P-odd and Naïve-T-odd asymmetries in W+jet production and top-decay processes

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R.Frederix, K.Hagiwara, T.Yamada & HY, arXiv:1407.1016,

K.Hagiwara, K.Hikasa & HY, Phys.Rev.Lett. 97 (2006) 221802,

K.Hagiwara, K.Mawatari & HY, JHEP 0712 (2010) 041.

ICHEP2014, Valencia, Spain, 7/2-9 (2014)

Outline

1. Parity-odd and naïve-T-odd observables
2. PQCD prediction in hard processes
3. Observability at collider experiments
   [W+jet @LHC]
4. Summary

Naïve-T-reversal, T-reversal and Parity reversal

- In this talk, I consider the following basic transformation which is related with time and parity reversal in quantum theory.

Naïve-T ($\tilde{\mathrm{T}}$, $\mathrm{T_N}$) :

$$(\vec{p},\vec{s}) \to (-\vec{p},-\vec{s}) \qquad \widetilde{\mathsf{T}}|i(\vec{p},\vec{s})\rangle = |\tilde{i}(-\vec{p},-\vec{s})\rangle$$

T :

$$(\vec{p},\vec{s}) \to (-\vec{p},-\vec{s}) \qquad \mathsf{T}|i(\vec{p},\vec{s})\rangle = \langle\tilde{i}(-\vec{p},-\vec{s})|$$

P :

$$(\vec{p},\vec{s}) \to (-\vec{p},\vec{s})$$

- Without spins of particles, naïve-T- and parity-reversal behave as the same.

Naïve-T-odd and Unitarity of S-matrix

De Rujula,Kaplan,De Rafael(71)

- Unitarity of S-matrix $SS^\dagger = 1 \quad S_{fi} = \delta_{fi} + i(2\pi)^4\delta^4(P_f - P_i)T_{fi}$

$$T_{fi} - T^*_{if} = iA_{fi} \quad \text{where } \underline{A_{fi} = \textstyle\sum_n T^*_{nf}T_{ni}(2\pi)^4\delta^4(P_n - P_i)}$$

absorptive part

gives $$|T_{fi}|^2 = |T_{if}|^2 - 2\,\mathrm{Im}(T^*_{if}A_{fi}) + |A_{fi}|^2$$

subtract $|T_{\tilde{f}\tilde{i}}|^2$

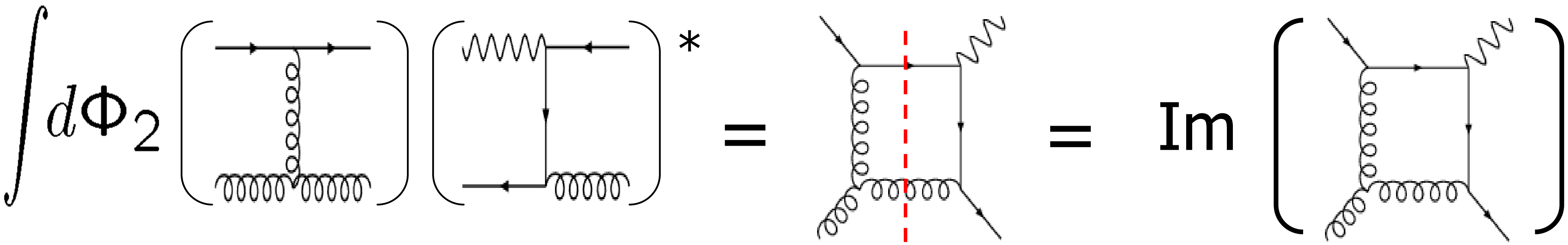
- Naïve-T-odd quantity

$$|T_{fi}|^2 - |T_{\tilde{f}\tilde{i}}|^2 = \underbrace{(|T_{if}|^2 - |T_{\tilde{f}\tilde{i}}|^2)}_{\text{Time-reversal violation}} - 2\,\mathrm{Im}(T^*_{fi}A_{fi}) - |A_{fi}|^2$$

→ emerges from the absorptive parts of the scattering amplitude

Absorptive part of scattering amplitudes

In perturbation theory, the absorptive part of scattering amplitudes can be calculated by the imaginary part of the loop amplitudes.



Cutkosky rule

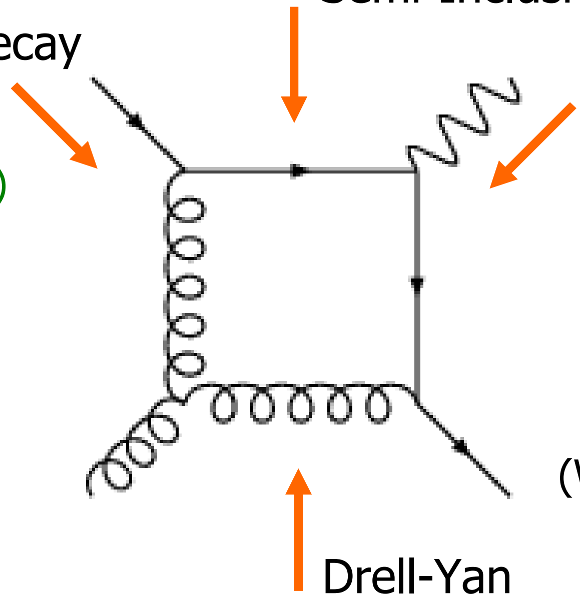
Therefore, measurement of naïve-T-odd quantities can test the perturbative predictions for the imaginary part of scattering amplitudes; i.e. the scattering phase or the strong phase.

pQCD prediction in hard processes

- Naïve-T-odd asymmetries in hard processes have been calculated in $e^+e^- \to$ 3jets, Semi-Inclusive DIS, DY and top decay processes.

Semi-Inclusive DIS
Hagiwara,Hikasa,Kai ('83)
Ahmed,Gerhmann (99)

Top-quark radiative decay
Hagiwara,Mawatari,HY (07)



$e^+e^- \to$ 3-jets
Korner,Kramer,Shcierholz,Fabricius, Schmitt ('80)
Brandenburg,Dixon,Shadmi ('96)

Drell-Yan
(W-jet) Hagiwara,Hikasa,Kai('84), Hagiwara,Hikasa HY('06), Frederix,Hagiwra,Yamada,HY(14)
(Z-jet) Hagiwara,Kuruma,Yamada ('92)
(SLSA) HY('06)

