W and Z bosons + jets
with CMS and ATLAS

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on behalf of the CMS and ATLAS Collaborations

QCD@LHC2013
2-6 September 2013
DESY, Hamburg
Related presentations (experimental)

- **Keynote talks, in particular**
  - **Kostas Kousouris**: QCD from LHC experiments

- **12:00 Wed 4 Sep: Plenary**
  - **Anne-Marie Magnan**: $W/Z$, heavy flavor, exp. (ATLAS+LHC)
    - $W/Z$+HF processes: $W+c$, $W+b(b)$ and $Z+b(b)$.

- **14:00 Tue 3 Sep: Hard QCD + PDF**
  - **François Corriveau**: Jet cross sections (ATLAS)
  - **Giannis Flouris**: Jet cross section (CMS)

- **14:00 Wed 4 Sep: Hard QCD: NLO, NNLO, EW**
  - **Masaki Ishitsuka**: $Z,W$+jets, $t\bar{t}$+jets and $W$+heavy flavours (ATLAS)

- **14:25 Wed 4 Sep: Hard QCD: NLO, NNLO, EW**
  - **Matteo Marone**: $Z,W$+jets, $t\bar{t}$+jets and $W$+heavy flavours (CMS)
**W/Z + jets: motivation**

- Test pQCD calculations to high precision
  - study of topological properties
  - study of jet multiplicity and kinematic properties
  - LHC energies and large data sets open huge phase-space
- Study and constrain parton density functions
- Important for searches
  - many heavy exotic particles are expected to decay to W/Z
  - searches require the exploration of high $p_T$
- Important background for
  - Higgs studies
  - BSM searches
- High production rate
- Simple decay signature

\[ Z \rightarrow \ell^+ \ell^- \]

\[ W \rightarrow \ell \nu \quad \ell = e, \mu \]
Outline

- W,Z analyses with jet reconstruction
  Probe high order pQCD
  Constrain parton densities
  - Z+jets
  - W+jets
  - (W+jets)/(Z+jets)

- Double parton interactions (DPI) in W + 2 jets

- Boosted W,Z analyses
  Test of high order pQCD
  Test of resummation techniques
  - Z $p_T$, W $p_T$, Z phi*
Z + jets

- LHC dataset allows measurement of
  - high jet multiplicities: up to 7 jets
  - up to high jet $p_T$: leading jet $p_T$ up to 700 GeV at $\sqrt{s}$ 7 TeV
Z + jets - inclusive jet multiplicities

- cross section for dressed electrons and particle jets in fiducial acceptance region
- normalized to inclusive cross section
  - cancel uncertainties on electron reco and integrated luminosity
- Jet energy scale is the dominant uncertainty
  - 20-30% effect in forward region

- Good description by fixed order NLO calculations and multi-leg MC + PS
  - MC@NLO agrees only for at most \( \geq 1 \) jet (one parton from NLO real emission), otherwise HERWIG PS fails to model jet multiplicities

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Jet multiplicity ratios are expected to follow one of two benchmark patterns:
- Scaling can be used to extrapolate the jet rate to higher multiplicities.
  - Useful in analyses using jet vetoes to separate signal from W/Z+jets background.

"Staircase" scaling:
- Ratio $R_{n+1}/n$ constant.
- Jet rate $\sigma_n \sim e^{-bn}$.
- Inclusive and exclusive ratios scale the same way.
- Expected in the absence of major kinematic cuts.
  - Low multiplicities: combined effect of Poisson-distributed multiplicity distributions and parton density suppression.
    - Emission of the first parton suppressed more strongly: $R_{1/0}$ by 60%.
  - High multiplicities: effect of non-abelian nature of QCD FSR.

"Poisson" scaling:
- Exclusive Ratio $R_{n+1}/n \sim \mu_n/(n+1)$.
- Jet rate $\sigma_n \sim \text{Poisson}(n | \mu_n)$.
- Emerges when large difference between Z+1jet and other jets energy scales.
  - Expected when jet acceptance cut much larger than hard process scale.
For $n > 1$, scaling is compatible with a constant

- MadGraph (multi-leg MC) agrees well with data (both UE tunes Z2 and D6T)
  - PYTHIA parton shower fails to describe the data for $N_{jets} \geq 2$
Z + jets - exclusive jet multiplicities

- no scale uncertainty (dark shaded)
- correlated between multiplicity bins (medium shaded)
- uncorrelated (light shaded), as prescribed in Phys.Rev.D85 (2012) 034011

- cross section well modeled by fixed order NLO pQCD
  - Transition between “Staircase” and “Poisson” scaling observed
Z + jets - jet transverse momentum

- Test of limitations of ME+PS generators and fixed order pQCD in regions where large logarithmic corrections and EW NLO corrections are expected to become important
  - $p_T$ jets, jet $p_T$ ratios, $Z$ $p_T$
- For leading jet, experimental precision exceeds theory precision

- Data consistent with fixed order NLO predictions of BLACKHAT+SHERPA
- ALPGEN predicts too hard a spectrum for large jet $p_T$
  - missing NLO EW+QCD corrections
- SHERPA prediction is 5-15% too low
- MC@NLO predicts too soft a spectrum
  - next to leading jets modeled via parton shower
  - since fraction of events with > 1 jet increases with leading jet $p_T$, soft $p_T$ spectrum from parton shower leads to increase discrepancy with data
Data consistent with fixed order NLO predictions of BLACKHAT+SHERPA for all multiplicities
ALPGEN predictions consistent with data
SHERPA predictions are too low by 5-15%
Z + jets - jet transverse momentum

- **Veto on second jet applied:** better agreement

- **No scale uncertainty** (dark shaded)
- **Correlated between multiplicity bins** (medium shaded)
- **Uncorrelated** (light shaded), as prescribed in Phys.Rev.D85 (2012) 034011

- **PT ratio of jet 1 and 2 for N_{jets} > 1**
  - ALPGEN prediction overestimates the data in the region 0.1-0.2
  - SHERPA underestimates the cross section by ~15%

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Z + jets - Z transverse momentum

- Complementary approach to $p_T$ differential cross section measurement
- Higher-order electroweak corrections expected to reduce the cross section by 5-20% for $Z p_T > 100$ GeV

