Summary Talk

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Michigan State/UC San Diego
August 30, 2018

Thanks to all the speakers!

Multi-Boson Interactions

- Gauge Invariance & Boson Self-Couplings
- Electroweak Symmetry Breaking
- VBS
- DiBosons
- EFT
- Resonances and Simplified Models
- VBS redux - HL-LHC in the Era of Precision
- Lessons and Questions

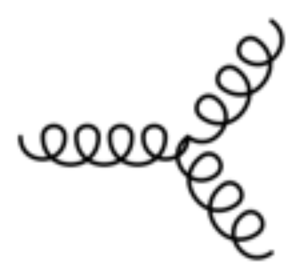
MBIs Intrinsic to Non-Abelian Theories

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \bar{\psi}(i\gamma_\mu D^\mu - m)\psi$$ **with** $$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f_{abc} A^b_\mu A^c_\nu$$

Leads to EOM: $$\partial^\mu G^a_{\mu\nu} = -g f_{abc} A^\mu_b G^c_{\mu\nu} - g\bar{\psi}\gamma_\nu t^a \psi$$

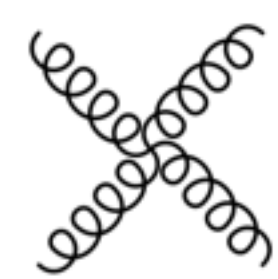
Contributes to color charge!

$$\mathcal{L}^{(3)} = -\frac{g}{2} f_{abc} \left(\partial^\mu A^\nu_a - \partial^\nu A^\mu_a\right) A^b_\mu A^c_\nu$$



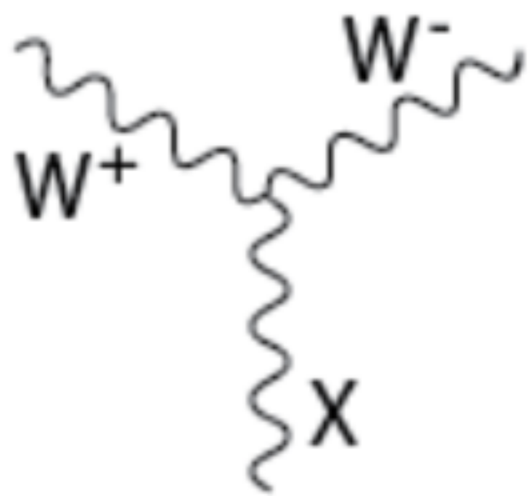
$\sim g$

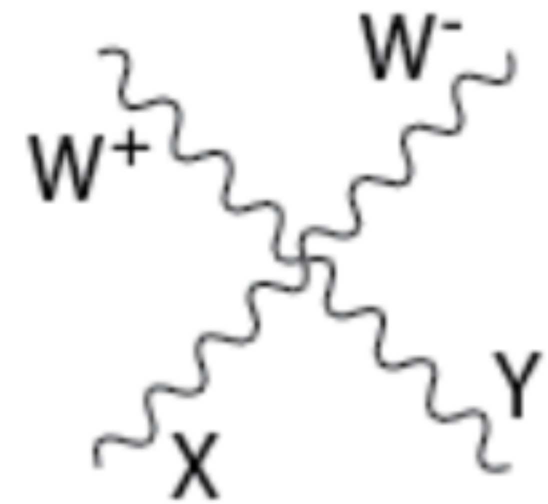
$$\mathcal{L}^{(4)} = -\frac{g^2}{4} f_{abc} f_{cde} A_{a\mu} A_{b\nu} A^\mu_c A^\nu_d$$



$\sim g^2$

Electroweak Tree-Level MBIs



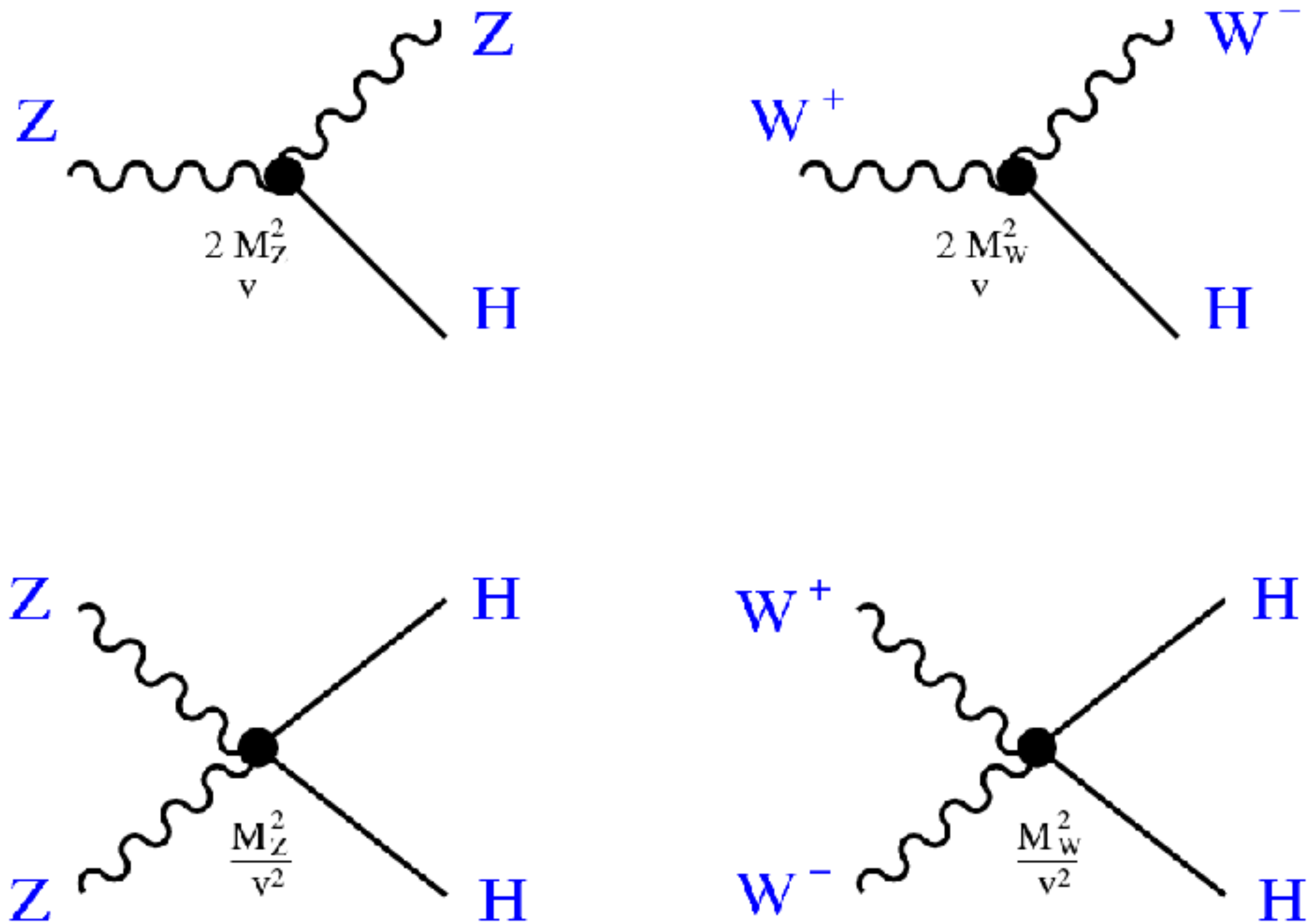


X = γ or Z

XY = γγ, ZZ, or W^+W^-

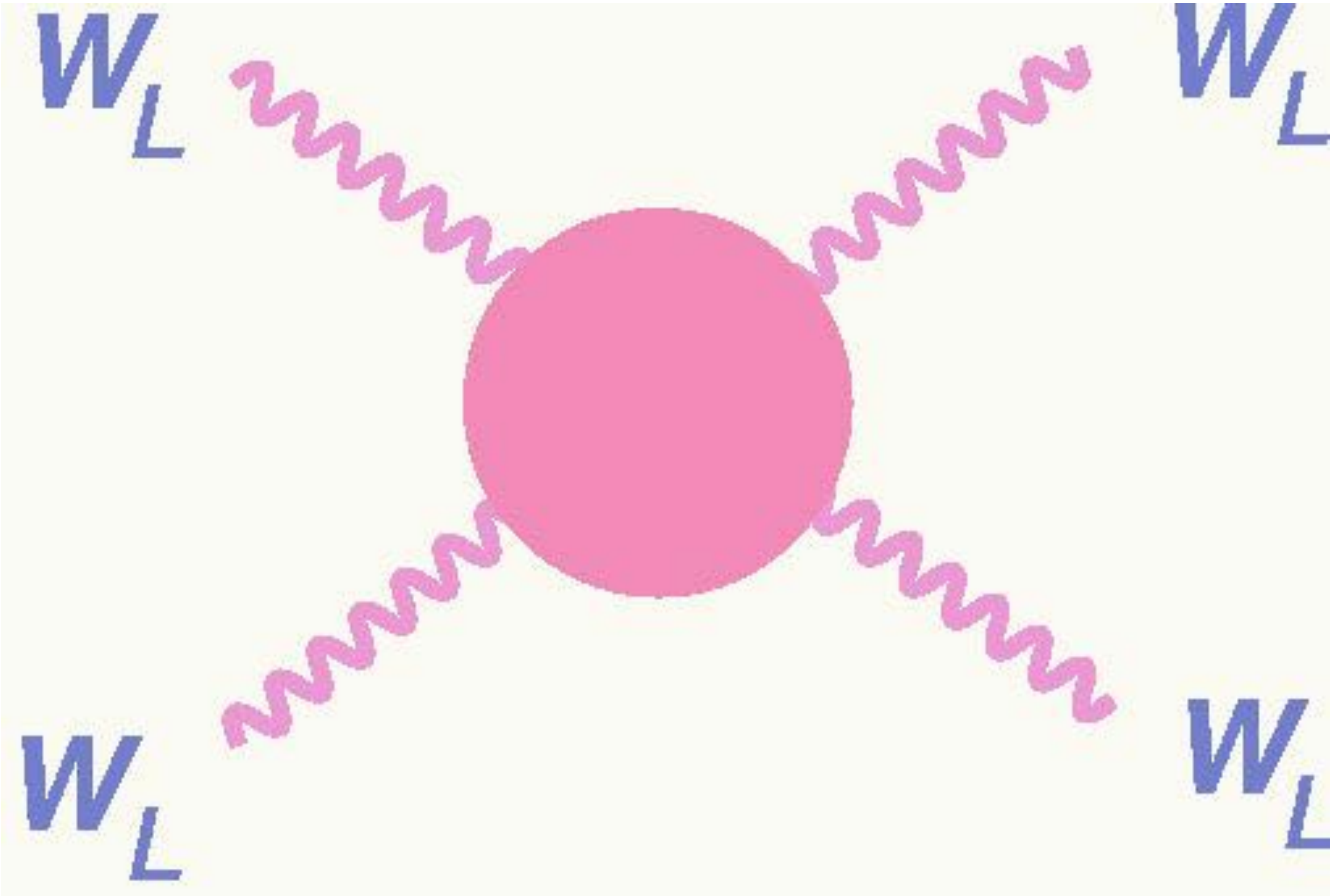
Coupling Strengths related to Fermion couplings…

EWSB: Higgs-VB Couplings

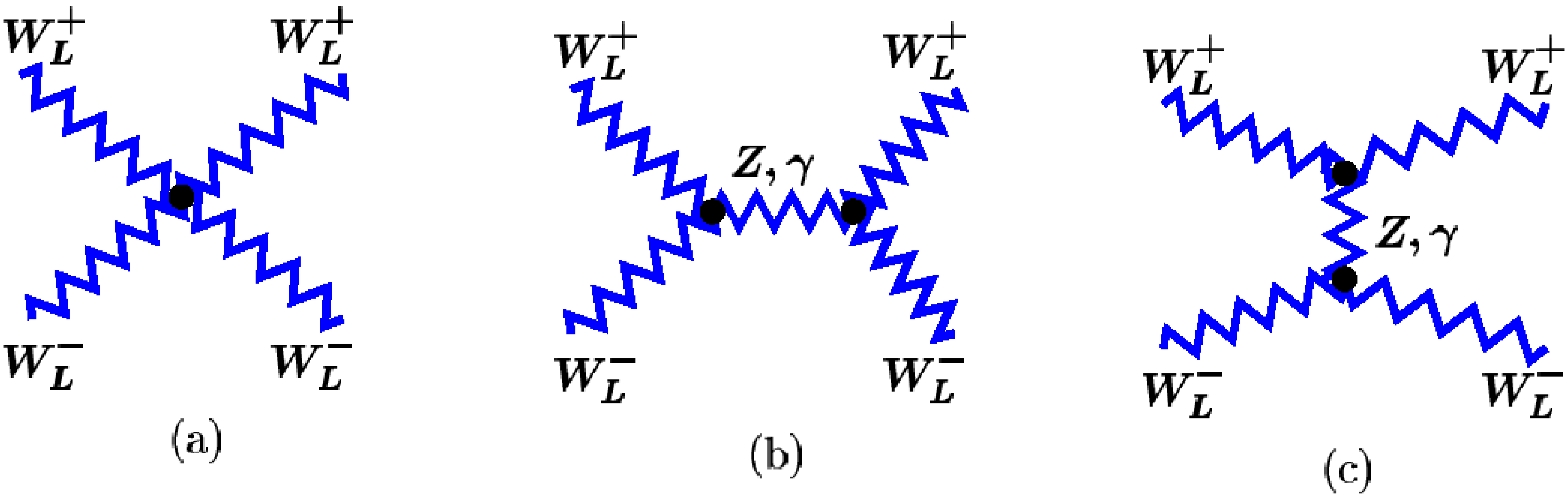


Electroweak Symmetry Breaking

Consider Loss of Unitarity in



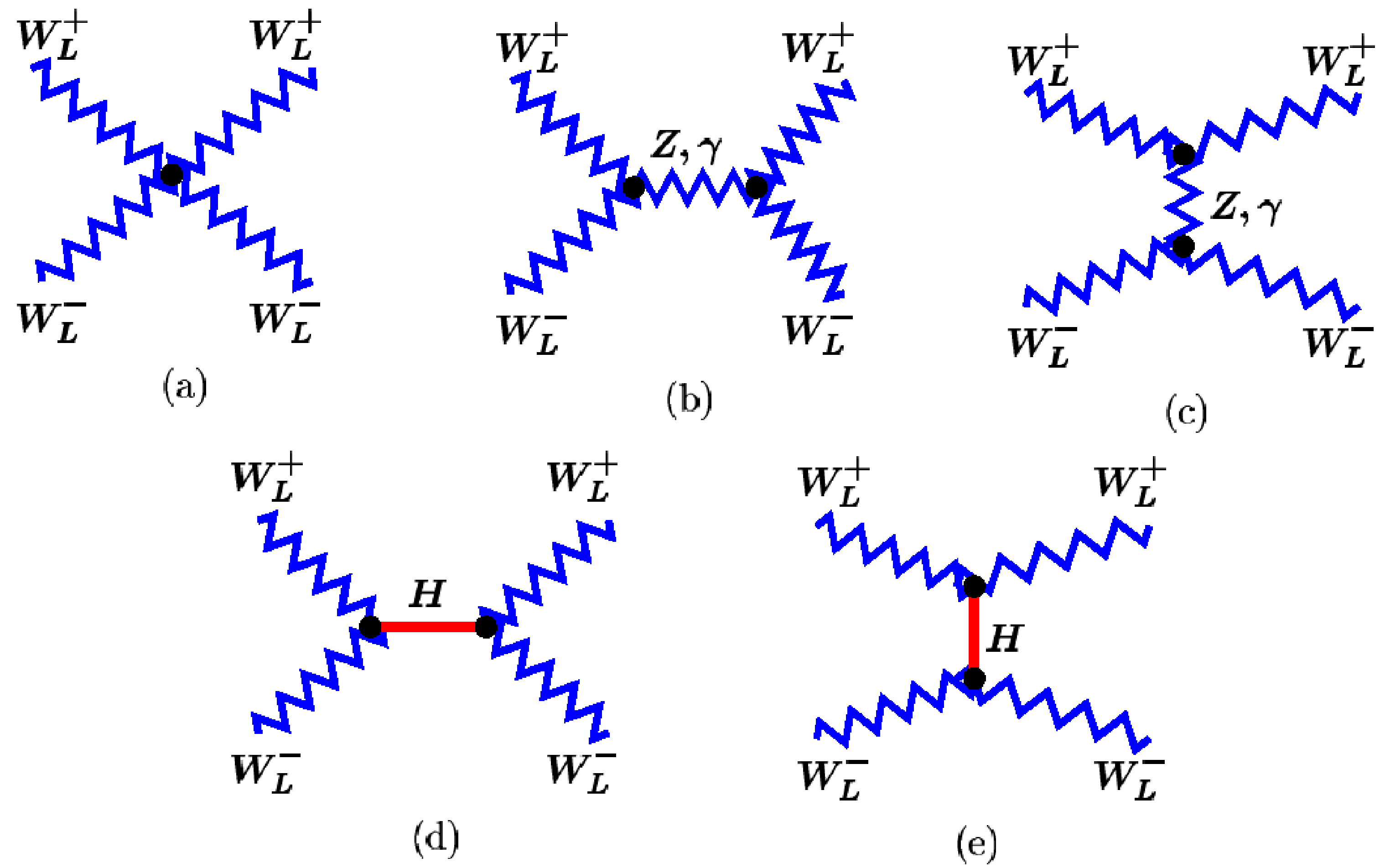
SU(2) x U(1) @ E^4



Graphs	$g^2 \frac{E^4}{m_w^4}$
(a)	$-3 + 6\cos\theta + \cos^2\theta$
(b)	$-4\cos\theta$
(c)	$+3 - 2\cos\theta - \cos^2\theta$
Sum	0

$$\epsilon_L^\mu(k) = \frac{k^\mu}{m_w} + \mathcal{O}\left(\frac{m_w}{E}\right)$$

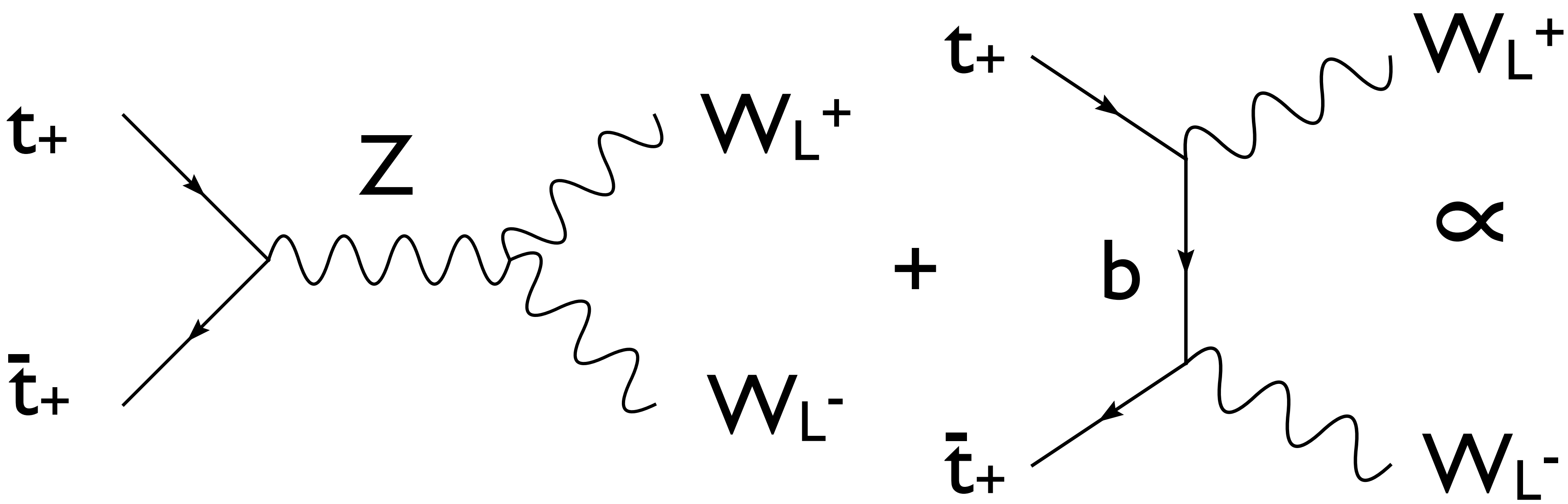
SU(2) x U(1) @ E^2



Graphs	$g^2 \frac{E^2}{m_w^2}$
(a)	$+2 - 6\cos\theta$
(b)	$-\cos\theta$
(c)	$-\frac{3}{2} + \frac{15}{2}\cos\theta$
$(d+e)$	$-\frac{1}{2} - \frac{1}{2}\cos\theta$
Sum including (d+e)	**0**

