Search for the Rare Higgs Boson Decays with the CMS Detector

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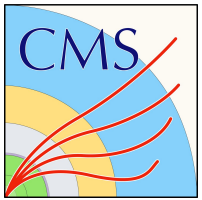
CMS Collaboration



APS DPF Meeting
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Outline

- **Motivation**
- **Lepton Detection**
- **Maximum Likelihood Fit**
- **Results**
- **Summary**

Channels Analyzed

Z boson and a J/ψ meson Channel

- $H \rightarrow Z\ J/\psi \rightarrow 4\mu$ ($2\mu 2e$)

Quarkonium Channels

- $H(Z) \rightarrow Y(nS)\ Y(mS) \rightarrow 4\mu$
- $H(Z) \rightarrow J/\psi\ J/\psi \rightarrow 4\mu$
- $H(Z) \rightarrow Y(1S)\ Y(1S) \rightarrow 4\mu$

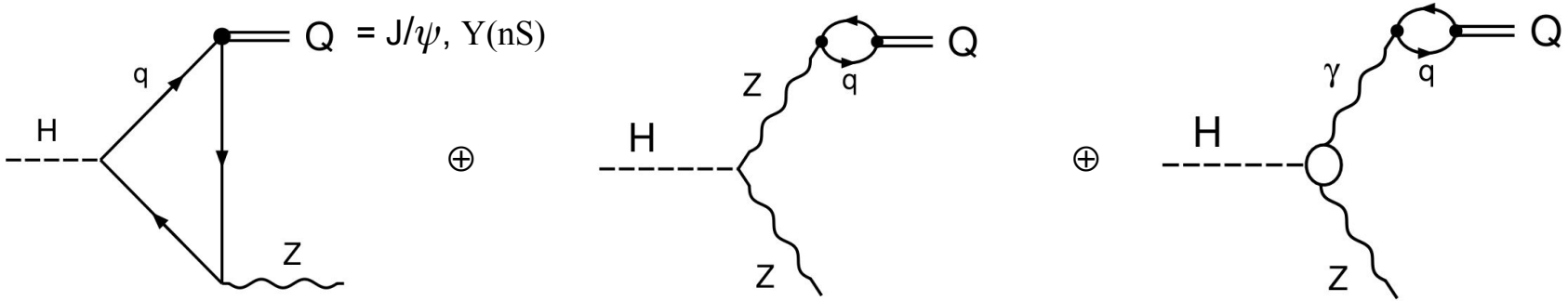
Feed-down Channels
(Using inclusive decay of $\psi(2S) \rightarrow J/\psi$)

- $H \rightarrow Z\ \psi(2S) \rightarrow 4\mu$ ($2\mu 2e$)
- $H \rightarrow \psi(2S)\ J/\psi \rightarrow 4\mu$
- $H \rightarrow \psi(2S)\ \psi(2S) \rightarrow 4\mu$

Motivation: Indirect Search for New Physics (BSM)

Transitions $H \to Z\ J/\psi\ (QQ)$ discussed here have two types of diagrams in SM:

Direct Diagram + Indirect Diagrams



BSM Physics

- Could be modify BF with new loops with new particles
- May enhance Yukawa couplings (light quarks!)
- Change interference (unlock destructive interference)
- BSM e.g. predicts up to 3 orders of magnitude BF change in related $H \to Q\ \gamma$

SM Predictions

- BF($H \to Z\ J/\psi$ / $Z\ \psi(2S)$) ~ 10^{-6} [1, 2]
- BF($H \to QQ$) ~ 10^{-5} ... 10^{-10} [3,4]

Input for $H \to Z\ \gamma$ (CP even/odd), $H \to ZZ^*$, and $Z\ X$ searches (X = dark boson or axion like particle)

[1] S. Alte et. al. , JHEP 12 (2016) 037
[2] A.K. Likhoded et.al. Mod. Phys. Lett. A 33(2018)
[3] V Kartvelishvili, AV Luchinsky, AA Novoselov, PRD 79 (2009) 114015]
[4] M. Bander, A. Soni, PLB 82 (1979) 411

Motivation: Strategy

Can **HL-LHC** reach SM BF in regime **10^{-5} .. 10^{-6}** ?

