Probing Electroweak Symmetry Breaking at the 14 TeV LHC

Kalanand Mishra, *Fermilab*

University of Pittsburgh January 31, 2014

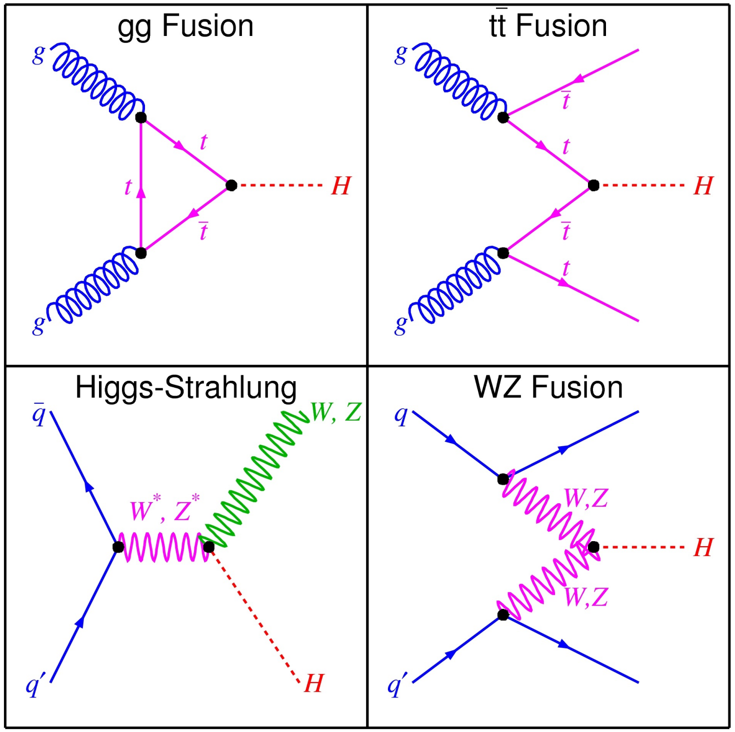
Outline

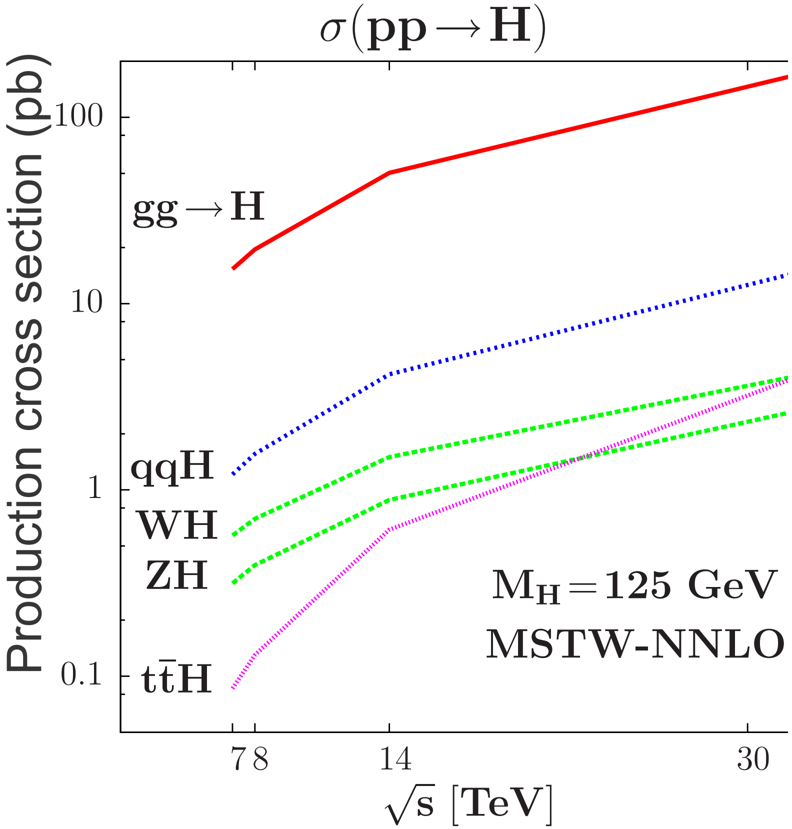
- **Current status of the Higgs sector**
- **My overall plans for LHC$_{14}$ until 2019**
- **Physics plans**
- **Detector/ upgrade plans**
- **Plans for integration in ATLAS**
- **Beyond 2019**
- **Summary**

… I will pick up from where I left in the colloquium talk

Current status of the Higgs sector, January 2014

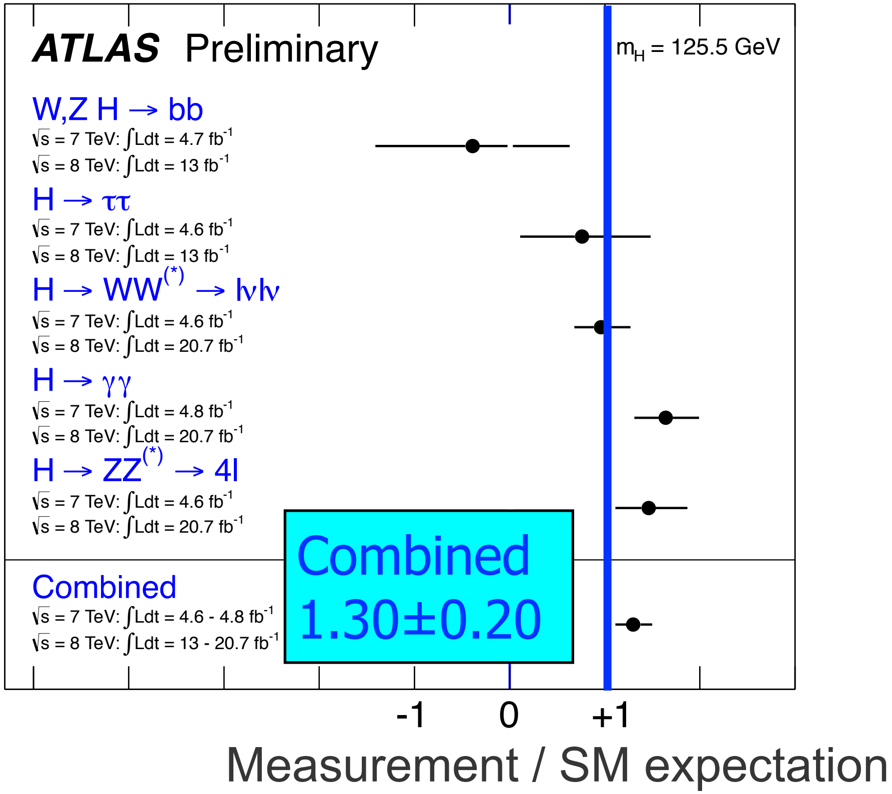
How do we produce Higgs bosons at the LHC ?



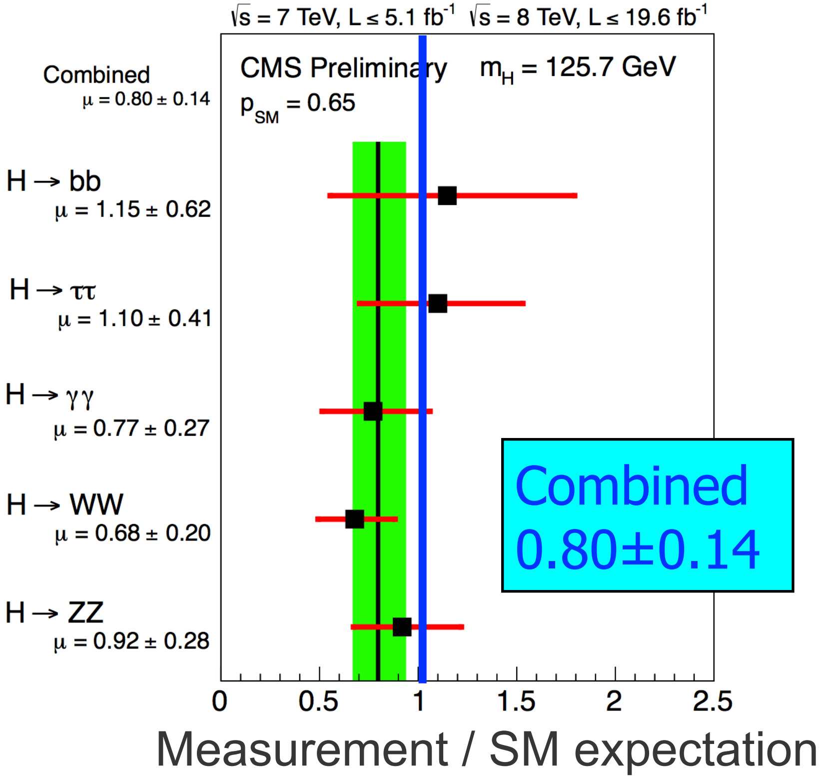


The gg fusion dominates − led to the discovery. Going forward, Higgs-Strahlung and vector boson fusion become more important.

Cross section x decay rate



Combined
1.30±0.20



Combined
0.80±0.14

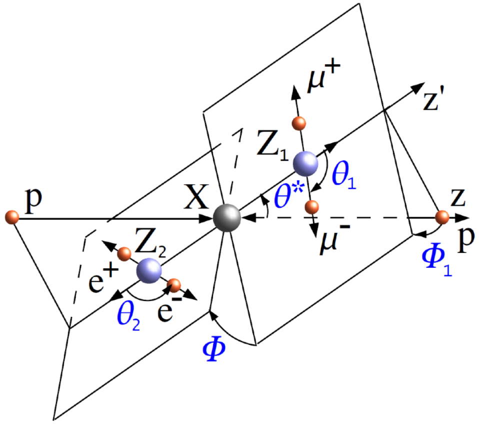
- So far consistent with SM, but ~10% deviations possible
- Goal for Run 2: precision measurement of the fermionic couplings (b and top quarks)

Higgs properties

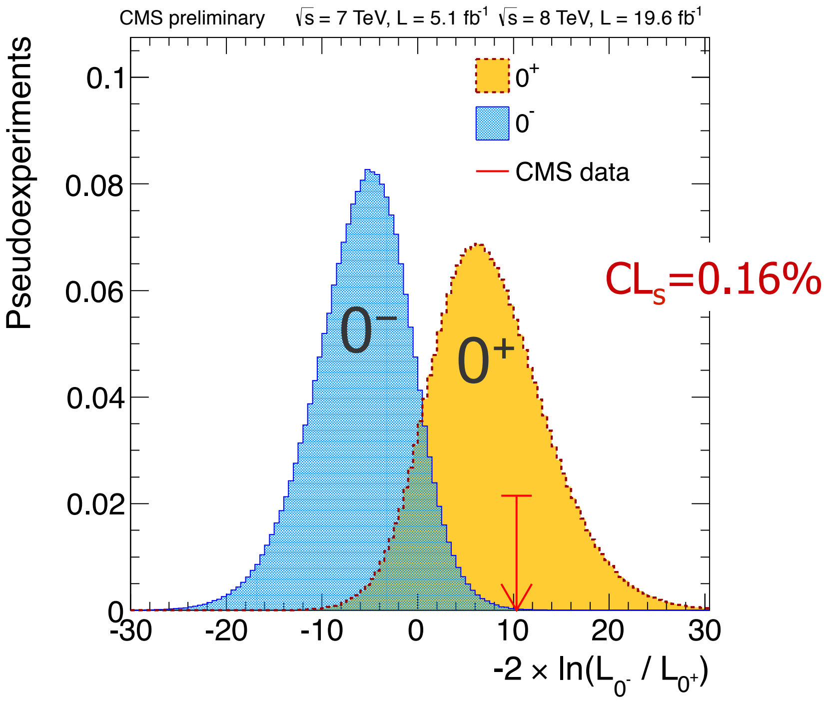
Mass

ATLAS: 125.5 ± 0.6 GeV
CMS: 125.7 ± 0.4 GeV

Spin-parity



J^P	CL_s
0^-	0.16%
2^+_{mgg}	1.5%
$2^+_{mq\bar{q}}$	<0.1%
1^-	<0.1%
1^+	<0.1%



CL_s=0.16%

Evidence for scalar nature 0^+ but CP admixture not completely excluded

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Here are the things I want to do with Run-2 data

In the post Higgs discovery era, focus on three key areas

1. New phenomena in WW scattering
2. Higgs coupling to b quark in the associated production mode (WH, ZH with H→$b\bar{b}$)
3. ATLAS Phase-1 upgrade (for the long shutdown 2018)

Additional interests

- Auxiliary measurements: high mass Higgs, gauge boson couplings, exotic searches, multi-boson, ttH, bbH, …
- Work closely with phenomenologists: effective field theory, electroweak corrections, jet substructure, boosted W/Z/Higgs/top, …

I'll elaborate on these elements in the following slides

Entire physics program using the final state

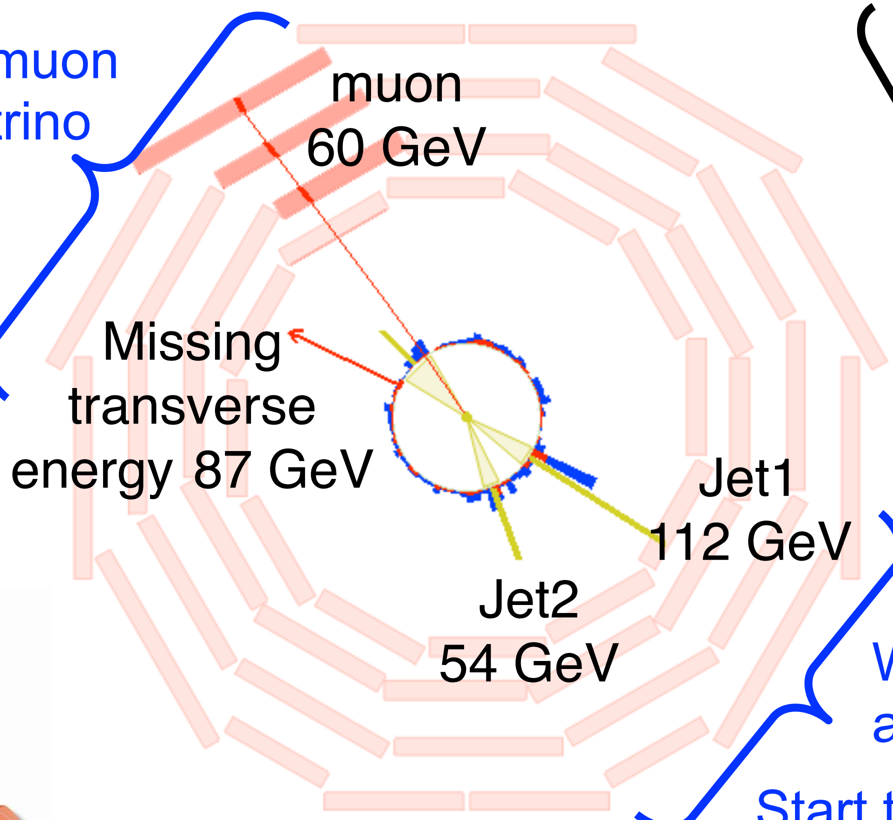
Lepton + { 2 skinny jets or 1 fat jet } + MET

(For ZH mode require an extra lepton instead of MET)

Three important cases:

- For p_T > 200 GeV, the two quarks merge into a single jet
- In the case of Higgs, the two jets (or subjets) are b-tagged
- For WW scattering, also require two forward tagged jets

The event topology



W → muon
+ neutrino

Lepton efficiency, fake rate

+ 2 tag jets

large rapidity gap and large invariant mass

Jet ID, energy scale

W → quark + antiquark

Start to merge at high p_T

W, Z tagging, subjet b-tagging

No-lose theorem: it's likely to succeed because

1. An SM-like Higgs boson does exist: Its coupling to b-quark will be a very exciting measurement, regardless of whether the coupling is consistent with the SM prediction or deviates by x%.

2. The same argument applies to WW scattering rate: Regardless of sensitivity to new physics, it is an important measurement of electroweak symmetry breaking.

3. I will bring valuable expertise: I have performed the most sensitive probes in this final state, and developed new tools and ideas. People in both experiments know me for these reasons.

4. Protection against failure: One can do many interesting measurements with this final state, some of which are not covered yet.

5. I've a good track record of working in a team: Will get students & postdocs involved, will forge collaborations to ensure success.

Can anchor a multi-year physics program

Step 1: Initial H→bb & WWjj measurements, reload w/ more data

Production rates, comparison with predictions, differential distributions, …

Step 2: Test new physics in both cases

Probe deviations from the SM prediction, test alternative hypotheses etc.

Step 3: Dissect by kinematics, then repeat the above steps

Differential in jet multiplicity, high energy regime

Step 4: Expand into new channels with 10x increase in dataset

ttH, HH, WWW, …

Step X: Seize opportunity

Through swiftness, new ideas, and proven track record to deliver on time

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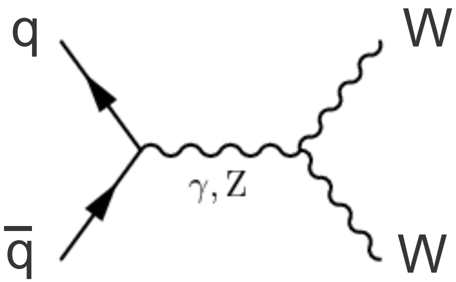
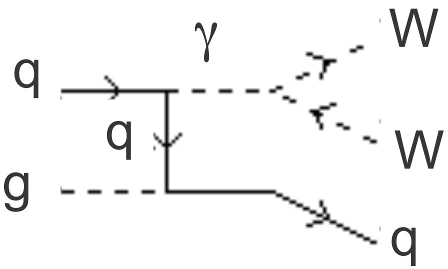
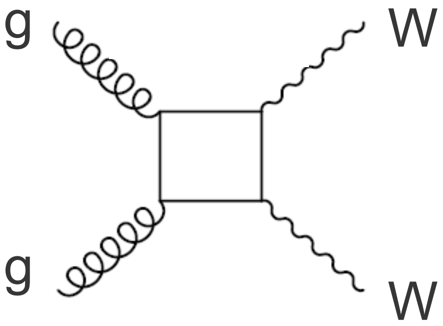
LHC as a vector boson collider

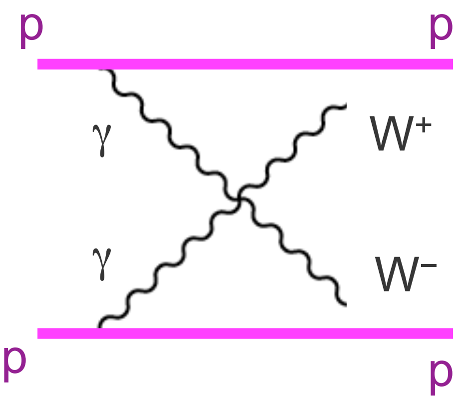
We primarily think of LHC as a parton-parton collider

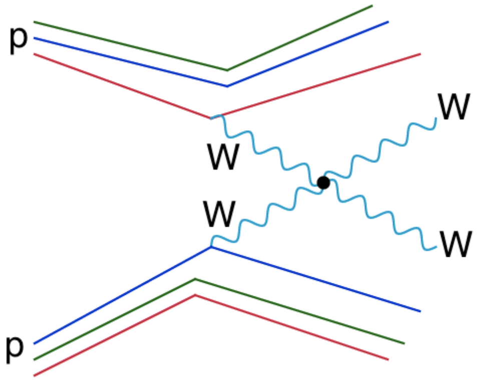






At high energies the LHC is also an excellent vector boson collider





~ 10^{-2} x partonic luminosity

What is so cool about it

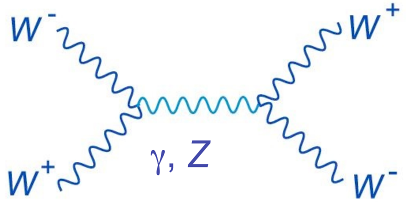
Can reveal cracks in the SM ➜ testing ground for new ideas

- Is H(126) solely responsible for electroweak symmetry breaking?
  - data allow room for additional Higgs or new physics
  - either may play a partial role
- Longitudinal WW scattering can probe such a possibility
  - Partial growth in WW scattering cross section is a generic feature in many extensions of the SM **(why, on the next slide)**
- Recent studies show sensitivity at LHC_{14}
  - with 40 fb^{-1} data in WW semi-leptonic final state

Kingman Cheung et al, arxiv: 1303.6335

Full cancellation or something else

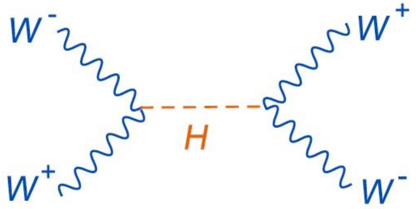
Without *a* Higgs boson



$$= \frac{g^2 E^2}{2m_W^2}(1+\cos\theta)$$

divergent: SM blows up as E^2

With Higgs boson



$$= -\frac{g^2 E^2}{2m_W^2}(1+\cos\theta)$$

no problem now!

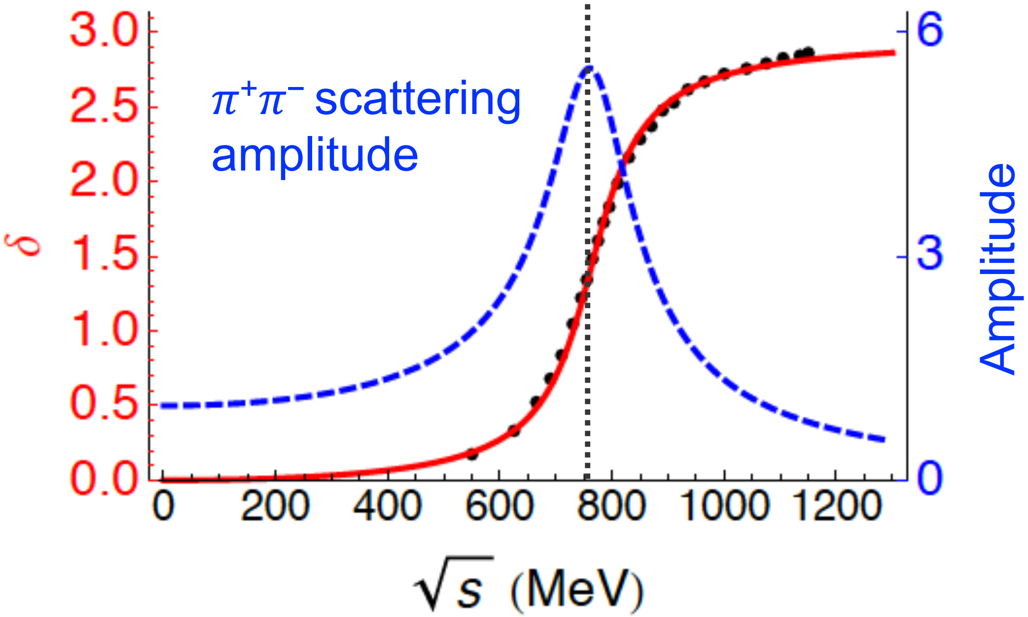
☑ Rationality is restored when something like Higgs steps in

- Is one Higgs enough ?
- Does it stop the divergence ?

For full calculation of the scattering cross section & an enlightening discussion, please see John Campbell's talk in CTEQ 2013 school

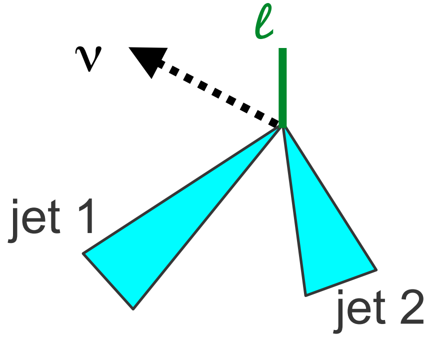
Have we seen this before …

- ☑ A good analogy is $\pi\pi$ scattering at low energy (BNL, 1973)
- ☑ Unitarized first by the ρ meson (mass 770 MeV) and then subsequently other higher mass light quarkonium states

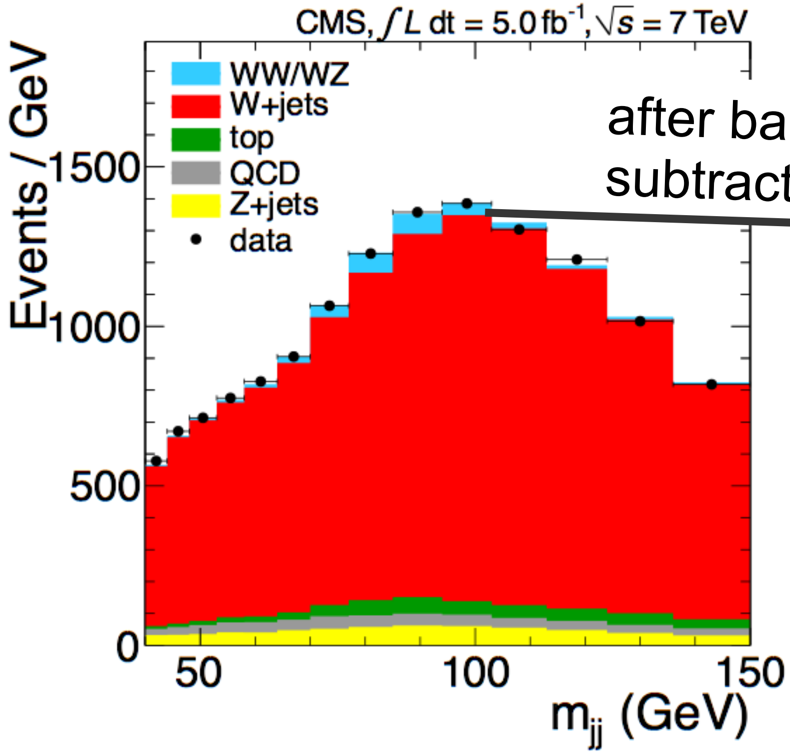


Hitoshi Murayama et al, arXiv: 1401.3761

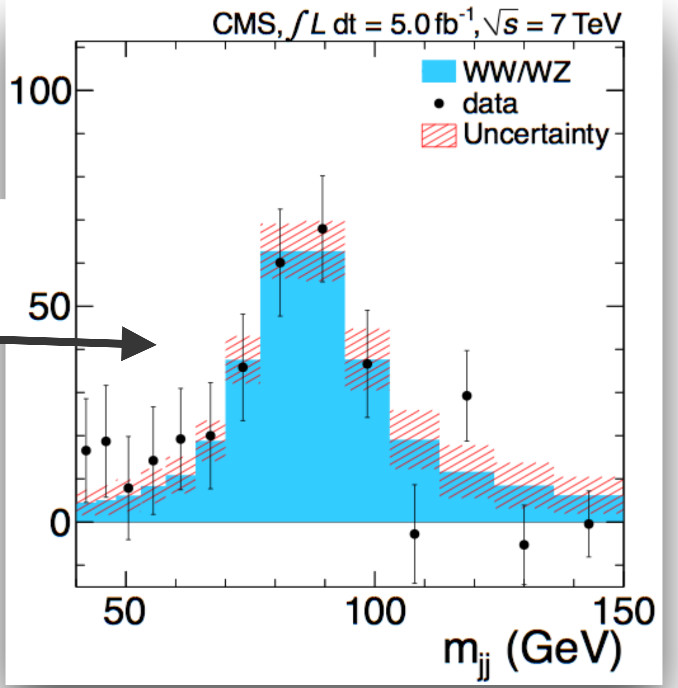
Reconstruction of hadronic W, $Z\rightarrow q\bar{q}$ signal



- Jet resolution doesn't allow to cleanly separate WW from WZ, so get admixture of the two



after background subtraction

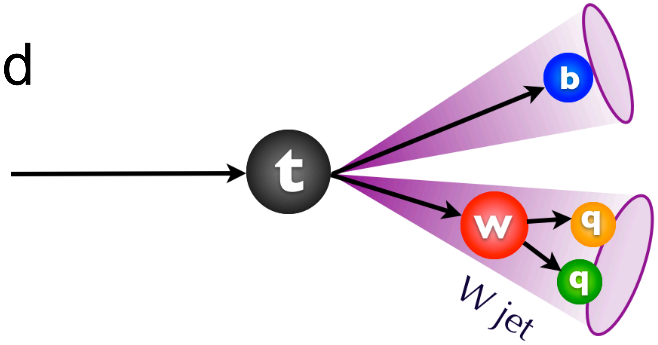


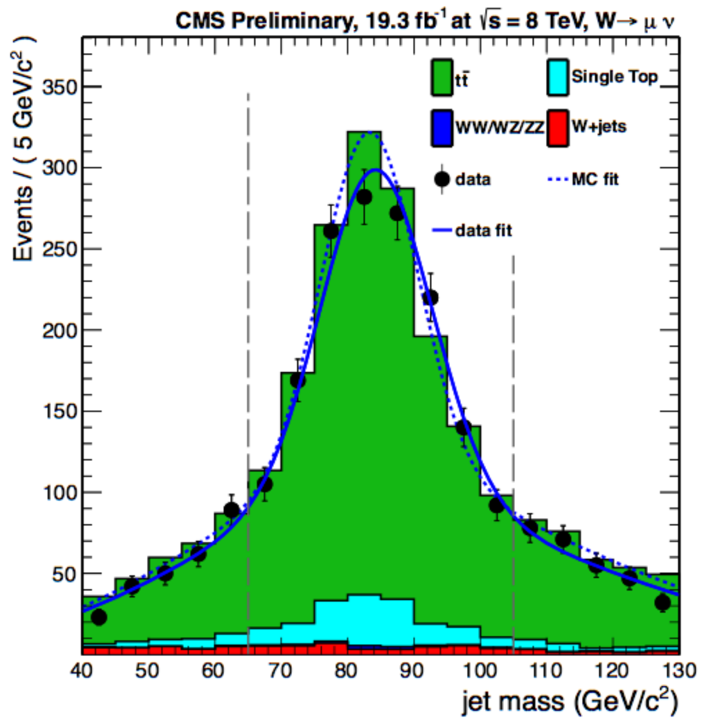
The first observation of diboson in semi-leptonic channel at LHC

Reconstruction of boosted W

Example: boosted top events (an excellent calibration sample)

- W jets can be identified using jet and subjet properties:
  - Jet mass = W mass
  - Two subjets
  - Subjet mass << jet mass
  - Both subjets should have similar momentum

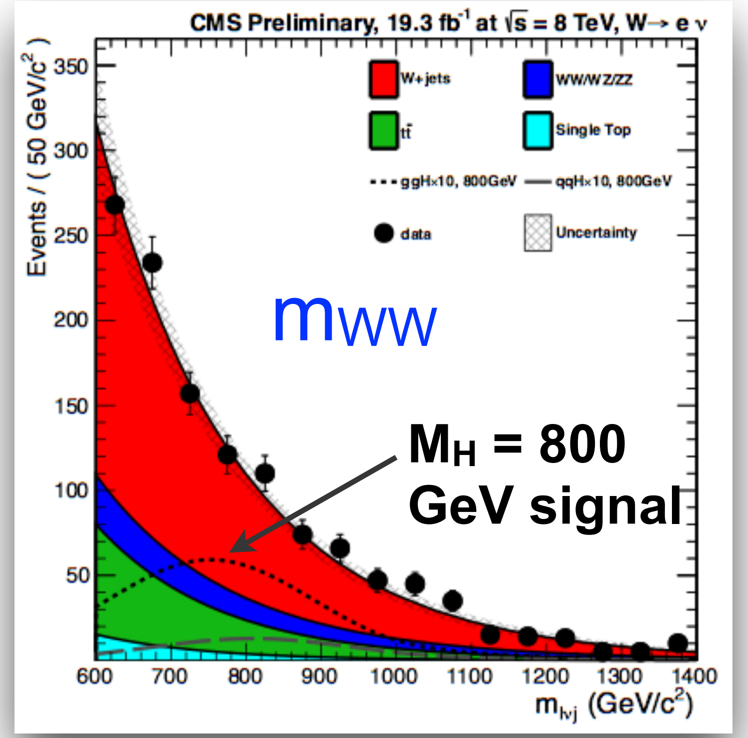




A pure sample of W decaying hadronically to a single jet (Cambridge-Aachen, R=0.8) in $t\bar{t}$ (→ ℓ+MET+jet) b-tagged events

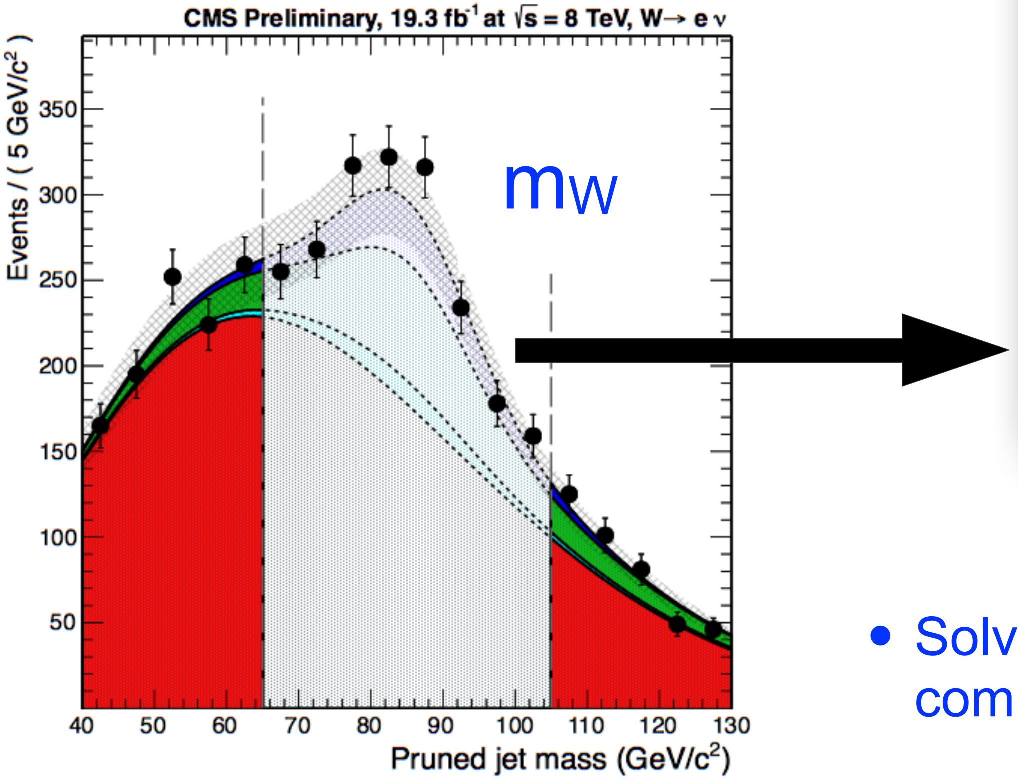
Reconstruction of WW mass spectrum

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG HIG-12-046, HIG-13-008



m_{WW}

M_H = 800 GeV signal



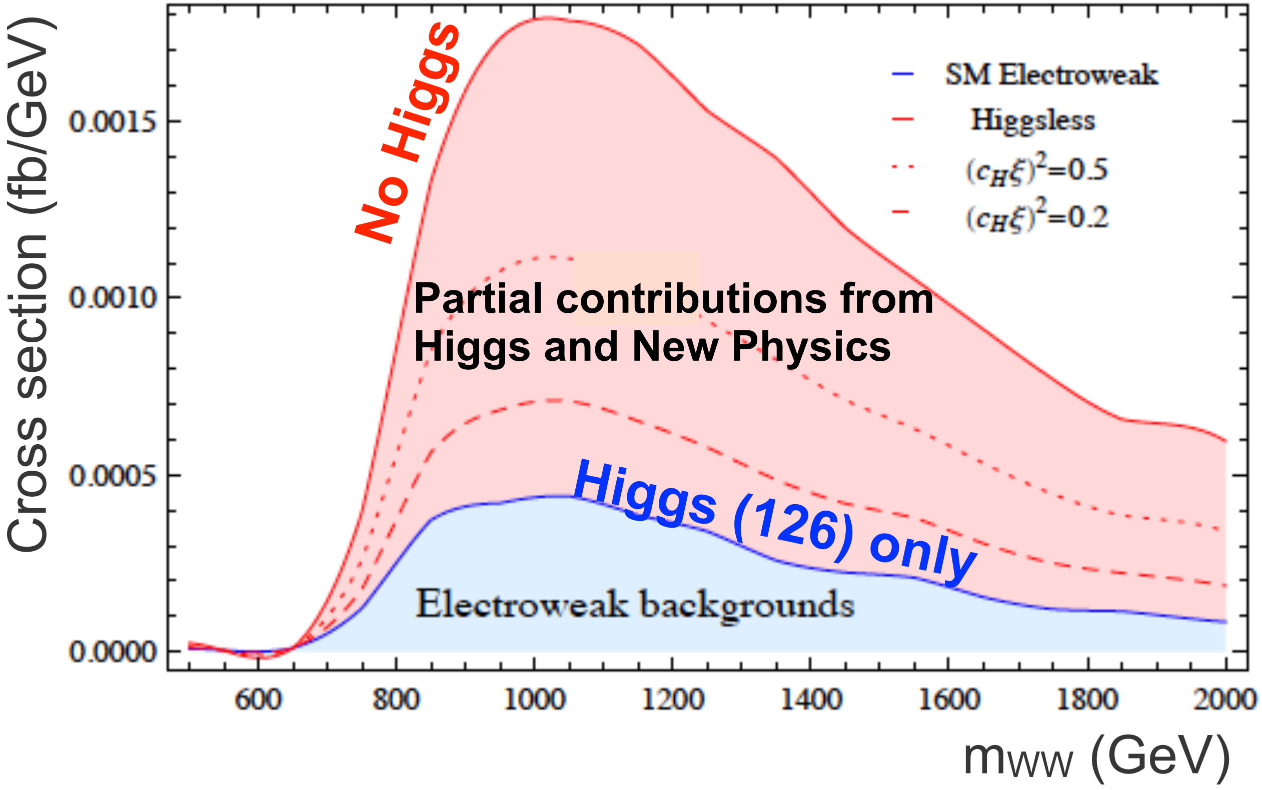
m_W

- Solve for the pz of the neutrino to compute full invariant mass

New physics in WW scattering would look like

Simple case: **Signal = ξ x Higgsless excess** where 0 < ξ < 1

Yanou Cui and Zhenyu Han, arXiv:1304.4599

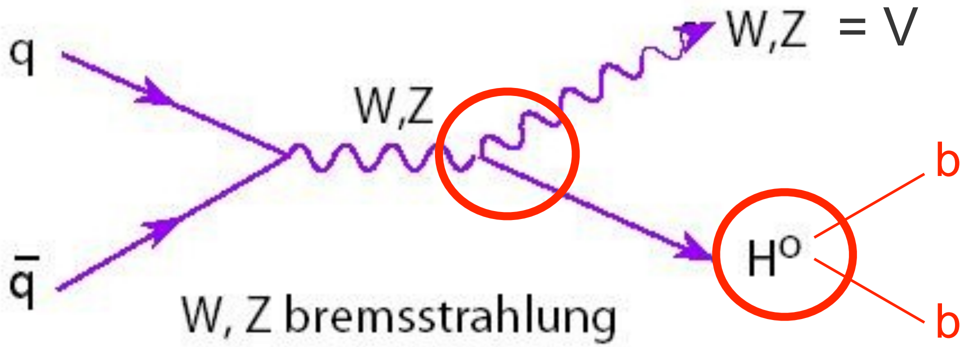


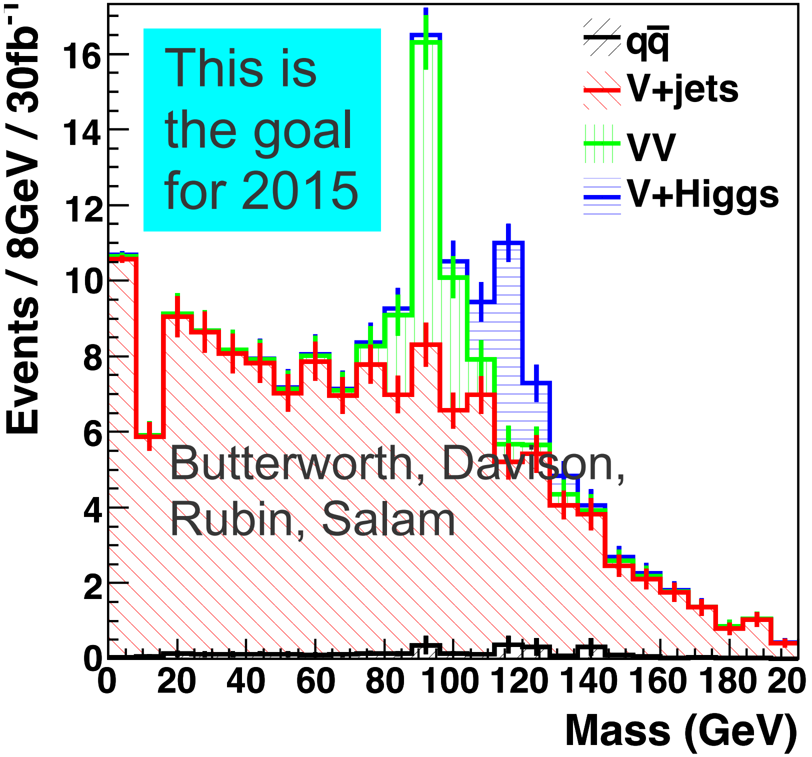
For more complicated scenarios, see Tao Han's summary talk at Dresden workshop

https://indico.desy.de/conferenceOtherViews.py?view=standard&confId=7512

In 2015 can discover large excesses such as in the Higgsless case with 5σ significance.

