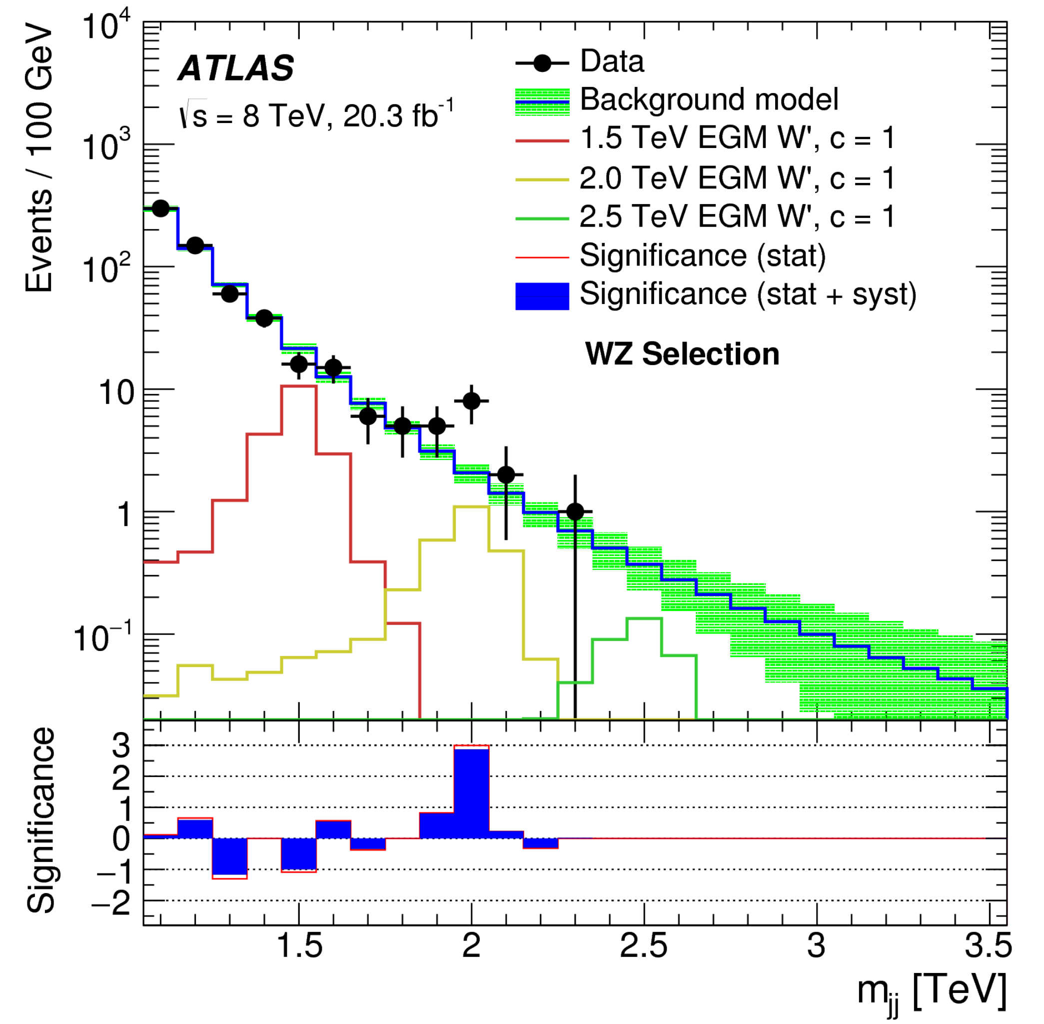
Things got more exciting…

CMS: 2.2σ at 1.8 TeV



ATLAS: 3.4σ at 2 TeV

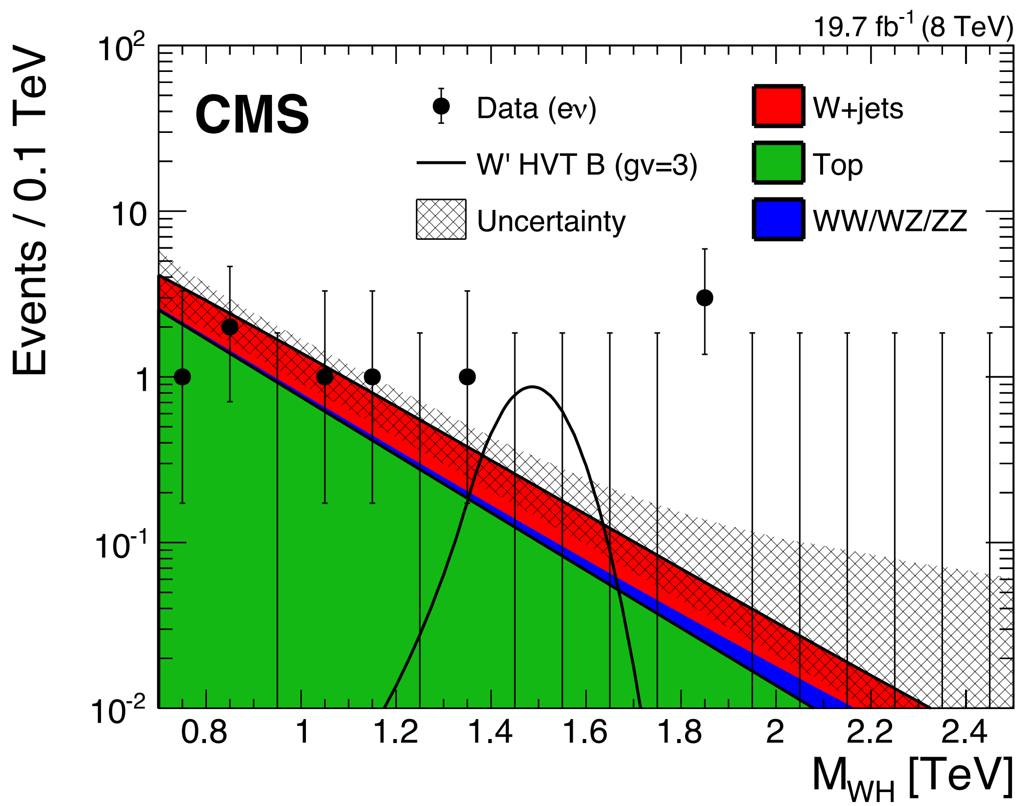
Search for WZ resonance in all-jet final state
WZ → $q\bar{q}q\bar{q}$



Observations with √s = 8 TeV data

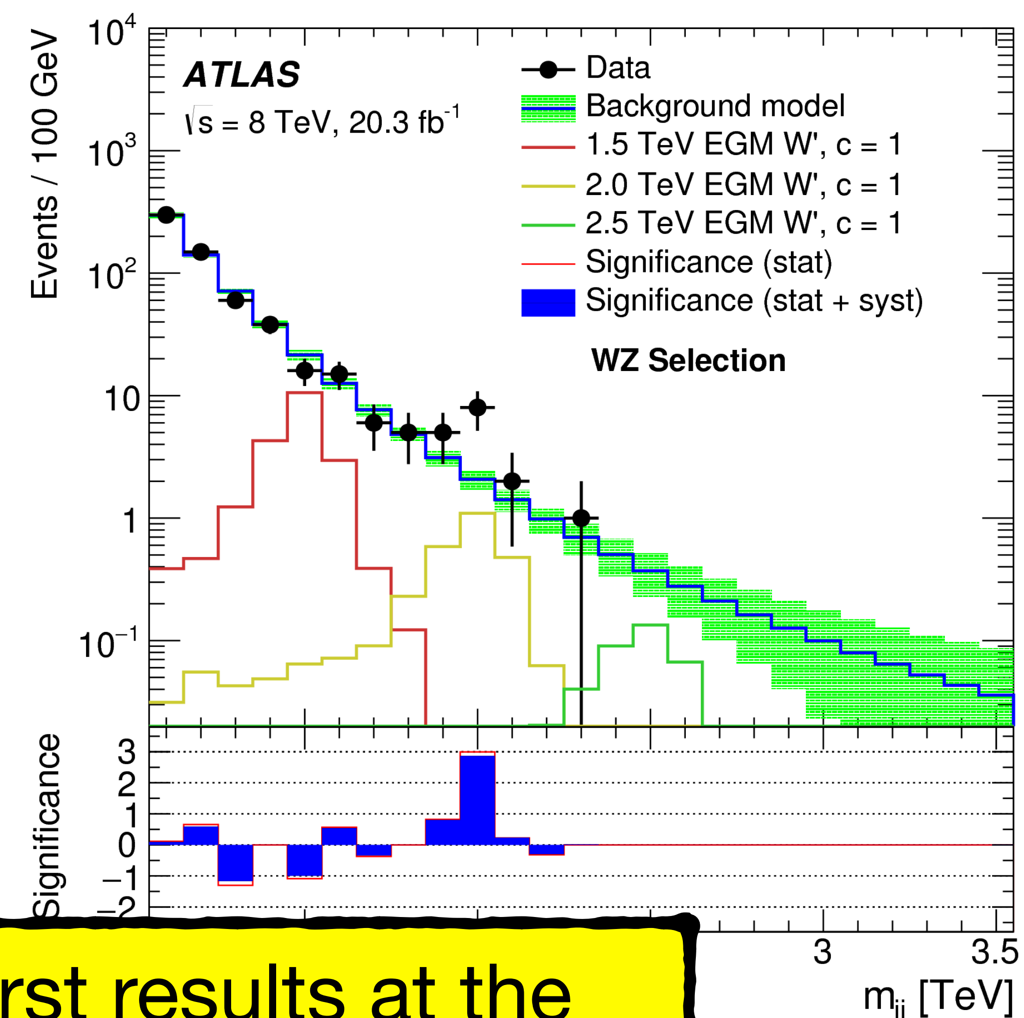
Things got more exciting…

CMS: 2.2σ at 1.8 TeV



ATLAS: 3.4σ at 2 TeV

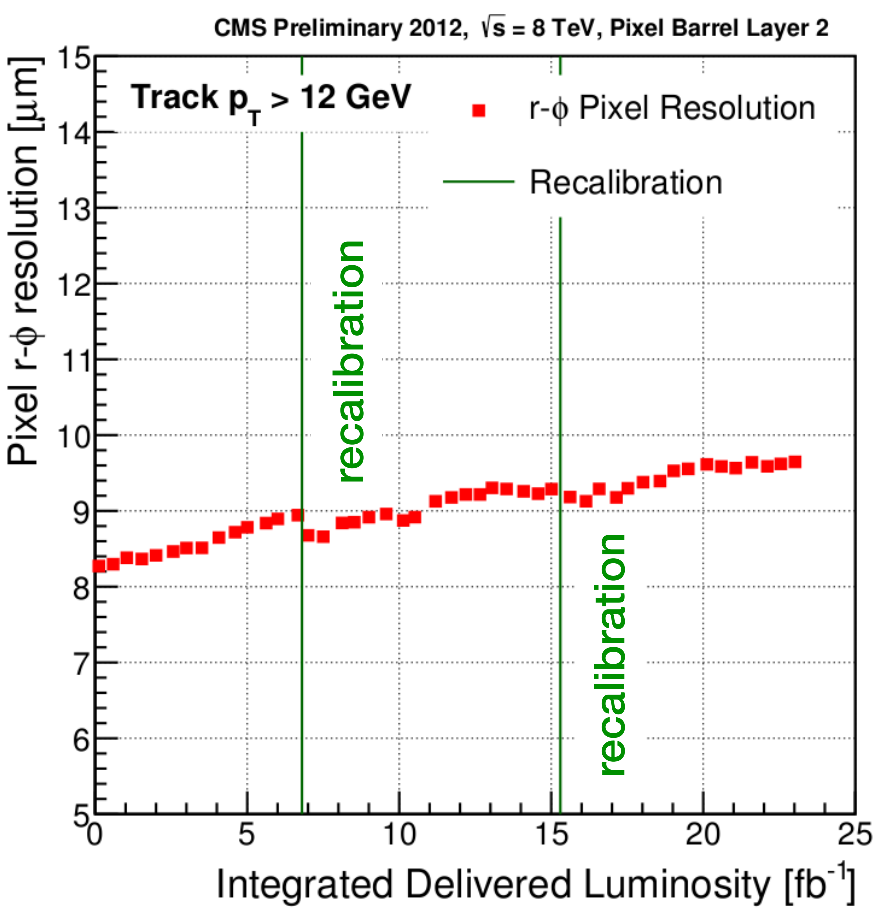
Search for WZ resonance in all-jet final state
WZ → qq̄qq̄



HIGH PRIORITY: provide first results at the restart of pp collisions at √s = 13 TeV!

In the meanwhile… optimize BPix for Run 2

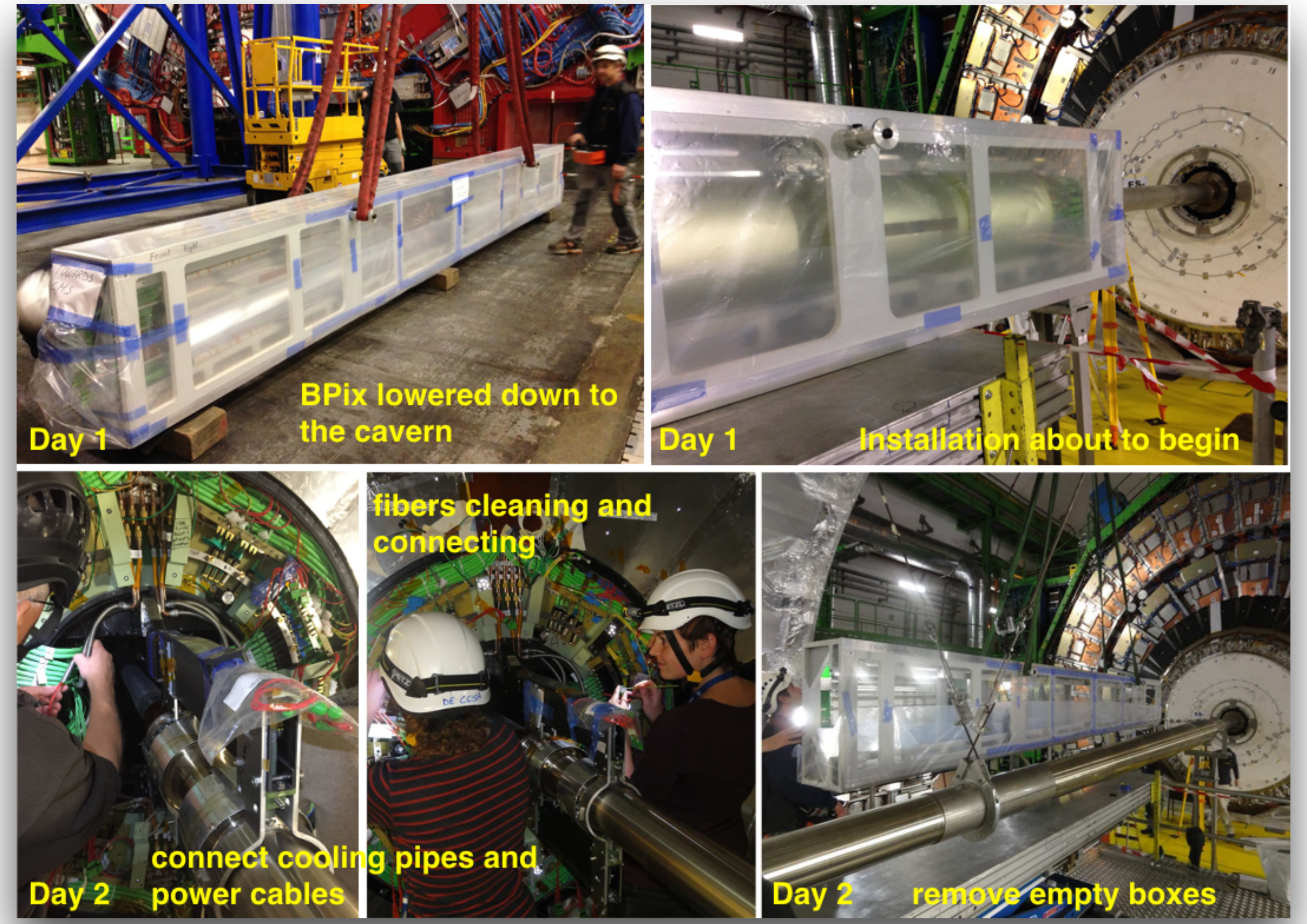
- The BPix was installed in 2008 and showed excellent performance up to 2016!
- However, subject to severe radiation damage
  - signal performance degradation ⇒ pixel hit resolution
- Several corrections needed to guarantee full performance
- During LS1 in ’13-‘14 (after Run 1) BPix installed in the clean room of LHC-P5
  - carefully tested the detector after the 2 years of operations
  - replaced malfunctioning components
  - exercised and optimized the calibration procedures in view of the commissioning and monitoring for Run 2



fraction of operational channels:
97.7% at the end of Run 1 ⇒ 99% at the end of LS1

BPix commissioning for Run 2

BPix reinstalled into CMS in December 2014



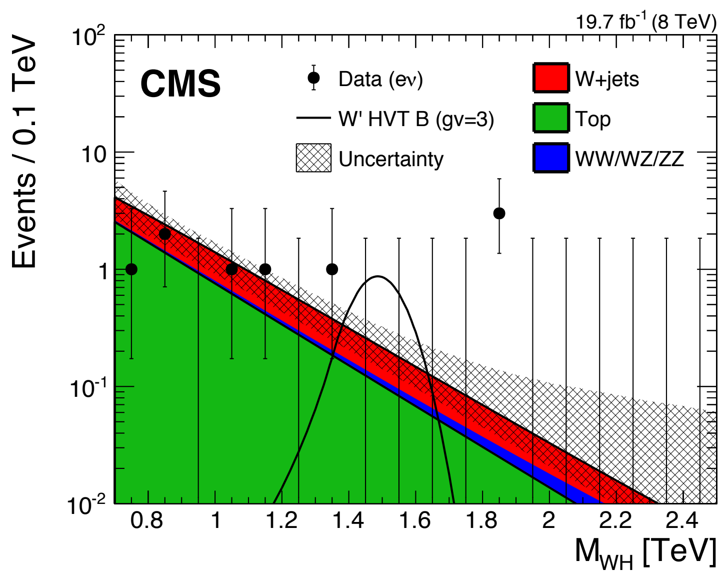
Major effort put to recalibrate the detector after the installation (~ 10 days)

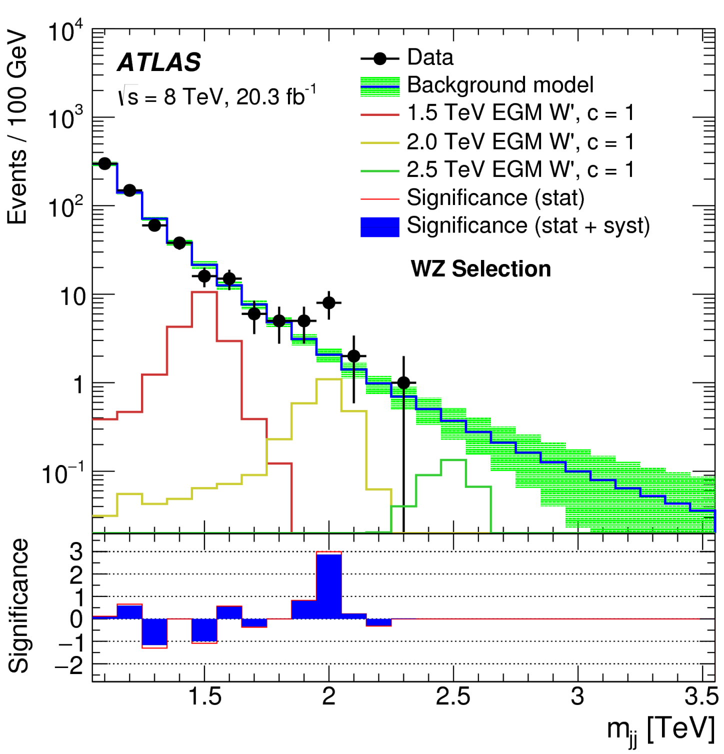
⇒ *ensured stable operations and excellent performance at the start of pp collisions at $\sqrt{s}$ = 13 TeV*

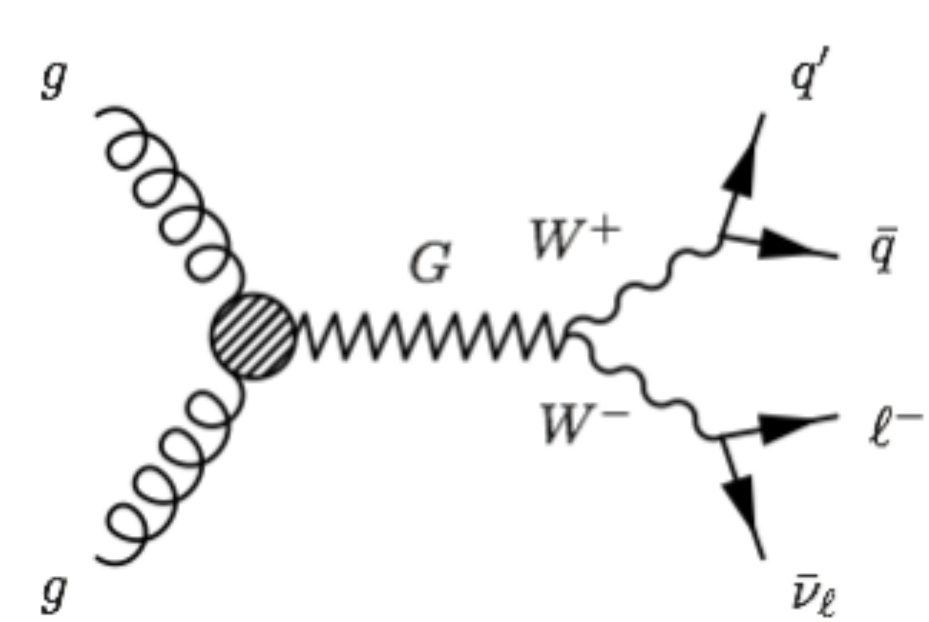
First results @ 13 TeV

Keeping in mind the previously observed excesses…

… search first in the WW/WZ→lepton+jet final state without b-tagging (simpler!)







Search for a WW or WZ resonance in the $\ell\nu q\bar{q}$ decay channel with $\sqrt{s}$ = 13 TeV data

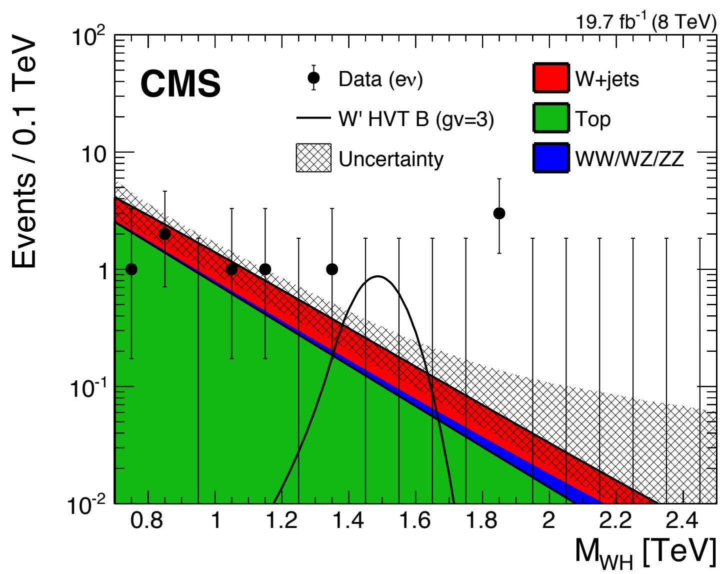
eprint: arxiv.1612.09159

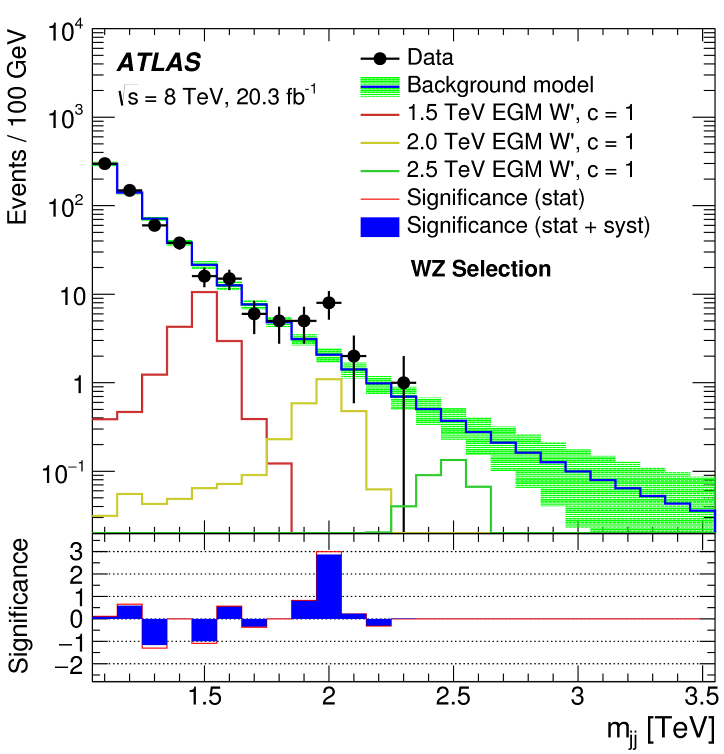
Submitted to JHEP

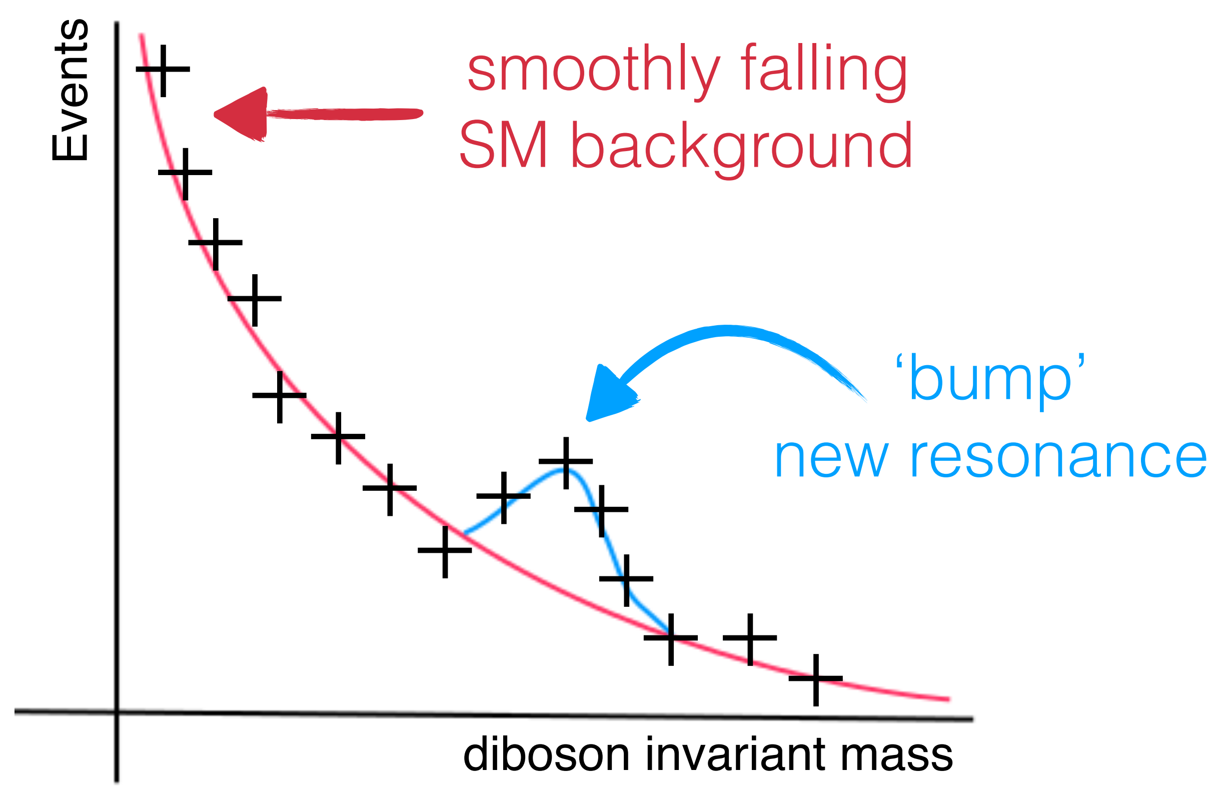
First results @ 13 TeV

Keeping in mind the previously observed excesses…

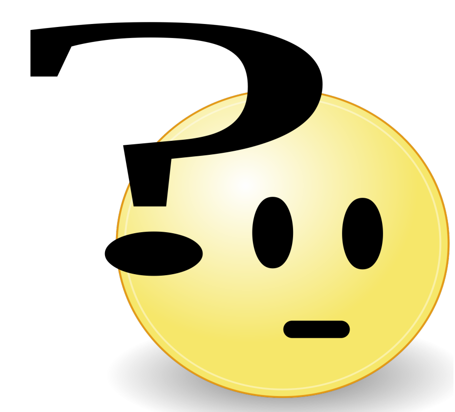
… you want to know the properties of a possible observed new signal!





