T-odd Asymmetry in W + jet events at the LHC

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in collaboration with

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Introduction

Absorptive Part of Scattering Amplitude

We study **theoretical calculation** & **direct measurement** of the absorptive part of a QCD amplitude.

Transition operator $\hat{T}$ is given as $\hat{S} = T\left[e^{-i\int \mathrm{d}^4x \hat{\mathcal{H}}_{\mathrm{int}}}\right] = \hat{1} + i\hat{T}$.

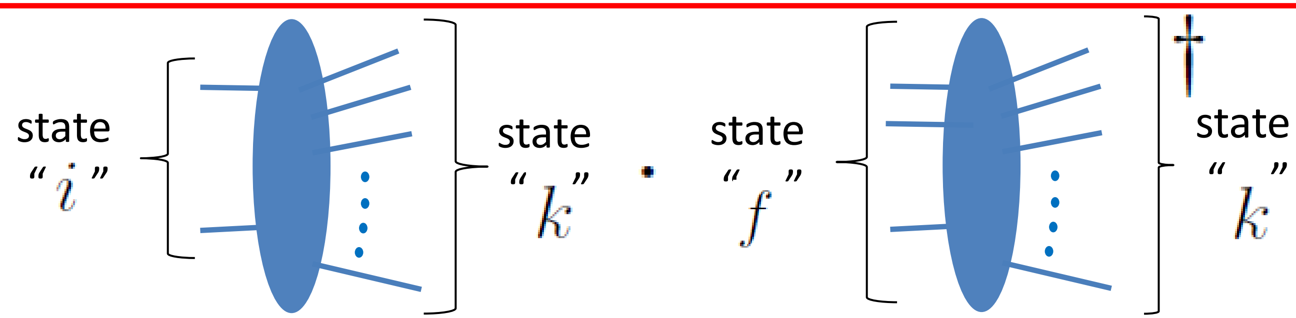
Unitarity of S-matrix $\hat{S}^\dagger\hat{S} = \hat{1}$ gives $-i(\hat{T} - \hat{T}^\dagger) = \hat{T}^\dagger\hat{T}$.

Absorptive part of transition amplitude from state " i **" to state "** f **"** is defined as

$$-i\langle f|(\hat{T} - \hat{T}^\dagger)|i\rangle = \langle f|\hat{T}^\dagger\hat{T}|i\rangle = \sum_{k\in\mathcal{H}} \langle f|\hat{T}^\dagger|k\rangle\langle k|\hat{T}|i\rangle \equiv A_{fi}$$

summation over complete set of states $\mathcal{H}$ →

$$A_{fi} \propto \sum_{k\in\mathcal{H}}$$



c.f. When the initial and final states are the same, we get the optical theorem:

$$A_{ii} = \mathrm{Im}\left(\langle i|\hat{T}|i\rangle\right) = \sum_{k\in\mathcal{H}} |\langle k|\hat{T}|i\rangle|^2 \propto \sigma_{\mathrm{tot}}$$

Measurement of Absorptive Part

Absorptive part can be measured through part of the cross section that is odd under naïve T-reversal, which we call "T-odd asymmetry".

any 3-momentum $\vec{k} \to -\vec{k}$, any spin $\sigma \to -\sigma$,
but the initial and final states are not interchanged.

proof:

We denote the naïve-T-reversal of states i , f by $\tilde{i}$, $\tilde{f}$, respectively.

We find

$$|\langle \tilde{f}\,|\hat{T}|\,\tilde{i}\,\rangle|^2 - |\langle f\,|\hat{T}|\,i\,\rangle|^2$$

T-odd asymmetry

$$= \underbrace{\left(|\langle \tilde{f}\,|\hat{T}|\,\tilde{i}\,\rangle|^2 - |\langle i\,|\hat{T}|\,f\,\rangle|^2\right)}_{\text{Odd under original T-reversal}} + 2\,\mathrm{Im}\left(\langle f\,|\hat{T}|\,i\,\rangle^* A_{fi}\right) + |A_{fi}|^2$$

Absorptive part

Experimentally, T-odd asymmetry is measured through a T-odd quantity, *e.g.*, $\vec{k}_1 \times \vec{k}_2 \cdot \vec{s}$ ($\vec{k}_i$: 3-momentum, $\vec{s}$: spin) .