Higgs coupling to the b quark





This is the goal for 2015

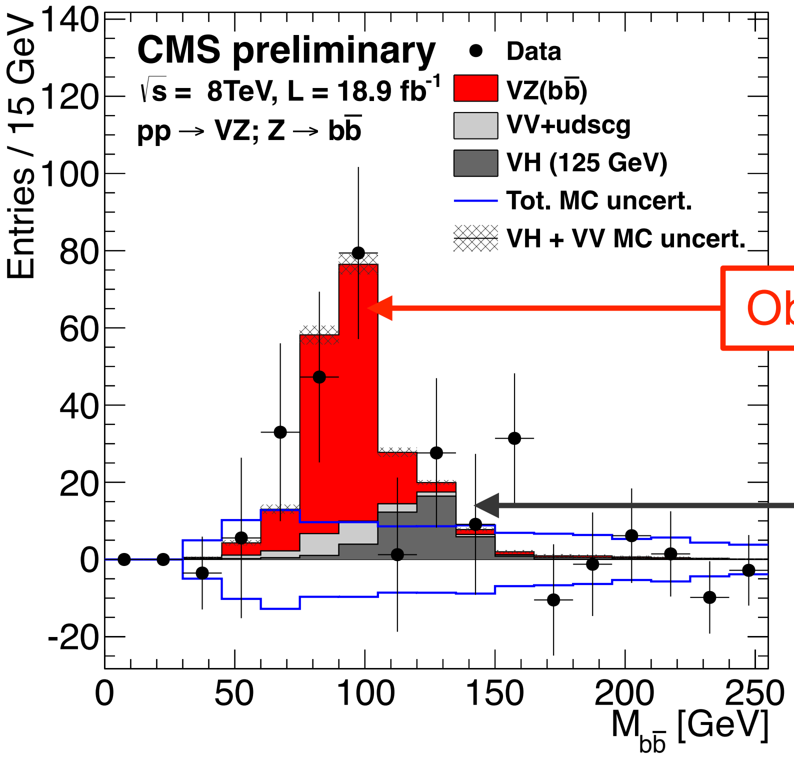
Butterworth, Davison, Rubin, Salam

arXiv: 0802.2470

- The best handle on Higgs coupling to down-type quark
  - boosted topology (where the two jets merge)
- Similar to boosted WW case
  - except: jet mass = Higgs mass, 2 b-tagged subjets

Evidence is building up

Un-boosted analysis, √s = 8 TeV, background subtracted

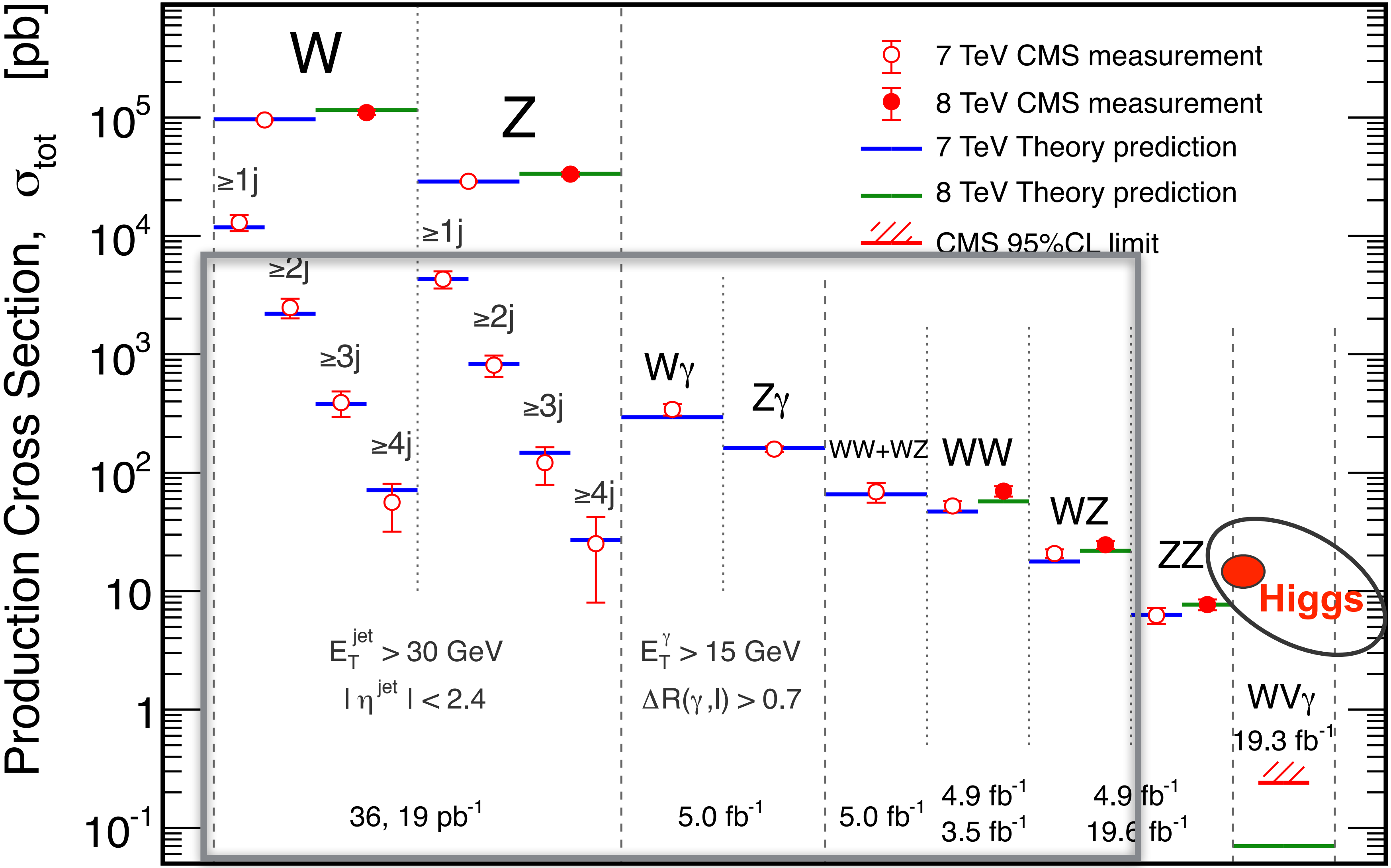


Observation of VZ with Z→bb

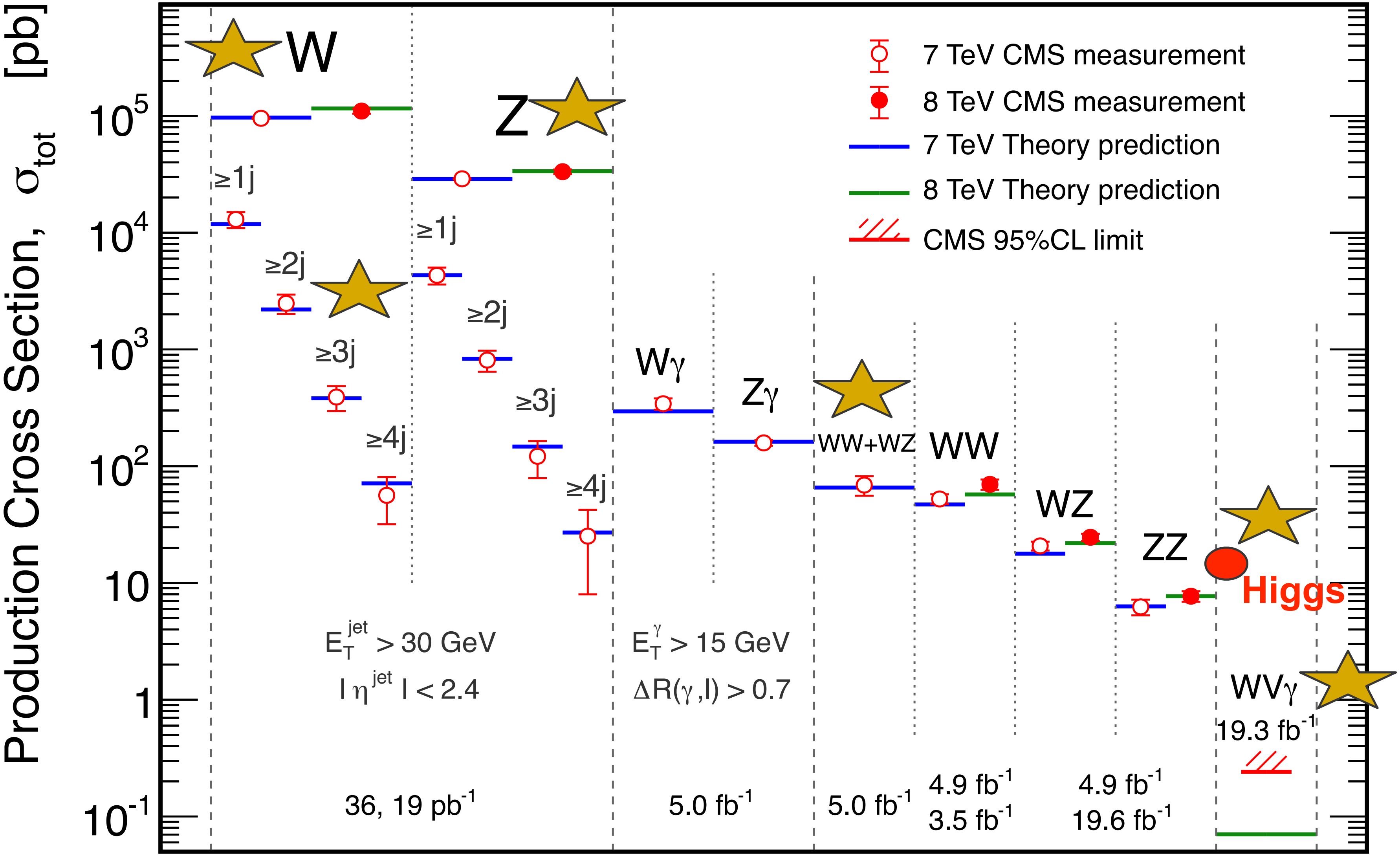
Hints of VH where H→bb

At 8 TeV the boosted topology had limited statistics, but at 13 TeV it will be the main driver. Expect > 3σ significance with 2015 data, 5σ possible.

Measurements of the background processes



My direct involvement



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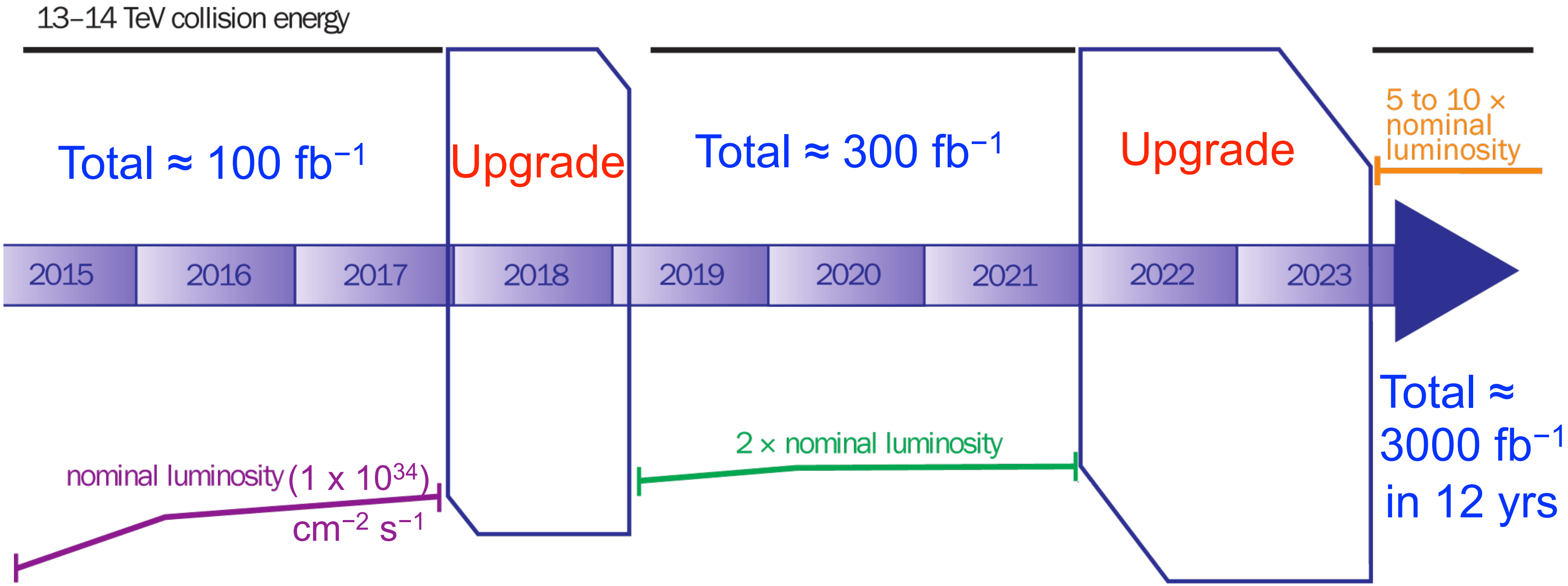
LHC 14 TeV program: the big picture

Current data size ≈ 25 fb^{-1} at 7/8 TeV



13–14 TeV collision energy

Total ≈ 100 fb^{-1}

Upgrade

Total ≈ 300 fb^{-1}

Upgrade

5 to 10 × nominal luminosity

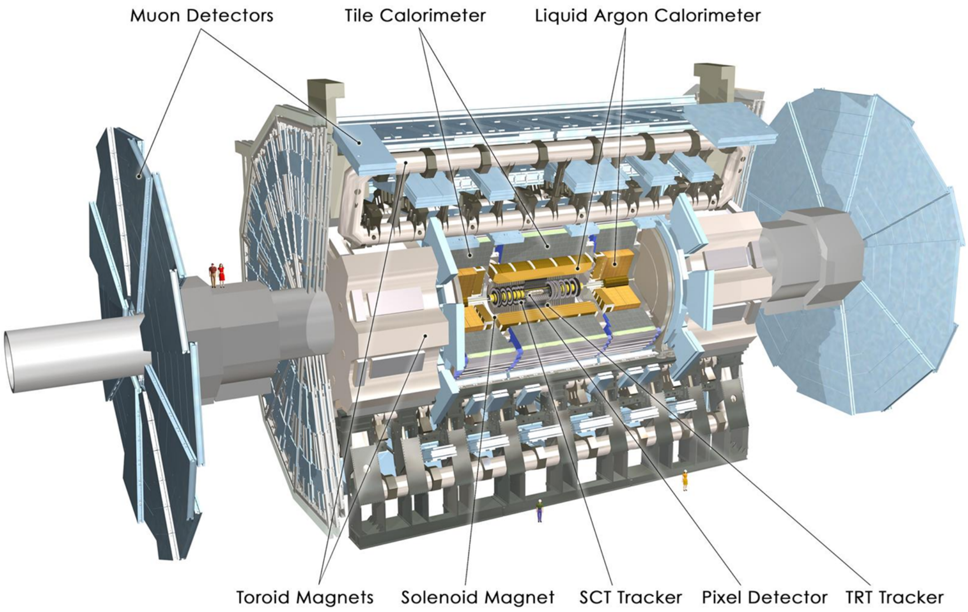
2015 2016 2017 2018 2019 2020 2021 2022 2023

nominal luminosity (1 x 10^{34}) $\text{cm}^{-2}\ \text{s}^{-1}$

2 × nominal luminosity

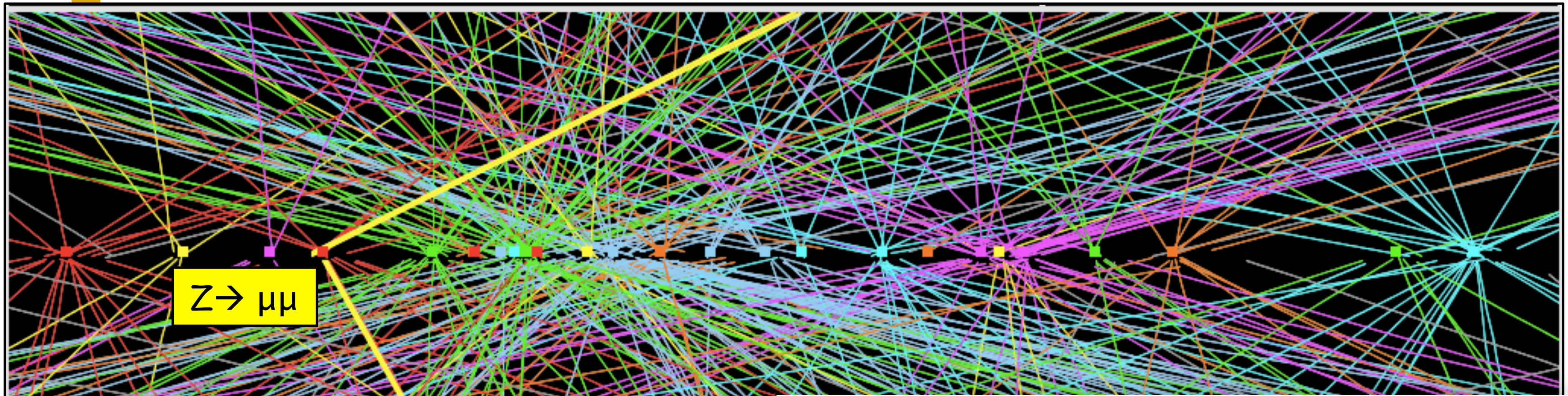
Total ≈ 3000 fb^{-1} in 12 yrs

ATLAS upgrade: why, when, how …

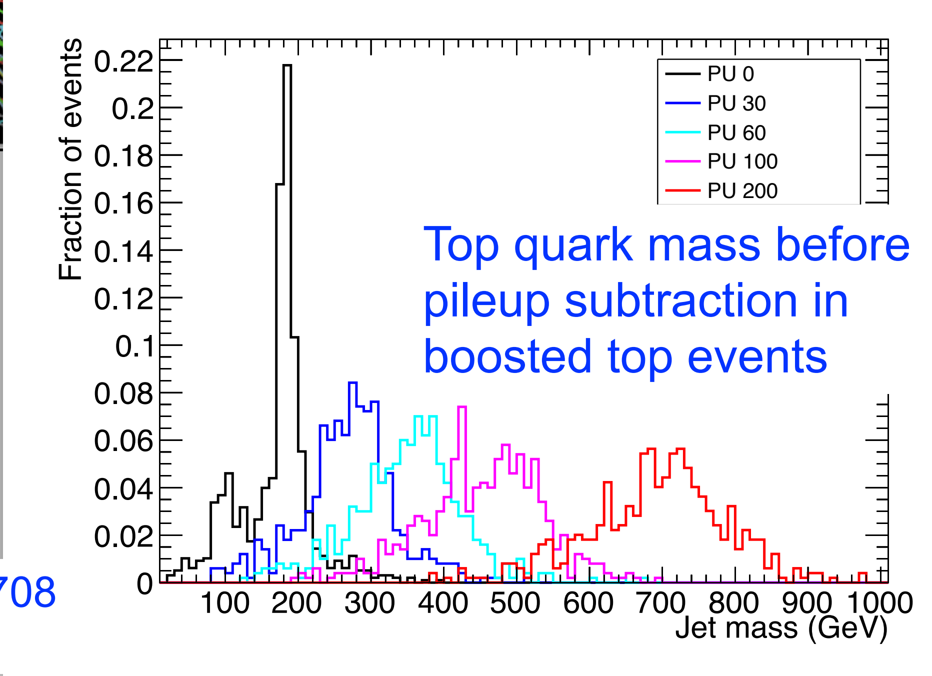


- **Why:** to keep trigger thresholds as low as possible for Higgs studies
  - Keep low inclusive/ di-object thresholds for e, μ, τ, γ
  - Despite high pileup
- **When:** phase-1:
  - During the shutdown of 2018
  - Major construction starting 2015
- **How:** next two slides ➜

Pileup



A Z boson event in ATLAS 2012 data with 25 reconstructed vertices

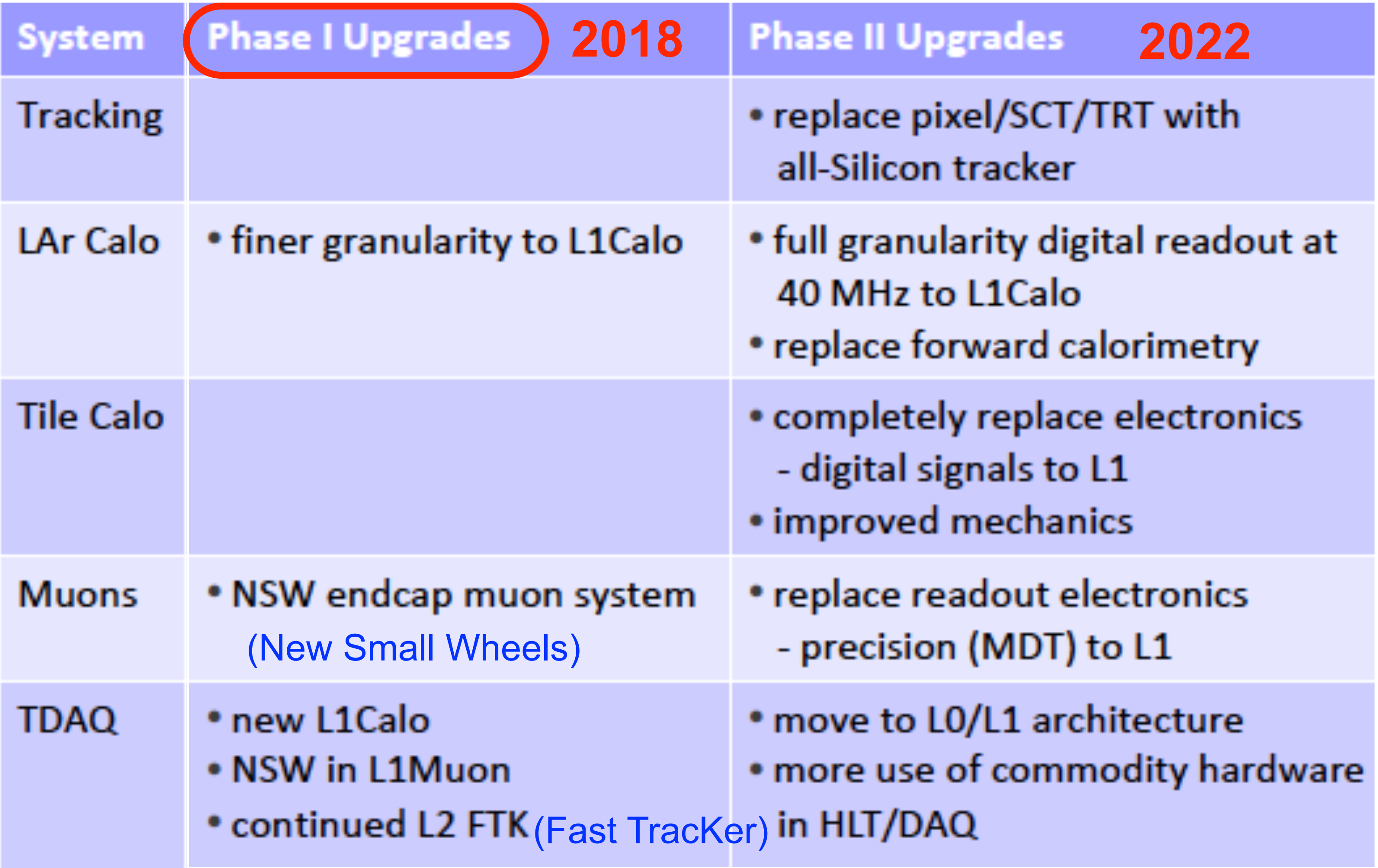


Top quark mass before pileup subtraction in boosted top events

Effect on object reconstruction →

BOOST 2012 report arXiv:1311.2708
To appear in *Eur J Phys* C

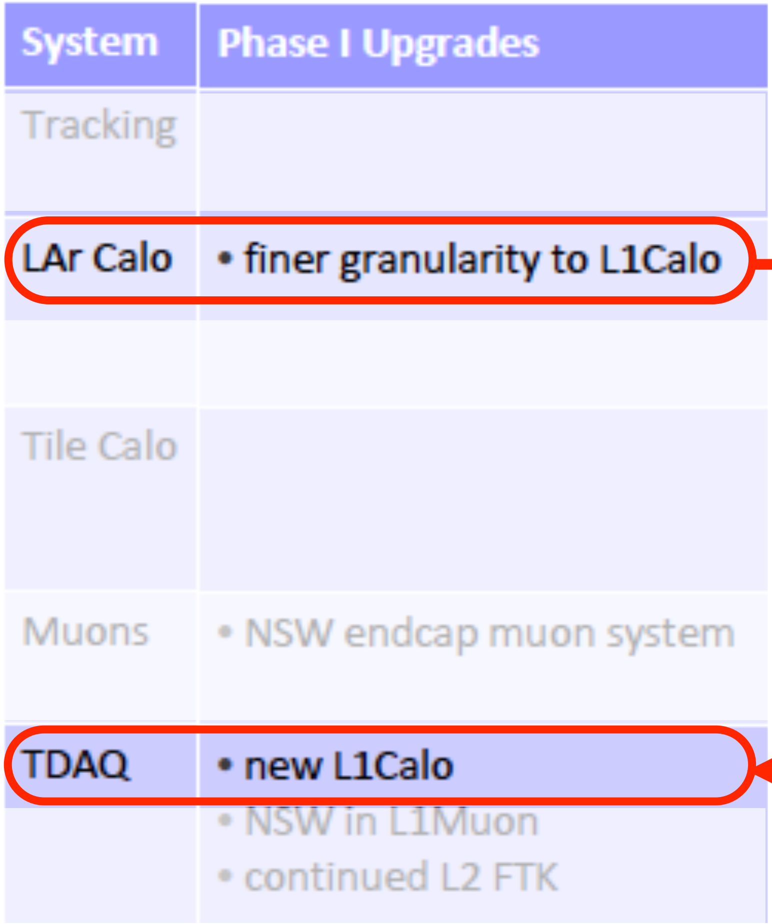
ATLAS upgrade plan presented to P5 in Dec 2013



System	Phase I Upgrades 2018	Phase II Upgrades 2022
Tracking		• replace pixel/SCT/TRT with all-Silicon tracker
LAr Calo	• finer granularity to L1Calo	• full granularity digital readout at 40 MHz to L1Calo • replace forward calorimetry
Tile Calo		• completely replace electronics - digital signals to L1 • improved mechanics
Muons	• NSW endcap muon system (New Small Wheels)	• replace readout electronics - precision (MDT) to L1
TDAQ	• new L1Calo • NSW in L1Muon • continued L2 FTK (Fast TracKer)	• move to L0/L1 architecture • more use of commodity hardware in HLT/DAQ

Source: H. Evans P5 HEP Workshop - Dec 5, 2013

Zooming in on Phase-1 upgrade



System	Phase I Upgrades
Tracking	
LAr Calo	• finer granularity to L1Calo
Tile Calo	
Muons	• NSW endcap muon system
TDAQ	• new L1Calo • NSW in L1Muon • continued L2 FTK

The projects

- Layer Sum Boards (ADCs, data format, optical xmit)
- Low Voltage (regulators and POL convertors)
- Back-end hardware and firmware
- FCAL Baseplanes

U.S. institutions

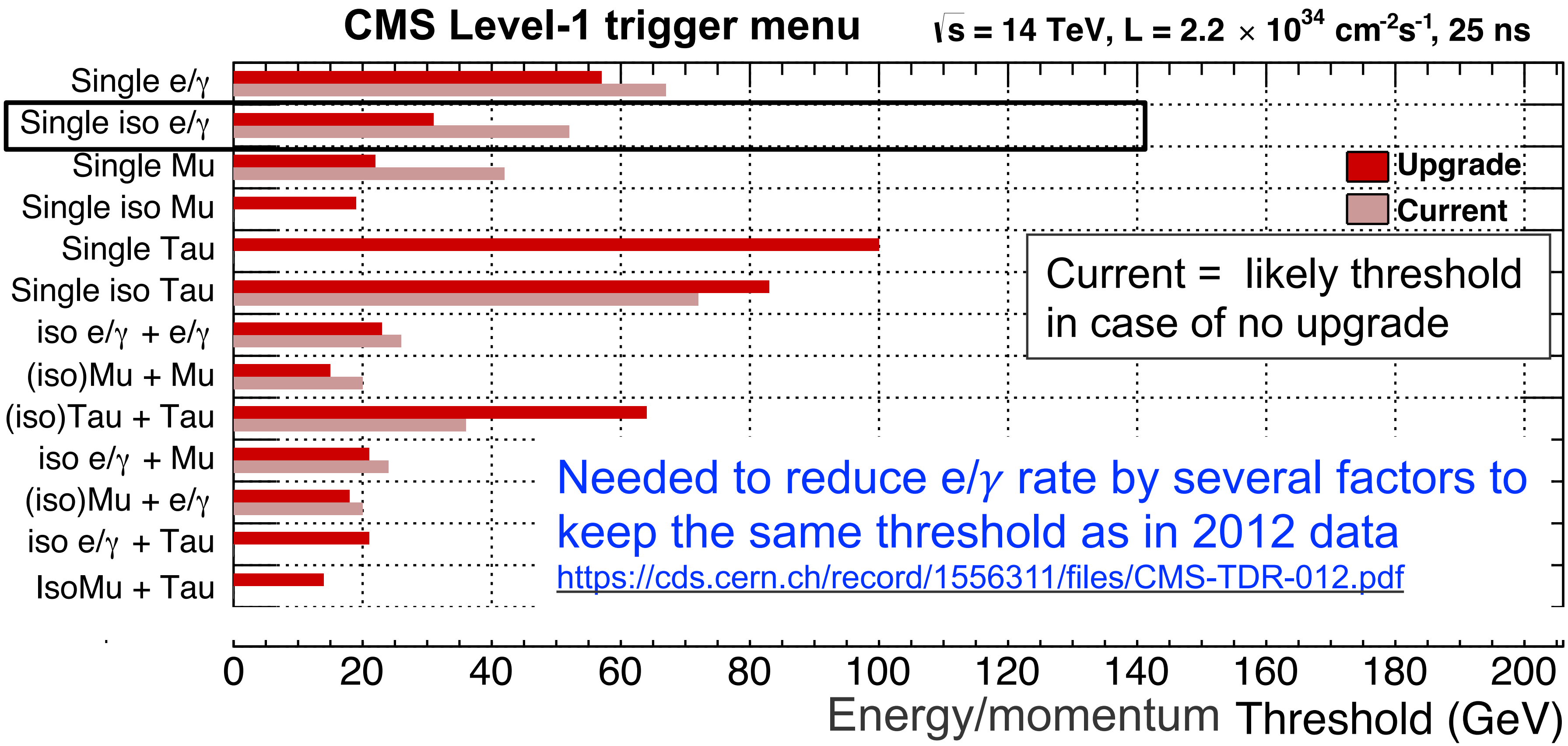
Arizona, BNL, Columbia, Oregon, Penn, Pitt, SMU, Stony Brook

Pitt: Front-end electronics which provides signal to hardware trigger

Source: H. Evans P5 HEP Workshop - Dec 5, 2013

CMS is trying to solve similar challenges

- I've been involved in calorimeter (Level-1) trigger upgrade for 2015
- Focused on the electron-photon-tau triggers



Current = likely threshold in case of no upgrade

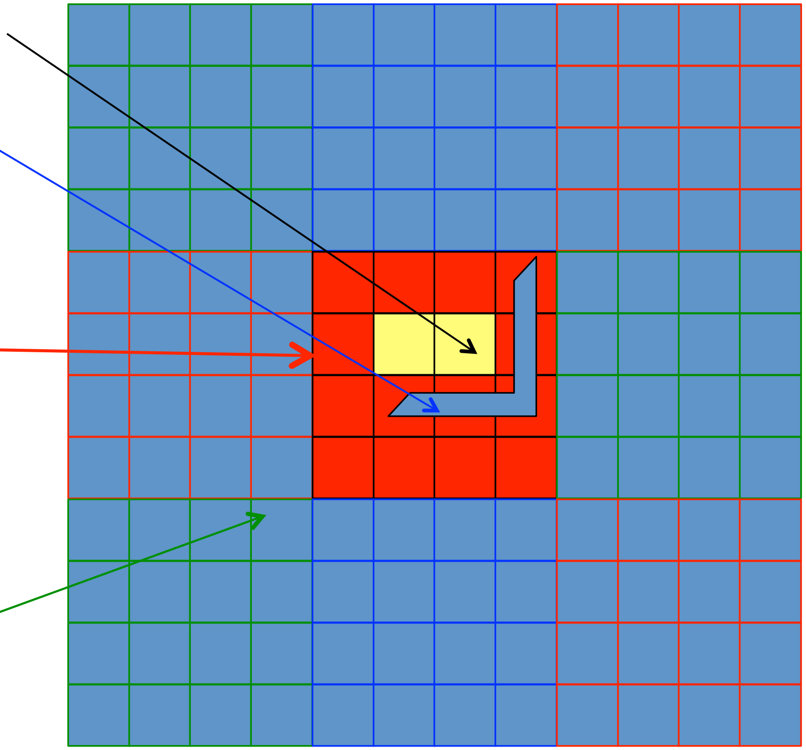
Needed to reduce e/γ rate by several factors to keep the same threshold as in 2012 data

https://cds.cern.ch/record/1556311/files/CMS-TDR-012.pdf

Where is the improvement coming from

- ☑ Improved object reconstruction at Level-1
- ☑ Pileup subtraction in jets and isolation sum at Level-1

2015 CMS Level-1 Calorimeter Trigger Algorithms



2x1 candidate is e/γ/τ using ECAL + HCAL

Local isolation for e/γ/τ

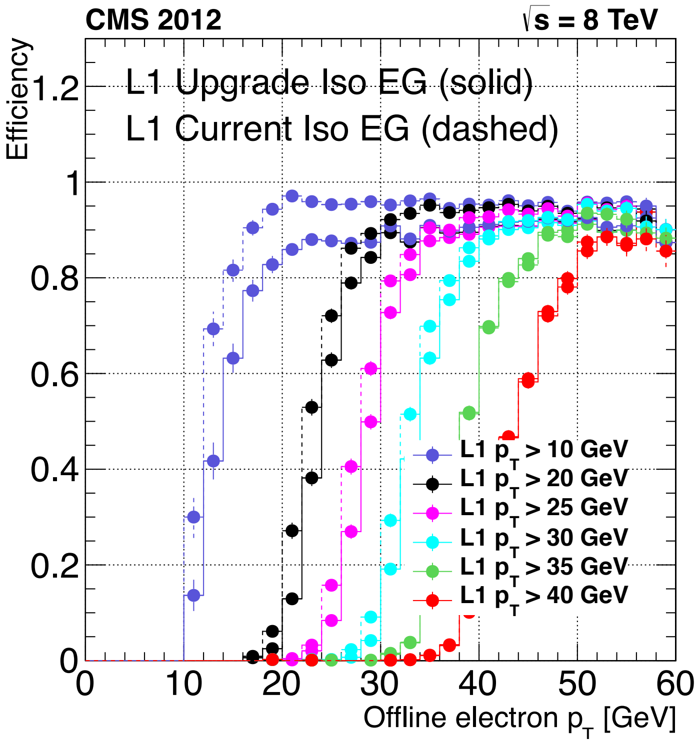
Regional ID

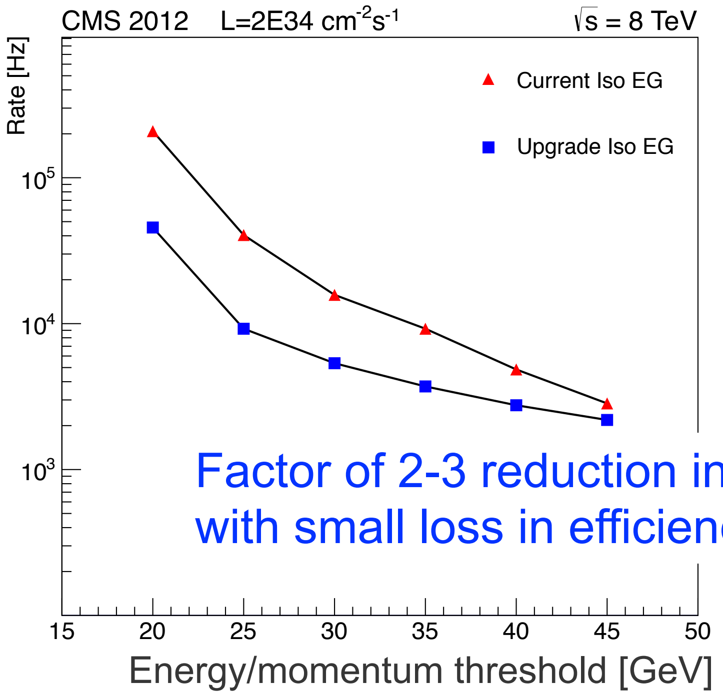
If 4x4 is EM rich it is an e/γ candidate

Pileup correction by 4x4 mean

My specific contributions to CMS upgrade

1. Developed pileup subtraction procedure
2. Computed trigger efficiencies and rates
3. Helping in the development of trigger emulator
4. Plan to help with firmware implementation of the algorithms and commissioning of the final electron/photon triggers





Factor of 2-3 reduction in rate with small loss in efficiency

My plans for ATLAS Phase-1 upgrade

Detailed plan for my integration into ATLAS in the next slides

- I am very excited about the opportunity to join Pitt’s ongoing involvement in the LAr front end electronics effort
- My skills are good match − and also complementary
- Important to present a coherent detector plan to ATLAS management and DOE ➜ for my integration in to the DOE grant in the next cycle
- In future, will consider the possibility to expand into Level-1 trigger territory depending on the resources and opportunity

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Plans for integration in ATLAS