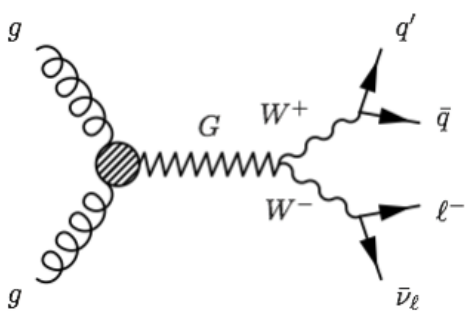


Spin?
Charge?



First results @ 13 TeV

Search for a WW and WZ→ℓνqq̄ resonances



Search for a WW or WZ resonance
in the ℓνqq̄ decay channel
with √s = 13 TeV data
eprint: arxiv.1612.09159
Submitted to JHEP

⇒ optimize the analysis to achieve

significant discrimination between different signal hypotheses:

W-mass category: enriched in WW resonances

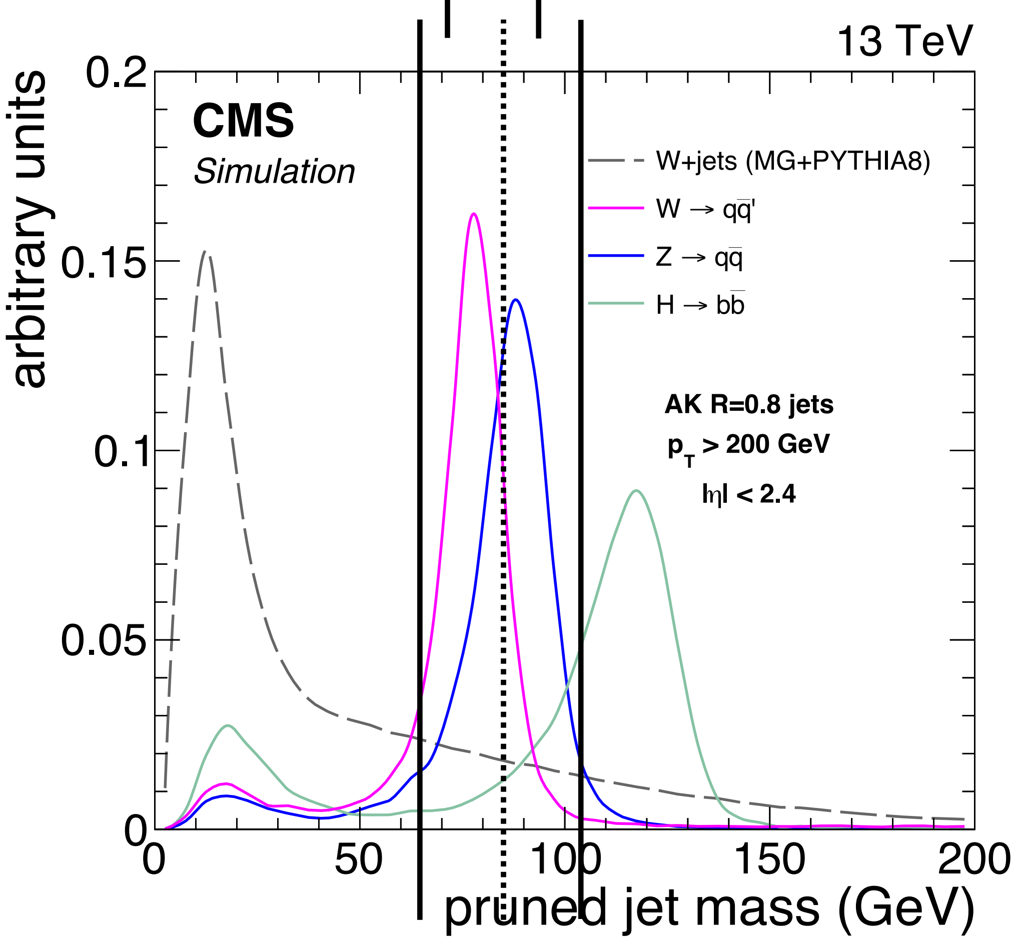
Z-mass category: enriched in WZ resonances

Separate the m_{jet} signal region in two exclusive categories:

- **W-mass region:** enriched in W-jets
  ⇒ find here a spin-2 G→WW or a spin-1 Z'→WW

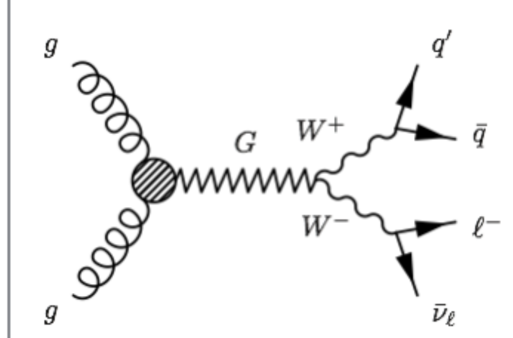
- **Z-mass region:** enriched in Z-jets
  ⇒ find here a spin-1 W'→WZ

Combine the two categories in the statistical analysis in case of absence of a signal → improve cross section limits by using all available data



First results @ 13 TeV

Search for a WW and WZ→ℓνq$\bar{q}$ resonances



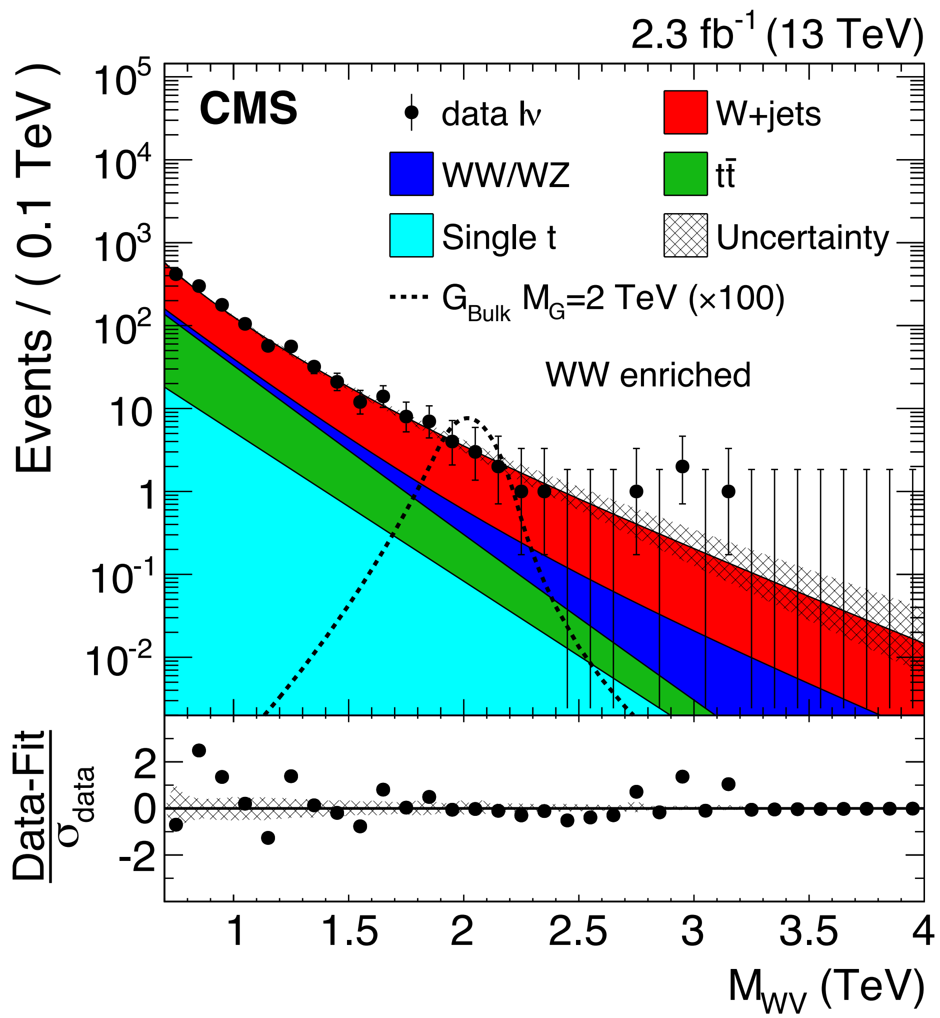
Search for a WW or WZ resonance in the ℓνq$\bar{q}$ decay channel with $\sqrt{s}$ = 13 TeV data

eprint: arxiv.1612.09159

Submitted to JHEP

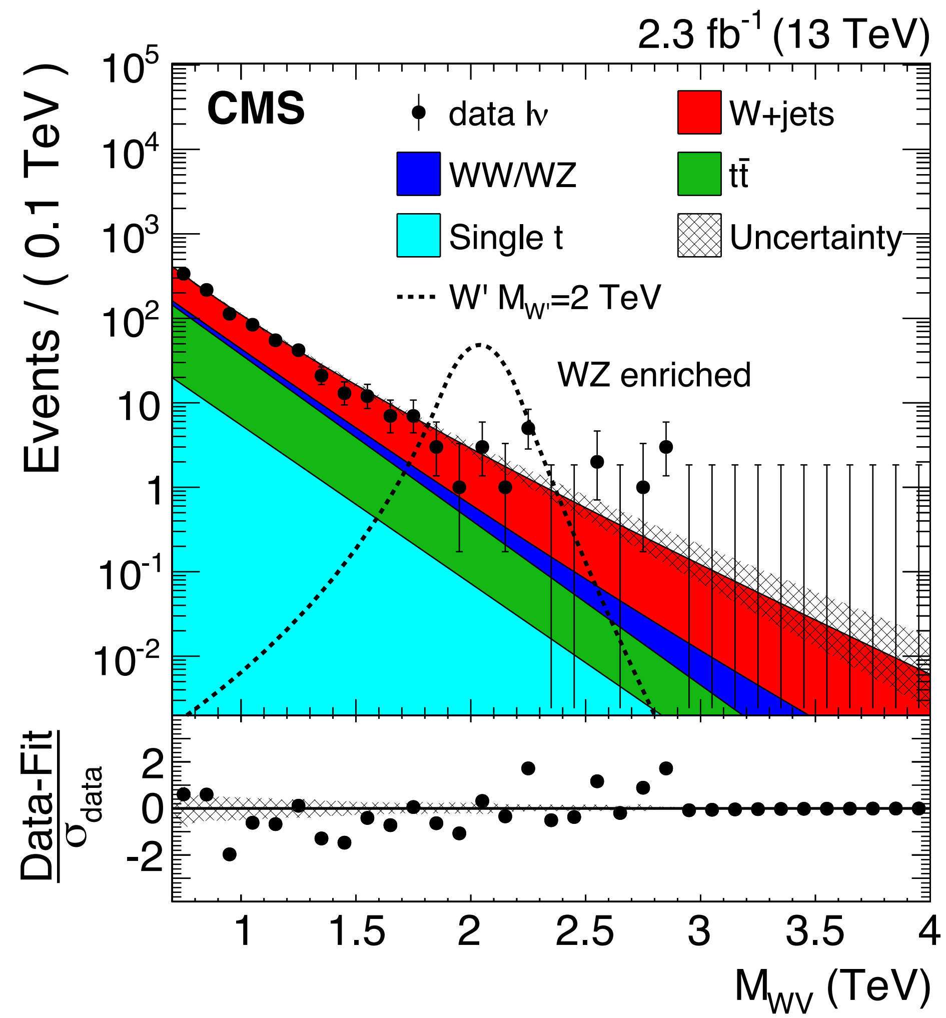
ℓν + W-jet

(WW-enriched cat.)



ℓν + Z-jet

(WZ-enriched cat.)

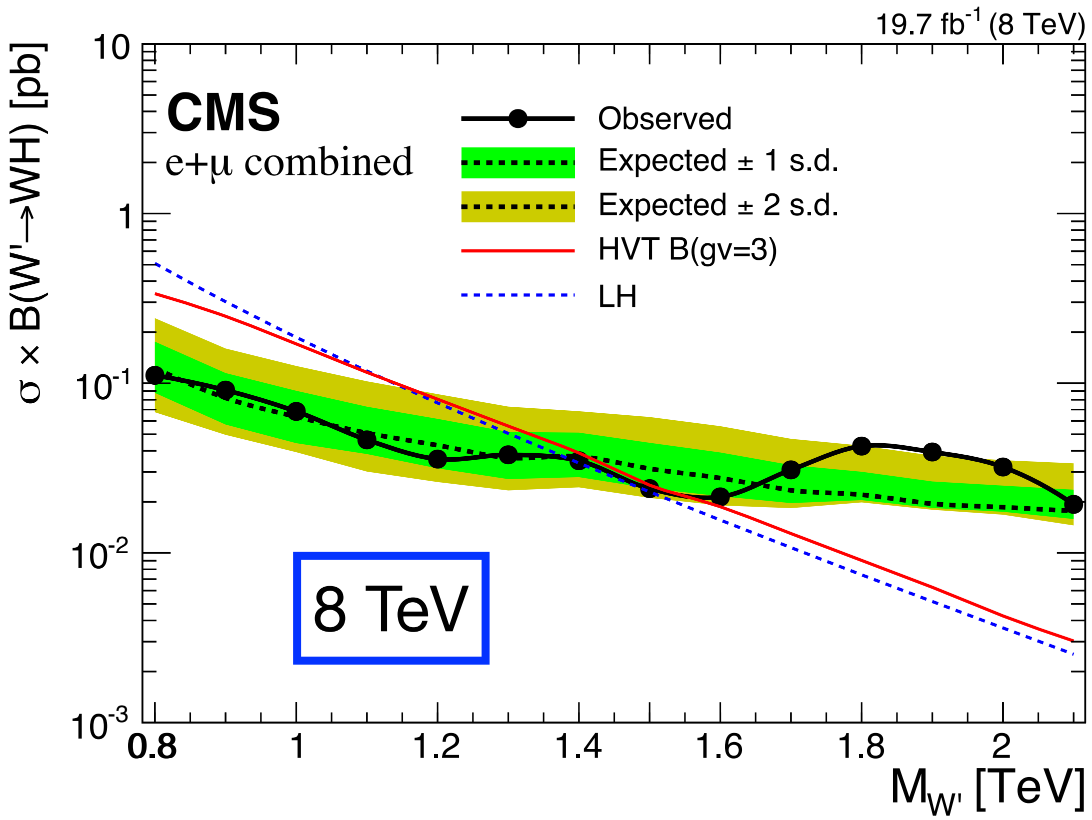


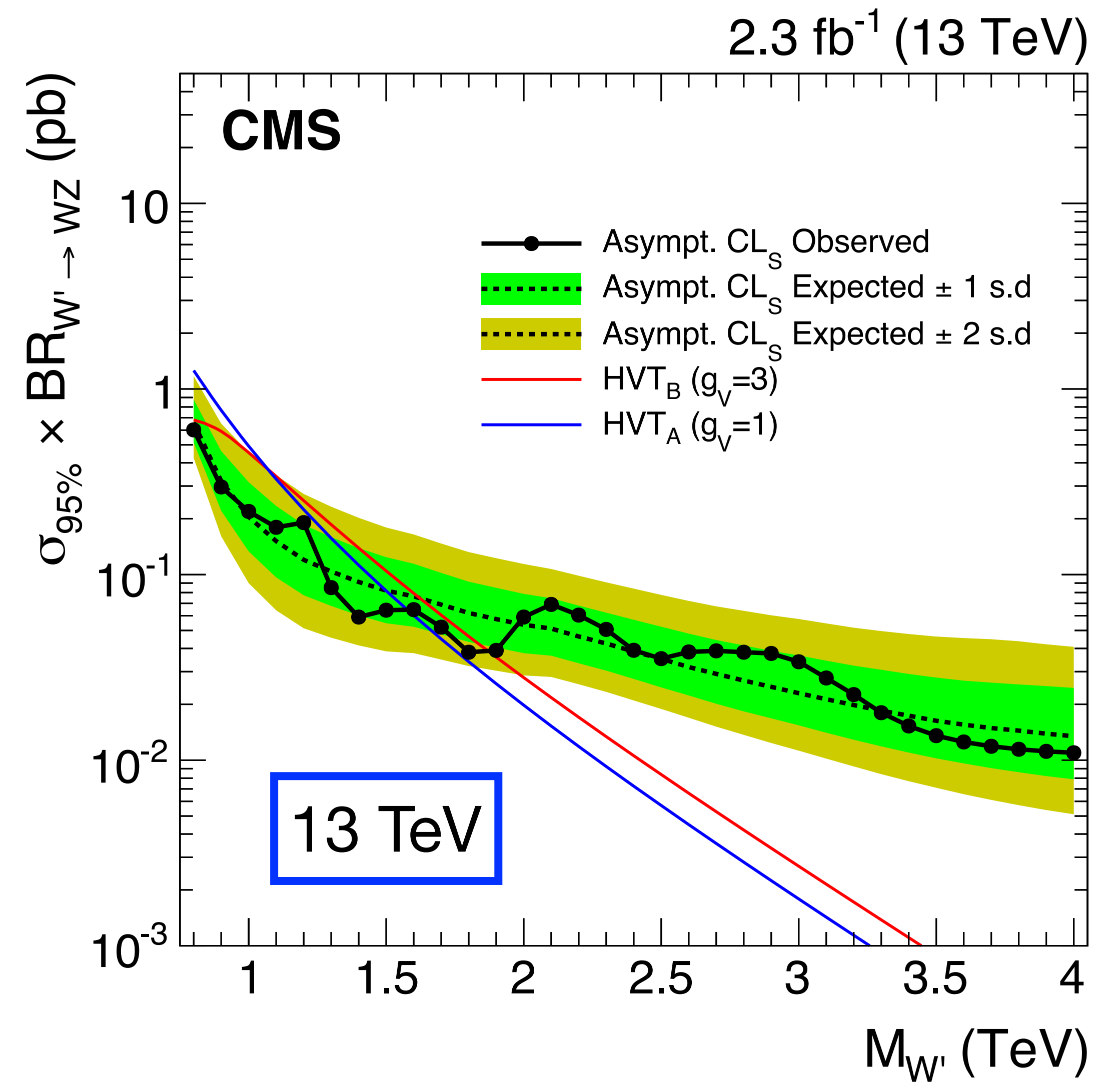
Excess at 2 TeV not confirmed!

Upper limits on the cross section

In absence of a significant excess set 95% CL upper limits on the cross section

⇒ try to exclude a new resonance up to a certain value of its mass





Limits on a W' resonance improved by 13 TeV results

8 TeV data:

exclude resonance with mass < 1.5 TeV

13 TeV data:

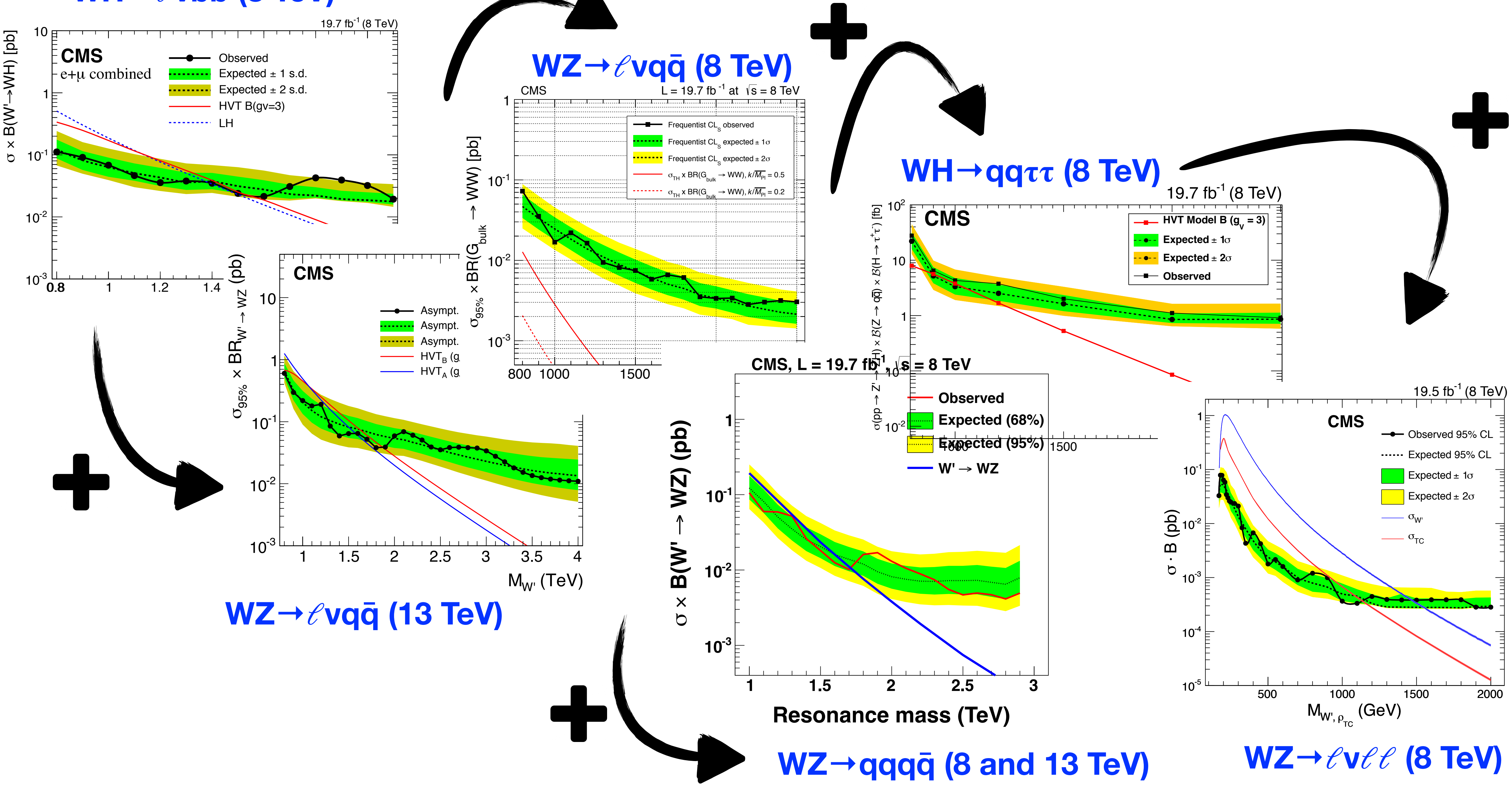
exclude resonance with mass < 1.9 TeV

Combination with other CMS searches

Excess at 2 TeV not confirmed… but we can do better!

⇒ combine all X→VV/VH CMS searches to maximize the sensitivity and obtain best limits!

WH→ℓvb$\bar{b}$ (8 TeV)



Combination with other CMS searches

Excess at 2 TeV not confirmed… but we can do better!