- BLACKHAT+SHERPA fixed order calculation too soft for the inclusive $\geq 1$ jet final state (but in agreement for the exclusive 1 jet final state)
  - attributed to missing higher-order jet multiplicities in the fixed-order calculation: use exclusive sums of NLO calculations to have better agreement
  - no indication for missing higher-order electroweak corrections in the large $Z p_T$ region
  - BLACKHAT calculation corrected for non-perturbative effects

- Both ALPGEN and SHERPA predict too hard a spectrum
  - discrepancy comparable to the expected higher-order electroweak corrections, but higher-order QCD corrections are also a possible cause

- MC@NLO describes the exclusive 1 jet final state better than the inclusive $\geq 1$ jet final state
Many physics signatures involved well separated forward jets

- knowledge of angular distributions can be used to separated signal from background

Experimental challenge: jet energy scale especially in the forward region

- NLO fixed order QCD and SHERPA overestimate cross section in the forward region
- ALPGEN predictions are in agreement with the data
- MC@NLO predicts too wide a rapidity distribution
Z + jets - jet and Z rapidities for $N_{\text{jet}} = 1$ (central)

- NLO predictions from MCFM
- MadGraph 5.1.1.0 + MLM scheme
- SHERPA 1.3.1 + CKKW scheme

All predictions agree with data within 5%
**Z + jets - ~ uncorrelated rapidities for N_{jet} = 1**

\[ Y_{\text{dif}} = \frac{|Y_Z - Y_j|}{2} \]

related to the polar scattering angle in the Z-j center of mass frame

\[ \cos \theta^* = \frac{\tanh(Y_{\text{dif}})}{\beta_Z^*} \]

\[ Y_{\text{sum}} = \frac{|Y_Z + Y_j|}{2} \]

~rapidity boost from lab to COM frame

\( Y_j \) and \( Y_Z \) highly correlated because there is usually a relatively high momentum quark interacting with a low momentum gluon or anti-quark

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- Good agreement between data and NLO calculations from MCFM
- SHERPA reproduces data better than MadGraph
  - difference introduced in matching ME to PS
  - large difference for more forward distributions
Z + jets - two leading jets $\Delta \Phi$ and $\Delta R$

$|\Delta \Phi|$ well modeled by BLACKHAT+SHERPA and ALPGEN

- SHERPA predicts a spectrum that is less pronounced
**Z + jets - $H_T$**

- $H_T$ is the scalar sum of jets and leptons $p_T$

- NLO fixed order $Z \geq 1$ jets deficit at large $H_T$
  - missing higher order QCD?
- ALPGEN, SHERPA agree with data

Better agreement with data is reached for NLO calculations when using **exclusive sums**

- $H_T > \sim 300$ GeV corresponds to an average jet multiplicity of more than 2 jets
- same outcome for $Z p_T$
Z+jets - azimuthal correlations $\Delta \Phi(Z, j_1)$

- $\Delta \Phi(Z, j_1)$: $\Delta \Phi$ between the Z and the leading jet for the inclusive multiplicities
  - $N_{jets} \geq 1, \geq 2, \geq 3$
  - normalized to unity

- $\Delta \Phi$ observable with largest systematics
  - 5-6% near 0, to 2% near $\pi$

- Agreement with POWHEG and SHERPA improve for larger multiplicities
- Multi-parton LO + PS do better than LO + PS !!
- PS important for NLO 1 jet in multijet environment
$N_{\text{jets}} \geq 3$
- $\Delta \Phi(Z, j_i)$
- normalized to unity

- Good agreement with POWHEG, MadGraph and SHERPA
- For $\Delta \Phi(Z, j_3)$, PYTHIA LO + PS agrees with data
  - PS contribution

$Z + \text{jets}$ - azimuthal correlations $\Delta \Phi(Z, j_i)$
Z+jets - azimuthal correlations $\Delta \Phi(j_i, j_k)$

- $N_{\text{jets}} \geq 3$
  - $\Delta \Phi(j_1, j_2)$
  - $\Delta \Phi(j_1, j_3)$
  - $\Delta \Phi(j_2, j_3)$
  - normalized to unity

- Isotropic for $p_T^Z > 150$ GeV
  - improved agreement with PYTHIA consistent with increased phase space available for parton emission

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**Z+jets - event shape: transverse thrust**

\[ \tau_T \equiv 1 - \max \sum_i \left| \frac{\vec{p}_{T,i} \cdot \vec{n}_\tau}{\sum i p_{T,i}} \right| \]

sum over Z and jets

\[ \tau_T \to 0 \]
\[ \ln \tau_T \to -\infty \]

\[ \tau_T \to 1 - \frac{2}{\pi} \]
\[ \ln \tau_T \to \approx -1 \]

- Transverse thrust, normalized to unity, ratio to MadGraph
  - dominant systematics from energy scale: 2%
  - at \( p_{T,Z} > 150 \text{ GeV} \), many events with spherical component

- POWHEG and MadGraph more consistent with data
- SHERPA and PYTHIA shifted to lower values (dijet-like)
- PYTHIA compares better for \( p_{T,Z} > 150 \text{ GeV} \)
Z+jets - EW Z+2 forward jets

- Z production in association with two jets at order $\alpha_4^{\text{EW}}$
  - includes TGC vertex (VBF), suppressed by a factor ~2.5 by interference terms
  - high $p_T$ jets with large rapidity distance
- $\sigma(\text{EW } \ell\ell jj)_{\text{NLO}} = 166 \text{ fb}$ (DY ~ 29.3 pb!)
  - $M_{jj} > 120 \text{ GeV, } M_{\ell\ell} > 50 \text{ GeV}$
  - $p_T j > 25 \text{ GeV, } |\eta_j| < 4$
  - CT10 and $\mu_R = \mu_F = 90 \text{ GeV}$
- Optimized event selection (S/B ~ 11%)
  - leptons: $\ell\ell$ with $p_T \ell > 20 \text{ GeV, } |\eta_\ell| < 2.4$
  - Z: $|M_{ee} - M_Z| < 20 \text{ GeV}$ (15 GeV for $\mu\mu$)
  - two leading $p_T$ jets in $|\eta| < 3.6$
    - $p_T(1) > 65 \text{ GeV; } p_T(2) > 40 \text{ GeV}$
    - $M_{jj} > 600 \text{ GeV}$
  - central Z in jj rest frame
    - $|y^*| = |y_Z - (y_{j1} - y_{j2})/2| < 1.2$
- Signal extraction with MVA
  - Boosted decision tree, including tagged jets and Z kinematics
  - $\sigma_{\text{meas, } \mu\mu ee}^{\text{EWK}} = 154 \pm 24(\text{stat}) \pm 46(\text{exp.syst.}) \pm 27(\text{th.syst.}) \pm 3(\text{lumi}) \text{ fb}$