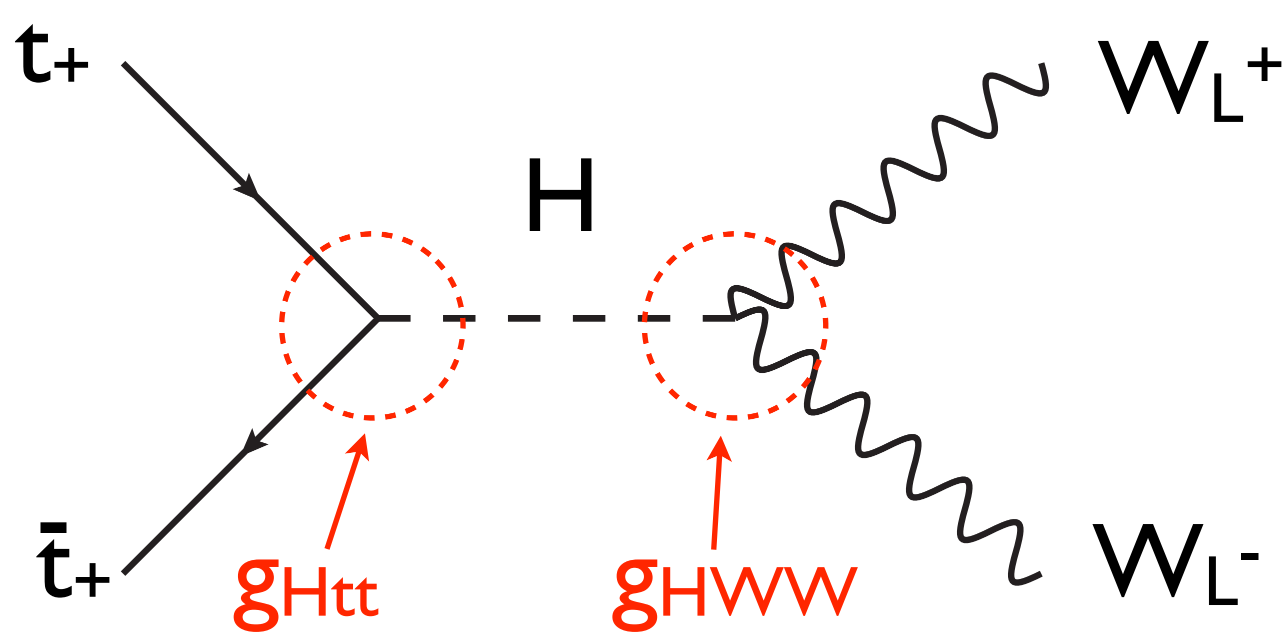
- $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound: $m_H < \sqrt{16\pi/3}\, v \simeq 1.0$ TeV
- If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow E < \sqrt{4\pi}\, v \simeq 0.9$ TeV

Fermion Scattering



$$\propto \frac{m_t E}{v^2}$$

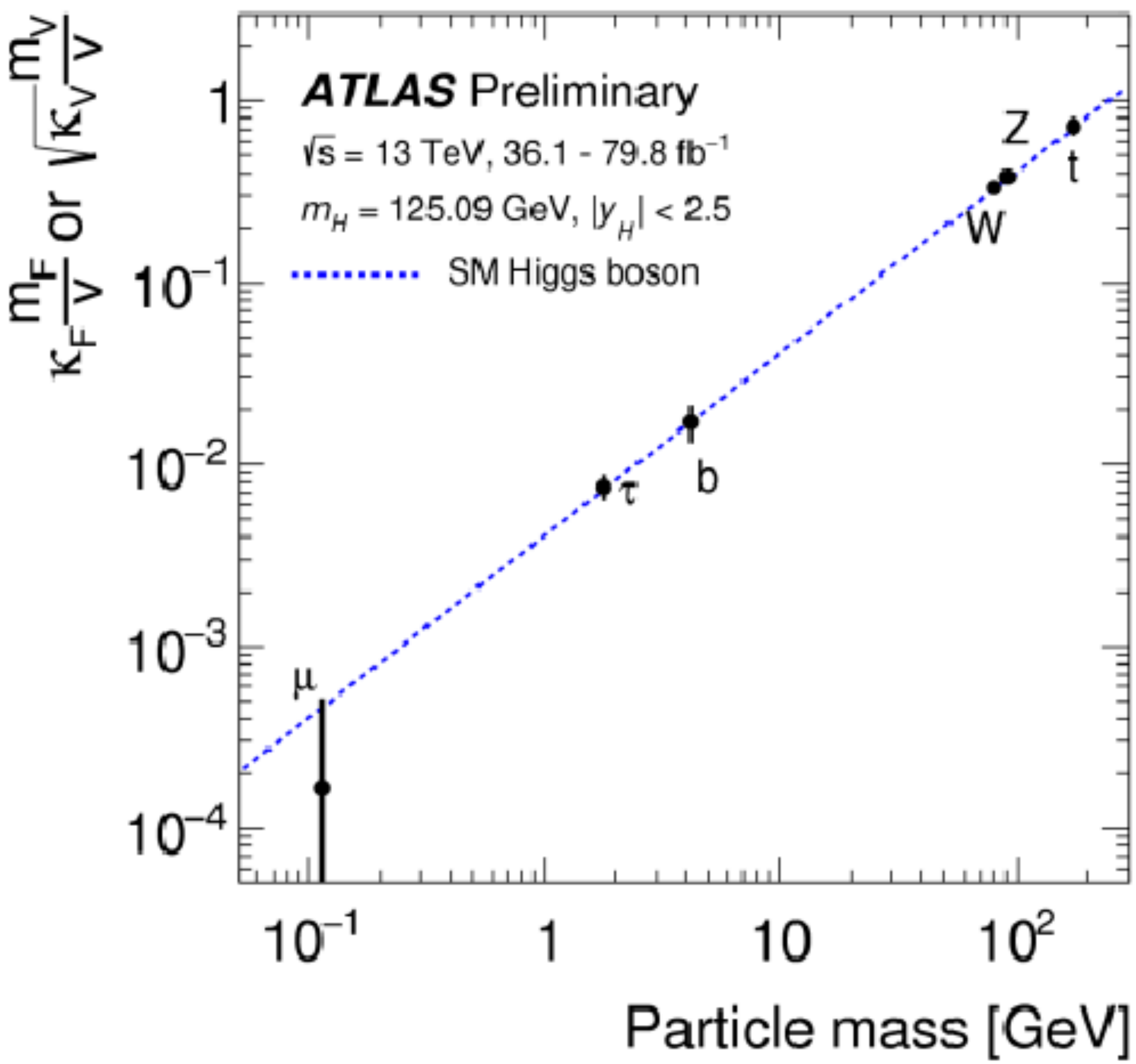
Bad high-energy behavior cancelled by:



Chanowitz, Furman, Hinchliffe

SM Coupling Relations

ATLAS-CONF-2018-031



Talk: Yang

Questions Remain

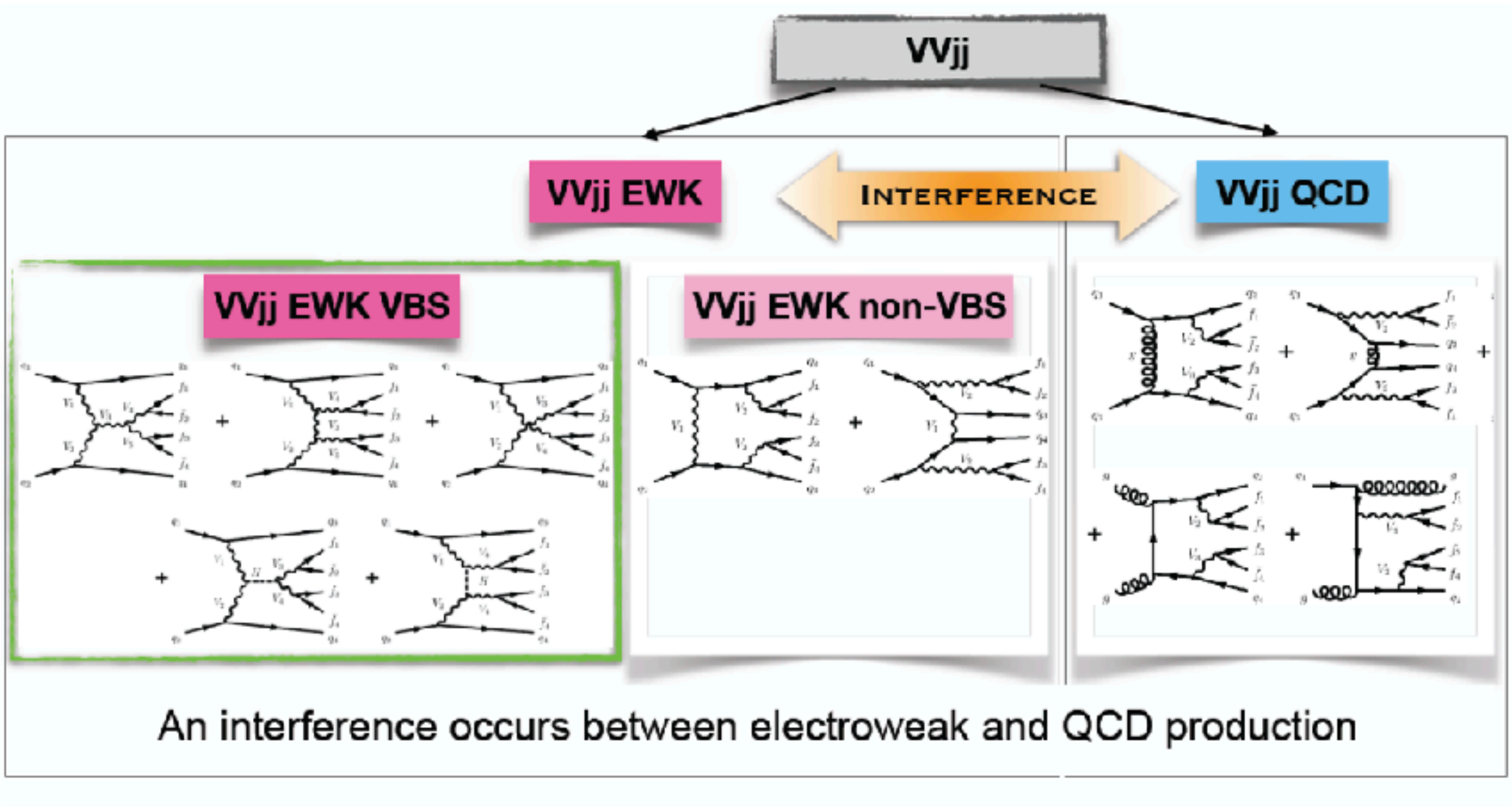
- Discovery of a light Higgs boson leaves still open questions:

  1. Nature of Electroweak Symmetry Breaking
  2. Higgs boson potential, all the way like the Standard Model!?
  3. Does it fulfill the US-fermion/Europe-boson rule?
  4. Is the 125 GeV state the only resonance in the system of EW vector bosons?
  5. How do EW vector bosons scatter? (true heart of weak interactions)
  6. Is there something related to the Little Hierarchy problem (strong or weak)
  7. Look for deviations in intricate cancellations of VBS amplitudes

Talk: Reuter

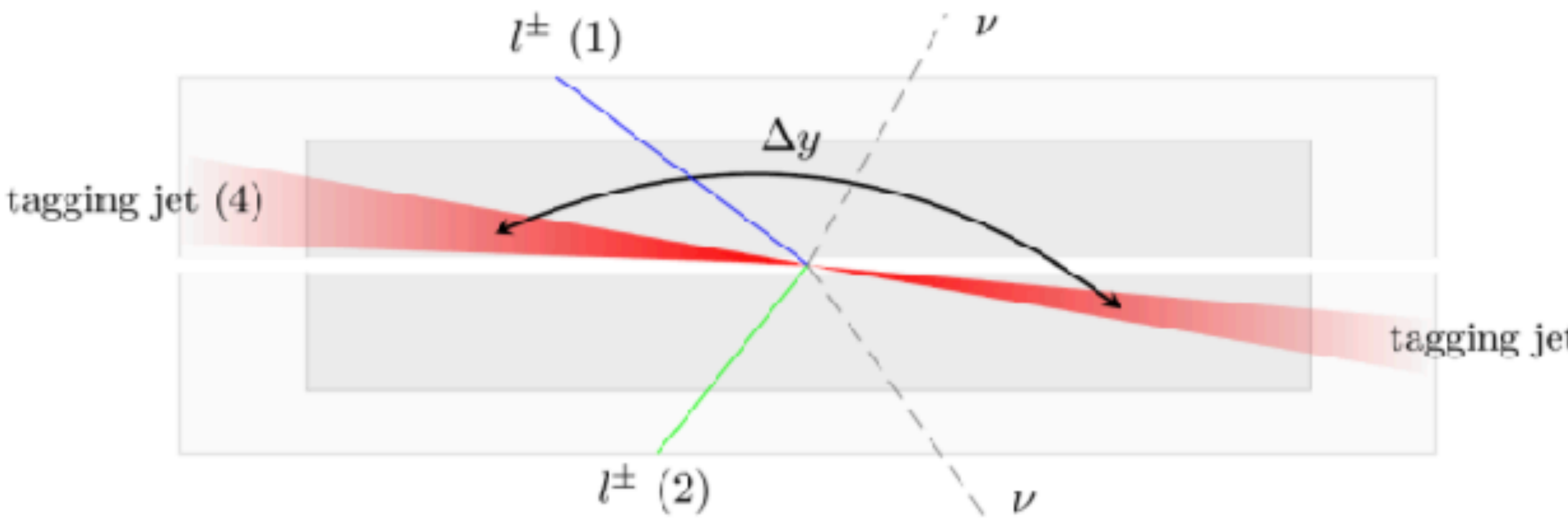
VBS

VBS - Signal and Bkgd



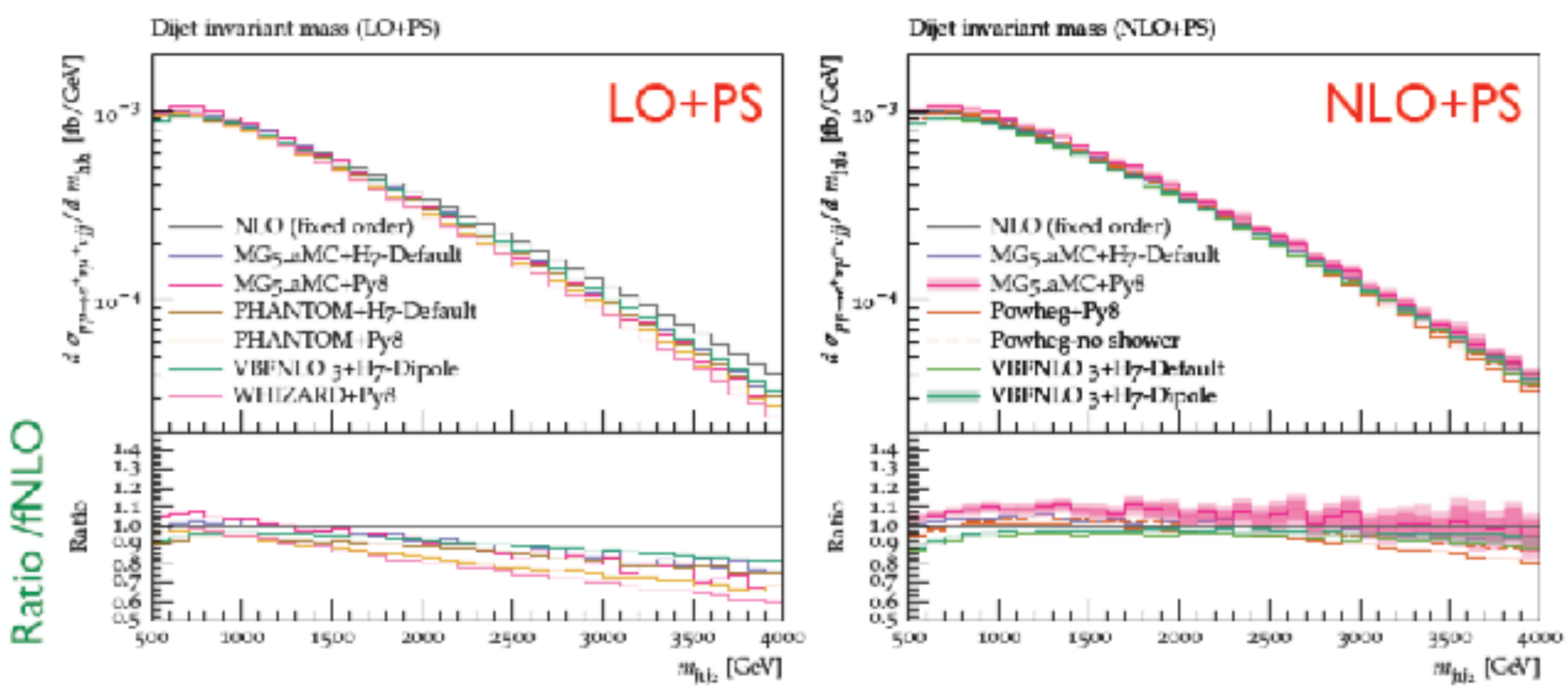
Talks: Yatsenko, Long

VBS - Event Characteristics



VBS has distinctive final states topology

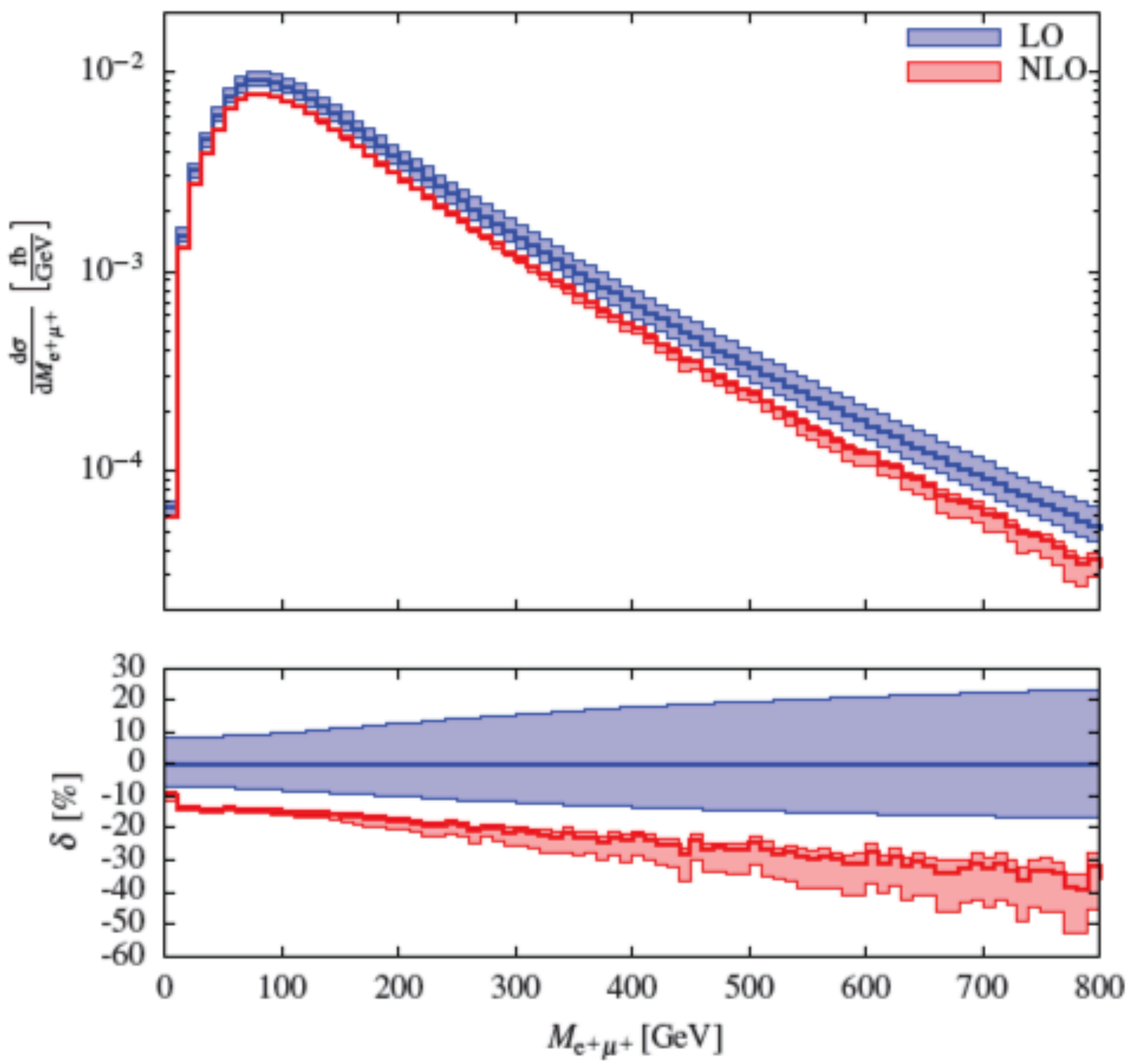
1. Two hadronic jets in forward and backward regions with very high energy (tagging jets)
2. Hadronic activity suppressed between the two jets (rapidity gap) due to absence of color flow between. interacting partons.
3. Two bosons are produced ~back-to-back.



