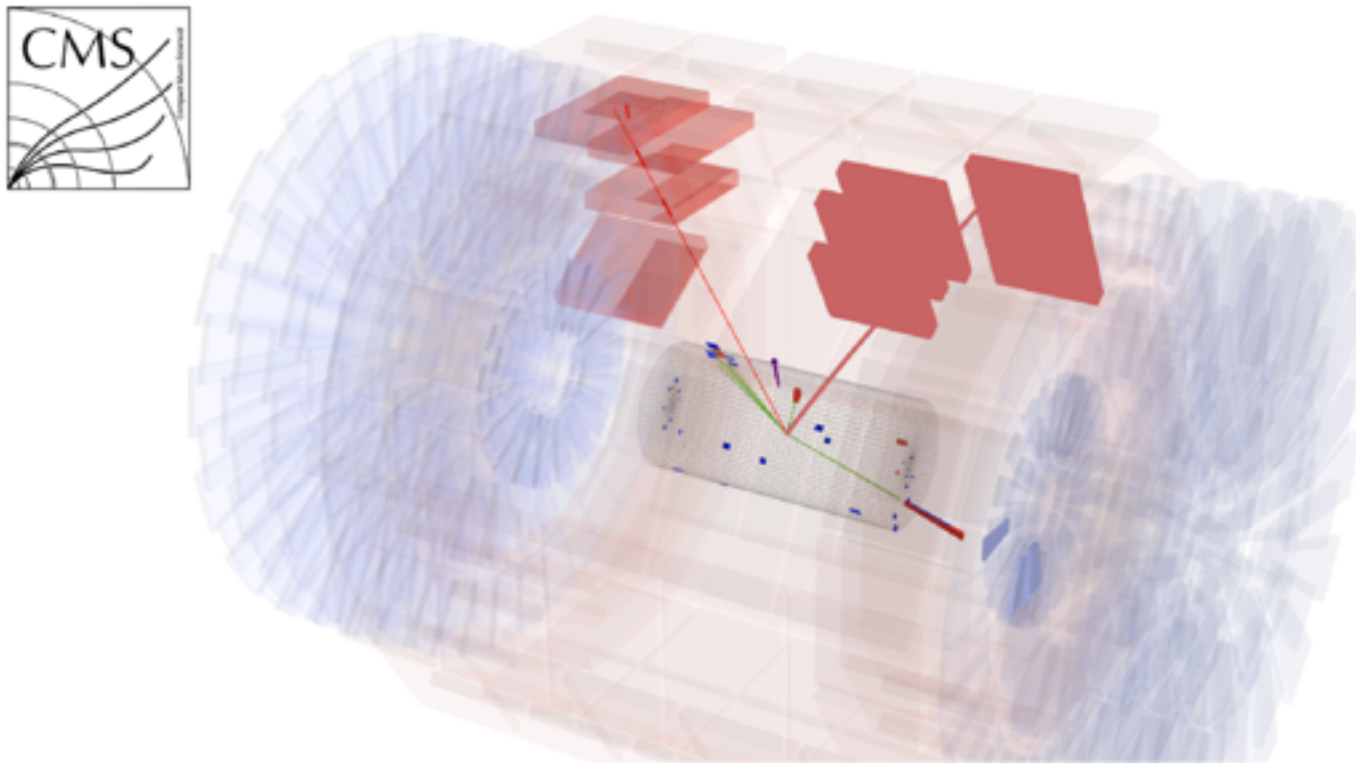
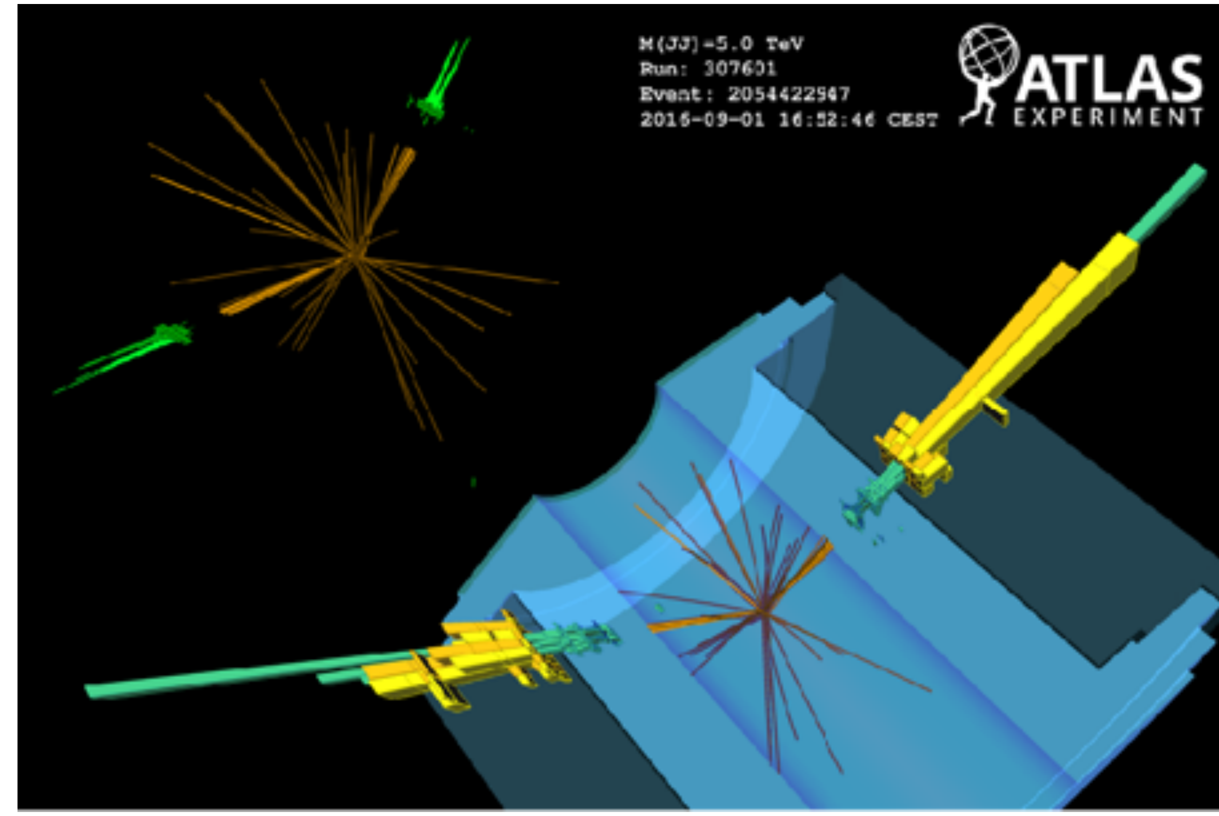
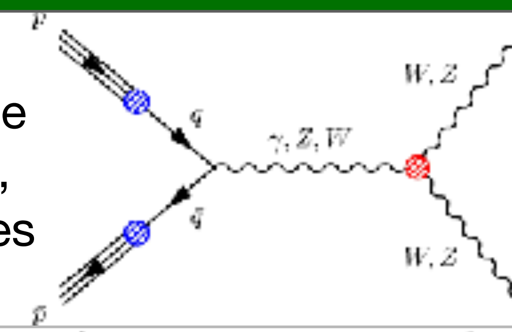
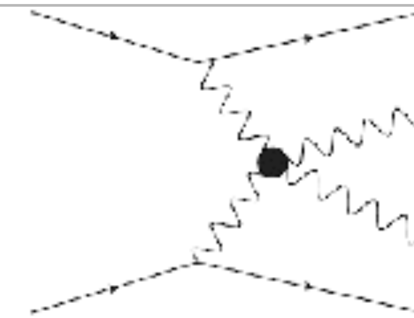
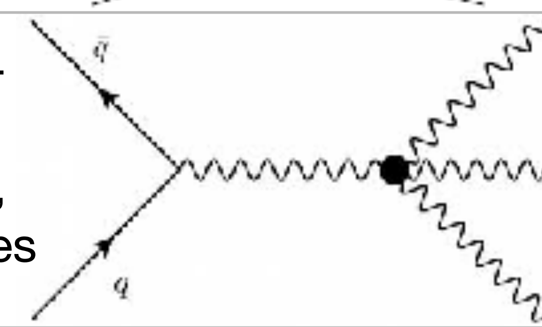
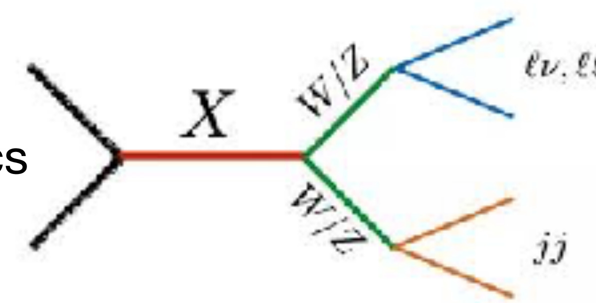




Multibosons at The Energy Frontier

R. Sekhar Chivukula
UC San Diego
July 25, 2019

Signals	Interactions/Physics	
Diboson: WW, WZ, ZZ, Wγ, Zγ, WH, ZH…	Triple-Gauge Couplings, EFT Analyses	
Vector Boson Fusion & Vector Boson Scattering	Electroweak Symmetry Breaking	
Triboson: WWγ, WWZ, ZZZ..	Quadratic-Gauge Couplings, EFT Analyses	
Resonances: WW, WZ, ZZ, Wγ, WH, ZH…	New Physics	

QCD Lagrangian

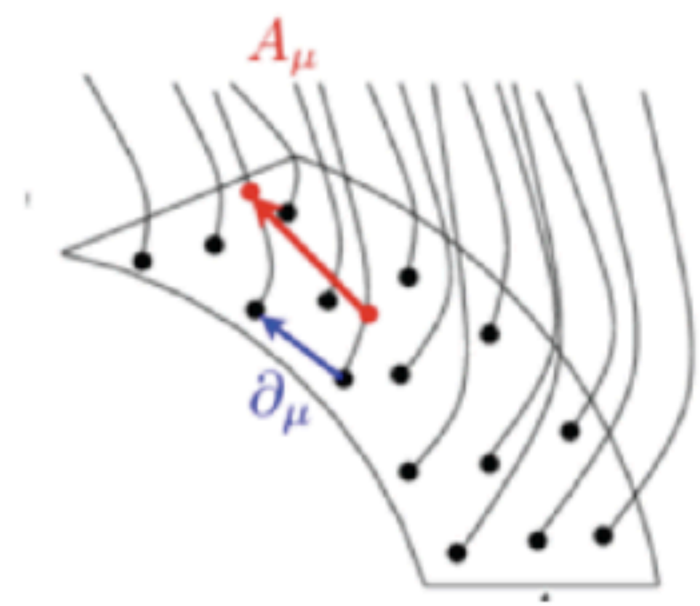
$$\vec{E}_a^2 - \vec{B}_a^2$$

$$J_\mu^a \cdot A^{a\mu}$$

$$L_{\mathrm{QCD}} = -\frac{1}{4} F_{\mu\nu}^{(a)} \; F^{(a)\mu\nu} + i \sum_q \overline{\psi}_q^i \; \gamma^\mu \; (D_\mu)_{ij} \; \psi_q^j$$
$$- \sum_q m_q \; \overline{\psi}_q^i \; \psi_{qi} \; ,$$

$$F_{\mu\nu}^{(a)} = \partial_\mu \; A_\nu^a - \partial_\nu \; A_\mu^a - g_s \; f_{abc} \; A_\mu^b \; A_\nu^c \; ,$$

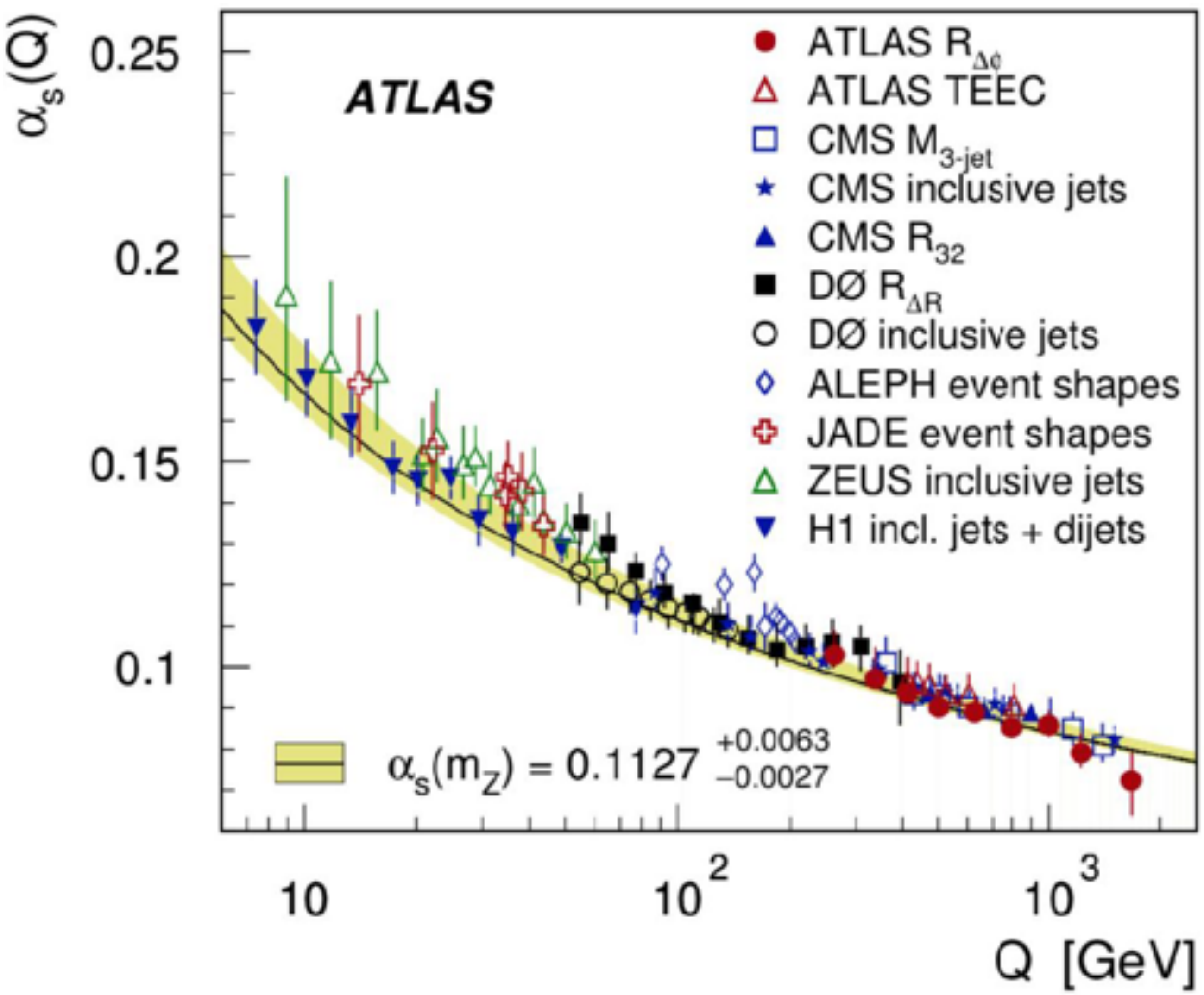
$$(D_\mu)_{ij} = \delta_{ij} \; \partial_\mu + i g_s \; \sum_a \frac{\lambda_{i,j}^a}{2} A_\mu^a \; ,$$



SU(3) gauge “symmetry”:
$$\psi_q(x) \rightarrow U(x)\psi_q(x)$$
$$A^\mu(x) \rightarrow U(x)A^\mu(x)U^\dagger(x) - \frac{1}{g_s}U(x)\partial^\mu U^\dagger(x)$$

Parameters: Quark masses and QCD coupling

Successes of QCD…



Running of α_S

Discovery of Three-Jet Events (40th Anniversary)

