Testing the mechanism of unitarization in WW scattering at the LHC

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arXiv:1201.2768 Doroba, Kalinowski, JK, Pokorski, Rosiek, Szleper, Tkaczyk

Outline

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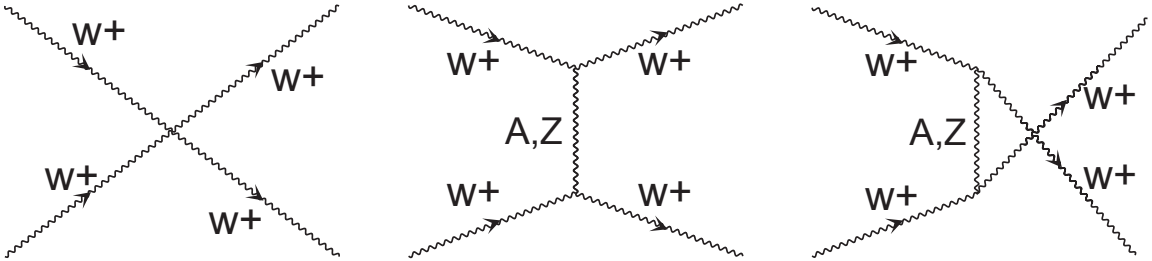
Unitarity conditions

- In theories with unitary S matrix, partial waves are bounded: $\left|\mathrm{Re}\left(\mathcal{T}^{j,s}_{\kappa,\kappa}\right)\right| \leqslant N_s^{-1} \xrightarrow[s\to\infty]{} \frac{1}{2}$ (for $2 \to 2$ elastic scattering)
- Longitudinal WW scattering in higgsless SM

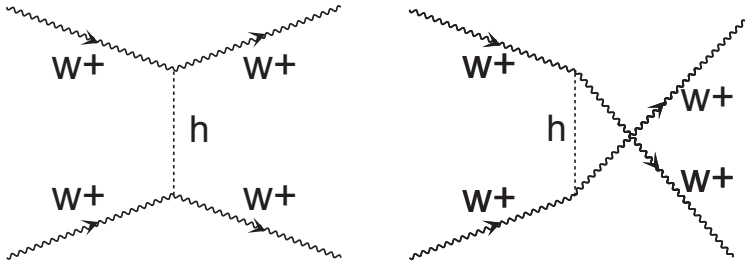


  - partial waves calculated perturbatively grow linearly with s
  - at tree level - hit unitarity bound at $\sim 1.2\,TeV$
- theory is effective and needs to be replaced by more fundamental at high energies
- or theory becomes strongly coupled at high energies and perturbation expansion fails $\Rightarrow$ new effective theory valid at unitarity violation region

Longitudinal WW scattering - unitarization

- unitarization: one or more elementary or composite new particles (Higgs, Higgs-like, Kaluza–Klein modes, . . .)
- all models have impact on scattering of W bosons
- example: longitudinal WW scattering in SM (with Higgs particle)

additional diagrams:



New physics

- prototype for new physics - higgsless SM "naively" unitarized:
  - for $M_{WW} \leqslant 1.2\,TeV$ higgsless SM
  - for $M_{WW} \geqslant 1.2\,TeV$ constant xsection
- Signal: $\sigma_{\text{higgsless}} - \sigma_{M_H=120\,GeV}$
  maximal possible deviation from SM that respects unitarity
- Background: $\sigma_{M_H=120\,GeV}$

Outline

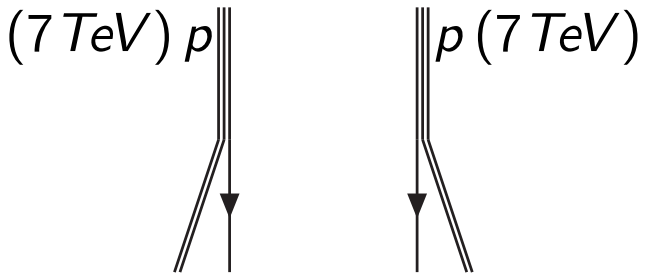
WW scattering in LHC

- proton beams

$(7\,TeV)\,p \Vert \qquad \Vert p\,(7\,TeV)$

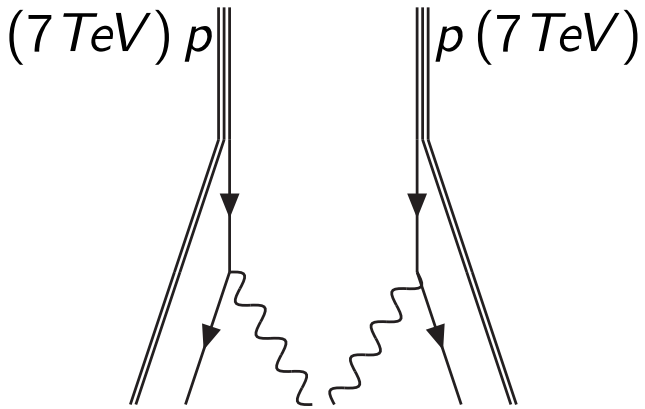
WW scattering in LHC

- proton beams
- partons



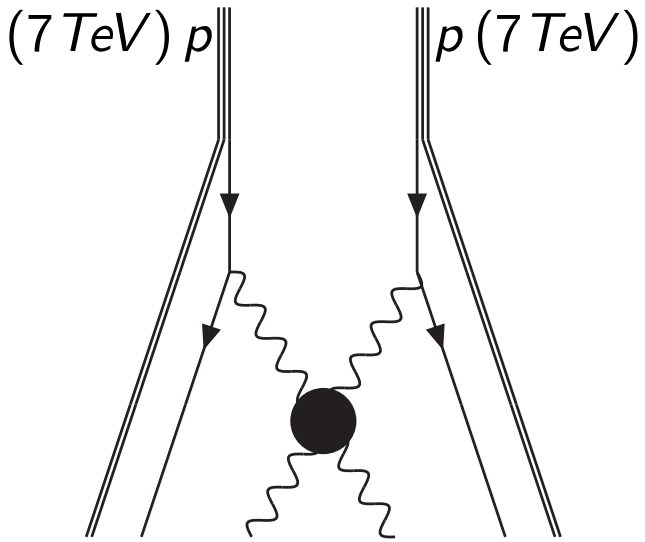
WW scattering in LHC

- proton beams
- partons
- gauge bosons production



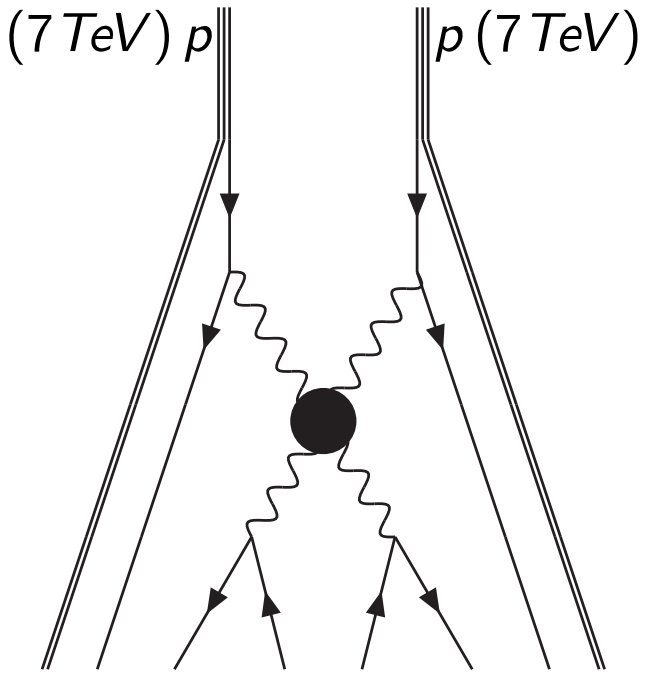
WW scattering in LHC

- proton beams
- partons
- gauge bosons production
- gauge bosons interaction



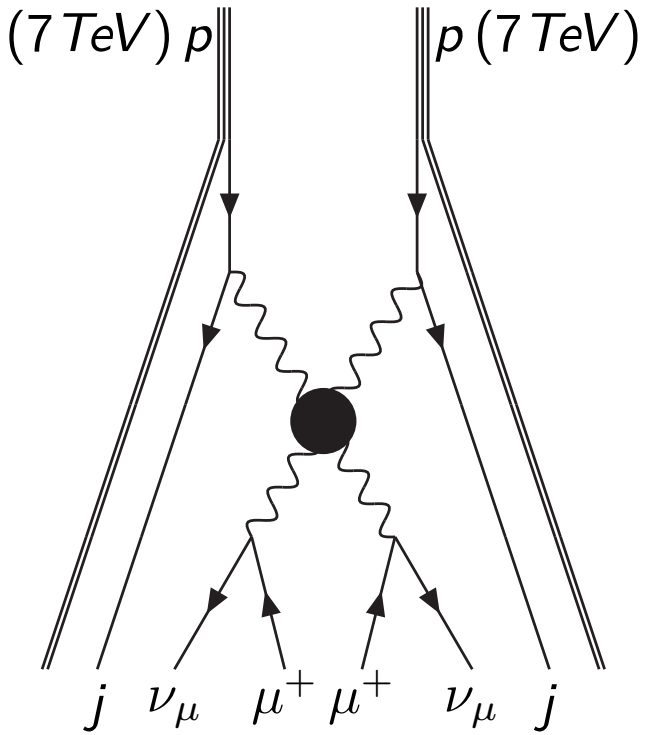
WW scattering in LHC

- proton beams
- partons
- gauge bosons production
- gauge bosons interaction
- gauge bosons decay



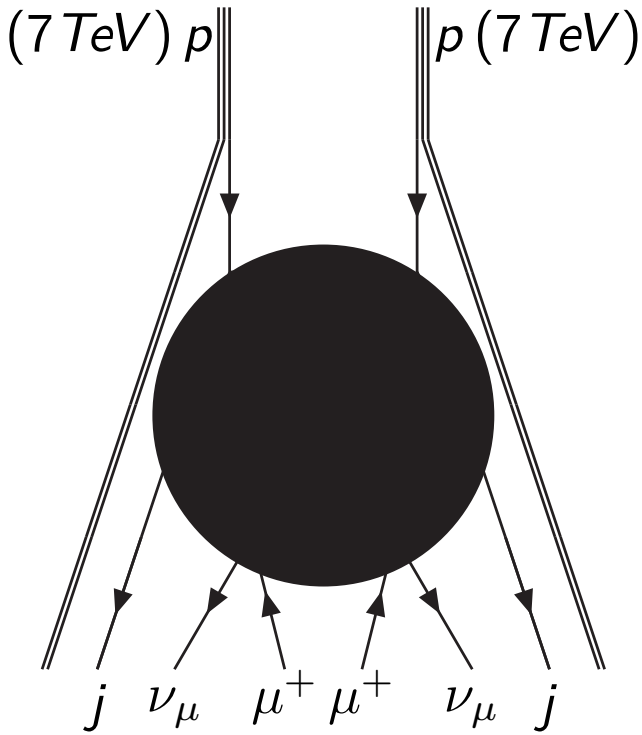
WW scattering in LHC

- proton beams
- partons
- gauge bosons production
- gauge bosons interaction
- gauge bosons decay
- $pp \rightarrow jj\mu^+\mu^+\nu_\mu\nu_\mu$



