Search for rare Higgs boson decays with mesons at HL-LHC

FTR-21-009

AWG Meeting

15/02/2022

Himal Acharya and Stefan Spanier

Motivation

Ball-park expectation for such channels in Run-2 optimistic (negligible background) –

$$BF = \frac{N_{95}}{\sigma_{pp\to H} \cdot \Gamma_i \cdot \varepsilon a \cdot L} \approx 10^{-4}$$

$N_{95} = N_s - N_b = 3 \quad N_b = 0$

$\sigma_{pp\to H} = 55\,pb$

$\Gamma_i = 0.01$

$\varepsilon a = 0.3$

$L = 140\,fb^{-1}$

Final states with SM expectation ~ 10^{-5} accessible with HL-LHC ?!
.. and limits for BSM scenarios

Motivation

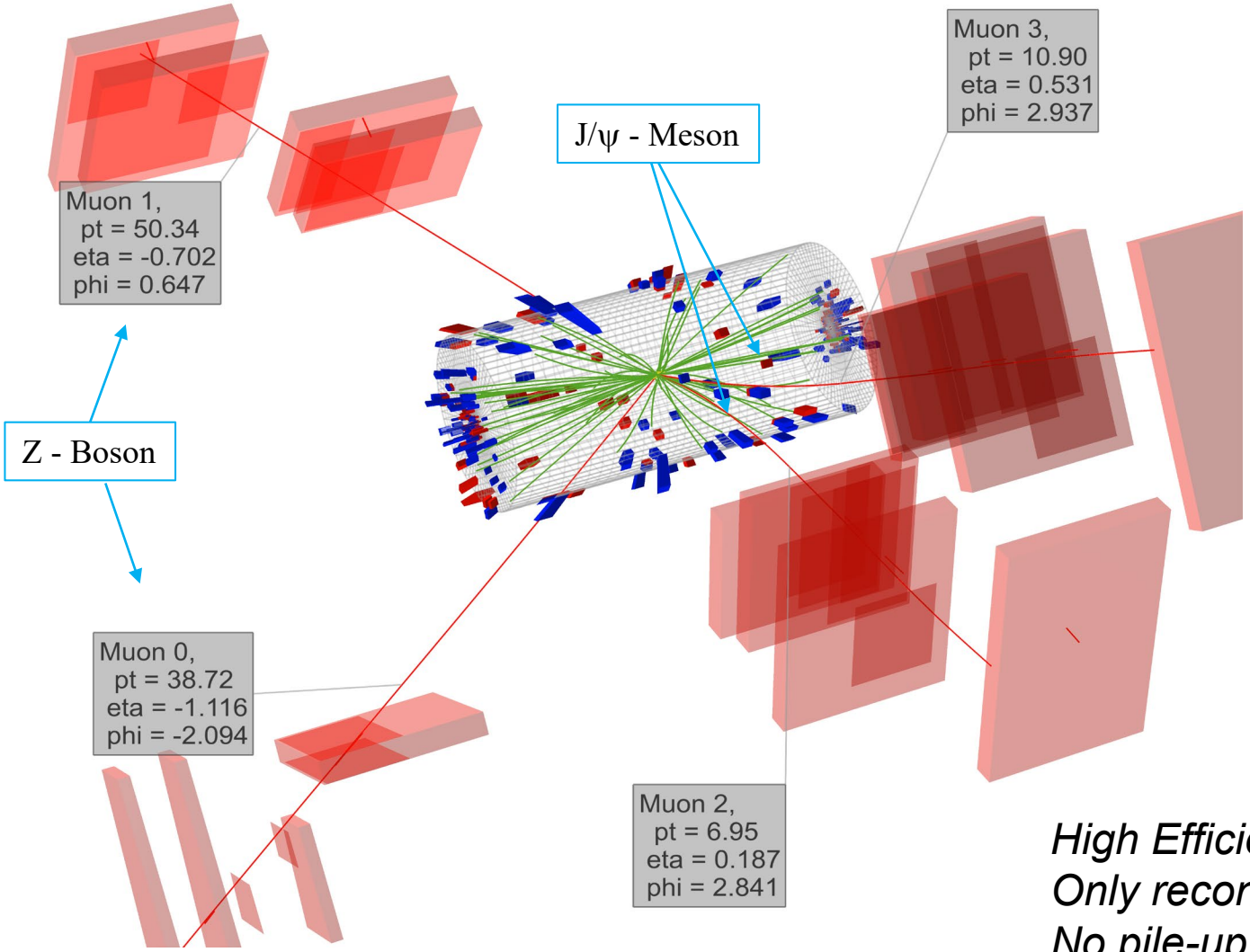
Recent Results on these rare decays:

Higgs Decay	SM BF	Present Limits	Lumi fb-1
$Z\ J/\psi$	2.3×10^{-6}	1.9×10^{-3}	137 today
$Z\ \gamma$	1.5×10^{-3}	5.5×10^{-3}	137
$Z\ \rho$	1.4×10^{-5}	1.2×10^{-2}	137
$Z\ \varphi$	4.2×10^{-6}	3.6×10^{-3}	137
$J/\psi\ J/\psi$	1.5×10^{-10}	3.8×10^{-4}	137
$J/\psi\ \gamma$	3×10^{-6}	7.6×10^{-4}	36
$Y\ Y$	10^{-5} .. 10^{-9}	3.5×10^{-4}	137 today
$Y\ \gamma$	7×10^{-9}	7×10^{-4}	36

[SMP-18-016, HIG-19-014, HIG-20-008, HIG-19-012, HIG-18-025]

Analysis

$pp \rightarrow H + X, H \rightarrow Z\ J/\psi \rightarrow 4\mu$ Simulated Event



High Efficiency
Only reconstruct 4 muon vertex
No pile-up dependence

Strategy

- Start with the Run-2 data analysis
- Re-optimize criteria for best UL and re-fit background (signal)

  - increase purity; efficiency ~ 20%
- Scale sample with luminosity 137 fb^{-1} → 3000fb^{-1} (4500fb^{-1})
- Scale sample with cross section from 13TeV to 14TeV (x ~1.126)

  [https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt1314TeV2014]
- Scale with lepton acceptance for HL-LHC detector (x ~1.13 .. 1.18)
- Re-fit sample and perform upper limit (Higgs combiner tool)

  - Upper limit in branching fraction @ 95% CL is calculated based on the CLs modified HybridNew method (1000 toys)

Reconstruction H → Z J/ψ

Muon:

track	d_{xy}<2mm , d_z < 5mm
ID	tight
p_T	> 6 GeV
$\lvert \eta \rvert$	< 2.4
Isolation	μ_{Iso} (track) < 0.5

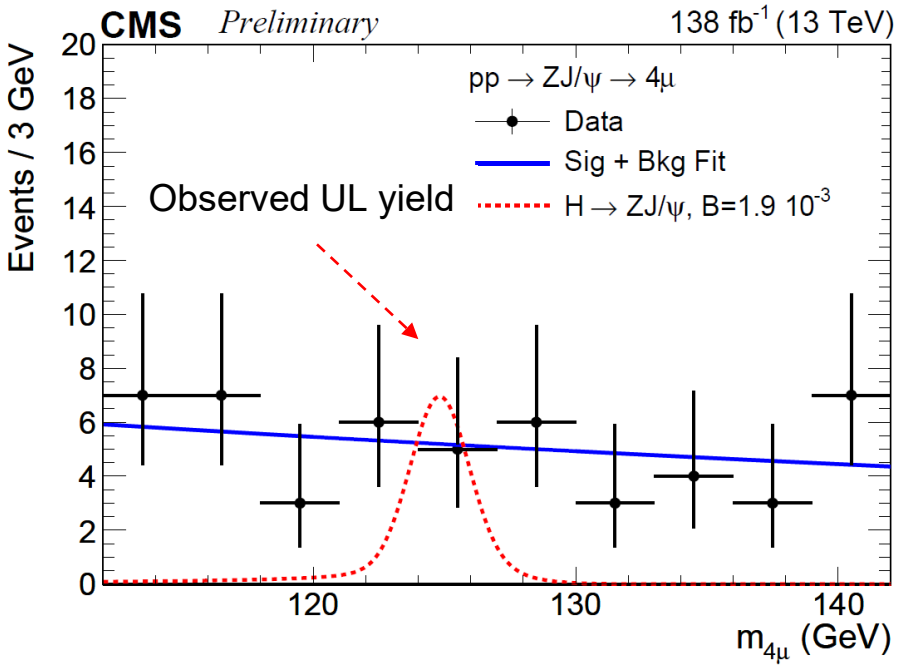
Dilepton:

$Prob_{vtx}$	> 1 %
p_T	> 5 GeV
m_Z	ϵ [80-100] GeV
$m_{J/\psi}$	ϵ [3.0-3.2] GeV

Four lepton:

$Prob_{vtx}$	> 1 %
m_{4l}	ϵ [112-142] GeV

Efficiency x Acceptance = 20%



scale

Unbinned maximum likelihood fit [1]

Background: model solely derived from data

Previously: Exponential + Uniform

New: linear function (slope) (exponential)

Signal: Gaussian + Crystal Ball
(2x Crystal Ball)

The pT cutoff is only affecting the two low-pt leptons

[1] https://root.cern/

Background Estimate H → Z J/ψ

… obtained with simulation for Run-2 conditions
(x 22 for 3,000fb^{-1})

Expected # background events in the Higgs signal region

$H \rightarrow ZZ^*$ (peaking)	1.3 +/- 0.2
$qq \rightarrow ZZ^*$	8.8 +/- 0.9
$gg \rightarrow ZZ^*$	0.9 +/- 0.1
Associated Production	expected dominant
Combinatorial background	in di-muon spectra small

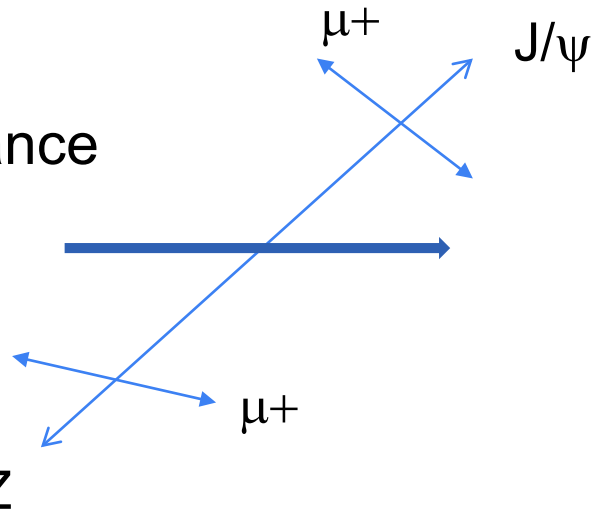
Background Scaling

Physics in background same from 13 to 14 TeV

- Start with the observed background, after pre-selection (443 events)
- Expect resonance pT distribution to stretch (~ 7%)
- Distribution still smooth (exponential)
- Decay resonances again into muons (leptons)

