Study of polarization fractions in $W^{\pm}W^{\pm}$ Vector Boson Scattering

Ulrike Schnoor
Michael Kobel, Carsten Bittrich, Stefanie Todt
ulrike.schnoor@cern.ch

Physikalisches Institut, Uni Freiburg

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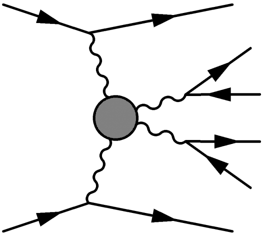
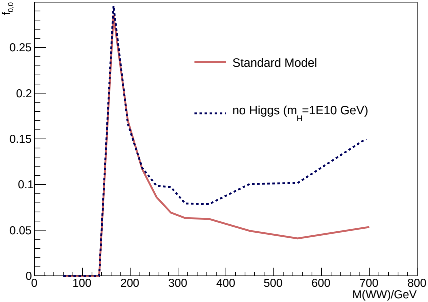
Longitudinal Vector Boson Scattering

Probing the mechanism behind electroweak symmetry breaking

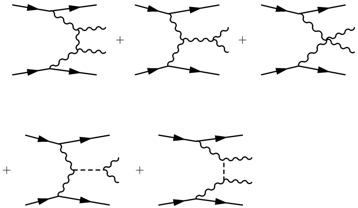
- Longitudinal degrees of freedom of W bosons generated through Higgs mechanism.
- Challenge: Separate $W_L W_L$ from $W_L W_T$ and $W_T W_T$ (containing left- and right-handed Ws)
- Looking at $W^{\pm}W^{\pm}$: first and so far only channel with observation of weak boson scattering





Longitudinal VBS

The scattering of longitudinal vector bosons violates unitarity in the absence of a SM Higgs boson:



Gauge bosons:

$$\mathcal{M}^{gauge} = -\frac{g_w^2}{4m_W^2}u + \mathcal{O}\left(\frac{E}{m_W}^0\right)$$

$\Rightarrow\sim E^2$, violates unitarity

Higgs exchange:
(s, t, u $>>$ m_W^2, m_H^2)

$$\mathcal{M}^{\text{Higgs}} = \frac{g_w^2}{4m_W^2}u$$

$\Rightarrow$ **terms cancel**

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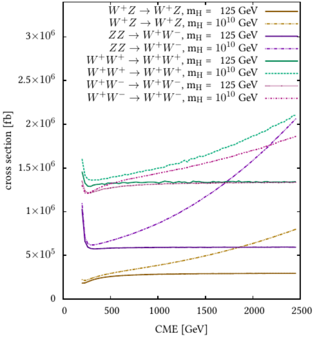

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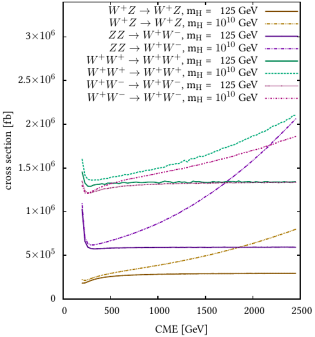

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$\Rightarrow$ **terms cancel**

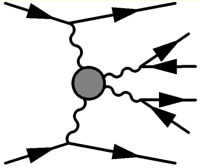
$\Rightarrow$ Probing the Higgs properties through the scattering of electroweak gauge bosons

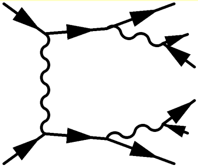
Outline

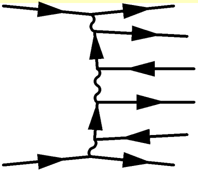
Definition of polarization fractions

Usual definition of $W^{\pm}W^{\pm}$ scattering:
electroweak production of $\ell^{\pm}\nu\ell^{\pm}\nu jj$ with $M(jj) > X$ GeV
($X = 150, 300, 500, \ldots$)

VBS	Irreducible EW	Non-resonant







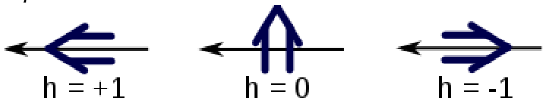
Intermediate Ws (resonant)	off-shell Ws

Polarization of W bosons only defined in case of 2 intermediate, on-shell W bosons.