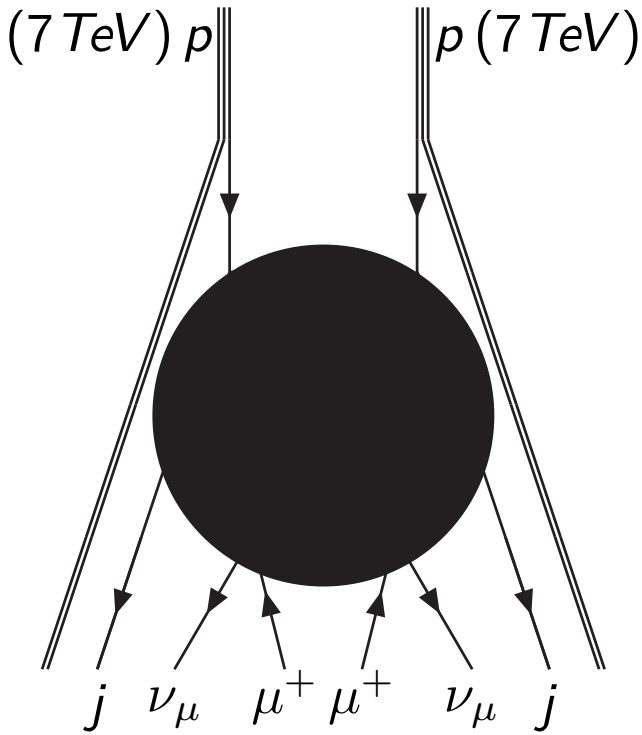
WW scattering in LHC

- proton beams
- partons
- gauge bosons production
- gauge bosons interaction
- gauge bosons decay
- $pp \longrightarrow jj\mu^+\mu^+\nu_\mu\nu_\mu$
- 5656 tree level diagrams in SM



WW scattering in LHC

- proton beams
- partons
- gauge bosons production
- gauge bosons interaction
- gauge bosons decay
- $pp \longrightarrow jj\mu^+\mu^+\nu_\mu\nu_\mu$
- 5656 tree level diagrams in SM
- mostly QCD

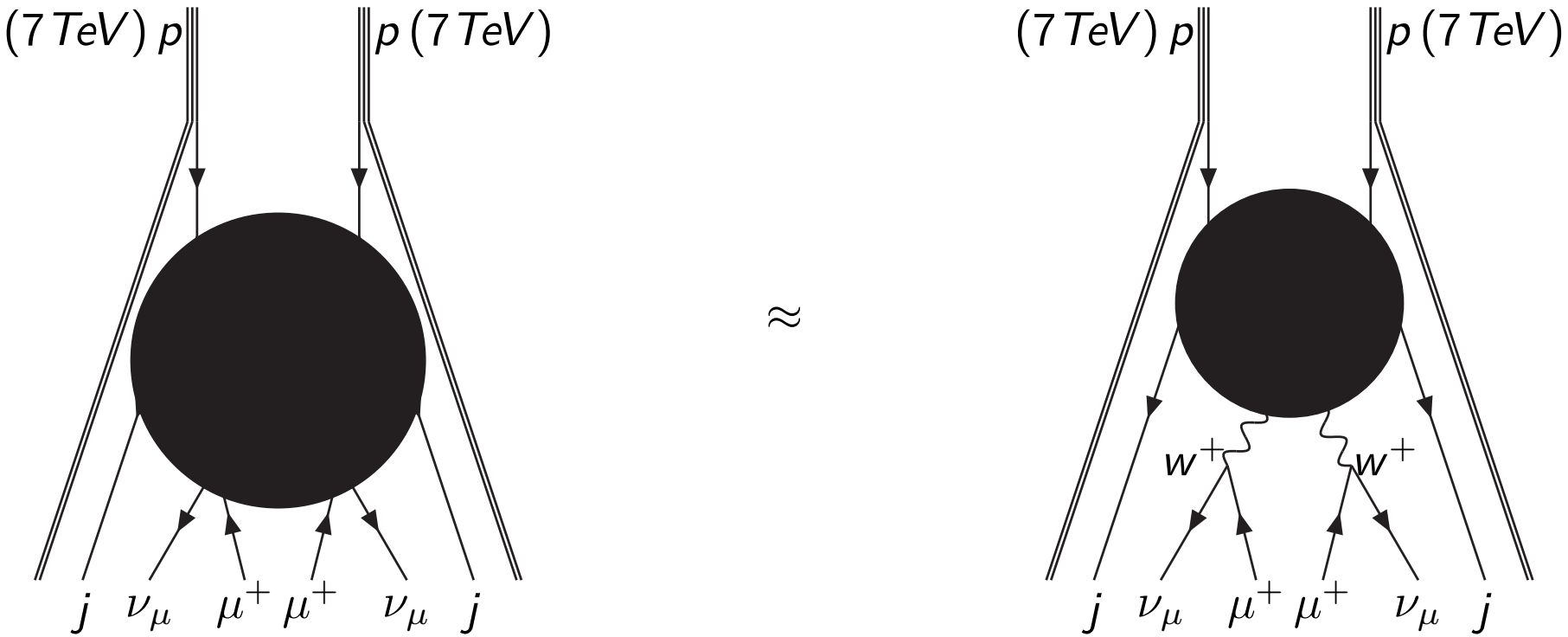


Basic cuts

- removing QCD background:
  - $\eta_{j1} \cdot \eta_{j2} < 0$ - jets in opposite directions
  - $2 < |\eta_j|$
- detector acceptance:
  - $|\eta_\mu| < 2$
  - $|\eta_j| < 5$