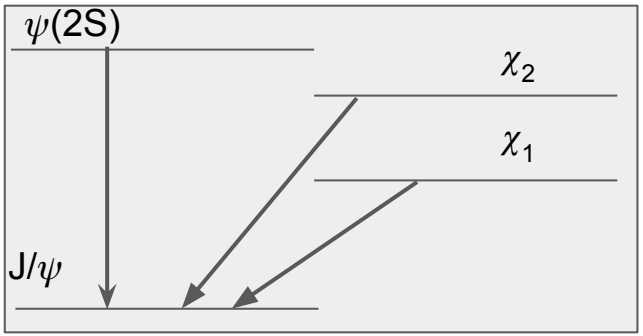
- Scaling with luminosity (x20) - by itself not enough in many channels

Strategy :

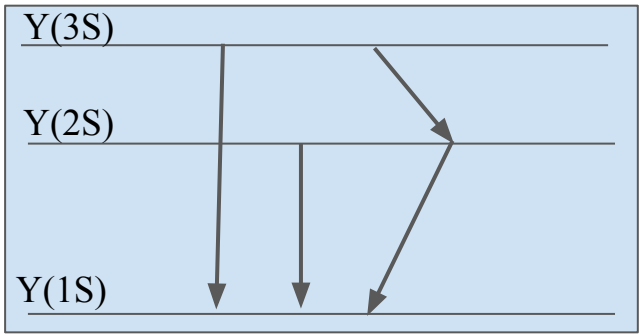
- Understanding background :
  - Reconstruction/selection strategy evolves with measurement/knowledge of background
- Combine different final states :
  - Include additional lepton final states - muon, electron pair decays of Z and Q)
  - Include additional Q channels - feed-down from higher mass states

Feedown Studies :

- BF(H→ ZQ) are comparable; E.g. BF(ψ(2S) →J/ψ)~0.6;



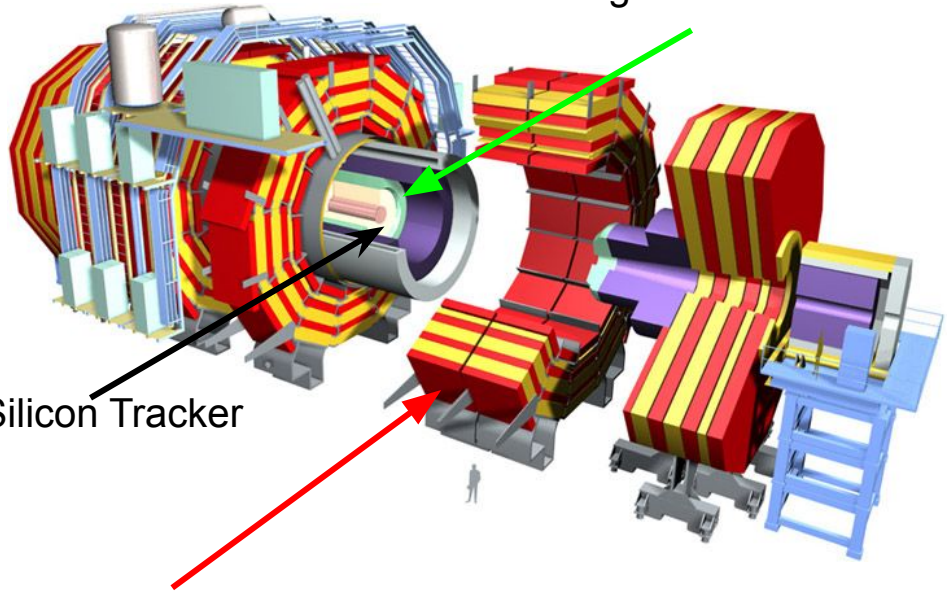
Mostly : ψ(2S) →J/ψ π π



Including: Y(nS)Y(mS) + feedown (X 5.82 in BF (H→ YY))