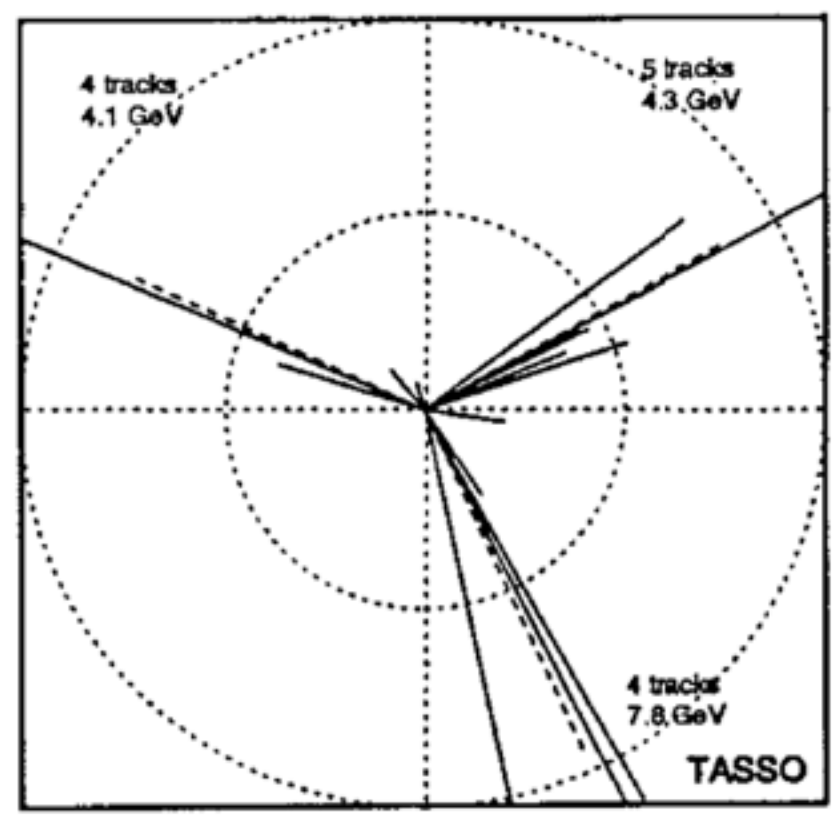
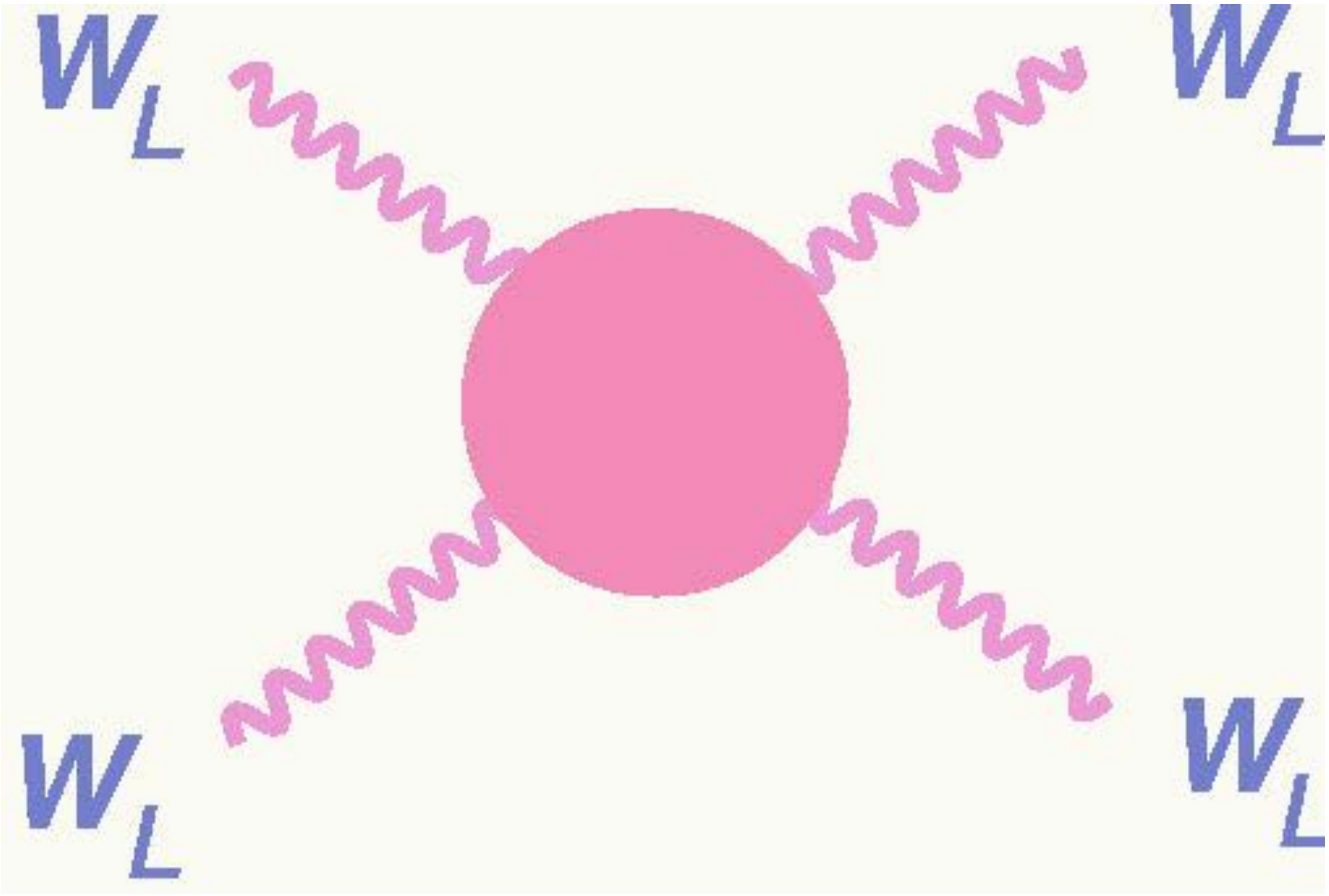


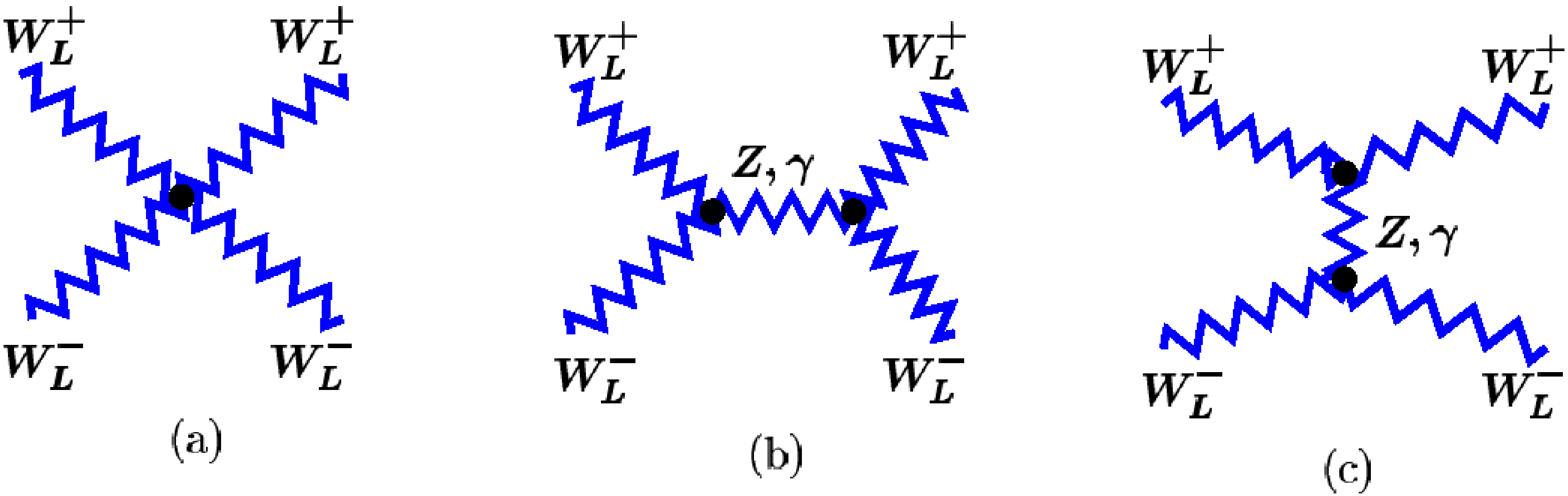
Figure 5: First three-jet event from PETRA. This event was shown in the Bergen Conference, June 1979

Vector Boson Scattering: A Signature Achievement of Run II at LHC

Consider Loss of Unitarity in



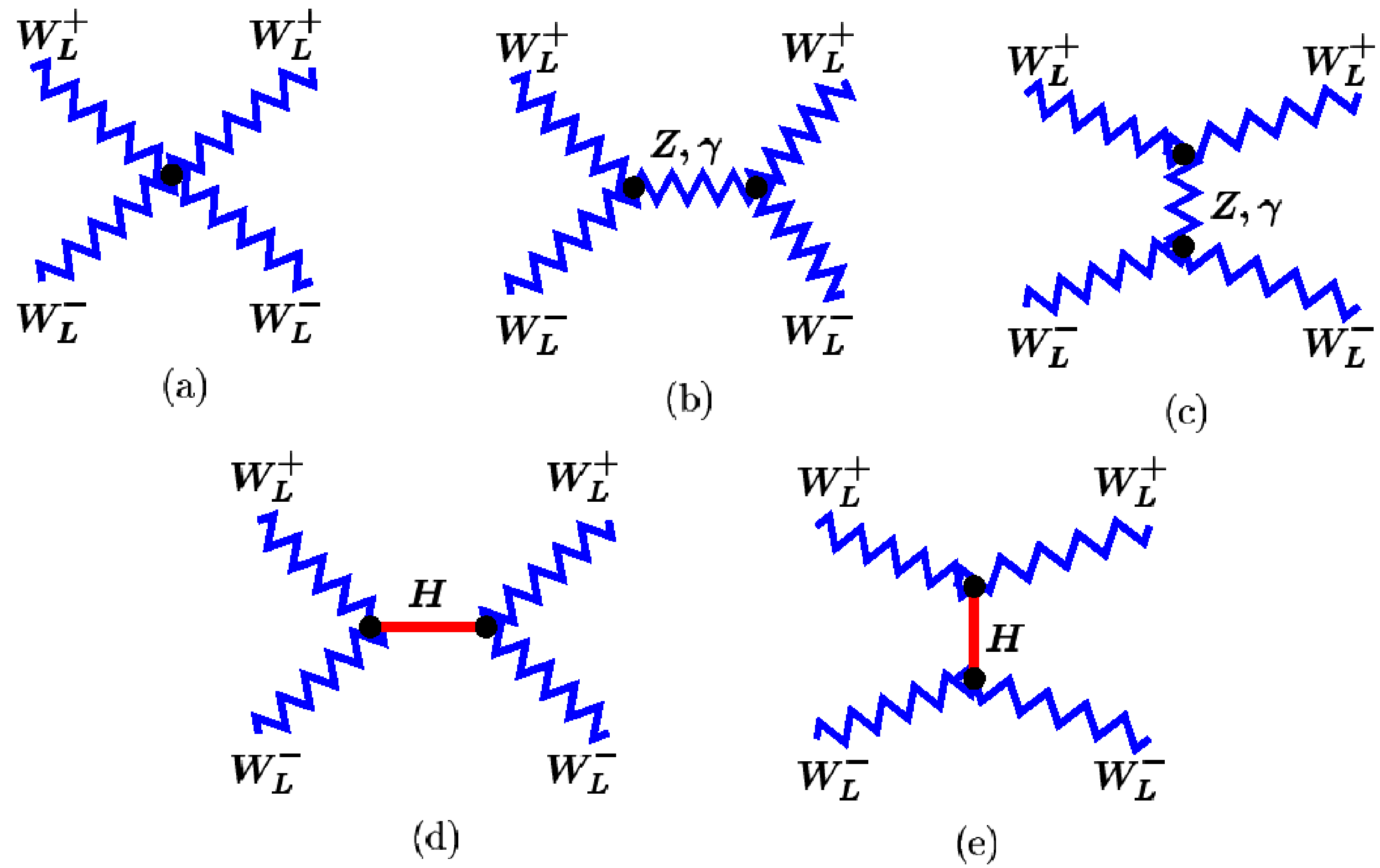
SU(2) x U(1) @ E^4



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

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

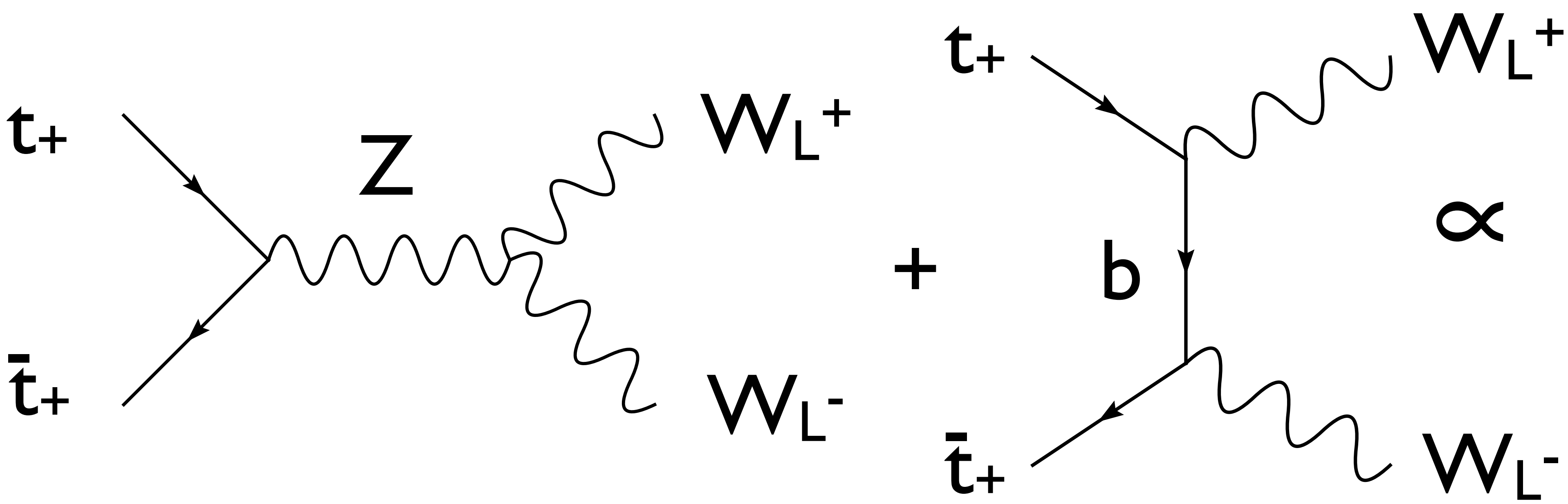
SU(2) x U(1) @ E^2



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**

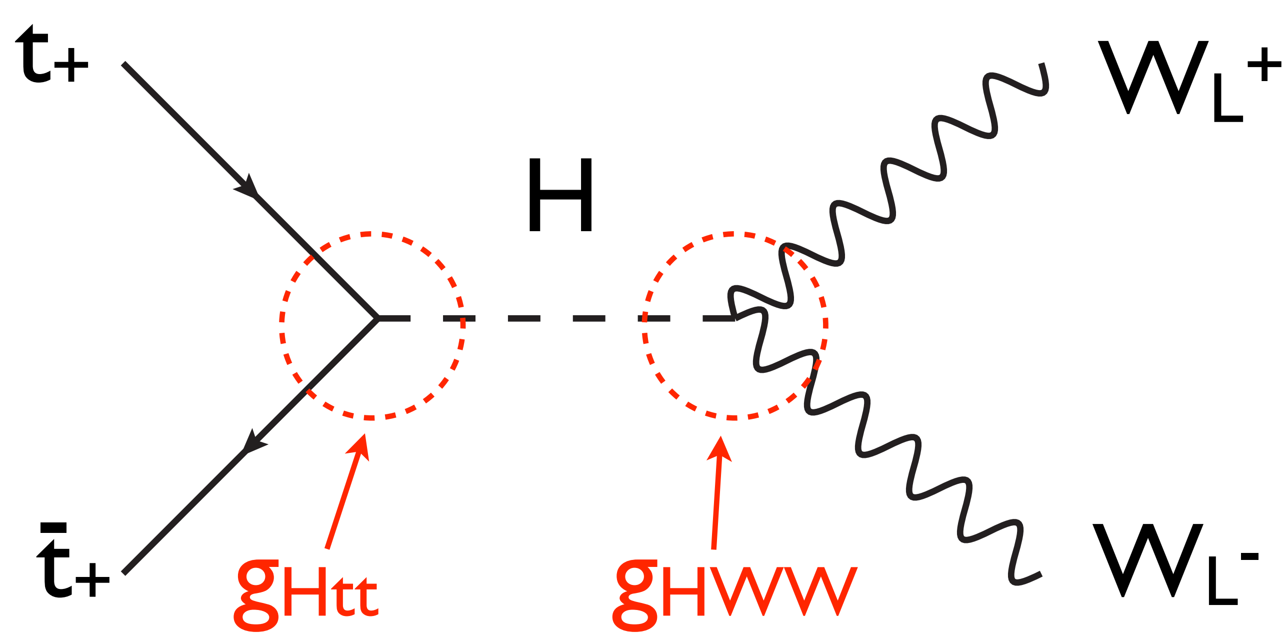
- $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound: $m_H < \sqrt{16\pi/3}\,v \simeq 1.0$ TeV
- If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow \quad E < \sqrt{4\pi}\,v \simeq 0.9$ TeV