Acceptance scaling

1. Extend η range and count Phase 1 acceptance
2. Scale pT range and count Phase 2



Relative Acceptance Change

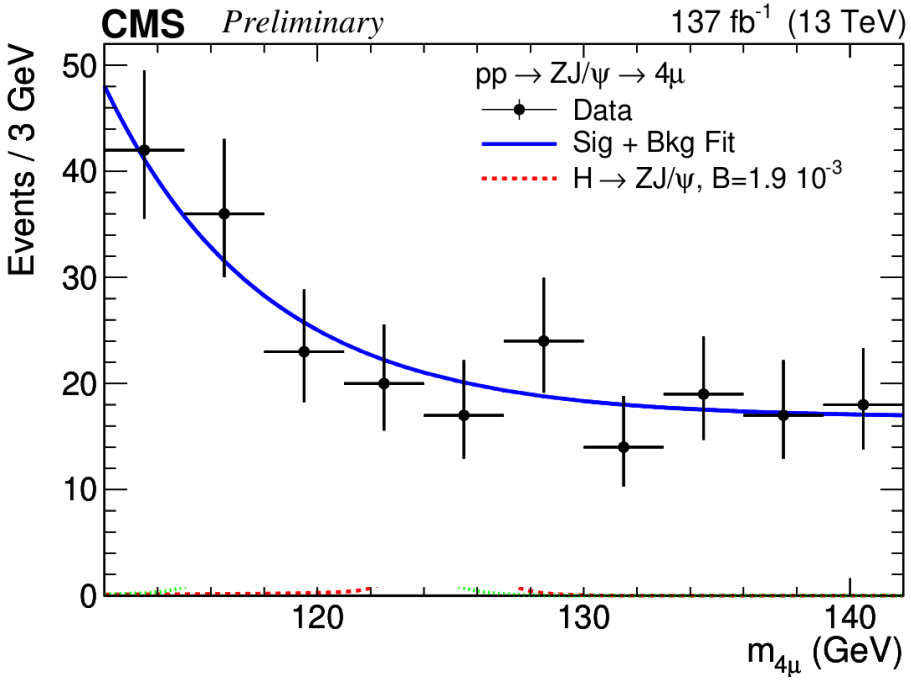
4μ	15 ± 2 %
2e2μ	17 ± 2 %
4e	17 ± 2 %

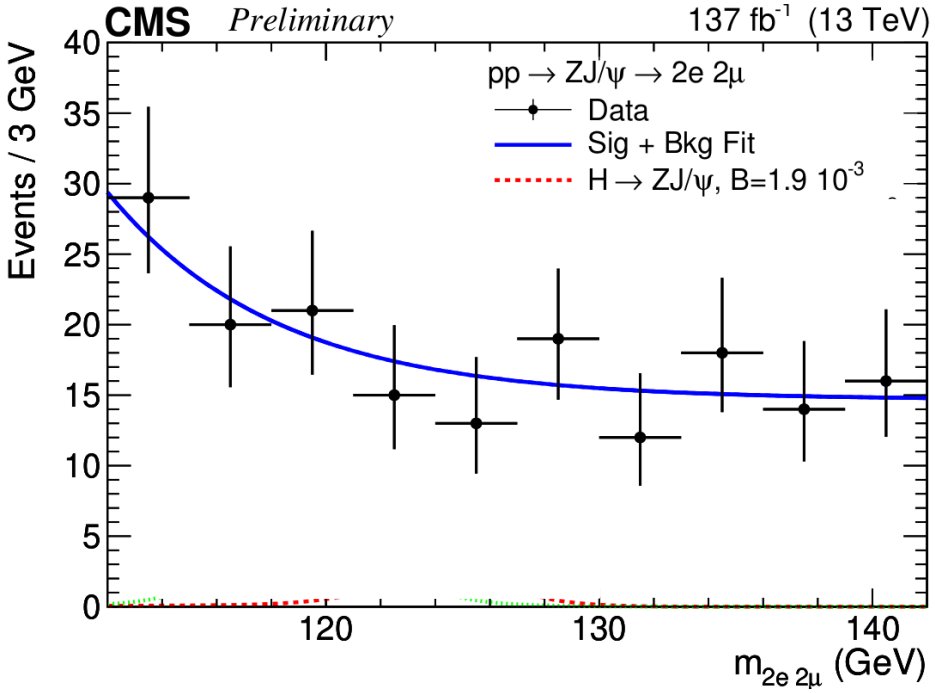
Assumed scaling as signal resulting in relative changes 13%, 18%, and 18%, respectively.

