VBS search at the ILC

2nd VBSCan Annual Meeting

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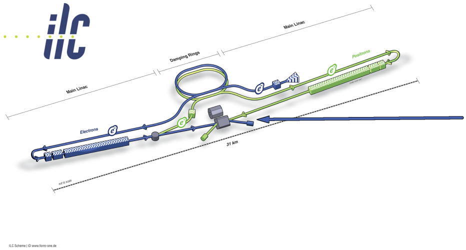
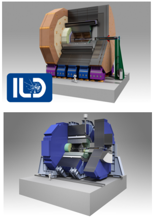
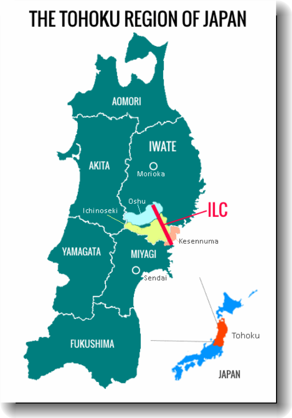
The International Linear Collider

A high-E e^+e^- machine







- Future linear e^+e^- Collider:
  $\sqrt{s} = 250\,\text{GeV}$ (First stage, extendable up to $1\,\text{TeV}$)
- Construction under political consideration
  in the Kitakami mountains, Tōhoku region, Japan
- Both beams (e^+, e^-) are polarized: $P_{e^-} = \pm 80\%$, $P_{e^+} = \pm 30\%$

The International Large Detector

A Particle Flow detector

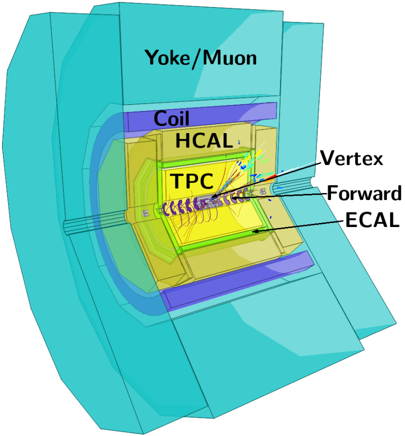


Figure : $\nu\nu + 4$ jets event in current ILD model.

Optimized for: **Particle Flow** and **precision physics**

Particle Flow:
Use only information from subdetector with best resolution

$\Longrightarrow$ **Resolution-driven design!**

- Highly granular calorimeters
  $\rightarrow$ ECAL: 30 layers of $5 \times 5\text{mm}^2$ pixels
  $\rightarrow$ HCAL: 48 layers of $1 \times 1\text{cm}^2$ pixels
  $\rightarrow$ In barrel $\lesssim 10\% X_0$ before CALs
- Efficient tracking using Time Projection Chamber
  $\rightarrow$ up to 224 points / track
  $\rightarrow$ dE/dx for particle-ID
- Full solid angle coverage
  $\rightarrow$ Coverage $\gtrsim 0.4^\circ$

Electroweak precision at the ILD

Energy resolution in a Particle Flow detector

- TPC + high-granularity calorimeters
  $\Rightarrow$ Cluster/Particle separation
- Particle Flow:
  - Find clusters & tracks $\xrightarrow{\text{Combine}}$ Particles
  - Charged particle info from tracker + PID (not CALs!)

$\Rightarrow$ **Jet Energy Resolution (JER) $\sim$ few %**

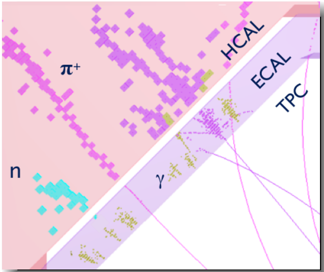
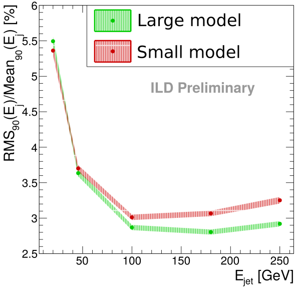


Figure : 250 GeV jet in the ILD [arXiv:1308.4537]



- Can separate hadronic W/Z decays! (BR~70%)
  $\rightarrow$ Precision EW physics in hadronic final states
- Separate W and Z by invariant dijet mass

