The electroweak contribution to top pair production: cross-sections and asymmetries





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## Hadronic top quark pair production is a "QCD process"  $\prod_{\alpha} d_{\alpha}$ In African B a COD process



lar<br>1  $\overline{\mathbf{LO}}$   $\mathcal{O}(\alpha_s^2)$ LO  $\binom{2}{s}$  $\bigcap_{\alpha=0}^{\infty}$ of qq¯ → γ, Z → tt

other quark species, after convolution with the parton with the parton distributions and summation, are symmetric  $\alpha$ 

peenakker et al. '91, Mangano, Nason, Ridolfi '92  $NLO$   $\mathcal{O}(\alpha_s^3)$ : *Nason et al. '89, Frixione et al. '95*  $LU$   $\mathcal{O}(\alpha_s^3)$ : Nason et al. '89, thus do not contribute the AF B) as  $F$ rtus to  $P$  and  $\frac{1}{2}$  → the set  $q$ Ridolfi '92  $\text{F}$ isione et al.  $\text{F}$ <sup>25</sup>  $P\,r$  is pairs in primary interactions originates originates original the strong interaction, interaction, i.e.,  $\frac{1}{2}$ 

 $\overline{\phantom{a}}$ 

q

g

### t  $\mathcal{L}$  Figure 49  $\ell$  born diagrams  $\mathcal{L}$  $\sum_{i=1}^{n}$ *Baernreuther, Czakon, Mitov '12*

<sup>s</sup>D<sup>0</sup> + α<sup>3</sup>

<sup>s</sup>D<sup>1</sup> <sup>+</sup> ··· <sup>=</sup>

D<sup>0</sup>

<sup>t</sup> <sup>t</sup>

α2

 $\mathcal{A}$ 

 $\mathcal{O}_{\mathcal{A}}$  B, starts at  $\mathcal{A}_{\mathcal{A}}$  B, starts at O(a3)  $\mathcal{A}_{\mathcal{A}}$ 

D

 $\ddot{ }$ 

 $S = \frac{S}{\text{Error}}$ , the particle substitution, substituti  $\mathcal{L}(\mathcal{H})=\mathcal{L}(\mathcal{H})$  and some is completely negligible). The squared terms  $\mathcal{H}=\mathcal{H}(\mathcal{H})$ 2 and Cho, I crogue of al. To and <u>many</u> others complete NNLO  $q\bar{q} \to t\bar{t}$ : beyond NLO: Beneke, Falgari, Schwinn  $\bar{t}$  : **beyond NLO** : Beneke, Falgari, Schwinn '09 Baernreuther, Czakon, Mitov '12 Czakon, Mitov, Sterman '09, Kidonakis' 10 *Ahrens, Ferroglia et al. '10 and many others* 

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 $\overline{\phantom{a}}$ 

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### <u>The EW contribution to top pair production</u>  $\mathbf{F}$ , whereas only some parts of  $\mathbf{F}$  are currently known  $\mathbf{F}$ other quark species, after convolution with the parton with the parton distributions and summation, are symmetric  $\alpha$ The EW contribution to top pair production Writing the denominator and the denominator and the definition of  $\mathcal{L}$  (for either of the definitions (1) and (2))

 $\sum_{i=1}^{n}$ - Cross section, charge - Cross section, charge asymmetry

<sup>s</sup>D<sup>1</sup> <sup>+</sup> ··· <sup>=</sup>

D<sup>0</sup>

 $E_{\text{IIC}}$ , to the parties  $\mathbf{L}$  $[**e**]$  $\overline{z}$ - LHC, Tevatron <sup>s</sup>N<sup>1</sup> + α<sup>4</sup>  $\frac{1}{\sqrt{1-\frac{1$ 

 $-a\overline{a} \rightarrow t\overline{t}$ ,  $a\overline{a} \rightarrow t\overline{t}$  $g \rightarrow u$ ,  $qq \rightarrow u$  $\iota$  $\bar{t}$   $\alpha \bar{\alpha} \rightarrow t \bar{t}$  $-gg \to t\bar t \; , \; \; q\bar q \to t\bar t \; ,$  $\bar{t}$ 

- $C_{\text{meas}}$  sootian above equipmentum  $\Gamma$ : fferential and integrated quantities  $\mathcal{S}$ C asymmetry  $\mathcal{S}$  - Differential and integration - Differential and integrated quantities yield contributions to AF B which are numerically not important [5].
	- LHC, Tevatron  $\mathcal{O}(\alpha^2)$ ,  $\mathcal{O}(\alpha_s^2 \alpha)$ , ...  $(\alpha_s, \alpha_s)$ , ...  $\mathcal{O}(u)$ ,  $\mathcal{O}(u_s u)$ , ...  $\mathcal{L}(\alpha)$ , it radius.

N<sup>1</sup>  $\overline{\phantom{a}}$  -  $\overline{\phantom{a}}$ - QED, Weak  $\alpha$  purely-electroweak and parton control co involving photons from the weak contributions with Z bosons. In the QED sector we obtain the  $\rightarrow t\bar{t}$  - QED, Weak

#### Weak corrections to the cross section yon contributions to the Cross Section ghosts need to be considered to be considered to cancel unphysical degrees of  $\sigma$  $W_{\alpha}$  and  $W_{\alpha}$  and contribute the ghosts do not contribute. In addition, given that we neglect that we n the masses of the *u*,*d*, *c*,*s* quarks the unphysical fields " and ! only contribute in the  $\mathcal{L}$  vertex corrections to the final gluon–top–antitop vertex. The renormalization is done in the renormalization in  $\mathcal{L}$ where  $\mathcal{A}$  is the strong constant and " the strong constant and " the velocity of the the process centre-

*Beenakker et al '94, Kuhn, Scharf, Uwer '06, Bernreuther, Fuecker, Si '06*  $\mathcal{O}(\alpha_s^2)$ <br>Moretti Nolten Ross '06 *Moretti, Nolten, Ross '06,* renormalized perturbation theory. That is the bare Lagrangian *L* is rewritten in terms <sup>=</sup> *L* (\$*R*,*AR*,*mR*,*gR*) +*Lct*(\$*R*,*AR*,*mR*,*gR*). (II.1) *Si '06* (*s* denotes the partonic centre-of-mass energy squared). The cosine of the scattering  $\alpha$ 2 Calculation Calculation Calculation<br>
2 Calculation<br>
3 Calculation<br>
3 Calculation<br>
3 Calculation<br>
3 C  $\overline{\phantom{a}}$  pairs in pairs in pairs in pairs in pairs in polynomials originates, via the strong interaction,  $\overline{\phantom{a}}$  $\overline{\phantom{a}}$  pairs in pairs in positions originates, via the strong interaction, via the strong interaction,  $\overline{\phantom{a}}$ 

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\boxed{\mathcal{O}(\alpha_s^2 \alpha)}
$$





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gg\to t\bar t
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2



## Weak corrections to the cross section





'NS −27 *Ahrens, Ferroglia et al.'11*

165 170 175 180

From  $s$  cale variation and PDFs are higger than  $FW<sub>0</sub>$ The first set of extraction with  $\frac{1}{2}$  is the engagement of  $\frac{1}{2}$ From  $S^2$  Results from the total and PDFs are higger The first set of the first set of the perturbative uncertainties and variations, the variation of the variation Errors from scale variation and PDFs are bigger than EW corrections

-3

## $M_{\text{th}}$   $\bigoplus_{i=1}^{M_{\text{th}}} \text{fferential distribution}$

╲



Differential distributions ! **-./%0%1% -./%0%1%2"3 45("6\*7\*+#(8%(",96),: 45("6\*7\*+#(8%(",96),:**  $\sum_{i=1}^{n}$ ! **/'75#("<%)'%-./%0%=>% /'75#("<%)'%-./%0%=>%2"3 &'(("&)\*'+,%?"&'7"% &'(("&)\*'+,%?"&'7"%**  $\text{trial}$  digtrikations<sup>1000</sup> 2000  $2000$ <br> $m_{\text{tt}}$  [GeV] n<br>0.5<br>**NNLO**<br>2017 1

 $\cdot$ .







