

Multiple Parton Interactions, top-antitop, $W+4j$ and $Z+4j$ production at the LHC

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Double interaction in a finely segmented detector



Facts and questions

- MPI established experimentally eg: $\gamma+3j$
- Each interaction hard enough to be treated by perturbative QCD
- $\sigma_{\text{DPI}} = \sigma_1 \sigma_2 / \sigma_{\text{eff}} / k$ $\sigma_{\text{eff}} \approx 14.5 \text{ mb}$ CDF $k=1,2$
- $\sigma_{\text{TPI}} = \sigma_1 \sigma_2 \sigma_3 / \sigma_{\text{eff}}'^2 / k$ $\sigma_{\text{eff}}' = \sigma_{\text{eff}} ?$

Treleani argues for $\sigma_{\text{eff}} \approx 12 \text{ mb}$ at the LHC

- Can MPI be a background to interesting physics ?
- Can MPI be studied in more complex environment than $2 \rightarrow 2 \otimes 2 \rightarrow 2$?

Flavour dependence, x-dependence

MPI,SPI,DPI,TPI: Multiple,Single,Double,Triple Parton Interactions

Method: $\sigma_1 \otimes \sigma_2 \otimes \dots$

- Generate events for the two processes separately: eg jj , jjW with MadEvent
- Superimpose one event from each sample
- No check on energy conservation (trivial to add)
- No flavour correlations (Treleani up to 40% reduction)
- No color correlations (irrelevant at generator level)
- Analyze: impose cuts on combined events

$lv+4j$ can be produced in MPI as:

$jj \otimes jjW$

$jjj \otimes jW$

$jjjj \otimes W$

$jj \otimes jj \otimes W$

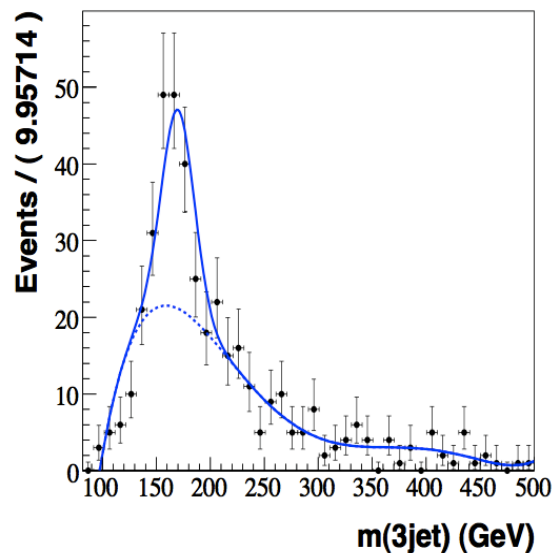
$W \rightarrow \mu\nu$ only

JHEP04(2009) 098
+ Z4j unpublished

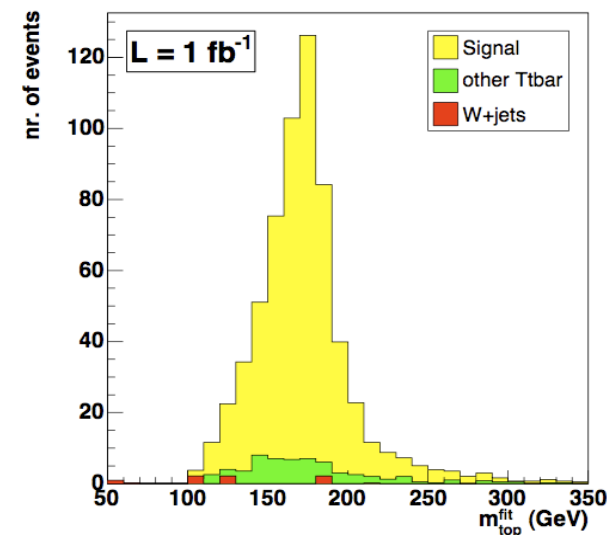
Single Parton Interactions: PHANTOM & MadEvent

t-tbar production: an ideal playground

- Early measurement at the LHC
- M_{top} is a fundamental parameter for the SM
- Best channel: semileptonic $lv+4j$
- Main background $W+4j$: 5 body final state



