Probing aQGCs at the International Linear Collider

DPG Spring Meeting - Aachen 2019

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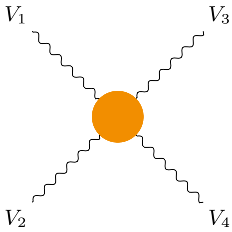
Vector Boson Scattering

$$\mathcal{L}_{U(1)\otimes SU(2)} = \ldots - \frac{1}{4} W_i^{\mu\nu} W^i_{\mu\nu}$$
$$W_i^{\mu\nu} = \ldots - g\epsilon_{ijk} W_j^{\mu} W_k^{\nu}$$

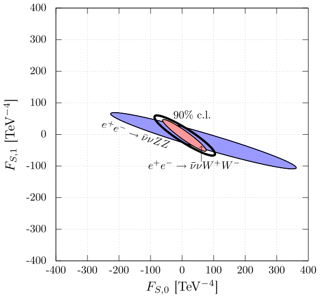
$\Longrightarrow$ **Quartic Gauge Coupling** (QGC):



- SM Higgs?
- Composite H?
- Extra H?
- High-E effects?
- ...

$\Longrightarrow$

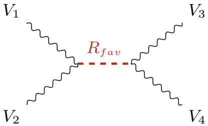
Limits!



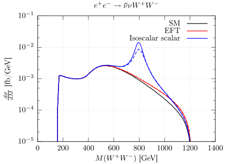
[arXiv:1607.03030]

Setting limits on BSM physics

BSM theory: Resonances, High-E physics

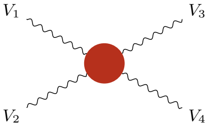


Phenomenology: Mass peaks, shape / normalization

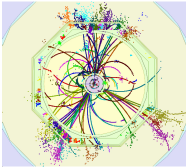


[EPJC(2017):77:120]

Modeling: Generalized Resonances, Effective Field Theories

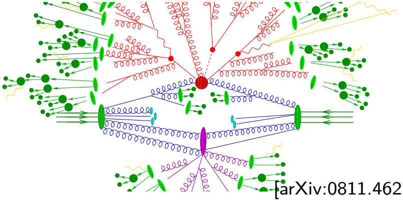
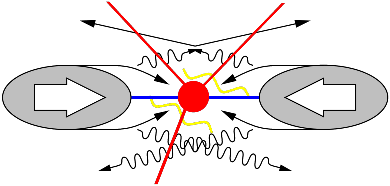


$\Longrightarrow$ **Experiment:**



$\Longrightarrow$ **Limits** on anomalous parameters

Which collision?

pp	e^+e^-
	

[arXiv:0811.4622]

pp

+ High $\sqrt{s}$

– Many uncertainties (initial state, theory, pile-up, ...)

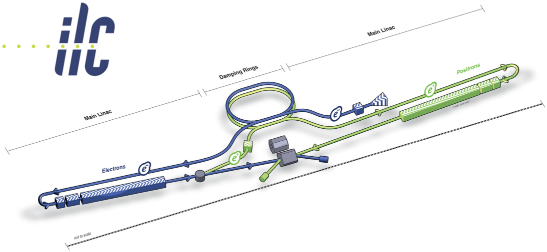
e^+e^-

+ Precise measurement (known initial state & theory, precise detectors, less beam-background)

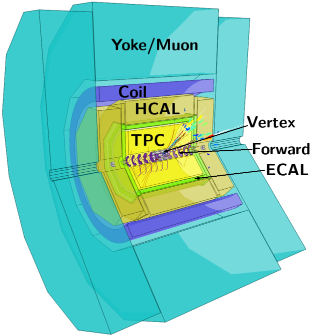
– Limited $\sqrt{s}$

$\Longrightarrow$ pp and e^+e^- are **complementary**!

