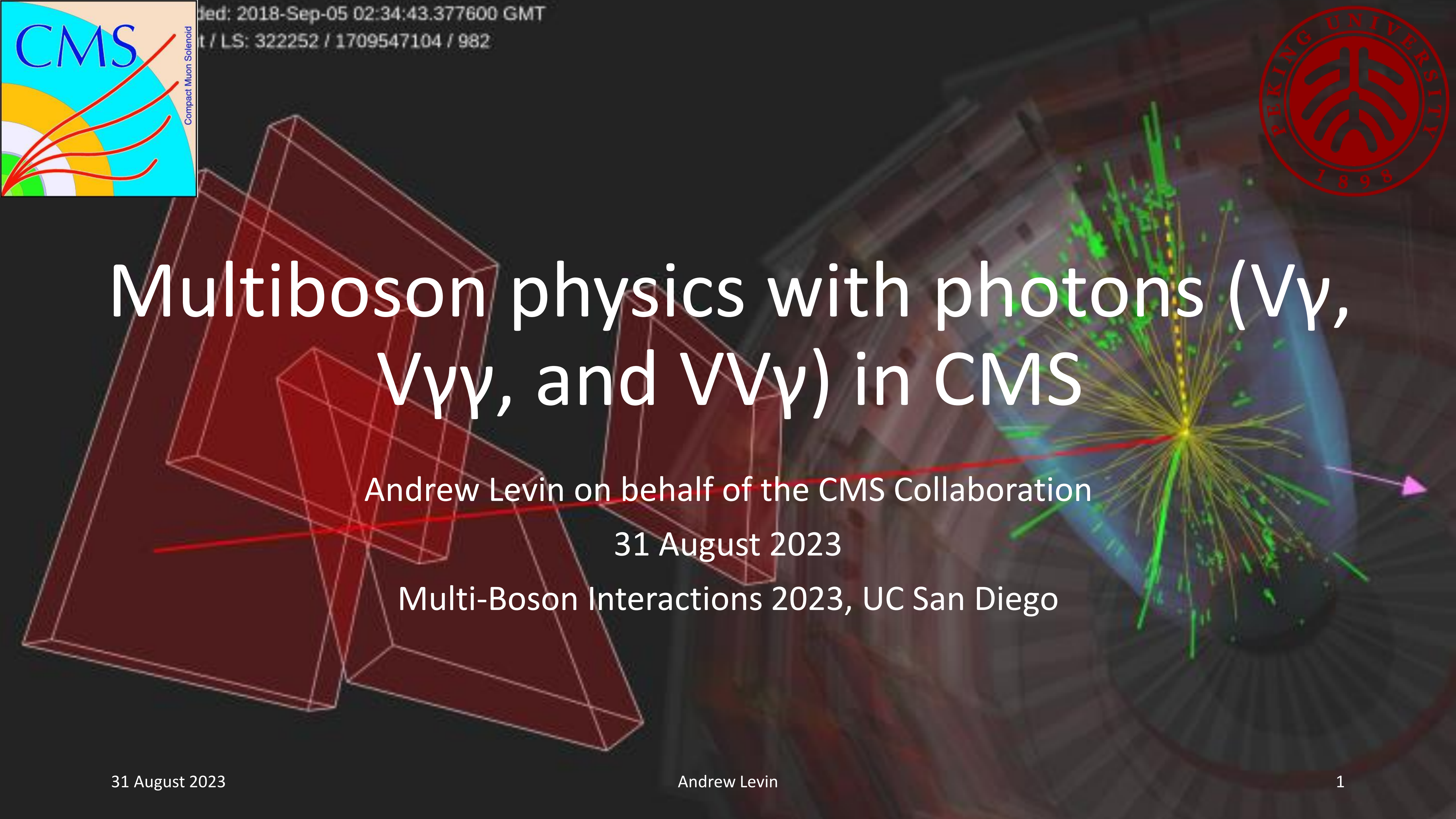


Multiboson physics with photons (Vγ, Vγγ, and VVγ) in CMS

Andrew Levin on behalf of the CMS Collaboration

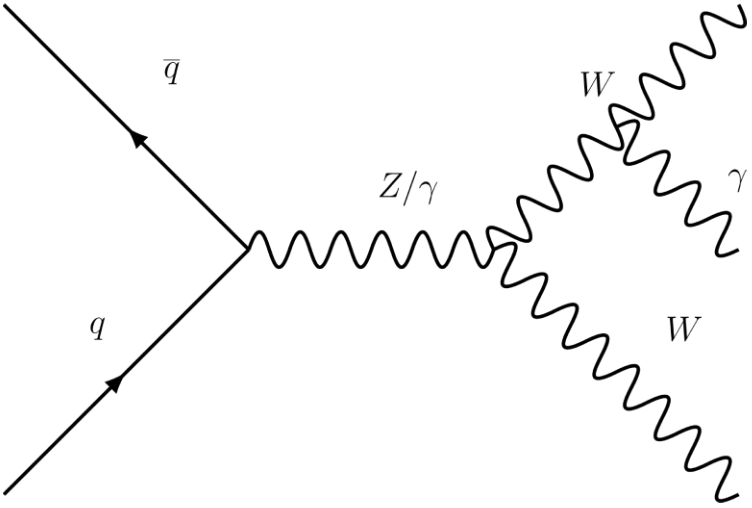
31 August 2023

Multi-Boson Interactions 2023, UC San Diego

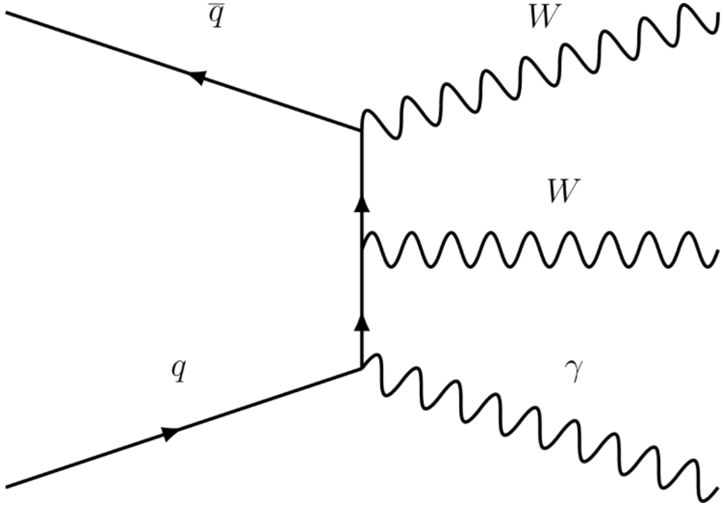
Introduction

- This talk will focus on our WWγ analysis released for Moriond 2023, based on the full 13 TeV dataset (138 fb^{-1})
- Title of preliminary result: *Observation of WWγ production and search for Hγ production generated by the coupling of the Higgs boson to light quarks*
- "WWγ" includes FSR photons
- Analysis strategy
  - Select eμ final state using double lepton high-level triggers
  - Perform WWγ measurements assuming SM for everything
  - Perform combined Hγ and WWγ assuming SM for everything else