$\rightarrow$ helicity well-defined though reference-frame dependent
[here: defined in Lab Frame]

Definition of polarization fractions

Helicity: $h = \vec{p} \cdot \vec{\epsilon}$



Definition according to the **final state** of the scattering:

$$W^\pm W^\pm \rightarrow W_L^\pm W_T^\pm$$
$$W^\pm W^\pm \rightarrow W_T^\pm W_L^\pm$$
$$W^\pm W^\pm \rightarrow W_T^\pm W_T^\pm$$
$$W^\pm W^\pm \rightarrow W_L^\pm W_L^\pm \qquad = \text{SIGNAL}$$

Notation: Transverse vs. Longitudinal

L: longitudinal   T: transverse

Notation: to distinguish left- and right-handed bosons:

0: longitudinal   -1: left-handed   +1: right-handed

Approximations

On-shell WW

Using two intermediate on-shell Ws instead of the full matrix element for $pp \to \ell^\pm \nu \ell^\pm \nu jj$ (narrow width approximation):
$pp \to W^\pm W^\pm jj \to \ell^\pm \nu \ell^\pm \nu jj$
$\Rightarrow$ neglecting contributions from non-resonant $\ell^\pm \nu \ell^\pm \nu jj$ production

Helicity projection

Using a diagonal spin density matrix, i.e. no interference between helicities is allowed

On-shell approximation

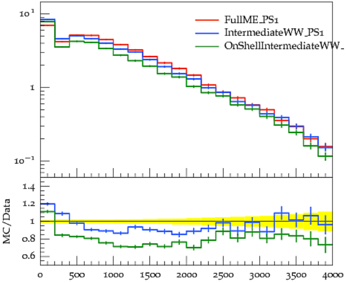
- FullME: generating $pp \to jj\ell^{\pm}\nu\ell^{\pm}\nu$
- Intermediate WW: only resonant diagrams $pp \to jjW^{\pm}W\pm \to jj\ell^{\pm}\nu\ell^{\pm}\nu$
- OnShellIntermediateWW: generating $pp \to jjW^{\pm}W\pm \to jj\ell^{\pm}\nu\ell^{\pm}\nu$ with on-shell Ws

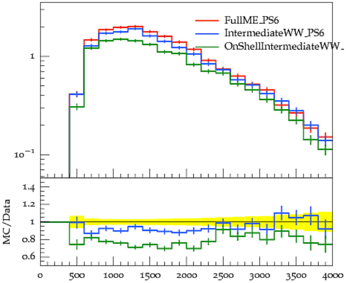
Generator Phase space:
$p_T(\ell) > 10$ GeV
$p_T(q) > 15$ GeV
$|\eta(\ell)| < 5$
$|\eta(q)| < 5$
$\Delta R(qq) > 0.4$

process	σ / fb
FullME	19.61 ± 0.06
IntermediateWW	19.56 ± 0.096
OnShellIntermediateWW	18.18 ± 0.08

Conclusion:
about 8 % difference between on-shell and full ME in this phase space

Distributions





$M(jj)$ distribution

top:

$p_T(\ell) > 25$ GeV
$p_T(j) > 30$ GeV
$|\eta(\ell)| < 2.5$
$|\eta(j)| < 5$
$M_{jj} > 20$ GeV

below:

$M_{jj} > 500$ GeV
$|\Delta\eta(jj)| > 4$

Interference between Polarizations

In order to estimate interference between polarizations, compare the full process to the process with diagonal spin density matrix.