The International Linear Collider



ILC Scheme | © www.form-one.de

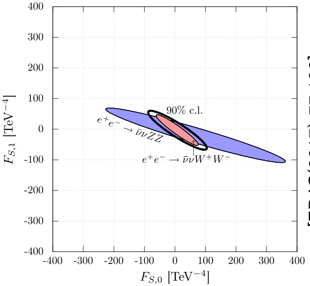


- **ILC**: Future e^+e^- collider, $\sqrt{s}$ extendible to 1 TeV
- **International Large Detector** (ILD): Particle Flow optimized detector $\Rightarrow$ **JER$\sim 3-4\%$**

Achievable anomalous QGC limits

ILC:

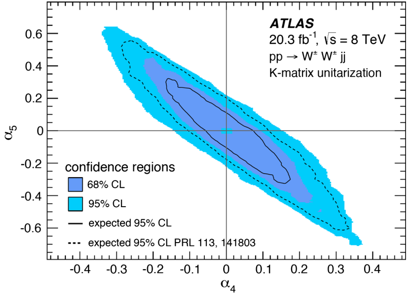
W^+W^- & ZZ hadronic @ ILD (1 TeV)



[EPJC(2017):77:120]

LHC:

$W^\pm W^\pm jj$ leptonic @ CMS



[Phys. Rev. D 96, 012007]

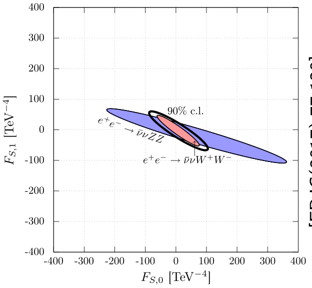
- dim.-8 EFT
- dim.-4 EFT

$$F_S \approx 300 - 500\,\text{TeV}^{-4} \Longleftrightarrow \alpha \approx 0.1$$

[INSPIRE:1616004]

- **Generator level study**
  + Typical cuts
  + Detector effect assumptions
- **Experimental results**

Assumptions of generator level study



[EPJC(2017):77:120]

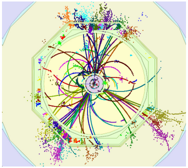
Study assumes **detector effects**:

- **Confusing Ws and Zs**:
  $m_W - m_Z \sim 10\,\text{GeV}$, width, detector resolution
  $\Longrightarrow$ **Confusion!**
- **Crucial** for analysis:
  Different couplings in WW and ZZ states!
- Assumption:
  true W $\to$ reconstr.: $88\%\ W$, $12\%\ Z$
  true Z $\to$ reconstr.: $88\%\ Z$, $12\%\ W$

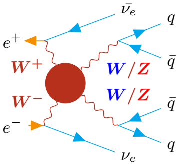
  $\Longrightarrow$ For WW/ZZ signals:
  true WW $\to$ reconstr.: $\mathbf{77.4\%}$ WW
  true ZZ $\to$ reconstr.: $\mathbf{77.4\%}$ ZZ

$\Longrightarrow$ **Can we verify this?**

Detector level analysis



- VBS analysis on **detector level**
  $\Longrightarrow$ Full ILD simulation of $1\,\text{TeV}$ e^+e^-

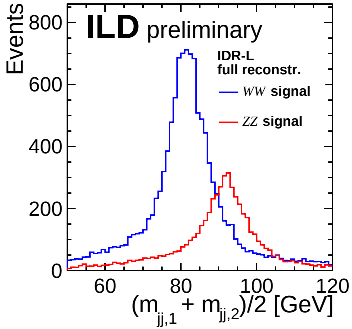


Analysis:

- Remove beam backgrounds: Exclusive jet clustering
- Cluster to 4 jets: e^+e^--k_t algorithm
- Pair 4 jets to 2 bosons: Require minimal $|m_{jj,1} - m_{jj,2}|$

$\Longrightarrow$ WW/ZZ separation by invariant masses

Detector level VS Assumptions



Generator level → Reconstructed

- WW events
- ZZ events

$\xrightarrow[\text{Analysis}]{\text{Simulation \&}}$ $\frac{m_{jj,1}+m_{jj,2}}{2}$