300

1 1.2  $\cdot$ .

Theory/Da<sup>®</sup>





### QED corrections to the cross section in different production subprocesses, without and with cuts.  $\epsilon$  in different production subprocesses, with cuts. With cuts. We are the with cuts. We are the with cuts.



 $\sim$  0.0  $\mu$ 

Tevatron LHC 14 TeV

 $T_{\rm eff}$  is  $T_{\rm eff}$  integrated hadronic cross section for the term integrated hadronic cross section for the t  $\sim$  1%  $\sim$  $\sim$  -2%  $\sim$  1%  $\approx$  1%

 $\mathcal{L}_{\mathcal{A}}$ 

Born correction Born correction

¯ production at the LHC, at NLO QED

corrections (right), for the gg and qq parton channel at the LHC. The effect of the *Hollik, Kollar '07*NLO CORRECTIONS IN THE DOMINANT GENERAL CORRECTIONS IN THE DOMINANT GENERAL CONTRACT GENERAL CONTRACT GENERAL CO

.HC comes from  $q\gamma \to t\bar{t}$ ,  $0.4$ OED) has photon PDF  $s \circ \sqrt{2D}$ , nos proton 1 D1. √ channel, the NLO contributions for the NLO contributions for an intervention are negative over the whole pT an<br>The Williams for the whole pT annihilation are negative over the whole pT and the whole pT and the whole pT an The dominant contribution at LHC comes from  $q\gamma$  - $\begin{bmatrix} \text{I} & \text{II} & \text{II} & \text{III} & \text{III} & \text{III} & \text{III} & \text{III} \\ \text{II} & \text{II} & \text{II} & \text{II} & \text{II} & \text{II} \end{bmatrix}$  $\sqrt{\left(\frac{1}{2}\right)^{2} \left(1-\frac{1}{2}\right)^{2}}$ The dominant contribution at LHC comes from  $g\gamma \to t\bar{t}$ , only one set of PDFs (MRST2004QED) has photon PDF.

#### Electroweak corrections to the cross section ¯ [1, 2] and to gluon fusion *gg* → *tt* ¯ [3–5], extending earlier work of1 [6], and the photonic corrections to the correct  $\Gamma$ leatrevisely served interactions and weak-interactions which we produo weak contections to the cross section 2 Calculational basis At leading order the production of tt **Electrowe**  $P(\mathbf{A})$  $\sum_{i=1}^{n}$ the cross sec  $\sim$  0.000 0.000  $\mu$ <sup>−</sup> |M|<sup>2</sup>(m<sup>2</sup> *qq*¯ → *tt* ¯ [1, 2] and to gluon fusion *gg* → *tt*  $\overline{3}$  (3–3), extending earlier work of  $16$ , and the  $16$ Electroweak corrections to the cross section *<sup>s</sup>*!) contributions of *W*,*Z* and Higgs boson exchange to quark-antiquark annihilation In this added to the cross section Electroweak corrections to the cross section rak corrections to the cross section Liecuro

that for the pair-invariant mass distribution and for the top-quark helicity asymmetry, which

¯ events, these

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\frac{\alpha_s^2 \alpha \alpha^2 |q\bar{q} \to t\bar{t}}{\alpha_s \alpha \alpha^2 |q\bar{q} \to t\bar{t} g g \to t\bar{t}}
$$
\n
$$
\frac{\alpha_s \alpha \alpha^2 |b\bar{b} \to t\bar{t}}{\alpha_s \alpha^2 \alpha_s^2 \alpha |g q(\bar{q}) \to t\bar{t} q(\bar{q})} \qquad \text{Bernreuther, Si '10}
$$

photonic corrections to hadronic top-quark pair production [7].