CMS Detector : Lepton Detection

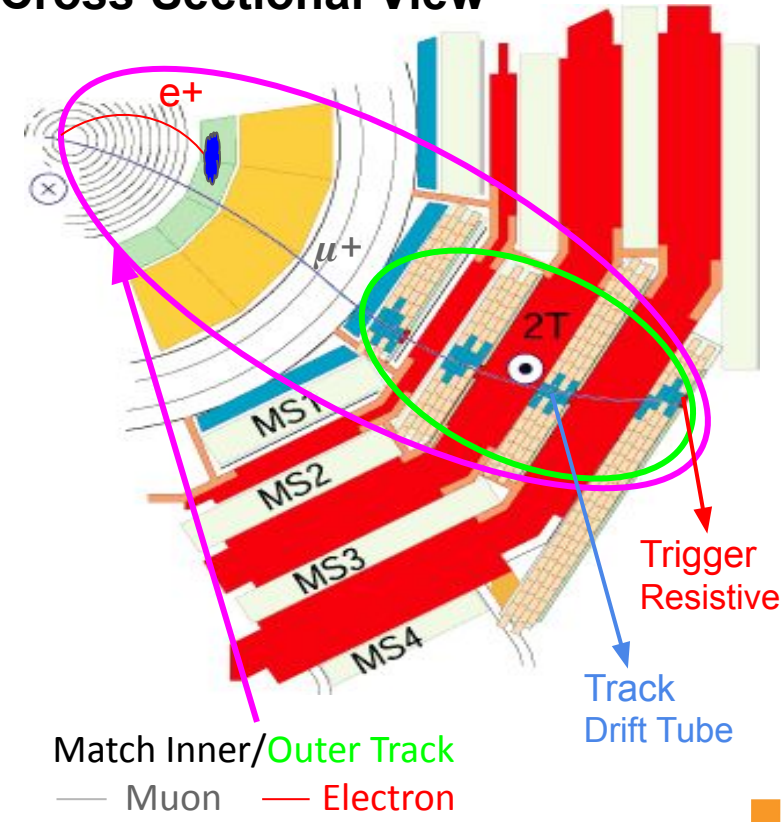
CMS Detector



Muon Detectors:

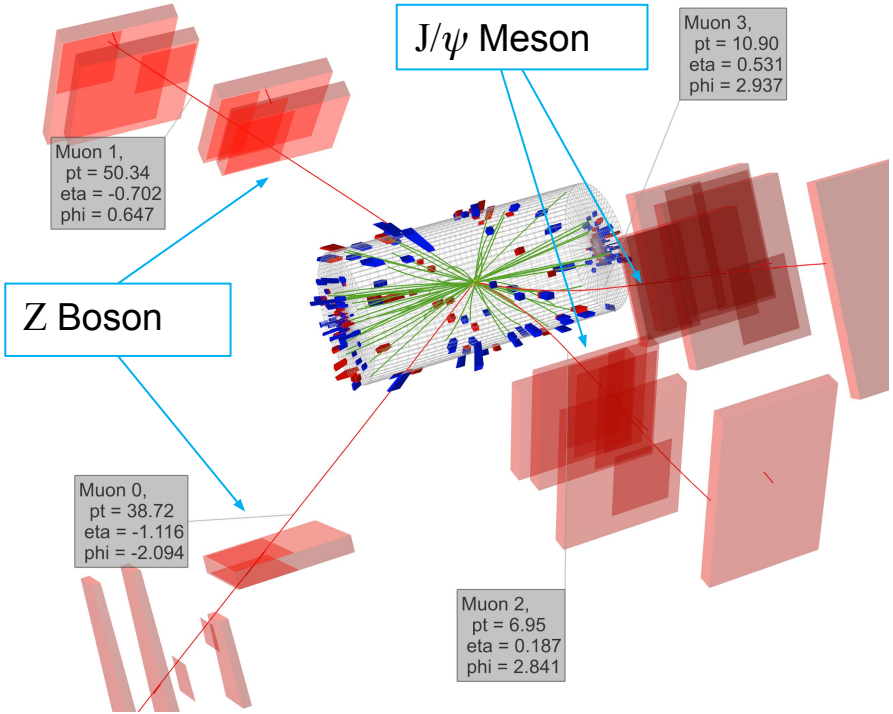
1. Drift Tubes
2. Cathode Strips Chambers
3. Resistive Plate Chambers (Trigger)