Physics

- I have worked closely with ATLAS JetMet, boosted object, Higgs, and Standard Model communities (Snowmass, BOOST, confs, …)
- Expect to build on this familiarity very quickly
- My future physics plan is a natural evolution of my current research

Detector/ upgrade projects

- Will make every effort to join ATLAS Phase-1 upgrade asap
- My skills are good match − and also complementary − to Pittsburgh's responsibility in the LAr calorimeter electronics
- Consulting with Pitt ATLAS team on
  - how to get involved in Pitt's current responsibility
  - future possibility to expand into Level-1 trigger territory (dependent on resources and opportunity)

Continued …

Plans for integration in ATLAS

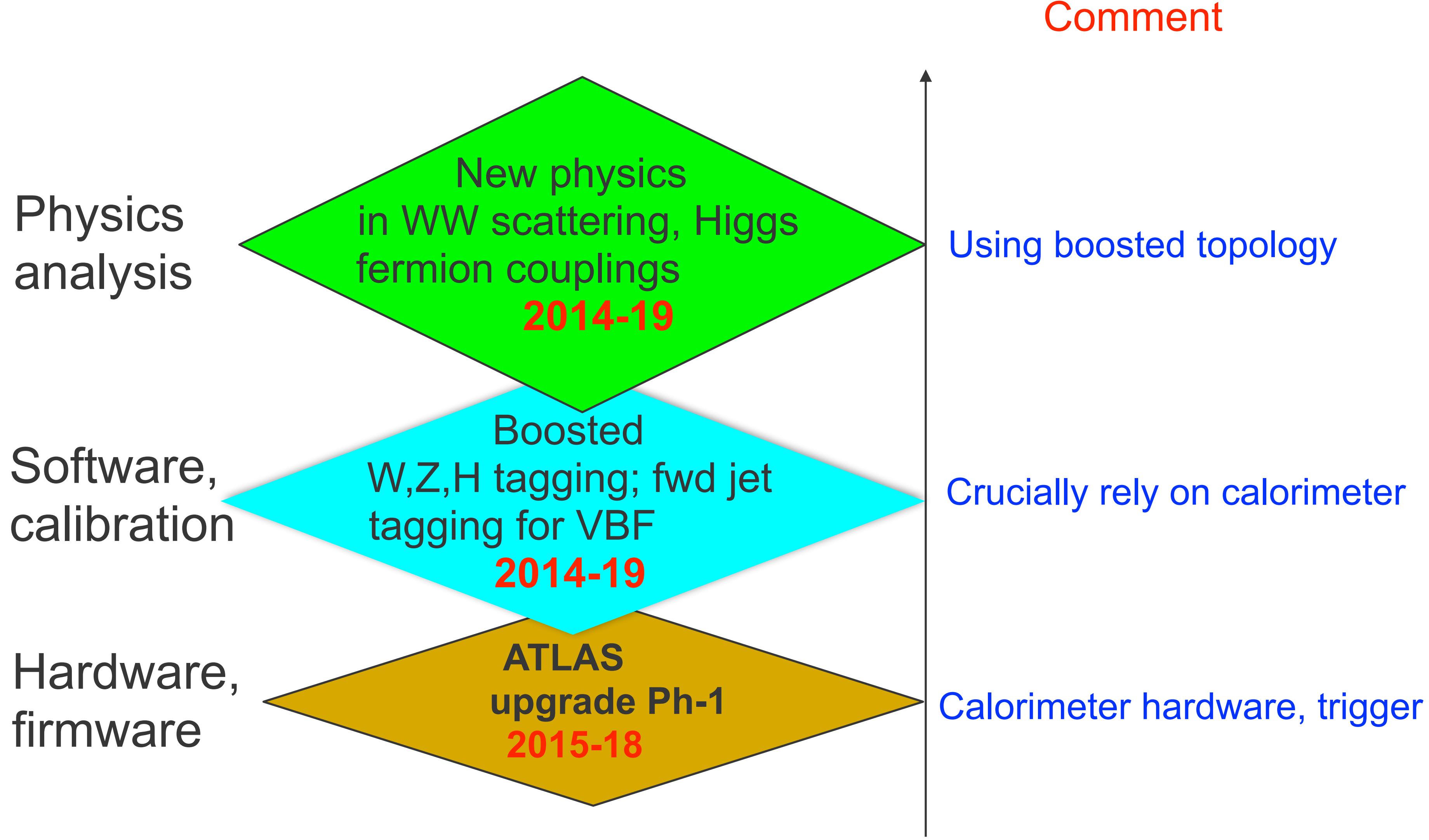
Logistics

- Will get informally involved in ATLAS asap
- Will move to CERN in late spring/summer to get to know ATLAS LAr calorimeter and Level-1 trigger teams
- Need 6 months service work (0.25 FTE) to become full member
  - Will start by taking shift during cosmic/commissioning runs
  - will explore the possibility to get involved with software/HLT efforts

Going forward (Fall 2014 and afterward)

- Depending on teaching responsibilities, plan to spend as much time as feasible at CERN
- Try to get US ATLAS ASC fellowship (can pay for travel to BNL/CERN)
- Work hard for the DOE Early Career award in 2015
- In consultation with other PIs, will work for a DOE grant to support my research program

Vision of vertical integration



Comment

Physics analysis

New physics in WW scattering, Higgs fermion couplings

2014-19

Using boosted topology

Software, calibration

Boosted W,Z,H tagging; fwd jet tagging for VBF

2014-19

Crucially rely on calorimeter

Hardware, firmware

ATLAS upgrade Ph-1

2015-18

Calorimeter hardware, trigger

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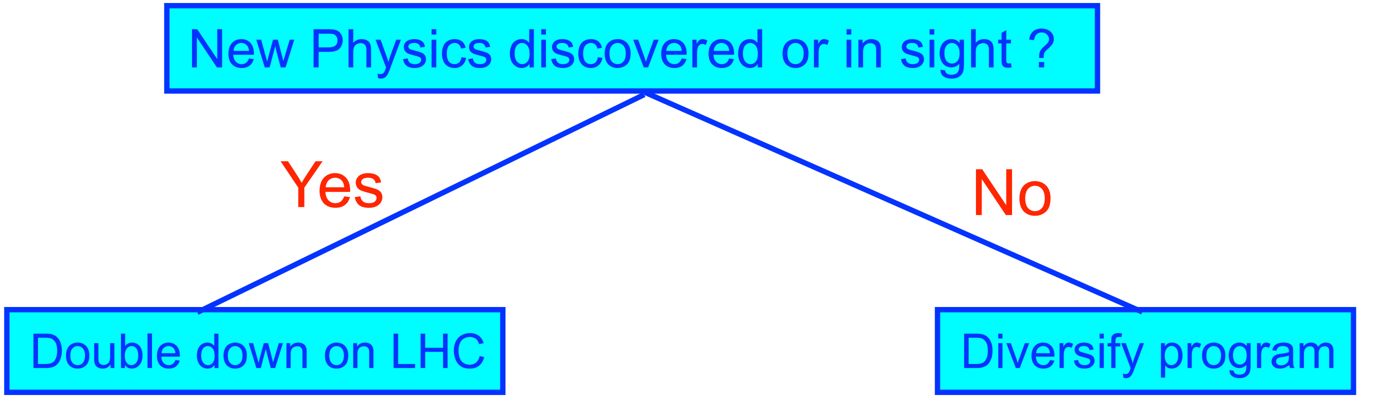
My plans beyond 2019

- Future is uncertain − dealing with this uncertainty is part of the plan
- Physics at LHC comes out fast − should have the main results from the LHC Run-2 (2015-18) completed by 2019
- Will recalibrate my research program in 2019 using a simple flow chart



New Physics discovered or in sight ?

Yes

Double down on LHC

Full steam ahead with ATLAS Phase-2 upgrade and analyze New Physics

No

Diversify program

Determined by the most exciting physics at the time: direct dark matter or LSST or LBNE or ILC

In the meanwhile, plan to take advantage of the PITT PACC and follow closely the LSST and direct dark matter detection experiments.

Outline

- Current status of the Higgs sector
- My overall plans for LHC_{14} until 2019
- Physics plans
- Detector/ upgrade plans
- Plans for integration in ATLAS
- Beyond 2019
- ☑ **Summary**

Summary

Plan to focus on three key areas

1. New phenomena in WW scattering
2. Higgs coupling to b quark in the associated production mode (WH, ZH with $H\to b\bar{b}$)
3. ATLAS Phase-1 upgrade (for the long shutdown 2018)

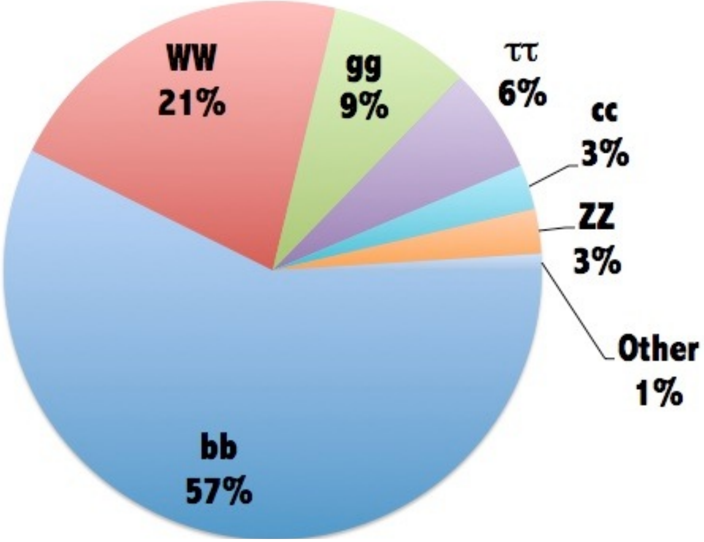
☑ I am very excited about the possibility to join the Pittsburgh ATLAS team to harvest data from LHC 14 TeV run

- plan to get involved as soon as possible
- so that I can hit the ground running

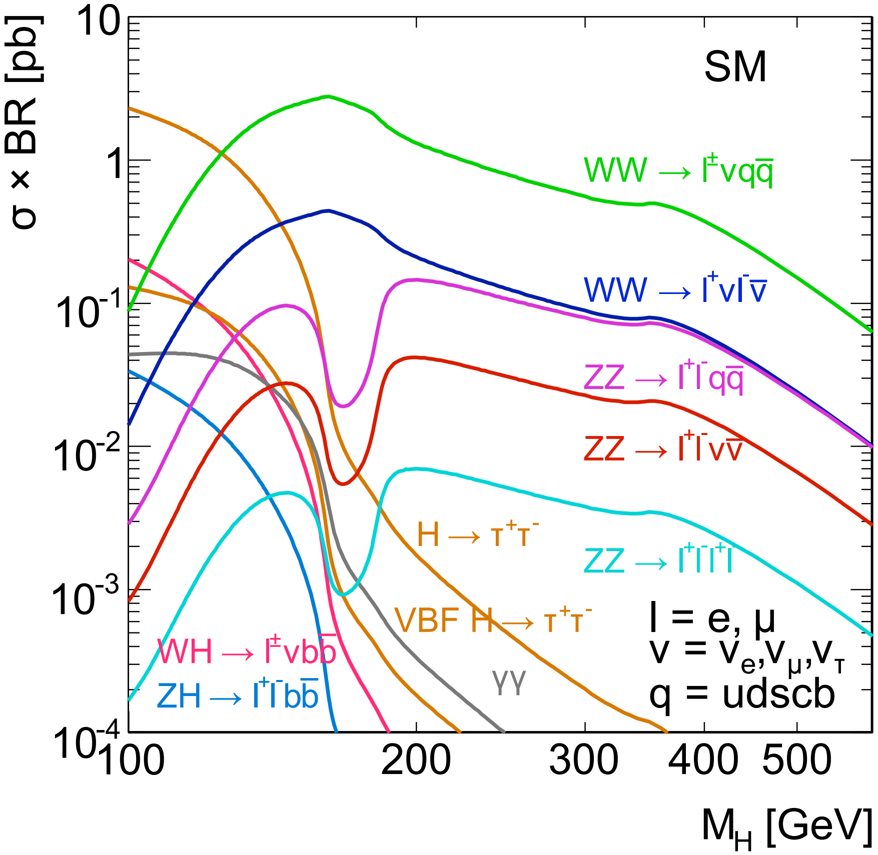
BACKUP SLIDES

How does it decay

Branching fraction of H(125)



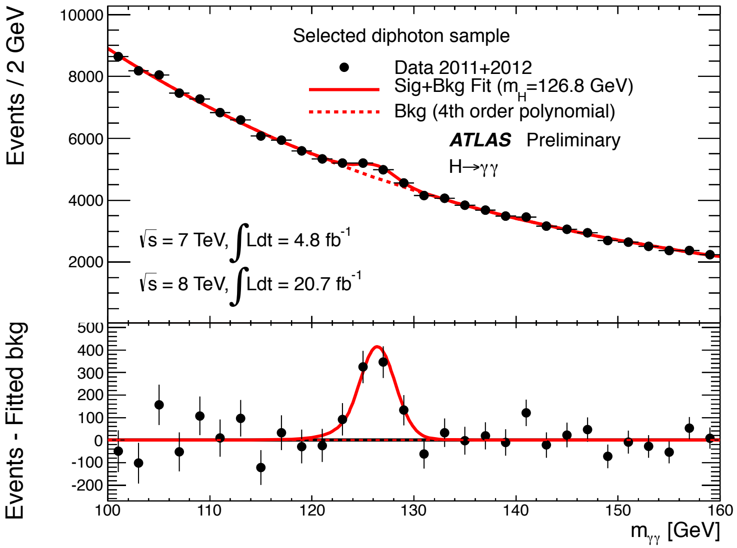
At LHC, we measure cross section x branching fraction

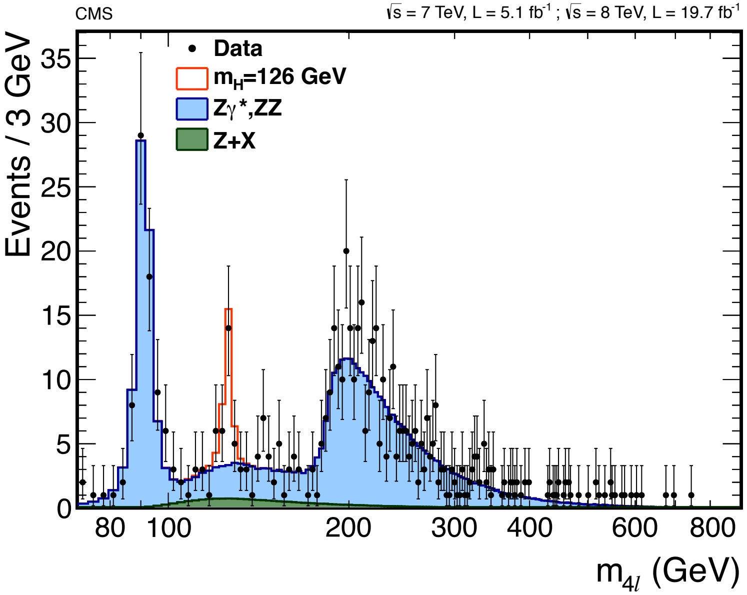


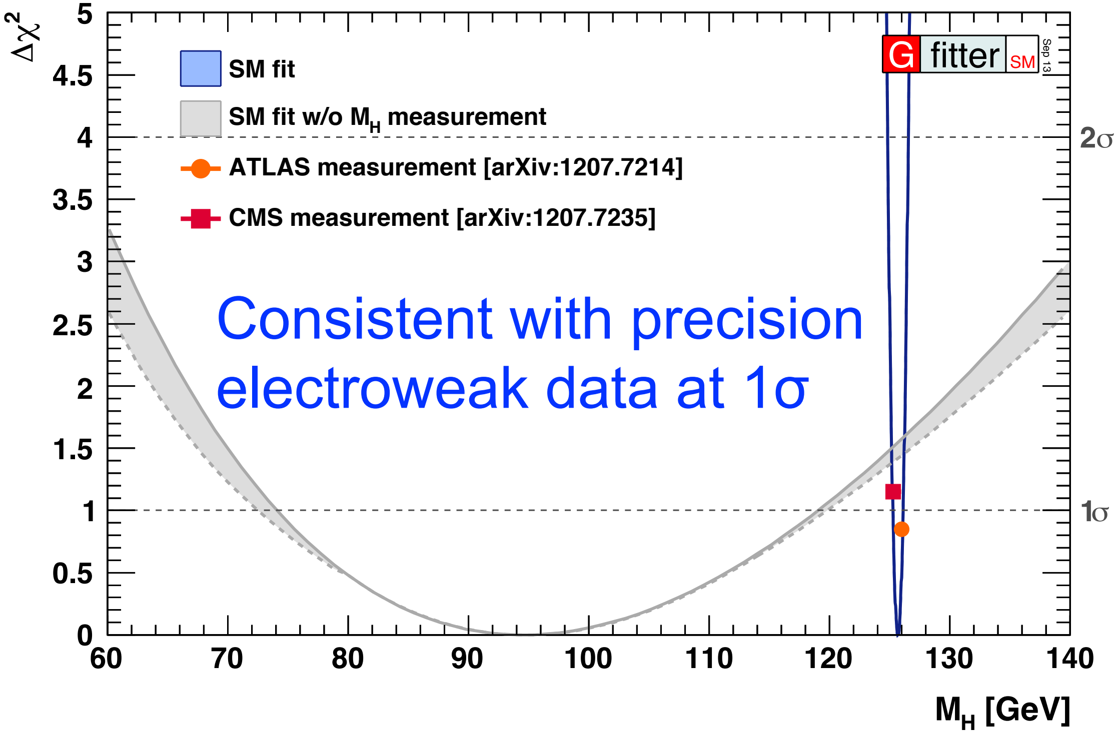
Higgs mass

Measured in diphoton and ZZ* decay modes

ATLAS: 125.5 ± 0.6 GeV
CMS: 125.7 ± 0.4 GeV

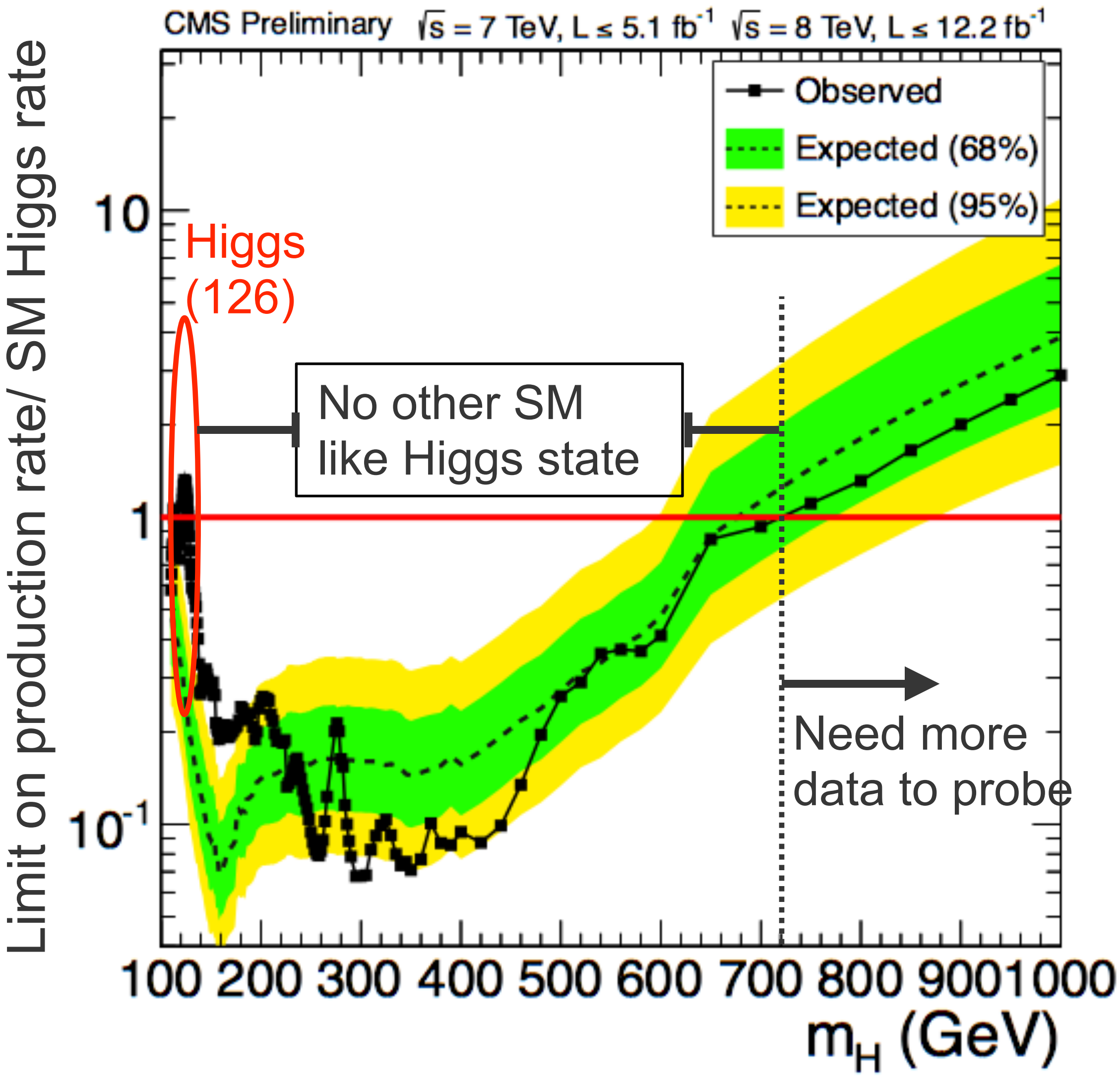






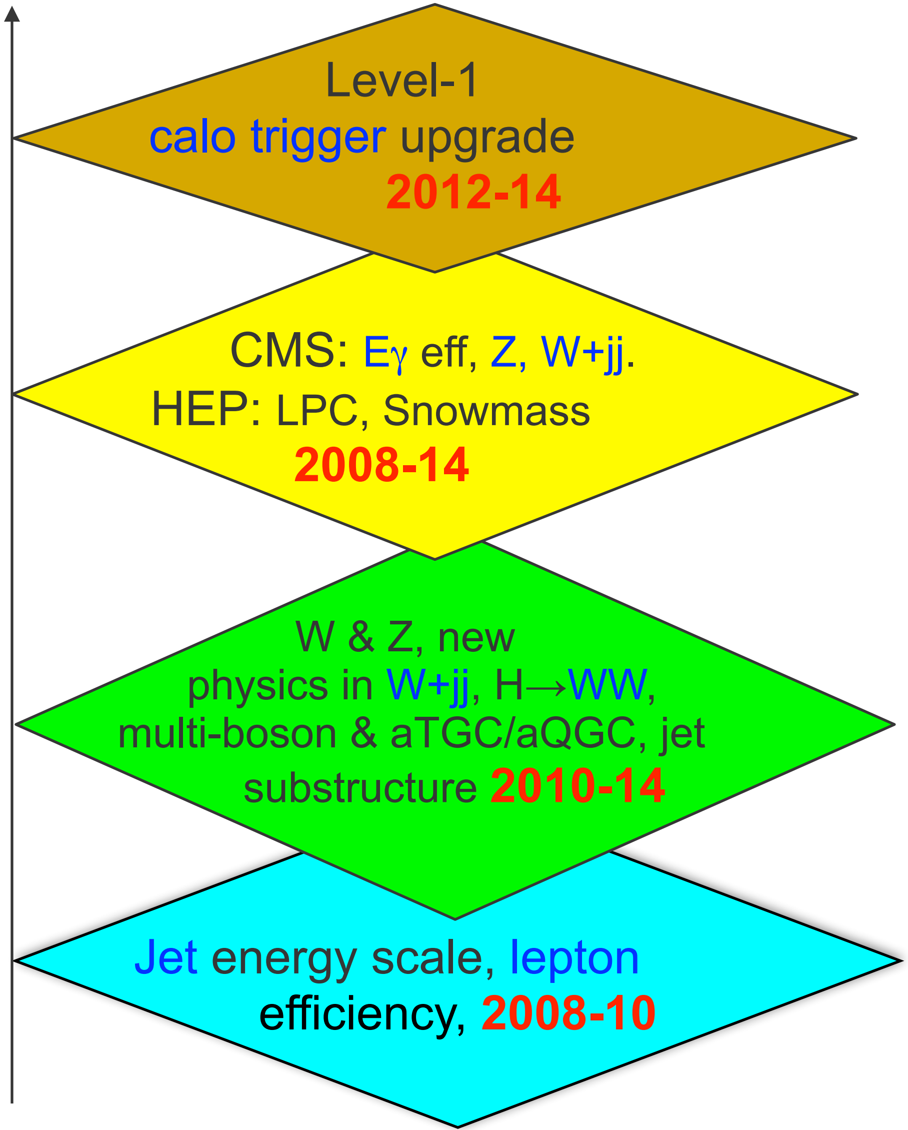
Consistent with precision electroweak data at 1σ

No hints of high mass or exotic Higgs so far



- Search including all WW and ZZ channels
  - I've been closely involved with this
- No additional Higgs states up to 700 GeV
- Interesting territory > 700 GeV yet to probe

Vertical integration as a postdoc



Major milestones

Hardware, firmware

Level-1 calo trigger upgrade 2012-14

Pileup subtraction for jets and lepton isolation at L1.

Leadership

CMS: $E\gamma$ eff, Z, W+jj.
HEP: LPC, Snowmass
2008-14

Editor / contact for most of my analyses. Organized workshops & confs. Led BOOST-12 pileup subgroup.

Physics analysis

W & Z, new physics in W+jj, $H\to WW$, multi-boson & aTGC/aQGC, jet substructure 2010-14

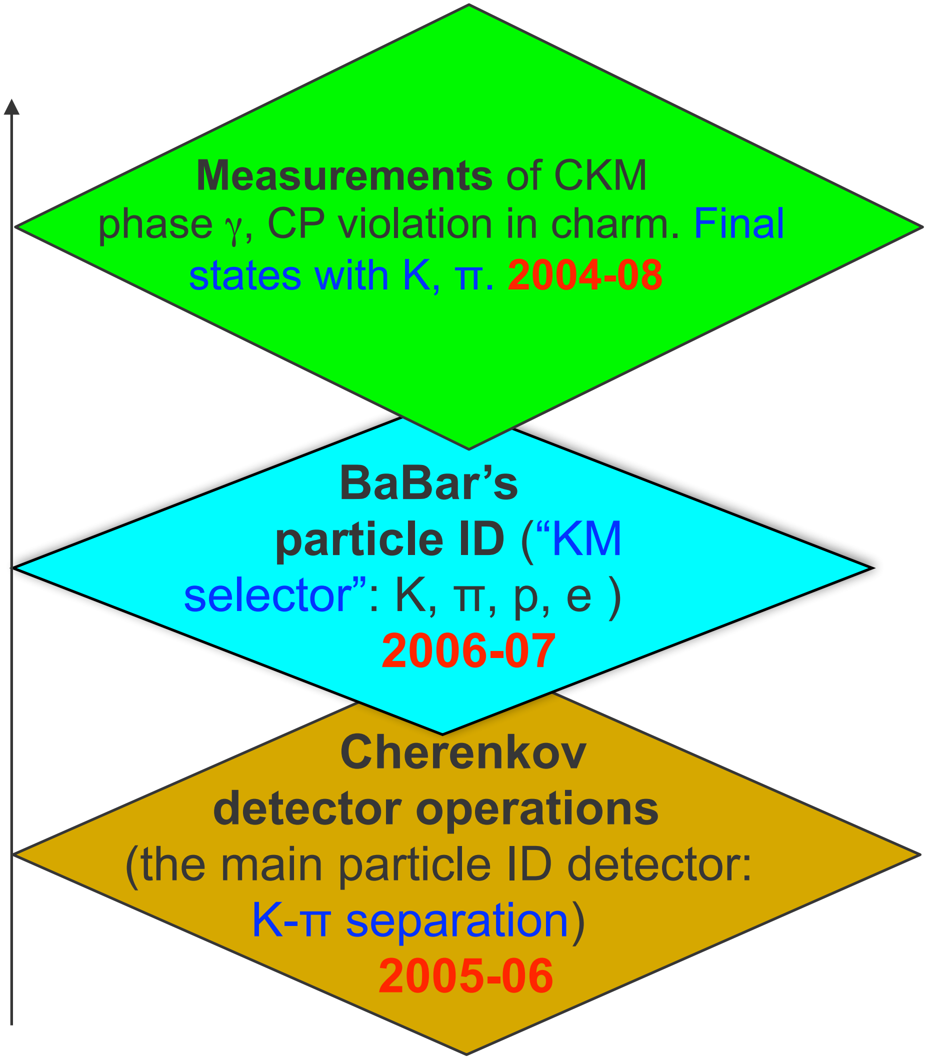
Got $H\to WW\to \ell\nu jj$ on the map! Stringent limit on aTGC /aQGC. Comprehensive measure of jet substructure.

Software, calibration

Jet energy scale, lepton efficiency, 2008-10

Achieved JES uncertainty < 3%, lepton reco/trig uncertainty < 1-2%.

Vertical integration as a grad student



Major milestones

Physics analysis

Measurements of CKM phase γ, CP violation in charm. Final states with K, π. **2004-08**

Pioneered the technique of combining phase info and decay rates. Set upper limit on direct CP violation in charm decays at 1% level.

Software, calibration

BaBar's particle ID ("KM selector": K, π, p, e) **2006-07**

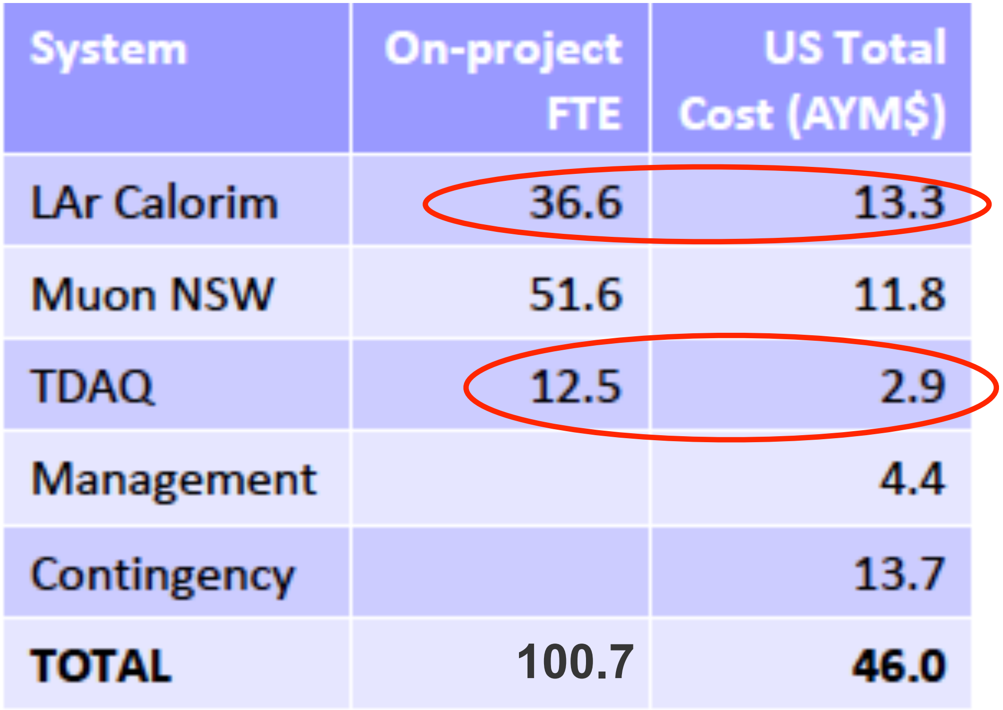
In use in BaBar to this date. Improved K-π mis-ID by a factor of 2, b-tag by 20%.

Hardware, firmware

Cherenkov detector operations (the main particle ID detector: K-π separation) **2005-06**

Ran operations during 2005-06. Led upgrade tasks during summer '05 shutdown

US-ATLAS upgrade project is well funded



System	On-project FTE	US Total Cost (AYM$)
LAr Calorim	36.6	13.3
Muon NSW	51.6	11.8
TDAQ	12.5	2.9
Management		4.4
Contingency		13.7
TOTAL	100.7	**46.0**

DOE+NSF 5-year project

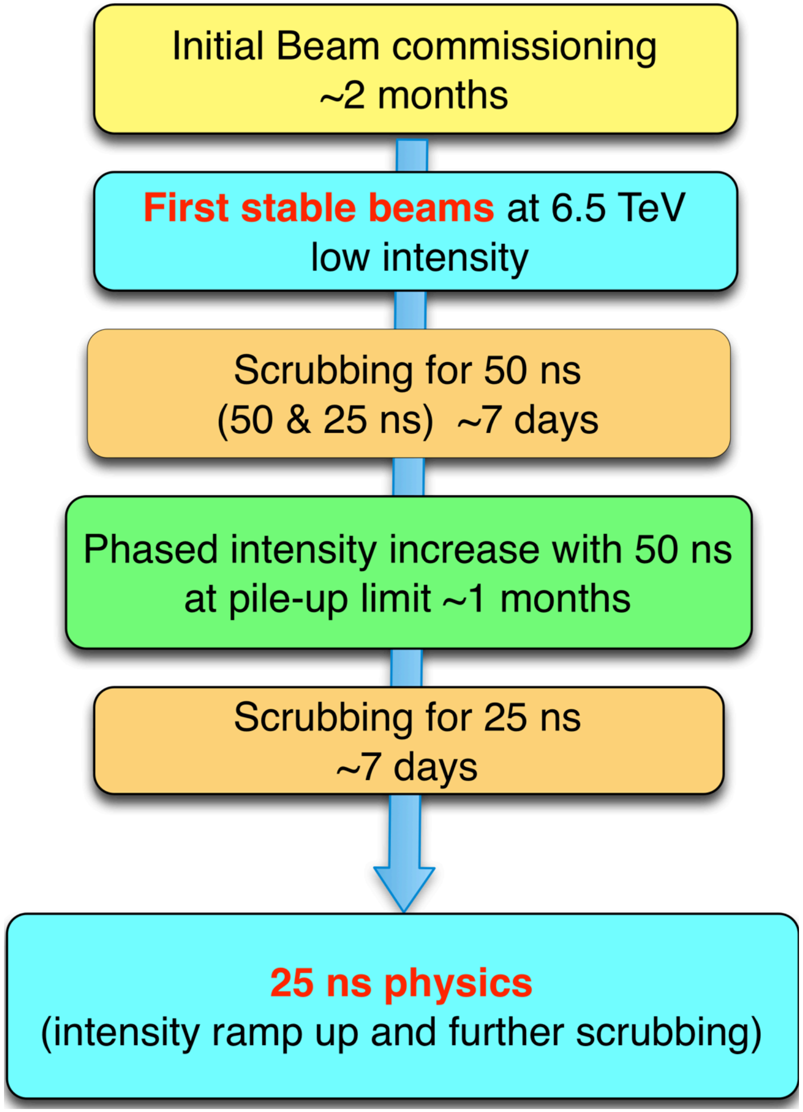
DOE CD-0 approval:	Aug. 2011
formal project launch:	Nov. 2012
NSF proposal submitted:	Jun. 2013
DOE CD-1 approval:	Sep. 2013

Total project cost over 5 yrs = 46 million US$

- LAr calorimeter + Level-1 calorimeter trigger is a significant fraction (≈ 1/3 rd) of the this effort

Source: H. Evans P5 HEP Workshop - Dec 5, 2013

The latest LHC startup plan for 2015



Initial Beam commissioning
~2 months

First stable beams at 6.5 TeV
low intensity

Scrubbing for 50 ns
(50 & 25 ns) ~7 days

Phased intensity increase with 50 ns
at pile-up limit ~1 months

Scrubbing for 25 ns
~7 days

25 ns physics
(intensity ramp up and further scrubbing)

February-March

March end

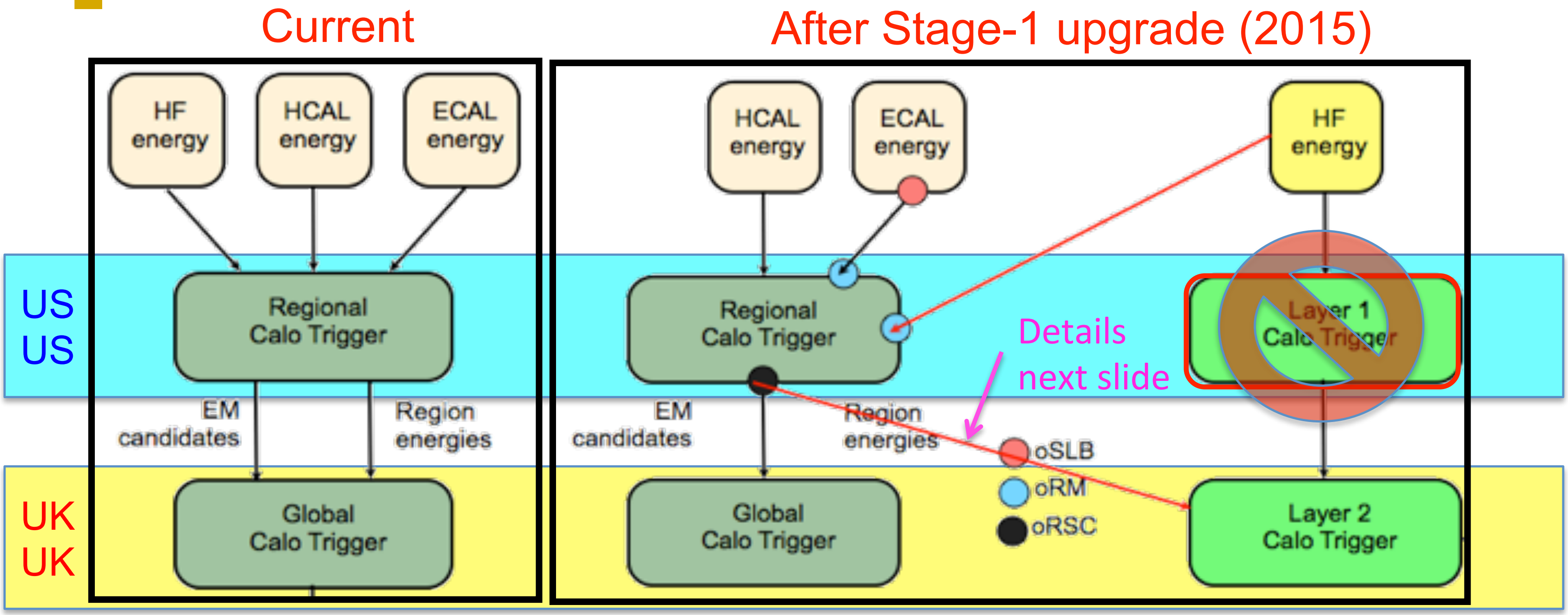
April

April-May

Energy: 6.5 TeV
Bunch spacing:
25 ns

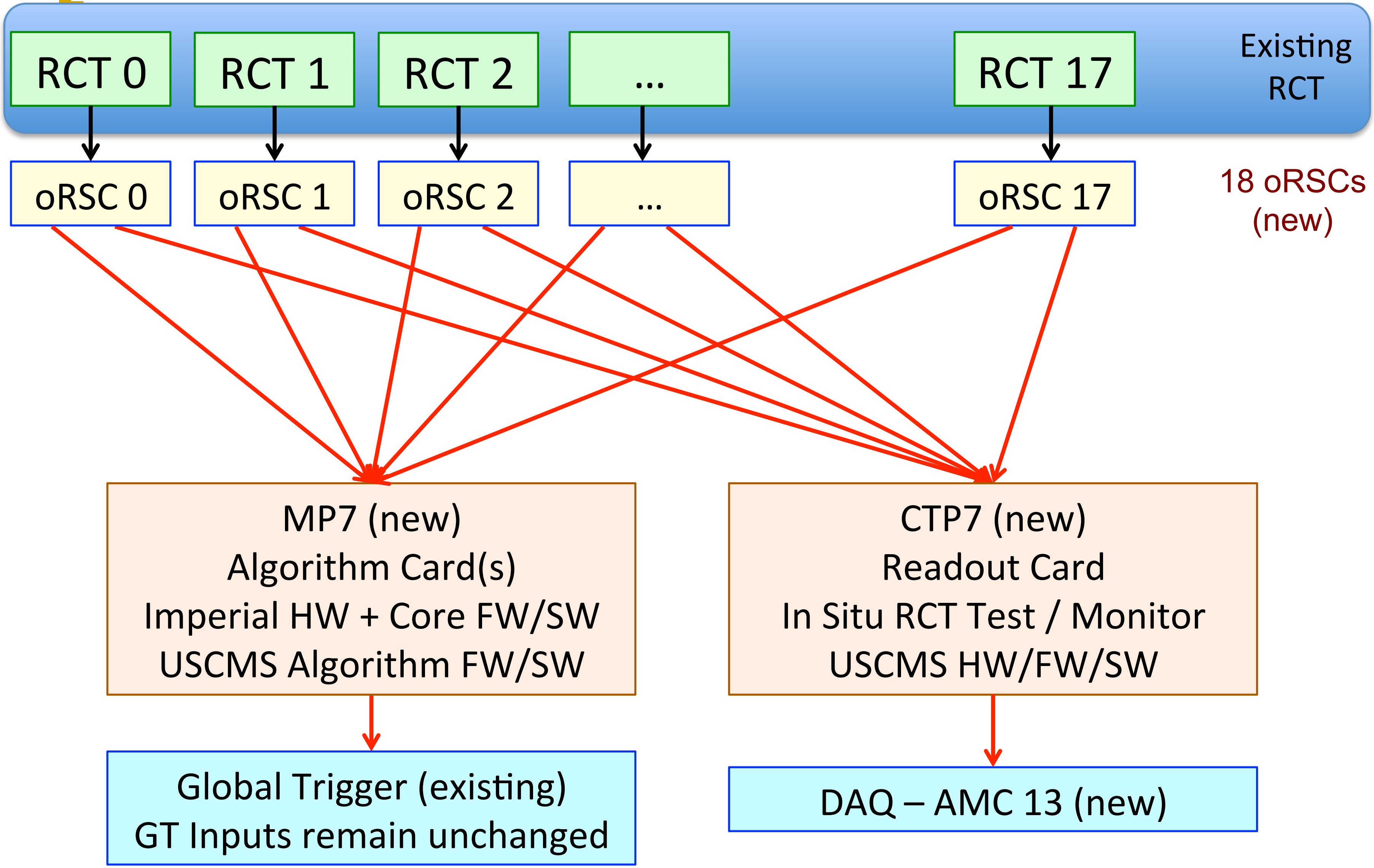
Stable running until 2018, except for breaks at the year end and machine maintenance downtime

