CMS Recent Results & Prospects for probing Higgs CP using H → ττ

Yuta Takahashi (CERN)

Physics Seminar @ KEK

30 September 2015

Outlook

- Introduction
- CMS status & First results at 13TeV
- Improvement of the tau identification
- Prospective study for measuring Higgs CP using $H \rightarrow \tau\tau$

What we learned from LHC run-1 ?

SM describes all observations very well

A fundamental scalar (aka Higgs boson) with m_H = 125 GeV that couples to mass

- *the* Higgs boson ?
- First scalar of many ?
- Elementary or composite ?
- Couples to Dark matter ?
- etc…

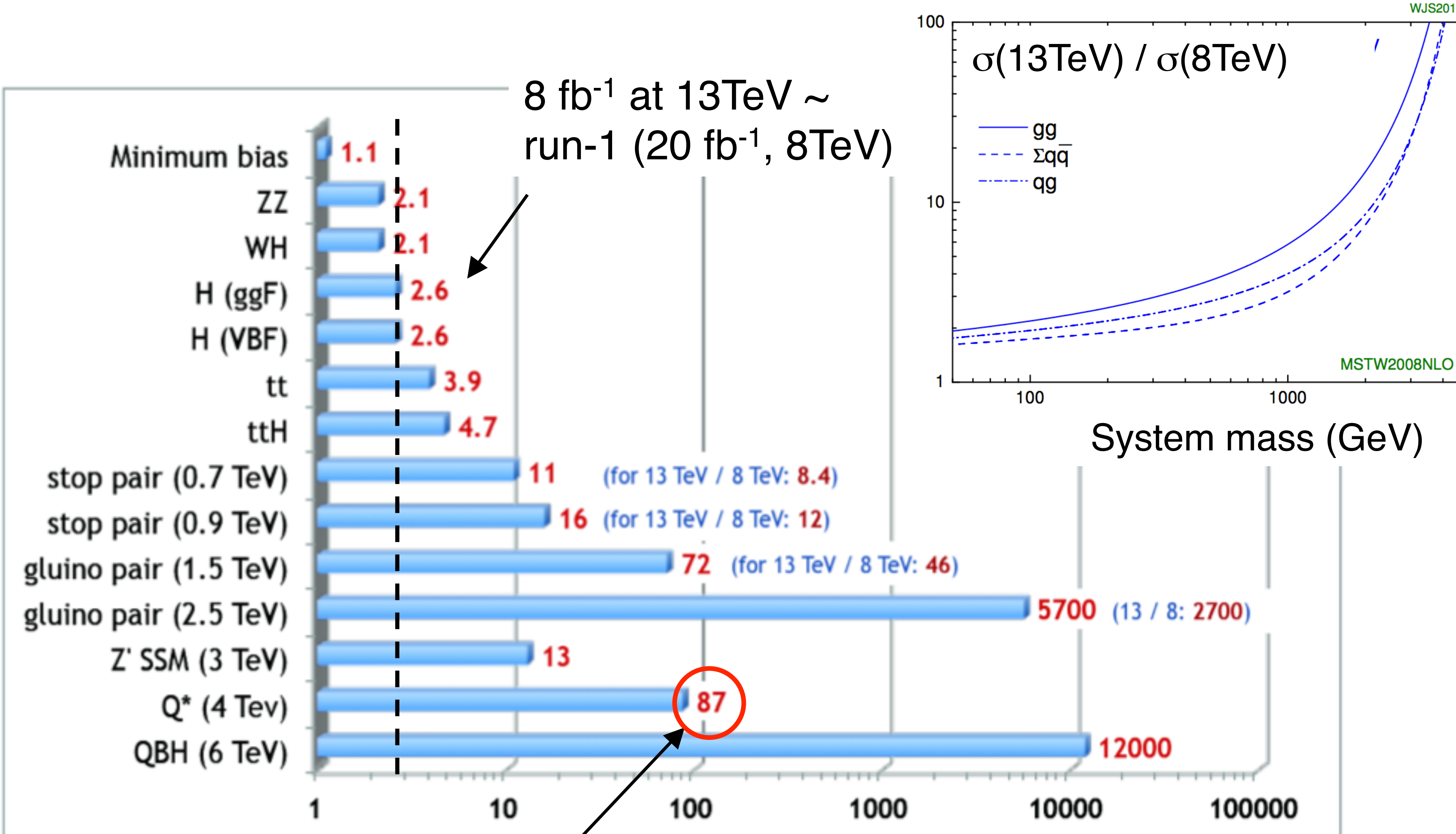
Precise measurement of the Higgs properties (couplings, **CP**, exotic decays,…)

No new physics (yet)

Direct search

Run-2 might give us an answer

8 fb^{-1} at 13TeV ~
run-1 (20 fb^{-1}, 8TeV)



230 pb^{-1} (13TeV) = run-1 (20 fb^{-1}, 8TeV) → Large benefit for NP search

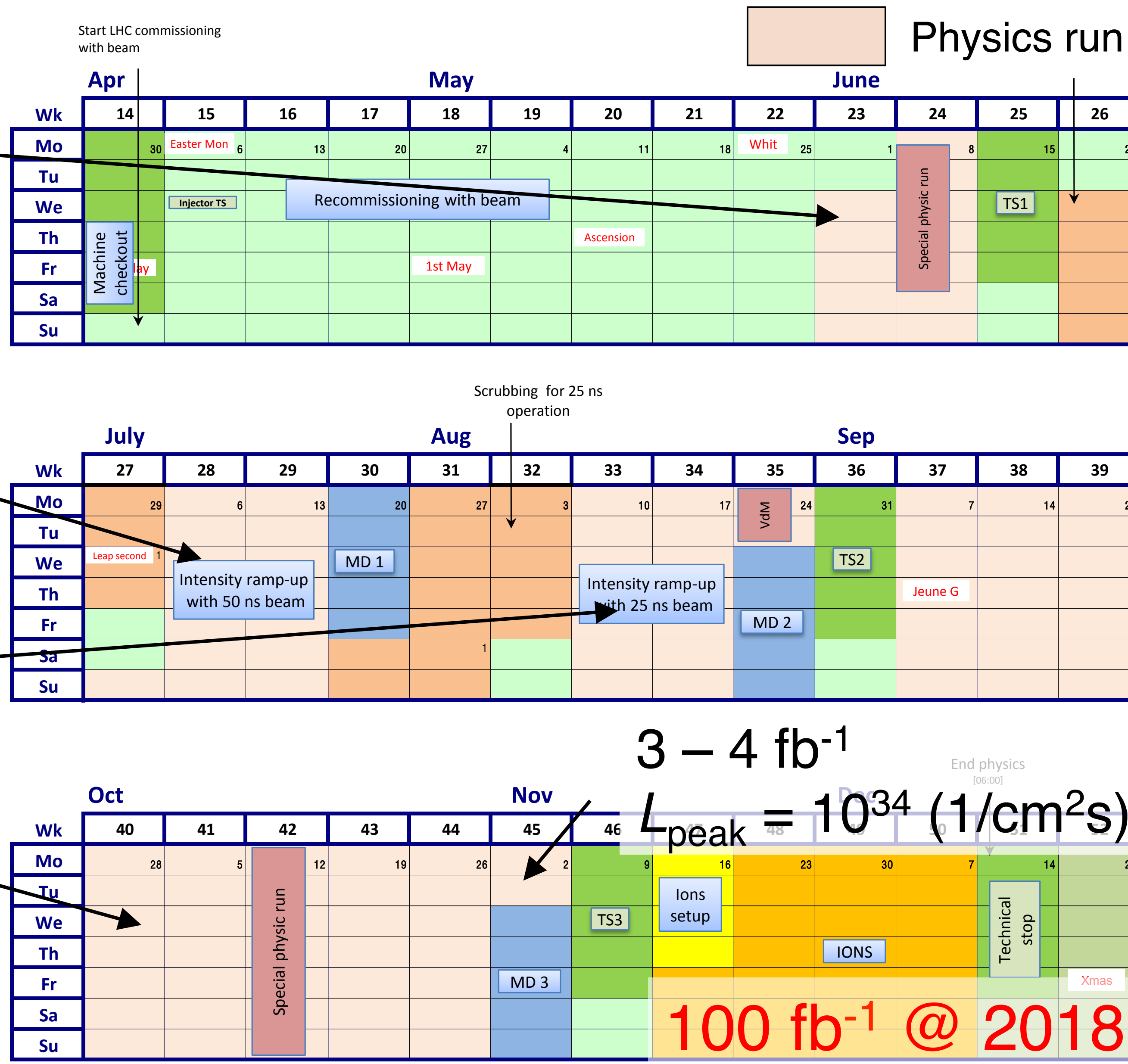
We are in run-2 (until 2018)

Started beginning of June

July: 100 pb^{-1} of data with 50ns bunch spacing

Aug: Start 25ns run

We are here (1.1 fb^{-1} so far)



3 – 4 fb^{-1}

$L_{peak} = 10^{34}$ $(1/cm^2s)$

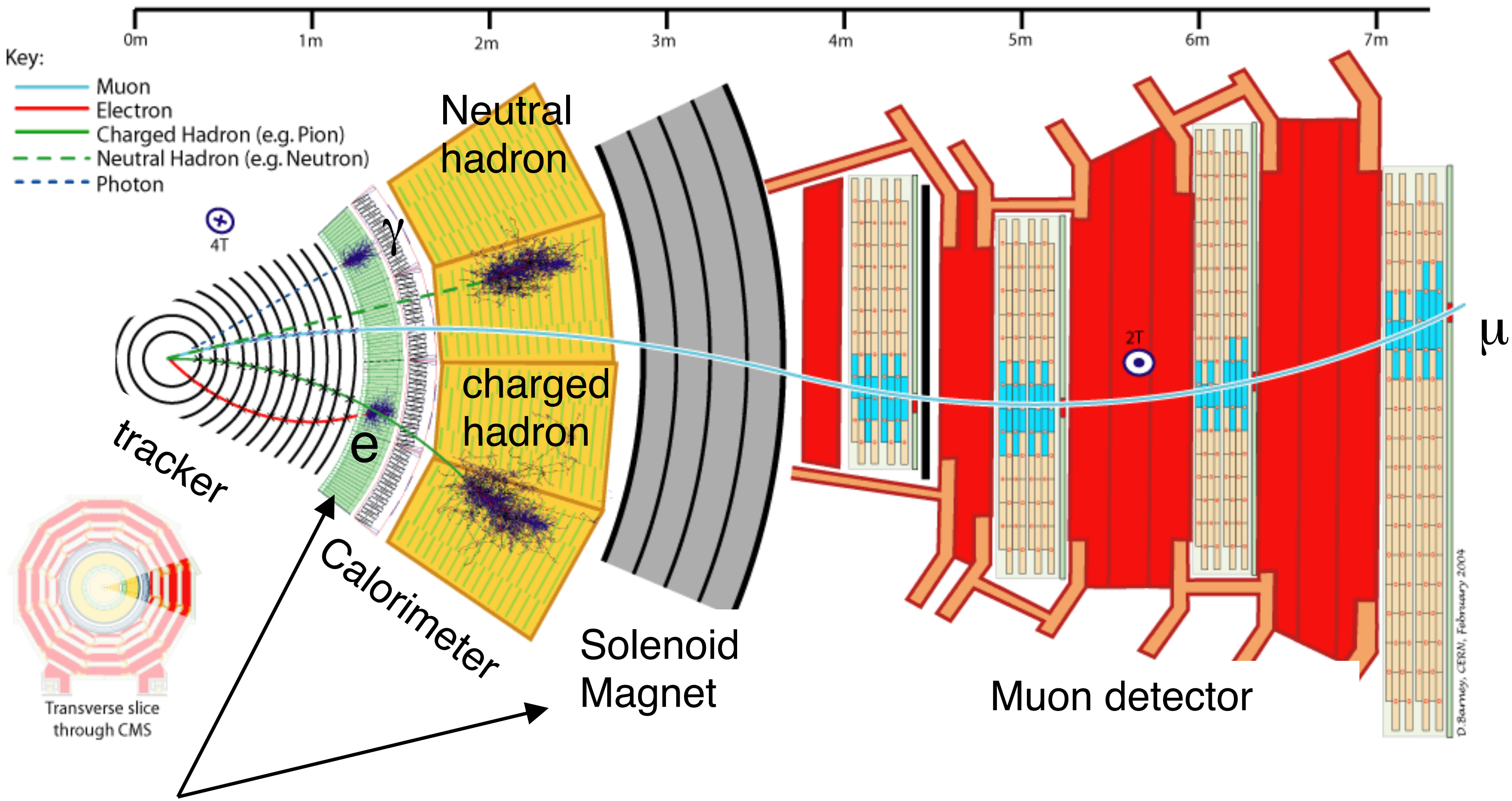
100 fb^{-1} @ 2018

Outlook

- Introduction
- CMS status & First results at 13TeV
- Improvement of the tau identification
- Prospective study for measuring Higgs CP using $H \rightarrow \tau\tau$

CMS detector

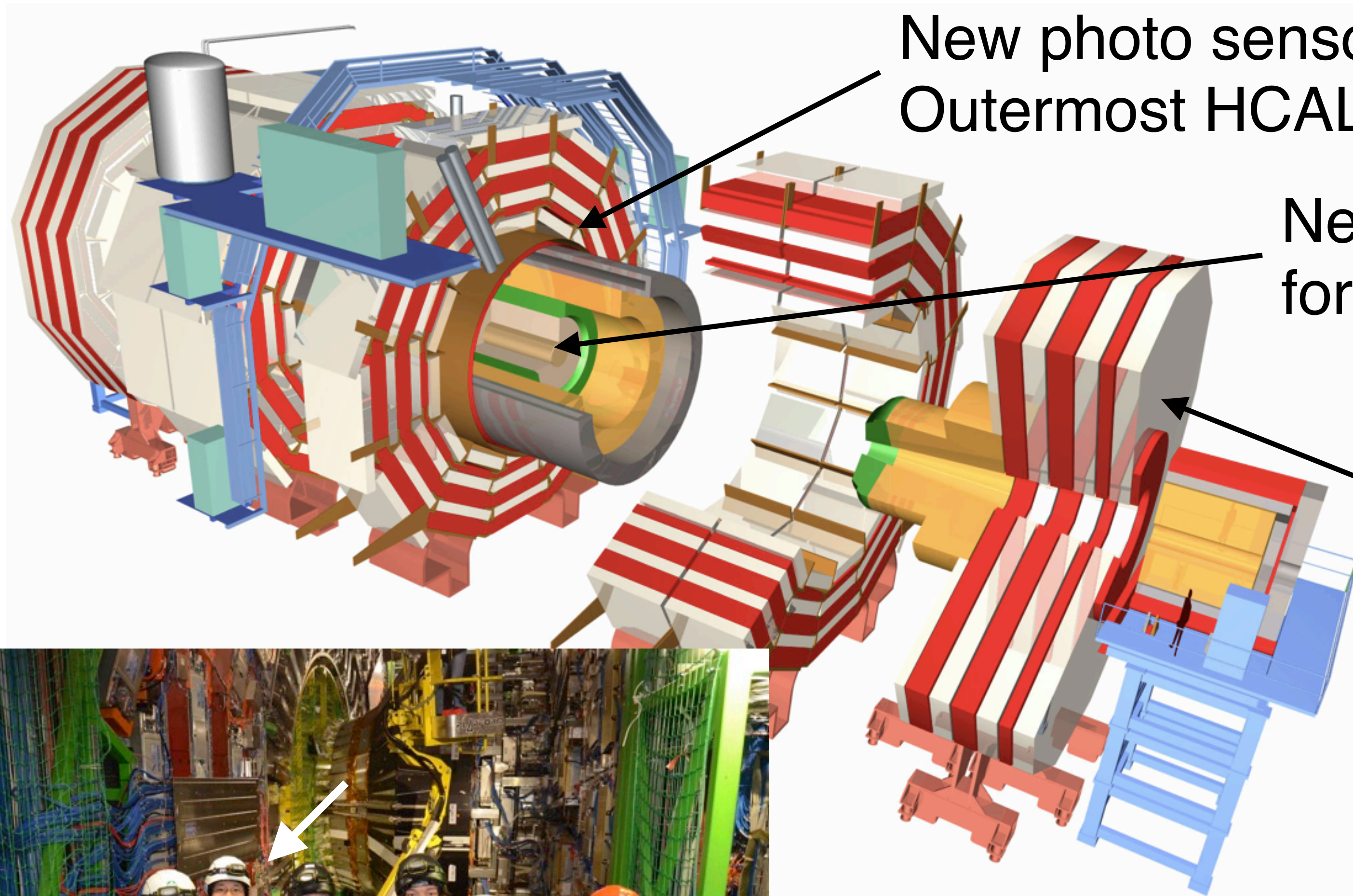
CMS : diameter 15m x length 22m
(ATLAS : diameter 25m x length 44m)



Strong B field (3.8T) + Total absorption type ECAL

→ Nice e/γ resolution ($\sigma_{m_{\gamma\gamma}}/m_{\gamma\gamma} \sim 0.8\%$)

Upgrade during long shutdown



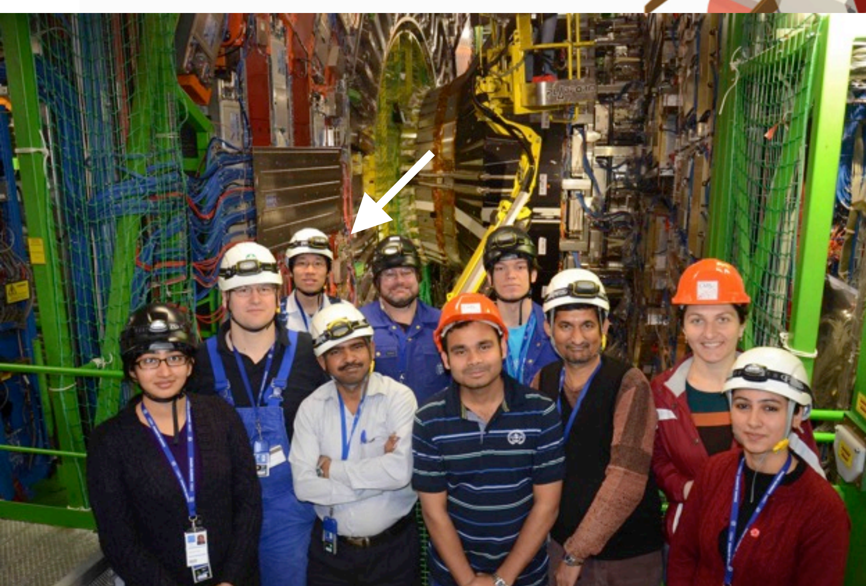
New photo sensors for the Outermost HCAL

New beam pipe for 4^{th} pixel layer

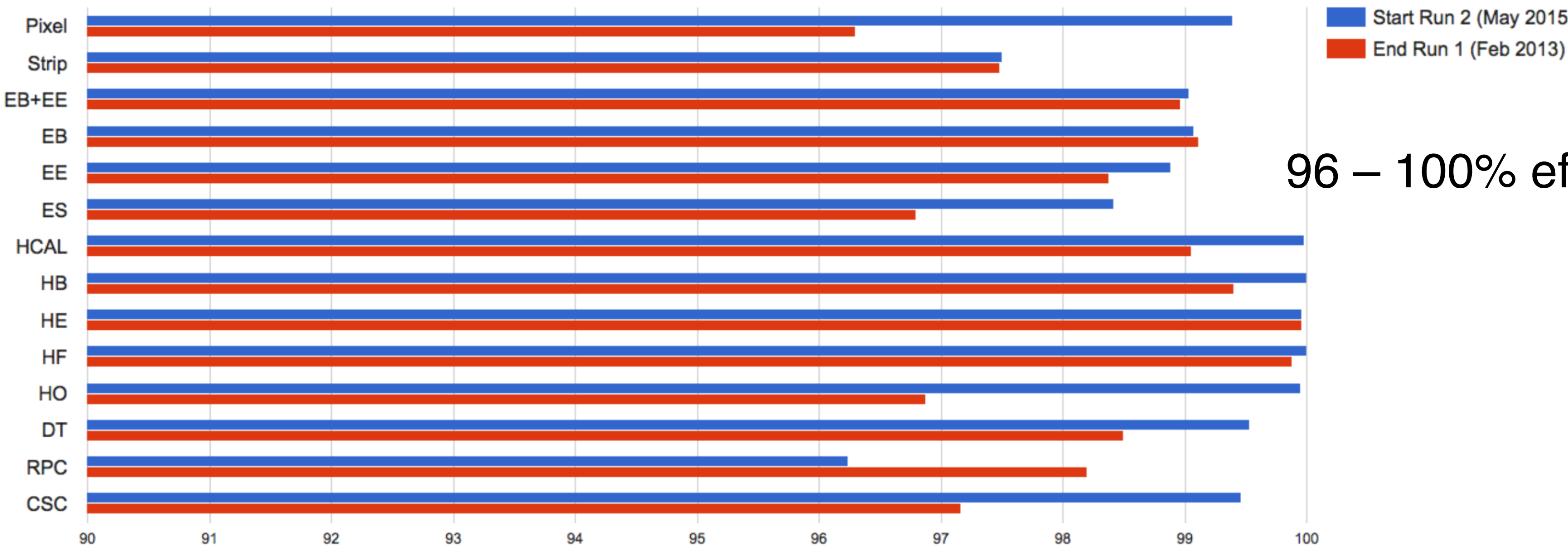
4^{th} muon station

DAQ

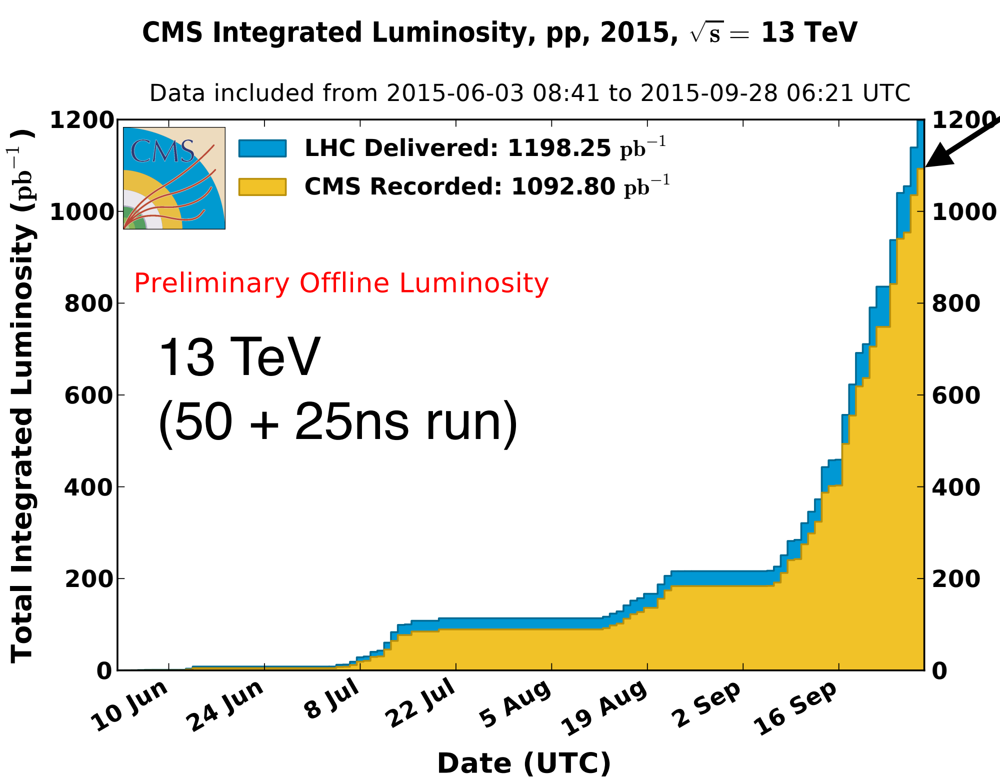
Trigger



Commissioning crew of Hadron calorimeter



96 – 100% eff.