WHIZARD $\geq$ 2.2.4: 3 options to specify spin density matrix:

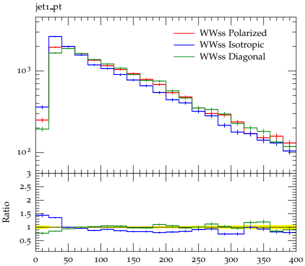
- full spin correlations
- diagonal spin density matrix
- isotropic decay

Compare:

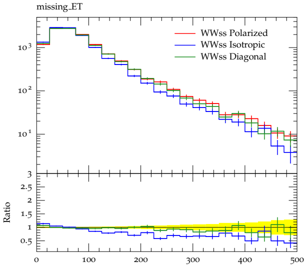
- polarized vs. diagonal: interference effects
- polarized vs. isotropic: influence of W, Z polarization

Interference of polarizations

Jet 1 p_T



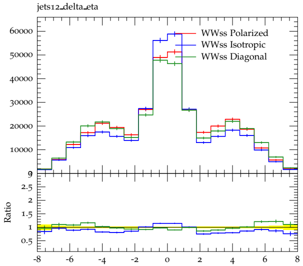
Missing E_T



- Diagonal spin density matrix: very small, flat difference
- Isotropic decay: larger deviations → the polarization does influence the kinematics

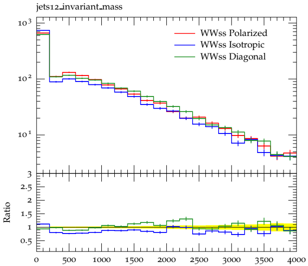
Interference of polarizations

Separation of tagging jets



$|\Delta\eta(jj)|$

Invariant Mass of tagging jets



M_{jj}

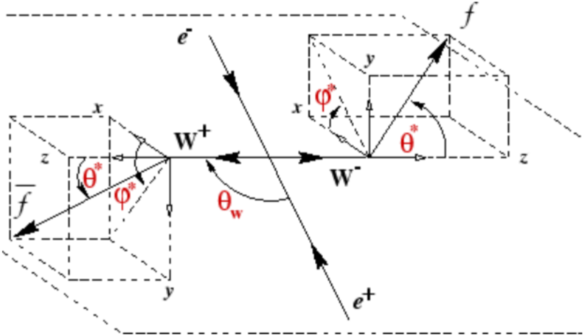
$\rightarrow$ Generally flat behavior

- Small flat difference between diagonal and full spin density matrix (green line)

$\Rightarrow$ Separation of polarizations does not lead to neglecting large interference effects.

Decay of the W bosons

Analytically known decay rates according to the decay angles $\theta*$ and $\phi*$



http://www.hep.ucl.ac.uk/∼jpc/all/ulthesis/node45.html

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta*} = \frac{3}{8}\left(1 \mp \cos\theta^*\right)^2 f_L + \frac{3}{8}\left(1 \pm \cos\theta^*\right)^2 f_R + \frac{3}{4}\sin\theta^{*2} f_0$$

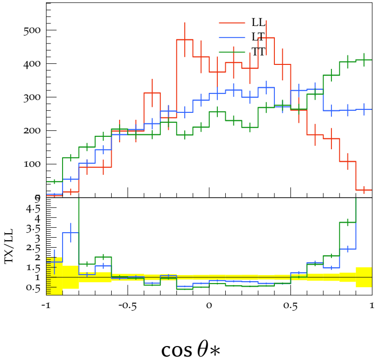
for $W^{\pm}$

Decay of the W bosons

- Produce $jjWW$ with known W polarizations
- Find $\theta*$ and $\phi*$ by drawing random numbers according to the analytical decay rate

$\rightarrow$ Rotate and boost the leptons to the lab frame.