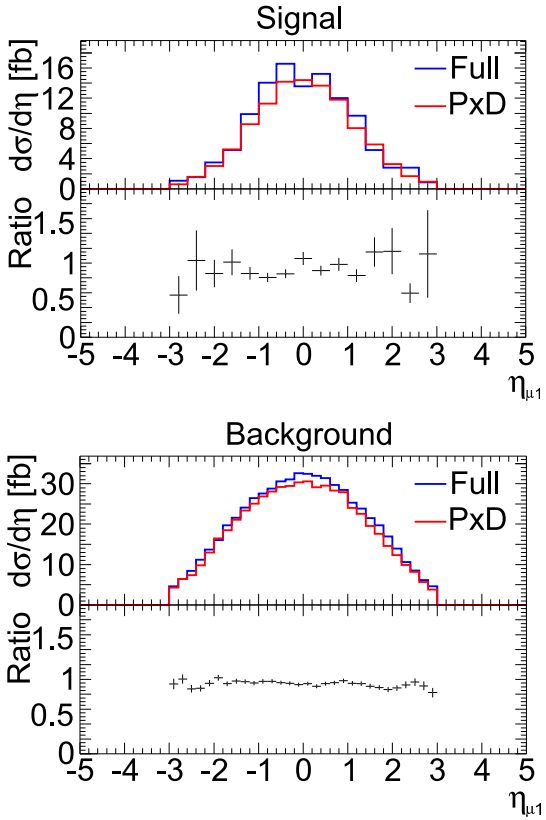
Bagger et al 1993,1995

"Production times Decay" Approximation

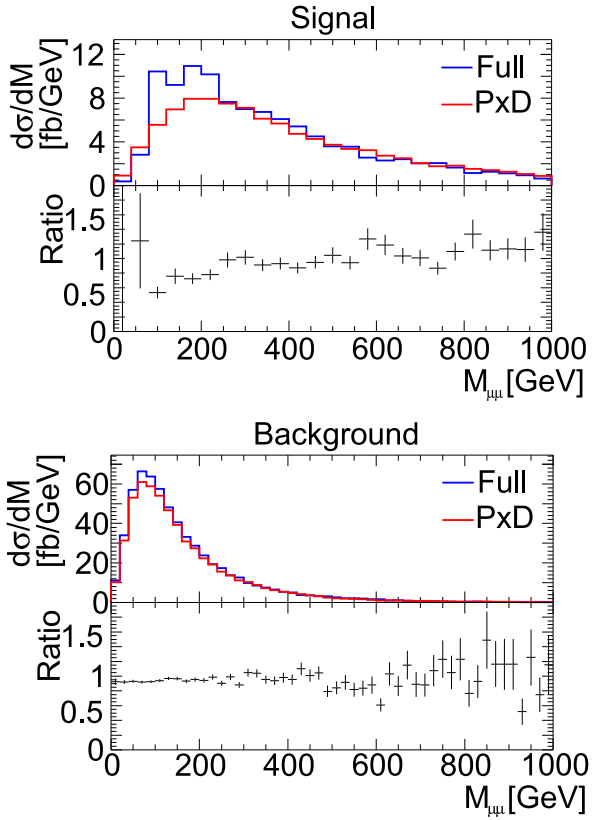


"Production times Decay" Approximation

Muon pseudorapidity

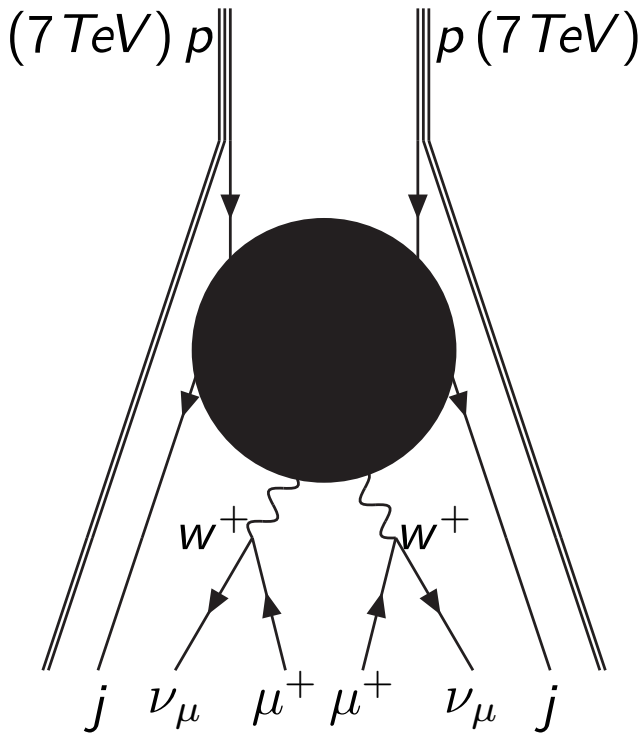


Muons invariant mass



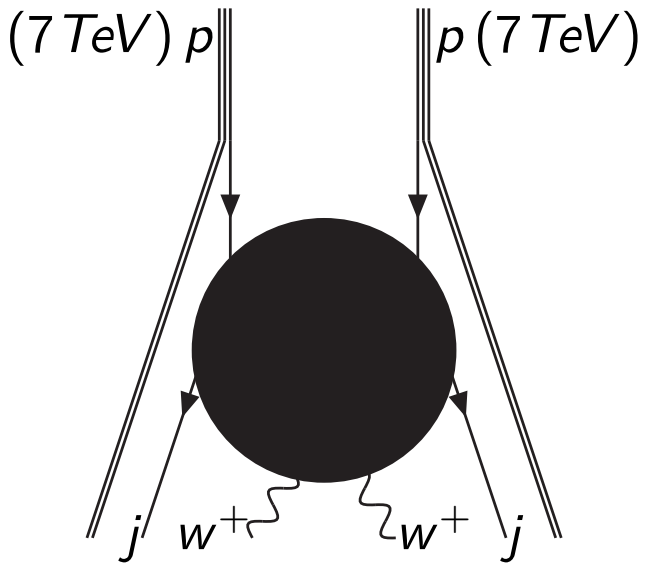
- signal: deficit of events at $M_{\mu\mu} < 200\,GeV$
- lepton kinematics adequately described
- $pp \to jj\mu^+\mu^+\nu_\mu\nu_\mu \quad \approx \quad pp \to jj(W^+ \to \mu^+\nu_\mu)(W^+ \to \mu^+\nu_\mu)$

From final leptons to final W



- we can focus on $pp \longrightarrow jjW^+W^+$

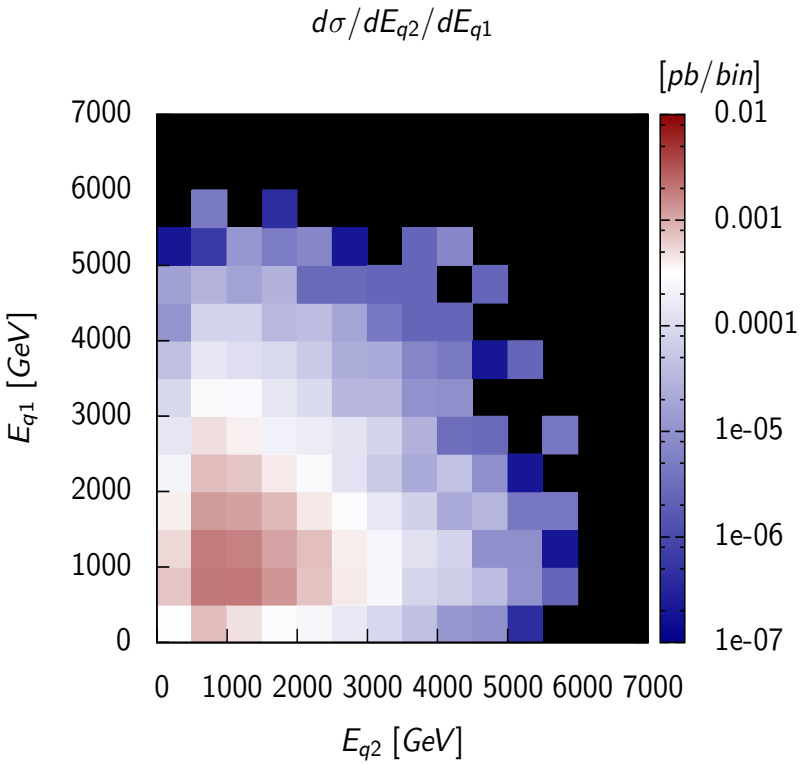
From final leptons to final W



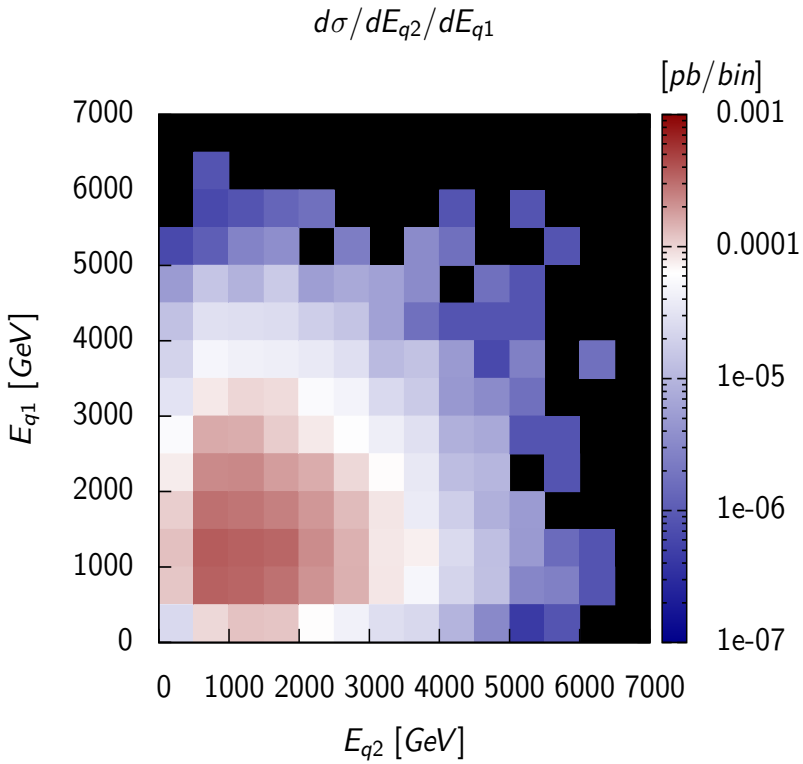
- we can focus on $pp \longrightarrow jjW^+W^+$
- 1428 tree level diagrams in SM

Initial quarks energies - basic cuts

background

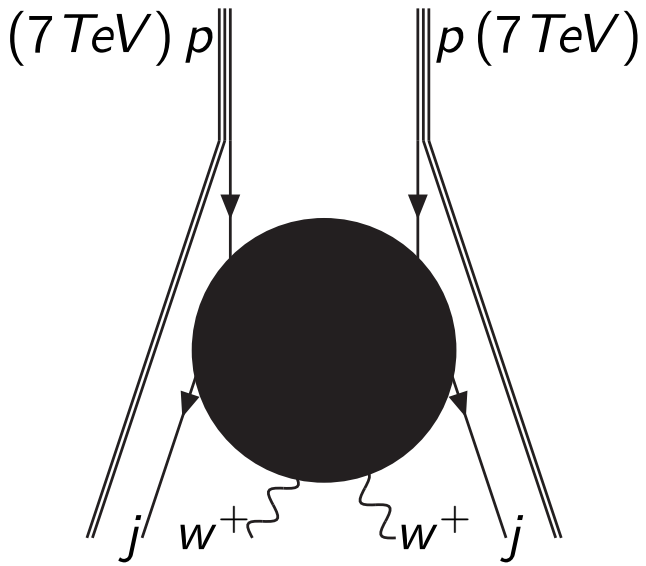


signal



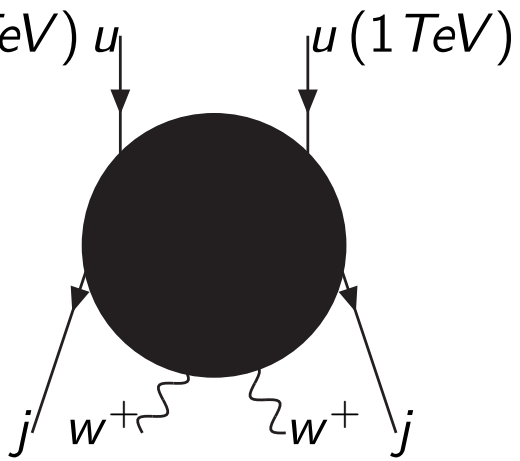
- $pp(7+7\,TeV) \to jjW^+W^+ \quad \approx \quad uu(1+1\,TeV) \to ddW^+W^+$

From protons to quarks



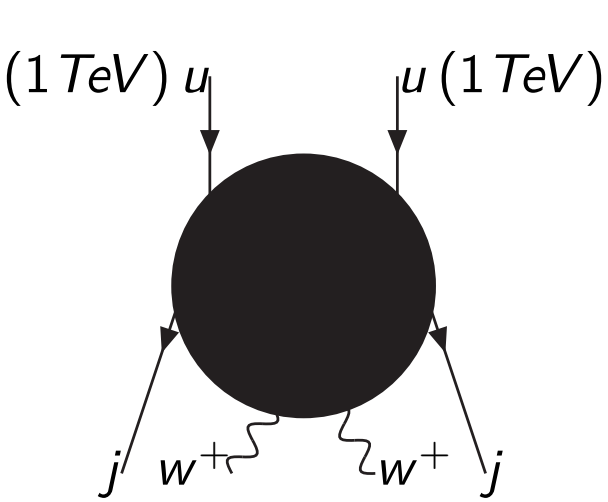
- we can focus on $uu \longrightarrow ddW^+W^+$

From protons to quarks

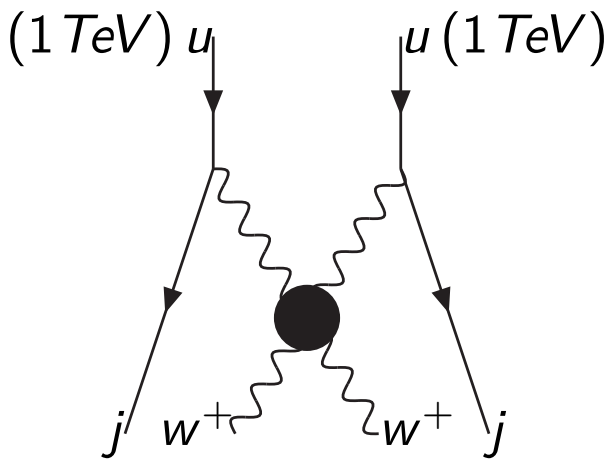


- we can focus on $uu \longrightarrow ddW^+W^+$
- 102 tree level diagrams in SM

Effective W Approximation (EWA)