1092 pb^{-1} (~35% with B = 0T)

- Magnet has been operated intermittently due to problems in cryogenic system (clogging effects of contaminants in compressor)
- Magnet can be operated but continuous up-time is still limited
- A strategy for complete component replacement or cleaning during the end of the year shutdown

Selected physics results @ 13TeV

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/ (preliminary results)

http://cms-results.web.cern.ch/cms-results/public-results/publications/ (publications)

- Charged hadron multiplicity v.s η (FSQ-15-001)
- Di-jet bump search (EXO-15-001)
- Ttbar cross-section
  - Di-lepton (TOP-15-003)
  - Semi-lepton (TOP-15-005)
  - Differential (TOP-15-010)
- Single-top (TOP-15-004)
- Ridge analysis (FSQ-15-002)
- W, Z inclusive cross-section (SMP-15-004)
- W', Z' search (DP-2015-037, DP-2015-039)

Soft-QCD

Hard-QCD

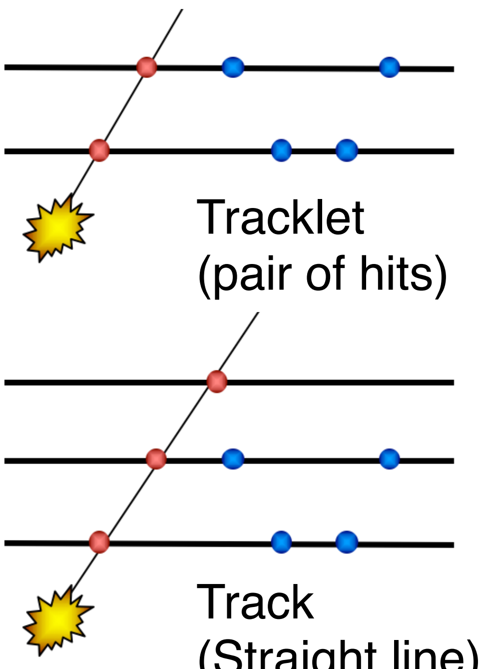
EWK

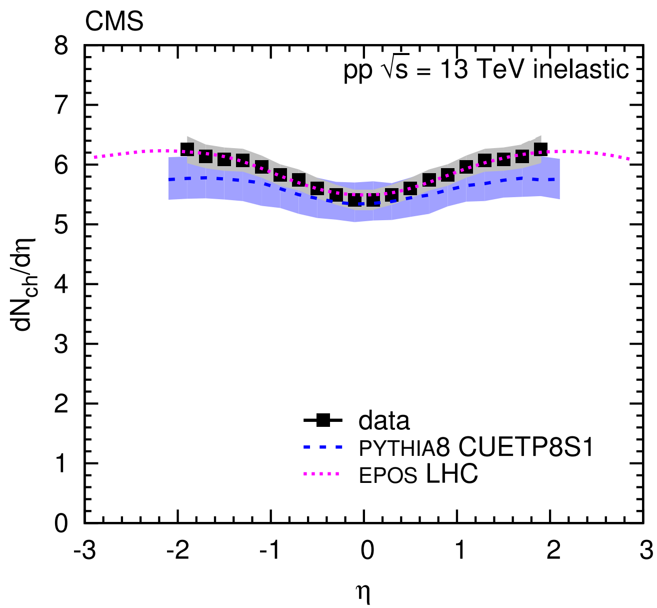
High mass EWK

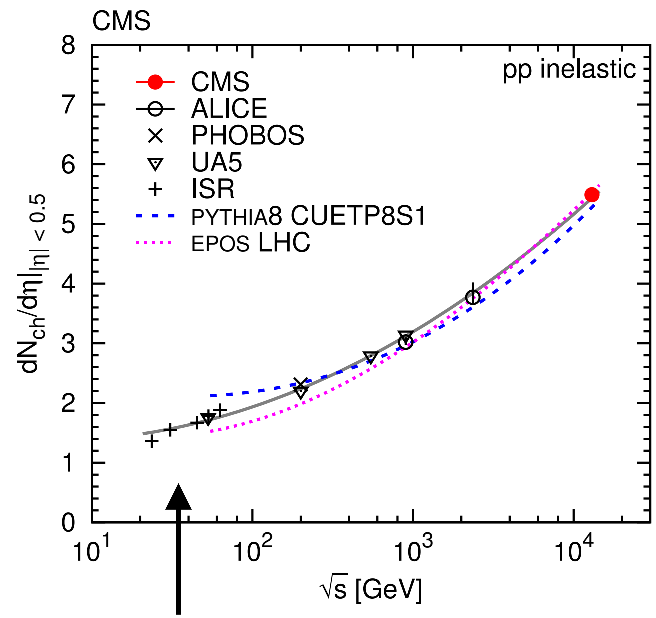
Charged Hadron multiplicity v.s η

- First publication from LHC after 1.5h of data-taking
- 0.5% pp interaction per bunch crossing (clean), B = 0T

Counting experiment using pixel detector





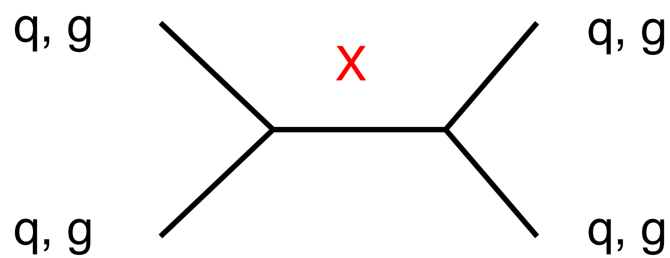


Relevant to the relative weight of soft / hard scattering

$$dN_{ch}/d\eta_{(|\eta| < 0.5)} = 5.49 \pm 0.01\ (\text{stat}) \pm 0.17\ (\text{sys})$$

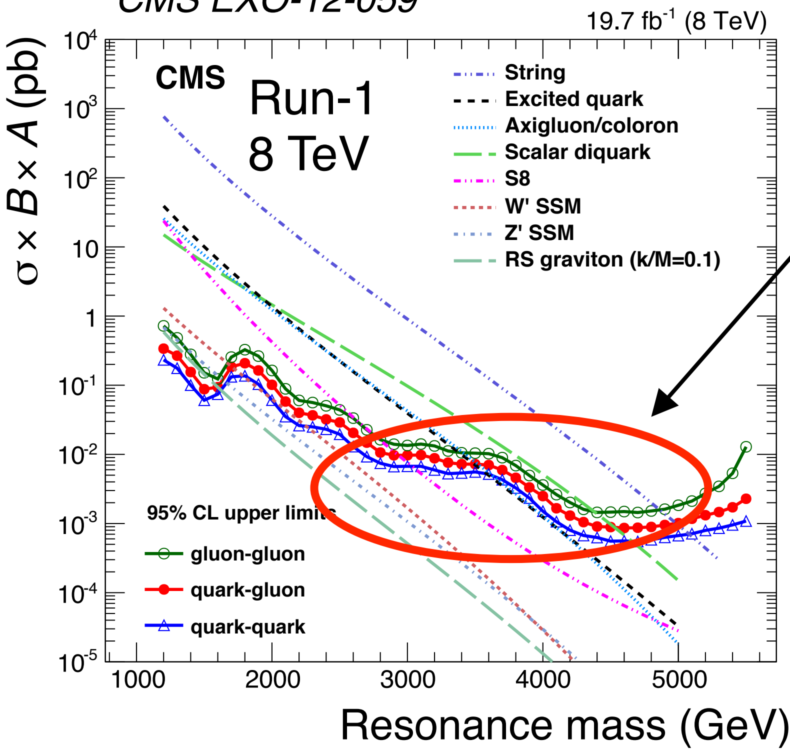
Relevant to tune theory / MC predictions at 13 TeV

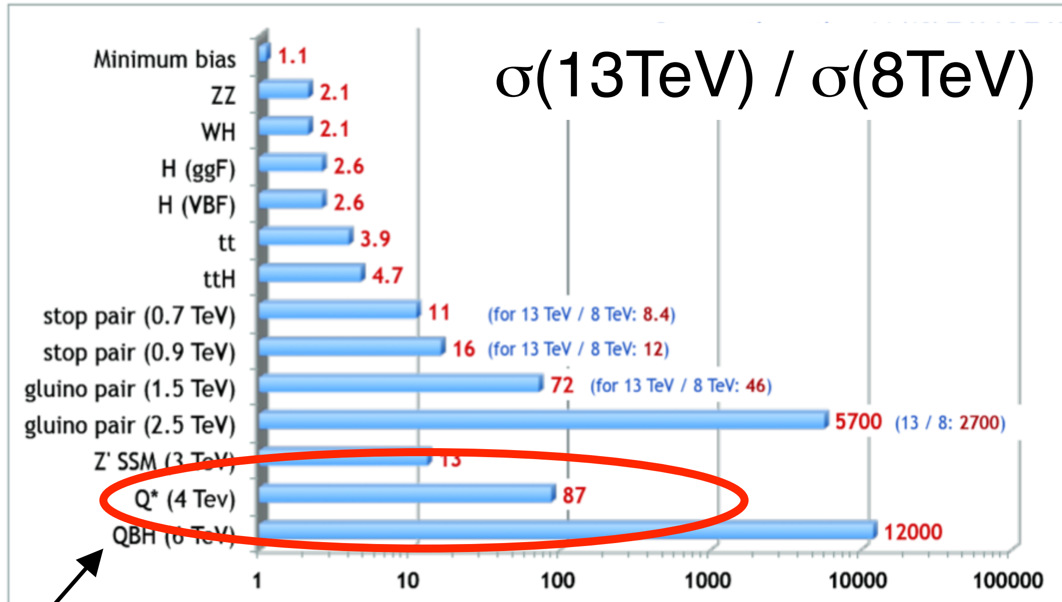
Search for di-jet resonance



Classical bump search

CMS EXO-12-059



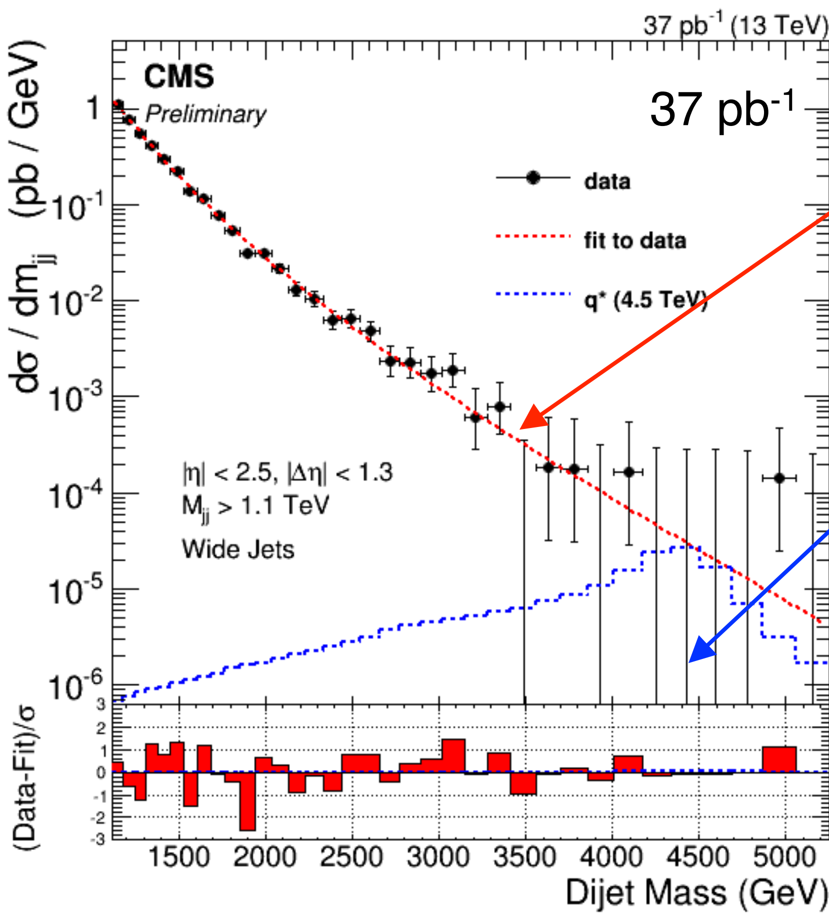


230 pb^{-1} (13TeV) ~ run-1

- One of the most beneficial analysis by jumping 8 → 13 TeV
- Quite simply analysis, hence suitable for an early analysis

Search for di-jet resonance

2 jets (p_T > 60 and 30 GeV) and $|\Delta\eta_{jj}| < 1.3$ (to kill t-channel prod.)



Background fitted by

$$\frac{d\sigma}{dm_{jj}} = p_0 \frac{(1-x)^{p_1}}{x^{p_2}}, \qquad x = \frac{m_{jj}}{\sqrt{s}}$$

q* (4.5 TeV) → qg

For M_{jj} > 3.5 TeV,

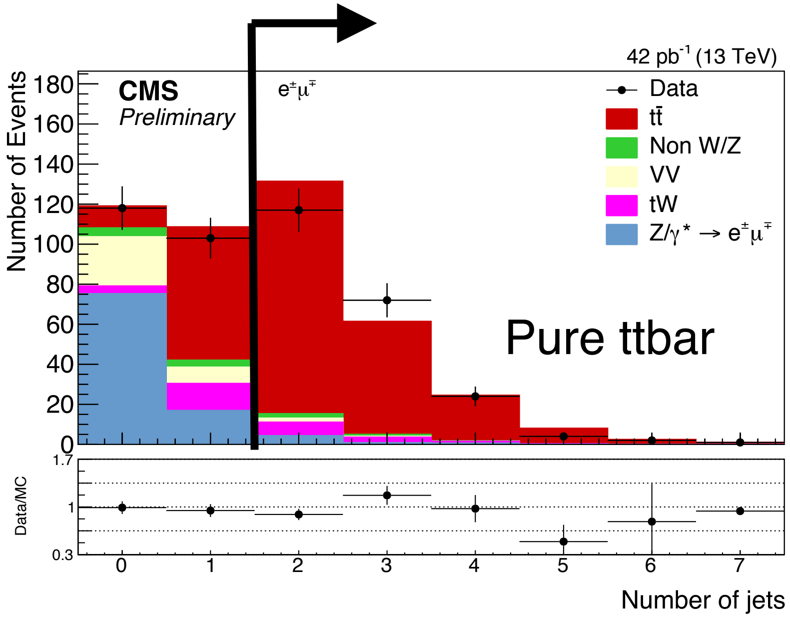
- 4 events obs.
  (4.6 Bkg. exp, 0.8 sig. exp)

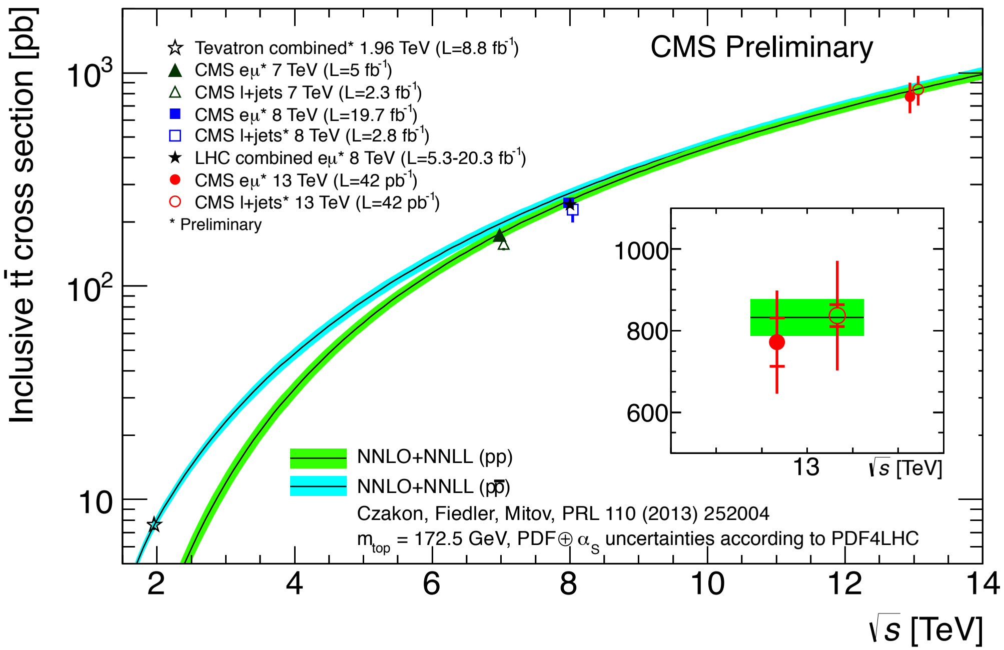
Model	Mass Limits (TeV)			
	Run 1 (20 fb^{-1})		Run 2 (42 pb^{-1})	
	Observed	Expected	Observed	Expected
String Resonance (S)	5.0	4.9	5.1	5.2
Excited Quark (q*)	3.5	3.7	2.7	2.9
Axigluon (A) / Coloron (C)	3.7	3.9	2.7	2.9
Scalar Diquark (D)	4.7	4.7	2.7	3.3
Color Octet Scalar (S8)	2.7	2.6	2.3	2.0

ttbar cross-section

- Fundamental for most of the physics analysis
  - σ_{tt}(13TeV) ~ 800pb → 1Hz @ $L = 10^{34}$ (/cm²s) → Top-factory
- Di-lepton, lep + jets used to extract cross-section