- Important benchmark processes in search for VBF H!!
  - Jet activity profiles: MadGraph-based predictions in agreement with data (reco level)
  - $\sigma(\text{EW } \ell\ell jj)$ extracted (~2.6$\sigma$), compatible with prediction (NLO QCD corrections)
W + jets

- W+jets complementary to Z+jets
  - larger statistics
  - larger systematics

CMS Experiment at LHC, CERN
Run 133874, Event 21466935
Lumi section: 301
Sat Apr 24 2010, 05:19:21 CEST

Electron $p_T = 35.6$ GeV/c
$M_{E_T} = 36.9$ GeV
$M_T = 71.1$ GeV/c$^2$
$W + \text{jets}$ - jet multiplicities

$\text{Br}(W \rightarrow \ell \nu)$ included in $\sigma$

- $\text{BLACKHAT+SHERPA} + \text{CTEQ6.6M} + \mu_{\text{R/F}} = H_T/2$
- ALPGEN 2.13 + CTEQ6L1 + $\mu_{\text{R/F}} = \sqrt{M_W^2 + \sum j p_T^2} + \text{MLM}$
- SHERPA 1.3.1 + CTEQ6.6M + default $\mu_{\text{R/F}} + \text{CKKM}$
- PYTHIA 6.4.21

**Fiducial Phase Space**

- $p_T > 20$ GeV, $|\eta| < 2.5$
- $E_T^{\text{miss}} > 25$ GeV
- $m_T(W) > 25$ GeV
- $p_T^{\text{jet}} > 40$ GeV
- $|y^{\text{jet}}| < 4.4$
- $\Delta R^{jj} > 0.5$

- $\text{BLACKHAT+SHERPA}$: good agreement
- $\text{SHERPA}$: worse agreement
  - attributed to differences in PDFs, $\alpha_s$ and factorization/renormalization scales
- PYTHIA is LO ME up to 1 jet...

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W + jets - first and second jet $p_T$

**Theory/Data**

- **ATLAS**
  - $W \rightarrow t\bar{t} + \text{jets}$
  - $W + \geq 2 \text{jets}$
  - $W + \geq 3 \text{jets}$
  - $W + \geq 4 \text{jets}$

**Blackhat + Sherpa, Alpgen:** good agreement

**Sherpa:** worse agreement
- attributed to differences in PDFs, $\alpha_s$ and factorization scales

**Data 2010, $\sqrt{s}=7$ TeV**

- **First Jet $p_T$ [GeV]**
  - $\int L dt = 36 \text{ pb}^{-1}$
  - $W + \geq 1 \text{jets}$
  - $W + \geq 2 \text{jets}$
  - $W + \geq 3 \text{jets}$, $x10^{-1}$
  - $W + \geq 4 \text{jets}$, $x10^{-2}$

- **Second Jet $p_T$ [GeV]**
  - $W + \geq 2 \text{jets}$
  - $W + \geq 3 \text{jets}$, $x10^{-1}$
  - $W + \geq 4 \text{jets}$, $x10^{-2}$

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**W + jets - $H_T$**

- $H_T$ is the scalar sum over $p_T$ of jets, the lepton, the neutrino ($E_{T\text{miss}}$)

- Probe NLO pQCD properties
- $H_T$ often used for $\mu_R$ and $\mu_F$

- **ALPGEN (Multi-leg LO) agrees well with the data**
- discrepancies in $W + \geq 1$ jets with (limited order) NLO calculations for mean $N_{\text{jets}} > 2$ at large $H_T$

- Agreement improved on $H_T$ with BLACKHAT by replacing NLO $W + \geq 1$ jet with exclusive NLO sums (matched by counting parton jets with $p_T > 30$ GeV):
  - $W + \geq 1 = (W + 1) + (W + 2) + (W + 3) + (W + \geq 4 \text{ jets})$
  - confirmed in Z+jets
\[(W + \text{jets})/(Z + \text{jets})\]

- Cancellation of many systematics
  - powerful test of pQCD
\( \frac{(W + \geq n \text{ jets})}{(Z + \geq n \text{ jets})} \)

- Normalized to the inclusive cross section

- Many important systematic uncertainties cancel in the ratio
  - most important remaining from the selection efficiency (possible bin correlations due to \( M_T \) cut)
  - difference in expected value in the \( e \) and \( \mu \) channel due to larger electron acceptance in \(|\eta|\)

- Both MadGraph and PYTHIA agree with data within 1 \( \sigma_{\text{exp}} \)
(W + 1 jet)/(Z + 1 jet)

- Ratio of production cross section of W and Z with exactly 1 jet as a function of the jet $p_T$ threshold
  - $71 < m_{\ell\ell} < 111$ GeV and $|\eta_{\text{jet}}| < 2.8$
  - Combination of the $e$ and $\mu$ channels in the fiducial volume
- At $p_T = 30$ GeV
  - $8.29 \pm 0.18(\text{stat}) \pm 0.28(\text{sys})$
- W and Z production are similar: ratio less sensitive to systematics limitations of $V + \text{jets}$
  - Remaining systematic dominated by the boson reconstruction
  - For jet $p_T$ threshold > 50 GeV, the uncertainty is statistically dominated

- LO and NLO predictions agree with data
- Larger data samples (2011, 2012) will allow a very precise test of pQCD
Double Parton Interaction

- Use $W + 2$ jets to probe DPI
  - Higher $\sqrt{s}$ and luminosity imply bigger impact of DPI, and at higher $p_T$
  - Relevant contribution for analyses such as:
    - $W+b$ cross section
    - $W+j/\psi$ cross section
    - final states with same sign $WW$
W + 2 jets - double parton interaction

- One muon with $p_T^{\mu} > 35$ GeV and $|\eta| < 2.1$
- $E_T^{\text{miss}} > 30$ GeV, $M_T > 50$ GeV
- Jets with $p_T > 20$ GeV and $|\eta| < 2.0$