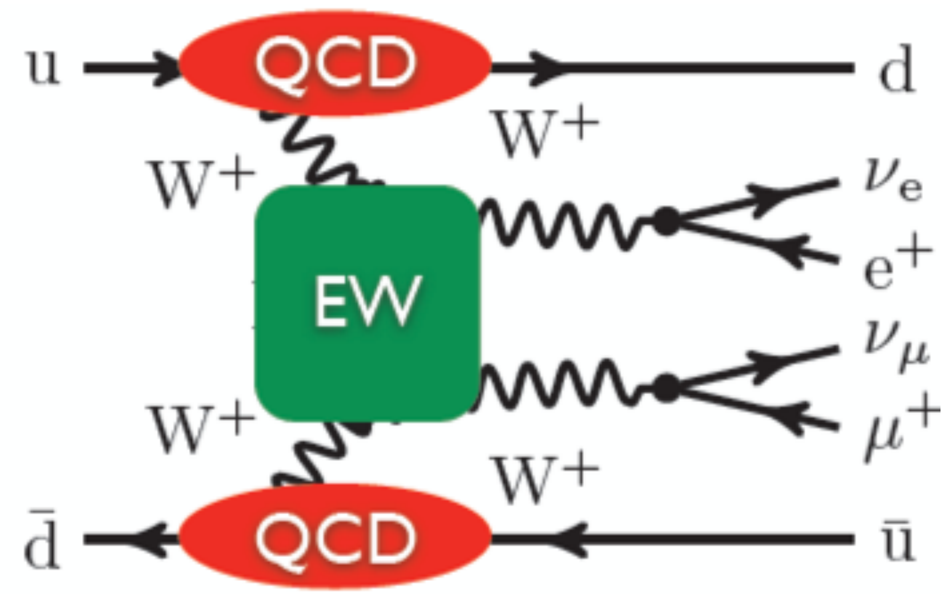
Talks: Yatsenko, Zaro, Hoeche

Precision VBS: Electroweak

W+W+jj



[Biedermann, Denner, MP; 1708.00268]



$$\sigma_{\mathrm{LL}} = \sigma_{\mathrm{LO}}\left[1 - \frac{\alpha}{4\pi} 4C^{\mathrm{ew}}_{\mathrm{W}} \log^2\left(\frac{Q^2}{M^2_{\mathrm{W}}}\right) + \frac{\alpha}{4\pi} 2b^{\mathrm{ew}}_{\mathrm{W}} \log\left(\frac{Q^2}{M^2_{\mathrm{W}}}\right)\right]$$

$$C^{\mathrm{ew}}_{\mathrm{W}} = \frac{2}{s^2_{\mathrm{w}}}$$

$$b^{\mathrm{ew}}_{\mathrm{W}} = \frac{19}{6s^2_{\mathrm{w}}}$$

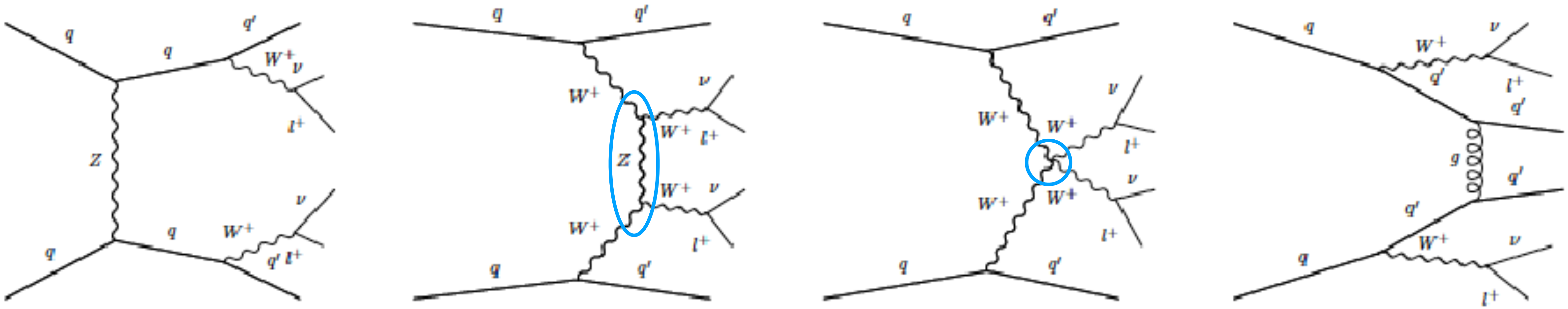
Talk: Zaro

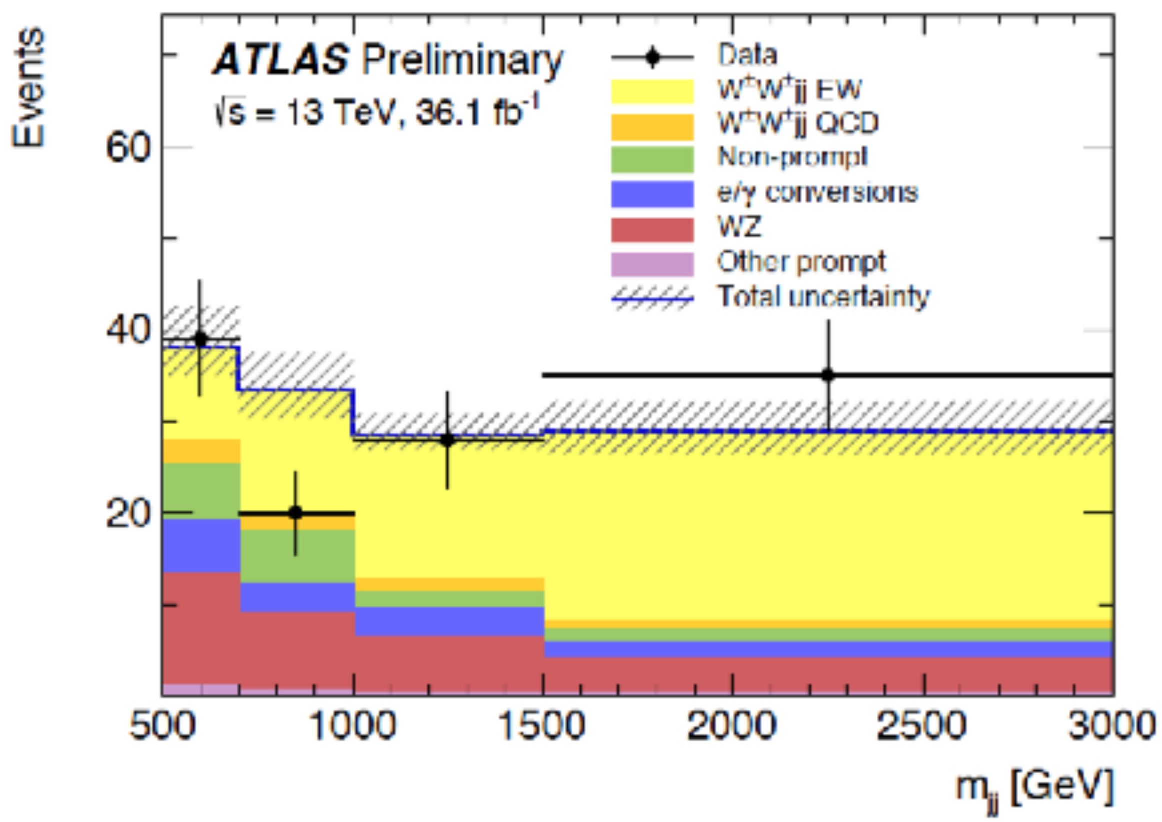
VBS: W± W±jj @ ~20%

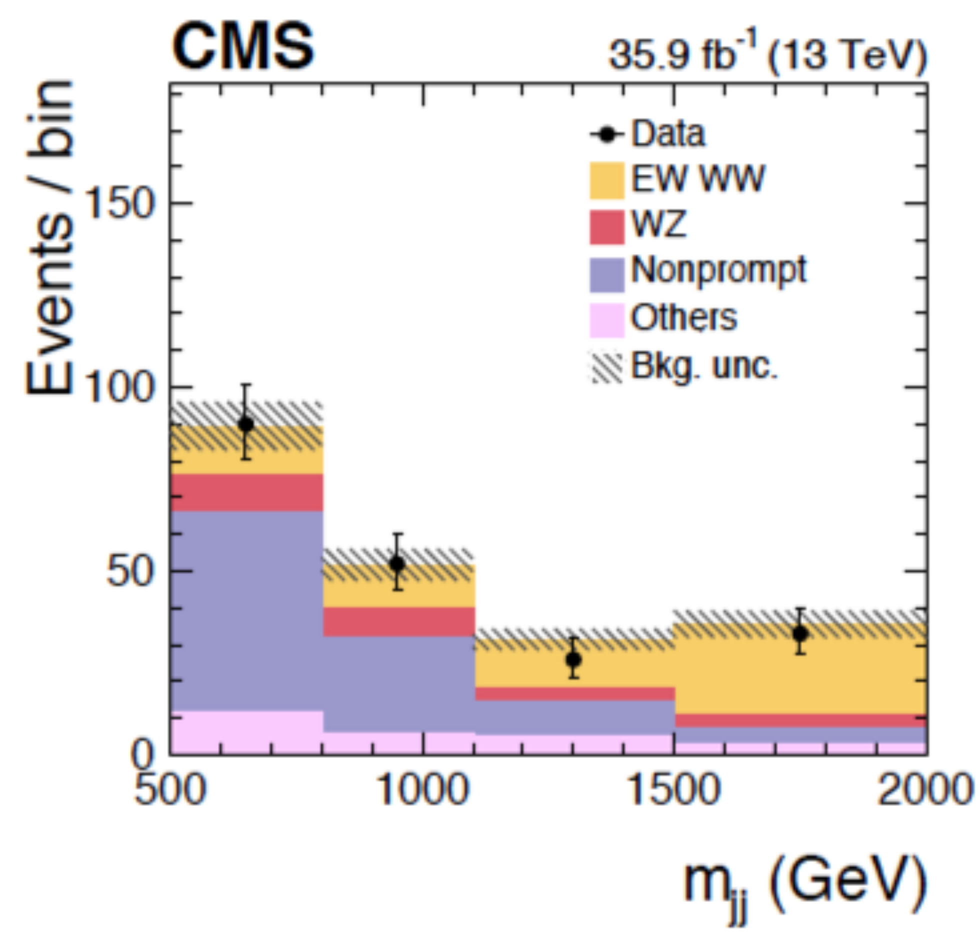
Electroweak:

+ t-channel h-exchange

QCD:





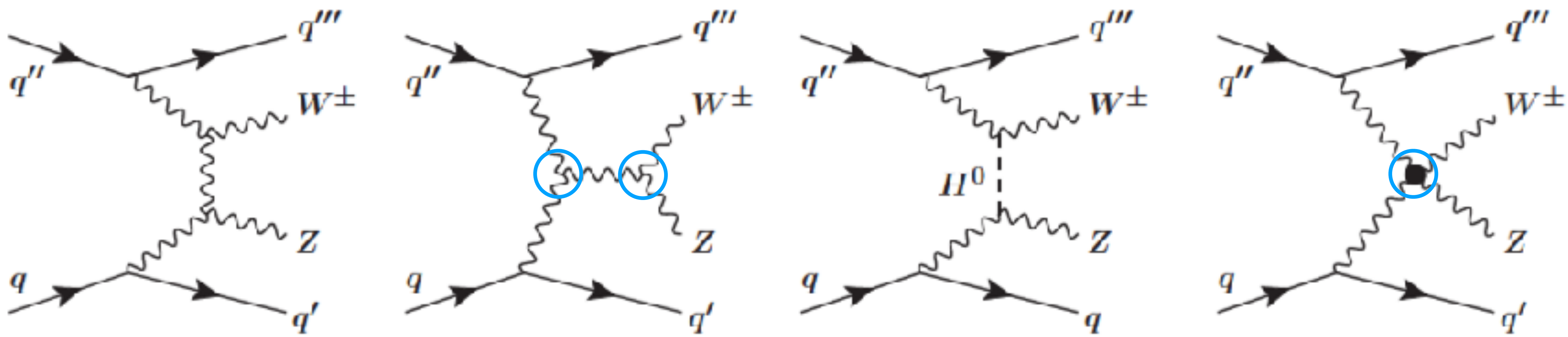


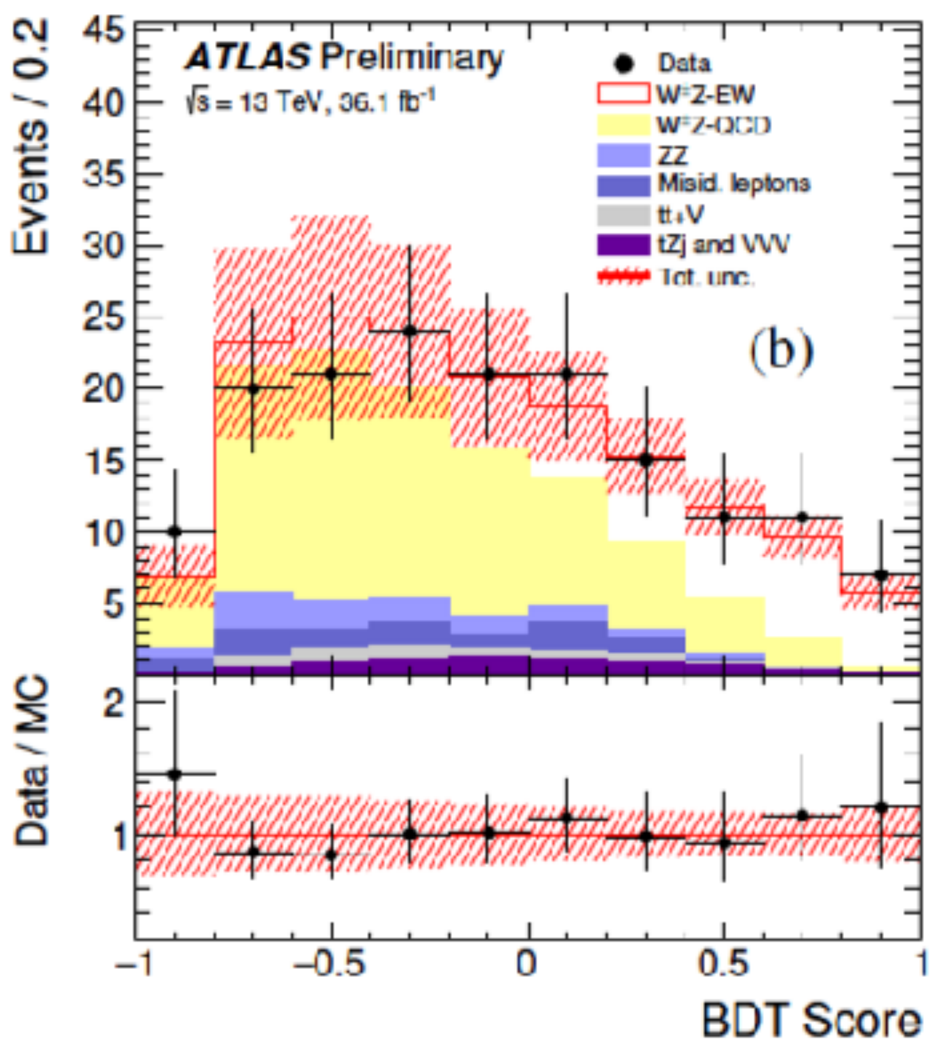
Chanowitz and Golden, PRL 61, 1053 (1988)
CMS: 1709.05822, ATLAS-CONF-2018-30

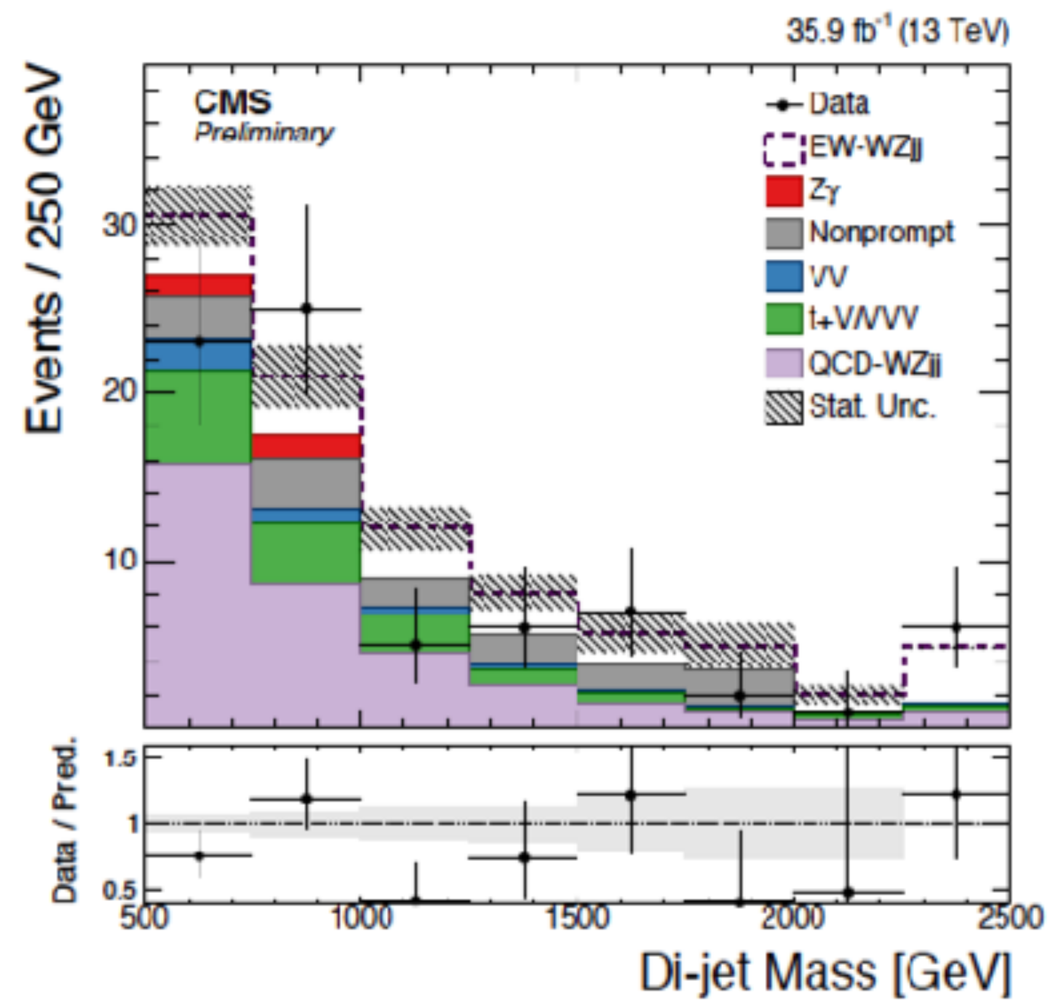
Talks: Bhattacharya, Yatsenko

VBS: WZjj @ ~25%

(EW VBS signal only)