$\approx$



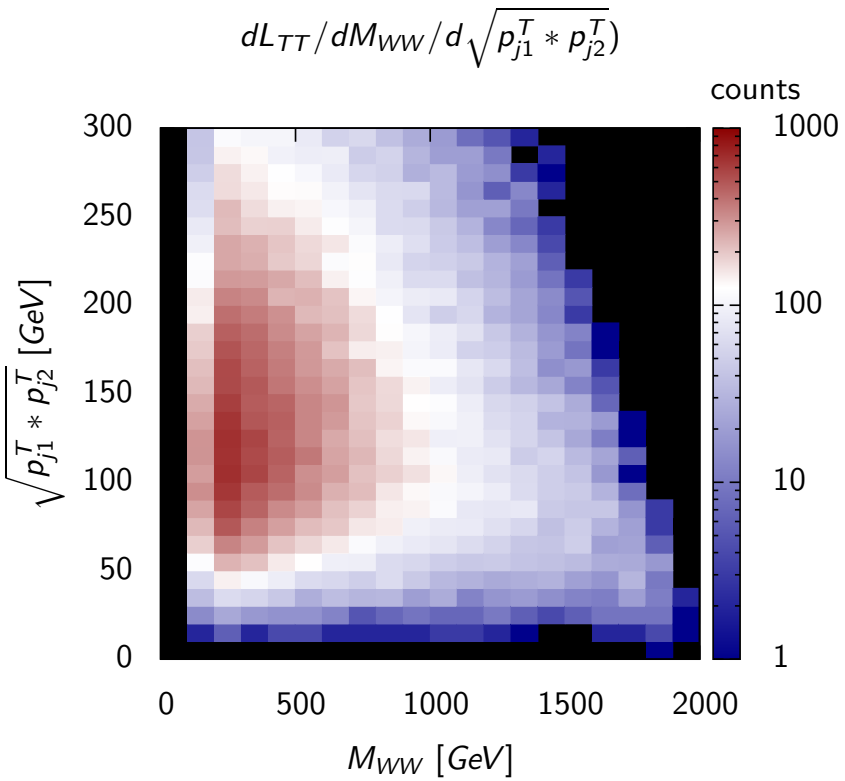
$$uu \longrightarrow ddW^+W^+$$

$$(u \longrightarrow dW^+)(u \longrightarrow dW^+) \longrightarrow dd(W^+W^+ \longrightarrow W^+W^+)$$

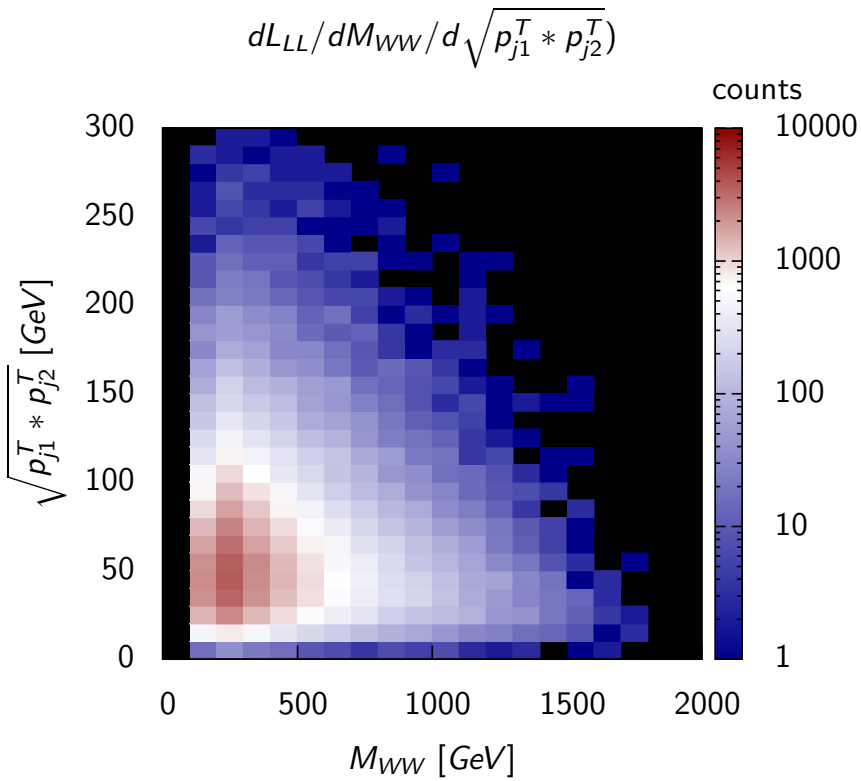
Cahn, Dawson 1984; Johnson et al 1987; Spiesberger et al 1996; Ballestrero et al 2006; Rattazzi et al 2012

WW luminosity

background $W_T W_T$



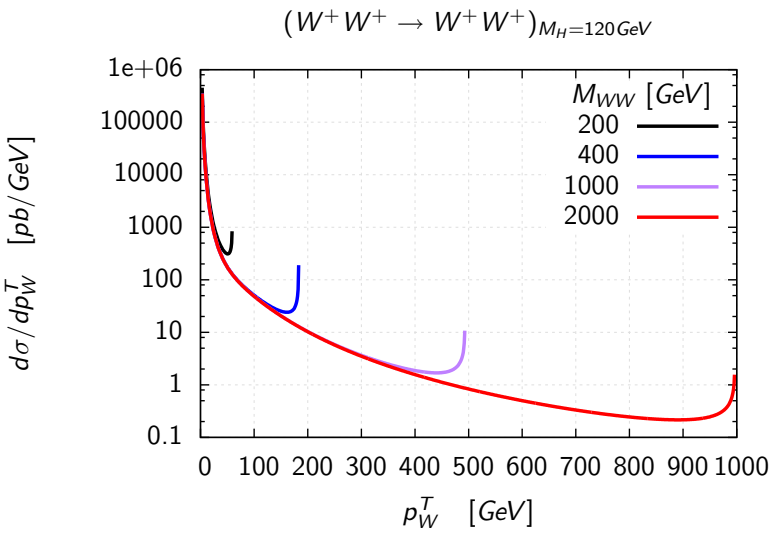
signal $W_L W_L$



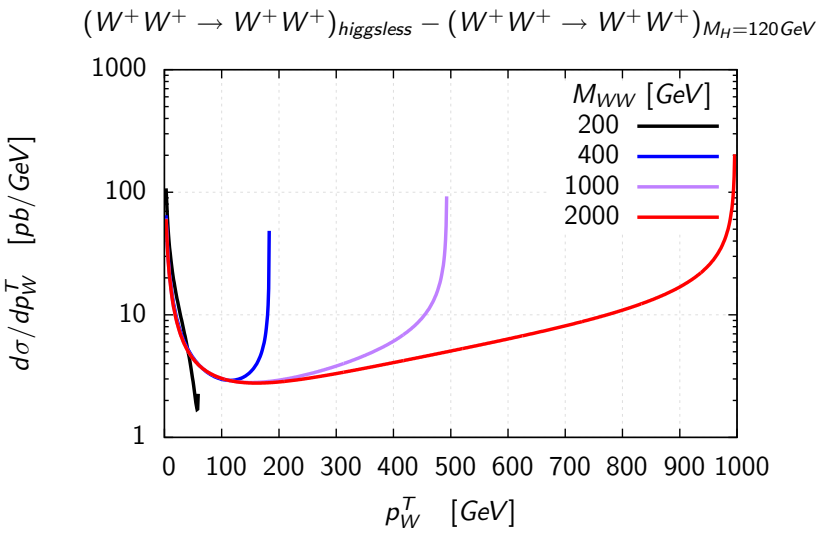
- signal dominates small jet transverse momentum region

WW scattering

Background



Signal



- signal dominates large W transverse momentum region for large WW invariant mass

Conclusions from EWA

Regions of signal over background enhancement:

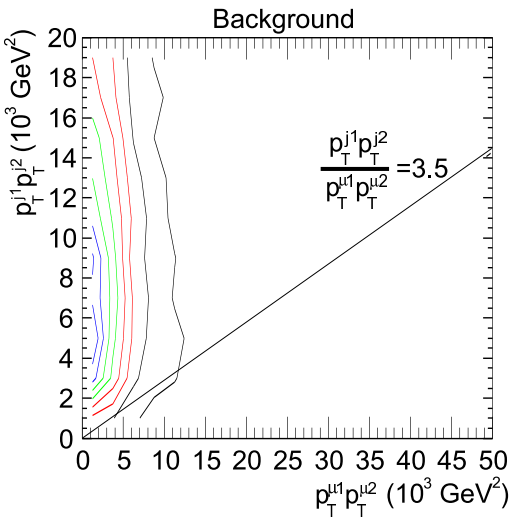
- WW scattering $\Rightarrow$ high p_W^T with respect to WW colision axis
  - larger M_{WW} $\Rightarrow$ higher p_W^T
- WW luminosity $\Rightarrow$ low $p_{j1}^T * p_{j2}^T$
  - larger M_{WW} $\Rightarrow$ lower $p_{j1}^T * p_{j2}^T$
  - $\Rightarrow$ small p^T of initial W $\Rightarrow$
    $\Rightarrow$ WW colision axis closer to pp colision axis
- conclusion: low $p_{j1}^T * p_{j2}^T$, high p_{W1}^T, p_{W2}^T with respect to beam axis
  - corelated through M_{WW}
  - corelated through angle of WW colision axis