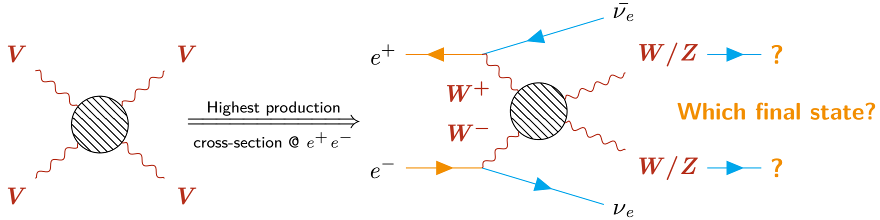
  $\rightarrow$ Benchmark: JER: $\sigma_E/E \sim 3-4\%$

- Tested in full detector MC simulation!

Vector Boson Scattering in e^+e^-

Making use of %-level JER

Goal: Measure Quartic Gauge Coupling $\Longrightarrow \sigma_{V_1 V_2 V_3 V_4}$



@ pp:

- Dominant QCD background
- Large pile up

$\Longrightarrow$ Search in semi-/leptonic final state

@ e^+e^-:

- Fully hadronic final state accessible!

$\Longrightarrow$ Search in **all** final states!

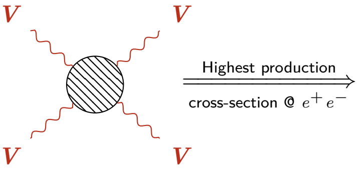
$\sigma(W/Z \to \text{hadrons}) \sim 70\%$

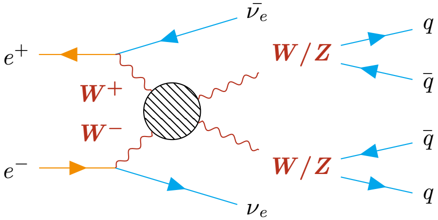
$\Longrightarrow$ Main analysis:
Hadronic final states!

Vector Boson Scattering in e^+e^-

Making use of %-level JER

Goal: Measure Quartic Gauge Coupling $\Longrightarrow \sigma_{V_1 V_2 V_3 V_4}$





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$\nu\bar{\nu} + WW/ZZ$ analysis strategy

Previous VBS studies in $\nu\bar{\nu} + WW/ZZ$:

- [LC-PHSM-2001-038] 2001 for TESLA
- [arXiv:1006.3396] 2009 for ILD Letter of Intent

$\Longrightarrow$ Follow the same **4 basics steps**:

1. **WW/ZZ event defintion**
2. **Detector simulation & event reconstruction**
3. **Event selection**
4. **EFT interpretation**

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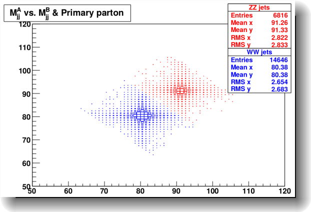
$\Longrightarrow$ Follow the same **4 basics steps**:

1. **WW/ZZ event defintion**
   - Define WW/ZZ-like topology in $\nu\bar{\nu}q\bar{q}q\bar{q}$:
   - e^-_L, e^+_R + correct q flavours
   - $147.0 < m^1_{qq} + m^2_{qq} < 171.0$ (WW), $171.0 < m^1_{qq} + m^2_{qq} < 195.0$ (ZZ)
   - $|m^1_{qq} - m^2_{qq}| \leq 20.0$GeV
   - $m_{\nu_e\bar{\nu}_e} \geq 100.0$GeV
2. **Detector simulation & event reconstruction**
3. **Event selection**
4. **EFT interpretation**



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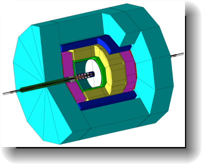
$\Longrightarrow$ Follow the same **4 basics steps**:

1. **WW/ZZ event defintion**
2. **Detector simulation & event reconstruction**
    - Fast or Full detector simulation
    - Event reconstruction with Particle Flow
    - Using *ilcsoft* (github.com/iLCSoft)



3. **Event selection**
4. **EFT interpretation**

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$\Longrightarrow$ Follow the same **4 basics steps**:

1. **WW/ZZ event defintion**
2. **Detector simulation & event reconstruction**
3. **Event selection**
   - Cuts on jet content $\rightarrow$ Reject $t\bar{t}$ events
   - $Y_{34} > 0.0001$ $\rightarrow$ Not less than 4 jets
   - $m_{missing}$, $E_{T,visible}$ and $p_{T,visible}$ cuts $\rightarrow$ Suppress 2- and 4-fermion and $ZWW/ZZZ(, Z \rightarrow \nu\nu)$ bkg
   - Missing momentum not very-forward $\rightarrow$ No particles into beam pipe
   - Cuts on highest energetic track $\rightarrow$ Suppress ISR$\rightarrow$hadrons events
   - Cuts on cone around most energetic track $\rightarrow$ Reject $t\bar{t} \rightarrow b\bar{b}q\bar{q}l\nu$
4. **EFT interpretation**

$\nu\bar{\nu} + WW/ZZ$ analysis strategy

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$\Longrightarrow$ Follow the same **4 basics steps**:

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4. **EFT interpretation**

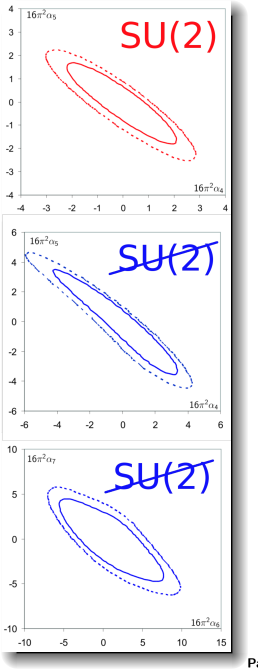
- Use dim-4 operators of EW-EFT to describe deviations

  $\longrightarrow$ Set limits on α_i

$$\mathcal{L}_0 = \mathcal{L}_{\text{SM}} + \sum_i \alpha_i \mathcal{L}_i^{\text{anomalous}}$$

$$\mathcal{L}_4 = (\text{tr}\{V_\mu V_\nu\})^2$$

$$\mathcal{L}_5 = (\text{tr}\{V_\mu V^\mu\})^2$$



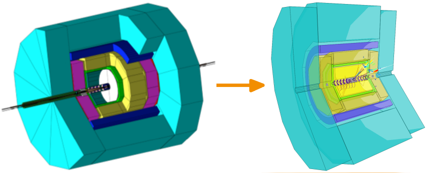
Updating the analysis

Bringing $\nu\nu q\bar{q}q\bar{q}$ to the 2010's

Previous analysis: **2009**

$\Longrightarrow$ Time to **update!**

- **New** detector model(s)
- **New** software (detector simulation, Particle Flow, ...)
- **New** physics knowledge (2009<2012)
- **New** background simulations
- ...



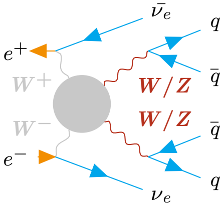
iLCSoft v01-06

↓

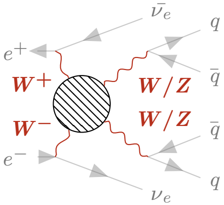
iLCSoft v-02-00-01

In progress:

- Event reconstruction
- Energy corrections



Planned: $\Longrightarrow$ aQGC analysis



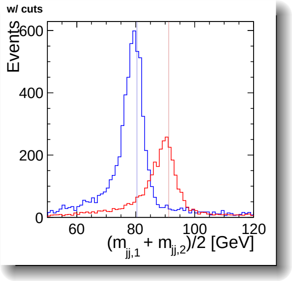
$\nu\bar{\nu} + WW/ZZ$ event reconstuction

Challenges to accurate final state picture

Final state:

- 4 jets
- p_{miss}

Reconstruct $\Longrightarrow$ WW/ZZ mass



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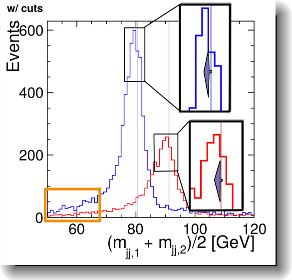
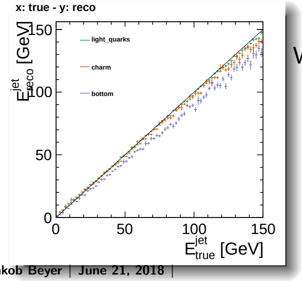


- Peaks shifted
- Long tails

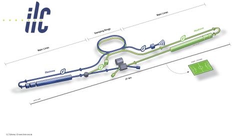
$\Longrightarrow$ Cause?