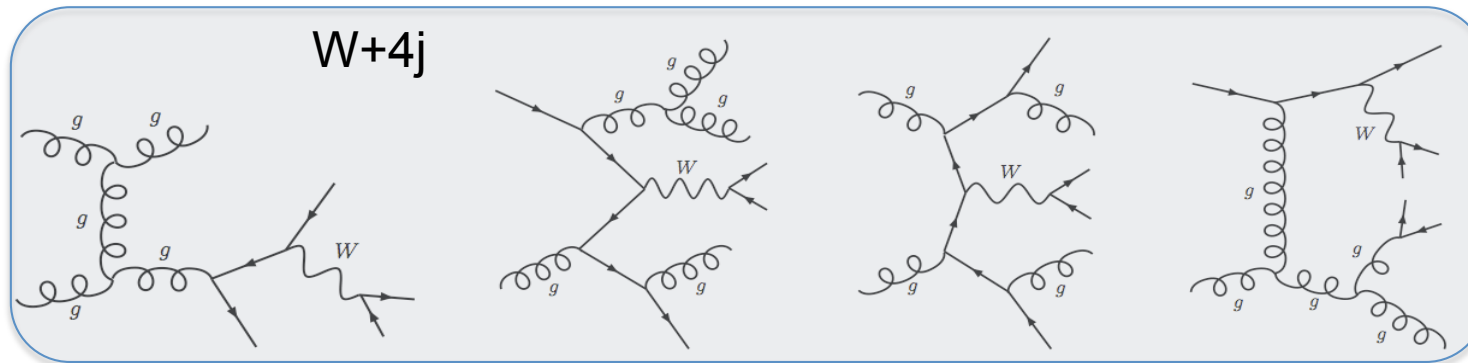
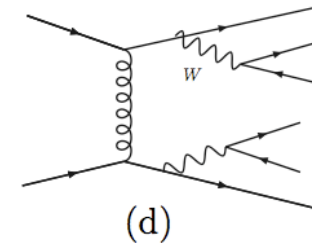
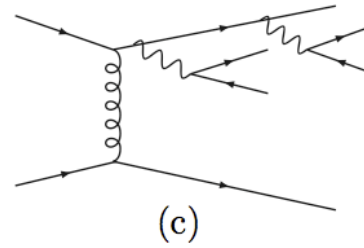
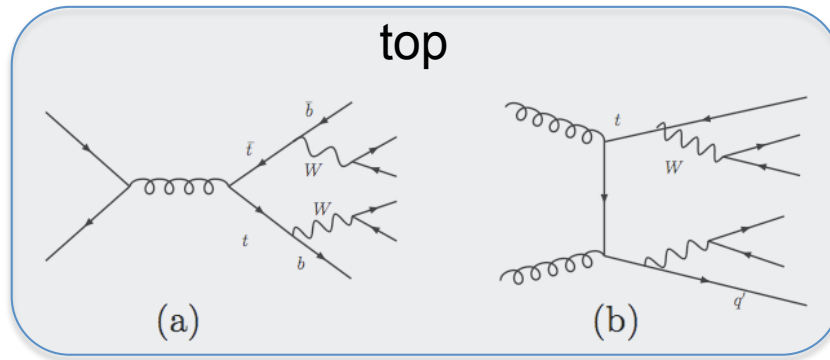
100 pb⁻¹ No b-tagging
Reconstruct from mass of jet triplet with largest p_T
Main background: W+4j