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$$|\langle \tilde{f}|\hat{T}|\tilde{i}\rangle|^2 - |\langle f|\hat{T}|i\rangle|^2 \quad \longleftarrow \text{T-odd asymmetry}$$

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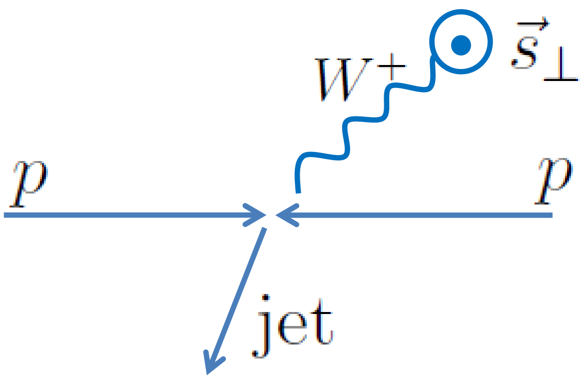
↑ This quantity is **P-even**, hence T-odd asymmetry appears **without P-violation**.

Measurement in $W + \mathrm{jet}$ events

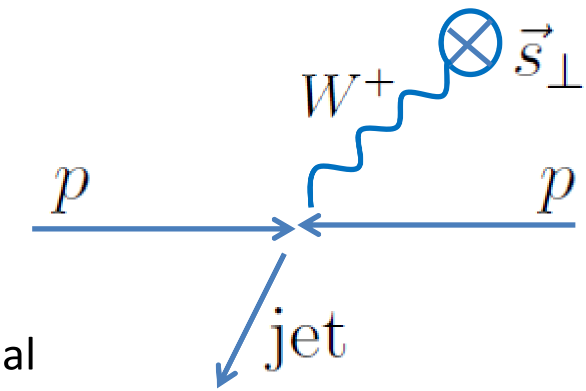
In this talk, we focus on $\boxed{p\,p \;\rightarrow\; W^+ \;+\; \mathrm{jet}}$ process at the LHC and study asymmetry of the quantity $\boxed{\vec{p}_{p1} \times \vec{p}_{W^+} \cdot \vec{s}_{\perp}}$.

($\vec{s}_{\perp}$ = spin of W^+ perpendicular to the scattering plane.)



V.S.

related by naïve-T-reversal



$\vec{s}_{\perp}$ can be measured through $W^+(\rightarrow\ \ell^+\,\nu)$ decay.

Distribution of ℓ^+ momentum perpendicular to the scattering plane, denoted by $(\vec{q}_l)_y$, is correlated with $\vec{s}_{\perp}$. Hence the asymmetry of $\vec{p}_{p1} \times \vec{p}_{W^+} \cdot \vec{s}_{\perp}$ can be measured through the quantity A ,

$$\boxed{A \;\equiv\; \frac{\sigma(\text{events with } (\vec{q}_l)_y > 0) \;-\; \sigma(\text{events with } (\vec{q}_l)_y < 0)}{\sigma(\text{events with } (\vec{q}_l)_y > 0) \;+\; \sigma(\text{events with } (\vec{q}_l)_y < 0)}}$$

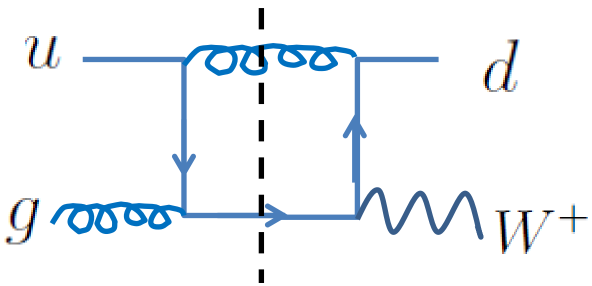
Calculation of Absorptive Part

We use **perturbative QCD** to calculate the cross section for $pp \rightarrow W^+ + \text{jet}$ process.