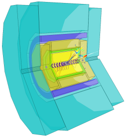
Problem with **heavy q jets**:

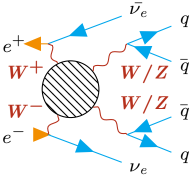


Why in heavy q jets?

- $B \to l\nu \Rightarrow$ **additional p_{miss}**
- Jet topology
  $\to$ jet content, boosted system
  $\Rightarrow$ **Particle Flow calibrated for single particles!**







Setup:

- e^+e^- collider, $\sqrt{s}$ up to 1 TeV, polarized beams
- ILD detector, optimized for Particle Flow event reconstruction

Achievable:

- JER $\sim$ 3-4% $\Longrightarrow$ Separation of hadronic W and Z decays!
- Previous studies: Limits on $\alpha_4, \alpha_5 \sim \mathcal{O}(0.01)$

Updating:

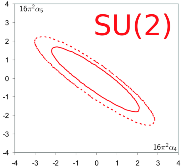
- Redoing analysis with new detector, physics, software, ...
- Working on accurate final state reconstruction specifically for $\nu\nu q\bar{q}q\bar{q}$

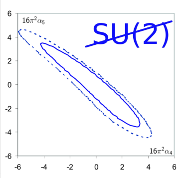
Additional material

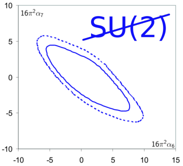
More plots

Limits on α_i

from 2009 paper [arXiv:1006.3396]







SU(2)

coupling	$\sigma-$	$\sigma+$
$16\pi^2\alpha_4$	-1.41	1.38
$16\pi^2\alpha_5$	-1.16	1.09

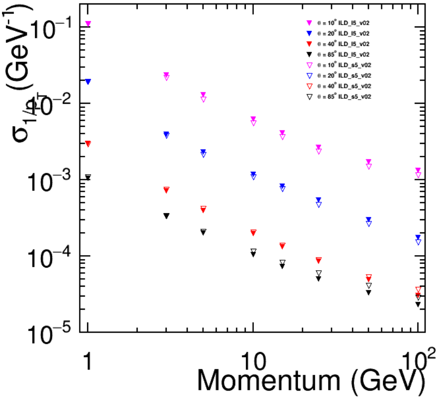
~~SU(2)~~

coupling	$\sigma-$	$\sigma+$
$16\pi^2\alpha_4$	-2.72	2.37
$16\pi^2\alpha_5$	-2.46	2.35
$16\pi^2\alpha_6$	-3.93	5.53
$16\pi^2\alpha_7$	-3.22	3.31
$16\pi^2\alpha_{10}$	-5.55	4.55