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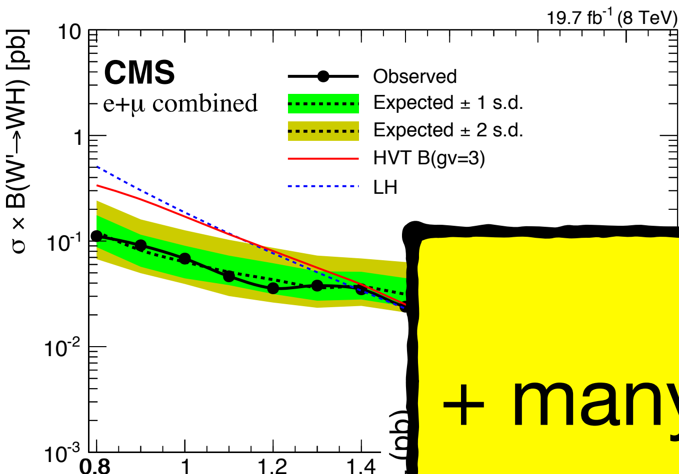
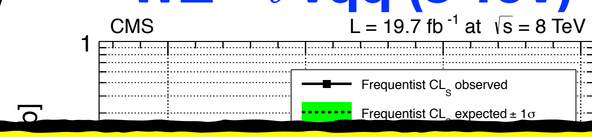
WH→ℓvb$\bar{b}$ (8 TeV)

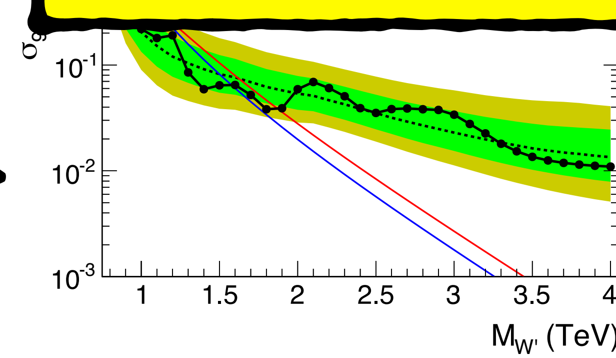


WZ→ℓvq$\bar{q}$ (8 TeV)

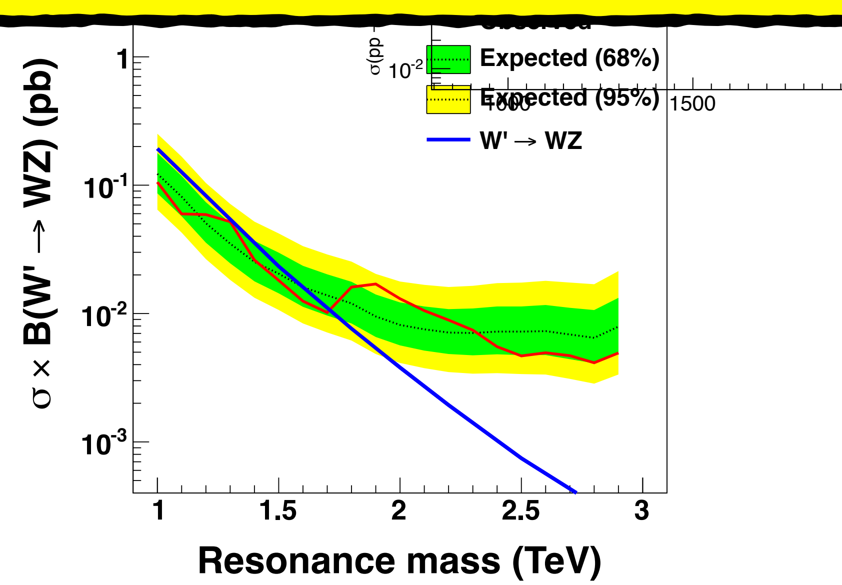


+ … + …

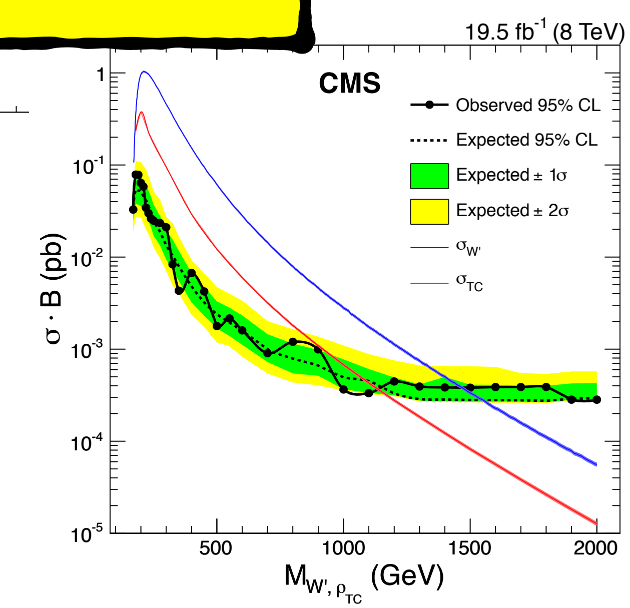
+ many other searches using the common special reconstruction and identification techniques for boosted bosons



WZ→ℓvq$\bar{q}$ (13 TeV)



WZ→qqq$\bar{q}$ (8 and 13 TeV)



WZ→ℓvℓℓ (8 TeV)

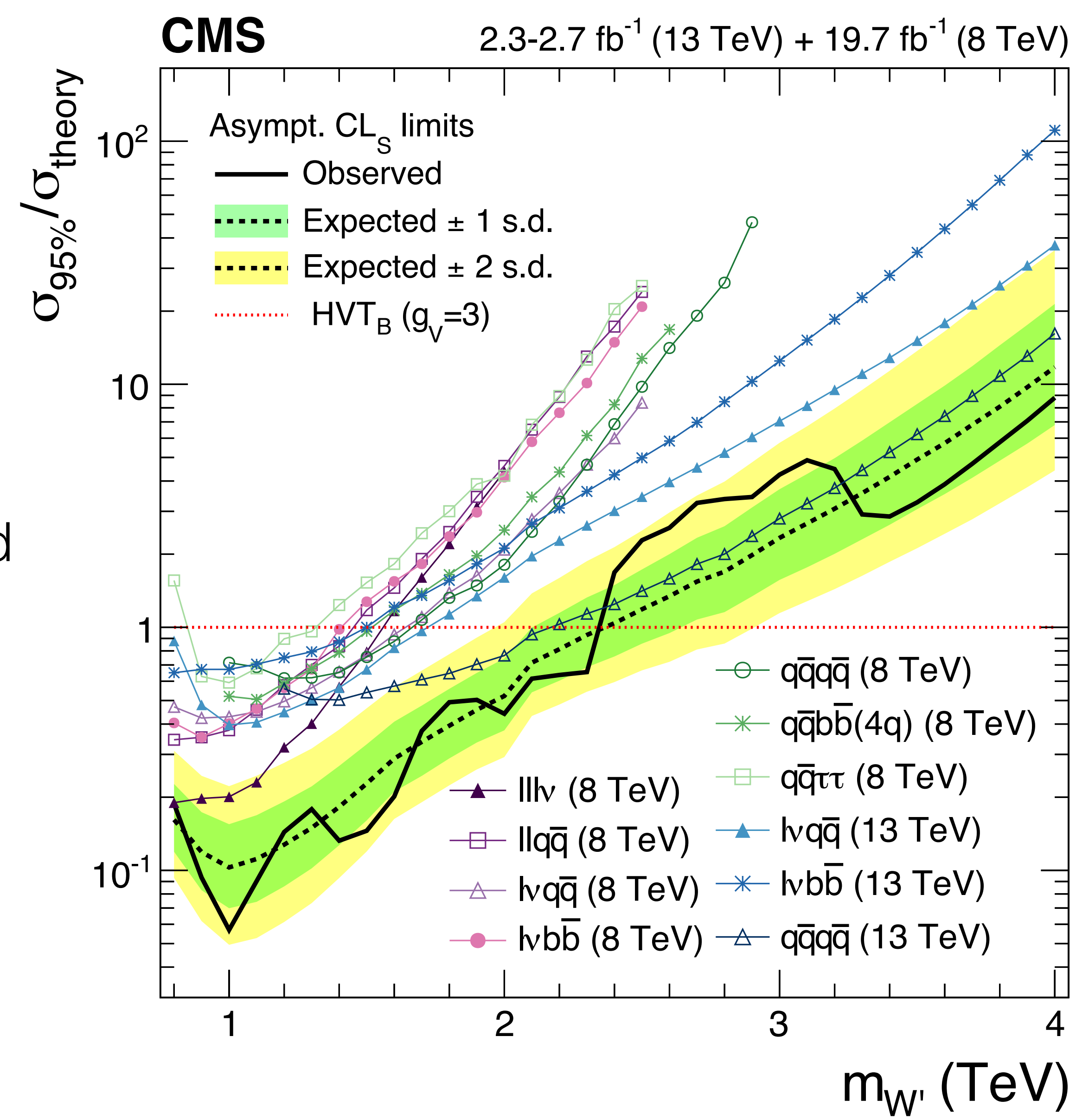
Combination with other CMS searches

- Combination performed under several benchmark models covering different spin, production, decay properties
    - most of 8 TeV analyses required re-interpretation of published results

- *First compilation of the overall experimental status of searches with boosted W, Z and Higgs bosons*

- *Overall sensitivity improved for all benchmarks:*
    - lower mass limit for a W' from 1.9 TeV → 2.3 TeV

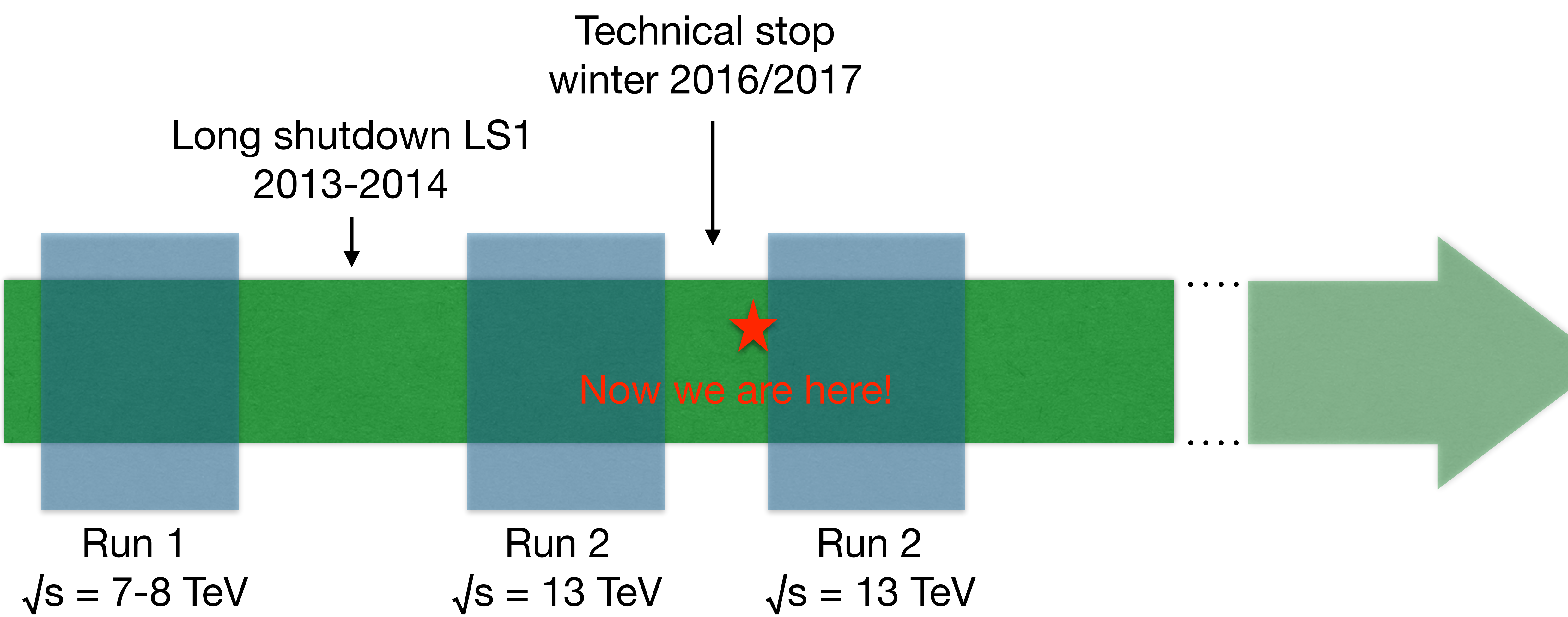
- Significance of the excess for a W' at ~ 2 TeV reduced from 2.2 to 0.8 σ → not confirmed by 13 TeV data!



Not the end of the story…

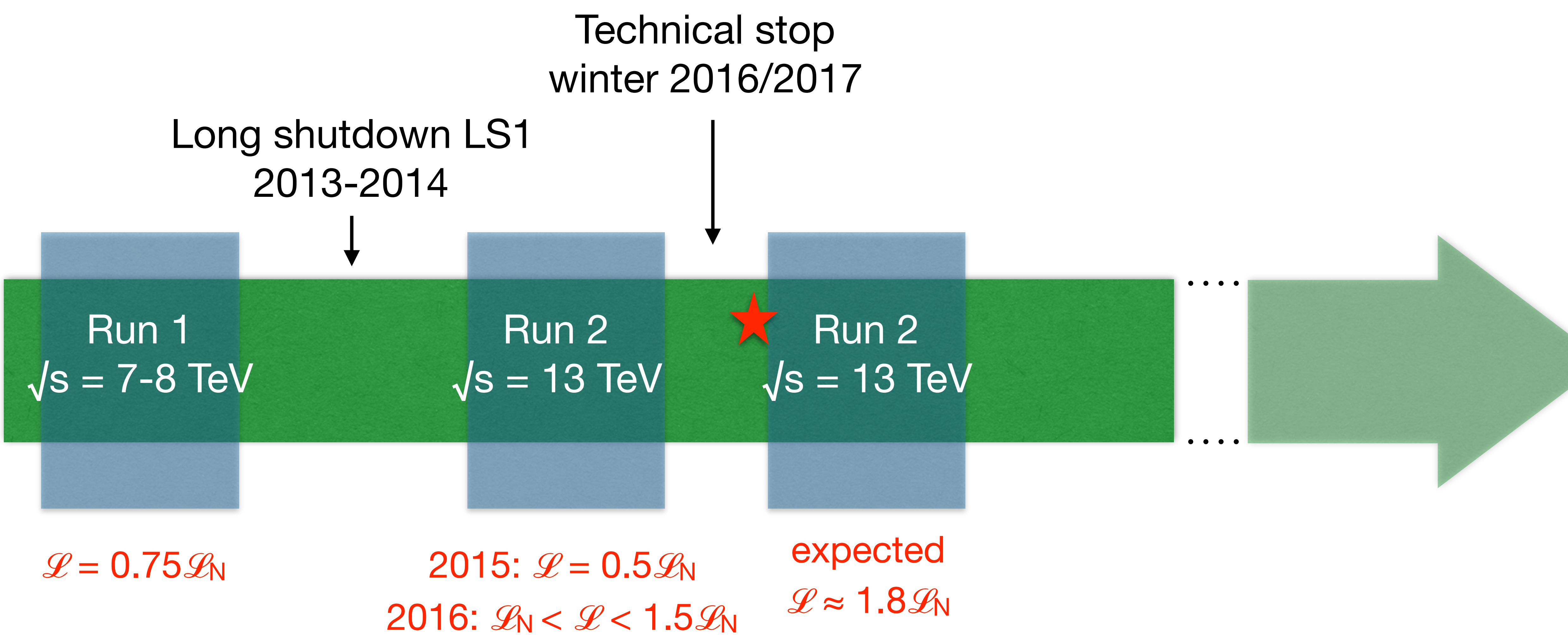
Large amount of data will be collected by the experiments in the next years

⇒ more precise measurement of the mass spectra and higher sensitivity to new signals showing up in the high-mass tails



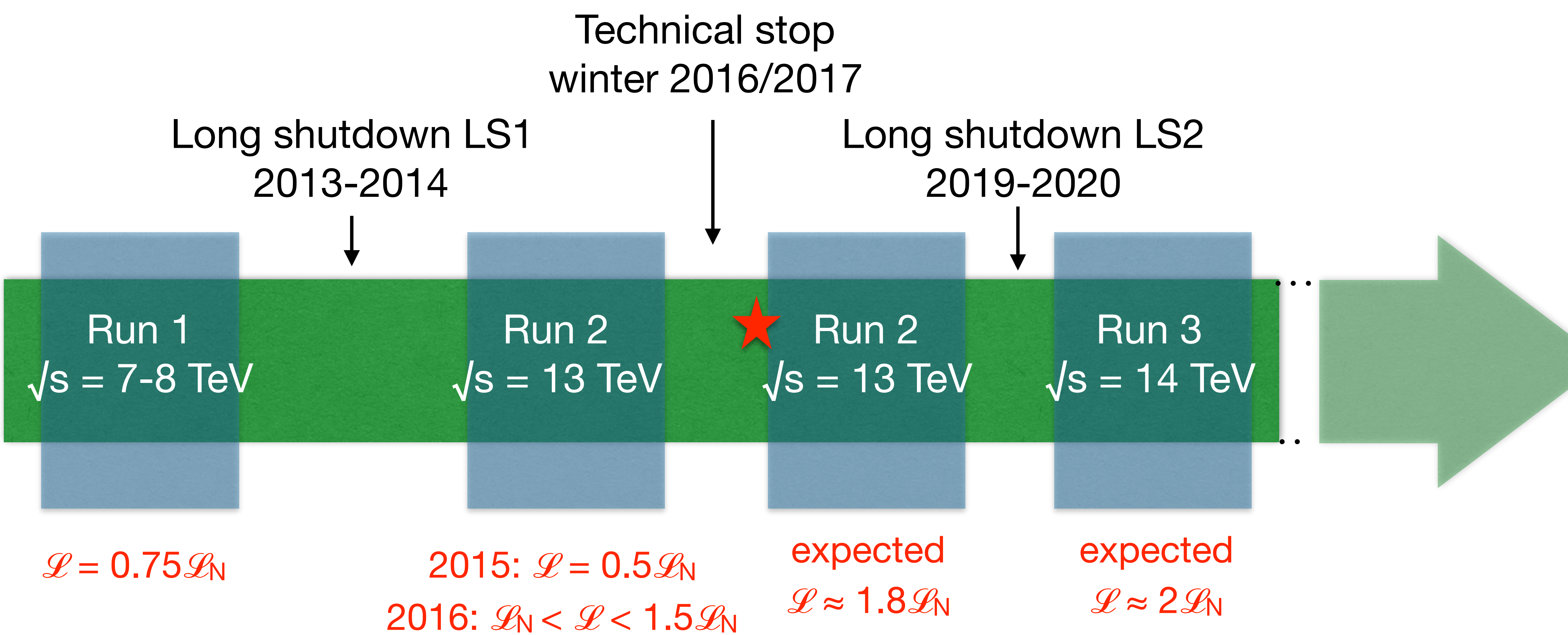
Not the end of the story…

Event rates and pileup $\propto$ instantaneous luminosity $\Rightarrow$ nominal LHC value: $\mathscr{L}_N = 1\text{x}10^{34}\ \text{cm}^{-2}\text{s}^{-1}$



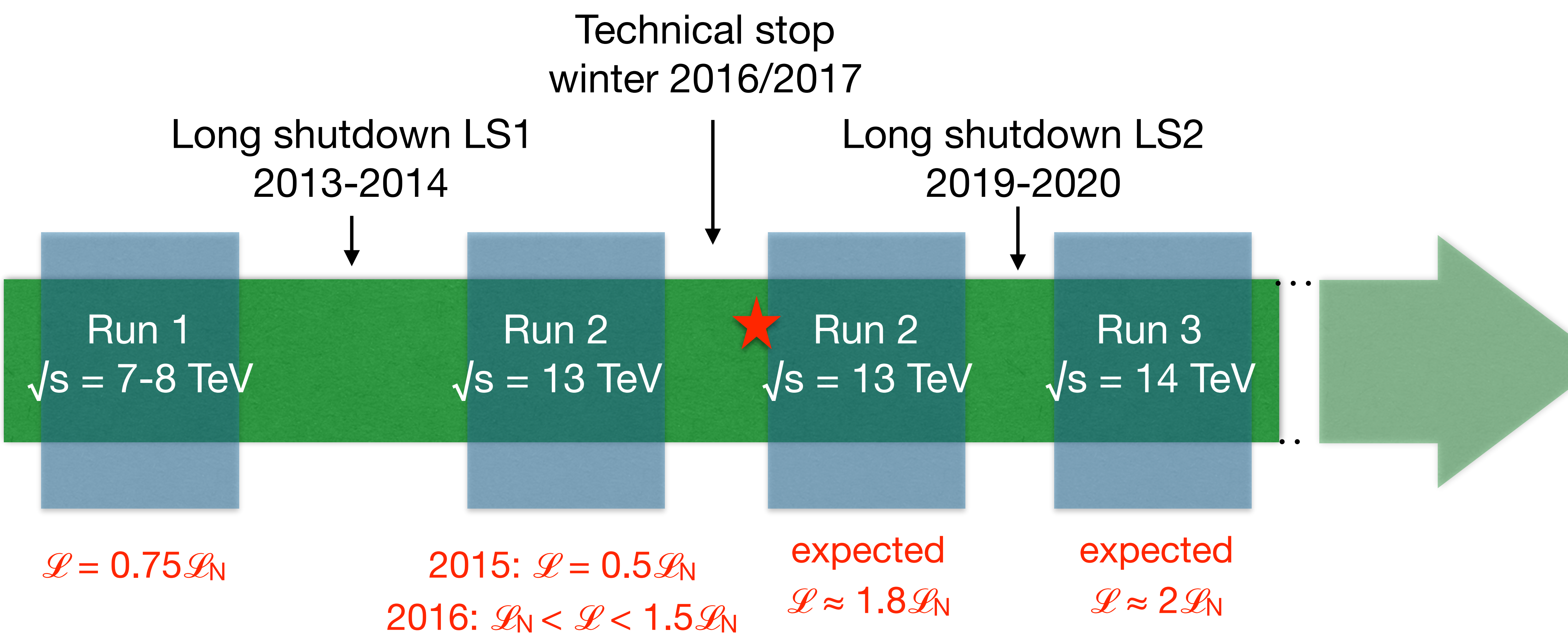
Not the end of the story…

Event rates and pileup ∝ instantaneous luminosity ⇒ nominal LHC value: $\mathscr{L}_N = 1\mathrm{x}10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



Not the end of the story…

Event rates and pileup ∝ instantaneous luminosity ⇒ nominal LHC value: $\mathscr{L}_N = 1\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$



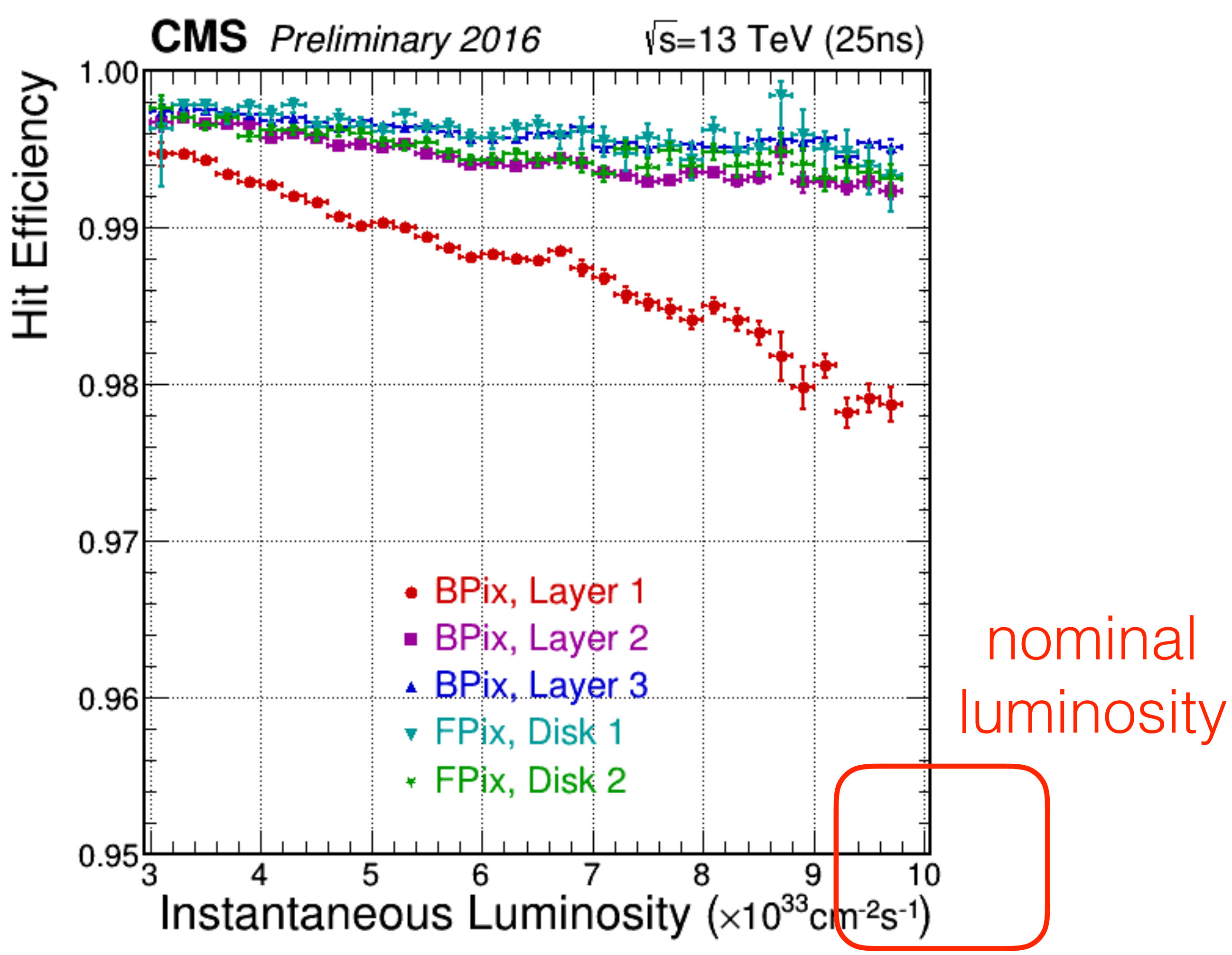
⇒ important to keep the excellent performance of the CMS detector!