- So far, no experimental measurements for these asymmetries

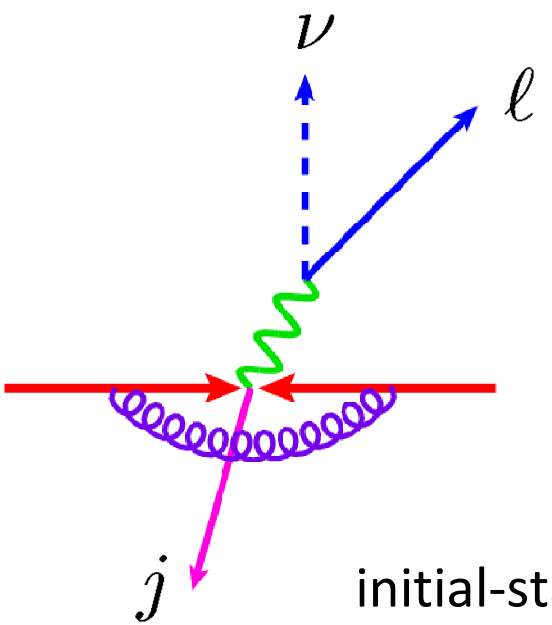
W+jet events, Top radiative decay at the LHC

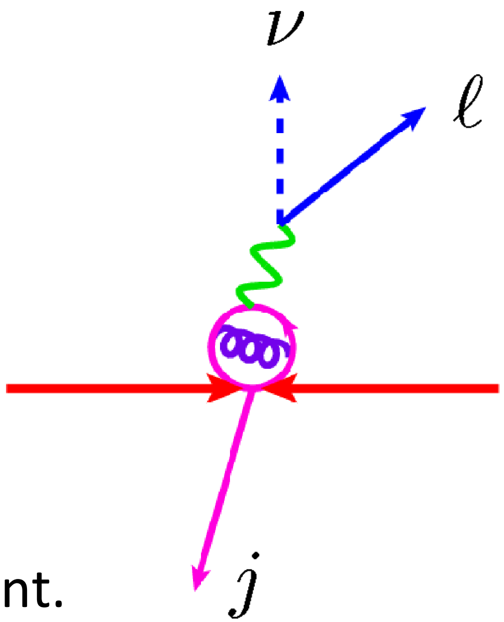
W+jet:

- huge cross section ~ 10nb
- simple event topology
- phases from initial-state int.

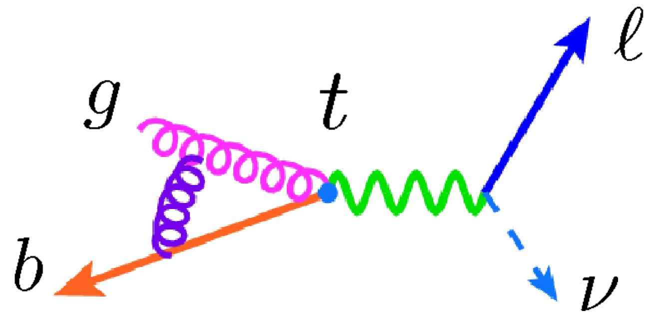
Top-quark radiative decay:

- large cross section ~ 0.2nb
- additional jet radiation
- complicated event topology
- phases from final-state int.





initial-state int.



final-state int.

W+jet : Lepton Angular Distributions

$$\frac{d^4\sigma}{dq_T^2 d\cos\hat{\theta} d\cos\theta d\phi} = F_1(1+\cos^2\theta) + F_2(1-3\cos\theta^2) + F_3 \sin 2\theta \cos\phi + F_4 \sin^2\theta \cos 2\phi + F_5 \cos\theta + F_6 \sin\theta\cos\phi$$ } P-even

$$+ F_7 \sin\theta \sin\phi + F_8 \sin 2\theta \sin\phi + F_9 \sin^2\theta \sin 2\phi$$ } P-odd

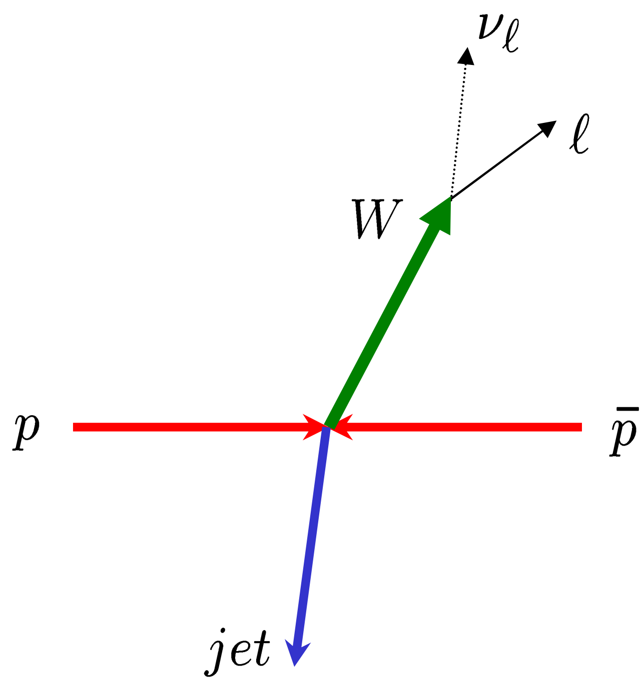
P : $\phi \rightarrow -\phi$

q_T: transverse momentum of W boson

$\cos\hat{\theta}$: scattering angle

θ, ϕ: lepton decay angles in W-rest frame

$F_{1-9}(q_T, \cos\hat{\theta})$: structure functions



P-even : $F_{1\sim6}$

LO (Born): Chaichian et.al.('82)
NLO (one-loop): Mirkes('92)

P-odd : $F_{7\sim9}$

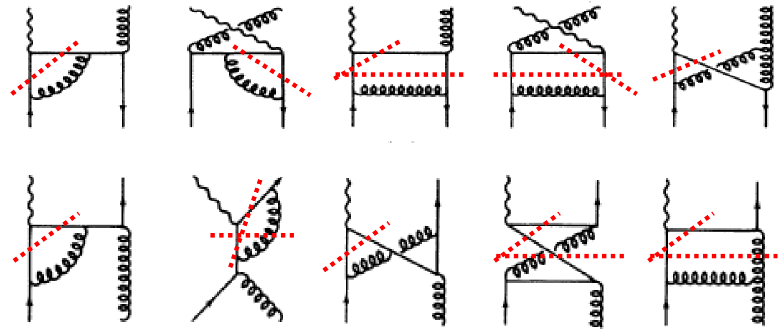
LO (one-loop): Hagiwara,Hikasa,Kai('84)
NLO: not known yet

W+jet : pQCD prediction at one-loop level

Hagiwara,Hikasa,Kai('84)