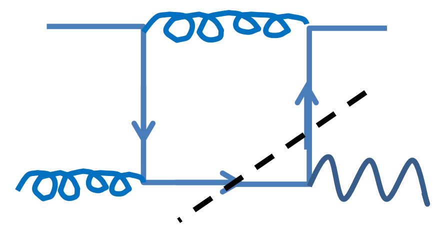
Then absorptive part becomes calculable with Cutkosky rules:

e.g., for subprocess $u\,g \rightarrow W^+\,d$ in the leading order of g_S ,

$$A_{fi} =$$



$$+$$



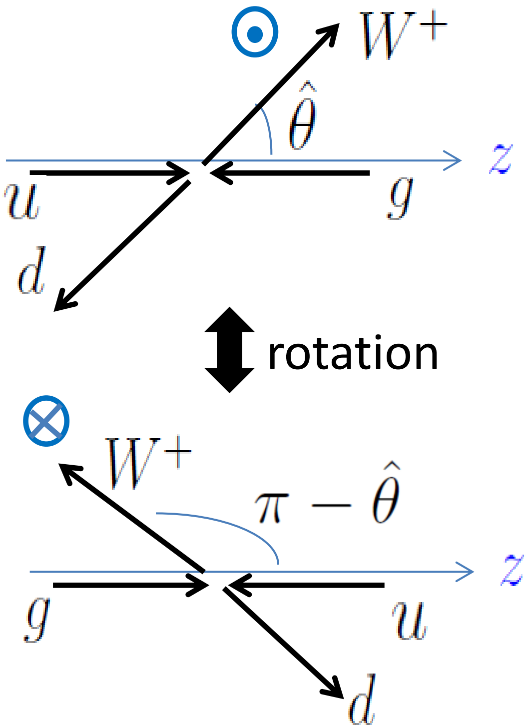
$$+ \quad \cdots\cdot \quad ,$$

where every loop propagator cut by ------ should be replaced with a delta function as $\dfrac{1}{(l+p)^2 - m^2 + i\epsilon} \rightarrow -2\pi i\,\delta((l+p)^2 - m^2)$.

Absorptive part appears at one-loop level in the leading order.

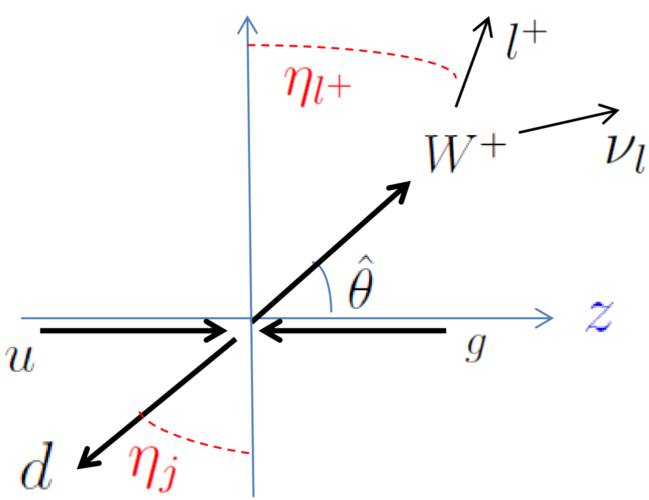
Observation of T-odd Asymmetry at the LHC

Problem of the Sign of $\cos\hat{\theta}$



$\vec{p}_{p1}\times\vec{p}_{W^+}\cdot\vec{s}_\perp$ **flips sign** with cosine of the scattering angle in parton center-of-mass frame, denoted by $\cos\hat{\theta}$. Hence we need to separate events with $\cos\hat{\theta}>0$ and $\cos\hat{\theta}<0$.