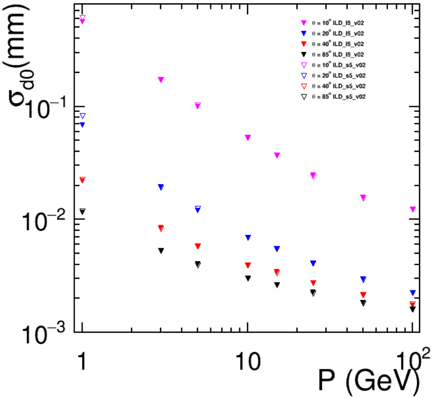
Track resolutions

For different detector models with up-to-date software

Momentum Resolution

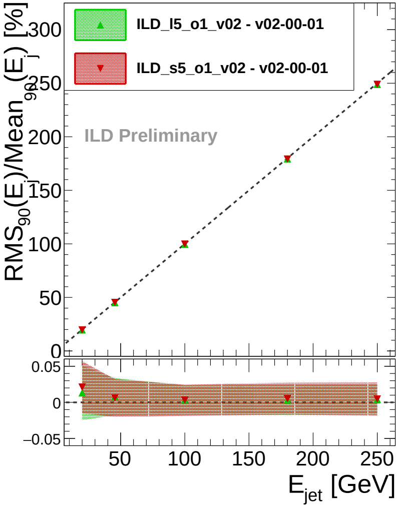


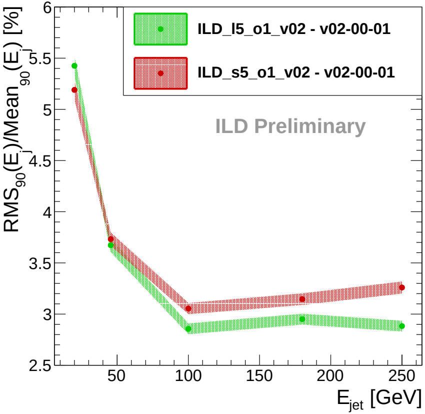
IP Resolution



Jet energy reconstruction

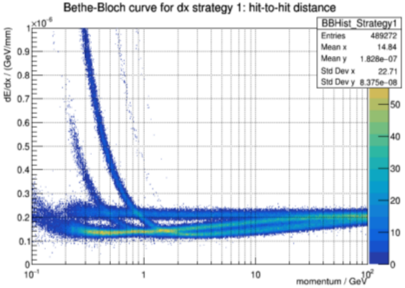
For different detector models with up-to-date software

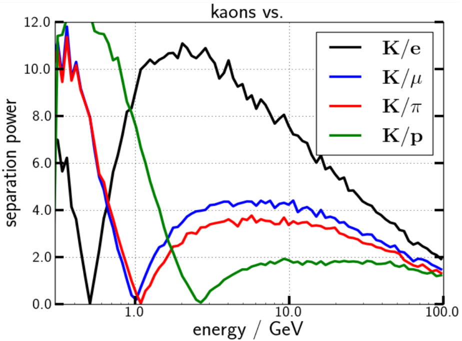




Particle-ID with dE/dx

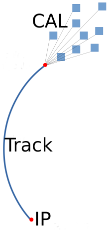
Advantages of a TPC





Using Time Of Flight for particle identification

Particle-ID from velocity



Goal: Use arrival time at CAL to determine particle mass

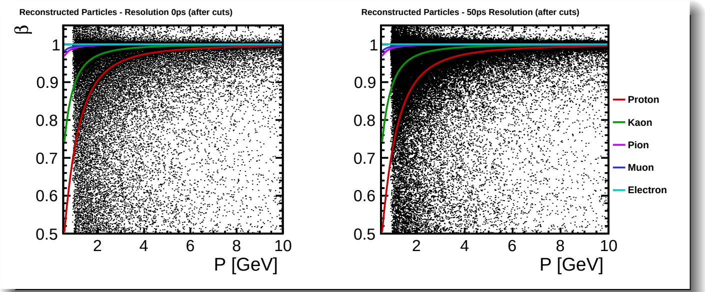
$$\beta = \frac{p}{\sqrt{m^2 + p^2}} = \frac{l_{\text{track}}}{t_{\text{arrival}}}$$

l_{track}: From momentum & curve in B field

t_{arrival}: Time of first hit closest to particle path

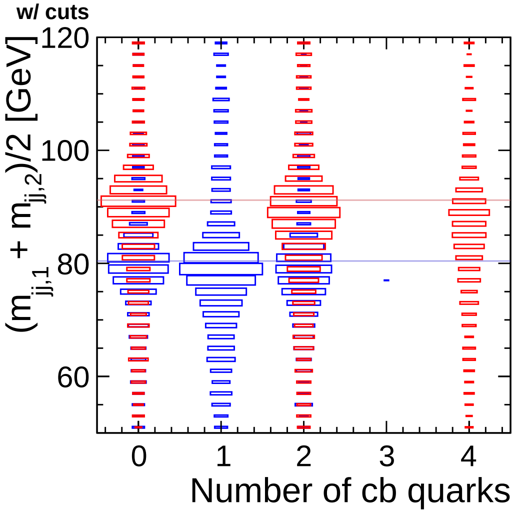
$\Longrightarrow$

- Test on $t\bar{t}$ events
- **Time resolution:** 0 ps, 50 ps
- Only particles hitting barrel ECAL