0.96 0.98 1  $\begin{bmatrix} 1.02 \end{bmatrix}$ 1.04 500 1000 1500 2000  $M_{tt}$  (GeV) 0.96 0.98 1 1.02 1.04 100 200 300 400 500  $p_T$  (GeV) *gq* (*q*¯) → *ttq*¯ (*q*¯) (*q* = *u*,*d*,*s*, *c*,*b*). (2)  $\begin{bmatrix} 1.02 \end{bmatrix}$ contain also be an objective in its particular in its particular in its particular in its particular in its par<br>Historic search (1) is a leading-order (LO) is a leading-order (LO) is a leading-order (LO) is a leading-order process in this scheme, while (2), *q* = *b*, is a next-to-leading order (NLO) QCD correction *<sup>s</sup>*!) corrections to the processes (2) were calculated already in [3] which  $\begin{bmatrix} 0.96 \\ 1 \end{bmatrix}$   $\begin{bmatrix} 0.96 \\ 0.96 \end{bmatrix}$ ¯ cross section – the contributions i) and ii) are insignificant. However, here we show that for the pair-invariant mass distribution and for the top-quark helicity asymmetry, which  $^{\rm 4.04}$ contain also **b** and **b** and **b** and **b** and **contain in its partonic sea.** Thus the reaction (1) is a leading-order (LO) is a process in the scheme, which is a next-to-leading order ( $\frac{1}{2}$ ,  $\frac{1}{2}$ ,  $\frac{1}{2}$  $\begin{array}{c} \begin{array}{c} \end{array} \end{array}$ *<sup>s</sup>*!) corrections to the processes (2) were calculated already in [3] which we include here for completeness. For several top quark observables – in particular, for  $\begin{picture}(180,170) \put(110,170){\line(1,0){10}} \put(110,170){\line(1,0){10}} \put(110,170){\line(1,0){10}} \put(110,170){\line(1,0){10}} \put(110,170){\line(1,0){10}} \put(110,170){\line(1,0){10}} \put(110,170){\line(1,0){10}} \put(110,170){\line(1,0){10}} \put(110,170){\line(1,0){10}} \put(110,170){\line(1,0){$ that for the pair-invariant mass distribution and for the top-quark helicity asymmetry, which is not the top-quark helicity asymmetry, which is not the top-quark helicity asymmetry, which is not the top-quark helicity asy are among the key of 1900 of tool-kit for search of tool-kit for the tool-kit for search of tool-kit for the t<br>M. (GeV) of the tool-kit for the tool-kit f sN1 + α4<br>SN1 + α4<br>SN1 + α4  $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$ <sup>s</sup>D<sup>0</sup> + α<sup>3</sup>  $\begin{bmatrix} 1 \\ 1.02 \end{bmatrix}$  $\frac{1}{2}$ The term of  $\begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix}$  have been calculated for  $\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ [5], whereas only some parts of N<sup>2</sup> are currently known [19, 20]. The inclusion of the N1D1/D<sup>0</sup> term without N<sup>2</sup> would hence be incomplete, and we have chosen to use only the lowest order cross  $\begin{array}{c} \hline \text{3.96} \end{array}$  $\begin{bmatrix} 0.96 \end{bmatrix}$ Rewriting N and D include the EW contributions yields the following the following expression for the following <br>Reversion for the following expression for the following expression for the following expression for the follo  $W_{\rm{H}}$  the denominator and the denominator of  $\overline{W}$ in powers of as we obtain  $\overline{N}$  $\bigwedge$  $\frac{1}{2}$  $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 &$ D<sup>0</sup>  $\frac{1}{\sqrt{N+1}}$  $\begin{picture}(180,10) \put(0,0){\line(1,0){10}} \put(10,0){\line(1,0){10}} \put(10,0){\line($  $\begin{picture}(180,170) \put(150,170){\line(1,0){10}} \put(150,170){\line(1,0){10}} \put(150,170){\line(1,0){10}} \put(150,170){\line(1,0){10}} \put(150,170){\line(1,0){10}} \put(150,170){\line(1,0){10}} \put(150,170){\line(1,0){10}} \put(150,170){\line(1,0){10}} \put(150,170){\line(1,0){10}} \put(150,170){\line(1,0){$  $\begin{bmatrix} 0.96 \\ 0.96 \end{bmatrix}$ الصند الساحد الساحد الساحد الساحد المساحد المساحد التي تحت التي تحت التي تحت التي تحت التي تحت التي تحت التي ت<br>2001 - 2001 - 2001 - 2001 - 2001 - 2001 - 2001 - 2001 - 2001 - 2001 - 2001 - 2001 - 2001 - 2001 - 2001 - 2002 s) the numerator, as designed in the numerator, as a designed in the numerator, as  $\frac{1}{200}$ . The numerator, as designed in  $\frac{1}{200}$  $M_{tt}^{\text{H}}\left( \text{GeV}\right)$  and  $p_{\text{T}}^{\text{H}}\left( \text{GeV}\right)$ and **1.04** <u>and *O* (1) and *O* (2) and *O</u>* **s**<br>[<del>internations to the reactions to the reaction</del>] *gq* (*q*¯) → *ttq*¯ (*q*¯) (*q* = *u*,*d*,*s*, *c*,*b*). (2) We employ here the so-called 5-flavor scheme [13], where the (anti)proton is considered to contain also be a particular in its par<br>Thus the reaction (1) is a letter order (1) is a letter (1) is a letter (1) is a letter (1) is a letter (1) is process in this scheme, while (2), *q* = *b*, is a next-to-leading order (NLO) QCD correction to (1). The *O*  $M_{\rm tt}$  (GeV). The  $M_{\rm tt}$  $\frac{1}{2}$  corrections to the processes (2) were calculated already in  $\frac{1}{2}$  which in  $\frac{1}{2}$  which is  $\frac{1}{2}$  which in  $\frac{1}{2}$  which is  $\frac{1}{2}$  which in  $\frac{1}{2}$  which is  $\frac{1}{2}$  which in  $\frac{1}{2}$  which is *gq* (*q*¯) → *ttq*¯ (*q*¯) (*q* = *u*,*d*,*s*, *c*,*b*). (2)  $\begin{bmatrix} 0.96 \end{bmatrix}$ contain also **b** and *b* and *b* and *b* and *b* and *c* disc partonic sea. Thus the reaction (C) is a leading-order (C) *gq* (*q*¯) → *ttq*¯ (*q*¯) (*q* = *u*,*d*,*s*, *c*,*b*). (2)  $\begin{bmatrix} 1 & 1.02 \end{bmatrix}$ contain also bear al<br>In the reaction of the reaction (1) is a leading-order (LO) is a leading-order (LO) is a leading-order (LO) is process in this scheme, while (2), *q* = *b*, is a next-to-leading order (NLO) QCD correction  $\begin{bmatrix} 0.96 \\ 1 \end{bmatrix}$  $\begin{bmatrix} 1 & 0.96 \end{bmatrix}$  corrections to the processes (3) were calculated already in  $\begin{bmatrix} 3 & 0 & 0 \end{bmatrix}$  $w_{tt}$  (GeV) and top  $w_{tt}$  (GeV) and  $w_{tt}$  (GeV) and  $p_{tt}$  (GeV) *gq* (*q*¯) → *ttq*¯ (*q*¯) (*q* = *u*,*d*,*s*, *c*,*b*). (2) We employ here the so-called 5-flavor scheme [13], where the (anti)proton is considered to contain also *b* and *b*¯ quarks in its partonic sea. Thus the reaction (1) is a leading-order (LO) process in this scheme, while (2), *q* = *b*, is a next-to-leading order (NLO) QCD correction المستخدم ال<br>المستخدم المستخدم ال  $w_{tt}$  (dev)  $p_{\text{T}}$  (dev) contain also **b**<br> $\frac{1}{2}$  quarks in its partonic search (1) is a leading-order (LO) is a leading-order (LO) is a leading-order (LO) process in this scheme, while (2), *q* = *b*, is a next-to-leading order (NLO) QCD correction  $\begin{bmatrix} 1 & 1 & 1 & 0 & 2 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 &$ we include here for completeness. For several top quark observables – in particular, for  $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$  and ii) and iii) and iii) are insignificant. However, here we show w that for the pair-invariant mass distribution and for the top-quark helicity asymmetry, which  $\mathsf{m}_{\mathsf{t}}$  (dev)  $\mathsf{p}_{\mathsf{T}}$  (dev) *gq* (*q*¯) → *ttq*¯ (*q*¯) (*q* = *u*,*d*,*s*, *c*,*b*). (2)  $\begin{array}{c} \n\hline\n\end{array}$ contain also **b** and **b** and **b** and **contain the reaction (1)** is a leading sea. The reaction (1) is a leading sea. Thus the reaction (1) is a leading sea. Thus the reaction (1) is a leading sea. The reaction (1) is a lea process in this scheme, while (2), *q* = *b*, is a next-to-leading order (NLO) QCD correction *s* 00 and  $\rm M_{t\bar{t}}$  (Gem  $^{\rm 4.04}$ contain also *b* and *b*¯ quarks in its partonic sea. Thus the reaction (1) is a leading-order (LO) process in this scheme, which is a next-to-leading order ( $\frac{1}{2}$ )  $\frac{1}{2}$  correction  $\frac{1}{2}$ *<sup>s</sup>*!) corrections to the processes (2) were calculated already in [3] which we include here for several top several top several top  $\mathbb{R}^n$  , for several top  $\mathbb{R}^n$  $\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\$  $m_{tt}$  (GeV) and for the pair-invariant mass distribution and  $\mathsf{p}_{\mathsf{T}}$  (GeV) as  $\mathsf{p}_{\mathsf{T}}$  (GeV)