$\Delta S = \Delta \Phi$ between W and dijet system
- ~random for DPI
- ~back-to-back for SPI

MadGraph+PYTHIA 6.4.25+Z2star tune
- with multiple parton interaction: good description of the data
- without multiple parton interaction: rate and shape not reproduced

PYTHIA 8.165+4C tune
- missing higher order diagram: predicts more back-to-back
\[ \hat{\sigma}^{(\text{tot})}_{W+2j}(s) = \hat{\sigma}^{(\text{SPI})}_{W+2j}(s) + \hat{\sigma}^{(\text{DPI})}_{W+2j}(s) = \hat{\sigma}^{(\text{SPI})}_{W+2j}(s) + \frac{\hat{\sigma}_{W0j}(s) \cdot \hat{\sigma}_{2j}(s)}{\sigma_{\text{eff}}(s)} \]

\[ \sigma_{\text{eff}}(s) = \frac{\hat{\sigma}_{W0j}(s) \cdot \hat{\sigma}_{2j}(s)}{f_{\text{DP}} \hat{\sigma}^{(\text{tot})}_{W+2j}(s)} \]

- DPI is characterized by the effective area parameter \( \sigma_{\text{eff}} \)
  - assumed to be independent of phase space and process. Naively expect \( \sim 50 \text{ mb} \)

\[ f_{\text{DP}} \]

Fraction of DPI events in \( W+2j \) data events extracted from template fit to the normalized distribution of transverse momentum balance

\[ \Delta_{n_{\text{jets}}} = \frac{| \vec{p}_{T1} + \vec{p}_{T2} |}{| \vec{p}_{T1} | + | \vec{p}_{T2} |} \]

small for DPI

\( p_T > 20 \text{ GeV and } |y| < 2.8 \)

\[ f_{\text{DP}}^{(D)} = 0.08 \pm 0.01 \text{ (stat.)} \pm 0.02 \text{ (sys.)} \]

\[ \sigma_{\text{eff}}(7 \text{ TeV}) = 15 \pm 3 \text{ (stat.)}^{+5}_{-3} \text{ (syst.)} \text{ mb} \]

Result consistent with previous measurements at lower energies
Inclusive Z and W $p_T$

- Tests of high order pQCD and resummation techniques
**Z p_T - at 7 TeV**

- **Total background:** 0.4% (mu) 1.5% (e), up to 3.5% at high Z p_T
- **Dominant exp uncertainties:**
  - lepton ID and reconstruction: 1-3%
  - lepton energy scale and resolution: 0.7-4.4% (smaller for mu-channel)
  - unfolding (mainly Z p_T modeling used in efficiency correction): 1.3-4.7%

**FEWZ:** $O(\alpha_s^2)$ pQCD:
- in central region, underestimates data by about 10%

**RESBOS:** NNLL resummation + $O(\alpha_s)$ + $O(\alpha_s^2)$ pQCD:
- describes the spectrum well over the entire range

**SHERPA, ALPGEN, PYTHIA**
- agree well with data
Data from special 8 TeV LHC configuration with low pileup (average 5, ~ as for 7 TeV data)

Overall best agreement with MadGraph + PYTHIA + Z2star tune

Low $p_T$ region affected by underlying event
- PYTHIA + Z2star tune gives best result
- Results validate POWHEG + PYTHIA + Z2star tune (obtained from low scales processes...)

High $p_T$ region good agreement with POWHEG + PYTHIA + Z2star tune, and with FEWZ 3.1

Comparison with 7 TeV data as expected
Resolution of hadronic recoil to obtain $W p_T$ not as good as the resolution of the lepton momenta to obtain $Z p_T$, but there are ~10 times more $W$ than $Z$!

- $p_T^W$ unfolded to particle level
  - by default it is defined from the Born level $W$ propagator

Z and $W$ results display similar features
Supports the expected universality of QCD effects in $W$ and $Z$ production
\[ Z \Phi_{\eta^*} \] - definition

- Higher accuracy achieved by measuring cross section as a function of \( \Phi_{\eta^*} \)
  - D0 PRL 106, 122001 (2011)

\[ \phi_{\eta}^* \equiv \tan \left( \phi_{\text{acop}} / 2 \right) \cdot \sin (\theta_{\eta}^*) \]

\[ \phi_{\text{acop}} \equiv \pi - \Delta \phi \]

\[ \cos (\theta_{\eta}^*) \equiv \tanh \left[ (\eta^- - \eta^+) / 2 \right] \]

- This quantity only depends on direction of the leptons
- Extremely precise experimentally
- Correlates with \( Z p_T \)

\[ \phi_{\eta}^* \approx \frac{p_T^{Z}}{M_{\ell\ell}} \]
Calculations using RESBOS provide the best description of the data

- NNLL resummation (scale $M_Z$) matched to $O(\alpha_s)$, corrected to $O(\alpha_s^2)$ using $k$-factors depending on $Z p_T$ and $y$.
- but unable to reproduce the detailed shape to better than 4%

- $\sim 3 \times 10^6$ di-lepton candidates
- angular resolution:
  - 0.4-0.6 mrad in $\phi$
  - 0.0010-0.0012 in $\eta$
- 0.6% background, half from multi-jet, dominating at low $\Phi_\eta^*$
- dominant experimental systematics
  - background 0.3%
  - angular resolution: 0.2%
- Total uncertainties:
  - 0.5% (low $\Phi_\eta^*$), stat $\approx$ sys
  - 0.8% (high $\Phi_\eta^*$), stat dominating
**Z \Phi_{\eta}^* - comparison with theory**

- Difference between RESBOS and data smaller than PDF uncertainty (4-6%)
- Experimental uncertainty an order of magnitude more precise than predictions

**Banfi et al:**
- NNLL matched to NLO from MCFM

Uncertainty includes:
- Resummation, \( \mu_R, \mu_F : \times 2 \) around \( M_Z \)
- PDF CTEQ6m error eigenvectors

**Fixed order calculations not expected to be adequate in low Z p_T region**
- FEWZ not shown for \( \Phi_{\eta}^* < 0.1 \)