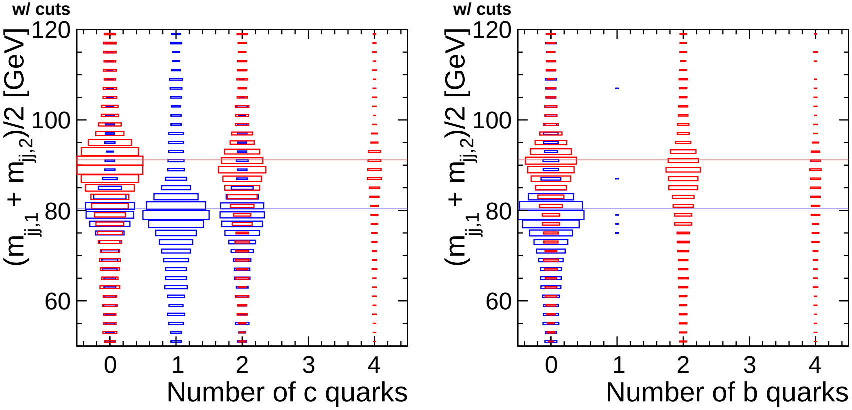
Quark flavour influence on mass reconstruction

Peak shift from heavy quarks



Quark flavour influence on mass reconstruction

Difference between c and b



Using Time Of Flight for particle identification

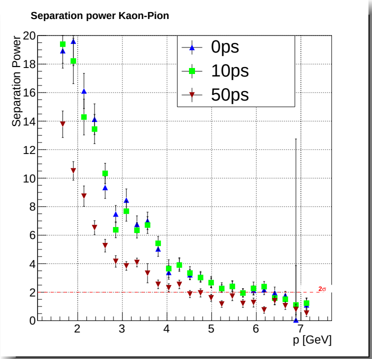
Particle-ID for low-p hadrons

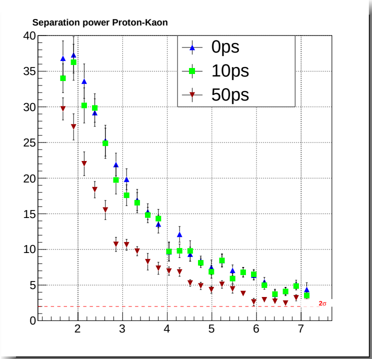
Gaussian fit at $p \Rightarrow$

Separation power: $$S = \frac{|\mu_1 - \mu_2|}{\sqrt{(\sigma_1^2 + \sigma_2^2)/2}}$$

μ_i: Mean for particle type i

σ_i: Std. dev. for particle type i

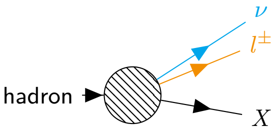




$\Rightarrow$ TOF usable for **low-p hadron ID** $\longrightarrow K - p$ up to 6GeV $\longrightarrow K - \pi$ up to 3.5GeV @ **50ps single hit resolution**

Measuring Vector Boson Scattering in hadronic final state

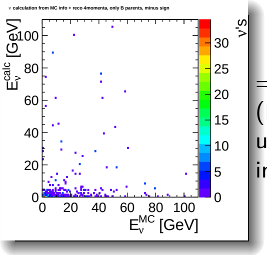
ν corrections



- Use lepton as tag for neutrino
- Two correction strategies:
  1. Use momentum conservation
     $\longrightarrow$ "**reconstruct**" individual ν
  2. ν spectra and $\nu - l$ correlation
     $\longrightarrow$ **average** correction

1. ν reconstruction $\rightarrow$ Problems:

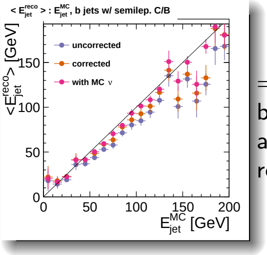
- Two solutions for p_ν
- Solutions very sensitive to momenta



$\Rightarrow$ **Not promising** (Even when still using some MC info...)

2. Averaged correction (similar to Claude's work)

- Guess E_ν from E_{lep} based on average in MC distributions



$\Rightarrow$ **Promising**, but: additional b jet reco. problems!