Annihilation subprocess : $q\bar{q}' \to Wg$

Compton subprocess : $qg \to Wq'$



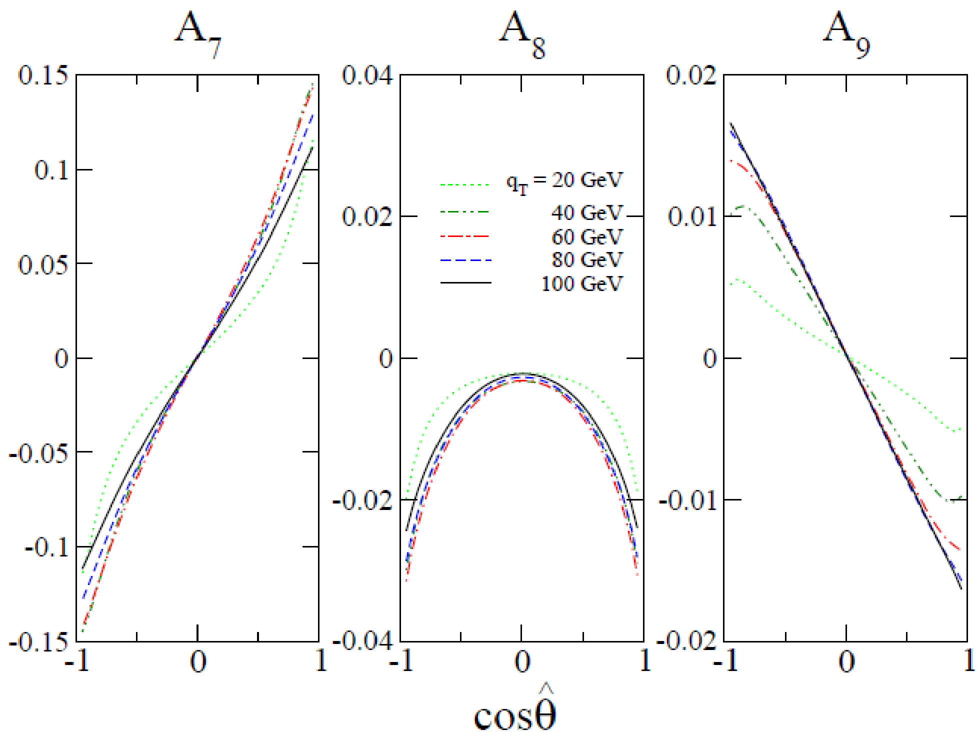
- Partonic asymmetry at the LHC

$$A_i(q_T^2, \cos\hat{\theta}) = F_i \,/\, F_1 \text{ for } i = 7, 8, 9$$

$$pp,\ \sqrt{S} = 8 \text{ TeV} \quad \text{with CTEQ6M}$$

in Collins-Soper frame

A_7 ~ 10-15%,
A_8 ~ a few %,
A_9 ~ a few %



W+jet : Measurement at the Tevatron and LHC

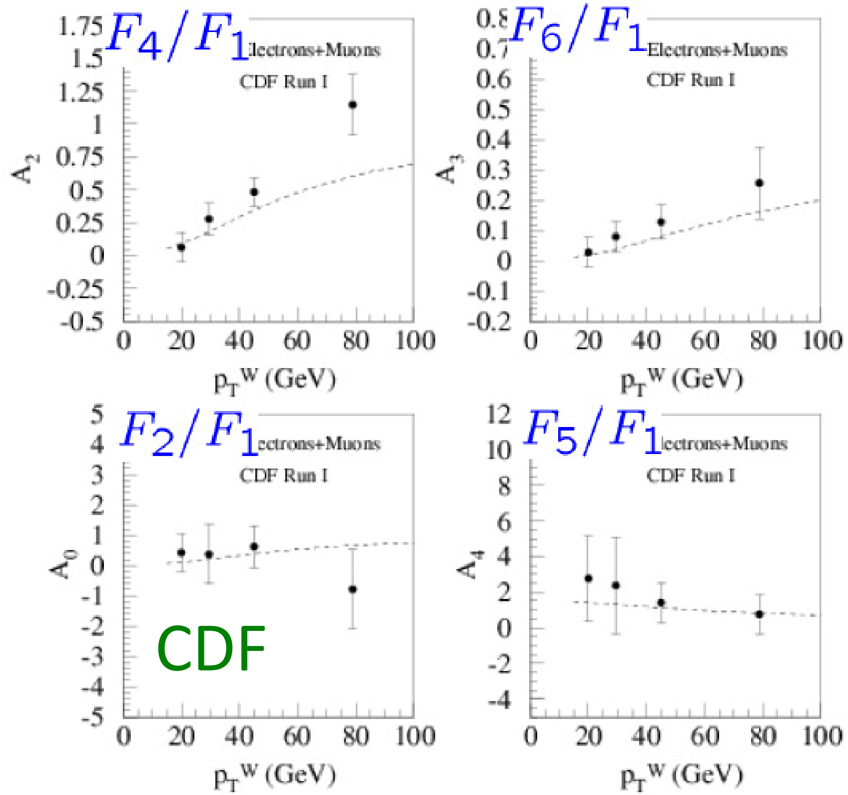
- In W+jet events, some of P-even distributions have been measured by CDF in Run-I.

→ agree with pQCD (NLO) within errors.

- At the LHC, only polar angular distributions has been measured, so far.

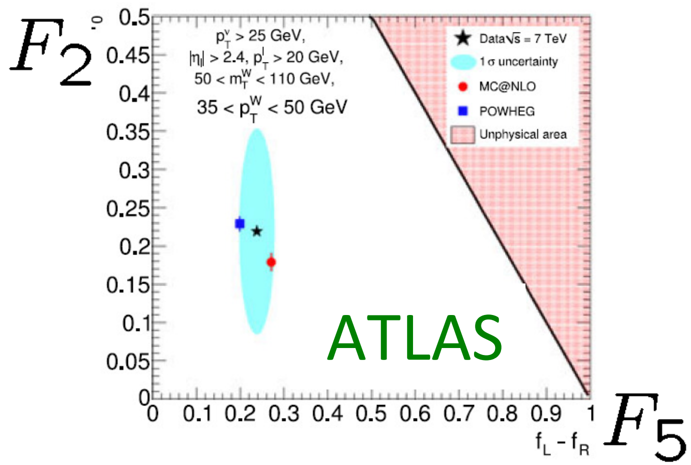
→ only helicity fraction of W-boson.
no azimuthal angle,
no interference of different helicity states.

- P-odd distributions have not been measured at all.



Frederix,Hagiwara,Yamada,HY(14)

- The aim of our study is to revisit the P-odd distribution in W+jet events at the LHC, and demonstrate its observability by using the NLO MC generator and fast detector simulation.



Simulation study beyond the Born level

Frederix,Hagiwara,Yamada,HY(14)

- (NLO) Event Generator which handle the parity-odd distributions

MG5_aMC@NLO (automatic, multipurpose) — One-loop level ME, NLO matching with PS (NLO for P-even, LO for P-odd)

LO MC (handmade, W+jet only) — LO for all $F_{1\text{-}9}$, LO matching with PS

P-even: $$F_{1-6} \propto \alpha_s \sigma_0 + \alpha_s^2 \sigma_1 + \cdots$$

P-odd: $$F_{7-9} \propto \alpha_s^2 \Delta\sigma_0 + \cdots$$

Born one-loop

→ HERWIG/PYTHIA + PGS/Delphes

to study QCD ISR/FSR and detector resolution effects.