In hadron collisions, $\cos\hat{\theta}$ is reconstructed by calculating ν_l's longitudinal momentum, but this gives one positive and one negative solutions for $\cos\hat{\theta}$.

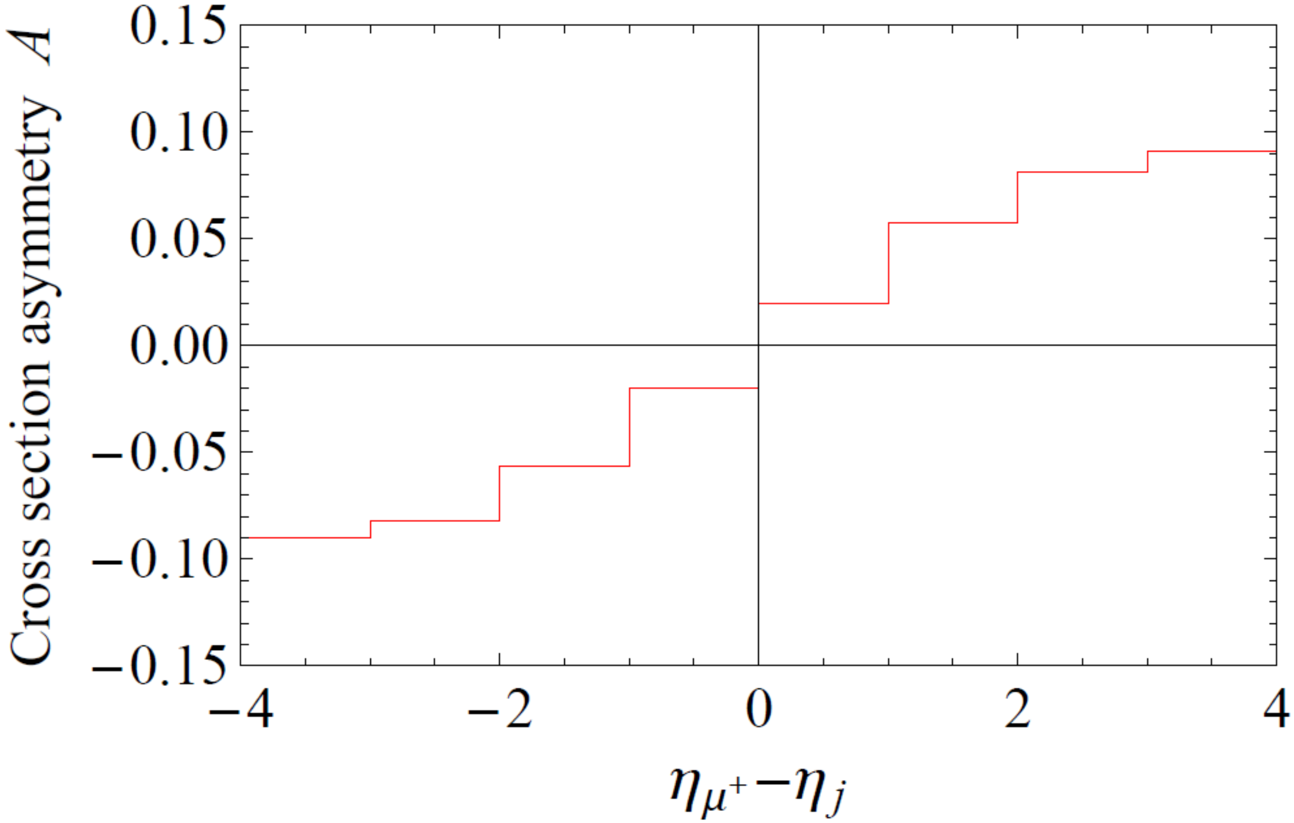


Instead, we use $\eta_{\ell^+}-\eta_j$, which is correlated with $\cos\hat{\theta}$.

We study the distribution of the asymmetry A in each bin of the pseudo-rapidity difference $\eta_{l^+}-\eta_j$.