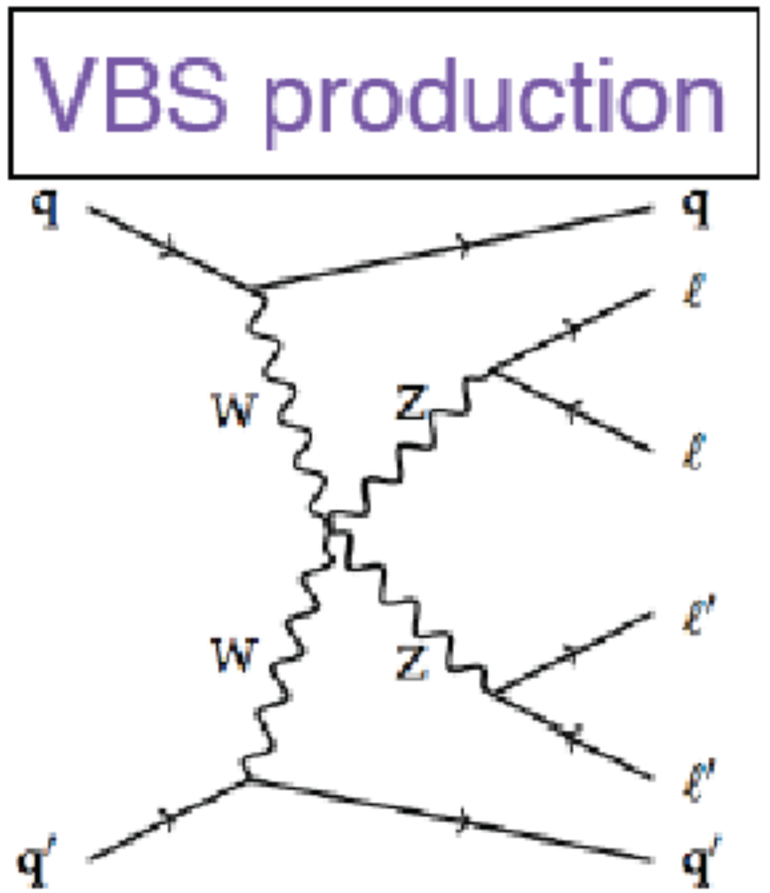


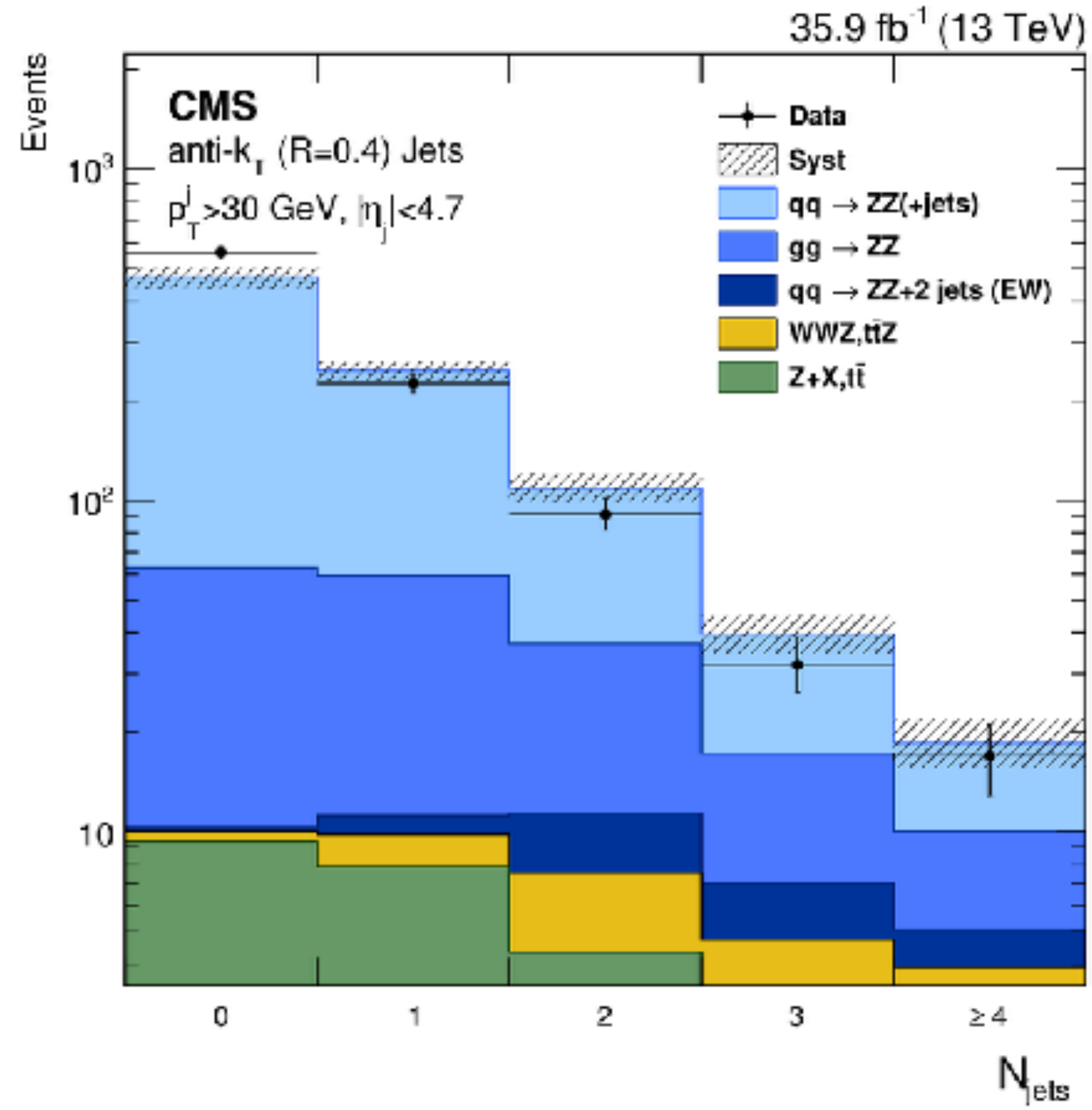


Talks: Bhattacharya, Yatsenko

CMS SMP-18-001, ATLAS-CONF-2018-033

VBS: ZZjj @~50%

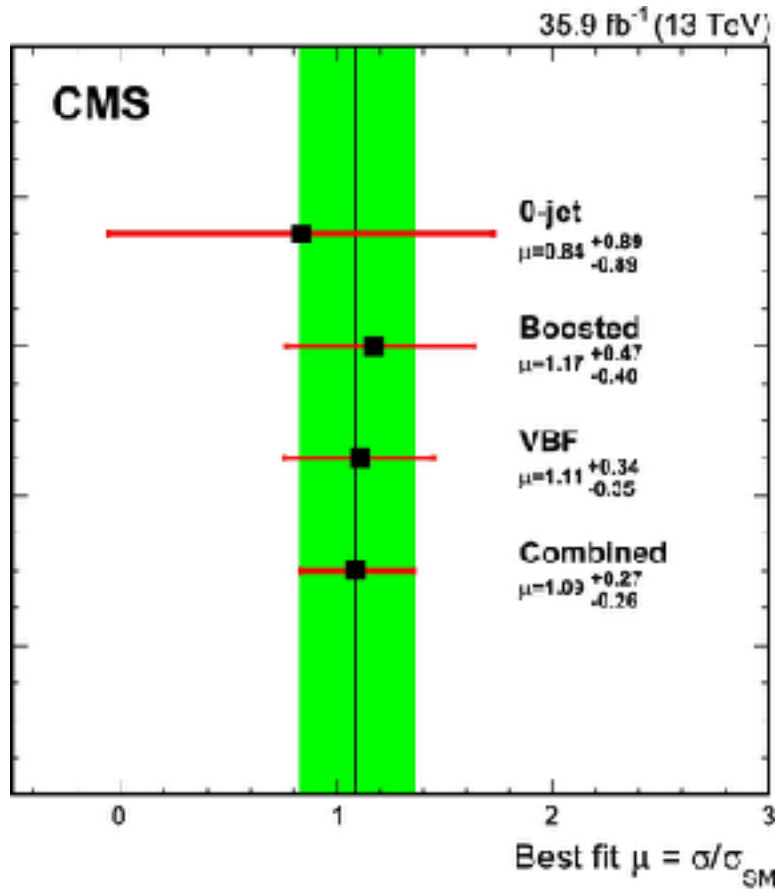


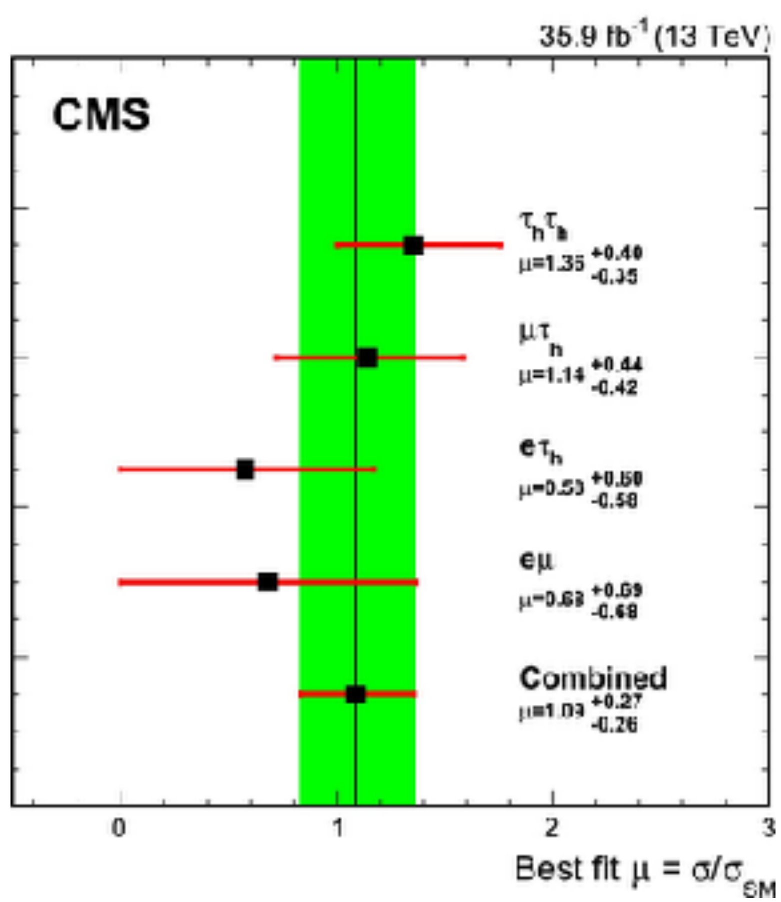


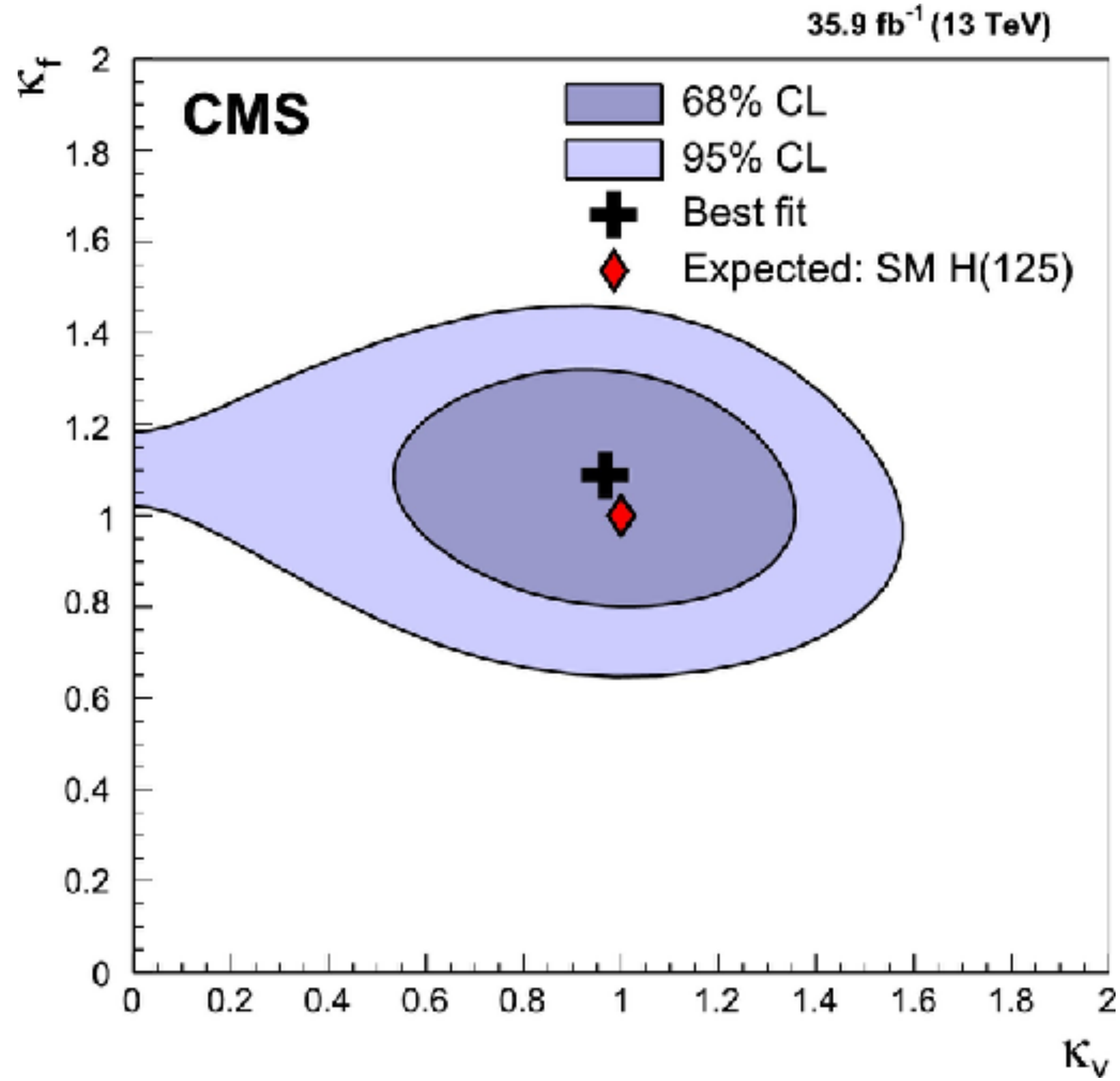
CMS: 1806.11073
Kenneth Long, ICHEP

Talks: Long

VBF H, H→ττ
4.7σ



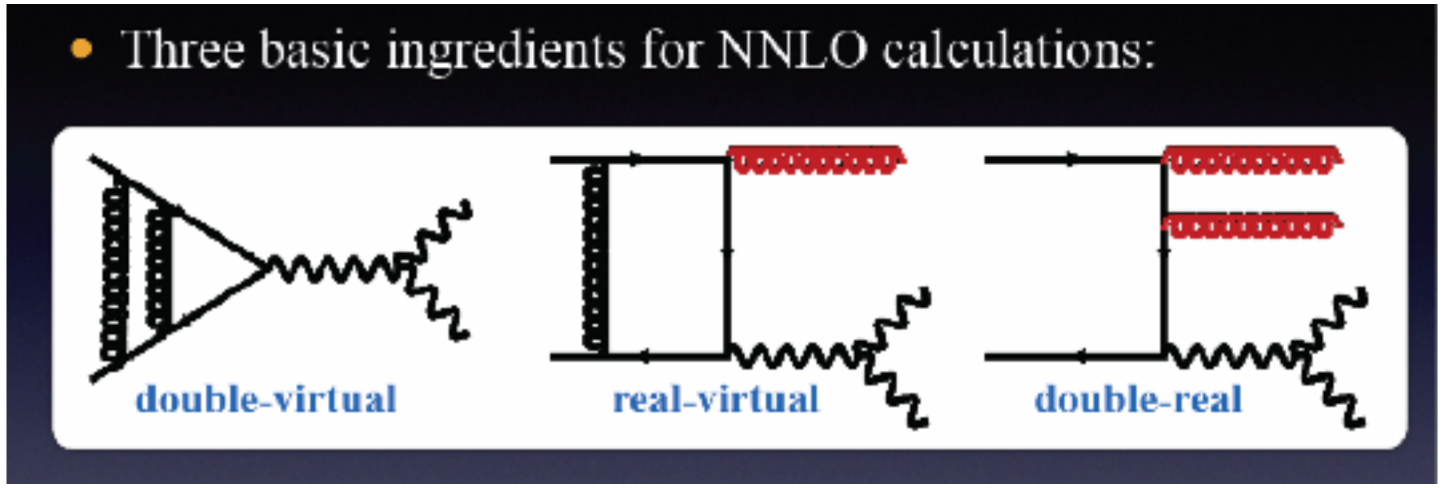


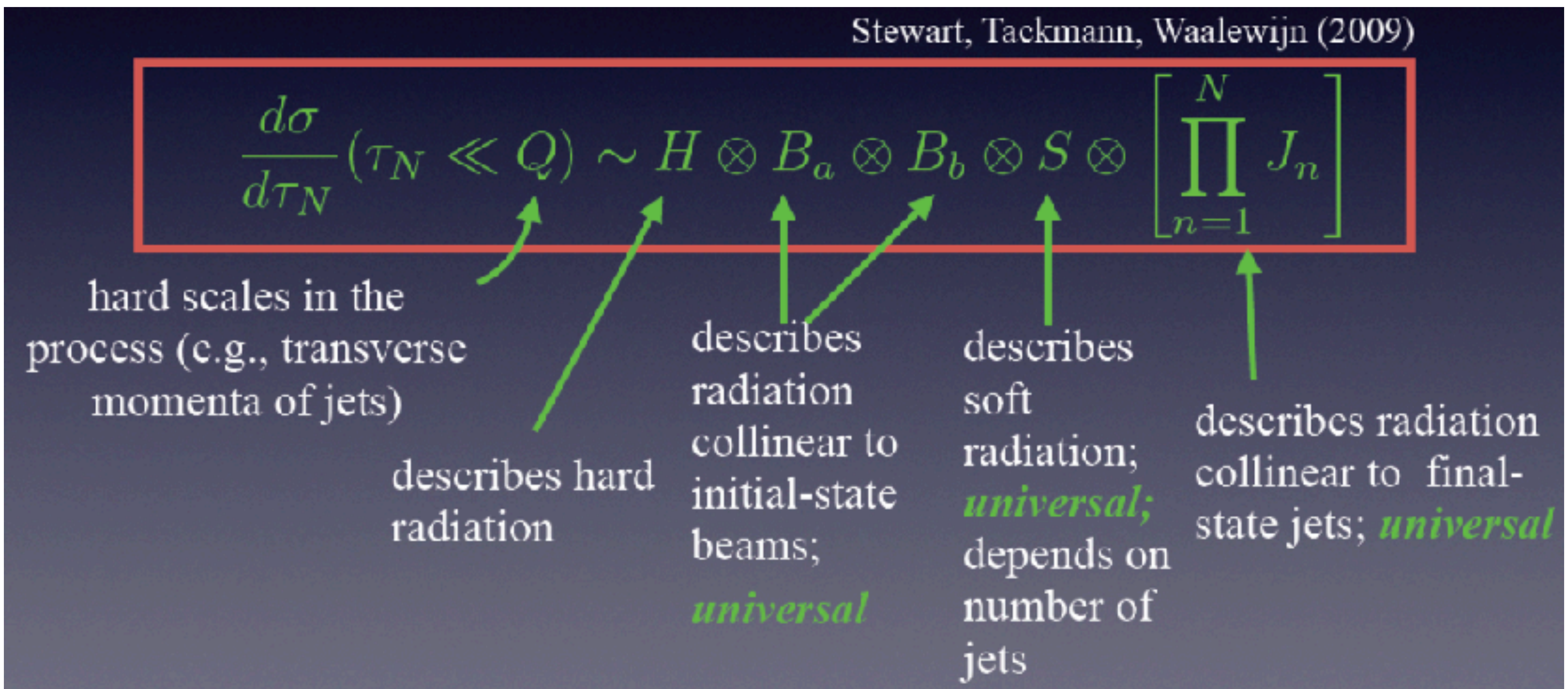


Talk: Lammers

DiBoson Production

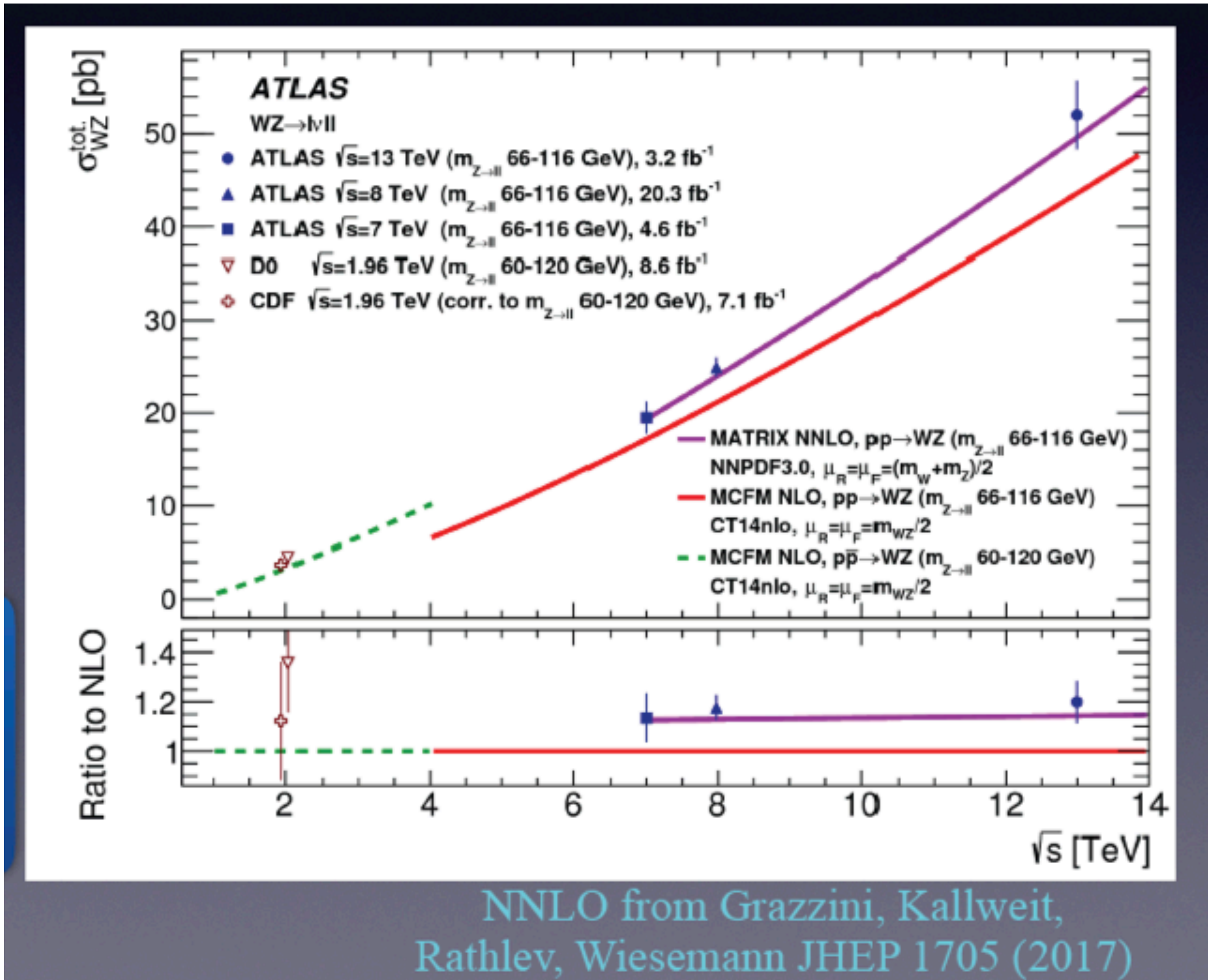
Precision DiBoson - QCD
qT and τ_N Subtraction Methods