Event selection and extraction of the P-odd term

- Huge W(→lν)+jet cross section : O(1) nb

- Selection cuts:

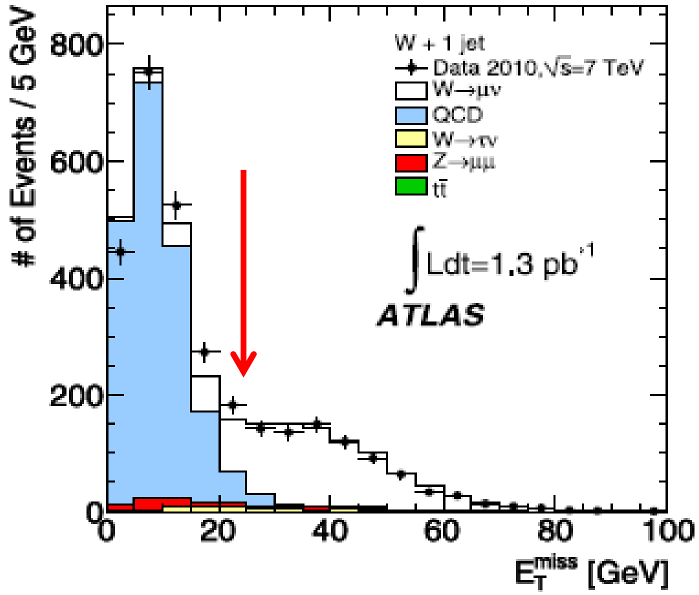
$p_T^\mu > 25$ GeV, $|\eta_\mu| < 2.5$: 0.94 nb

$\not{E}_T > 25$ GeV : 0.75 nb

$Q_T > 30$ GeV : 0.29 nb

$M_T^W > 60$ GeV : 0.29 nb

$p_T^j > 30$ GeV, $|\eta_j| < 5$: 0.13 nb



$0.13 \text{ nb} \times 20 \text{ fb}^{-1} = 2.6 \times 10^6$ events

- Background : QCD, $Z \to \mu^+\mu^-$, $W^+ \to \tau^+\nu_\tau$

< 10% level

- Extraction of the **F₇** distribution

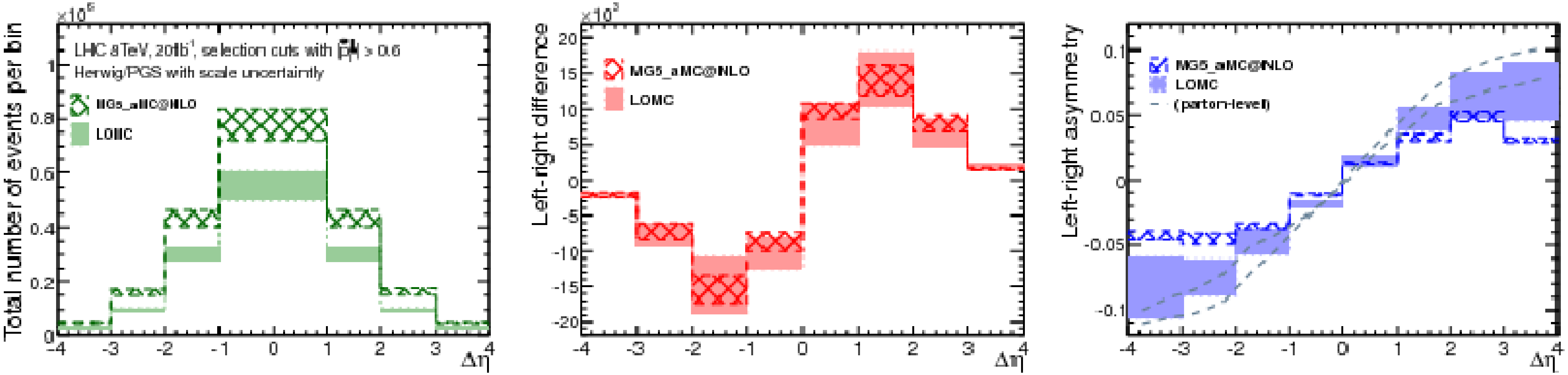
$\sin\theta \sin\phi = p_\ell^\perp/(m_W/2)$ lepton momentum component perpendicular to the scattering plane

→ left-right asymmetry wrt. scatt. plane

$\cos\hat{\theta}$ suffered from the two-fold ambiguity.
Instead, we propose to use $\Delta\eta = \eta_\ell - \eta_{jet}$

Results : MG5_aMC@NLO vs. LOMC

- $\Delta\eta$ (=η_l-η_j) distributions [detector sim. by using HERWIG/PGS]



$\sigma(p_\ell^\perp > 0) + \sigma(p_\ell^\perp < 0)$ $\sigma(p_\ell^\perp > 0) - \sigma(p_\ell^\perp < 0)$ Asymmetry

- P-odd cross-section unchanged → consistent with the order of calculation.
- Reduction of the asymmetry in MG5_aMC@NLO,
  due to the K-factor (~ 1.5 - 2) in the denominator (total cross-section).
- Scale uncertainty is largely reduced in MG5_aMC@NLO (NLO matching with PS!)
- (Small) detector smearing by misidentifying hard jet from ISR/FSR jets.

Prospects for the naïve-T-odd asymmetries

- At the LHC,
  - **W plus 1-jet event** is promising !

    one-loop analytic calc. is known, experimentally simple.
  - **Top-quark radiative decay**:

    one-loop analytic calc. also known,
    experimentally challenging (boosted top, subjet structure,,,)
  - **W plus 2-jets / Z / γ ,,,** :

    analytic calc. not known, but now we have MG5_aMC@NLO !!
    measurements at the 14TeV run will be interesting.
- At the ILC,
  - **Top-quark radiative decay** can be measured in a clean environment.
  - **Z → 3-jets decay** handedness may be measured, e.g. at the Giga-Z factory.