Fermion Scattering



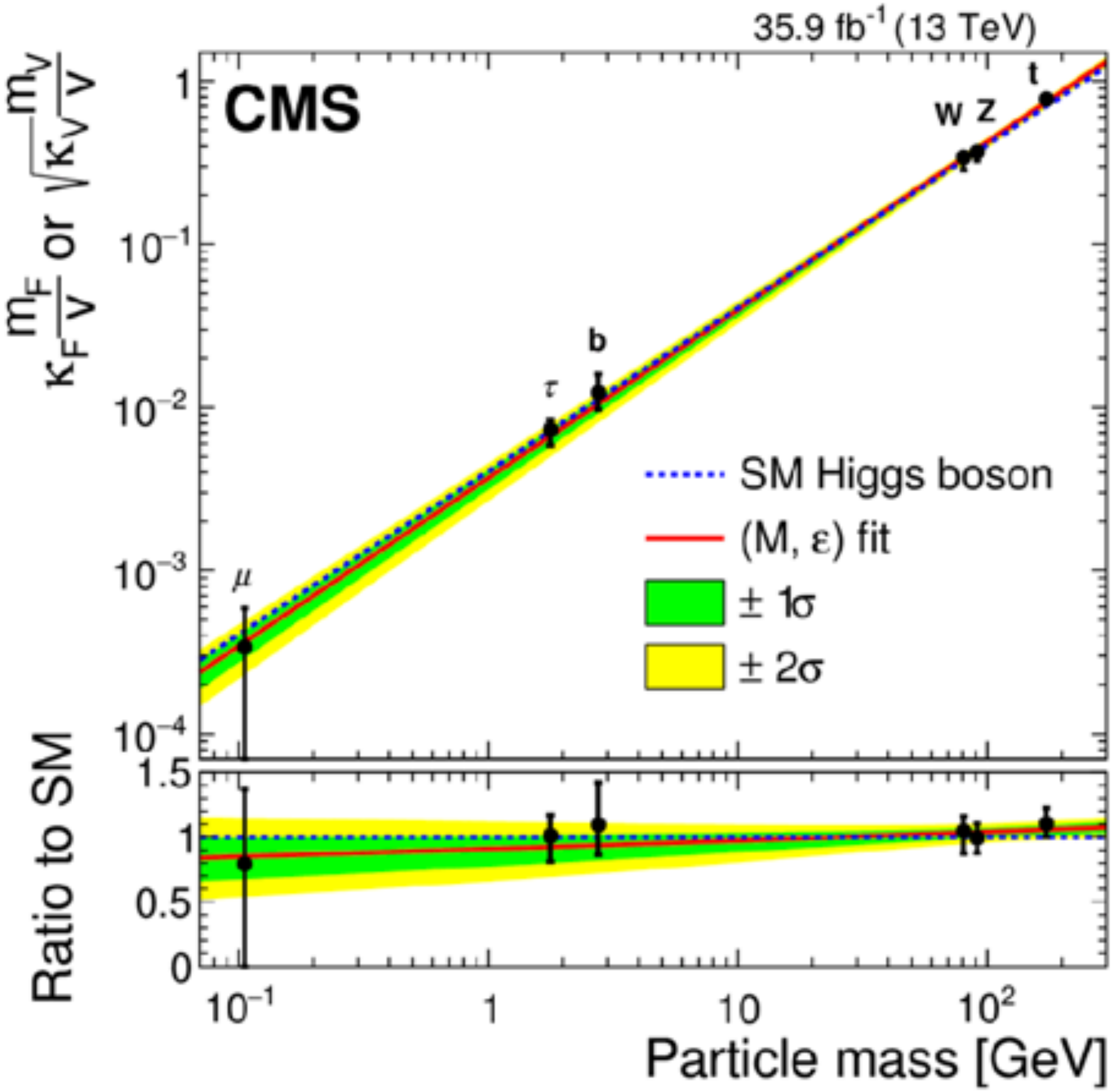
$$\propto \frac{m_t E}{v^2}$$

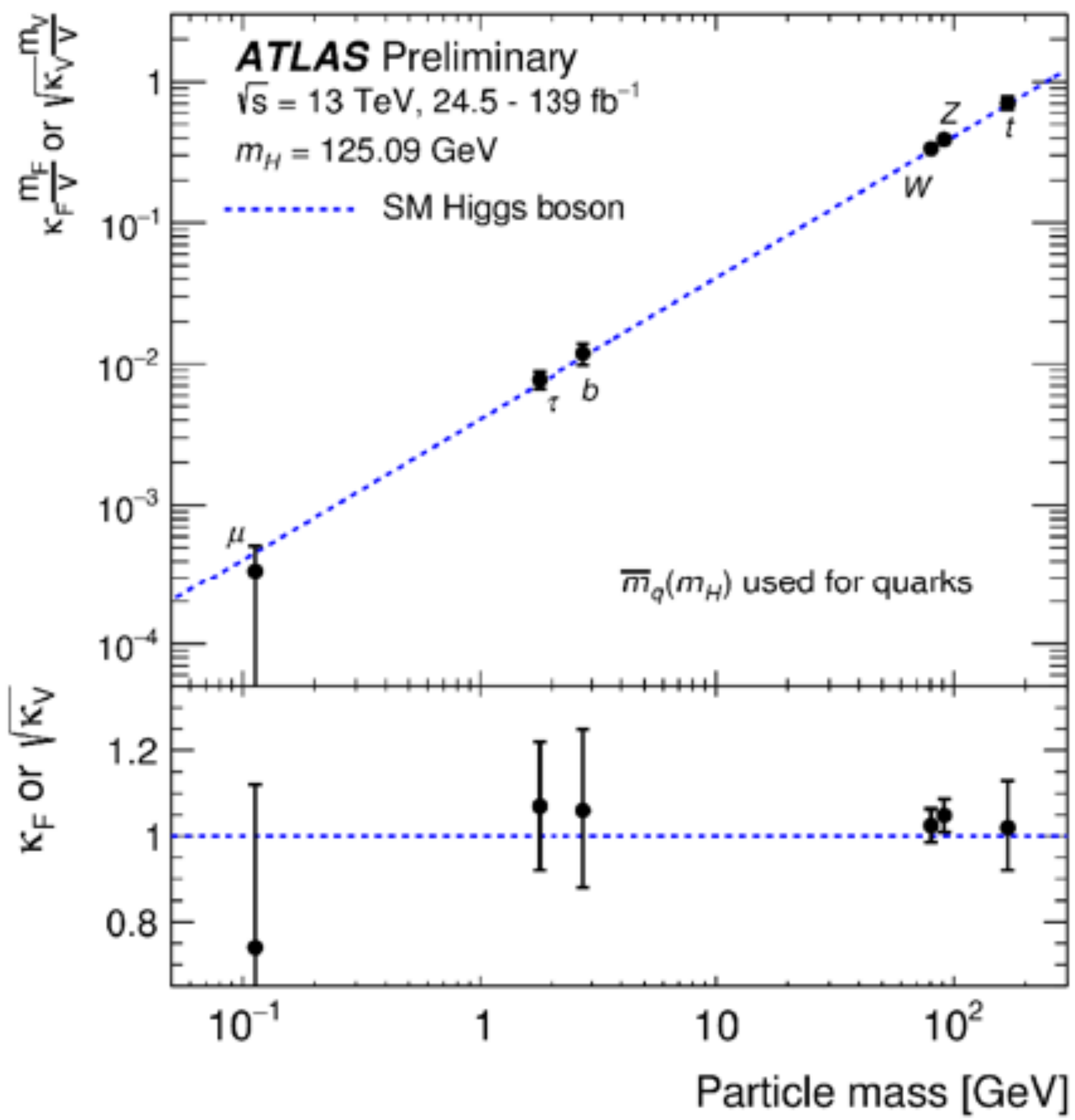
Bad high-energy behavior cancelled by:



Chanowitz, Furman, Hinchliffe

SM Coupling Relations

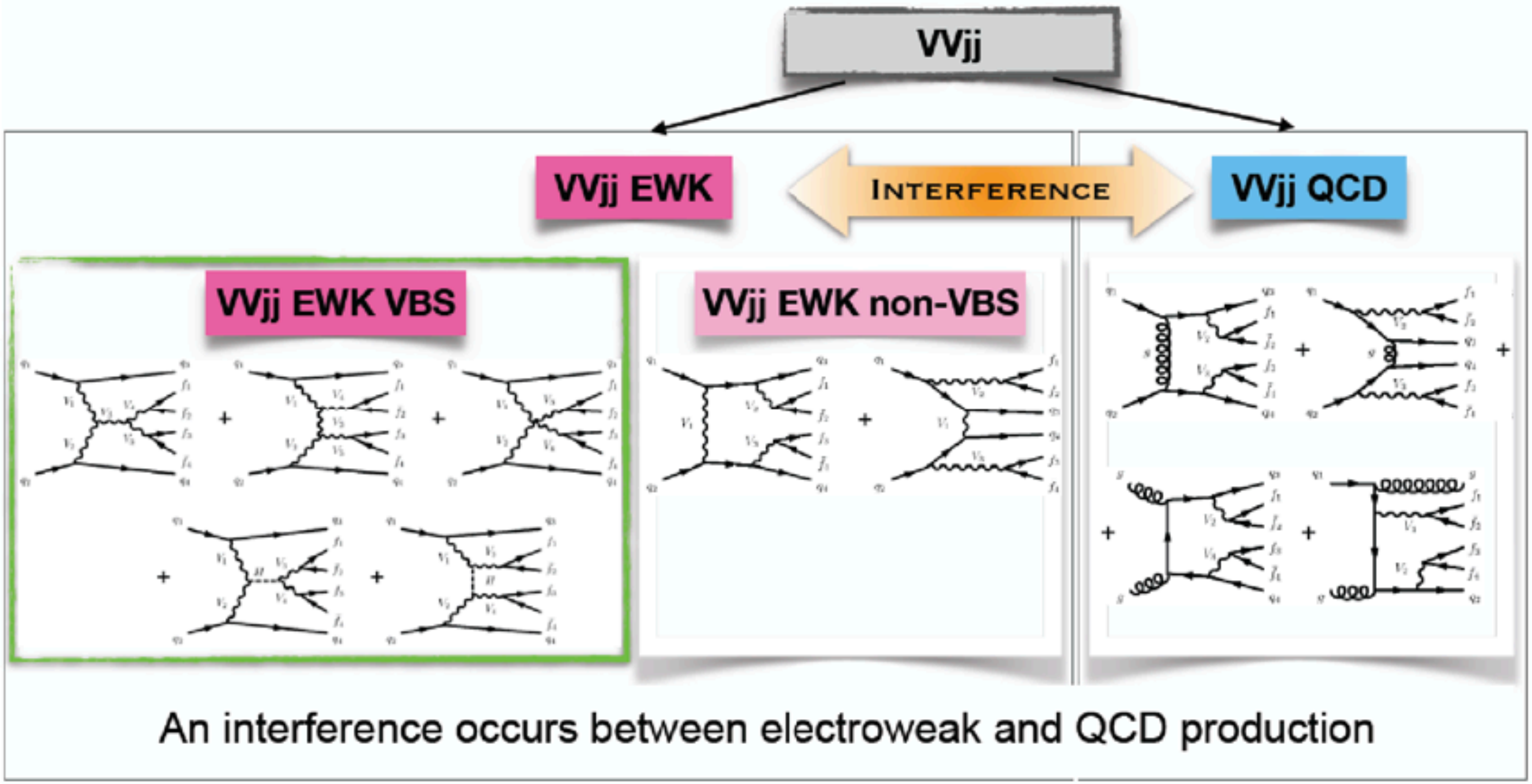




Questions Remain in Electroweak Sector

- **Is this Higgs THE (one and only) Higgs?**
  - Are there other states associated with a light Higgs boson, e.g. SUSY partners, vector-like quarks (especially states related to top), heavy vector resonances coupling to dibosons?
  - Are the EW multi-gauge couplings SM-like?
  - Are there other states involved in EWSB, which would show up in VBS?
- Can we measure the three-Higgs coupling, and begin to constrain the potential? (HL-LHC…)

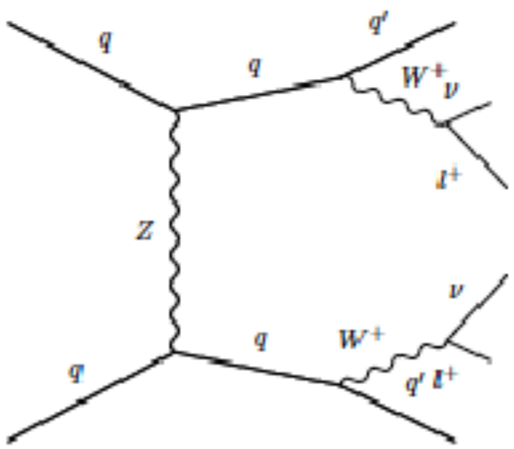
VBS - Signal and Bkgd

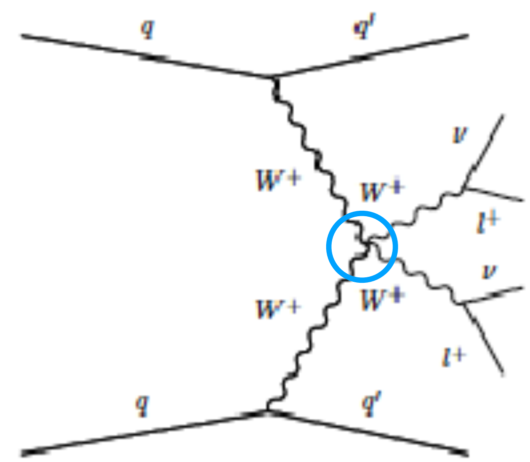


VBS: W± W±jj @ ~20%

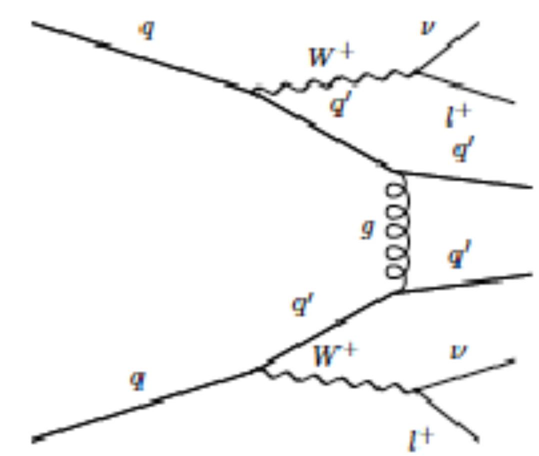
Electroweak:

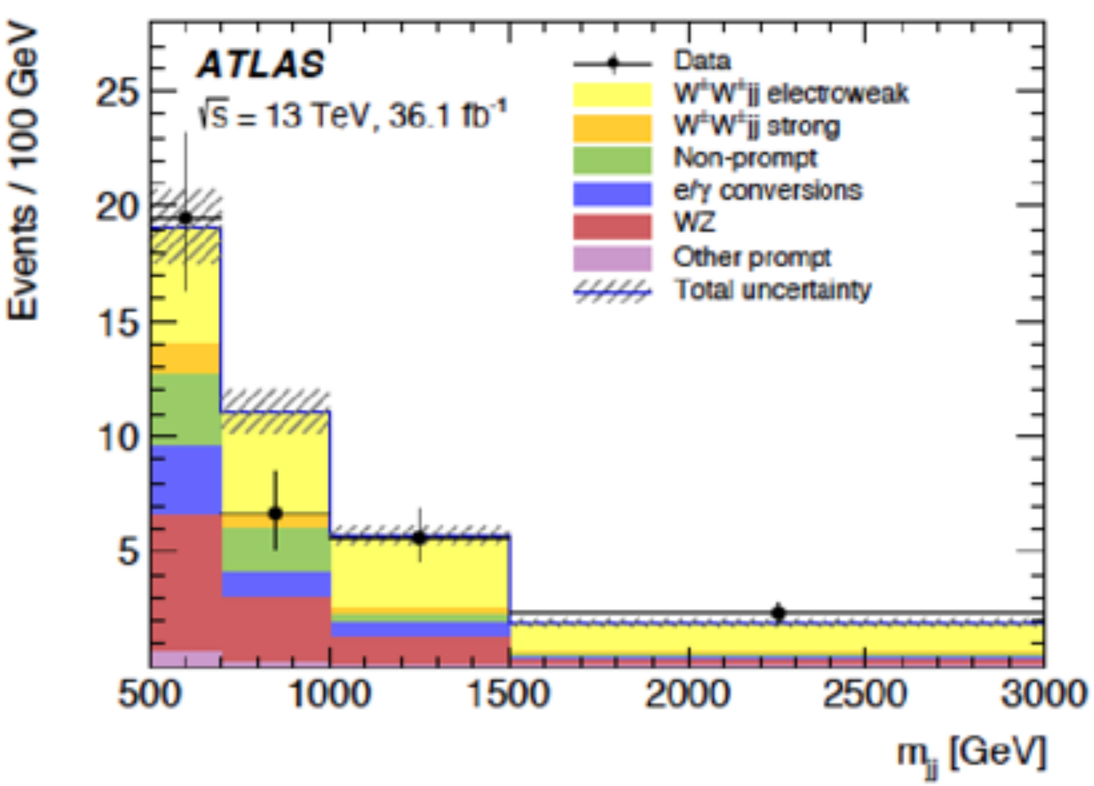
+ t-channel h-exchange

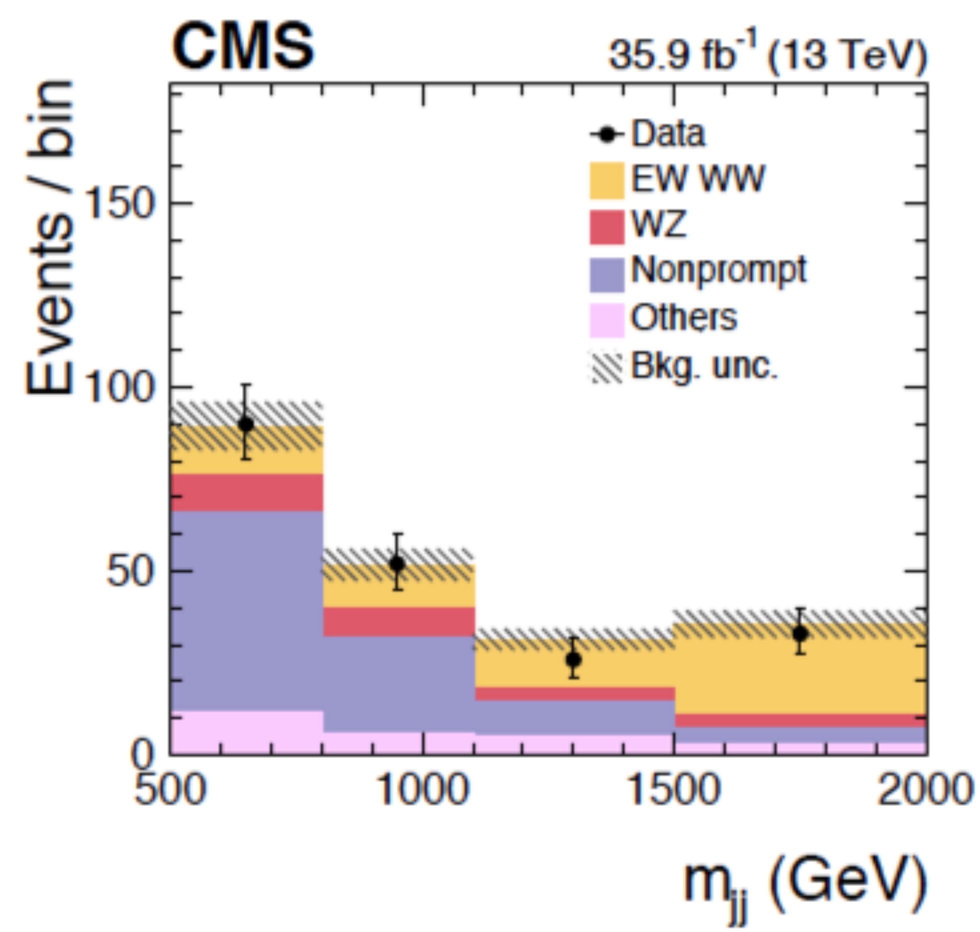




QCD:



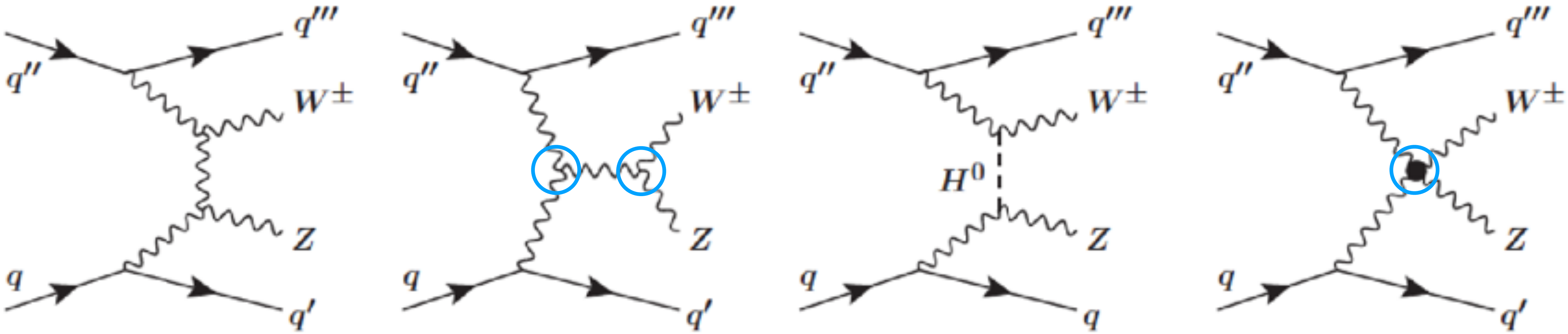


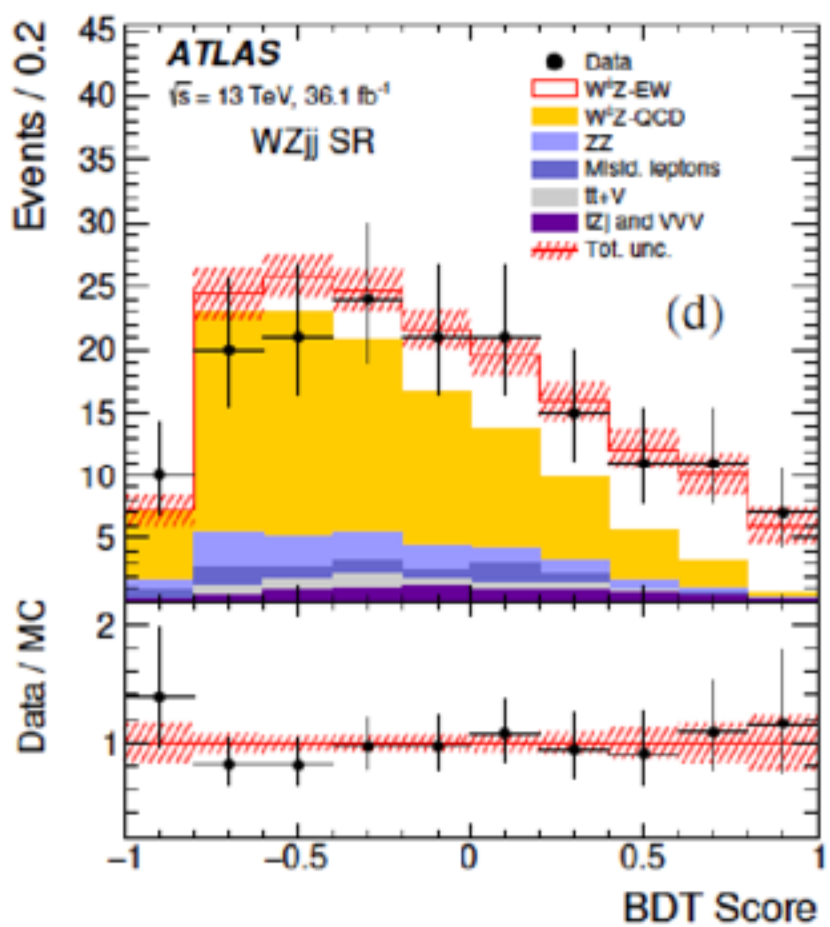


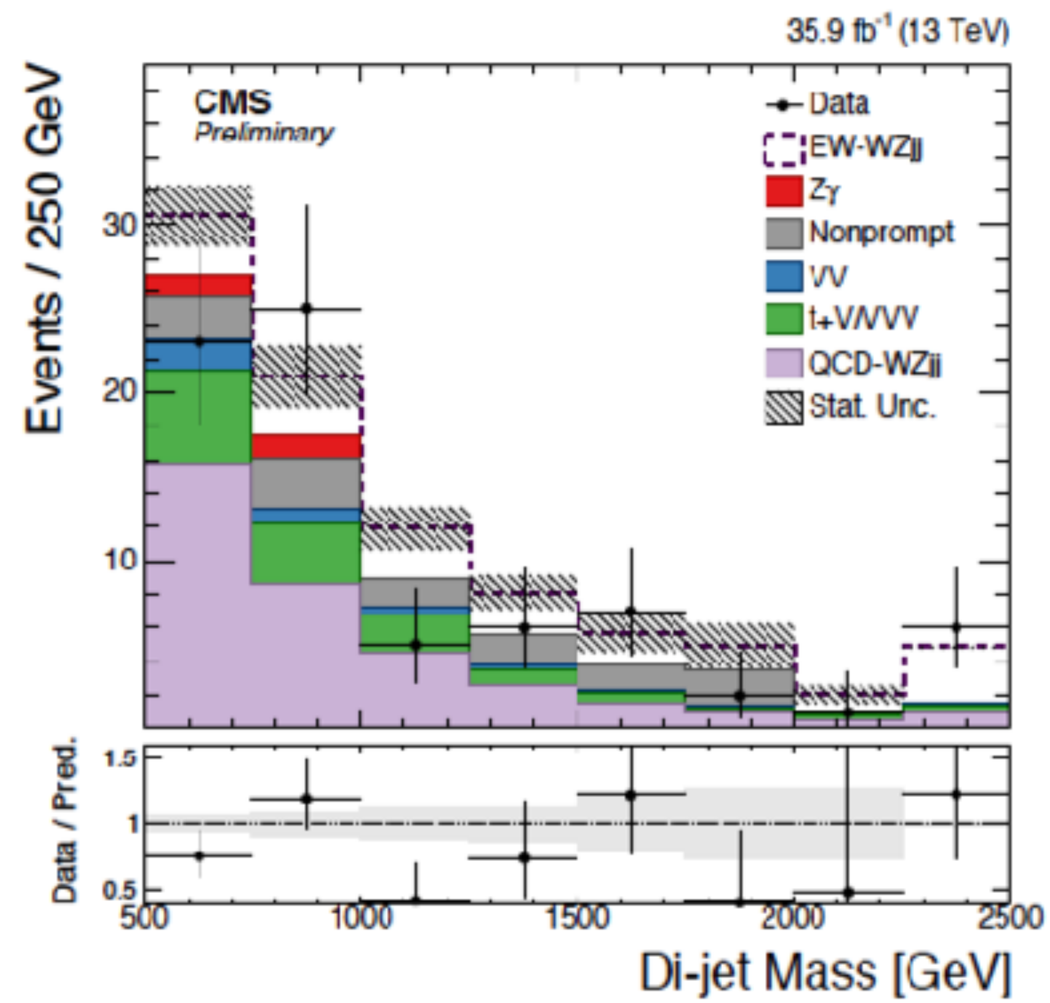
Chanowitz and Golden, PRL 61, 1053 (1988)
CMS: 1709.05822, ATLAS: 1906.03203

VBS: WZjj @ ~25%

(EW VBS signal only)