**FEWZ uncertainty include**
- \( \mu_R, \mu_F : \times 2 \) around \( M_Z \)
- PDF CT10 error eigenvectors
- vary \( \alpha_s \) within range (90%CL)
Conclusions W/Z + jets

- ATLAS and CMS have performed a wide range of W/Z + (light) jets measurements at the LHC
  - stringent tests of pQCD
- In general, good agreement between data and predictions
  - but discrepancies observed in several regions
    - fixed order NLO + PS fails to describe the data: missing higher order effects
      - challenges for certain types of observables, such as $H_T$
      - tension with very precise $Z \Phi_{\eta}^*$ distribution
    - LO ME or NLO, interfaces with parton shower models, provide input for generator tuning
  - needed for background predictions
- $W + 2$ jets study of double parton interactions
  - successful measurement of $\sigma_{\text{eff}}$ and of DPI sensitive observables
- Stay tuned: more data being analyzed!
Backup Slides
Z+jets - analysis strategy

1. Detector level (data)
   - Unfolding for detector effects

2. Particle level
   - Correction for non-perturbative and QED radiation effects

3. Parton level (BH+SHERPA)
Z+jets - cross section

- Main backgrounds
  - multi-jets in situ (0.4 - 1.5%)
  - ttbar in situ (0.2 - 26%)
  - diboson (0.2 - 1.2%)

- Iterative Bayesian unfolding method

- Differential measurements on dressed level, separately for e and µ channels

- Results from each channel extrapolated to common phase space region:
  - e, µ: $p_T > 20$ GeV, $|\eta| < 2.5$
    - dressed: add photon in $\Delta R < 0.1$
  - Z: opposite sign leptons
    - $66 < M_{\ell\ell} < 116$ GeV
  - jets: anti-kt, R=0.4, $p_T > 30$ GeV
    - $|y| < 4.4$, $\Delta R(j, \ell) > 0.5$
**Z + jets - MC signal events and NLO calculations**

- **MC signal event samples:** Z (→ee or →μμ) + jets (VBF production neglected)
  - ALPGEN 2.13 (0 ≤ Npartons ≤ 5)
    - HERWIG v6.520 (PS) + JIMMY v4.31 (UE AUET2-CTEQ6L1 tune)
    - PDF: CTEQ6L1 (LO)
    - QED FSR: PHOTOS
  - ALPGEN 2.14 (0 ≤ Npartons ≤ 5)
    - PYTHIA v6.425 (PERUGIA2011C tune)
    - PDF: CTEQ6L1 (LO)
    - QED FSR: PHOTOS
  - SHERPA 1.4.1 (0 ≤ Npartons ≤ 5)
    - PDF: CT10
    - MEnloPS approach
    - QED FSR: YFS method
  - MC@NLO v4.01
    - HERWIG
    - normalized to NNLO inclusive W production
  - Pileup events: minimum bias event from PYTHIA with AMBT1 tune
    - events reweighted to ensure the same distribution on the number of primary vertices as for data, average number of nine interactions per bunch crossing

- **NLO pQCD predictions**
  - BLACKHAT-SHERPA fixed order
    - Z+≥0j, Z+≥1j, Z+≥2j, Z+≥3j, Z+≥4j,
    - PDF: CT10
    - renormalization and factorization scales set to HT/2
    - anti-kt R=0.4 at parton level
    - corrected for fragmentation, QED-FSR, UE
    - (distributions for particle-level jets)/ (distribution for parton-level jets with no UE)
### Z+jets - systematic uncertainties

<table>
<thead>
<tr>
<th>$Z (\rightarrow ee)$</th>
<th>$\geq 1$ jet</th>
<th>$\geq 2$ jets</th>
<th>$\geq 3$ jets</th>
<th>$\geq 4$ jets</th>
<th>$p_T^{\text{jet}}$ in [30–500 GeV]</th>
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<tbody>
<tr>
<td>electron reconstruction</td>
<td>2.8%</td>
<td>2.8%</td>
<td>2.8%</td>
<td>2.8%</td>
<td>2.6–2.9%</td>
</tr>
<tr>
<td>jet energy scale, resol.</td>
<td>7.4%</td>
<td>10.1%</td>
<td>13%</td>
<td>17%</td>
<td>4.3–9.0%</td>
</tr>
<tr>
<td>backgrounds</td>
<td>0.26%</td>
<td>0.34%</td>
<td>0.44%</td>
<td>0.50%</td>
<td>0.2–3.2%</td>
</tr>
<tr>
<td>unfolding</td>
<td>0.22%</td>
<td>0.94%</td>
<td>1.2%</td>
<td>1.9%</td>
<td>1.4–6.8%</td>
</tr>
<tr>
<td>total</td>
<td>7.9%</td>
<td>10.5%</td>
<td>13%</td>
<td>17%</td>
<td>5.5–12.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$Z (\rightarrow \mu\mu)$</th>
<th>$\geq 1$ jet</th>
<th>$\geq 2$ jets</th>
<th>$\geq 3$ jets</th>
<th>$\geq 4$ jets</th>
<th>$p_T^{\text{jet}}$ in [30–500 GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon reconstruction</td>
<td>0.86%</td>
<td>0.87%</td>
<td>0.87%</td>
<td>0.88%</td>
<td>0.8–1.0%</td>
</tr>
<tr>
<td>jet energy scale, resol.</td>
<td>7.5%</td>
<td>9.9%</td>
<td>13%</td>
<td>16%</td>
<td>3.2–8.7%</td>
</tr>
<tr>
<td>backgrounds</td>
<td>0.093%</td>
<td>0.20%</td>
<td>0.41%</td>
<td>0.66%</td>
<td>0.1–1.9%</td>
</tr>
<tr>
<td>unfolding</td>
<td>0.30%</td>
<td>0.68%</td>
<td>0.52%</td>
<td>1.3%</td>
<td>0.5–6.2%</td>
</tr>
<tr>
<td>total</td>
<td>7.6%</td>
<td>10.0%</td>
<td>13%</td>
<td>16%</td>
<td>4.4–10.2%</td>
</tr>
</tbody>
</table>

- Jet energy scale dominant component of the total uncertainty
  - in particular in the forward region: 20 - 30%
Figure 1. Simplest primary (left) and secondary contributions (right) assuming a core process with a hard quark line.