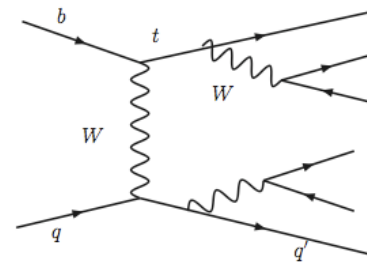
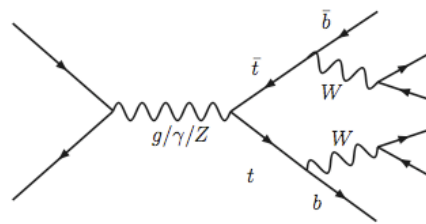
1 fb⁻¹ b-tagging
Full reconstruction of final state
Main background: misidentification and combinatorics

$$\alpha^4 \alpha_s^2$$

Three perturbative orders
contribute to $4j+lv$



$$\alpha^2 \alpha_s^4$$



$$\alpha^6$$

MPI

$$p_{T_j} \geq 30 \text{ GeV}, \quad |\eta_j| \leq 5.0,$$

$$p_{T_\ell} \geq 20 \text{ GeV}, \quad |\eta_\ell| \leq 3.0,$$

$$M_{jj} \geq 60 \text{ GeV}$$

generation cuts

LHC luminosity:
 Low 30 fb⁻¹/year
 High 100 fb⁻¹/year
 Total 300 fb⁻¹/year

Process	Cross section	Combined
jj	1.44e8 pb	4.03 pb
$jj(\mu^- \bar{\nu}_\mu + \mu^+ \nu_\mu)$	6.54e2 pb	
jjj	7.64e6 pb	0.68 pb
$j(\mu^- \bar{\nu}_\mu + \mu^+ \nu_\mu)$	1.82e3 pb	
$jjjj$	1.16e6 pb	0.88 pb
$\mu^- \bar{\nu}_\mu + \mu^+ \nu_\mu$	1.09e4 pb	

Process	Cross section	Combined
jj	1.44e8 pb	0.27 pb
jj	1.44e8 pb	
$\mu^- \bar{\nu}_\mu + \mu^+ \nu_\mu$	1.09e4 pb	

$$\sigma < \sigma_1 \sigma_2 / \sigma_{\text{eff}}$$

t-tbar

W+4j

DPI

TPI

EW negligible

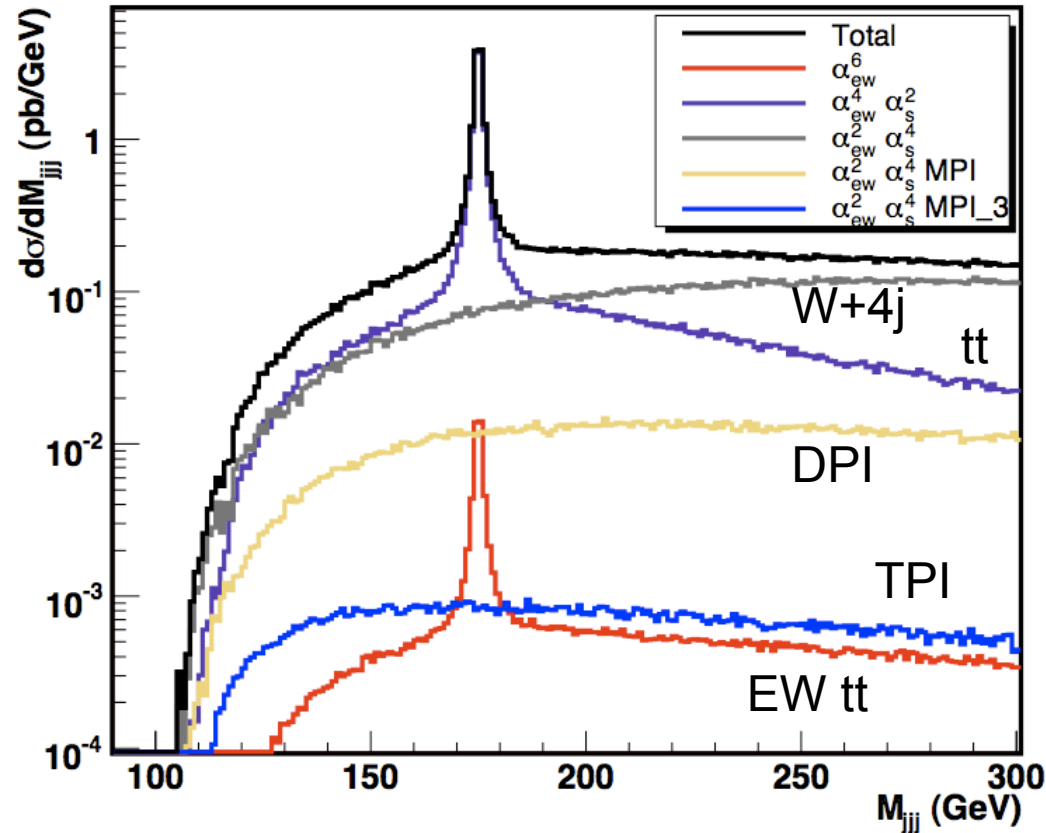
Process	Cross section	Cross section
$\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$	25.0 pb	22.0 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$	64.7 pb	58.9 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{\text{DPI}}$	5.6 pb	5.3 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{\text{TPI}}$	0.27 pb	0.26 pb
$\mathcal{O}(\alpha_{EM}^6)$	0.22 pb	0.20 pb