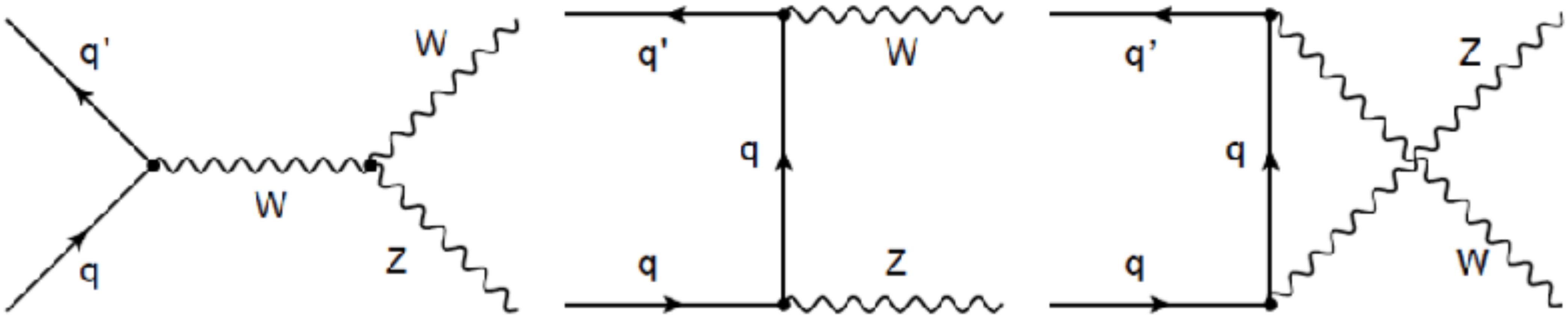
Talk: Boughezal

Precision DiBoson
WZ QCD NNLO Results

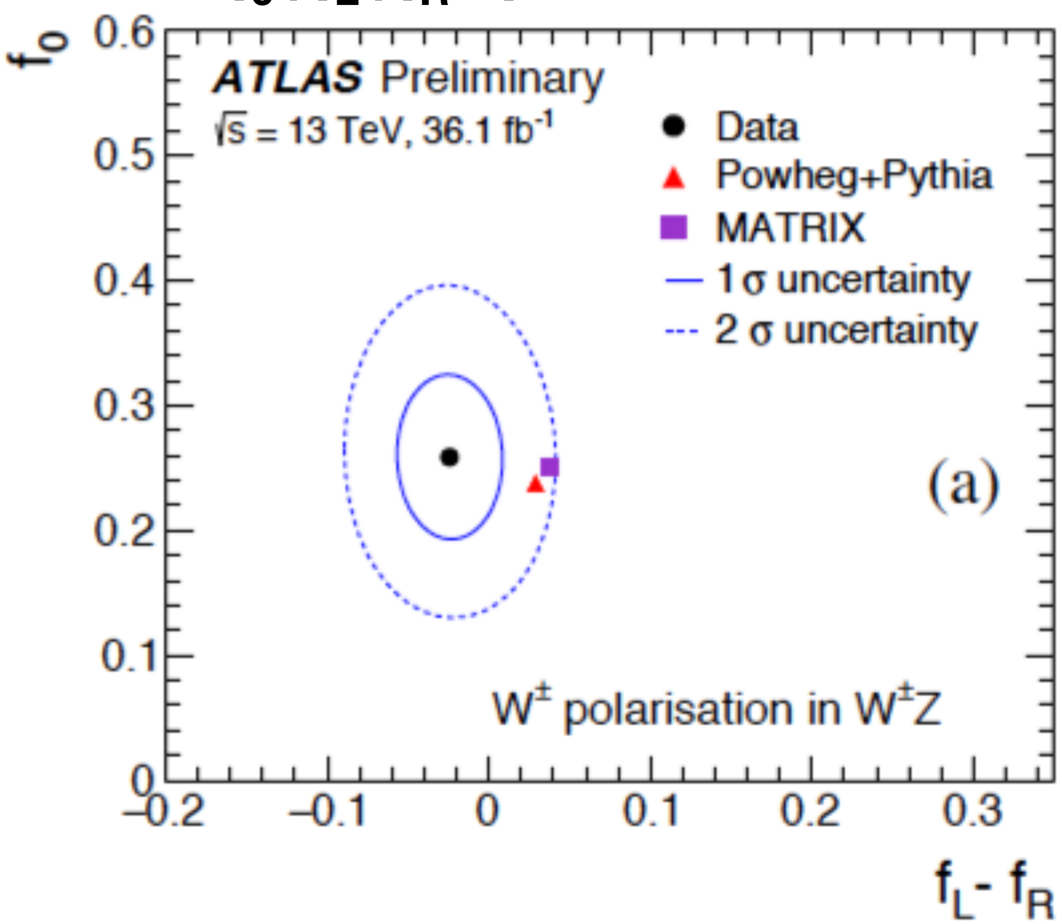


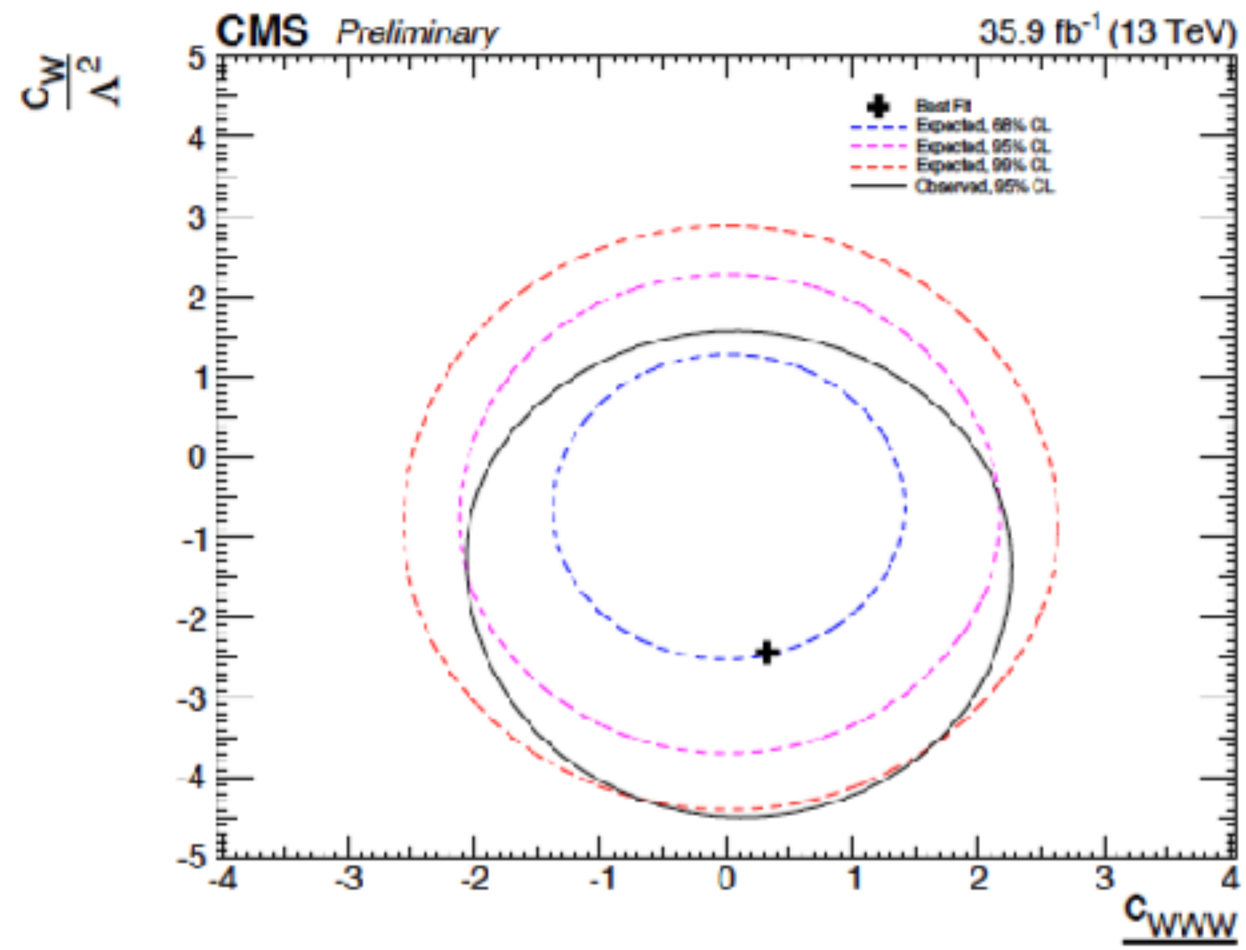
Talk: Boughezal

Diboson WZ→3lv @~5%



$f_0+f_L+f_R=1$



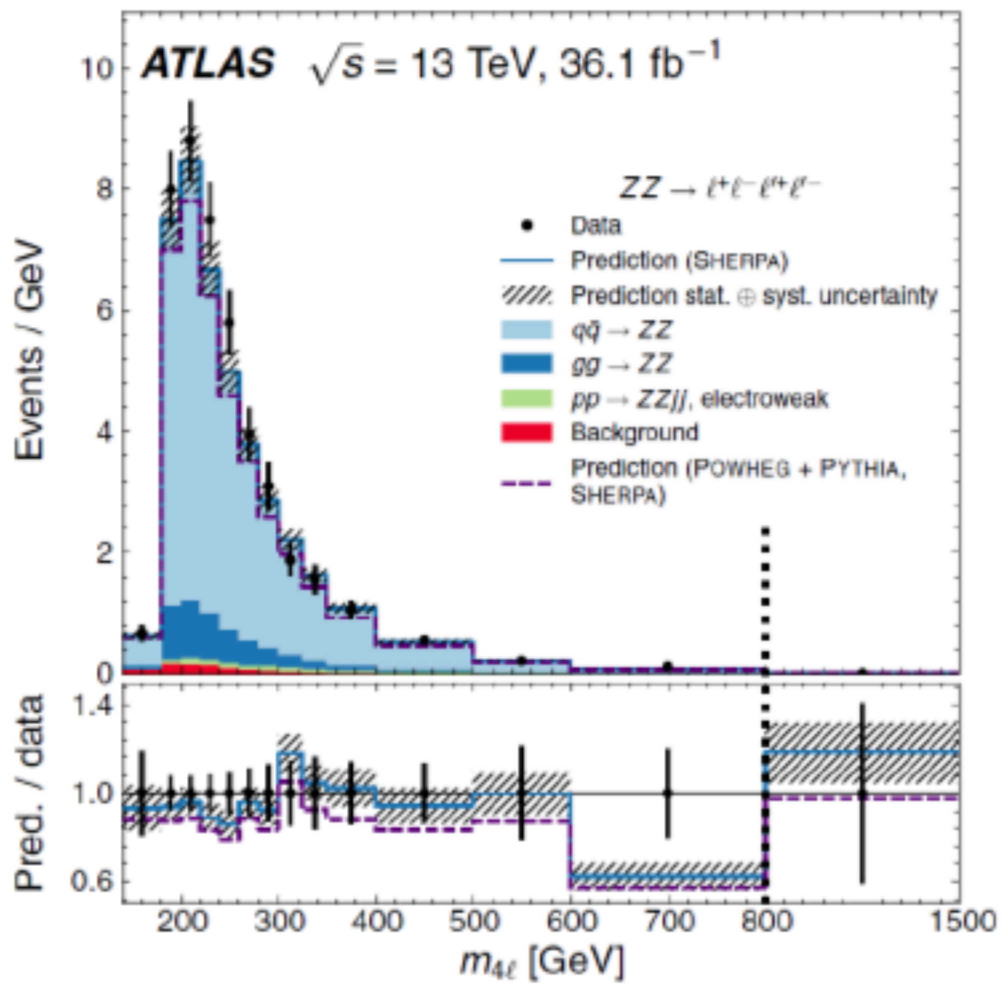


$$\delta\mathcal{L}_{AC} = c_{WWW}\,\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] + c_W\,(D_\mu H)^\dagger W^{\mu\nu}(D_\nu H) + c_b\,(D_\mu H)^\dagger B^{\mu\nu}(D_\nu H)$$

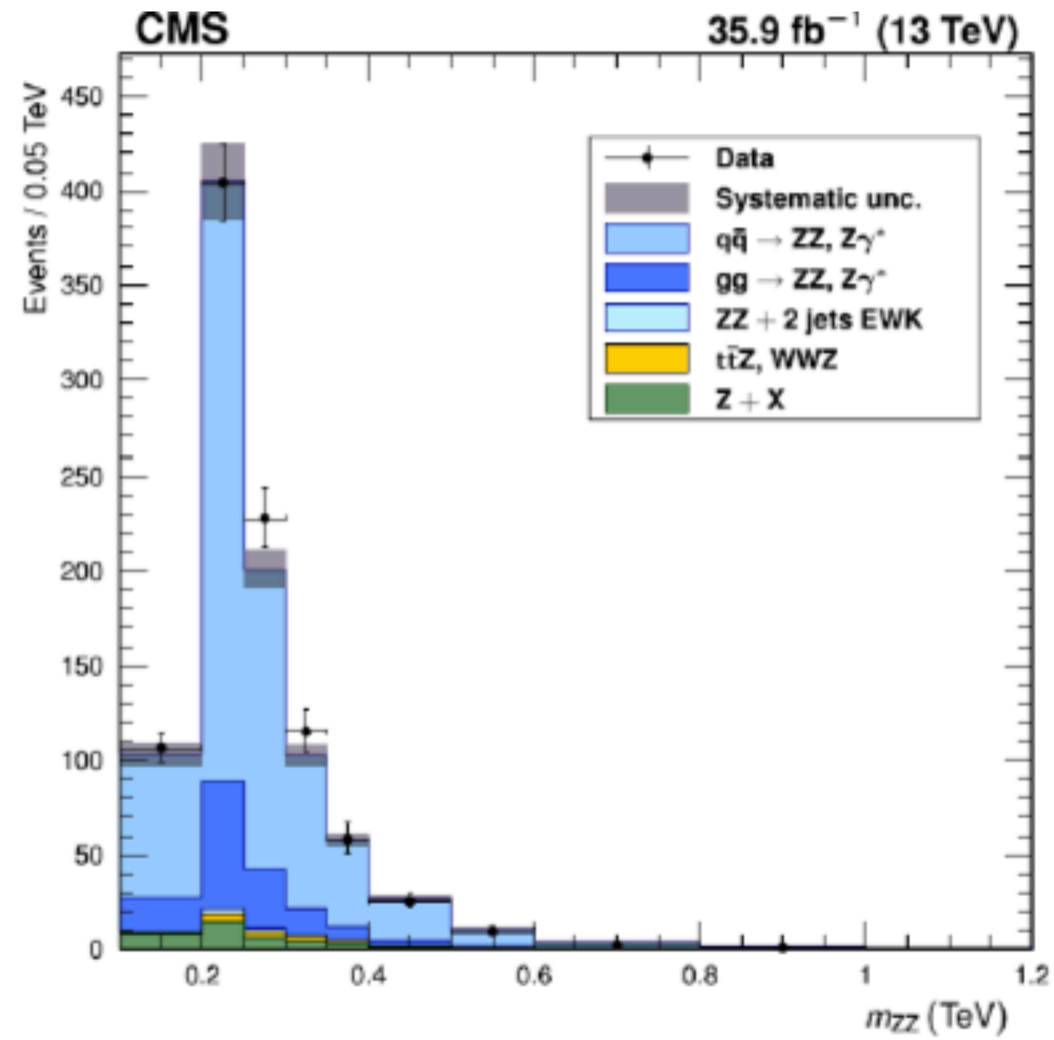
CMS: SMP-18-002
ATLAS-CONF-2018-34

Talks: Bhattacharya

Diboson ZZ→4l @~5%



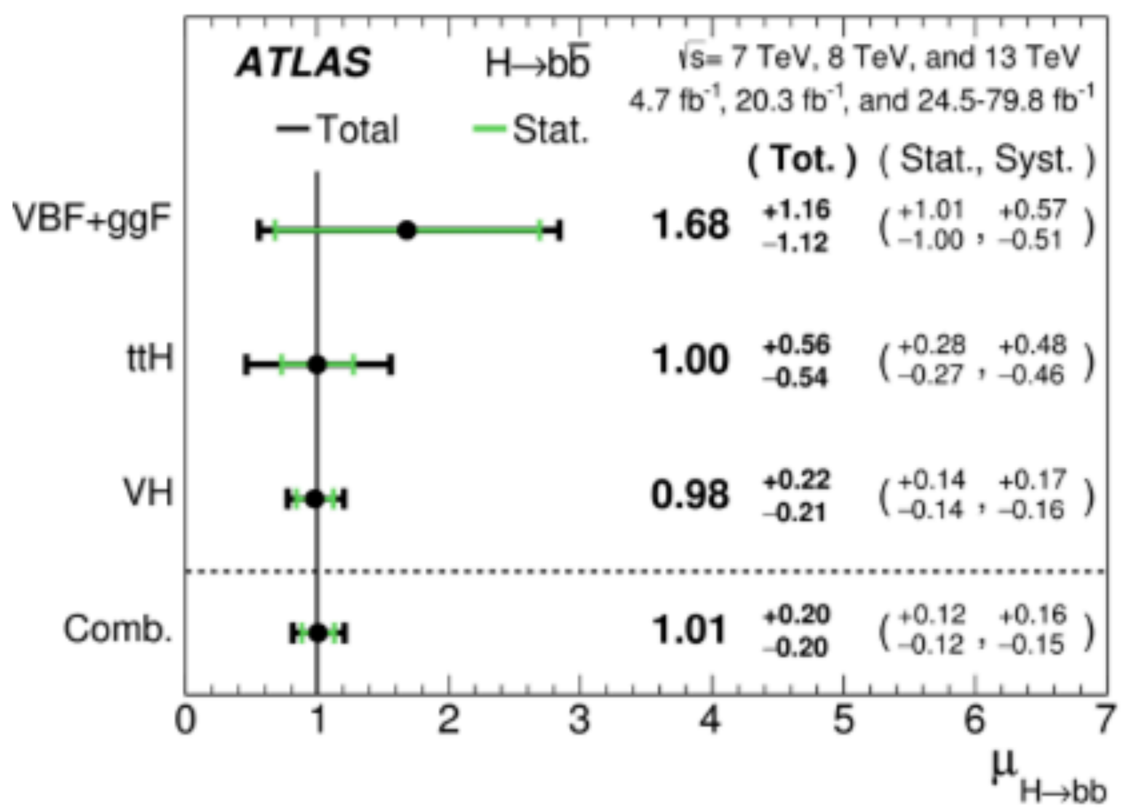
Phys. Rev. D **97**, 032005 (2018)



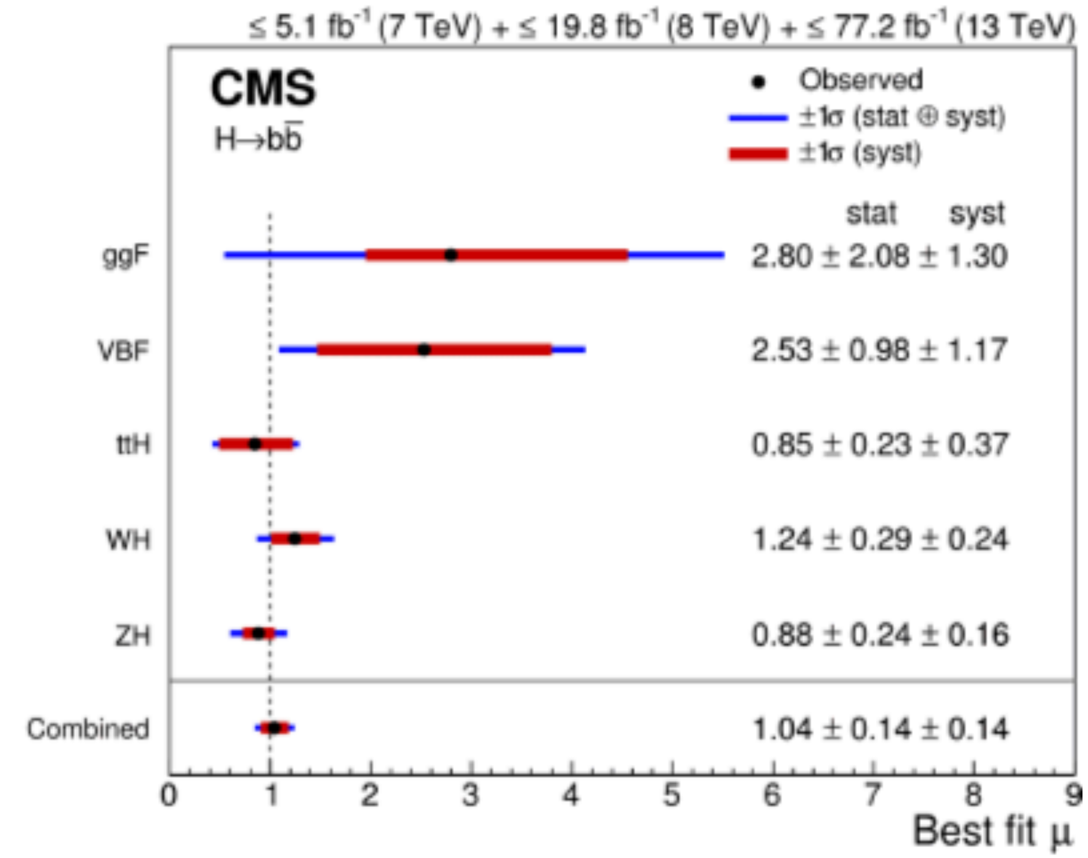
Eur. Phys. J. C 78 (2018) 165

Talks: Bing

VH, H→bb @~20%



Observed significance 5.4σ (Expected 5.5σ)



Observed significance 5.5σ (Expected 5.6σ)