Summary

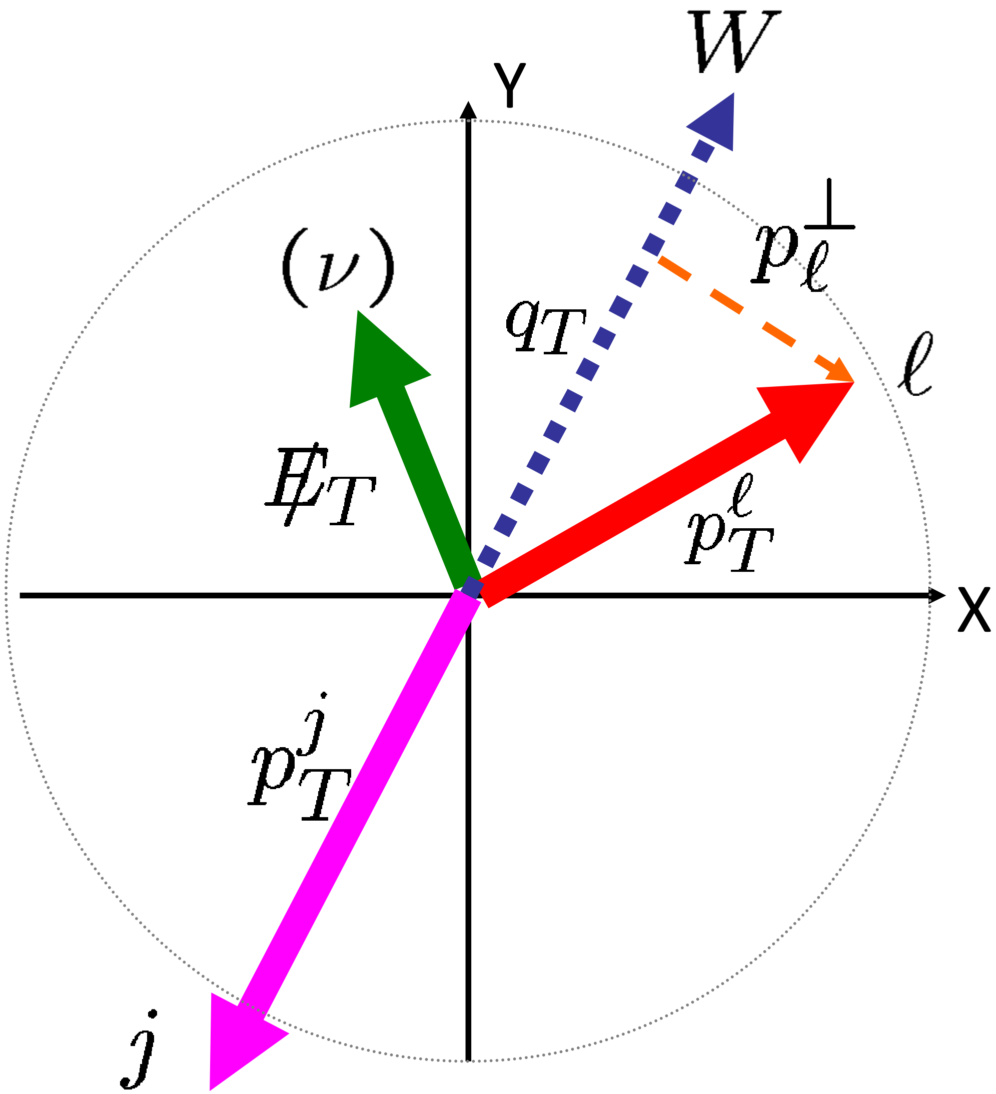
- Naïve-T-odd asymmetry emerges from the absorptive part of scattering amplitudes. In hard processes, it can be predicted by perturbation calculation, and comparison with experimental measurement would be an interesting test.
- We study the naïve-T-odd (P-odd) asymmetry in W+jet production at the LHC, using the NLO-EG MG5_aMC@NLO: QCD PS and detector effects for the measurement are estimated, and theoretical uncertainties by scale variation and due to the lack of NLO P-odd distributions are argued.
- If observed, it will be a first confirmation of the imaginary part of scattering amplitudes at the one-loop level.

Measurement at collider experiments

- Events display in the transverse plane

$(p^y)_l$ is invariant under the Lorentz Boost from lab. frame to the W-rest frame

$$p_\ell^\perp = p_y^\ell(W\text{rest}-\text{frame}) = \frac{m_W}{2}\sin\theta\sin\phi$$



Missing E_T resolution may be crucial for the accuracy of $(p^l)_y$ measurement

One-loop calculation

Origin of the imaginary part in the loop (Feynman) integrals;

$$\begin{cases} \log(x - i\epsilon) \to -i\pi\,\theta(-x) \\ \mathrm{Li}_2(x - i\epsilon) \to i\pi \ln(x)\,\theta(x-1) \end{cases}$$

$$\frac{1}{\Delta - i\epsilon} \to \mathrm{P}\frac{1}{\Delta} + i\pi\,\delta(\Delta)$$

in the integrand

Methods of calculation;

1. Analytic calculation by standard Feynman parameter integrals
2. Express by loop scalar functions and use the fortran code "FF"

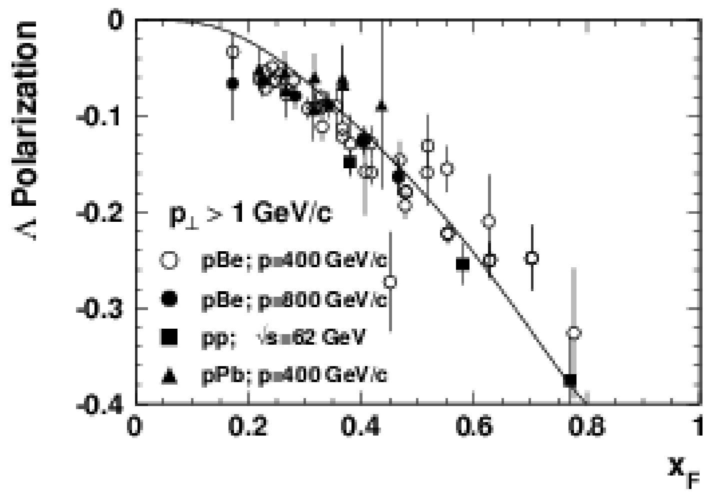
Passarino,Veltman ('79), Oldenborgh ('91)

- IR divergences are regulated by using gluon mass scheme or DR.
- Check of the results by the gauge invariance

$\tilde{T}$-odd asymmetry in hadron physics

(P-even, pure QCD effect)

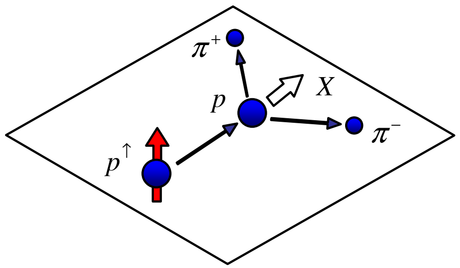
- Large $\tilde{T}$-odd asymmetries have been observed in hadron spin physics



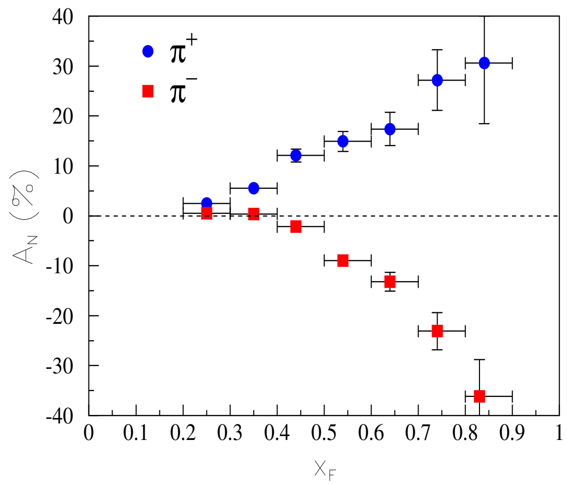
1. Λ-polarization $\sim \langle \vec{p}_p \times \vec{p}_\Lambda \cdot \vec{s}_\Lambda \rangle$
   in $p + N \to \Lambda^\uparrow + X$