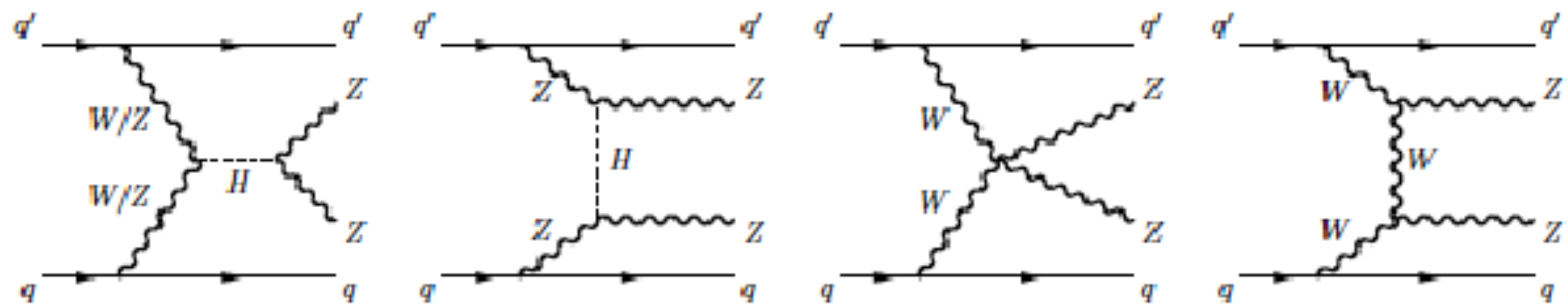


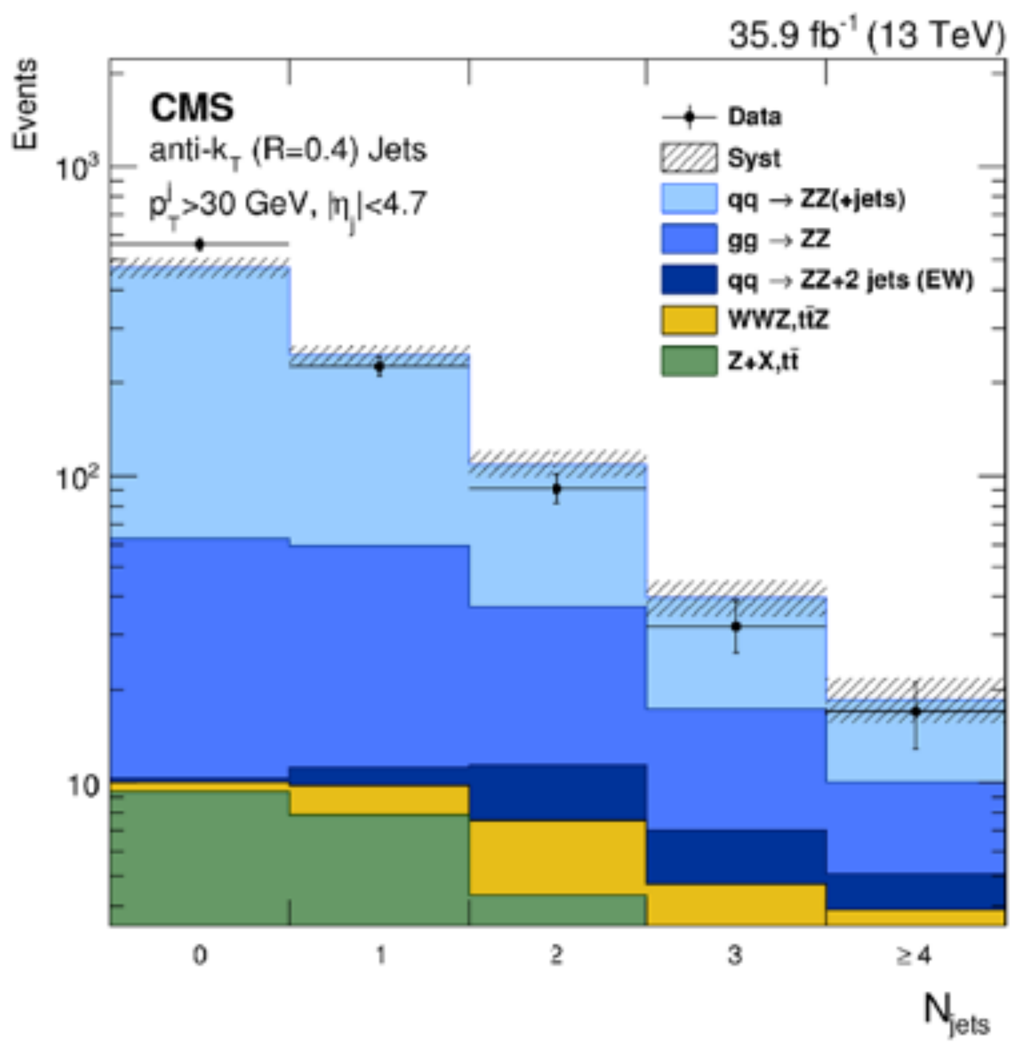


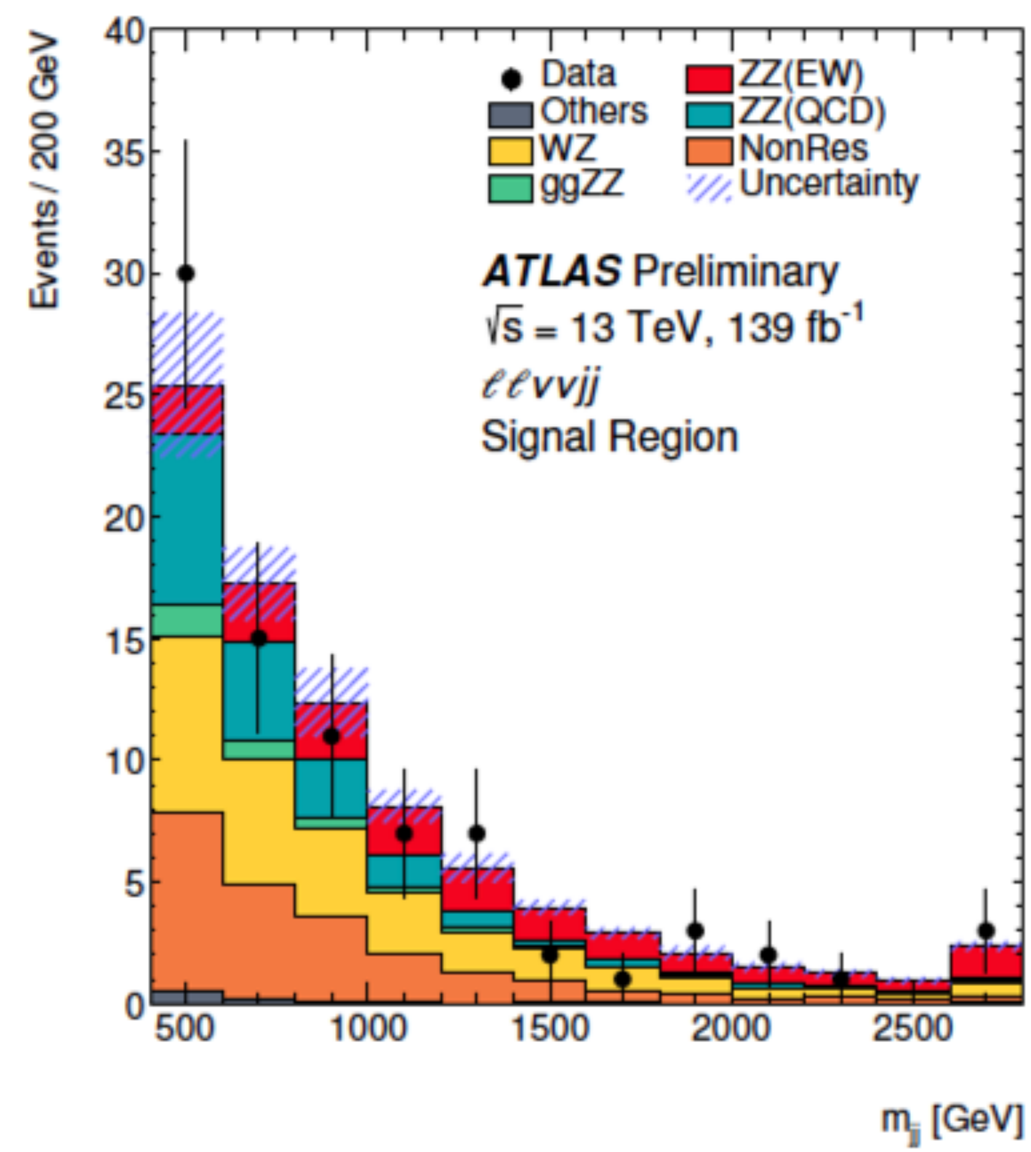


CMS SMP-18-001, ATLAS: 1812.09740

VBS: ZZjj @~20%



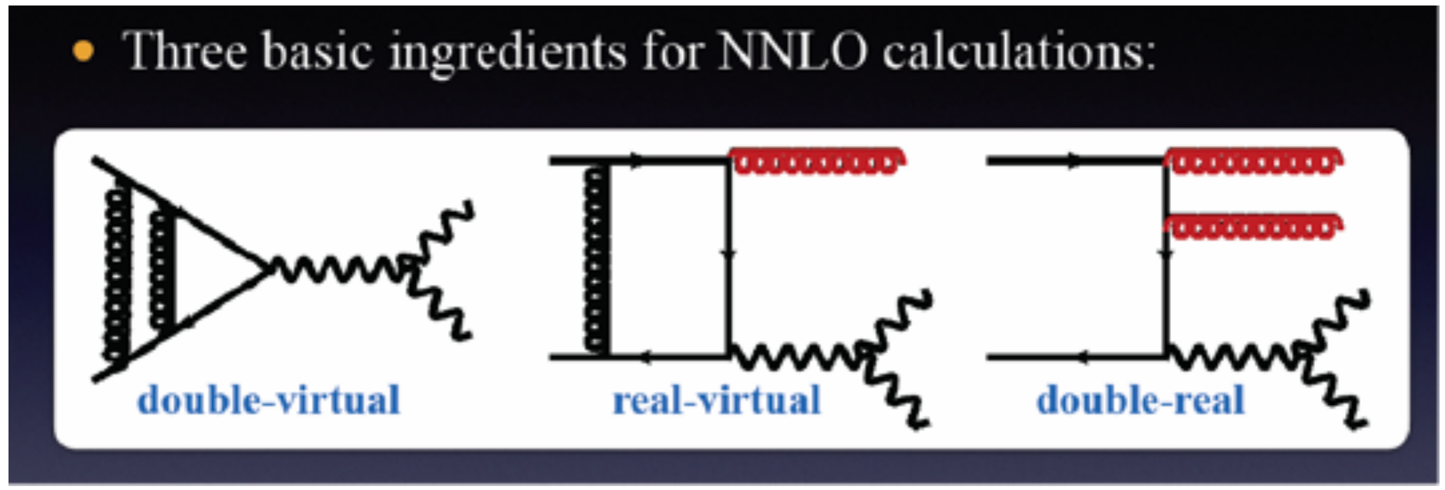




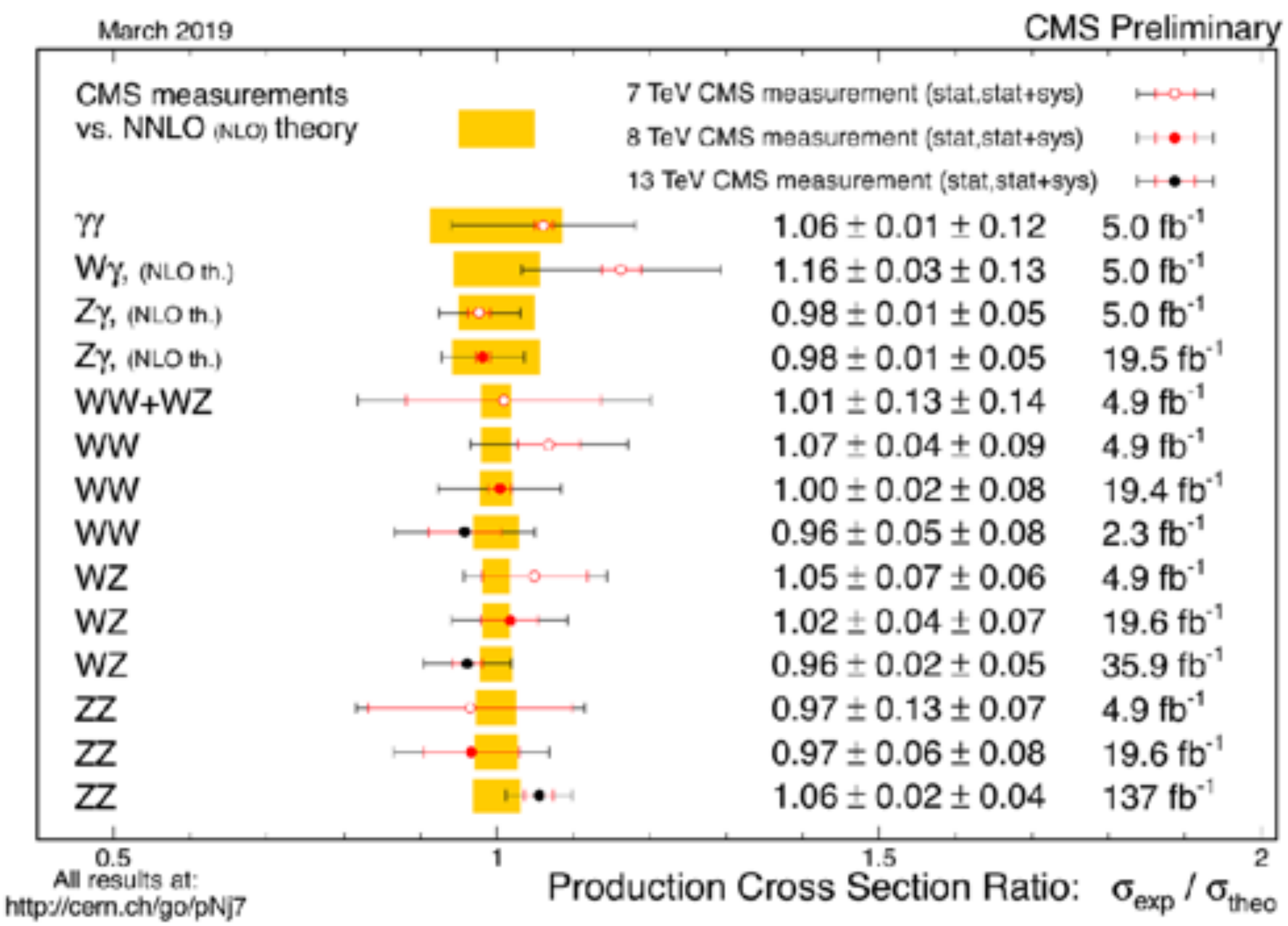
CMS: 1806.11073
ATLAS-CONF-2019-033

Diboson Production

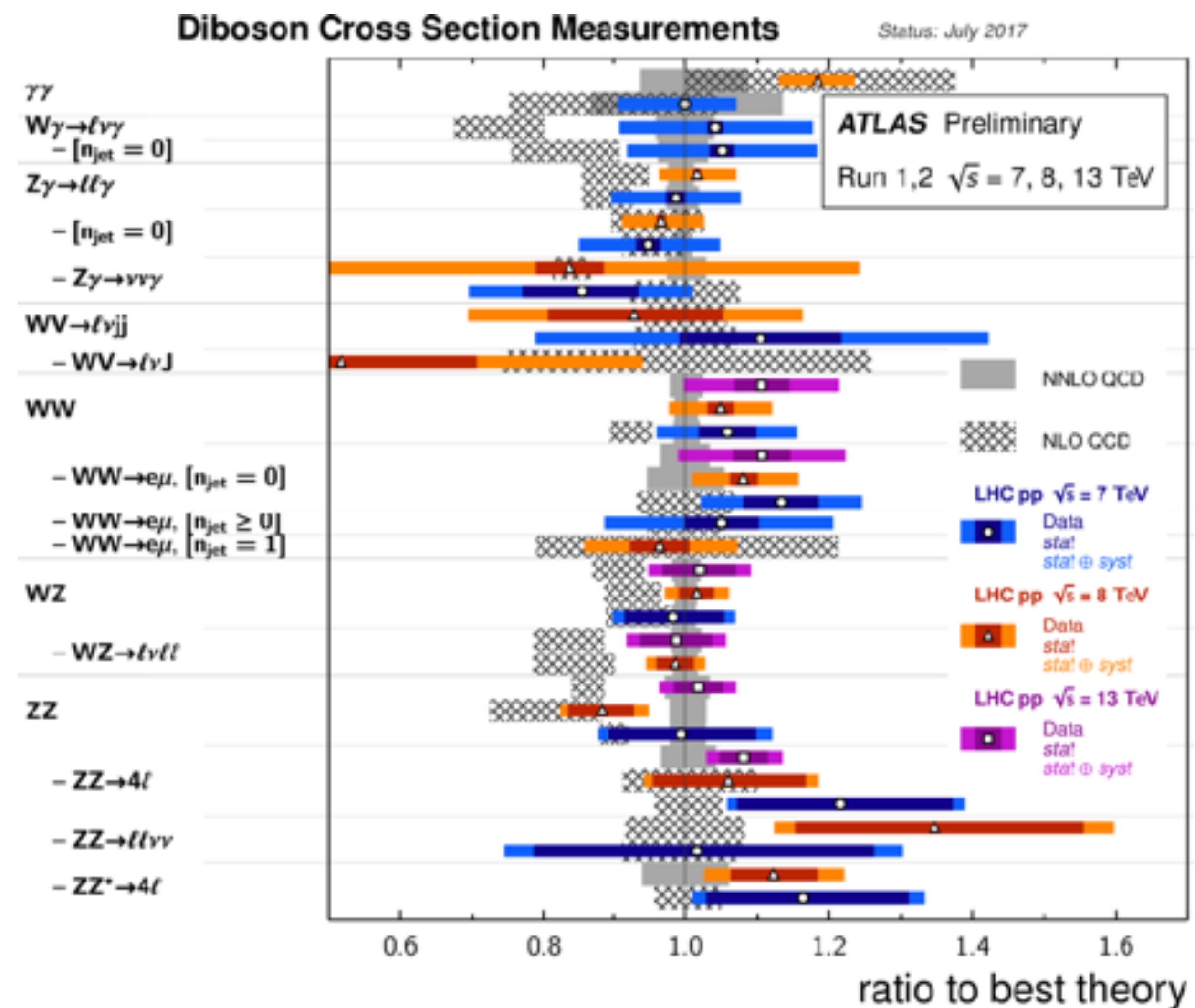
Diboson



Three basic ingredients for NNLO calculations:
double-virtual
real-virtual
double-real