$$\Delta R(jj) > 0.5 \quad \Delta R(jl^\pm) > 0.5$$



Isolation cuts

M_{jjj}



$$M_{\text{top}} = 175 \text{ GeV}$$

M_{jjj} = mass of jet triplet with max p_T

$W \rightarrow \mu\nu$ only

Process	Cross section
$\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$	10.8 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$	0.76 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{\text{DPI}}$	0.12 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{\text{TPI}}$	0.01 pb
$\mathcal{O}(\alpha_{EM}^6)$	0.04 pb

$$170 \text{ GeV} < M_{\text{jjj}} < 180 \text{ GeV}$$

$$W+4j / tt \approx 7\%$$

$$MPI/tt \approx 1\%$$

Not a problem for mass measurement. Cross section ?
Negligible when b-tagging available

Looking for MPI in $l\nu$ +4j

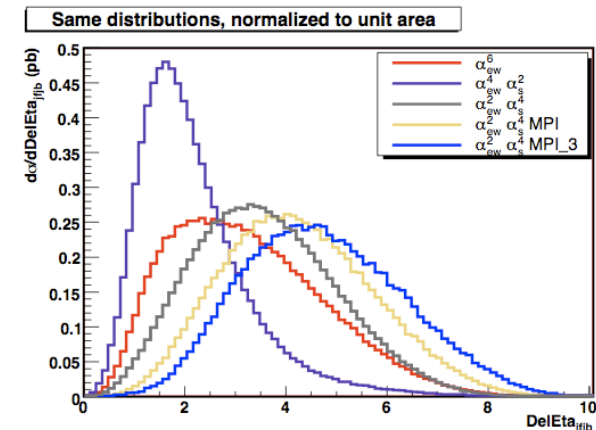
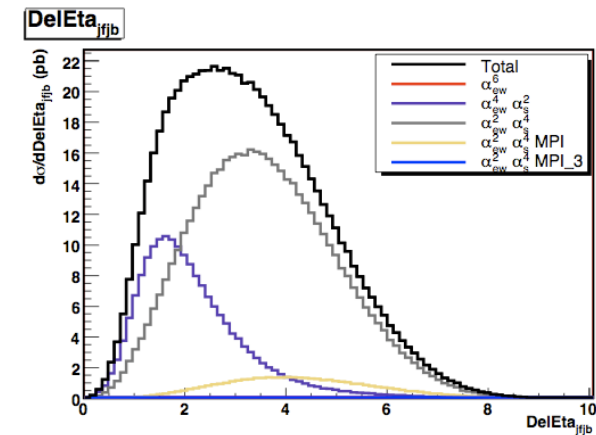
- Get rid of t-tbar
 $|M_{jjj}-M_t|>10$ GeV
- MPI gives larger separation
of forward/backward jets
 $|\Delta\eta(j_{fb})|>3.8$