#### Katio (NLO<sub>QCD</sub>+electroweak)/NLO<sub>QCD</sub> corrections do matter if one aims at predictions with a precision at the percent level. The amplitude of (1) receives, in Born approximation and putting *mb* = 0, the following Ratio (NLOQCD+electroweak)/NLOQCD  $\overline{u}$ ο (NLO<sub>QCD</sub>+electroweak)/NLO<sub>QCI</sub> Natio (INLOQCD | CICCHOWCAN)/INLOQCD α2N˜<sup>0</sup> + α<sup>3</sup>  $\overline{\phantom{a}}$  $\mathbf{p}_{\text{at}}$  (NL *<sup>s</sup>*!) corrections to the processes (2) were calculated already in [3] which  $R$ atio (NI  $Q_{\text{con}}$ +electroweak)/NI  $Q_{\text{con}}$ Ratio (NLO<sub>QCD</sub>+electroweak)/NLO<sub>QCD</sub>  $P<sub>ofio</sub>$  (N  $\overline{\phantom{a}}$  cross section – the contributions insignificant. However, here we show  $\overline{\phantom{a}}$

#### Asymmetries ¯)−*N*(*yt* ¯ > *yt*)  $\Lambda$   $\sim$  5400 (6) 0.038 (13) 0.040 (6) 0.088 (13) 0.040 (6) 0.123 (18) 0.123 (13) 0.123 (13) 0.123 (13) 0.123 (13) 0.123 (13) 0.123 (13) 0.123 (13) 0.123 (13) 0.123 (13) 0.123 (13) 0.123 (13) 0.123 (13) 0.123 (13) 0.123  $\Delta$  cymmetries  $\Delta$  or  $\Delta$  $\Delta$ symmetries  $\overline{1}$  royumicu ico.  $\Delta$  symmetries  $\bigcap$   $\bigcap$   $\bigcup$   $\bigcup$

LHC 14 TeV 0.0077 (4) 0.0059 (3) 0.0100 (4)

*Tevatron anomalies and LHC cross-checks* Germán Rodrigo

¯ have been measured simultaneously, one defines the

 $\mathcal{L}_\mathrm{max}$  and  $\mathcal{L}_\mathrm{max}$  and  $\mathcal{L}_\mathrm{max}$  (8)  $\mathcal{L}_\mathrm{max}$  (8)  $\mathcal{L}_\mathrm{max}$  (8)  $\mathcal{L}_\mathrm{max}$  (8)  $\mathcal{L}_\mathrm{max}$ 

Assuming that the rapidities of *t* and *t*

*<sup>C</sup> <sup>A</sup><sup>y</sup>*

¯ (*Y*cut = 0.7), at different LHC energies. Summary of recent measurements by CMS and ATLAS.

SM 0.087 (10) 0.067 (10) 0.077 (10) 0.077 (10) 0.128 (10) 0.128 (10) 0.128 (15) 0.128 (15) 0.193 (15) 0.193 (1<br>2001 - Edition Company (15) 0.193 (15) 0.193 (15) 0.193 (15) 0.193 (15) 0.193 (15) 0.193 (15) 0.193 (15) 0.19







At LO partonic processes are not asymmetric. QCD produces the asymmetry only at NLO!  $\frac{1}{\sqrt{t}}$  NLO in the cross-section, LO in AFB At LO partonic process  $\mathcal{L}$  and  $\mathcal{L}$  are produces the asymmetry only at NLO!

q

t

q

t

 $\vert$ 

$$
A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}
$$

ge In the contribution only from interaction between gg initial state doesn't contribute to Tevatron and LHC asymmetry numerator!  $1 \tfrac{1}{\sqrt{2}}$  $\frac{a}{2}$ q-qbar QCD contribution only from interaction between initial and final state!



### $\mid \alpha \mid$  $\tilde{N}_1$  $D_0$ -<br>V 1

#### It's useful to divide electroweak contribution into QEL  $(hchoton)$  on QED (photon) and weak (Z) part.  $\overline{\phantom{0}}$ 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020<br>2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 δ<sub>Α</sub> δ<sub>ε</sub>  $\mathbf{v}$  weak contrib ation mid  $\mathbf{u}$   $\mathbf{v}$ QCD there are two different color structures and the result depends on d<sup>2</sup> = dABC dABC =  $\overline{a}$ electr ectroweak cc t t q qi t lu routron y γ q  $\mathcal{L} = \mathcal{L} - \mathcal{L}$ ribution into is numerically negligible.  $\overline{\mathbf{y}}$

At

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<u>t</u>

 $\frac{1}{t}$   $\frac{q}{t}$   $\frac{t}{t}$ 

 $q\bar{q} \rightarrow ttg$ 

 $\frac{t}{a}$   $q$ 

t Dt

Et

¯

' '

 $t$   $\frac{q}{q}$   $\frac{t}{q}$ 

 $\overline{q}$ 

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 $\frac{y}{\gamma}$ 

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t

 $\zeta_t$  and the set of boxes and

 $\sum_{\alpha,\beta} g_{\alpha\beta}$  of  $\sum_{\alpha,\beta} g_{\alpha\beta}$ 

 $t \nearrow$  and the three gluon propagator three gluon propagator three gluon propagator that appears in the O( $a$ 

 $\overline{ }$ 

t

Ftt

Figure 4: Three different way of replacing one gluon with a photon in the photon in the photon in the propagator of the propagator of the photon in the

calculations and we found that, in front of the found that, in front of the found the found that, in [8], there show in [8], the found that, in [8], the found that, in [8], the found that is a shown in [8], the found that

be an overall factor three, which comes from the three different replacements of the gluon propagator

 $\frac{1}{4}$ . Following the color structure argument we can identify the color structure and the couplin

 $\frac{1}{2}$  M2

 $T = \frac{1}{2}$ 

δAC δBDT r(t

 $\frac{1}{\Gamma}$  is zero because the color structure, so we do not we do not

QCD there are two different color structures and the result depends on d<sup>2</sup> = dABC dABC =

 $\frac{1}{2}$  due to the three cases shown in  $\frac{1}{2}$  due to the three cases shown in  $\frac{1}{2}$ 

 $\overline{\phantom{a}}$ 

 $\mathcal{L}_\mathcal{D} = \{ \mathcal{L}_\mathcal{D} \mid \mathcal{L}_\mathcal{D} \}$  cases, and obtain the ratio of them.

 $\frac{1}{\sqrt{2}}$ 

 $44.4$  (if  $A$ BC),  $\frac{1}{2}$  (if  $\frac{1}{2}$ 

in the QCD case and the substitution of a gluon with a photon.

Figure 1: Real emissions of gluon: photon in the propagator

 $\frac{1}{\Gamma}$ 

s) terms that contributes to N come from four particles to N come from four particles to N come from four part<br>The system of  $\frac{1}{2}$ 

 $\mathbf{q}$ 

![](_page_13_Picture_2.jpeg)

 $\left| QED \right|$  QED can be easily obtained from QCD calculation and the substitution of one gluon into one photon in the squared amplitudes. gluon into one photon in the squared amplitudes.  $t$ At Bt <sup>C</sup> ) = <sup>1</sup>  $\mathbf{4} \cdot \mathbf{4} = \mathbf{4} \cdot \mathbf{4} \cdot \mathbf{4}$  $\overline{a}$ ned from QCD calculation and the substitution of one  $\sim$  subprocess can be evaluated through the results obtained for  $\sim$  to  $\sim$ in the  $\overline{C}$  case and the substitution of a gluon with a photon. The substitution of a gluon with a photon. **OED** can be easily obtained from QCD calculation and the substitution of one  $F_{\rm eff}$  as a real emission in the propagator in the propag the QED sector we obtain contributions to O(α<sup>2</sup>

 $\overline{\left|{\cal M}^{t \bar t g}\right|^2_\ell}$ 

 $\overline{\phantom{a}}$ 

ਿੰਦਰ ਤਾਂ subprocess can be evaluated through the results obtained for qq¯ → ttg¯ → ttg¯ → ttg¯ → ttg¯ → ttg¯ →<br>ਹਵਾਲਾ → ttg¯ → tt

 $\overline{\mathcal{A}}$ 

 $\overline{\phantom{a}}$ 

+ 2Re<br>
+ 2Re!<br>
+ 2Re!<br>
+ 2Re!<br>
+ 2Re!