CMS pixel & LHC schedule

Original pixel detector not designed for the high luminosities expected in the next years

→ high track density, trigger rates, pileup and radiation doses

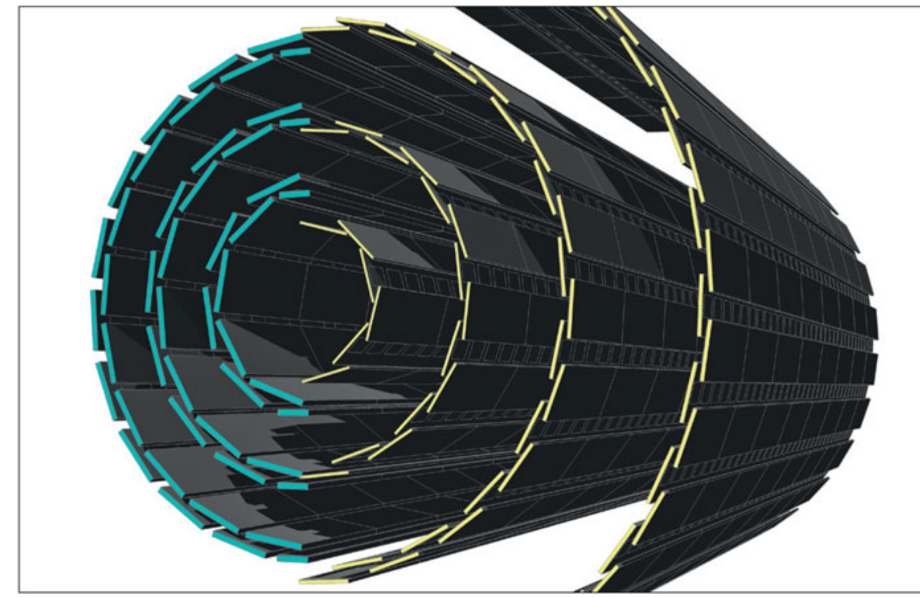
→ degradation of pixel hit efficiency and resolution



Pixel Phase 1 Upgrade

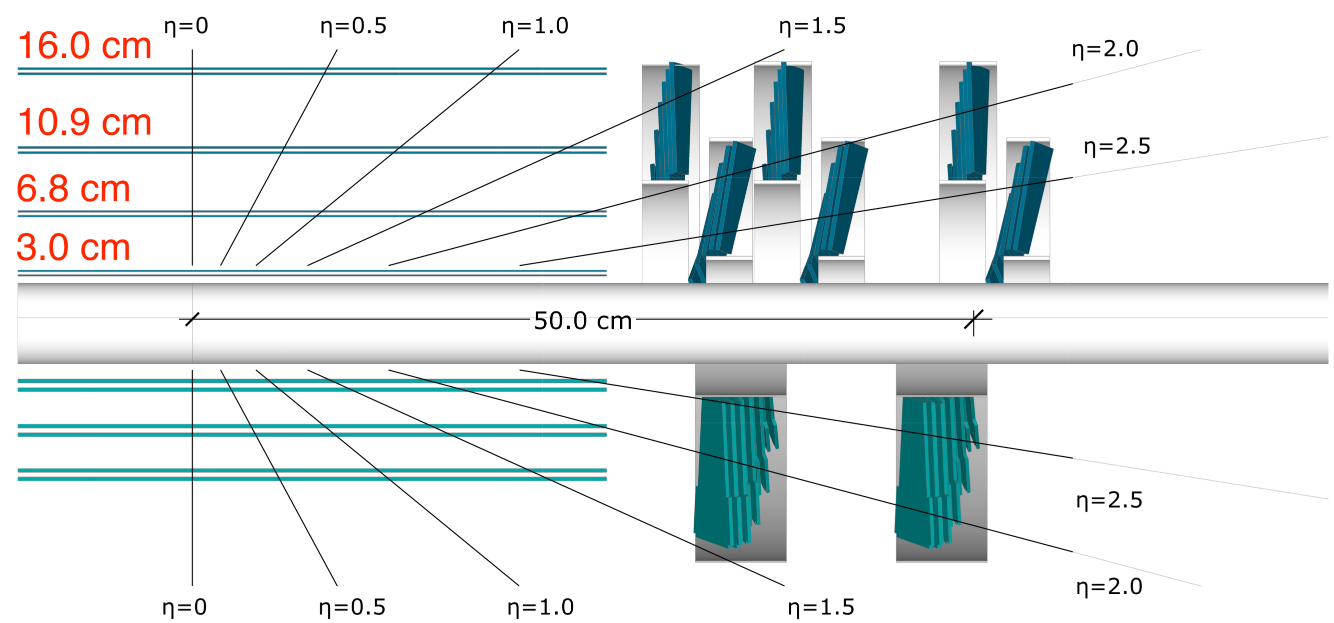
Planned upgrade of the pixel detector

→ keep and even improve level of performance under the upcoming harsh LHC conditions

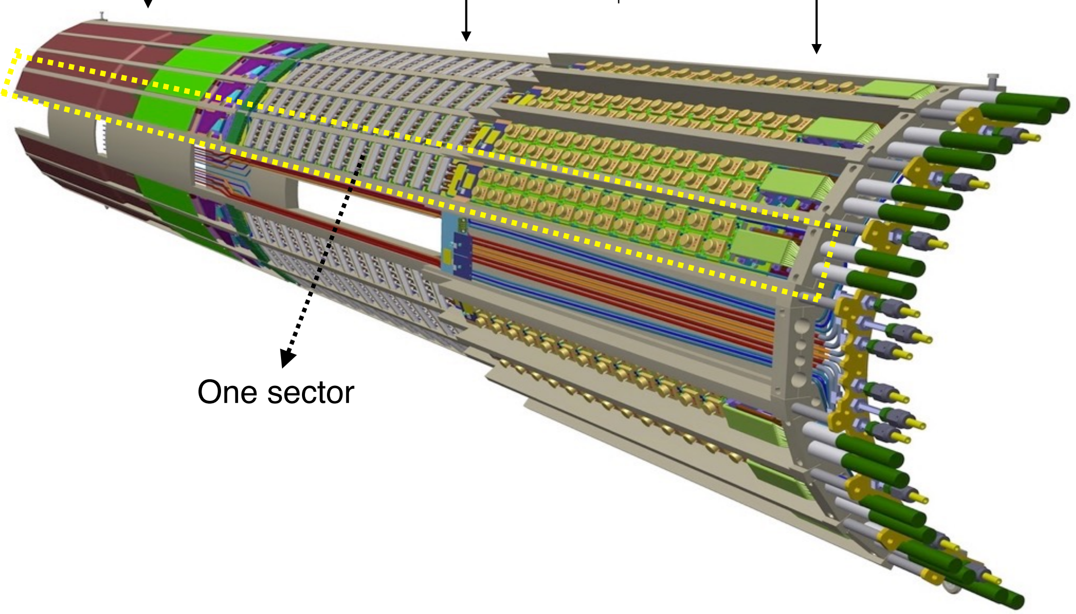


Main new features:

- Improved track reconstruction by adding a new layer (3 → 4)
- Improved track impact parameter resolution by moving first layer closer to the beam (4 cm → 3 cm)
- Further tracking improvements thanks to optimized engineering of mechanical design and services → reduction of passive material
- developed faster front-end electronics with low dead time
  - increased data buffer size
  - from 40 MHz analog readout ➔ to 400 Mb/s digital readout

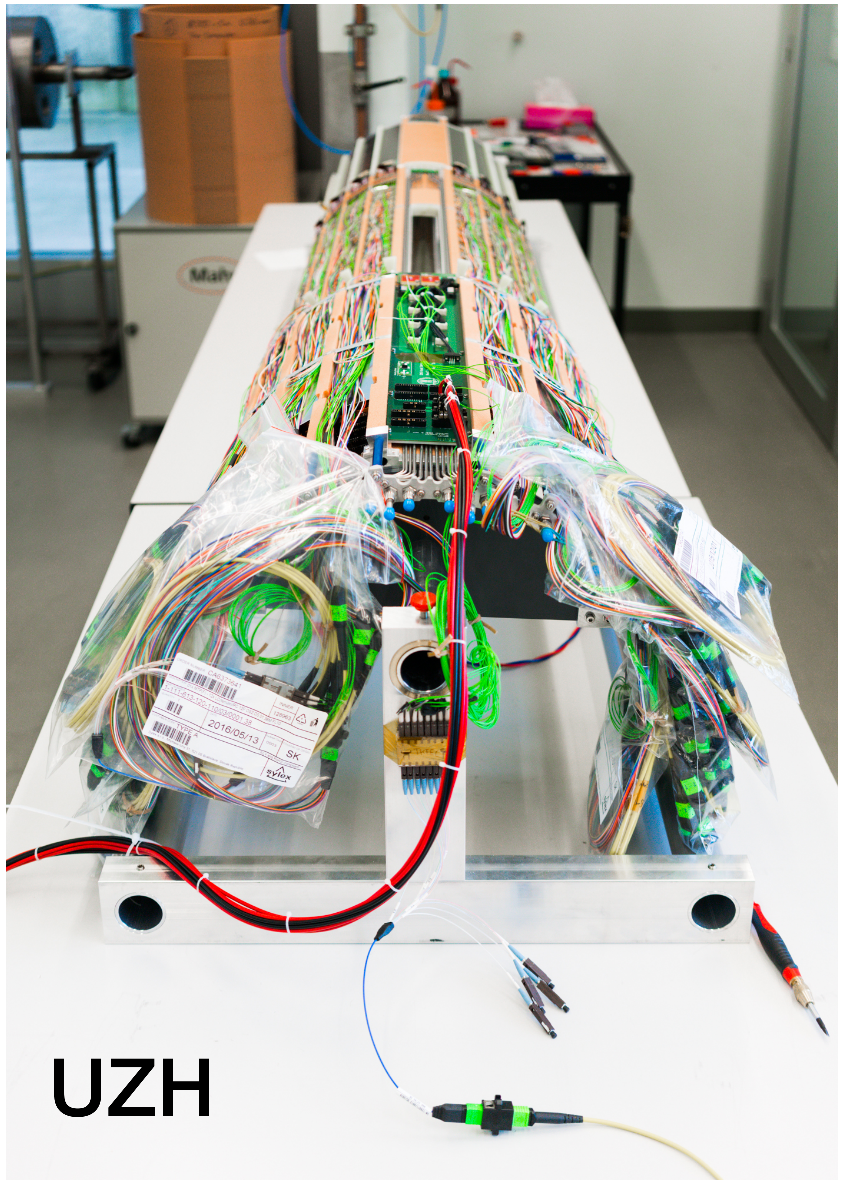


UZH responsibilities



4 supply tubes carry the services along the beam pipe:

- cooling lines
- power converters and distribution
- electronics for detector readout and control

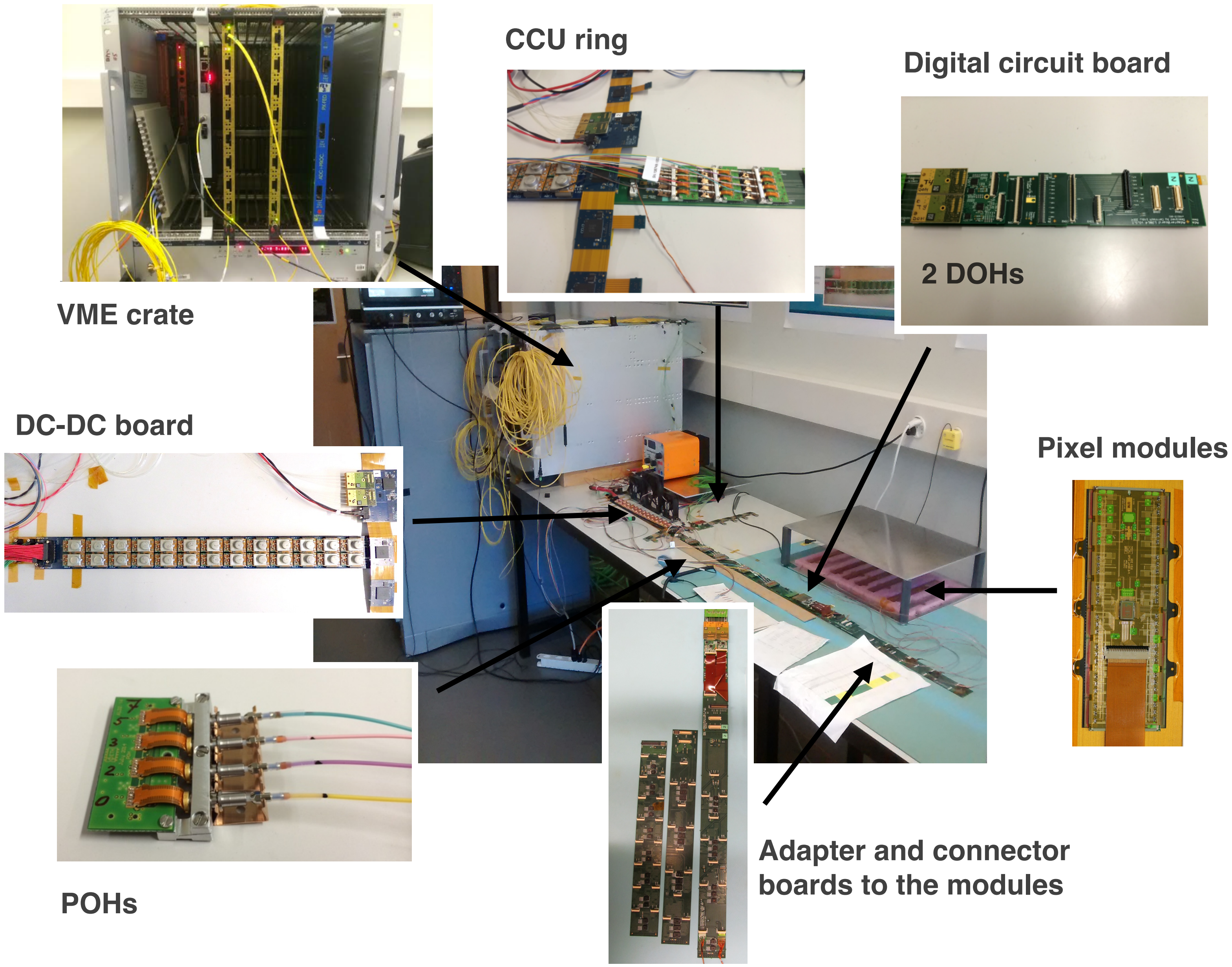


The University of Zurich was responsible for design, construction, integration and testing of the supply tubes

Very nice work! :)

major effort of
Lea Caminada, Peter Robman, Benjamin Kilminster,
Florencia Canelli, Riccardo del Burgo,
Yuta Takahashi, Alberto Zucchetta

Test stand at UZH



Test stand set up at UZH in 2014:

- evaluate all upgrade detector components prior to full production
- establish test and calibration procedures for detector assembly and commissioning

- Contributed to the integration of the test system setup and implemented some of its functionalities
- Employed the system to develop brand new calibration procedures required to operate with the upgrade digital readout and new detector components

Summary

- Searches for diboson resonances decaying into a pair of W, Z and Higgs bosons allow new natural theories to be directly probed at the LHC

- Lepton+jet final states provide high sensitivity to the search:

  - ***WH → $\ell\nu b\bar{b}$ and WZ/WW → $\ell\nu q\bar{q}$ decay channels probed***

- Nothing found so far in $\sqrt{s}$ = 8 TeV and 13 TeV data… but more data coming!

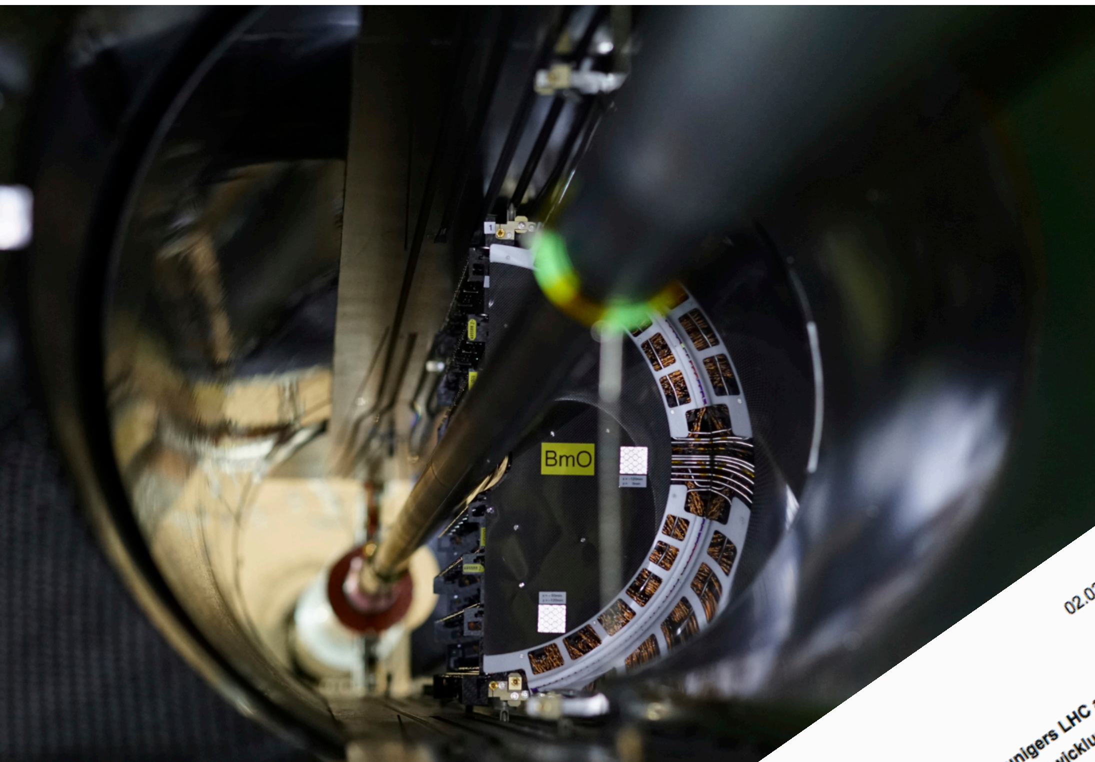
- In addition to more data, it is important to keep the excellent performance of the CMS detector to search for new and rare physical phenomena

- Contributions have been made to ***optimize the CMS pixel sub-detector performance*** for the restart of pp collisions at $\sqrt{s}$ = 13 TeV

- Moreover, ***the new upgrade pixel detector necessitate new calibration procedures***

  - aimed at ensuring the ability of the detector to collect pixel hits in pp collisions

Upgraded detector just installed!



Watch the video
https://www.youtube.com/watch?v=rBTx1JMGFtQ&feature=youtu.be

Looking forward to start taking data this summer!

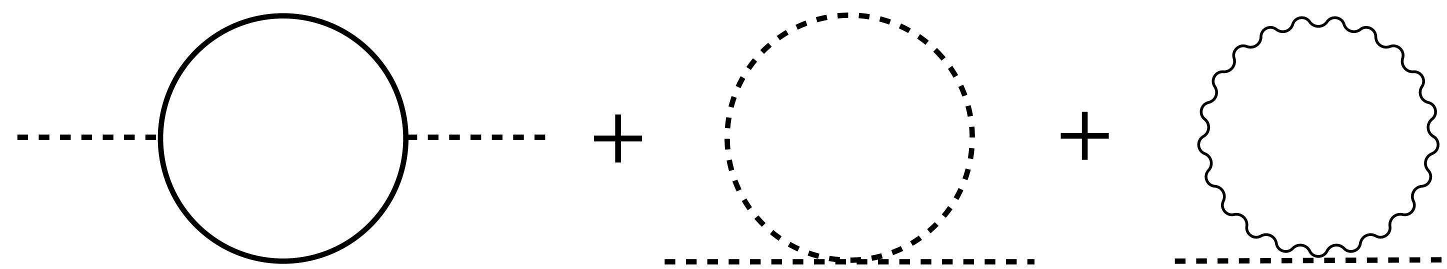
Backup

Need for beyond standard model

The hierarchy problem

physical value

t H W/Z

$(125\ \mathrm{GeV})^2 = m_H^2 -$ 

tree-level mass
fundamental parameter
of the theory

top quark loop

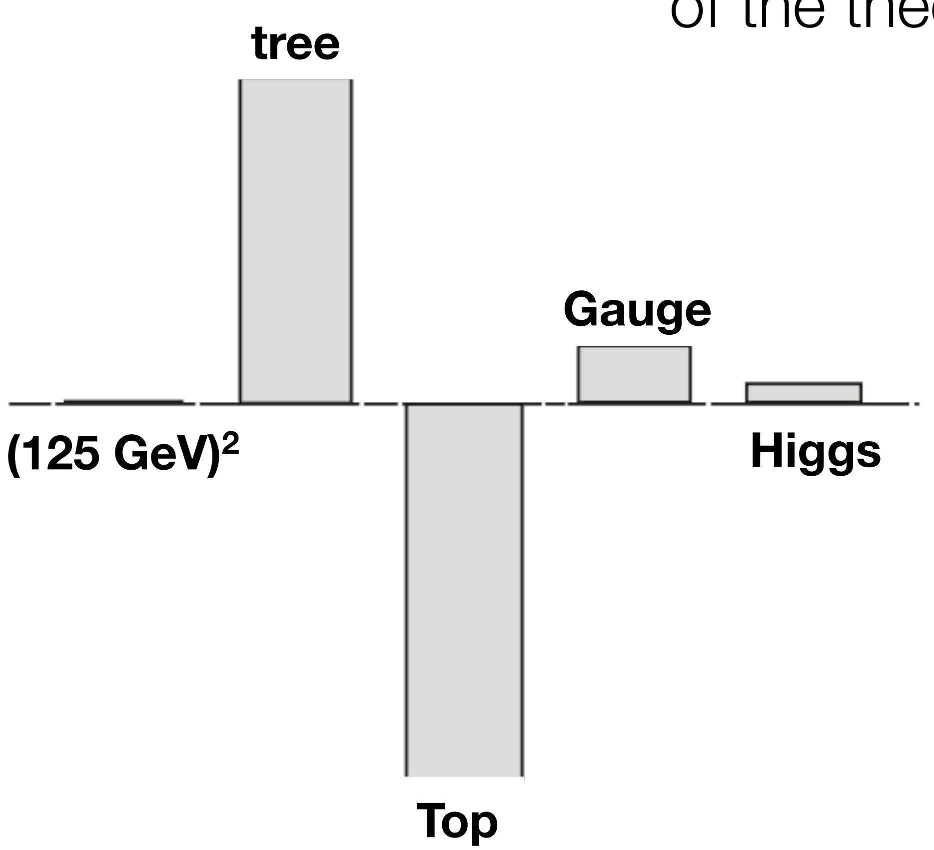
Higgs boson loop

gauge boson loop

quantum corrections = $\delta m_H^2 \propto \Lambda^2$

with Λ = cut-off scale at the Planck mass = $O(10^{19})$

… this large fine tuning seems “unnatural”!



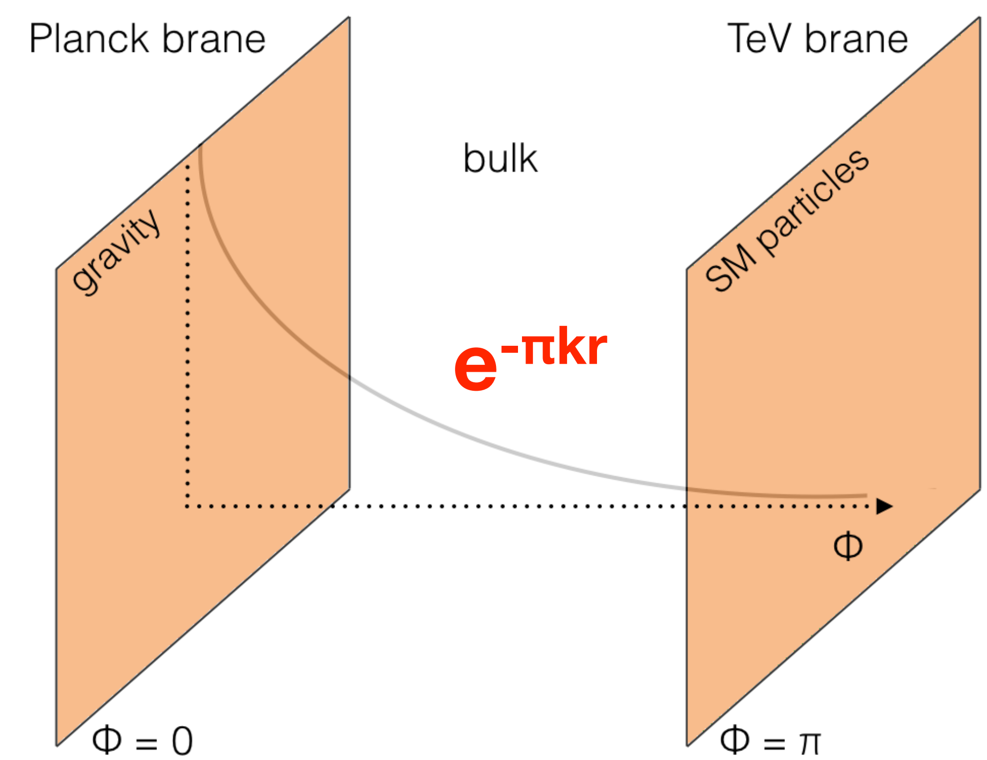
New “natural” theories

Warped extra dimensions (Randall-Sundrum model)

- RS1 model with 1 extra dimension Φ
- Two 4D surfaces:
  - Planck brane (Φ=0) → gravity is strong
  - TeV brane (Φ=π) → SM particles live here
- Physical masses and scales in 4D related to 5D fundamental values by exponential factor:

$$e^{-\pi kr}$$

$\Longrightarrow$ with kr ~ 12



k = curvature of the 5th dimension
r = radius of the 5th dimension

Electroweak scale = 10^2 GeV ~ $e^{-\pi kr}$ x (planck scale) = $e^{-\pi kr}$ x 10^{19} GeV

(4D physical scale) (5D fundamental scale)