Cross-Sectional View

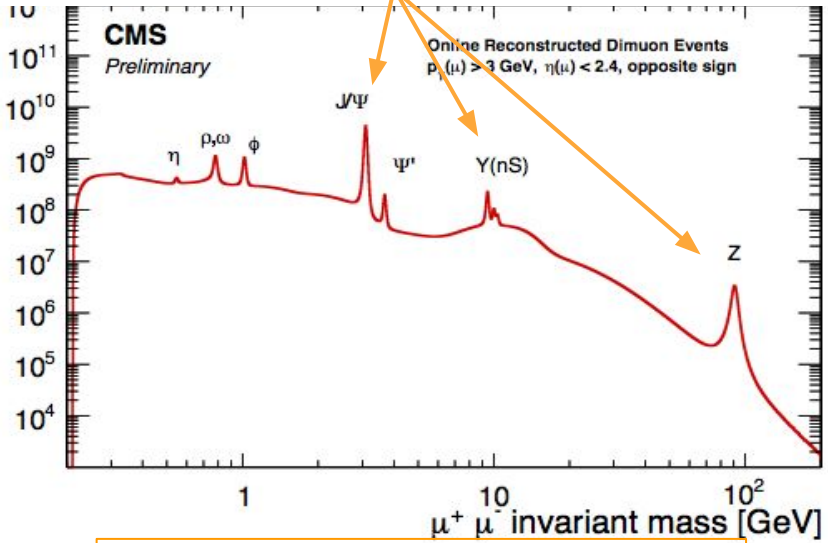


CMS Detector : Event Display and Trigger

e.g. $H \rightarrow Z\ J/\psi \rightarrow 4\mu$ Simulated Event



Trigger Muons + Dimuon Invariant Mass (HLT)



Single Lepton Trigger
- Single lepton with Pt > 27 GeV
- Efficiency > 95 %

Quarkonium Trigger
- 3 muons, J/ψ (Υ) candidate
- Efficiency > 85 %

[1] PoS (EPS-HEP 2019) 139

Maximum Likelihood Fit: $Z\ J/\psi$

Blinded

Reconstruction and selection optimized for signal upper limit

Perform extended Maximum Likelihood fit
Likelihood input for upper limit calculation (CLs Method)
Status: Analysis blind → expected upper limits

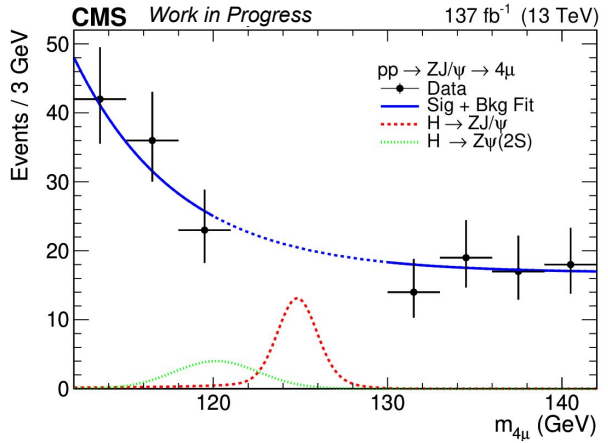
PDF modeling

- Higgs boson signal (from simulation):
  - PDFs with Gaussian $4l$ mass resolution, radiative loss tail
- Background (Associated Production + Combinatorics)
  - Obtained from sideband data:
    → Exponential + Uniform function

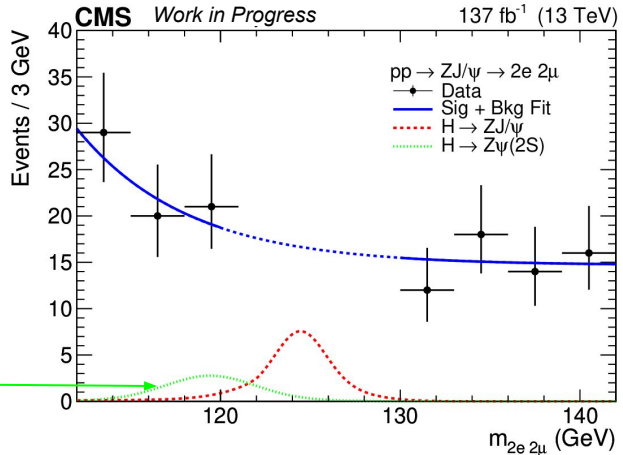
Feed-down Channels:

- Signals similar, kinematically shifted (for now)

Feed-down Signals scaled with all BF and acceptance x efficiency.