For hadron collider processes involving two parton densities $f(x, Q)$ we define the PDF correction factor to the ratio of successive jet ratios $R_{(n+1)/n}/R_{(n+2)/(n+1)}$

$$B_n = \left| \frac{f(x^{(n+1)}, Q)}{f(x^{(n)}, Q)} \frac{f(x^{(n+2)}, Q)}{f(x^{(n+1)}, Q)} \right|^2. \quad (3.9)$$

The square in the definition of $B_n$ reflects the two PDFs in hadron collisions. If for example the partonic ratio of two successive jet ratios is $R_{(n+1)/n}/R_{(n+2)/(n+1)} \sim c$ then the proper hadronic ratio becomes $B_n c$. We fix $Q$ for simplicity, but this only mildly affects our results.
Figure 5. Left panel: estimated PDF suppression for inclusive (solid) and jet-associated (dashed, $p_T^{lead} \geq 100$ GeV) Drell-Yan kinematics. We assume an initial state with $d$-quarks only. Right panel: same for Higgs production in gluon fusion with $m_H = 125$ GeV. The uncertainty encompasses two representative kinematical limits of the multi-jet final state, described in the text.
Z + jets - exclusive jet multiplicities

- Exclusive jet multiplicities for VBF pre-selection

- Scaling properties useful in analyses using jet vetoes
- data consistent with BLACKHAT+SHERPA, and SHERPA
- ALPGEN overestimates $R_{3/2}$
Z + jets - average jet multiplicities

ATLAS

\[ \frac{N_{\text{jet}}}{\sigma} \]

\[ \int L \, dt = 4.6 \, \text{fb}^{-1} \]

Z/\gamma*(\rightarrow \mu^+ \mu^-) + jets

anti-\kappa jets, R = 0.4,

\[ p_T^{\text{jet}} > 30 \, \text{GeV}, |y^{\text{jet}}| < 4.4 \]

Data 2011 (\sqrt{s} = 7 \, \text{TeV})

Z+jets(ALPGEN)

Z+jets(SHERPA)

MC / Data

\[ p_T^{\mu\mu} \, [\text{GeV}] \]

\[ H_T \, [\text{GeV}] \]

ATLAS

\[ \frac{N_{\text{jet}}}{\sigma} \]

\[ \int L \, dt = 4.6 \, \text{fb}^{-1} \]

Z/\gamma*(\rightarrow e^+ e^-) + \geq 1 \, \text{jet}

anti-\kappa jets, R = 0.4,

\[ p_T^{\text{jet}} > 30 \, \text{GeV}, |y^{\text{jet}}| < 4.4 \]

Data 2011 (\sqrt{s} = 7 \, \text{TeV})

Z+jets(ALPGEN)

Z+jets(SHERPA)

MC / Data
Z + jets - $Z$ transverse momentum

exclusive 1 jet

$\int L \, dt = 4.6 \text{ fb}^{-1}$

anti-$k_T$ jets, $R = 0.4$

$P_T > 30 \text{ GeV}, |\eta| < 4.4$

normalized to inclusive cross section

inclusive $\geq 1$ jet

$\int L \, dt = 4.6 \text{ fb}^{-1}$

anti-$k_T$ jets, $R = 0.4$

$P_T > 30 \text{ GeV}, |\eta| < 4.4$

Better agreement with data if inclusive final state in calculations is replaced by exclusive sums

exclusive sum: $Z + \geq 1 = (Z + 1) + (Z + \geq 2)$

- no scale uncertainty (dark shaded)
- correlated between multiplicity bins (medium shaded)
- uncorrelated (light shaded), as prescribed in Phys.Rev.D85 (2012) 034011

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$Z + \text{jets}$ - two leading jets $\Delta y$ and invariant mass

- Important for VBF Higgs analysis!

- BLACKHAT+SHERPA and ALPGEN predictions are in agreement with the data
W/Z + jets are irreducible backgrounds to Higgs analyses, in particular through VBF production.

VBF signature
- two forward jets (large $|\Delta y|$)
- high dijet mass
- central jet gap

Study of Z+jets events with a VBF preselection
- test Z+jets modeling
- test of ME and PS matching

3rd jet veto efficiency
- fraction of events passing veto requirement on 3rd jet in central region $|\eta| < 2.4$ as function of veto scale

BLACKHAT+SHERPA and SHERPA predictions are in agreement with the data.
ALPGEN underestimate the veto efficiency (due to overestimate of $R_{3/2}$).
Z+jets - event shapes and azimuthal correlations

- **Leptons**
  - $p_T > 20$ GeV
  - $|\eta| < 2.4$
  - isolated
- **71 < $m_{\ell\ell}$ < 111 GeV**
- **Jets from particle flow**
  - $p_T > 50$ GeV
  - $|\eta| < 2.5$
  - $\Delta R_{j\ell} > 0.4$
- **Analysis procedure**
  - select $Z \rightarrow \ell\ell$
  - subtract background
  - unfold to particle level
  - combined channels
- **Dominant systematics**
  - jet energy scale
  - jet $p_T$ resolution
  - background subtraction
  - unfolding procedure
- **ttbar dominant background**
  - 1.1% for $N_{jets} \geq 1$
  - 8% for $N_{jets} \geq 3$

- **Z+jets signal generators considered**
  - MadGraph 5.1.1.0 + PYTHIA 6.4.2.4 + Z2 tune + CTEQ6L1 LO up to 4 final state partons
  - SHERPA 1.3.1 + default tune + CTEQ6m LO up to 4 final state partons
  - POWHEG + PYTHIA 6.4.2.4 + Z2 tune + CT10 NLO $Z+1$ jet
  - PYTHIA 6.4.2.4 + Z2 tune
$Z+jets$ - azimuthal correlations $\Delta \Phi(Z, j_1)$

- $\Delta \Phi(Z, j_1)$: $\Delta \Phi$ between the $Z$ and the leading jet for the inclusive multiplicities
  - $N_{jets} \geq 1, \geq 2, \geq 3$
  - normalized to unity
  - ratios to MadGraph
- $\Delta \Phi$ observable with largest systematics
  - 5-6% near 0, to 2% near $\pi$