- Opposite-sign e + muon with $p_T > 20$ GeV
- ≥ 2 jets with $p_T > 30$ GeV

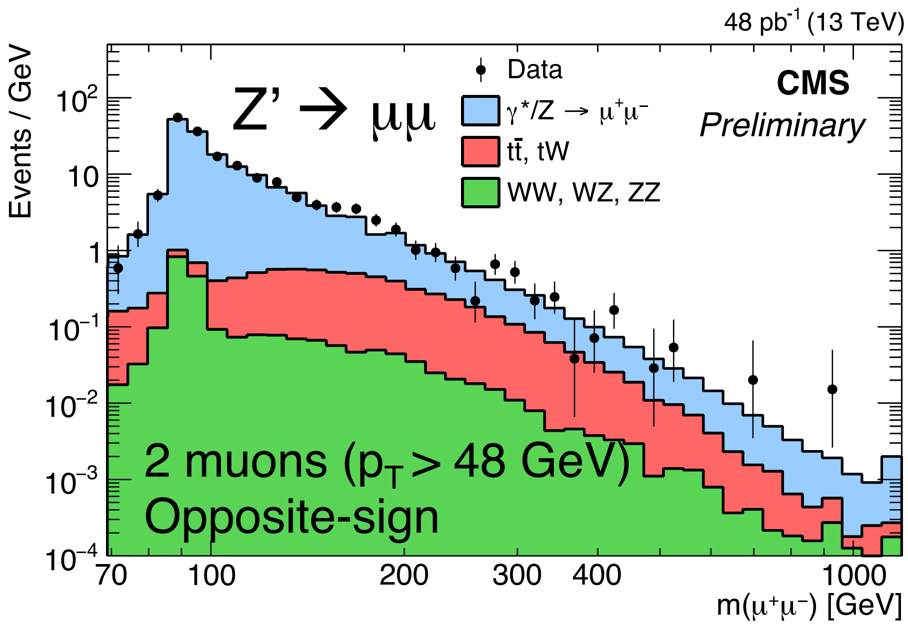


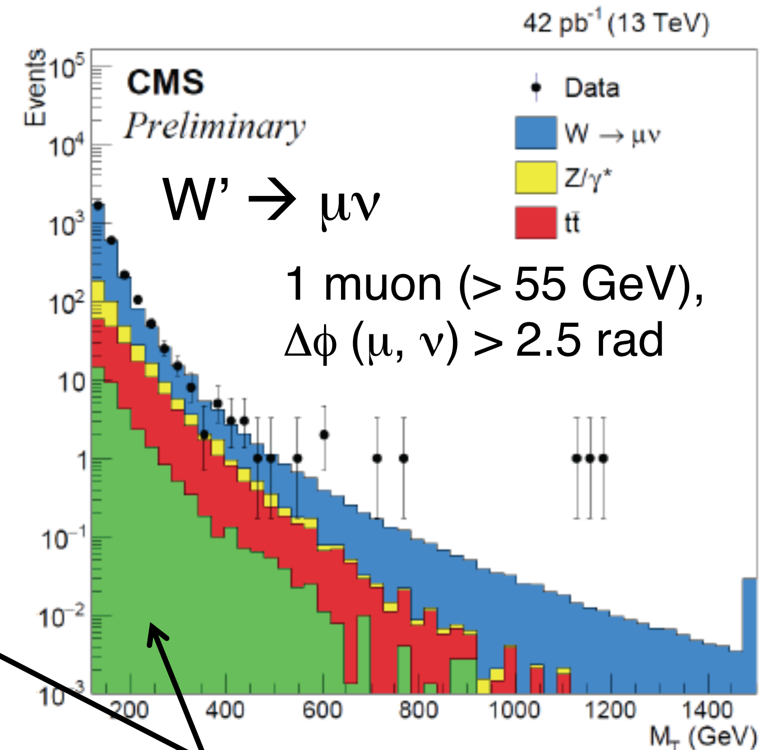


σ_{tt} (eμ) = 722 ± 60 (stat) ± 62 (sys) ± 93 (lum) pb
σ_{tt} (l+j) = 836 ± 27 (stat) ± 84 (sys) ± 100 (lum) pb

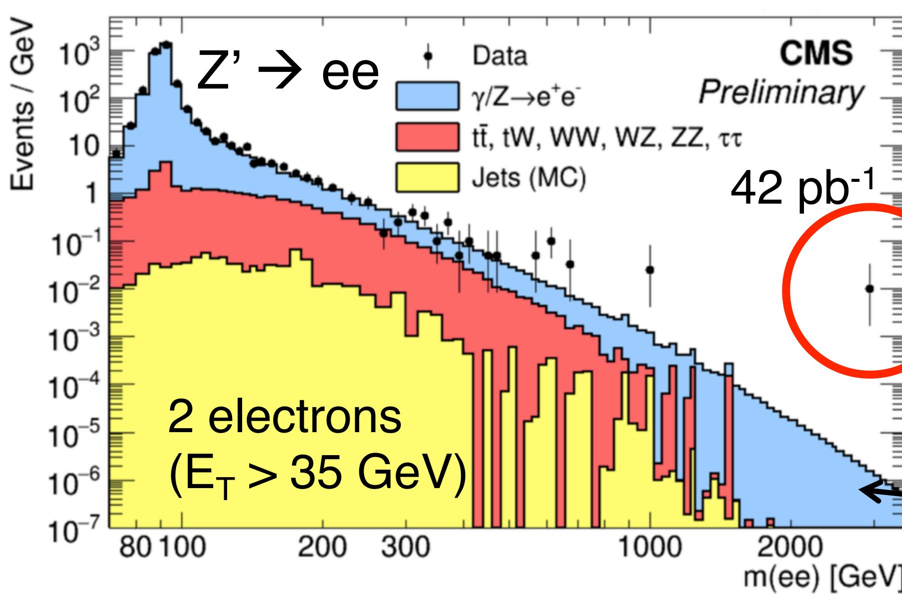
cf) $\sigma_{tt}^{NNLO} = 832^{+40}_{-46}$ pb

W', Z' : early look at 13TeV





Early alignment data used

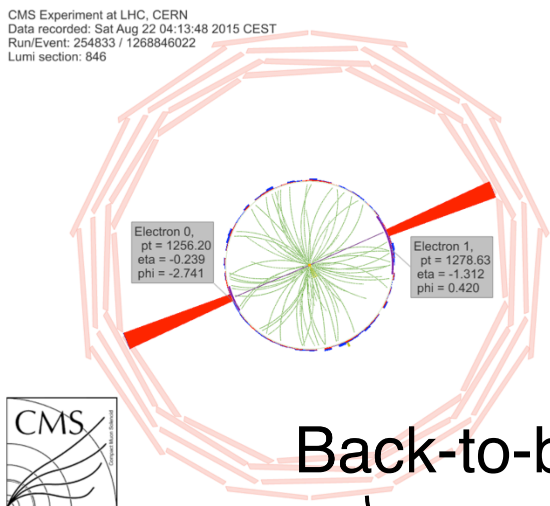


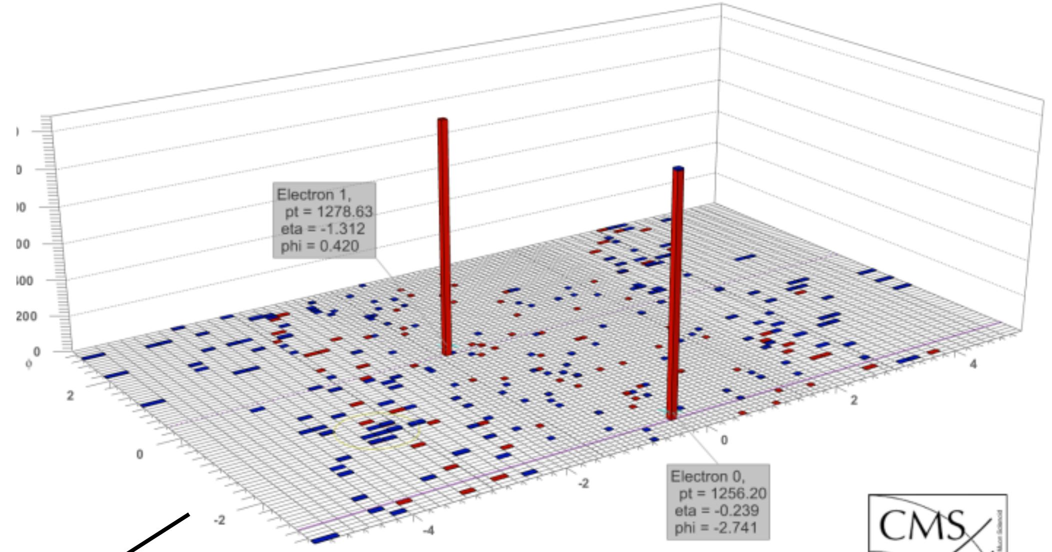
Electrons are not affected by miss-alignment

2.9 TeV

Exp. Bkg (M > 2 TeV) ~ 0.007

Spectacular ee event





Back-to-back

Energy balanced (resonance-like)

	electron 0	electron 1
E_T	1260 GeV	1280 GeV
η	-0.24	-1.31
ϕ	-2.74 rad	0.42 rad
charge	-1	+1
mass	2.91 TeV	
$\cos\theta^*_{CS}$	-0.49	

- Run-1 upper limit : σ = 4.4 fb @ 13TeV
- If this is signal, 1event @ 42pb^{-1} → σ = 24 fb (we are just lucky ?)

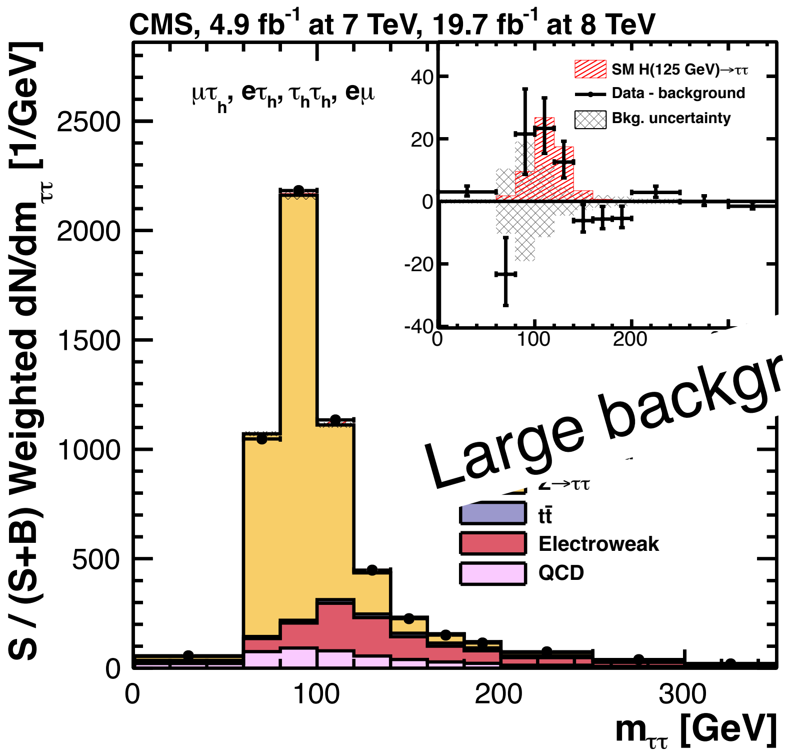
Negative Colins-Soper angle (DY bkg peaks towards positive)

Outlook

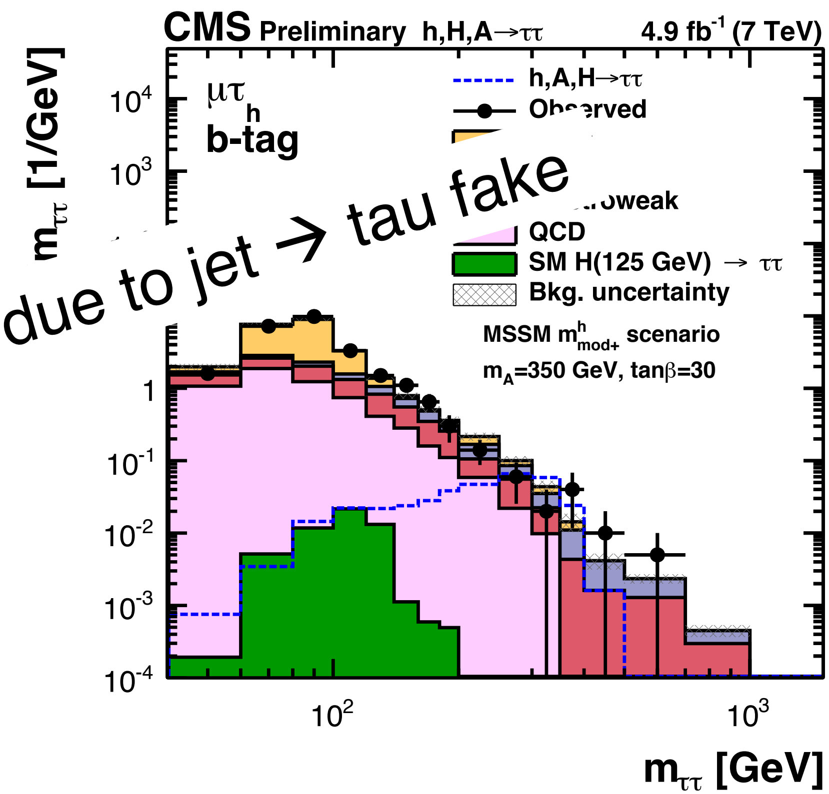
- Introduction
- CMS status & First results at 13TeV
- Improvement of the tau identification
- Prospective study for measuring Higgs CP using $H \rightarrow \tau\tau$

Tau ID plays an important role

JHEP 05 (2014) 104



CMS-PAS-HIG-14-029



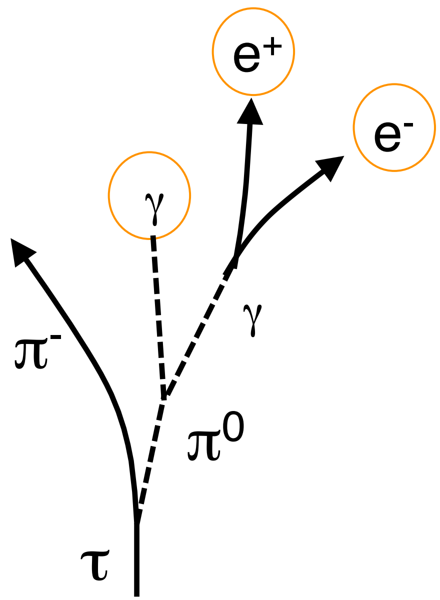
Large background due to jet → tau fake

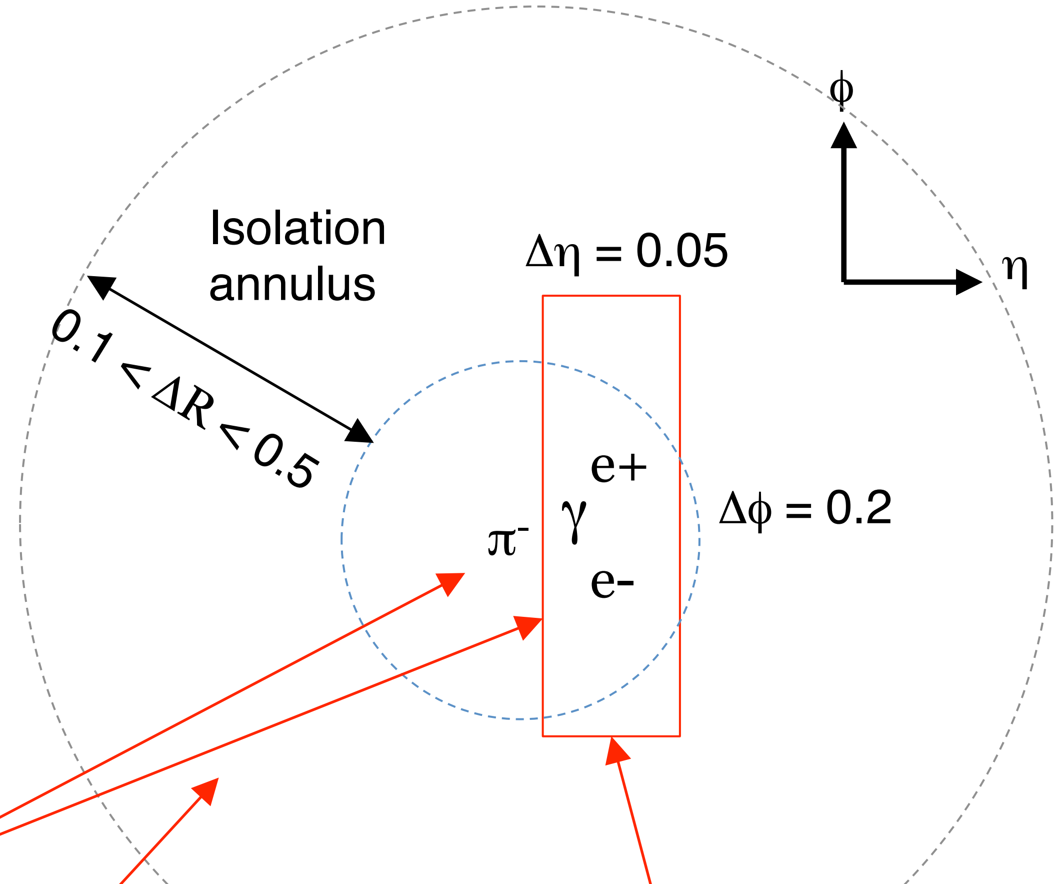
Run-1
- Tau ID efficiency : 50 – 60% @ 1% fake rate
- Tau energy scale : 0.95 – 1

High tau ID eff. up to high p_T (for heavy Higgs analysis) is needed

τ_h identification @ CMS run-1

$\tau^- \longrightarrow \pi^-\pi^0\nu$ (Br = 26%)





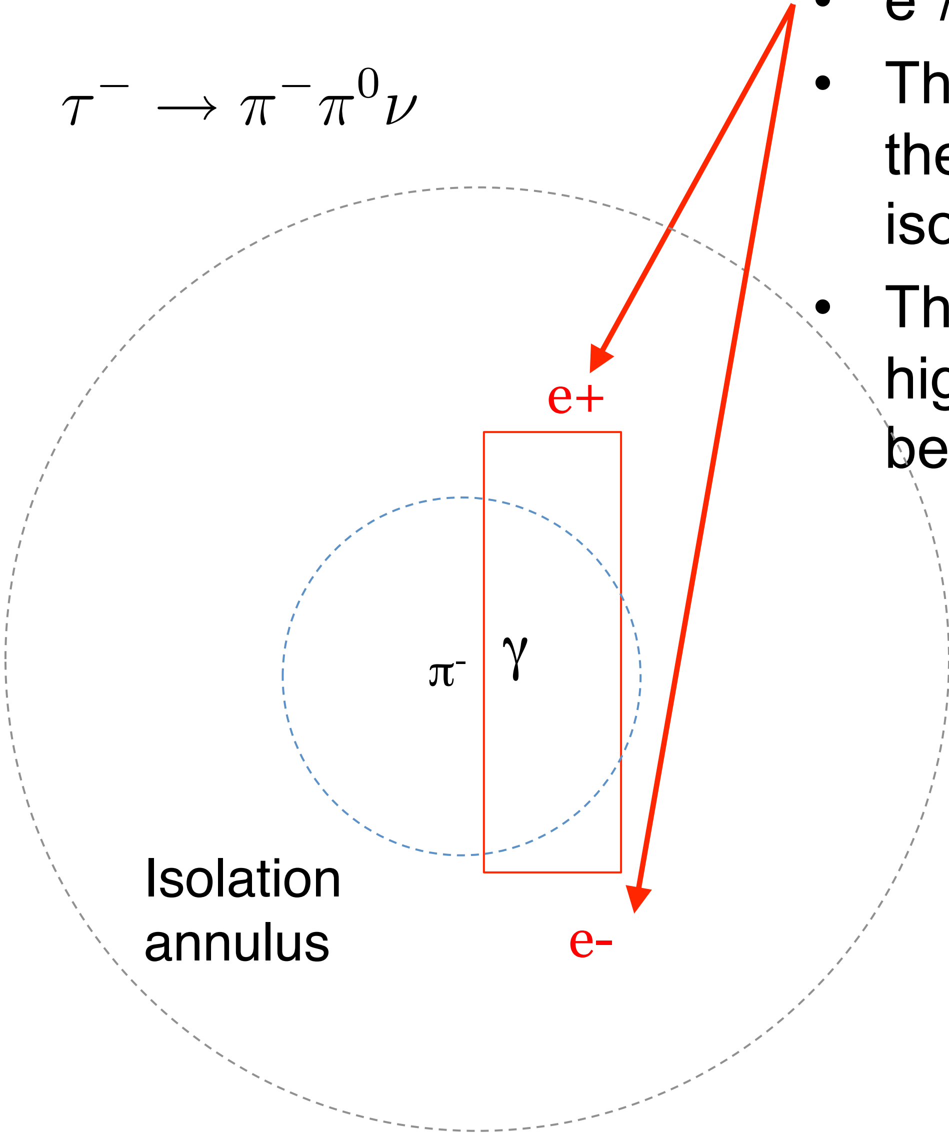
2. Calculate m(π^- + strip), See compatibility with tau

1. Reconstruct π^0 from observed γ, $e^\pm$ within a fixed-size window (strip)

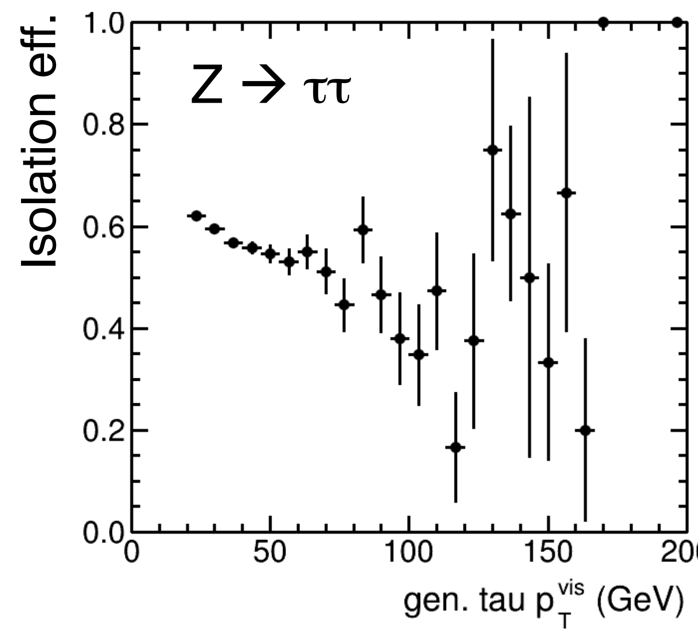
3. To separate real taus from QCD jets, require the energy deposit in isolation annulus < 2 GeV