WW/ZZ separation:

- 1D separation cut in $\frac{m_{jj,1}+m_{jj,2}}{2}$
- Point with equal separation:

true WW $\rightarrow$ reconstr.: **71%** WW

true ZZ $\rightarrow$ reconstr.: **71%** ZZ

(Reminder: previous assumption **77.4%**)

$\Longrightarrow$ **What limits separation / should be optimized?**

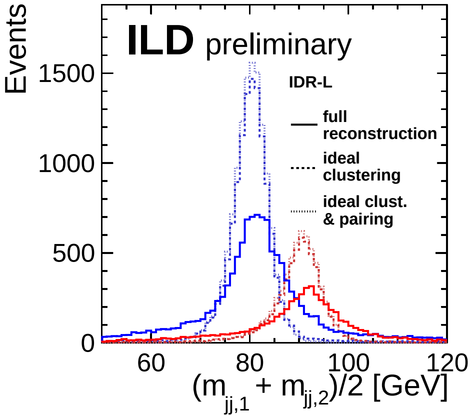
Identifying challenges

From MC info:

Colour neutral ⟶ partons ⟶ jet particle ⟶ reconstr. particles

connections known!

⟹ ***Cheat*** reconstruction step ⟹ See influence!

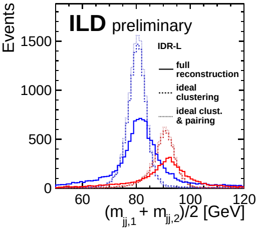


- **Ideal clustering:**
  Cheat jet particle finging
  ⇒ clustering algorithm &
  removing beam bkg.
- **Ideal pairing:**
  Cheat combining jets to bosons

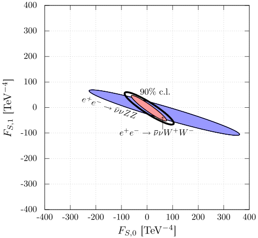
⟹ Limiting factor:
Jet clustering!

WW/ZZ separation
w/ cheated clustering: $\mathbf{86\%}$
(full reco: 71%, prev. assump.: 77%)

Conclusion



- Detector level analysis needs improvement
  $\Longrightarrow$ Identified problem: **Jet clustering**
- Future studies:
  - Improve clustering
  - Use more sophisticted separation (flavor tag!)
- Assumptions in gen. level study reasonable

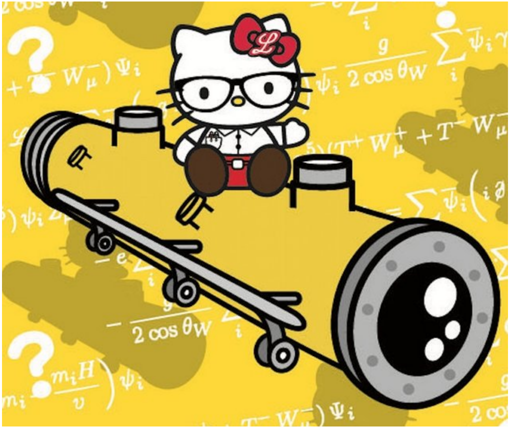


[EPJC(2017):77:120]

Future high-$\sqrt{s}$ e^+e^- facility complementary to hadron machines!

ILC Supporters

BACKUP



[Twitter:LCNewsline (26.07.2016)]

Theory in [EPJC(2017):77:120]

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{known}} + \sum_i \frac{c_i}{\Lambda_i^{D_i - d}} \mathcal{O}_i$$