- Agreement with POWHEG and SHERPA improve for larger multiplicities
- For $N_{jets} = 1$, $\Delta \Phi(Z, j_1) \approx \pi$
  - large $N_{jets}$: more isotropic
  - also for $p_T^Z > 150$ GeV
- Multi-parton LO + PS do better than LO + PS!!
  - see $\Delta \Phi(Z, j_1)$
- PS important for NLO 1 jet in multijet environment
**Z+jets - azimuthal correlations $\Delta \Phi(Z, j_i)$**

- $N_{jets} \geq 3$
  - $\Delta \Phi(Z, j_i)$
  - normalized to unity
  - ratios to MadGraph

- Good agreement with MadGraph, POWHEG and SHERPA

- For $\Delta \Phi(Z, j_3)$, PYTHIA LO + PS agrees with data
  - PS contribution

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**Z+jets - azimuthal correlations $\Delta\Phi(j_i, j_k)$**

- $N_{\text{jets}} \geq 3$
  - $\Delta\Phi(j_1, j_2)$
  - $\Delta\Phi(j_1, j_3)$
  - $\Delta\Phi(j_2, j_3)$
  - normalized to unity
  - ratios to MadGraph

- Isotropic for $p_T^Z > 150$ GeV
  - improved agreement with PYTHIA consistent with increased phase space available for parton emission

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Z+jets - EW Z+2 forward jets

- Correlation between soft hadronic activity (H_T) and dijet rapidity span and M_{jj} (reco level)
  - H_T = scalar sum of jet p_T's for |\eta_j| > 4.7
  - reco level: no background subtraction, no unfolding
  - tagged jets: p_T1 > 65 GeV; p_T2 > 40 GeV in |\eta_j| < 3.6

- MadGraph-based predictions in agreement with data
Z+jets - EW Z+2 forward jets

- Radiation pattern as a function of the dijet rapidity span
  - reco level: no background subtraction, no unfolding
  - $p_T^{j} > 40$ GeV

MadGraph-based predictions in agreement with data

Clear correlation between hadronic activity and rapidity span

CMS-FSQ-12-019
arXiv:1305.7389
W + jets

- Probe NLO pQCD properties by studying $H_T$
- Missing transverse momentum
  - $E_{T\text{miss}}$ calculated from the energy deposits in calorimeter cells inside 3D clusters with $|\eta| < 4.5$. The clusters are calibrated to hadronic scale including corrections to account for dead material and out-of-cluster energy losses. It is also corrected for the muon momentum and its energy deposited in the calorimeter.
  - $m_T(W)$ is given by $\sqrt{2p_T^\ell p_T^{\nu} (1 - \cos(\phi^\ell - \phi^{\nu}))}$
    - where the neutrino momentum components are the corresponding $E_{T\text{miss}}$ components.
- Unfolding of efficiency and resolution effects
  - iterative Bayesian method
W + jets - systematics

- W+jets complementary to Z+jets
- Large background contamination
  - multi-jets at low N_{jets}: 5-10% (e); 5% (µ)
  - ttbar at N_{jets} ≥ 3: ~4-60% for N_{jets} = 1 to 4
- Systematic dominated
  - 10% stat and 40% sys for N_{jets} = 4
- Main systematic uncertainties
  - Jet energy scale (2.5%-14%, p_T, η dependent)
    - 10% on cross section for N_{jets} = 1
    - 40% on cross section for N_{jets} = 4
  - Jet energy resolution (10%)
    - 1-6% on cross section
  - top background
    - 20% on cross section for N_{jets} = 4
  - QCD background
    - 11-20% on cross section for N_{jets} = 4
- NLO theoretical uncertainties (BLACKHAT)
  - μ_R and μ_F: 4-15%
  - PDF + α_S: 2-6%
  - Hadronization and underlying event model: 2-5%

Fiducial Phase Space

- \( p_T > 20 \text{ GeV}, \mid \eta \mid < 2.5 \)
- \( E_T^{\text{miss}} > 25 \text{ GeV} \)
- \( m_T(W) > 40 \text{ GeV} \)
- \( p_T^{\text{jet}} > 30 \text{ GeV} \)
- \( |y^{\text{jet}}| < 4.4 \)
- \( \Delta R^{lj} > 0.5 \)

ATLAS

W→lν + jets

Cross section

Fractional Uncertainty

Sum of Other Uncertainties

Inclusive Jet Multiplicity, N_{jet}
MC signal event samples: W + jets (0 ≤ N_{partons} ≤ 5)
  - ALPGEN 2.13
    - HERWIG (PS) + JIMMY v4.31 (UE AUET1)
    - PDF: CTEQ6L1 (LO)
    - factorization scale set to Q^2 = M_W^2 + sum of all partons p_T^2
    - MLM parton-jet matching scheme performed at p_T^{jet} = 20 GeV (cone R = 0.7)
  - SHERPA 1.3.1
    - CTEQ6.6M (NLO)
    - CKKW parton-jet matching scheme
    - default μ_R and μ_F and UE tune
    - normalized to NNLO inclusive W production
  - Pileup events: minimum bias event from PYTHIA with AMBT1 tune
    - events reweighted to ensure the same distribution on the number of primary vertices as for data

NLO QCD predictions
  - BLACKHAT-SHERPA (for N_{jet} ≤ 4)
    - PDF: CTEQ6.6M (used for both LO and NLO calculations)
  - MCFM v5.8 (for N_{jet} ≤ 2)
    - PDF: CTEQ6L1 (LO) and CTEQ6.6M (NLO)
    - renormalization and factorization scales set to H_T/2
    - corrected for non-pQCD effects, hadronization, UE
      - (distributions for particle-level jets)/(distribution for parton-level jets with no UE)
W + jets - first jet y and Δy to lepton

- Distributions sensitive to the PDFs used for the LO and NLO ME.

- BLACKHAT-SHERPA deviation at high y may be caused by issues with gluon PDF at high x.