Limitation of run-1 τ_h ID

$\tau^- \to \pi^- \pi^0 \nu$



- e^+/e^- sometimes goes outside strip
- This will produce energy deposit in the isolation annulus, causing isolation cuts (< 2GeV) to fail
- The effect is more pronounced at higher tau p_T, as the decay product becomes higher p_T

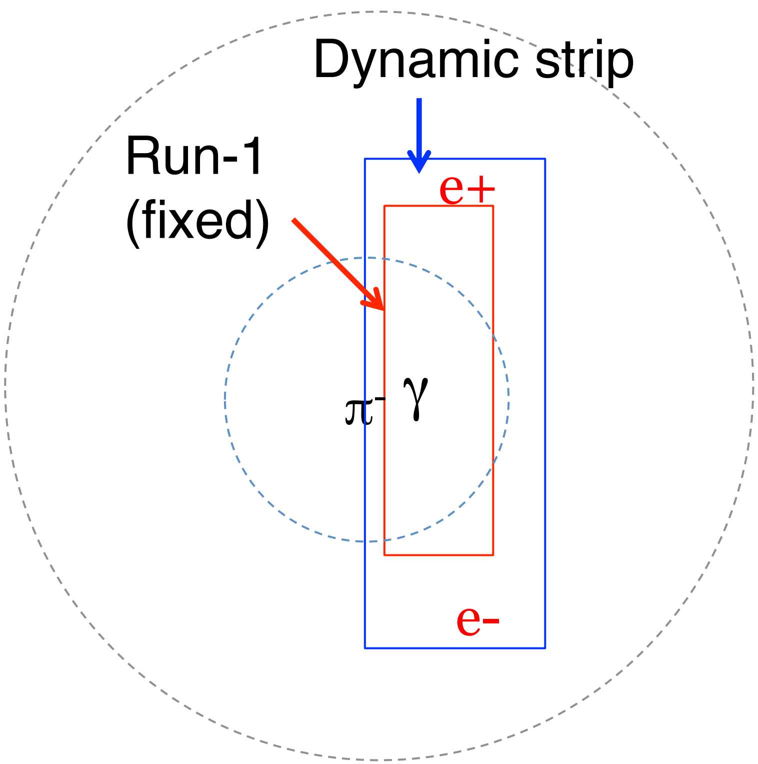


Better τ_h Identification for run-2

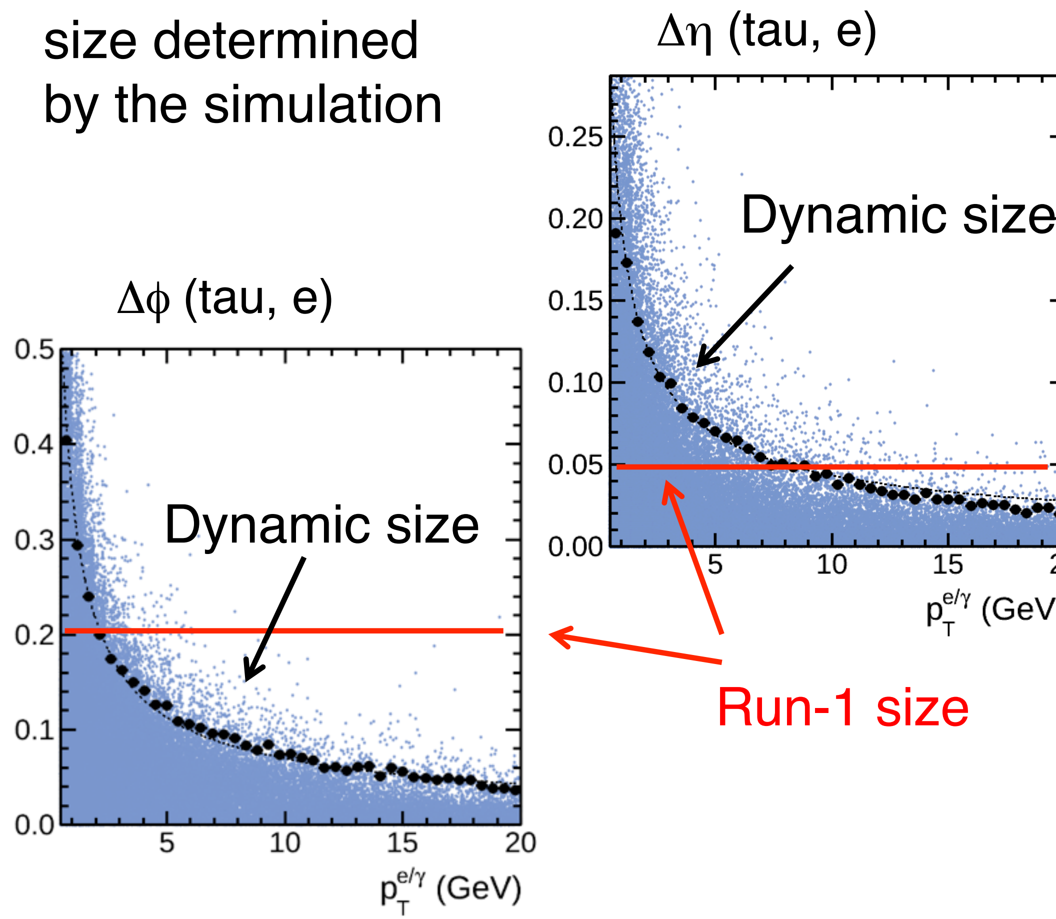
The extent by which e^+/e^- goes outside strip depends on $p_T(e)$

→ low p_T electron can easily go outside strip

→ Dynamically change the strip size as a function of $p_T(e)$

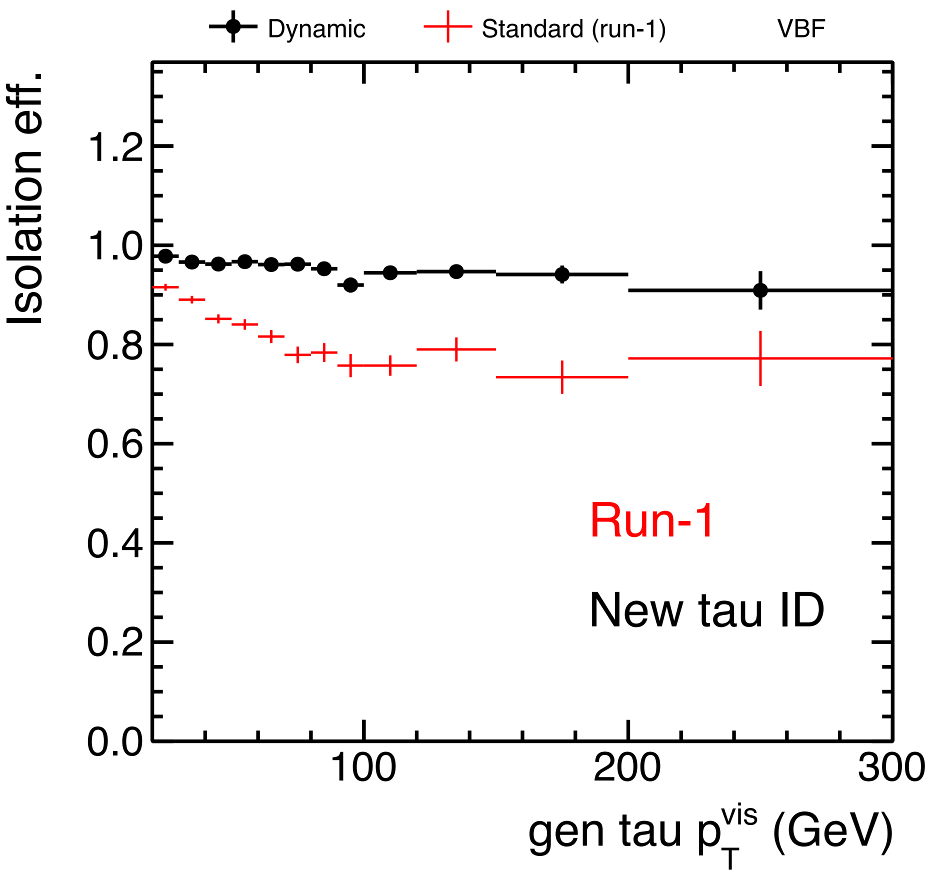


size determined
by the simulation

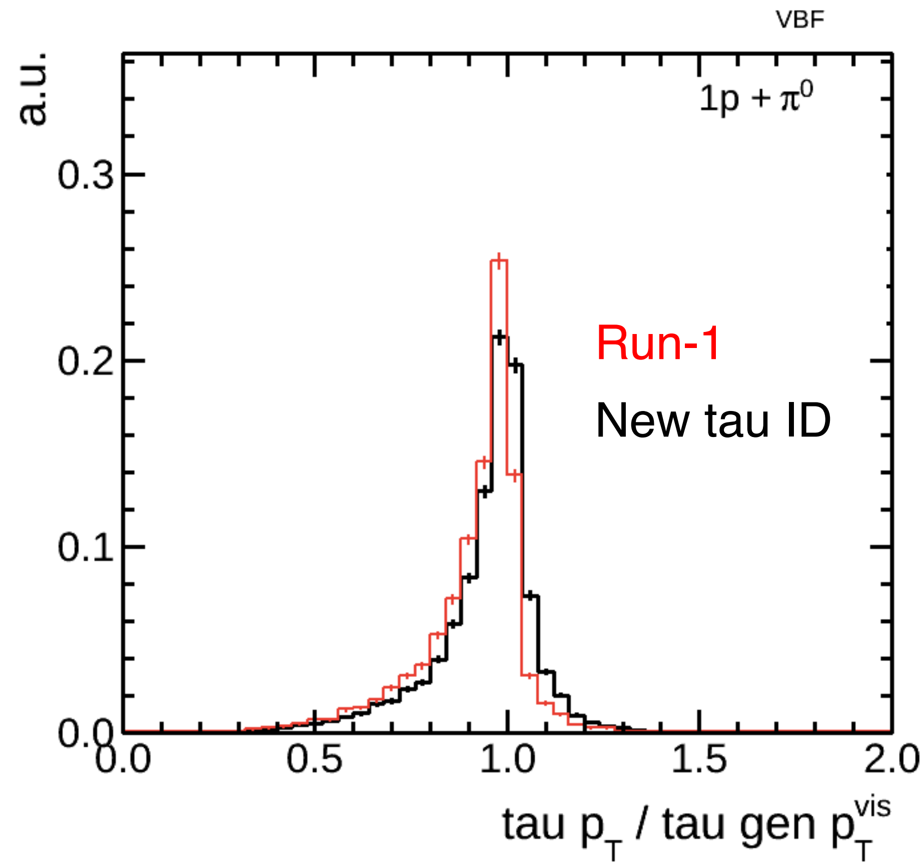


Performance improvement

Isolation efficiency



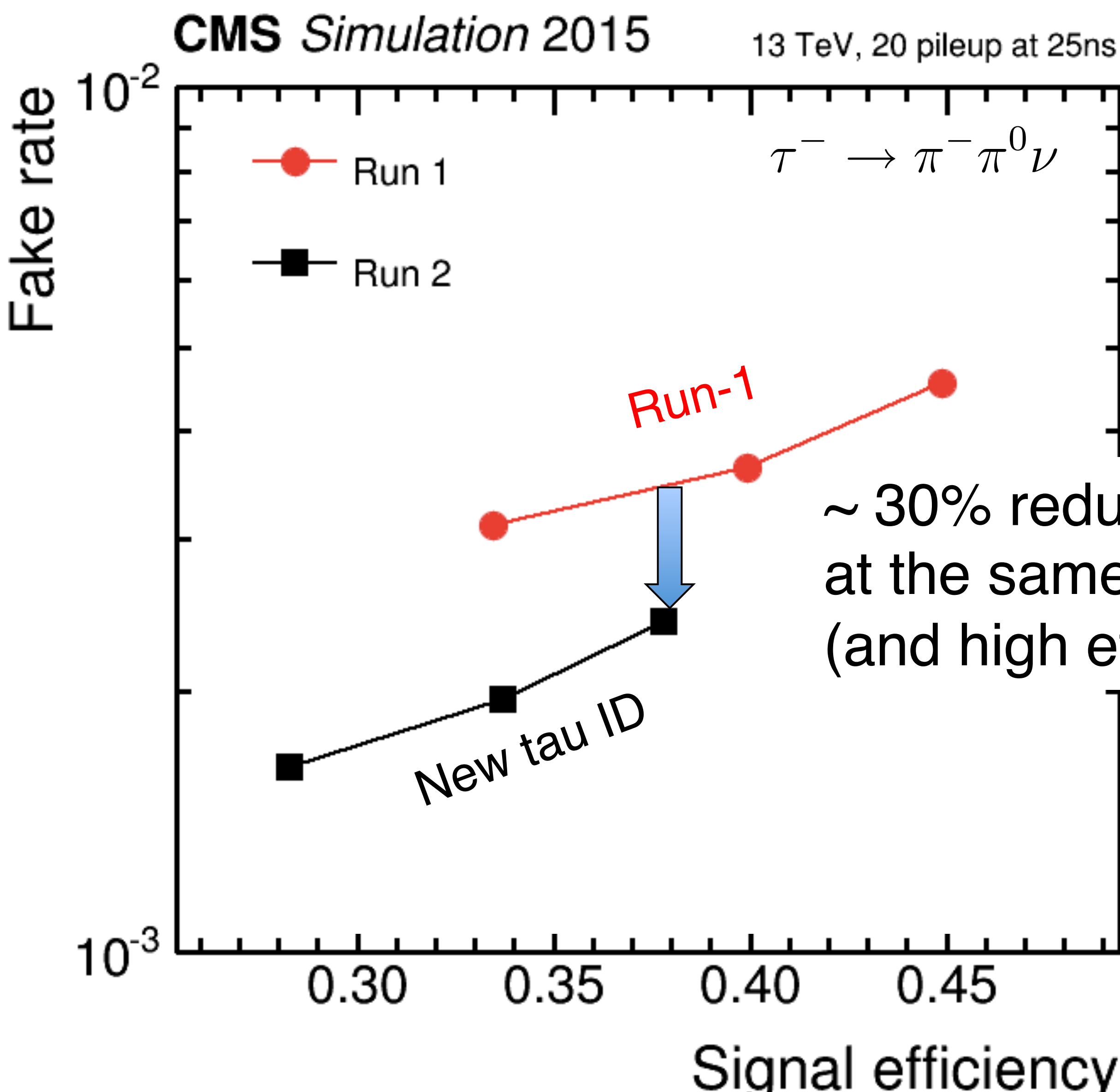
Energy response



- Efficiency improved
- Efficiency drop recovered

Better energy response compared to run-1

With a re-optimization of the new algorithm …



~ 30% reduction of the fake rate at the same efficiency point (and high efficiency at high tau p_T)

- Proposal
- Pioneered all the development
- adopted as the default algorithm for CMS run-2

Outlook

- Introduction
- CMS status & First results at 13TeV
- Improvement of the tau identification
- Prospective study for measuring Higgs CP using $H \rightarrow \tau\tau$

Why Higgs CP is interesting ?

- SM : One Higgs, CP eigenstate; CP even
- BSM models
  - MSSM : 3 Higgs, CP eigenstate; even (h^0, H^0) and odd (A)
- More generally
  - Observed Higgs does not necessarily to be CP eigenstate
    → Mixed state of CP even and odd

$$|H\rangle = \cos\alpha|\mathrm{even}\rangle + \sin\alpha|\mathrm{odd}\rangle$$

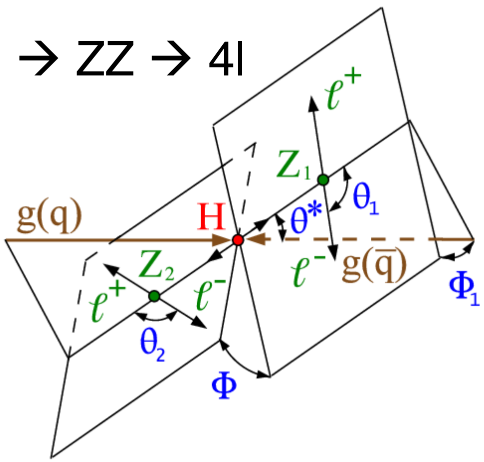
α : CP mixing angle
$$\begin{cases} \text{SM} : \alpha = 0 \\ \text{CP odd} : \alpha = \pi/2 \\ \text{Max. mixing} : \alpha = \pi/4 \end{cases}$$

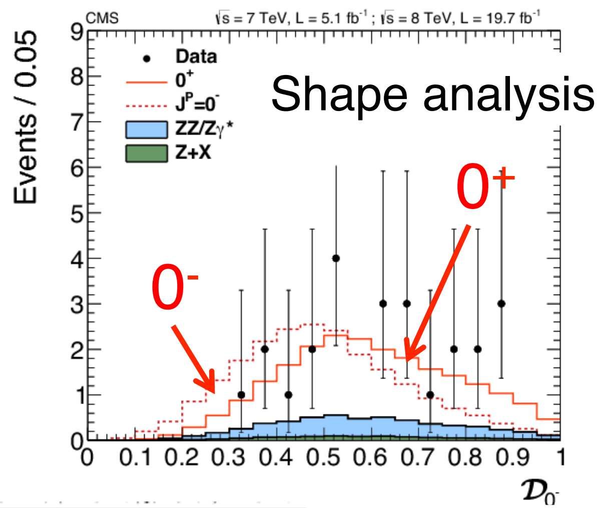
Measuring the CP property (mixing angle) = probe for NP

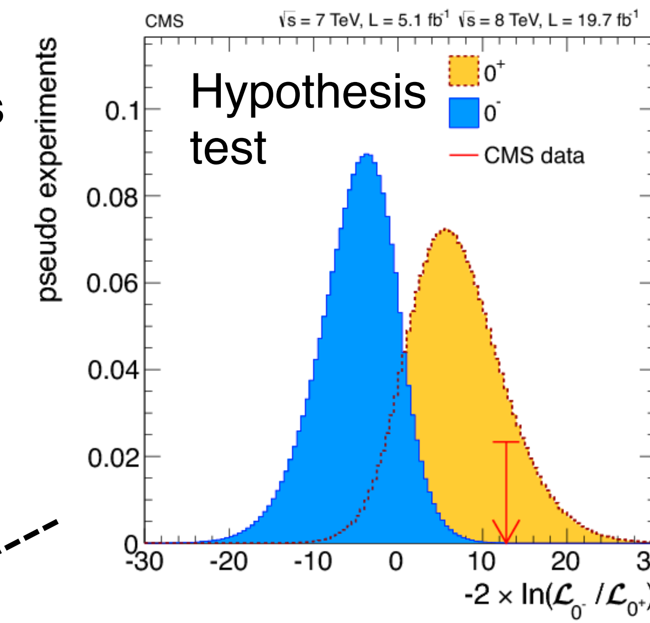
What do we know about CP ?

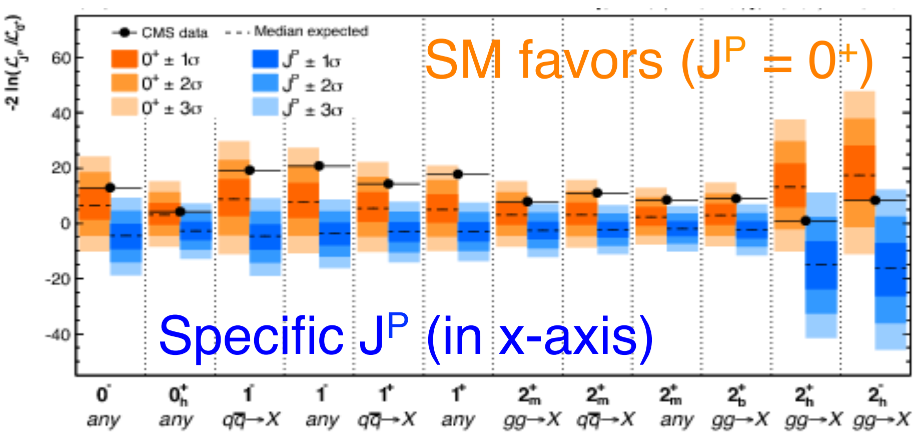
- Higgs decays are used
  - H → γγ : C = +1
  - Kinematic distributions in bosonic decay to test J^P

H → ZZ → 4l







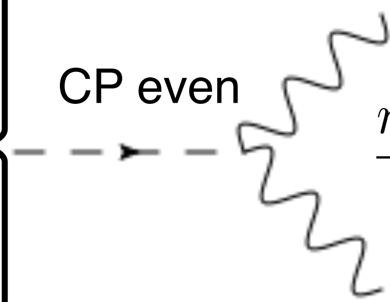


C = +1, P = +1

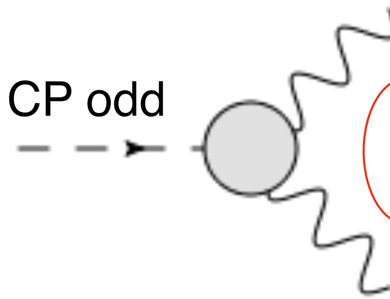
→ Higgs is CP even (?)