2. A_N in $p + p^\uparrow \to \pi + X$

$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \sim \langle \vec{p}_p \times \vec{s}_p \cdot \vec{p}_\pi \rangle$$



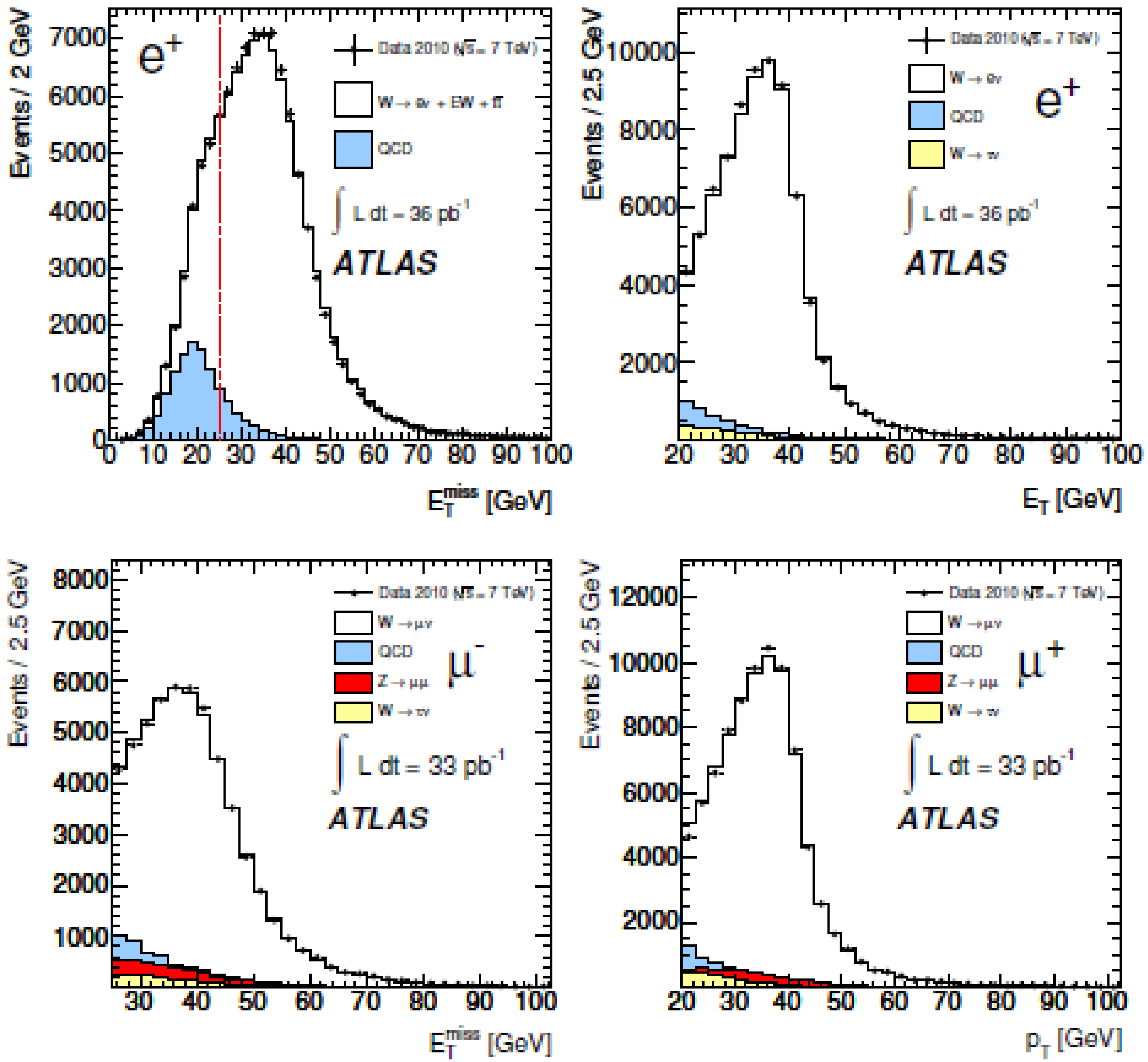
FNAL-E704:



- STSA needs chirality-flip amplitude, in addition to the complex phase
  - Non-perturbative QCD effects inside nucleon
    1. Transverse-momentum-dependent PDF
    2. Higher-twist effects

$W \to \ell\nu$ selection

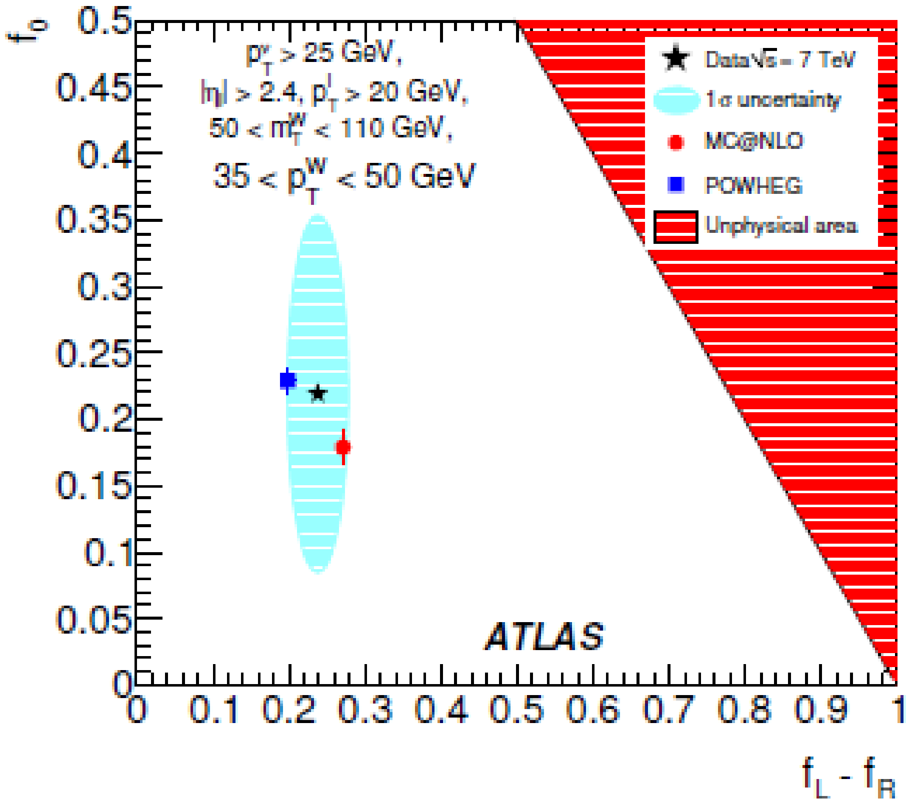
- Single lepton triggers with high efficiency
- $p_{T,l} > 20\ GeV$
  $|\eta_e| < 2.47$, $|\eta_\mu| < 2.4$
  (elec. excl. calo crack)
  isolated leptons
  $E_{\mathrm{T}}^{\mathrm{miss}} > 25\ GeV$
  $m_T > 40\ GeV$
- QCD from data fitting E_T^{miss} (e) and studying control regions in $iso - E_T^{miss}$ plane (μ)
- $131 - 140\,K$ candidates with $7 - 9\,\%$ background