CMS current & Stage-1 calorimeter trigger



- Stage 1 Calorimeter Trigger Upgrade
  - Improved processing of current RCT with new oRSC
  - Converts current system to optical
  - New HF (fwd calo) data is available to upgrade path⇐ descope
    - HF Data still available via legacy path through oRSC
  - Prepare for the Stage 2 Upgrade
  - Layer 1 cards will also read out RCT in Stage 1

CMS stage-1 Upgrade in 2015



Existing RCT

RCT 0

RCT 1

RCT 2

…

RCT 17

oRSC 0

oRSC 1

oRSC 2

…

oRSC 17

18 oRSCs (new)

MP7 (new)
Algorithm Card(s)
Imperial HW + Core FW/SW
USCMS Algorithm FW/SW

CTP7 (new)
Readout Card
In Situ RCT Test / Monitor
USCMS HW/FW/SW

Global Trigger (existing)
GT Inputs remain unchanged

DAQ – AMC 13 (new)

Dealing with high pileup conditions

Created a huge experimental challenge

So much that the entire community with stake in its resolution got together …

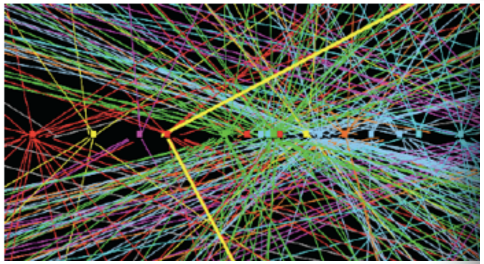
Jet substructure performance at high luminosity
BOOST 2012 working group

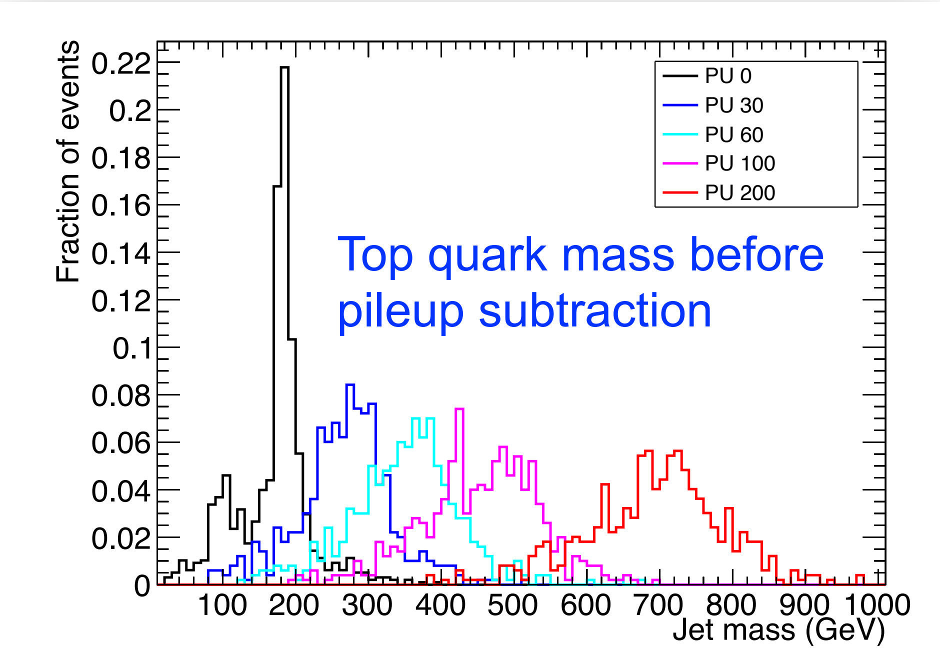
Conveners: Gregory Soyez and Ariel Schwartzman

Pile-up subtraction plus grooming

Coordinator: Mishra Kalanand

- Study the application of jet-areas pile-up subtraction during grooming

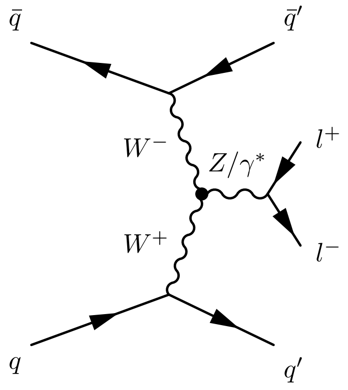


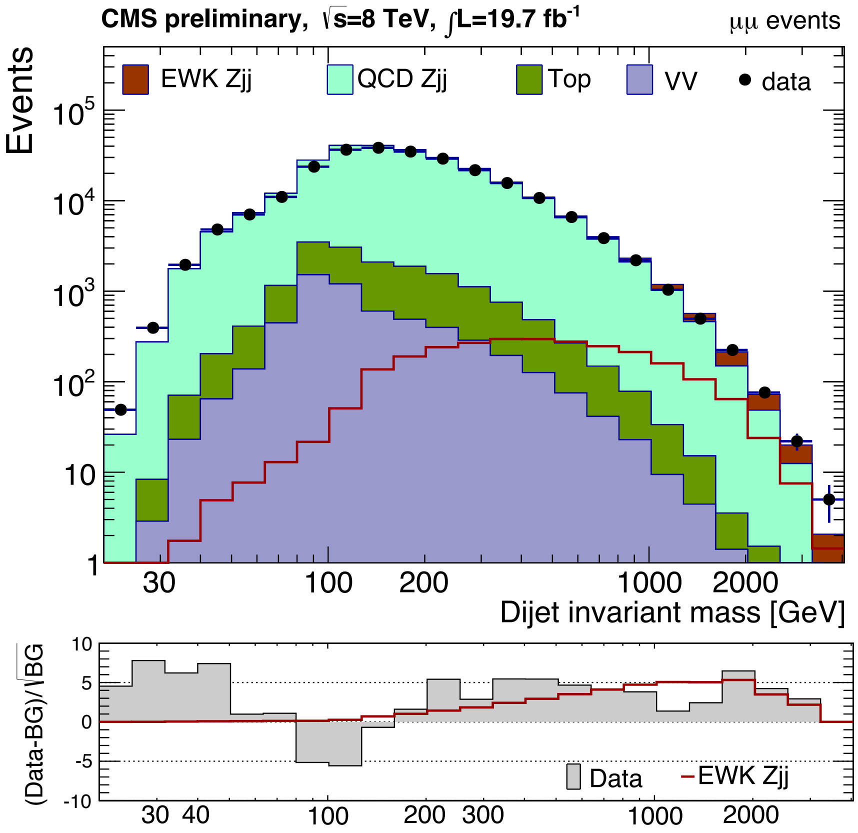


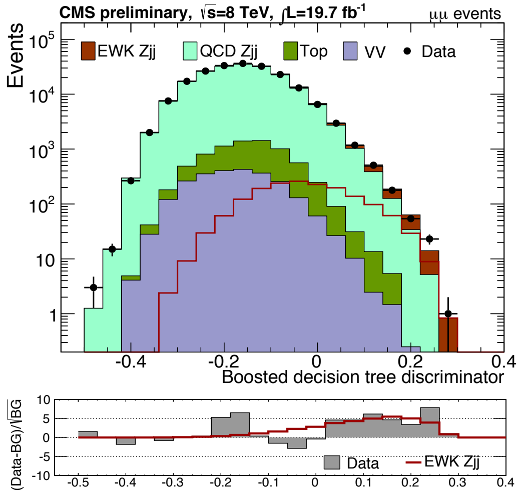
Top quark mass before pileup subtraction

BOOST 2012 report
arXiv:1311.2708
To appear in *Eur J Phys* C

Measurement of VBF production of Z





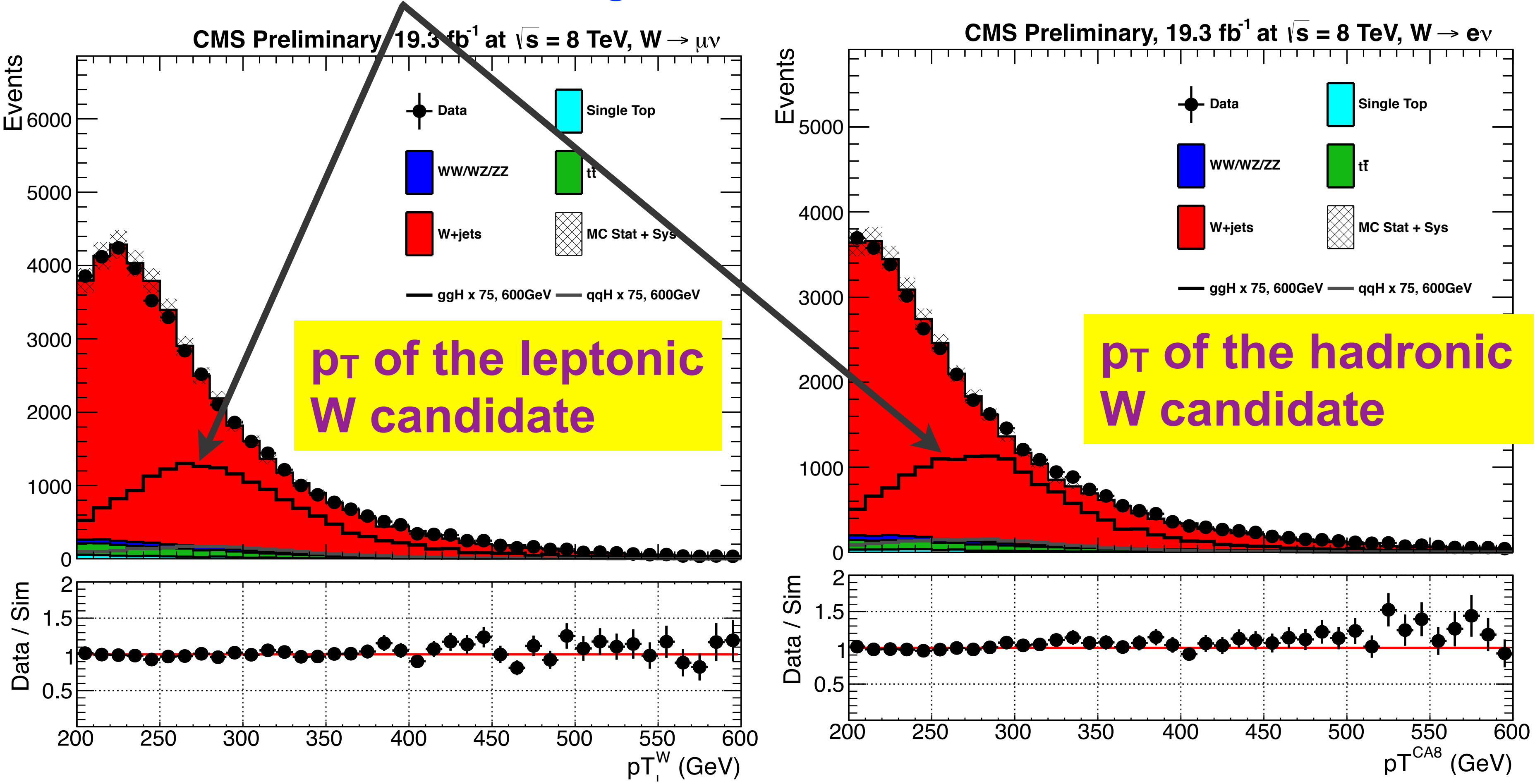


The measurement of the electroweak production cross section of a Z-boson with two forward/backward jets (EWK Z jj): **σ=226 ± 26 (stat) ± 35 (syst) fb**

Consistent with SM expectations

Why the boosted analysis?

Because the signal events have boosted Ws

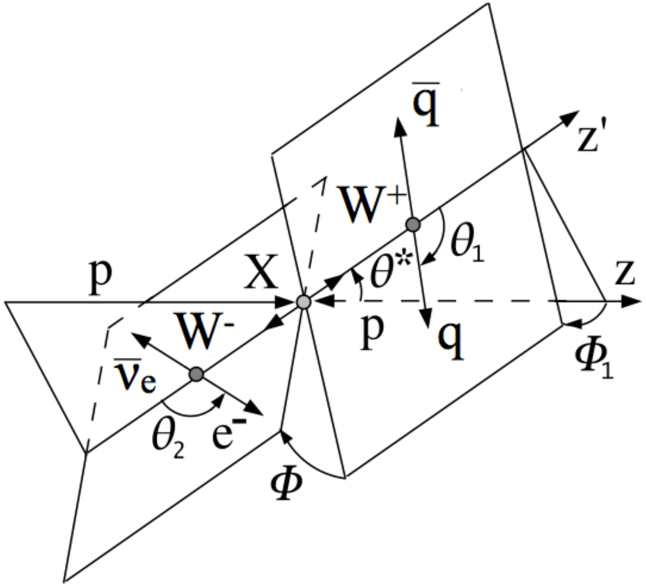


p_T of the leptonic W candidate

p_T of the hadronic W candidate

Also, otherwise the background becomes overwhelming

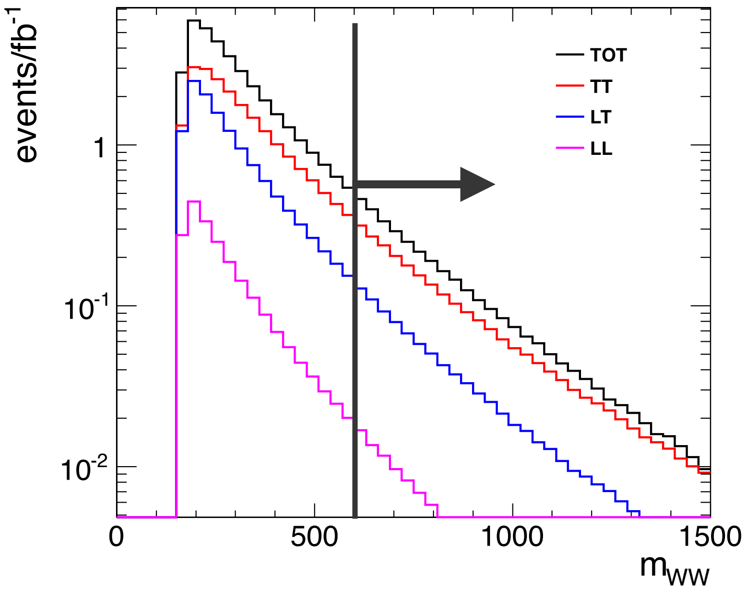
Enhancing the longitudinal W components

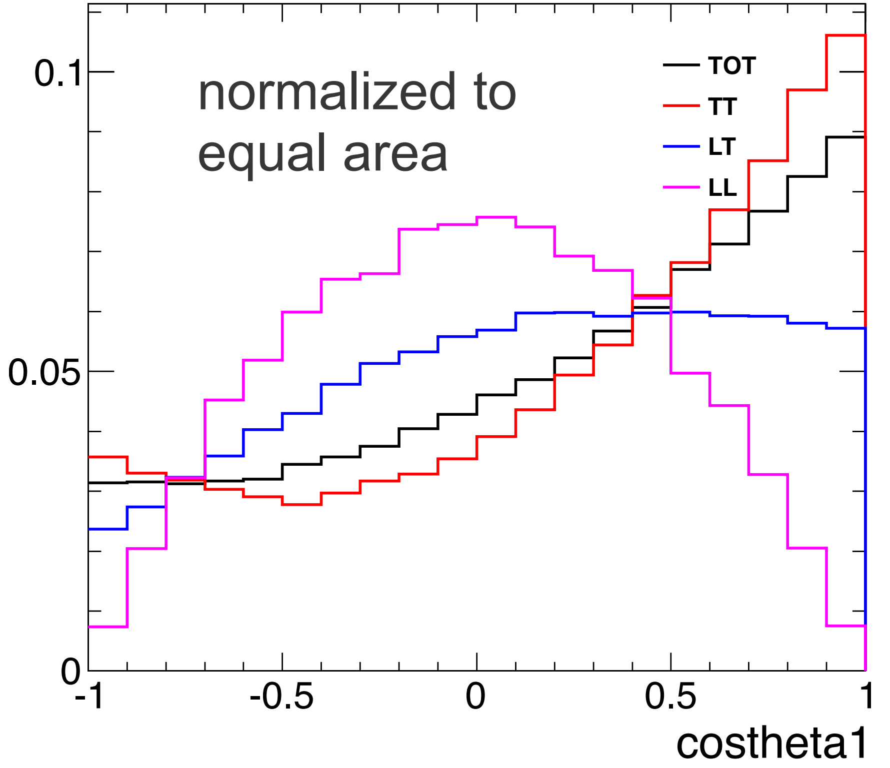


WW kinematics described by 5 angles

$\{\theta_1, \theta_2, \theta^*, \phi, \phi_1\}$

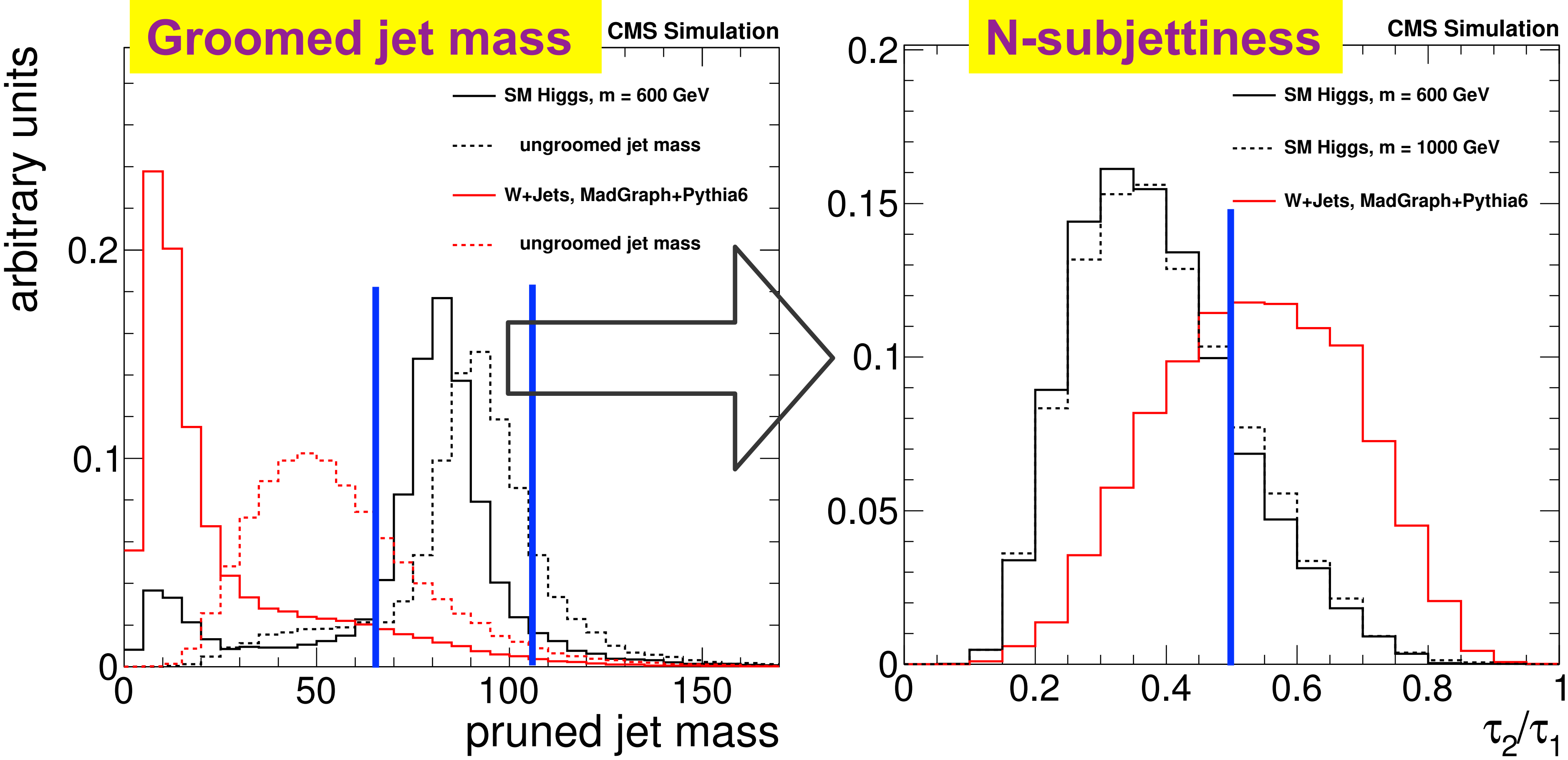
- These angles can help enhance W_LW_L





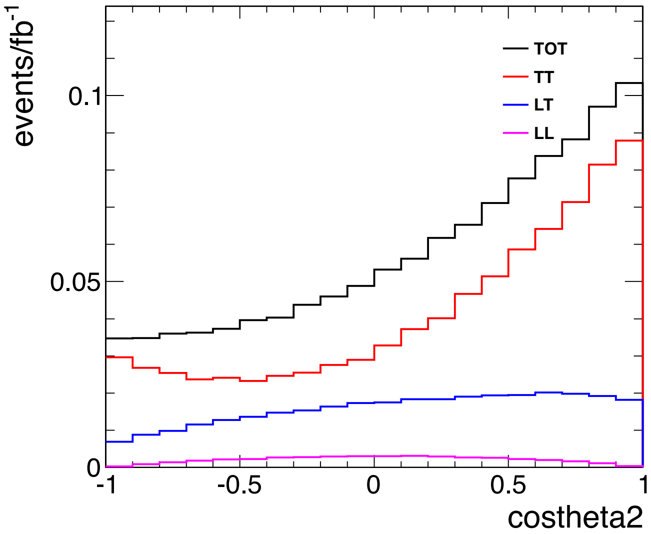
normalized to equal area

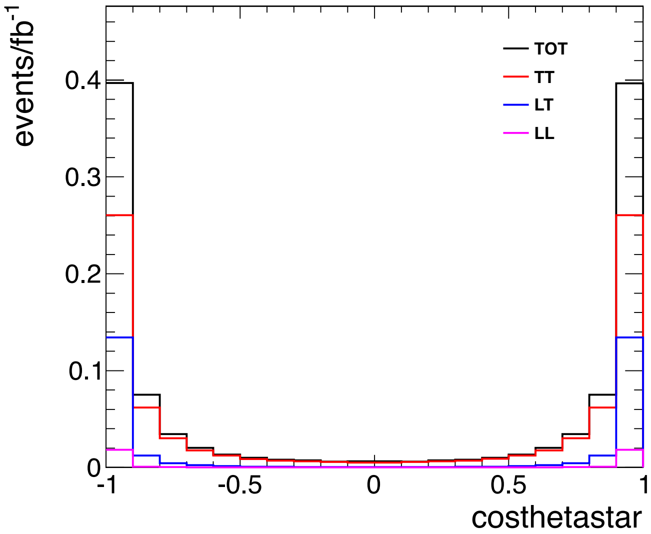
W tagging tools

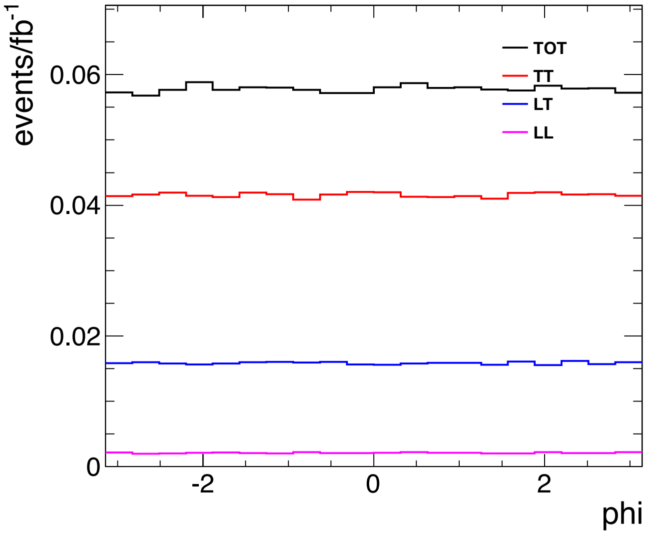


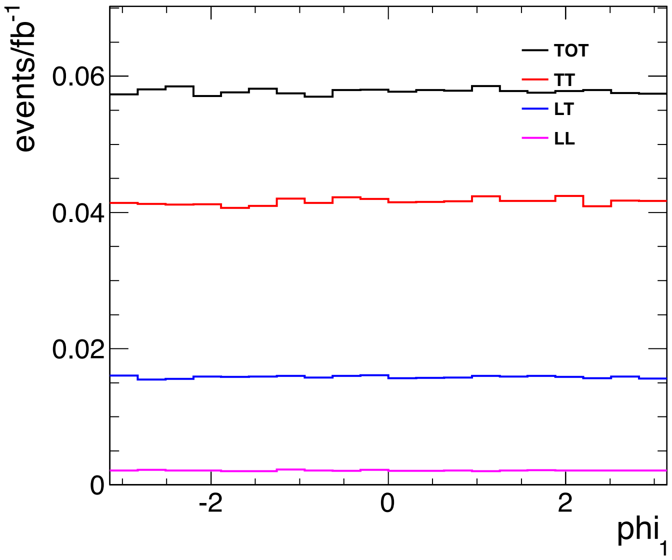
These two essentially gave the max discrimination. Tried additional observables, e.g., mass drop & MVA, but w/o much gain. Why?

Other angles



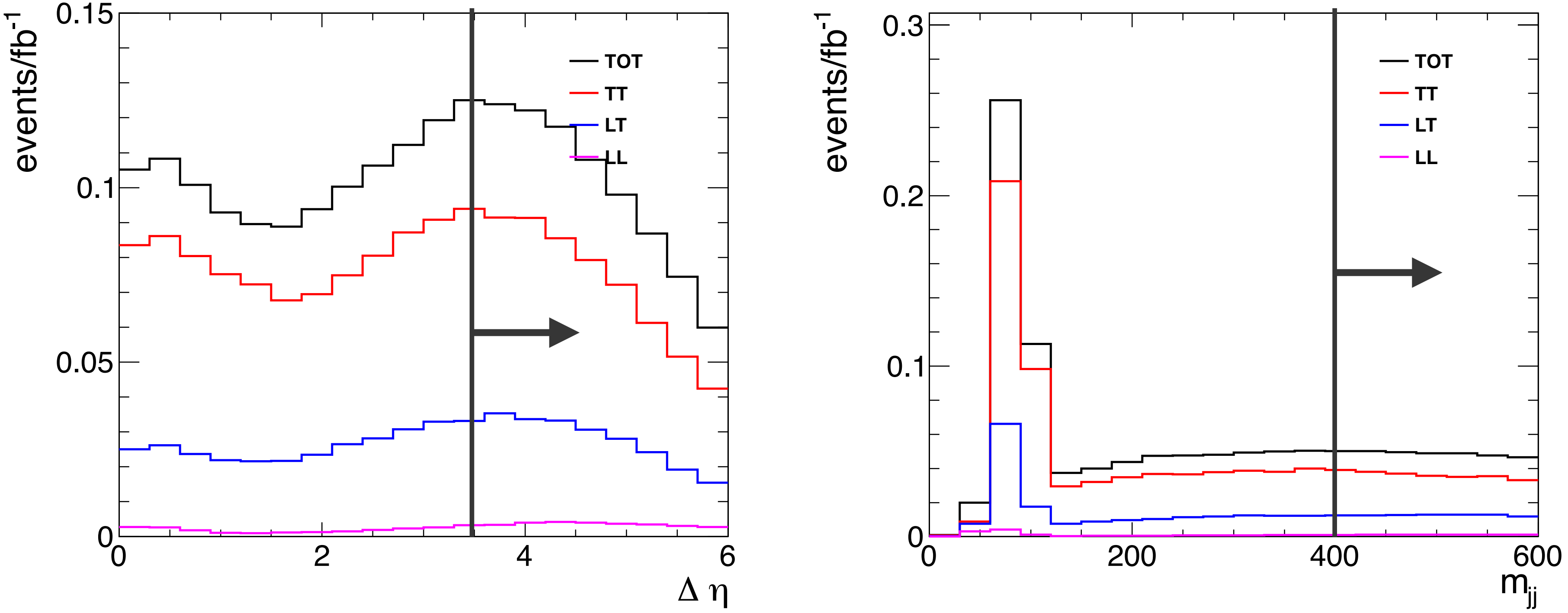






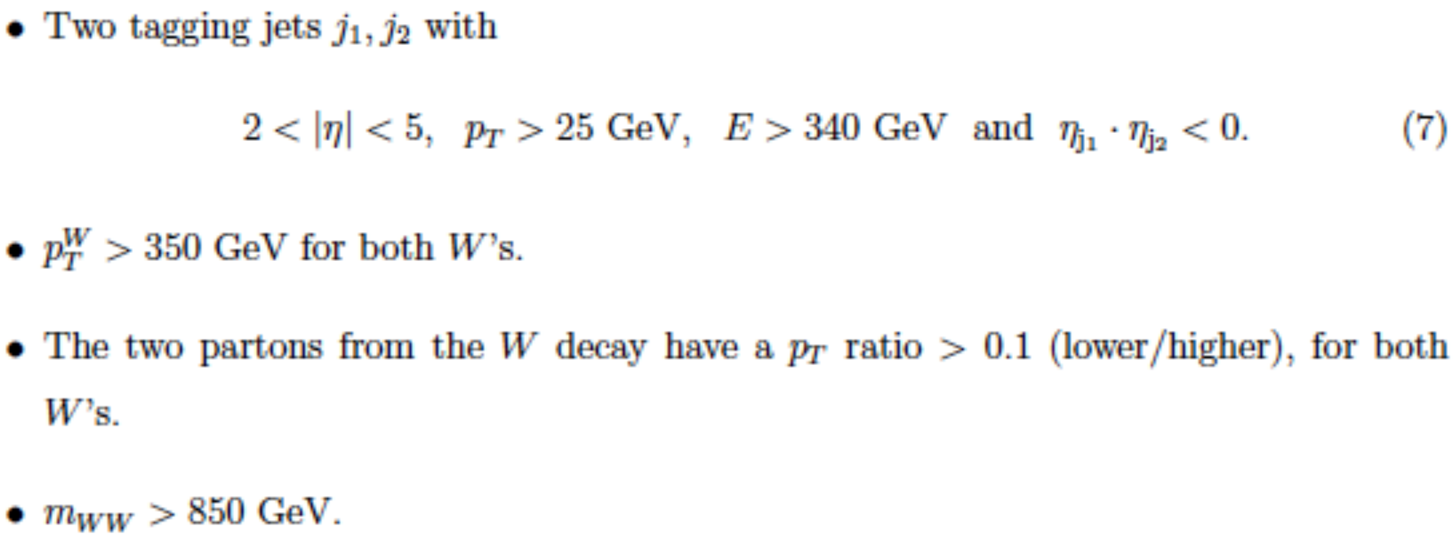
Event characteristics

Tag jets with large rapidity gap and large invariant mass



Typical cuts, events generated using VBFNLO

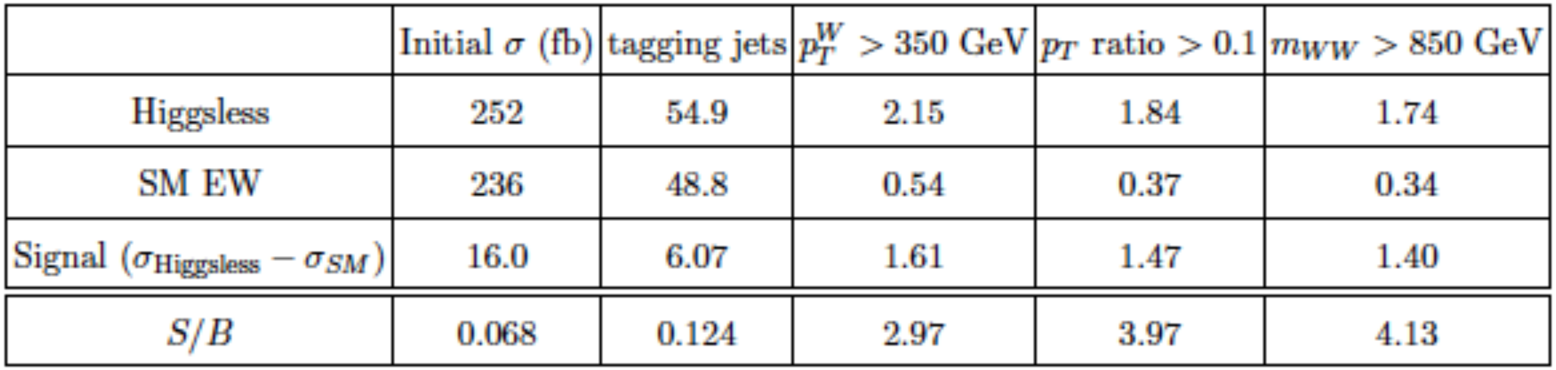
Event selection & efficiency in arXiv:1304.4599



- Two tagging jets j_1, j_2 with

$$2 < |\eta| < 5, \quad p_T > 25 \text{ GeV}, \quad E > 340 \text{ GeV} \quad \text{and} \quad \eta_{j_1} \cdot \eta_{j_2} < 0. \tag{7}$$

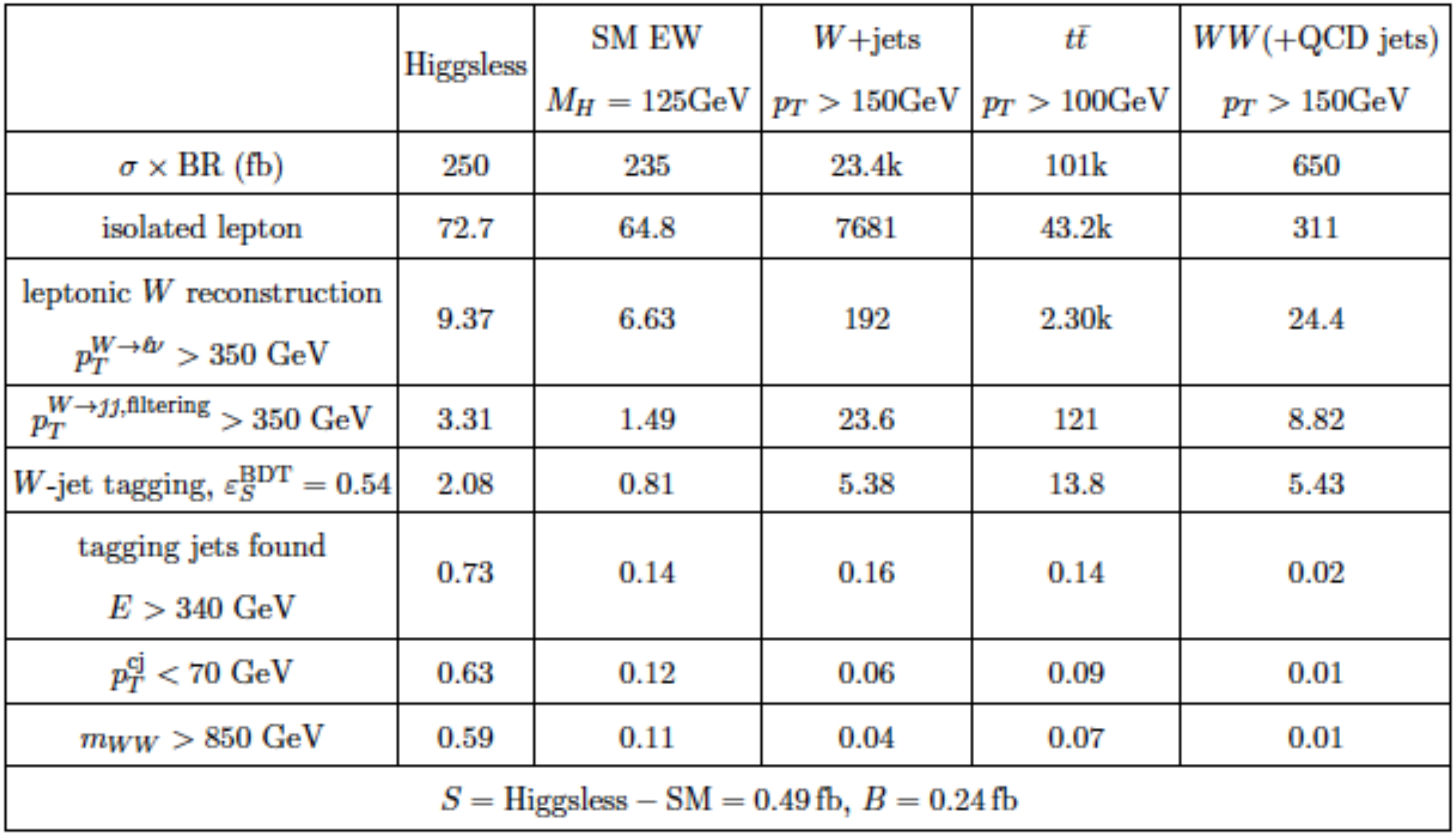
- $p_T^W > 350$ GeV for both W's.
- The two partons from the W decay have a p_T ratio > 0.1 (lower/higher), for both W's.
- $m_{WW} > 850$ GeV.