This is not the end of the story

$\mathcal{L} =$ cos(α) { CP even



$\frac{m_V^2}{v} h V_\mu V^\mu$ } + sin(α) { CP odd



$\frac{1}{\Lambda} A V_{\mu\nu} \tilde{V}^{\mu\nu}$ }

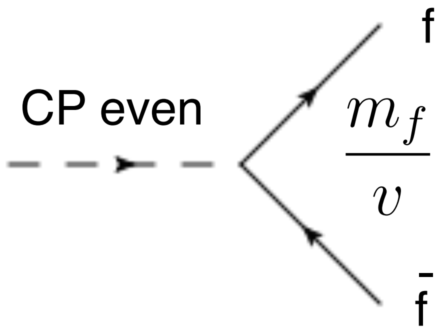
If Λ is large (seems to be), contribution of this term to the final distribution ~ 0 (irrespective of α)

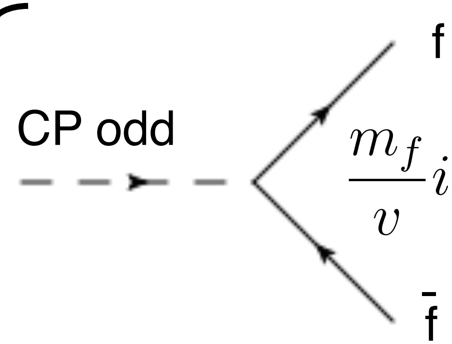
Final Data distribution looks like "CP even"
→ Hypothesis test always prefers CP even (shape analysis !)

We can constrain α by the signal rate (μ-value) ∝ f(α, Λ)
→ We have to assume Λ (model dependent)

On the other hand – fermionic coupling

$$\mathcal{L} = \cos(\alpha)\left\{ \text{CP even} \quad \frac{m_f}{v} h f_i \bar{f}_i \right\} + \sin(\alpha)\left\{ \text{CP odd} \quad \frac{m_f}{v} i\gamma_5 A f_i \bar{f}_i \right\}$$





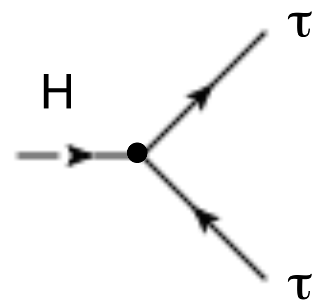
- Both CP even and odd can decay into $f\bar{f}$ in tree level (no suppression)
  - Both CP even and odd can contribute to the final distribution equally
- Hypothesis test can evaluate CP without any assumption about NP (model independent)

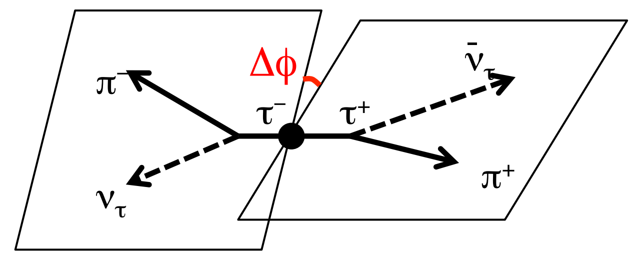
Conclusion: Higgs CP can be better studied using fermionic coupling

2 methods using fermionic coupling

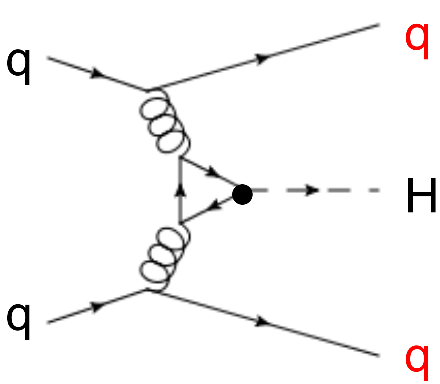
Tau polarization method

- Studied in the context of ILC
- Use H → ττ and look at Δφ e.g. between tau decay planes (difficult, especially at high PU)

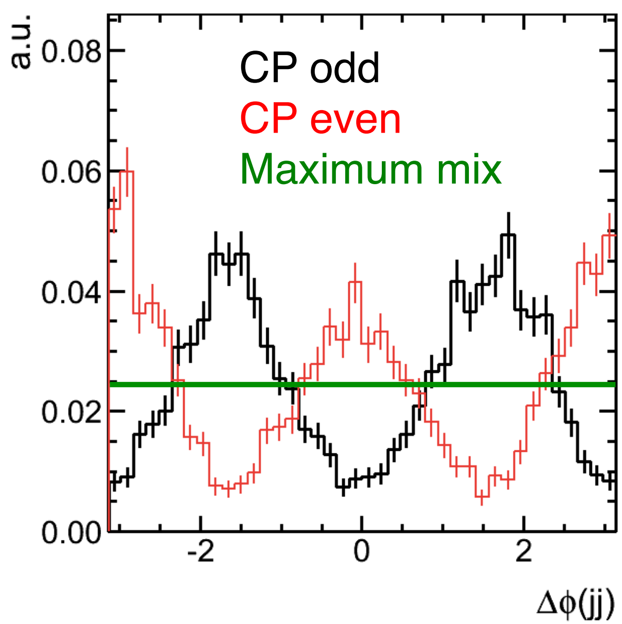




Gluon fusion + 2 jets method (I want to do this)



Look at Δφ between 2jets

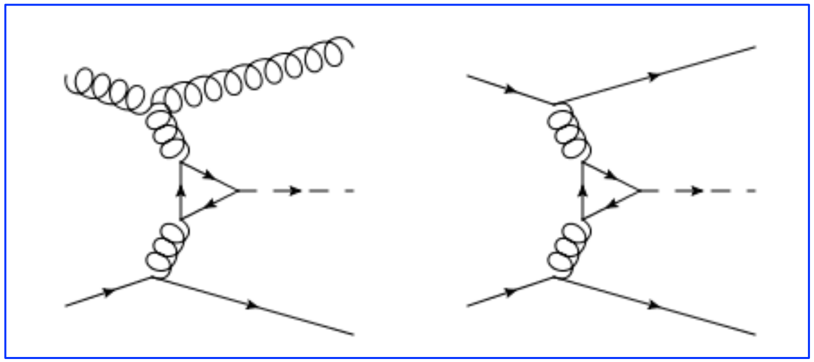


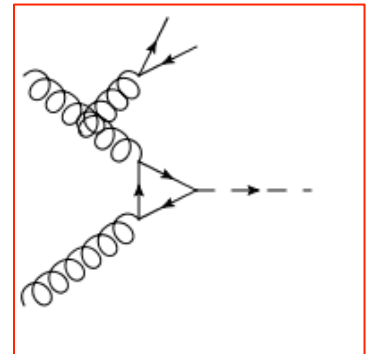
- A priori easier than polarization method
- Irrespective of Higgs decay (combinable)
- Not much studied yet

VBF doesn't show this (flat) ($|M|^2$ does not depend on α)

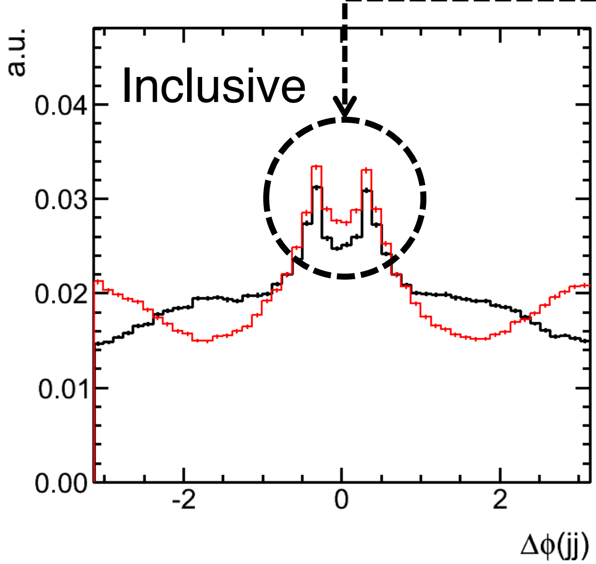
Gluon fusion + 2 jets includes "not-interesting" events

Exhibit modulation

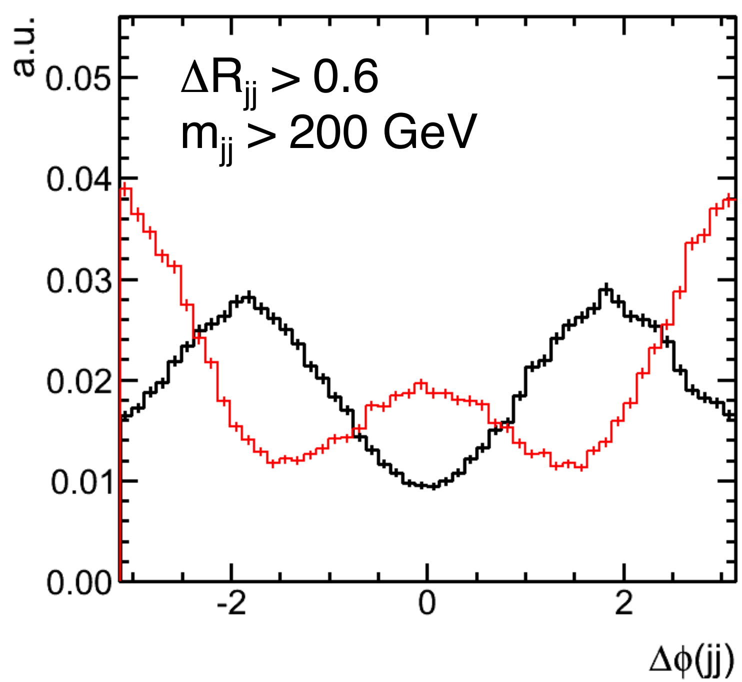




Doesn't bring CP info. (gluon split)



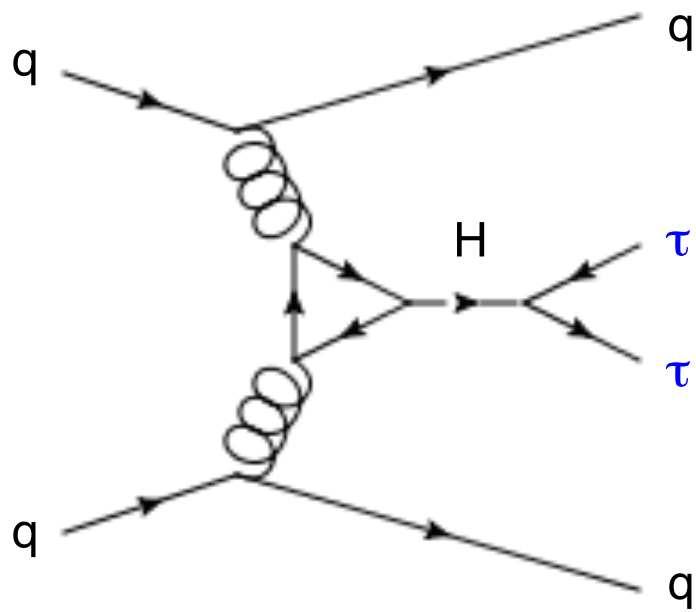
CP odd CP even



- More VBF-like selection (ΔR_{jj}, m_{jj}), we get less gluon-fusion

→ Need optimization

Feasibility study using H → ττ

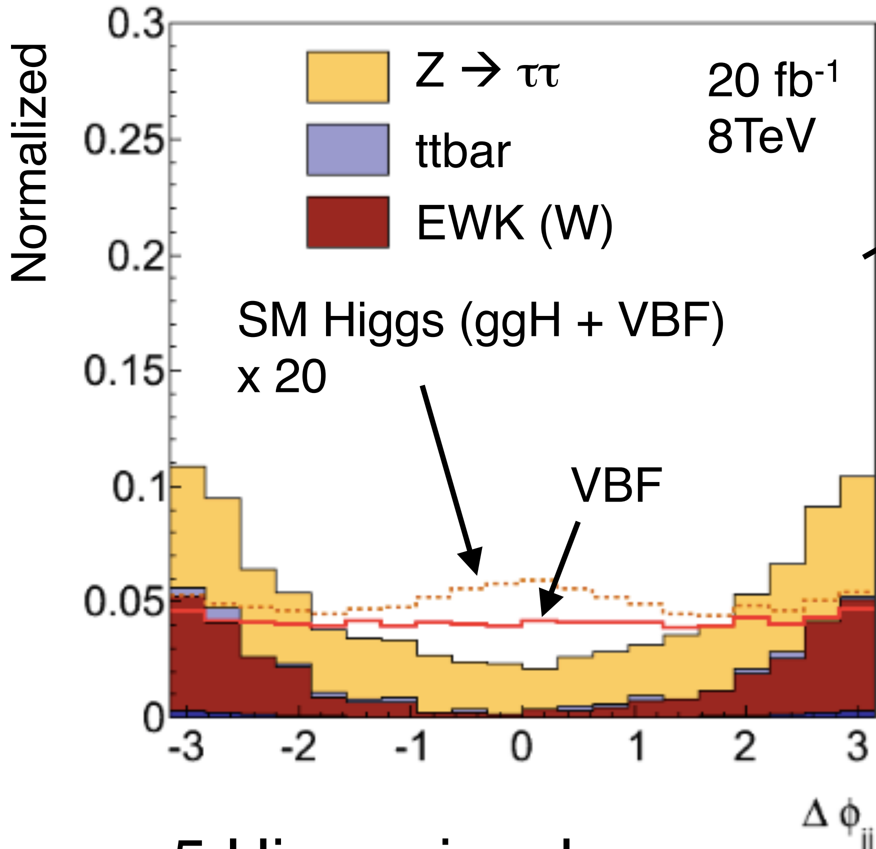


ττ : high S/B in 2 jets phase space

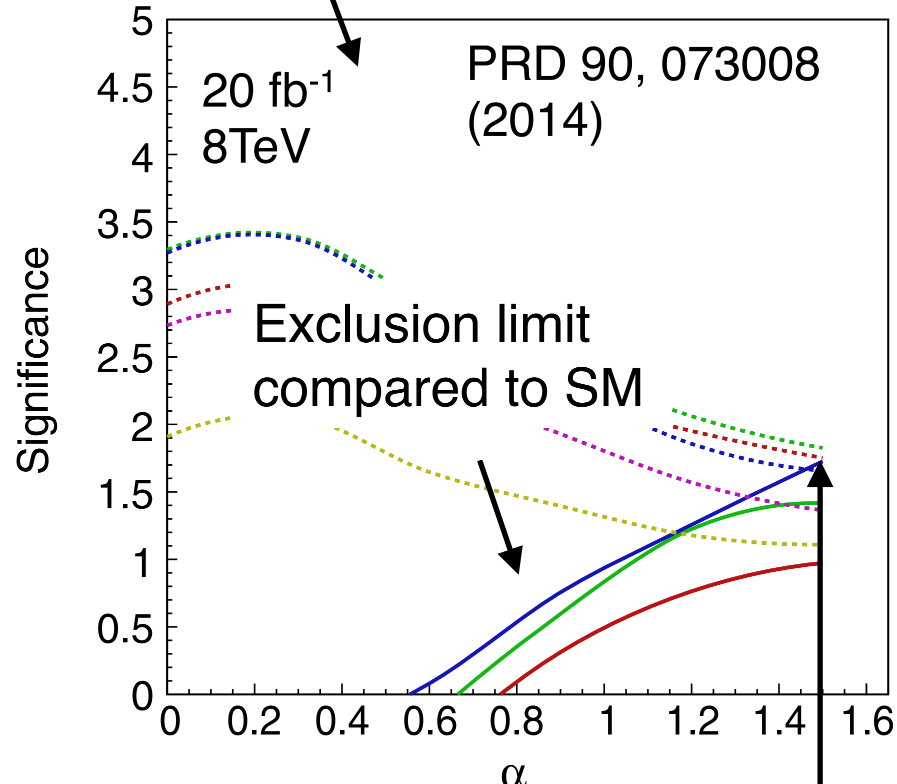
decay	Obs. μ-value (run-1) @ 2 jets
H → γγ	$1.514^{+0.551}_{-0.476}$
H → WW	$0.623^{+0.593}_{-0.479}$
H → ττ	$0.948^{+0.431}_{-0.379}$
H → ZZ	$1.549^{+0.953}_{-0.661}$

- Same event selection used for H → ττ analysis in run-1
- ≥ 2 jets → calculate Δϕ(jj) using leading, sub-leading jet
- Apply VBF like selection to reject not-interesting events
  - ΔR(jj) > 0.6, mjj > 200 GeV

Sensitivity check using run-1 data



Hypothesis test of data with SM (α=0) v.s various α



5 Higgs signal :
(75% VBF, 25% ggH)
Data : blinded

Exclude pure CP odd at 2σ

(encouraging !)

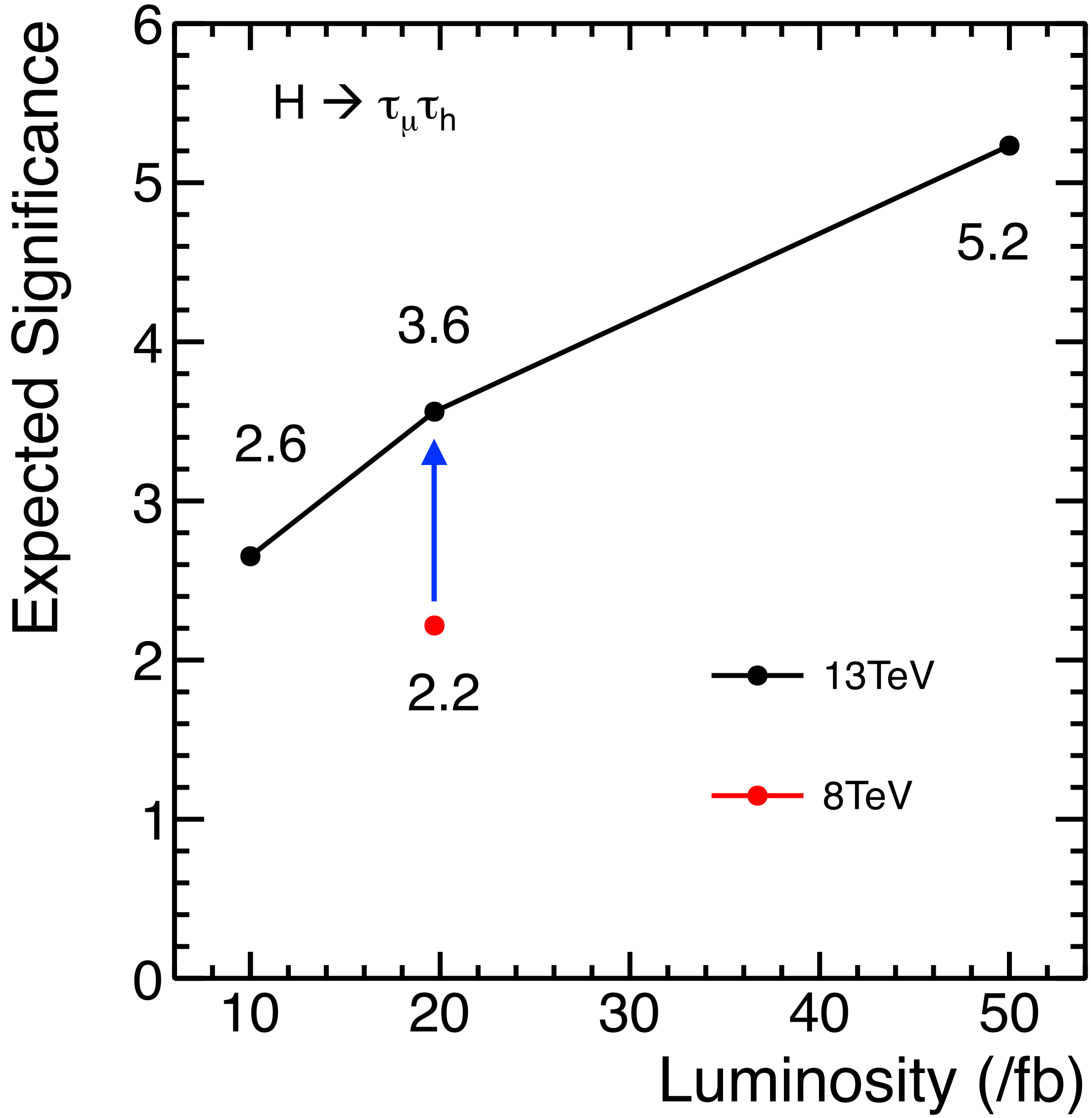
Summary

- CMS is in full swing
  - Highly operative after upgrade (both h/w and s/w) during long shutdown period
  - Cryogenics issue is still there but believed to be solved soon
  - Preliminary physics results seem encouraging
- New tau identification is developed and will improve physics performance with tau in run-2
- Higgs CP property can be a nice probe for NP
  - Fermionic coupling will allow model-independent measurement of the Higgs CP property
  - Feasibility study using run-1 data with $\tau\tau$ final state suggests that run-2 data will provide interesting results