$W \rightarrow \mu\nu$ only

Basic cuts

Iso cuts

Process	Cross section	Cross section
$\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$	25.0 pb	22.0 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$	64.7 pb	58.9 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{DPI}$	5.6 pb	5.3 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{TPI}$	0.27 pb	0.26 pb
$\mathcal{O}(\alpha_{EM}^6)$	0.22 pb	0.20 pb



Process	Cross section
$\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$	1.16 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$	24.01 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{DPI}$	2.91 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{TPI}$	0.16 pb
$\mathcal{O}(\alpha_{EM}^6)$	0.05 pb

S/B $^{1/2}$ =
5.8(6.1)
L=100 pb $^{-1}$
MPI/4jW=1/8

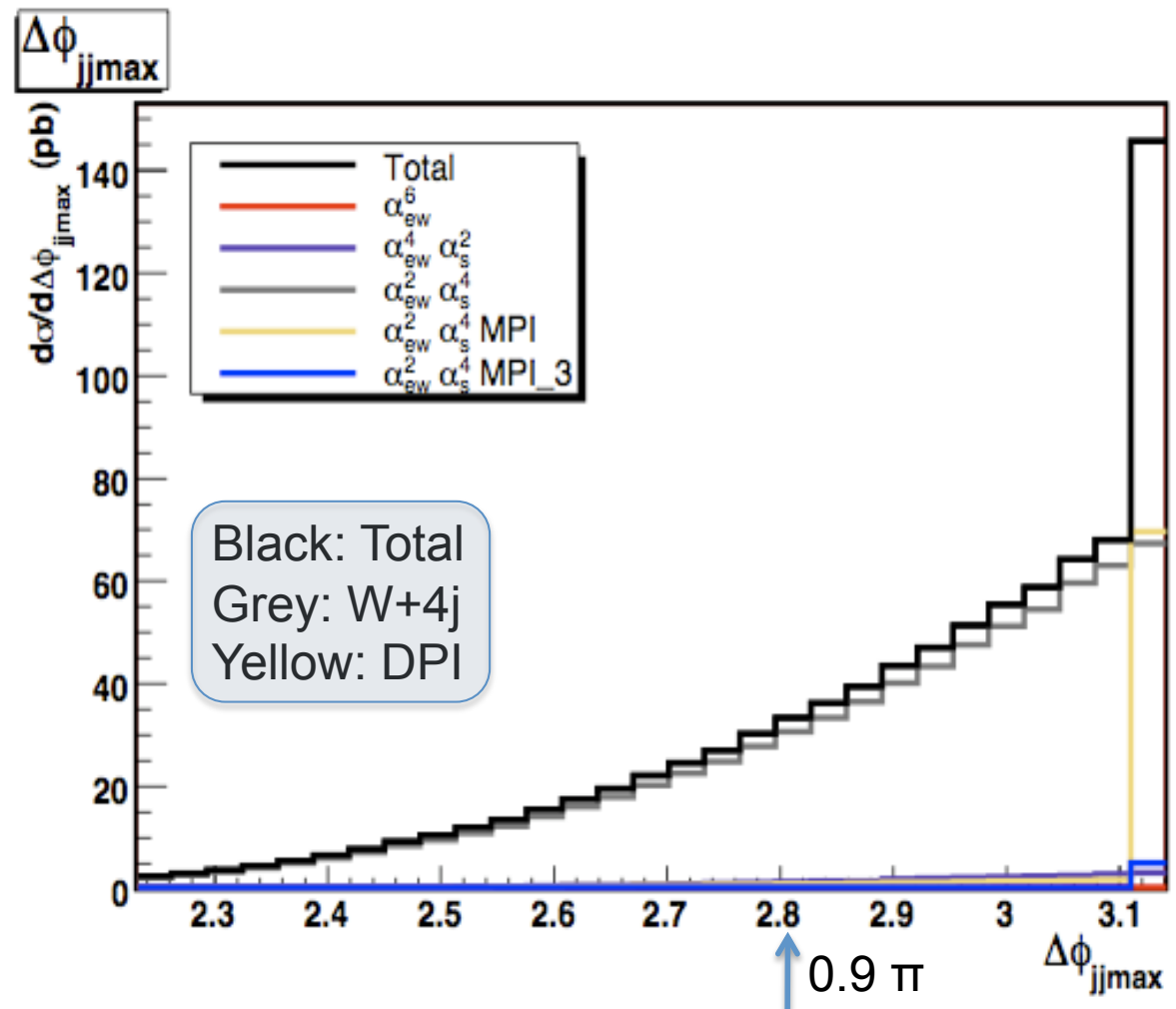
$jj \otimes jj W$ is dominant \rightarrow expect $\Delta\phi = \pi$ jet pair as in $\gamma + 3j$ or $Z + 3j$