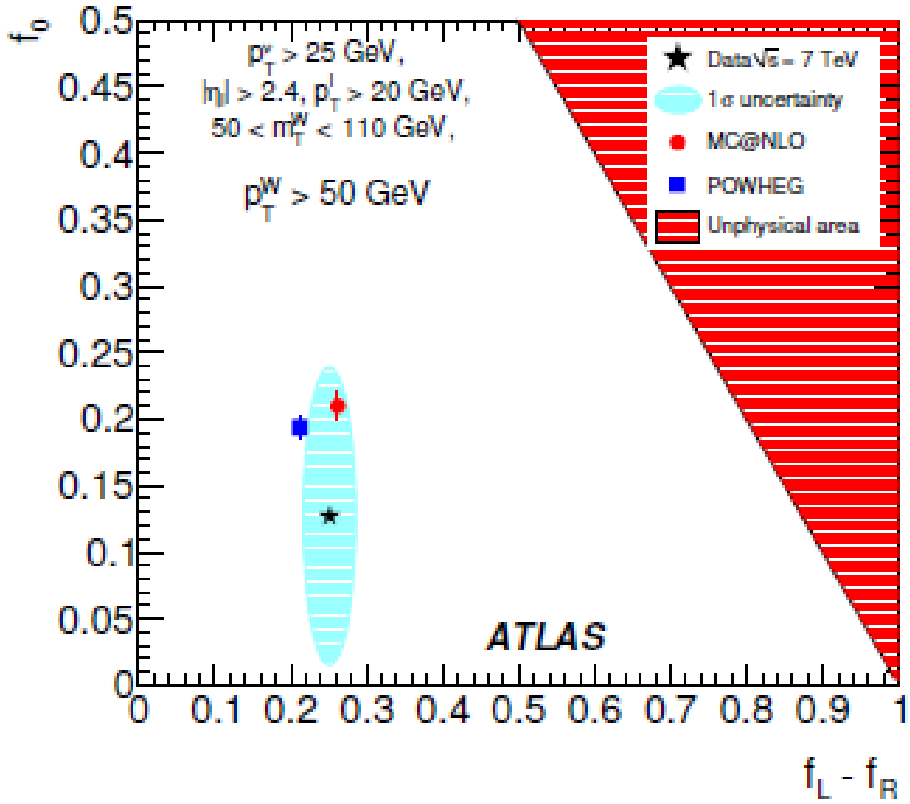


W polarization at high p_T

Eur. Phys. J. C72 (2012) 2001

- ⋆ Helicity fractions, f_0 and $f_L - f_R$, measured from angular distribution in transverse plane: $cos\theta_{2D} = \vec{p_T^{\ell *}} \cdot \vec{p_T^W} \ / \ |\vec{p_T^{\ell *}}||\vec{p_T^W}|$
  - ✓ Measurements done for $35 < p_T^W < 50\ GeV$ and $p_T^W > 50\ GeV$ regions





- ⋆ $f_L - f_R$ measured with 12–14% syst. uncertainty, dominated by hadronic recoil scale uncertainty (statistical uncertainty in 6–8% range)
- ⋆ Results compared to NLO QCD predictions from MC@NLO, POWHEG MCs