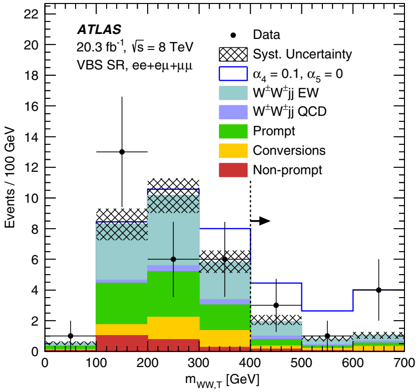
$$\mathcal{L}_{S,0} = F_{S,0} \text{Tr}\left[(D_\mu H)^\dagger D_\nu H \right] \text{Tr}\left[(D^\mu H)^\dagger D^\nu H \right] ,$$
$$\mathcal{L}_{S,1} = F_{S,1} \text{Tr}\left[(D_\mu H)^\dagger D^\mu H \right] \text{Tr}\left[(D_\nu H)^\dagger D^\nu H \right] ,$$

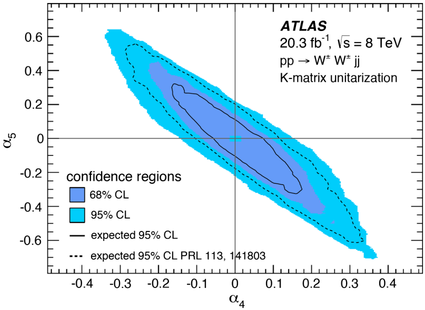
with $F_{S,i} = c_i/\Lambda^4$.

T-Matrix unitarisation: $S = 1 + iT$, T_0 not unitarised

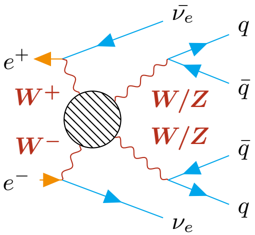
$$T(T_0) = \frac{1}{\text{Re}\left(T_0^{-1}\right) - \frac{i}{2}\mathbb{1}}$$

LHC aQGC sensitivy from [Phys. Rev. D 96, 012007]





Generator level signal definition



All signal events:

- $e_L^-, e_R^+ \Rightarrow$ Can radiate Ws
- $\nu\bar{\nu} = \nu_e\bar{\nu}_e \Rightarrow$ Could have radiated 2 Ws
- $m_{\nu_e\bar{\nu}_e} \geq 100.0\text{GeV} \Rightarrow \nu_e\bar{\nu}_e$ not from Z

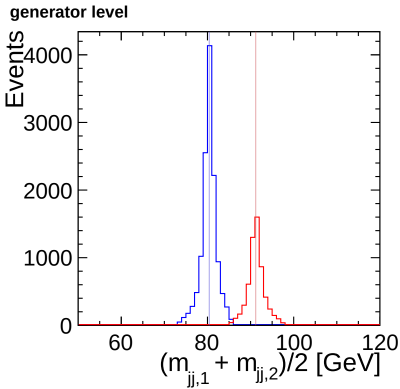
WW events:

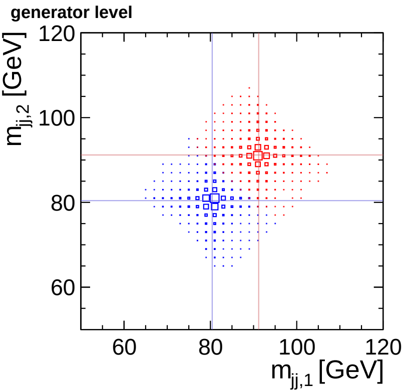
- Two up-type–down-type pairs: $q_u\bar{q}'_d + q''_d\bar{q}'''_u$
- $147.0 < m_{q_u\bar{q}'_d} + m_{q''_d\bar{q}'''_u} < 171.0$
- $|m_{q_u\bar{q}'_d} - m_{q''_d\bar{q}'''_u}| \leq 20.0\text{GeV}$

ZZ events:

- Two same-flavour pairs: $q\bar{q} + q'\bar{q}'$
- $171.0 < m_{q\bar{q}} + m_{q'\bar{q}'} < 195.0$
- $|m_{q\bar{q}} - m_{q'\bar{q}'}| \leq 20.0\text{GeV}$

Generator level signal definition





High level reconstruction

Processors used before analysis:

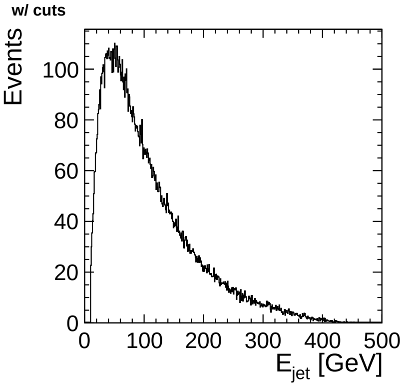
- **IsolatedLeptonTaggingProcessor:**
  Tagging of isolated leptons (using new weights)
- **FastJetProcessor:**
  `Exclusive kt_algorithm (E_scheme)` with radius parameter 1.3 and clustering to 4 jets. Removes overlay background, afterwards only use reconstructed particles which were in these jets.
- **FastJetProcessor:**
  `Exclusive ee_kt_algorithm (E_scheme)` clustering to 4 jets. These are taken as the actual jets.

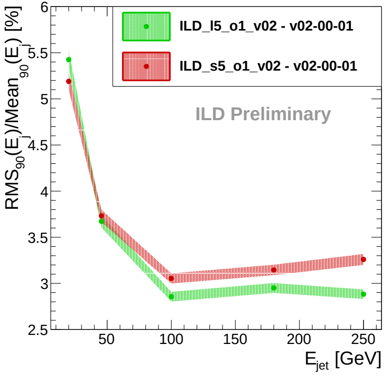
Additional steps in analysis:

- Pair up jets into 2 boson-dijet candidates by minimizing $|m_{jj,1} - m_{jj,2}|$

Jet energy distribution

Influence of JER on this sample

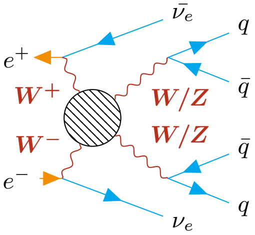




Vector Boson Scattering @ ILC

The benchmark

Looking for Vector Boson Scattering:



- **Goal:** Limits on anomalous Quartic Gauge Couplings

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{known}} + \sum_i F_{S,i}\mathcal{O}_i$$

- WW and ZZ measure different couplings!

$\Longrightarrow$ **Separate WW and ZZ!**

$\Longrightarrow$ **Detector Benchmark:** Precise Jet Energy Resolution

$\longrightarrow$ **Mass-separation of WW and ZZ peaks**

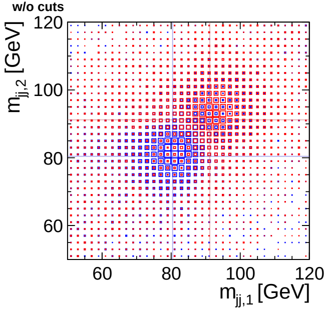
VBS Benchmark plots

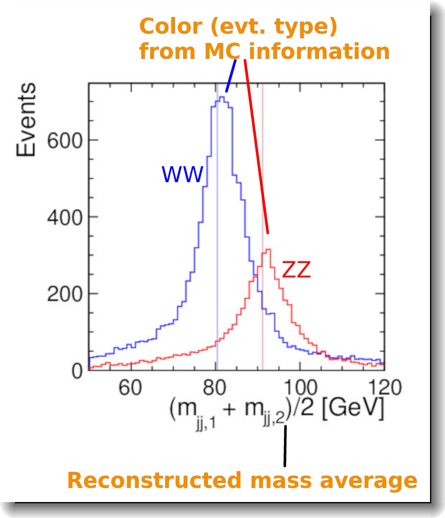
Basic construct

Example for performance plots:

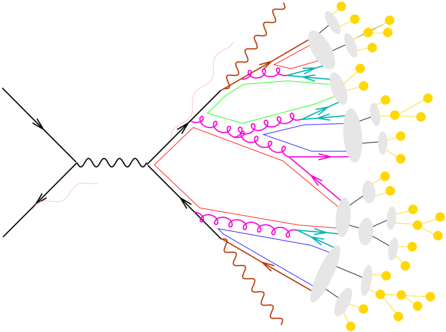
- ILD l5_o1_v02
- iLCSoft v02-00-02
- Full reconstruction