Thank you for your attention

Spare slide

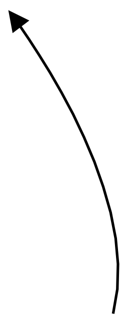
Projection studies



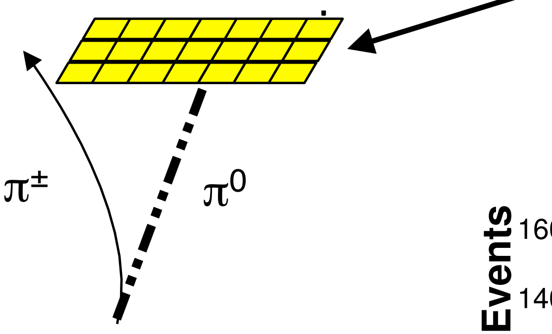
S.Smith (summer student)
& Yuta Takahashi

Hadronic tau (τ_h) reconstruction based on charged hadron + γ

$\tau^- \rightarrow \pi^-\nu$ (12%)

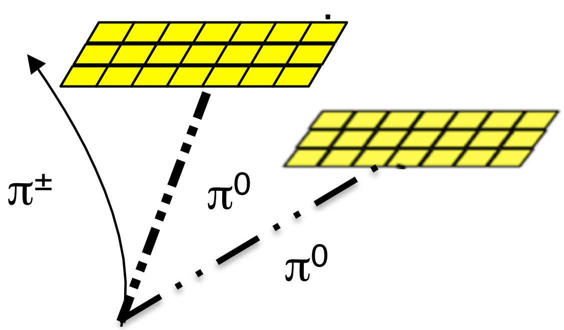


$\tau^- \rightarrow \pi^-\pi^0\nu$ (26%)

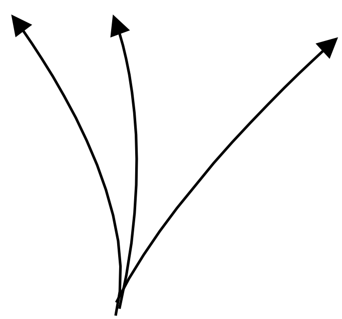


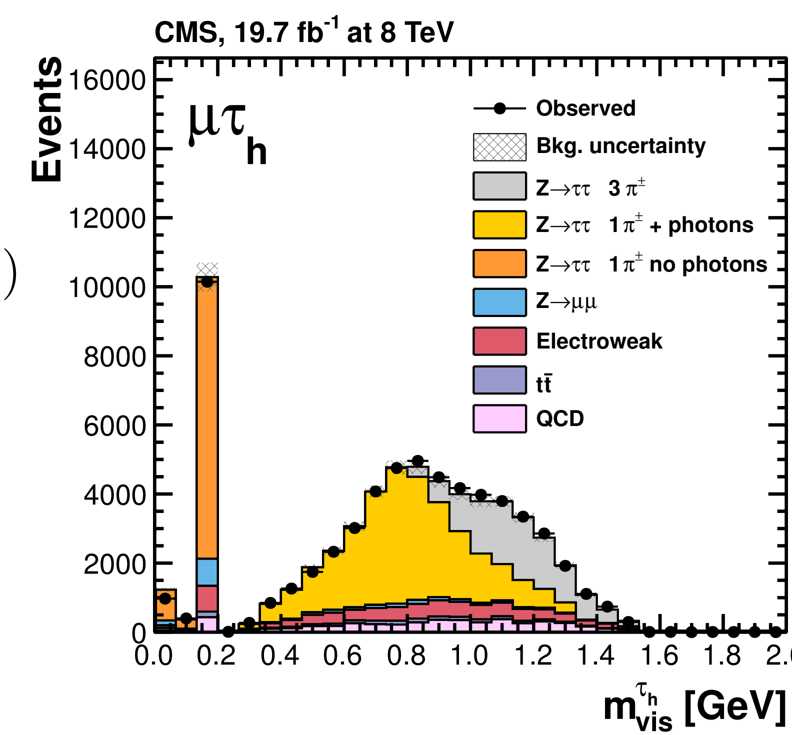
Photon cluster
(2 photons from $\pi^0 \rightarrow \gamma\gamma$)

$\tau^- \rightarrow \pi^-\pi^0\pi^0\nu$ (11%)

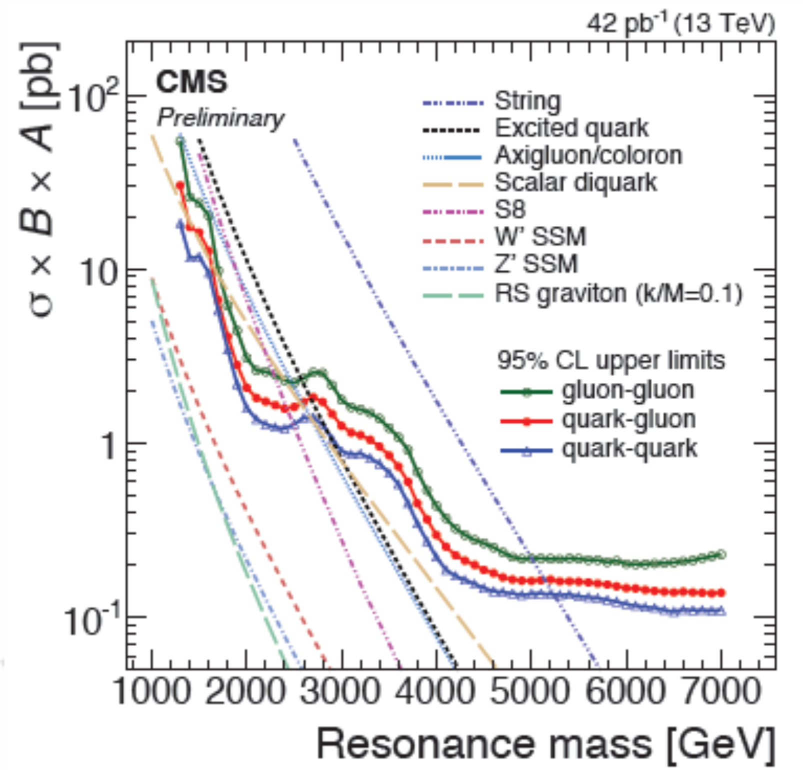


$\tau^- \rightarrow \pi^-\pi^+\pi^-\nu$ (10%)





Make full use of substructures inside jets to reconstruct τ_h



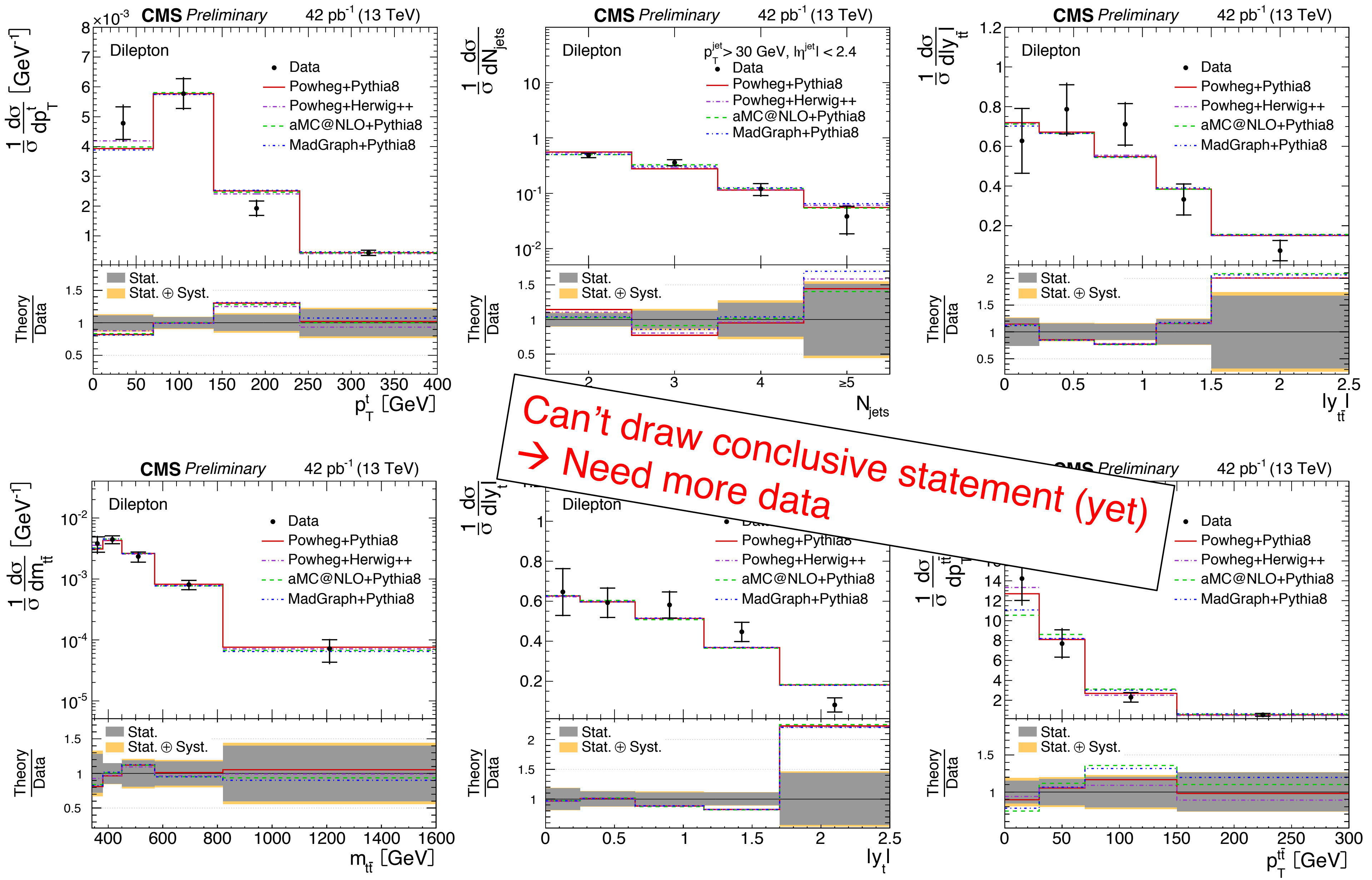
CMS PAS EXO-15-001

- Observed limits at 95% CL on cross section of qq, qg, gg resonances
- Get worse when there are gluons in the final state because radiation increases and resolution degrades
- Extend to 7 TeV in di-jet mass for the first time
- plateaus at high mass due to absence of events

Confirms Run2 is already more sensitive than Run1 for M> 5 TeV

Model	Mass Limits (TeV)			
	Run 1 (20 fb^{-1})		Run 2 (42 pb^{-1})	
	Observed	Expected	Observed	Expected
String Resonance (S)	5.0	4.9	5.1	5.2
Excited Quark (q*)	3.5	3.7	2.7	2.9
Axigluon (A) / Coloron (C)	3.7	3.9	2.7	2.9
Scalar Diquark (D)	4.7	4.7	2.7	3.3
Color Octet Scalar (S8)	2.7	2.6	2.3	2.0

Ttbar differential cross-section

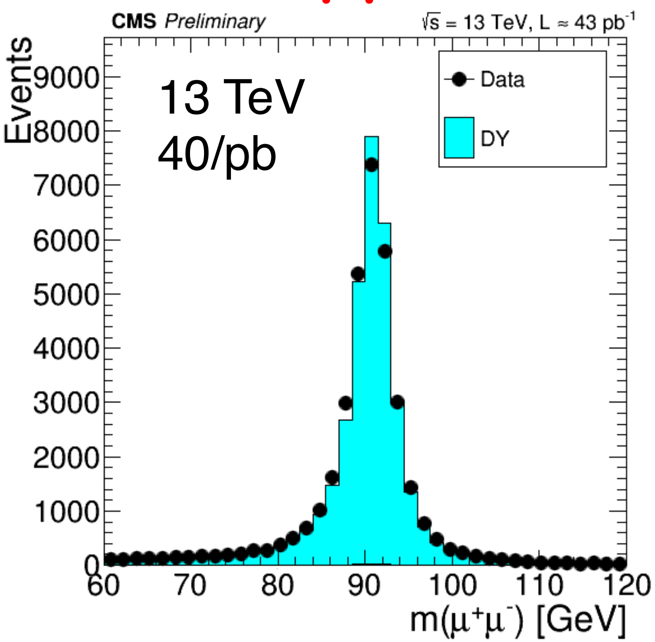


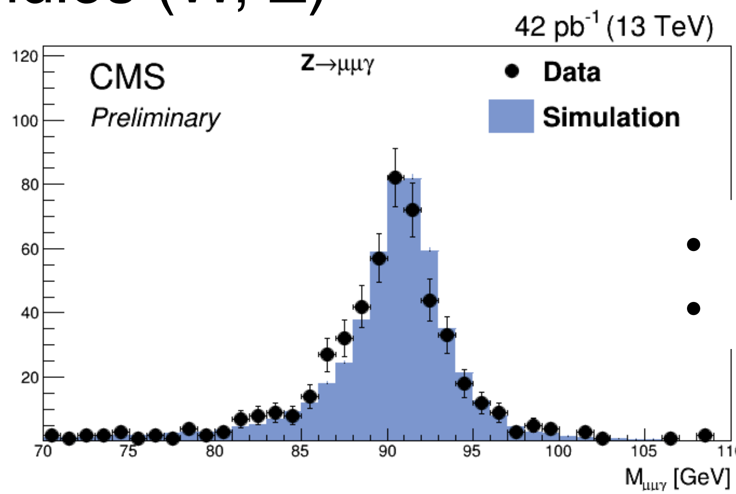
Can't draw conclusive statement (yet)
→ Need more data

Particle Identification @ 13TeV

- Use standard candles (W, Z)

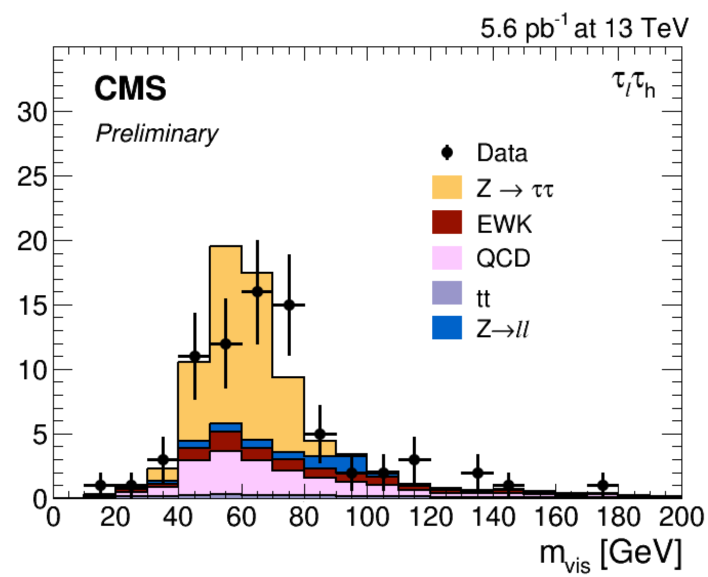
Z → μμ / ee





Z → μμγ

- μ p_T > 20, 10 GeV
- γ p_T > 10 GeV



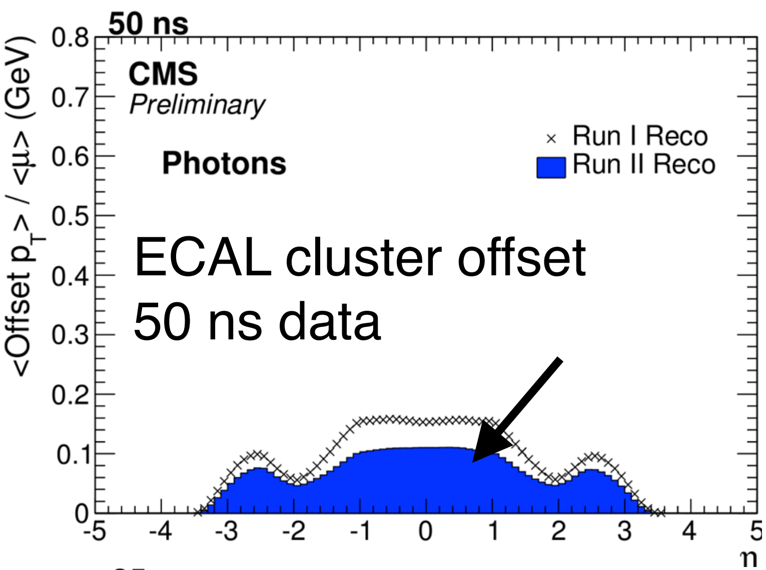
Z → $\tau_{lep}\tau_{had}$

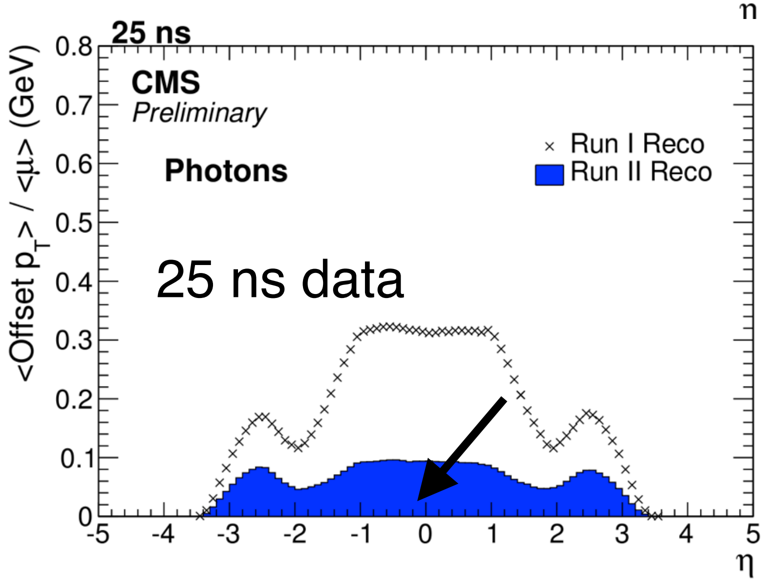
- μ p_T > 18 GeV or e p_T > 20 GeV
- τ p_T > 20 GeV

- Opposite-sign di-lepton
- p_T > 20, 10 GeV
- |η| < 2.4

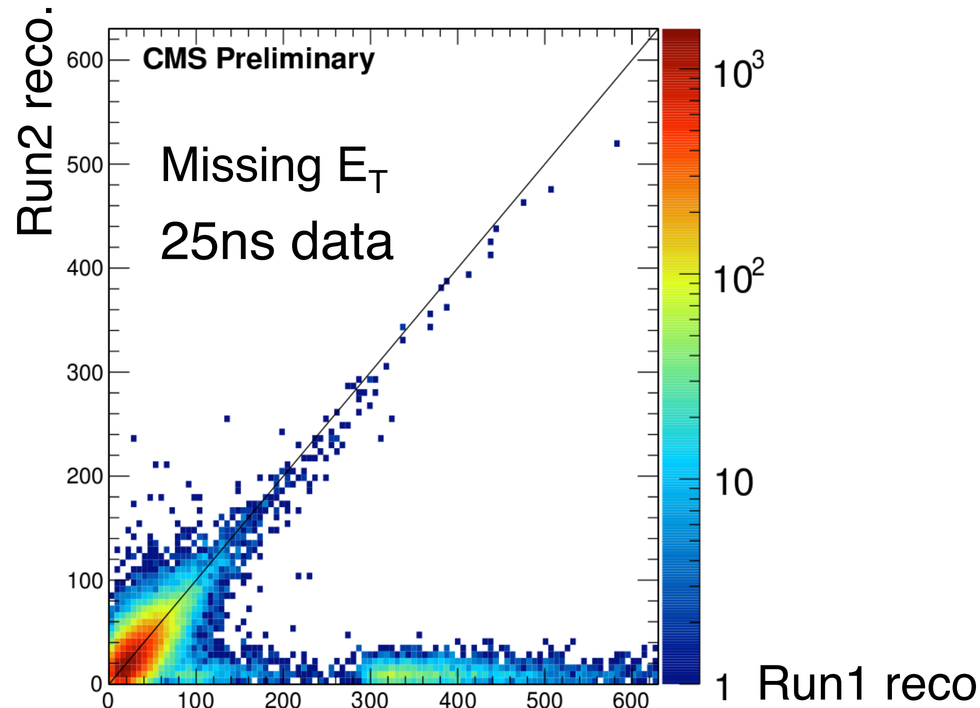
More to be done; Scale factor (data/MC), energy scale, resolution, etc…

PU mitigation (50ns → 25ns)