	Initial σ (fb)	tagging jets	$p_T^W > 350$ GeV	p_T ratio > 0.1	$m_{WW} > 850$ GeV
Higgsless	252	54.9	2.15	1.84	1.74
SM EW	236	48.8	0.54	0.37	0.34
Signal ($\sigma_{\text{Higgsless}} - \sigma_{SM}$)	16.0	6.07	1.61	1.47	1.40
S/B	0.068	0.124	2.97	3.97	4.13

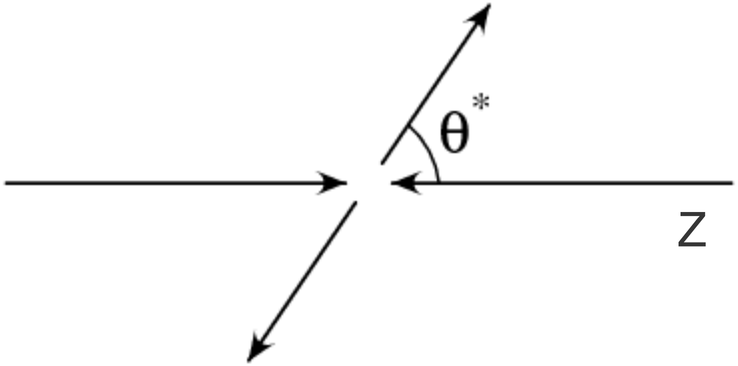
Event selection & efficiency in arXiv:1304.4599

Boosted analysis



	Higgsless	SM EW $M_H = 125\mathrm{GeV}$	W+jets $p_T > 150\mathrm{GeV}$	$t\bar{t}$ $p_T > 100\mathrm{GeV}$	WW(+QCD jets) $p_T > 150\mathrm{GeV}$
$\sigma \times \mathrm{BR}$ (fb)	250	235	23.4k	101k	650
isolated lepton	72.7	64.8	7681	43.2k	311
leptonic W reconstruction $p_T^{W\to\ell\nu} > 350$ GeV	9.37	6.63	192	2.30k	24.4
$p_T^{W\to jj,\mathrm{filtering}} > 350$ GeV	3.31	1.49	23.6	121	8.82
W-jet tagging, $\varepsilon_S^{\mathrm{BDT}} = 0.54$	2.08	0.81	5.38	13.8	5.43
tagging jets found $E > 340$ GeV	0.73	0.14	0.16	0.14	0.02
$p_T^{\mathrm{cj}} < 70$ GeV	0.63	0.12	0.06	0.09	0.01
$m_{WW} > 850$ GeV	0.59	0.11	0.04	0.07	0.01
$S = \mathrm{Higgsless} - \mathrm{SM} = 0.49\,\mathrm{fb}$, $B = 0.24\,\mathrm{fb}$					

Transverse and longitudinal polarizations



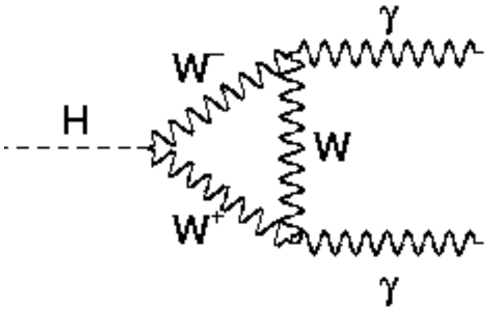
$$P_{\text{Longitudinal}} = (3/4)\sin^2\theta^*$$

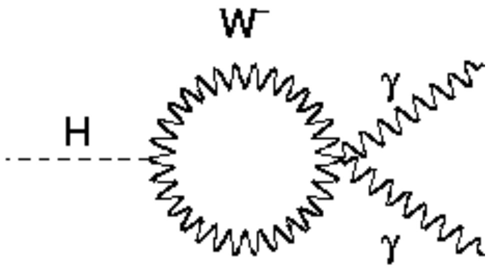
$$P_{\text{Left}} = (3/8)\,(1 - \cos\theta^*)^2$$
$$P_{\text{Right}} = (3/8)\,(1 + \cos\theta^*)^2$$

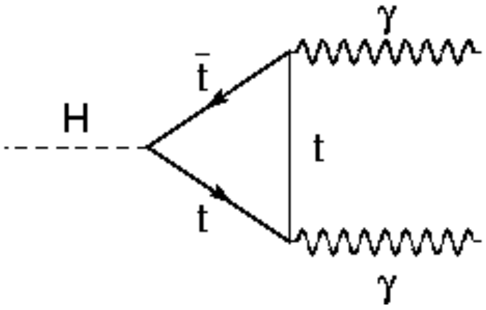
The uncertainty in efficiency x acceptance due to any polarization effects is already inbuilt via PDF uncertainties.

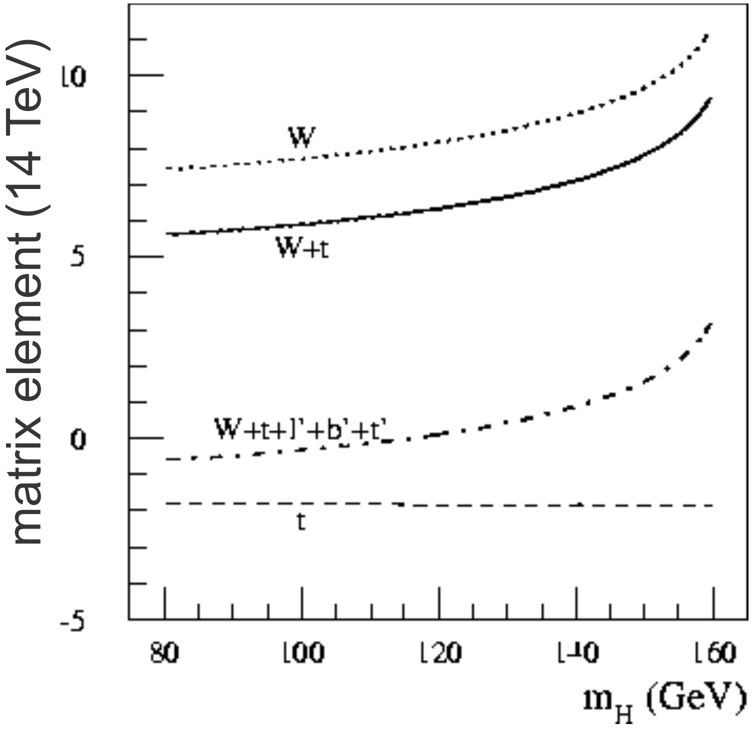
The polarization fractions can be minimally modified by high order corrections. But this is not independent of PDFs and other SM coupling parameters.

Higgs decay to two photons









Notice that the W loop diagram dominates, however the top loop diagram has opposite sign. Heavy fermions in the loop can further bring down the rate.

Higgs boson observation in a nutshell

For a mass of $m_H = 125.7 \pm 0.4$ GeV

Decay	Expected	Observed
ZZ	7.1 σ	6.7 σ
γγ	3.9 σ	3.2 σ
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.1 σ
ττ	2.6 σ	2.8 σ

bosons

3.4 σ combined!

fermions

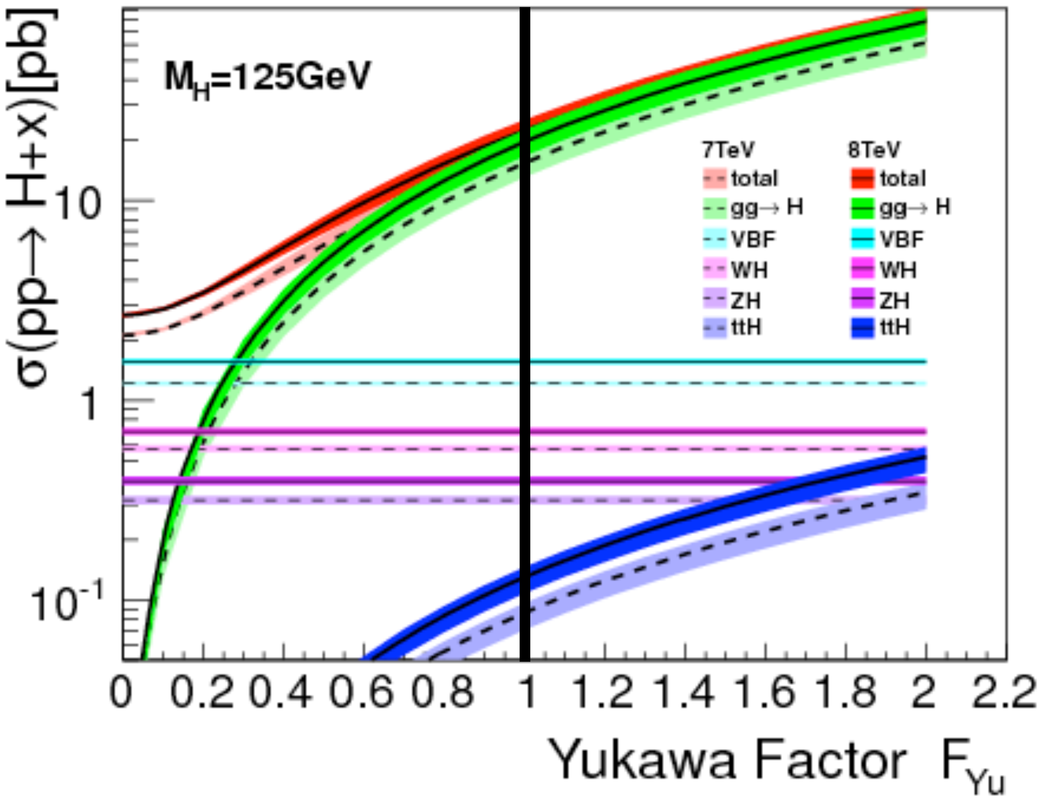
bb: includes VH and VBF, WW: includes ggF, VH, VBF

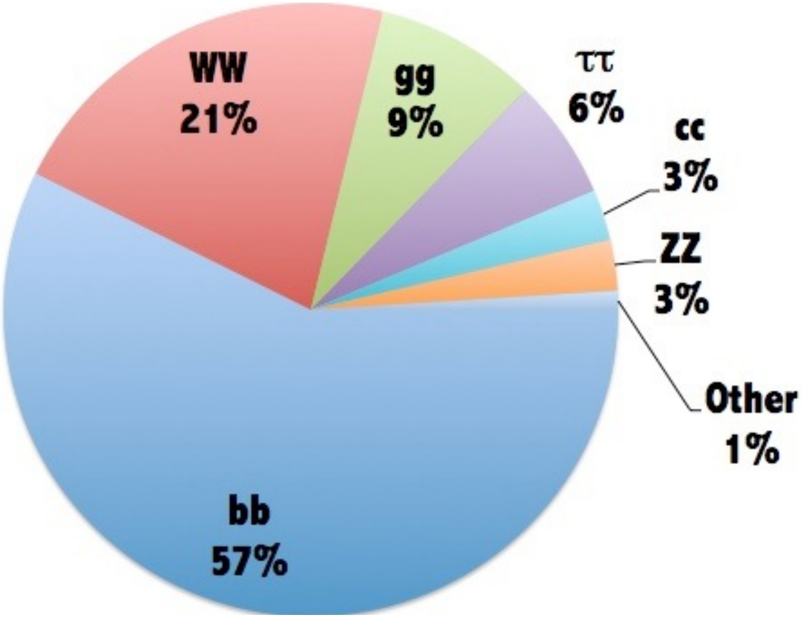
What the Higgs observation tells us immediately

Mass: $m_H = 125.7 \pm 0.4$ GeV

Given H mass, the SM predicts cross section & BR precisely.

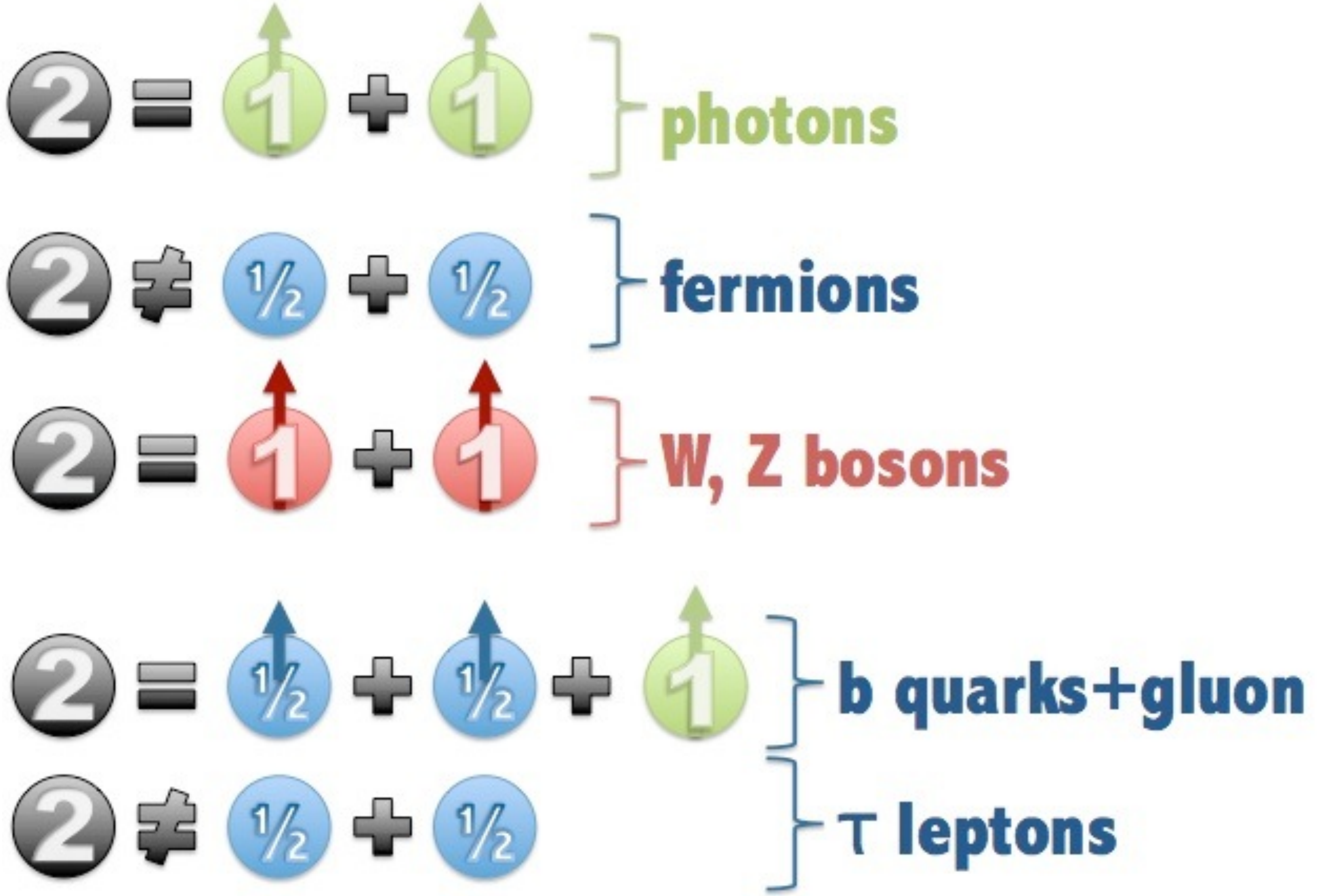
And its quantum numbers: **$J^P = 0^+$**





H (125) branching fraction

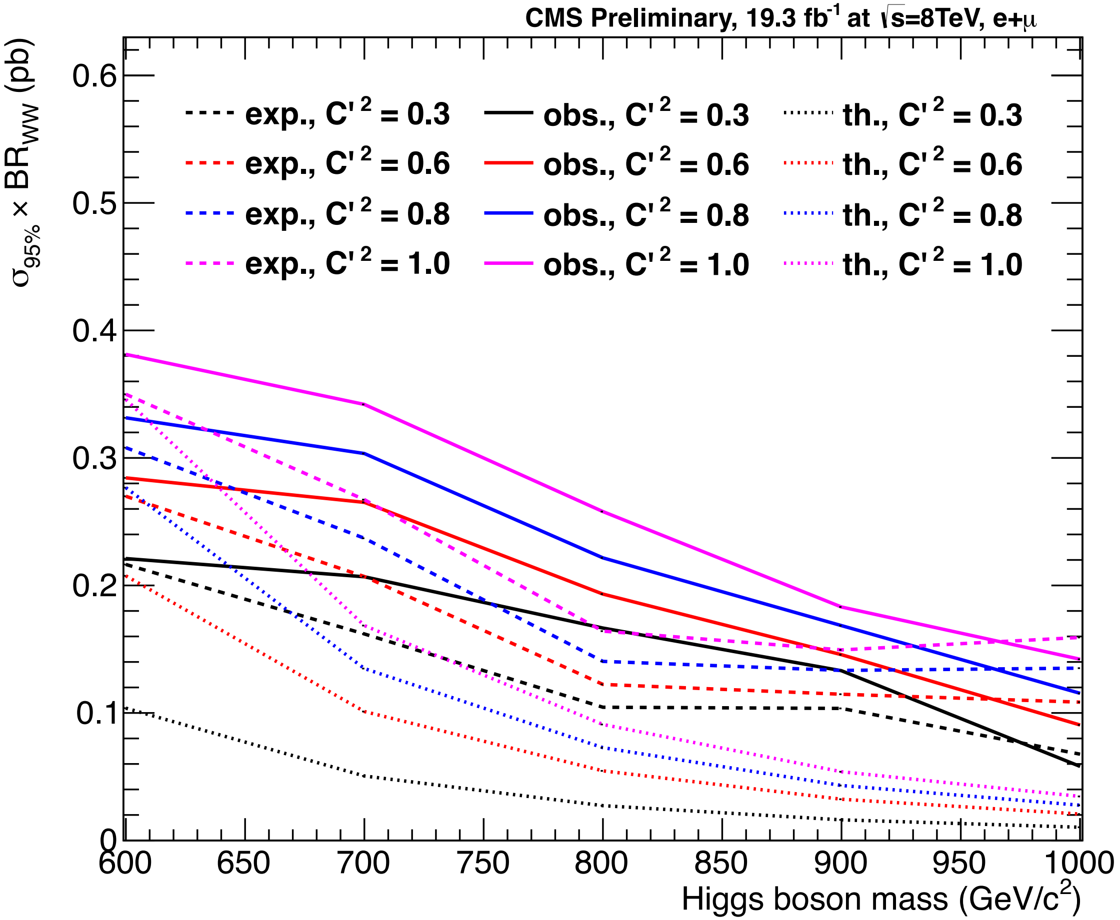
Side note: why spin-2 can decay to bb but not ττ



Let's allow heavy Higgs to mix with H(126)

Heavy Higgs mixes with H(126) and modifies its coupling

$$C^2 + C'^2 = 1$$



C'=0 ⇒ No heavy Higgs state. We only see H(126) tail.

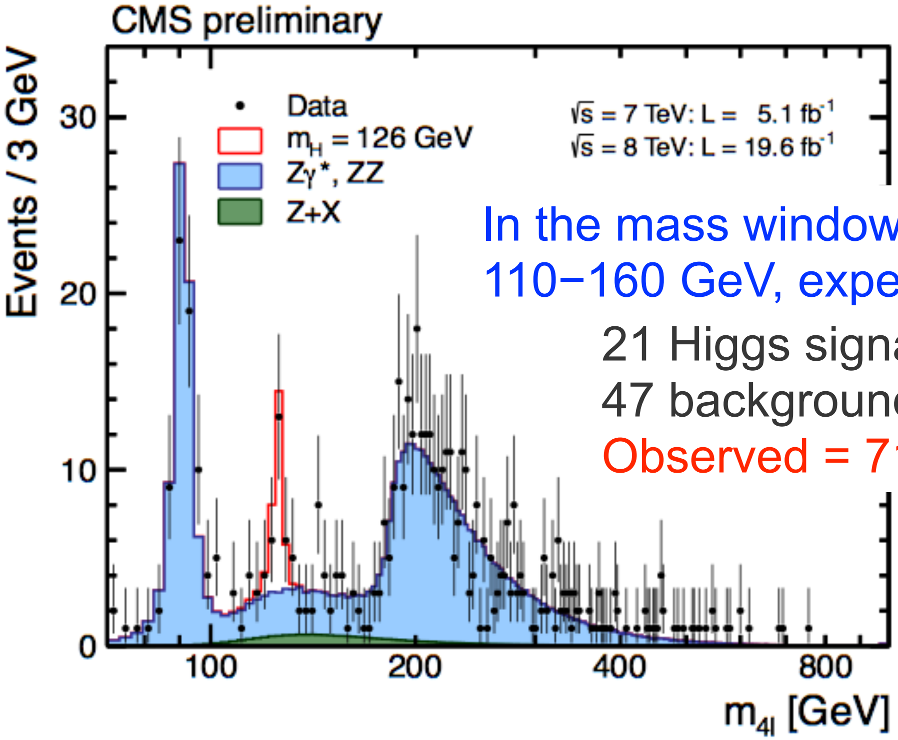
C'=1 ⇒ Full contribution from heavy Higgs only.

Typically C'^{2} > 0.6 excluded for heavy Higgs < 600 GeV, closing in on 600-1000 GeV.

Enough events to measure spin-parity

In H→ZZ* full final state reconstruction sensitive to J^P

- 2 masses (M_{Z1}, M_{Z2}), 5 angles
- Form a matrix-element based discriminant

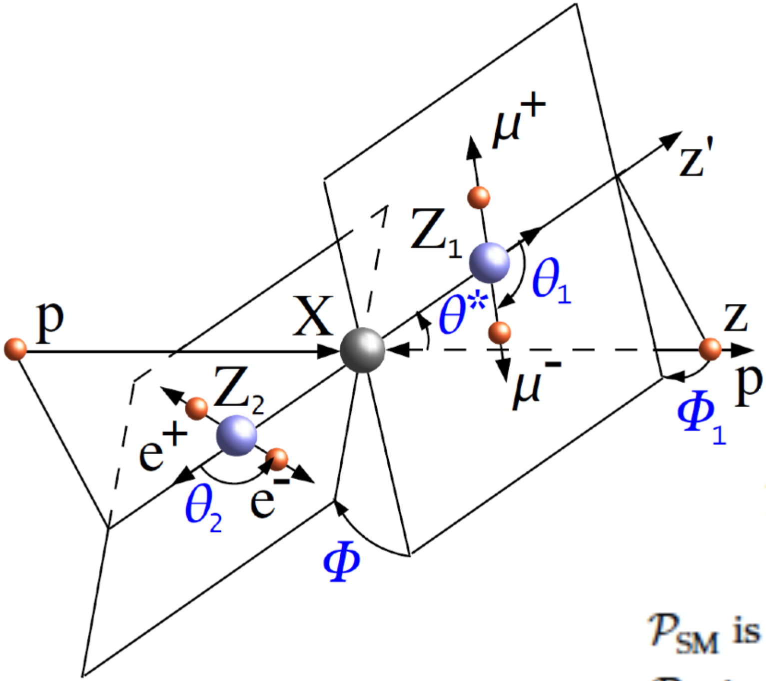


In the mass window 110−160 GeV, expect

21 Higgs signal

47 background

Observed = 71



$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\text{SM}}}{\mathcal{P}_{\text{SM}} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})}{\mathcal{P}_{\text{SM}}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})}\right]^{-1}$$

$\mathcal{P}_{\text{SM}}$ is the probability distribution for the SM Higgs boson hypothesis.

$\mathcal{P}_{J^P}$ is the probability distribution for an alternative model.

Interesting Q: how much CP odd allowed by data?

Measure fraction of CP-violating contribution

Most general spin-0 H → VV amplitude

$$A = v^{-1}\left(\underline{a_1 m_Z^2 \epsilon_1^* \epsilon_2^*} + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \underline{a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}\right)$$

$$= \underline{A_1} + A_2 + \underline{A_3}$$

At LO, SM **a1 = 1,** a2 = a3 = 0

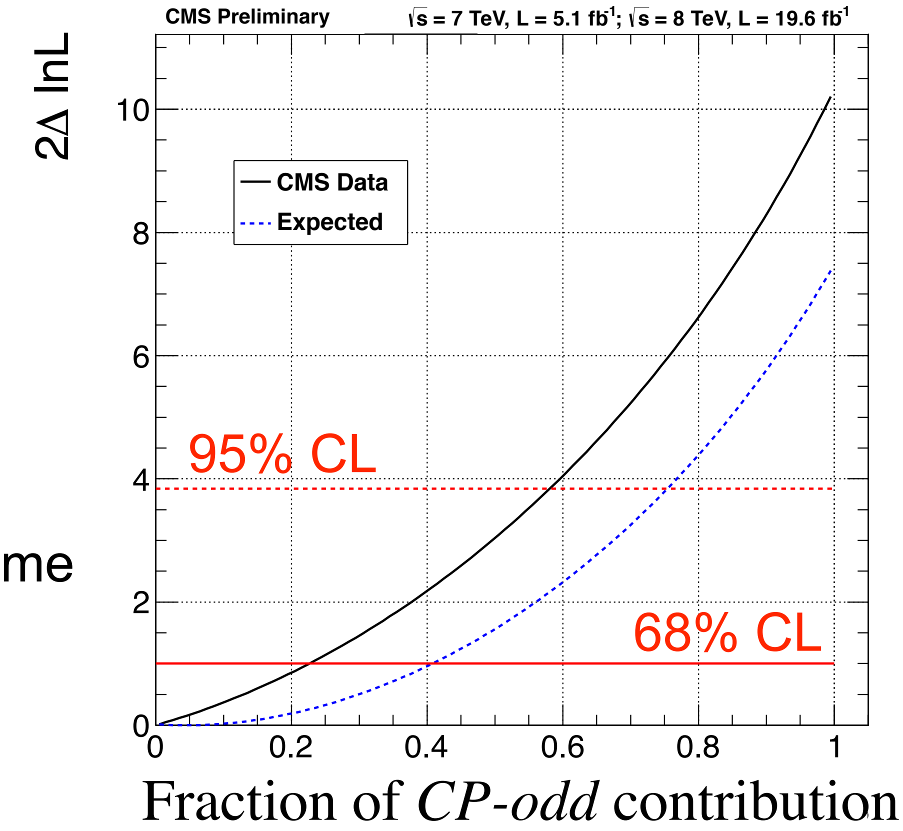
A3 : CP odd amplitude

Fit for $f_{a3} = |A_3|^2 / |A_1|^2 + |A_3|^2$

- check presence of CP violation (assume a_2=0, interference term negligible)

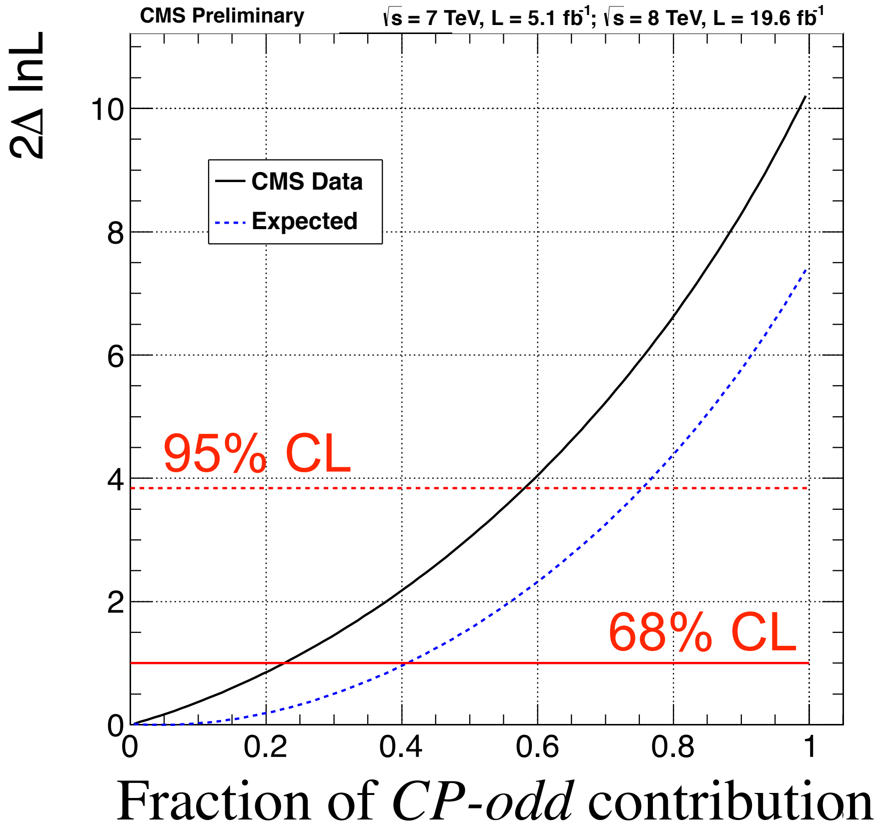
$f_{a3} = 0.00^{+0.23}_{-0.00}$

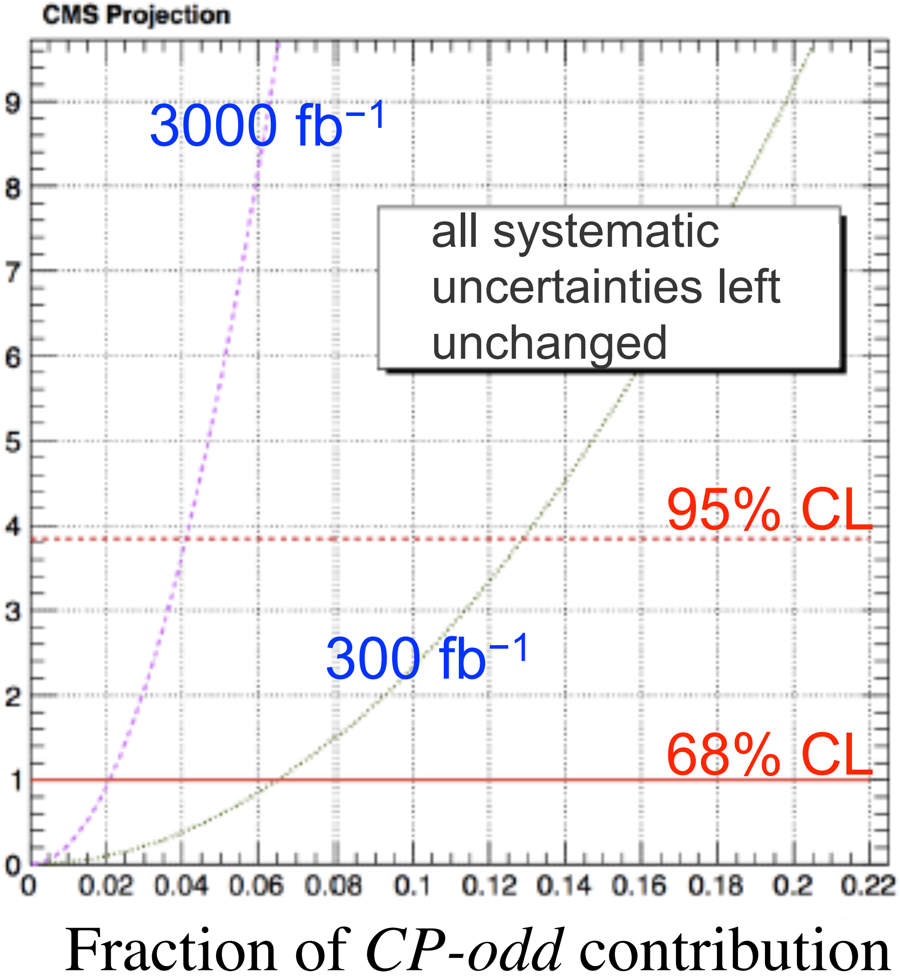
$f_{a3} < 0.58$ @95%CL



Any CP violation in Higgs sector?

Significant CP odd contribution allowed by current data



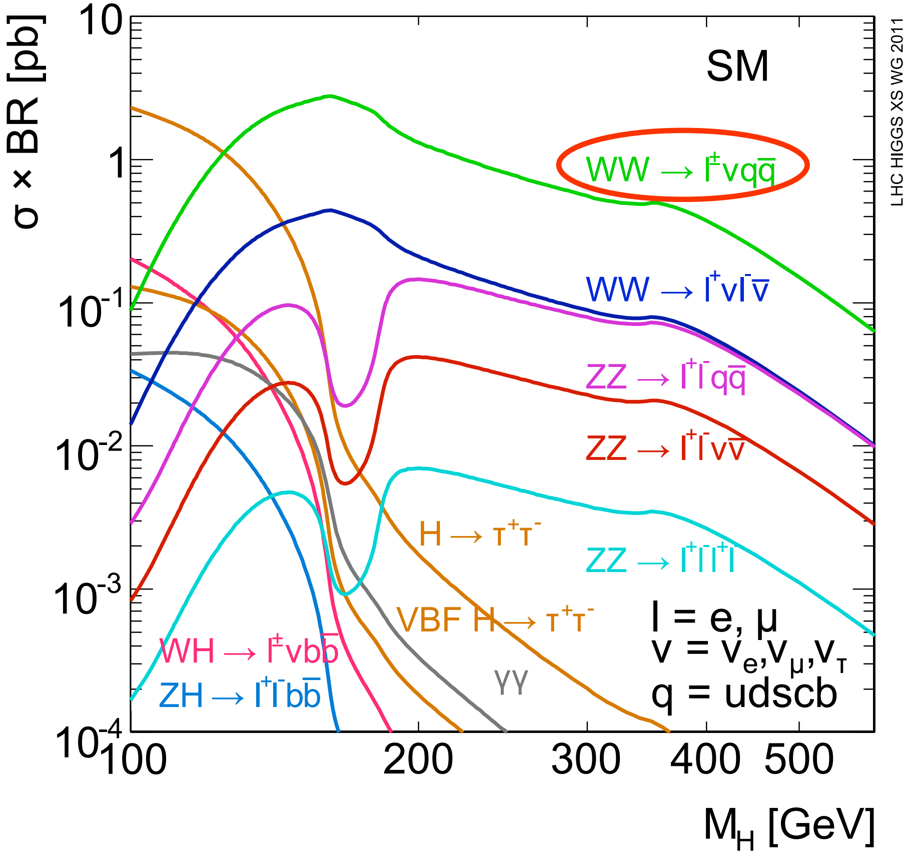


all systematic uncertainties left unchanged

CP violation probe down to 1−10% possible by 2017−20

Search for high mass Higgs states

Why in *this* final state? It wasn't planned in the ATLAS/CMS TDR!



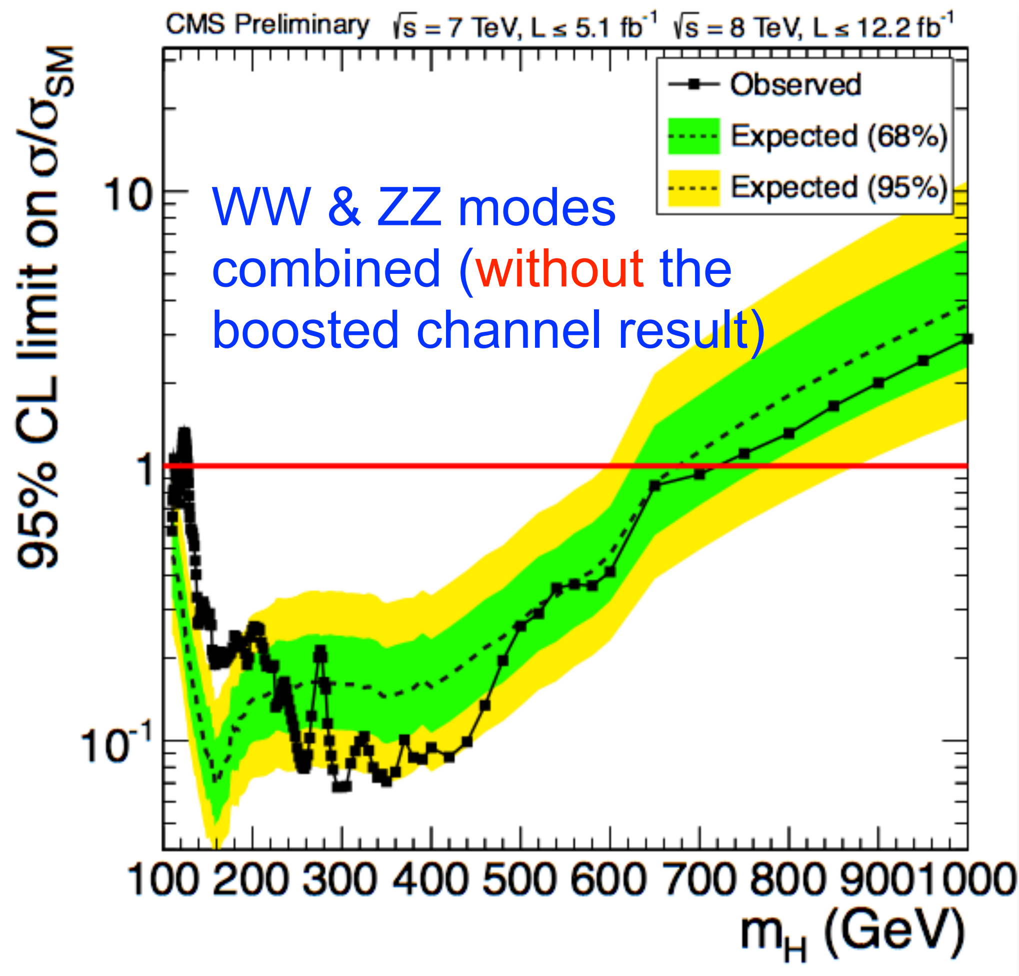
- $H \to WW \to \ell\nu q\bar{q}$ has the largest production rate over most of the mass range
  - ☑ Using W mass constraint, the decay is sufficiently reconstructed to produce a mass peak
- Principal drawback is the large W +jets background
  - Employ data-driven techniques to understand and control this process.

The main thrust of the analysis is to model this background well.

Constraints on higher mass Higgs states

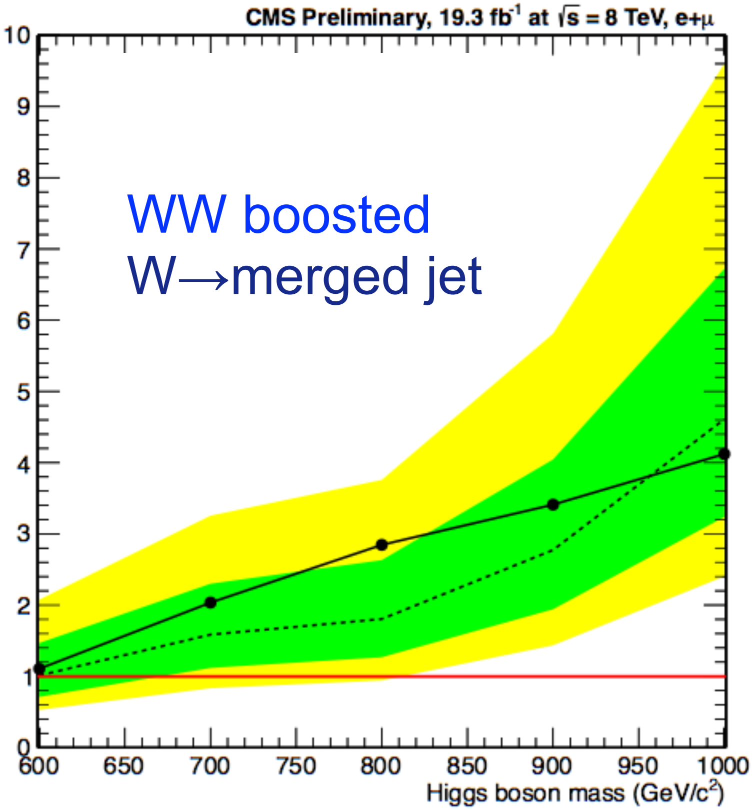
No new states up to 600 GeV.