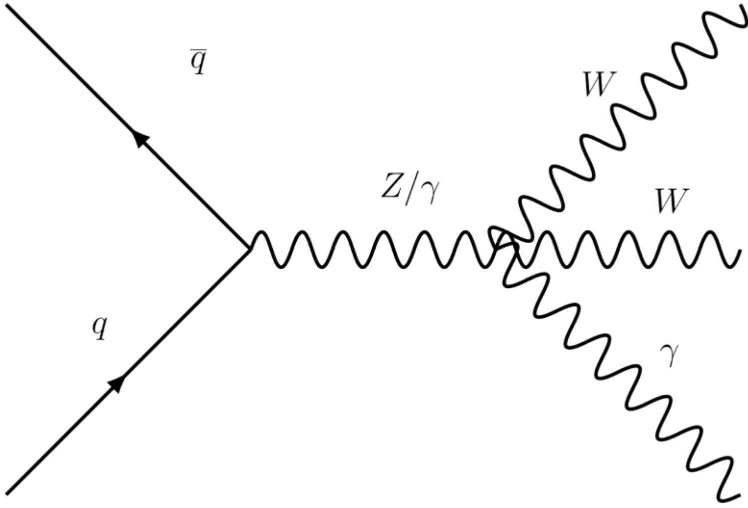
Relevant Feynman diagrams



Two triple gauge couplings (TGCs)



Initial state radiation (ISR)



Quartic gauge coupling (QGC)

Outline of rest of talk

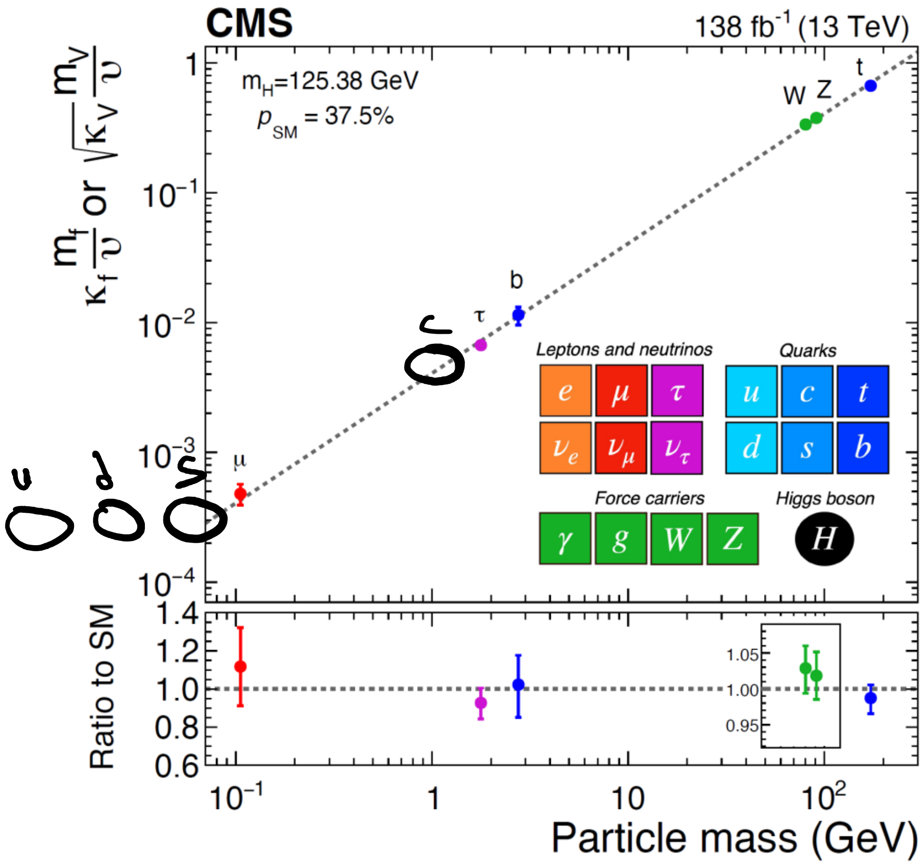
- Related experimental studies
- Theoretical background
- Signal sample generation
- Experimental methods
- WWγ results
- Hγ results
- Conclusions

Related studies (WWγ)

- Last measurement of WWγ from CMS is based on 8 TeV data and focuses on dimension 8 operator limits
- Most recent measurement of WWγ from ATLAS is also based on 8 TeV data and reports a significance of 1.4 σ (compared to 1.6 σ expected) for WVγ, where V = W/Z
- On the other hand, WZγ has been measured by ATLAS using the 13 TeV data, with an observed significance of 5.0 σ (compared with 6.3 σ expected)
- No ZZγ results from either collaboration

Related studies (Higgs to u/d/s/c couplings)

- Direct Higgs-charm coupling analysis from ATLAS based on VH production
  - $|\kappa_c| < 8.5$ observed, $|\kappa_c| < 12.4$ expected
- Direct Higgs-charm coupling analysis from CMS based on VH production
  - $1.1 < |\kappa_c| < 5.5$ observed, $|\kappa_c| < 3.4$ expected

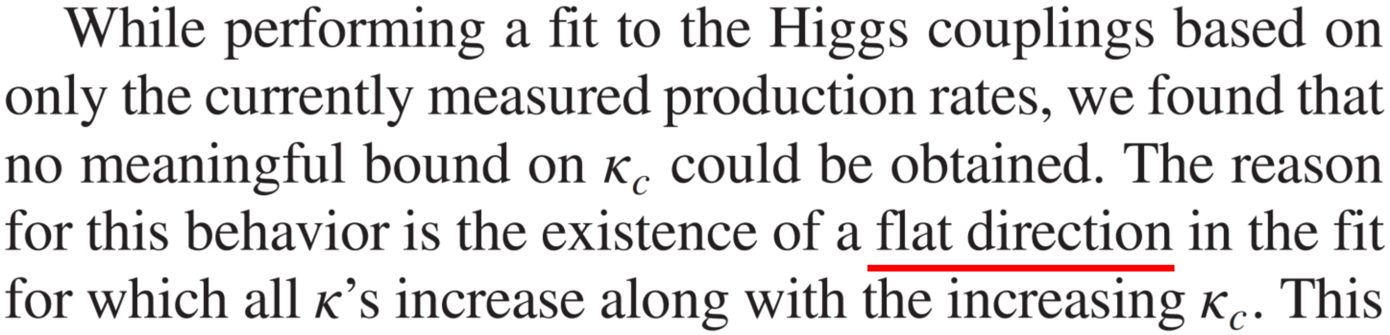


κ framework analysis

- The κ framework scales Higgs coupling strengths without modifying the tensor structure
- κ_X scales the coupling of the Higgs to X, where X can be W, Z, γ, V, etc.
- $\kappa_X = 1$ for all X in the SM
- Moving a single κ_X away from 1 affects other Higgs measurements
- We use the “flat direction” method, which preserves the cross section times branching fraction for all other Higgs processes
- Method does not preserve total Higgs width
- Proper way would be to redo global fit (way too computing intensive)

Flat direction scenario

- The term “flat direction” comes from a 2019 paper by Coyle, Wagner, and Wei:



While performing a fit to the Higgs couplings based on only the currently measured production rates, we found that no meaningful bound on κ_c could be obtained. The reason for this behavior is the existence of a flat direction in the fit for which all κ’s increase along with the increasing κ_c. This