$\left. \begin{array}{l} jjj \otimes j W \\ jjjj \otimes W \end{array} \right\}$ no such feature

$$|\Delta\phi(jj)_{\max}| > 0.9 \cdot \pi$$

Process	Cross section
$\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$	0.75 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$	15.61 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{\text{DPI}}$	2.61 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{\text{TPI}}$	0.16 pb
$\mathcal{O}(\alpha_{EM}^6)$	0.03 pb

MPI/tot = 17%



Triple Parton Interactions: so far unobserved

Two jet pairs back to back in the transverse plane

DY W with “zero” pT (also in DPI: less effective)

Process	Cross section
$\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$	0.75 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$	15.61 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{\text{DPI}}$	2.61 pb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{\text{TPI}}$	0.16 pb
$\mathcal{O}(\alpha_{EM}^6)$	0.03 pb

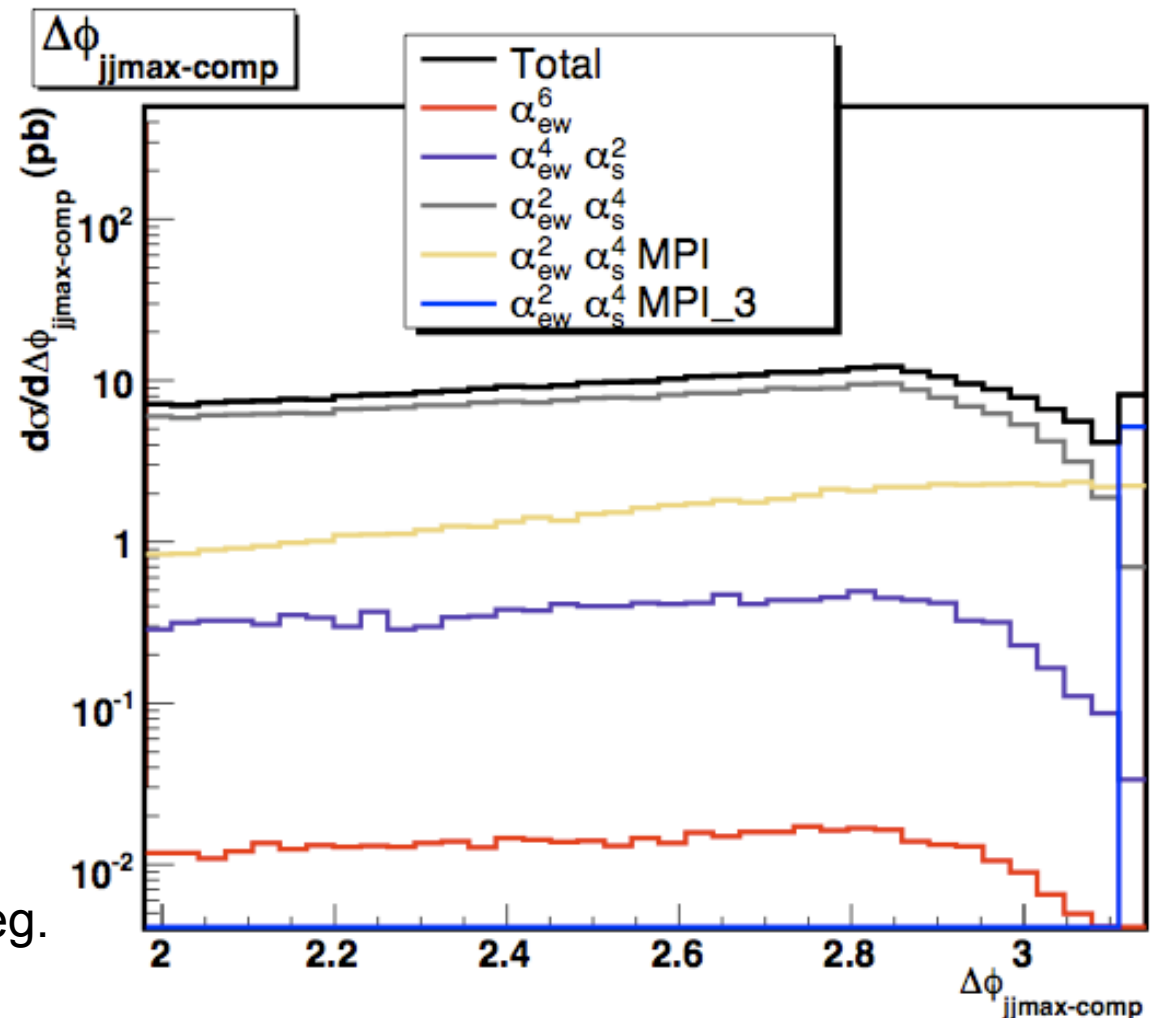
$$|\Delta\phi(jj)_{\text{max}}| > 0.9 \cdot \pi$$