- Decay angle distribution (truth level) $\longrightarrow$



Polarization fractions

loose phase space
$\Delta R(jj) > 0.4$, $|\eta(j)| < 5$, $p_T(q) > 10$ GeV, $M(qq) > 150$ GeV

tight phase space
$\Delta R(jj) > 0.4$, $|\eta(j)| < 5$, $p_T(q) > 30$ GeV, $M(qq) > 500$ GeV

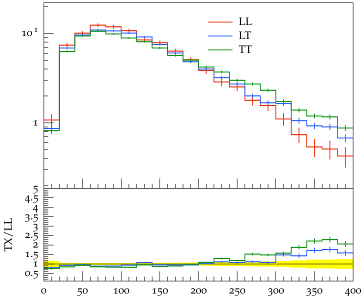
Polarization $W_x W_y$	in loose PS	in tight PS
0, 0	9 %	8 %
0, -1	25 %	24 %
0, +1	15 %	15 %
-1, +1	20 %	22 %
+1, +1	9 %	9 %
-1, -1	22 %	22 %

Plots in the following are scaled to $\sigma = 1$ to compare separation power of templates rather than polarization fraction

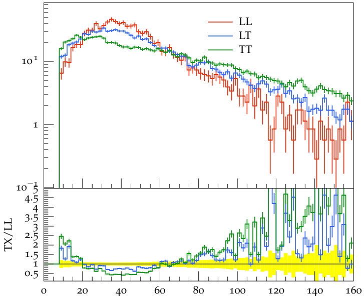
Kinematic behavior of longitudinal VBS

Goal: Separate $W_L W_L$ from $W_L W_T$ and $W_T W_T$ $\rightarrow$ find useful variable for template fit

Lepton and jet kinematics



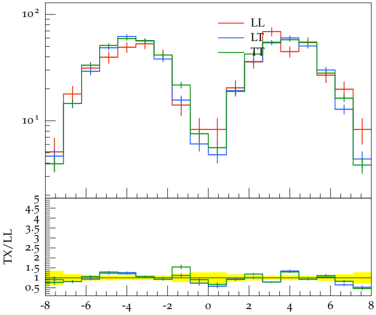
$p_T(j)$



$p_T(\ell)$

$\Rightarrow$ $W_L W_L$ features lower jet p_T, rather moderate lepton p_T

VBS-favoring variables



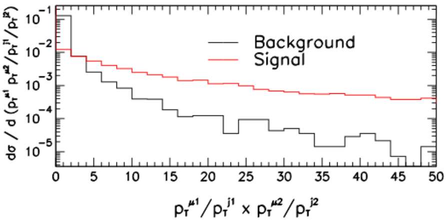
$|\Delta\eta(jj)|$

- "Typical" VBS cut variables do not favor $W_L W_L$ over $W_L W_T$ and $W_T W_T$ scattering: e.g. $M(jj)$, $|\Delta\eta|$, and lepton centrality give no separation power
- Look for variables suitable to distinguish between W polarizations

Variables for longitudinal scattering extraction

Optimized selection for the longitudinal component, find variables such as [arXiv:1201.2768]

$$R = \frac{p_T(\ell_1)p_T(\ell_2)}{p_T(j_1)p_T(j_2)}$$



Signal: longitudinal $W^\pm W^\pm$ scattering *without* SM Higgs

Background: electroweak $W^\pm W^\pm jj$ production with a SM Higgs with mass m_H = 120 GeV

Variables for longitudinal scattering extraction

Optimized selection for the longitudinal component, find variables such as [arXiv:1201.2768]

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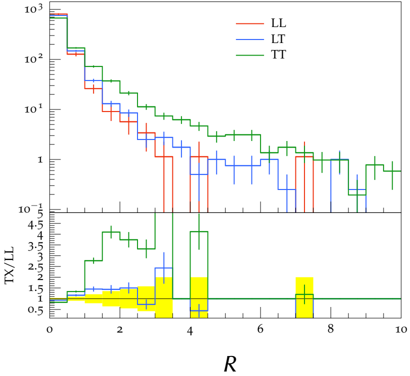
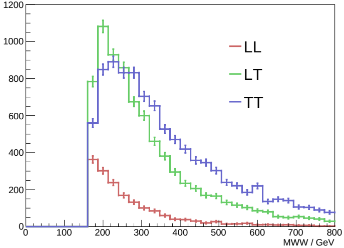