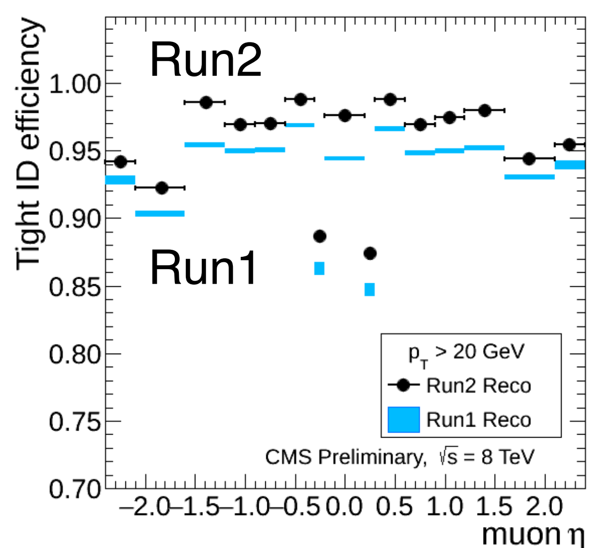




pile-up invariant



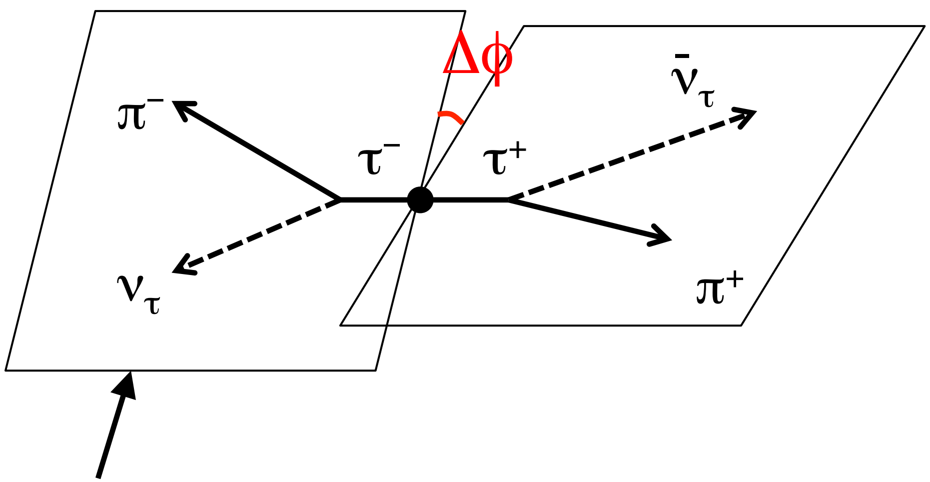
Large tails of run1 Reco. removed



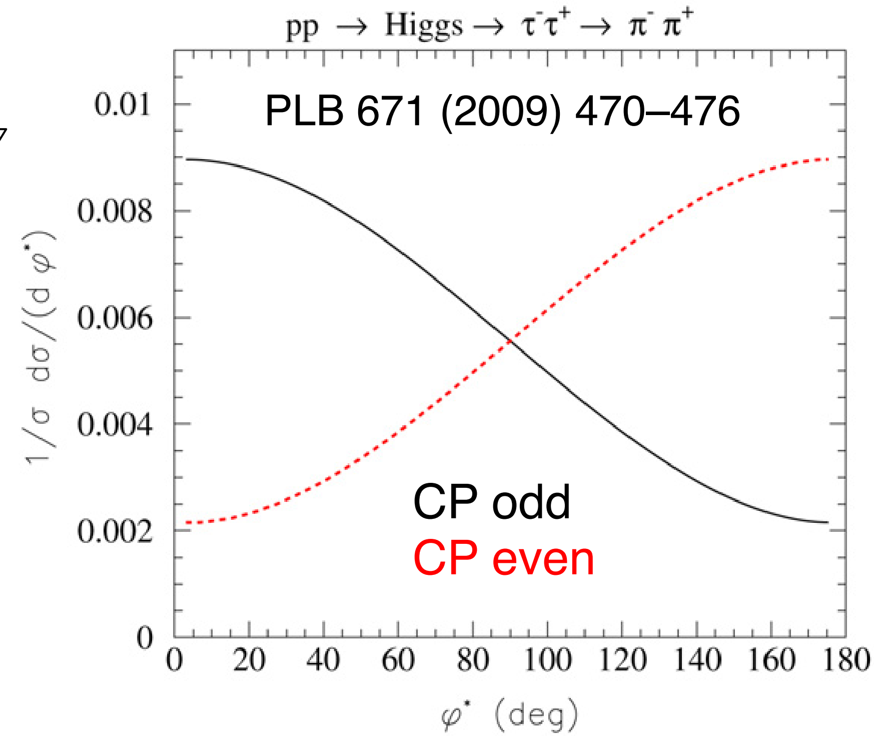
Improve ID eff.
at the same fake rate

Tau polarization method

- Use H → ττ and look for Δϕ between tau decay planes at the Higgs rest frame



Tau plane is reconstructed by impact parameter vector and $\pi^\pm$ momentum



- Difficult to reconstruct Higgs rest frame
- Only specific tau decay ($\tau^\pm \rightarrow \pi^\pm\nu$, $\tau^\pm \rightarrow \pi^\pm\pi^0\nu$) is sensitive

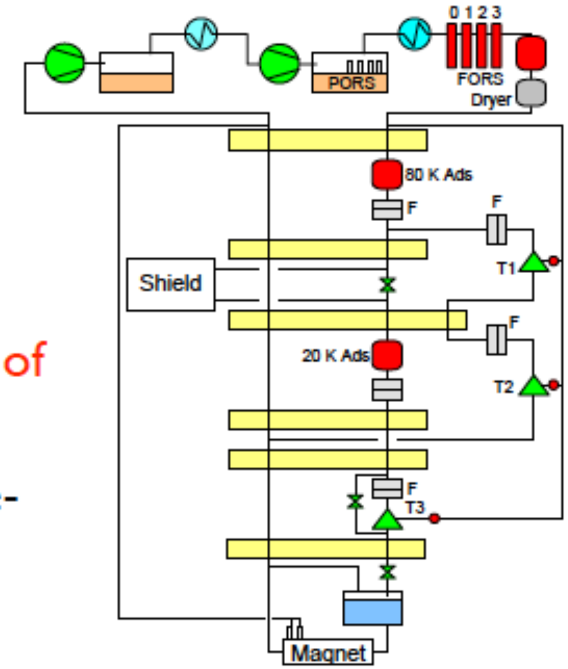
Large data (at least 300 fb^{-1}) is needed to address the question

Cross-section for ggH+2jets

TABLE I. The gluon fusion and weak boson fusion signal cross sections at the generator level before event selection and Higgs decay for 8 (left) and 14 TeV (right).

α	8 TeV GF cross section (fb)	8 TeV WBF cross section (fb)	14 TeV GF cross section (fb)	14 TeV WBF cross section (fb)
0.00	250	467	1141	1481
0.30	278	426	1268	1351
0.60	352	318	1606	1009
0.90	447	181	2038	572
1.20	529	61	2411	194

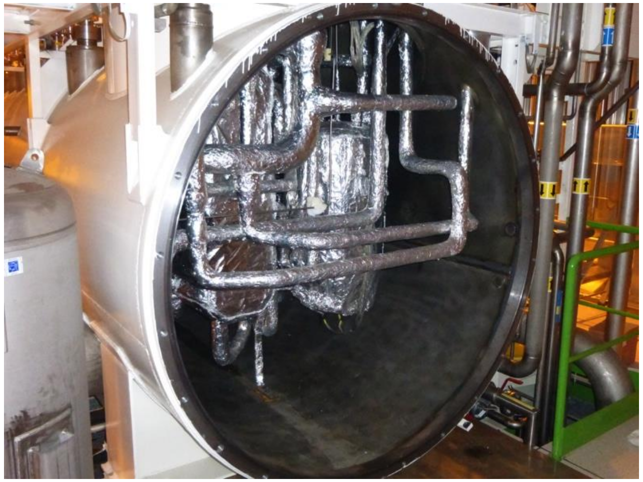
Magnet cryogenics issues



- The restart of the CMS magnet after LS1 was more complicated than anticipated due to problems with the cryogenic system in providing liquid Helium.
- Inefficiencies of the oil separation system of the compressors for the warm Helium required several interventions and delayed the start of routine operation of the cryogenic system.
- The data delivered during the first two weeks of LHC re-commissioning with beams at low luminosity have been collected with B=0
- Currently the magnet can be operated, but the continuous up-time is still limited by the performance of the cryogenic system requiring more frequent maintenance than usual.
- A comprehensive program to re-establish its nominal performance is underway. These recovery activities for the cryogenic system will be synchronized with the accelerator schedule in order to run for adequately long periods.
- A consolidation and repair program is being organized for the next short technical stops and the long TS at the end of the year.

Magnet cryogenics

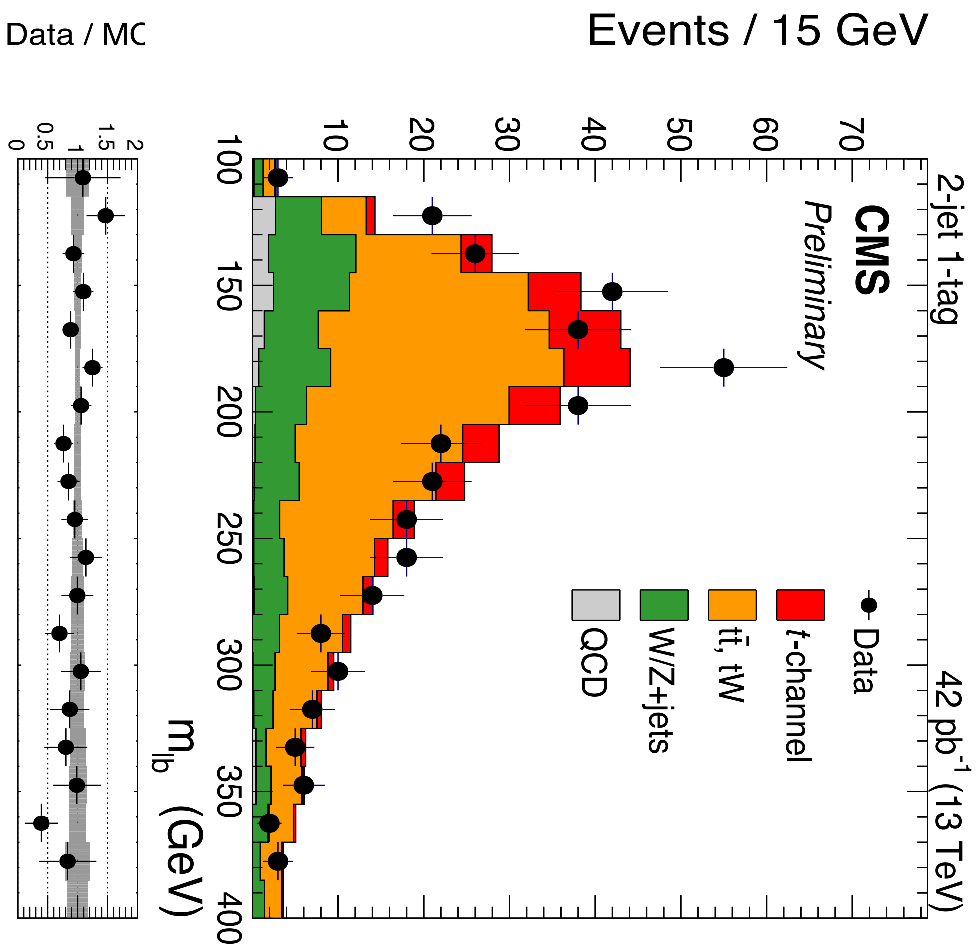
- Cryo cold box instabilities since March
  - Suspected oil contamination from compressor plant
- Many invasive campaigns of cleaning and replacement since Apr 1st
  - Many thanks to TE and EN departments for exceptional effort
- Cold box opened on 1st Sep., restarted on 8th Sep [ramped to 3.8 T on 15th Sep]
  - Insertion of additional 10 and 30 μm filters
    - augment filters which were clogging by much larger surface area filters used in the main LHC cryo plants.
  - Work ongoing to clear remaining contamination
- Precautionary preparations for comprehensive cleaning campaign (YETS 2015-16 or sooner)

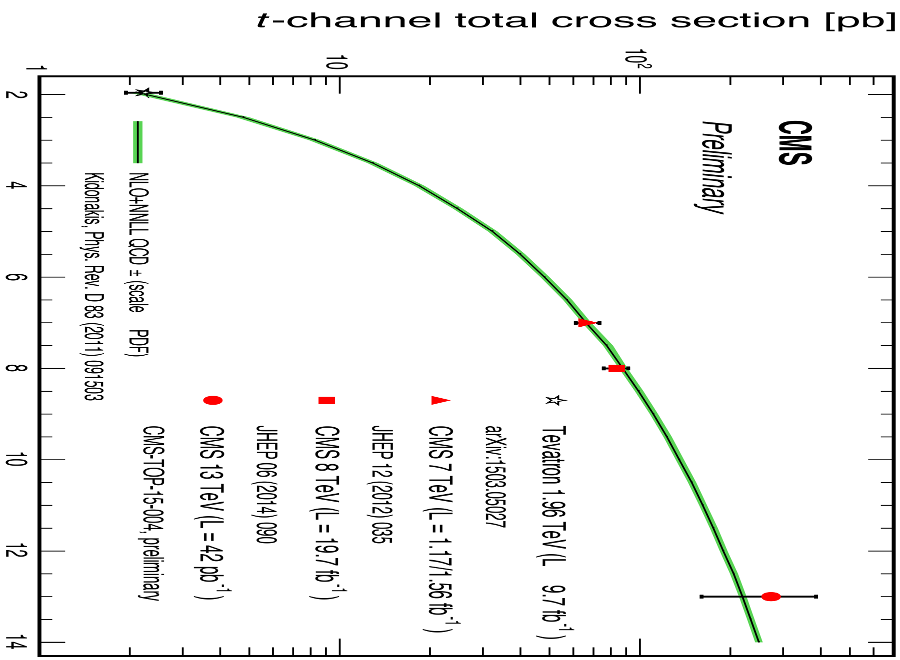


Single top cross section

- t-channel single top cross section @13 TeV measured:
  - μ + jet channel

$$\sigma_{t\text{-ch.}} = 274 \pm 98\,(\text{stat.}) \pm 52\,(\text{syst.}) \pm 33\,(\text{lumi.})\,\text{pb},$$

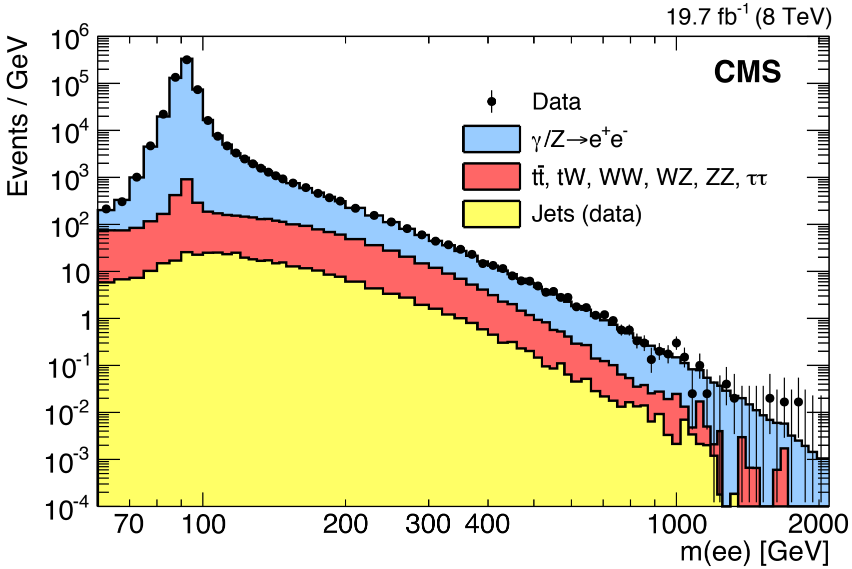


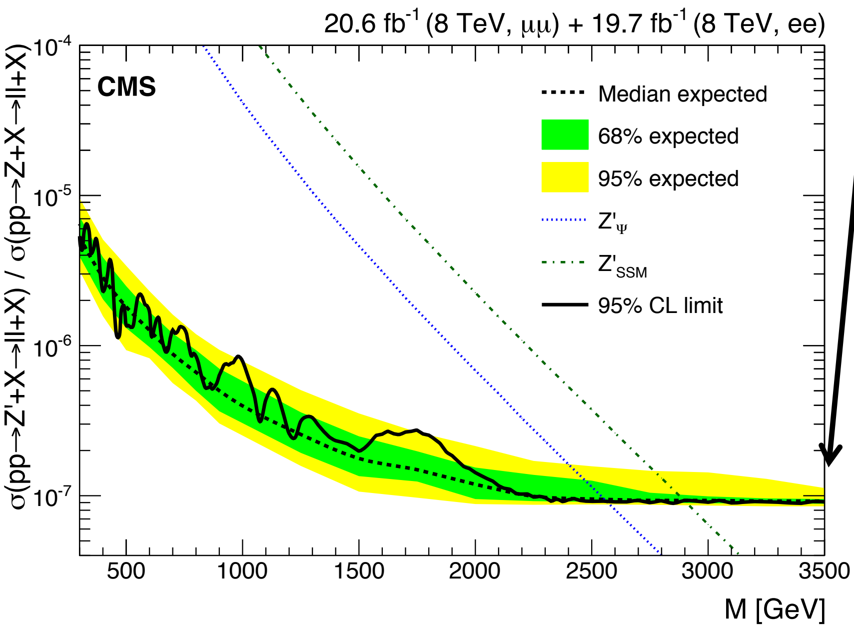


$$|V_{tb}| = 1.12 \pm 0.24\,(\text{exp.}) \pm 0.02\,(\text{theo.})$$

TOP-15-004

Run-1 Z' limit





- First of all, this could be DY Bkg. (bkg. uncertainty being checked)
- We excluded a cross-section of 0.22fb at inv. mass 3TeV
  - translate into 4.4fb @ 13TeV
- Cross-section of 1 events @ 65pb^{-1} is ~24fb (but 4fb is within 1 sigma)

- In the case of true NP, there are many possibilities not excluded by data
  - Not narrow resonance
  - Reflection of something at high mass
  - Spin2 particle …
- Still, most natural explanation is relatively narrow Z' resonance
- 1 event with several hundreds of pb^{-1} (we are lucky if this is true)

ee event

- There are non-negligible uncertainties in the background at high-mass
  - In particular, for the contribution of the gg → dilepton process. But even assuming a large contribution in relative terms with respect to DY, its contribution will be small in absolute term

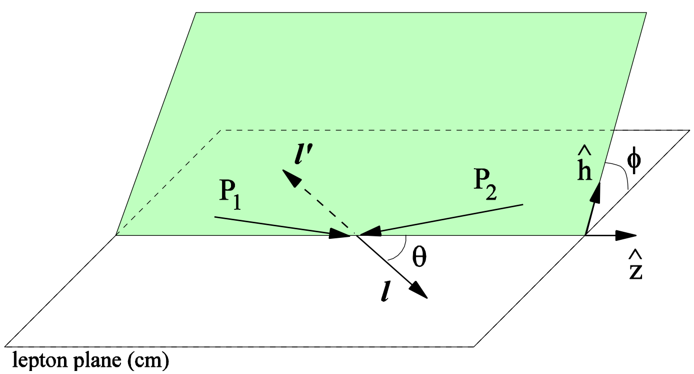
- Follow up on-going
  - Analyze 0T runs for di-electron channels
  - Analyze Di-muon channel (alignment matters)
  - Di-tau …

Particle flow

- Attempt to reconstruct all stable particles in an event
  - Photons
  - Charged and neutral hadrons
  - Electrons
  - Muons
- Information from sub-detectors is combined in best possible way, based on resolution
- List of particles is returned, as if it came from a MC generator
- Higher-level physics objects can be built from list of particles
  - Hadronic taus
  - (b-tagged) Jets
  - Missing transverse energy

Collins-Soper angle

- CS frame = The rest frame of the lepton pairs
- CS angle is manifestly covariant under rotation about the Z'-axis in the CS frame



$$h_1 + h_2 \to \gamma^* + x \to l^+ + l^- + x \quad (q + \bar{q} \to \gamma^*)$$