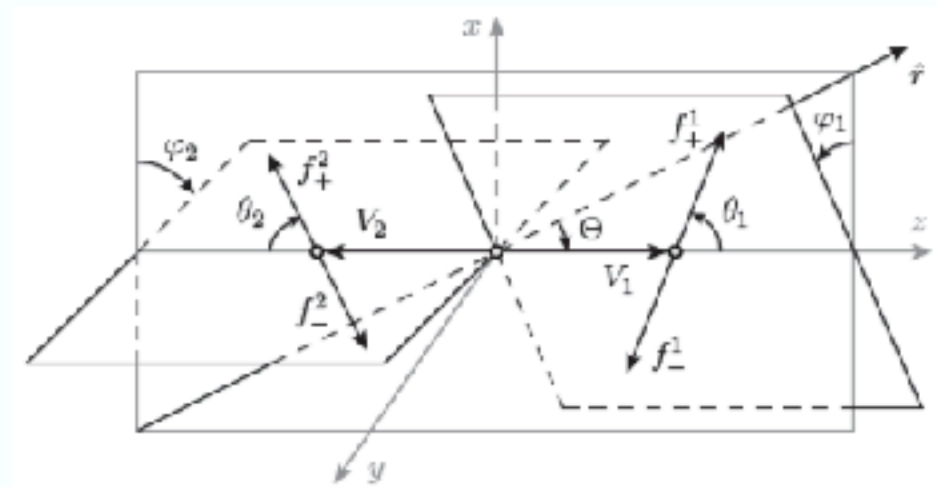
arXiv:1808.08238
arXiv:1808.08242

Talk: Krohn

“Interference Resurrection”
Probing Interactions in Distributions

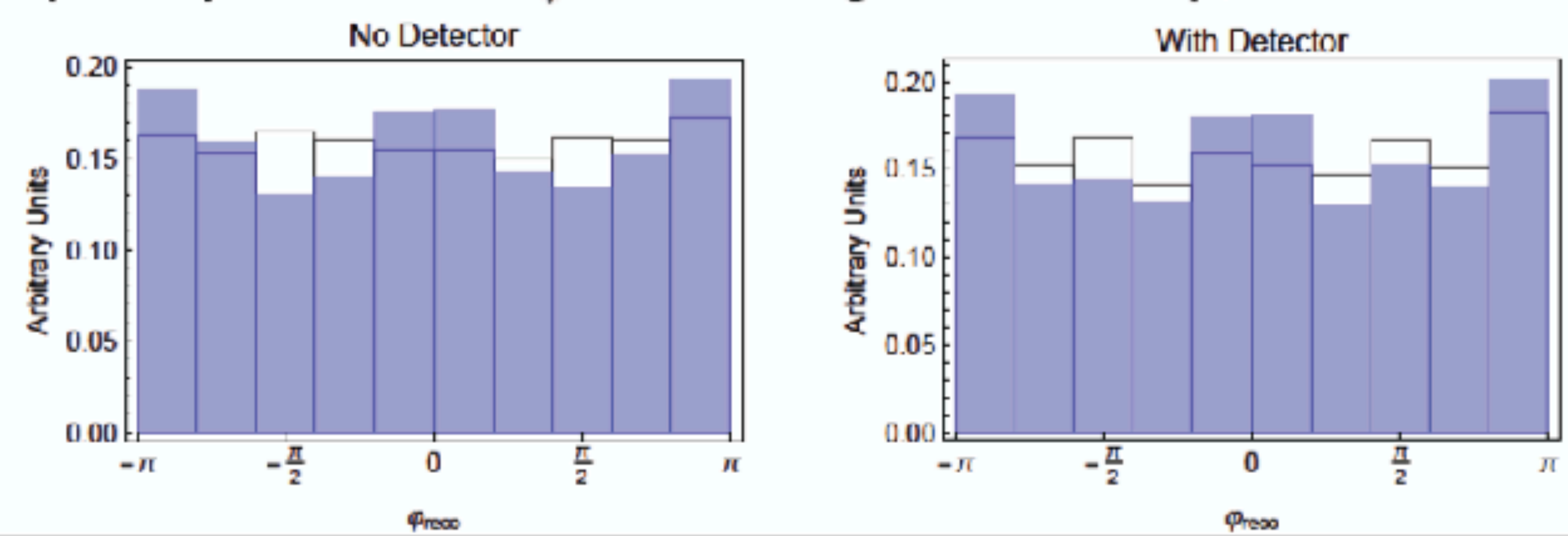
$$\mathcal{O}_{3W} = \epsilon^{ijk} W_{\mu}^{i\nu} W_{\nu}^{j\rho} W_{\rho}^{k\mu}$$

Measuring diboson diff. cross-sections is not enough



Simplest case is **Wγ**: “Interference” $\propto \sin\theta \cos 2\varphi$

Compulsory to measure φ. Measuring θ would help, Θ as well

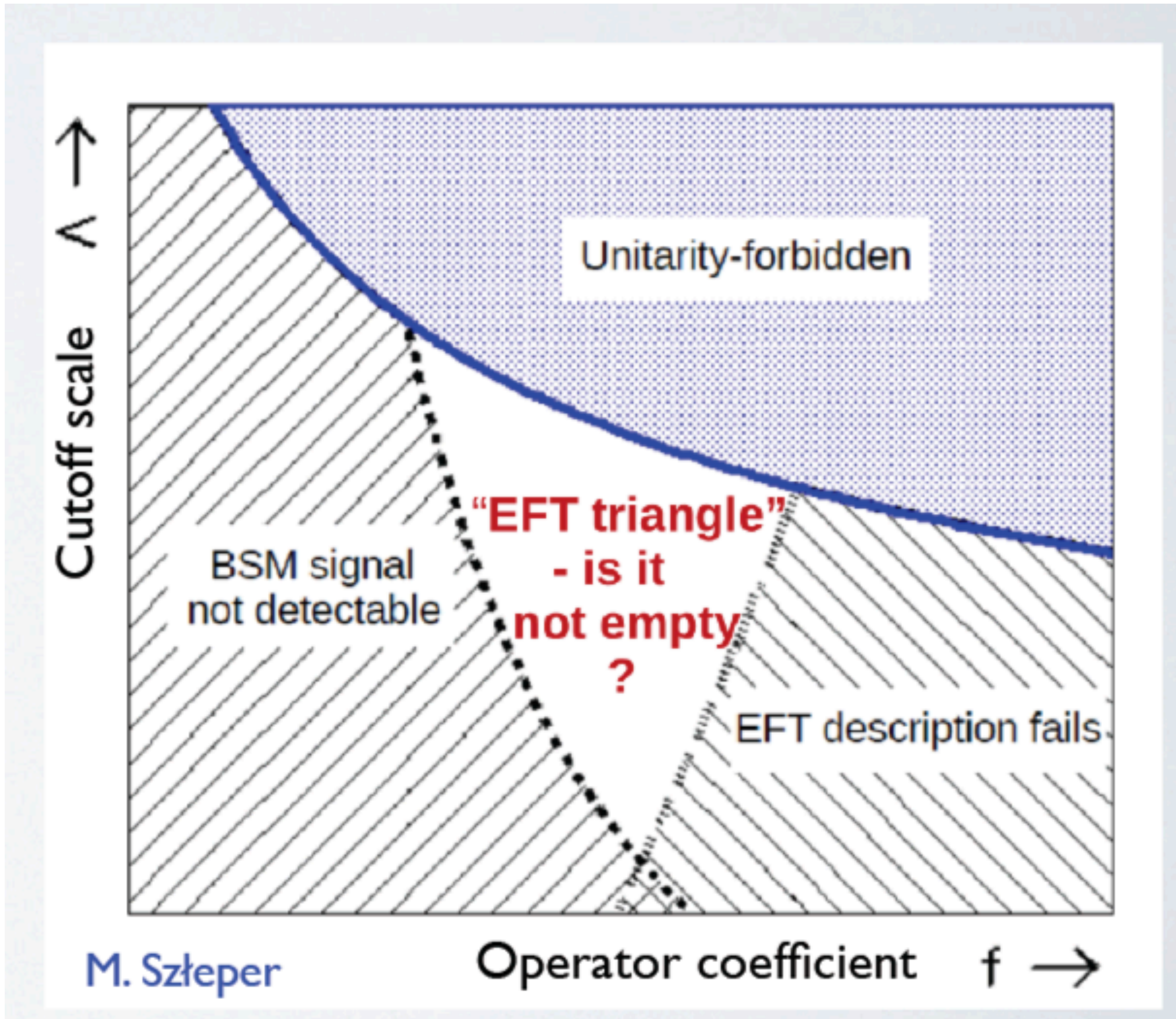


Talk: Wulzer

Panico, Riva, Wulzer 1708.07823

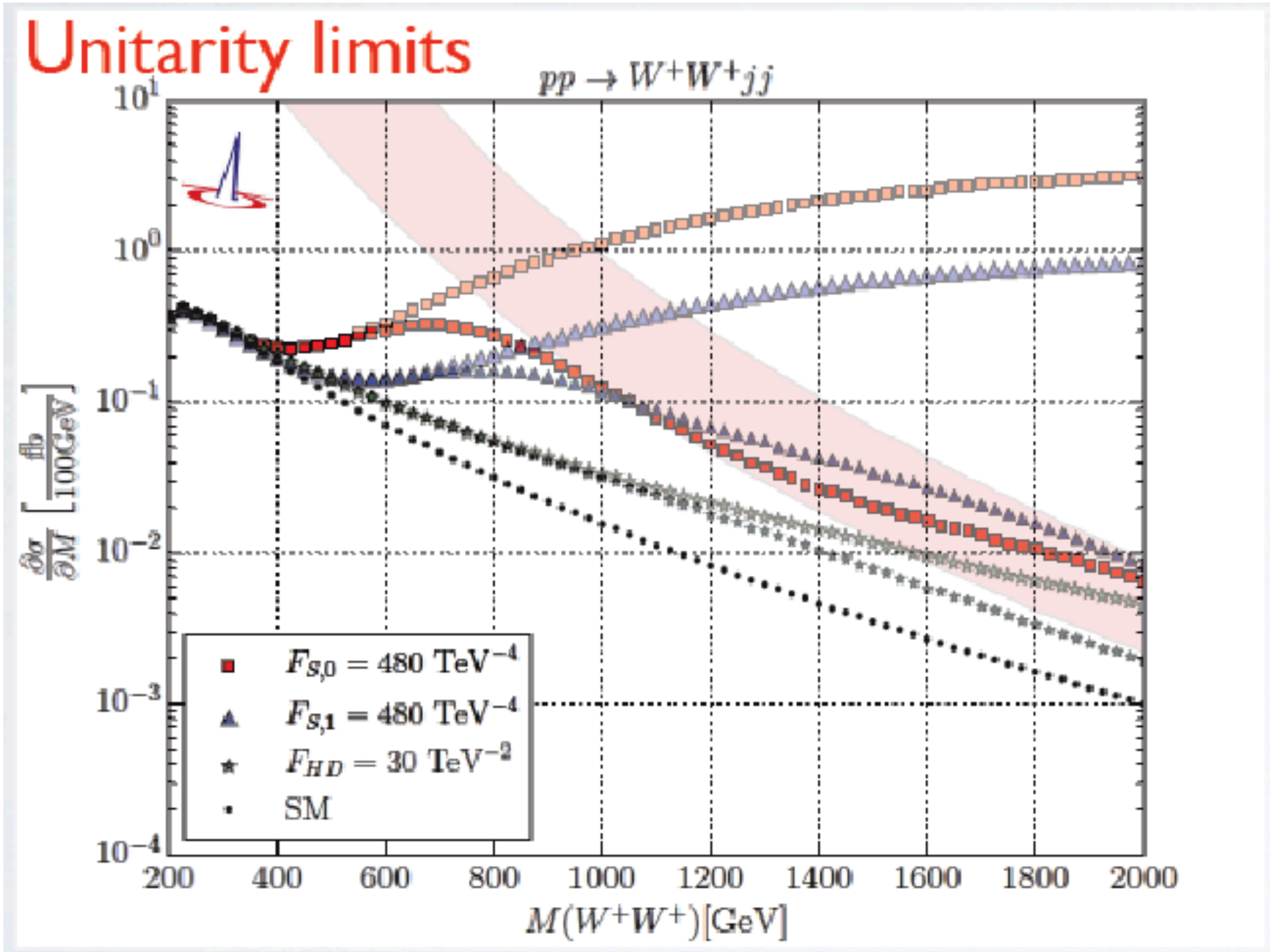
EFT

Limits on EFT



Talk: Reuter

Unitarity Limits

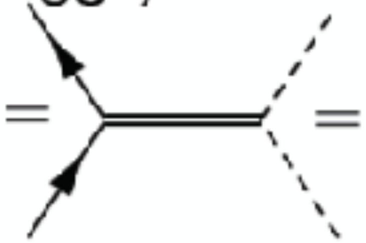


Talk: Reuter

Kilian, Ohl, Reuter, Sekulla 1408.6207

LHC reach vs. Model-Type

Strongly-coupled quarks
(and Higgs)

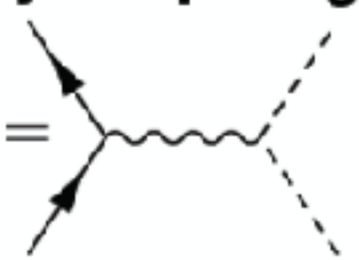


$$a_q^{(3)} = \frac{16\pi^2}{M^2}$$

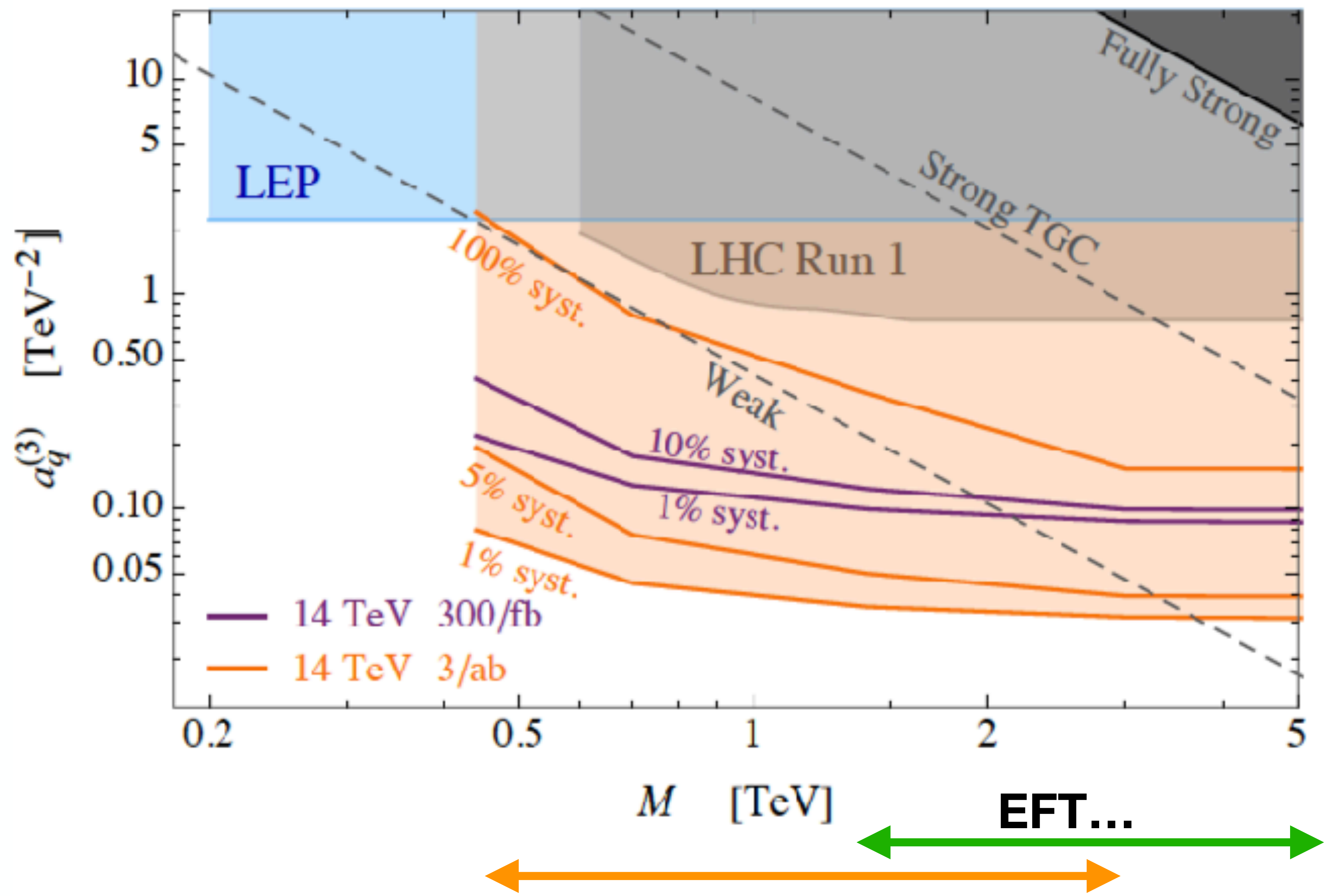
Weakly-coupled quarks,
strongly coupled gauge

$$a_q^{(3)} = \frac{4\pi\, g_W}{M^2}$$

Weakly-coupled quarks,
weakly coupled gauge



$$a_q^{(3)} = \frac{g_W^2}{M^2}$$



EFT…

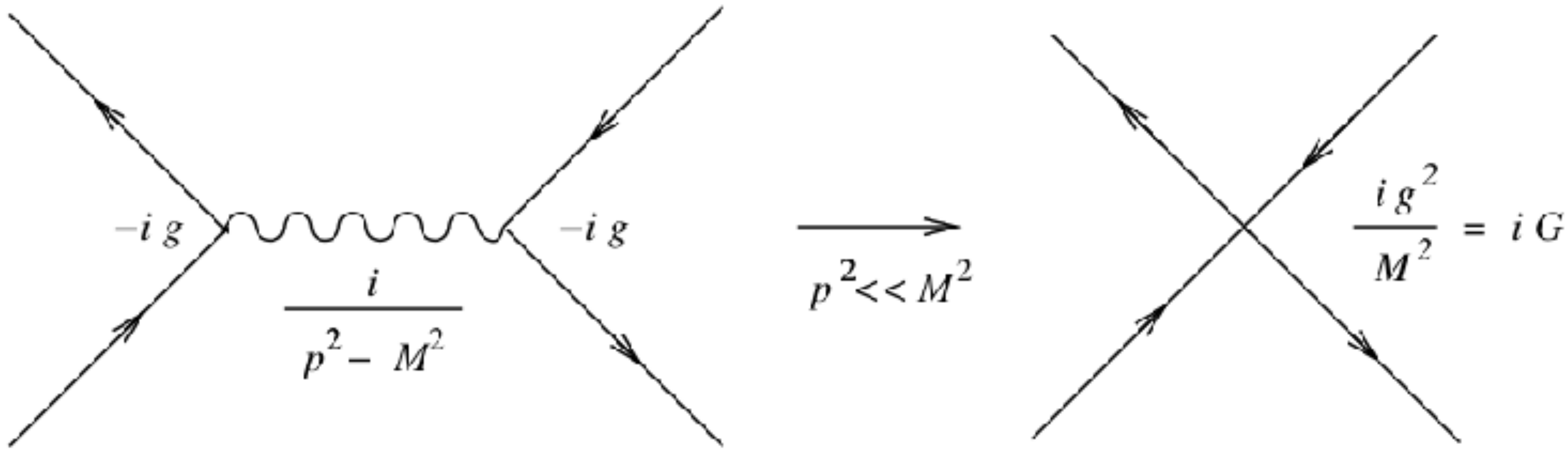
Resonance Searches!

Talk: Wulzer

Franceschini, Panico, Pomarol, Riva and Wulzer, 1712.01310

VBS/MultiBoson: Not Likely to be a “discovery” mode

Resonance: **Four-Fermion Operators:**



u,d,g,γ,W,Z

j,t,b,g,γ
e/μ,τ,ν,W,Z,h

However: VBS/Mutliboson needed to understand relationship of new physics to EWSB.