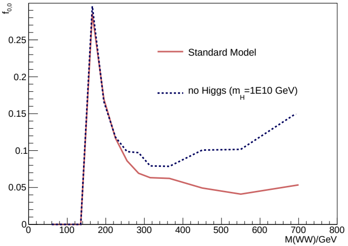
Changed signal definition after Higgs discovery:
SM Higgs included;
signal is $W_L W_L$ (SM)
$\rightarrow$ R variable not optimal

Diboson invariant mass

- M(WW) is sensitive to W polarizations
- M(WW) is sensitive to new physics in the electroweak sector

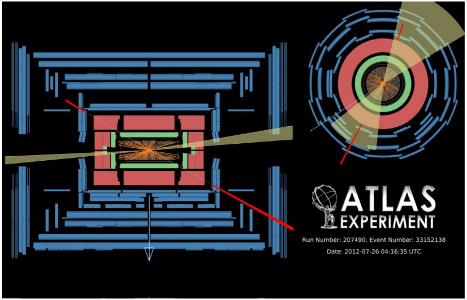


Contributions from the different polarizations in dependence of M(WW)



Fraction of longitudinal scattering in dependence of M(WW)

Mass reconstruction



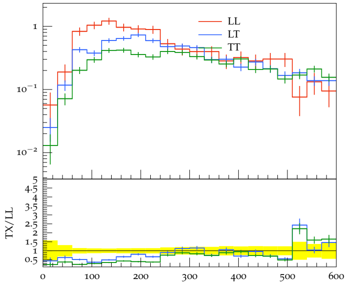
Two leptons + MET: Several different ways to approximate the WW-invariant mass

Traditional variables

- Visible mass: $M_{vis} = M(\ell, \ell) = [E(\ell_1) + E(\ell_2)]^2 - [\vec{p}(\ell_1) + \vec{p}(\ell_2)]^2$
- Effective mass: $M_{eff} = p_T(\ell_1) + p_T(\ell_2) + E_{\mathrm{T}}^{\mathrm{miss}}$
- Collinear mass: Assume the W decay products to be collinear; reconstruct neutrino momenta to get W momenta $p(W_i) \rightarrow M_{coll}^2 = (p^\mu(W_1) + p^\mu(W_2))^2$

Collinear mass

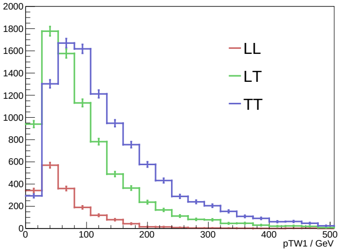
Collinar approximation:
Determine neutrino momenta using approximation that neutrino is collinear to the lepton.



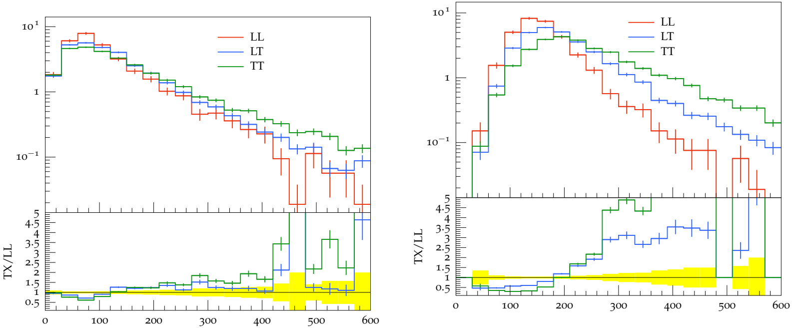
M_{coll}

- Rather low separation power

→ Ws are not highly boosted:



Visible and effective Mass

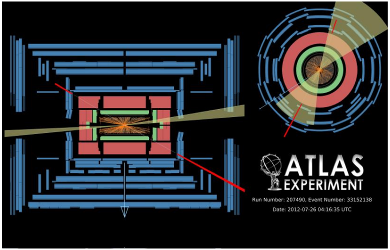


Visible mass defined as $M_{vis} = M(\ell, \ell)$

Effective mass defined as $M_{eff} = p_T(\ell_1) + p_T(\ell_2) + E_{\mathrm{T}}^{\mathrm{miss}}$