- $\text{yield} = \dfrac{\kappa_q^2\kappa_H^2}{\left(1 - \mathrm{BR}(H\to qq)\right)\kappa_H^2 + \mathrm{BR}(H\to qq)\kappa_q^2}$

where

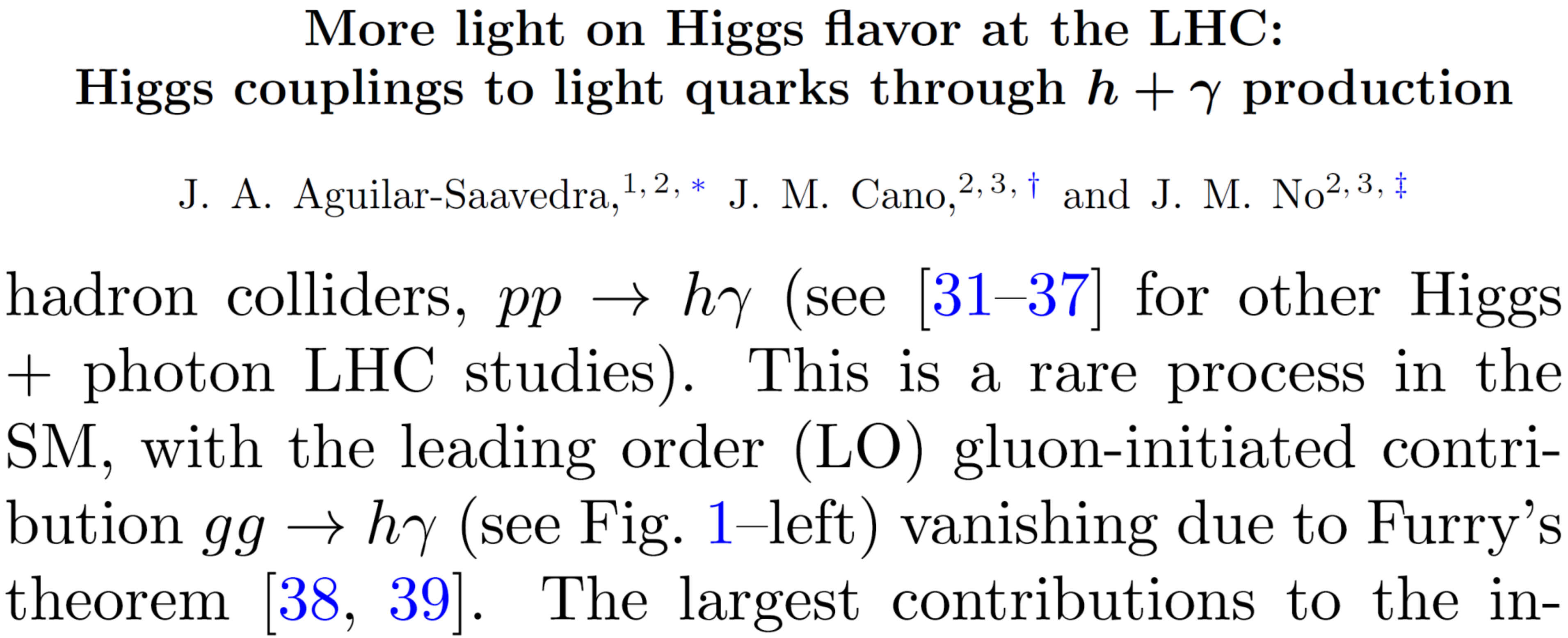
$$\kappa_H^2 = \left(1 - \mathrm{BR}(H\to qq) + \sqrt{(1 - \mathrm{BR}(H\to qq))^2 + 4\cdot \mathrm{BR}(H\to qq)\kappa_q^2}\right)/2$$

BR(H → uu) = 10^{-8}, BR(H → dd) = 10^{-8}, BR(H → ss) = 0.000246, BR(H → cc) = 0.029

Signal sample generation

- Generated with MadGraph_aMC@NLO
  - use loop_sm model
  - generate p p > e+ ve mu- vm~ a [QCD]
  - add process p p > mu+ vm e- ve~ a [QCD]
  - min p_T = 10 GeV
- For cc → Hγ signal
  - use model based on loop_sm that takes into account the running of the c quark mass
  - generate cc → h a [QCD]
  - decay the Higgs boson using JHU generator
  - min p_T = 5 GeV
- For other qq → Hγ (where q = u, d, s) signal
  - use Higgs Effective Lagrangian model (HEL)
  - generate qq → h a NP == 0
  - decay the Higgs boson using the JHU generator
  - min p_T = 5 GeV

Main theory reference for Hγ part of analysis



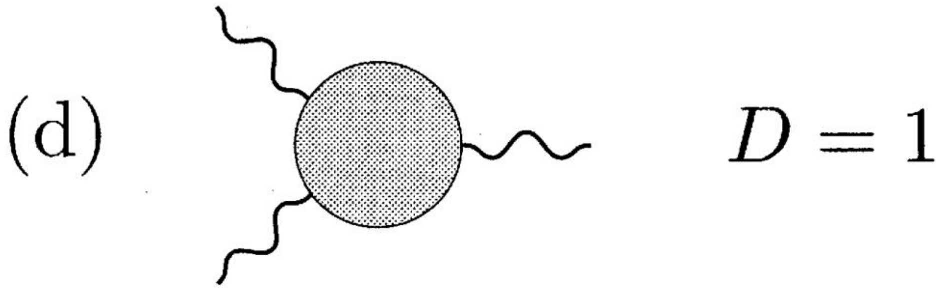
More light on Higgs flavor at the LHC:
Higgs couplings to light quarks through $h + \gamma$ production

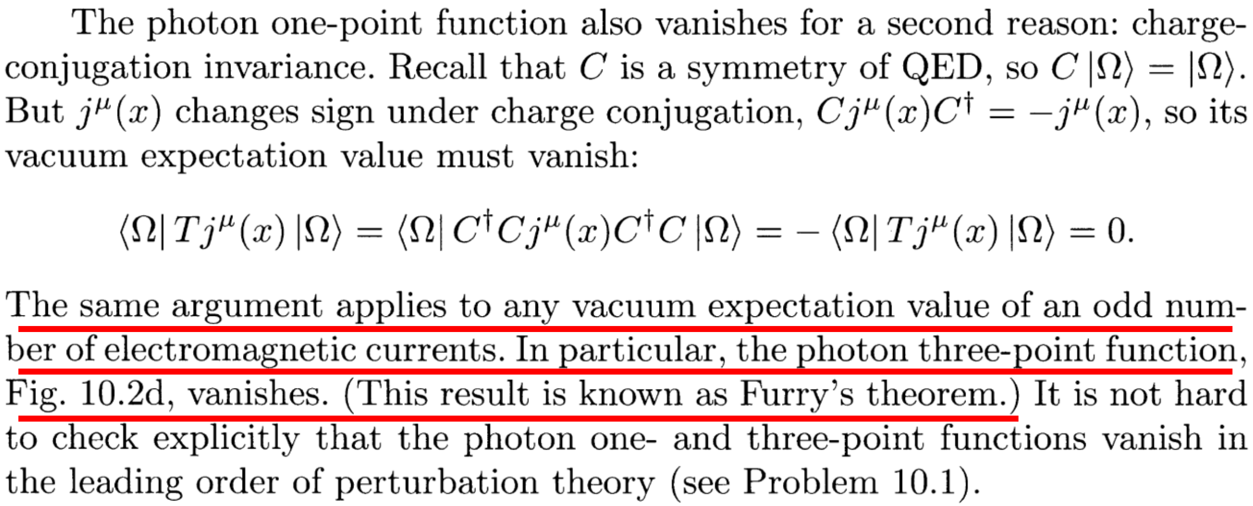
J. A. Aguilar-Saavedra,[1, 2, *] J. M. Cano,[2, 3, †] and J. M. No[2, 3, ‡]

hadron colliders, $pp \to h\gamma$ (see [31–37] for other Higgs + photon LHC studies). This is a rare process in the SM, with the leading order (LO) gluon-initiated contribution $gg \to h\gamma$ (see Fig. 1–left) vanishing due to Furry's theorem [38, 39]. The largest contributions to the in-