 ${\cal O}(\alpha_s^3)$ 

 $\overline{\phantom{a}}$ 

 $q\bar{q}$ 

q

=

 $\stackrel{\cdot }{q}$ 

g

 $\overline{q}$ 

![](_page_13_Figure_4.jpeg)

 $\overline{|\mathcal{M}^{t\bar{t}}|}$ 2

### $\mid \alpha \mid$  $\tilde{N}_1$  $D_0$ -<br>V 1

#### It's useful to divide electroweak contribution into QEL  $(hchoton)$  on QED (photon) and weak (Z) part.  $\overline{\phantom{a}}$ (phc electrow q<br>L ak  $(7)$  par g q<br>L t t 1 g  $\overline{\phantom{0}}$ 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020<br>2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020 - 2020  $\mathbf{v}$  weak contrib ation mit  $\mathbf{U}$  $\mathbf{u}$   $\mathbf{v}$ QCD there are two different color structures and the result depends on d<sup>2</sup> = dABC dABC =  $\overline{a}$ electr ectroweak cc t t wide electroweak contribution into ¯ ¯ vide electroweak contribution mito  $\partial$  weak  $\overline{Z}$  that the three different replacements of the gluon propagator propagator propagator propagator propagator  $\overline{Z}$  $\alpha$  weak  $(2)$  parcit q qi t lu routron y γ q  $\overline{\mathbf{u}^{\text{tion}}}$  $\mathbf{a}$  + ttp and  $\mathbf{a}$ ribution into is numerically negligible.  $\mathfrak{c}$ g  $\overline{\mathbf{y}}$

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δ<sub>Α</sub> δ<sub>ε</sub>

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![](_page_14_Picture_2.jpeg)

Ftt

Figure 4: Three different way of replacing one gluon with a photon in the photon in the photon in the propagator of the propagator of the photon in the

 $\overline{\phantom{a}}$ ¯  $\mathbf{q}$ 

![](_page_14_Figure_3.jpeg)

 $\mathbf{F}_{\mathbf{f}}$  . Following the color structure and the color structure and the color structure and the couplings of  $\mathbf{F}_{\mathbf{f}}$ 

$$
A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}
$$
 *Hollik, D.P. '11*

$$
R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}
$$
 from Q

QED correction can be obtained from  $QCD \times R_{QED}$ 

$$
A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}
$$
 *Hollik, D.P. 'II*

$$
R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}
$$
 from Q

QED correction can be obtained from  $QCD \times R_{QED}$ 

![](_page_16_Picture_3.jpeg)

The same diagrams as QED part, but  $\gamma \rightarrow Z$ .

Z is not massless  $\rightarrow$  If we write Weak=QCD  $\times$  R<sub>Weak.</sub> RWeak does not depend only on couplings and color factor

$$
A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}
$$
 *Hollik, D.P. '11*

g

g<br>G

$$
R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}
$$
 from Q<sup>o</sup>

t

QED correction can be obtained from  $QCD \times R$ QED

t

g

g<br>G

![](_page_17_Picture_3.jpeg)

The same diagrams as QED part, but  $\gamma \rightarrow Z$ . t s QED part, but  $\gamma \rightarrow Z$ .

Figure 1: Born diagrams

t

Z is not massless  $\rightarrow$  If we write Weak=QCD  $\times$  Rweak. R<sub>Weak</sub> does not depend only on couplings and color factor

![](_page_17_Figure_6.jpeg)

We can also rewrite N and D including EW corrections, and the leading contributions, and the leading contributions, and the leading contributions, and the leading contributions, and the leading contribution (excluding cont

![](_page_17_Picture_7.jpeg)

 $\mathfrak{c}$  $\sum_{a}$  *t*Different couplings for different  $\frac{1}{2}$ chiralities produce asymmetric terms in the cross-section

 $d\sigma_{asym}$  $\frac{d\sigma_{asym}}{d\cos\theta} = 2\pi\alpha^2\cos\theta\Big($  $1 - \frac{4m_t^2}{ }$ t s  $\int_{R} \frac{Q_q Q_t A_q A_t}{\sqrt{Q} \sqrt{Q}}$  $\frac{\partial^2 q\partial^2 t \partial q \partial t}{(s-M_Z^2)} + 2\kappa^2 A_q A_t V_q V_t$ s  $(s-M_Z^2)^2$  $\overline{\phantom{a}}$ 

#### (  $\sim$  mt/2, that is the cross sections, that is the cross ard asymmetry and  $\mathcal{I}$ and the correspondent contributions to the asymmetry in Tab. 4.  $\Gamma$  assembly depended and the evaluation of the  $\Gamma$ . Forward-backward asymmetry (  $\sim$  mt/2, that is the cross sections, that is the cross section sections, that is the cross sections, that is the cross sections, that is the cross sections, that i

but the values of as( $\mu$ ) given by the two distributions is different for fixed  $\mu$  , so we used as  $\mu$ 

![](_page_18_Picture_866.jpeg)

![](_page_18_Picture_867.jpeg)

 $\mu = 2m_t$   $R_{QED}^{u\bar{u}} = (0.192, 0.214, 0.237)$  $\frac{170}{1.94}$   $\frac{1}{6}$   $\frac{1}{6}$   $\frac{1}{6}$   $\frac{1}{2}$   $\frac{1}{$  $\overline{0.92\%}$   $R_{QED}^{d\bar{d}} = (-0.096, -0.107, -0.119)$  $\overline{CD}$ <sup>s</sup>) uu¯ 4.66% 4.19% 3.78%

> $\alpha$ <sup>o</sup> 0.110 0.1 O(α<sup>2</sup>  $\overline{\mathbf{S}}$ - R<sub>QED</sub> depend only on the Tello AFB definitions and cuts - ROED depend only on the renormalization scale, not on AFB definitions and cuts

![](_page_18_Figure_5.jpeg)

#### $\mathcal{A}$  comparison of the ratio of the ratio of the ratio of the  $\mathcal{A}$ ard asymmetry  $\frac{1}{2}$  $\mathbf{v}$ Forward-backward asymmetry

<sup>s</sup>) from the various partonic channels

The asymmetry with cuts is the total result,

$$
R_{EW}^{t\bar{t}} = \frac{N_{\mathcal{O}(\alpha_s^2 \alpha) + \mathcal{O}(\alpha^2)}^{t\bar{t}}}{N_{\mathcal{O}(\alpha_s^3)}^{t\bar{t}}} = (0.190, 0.220, 0.254) \qquad R_{EW}^{t\bar{t}}(M_{t\bar{t}} > 450 \text{ GeV}) = (0.200, 0.232, 0.266)
$$
\n
$$
R_{EW}^{\overline{p\bar{p}}} = \frac{N_{\mathcal{O}(\alpha_s^2 \alpha) + \mathcal{O}(\alpha^2)}^{p\bar{p}}}{N_{\mathcal{O}(\alpha_s^3)}^{\overline{p\bar{p}}}} = (0.186, 0.218, 0.243) \qquad R_{EW}^{t\bar{t}}(|\Delta y| > 1) = (0.191, 0.216, 0.246)
$$

4 Conclusions and Conclusions and Conclusions and Conclusions and Conclusions and Conclusions and Conclusions

The final result for the two definitions of  $\mathcal{A}_B$  as follows,  $\mathcal{A}_B$  can be summarized as follows,  $\mathcal{A}_B$ 

Table 1: Integrated cross sections at O(α<sup>2</sup>

 $R_{EW}^{t\bar t}(M_{t\bar t} > 450\,\,{\rm GeV}) = (0.200, 0.232, 0.266)$ 

 $R_{EW}^{t\bar t}(|\Delta y| > 1) = (0.191, 0.216, 0.246).$ It is, however, not enough to improve the situation.