And 2D version:





Following jet formation

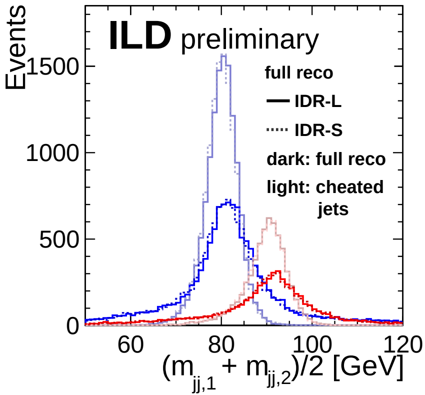


- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \longrightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\longrightarrow$ hadrons
- hadronic decays

[Lecture D. Zeppenfeld 2005]

Mass distributions: removing semi-leptonic decays

Two levels:
- **Full reco:** See previous slides
- **Cheated jets:** Use `TrueJet`
  $\rightarrow$ cheated clustering, pairing and overlay removal



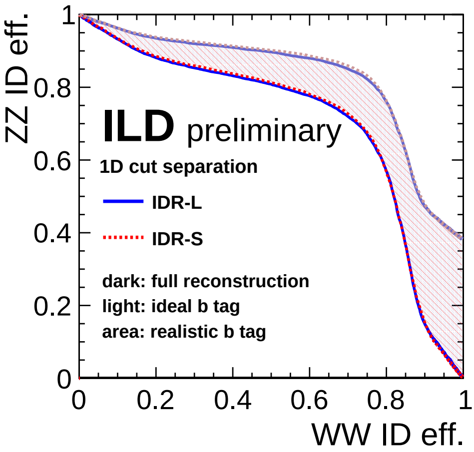
$\Longrightarrow$
- **Detector model impact minimal**
- **Significant:** Semi-leptonic decays, jet finding

Separation curves

Idea: Scan this distribution: $m_{\text{cut}} \rightarrow < m_{\text{cut}} \Rightarrow$ Reco-WW

$> m_{\text{cut}} \Rightarrow$ Reco-ZZ

$\longrightarrow$ Efficiencies to find true-WW as reco-WW? (same w/ ZZ)



- x: Eff. to identify WW correctly
  y: Eff. to identify ZZ correctly
- Simplified but easy approach
- $+$ Simple test of b tag influence:
  Event contains gen.-level b?
  $\Longrightarrow$ Is reco-ZZ!

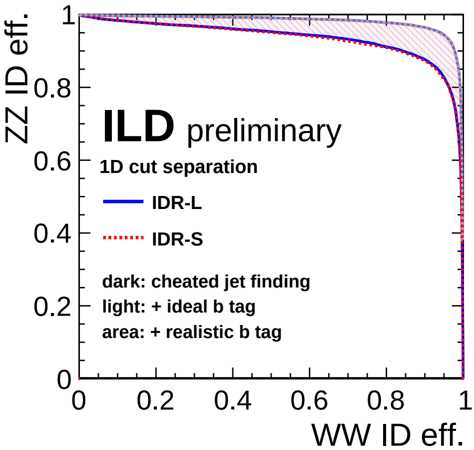
Two versions:

1. Full reconstruction
2. Using cheated jets

Separation curves

Idea: Scan this distribution: $m_{\text{cut}} \rightarrow < m_{\text{cut}} \Rightarrow$ Reco-WW
$> m_{\text{cut}} \Rightarrow$ Reco-ZZ

$\longrightarrow$ Efficiencies to find true-WW as reco-WW? (same w/ ZZ)



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- + Simple test of b tag influence:
  Event contains gen.-level b?
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Two versions:

1. Full reconstruction
2. Using cheated jets

Separation & masses: Cheating steps