arxiv:2008.12538

Furry’s theorem



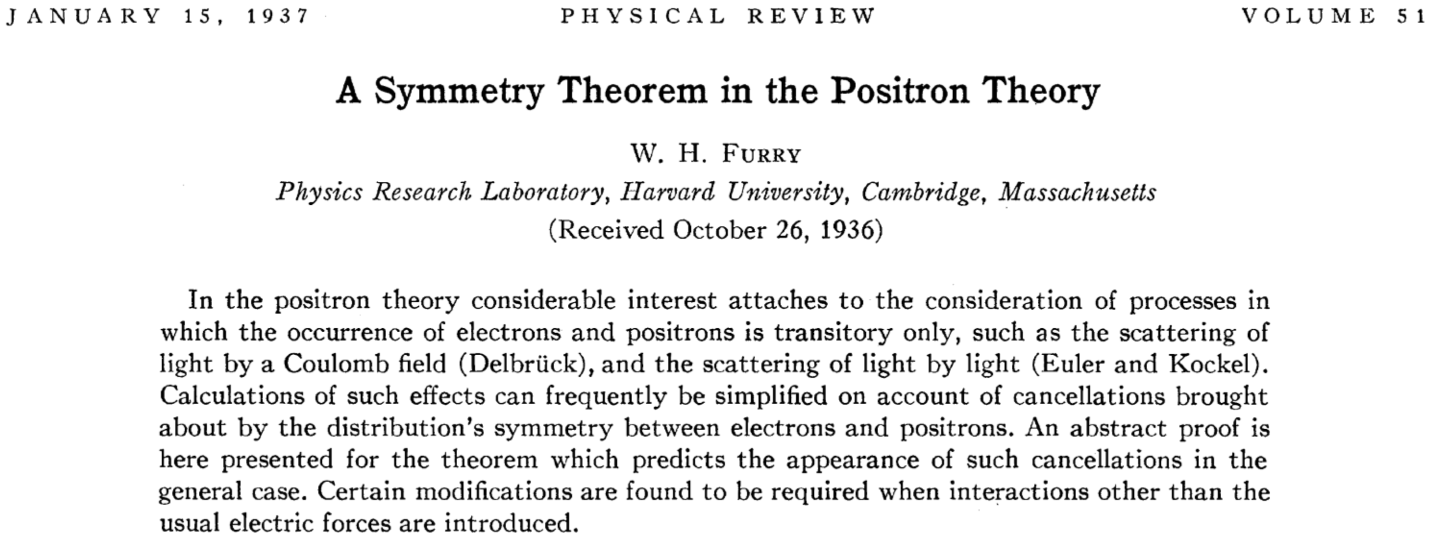


The photon one-point function also vanishes for a second reason: charge-conjugation invariance. Recall that C is a symmetry of QED, so $C\left|\Omega\right\rangle = \left|\Omega\right\rangle$. But $j^\mu(x)$ changes sign under charge conjugation, $Cj^\mu(x)C^\dagger = -j^\mu(x)$, so its vacuum expectation value must vanish:

$$\left\langle\Omega\right| Tj^\mu(x) \left|\Omega\right\rangle = \left\langle\Omega\right| C^\dagger C j^\mu(x) C^\dagger C \left|\Omega\right\rangle = -\left\langle\Omega\right| Tj^\mu(x) \left|\Omega\right\rangle = 0.$$

The same argument applies to any vacuum expectation value of an odd number of electromagnetic currents. In particular, the photon three-point function, Fig. 10.2d, vanishes. (This result is known as Furry’s theorem.) It is not hard to check explicitly that the photon one- and three-point functions vanish in the leading order of perturbation theory (see Problem 10.1).

Source: *An Introduction to Quantum Field Theory* by Peskin and Schroeder



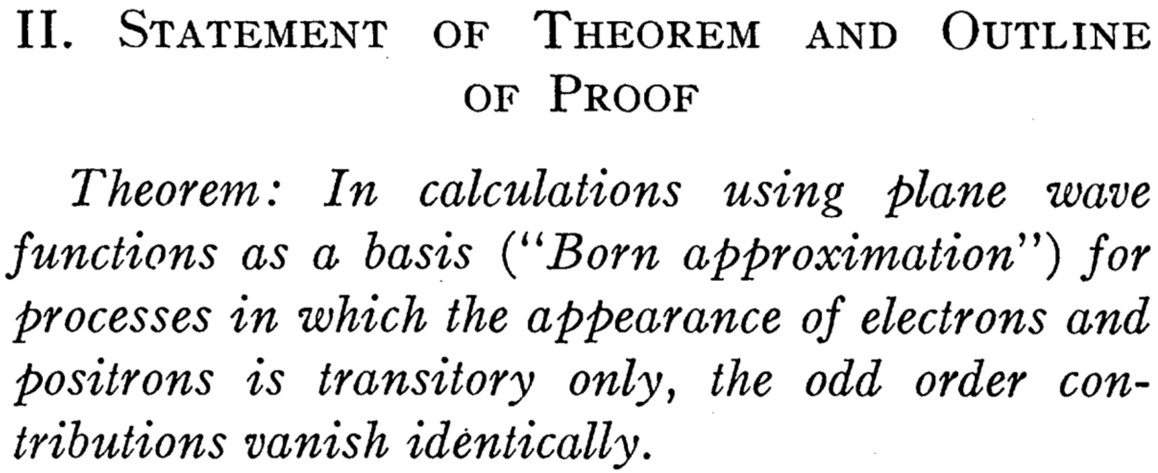
JANUARY 15, 1937 PHYSICAL REVIEW VOLUME 51

A Symmetry Theorem in the Positron Theory

W. H. FURRY
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts

(Received October 26, 1936)

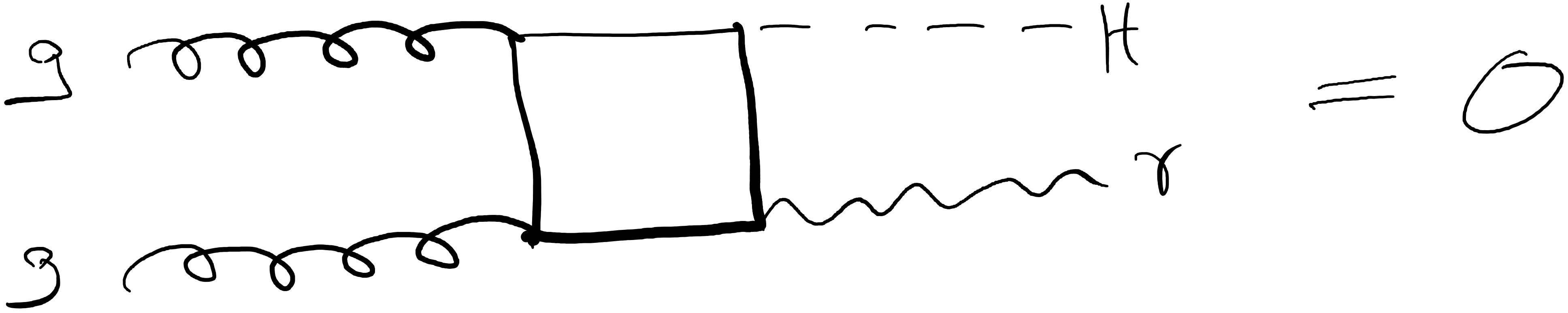
In the positron theory considerable interest attaches to the consideration of processes in which the occurrence of electrons and positrons is transitory only, such as the scattering of light by a Coulomb field (Delbrück), and the scattering of light by light (Euler and Kockel). Calculations of such effects can frequently be simplified on account of cancellations brought about by the distribution’s symmetry between electrons and positrons. An abstract proof is here presented for the theorem which predicts the appearance of such cancellations in the general case. Certain modifications are found to be required when interactions other than the usual electric forces are introduced.