Lepton final states H → Z J/ψ

Run-2 upper limit in branching fraction calculation combines

the 4μ and $2e2\mu$ final states (comparable systematic uncertainties)





Reconstruction H → Y(nS)Y(mS)

Muon:

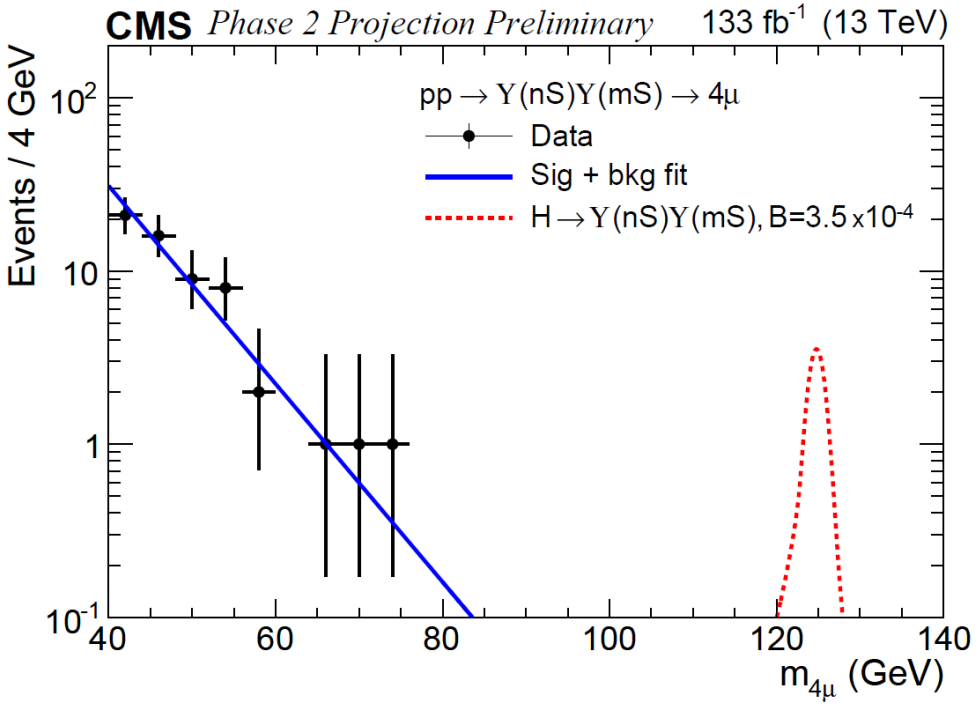
track	d_{xy}<3mm , d_z < 20cm
ID	soft
p_T	> 4 GeV
$\lvert \eta \rvert$	< 2.4
Isolation	μ_{Iso} (track) < 0.5

Dilepton:

$Prob_{vtx}$	> 1 %
p_T	> 5 GeV
m_Y	ϵ [9.0-10.7] GeV

Four lepton:

$Prob_{vtx}$	> 1 %
p_T	> 5 GeV
$\lvert y_{4\mu} \rvert$	< 1.7
$\lvert y_{Y1} - y_{Y2} \rvert$	< 2.3
$\lvert \phi_{Y1} - \phi_{Y2} \rvert$	> 1 rad
m_{4l}	ϵ [40-140] GeV



Efficiency x Acceptance = 31%

No re-optimization

Unbinned maximum likelihood fit [1]

Background: Exponential (Power law)