$\rightarrow$ Including the $E_{\mathrm{T}}^{\mathrm{miss}}$ information increases separation power

Mass-bound variables



- Transverse projection and forming of four-momenta are non-commuting operations
- Depending on
  - order of projection and four-momentum partitioning
  - type of transverse projection

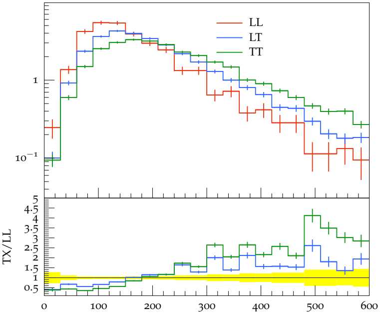
$\Rightarrow$ multiple ways to construct invariant mass from $p_\mathrm{T}(\ell_1)$, $p_\mathrm{T}(\ell_2)$, and $E_\mathrm{T}^\mathrm{miss}$

Mass bound variables

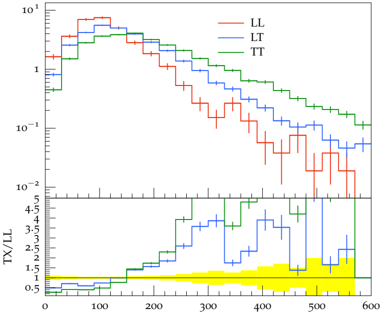
- $M_{\circ 1} = (|\vec{p}_T(\ell_1)| + |\vec{p}_T(\ell_2)| + |\vec{p}_{Tmiss}|)^2 - (\vec{p}_T(\ell_1) + \vec{p}_T(\ell_2) + \vec{p}_{Tmiss})^2$
- $M_{1\top} = \left(\sqrt{M_{\ell\ell}^2 + \vec{p}(\ell_1) + \vec{p}(\ell_2)} + |\vec{p}_{Tmiss}|\right)^2 - (\vec{p}(\ell_1) + \vec{p}(\ell_2) + \vec{p}_{Tmiss})^2$

introduced in hep-ph/1105.2977

Mass-bound variables



$M_{1\top}$



$M_{\circ 1}$

$M_{\circ 1}$ gives the highest separation power of the investigated mass variables

Conclusions and outlook

- Established a method to create event samples for electroweak production of $\ell^{\pm}\nu\ell^{\pm}\nu jj$ with known helicity according to exact decay angles
- Checked approximations necessary for a definition of polarization
- Studied mass reconstruction variables for possible templates to distinguish $W_L W_L$ from $W_L W_T$ and $W_T W_T$ with some promising candidates
- Next step: Implement this in a detector (fast) simulation for prospects at future LHC

Backup

Backup slides

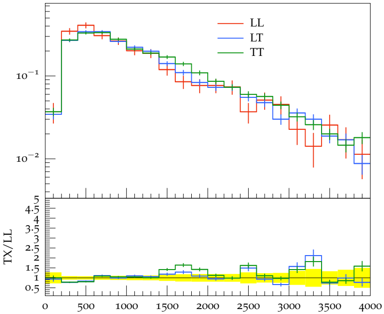
References

K. Doroba, J. Kalinowski, J. Kuczmarski, S. Pokorski, J. Rosiek, M. Szleper, and S. Tkaczyk, *The $W_L W_L$ scattering at the LHC: improving the selection criteria*, Physical Review D **86** no. 3, (2012). http://arxiv.org/abs/1201.2768. arXiv: 1201.2768.

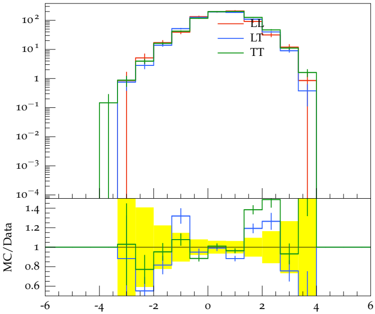
W. Kilian, T. Ohl, and J. Reuter, *WHIZARD: Simulating Multi-Particle Processes at LHC and ILC*, Eur.Phys.J. **C71** (2011) 1742, arXiv:0708.4233 [hep-ph].