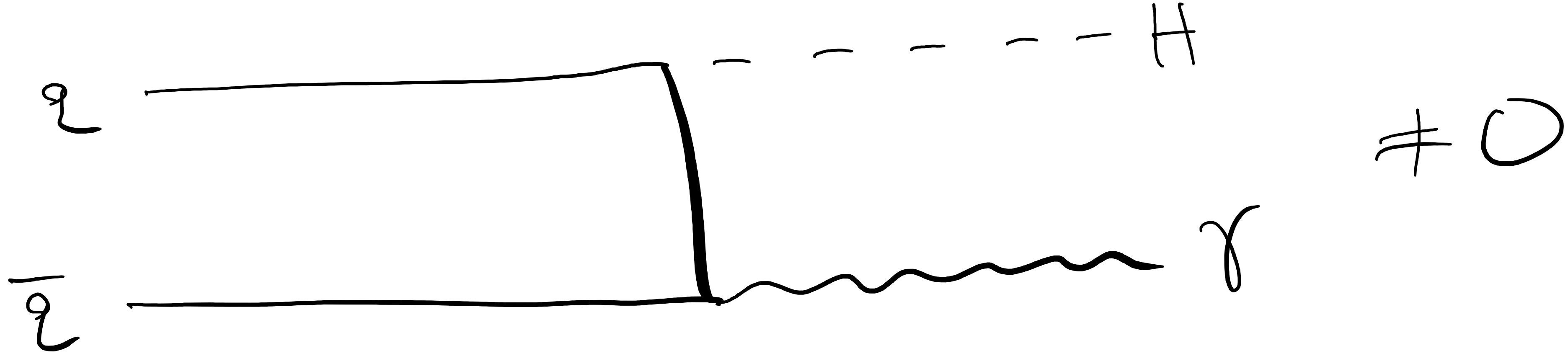


II. STATEMENT OF THEOREM AND OUTLINE OF PROOF

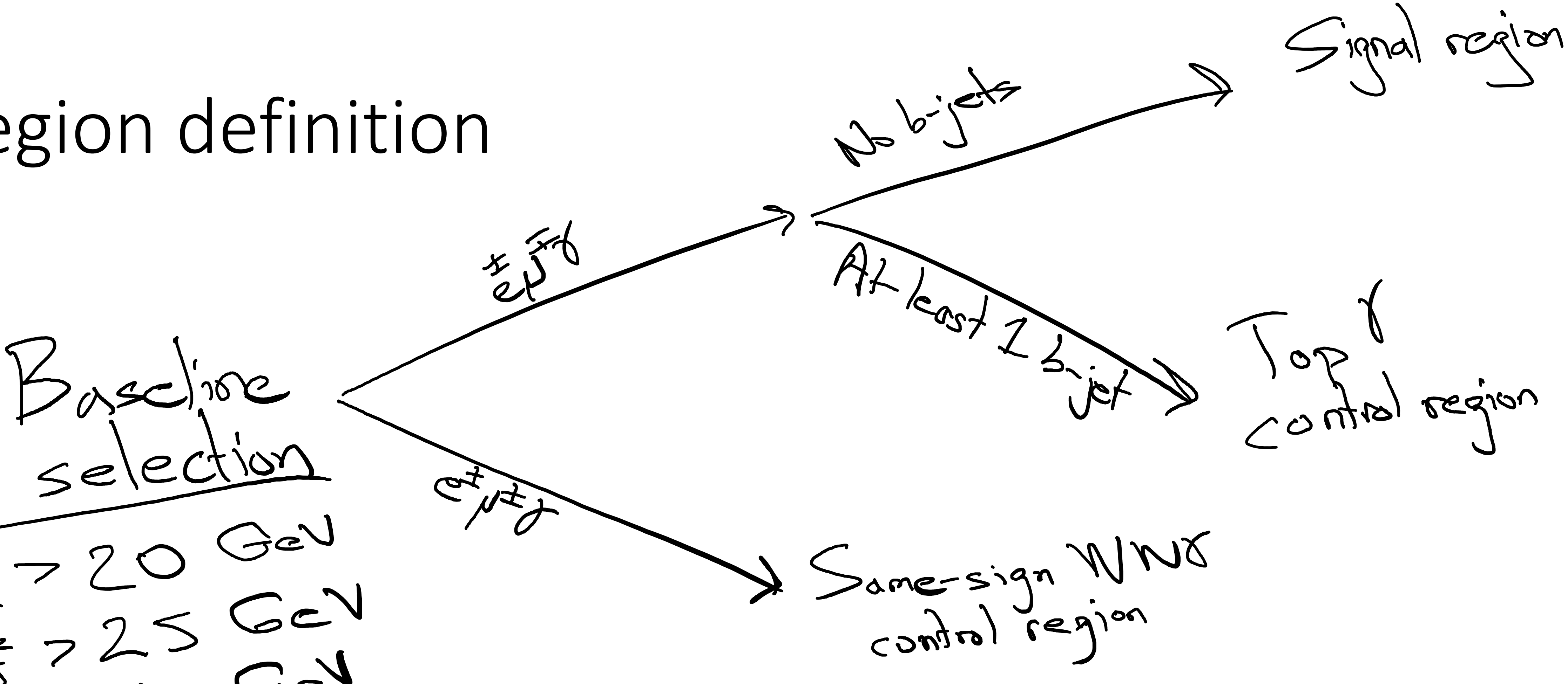
Theorem: In calculations using plane wave functions as a basis (“Born approximation”) for processes in which the appearance of electrons and positrons is transitory only, the odd order contributions vanish identically.

Application of Furry’s theorem to pp → Hγ





Region definition

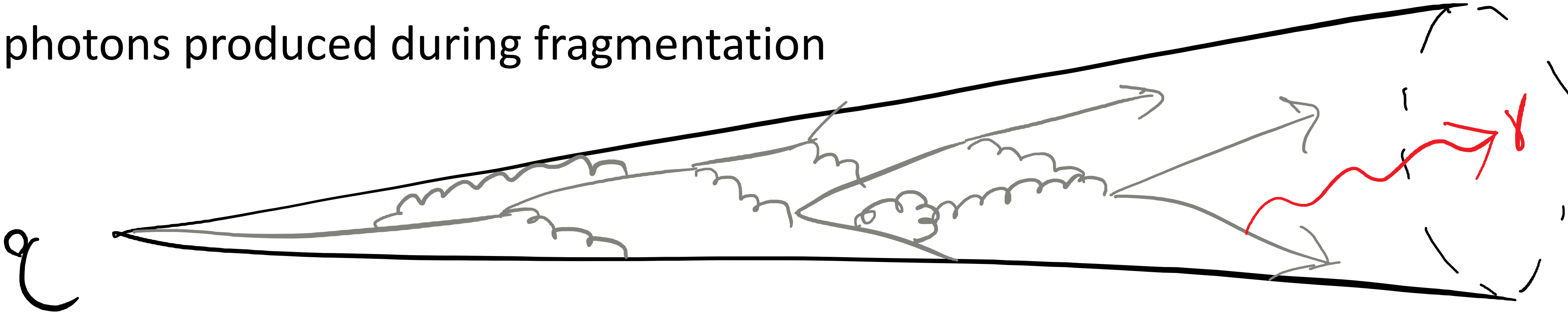


- $p_T^\mu > 20$ GeV
- $p_T^e > 25$ GeV
- $m_{\ell\ell} > 10$ GeV
- $p_T^{\ell\ell} > 15$ GeV
- $p_T^\gamma > 20$ GeV
- MET > 20 GeV

Non-prompt photon sources

- Includes both instrumental and genuine photons produced during fragmentation
  - Instrumental