Signal: Gaussian + Crystal Ball

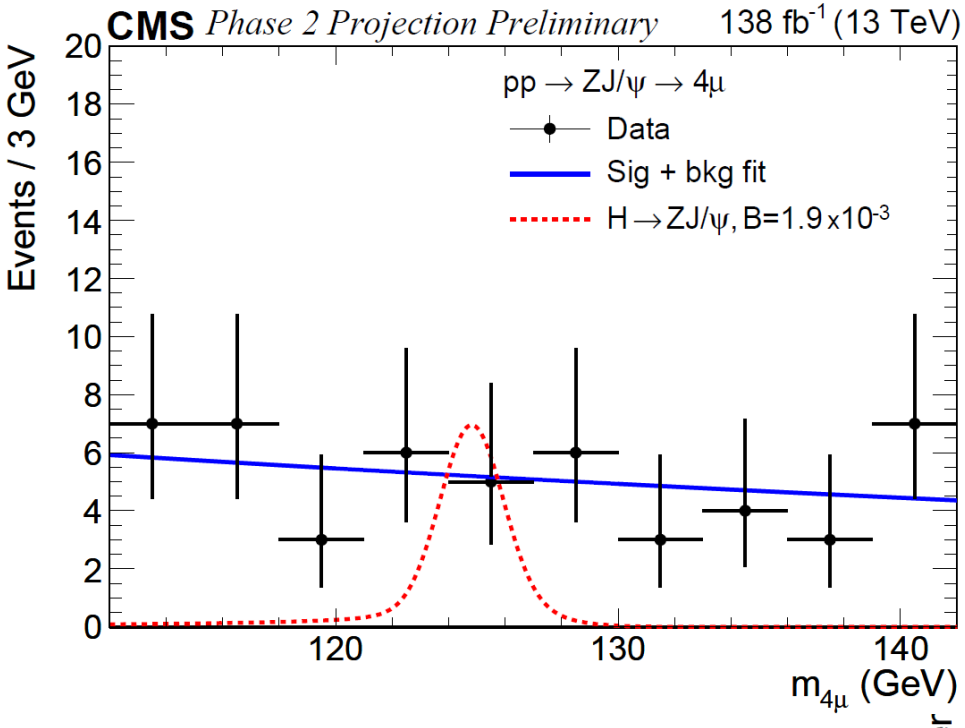
[1] https://root.cern/

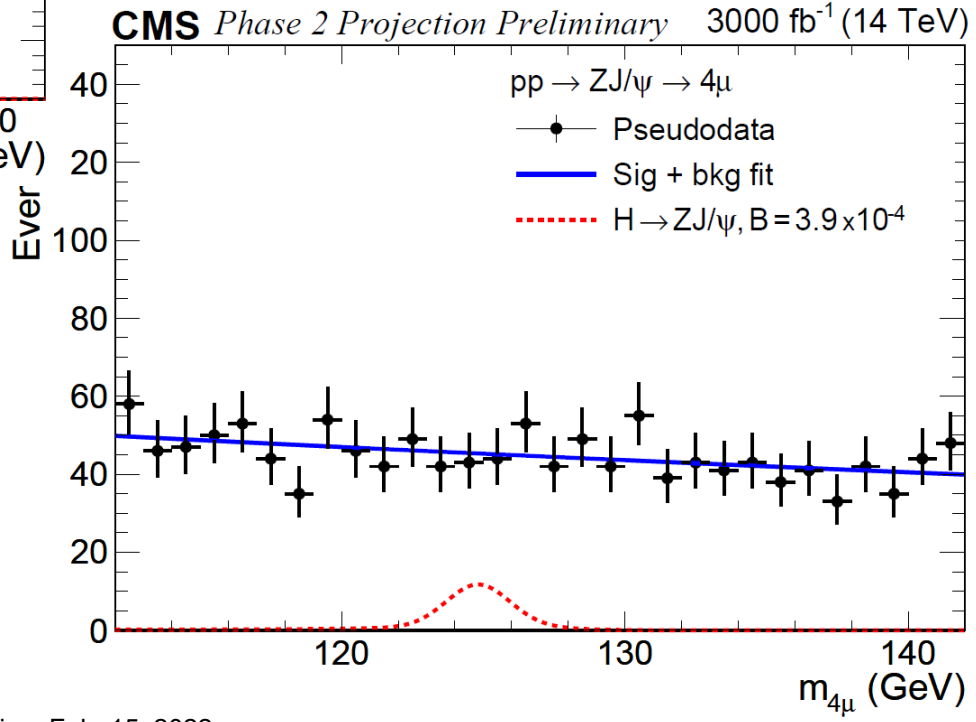
Reconstruction H → Y(nS)Y(mS)

Other backgrounds? No predictions.
Will deal with as encounter – not objective (speculation) here
B~10^{-5} can be reached, which will decide on SM diagrams

- If peaking, will show up
  Can possibly be distinguished, e.g. dilepton invariant mass other observables
- Freak event
  Will require careful study

Improved plots





Improved plots