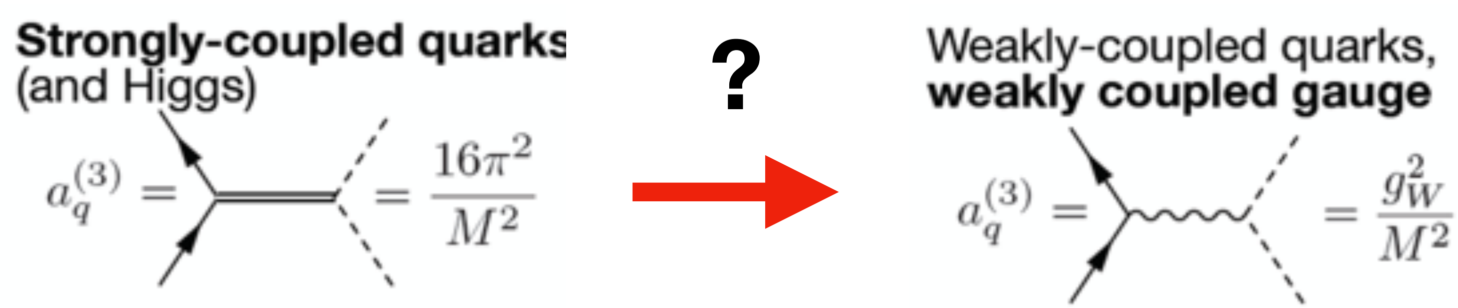
Talks: Agashe

Eichten, Lane, Peskin, PRL 50 (1983) 811

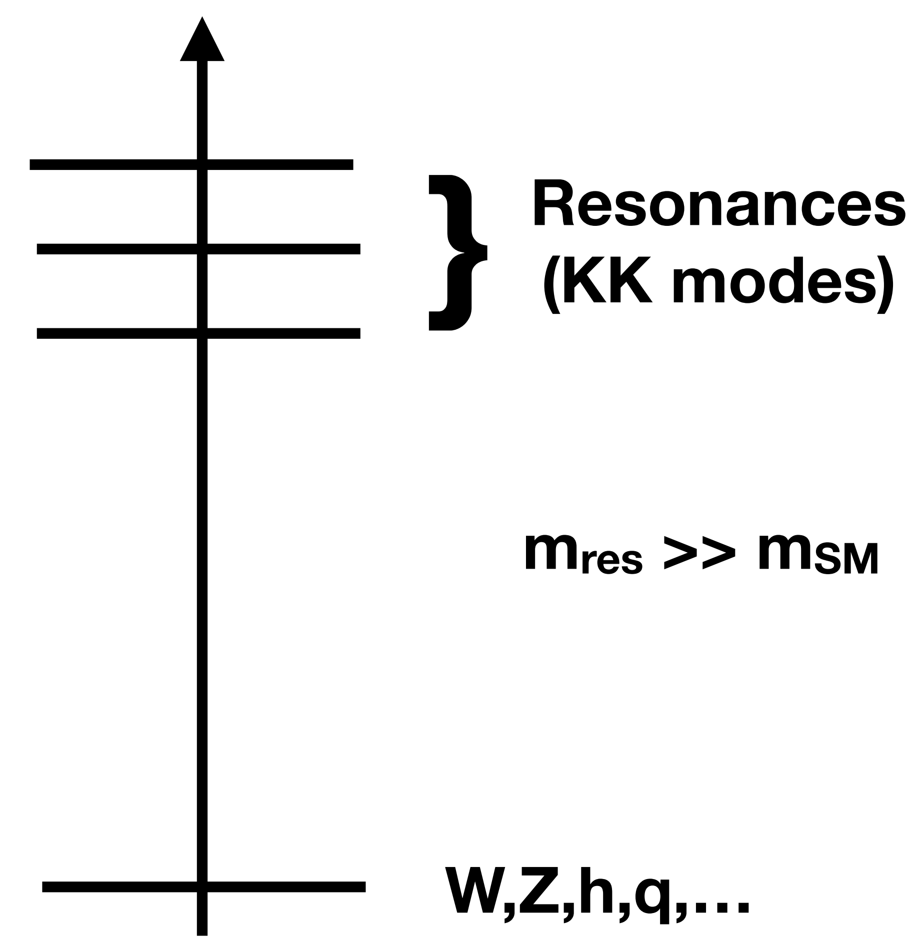
Are we forced to have weak coupling to composite sector?

1. Weinberg's Theorem: $m_{res}/m_{SM} \to 0$, vector bosons couple to conserved currents

2. In many models, large hierarchy (large-N, etc.) associated with weak coupling of composite states.



Composite Spectrum



Utility of EFT: What question is being asked?

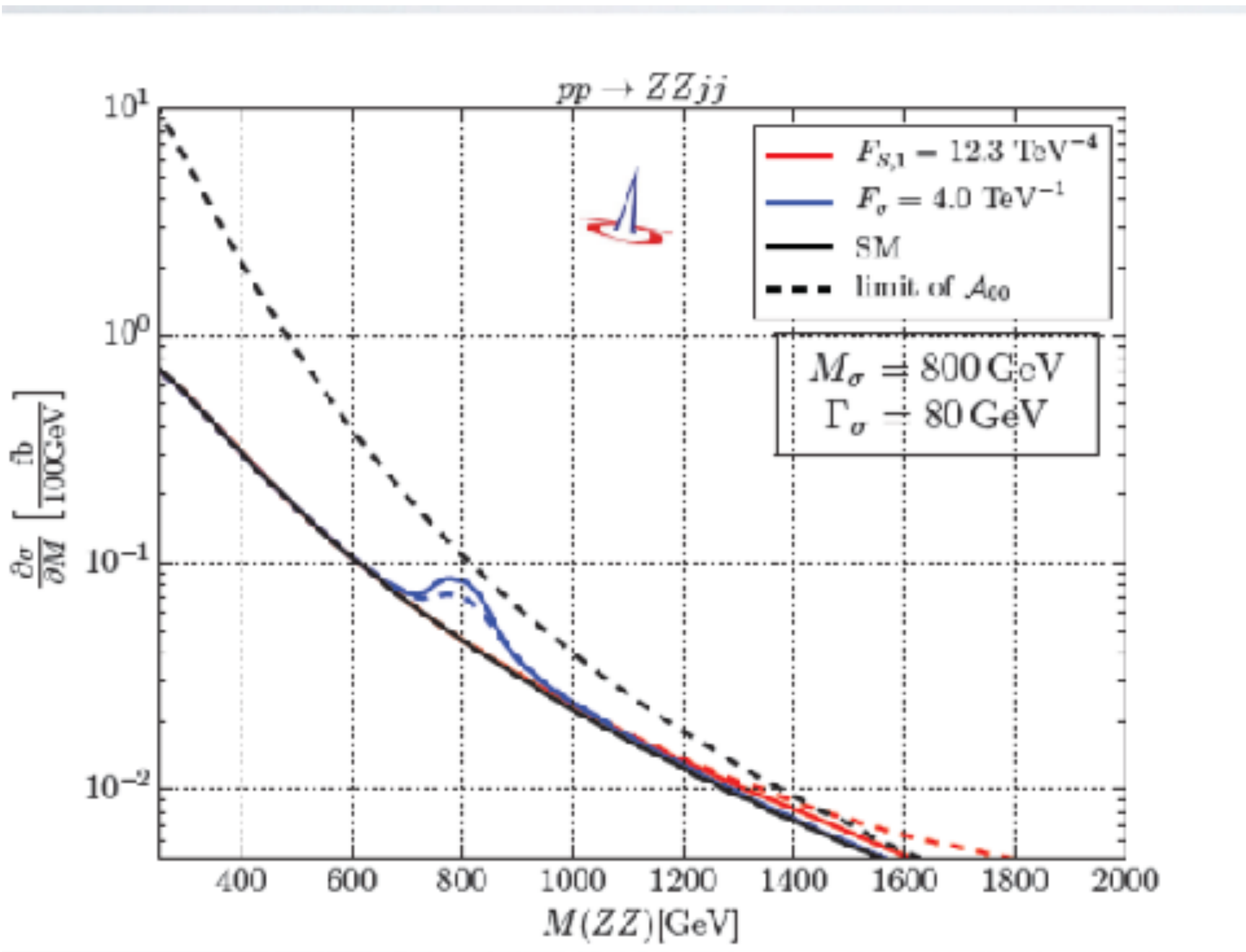
- Validation of SM: Need a self-consistent parameterization of deviations in experimental predictions from the SM to express how accurately SM describes the data. ***EFT sufficient - even one operator at a time.***

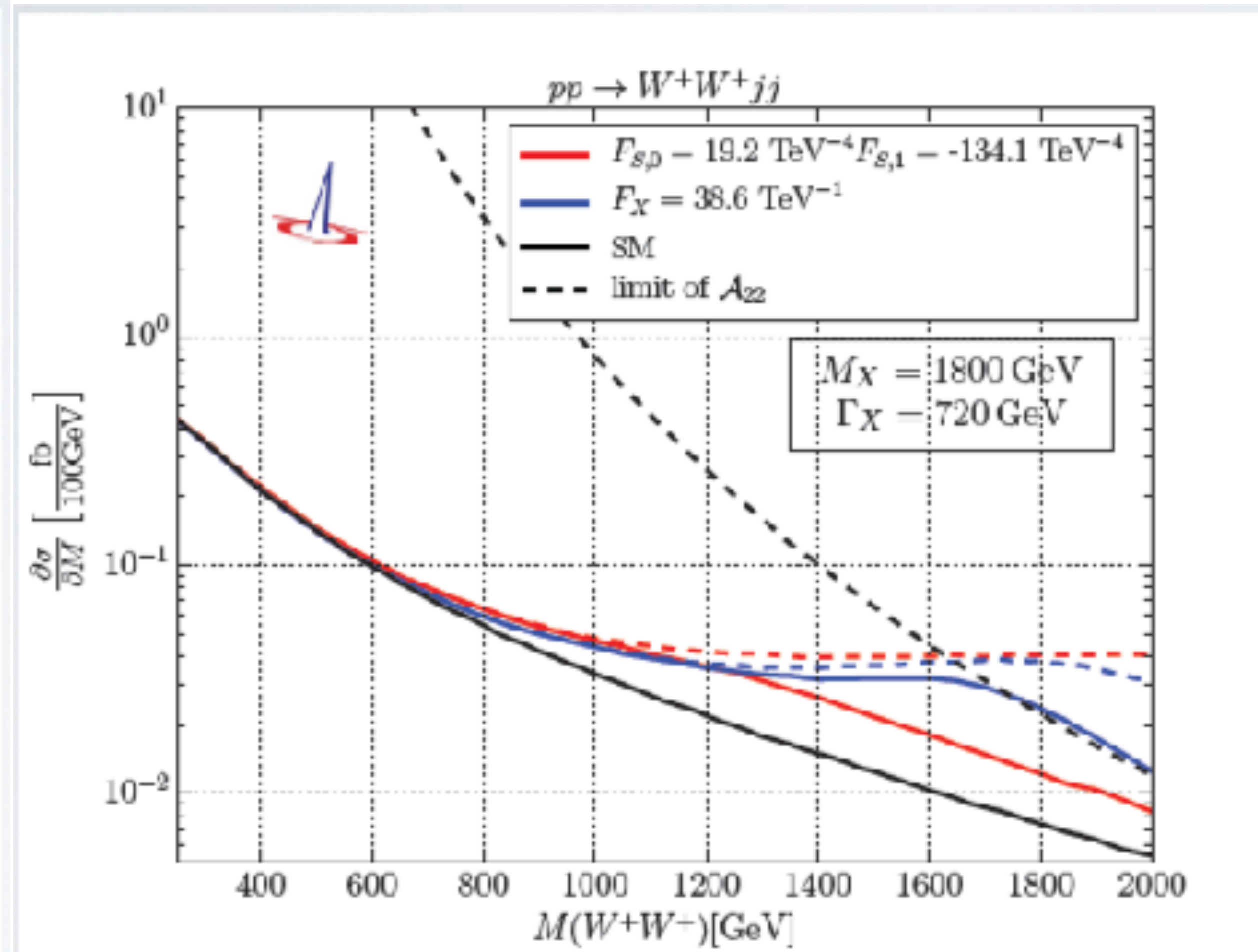
- Limits on New Physics: Need a self-consistent parameterization of an (arguably) complete set of possible deviations from the SM, to probe multiple distributions and look for various possibilities. ***EFT sufficient - preferably with multiple operators. (Beware of "blind directions")***

- Characterize Observed Deviation: Interpret correlation of deviations in terms a particular new physics model, include possible resonance. ***Simplified Limits more relevant.***

(Talks: Lewis, Gonçalves; Han)

Simplified Model vs. EFT





EFT breaks down if resonance is within kinematic reach…

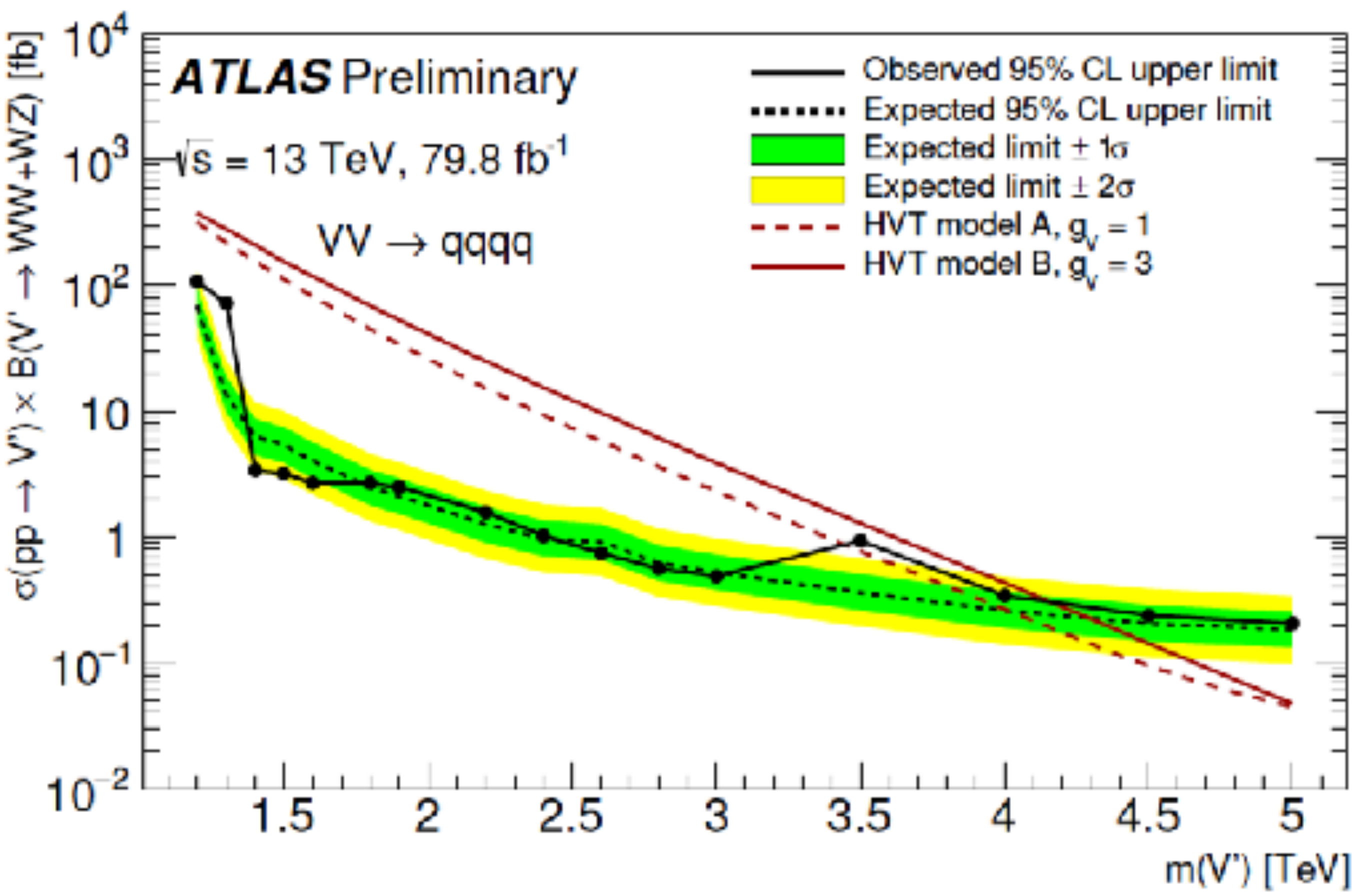
Kilian/Ohl/JRR/Sekulla: 1511.00022

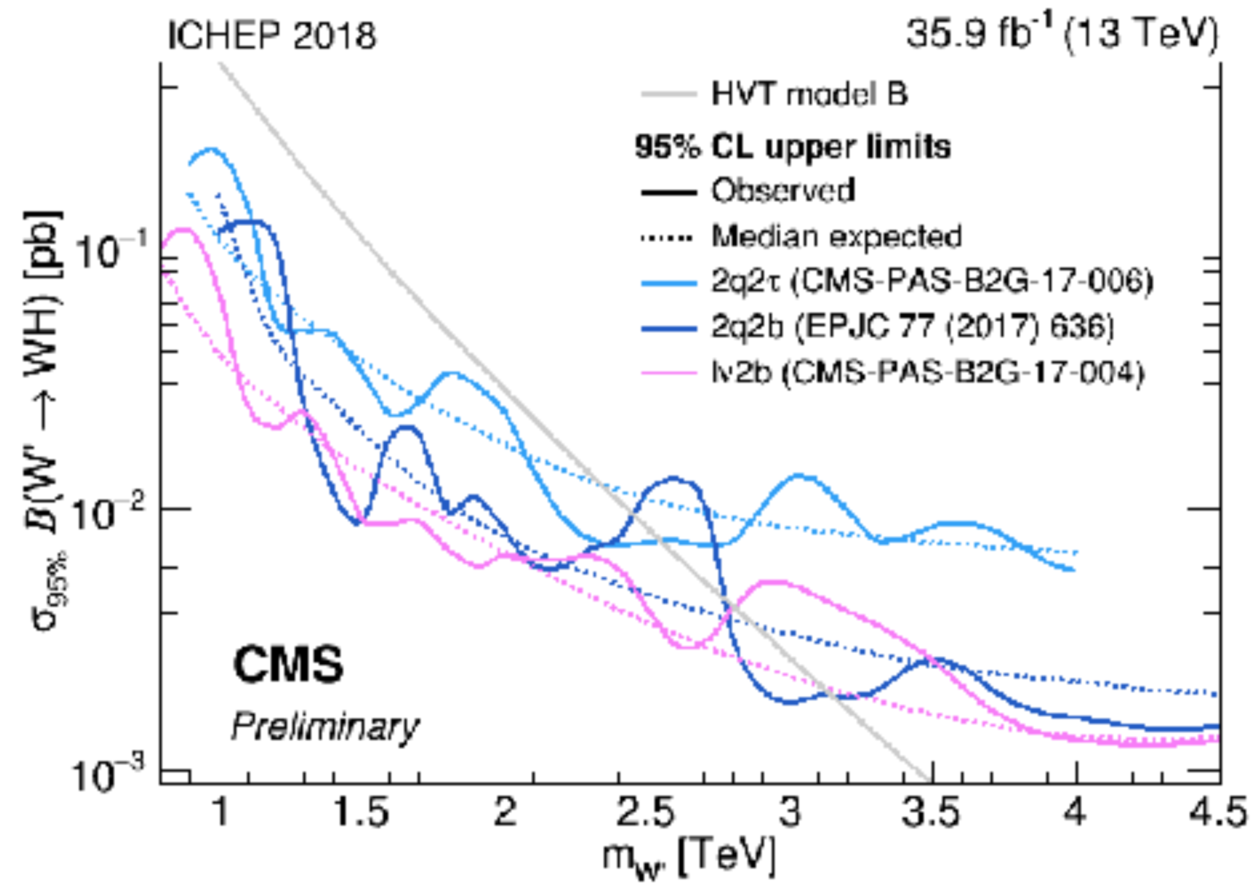
Brass/Fleper/Kilian/JRR/Sekulla: 1807.02512