Eur. Phys. J. C 73, 2469 (2013)



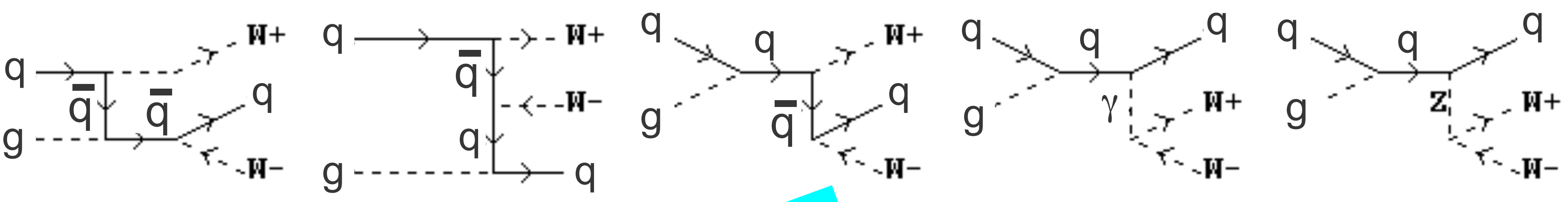
WW & ZZ modes combined (without the boosted channel result)

But interesting territory > 600 GeV to probe at Run-2

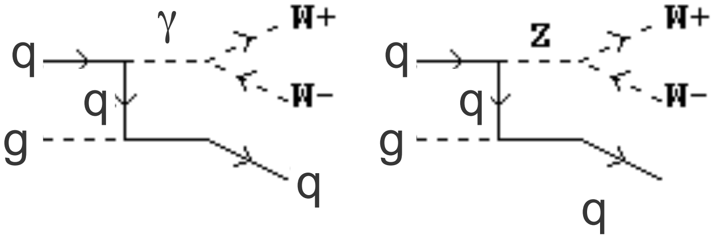


WW boosted
W→merged jet

Large NLO & radiative corrections (≳50% of LO)

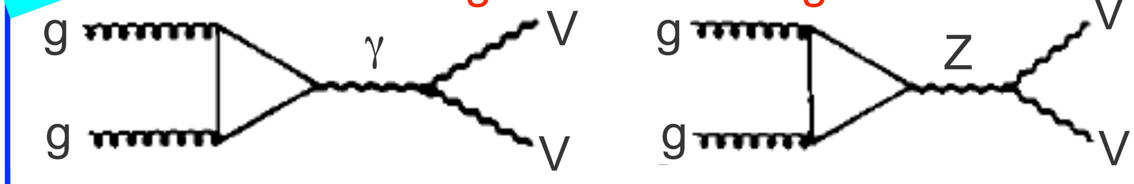


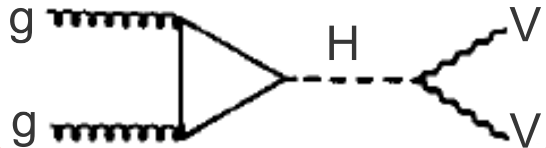
Quark−gluon diagrams



~6% gg contribution

Gluon−gluon fusion diagrams





H(125) can contribute up to 5% for WW*

Box diagrams

Plus VBF, MPI, ... diagrams

Some representative diagrams @NLO

Born

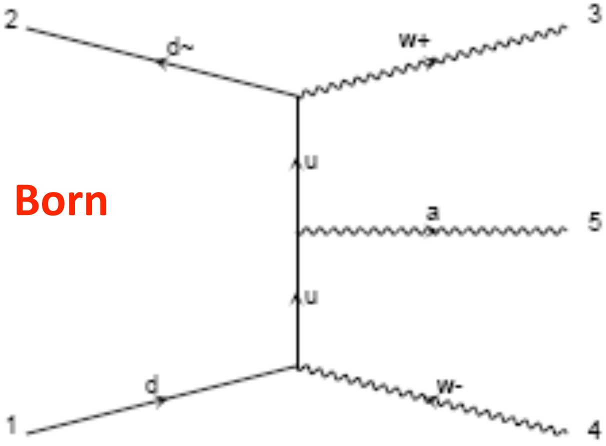
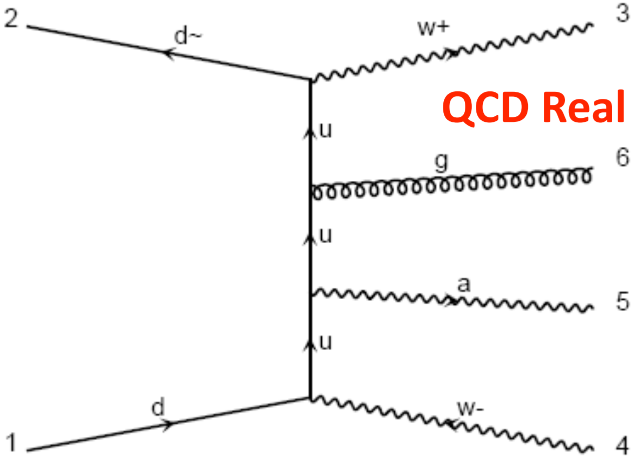


diagram 7 QCD=0, QED=3

QCD Real emission



real diagram 1 QCD=1, QED=3

One-loop QCD

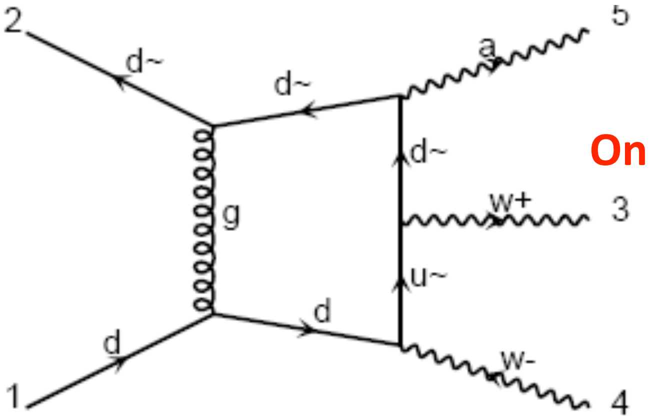


diagram 38 QCD=2, QED=3

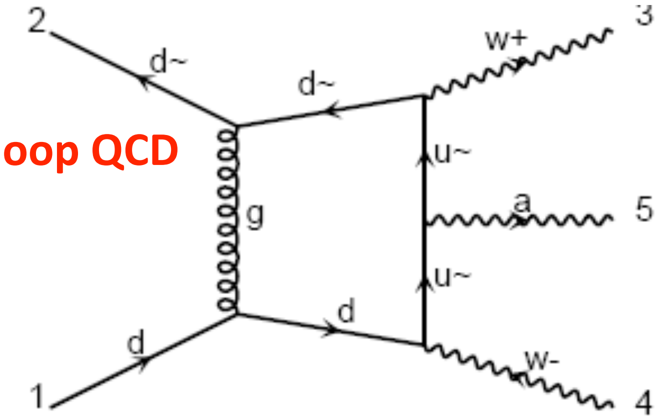


diagram 39 QCD=2, QED=3

Triggers

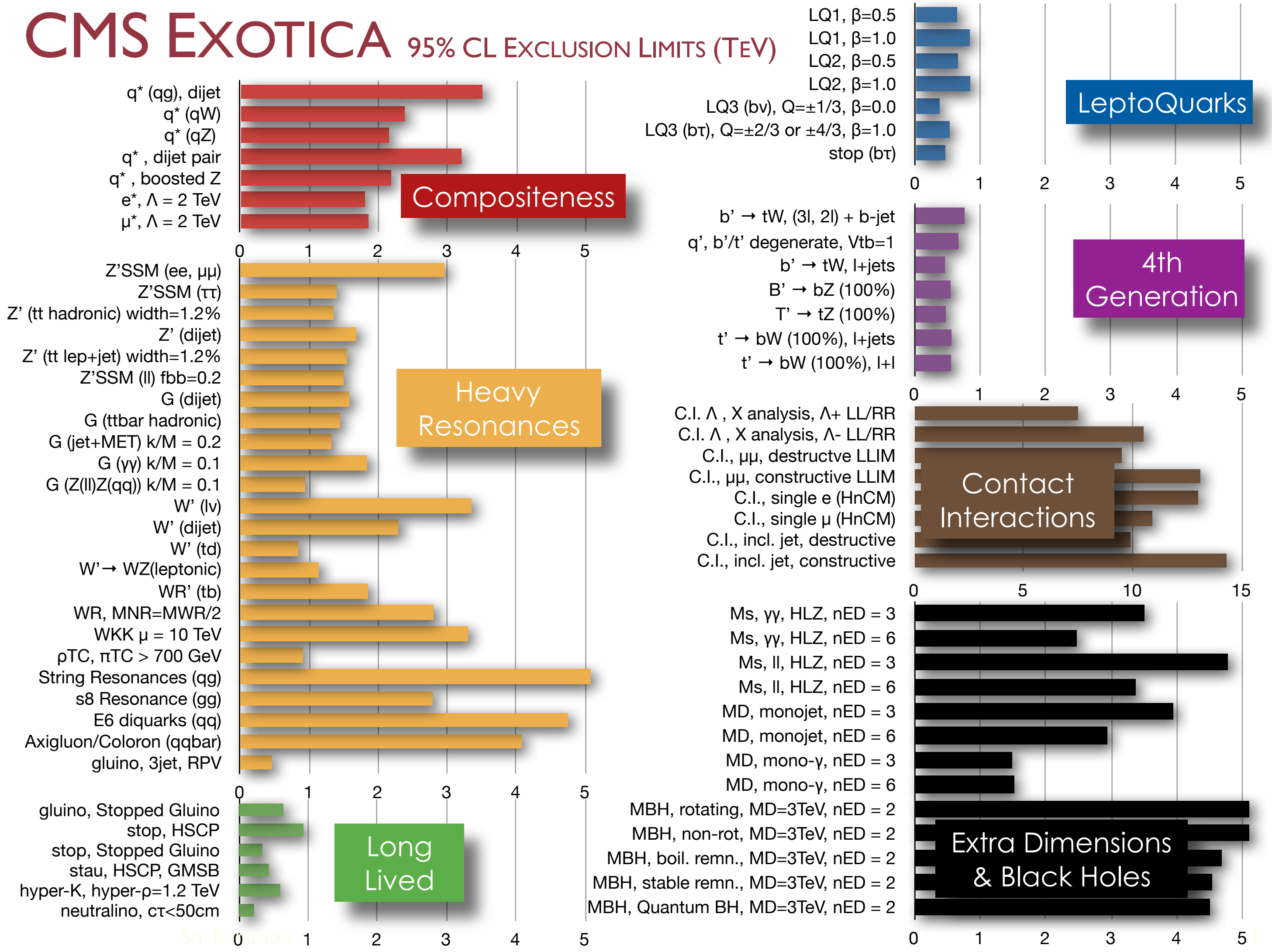
✦All analyses shown here use single or di-lepton triggers

✦ Typical single lepton triggers require
- one isolated lepton
- threshold: 24 GeV for muon, 27 GeV for electron
- MET > 20 GeV in case of electron

✦Typical dilepton triggers require
- two leptons, at least one isolated
- each with threshold that varies between 5−20 GeV

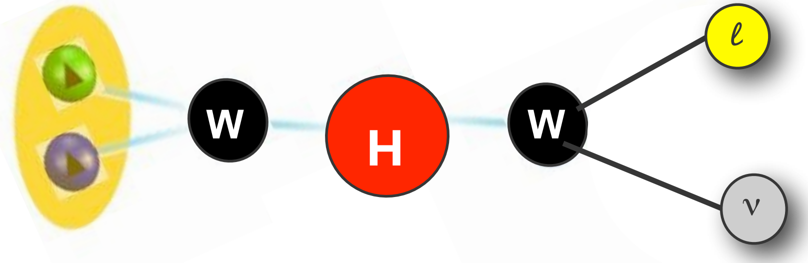
✦Offline analysis-level thresholds are higher than that in trigger. Simulation is corrected for trigger & selection efficiency.

But what kind of new physics?



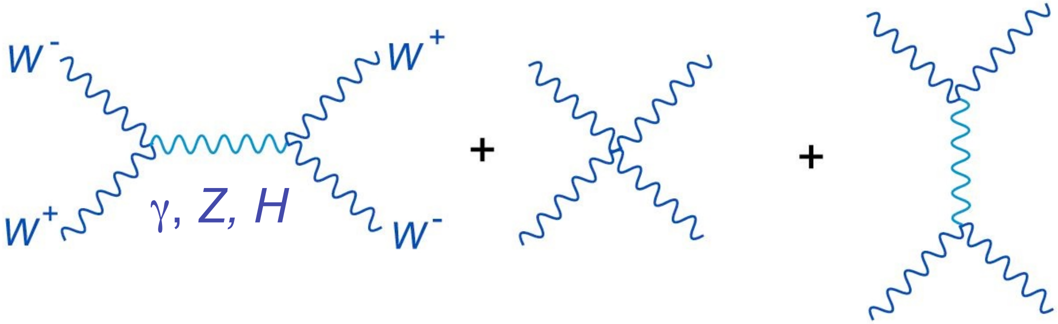
Production of heavy boson pairs

☑ Probe Higgs boson directly



I'll focus on the case when one W decays to a lepton (electron or muon) and neutrino, while the other W decays to quark-antiquark pair.

☑ Probe both Higgs & New Physics



Standard Model

= expected

new type of couplings

= new physics

Linear realization of EWK symmetry breaking

All dimension-8 operators
(includes light Higgs)

hep-ph/0606118
Eboli et. al.

$$\mathcal{L}_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right]$$

$$\mathcal{L}_{S,1} = \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi \right]$$

L_M have D6 equivalents (a_0, a_c), <u>L_T are novel to D8</u>

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu} B^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu} B^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$

$$\mathcal{L}_{M,4} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\mu \Phi \right] \times B^{\beta\nu}$$

$$\mathcal{L}_{M,5} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi \right] \times B^{\beta\mu}$$

$$\mathcal{L}_{M,6} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\nu} D^\mu \Phi \right]$$

$$\mathcal{L}_{M,7} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi \right]$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right]$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu} \right]$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha} \right]$$

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times B_{\alpha\beta} B^{\alpha\beta}$$

$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times B_{\mu\beta} B^{\alpha\nu}$$

$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times B_{\beta\nu} B^{\nu\alpha}$$

$$\mathcal{L}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}$$

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$,$\mathcal{L}_{M,6}$,$\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$,$\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$,$\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$,$\mathcal{L}_{T,1}$,$\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$,$\mathcal{L}_{T,6}$,$\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$,$\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

Non-linear realization (old idea, w/o a light Higgs)

- In the two realizations
  - -Linear: all lowest order independent aQGCs are dimension 8
  - -Nonlinear: a number of dimensions, QGCs involving γ are dim 6

- Consider WWγγ, the largest contributing nonlinear terms are
  - -Non-linear: limits set on a/Λ^2

$$L_6^0 = -\frac{e^2}{16\Lambda^2} \boxed{a_0} F^{\mu\nu} F_{\mu\nu} \vec{W}^\alpha \cdot \vec{W}_\alpha$$

$$L_6^c = -\frac{e^2}{16\Lambda^2} \boxed{a_c} F^{\mu\alpha} F_{\mu\beta} \vec{W}^\beta \cdot \vec{W}_\alpha$$

hep-ph/9304240,
two-parameter chiral
Lagrangian for QGC

  - -Equivalent linear terms L_{M0}, ..., L_{M7}, limits set on q/Λ

$$\frac{\boxed{q_i}}{\Lambda^4} = \frac{8a_i}{\Lambda^2 M_W^2}$$

Straightforward conversions

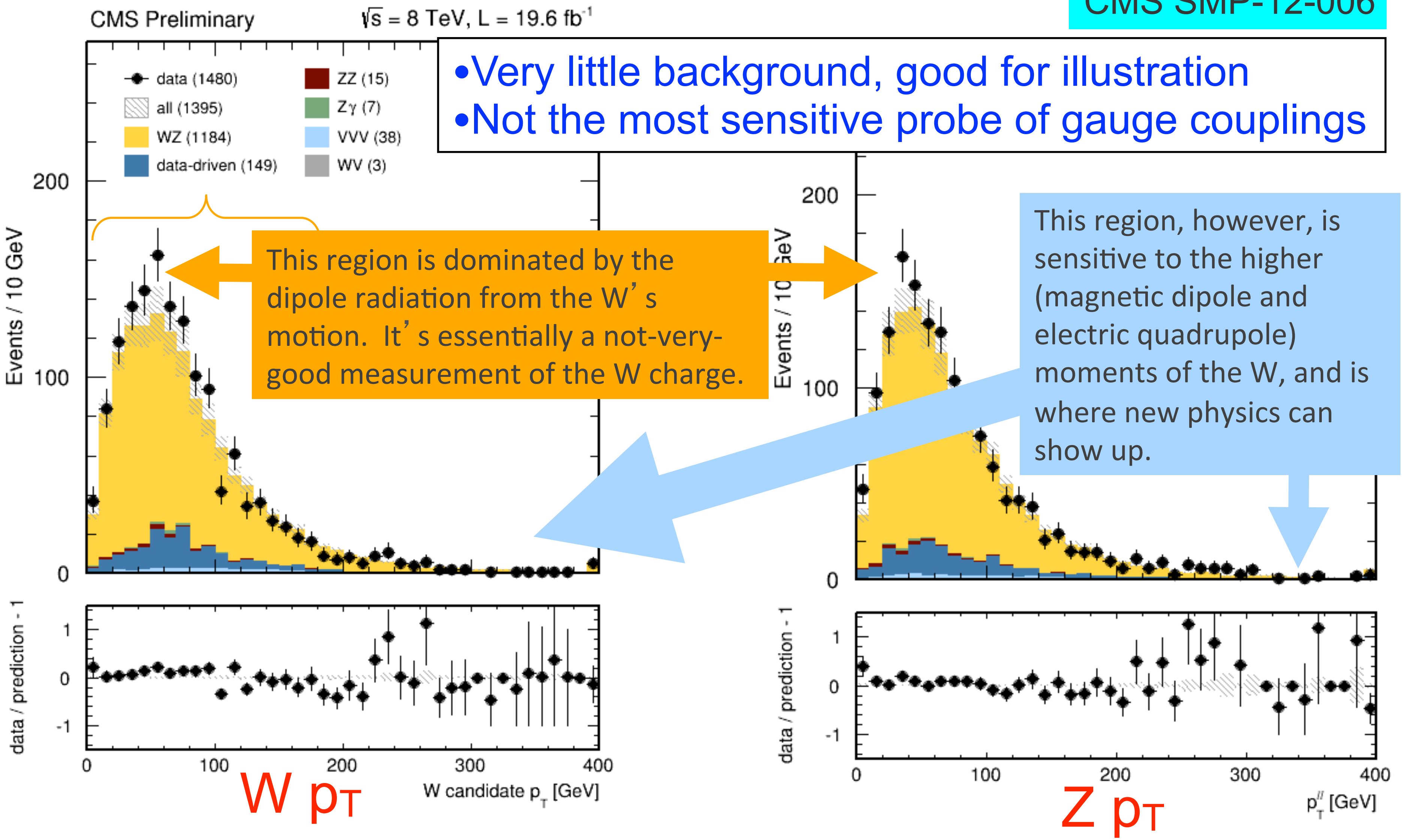
Burden of legacy

- Adopt linear approach for setting aQGC limits
- However, in order to easily compare with the existing results
  - -use D6 equivalent for operators that exist in both approaches

E.g., W charge & dipole moment in WZ events

CMS SMP-12-006

- Very little background, good for illustration
- Not the most sensitive probe of gauge couplings



This region is dominated by the dipole radiation from the W's motion. It's essentially a not-very-good measurement of the W charge.

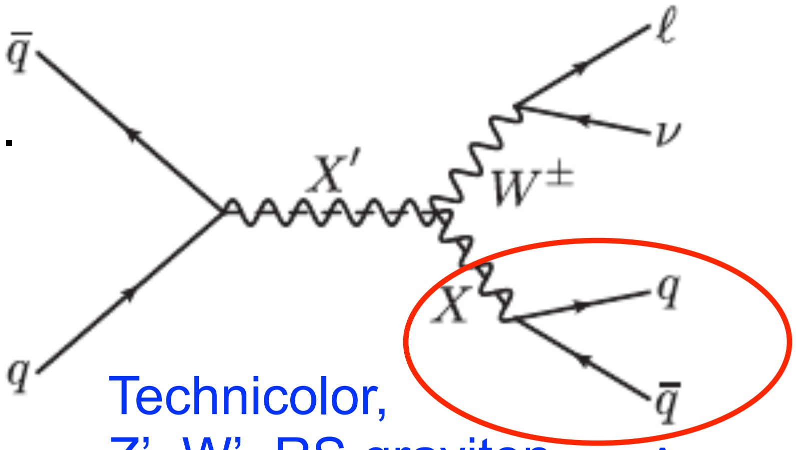
This region, however, is sensitive to the higher (magnetic dipole and electric quadrupole) moments of the W, and is where new physics can show up.

W p_T

Z p_T

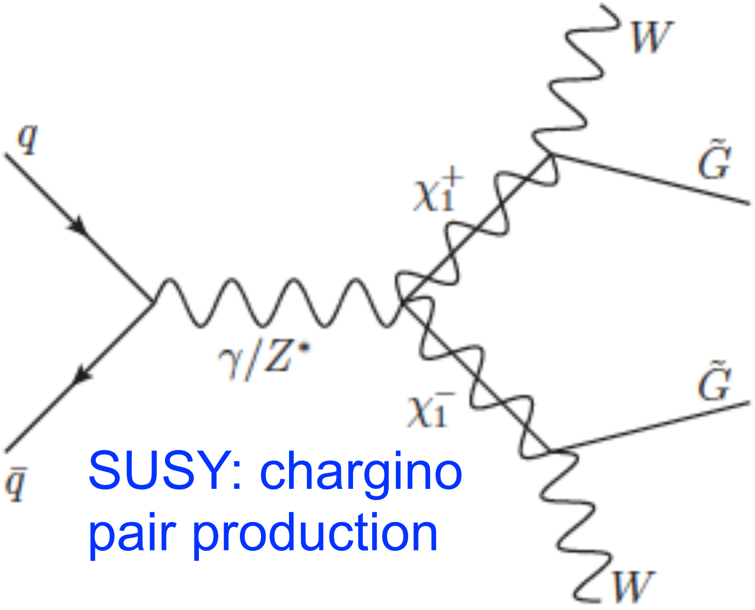
Sensitive to new physics even at “low scale”

New physics can enhance WW/WZ production or can produce new particles.



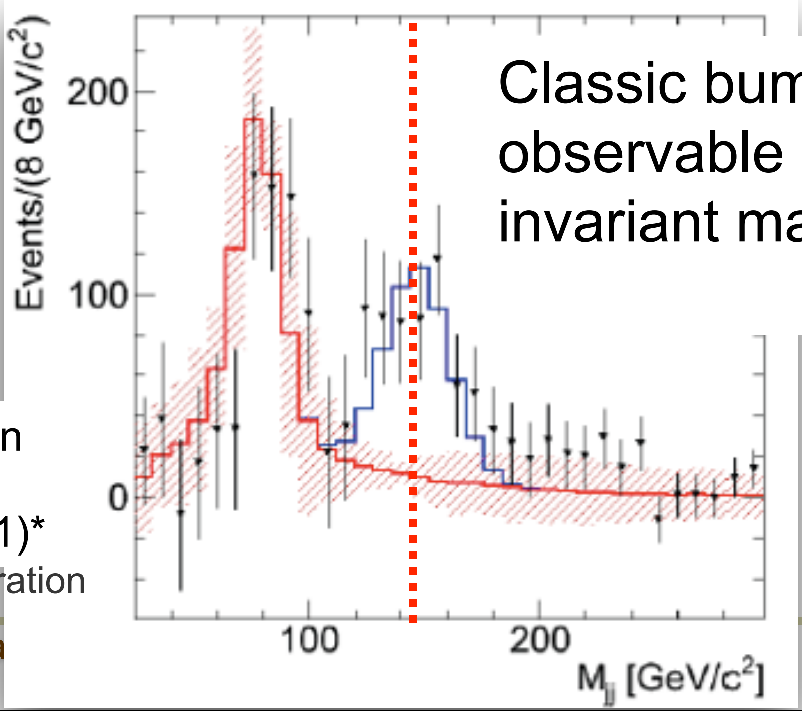
Technicolor, Z’, W’, RS graviton

A new particle



LSP

SUSY: chargino pair production

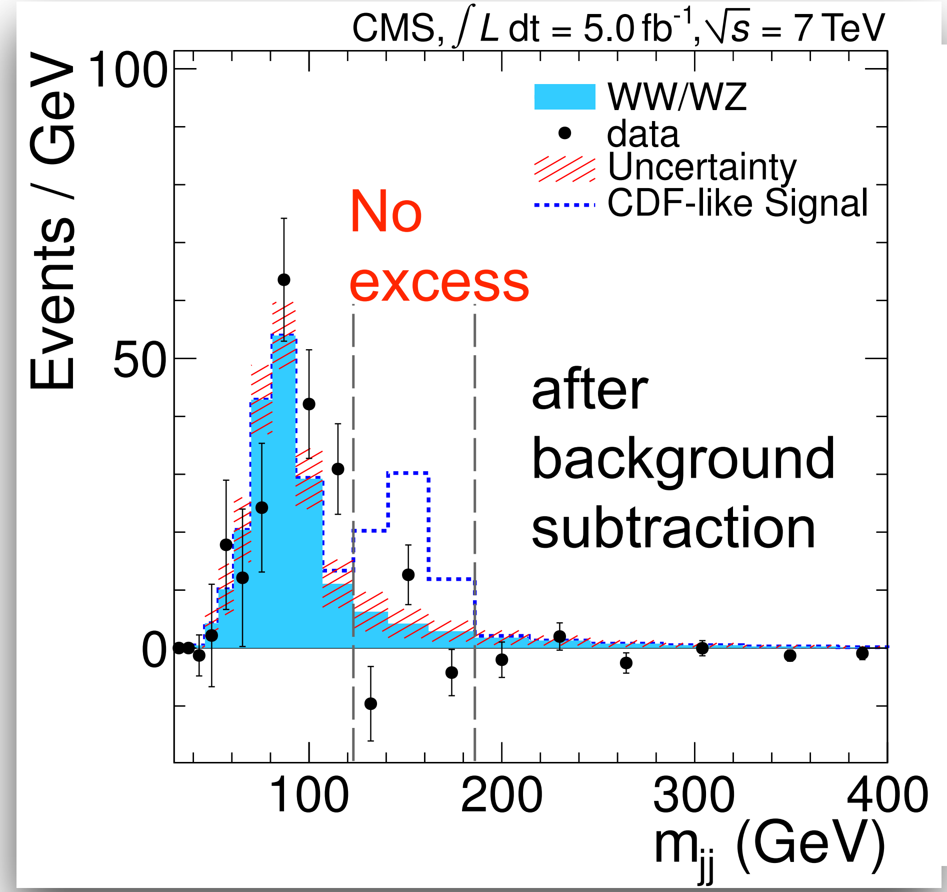


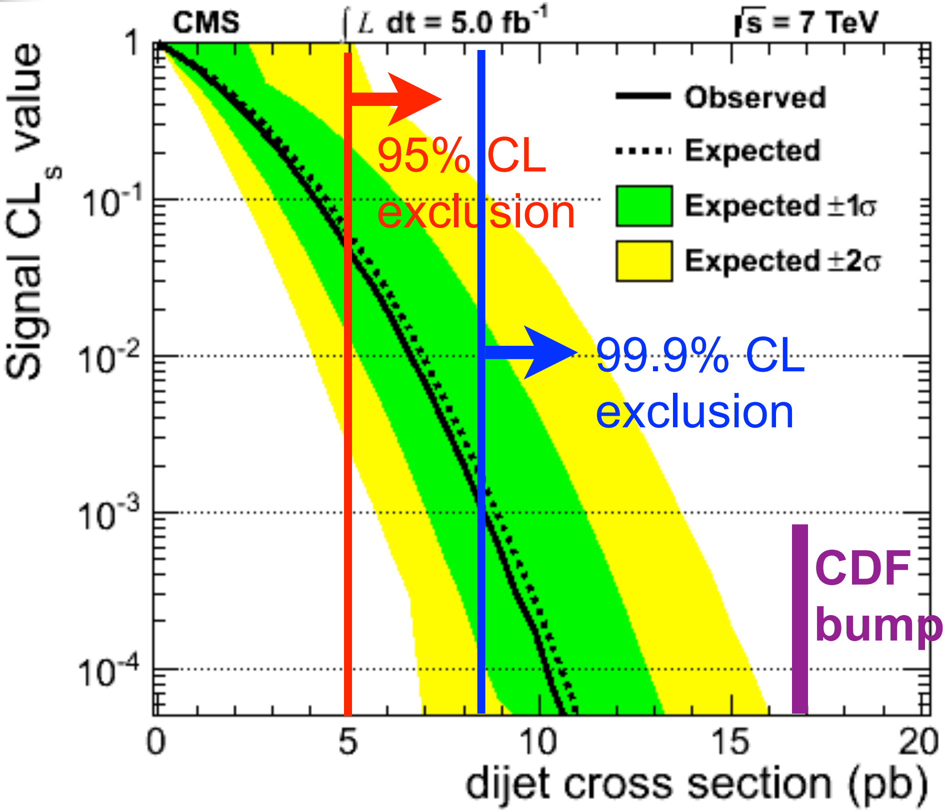
Classic bump hunt: observable is the invariant mass

CDF Collaboration
Phys. Rev. Lett.
106,171801 (2011)*

*Now found to be a mis-calibration

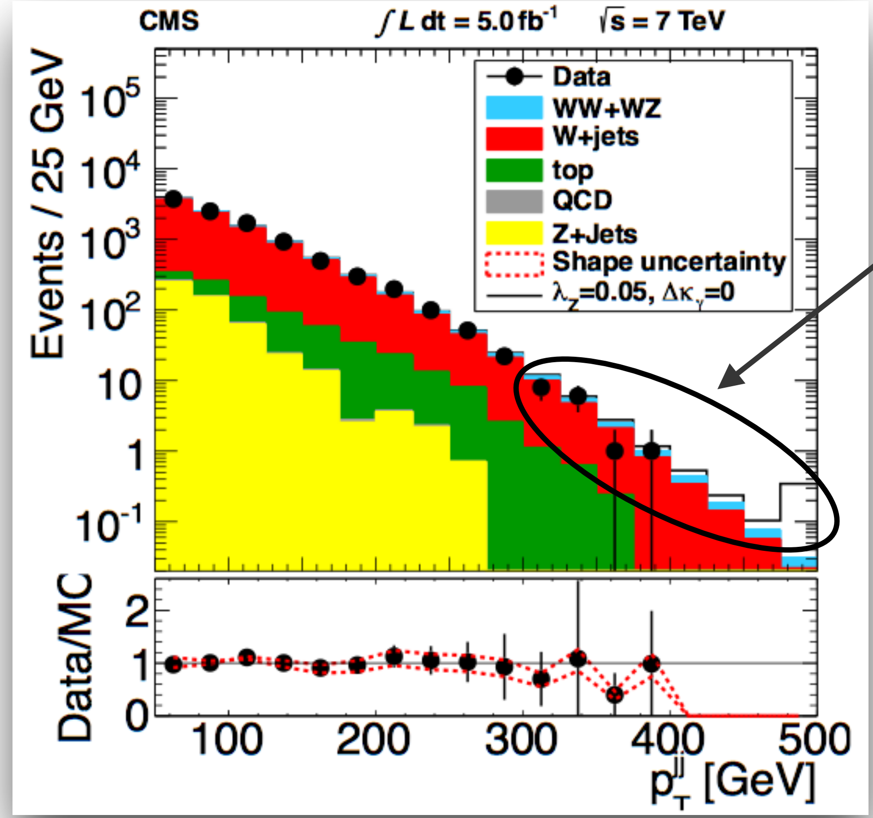
Following CDF 2011 result increased m_{jj} window



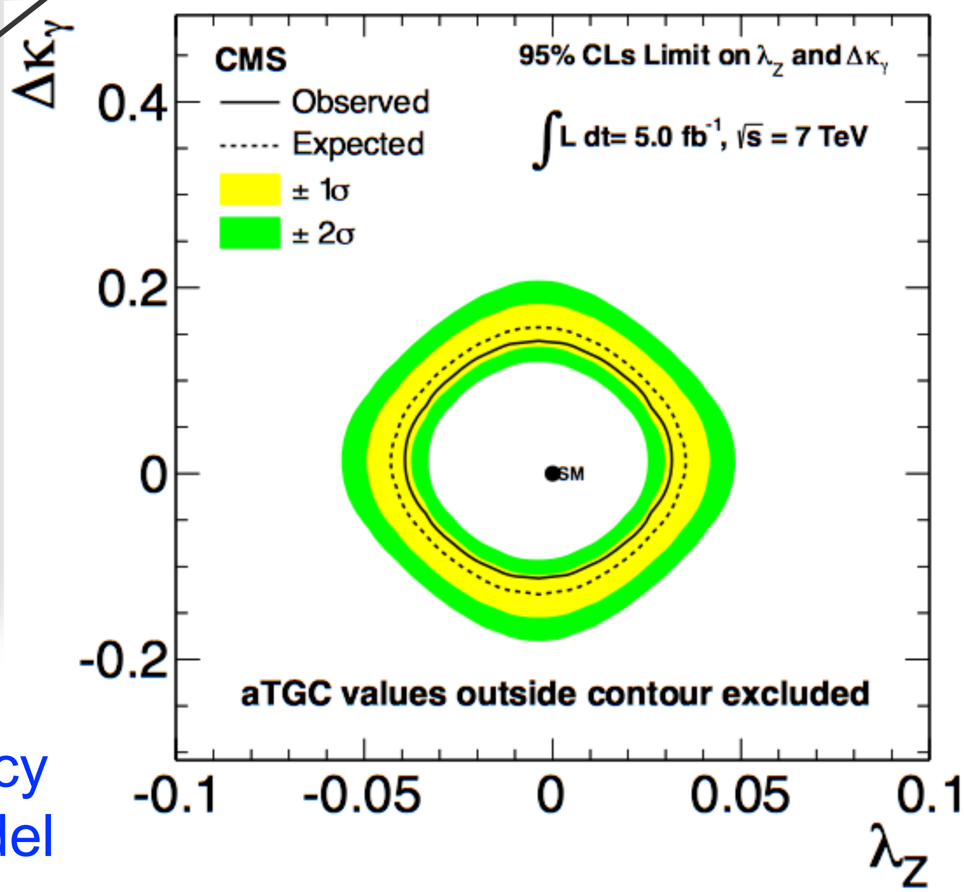


Excluded several classes of new physics models such as low scale technicolor, leptophobic Z', ... etc.

Measurement in data

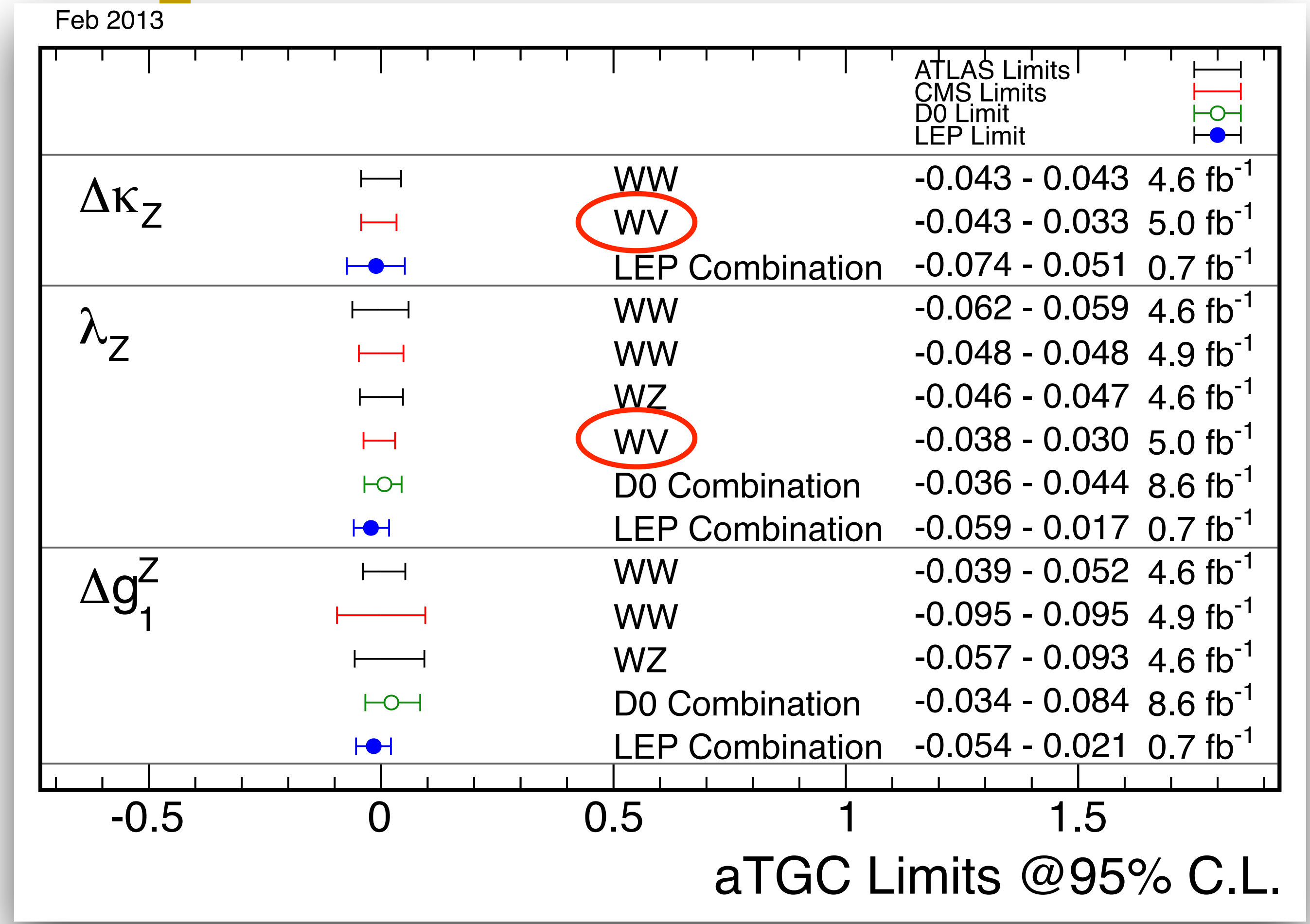


Anomalous events can show up at large W p_T.