TPI/DPI/Bkg

1 / 16 / 100

1600 events for $L=10 \text{ fb}^{-1}$

TPI more than 50% of last bin: 2 deg.



Looking for MPI in $Z(l^+l^-)+4j$

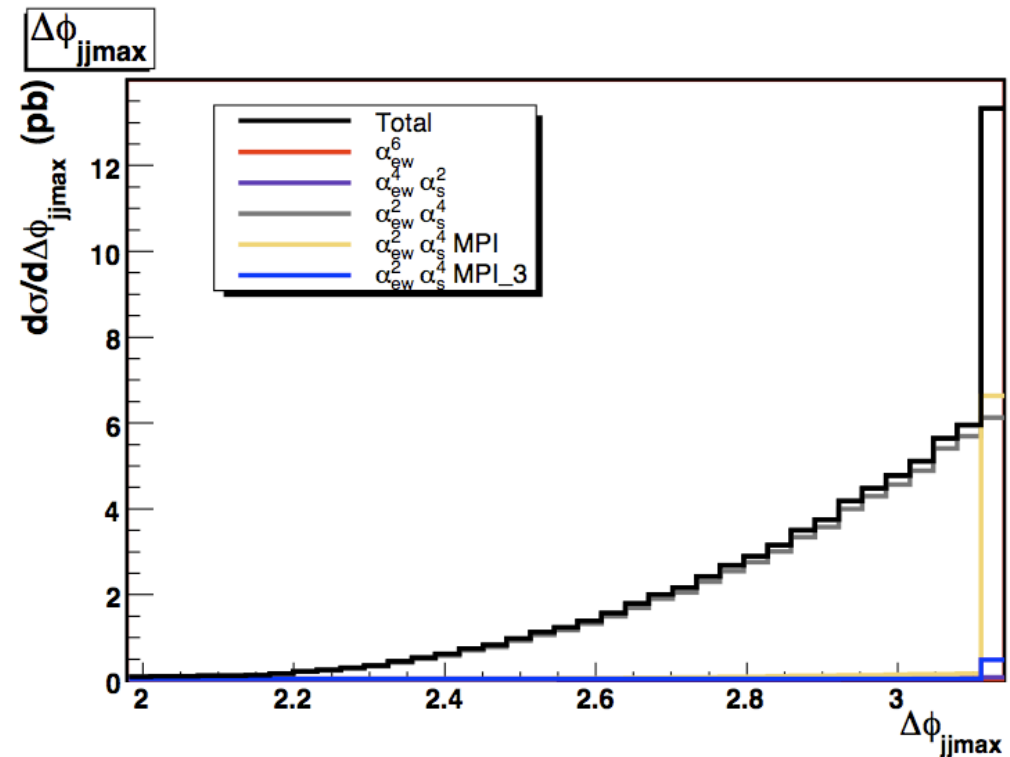
$$p_{T_j} \geq 30 \text{ GeV}, \quad |\eta_j| \leq 5.0,$$