¯ > 450 GeV.

production shows that they provide a non-negligible fraction of the  $\mathcal{L}_\mathbf{t}$  induced asymmetry with  $\mathcal{L}_\mathbf{t}$ 

 $\mathbf{F}\mathbf{W}$  $E$  w corrections to  $A_{FB}$  depends on taction scale, a definitions and cuts. <sup>s</sup>α) contribution of uu¯ → tt  $\frac{1}{2}$  to the asymmetry is even bigger than the  $\frac{1}{2}$ <sup>s</sup>) contribution of  $\theta$  and  $\theta$  depends on factor scale, and very slightly on  $\Lambda_m$ EW corrections to AFB depends on fac/ren scale, and very slightly on AFB

invariant-mass cut Mtt

#### $\mathcal{A}$  comparison of the ratio of the ratio of the ratio of the  $\mathcal{A}$ ard asymmetry increase of Rtt  $\overline{\phantom{a}}$  $\mathbf{v}$ F B B B Attend the various section of the various part of the Forward-backward asymmetry

<sup>s</sup>) from the various partonic channels

The asymmetry with cuts is the total result,

$$
R_{EW}^{t\bar{t}} = \frac{N_{\mathcal{O}(\alpha_s^2 \alpha) + \mathcal{O}(\alpha^2)}^{t\bar{t}}}{N_{\mathcal{O}(\alpha_s^3)}^{t\bar{t}}} = (0.190, 0.220, 0.254) \qquad R_{EW}^{t\bar{t}}(M_{t\bar{t}} > 450 \text{ GeV}) = (0.200, 0.232, 0.266)
$$
\n
$$
R_{EW}^{p\bar{p}} = \frac{N_{\mathcal{O}(\alpha_s^2 \alpha) + \mathcal{O}(\alpha^2)}^{p\bar{p}}}{N_{\mathcal{O}(\alpha_s^3)}^{p\bar{p}}} = (0.186, 0.218, 0.243) \qquad R_{EW}^{t\bar{t}}(|\Delta y| > 1) = (0.191, 0.216, 0.246)
$$

to note that the band indicating the scale variation of the prediction does not account for all the

4 Conclusions and Conclusions and Conclusions and Conclusions and Conclusions and Conclusions and Conclusions

Npp¯

<sup>s</sup>α)+O(α2)

consider this as an uncertainty from the incomplete NLO calculation (see also the discussion in [5]).

The final result for the two definitions of  $\mathcal{A}_B$  as follows,  $\mathcal{A}_B$  can be summarized as follows,  $\mathcal{A}_B$ 

<sup>O</sup>(α<sup>2</sup>

Table 1: Integrated cross sections at O(α<sup>2</sup>

theoretical uncertainties. For example, the O(α<sup>4</sup>

 $\overline{\phantom{a}}$ 

 $\overline{\phantom{a}}$ 

section, i.e. the denominator of AF B in (1) and (2). The antisymmetric cross section, the numerator

 $R_{EW}^{t\bar t}(M_{t\bar t} > 450\,\,{\rm GeV}) = (0.200, 0.232, 0.266)$ 

 $R_{EW}^{t\bar t}(|\Delta y| > 1) = (0.191, 0.216, 0.246).$ It is, however, not enough to improve the situation.

¯ > 450 GeV.

production shows that they provide a non-negligible fraction of the  $\mathcal{L}_\mathbf{t}$  induced asymmetry with  $\mathcal{L}_\mathbf{t}$ 

 $\mathbf{F}\mathbf{W}$  $E$  w corrections to  $A_{FB}$  depends on taction scale, a definitions and cuts and  $\frac{1}{2}$  as  $\frac{1}{2}$  as  $\frac{1}{2}$  as  $\frac{1}{2}$  as  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  are  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  are  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1$ <sup>s</sup>α) contribution of uu¯ → tt  $\frac{1}{2}$  to the asymmetry is even bigger than the O( $\frac{1}{2}$ <sup>s</sup>) contribution of  $\frac{f_0}{f_0}$  and  $\frac{f_0}{f_0}$  on  $\frac{f_0}{f_0}$  and  $\frac{f_1}{f_0}$  and  $\frac{f_0}{f_0}$  and  $\frac{f_1}{f_0}$ ¯ EW corrections to AFB depends on fac/ren scale, and very slightly on AFB  $\overline{EW}$  corr s to  $\frac{1}{2}$  $\int_{\mathbb{R}} \cos 4x \cos 2x \cos 4x$ allu

invariant-mass cut Mtt

 $=$  (18)  $\pm$  (18)  $\$ 

 $\overline{\rm EW}$  corrections to  ${\rm A}_{\rm ER}$  are more important than  $\overline{\rm EW}$  corrections. Figure 7 displays the theoretical prediction versus the experimental data. The prediction is  $\mathbf{r}$ to total cross-section. 2 Reasons: F B. It is important the same overall sign, thus enlarging the Standard Model prediction for the asymmetry at the observed dependence of  $\sim$ new physics below the TeV scale; it is, however, difficult to interpret these deviations as long as the NLO  $\alpha$  calculation for the asymmetry is not available.  $\overline{\text{O}}$ EW corrections to AFB are more important than EW corrections  $\text{r}_\text{OGB}$  same  $\text{r}_\text{OGB}$   $\text{r}_\text{OGB}$   $\text{r}_\text{OGB}$ to total cross-section. 2 Reasons: <sup>O</sup>(α<sup>3</sup> s)  $\frac{1}{2}$  we converte the estimate of  $\frac{1}{2}$ . This shows the electronic that the electronic contribution to total cross-section.  $\angle$  Keasons.