Outline

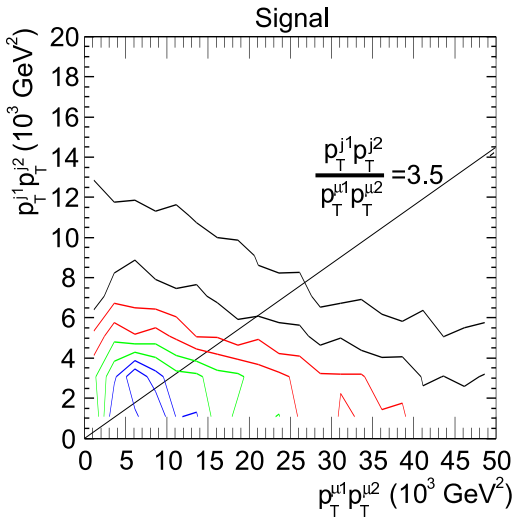
New cut - lepton level

$$pp \to jj\mu^+\mu^+\nu_\mu\nu_\mu:$$

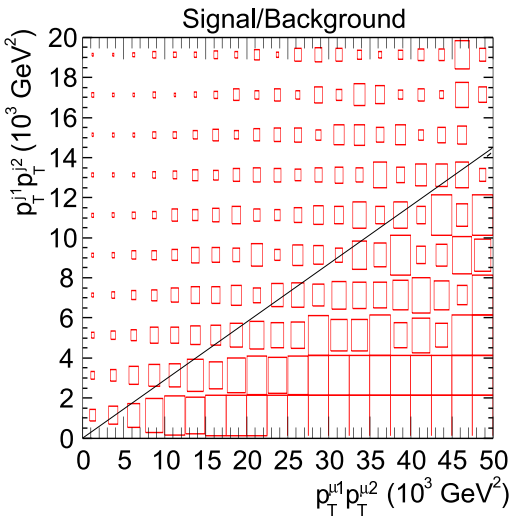
background



signal



signal/background



- $\frac{p_{j1}^T \cdot p_{j2}^T}{p_{\mu1}^T \cdot p_{\mu2}^T} < 3.5$

New selection criteria

Conventional criteria

- 2 same sign leptons,
- 2 jets with $2 < |\eta_j| < 5$ and opposite directions,
- $M_{j_1 l_2}, M_{j_2 l_1} > 200\,GeV$,
- $M_{jj} > 400\,GeV$,
- $\Delta\phi_{ll} > 2.5$,
- $\Delta R_{jl} > 0.4$,
- $p_l^T > 40\,GeV$,
- $|\eta_l| < 1.5$,
- $M_{ll} > 200\,GeV$,

New selection criteria

- 2 same sign leptons,
- 2 jets with $2 < |\eta_j| < 5$ and opposite directions,
- $M_{j_1 l_2}, M_{j_2 l_1} > 200\,GeV$,
- $M_{jj} > 500\,GeV$,
- $\Delta\phi_{ll} > 2.5$,
- $\frac{p_{j1}^T \cdot p_{j2}^T}{p_{l1}^T \cdot p_{l2}^T} < 3.5$,

Improvement

$pp \longrightarrow jjl^+l^+$:

Sample	Initial[1] σ	Final[2] σ conventional	Final[2] σ new	new / conventional
Signal	9.1 fb	0.1086 fb	0.1163 fb	107%
Irr. background	104.5 fb	0.0494 fb	0.0224 fb	45%
$t\bar{t}$ background	-	0.0225 fb	0.0171 fb	76%

$pp \longrightarrow jjl^-l^-$:

Sample	Initial[1] σ	Final[2] σ conventional	Final[2] σ new	new / conventional
Signal	2.58 fb	0.0255 fb	0.0280 fb	110%
Irr. background	20.35 fb	0.0128 fb	0.0059 fb	46%
$t\bar{t}$ background	-	0.0225 fb	0.0171 fb	76%

[1] with $2 < |\eta_j| < 5$ cut

[2] lepton reconstruction and sign matching and the unitarity bound included

Summary

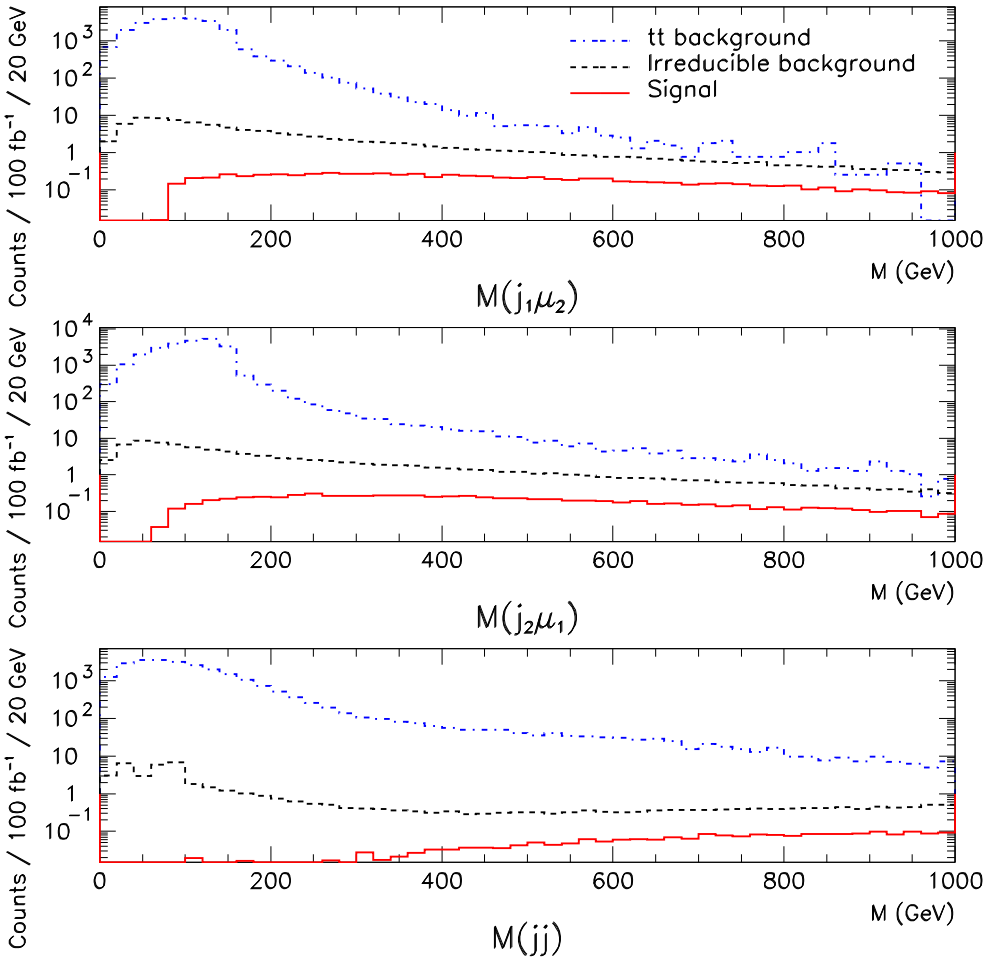
- lepton kinematics is adequately described by production times decay approximation
- after imposing QCD-removing cuts proton-proton $(7 + 7\,TeV)$ collision reduces to quark-quark$(1 + 1\,TeV)$ collision
- relevant aspects of quark-quark collision can be seen in Effective W Approximation
- basic properties of WW luminosity and WW scattering indicate high discriminating power of ratio of products of transverse momenta
- new selection criteria based on p^T products ratio allow improvement of S/B per $100 fb^{-1}$
  from $11/7$ to $12/4$ for $++$ channel
  from $13/11$ to $14/6$ for $++$ and $--$ channel

Backup

Backup

$t\bar{t}$ background

- efficiency of lepton sign matching $\approx 99\%$
- Selection criteria
  - $M_{j_1 l_2}, M_{j_2 l_1} > 200 GeV$,
  - $M_{jj} > 400 GeV$,
  - $\Delta\phi_{ll} > 2.5$,



W^+W^- channel

- irreducible background:
  - large gluon-gluon contribution
  - contribution from diagrams with both Ws emitted from one quark line
  - background extends to lower jet transverse momenta
  - R_{p_T} ratio as effective as lepton transverse momenta on their own
  - $p_T^{l_1} + p_T^{l_2}$ or the product $p_T^{l_1} \cdot p_T^{l_2}$ - slightly larger efficiency than combined cuts on the individual p_T^l
- reducible background:
  - top production not restricted to small experimental effects
- results:

Sample	Initial[1] σ	Final[2] σ
Signal	19.1 fb	0.1191 fb
Irr. background	3 370.0 fb	0.1315 fb
$t\bar{t}$ background	-	0.3610 fb

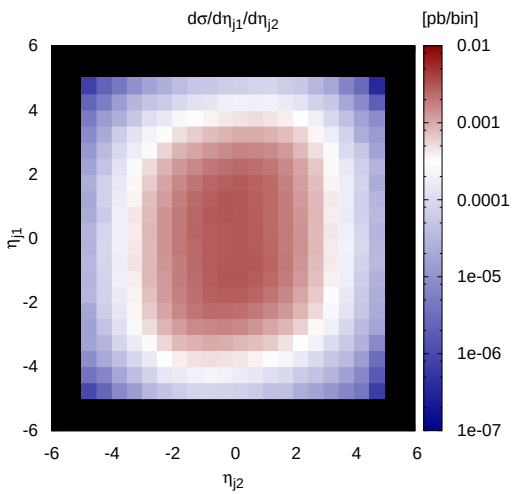
[1] with $2 < |\eta_j| < 5$ cut [2] lepton reconstruction and sign matching, branching fractions and the unitarity bound included

- S/B 0.24 in opposite-sign channel vs 3.2 in same-sign channel

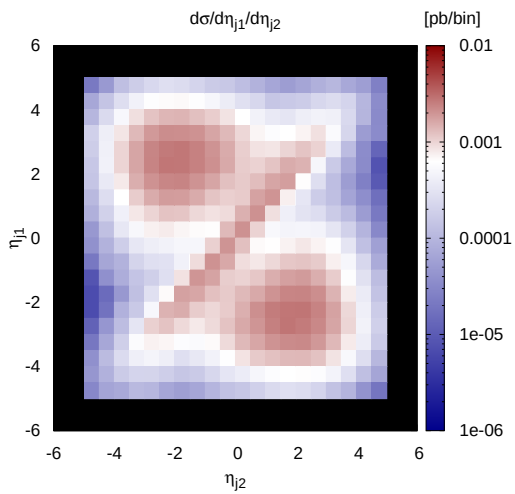
QCD background - opposite jets

pseudorapidity: $\eta = -\ln\left[\mathrm{tg}\left(\frac{\theta}{2}\right)\right]$