$$p_{T_\ell} \geq 20 \text{ GeV}, \quad |\eta_\ell| \leq 3.0,$$

$$M_{jj} \geq 60 \text{ GeV}, \quad M_{ll} \geq 20 \text{ GeV}$$

$$\Delta R(jj) > 0.5 \quad \Delta R(jl^\pm) > 0.5$$

$$|\Delta\eta(j_f j_b)| > 3.8$$



Basic

iso

Delta_jfjb

Process	Cross section	Cross section	Cross section
$\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$	106.6 fb	87.7 fb	26.3 fb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$	6404.67 fb	5626.6 fb	2209.7 fb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{\text{DPI}}$	515.5 fb	469.1 fb	272.7 fb
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)_{\text{TPI}}$	23.2 fb	21.4 fb	15.1 fb
$\mathcal{O}(\alpha_{EM}^6)$	16.5 fb	13.9 fb	7.6 fb

$$\begin{aligned} \text{S/B } \frac{1}{2} &= \\ 5.8(6.1) \\ L=1 \text{ fb}^{-1} \end{aligned}$$

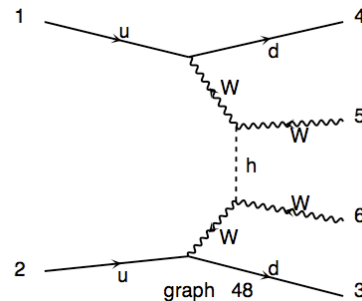
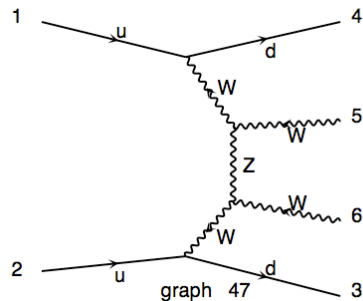
$$\text{MPI}/4jW=1/8$$

Z's much easier to identify; No bkg from b-quark decays

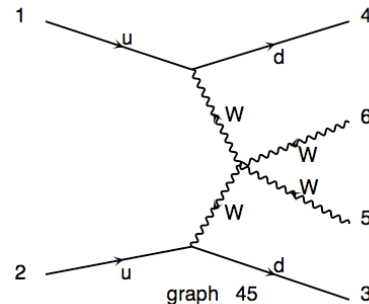
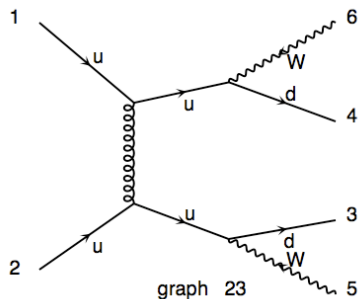
Looking for MPI in $W^{+/-}W^{+/-}+0j$

Can only be produced with at least two additional jet in SPI: $\alpha_s^2\alpha^4$, α^6

In DPI it can be produced as $DY\otimes DY$: α^4 leptonic decays included



$WW \rightarrow e\mu$ only



$$p_{T_\ell} \geq 20 \text{ GeV}, \quad |\eta_\ell| \leq 3.0$$

No j with

$$p_{T_j} \geq 30 \text{ GeV}$$

Process	Cross section	Cross section
$\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$	13.67 fb	0.86 fb
$\mathcal{O}(\alpha_{EM}^4)_{\text{DPI}}$	4.30 fb	4.30 fb

Conclusions

MPI provide a small but non negligible background to t - \bar{t} if no b -tag available

MPI can be studied in $W+4j$ and $Z+4j$ channels above QCD background exploiting $\Delta\phi=\pi$ jet pairs

TPI can hopefully be measured in $W+4j$ production

More careful analysis including correlations between interactions needed