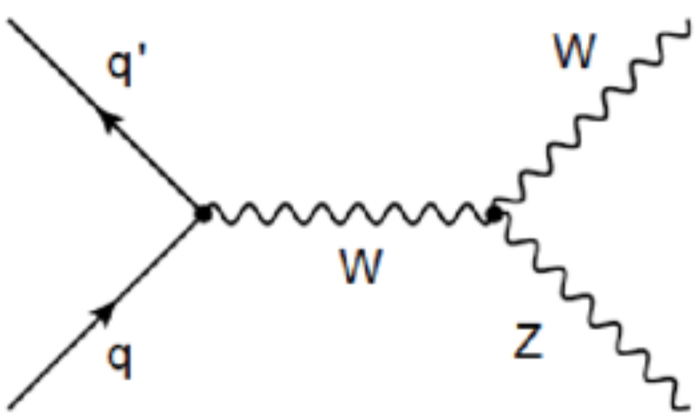


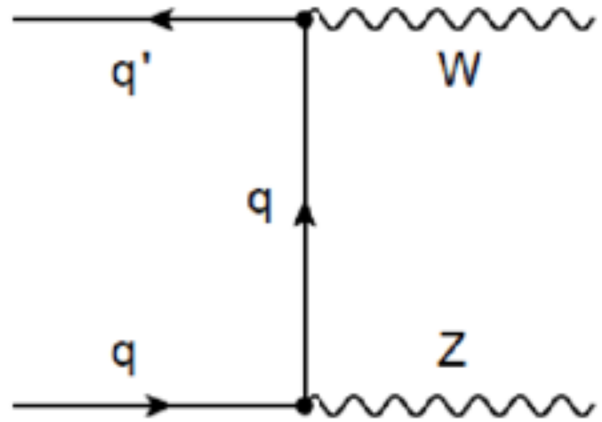
March 2019
CMS Preliminary
CMS measurements
vs. NNLO (NLO) theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
γγ 1.06 ± 0.01 ± 0.12 5.0 fb⁻¹
Wγ, (NLO th.) 1.16 ± 0.03 ± 0.13 5.0 fb⁻¹
Zγ, (NLO th.) 0.98 ± 0.01 ± 0.05 5.0 fb⁻¹
Zγ, (NLO th.) 0.98 ± 0.01 ± 0.05 19.5 fb⁻¹
WW+WZ 1.01 ± 0.13 ± 0.14 4.9 fb⁻¹
WW 1.07 ± 0.04 ± 0.09 4.9 fb⁻¹
WW 1.00 ± 0.02 ± 0.08 19.4 fb⁻¹
WW 0.96 ± 0.05 ± 0.08 2.3 fb⁻¹
WZ 1.05 ± 0.07 ± 0.06 4.9 fb⁻¹
WZ 1.02 ± 0.04 ± 0.07 19.6 fb⁻¹
WZ 0.96 ± 0.02 ± 0.05 35.9 fb⁻¹
ZZ 0.97 ± 0.13 ± 0.07 4.9 fb⁻¹
ZZ 0.97 ± 0.06 ± 0.08 19.6 fb⁻¹
ZZ 1.06 ± 0.02 ± 0.04 137 fb⁻¹
0.5
1
1.5
2
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo

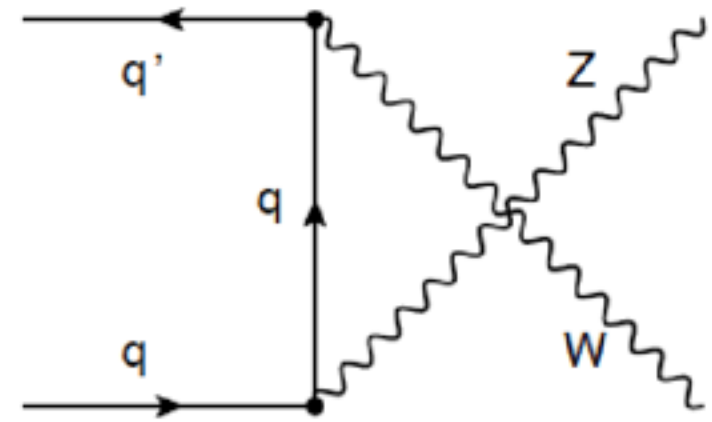


Diboson Cross Section Measurements
Status: July 2017
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
γγ
Wγ→ℓνγ
– [njet = 0]
Zγ→ℓℓγ
– [njet = 0]
– Zγ→ννγ
WV→ℓνjj
– WV→ℓνJ
WW
– WW→eμ, [njet = 0]
– WW→eμ, [njet ≥ 0]
– WW→eμ, [njet = 1]
WZ
– WZ→ℓνℓℓ
ZZ
– ZZ→4ℓ
– ZZ→ℓℓνν
– ZZ*→4ℓ
NNLO QCD
NLO QCD
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
0.6
0.8
1.0
1.2
1.4
1.6
ratio to best theory

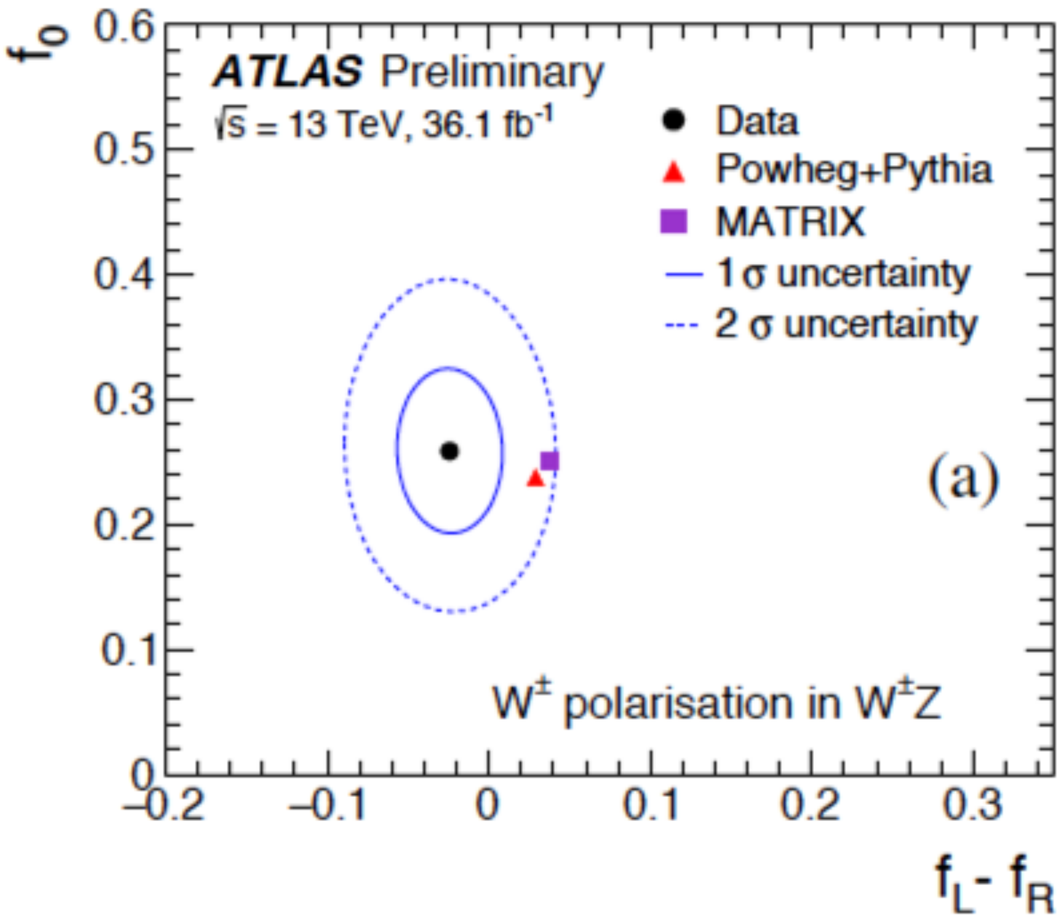
Diboson WZ→3lν @~5%

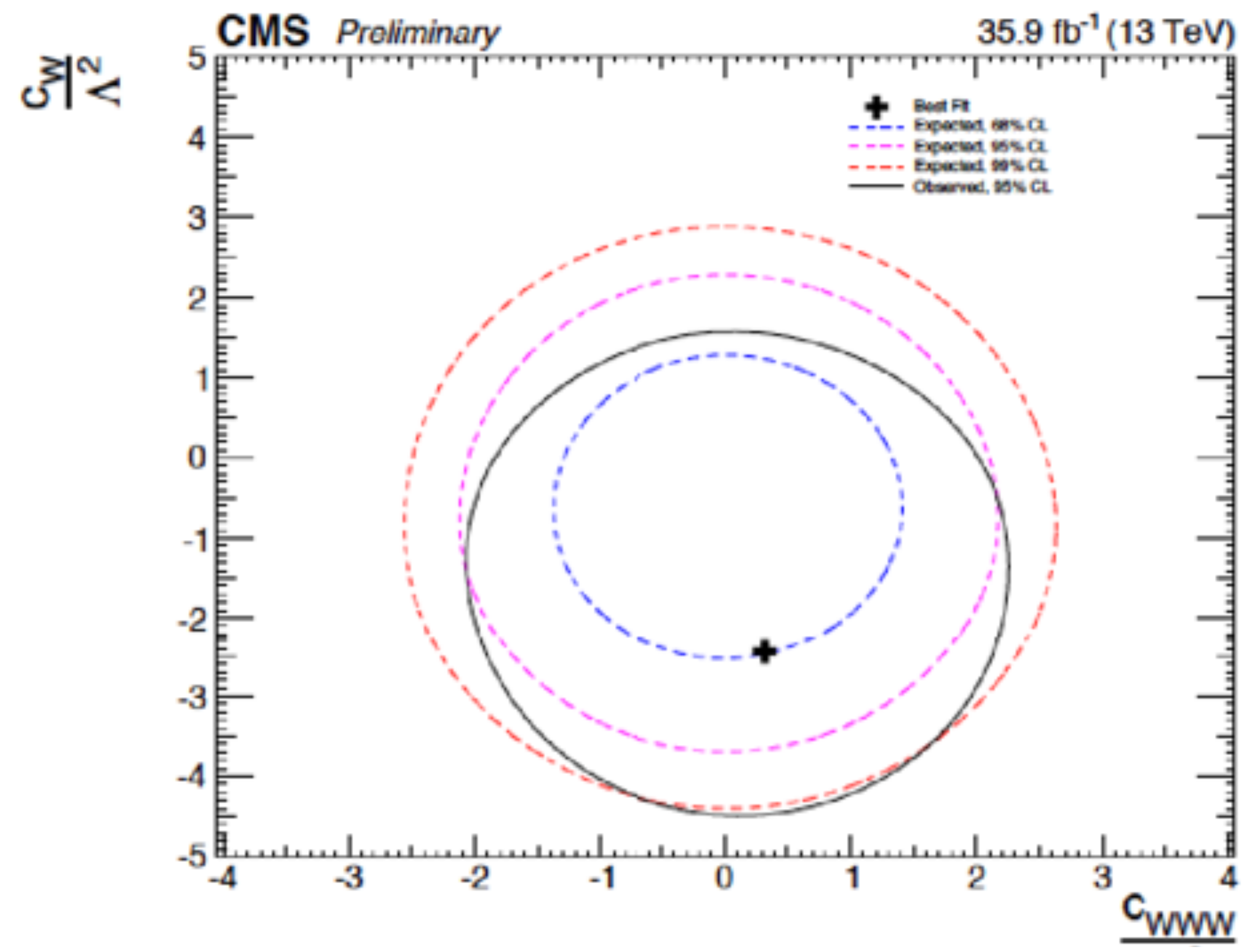






$f_0+f_L+f_R=1$



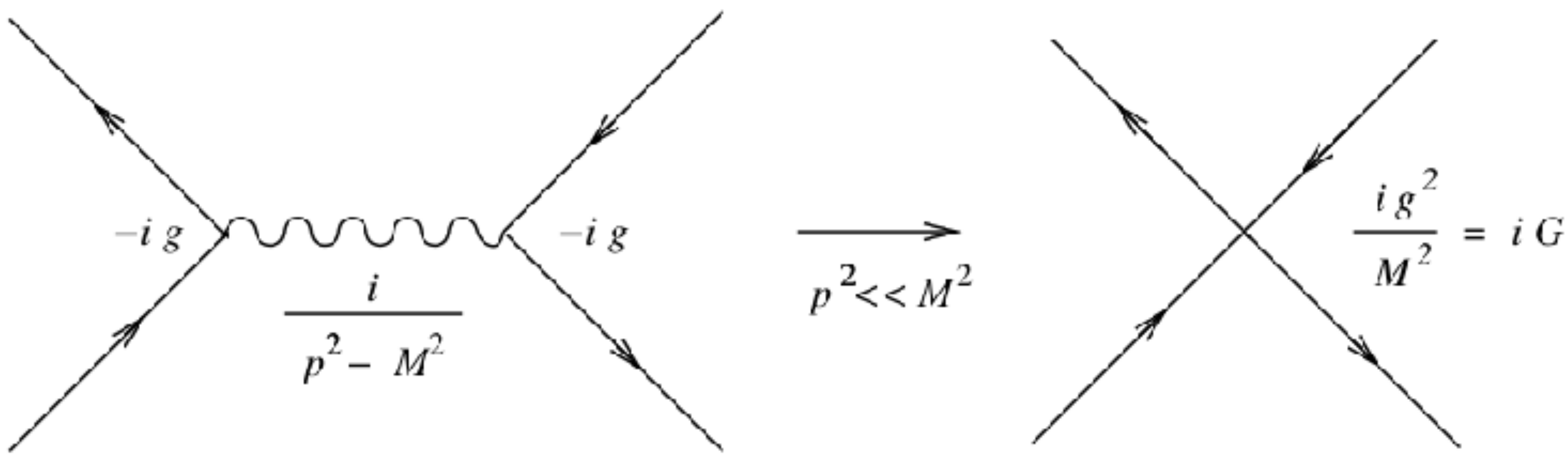


$$\delta\mathcal{L}_{AC} = c_{WWW}\,\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] + c_W\,(D_\mu H)^\dagger\, W^{\mu\nu}\,(D_\nu H) + c_b\,(D_\mu H)^\dagger\, B^{\mu\nu}\,(D_\nu H)$$

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

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

Resonance: **Four-Fermion Operators:**



u,d,g,γ,W,Z

j,t,b,g,γ
e/μ,τ,u,W,Z,h

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

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

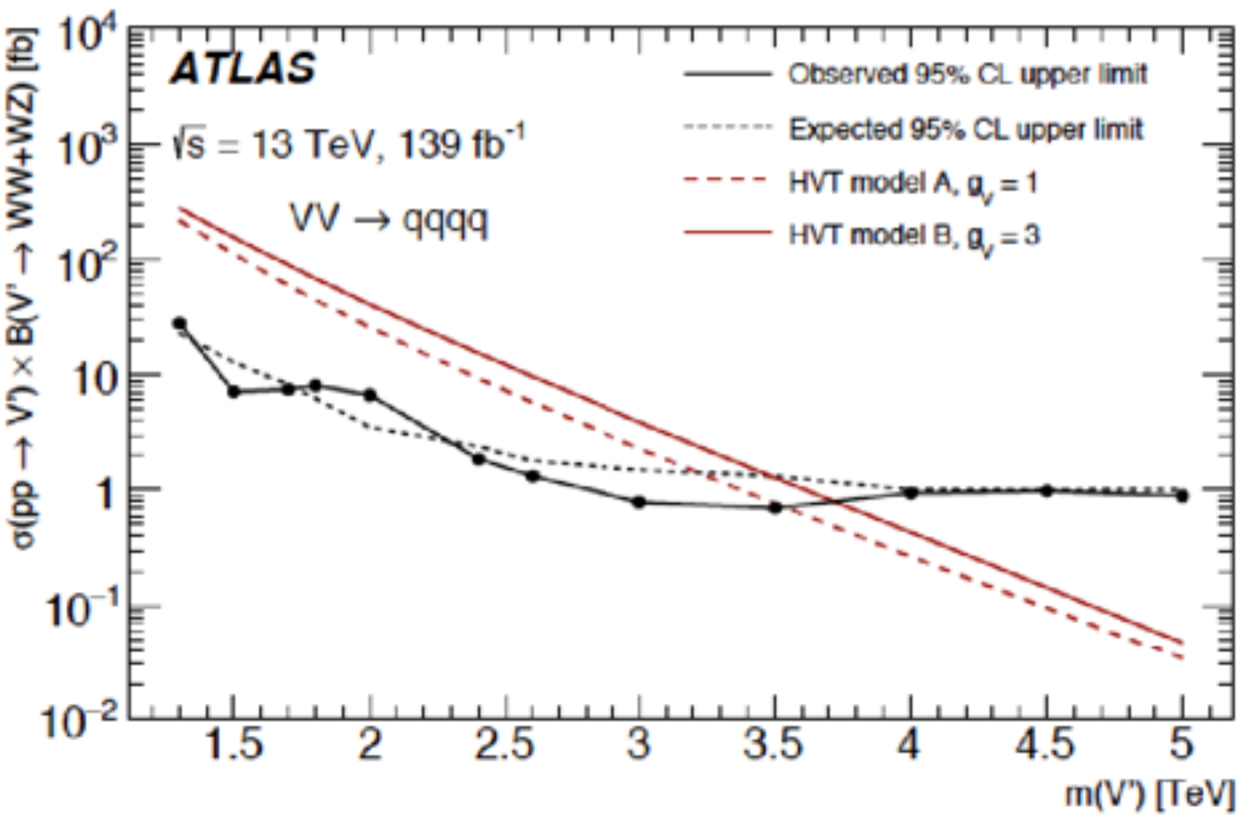
Utility of Effective Field Theory: What question is being asked?