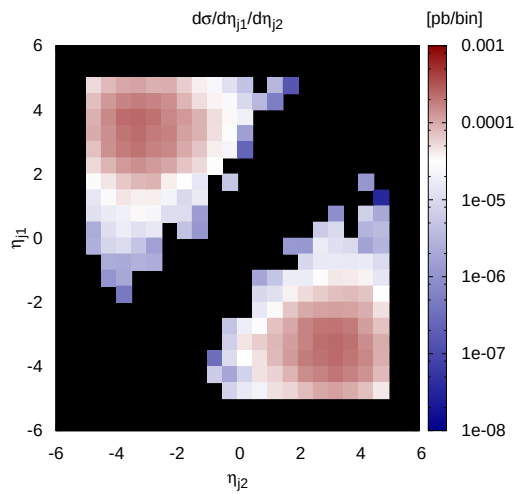
QCD background



EW background



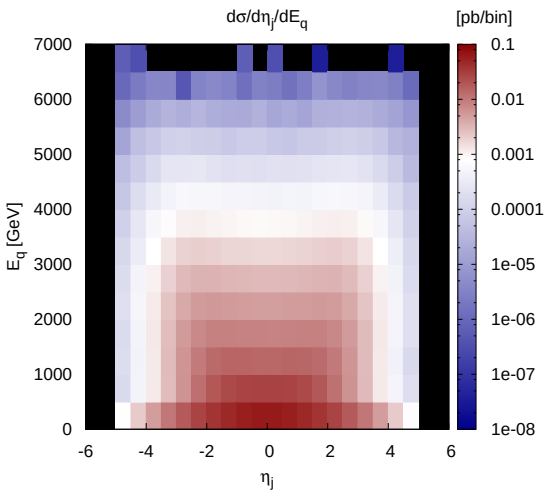
signal



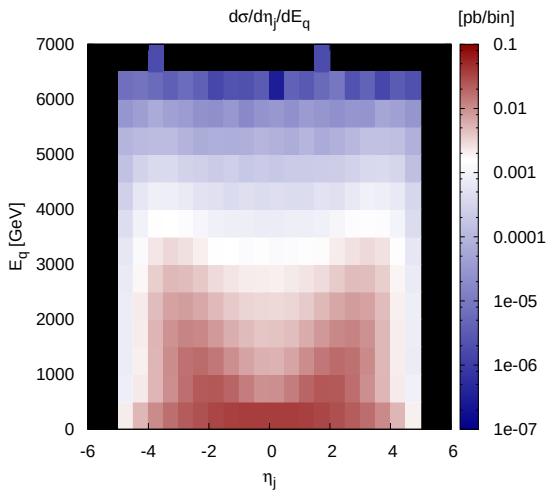
- cut $\eta_{j1} \cdot \eta_{j2} < 0$ - jets in opposite directions

QCD background - jets angular distributions

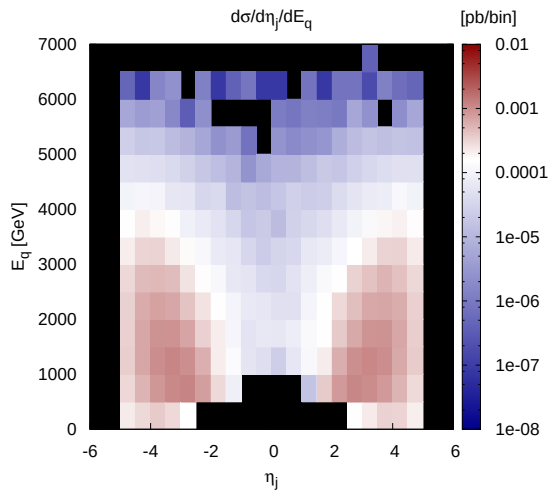
QCD background



EW background



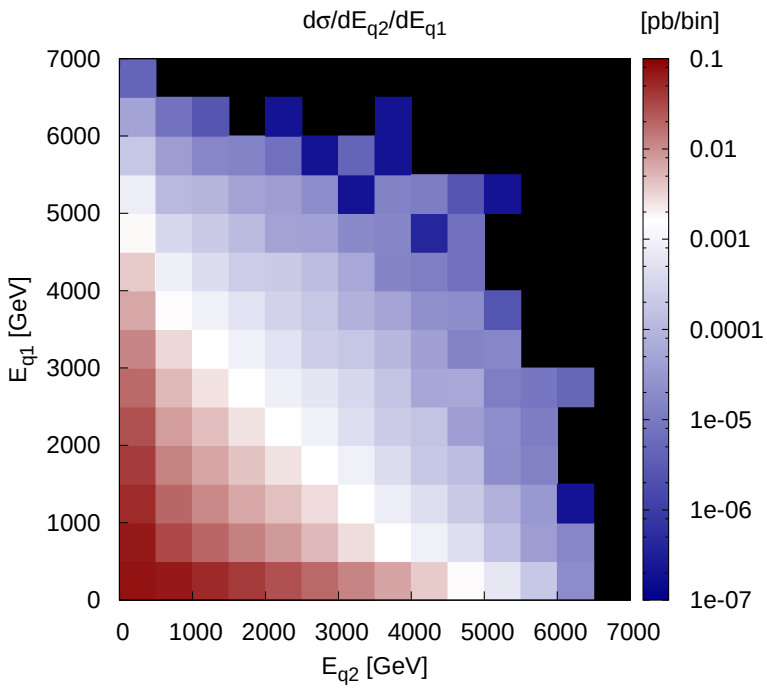
signal



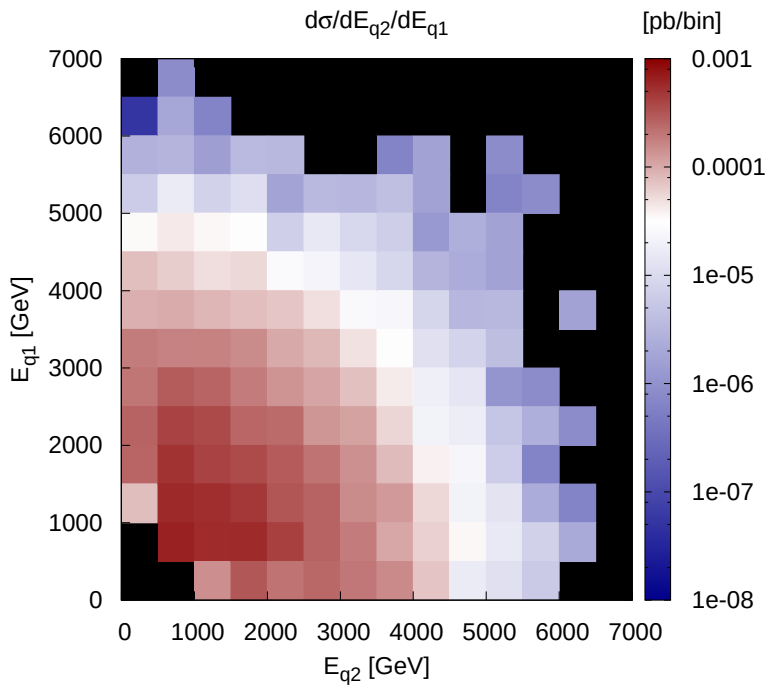
- cut $2 < |\eta_j|$

Initial quarks energies - no cuts

background



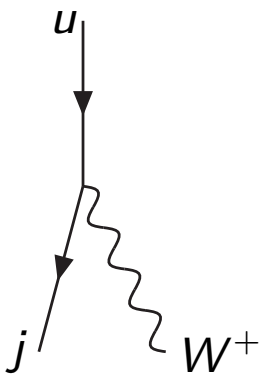
signal



- most background events came from low energy quarks

Effective W Approximation (EWA)

Probability for u quark to emit longitudinal/transverse (L/T) W^+ with fraction of energy x and virtuality q^2:



$$\frac{\mathrm{d}P_L}{\mathrm{d}x\,\mathrm{d}q^2} \sim \frac{M_W^2 x\left(\frac{2}{(x-\frac{q^2}{S})^2} - \frac{2}{x-\frac{q^2}{S}}\right)}{(q^2-M_W^2)^2}$$

$$\frac{\mathrm{d}P_T}{\mathrm{d}x\,\mathrm{d}q^2} \sim \frac{-q^2 x\left(\frac{2}{(x-\frac{q^2}{S})^2} - \frac{2}{x-\frac{q^2}{S}} + 1\right)}{(q^2-M_W^2)^2}$$

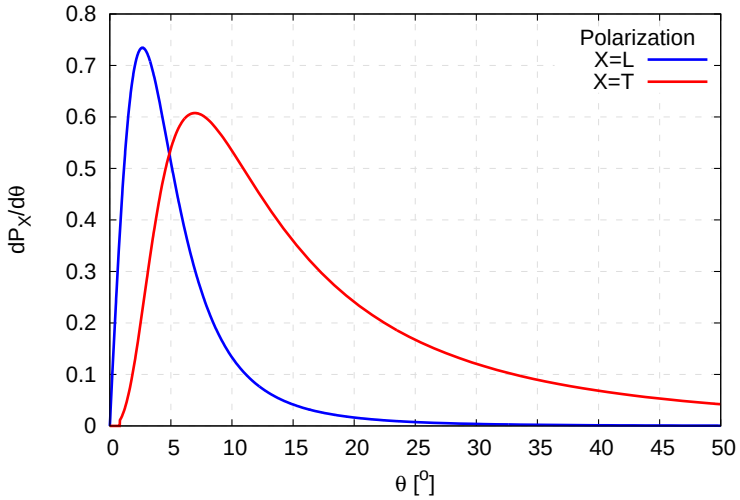
$$x = \frac{E_W}{E_u}, \quad q^2 = E_W^2 - \vec{p}_W^2 = 2E_j E_u(\cos\theta_j - 1) \sim \theta_j^2 + \mathcal{O}(\theta_j^4)$$

Cahn, Dawson 1984; Johnson et al 1987; Spiesberger et al 1996; Ballestrero et al 2006; Rattazzi et al 2012