-LO total cross section  $\mathcal{O}(\alpha_s^2)$ , LO numerator of AFB  $\mathcal{L}$  by about 30% section  $\mathcal{L}(\alpha_s)$ ,  $\mathcal{L}$  constructed size new physics below the TeV scale; it is, however, difficult to interpret these deviations as long as the -LO total cross section  $\mathcal{O}(\alpha_s^2)$ , LO numerator of AFB  $\mathcal{O}(\alpha_s^3)$  $\binom{3}{s}$ 

overall sign, thus enlarging the Standard Model prediction for the asymmetry (the electroweak

 $\overline{\phantom{a}}$  pairs in pairs in pairs in pairs in pairs in pairs in the strong interaction,  $\overline{\phantom{a}}$ 

<sup>s</sup>) term in N is missing, and we did not include the

 $\sim$  The dominant FW contribution  $\mathcal{O}(\alpha^2 \alpha)$  QFD to the -The dominant EW contribution,  $\mathcal{O}(\alpha_s^2 \alpha)$  QED, to the A<sub>FB</sub> comes from boxes: 3 times the number of diagrams of QCD case. QED contribution to total cross-section comes "from vertex corrections": same number of diagrams of QCD case.  $\Gamma$  be deminent  $\Gamma W$  contribution  $\mathcal{O}(q^2)$ almost inside the experimental 1σ range for Att ¯ F B and inside the 20 range for App  $\overline{C}$ F B. It is important - The dominant E w contribution,  $\mathcal{O}(\alpha_s \alpha)$  QED, to the *F* QED contribution to total cross-section comes "from vertex corrections":  $\mathcal{L}_{\mathcal{A}}$  which are numerically not important  $\mathcal{L}_{\mathcal{A}}$  which are numerically not important  $\mathcal{L}_{\mathcal{A}}$ -The dominant EW contribution,  $\mathcal{O}(\alpha_s^2 \alpha)$  QED, to the A<sub>FB</sub> comes from boxes: same number of diagrams of QCD case. namely the O(α<sup>3</sup>

#### Charge asymmetry forward/backward region, A<sup>E</sup> will in general be larger than |AC|. On the other hand, the each of these observables in order to optimize the statistical sensitivity of AE. −<br>− events, oqqo → ttp://ottp://ottp://ottp://ottp://ottp://ottp://ottp://ottp://o ¯, is enhanced in the for a charge asymmetry  $\mu$ event numbers decrease rapidly with increasing  $\sim$

At LHC same partonic processes, but different partonic luminosities. At I HC same partonic processes but different r At LITU saine partonic processes, out unierent partonic funni

Gluon-gluon luminosity is larger, so asymmetry is smaller. Gluon-quark initial state starts to be "interesting". events with Mtt ≥ McChoose Mc<br>2005 March 2006 McChoose McCh  $\begin{array}{l} \hbox{Gluon_oluon luminosity is larger so asymmetry is smaller.} \end{array}$ contributions to the numerator and the resulting values of AC(yc = 1) at 7 TeV center-of-or-organized values of  $\frac{1}{2}$  TeV center-of-organized values of  $\frac{1}{2}$  TeV center-of-organized values of  $\frac{1}{2}$  TeV center-o *H*<sub>1</sub> → *t*<sub>1</sub> *t*<sub>2</sub>  $\frac{1}{2}$   $\frac{1}{2}$ 

The ratio of integrated luminosities  $u\bar{u}/d\bar{d}$  at Tevatron is 4:1, at LHC 2:1. Cancellation between QED contributions is bigger. EW contribution at LHC in general is smaller (between 15% and 20% of QCD contribution). s) QCD is now ∼ 13%, which, as also is now ∼ 13%, which, as also is now ∼ 13%, which, as also is now ∼ 13%, which, as a  $q=\frac{1}{2}q^2+\frac{1}{2}q^$  $\overline{13}$  is now ∼ 13%, which, as also The ratio of integrated luminosities  $u\bar{u}/d\bar{d}$  at Tevatron is 4:1,  $\frac{1}{2}$  of integrated lyminesities  $\frac{1}{2}$  of ally of integrated funditiosities  $|u u/uu|$  at al is smaller (between 15% and 20% (3) α*N*˜<sup>1</sup>  $\frac{1}{2}$  of  $\frac{1}{2}$  (hetween  $\frac{1}{2}$   $\frac{50}{2}$  and  $\frac{200}{2}$  of OC

$$
R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}
$$

 $q_{\rm{max}}$  in time to the initiated contributions relative to the  $\alpha$ 

in the SM. Because the SM. Because the fraction of  $\sigma$ 

![](_page_21_Picture_1161.jpeg)

14 TeV QCD: A<sup>E</sup> (%) 0.12 (1) 0.32 (1) 1.28 (5)

*Bernreuther, Si '12*

¯

## CONCLUSION

The electroweak contribution to total cross-section is still smaller than QCD uncertainty. It could be seen in differential distribution, with high luminosity.

Total electroweak contribution to the asymmetries is not negligible and increases QCD result by a factor  $\sim$  1.2 (Tevatron),  $\sim$  1.15 (LHC)

EW cannot explain  $A_{FB}(M_{INV}>450$  GeV), but new models cannot forget its contribution when they try to fill the gap between theory (SM) and experiment.

## THANK YOU FOR THE ATTENTION!

# EXTRA SLIDES

#### Hadronic process = partonic process ⊗ PDF that the initial state pp¯ is basic to get:  $\overline{\phantom{a}}$  $\overline{\mathcal{O}}$   $\overline{\mathcal{O}}$   $\overline{\mathcal{O}}$  $\alpha_{\text{max}} = \text{next } \alpha$  $Hadronic process = partonic process \otimes PDF$

 $\mathcal{L}$ 

Under a CP transformation a top quark with rapidity y becomes an antitop with rapidity y becomes an antitop wi

 $\frac{1}{2}$ 

¯

 $\overline{\phantom{0}}$ ¯ <sup>&</sup>gt; 0) (5a)  $\sigma(H_1H_2 \to t\bar{t}+X) = \sigma(p_1p_2 \to t\bar{t}+X) \otimes \left[f_{p_1,H_1}(x_1)f_{p_2,H_2}(x_2) + f_{p_1,H_2}(x_1)f_{p_2,H_1}(x_2)\right]$ 

Partonic process can be produced in two different directions Obviously also an Att processor in the cancel car can out for  $\mathbf{1}_{\mathbf{2}_{\mathbf{1}}}$  ( $\mathbf{2}_{\mathbf{2}_{\mathbf{2}}}$  ( $\mathbf{3}_{\mathbf{2}_{\mathbf{2}}}$  ( $\mathbf{3}_{\mathbf{2}_{\mathbf{2}}}\in\mathbb{R}$  ) for  $\mathbf{3}_{\mathbf{2}_{\mathbf{2}}}\in\mathbb{R}$  (see Fig.  $\frac{1}{2}$ duced in tw "<br>""<br>"" "

1

![](_page_24_Figure_3.jpeg)