  - Genuine photons produced during fragmentation

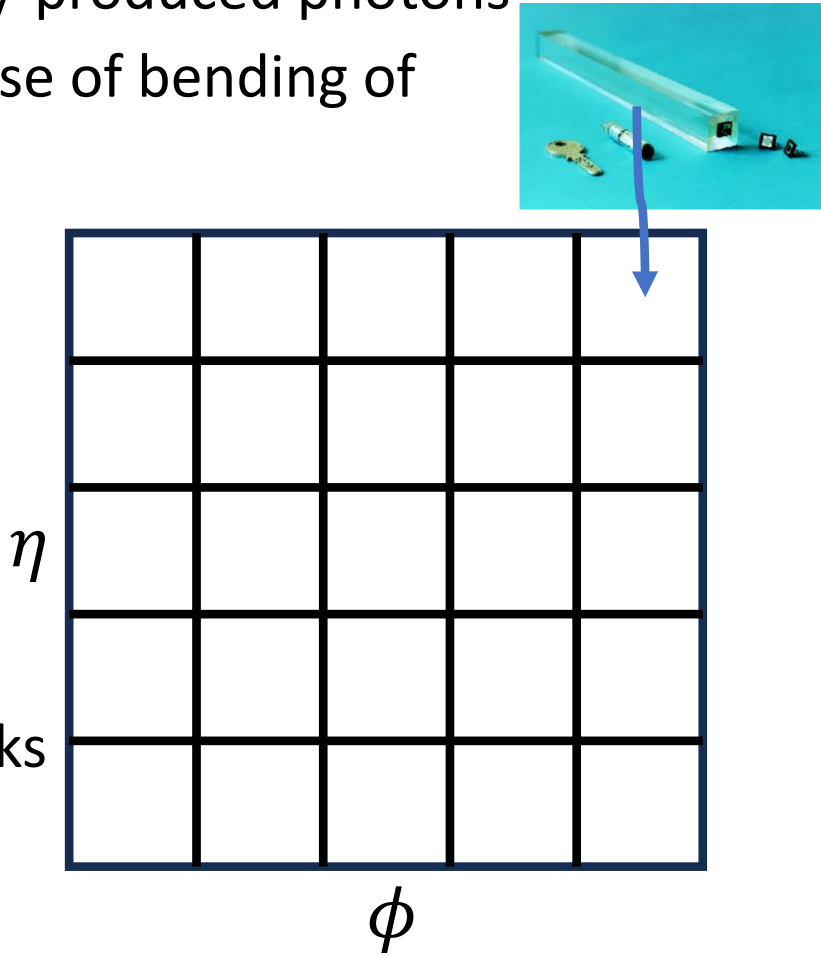


Method to estimate non-prompt photons

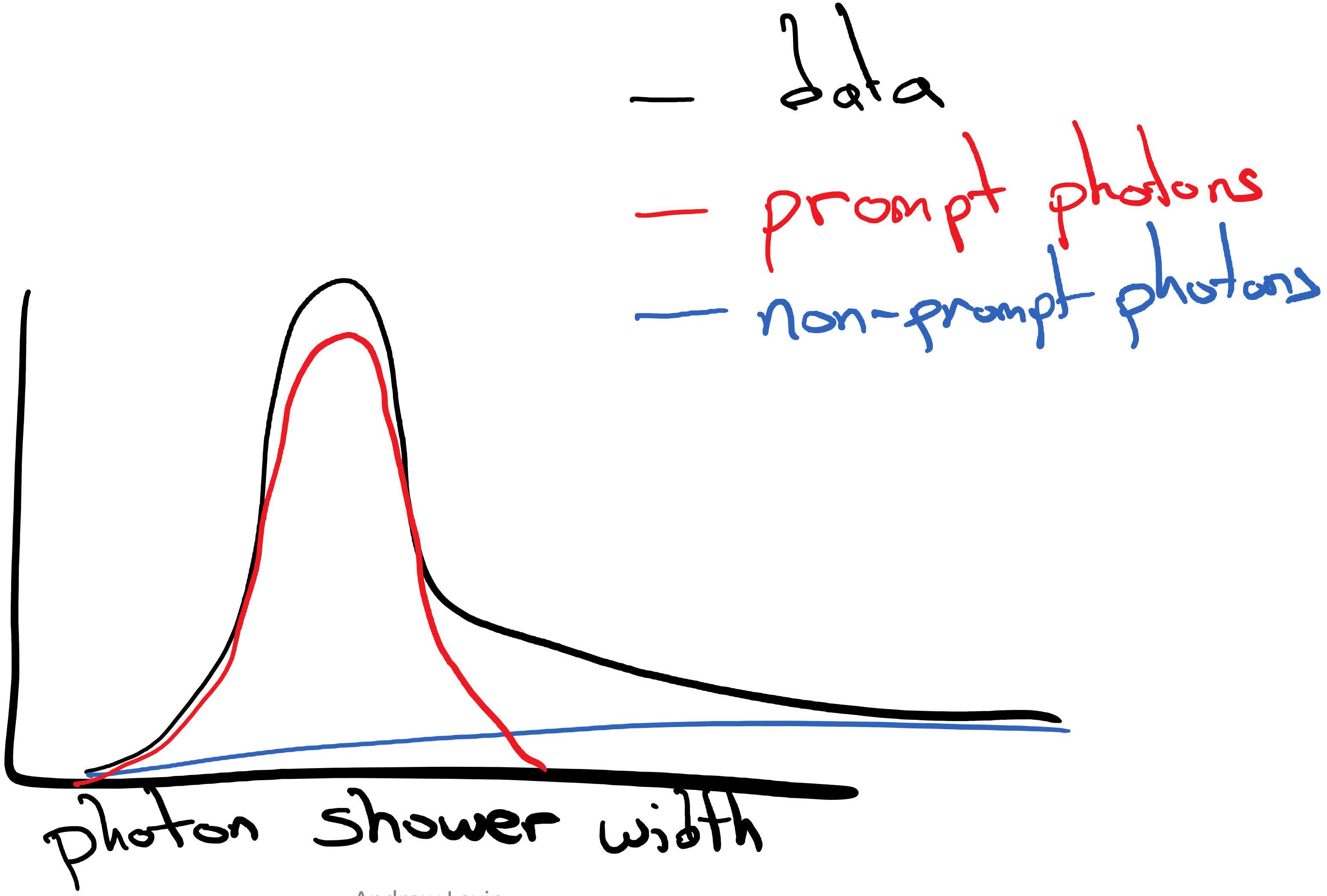
- Our non-prompt photon background estimate is based on per-photon factors: $\text{rate}_{\text{our } \gamma \text{ selection}}/\text{rate}_{\text{mutually exclusive } \gamma \text{ selection}}$
- These factors are calculated in Z(→ee)+jets events
- The method relies on two variables to obtain the numerator:
  - A relative isolation variable (where the isolation sum is restricted to charged particles, as defined using the particle flow algorithm, cone size = 0.3)
  - A variable that quantifies the transverse spread of the photon's electromagnetic shower
- We use a sideband of the first variable to obtain the shape of the second variable for non-prompt photons, and then perform a fit of the prompt and non-prompt fractions
- Assumes the variables are independent, systematic uncertainties are applied to cover the extent this is not true

Photon shower width variable

- π^0 decays deposit energy over broader area than promptly-produced photons
- Width of photon shower is different in and η and ϕ because of bending of bremsstrahlung/conversion legs in magnetic field
- $\sigma_{\eta\eta}^2 = \frac{\sum_i^{5\times5} w_i(\eta_i - \eta_{5\times5})^2}{\sum_i^{5\times5} w_i}$
  - $\eta_i = \text{pseudorapidity of the ith crystal within the } 5\times5 \text{ cluster}$
  - $\eta_{5\times5} = \text{pseudorapidity of the entire } 5\times5 \text{ cluster}$
  - $w_i = \max\left(0, 4.7 + \log {}^{E_i}/_{E_{5\times5}}\right)$
  - $E_i = \text{energy of the ith crystal within the } 5\times5 \text{ cluster}$
  - $E_{5\times5} = \text{energy of entire } 5\times5 \text{ cluster}$
- Discrete sum found to have better performance near cracks