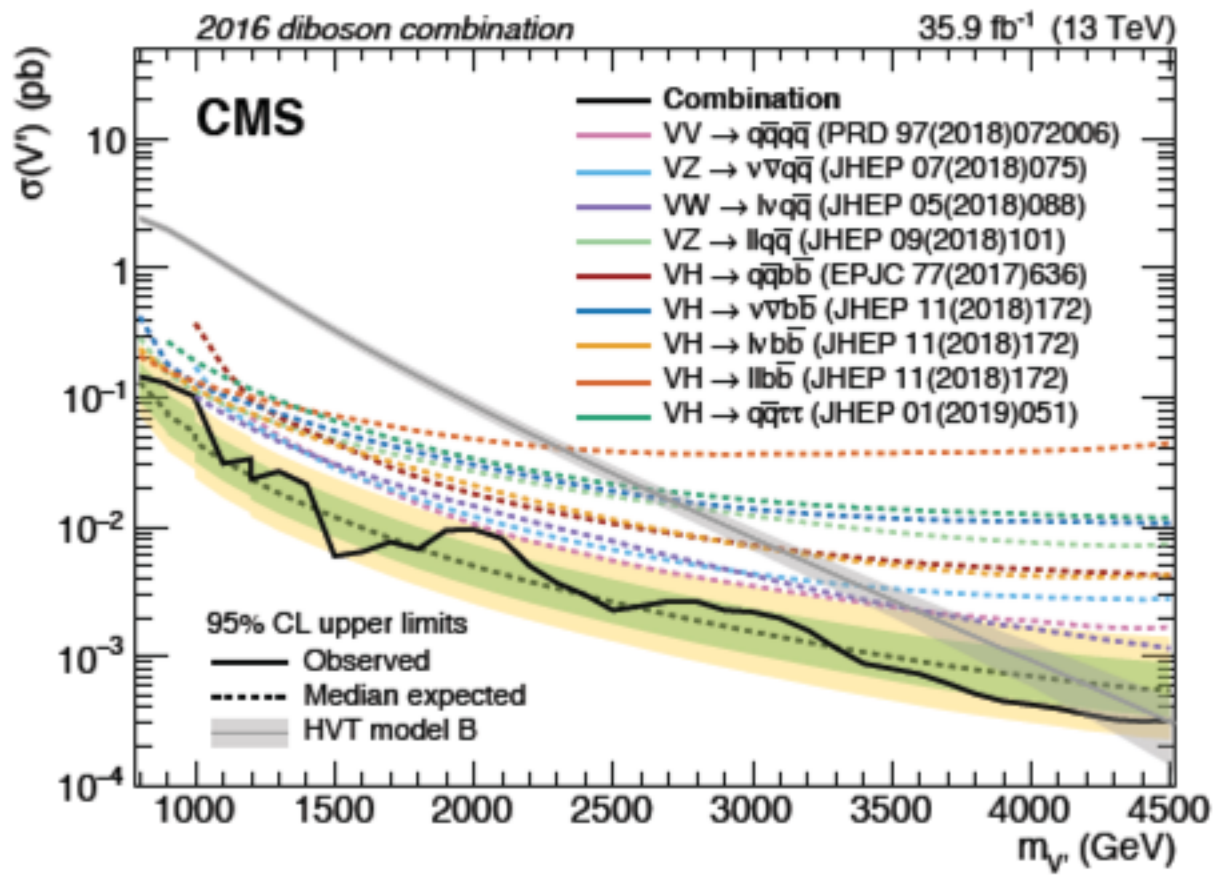
- <u>Validation of SM</u>: Need a self-consistent parameterization of deviations in experimental predictions from the SM to express how accurately SM describes the data. ***EFT sufficient - even one operator at a time.***

- <u>Limits on New Physics</u>: 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")***

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

Limits on Diboson (VV) Resonances



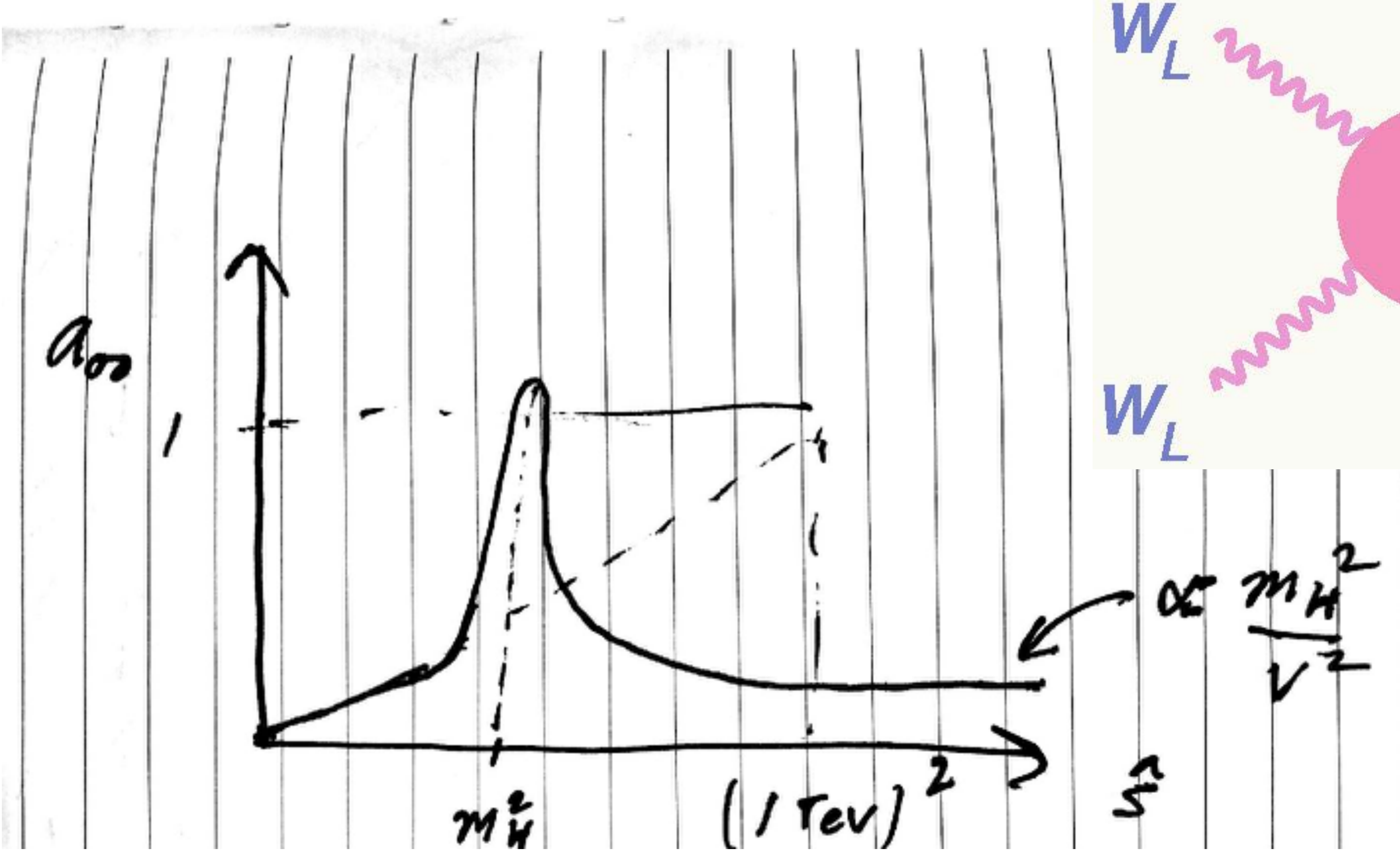


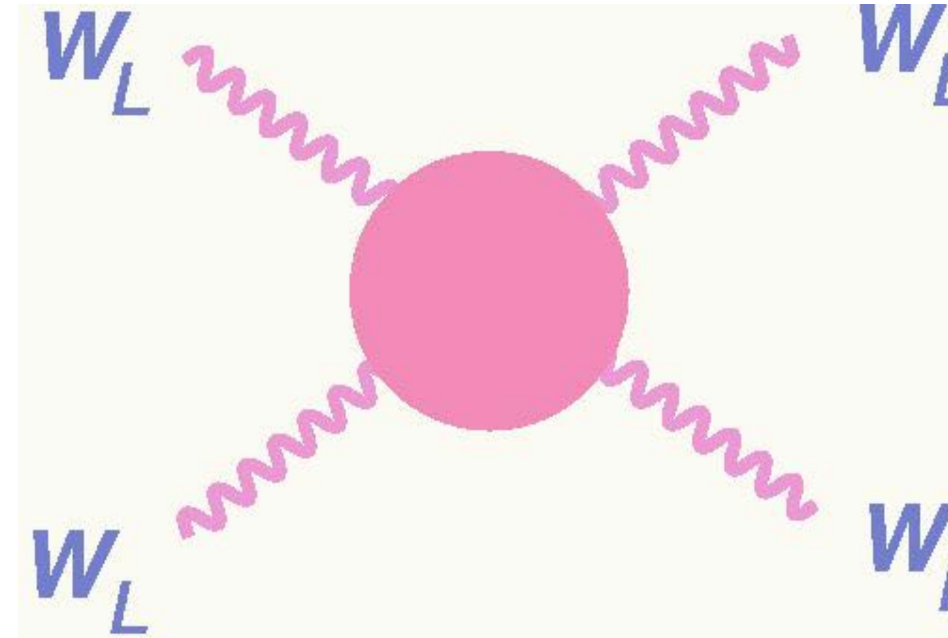
Boosted W/Z

ATLAS: 1906.08589, CMS: 1906.00057

The Future

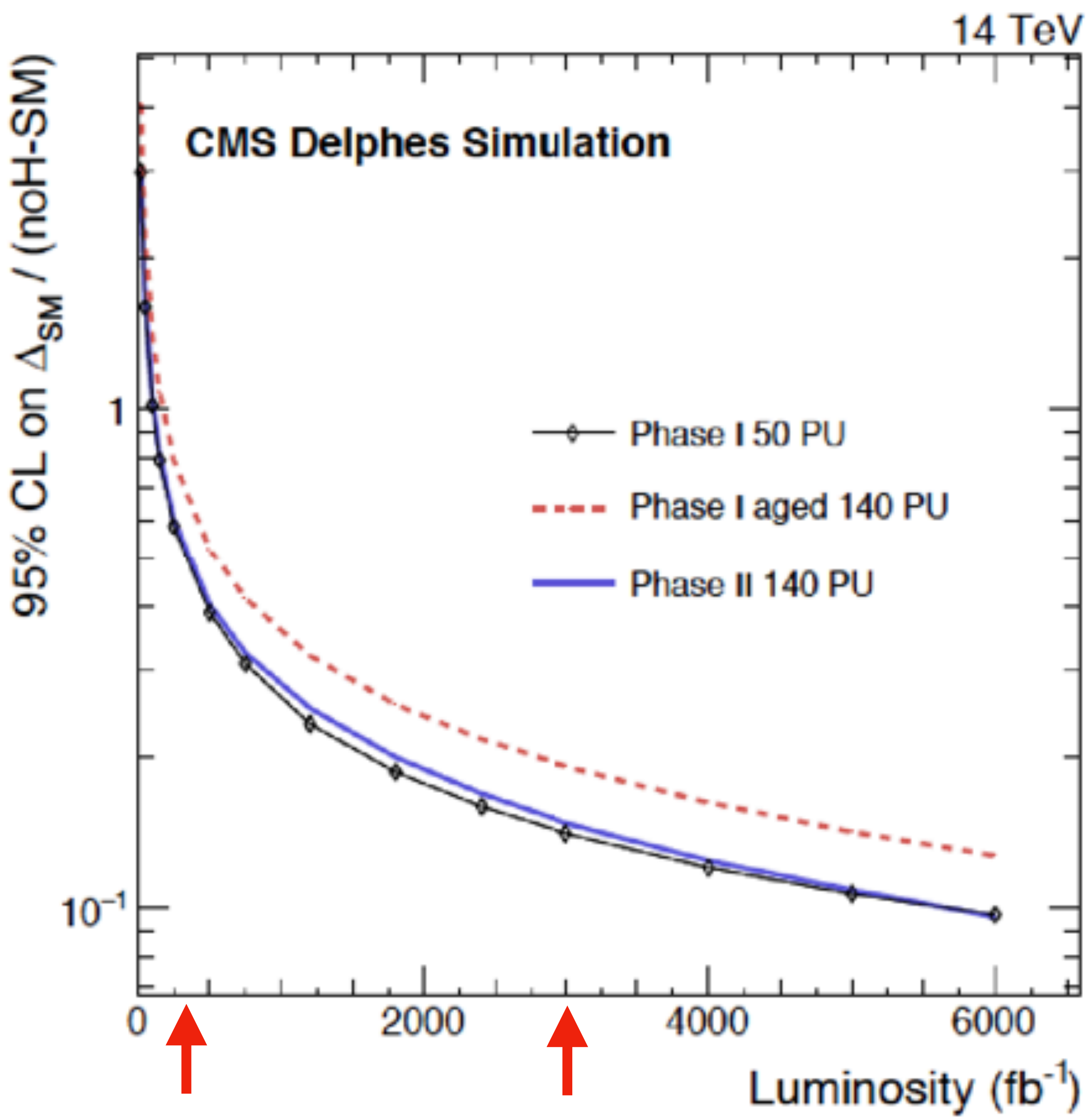
VBS - “High-Energy” Behavior

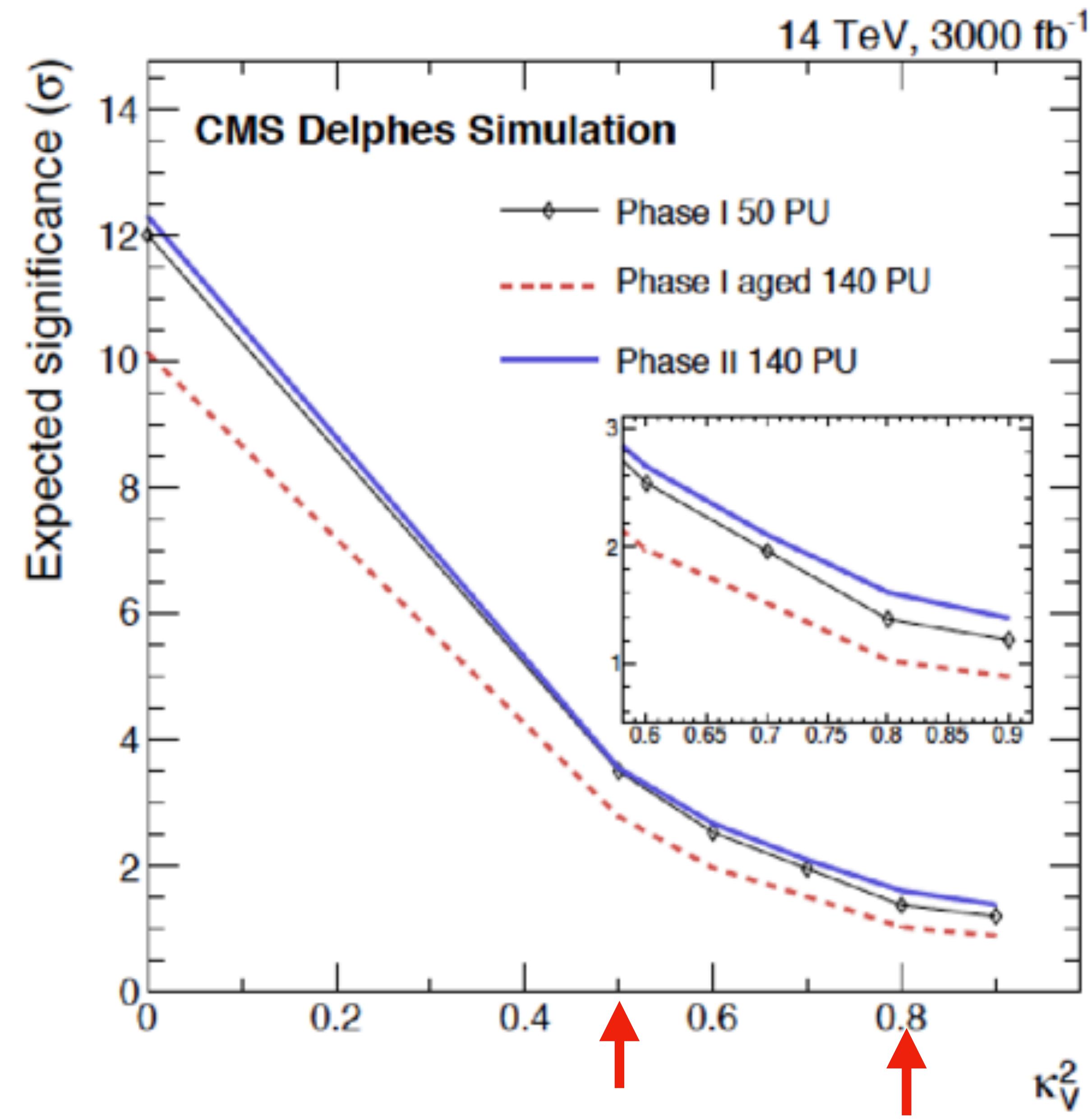




Can it be demonstrated that VBS is weak at high energies?