Parity-odd asymmetries

$A_i(q_T^2, \cos\widehat{\theta}) = F_i \,/\, F_1$ for $i = 7, 8, 9$

Tevatron

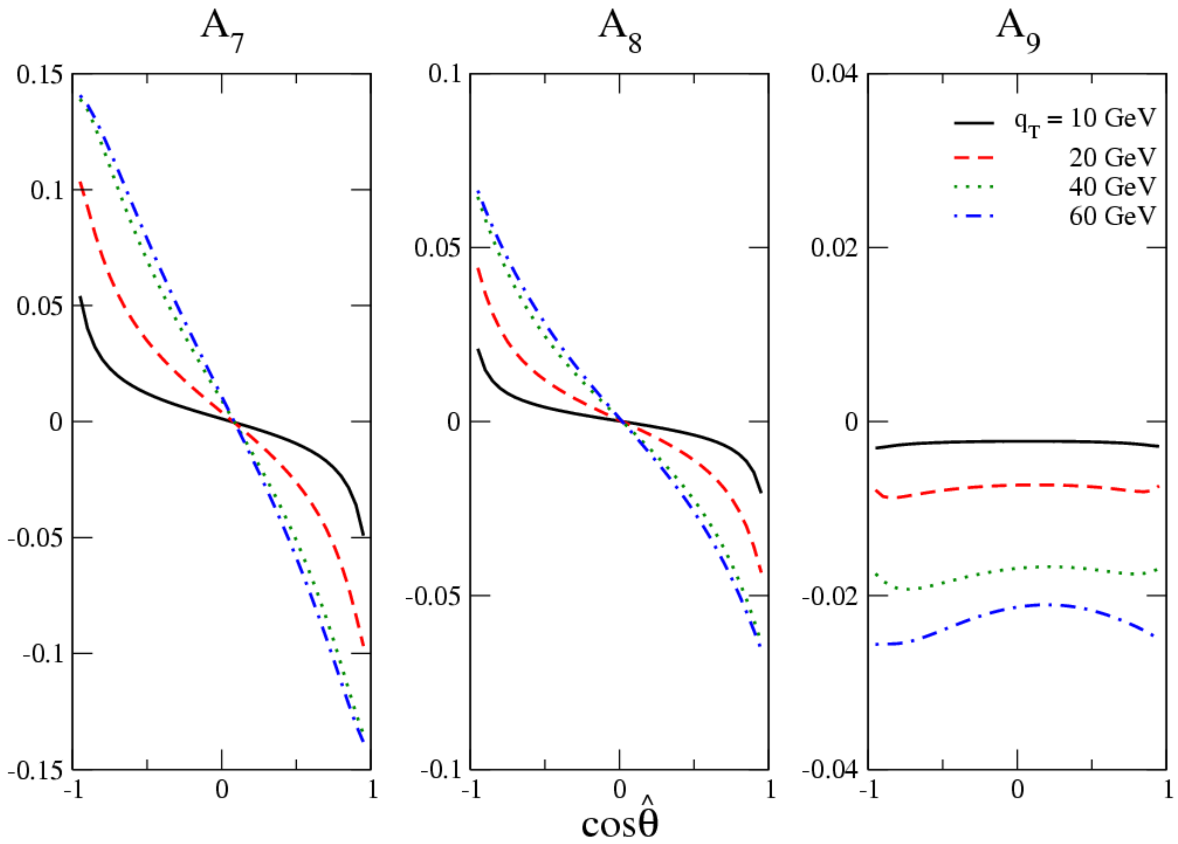
$p\bar{p}, \ \sqrt{S} = 1.96$ TeV

with CTEQ6M

A_7 ~ 5-15%,

A_8 ~ a few to 5%,

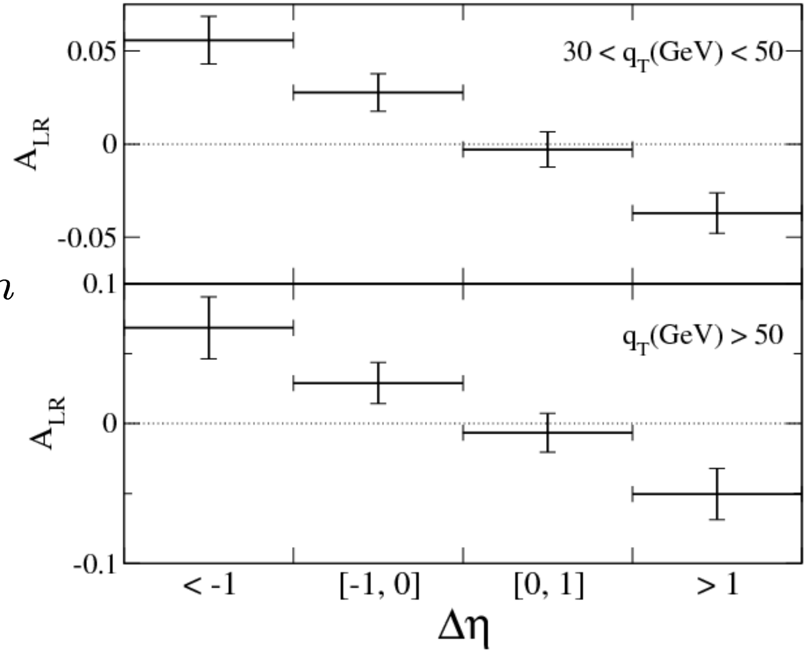
A_9 ~ a few %



$\sin\theta \sin\phi$ $\sin 2\theta \sin\phi$ $\sin^2\theta \sin 2\phi$

Measurement at Tevatron

Hagiwara,Hikasa,HY (06)



- Left-right asymmetry $\longleftrightarrow A_7$

$$A_{LR}(\Delta\eta, q_T) = [N(p_y^\ell > 0) - N(p_y^\ell < 0)]/N_{sum}$$

~5% at large Δη

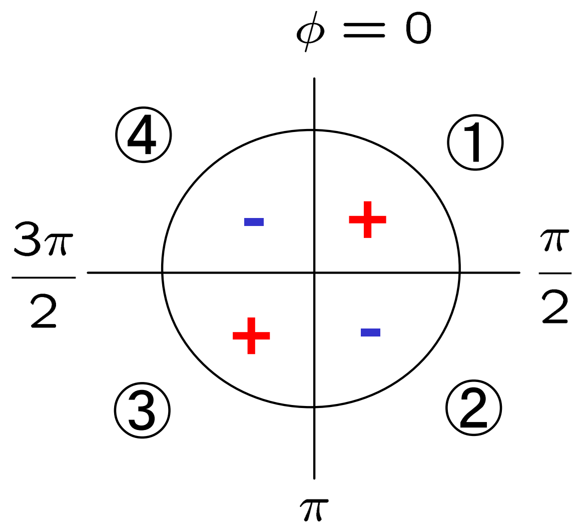
more than 5σ deviation
from zero-asymmetry is expected

- sign(sin2φ) asymmetry $\longleftrightarrow A_9$

$$A_Q = [① - ② + ③ - ④]/N_{sum}$$

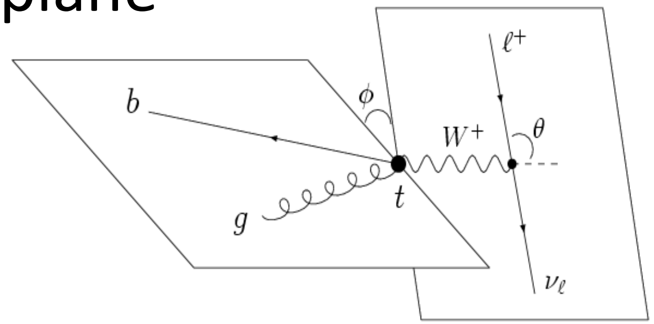
$$\sim -0.9\% \pm 0.5 \ (2\sigma)$$

(combining all Δη and q_T)

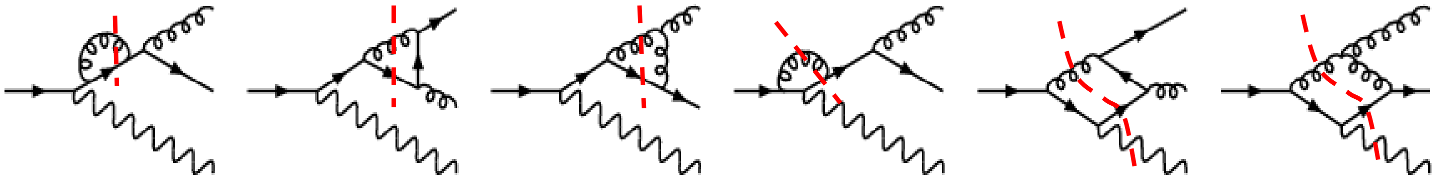


Top-quark radiative decay at one-loop level

- Extra radiation is required to define the decay plane



- One-loop diagrams for the absorptive part:



- Lepton angular distributions:

$$\frac{d\Gamma}{dz_1 dz_2\, d\cos\theta\, d\phi} = K \sum_{\lambda,\lambda'} H_{\lambda\lambda'}(z_1, z_2)\, L_{\lambda\lambda'}(\theta,\phi)$$

$$= K\Big[F_1(1+\cos^2\theta) + F_2(1-3\cos^2\theta) + F_3 \sin 2\theta \cos\phi + F_4 \sin^2\theta \cos 2\phi$$

$$+ F_5 \cos\theta + F_6 \sin\theta\cos\phi + \boxed{F_7 \sin\theta \sin\phi + F_8 \sin 2\theta \sin\phi + F_9 \sin^2\theta \sin 2\phi}$$

Hagiwara,Mawatari,HY(07)