W luminosity

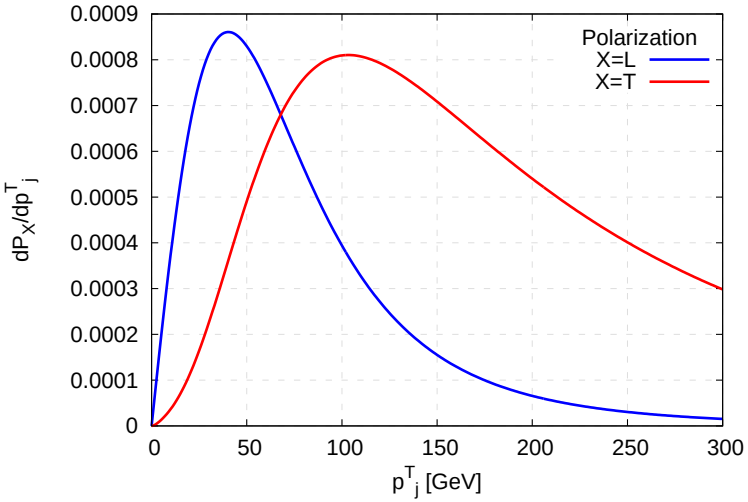
Properties of W emission encoded in jets:

jet angular distribution



signal: smaller θ_j

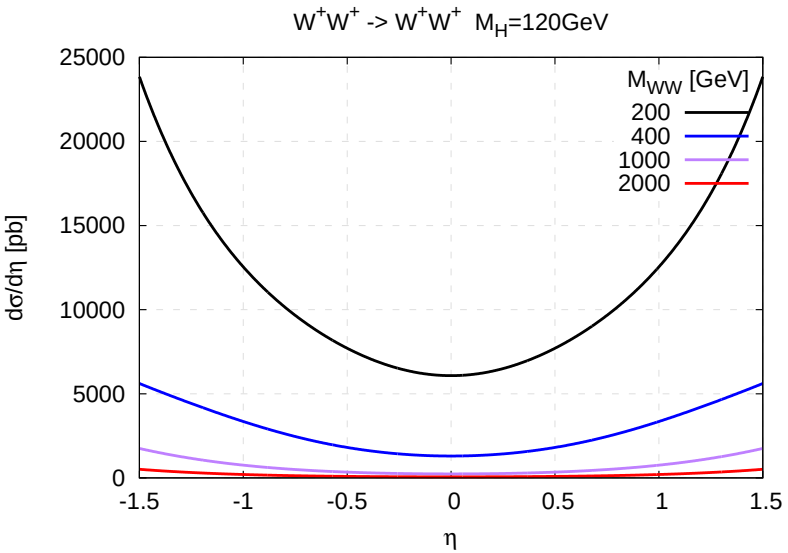
jet transverse momentum



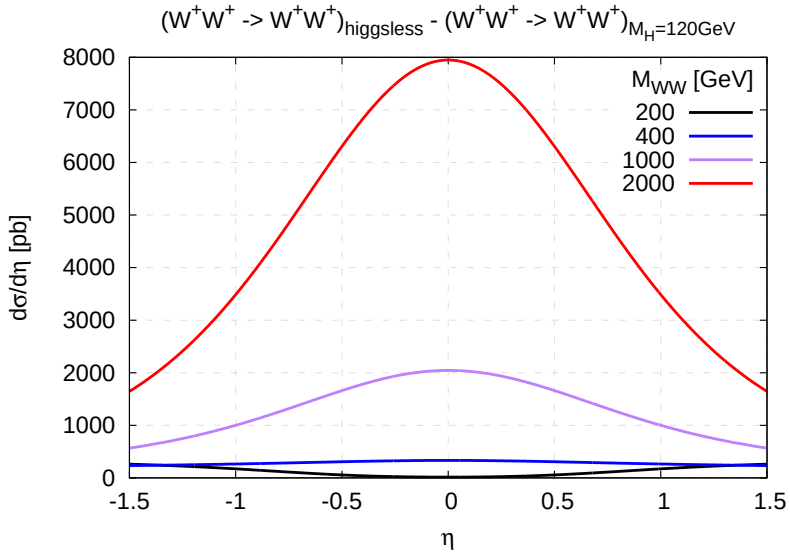
signal: smaller p_j^T
$\Rightarrow$ smaller θ_j
$\Rightarrow$ smaller E_j (larger E_W)
independent of boosts along beam axis

WW scattering - pseudorapidity

Background



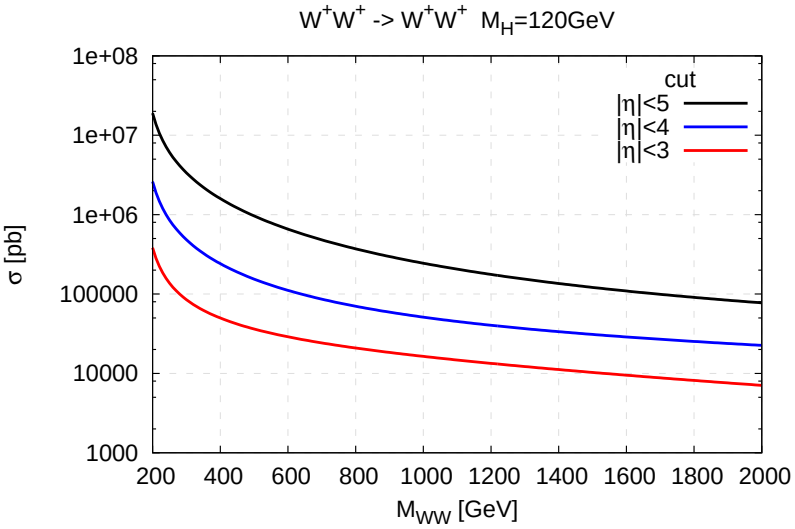
Signal



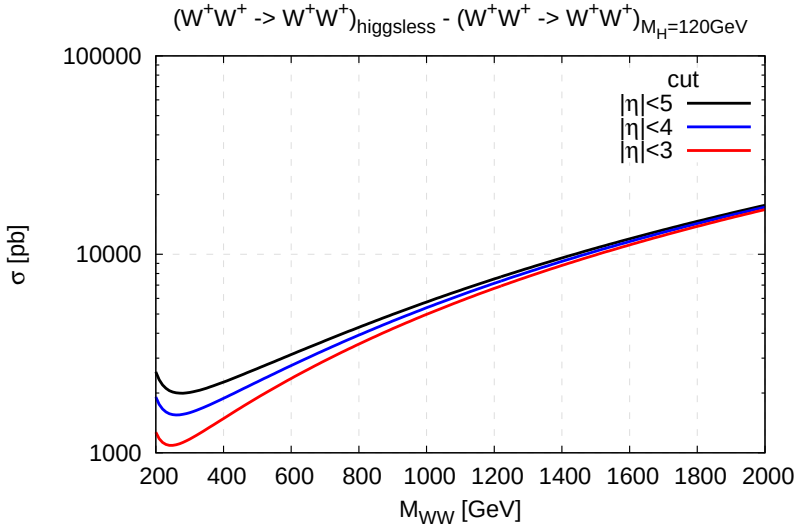
- signal dominates in central region (small pseudorapidity)
- collinear singularities at infinities

WW scattering - invariant mass

Background



Signal

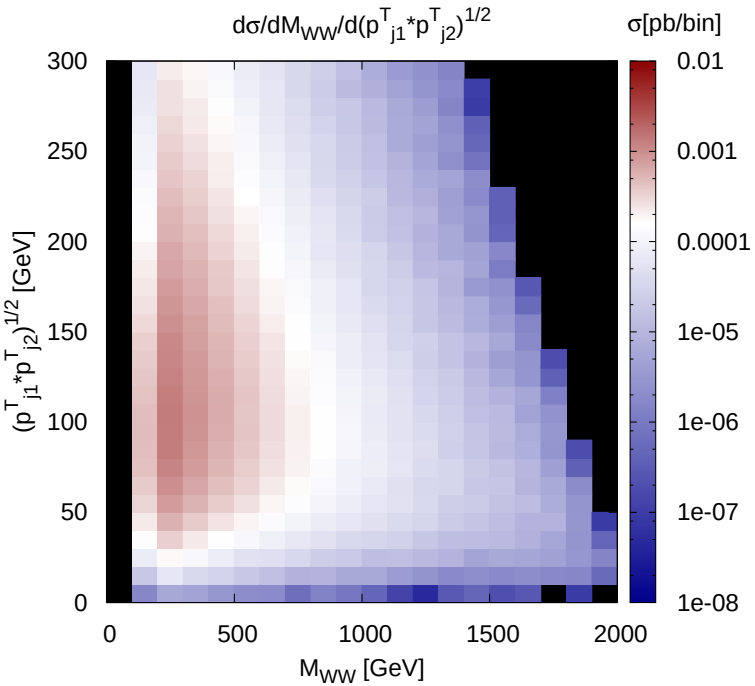


- signal dominates for large invariant mass
- normalization depends on how we cut collinear singularities but shapes do not

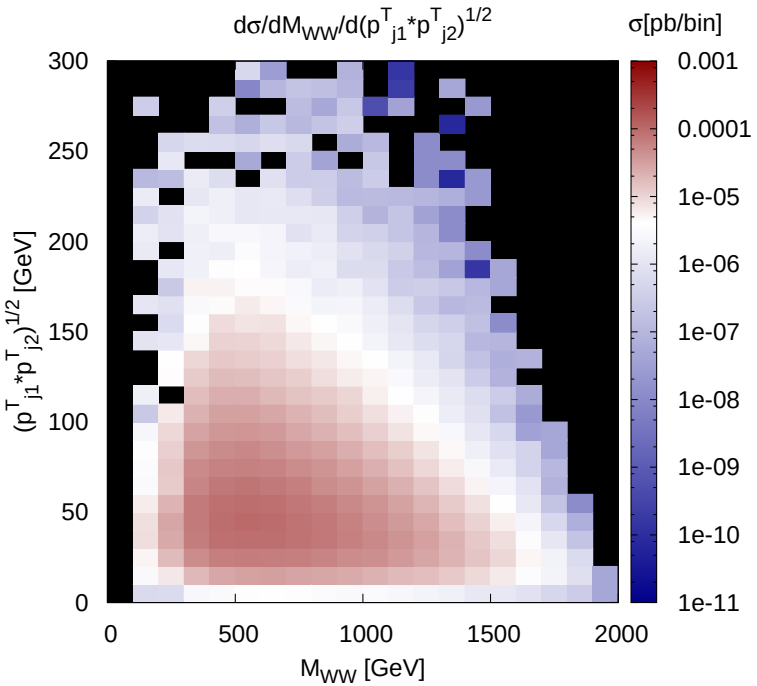
pT vs Mww - Quark Level

$uu \longrightarrow ddW^+W^+$:

background



signal

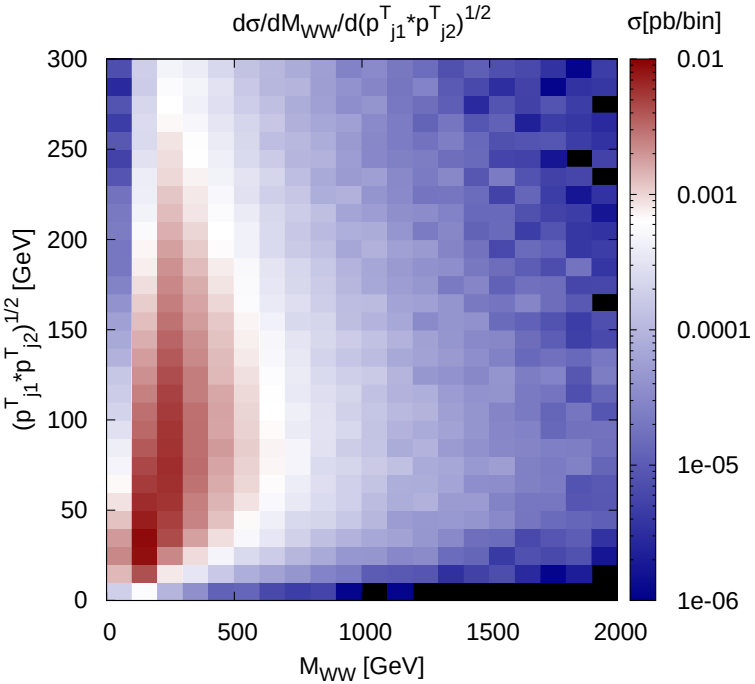


- $p_{j1}^T * p_{j2}^T$ properties remain at quark level

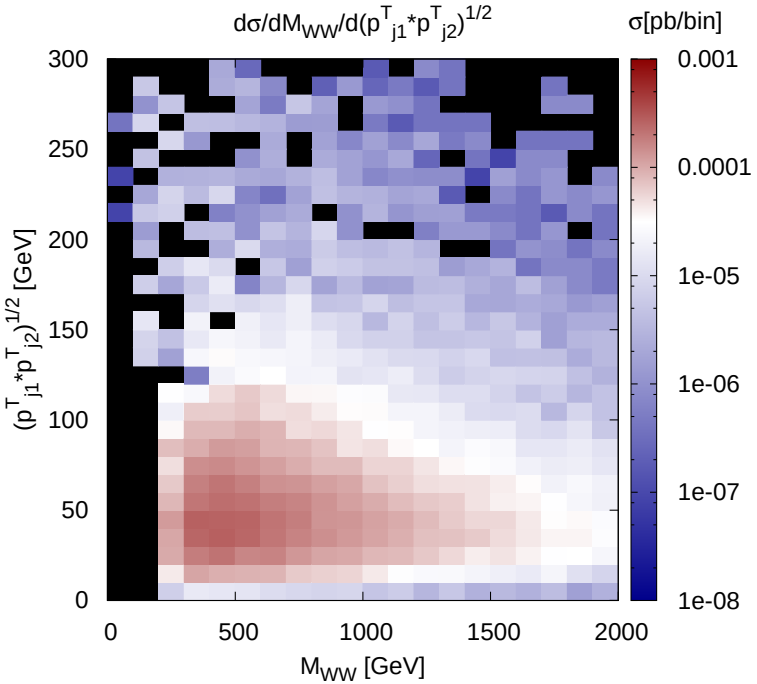
pT vs Mww - Proton Level

$pp \longrightarrow jjW^+W^+$:

background



signal

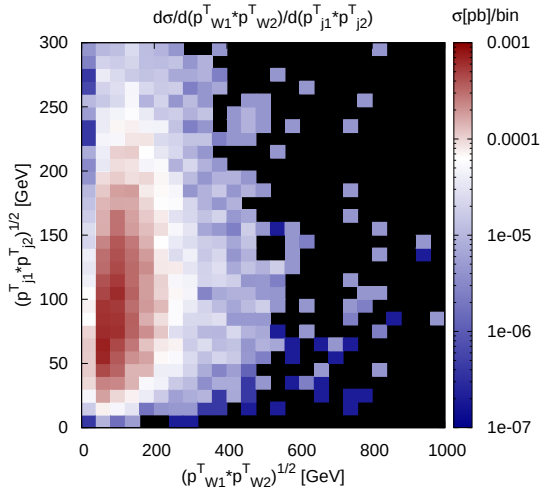


- $p_{j1}^T * p_{j2}^T$ properties remain at proton level

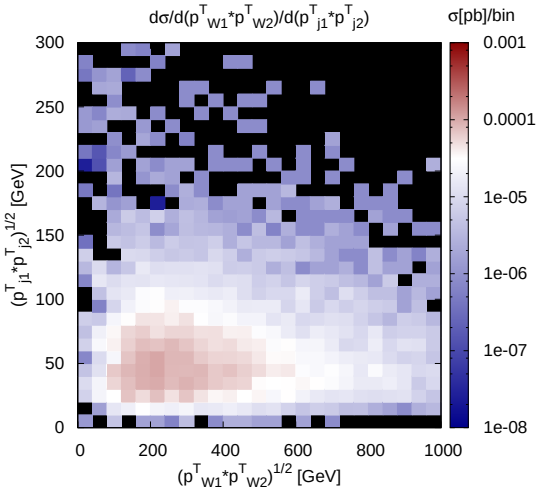
New cut - proton level

$pp \longrightarrow jjW^+W^+$:

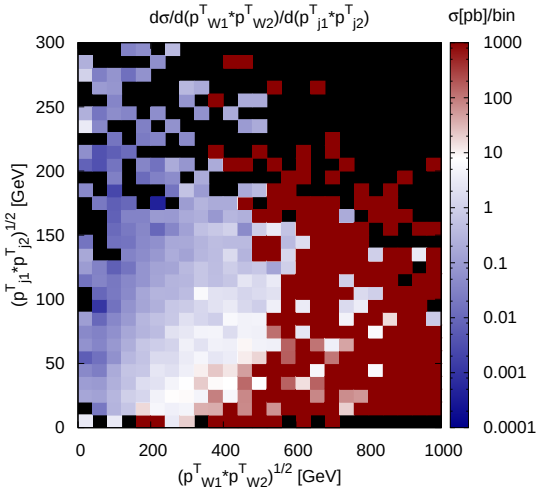
background



signal



signal/background



- $\frac{p_{j1}^T \cdot p_{j2}^T}{p_{W1}^T \cdot p_{W2}^T} < const.$

Unitarity

$$\langle \beta_{out} | \alpha_{in} \rangle = S_{\beta\alpha} = \langle \beta_0 | \, S_0 \, | \alpha_0 \rangle$$

with: $S_0 = 1 - iT_0$

$$S_0^\dagger S_0 = S_0 S_0^\dagger = 1 \quad \Rightarrow \quad -i\left(T_0^\dagger - T_0\right) = T_0^\dagger T_0$$

partial waves:

$$\langle P, j', \kappa' | \, T_0 \, | (\sqrt{s}, 0, 0, 0), j, \kappa \rangle = \\ = (2\pi)^4 \delta^{(4)}\left(P - (\sqrt{s}, 0, 0, 0)\right) 64\pi^2 \delta_{j',j} \mathcal{T}^{j,s}_{\kappa',\kappa}$$

$$-i\left(\overline{\mathcal{T}^{j,s}_{\kappa,\kappa'}} - \mathcal{T}^{j,s}_{\kappa',\kappa}\right) = \int \overline{\mathcal{T}^{j,s}_{\kappa'',\kappa'}} \mathcal{T}^{j,s}_{\kappa'',\kappa} \, \mathrm{d}\kappa''$$

for $\kappa' = \kappa$:

$$-2\,\mathrm{Im}\left(\mathcal{T}^{j,s}_{\kappa,\kappa}\right) = \int \left|\mathcal{T}^{j,s}_{\kappa'',\kappa}\right| \, \mathrm{d}\kappa'' \\ = \int\limits_{\{\kappa\}} \left|\mathcal{T}^{j,s}_{\kappa'',\kappa}\right|^2 \, \mathrm{d}\kappa'' \qquad + \int\limits_{D\setminus\{\kappa\}} \left|\mathcal{T}^{j,s}_{\kappa'',\kappa}\right|^2 \, \mathrm{d}\kappa''$$

Two particle states

two particle state: $\kappa = (\lambda_1, \lambda_2)$

$$\int\limits_{\{\kappa\}} f(\kappa'')\,\mathrm{d}\kappa'' = N_s \sum_{\substack{\lambda_1''=\lambda_1 \\ \lambda_2''=\lambda_2}} f(\lambda_1'', \lambda_2'') = N_s f(\kappa)$$

normalization factor: $N_s = 2\frac{\sqrt{s^2+m_1^4+m_2^4-2sm_1^2-2sm_2^2-2m_1^2m_2^2)}}{s}$

$$-2\,\mathrm{Im}\left(\mathcal{T}^{j,s}_{\kappa,\kappa}\right) = N_s \left|\mathcal{T}^{j,s}_{\kappa,\kappa}\right|^2 + \int\limits_{D\setminus\{\kappa\}} \left|\mathcal{T}^{j,s}_{\kappa'',\kappa}\right|^2 \mathrm{d}\kappa''$$

$$\left|\mathcal{T}^{j,s}_{\kappa,\kappa} + iN_s^{-1}\right|^2 = N_s^{-2} - N_s^{-1} \int\limits_{D\setminus\{\kappa\}} \left|\mathcal{T}^{j,s}_{\kappa'',\kappa}\right|^2 \mathrm{d}\kappa'' =: (R^{j,s}_{\kappa})^2 \geqslant 0$$

Unitarity conditions

$$\left|\mathcal{T}^{j,s}_{\kappa,\kappa}\right| \leqslant R^{j,s}_{\kappa} + N_s^{-1} \leqslant 2N_s^{-1} \xrightarrow[s\to\infty]{} 1$$

$$\left|\mathrm{Re}\left(\mathcal{T}^{j,s}_{\kappa,\kappa}\right)\right| \leqslant R^{j,s}_{\kappa} \leqslant N_s^{-1} \xrightarrow[s\to\infty]{} \frac{1}{2}$$

$$0 \leqslant (R^{j,s}_{\kappa})^2 \Rightarrow \int\limits_{D\setminus\{\kappa\}} \left|\mathcal{T}^{j,s}_{\kappa'',\kappa}\right|^2 \leqslant N_s^{-1}$$

for $\kappa' = (\lambda_1', \lambda_2') \neq \kappa$:

$$N_s \left|\mathcal{T}^{j,s}_{\kappa',\kappa}\right|^2 + \int\limits_{D\setminus\{\kappa,\kappa'\}} \left|\mathcal{T}^{j,s}_{\kappa'',\kappa}\right|^2 \leqslant N_s^{-1}$$

$$\left|\mathcal{T}^{j,s}_{\kappa',\kappa}\right| \leqslant \sqrt{N_s^{-2} - N_s^{-1} \int\limits_{D\setminus\{\kappa,\kappa'\}} \left|\mathcal{T}^{j,s}_{\kappa'',\kappa}\right|^2} \leqslant N_s^{-1} \xrightarrow[s\to\infty]{} \frac{1}{2}$$