Parton-level Analysis

First, simply integrating the leading order analytic formulae of the diff. cross section of $pp \to W^+(\mu^+\nu) + 1\,\mathrm{parton}$ process and imposing realistic selection cuts, we obtain



pp collisions with $\sqrt{s} = 8\ \mathrm{TeV}$.

$\mu_R = \mu_F = q_T$

W boson transverse momentum

$$\left[\begin{array}{l} p_{jT} > 30\ \mathrm{GeV} \\ p_{\mu^+ T} > 25\ \mathrm{GeV} \\ \not{p}_T > 25\ \mathrm{GeV} \\ |\vec{p}_{\mu T} + \vec{\not{p}}_T| > 30\ \mathrm{GeV} \\ M_T > 60\ \mathrm{GeV} \\ |(q_l)_y| > 0.6(M_W/2) \end{array}\right.$$

T-odd asymmetry can be **as large as 10 %**.

Detector-level Analysis

Detector-level analysis for measurement of T-odd asymmetry has become feasible very recently, with the invention of

"**MadGraph5_aMC@NLO**", J. Alwall *et al.* (2014)

which generates events based on one-loop level calculation of matrix elements.

We use "**MadGraph5_aMC@NLO**" to generate

$pp \to W^+(\to \mu^+ \nu_\mu) + 1 \text{ jet}$ events with $\sqrt{s} = 8 \text{ TeV}$,

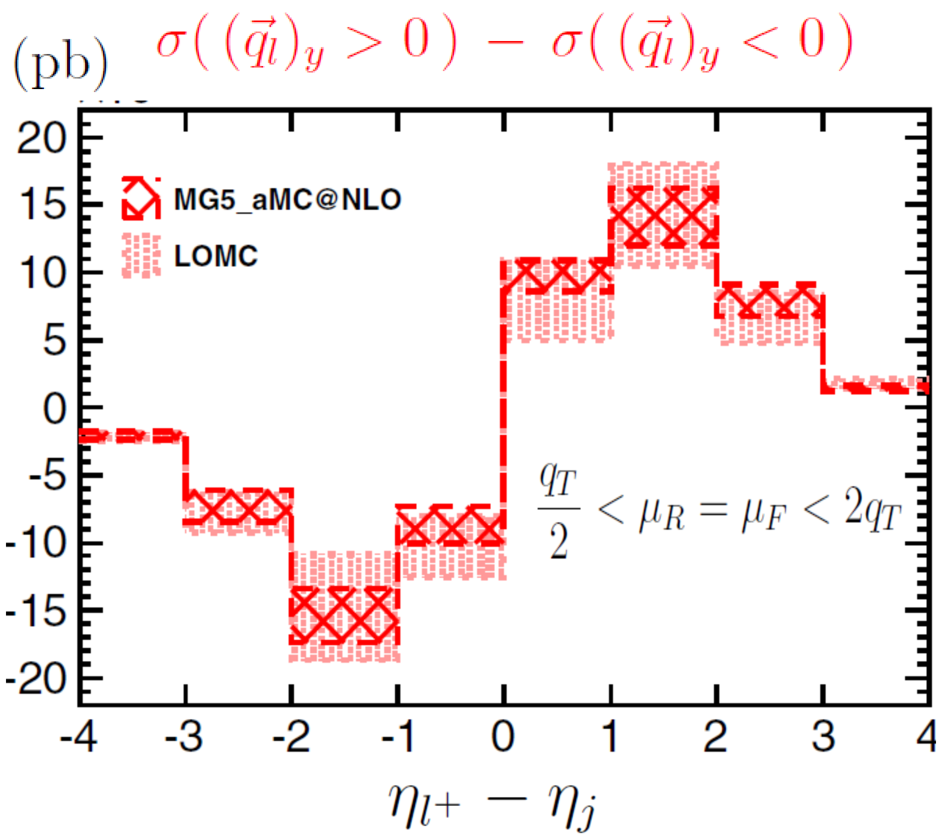
G. Corcella *et al.* (2010)