Higgs boson model: Gaussian + Crystal Ball(CB)



Higgs boson model: Double Crystal Ball

Maximum Likelihood Fit: Quarkonium Channels

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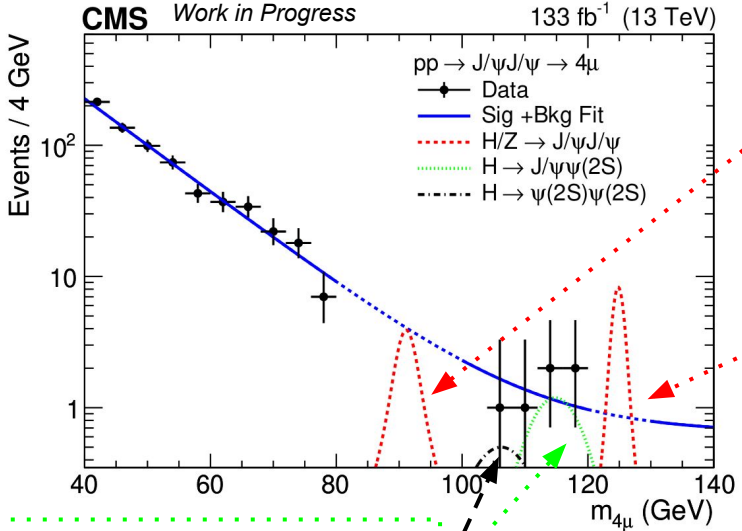
Similar Reconstruction and optimization strategy is applied for quarkonium channels :

⇒ Very clean (background)

According to simulation

→ Contribution from ZZ* is negligible in Run 2 data (HL-LHC?)

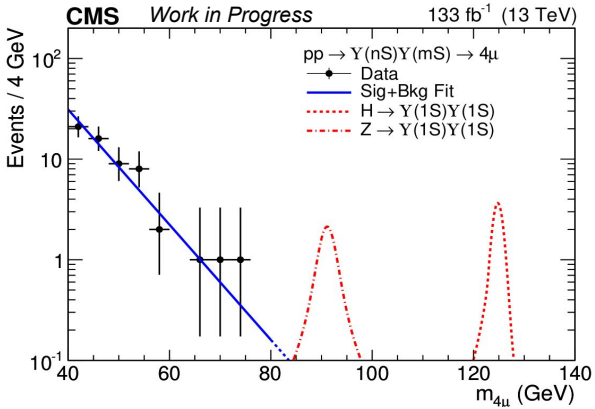


Z boson Signal

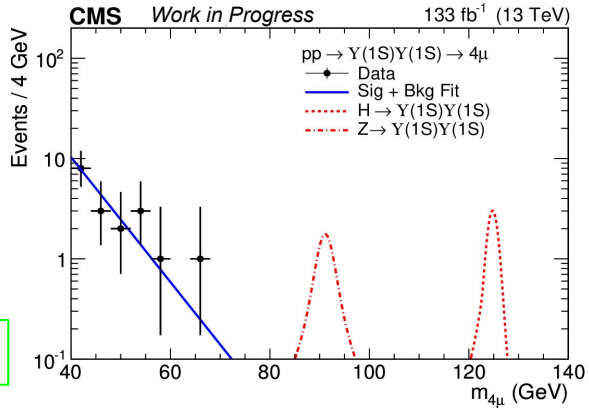
Higgs boson Signal

Feed-down Signals scaled with acceptance x efficiency

Efficiency × Acceptance ~ 30 %



Υ(nS) Υ(mS) Channel



Υ(1S) Υ(1S) Channel

Systematics

Exclusion limits @ 95% CL

- CLs, Modified frequentist approach [1,2] with Higgs Combiner Tool [3]

Dominant Systematic Uncertainties:

- **Theory [4,5] :**

  Parton distribution function (PDF) choice and coupling constant choice (α_s)