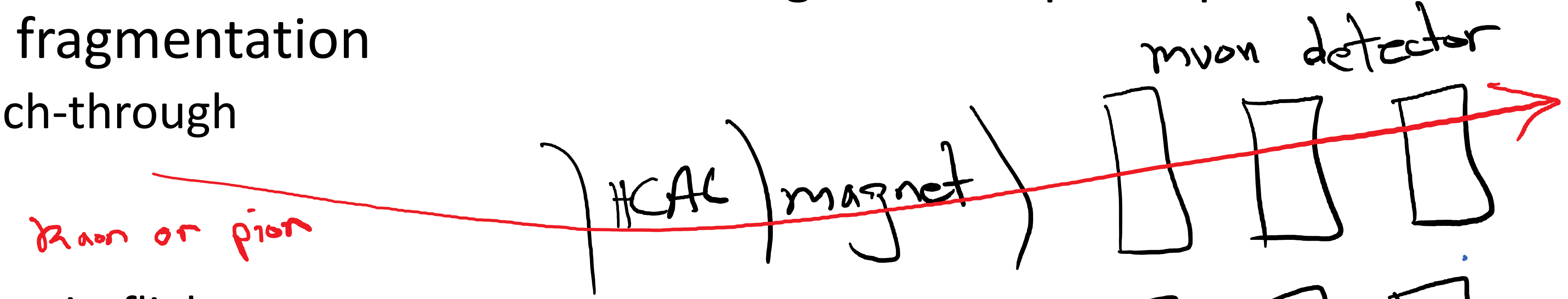


Schematic of fit to photon shower width

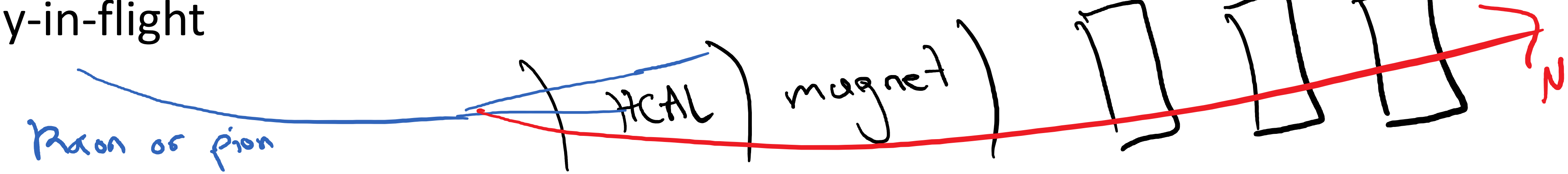


Non-prompt lepton sources

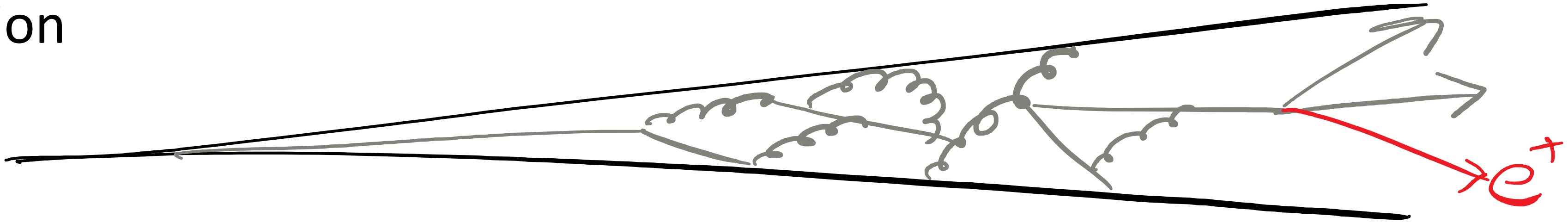
- Again includes both instrumental and genuine leptons produced during fragmentation
  - Punch-through



  - Decay-in-flight



  - Fragmentation



Non-prompt lepton estimate

- Similar to the non-prompt estimate, our non-prompt lepton background estimate is based on per-lepton factors: $\text{rate}_{\text{our lepton selection}}/\text{rate}_{\text{mutually exclusive lepton selection}}$
- However, one difference is that the nonprompt lepton background includes both single and double fake lepton events (we assume that the two factorize)
- The mutually exclusive lepton selection involves adjusting the isolation or quality requirements (such as on the number of hits or the electromagnetic shower width)
- The per-lepton factors are calculated as a function of lepton η and p_T in a region with one lepton and low missing energy and transverse mass

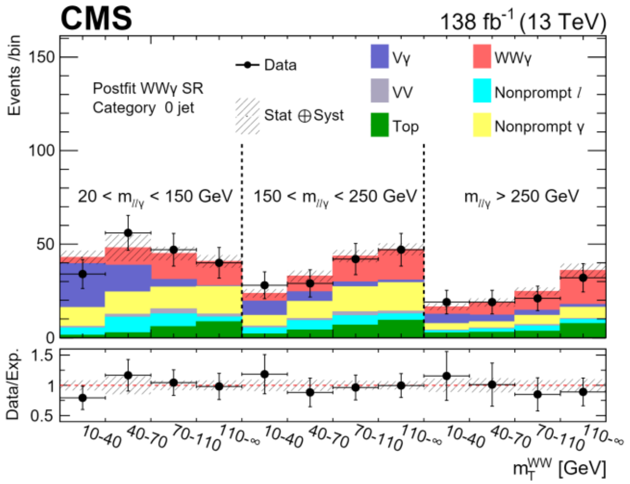
Fitting strategy

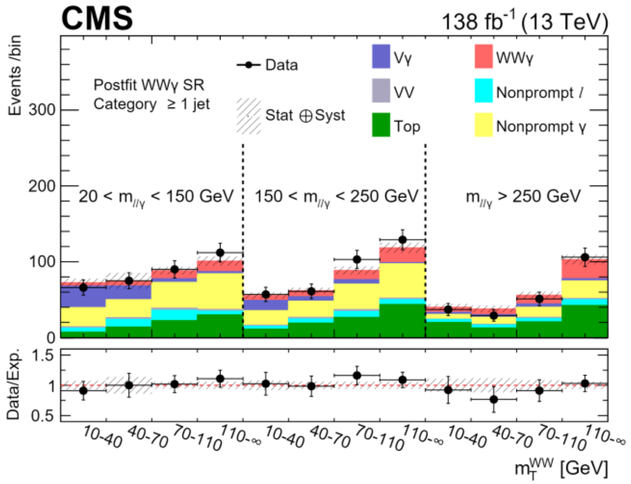
- Perform a simultaneous fit of the signal region and the two control regions
- For WWγ signal extraction: WWγ and top background normalizations are freely floating
- For Hγ signal extraction: Hγ, WWγ, and top background normalizations are freely floating
- Binning
  - Topγ CR: single bin
  - SSWWγ CR: 4 m_T bins ([0,40,70,110,∞] GeV)
  - SR: 4 m_T bins ([0,40,70,110,∞] GeV) × 3 $m_{ll\gamma}$ bins ([20,150,250,∞] GeV) × 2 jet bins (0 or ≥ 1 jet with p_T > 20 GeV)