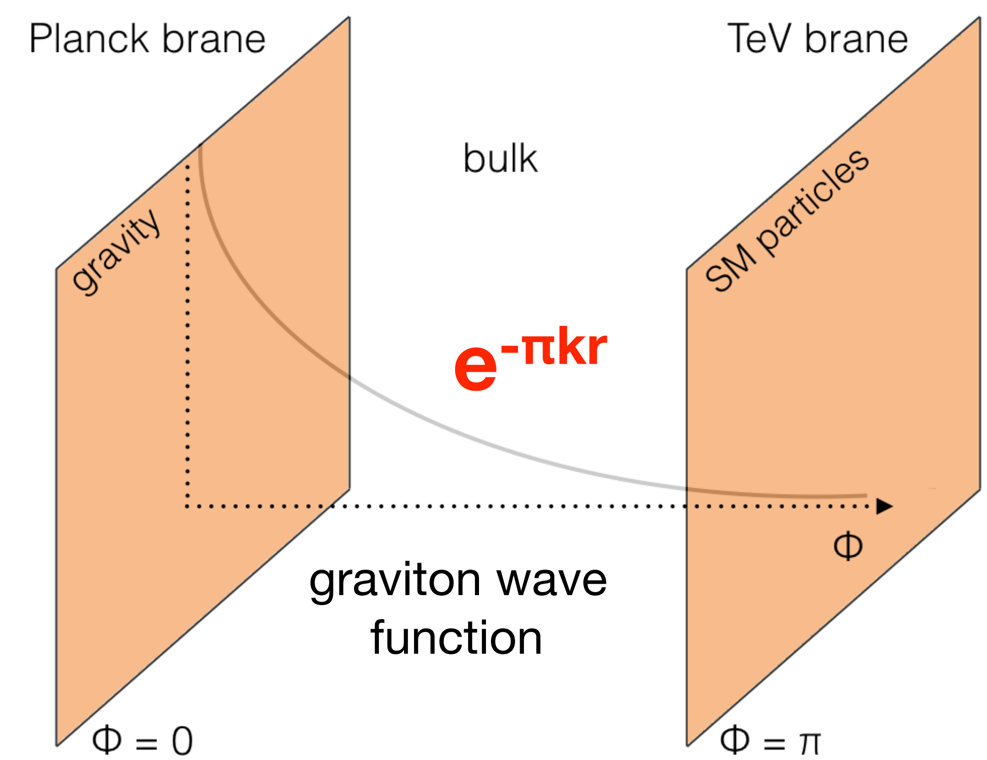
New “natural” theories

Warped extra dimensions

[Randall-Sundrum RS1 model: PRL 83 (1999) 3370)]

why gravitational force 10^{24} times weaker than the electroweak? ⇒ “unnatural”

- we live in a warped 5-dimensional universe
- gravity propagates in the extra dimension
- gravity is weak from a 4D point of view
- fundamental scales and masses are the 5D values
- predict Kaluza-Klein excitations of a *spin-2 graviton*



Bulk graviton model

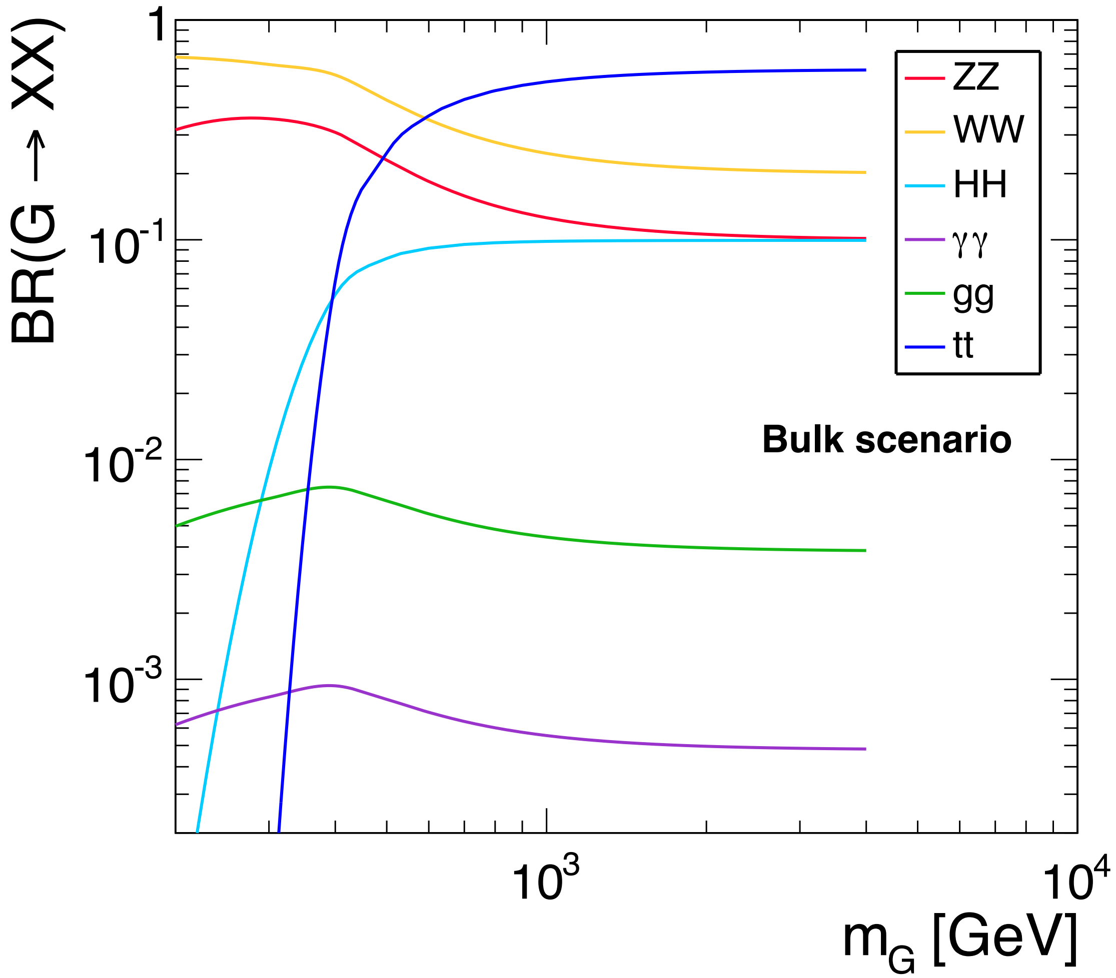
- extension of the original RS1 model
- allow SM fields to propagate in the extra dimension
- justify different Yukawa couplings of the Higgs boson
- dominant branching ratios of the graviton to a pair of SM bosons (WW,ZZ,HH)

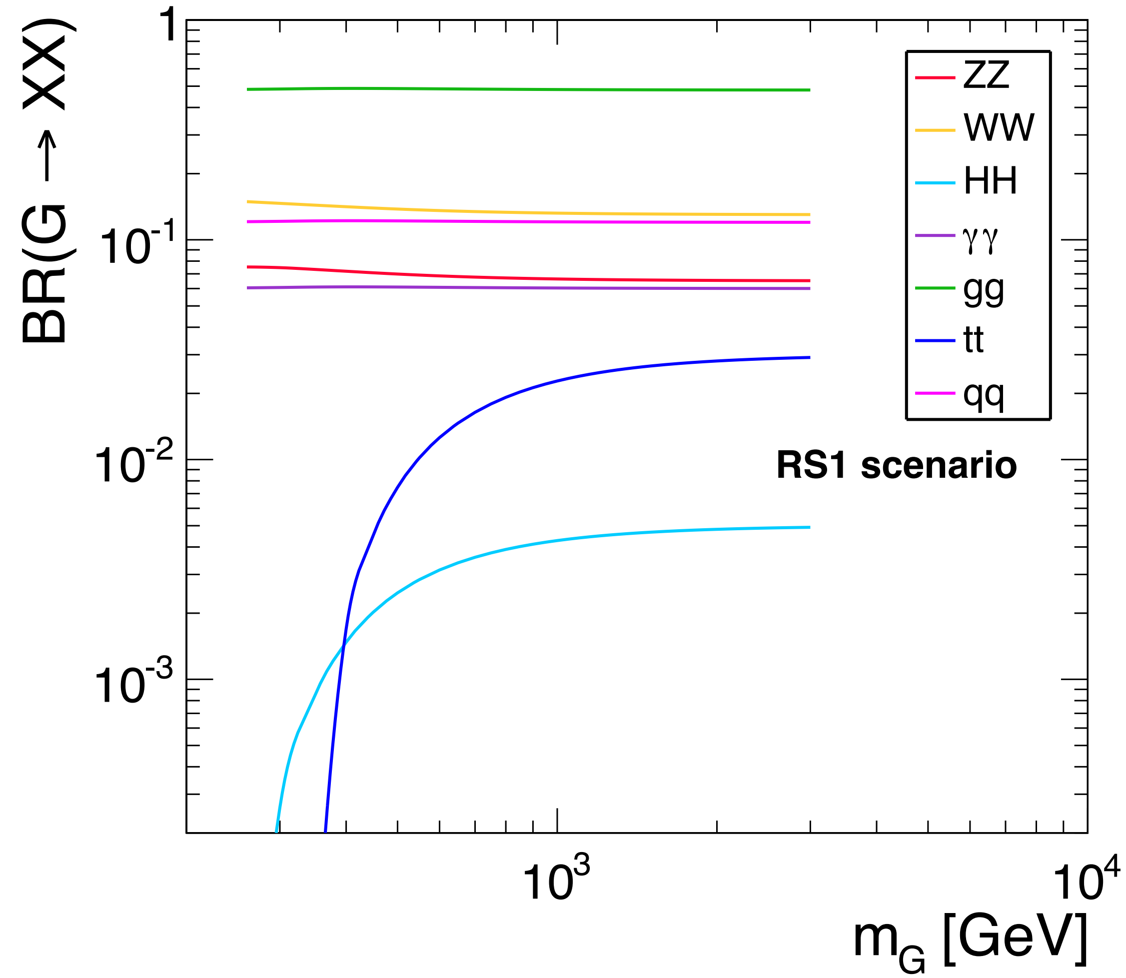
Bulk graviton decays

$G \to \gamma\gamma$
$G \to qq/gg$
$G \to \ell\ell$
} suppressed decays

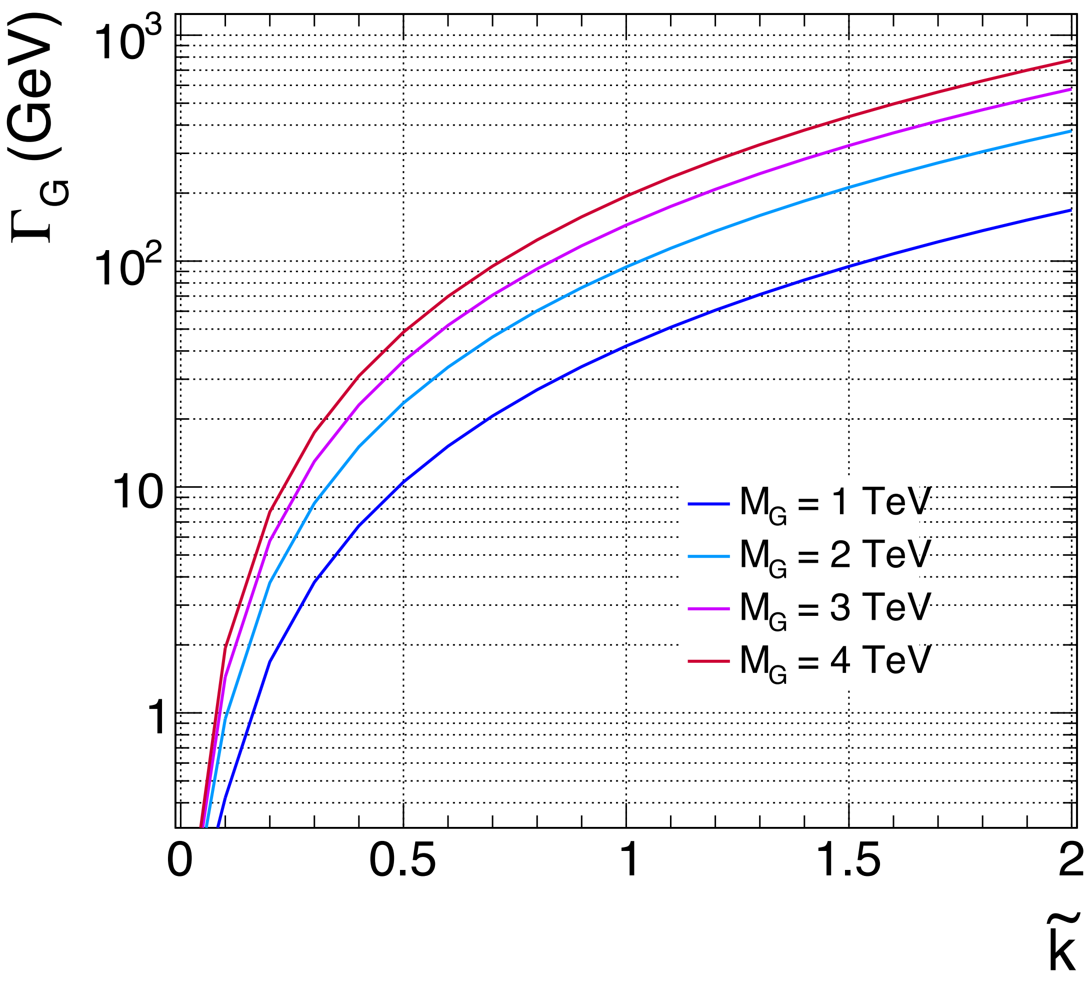
$G \to t\bar{t}$
$G \to HH$
$G \to WW/ZZ$
} enhanced decays

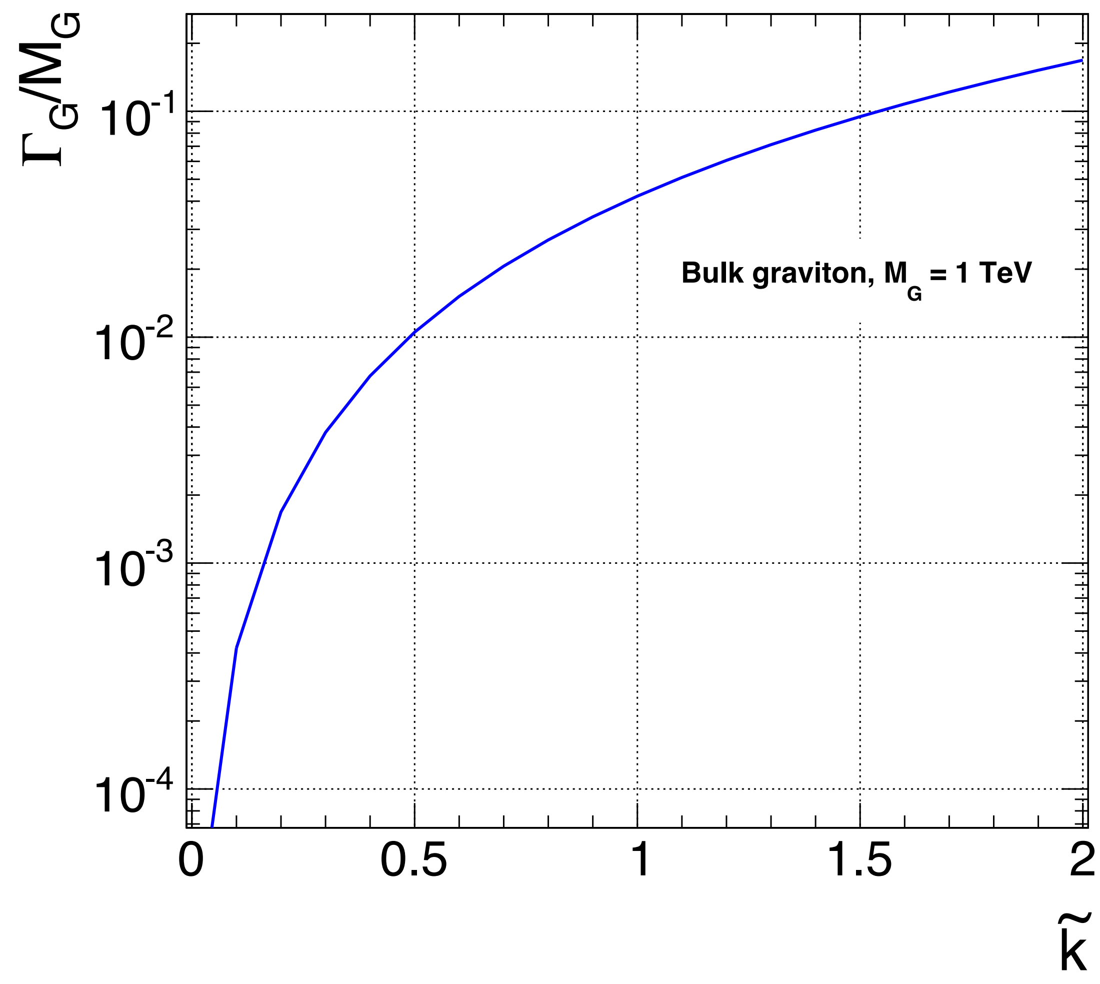
Warped extra dimensions





Warped extra dimensions





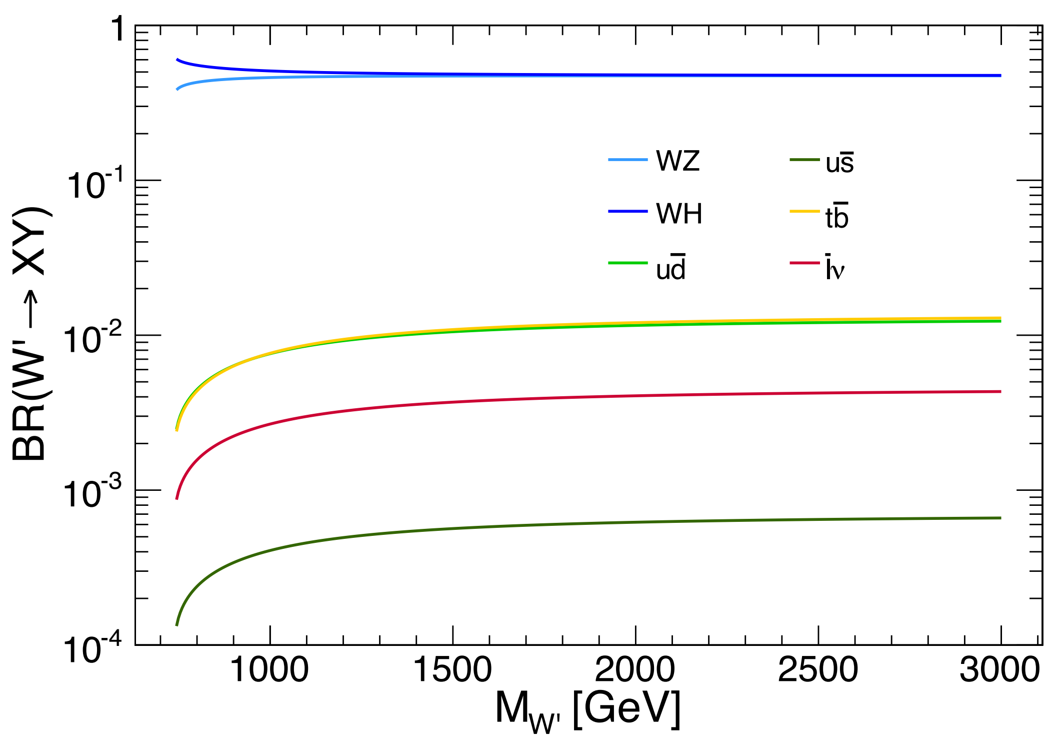
JHEP 09 (2014) 060
(Torre, Wulzer, Pappadopulo, Thamm)

Heavy Vector Triplet

- A simplified Lagrangian has been proposed describing the production and decay of spin-1 heavy resonances such as the charged W' and neutral Z'
- It describes a large class of models in terms of only four parameters
  - g_V = interaction strength
  - c_H = coupling of the resonance to Higgs and vector bosons
  - c_F = coupling to fermions
  - $M_{V'}$ = mass of the new resonance
- Main production mechanism for most of the parameter space: quark annihilation
- Model B: suppressed coupling to fermions and dominant BRs to VV (ex: Composite Higgs)
- Model A: similar BRs to fermions and V's (ex: weakly coupled resonances as in SSM)

BR(W'→XY) in model B

($g_V = 3$, $c_H = -1$, $c_F = 1$)



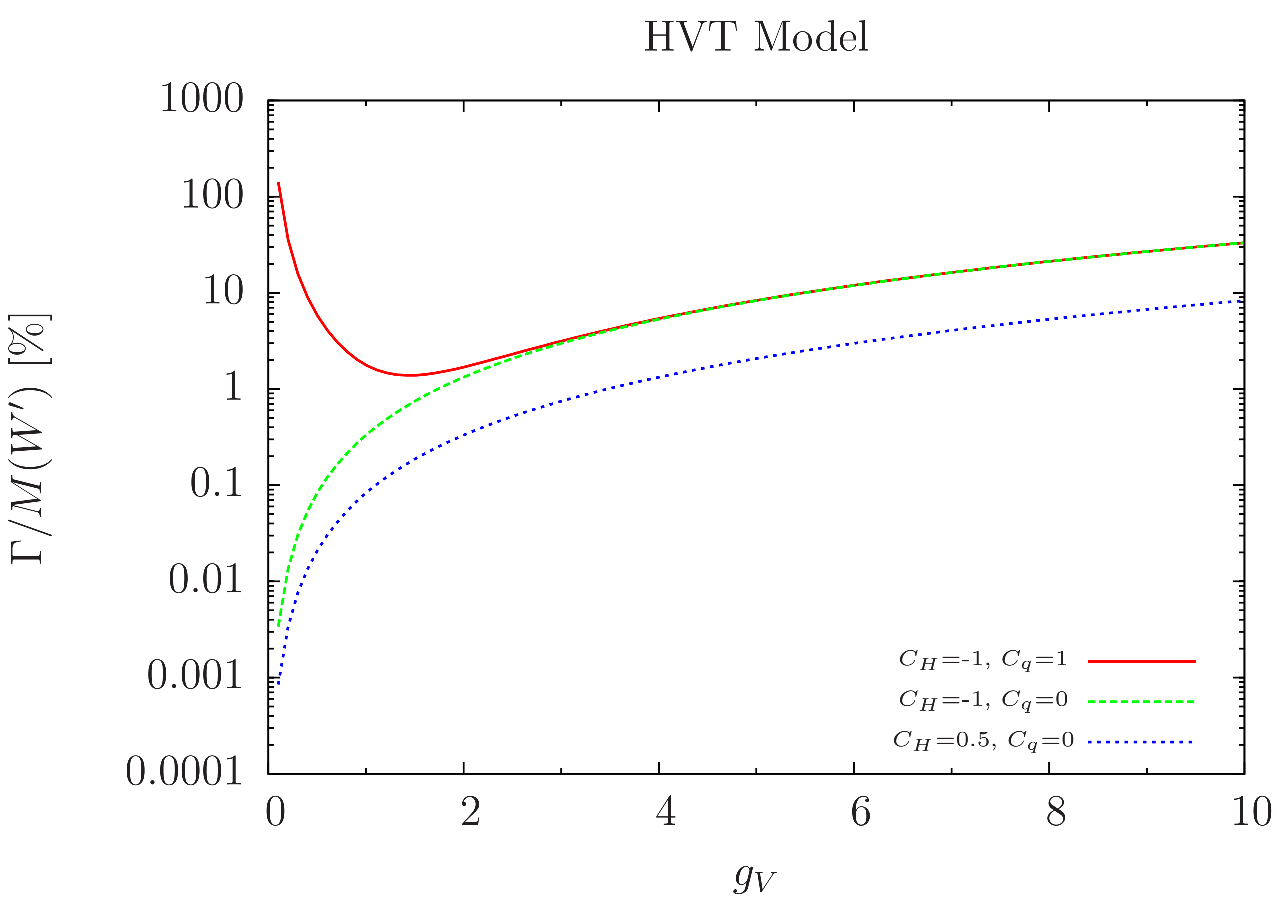
- Important features: ⟶
  - $M(X^\pm) \approx M(X^0)$
  - $BR(X^\pm \to WZ) \approx BR(X^\pm \to WH) \approx BR(X^0 \to WW) \approx BR(X^0 \to ZH)$
  - $\sigma(X^\pm) \approx \sigma(X^0)$

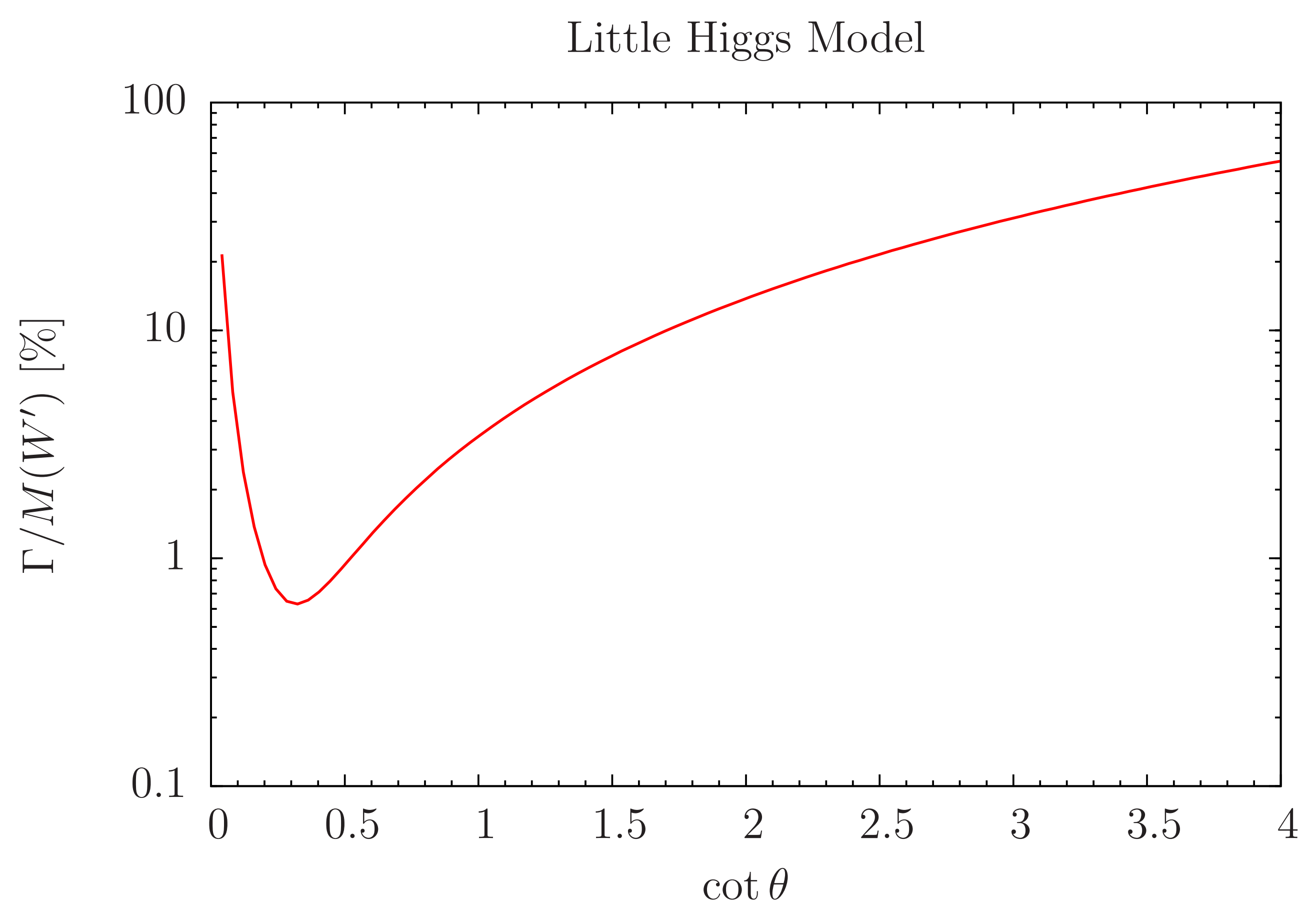
HVT and Little Higgs models

Model B:
$g_V = 3$, $c_H = -1$, $c_F = 1$

Model A:
$g_V = 1$, $c_H = -0.6$, $c_F = 1.3$

Chosen parameters:
$\cot 2\theta = 2.3$, $\cot\theta = -0.2$





Relative width less than 5% for:

$0.95 < g_V < 3.76$, $c_H = -1$, $c_F = 1$

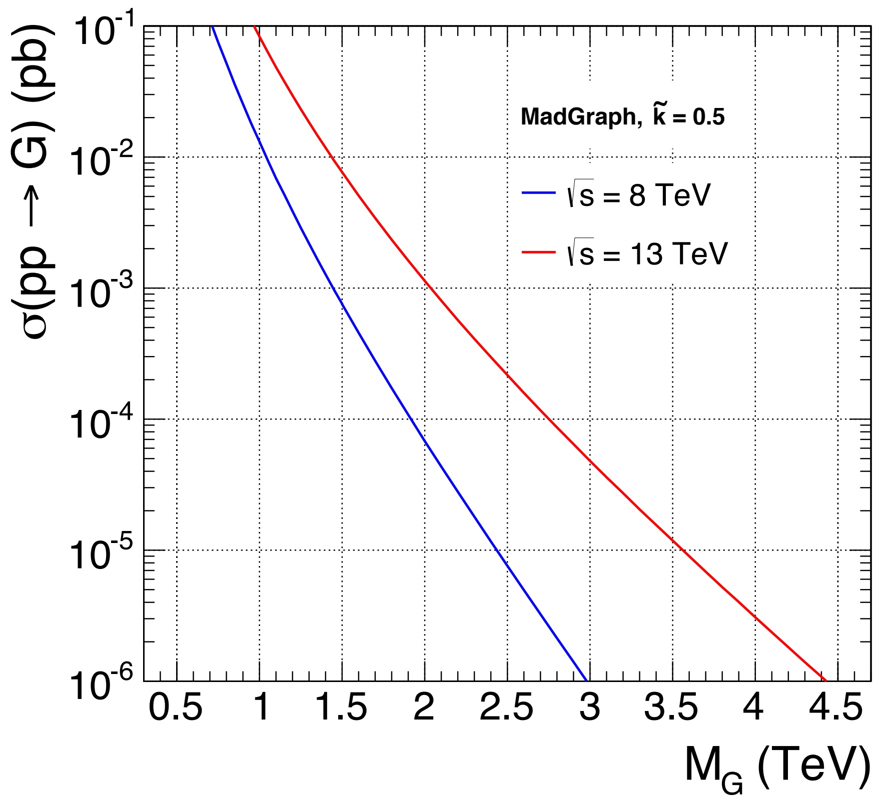
$g_V < 3.9$, $c_H = -1$, $c_F = 0$

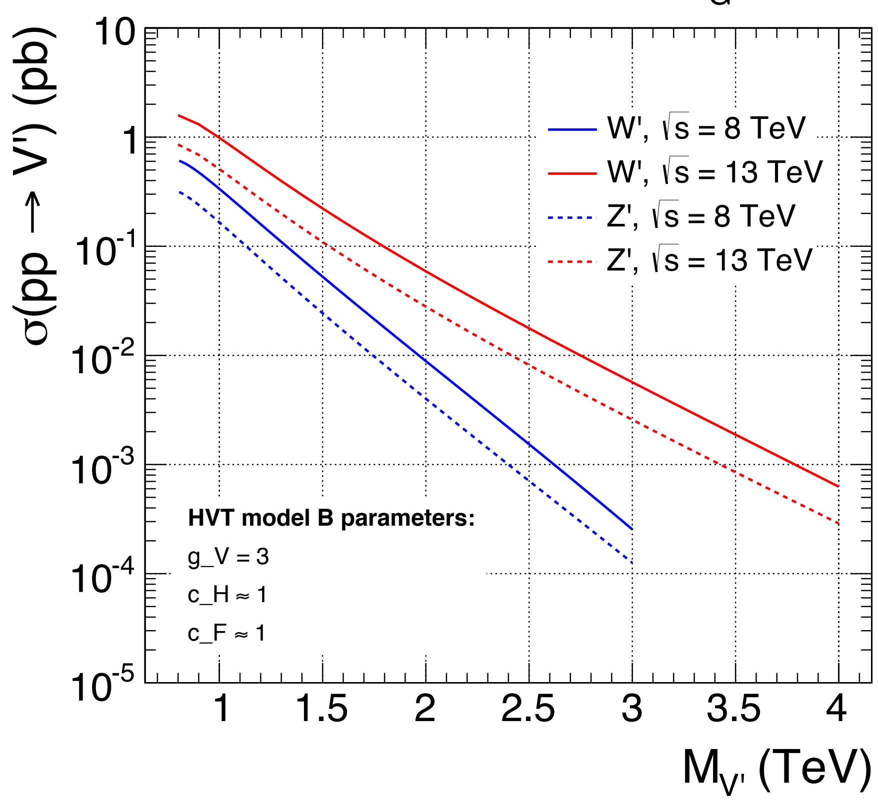
$g_V < 7.8$, $c_H = 0.5$, $c_F = 0$

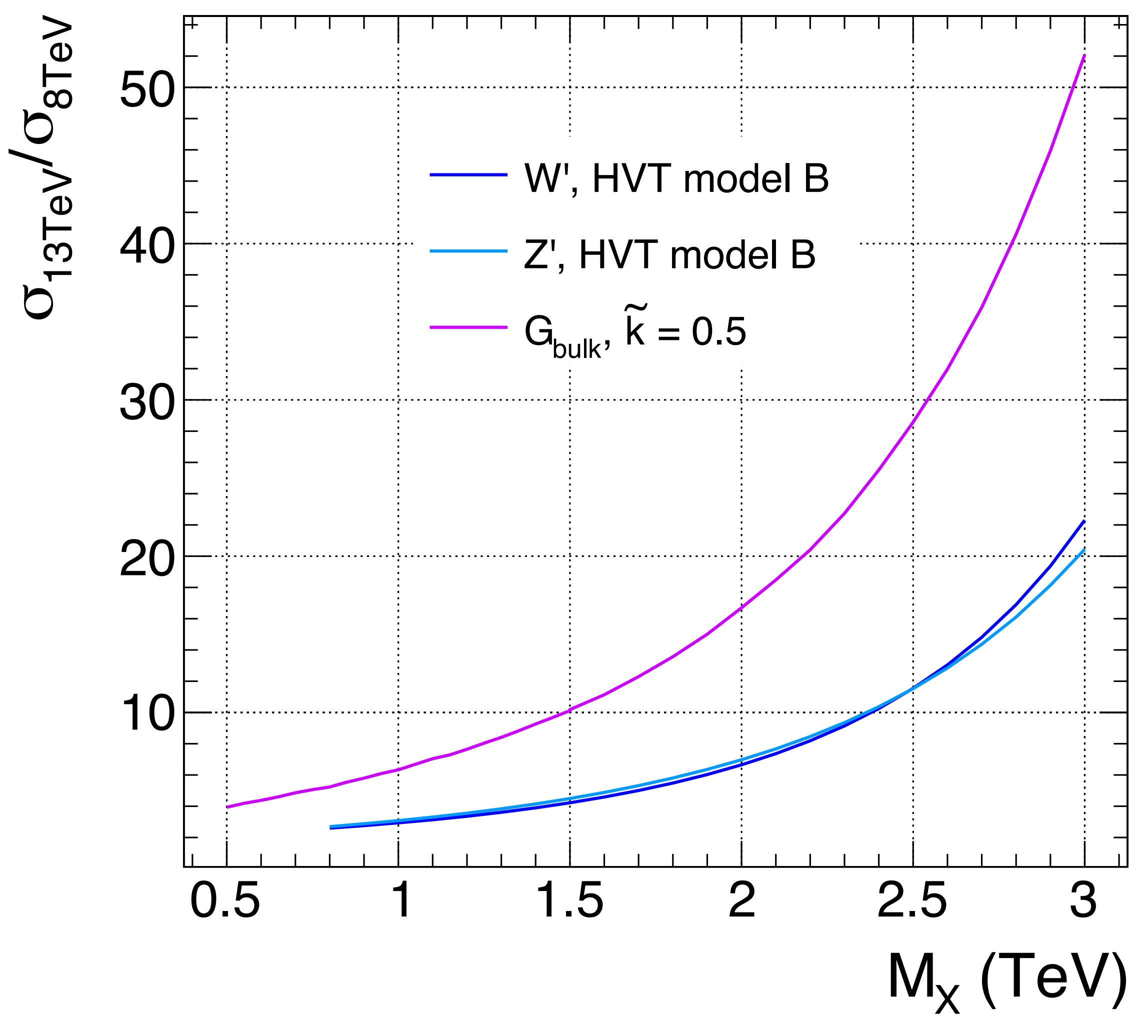
Relative width less than 5% for:

$0.084 < |\cot\theta| < 1.2$

Cross sections







Phys.Rev.D 80 051501
arxiv.0912.0033

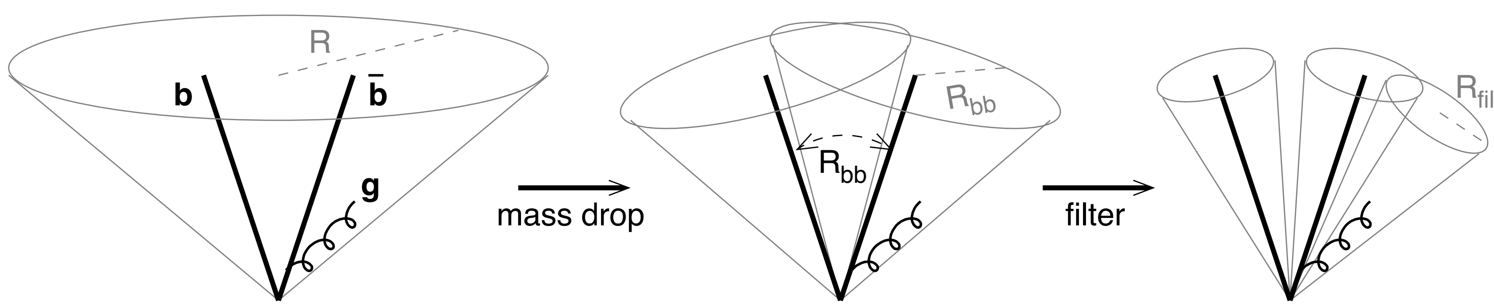
Resolving jet substructure (I)

Jet pruning algorithm

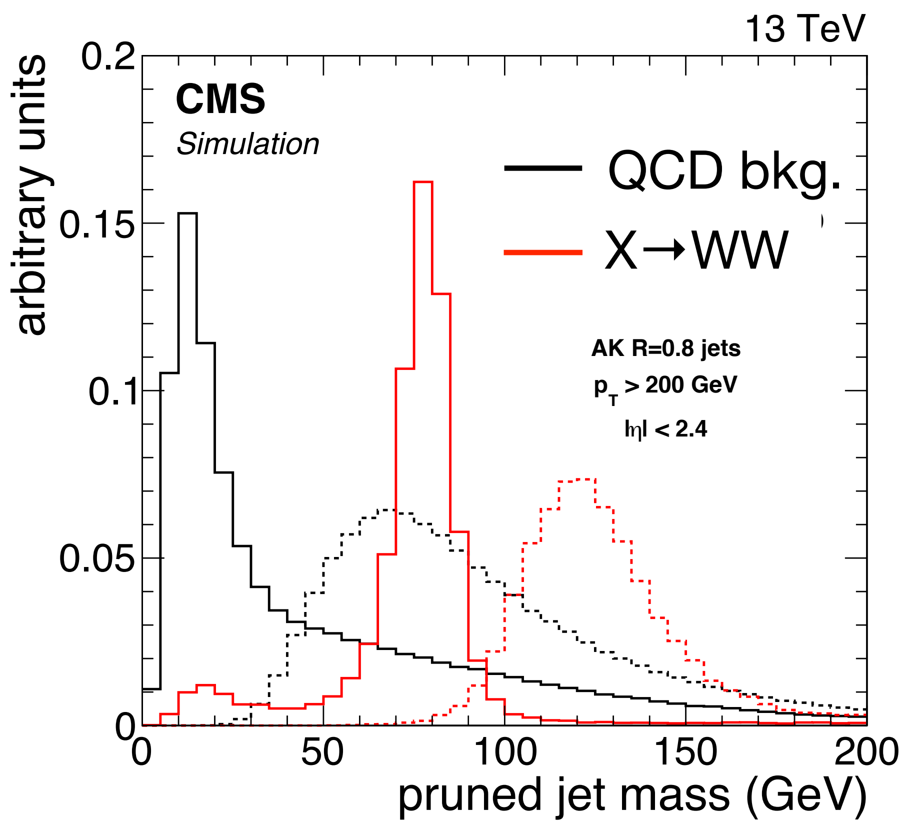
- Recluster jet constituents and for each recombination evaluate the hardness and angular separation

$$z = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,JET}} > 0.1$$

$$\Delta R < 0.5 \frac{M_{JET}}{p_{T,JET}}$$



- Filters out soft and large-angle QCD emissions that raise the mass of the typical QCD jet
    - mass of QCD jets shifted to low values while maintaining the mass of signal jets close to the boson mass



Resolving jet substructure (II)

JHEP03(2011)015

N-subjettiness observable

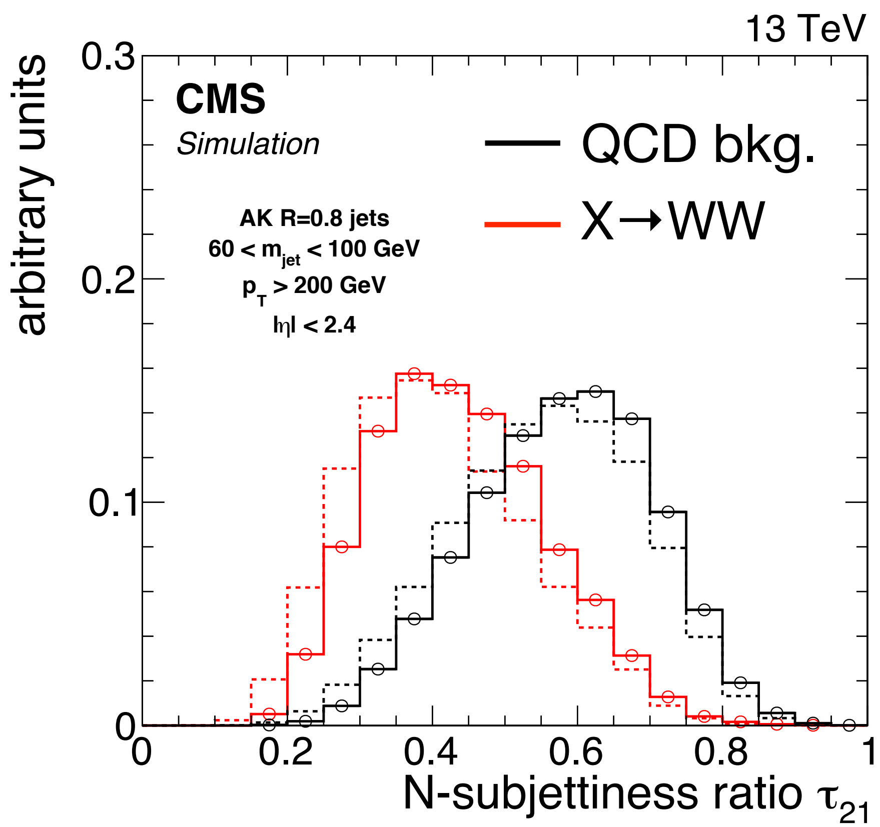
- Jet shape observable that quantifies the compatibility of the jet clustering with the hypothesis of N subjets

- Recluster the jet until N subjets remain
- calculate p_T-weighted sum over jet constituents of distances from closest subjet axis

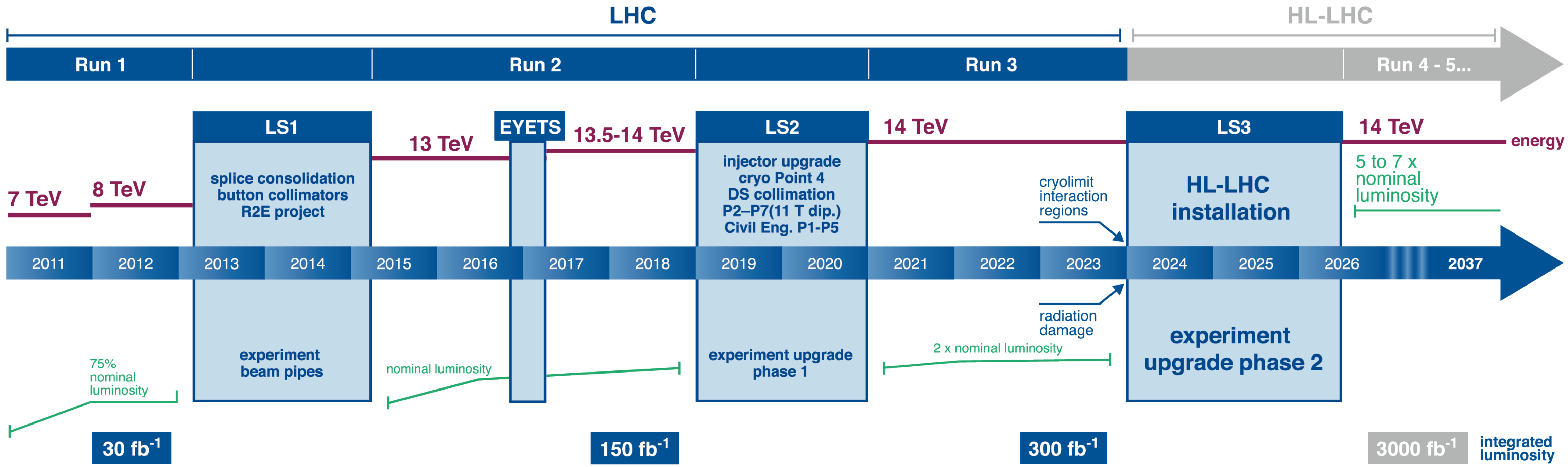
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\} \quad \text{with} \quad d_0 = \sum_k p_{T,k} R_0$$

- $\tau_N \approx 0$ if the constituents of the jet can be arranged in N subjets

⇒ best discriminant: $\tau_{21} = \tau_2/\tau_1$



The Large Hadron Collider



By the end of 2016 LHC delivered L ~ 80fb^{-1} of integrated luminosity

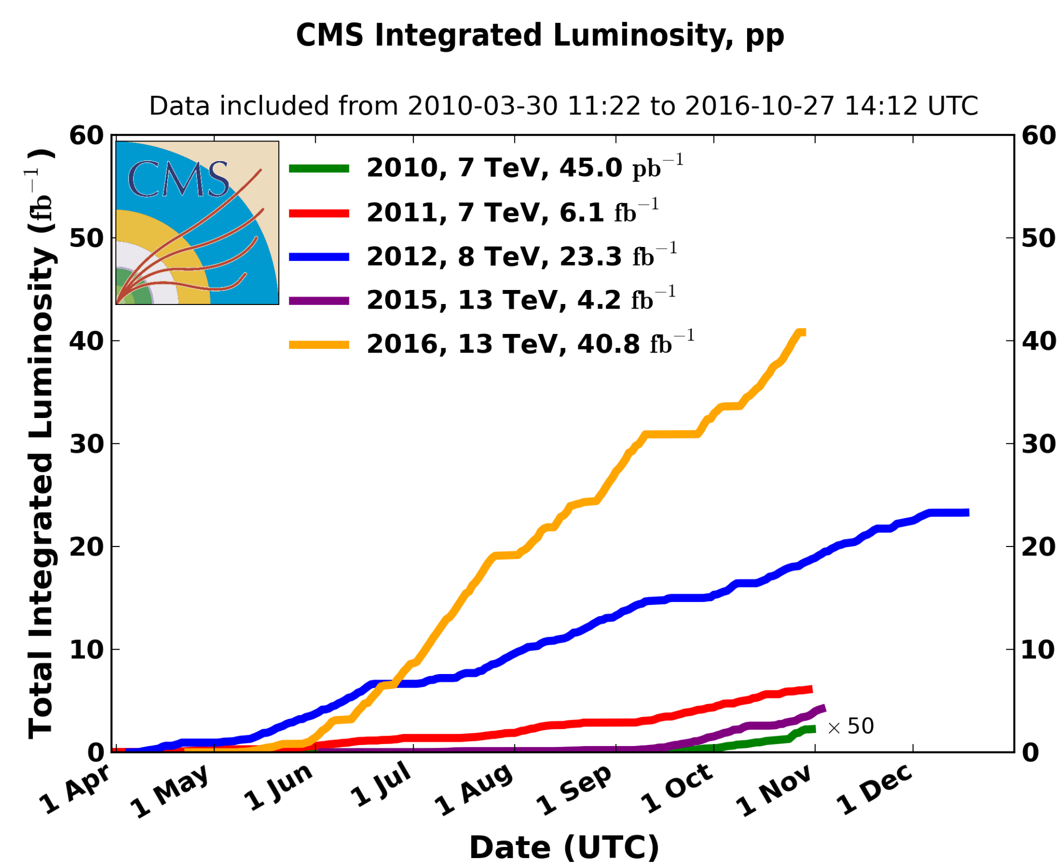
$$N_{ev} = \sigma \int \mathscr{L} dt = \sigma \cdot L$$

σ = cross section → depends on the physics process

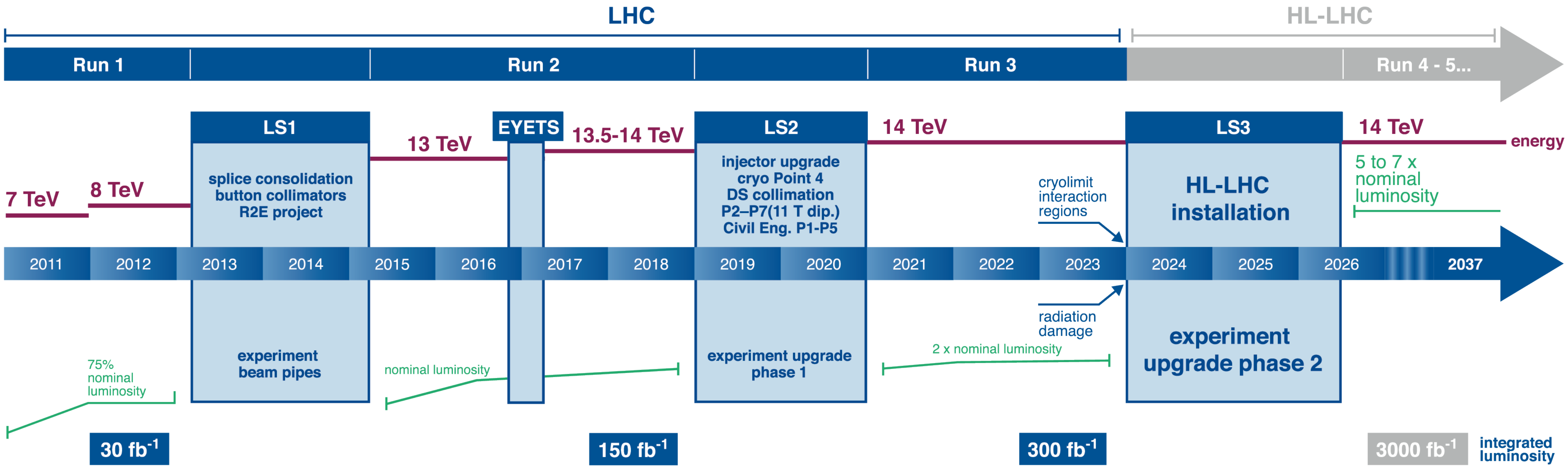
$\mathscr{L}$ = instantaneous luminosity → depends on the LHC parameter

nominal $\mathscr{L}$ = $1 \times 10^{34} cm^{-2} s^{-1}$ ⇒ reached in 2016!