- ALPGEN has a different distribution.
Test of hard parton radiation at large angles and of matrix element to parton shower matching schemes
- $\Delta R \sim \Delta \Phi \sim \pi$: most jets modeled via ME calculation
- $\Delta R$ small (collinear radiation): most jets modeled via the parton shower

- ALPGEN and BLACKHAT+SHERPA agree well with data
- SHERPA worse agreement (attributed to differences in PDFs, $\alpha_s$ and factorization scales)
**W + jets - $k_T$ splitting**

- **$k_T$ clustering sequence mimics the reverse QCD evolution**
  - measurement probes QCD evolution
  - test of LO and NLO MC generators and analytical calculations

- **$k_T$ distance measure**
  - distance between two particle momenta $p_i, p_j$
  - distance $p_i$ to beam
  \[ d_{ij} = \min \left( p_{T,i}^2, p_{T,j}^2 \right) \frac{\Delta R_{ij}^2}{R^2} \]
  \[ d_{iB} = p_{T,i}^2 \]

- **Clustering sequence**
  1. Calculate all $d_{ij}$ and $d_{iB}$
  2. Find their minimum, $d_{\text{min}}$
     - (a) If $d_{\text{min}}$ is a $d_{ij}$, combine $i$ and $j$: $p_{ij} = p_i + p_j$
     - (b) If $d_{\text{min}}$ is a $d_{iB}$, remove $i$ from the list and declare it a jet
  3. Return to step 1 or stop if no particle remains

- **Define $d_k$ as $d_{\text{min}}$ found when clustering $k+1$ to $k$ particles**
  - $\sqrt{d_0}$ corresponds to $p_T$ of highest $p_T$ jet (last step)
$W + \text{jets}$ - $k_T$ splitting

- LO multi-leg predictions (ALPGEN, SHERPA) perform better than NLO+PS generators (MC@NLO, POWHEG) in hard region
- Significant differences also in soft region, probing QCD resummation
- Largest experimental uncertainty: cluster energy scale and pileup
  - Statistical uncertainty dominating only in hard region

**W + jets - k_T splitting**

- $d_{k+1}/d_k$ ratio: most generators just outside experimental uncertainty band
- Best description with HERWIG-based generators (**ALPGEN, MC@NLO**)
- Largest experimental uncertainty: cluster energy scale and unfolding
  - Systematics dominated

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**Z \ p_T**

- **Total background:** 0.4% (mu) 1.5% (e), up to 3.5% at high \( Z p_T \)
- **Dominant exp uncertainties:**
  - lepton ID and reconstruction: 1-3%
  - lepton energy scale and resolution: 0.7-4.4% (smaller for mu-channel)
  - unfolding (mainly \( Z p_T \) modeling used in efficiency correction): 1.3-4.7%

- **PYTHIA 6.4 using MRST2007LO***
  - LO + PS
- **SHERPA v1.2.3 using CTEQ6.6 and**
  - LO with up to 5 additional hard partons + PS
- **ALPGEN v2.13 using CTEQ6L1 and**
  - LO with up to 5 additional hard partons
  - interfaced to HERWIG v6.510 (PS) and Jimmy (UE)
- **MC@NLO using CTEQ6.6**
  - NLO
  - HERWIG v6.510 (PS) and Jimmy (UE)
- **POWHEG v1.0 using CTEQ6.6**
  - NLO
  - PYTHIA 6.4 (PS + UE)

**MC Generators**
- All interfaced to PHOTOS (QED FSR)
- Pileup: overlay of simulated minimum bias events
- GEANT4 simulation of ATLAS
- Pileup and resolution corrected to data

**FEWZ v2.0 using MSTW2008**
- \( O(\alpha_s) + O(\alpha_s^2) \)

**RESBOS using CTEQ6.6**
- NNLL resummation (scale MZ) (Collins-Soper-Sterman)
- \( + O(\alpha_s) + O(\alpha_s^2) \) corrections

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W $p_T$ - MC generators

- Pythia 6.421 using MRST2007LO*
  - LO + PS
- MC@NLO v3.41 using CTEQ6.6
  - NLO
  - Herwig v6.510 (PS) and Jimmy v4.1 (UE)
- Powheg v1.0 using CTEQ6.6
  - NLO
  - Pythia 6.4 (PS + UE)
- Alpgen v2.13 using CTEQ6L1
  - LO with up to 5 additional hard partons
  - interfaced to Herwig v6.510 (PS) and Jimmy v4.31 (UE)
- Sherpa v1.3.0 using CTEQ6L1
  - LO with up to 5 additional hard partons + PS
  - Catani-Seymour subtraction based parton shower model
  - matrix element merging with truncated showers
  - high multiplicity matrix elements generated by COMIX
- MC Generators
  - All interfaced to Photos v2.15.4 (QED FSR)
  - tauts decayed by TAUOLA v1.0.2
  - Pileup: overlay of simulated minimum bias events (ATLAS MC09 tunes)
  - GEANT4 simulation of ATLAS
  - Pileup and resolution corrected to data

- RESBOS using CTEQ6.6
  - NNLL resummation (scale MZ) + $O(\alpha_s) + O(\alpha_s^2)$ correction
  - renormalization and factorization scale set to MW
- DYNNLO v1.1 and MCFM v5.8 for $W + 1$ parton
  - LO $O(\alpha_s)$ uses MSTW2008 NLO
  - NLO $O(\alpha_s^2)$ uses MSTW2008 NNLO
  - renormalization and factorization scale set to MW
  - do not include resummation effects: not expected to do well at very low $W p_T$
- FEWZ v2.0 using MSTW2008
  - $O(\alpha_s)$
$W$ $p_T$ - reconstructed $p_T$

- $p_T^R$ is the reconstructed $p_T^W$ from the hadronic recoil
\( W \ p_T - \text{unfolded true } p_T \)

- \( p_T^W \) is the true \( p_T^W \) unfolded from \( p_T^R \)
  - by default it is defined from the Born level \( W \) propagator
W $p_T$ - unfolded true $p_T$

RESBOS, DYNLO and MCFM at $O(\alpha_s^2)$, Sherpa, Alpgen, Pythia describes the spectrum well (within 10-20%) over the entire range $O(\alpha_s)$ approximation insufficient to describe the data.
Z $\Phi_\eta^*$ - comparison with MC generators

**MC Generators**
- at $\Phi_\eta^* < 0.1$ best description from **SHERPA** and **ALPGEN**
- at low $\Phi_\eta^*$, best description from **RESBOS**
- Pythia8 best parton shower description when interfaced to **POWHEG**

**Useful information for MC tuning**

- $\sqrt{s} = 7$ TeV
- $|\eta| < 2.4$
- $p_T > 20$ GeV
- $66$ GeV $< m_{\ell\ell} < 116$ GeV
- $\int L \, dt = 4.6$ fb$^{-1}$