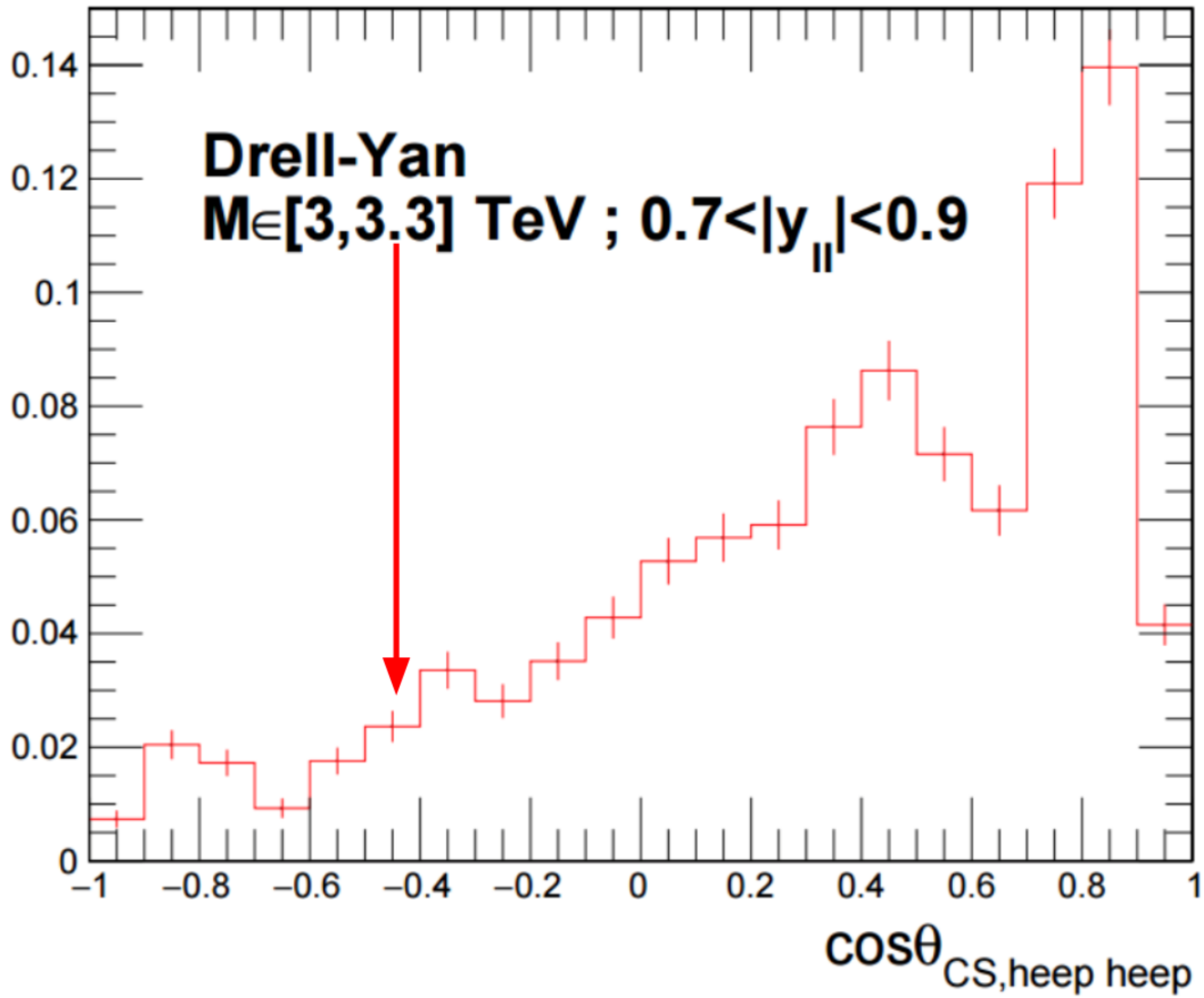
Θ and Φ are the decay polar and azimuthal angles of the μ^+ in the dilepton rest-frame

Collins-Soper frame

In case of H→γγ

$$\cos\theta^*_{\mathrm{CS}} = 2 \times \frac{E^{\gamma 2} p_z^{\gamma 1} - E^{\gamma 1} p_z^{\gamma 2}}{m_{\gamma\gamma}\sqrt{m_{\gamma\gamma}^2 + (p_{\mathrm{T}}^{\gamma\gamma})^2}}$$

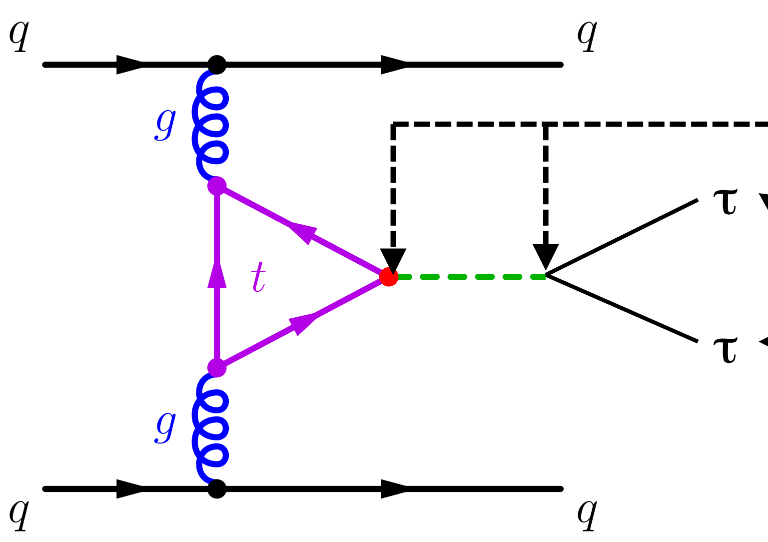
(DY events with similar kinematics present a positive FB asymmetry)



Feasibility study

decay	obs. μ-value (run-1) @ 2 jets phase space
$H \rightarrow \gamma\gamma$	$1.514^{+0.551}_{-0.476}$
$H \rightarrow WW$	$0.623^{+0.593}_{-0.479}$
$H \rightarrow \tau\tau$	$0.948^{+0.431}_{-0.379}$
$H \rightarrow ZZ$	$1.549^{+0.953}_{-0.661}$

- Tag a Higgs boson + 2 jets
  - Use $H \rightarrow \tau\tau$ final state



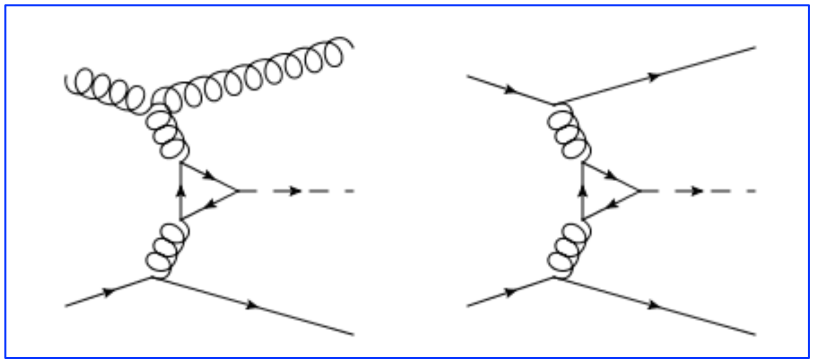
All fermionic coupling

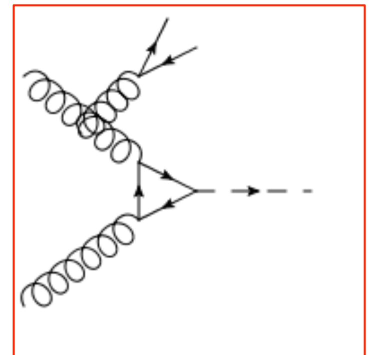
Considered final states:
$\tau_\mu\tau_h$, $\tau_e\tau_h$, $\tau_e\tau_\mu$, $\tau_h\tau_h$
(use similar selection as run-1)

- Reconstruct $\Delta\phi(jj)$ using leading and sub-leading jets
- To enhance $\Delta\phi(jj)$ discrimination power, apply:
  - $\Delta R(jj) > 0.6$, $m_{jj} > 200$ GeV, Higgs $p_T > 70$ GeV

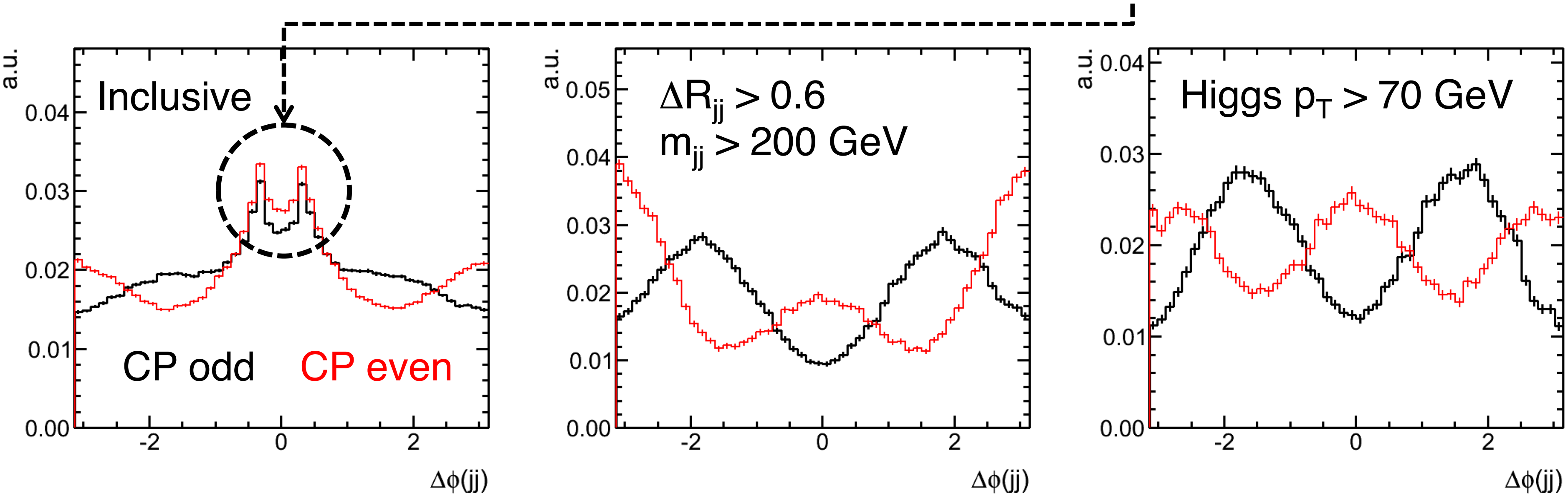
Gluon fusion + 2 jets includes "not-interesting" events

Exhibit modulation



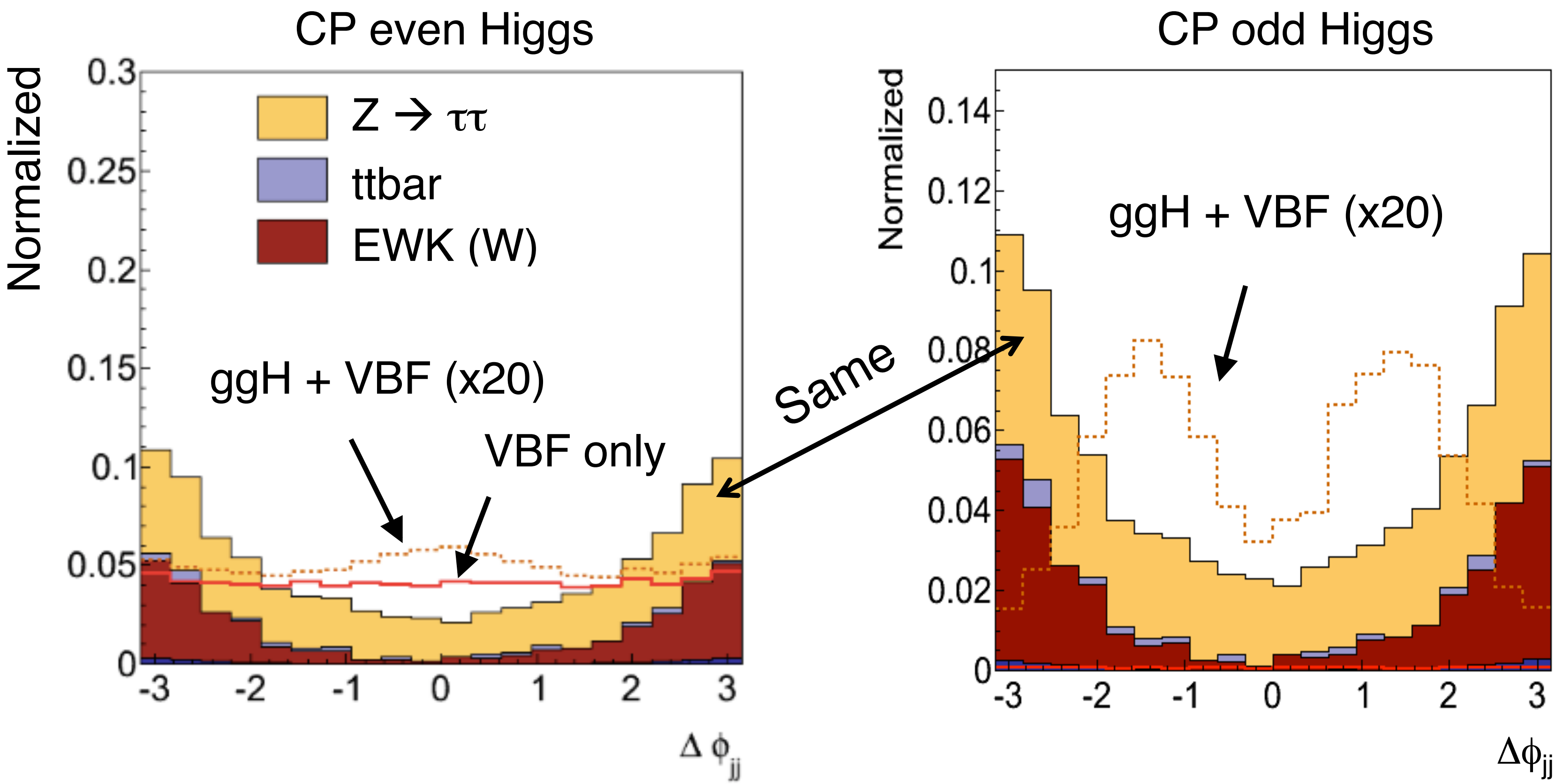


Doesn't bring CP info. (gluon split)



VBF-like selection helps separating "interesting" events. But, more VBF-like selection, less gluon-fusion → Need optimization

Sensitivity check using run-1 data



~5 Higgs signal (25% from ggH)

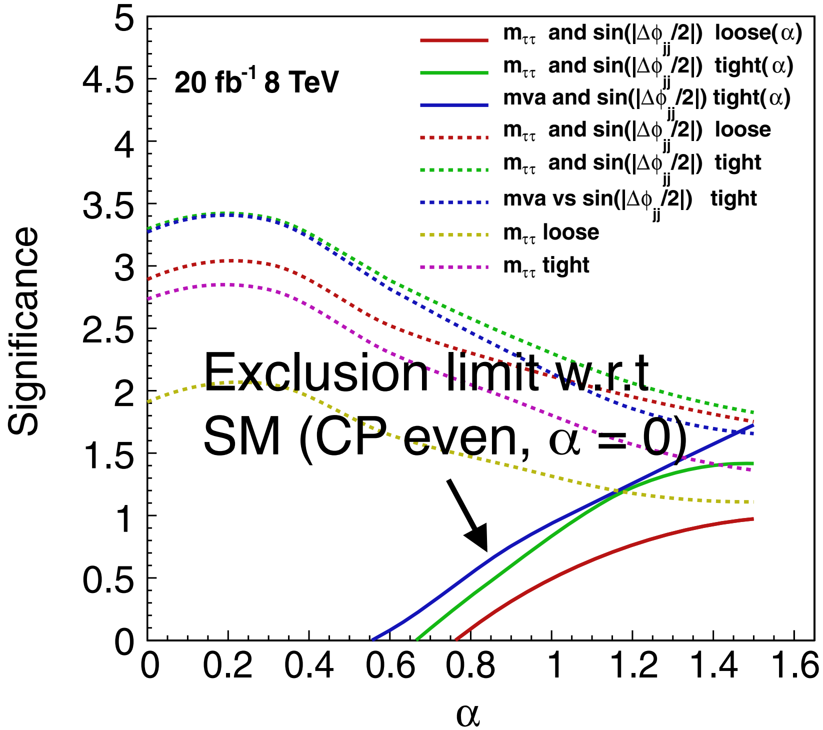
~100% ggH

- Likelihood fit of Δφ with signal & bkg. template
  - Signal template with several mixing angle (0 – π/2)

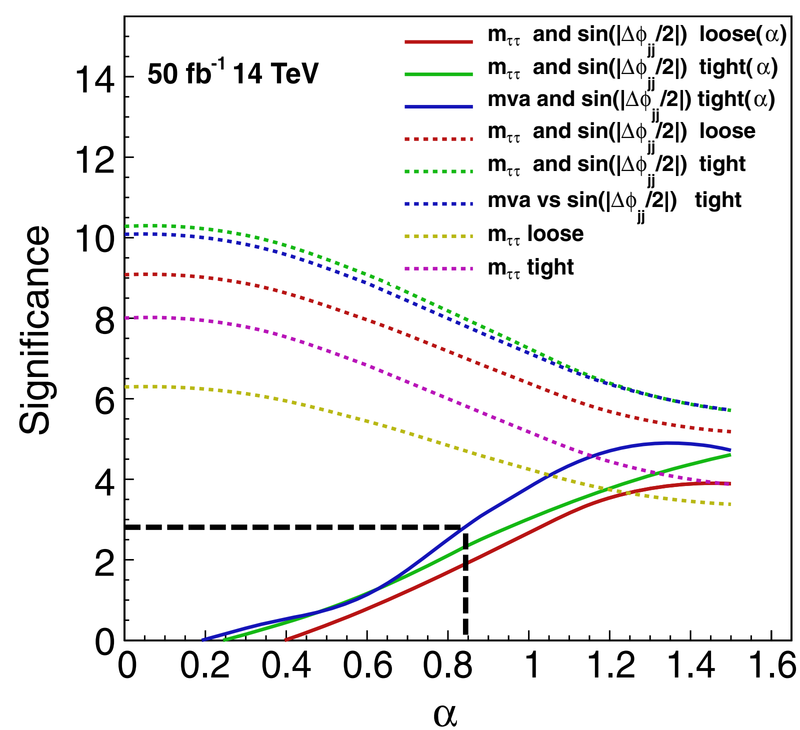
Expected sensitivity

PRD 90, 073008 (2014)

20 fb^{-1}, 8TeV



50 fb^{-1},14TeV

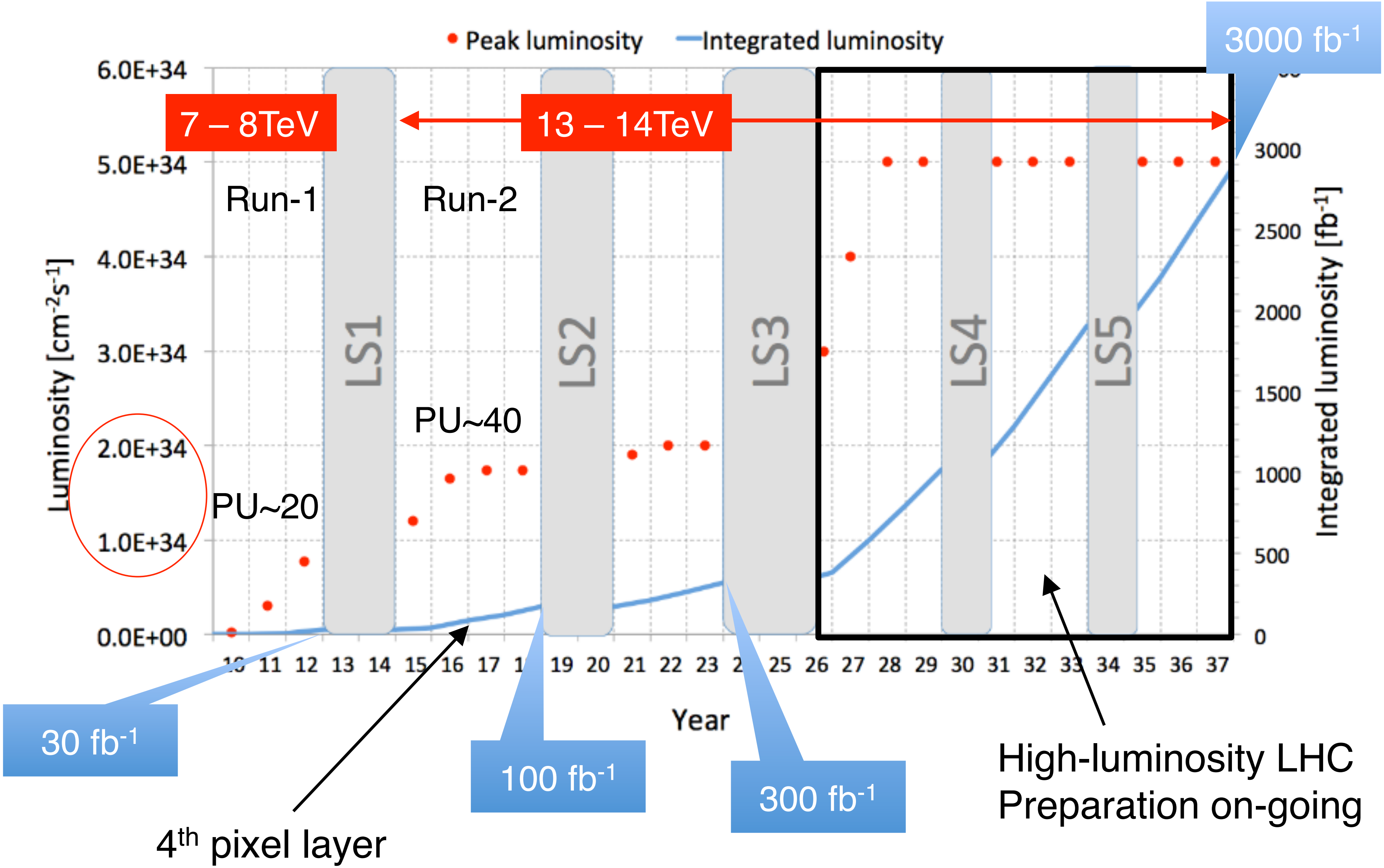


Exclude pure CP odd with 2σ level
(completely model independent)

$\alpha > 0.9$ rad excluded
with 3σ at 50 fb^{-1} at 14TeV

- Encouraging results for run-2
- Feasibility study on-going with realistic detector simulation

Run-2 will continue until 2018



mass range	SM Bkg Expection
>1 TeV	0.21
> 2 TeV	0.007
> 2.5 TeV	0.002