Talk: Reuter

Resonances

Limits on Diboson (VV) Resonances



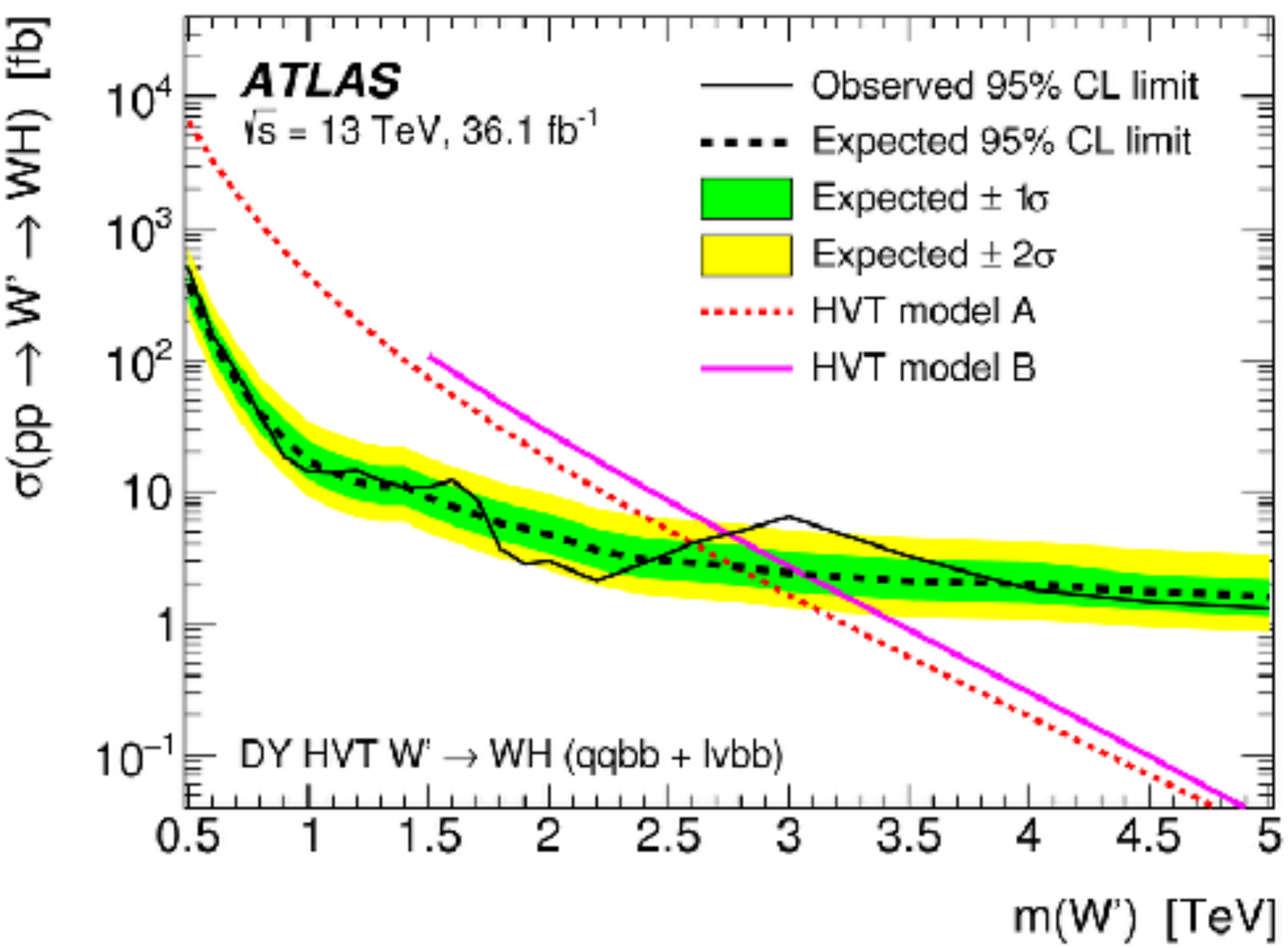


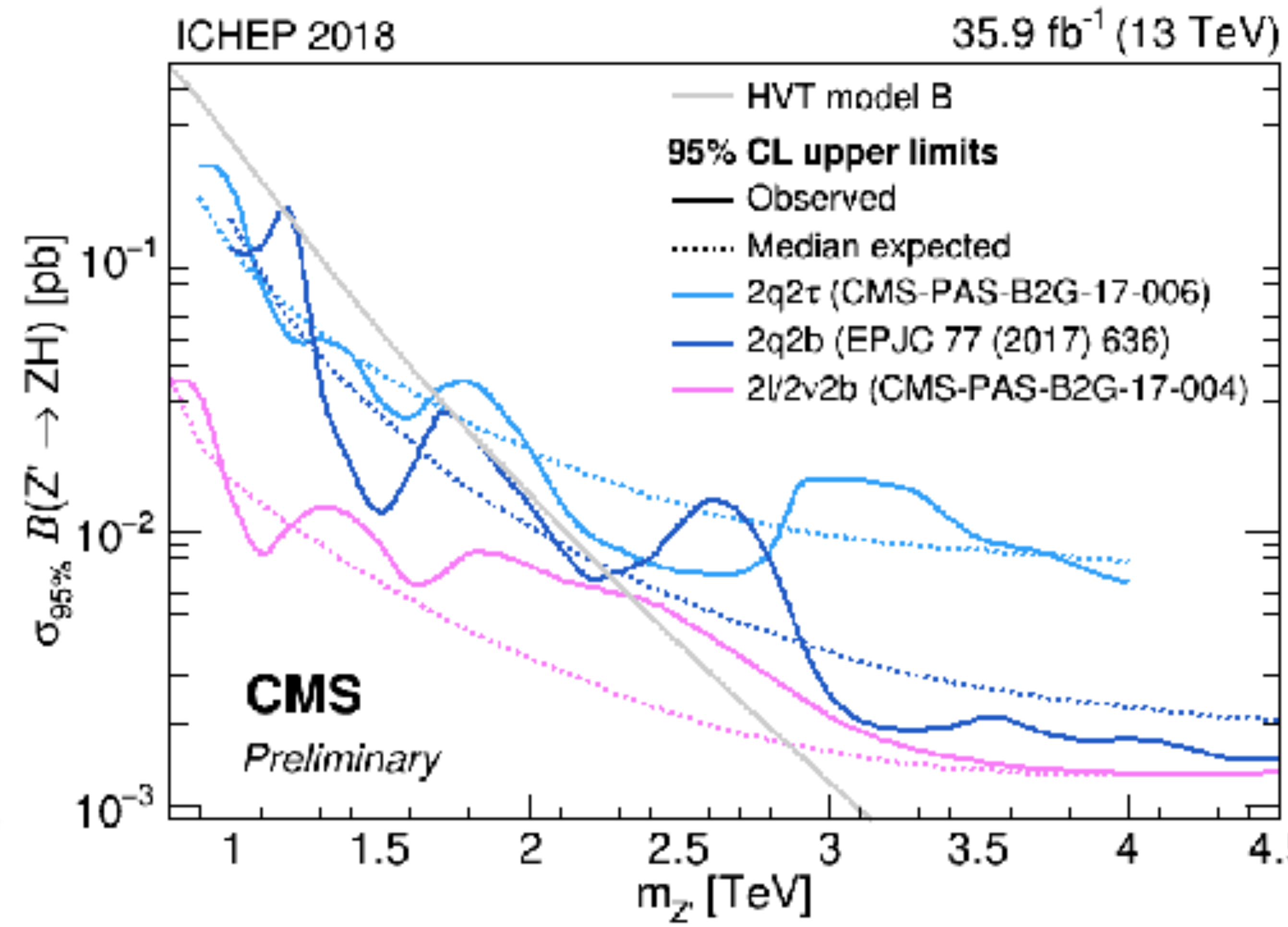
Boosted W/Z

ATLAS-CONF-2018-16, CMS ICHEP 2018

Talk: Damgov

Limits on Diboson (Vh) Resonances





Boosted W/Z

ATLAS: 1808.02380, CMS ICHEP 2018

Talk: Damgov

Bump Hunting … Stay Tuned

Excesses (or not?)

Mass [GeV]	ATLAS		CMS	
20	$\sim 3\sigma$ excess in $H \to Z_d Z_d \to$ 4leptons		N/A	
95	Not observed(w/1σ excess)		Local 3σ in $\gamma\gamma$	
250	Local 3.6σ in 4L		Good agreement(w/1σ excess)	
400-450	Local 3.6σ in bbA$\to$Zh @450GeV	Not observed in 4b, $\sim 1\sigma$ in bb$\gamma\gamma$ and bb$\tau\tau$	$\sim 2\sigma$ in bbA$\to$Zh but @400GeV	$\sim 2.6\sigma$ excess in 4b@450GeV But not observed in bb$\gamma\gamma$, bb$\tau\tau$
400-500	Local 3σ in VBF WZ$\to$lvll (not observed in lvqq and llqq)		N/A	
700	Local 3.6σ in 4L	Not observed in llvv channel	No excess observed	

Talk: Nobe

TriBoson

Status and Prospects

- **Channels currently observed: *Z(→ll)γγ***
  - 1st unfolded distribution to pursue?
- **Channels with evidence: *W(lν)γγ***
  - 5-sigma observation at 13TeV?

- **Next evidence channels?**
  - W(lν) W(lν)γ possibly first evidence channel with two heavy vector bosons (S/B~1)
  - Z(νν)γγ, S/B>0.5, also golden channel for aQGC among triboson
  - WWW with semi-/fully-leptonic combination?

- **Other low-bgd but also low-rate channels worth prioritization?**
  - lνllγ (WZγ), lνlνll (WWZ) , 4lγ (ZZγ), lνllll (WZZ), 6l (ZZZ), …
- **High background channels to attack…**
  - 2l2jγ (ZVγ), 4l2j (ZZV), lνlljj (WZV), 2l2b2j (ZZV), …

Talk: Shu

VBS Redux

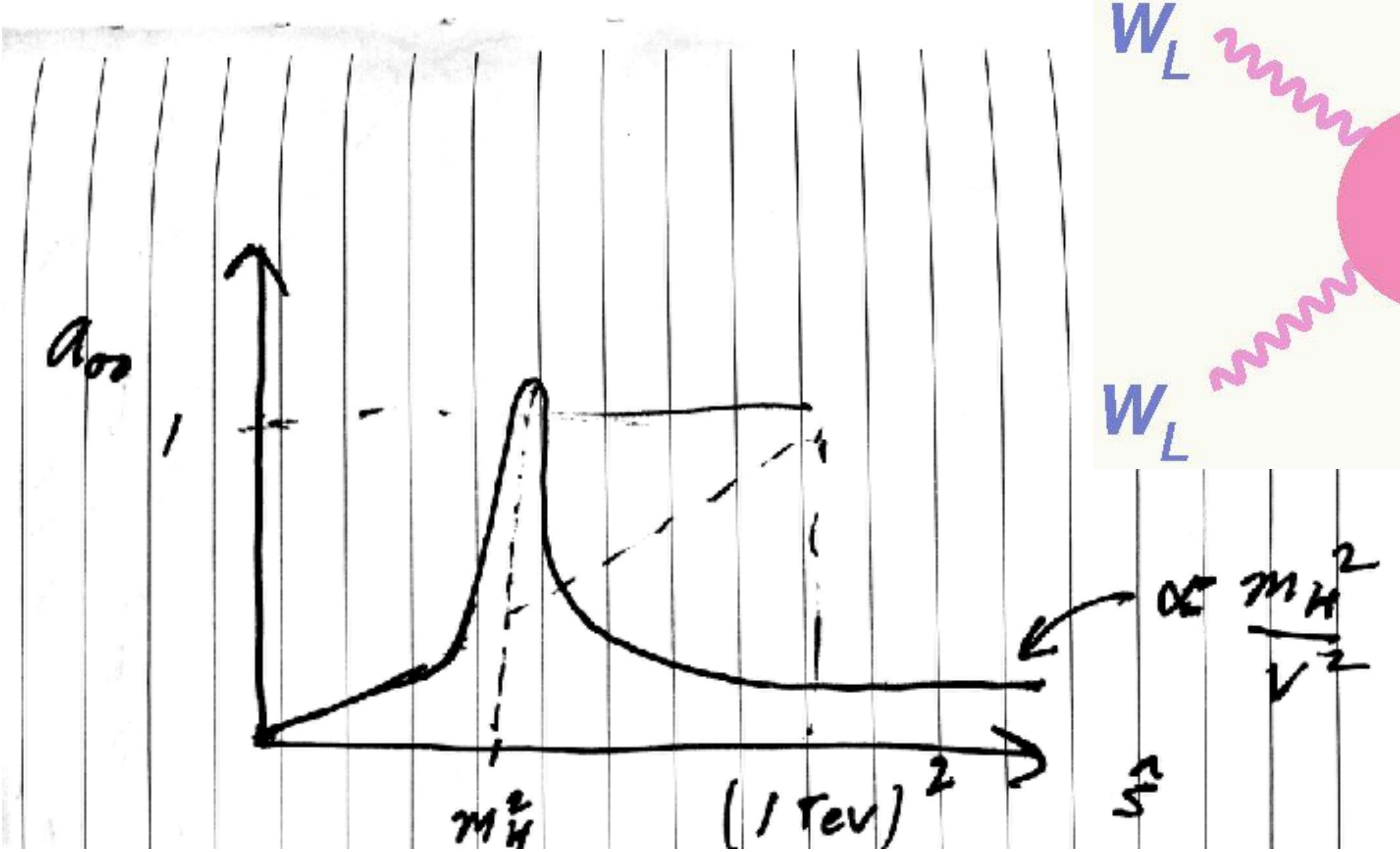
Questions Remain

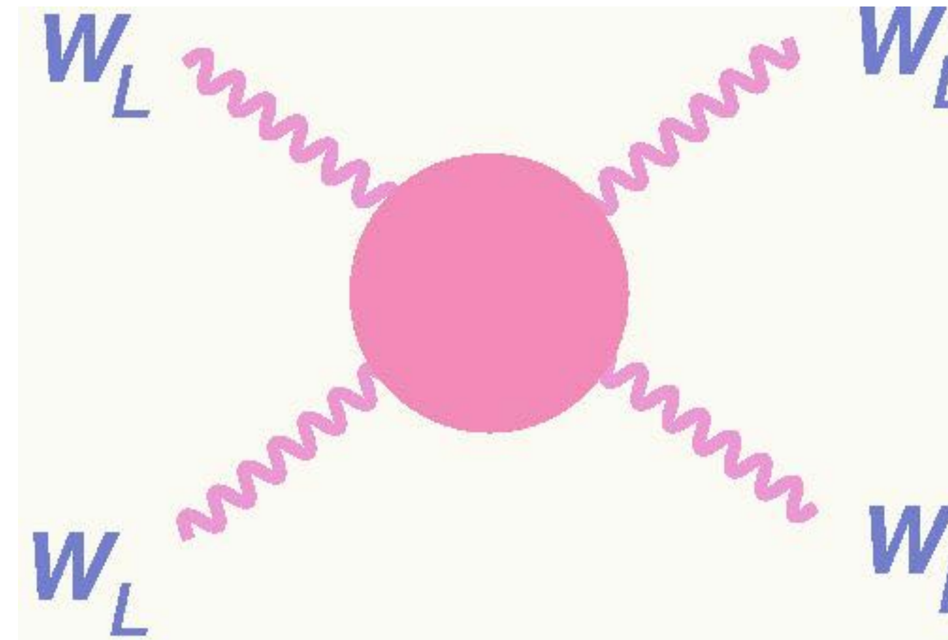
- Discovery of a light Higgs boson leaves still open questions:

1. Nature of Electroweak Symmetry Breaking
2. Higgs boson potential, all the way like the Standard Model!?
3. Does it fulfill the US-fermion/Europe-boson rule?
4. Is the 125 GeV state the only resonance in the system of EW vector bosons?
5. How do EW vector bosons scatter? (true heart of weak interactions)
6. Is there something related to the Little Hierarchy problem (strong or weak)
7. Look for deviations in intricate cancellations of VBS amplitudes

Talk: Reuter

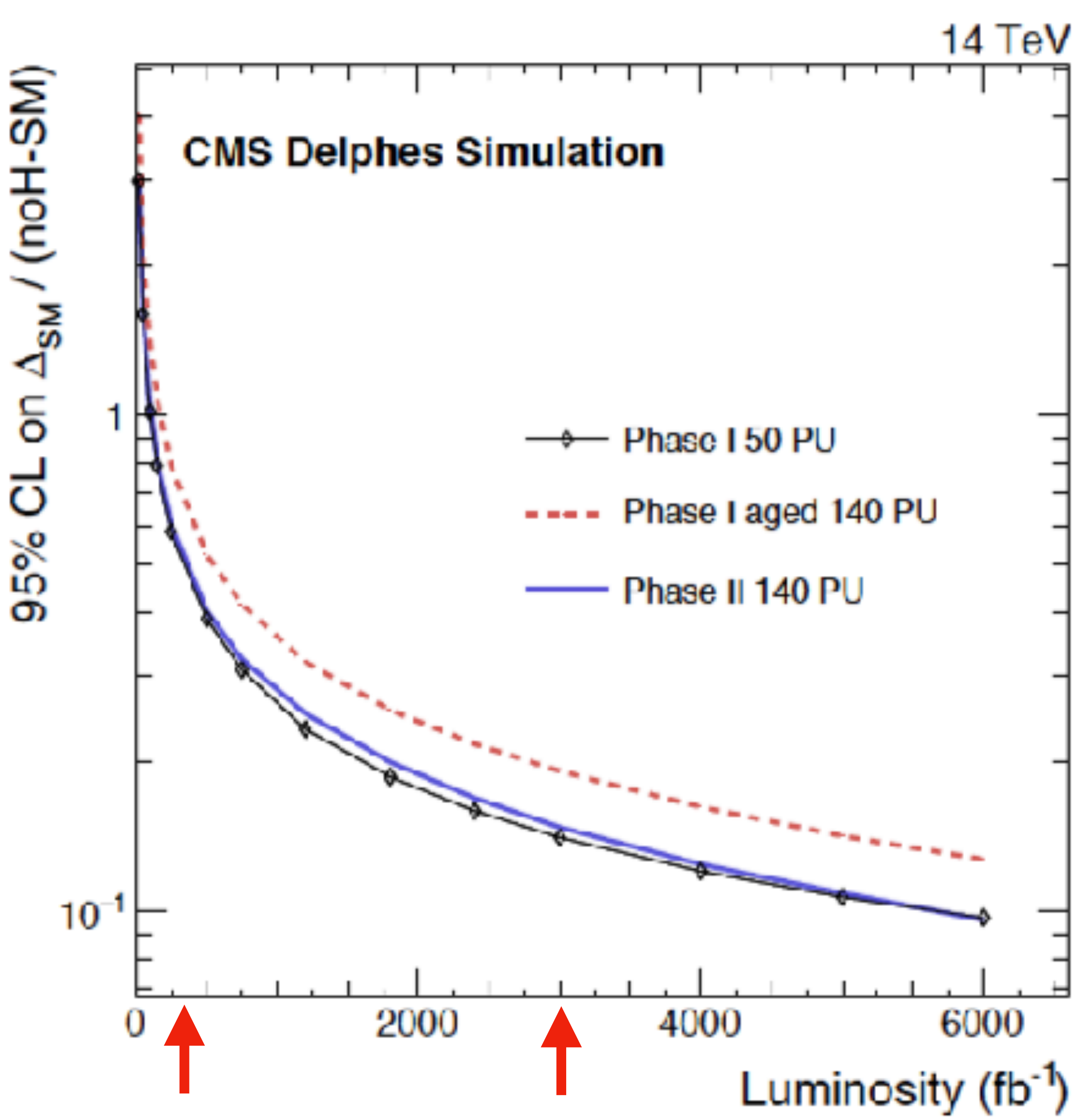
VBS - “High-Energy” Behavior

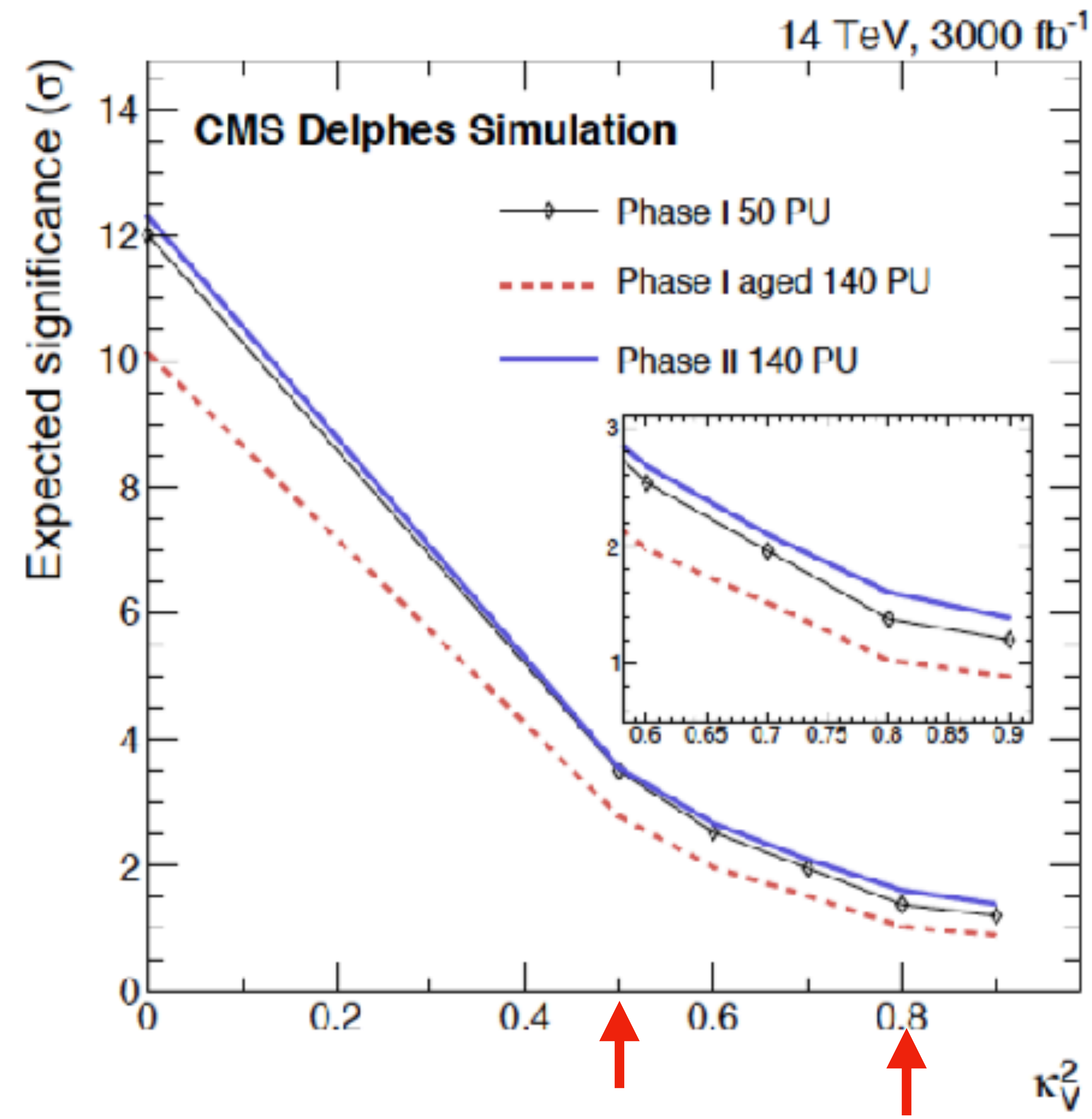




Can it be demonstrated that VBS is weak at high energies?

CMS Study of W± W±





~40% ~20% >50% @5σ >80% @2σ

Hat tip - Matt Herndon

CMS PAS SMP-14-008

Headline News 2025

Lessons and Questions

- EFT vs. Simplified Models - complementary, answer different questions, useful in different situations. Simplified models/ Resonance searches - do we have the right menu of models?

- In the precision multi-boson era, distributions (including especially polarization measurements) will yield much more information, allow different effects to be distinguished.

- VBS/MultiBoson not a discovery mode, but essential to understand relationship of new physics to EWSB.

- HL-LHC can answer whether h-exchange is responsible for the (majority of) $W_L W_L$ unitarization. We should present results in that way … and celebrate.

Thanks to all the organizers and to LCTP for a wonderful workshop!