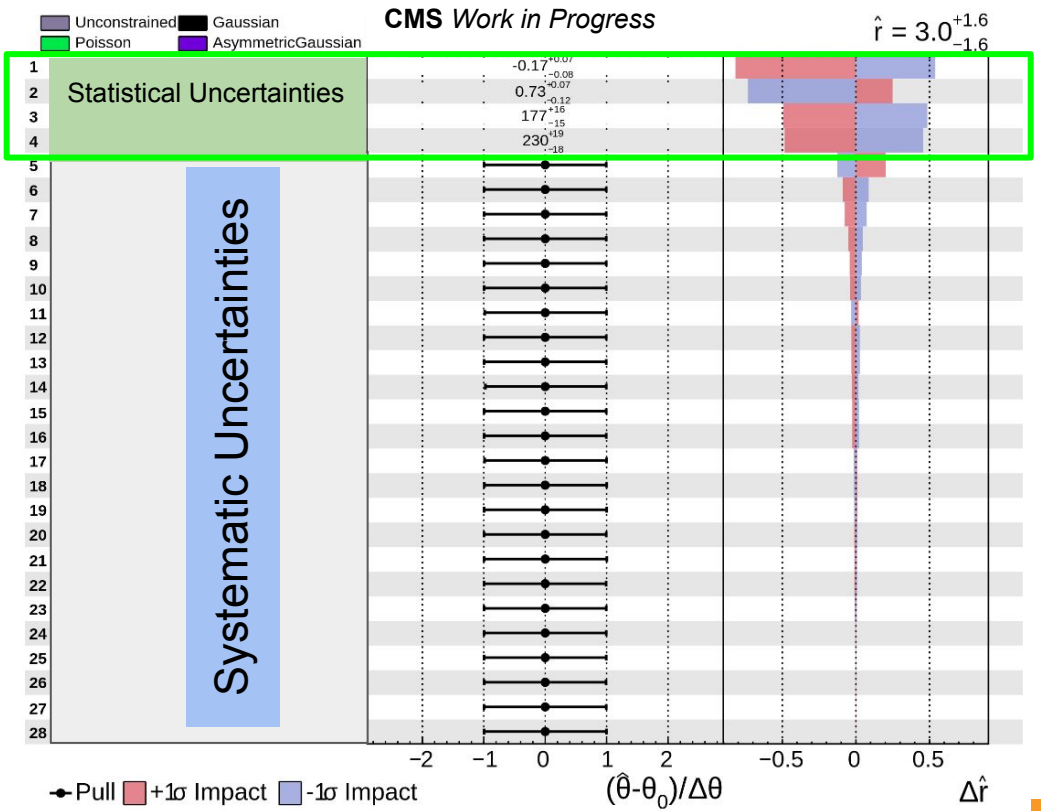
  QCD Renormalization and factorization

- **Efficiencies :** Trigger, lepton reconstruction

Others :

- Luminosity
- Branching fractions (PDG)
- Maximum likelihood fit modeling
- Momentum scale and resolution

e.g. $H \rightarrow Z\,J/\psi \rightarrow 4l$ Channel Impact Plot



[1] J. Thomas, Nucl. Instrum. Meth. A 434 (1999) 435
[2] Read, Alexander L., J. Phys. G 28 (2002) 2693
[3] http://cms-analysis.github.io/HiggsAnalysis-CombinedLimit/
[4] D. de Florian et al, CERN Report CERN-2017-002-M, 2017
[5] NNPDF Collaboration, Eur. Phys. J. C 77 (2017) 663

Expected Upper Limits

Blinded

… are set with the background only hypothesis using generated events

Higgs Decay	Run 2 expected BF	SM BF	Published Limits
$Z\ J/\psi$	2.6×10^{-3}	2.3×10^{-6}	1.8 [1]
$Z\ \psi(2S)$	7.2×10^{-3}	1.5×10^{-6}	-
$J/\psi\ J/\psi$	4.6×10^{-4}	1.5×10^{-10}	1.8×10^{-3} [2]
$J/\psi\ \psi(2S)$	1.2×10^{-3}	Not Calculated	-
$\psi(2S)\ \psi(2S)$	3.5×10^{-3}	Not Calculated	-
$\Upsilon(nS)\ \Upsilon(mS)$	3.5×10^{-4}	Not Calculated	1.4×10^{-3} [2]
$\Upsilon(1S)\ \Upsilon(1S)$	1.7×10^{-3}	2.0×10^{-9}	-