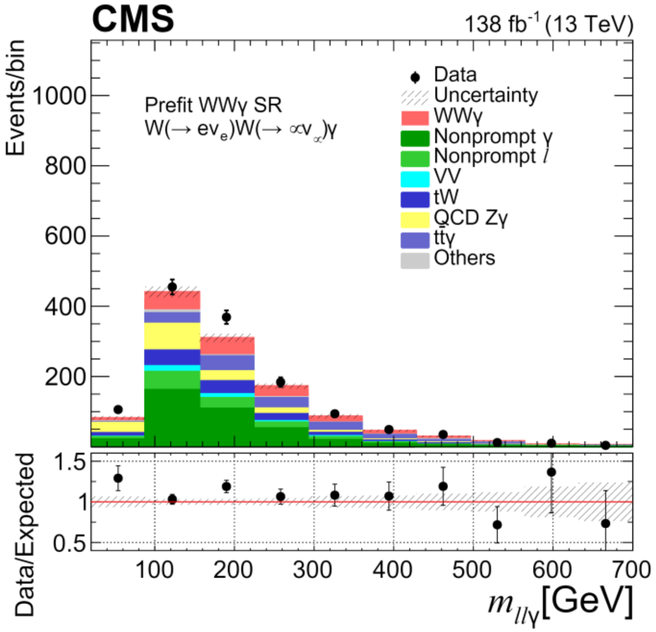
Composition of signal and control regions

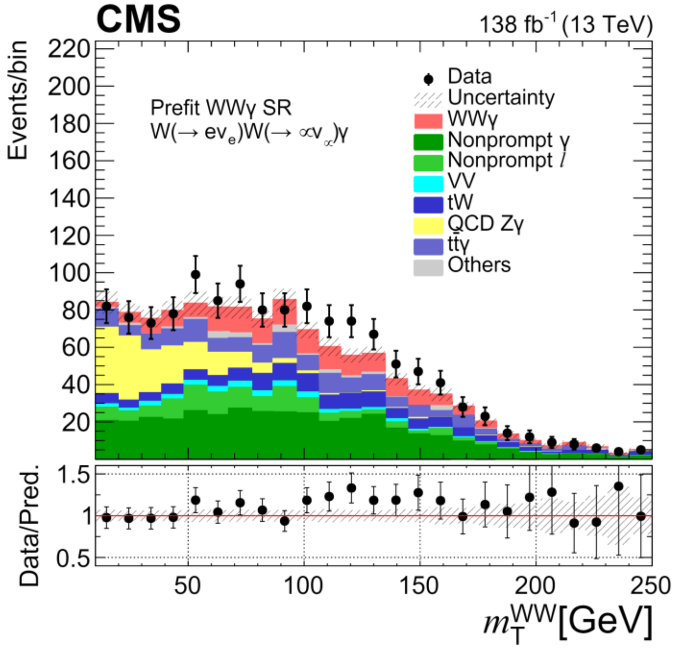
Process	Signal region	SSWWγ CR	Topγ CR
WWγ	254 ± 47	1.0 ± 0.2	12.8 ± 2.7
QCD Vγ	167 ± 14	12.2 ± 2.2	12.6 ± 1.2
VV	36.7 ± 3.5	24.9 ± 1.7	2.0 ± 0.3
Top	328 ± 32	2.4 ± 0.6	2434 ± 85
Nonprompt l	122.9 ± 9.7	197 ± 14	40 ± 11
Nonprompt γ	410 ± 32	19.9 ± 1.6	793 ± 62
Total	1318 ± 43	257 ± 14	3294 ± 57
Data	1330	259	3287

Signal region







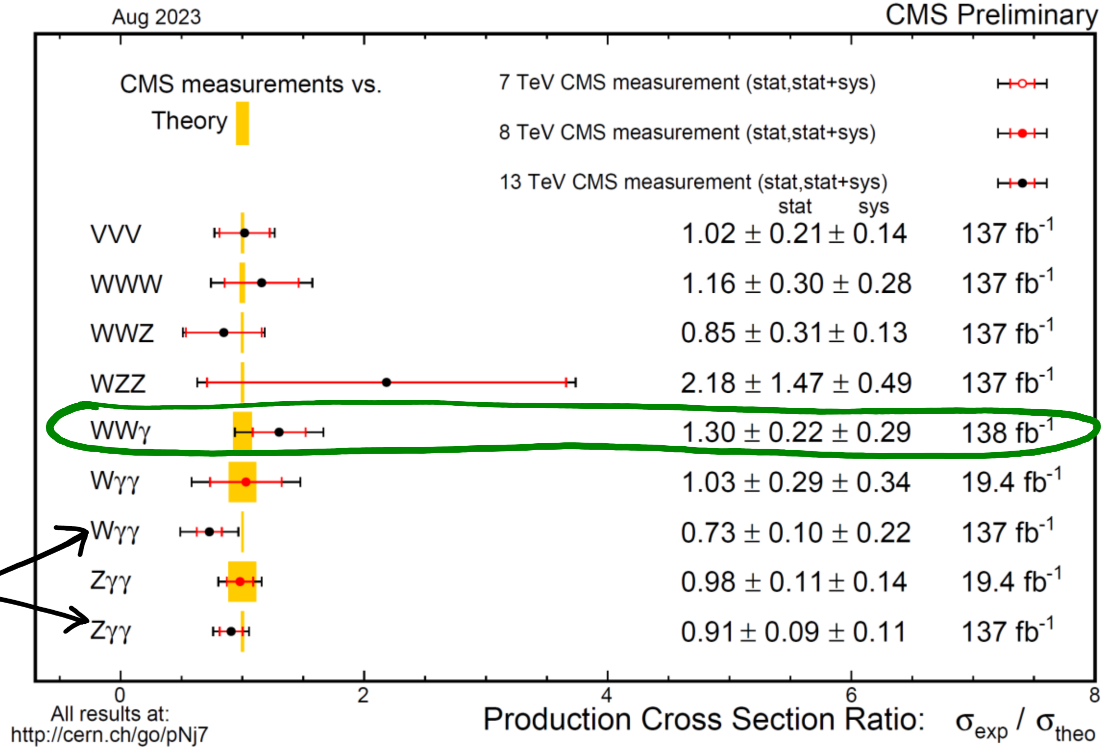


WWγ significance and cross section

- Observed (expected) significance for WWγ signal: 5.6 (4.7) σ
- Fiducial cross section measurement: 6.0 ± 0.7 (stat) ± 0.8 (syst) ± 0.6 (modeling) fb = 6.0 ± 1.2 fb
- MG5_aMC NLO-QCD prediction:

4.61 ± 0.34 (scale) ± 0.05 (PDF) fb

- Fiducial region definition
  - $p_T^e > 25$ GeV, $|\eta^e| < 2.5$
  - $p_T^\mu > 20$ GeV, $|\eta^\mu| < 2.4$
  - $m_{ll} > 10$ GeV
  - $p_T^{ll} > 15$ GeV
  - $p_T^\gamma > 20$ GeV
  - ΔR(l,γ) > 0.5, ΔR(l,l) > 0.5



From 2021

u/d/s/c cross section and κ framework limits

process	**obs (exp) limit on xs**	**obs (exp) limit on $\lvert\kappa_q\rvert$**	**obs (exp) limit on $\left\lvert {y_q}/{y_b^{SM}} \right\rvert$**
$uu \rightarrow H+\gamma \rightarrow e\mu\nu_e\nu_\mu\gamma$	85 (67) fb	16000 (13000)	Not yet public
$dd \rightarrow H+\gamma \rightarrow e\mu\nu_e\nu_\mu\gamma$	72 (58) fb	17000 (14000)	Not yet public
$cc \rightarrow H+\gamma \rightarrow e\mu\nu_e\nu_\mu\gamma$	68 (49) fb	1700 (1300)	Not yet public
$ss \rightarrow H+\gamma \rightarrow e\mu\nu_e\nu_\mu\gamma$	87 (67) fb	200 (110)	Not yet public

Conclusions

- Reported first observation of the process pp → WWγ
- Main results
  - Observed (expected) significance: 5.6 (4.7) standard deviations
  - Measured fiducial cross section: 6.0 ± 0.7 (stat) ± 0.8 (syst) ± 0.6 (modeling) fb
  - Limits on Higgs couplings to light quarks based on pp → Hγ → WWγ
- Paper in final stages before submission
- Working on both HepData entry and Rivet routine