CMS Study of W± W±





~40% ~20%

>50% @5σ >80% @2σ

Hat tip - Matt Herndon

CMS PAS SMP-14-008

Headline News 2030?

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.
- (If there is time, ask me about gravity…)

Backup - Spin-2

Quantizing Massive Gravitons

- Add in a Fierz- Pauli Mass term - breaks diffeomorphism invariance.

$$\mathcal{L}_{\rm FP} = -\frac{m^2}{2}(h_{\mu\nu}^2 - h^2)$$

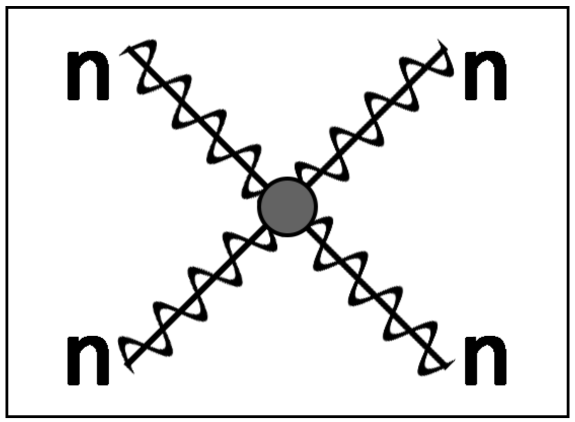
- Massive spin-2 particles also have a longitudinal polarization now.

$$\epsilon^0_{\mu\nu} = \frac{1}{\sqrt{6}}[\epsilon^+_\mu \epsilon^-_\nu + \epsilon^+_\mu \epsilon^-_\nu - 2\epsilon^0_\mu \epsilon^0_\nu]$$

- In the high energy limit $\epsilon^0_{\mu\nu} \rightarrow \frac{k_\mu k_\nu}{m^2}$

- We need only consider this spin-0 mode to understand leading high-energy behavior.

Naive expectation



$$\rightarrow \frac{s^5}{m^8 M_{pl}^2}$$

$$\epsilon^0_{\mu\nu} \rightarrow \frac{k_\mu k_\nu}{m^2}$$

This expectation is realized if one simply adds mass to the 4D Graviton

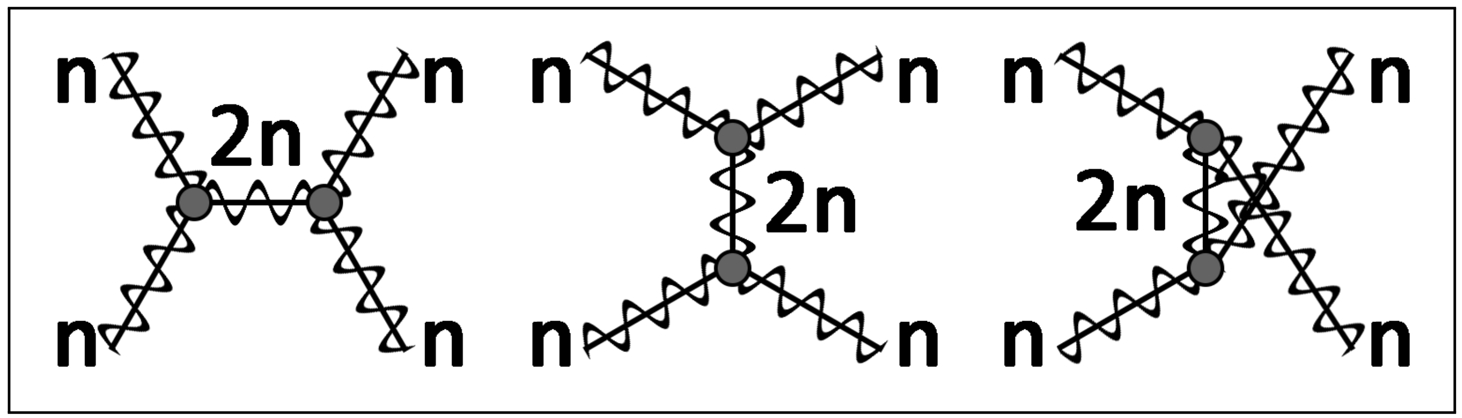
$$M(SSSS) = -\frac{5(1-6c_1-4c_2)^2}{432\Lambda_5^{10}} stu(s^2+t^2+u^2) + \cdots$$

Cheung and Remmen, arXiv:1601.04068

Unitarity is violated at a scale $\Lambda_5 = (M_{pl} m^4)^{1/5} \ll M_{pl}$

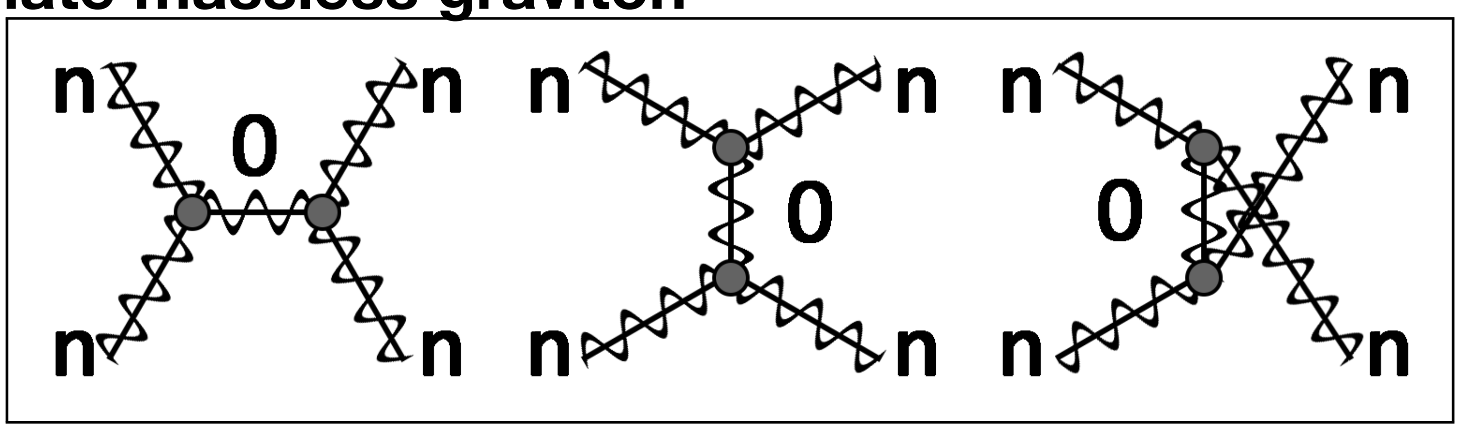
This growth cannot occur in a compactified 5-D model … Compactification is an IR phenomenon, UV behavior determined by power-counting is |Amp| $\propto E^3/(M_{Pl})^3$!

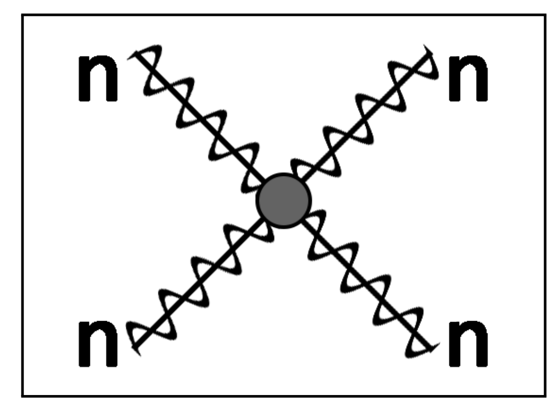
Expectations for Massive KK Spin-2 Modes: Torus

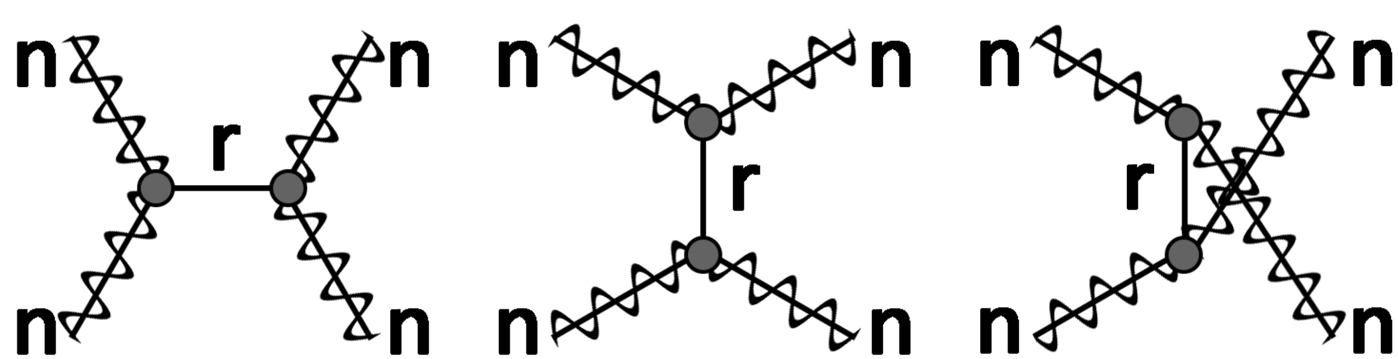


Intermediate massless graviton

“Seagull”







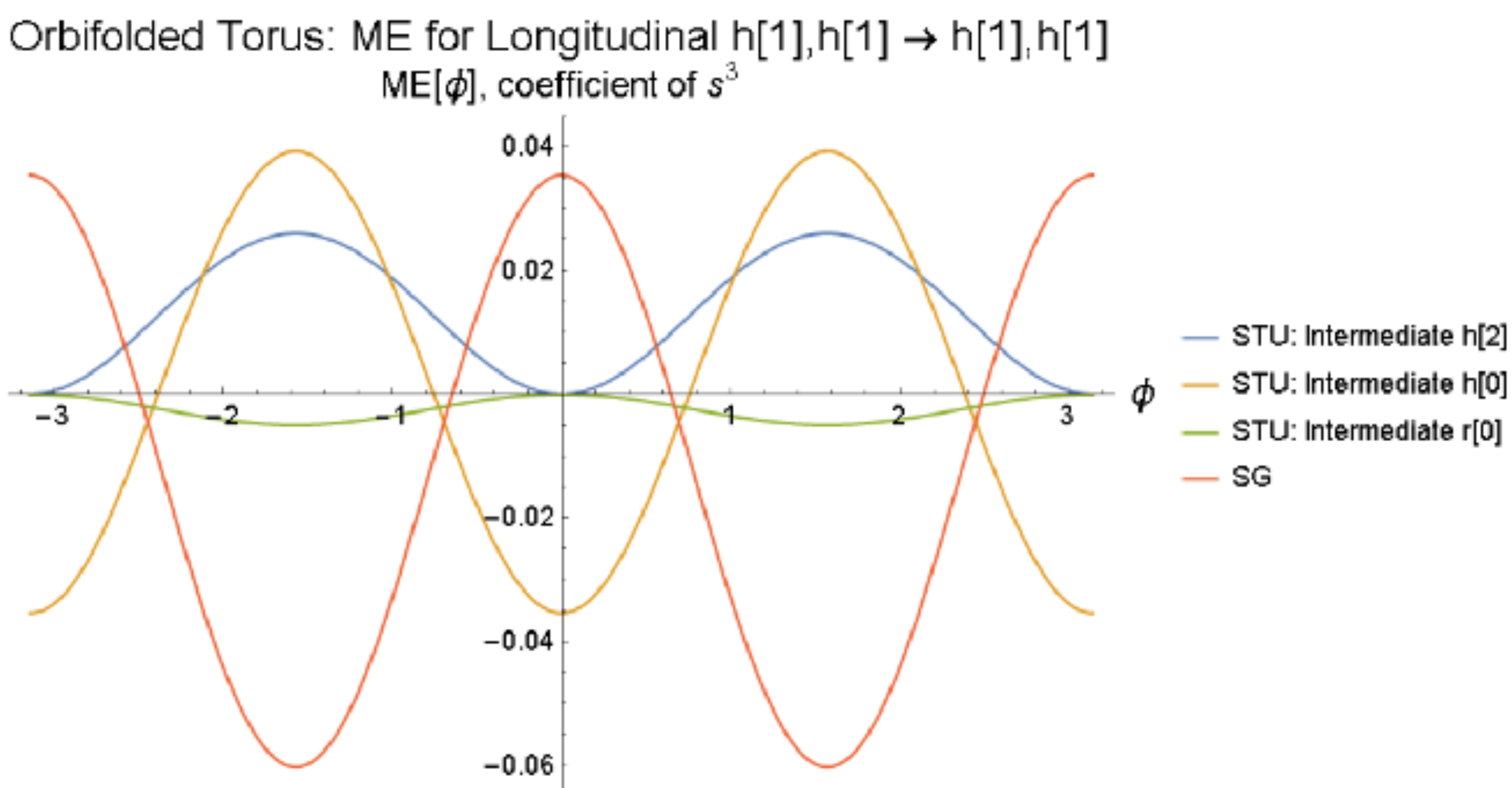
Intermediate radion

	s^5	s^4	s^3	s^2
$2n$	$\frac{r_c^7\kappa^2(7+\cos(2\theta))\sin^2\theta}{9216n^8\pi}$	$\frac{r_c^5\kappa^2(-13+\cos(2\theta))\sin^2\theta}{1152n^6\pi}$	$\frac{r_c^3\kappa^2(97+3\cos(2\theta))\sin^2\theta}{1152n^4\pi}$	$-\frac{r_c\kappa^2(179-116\cos(2\theta)+\cos(4\theta))}{1152n^2\pi}$
0	$\frac{r_c^7\kappa^2(7+\cos(2\theta))\sin^2\theta}{4608n^8\pi}$	$\frac{r_c^5\kappa^2(9-140\cos(2\theta)+3\cos(4\theta))}{9216n^6\pi}$	$\frac{r_c^3\kappa^2(-15+270\cos(2\theta)+\cos(4\theta))}{2304n^4\pi}$	$-\frac{r_c\kappa^2(175-624\cos(2\theta)+\cos(4\theta))}{1152n^2\pi}$
Seagull	$-\frac{r_c^7\kappa^2(7+\cos(2\theta))\sin^2\theta}{3072n^8\pi}$	$\frac{r_c^5\kappa^2(63-196\cos(2\theta)+5\cos(4\theta))}{9216n^6\pi}$	$\frac{r_c^3\kappa^2(692\cos(2\theta)+5(-37+\cos(4\theta)))}{4608n^4\pi}$	$\frac{r_c\kappa^2(7+\cos(2\theta))}{4608n^4\pi}$
Radion	–	–	$\frac{r_c^3\kappa^2\sin^2\theta}{64n^4\pi}$	$\frac{r_c\kappa^2(7+\cos(2\theta))}{96n^2\pi}$
Sum	0	0	0	0

Amplitude is 0 and everything cancels up to order s^2

Radion diagrams start contributing at order s^3

Order s persists - and KK mode.
Sum will reproduce expected E^3 behavior



RSC, Foren, Mohan, Sengupta, Simmons - 1906.11098