So far good consistency with the Standard Model

Constraints on triple vertex couplings



Obtained assuming equal coupling relation

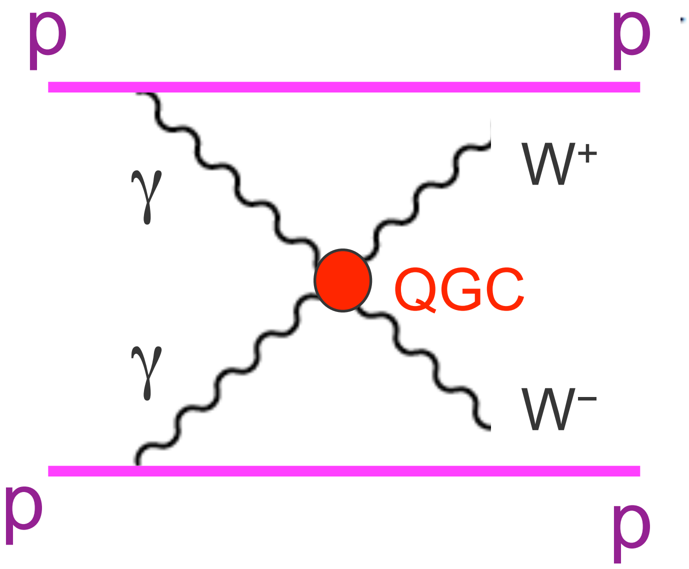
$$\lambda_Z = \lambda_\gamma = \lambda$$

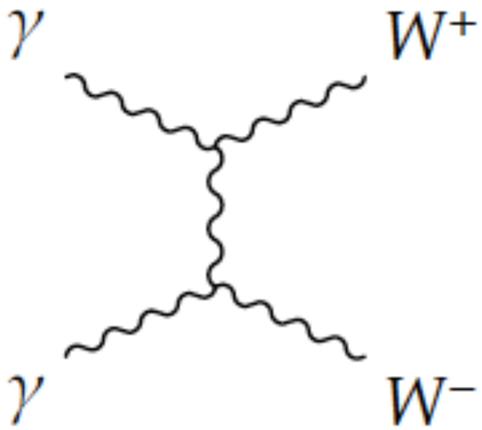
$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot \tan^2\theta_W$$

Dipole moment of W constrained at $\mathcal{O}(10^{-2})$, quadrupole moment at $\mathcal{O}(10^{-4})$.

Compare this to muon “g−2” which differs by < 0.001% from the SM value !!!

Quartic couplings in γγ→WW process

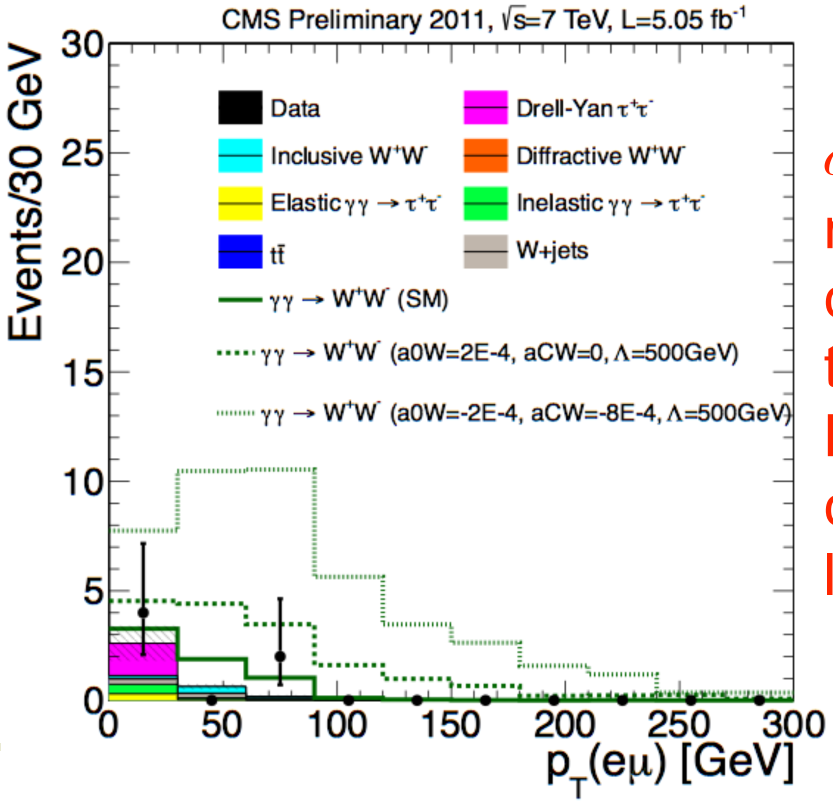




Limits on aQGC without form-factors:

$$-2.80 \times 10^{-6} < a_0^W/\Lambda^2 < 2.80 \times 10^{-6}\ \mathrm{GeV}^{-2}$$

$$-1.02 \times 10^{-5} < a_C^W/\Lambda^2 < 1.02 \times 10^{-5}\ \mathrm{GeV}^{-2}$$



$o(10^2)$ x more constraining than the LEP combined limit

Probing quartic couplings via WVγ production

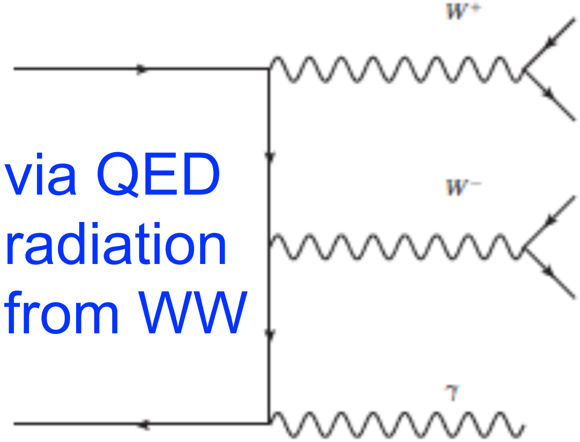
References:

1.) Yang et al, arXiv: 1211.1641

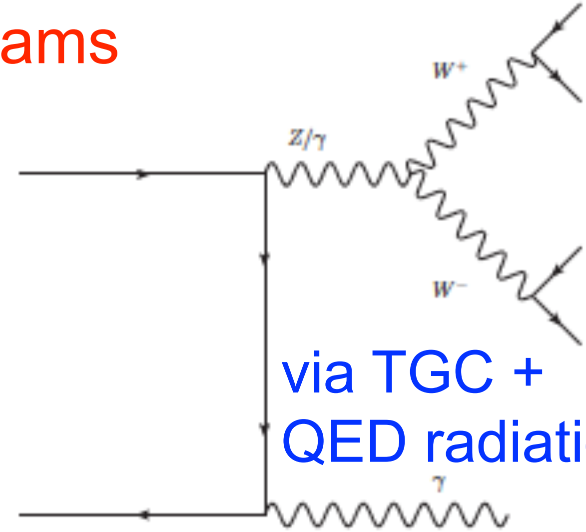
2.) LEP combination, hep-ex/0612034

3.) Bozzi et al, arXiv: 0911.0438

Leading order diagrams



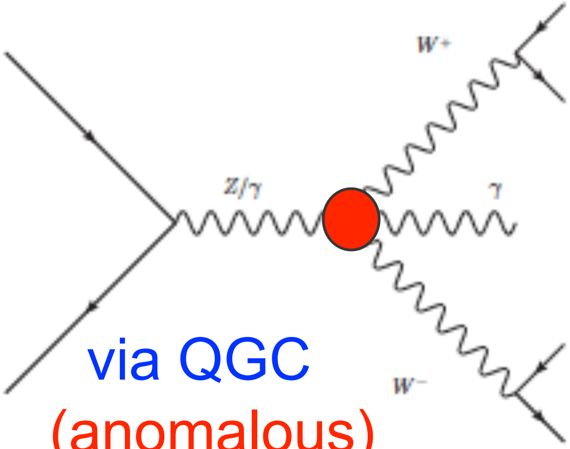
via QED radiation from WW



via TGC + QED radiation

- SM production highly suppressed
  - By a factor of 10^3 compared to WW
- aQGC at WW$\gamma\gamma$ and WWγZ vertices

can enhance production for high photon p_T events by several factors



via QGC (anomalous)

Limits on WWγγ and WWZγ couplings

SMP-13-007

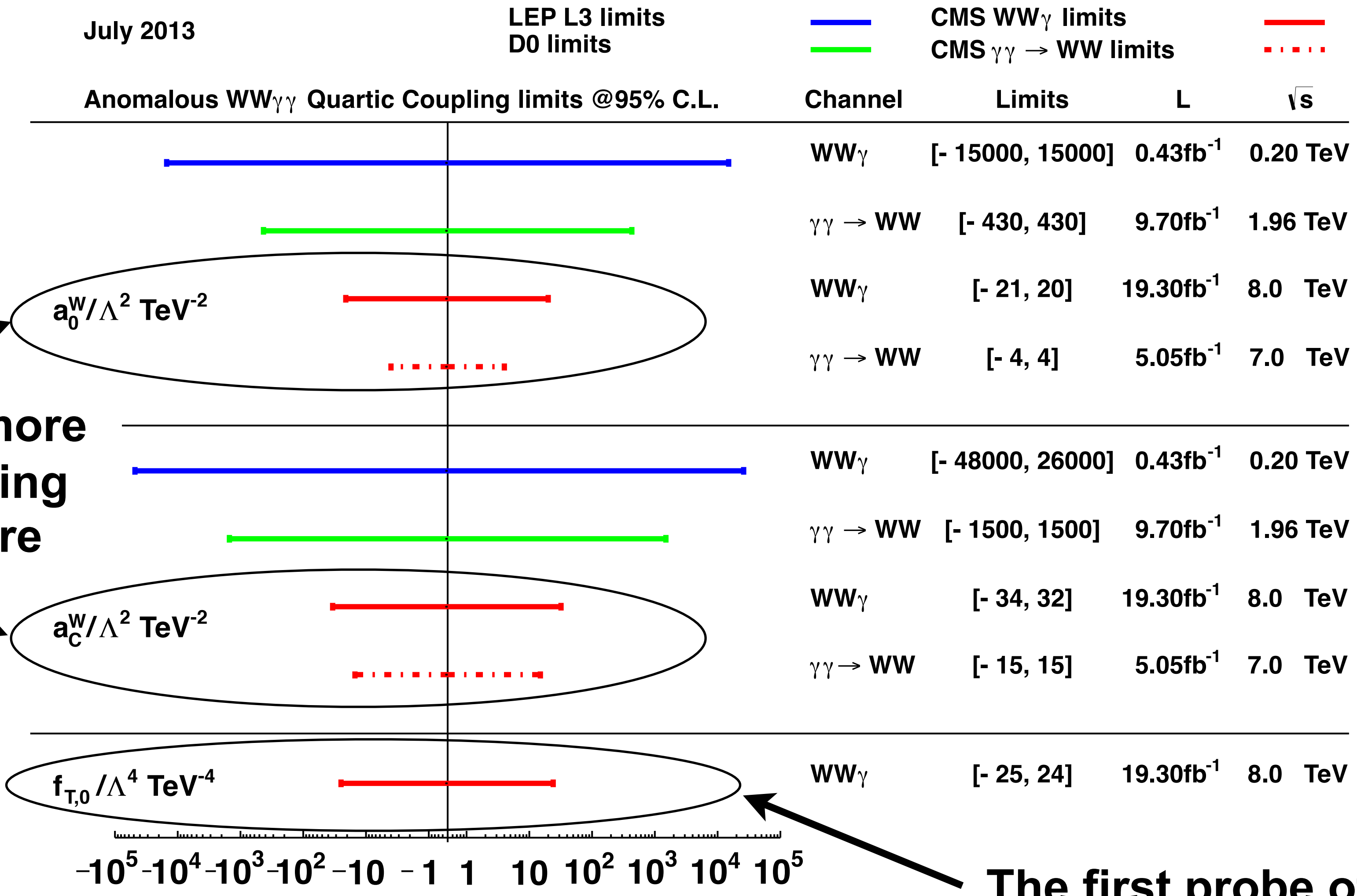
Observed Limits	Expected Limits
$-21\ (\mathrm{TeV}^{-2}) < a_0^W/\Lambda^2 < 20\ (\mathrm{TeV}^{-2})$	$-24\ (\mathrm{TeV}^{-2}) < a_0^W/\Lambda^2 < 23\ (\mathrm{TeV}^{-2})$
$-34\ (\mathrm{TeV}^{-2}) < a_C^W/\Lambda^2 < 32\ (\mathrm{TeV}^{-2})$	$-37\ (\mathrm{TeV}^{-2}) < a_C^W/\Lambda^2 < 34\ (\mathrm{TeV}^{-2})$
$-25\ (\mathrm{TeV}^{-4}) < f_{T,0}/\Lambda^4 < 24\ (\mathrm{TeV}^{-4})$	$-27\ (\mathrm{TeV}^{-4}) < f_{T,0}/\Lambda^4 < 27\ (\mathrm{TeV}^{-4})$
$-12\ (\mathrm{TeV}^{-2}) < \kappa_0^W/\Lambda^2 < 10\ (\mathrm{TeV}^{-2})$	$-12\ (\mathrm{TeV}^{-2}) < \kappa_0^W/\Lambda^2 < 12\ (\mathrm{TeV}^{-2})$
$-18\ (\mathrm{TeV}^{-2}) < \kappa^W/\Lambda^2 < 17\ (\mathrm{TeV}^{-2})$	$-19\ (\mathrm{TeV}^{-2}) < \kappa^W/\Lambda^2 < 18\ (\mathrm{TeV}^{-2})$

Order of magnitude improvement over LEP, but less stringent than γγ→WW. In the dipole units, these limits are probing QGC *O*(100% SM) !!

Observed Limits	Expected Limits
$-77\ (\mathrm{TeV}^{-4}) < f_{M,0}/\Lambda^4 < 81\ (\mathrm{TeV}^{-4})$	$-89\ (\mathrm{TeV}^{-4}) < f_{M,0}/\Lambda^4 < 93\ (\mathrm{TeV}^{-4})$
$-131\ (\mathrm{TeV}^{-4}) < f_{M,1}/\Lambda^4 < 123\ (\mathrm{TeV}^{-4})$	$-143\ (\mathrm{TeV}^{-4}) < f_{M,1}/\Lambda^4 < 131\ (\mathrm{TeV}^{-4})$
$-39\ (\mathrm{TeV}^{-4}) < f_{M,2}/\Lambda^4 < 40\ (\mathrm{TeV}^{-4})$	$-44\ (\mathrm{TeV}^{-4}) < f_{M,2}/\Lambda^4 < 46\ (\mathrm{TeV}^{-4})$
$-66\ (\mathrm{TeV}^{-4}) < f_{M,3}/\Lambda^4 < 62\ (\mathrm{TeV}^{-4})$	$-71\ (\mathrm{TeV}^{-4}) < f_{M,3}/\Lambda^4 < 66\ (\mathrm{TeV}^{-4})$

The first ever limit on WWZγ couplings κ_0^W and κ_c^W. The first limit on dim 8 parameters f_M.

Constraints on 4-vertex couplings



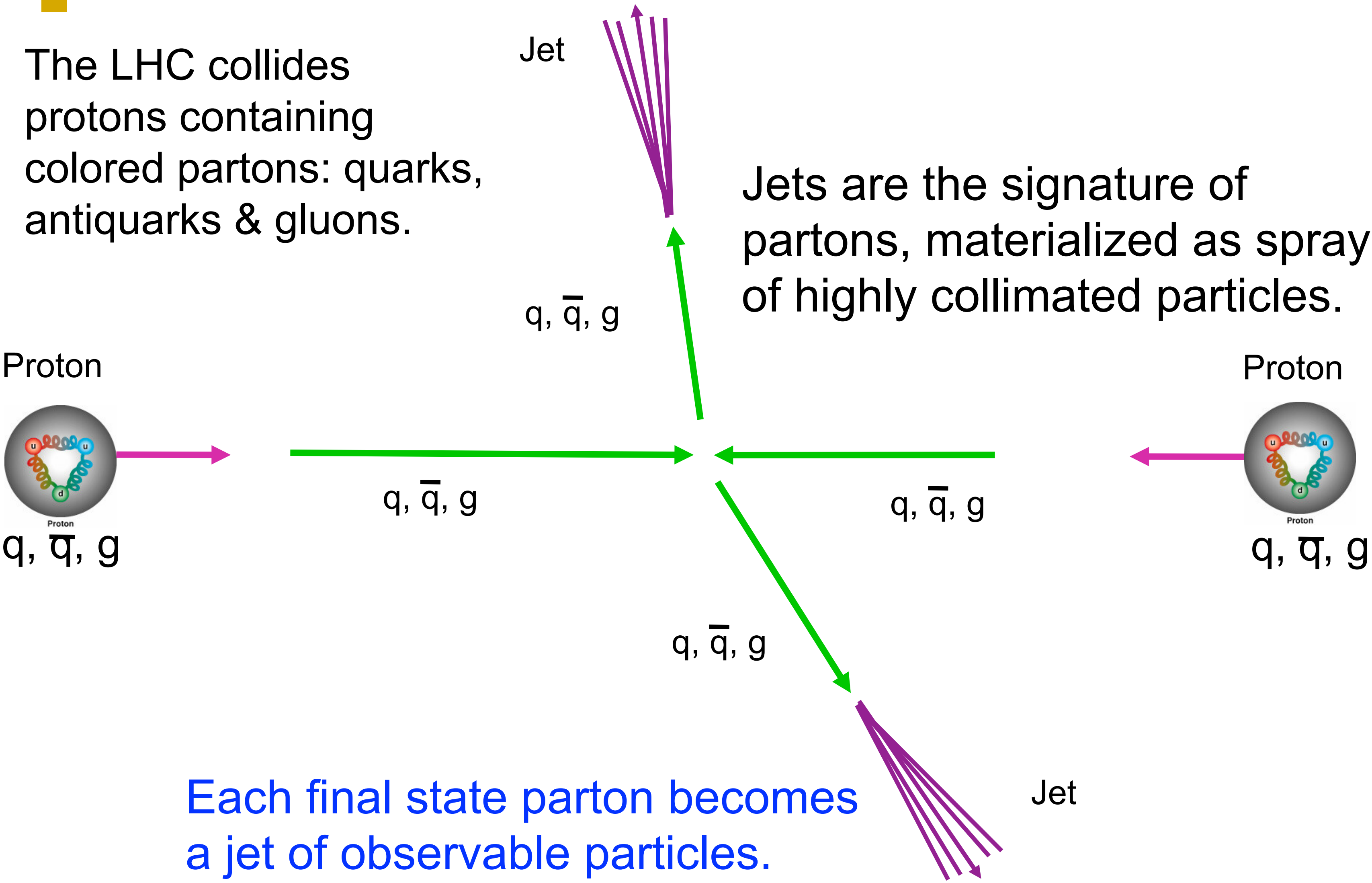
Channel	Limits	L	$\sqrt{s}$
WWγ	[- 15000, 15000]	0.43fb^{-1}	0.20 TeV
$\gamma\gamma \rightarrow$ WW	[- 430, 430]	9.70fb^{-1}	1.96 TeV
WWγ	[- 21, 20]	19.30fb^{-1}	8.0 TeV
$\gamma\gamma \rightarrow$ WW	[- 4, 4]	5.05fb^{-1}	7.0 TeV
WWγ	[- 48000, 26000]	0.43fb^{-1}	0.20 TeV
$\gamma\gamma \rightarrow$ WW	[- 1500, 1500]	9.70fb^{-1}	1.96 TeV
WWγ	[- 34, 32]	19.30fb^{-1}	8.0 TeV
$\gamma\gamma \rightarrow$ WW	[- 15, 15]	5.05fb^{-1}	7.0 TeV
WWγ	[- 25, 24]	19.30fb^{-1}	8.0 TeV

o(100) x more constraining than before

The first probe of this parameter

Particle jets

The LHC collides protons containing colored partons: quarks, antiquarks & gluons.



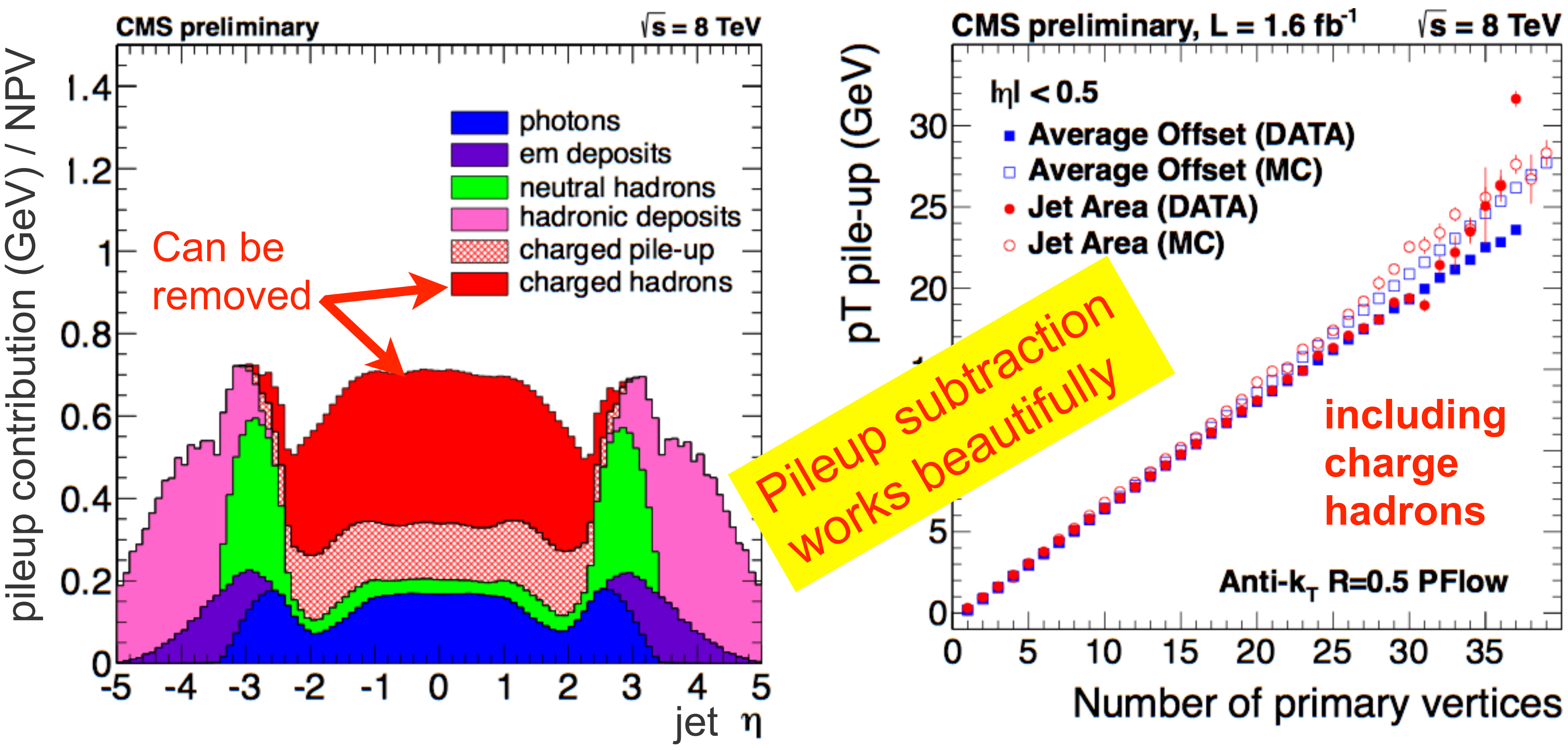
Jets are the signature of partons, materialized as sprays of highly collimated particles.

Each final state parton becomes a jet of observable particles.

Dealing with pileup: subtract its contribution

✦Pileup affects jet energy, MET, and lepton isolation

- Example: pileup contribution to jet p_T per primary vertex.
- Measure in data using several methods. Get consistent results.



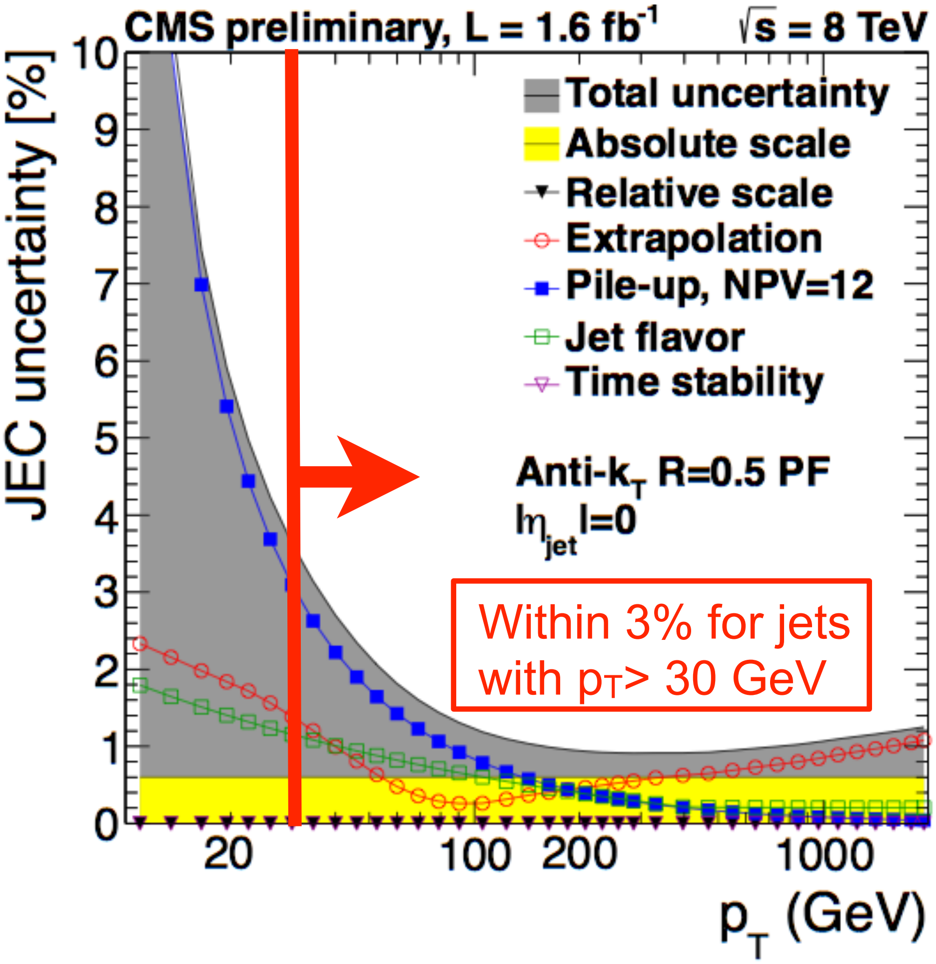
Can be removed

Pileup subtraction works beautifully

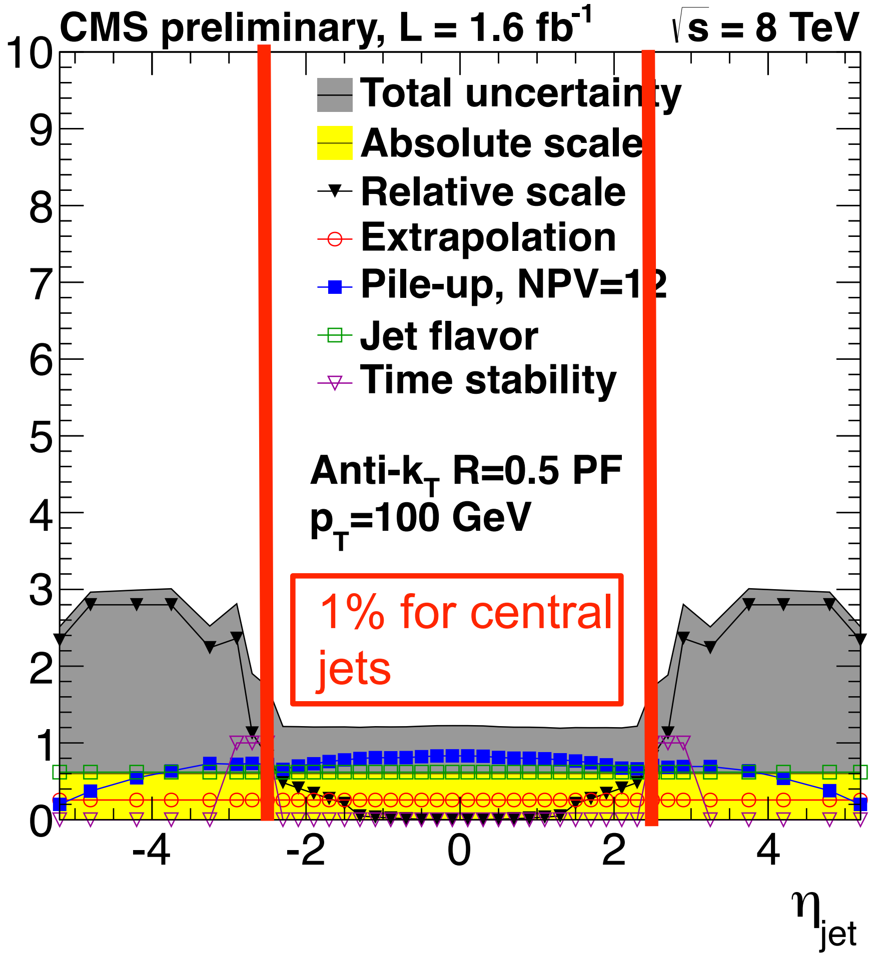
including charge hadrons

Good understanding of detector performance

- ✦An example: jet energy scale
  - Well calibrated

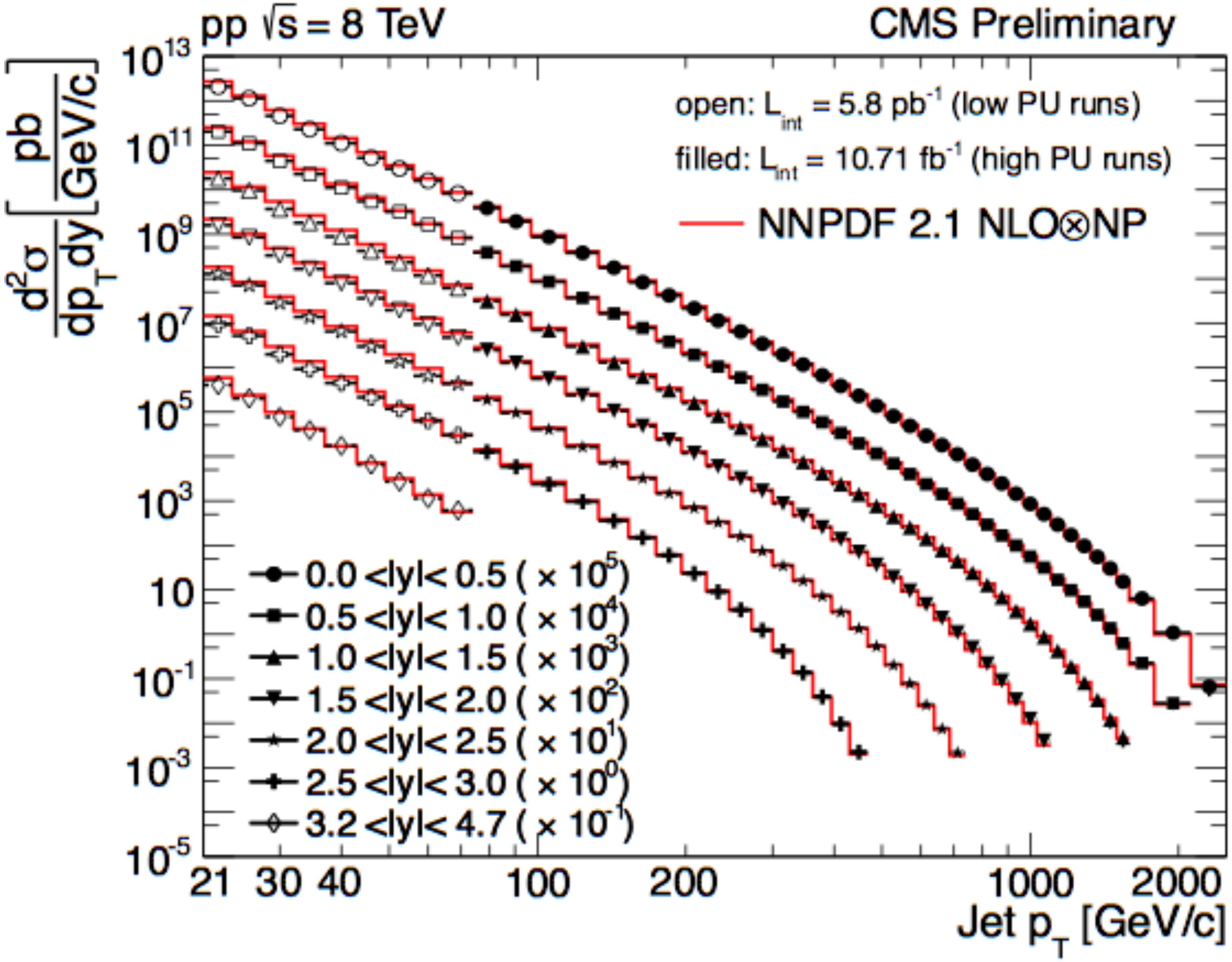


Within 3% for jets with p_T> 30 GeV



1% for central jets

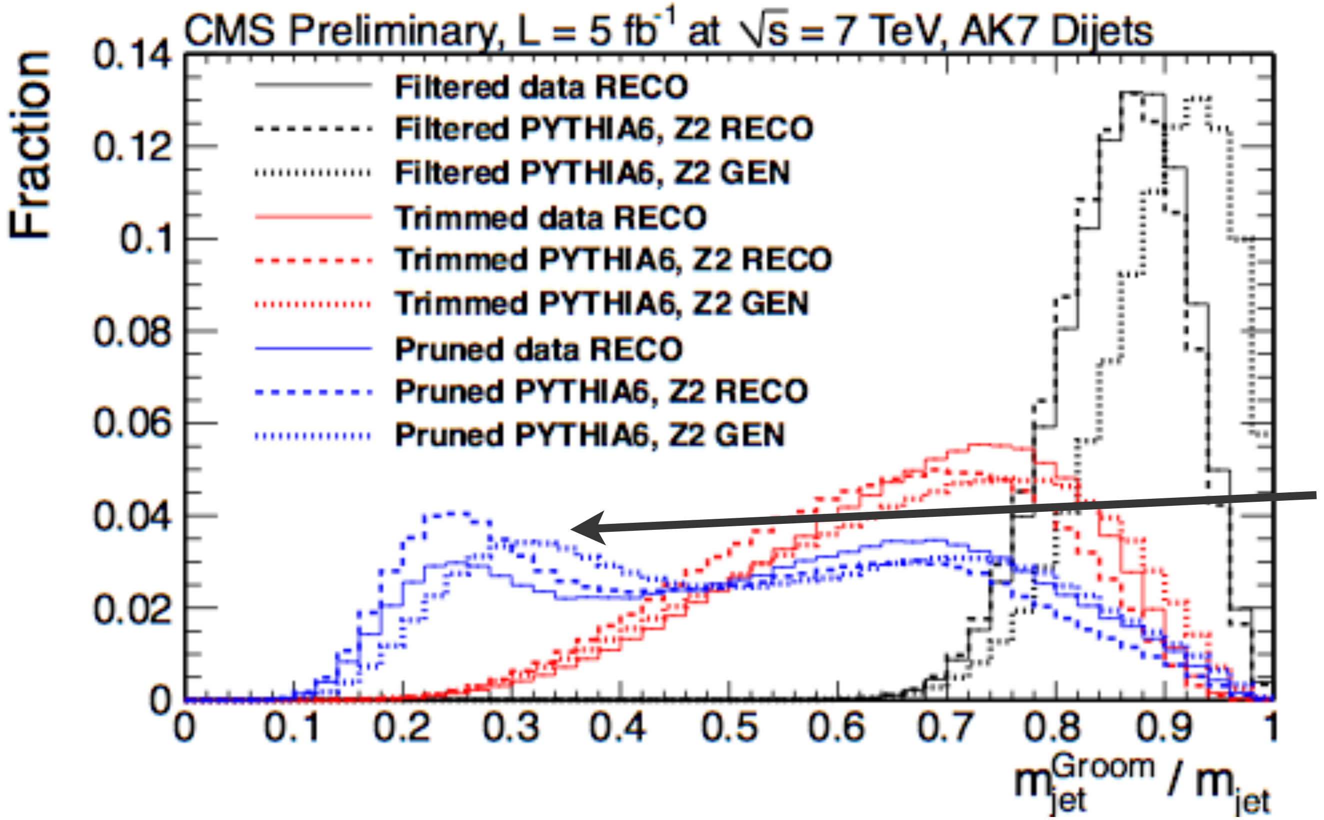
Excellent understanding of jet production at LHC



Probe jet production rate (i.e., the effect of the strong force) over 15 orders of magnitude !!!

No surprises up to 2 TeV transverse momentum.