A. J. Barr, T. J. Khoo, P. Konar, K. Kong, C. G. Lester, K. T. Matchev, and M. Park, *Guide to transverse projections and mass-constraining variables*, Phys. Rev. **D84** (2011) 095031, arXiv:1105.2977 [hep-ph].

Kinematics: VBS-like variables



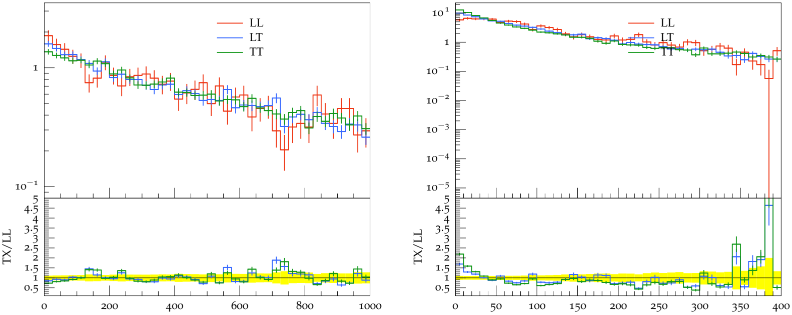
$M(jj)$



Lepton centrality ζ

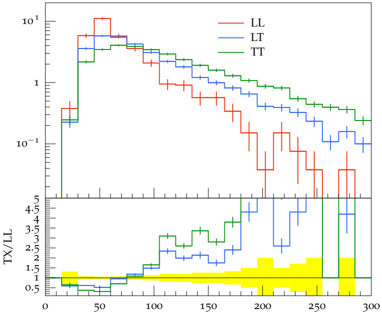
$\zeta = \min\{\min\{\eta_{l1}, \eta_{l2}\} - \min\{\eta_{j1}, \eta_{j2}\}, \max\{\eta_{j1}, \eta_{j2}\} - \max\{\eta_{l1}, \eta_{l2}\}\}$

Kinematics: longitudinal momentum



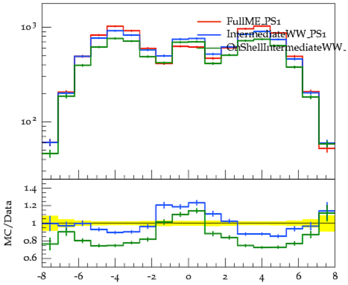
$p_Z(j)$ $p_Z(\ell)$

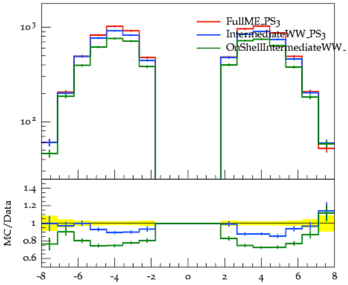
Kinematics

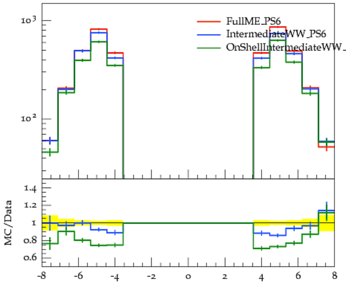


$p_T(\ell_1)$

Distributions







$|\Delta\eta(jj)|$ in PS1, PS3, PS6

Projection and mass reconstruction

While projection of a three-vector $\vec{p}$ on the transverse plane, $\vec{p}_T$, is well-defined, the "projection" of energy is ambiguous.

- Mass-preserving projection: $e_\top = \sqrt{E^2 - p_z^2} = \sqrt{M^2 + \vec{p}_T^2}$
- Mass-less projection: $e_\circ = |\vec{p}_T|$

Mass-bound variables names carry the order of projection, partitioning, and the number of steps for minimization (here $N = 1$).
E.g. $M_{\circ 1}$ is based on a mass-less projection before four-momentum partitioning. $M_{1\top}$ is based on partitioning first, then mass-preserving projection.