⇒ Unblinding of several channels - signals?
⇒ Wide spread test of feasibility towards HL-LHC

⇒ Publication (my thesis) is in preparation

[1] Phys. Rev. Lett., 125 (2020) 221802 (ATLAS)
[2] Physics Letters B, Volume 797, 10 October 2019, 134811 (CMS)

Summary

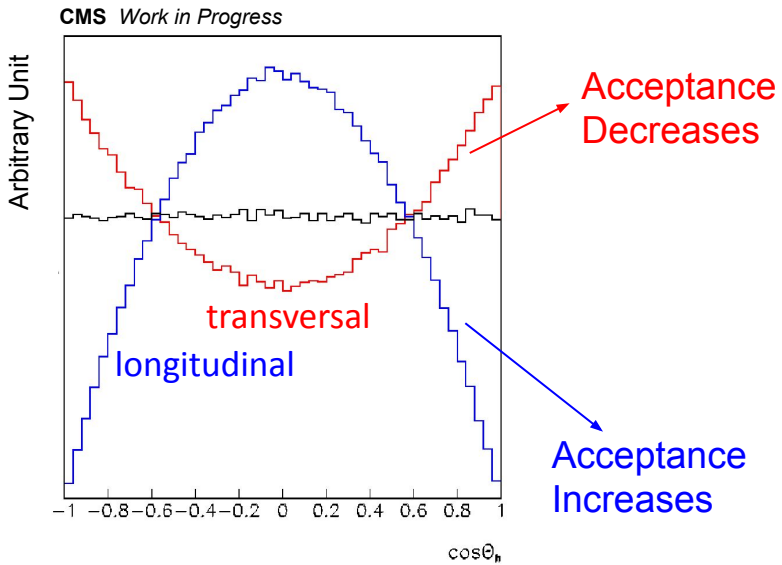
- Rare decays are a promising laboratory
  - For the search of new physics beyond SM
  - Probe new Higgs Yukawa couplings and loop contributions
- For the first time several channels are evaluated for feasibility
  - Different lepton decays
  - Use also inclusive decay of $\psi(2S)$ to J/ψ
- Several channels are very clean
  - Only a few signal events would hint new physics
- The $H \rightarrow Z\ J/\psi$ decay is promising for the search at HL-LHC

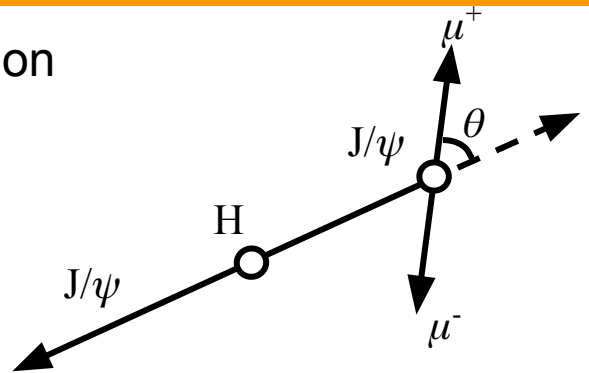
Thank you

BACKUP SLIDES

Polarization Effect: Higgs to vector boson decay

- Acceptance depends on decay angular distribution





$$P(\theta) \propto 1 + \lambda_\theta \cos^2\theta$$

Simulation with $\lambda_\theta = 0$

Transversely polarized ($\lambda_\theta = +1$)
BF upper limits increases

Longitudinally polarized ($\lambda_\theta = -1$)
BF upper limits decreases

Ref. [1-3] predict longitudinal polarization will dominate

[1] A. Likhoded and A. Luchinsky, Mod. Phys. Lett. A 33 (2018) 1850078
[2] V. Kartvelishvili, A. Luchinsky, and A. Novoselov, Phys. Rev. D 79 (2009) 114015,
[3] Seong Youl Choi, PHYSICAL REVIEW D 98, 115037 (2018)