Peep inside the merged jet, use grooming



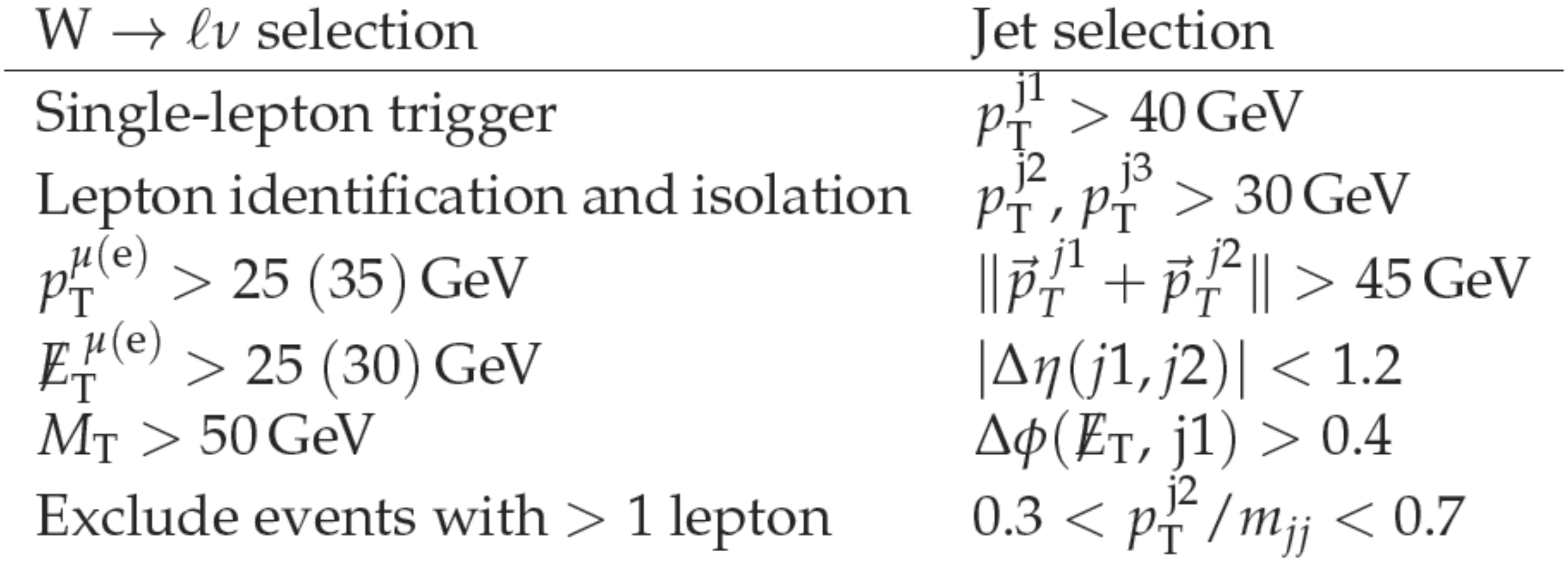
Pruning is the most aggressive, filtering is the least aggressive

bimodal structure provides good separation for qq signal

Comparison of grooming algorithms at particle level (GEN), reconstructed simulation (RECO) and data

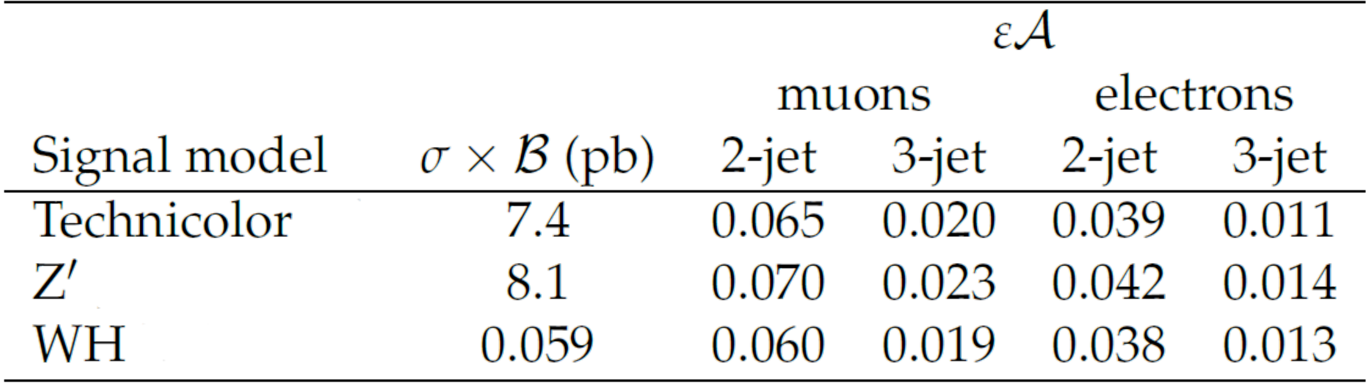
CMS analysis

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11017



$W \to \ell\nu$ selection	Jet selection
Single-lepton trigger	$p_T^{j1} > 40\,\mathrm{GeV}$
Lepton identification and isolation	$p_T^{j2}, p_T^{j3} > 30\,\mathrm{GeV}$
$p_T^{\mu(e)} > 25\ (35)\,\mathrm{GeV}$	$\lVert \vec{p}_T^{\,j1} + \vec{p}_T^{\,j2} \rVert > 45\,\mathrm{GeV}$
$\not{E}_T^{\mu(e)} > 25\ (30)\,\mathrm{GeV}$	$\lvert\Delta\eta(j1, j2)\rvert < 1.2$
$M_T > 50\,\mathrm{GeV}$	$\Delta\phi(\not{E}_T, \mathrm{j1}) > 0.4$
Exclude events with > 1 lepton	$0.3 < p_T^{j2}/m_{jj} < 0.7$

Efficiency x Acceptance for a few typical models



		$\varepsilon\mathcal{A}$			
		muons		electrons	
Signal model	$\sigma \times \mathcal{B}$ (pb)	2-jet	3-jet	2-jet	3-jet
Technicolor	7.4	0.065	0.020	0.039	0.011
Z'	8.1	0.070	0.023	0.042	0.014
WH	0.059	0.060	0.019	0.038	0.013

W+jets shape uncertainty

Two relatively unknown parameters in W+jets shape

- Factorization/renormalization scale (μ)
- Matrix Element – Parton Shower matching threshold (q)

Need to vary them in the fit to get a good modeling of data:

$$\mathcal{F}_{\mathrm{W+jets}} = \alpha\ \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q'^2) + \beta \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu'^2, q_0^2) + (1 - \alpha - \beta) \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q_0^2),$$

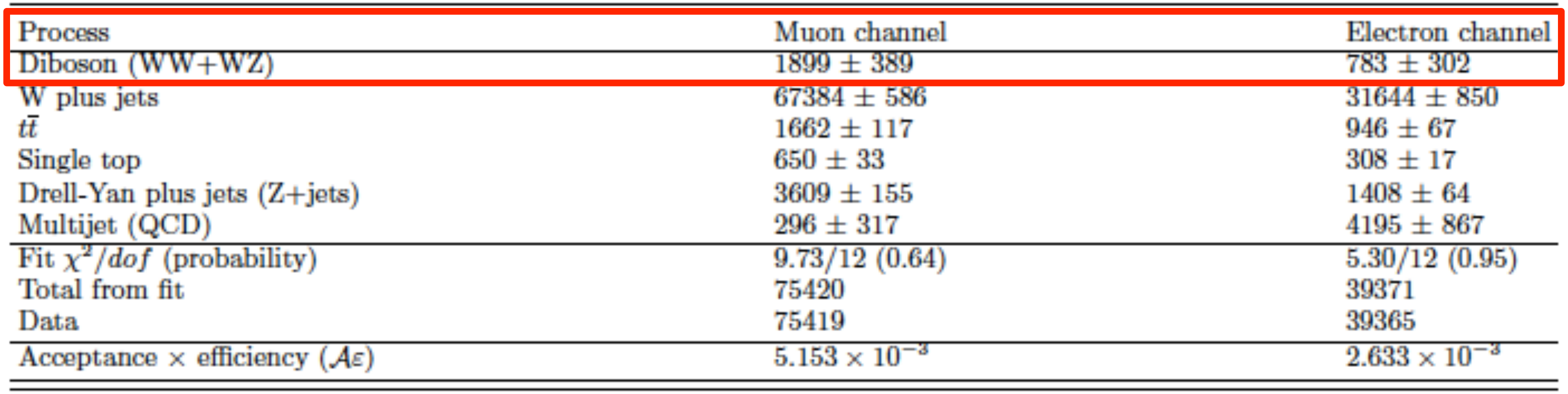
where $0 < \alpha < 1$, $0 < \beta < 1$

- α and β are consistent between muon and electron data
- Data prefer smaller value for ME-PS threshold than 20 GeV

Fit to extract diboson signal

- Diboson contribution floated completely
- QCD constrained using data (i.e., fit to MET distribution)
- Other backgrounds constrained using the most state of the art theory predictions (NLO or NNLO)

Fit results

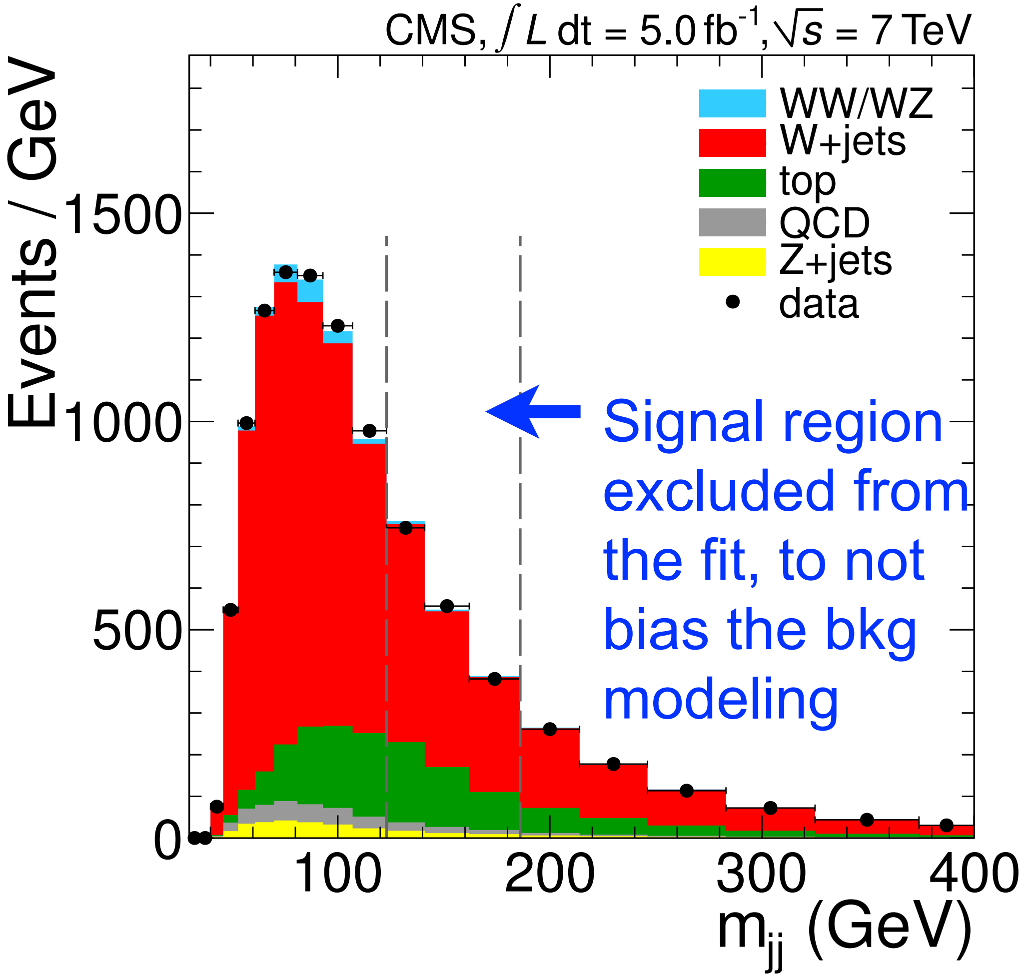


Process	Muon channel	Electron channel
Diboson (WW+WZ)	1899 ± 389	783 ± 302
W plus jets	67384 ± 586	31644 ± 850
$t\bar{t}$	1662 ± 117	946 ± 67
Single top	650 ± 33	308 ± 17
Drell-Yan plus jets (Z+jets)	3609 ± 155	1408 ± 64
Multijet (QCD)	296 ± 317	4195 ± 867
Fit χ^2/dof (probability)	9.73/12 (0.64)	5.30/12 (0.95)
Total from fit	75420	39371
Data	75419	39365
Acceptance × efficiency ($\mathcal{A}\varepsilon$)	5.153×10^{-3}	2.633×10^{-3}

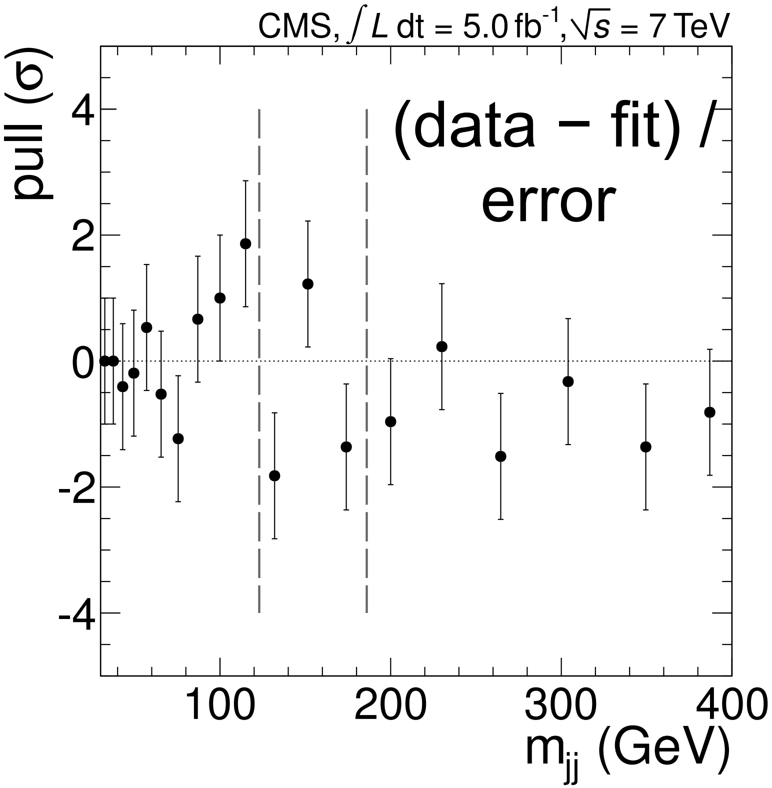
Channel	Observed	Expected (NLO)
Muon	1900 ± 400	1700
Electron	800 ± 300	870

Theory has about 5% uncertainty

Modeling of dijet mass spectrum



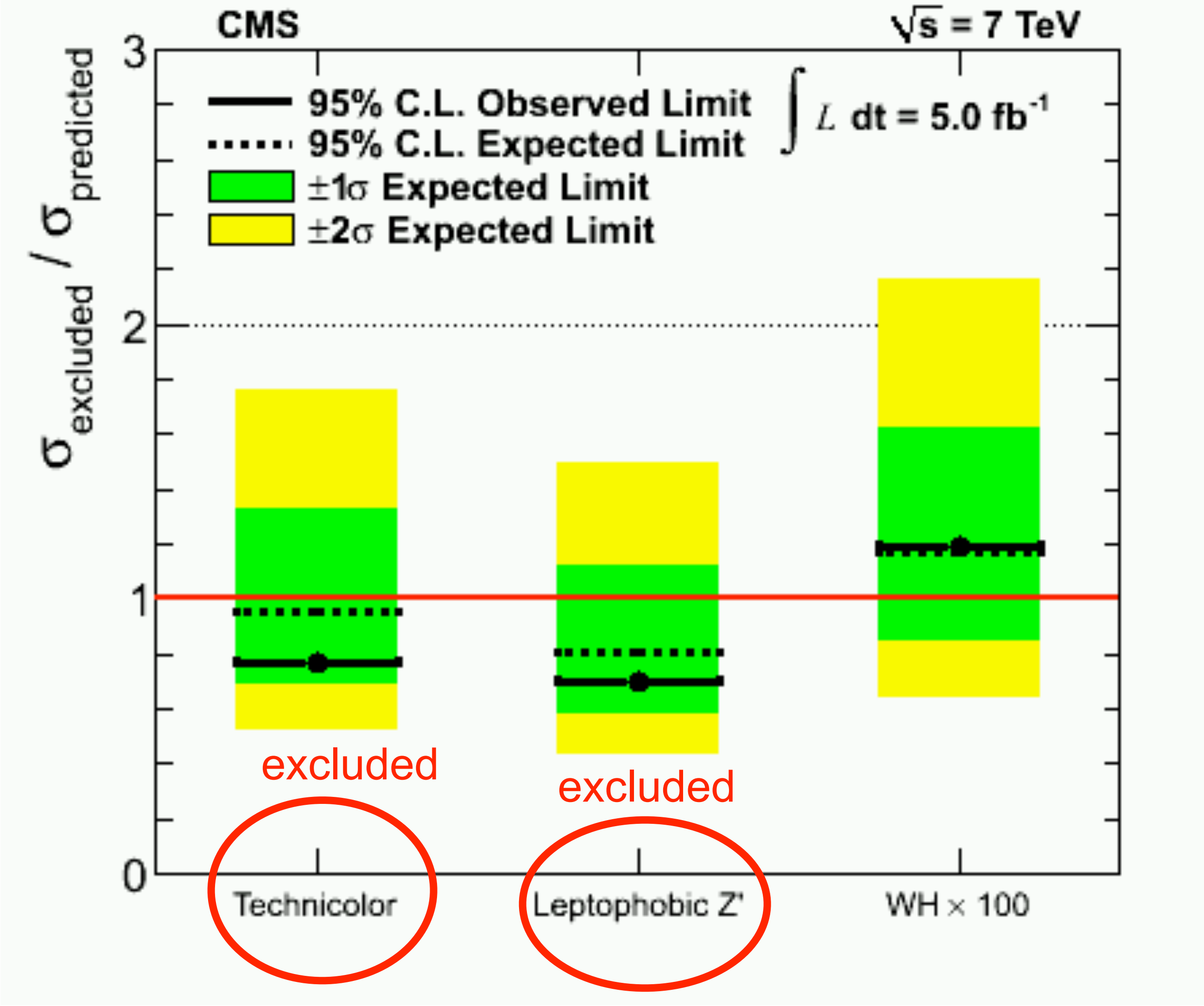
Signal region excluded from the fit, to not bias the bkg modeling



(data − fit) / error

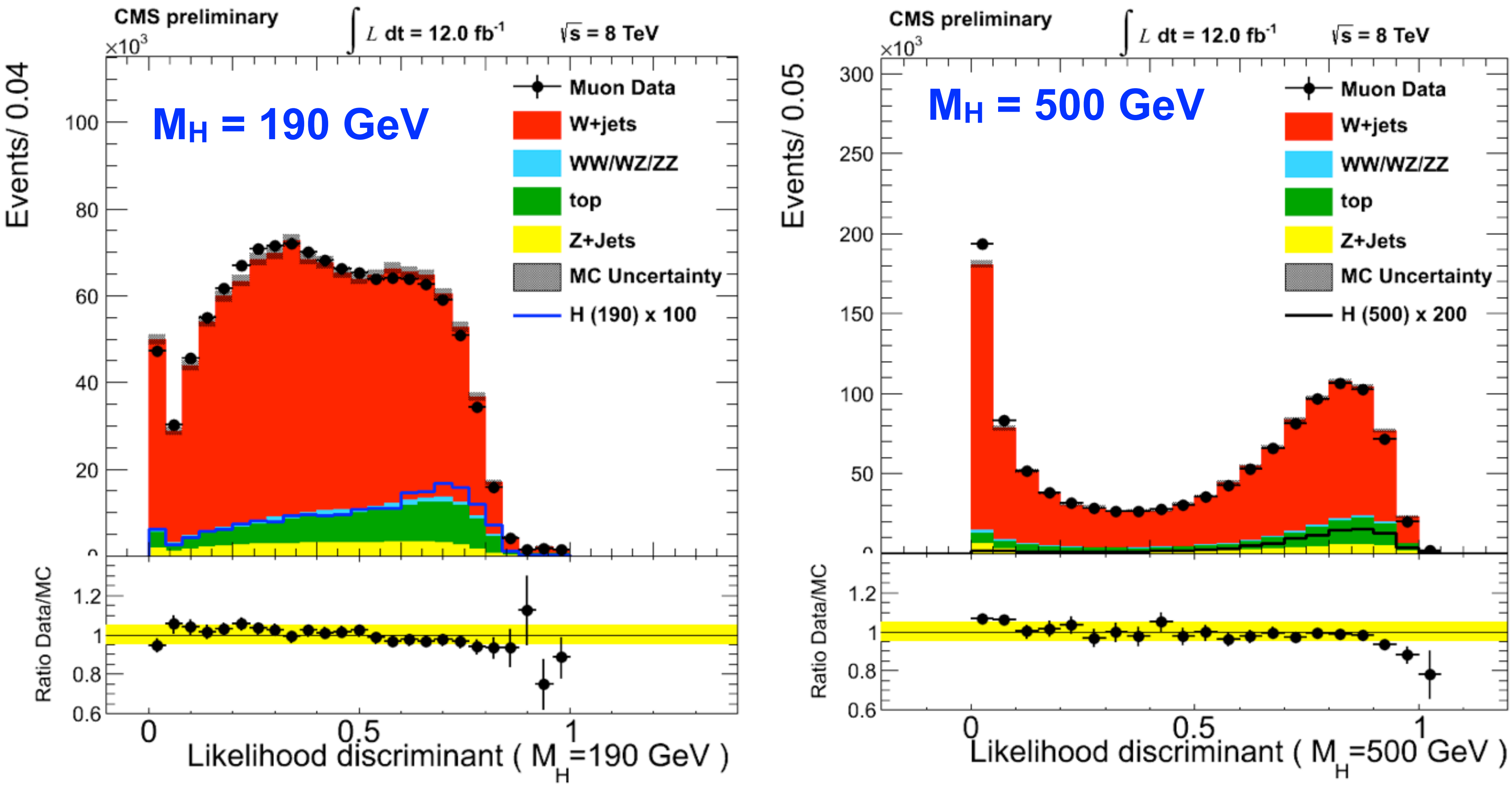
Good modeling of data. Same procedure as in semi-leptonic WW+WZ analysis.

Also excluded several new physics models



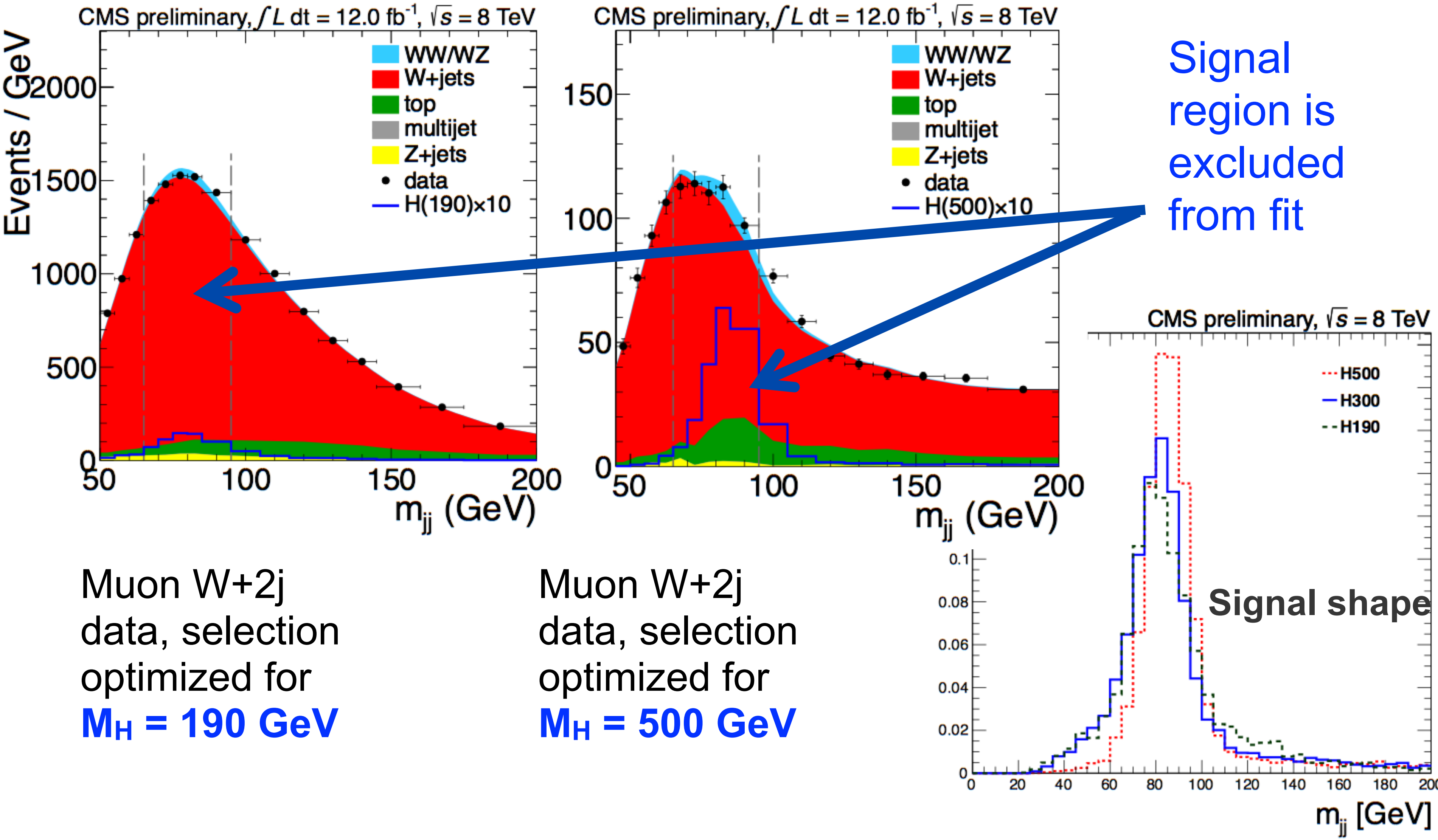
Exclude several classes of BSM models

Examples of likelihood output



Optimize 48 likelihoods: 12 mass points (M_H:170, 180, 190, 200, 250,.., 600 GeV) x 2 lepton flavors x 2 Njets (i.e., =2 or 3)

Use m_{jj} fit to obtain background normalization



Signal region is excluded from fit

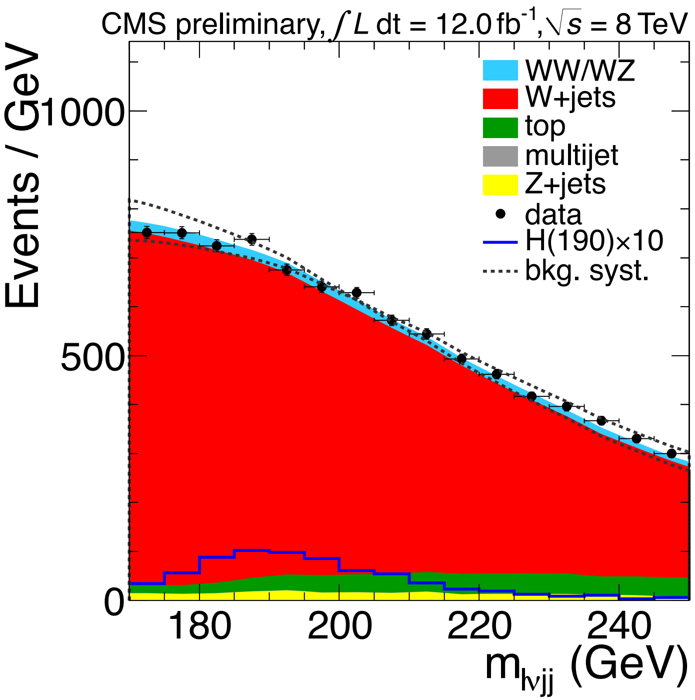
Muon W+2j data, selection optimized for **M_H = 190 GeV**

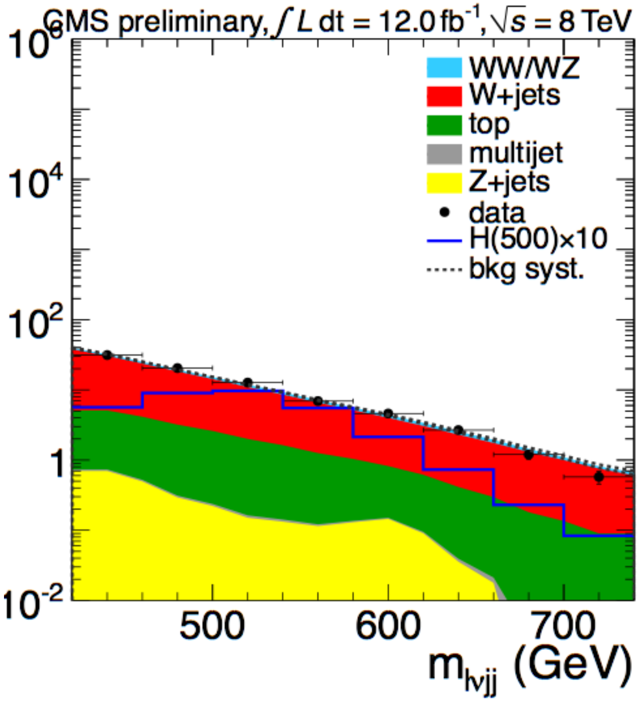
Muon W+2j data, selection optimized for **M_H = 500 GeV**

Signal shape

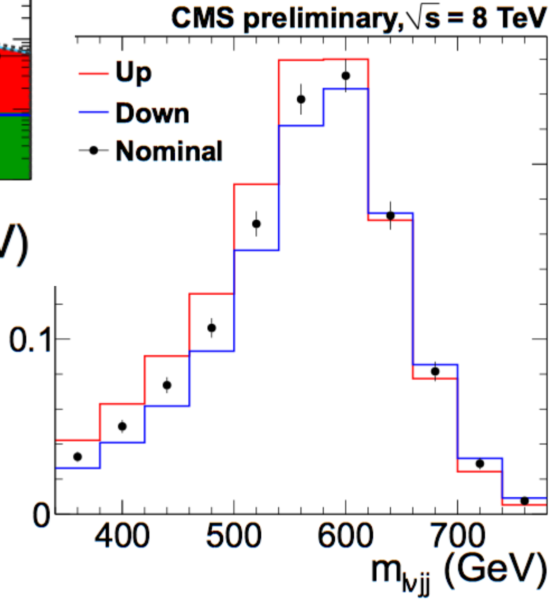
Now plot m_{WW} spectrum in signal region

Use data sidebands to model W+jets background shape





Signal syst for M_H = 600 GeV: dominated by **interference btw $gg \to WW$ and $gg \to H \to WW$**



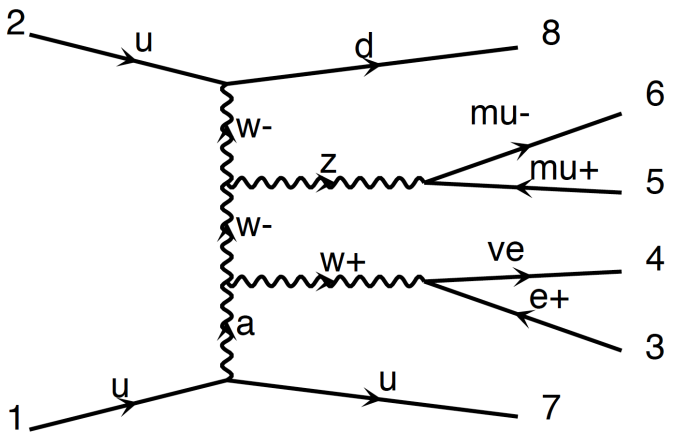
Muon W+2j data with m_{jj} in range [65, 95] GeV, selection optimized for **M_H = 190 GeV**

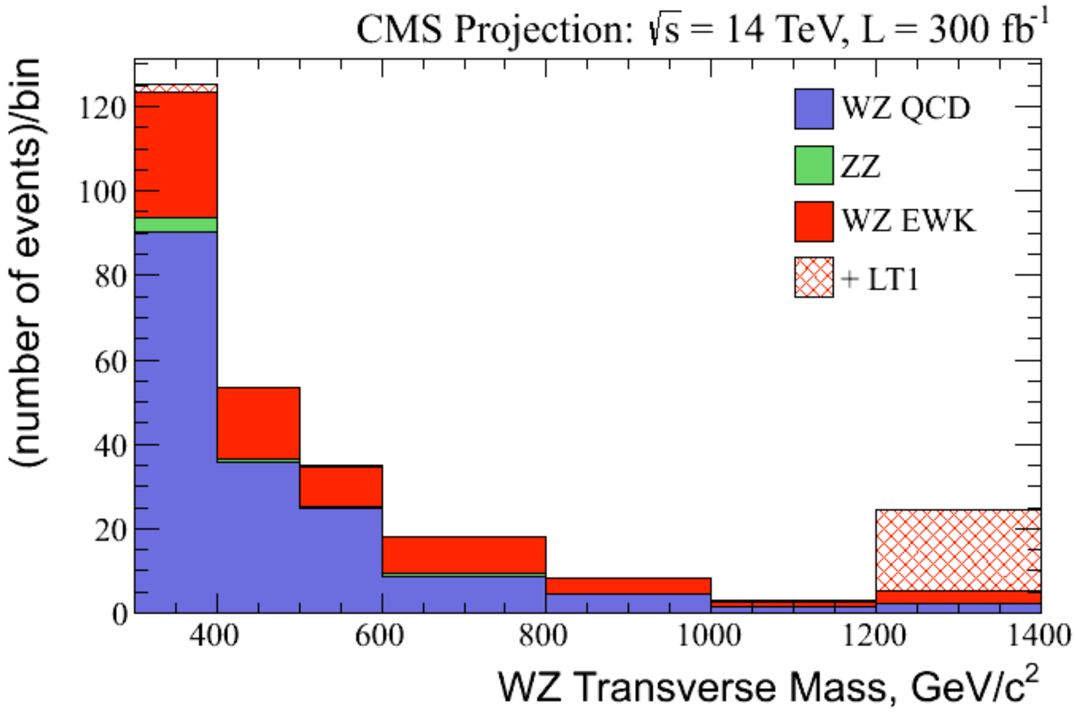
Muon W+2j data with m_{jj} in range [65, 95] GeV, selection optimized for **M_H = 500 GeV**

Some projections for VV scattering

CMS FTR-13-006

Projections done for WZ (all leptonic) scattering at 14 TeV





Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1} f_{T1}/Λ^4 at 3000 fb^{-1}	0.8 TeV^{-4} 0.45 TeV^{-4}	1.0 TeV^{-4} 0.55 TeV^{-4}

Peak performance through the years

"What's past is prologue"

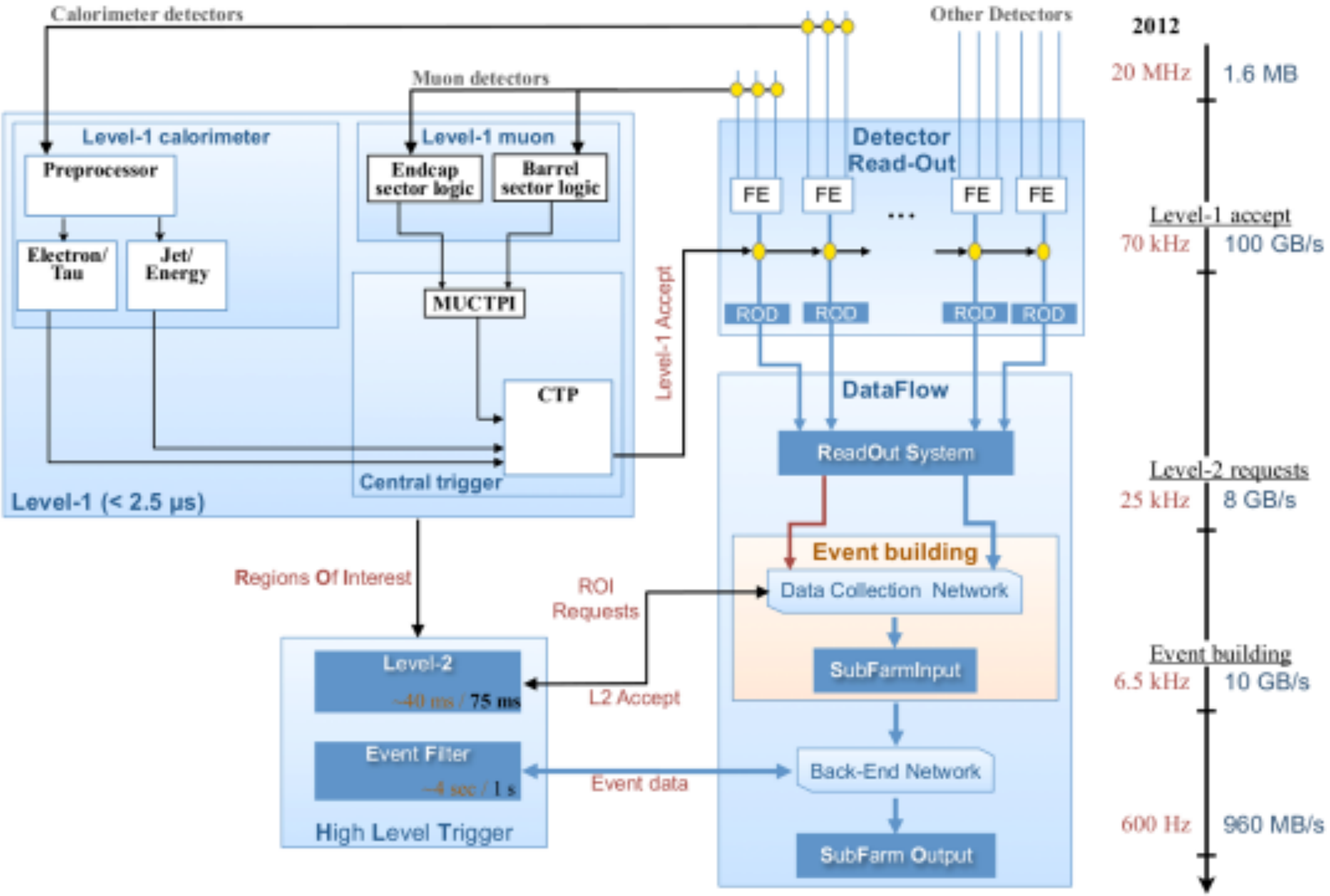
	2010	2011	2012	Nominal
Energy [TeV]	3.5	3.5	4	7
Bunch spacing [ns]	150	50	50	25
No. of bunches	368	1380	1380	2808
beta* [m] ATLAS and CMS	3.5	1.0	0.6	0.55
Max **bunch intensity** [protons/bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
Normalized **emittance** [mm.mrad]	~2.0	~2.4	~2.5	3.75
Peak luminosity [$cm^{-2}s^{-1}$]	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}	1.0×10^{34}

Run-2 post long shutdown

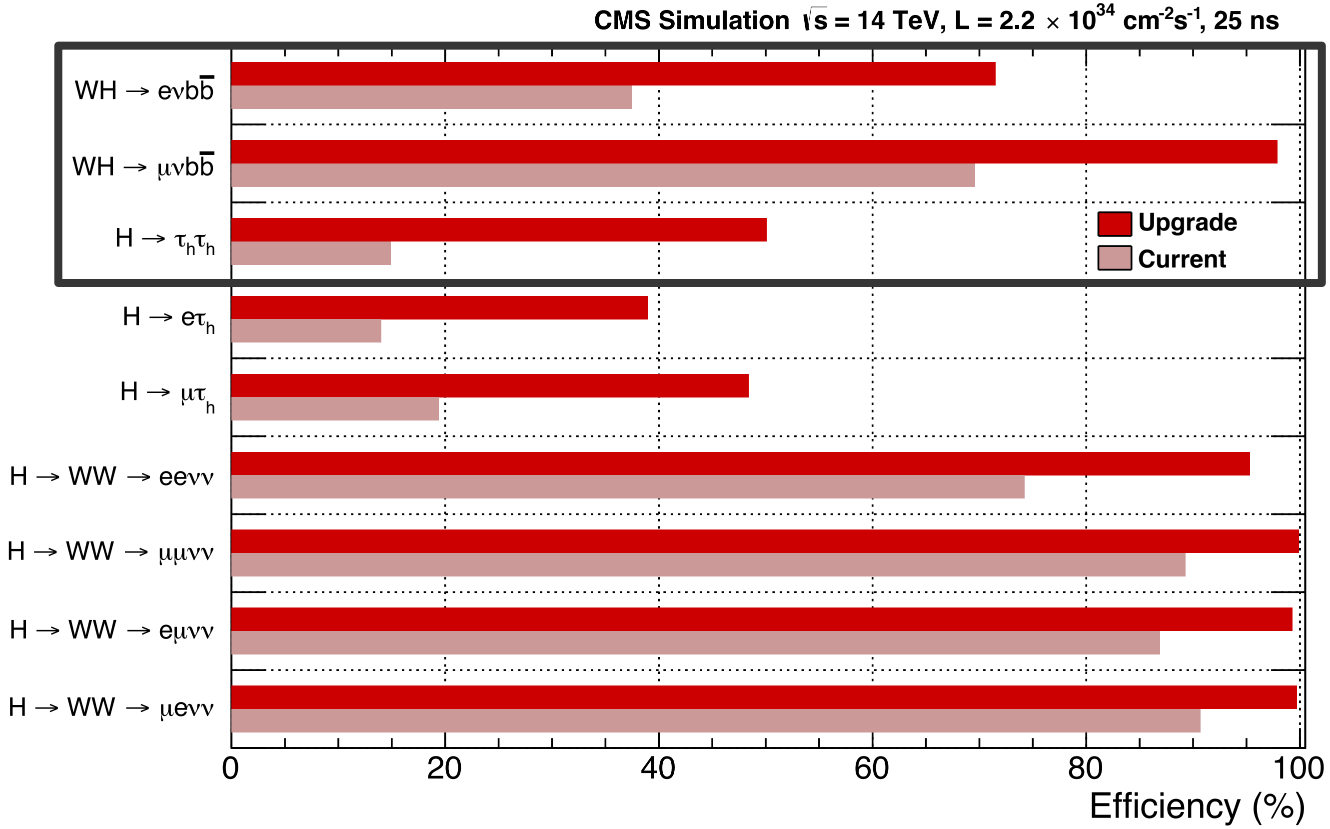
Energy: 6.5 TeV
Beta*: 40 – 50 cm
Bunch spacing: 25 ns

	Number of bunches	Ib LHC [1e11]	Emit LHC [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi per year [fb^{-1}]
25 ns	2590	1.15	1.9	**1.7e34**	49	~45

ATLAS trigger/DAQ



Effect on Higgs boson reconstruction efficiency



Remarks:

1.) Hadronic taus are now reco'ed as Egamma objects. Previously they were reconstructed as jets.

2.) Take advantage of the 2x finer granularity of the ECAL clustering.