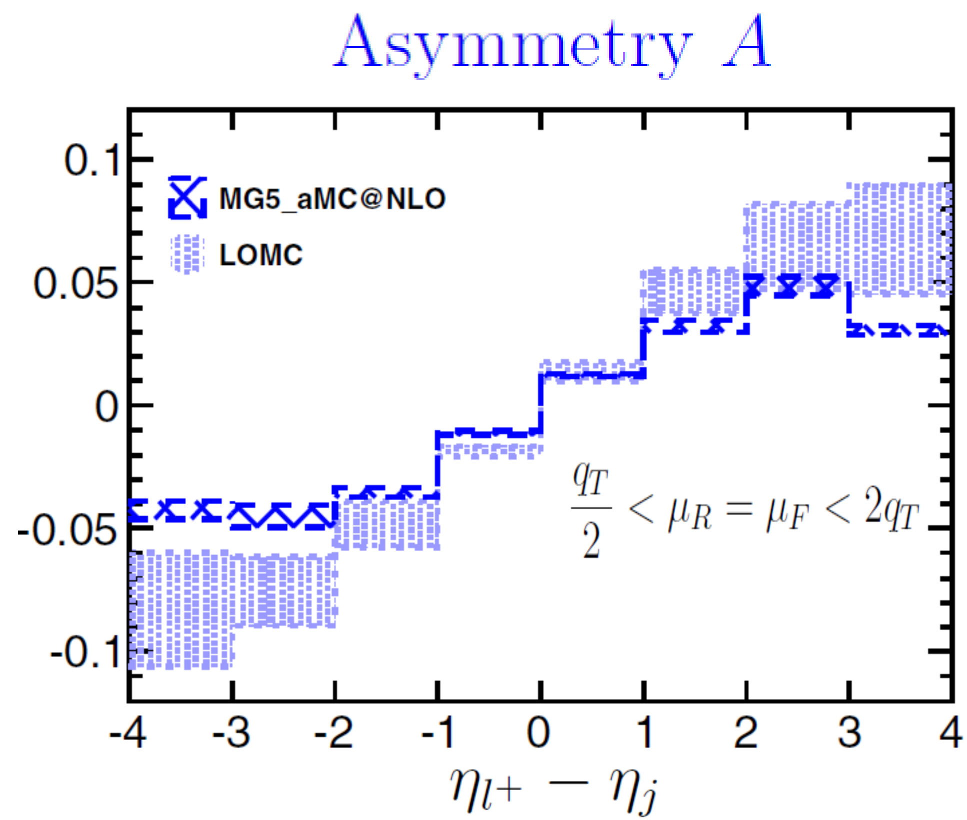
"**HERWIG6**" to simulate parton showering and hadronization,

J. Conway *et al.* (2012)

and "**PGS4**" to simulate detector responses and jet clustering at the LHC.

Result of Detector-level Analysis





Asymmetry can be **as large as 5 % even at detector-level**.

With $20\ \mathrm{fb}^{-1}$ of data, the statistical error of the asymmetry A,
$\delta A = \sqrt{(1 - A^2)/N_{\mathrm{evt}}}$, is 0.11 % , 0.15 %, 0.25 %, 0.45%
for $|\eta_{l+} - \eta_j|$ bins of [1,2], [2,3], [3,4], [4,5].

Summary

- Absorptive part of a scattering amplitude can be measured through T-odd asymmetry of the cross section.
- We have focused on $p\,p \;\rightarrow\; W^+ \;+\; \mathrm{jet}$ process, where the absorptive part is calculable with perturbative QCD, and study the asymmetry of $\vec{p}_{p1} \times \vec{p}_{W^+} \cdot \vec{s}_\perp$.
- We have done detector-level Monte Carlo simulations of $p\,p \;\rightarrow\; W^+(\mu^+, \nu_\mu) + \mathrm{jet}$ process for 8 TeV LHC, and shown that T-odd asymmetry is observable with negligible statistical error with $20\ \mathrm{fb}^{-1}$ of data.