2012 → 80% x nominal
2015 → 50% x nominal



The Large Hadron Collider

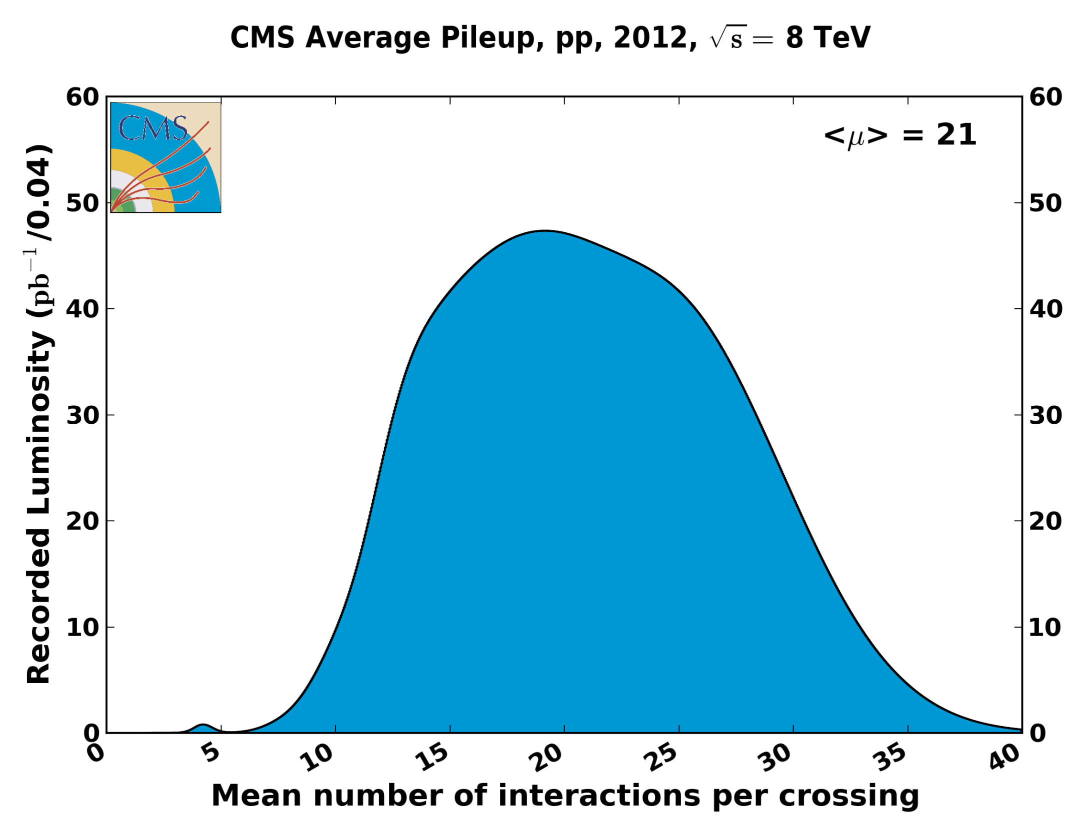


High $\mathscr{L} \Rightarrow$ large number of simultaneous pp interactions per bunch crossing (pileup)

Average pileup $\langle\mu\rangle \propto \sigma_{in} \cdot \mathscr{L}$ $\Rightarrow$ 2012: $\langle\mu\rangle = 21$
2015: $\langle\mu\rangle = 14$
2016: $\langle\mu\rangle = 25$

σ_{in} = cross section for inelastic collisions

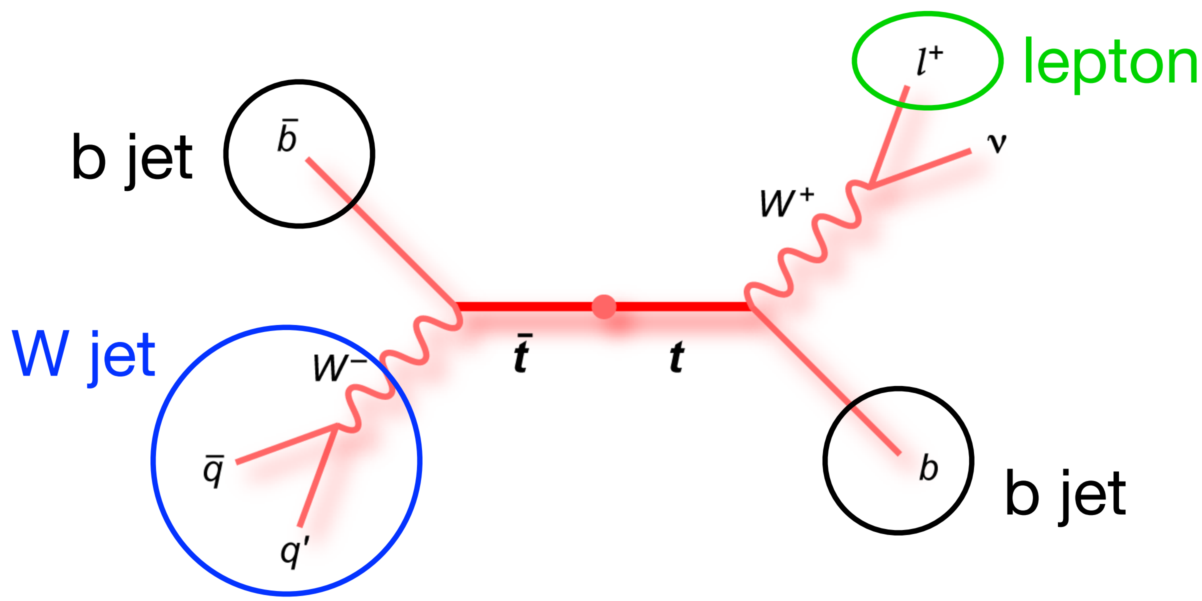
$\Rightarrow$ challenge for the detectors!

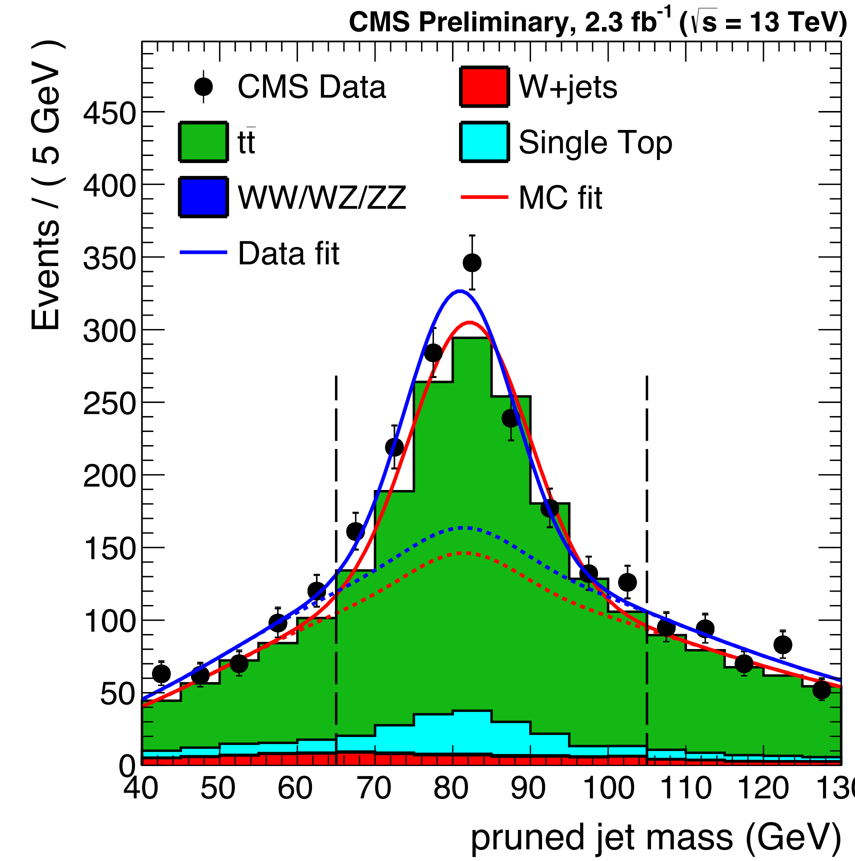


V-tagging for V→q$\bar{q}$

- Discrepancies in the m_{jet} and τ_{21} modelling in simulation can bias the signal efficiency

- cross check modelling in a pure sample of real merged W jets given by **pp→t$\bar{t}$ events** in the **lepton + W-jet + b-jet** final state





JME-16-003

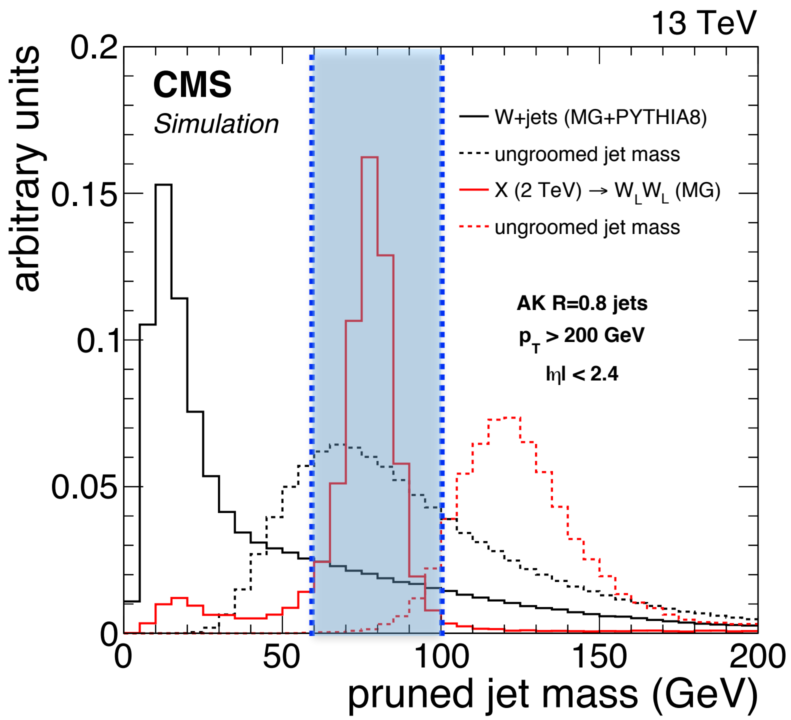
- extract a **scale factor for V tagging efficiency:** ⟶ Scale factor for $\tau_{21} < 0.6$: 1.01 ± 0.03 (stat.+syst.)
  - subtract combinatorial background due to events where the b jet is in the proximity of the W
  - fit the W-jet signal + background model to data and simulation

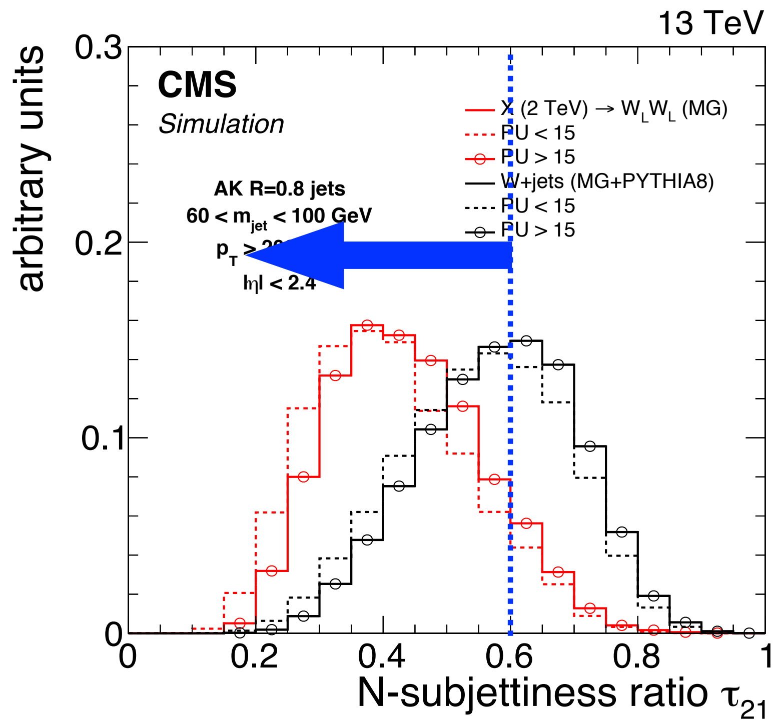
- The procedure also yields W jet mass scale and resolution ⟶

	W mass peak [GeV]	W mass resolution [GeV]
Data	84.1 ± 0.4	8.4 ± 0.6
Simulation	82.7 ± 0.3	7.6 ± 0.4

V-tagging for V→qq̄

pruning + N-subjettiness τ_{21} ⟶ V-tagging:

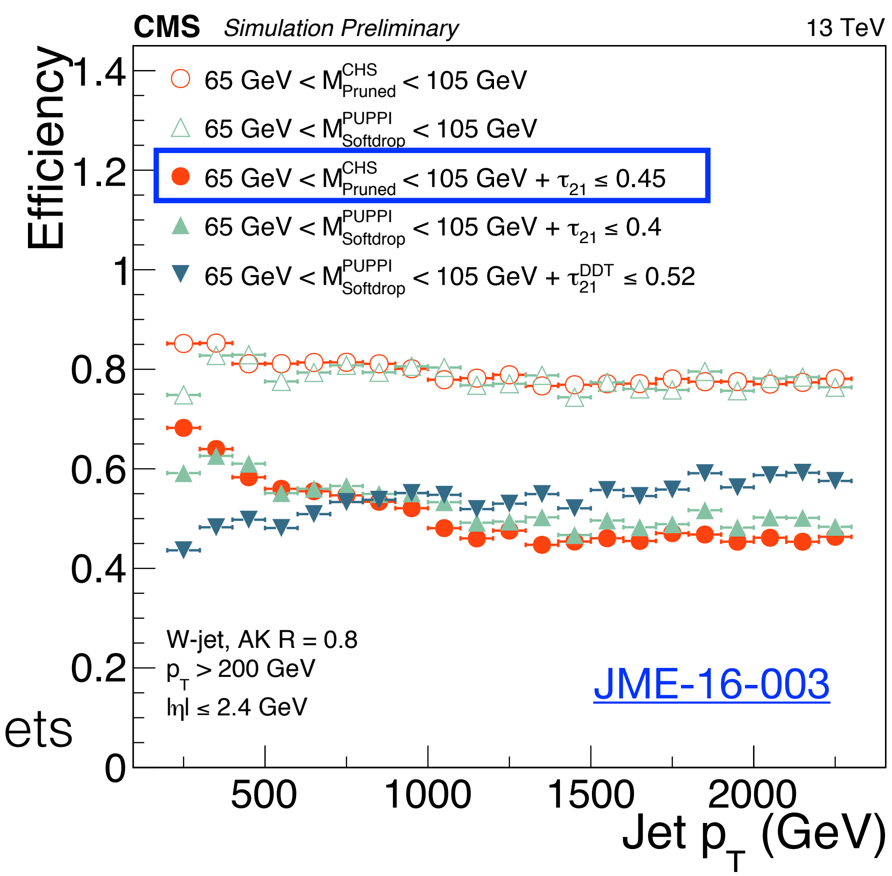




identification of V-jets

Selections optimized in each individual X→diboson analysis:

- take into account specific signal efficiency and background rates



Working point for this analysis in lepton+jet final state:

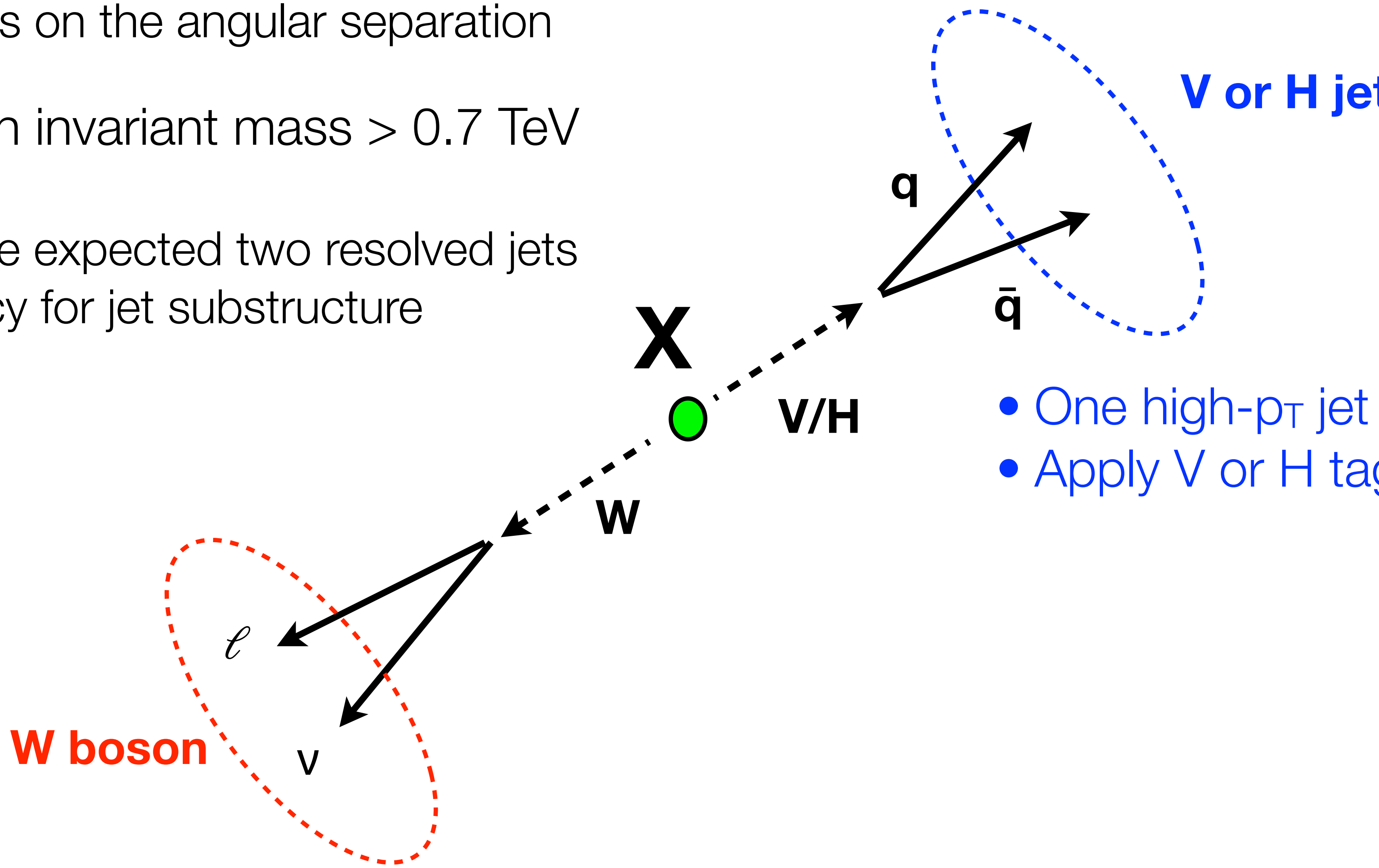
τ_{21} selection	m_{jet} selection	Signal efficiency	Mistagging rate
$\tau_{21} < 0.6$	(65 < m_{jet} < 105) GeV	76 %	5 %

from simulation @ jet p_T = 500 GeV

from data sample of QCD jets @ jet p_T = 500 GeV

X→WV/WH: selections

- Require the two bosons to be emitted back-to-back
  - apply selections on the angular separation
- Require diboson invariant mass > 0.7 TeV
  - below this value expected two resolved jets → low efficiency for jet substructure algorithms



- One high-p_T jet with R = 0.8
- Apply V or H tagging

- One high-p_T isolated electron or muon
- The lepton also provides an efficient trigger path
- Large E_T^{miss}
- Reconstruct high-p_T $W \rightarrow \ell\nu$

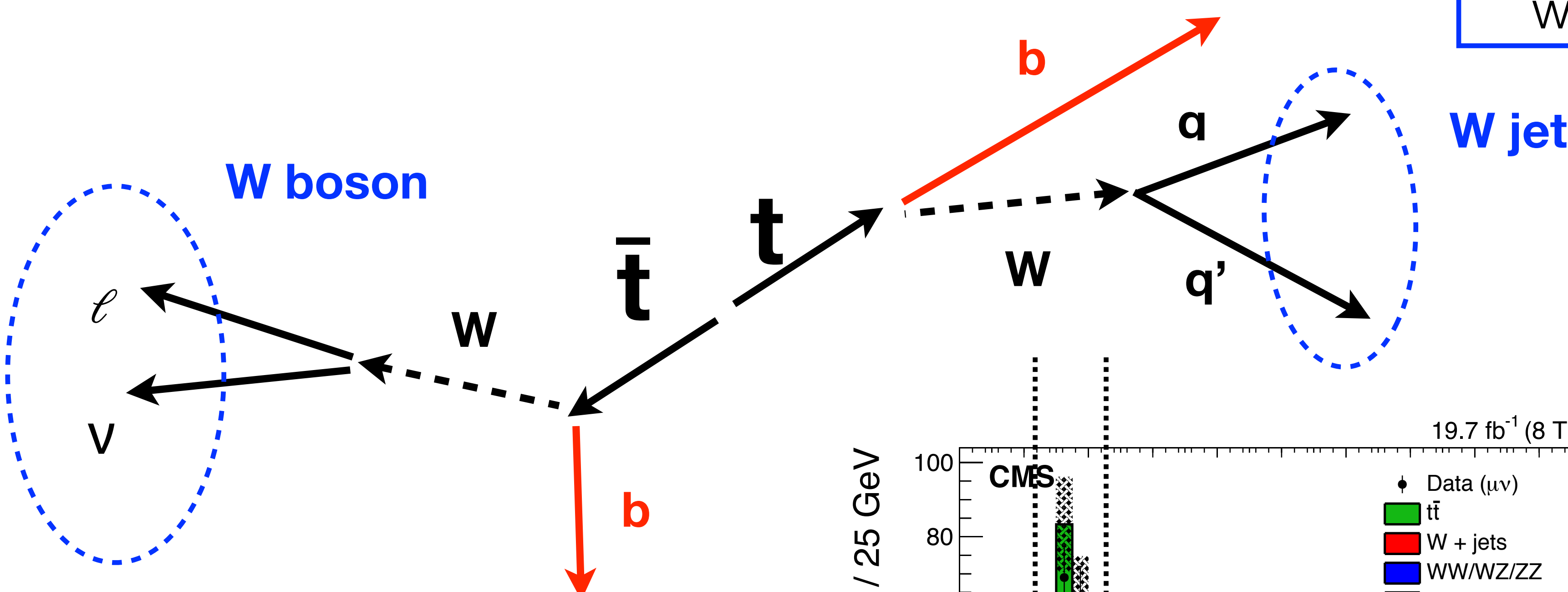
Rejection of $t\bar{t}$ background

Main SM backgrounds:

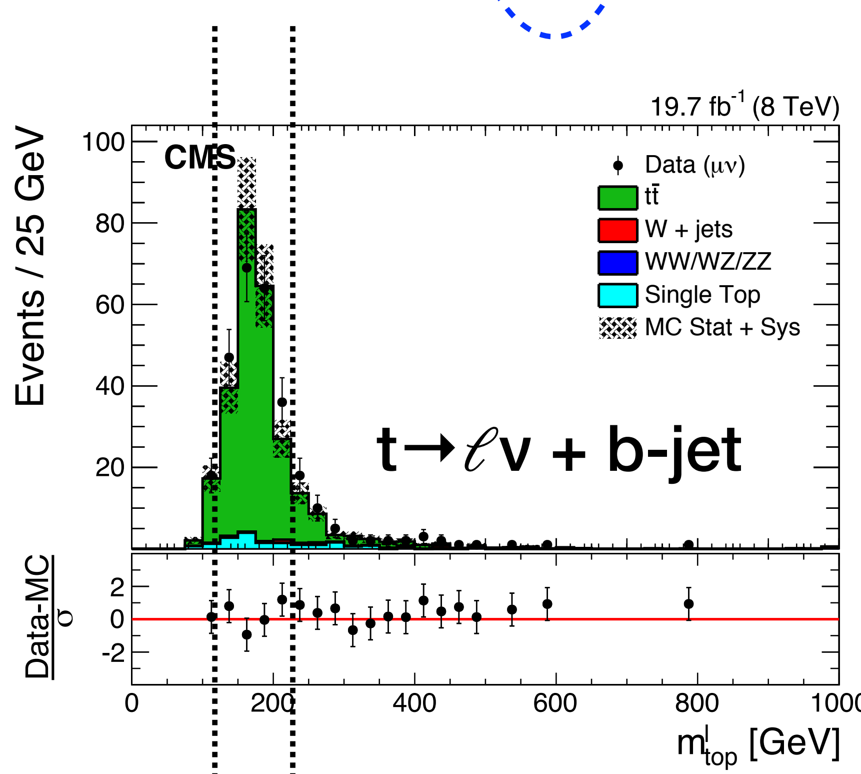
- W boson production in association with QCD jets
- **top quarks pair production ($t\bar{t}$)**
- single top production
- non-resonant diboson production (WW/WZ/ZZ)

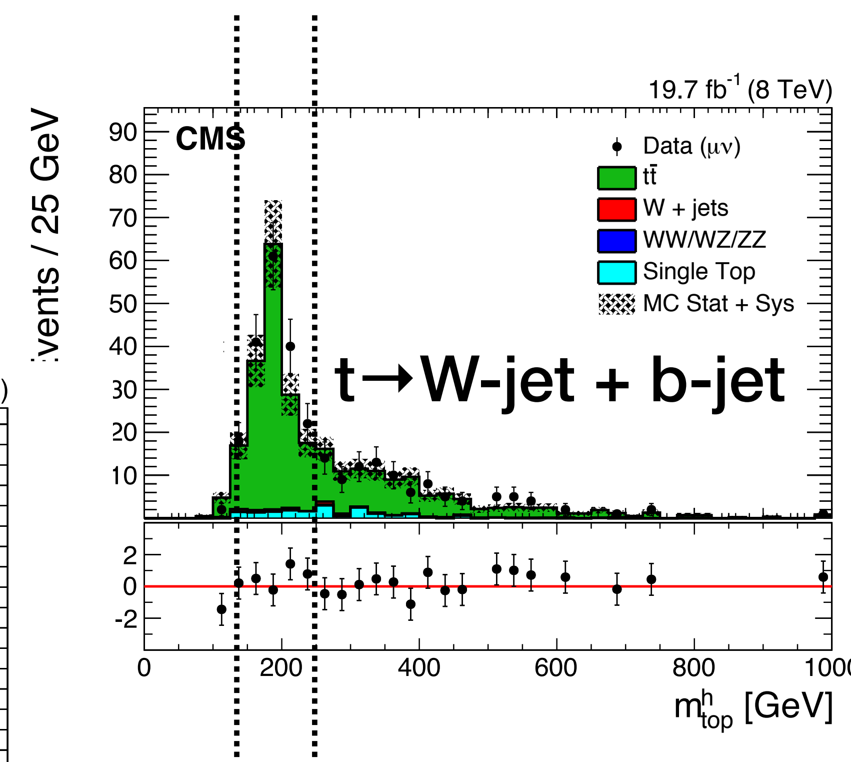
Reject $t\bar{t}$ background:

- no b-tagged jets outside the signal W or H-jet cone
- reconstruct the mass of each top quark and veto events compatible with it



to reconstruct t→ℓν+b-jet apply W mass constrain as for the signal

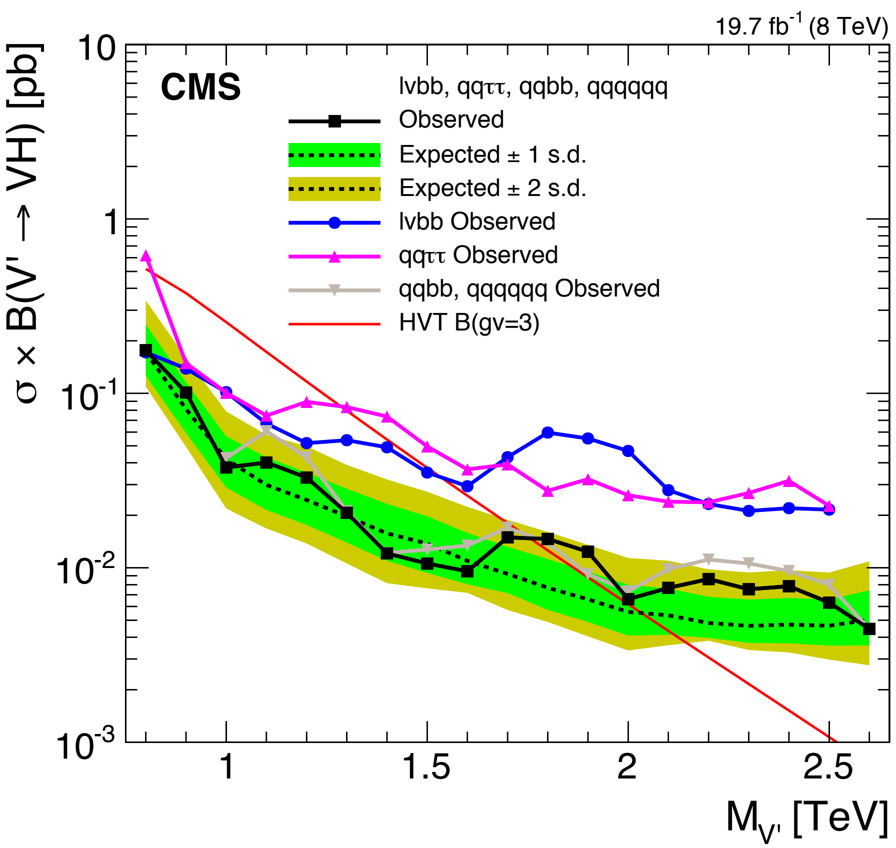


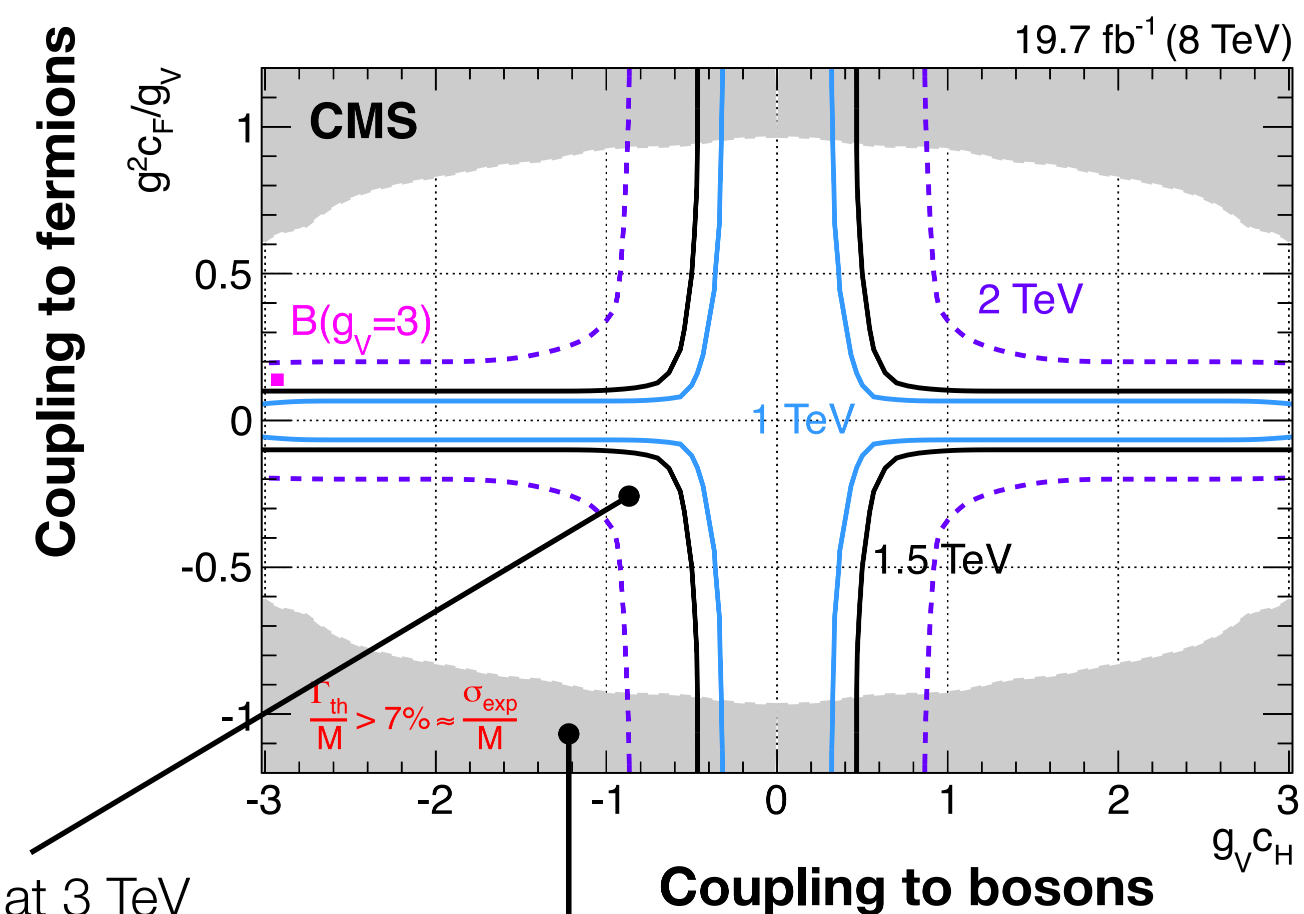


Cross section and coupling limits

- Statistical interpretation of the results with 1D unbinned shape analysis of reconstructed WH invariant mass
- Limits combined with other 8 TeV VH searches: $\ell\nu$bb + qqbb(4q) + qq$\boldsymbol{\tau\tau}$

95% CL combined observed and expected limits on σ(pp→V')*BR(V'→VH) → Scan of the HVT couplings and observed 95% CL exclusion contours



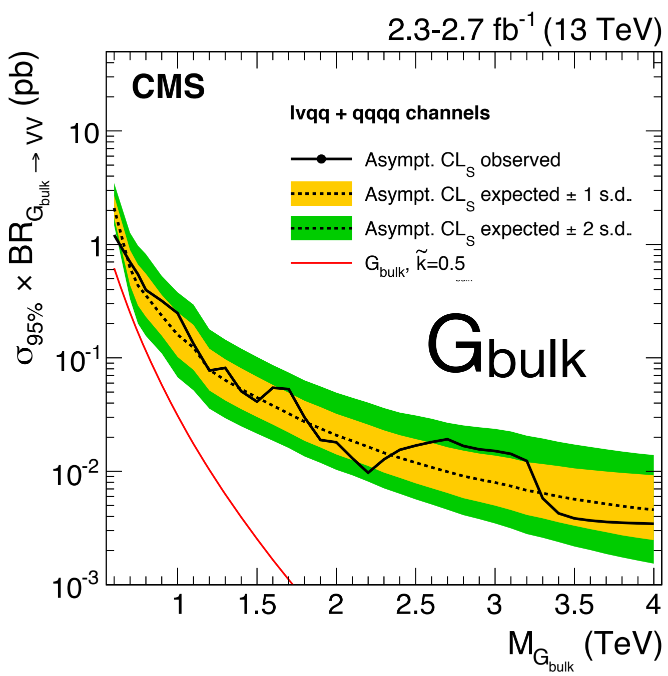


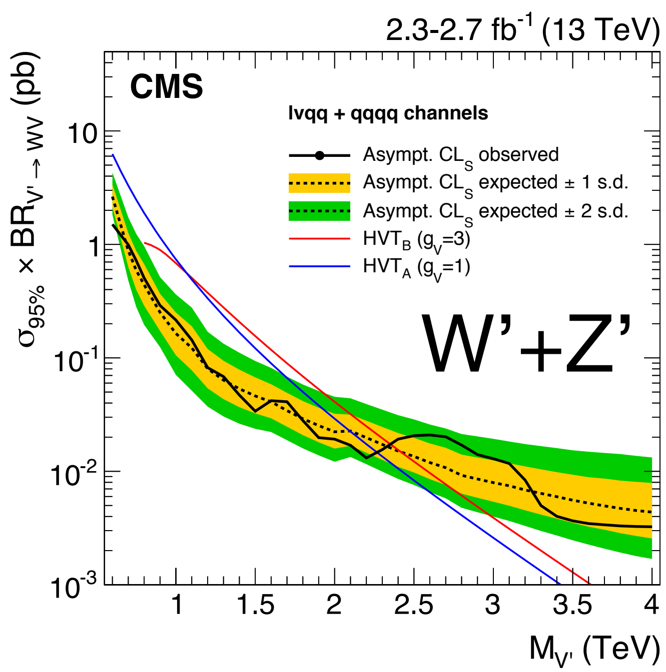
Region excluded by the VH combination at 3 TeV

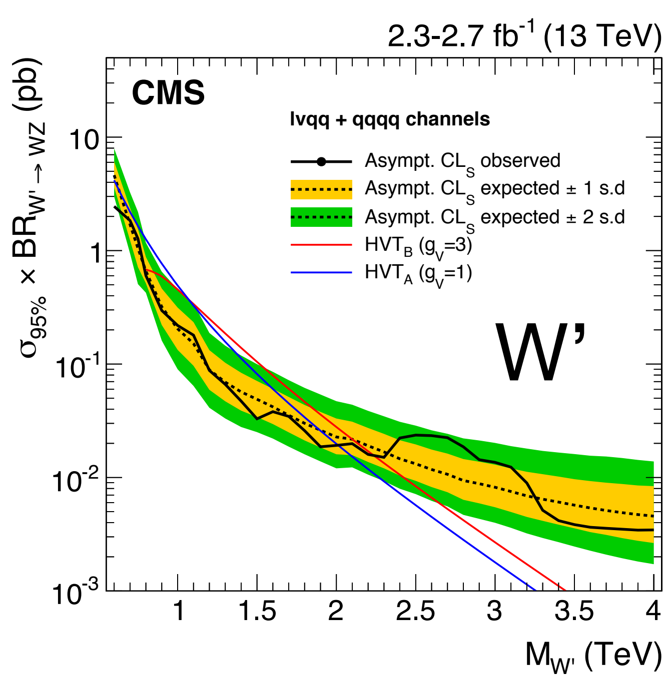
narrow width approximation not valid

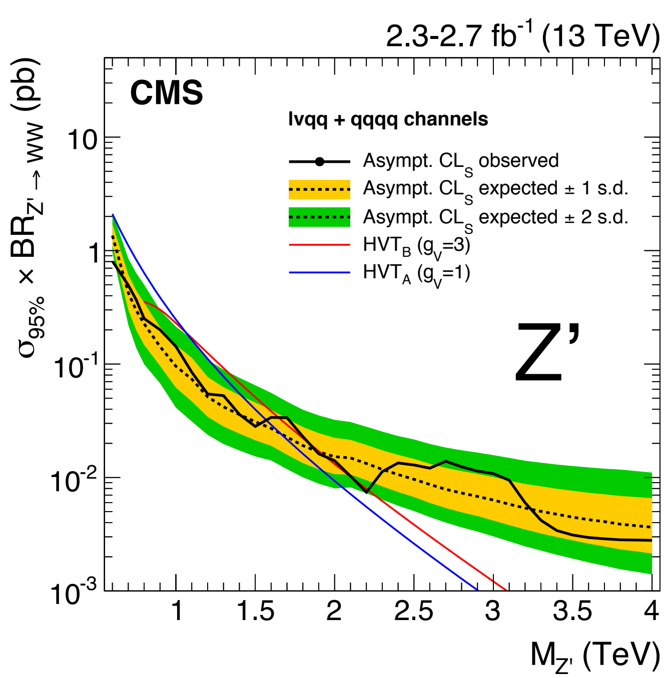
Eur. Phys. J. C 76 (2016) 237

Cross section limits

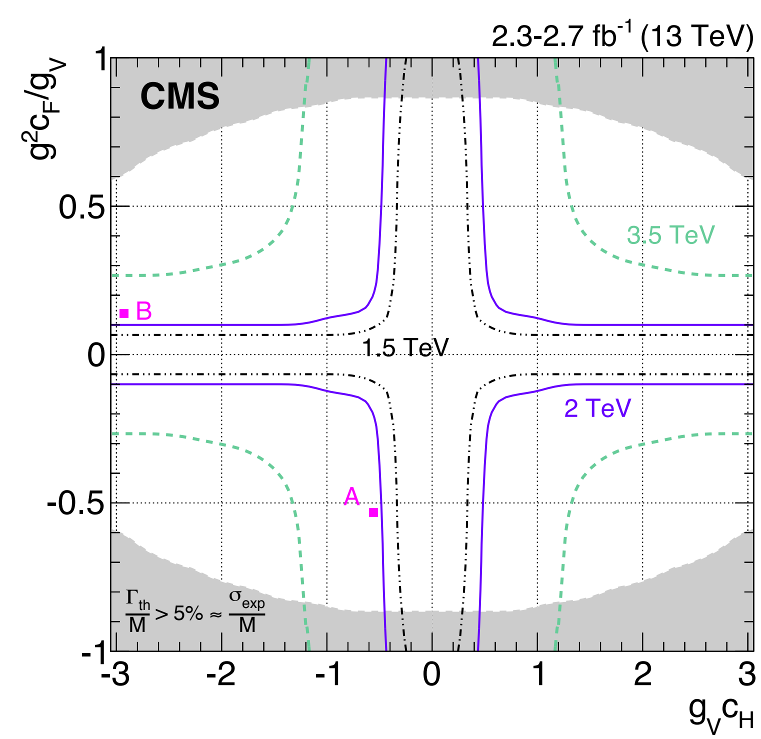








- As for WH analysis: 1D unbinned shape analysis of reconstructed WV invariant mass
- Results combined with dijet channel (VV → qqqq → 2 AK8 jets)
- Several benchmark models are used for the interpretation **(NEW!)**
  - singlet W'/Z'
  - vector triplet (W'+Z')
  - bulk graviton model

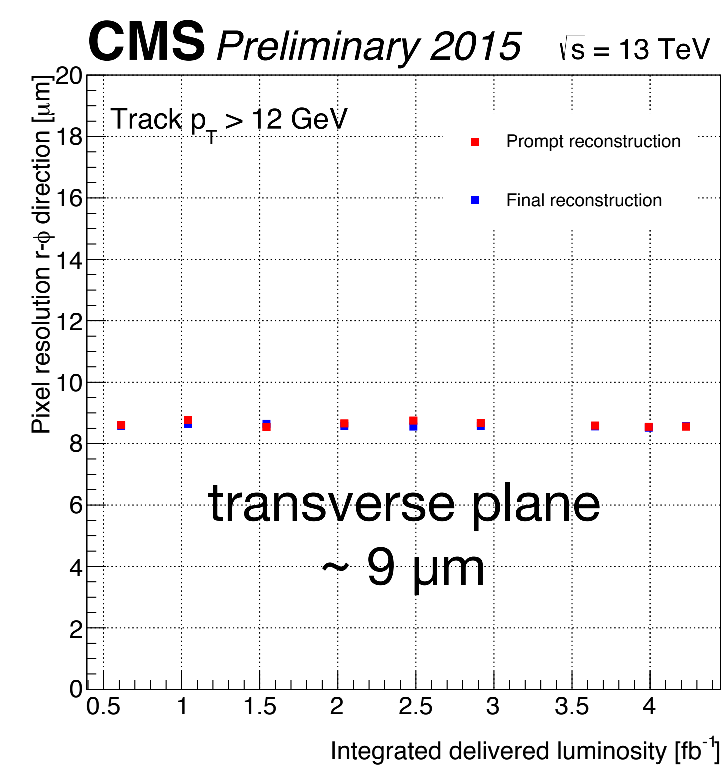


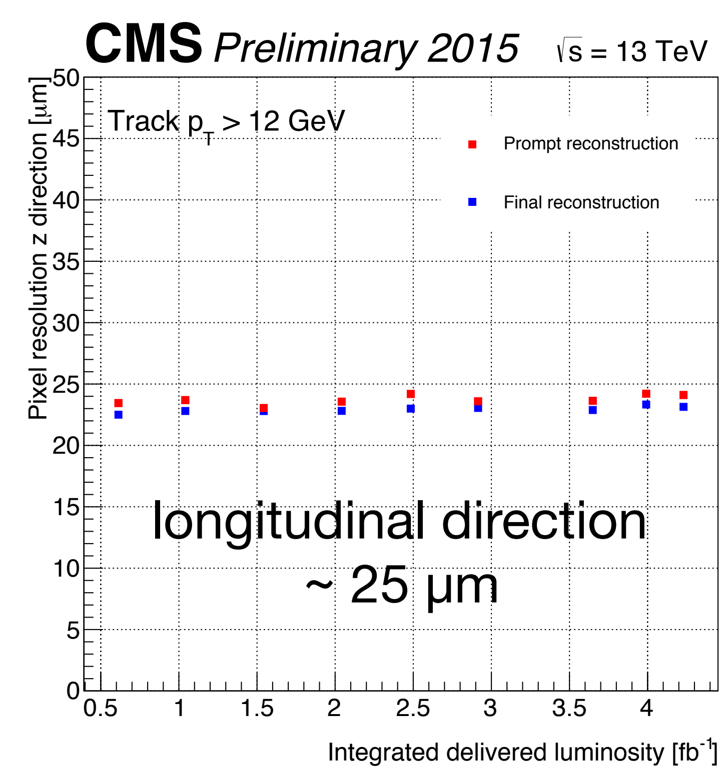
- Low-mass results not statistically combined but attached: mass point of transition decided based on best limits between low- and high-mass

BPix commissioning for Run 2

Excellent pixel hit resolution in 2015!

- Installation and quick tests in December ’14 (~ 1 week)
  - establish problems due to poor optical connections
  - solved by cleaning fibers and connectors
- To keep the excellent performance decision made during LS1 to operate the detector at -10°C (0°C in 2012)
  - low temperature necessary to reduce effects of radiation damage
- Commissioning in January ’15
  - detector settings highly depend on operating temperature ⇒ performed full detector calibration at -10°C (~ 8 days)
- This work allowed for stable and successful operation at restart of pp collisions
- Calibrations performed throughout 2015 and 2016 to keep the performance



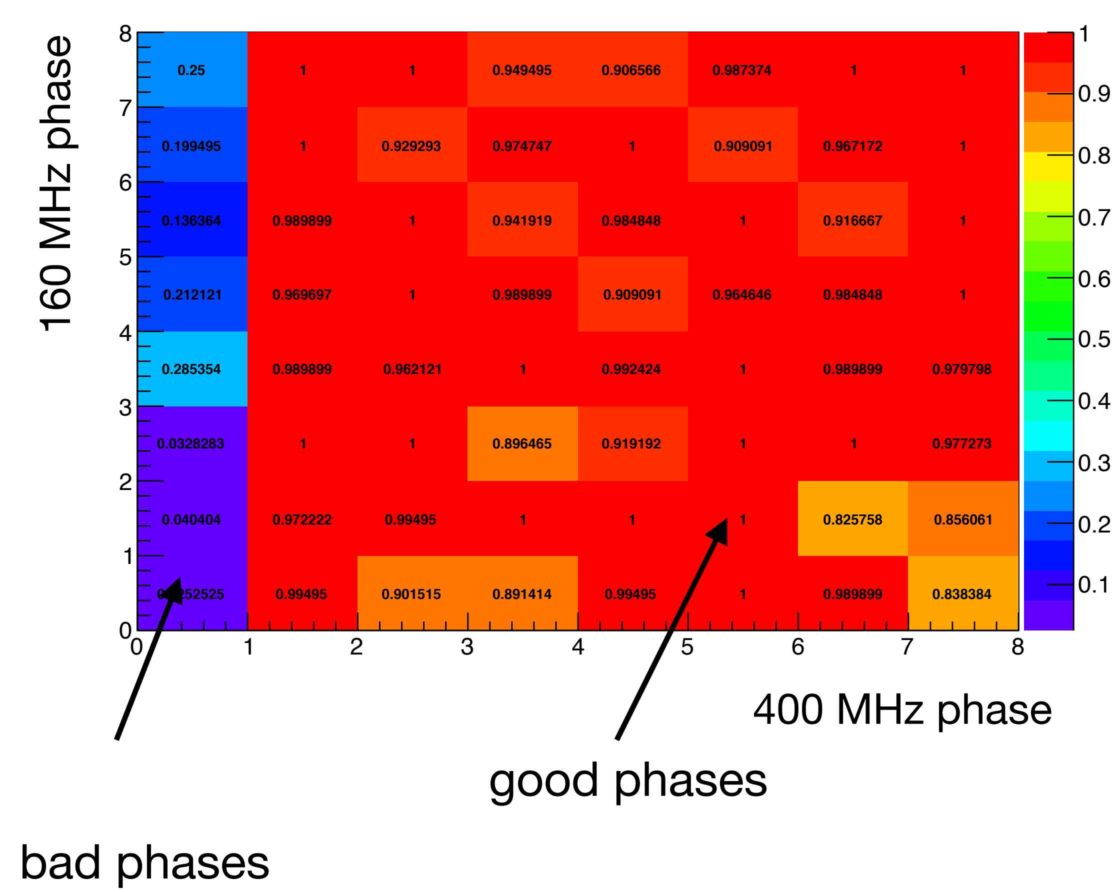


New calibration procedures

- Implemented a sequence of calibrations for detector commissioning based on VME-DAQ
  - provide a step-by-step check out of the full detector functionality after integration with ST
  - start with settings from module testing and produce new ones at each step
  - required implementation in POS of new Phase-1 BPix features
- New code currently being merged with uTCA POS code
  - hopefully fully merged and ready for commissioning in December or use VME code

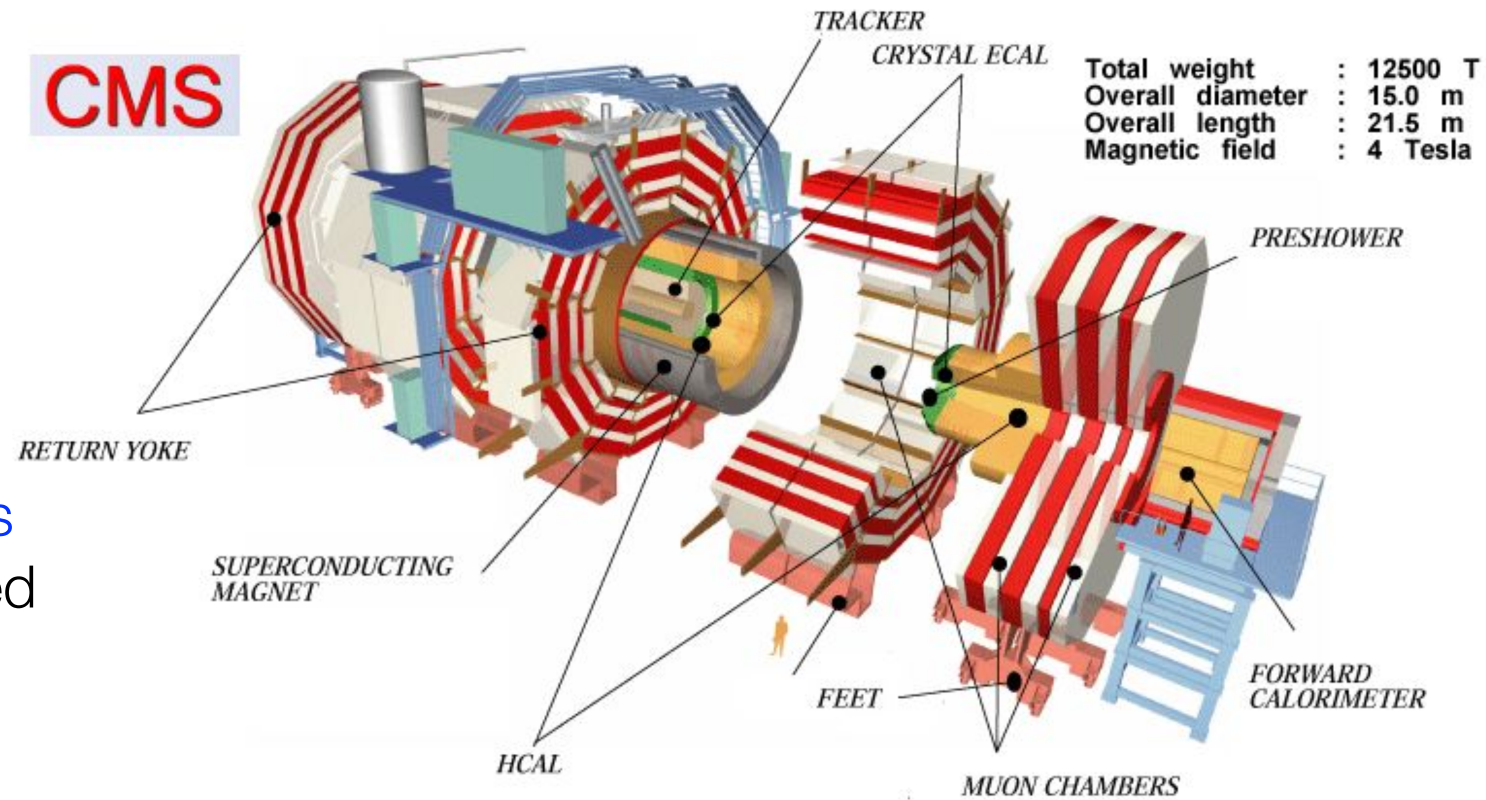
Example of calibration: TBM PLL delay

- The TBM chip on the pixel module sends a specific data package each time a trigger is received
- The data transmission timing has to be adjusted such that the package is correctly decoded by the DAQ system
- It can be adjusted changing the phase of 2 PLLs (400 MHz and 160 MHz) in the TBM



The CMS detector

Superconducting magnet generates a 3.8 T magnetic field



Silicon Tracker:

- reconstruct charged particle tracks
- measure momenta from curvature in the magnetic field
- measure position of pp interaction vertices
- measure secondary vertices from long lived particles (i.e. B hadrons)

Electromagnetic calorimeter (ECAL):

- identify electrons and photons and measure their energy

Hadronic calorimeter (HCAL):

- identify charged and neutral hadrons and measure their energy

Muon gas detectors: muons identification

Trigger system:

- select interesting events by reducing the rate of $O(10^5)$ to allow for data storage

Collected data sets used in this work:

LHC period	$\sqrt{s}$	Integrated luminosity
Run 1 (2012)	8 TeV	19.7 fb^{-1}
Run 2 (2015)	13 TeV	2.3 fb^{-1}


cold boxes
detector
supply tubes

Reinstallation of BPix into CMS

December 2014