At LHC  $H_1=H_2 \rightarrow A_{FB}=0$ At Tevatron only processes with  $p_1$  or  $p_2 = (up, antiup, down, antidown)$  can produce asymmetric terms!  $\Delta$  + T HC  $H_1=$  $H_2 \rightarrow \Delta$  to  $=$  0  $\frac{1}{\sqrt{1 + \frac{1}{\sqrt{1 +$ At IC valid billy processes while  $p_1$  or  $p_2 - (up, aminup, amindown)$  can be a given by an and  $p_1$  or  $p_2 - (up, aminup)$ .  $WIII$  $p1$  OI produce asymmetre terms.  $H_2 \longrightarrow A_{FB} = 0$ F B with or with or with or with or with or with or with  $\sim$ only processes with  $p_1$  or  $p_2 = (up, antiup, down, antidown)$  can Now we can start to look at the partonic subprocesses that generate a term is that generate a term  $\alpha$  $\sim$  $\overline{\text{F}(\text{up}, \text{antiup}, \text{down}, \text{antidown})}$ can asymmetric terms:  $an$  $\frac{1}{2}$ atron only pr  $\frac{1}{2}$ F B (2)  $h[p_1 \text{ or } p_2 = (up, \text{antiup}, \text{down}, \text{antidown})]$ can AEW F B B  $\sim$  0.25 × AQCD  $\sim$  $\mathbb{E}_{\mathbf{S}}\left[\mathbf{S}^{\mathbf{S}}\right]$  ,  $\mathbb{E}_{\mathbf{S}}\left[\mathbf{S}^{\mathbf{S}}\right]$  ,  $\mathbb{E}_{\mathbf{S}}\left[\mathbf{S}^{\mathbf{S}}\right]$  ,  $\mathbb{E}_{\mathbf{S}}\left[\mathbf{S}^{\mathbf{S}}\right]$  ,  $\mathbb{E}_{\mathbf{S}}\left[\mathbf{S}^{\mathbf{S}}\right]$  ,  $\mathbb{E}_{\mathbf{S}}\left[\mathbf{S}^{\mathbf{S}}\right]$  ,  $\mathbb{E}_{\mathbf{$  $\sim$  (up, antiup, down, antiuown) can AEW  $\frac{1}{2}$   $\ln$  $\mathbb{R}$ AEW F B <sup>∼</sup> <sup>0</sup>.<sup>25</sup> <sup>×</sup> <sup>A</sup>QCD

AEW

F B <sup>∼</sup> <sup>0</sup>.<sup>25</sup> <sup>×</sup> <sup>A</sup>QCD

Diagrams contributing to orders  $\alpha_s \alpha_s^2 \alpha_s^2 \alpha$  of  $gq(\bar{q}) \rightarrow t\bar{t}q(\bar{q})$   $(q = u, d, s, c, b)$ 

![](_page_25_Figure_1.jpeg)

![](_page_26_Picture_0.jpeg)

obtained by s-channel *γ, Z amplitudes contains a term (9) that contains a term (9)* that contains to AF B thanks to the AF B thanks to the AF B thanks to AF B thanks to the AF B thanks to the AF B thanks to the AF B thank

At LO partonic processes are not asymmetric. QCD produces the asymmetry only at NLO! NLO in the cross-section, LO in AFB  $\sqrt{1 + \frac{1}{\sqrt{1 + \frac{1}{$  $\alpha$  (and  $\alpha$ ) is a section of  $\alpha$  at LO partonic processes are not asymmetric.  $|QCD$  produces the asymmetry only at NLO! partonic cross section is symmetric under y<sup>t</sup> → −yt. The exclusion of gg → tt  $t$  at LO partonic processes are not asymmetric.  $\sim$  D partome processes are not asymmetric.  $\frac{1}{x}$   $\frac{1}{y}$   $\mathcal{A}_q$  and  $\mathcal{A}_r$  we can be used the cross-section, LO in A<sub>FB</sub>

![](_page_26_Figure_2.jpeg)

OCD only at LO, but there is also electroweak theory.  $Q(\alpha, \alpha) = 0$  $\sqrt{2}$  only at EO, out there is also electrowed theory.  $\sqrt{U(ug\alpha)-U}$  $OCD$  only at  $LO$  but there is also electrow  $\sqrt{C}$  can also, our there is also electrowed theory.  $\sqrt{C(\alpha_s \alpha) - \alpha}$ QCD only at LO, but there is also electroweak theory.

$$
\boxed{\mathcal{O}(\alpha_s \alpha) = 0}
$$

 $+$ 

α<br>20 Ιουλίου<br>20 Ιουλίου

+ ··· (8)

 $+$ 

 $\sim$  and  $\sim$   $\sim$ 

¯ and qq¯ → tt

$$
A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}
$$

¯+

<sup>2</sup> we obtain <sup>D</sup><sup>0</sup> the LO cross section, from |Mqq¯→γ→tt  $\alpha_s$ <sup>2</sup>D<sub>0</sub> is the LO cross section, now AF B =  $\alpha_s^2 D_0$  is the LO cross section, now we see the terms in N  $\frac{1}{2}$  $\overline{\phantom{a}}$ 2

<sup>1</sup>We know that there are PDFs with <sup>s</sup>(x) != ¯s(x), but the effect is negligible.

![](_page_27_Picture_956.jpeg)

 $(A_{FB}^{t\bar t})^{EW}$ 

 $\overline{(A_F^{t\bar t}}% ,A_F^{t\bar t})^{2h}$ 

 $(h)$   $A^{p\bar{p}}$ 

(a) $A_{FB}^{t\bar{t}}$					(b) $A_{FB}^{p\bar{p}}$				
	$A_{FB}^{t\bar{t}}$	$\mu = m_t/2$	$\mu = m_t$	$\mu=2m_t$	$A_{FB}^{p\bar{p}}$	$\mu=m_t/2$	$\mu = m_t$	$\mu=2m_t$	
	$\mathcal{O}(\alpha_s)$ $u\bar{u}$	7.01%	$6.29\%$	$5.71\%$	$\mathcal{O}(\alpha_s)$ $u\bar{u}$	4.66%	4.19%	$3.78\%$	
	dd $\mathcal{O}(\alpha_s)$	1.16%	1.03%	$0.92\%$	${\cal O}(\alpha_s)$ dd	0.75%	$0.66\%$	$0.59\%$	$R_{QED}^{u\bar{u}} = (0.192, 0.214, 0.237)$
	${\cal O}(\alpha)_{QED}$ $u\bar{u}$	1.35%	1.35%	1.35%	${\cal O}(\alpha)_{QED}$ $u\bar{u}$	$0.90\%$	$0.90\%$	$0.90\%$	
	$d\bar{d}$ ${\cal O}(\alpha)_{QED}$	$-0.11\%$	$-0.11\%$	$-0.11\%$	$d\bar{d}$ $\mathcal{O}(\alpha)_{QED}$	$-0.07\%$	$-0.07\%$	$-0.07\%$	$R_{QED}^{d\bar{d}} = (-0.096, -0.107, -0.119)$
	${\cal O}(\alpha)_{weak}$ $u\bar{u}$	$0.16\%$	$0.16\%$	$0.16\%$	$\mathcal{O}(\alpha)_{weak}$ $u\bar{u}$	$0.10\%$	$0.10\%$	$0.10\%$	
	$d\bar{d}$ ${\cal O}(\alpha)_{weak}$	$-0.04\%$	$-0.04\%$	$-0.04\%$	$d\overline{d}$ ${\cal O}(\alpha)_{weak}$	$-0.03\%$	$-0.03\%$	$-0.03\%$	
	$\mathcal{O}(\alpha^2/\alpha_s^2)$ $u\bar{u}$	$0.18\%$	$0.23\%$	$0.28\%$	$\mathcal{O}(\alpha^2/\alpha_s^2)$ $u\bar{u}$	$0.11\%$	$0.14\%$	$0.17\%$	
	${\cal O}(\alpha^2/\alpha_s^2)$ $d\bar{d}$	$0.02\%$	$0.03\%$	$0.03\%$	$\mathcal{O}(\alpha^2/\alpha_s^2)$ $d\overline{d}$	$0.01\%$	$0.02\%$	$0.02\%$	
	$p\bar p$ tot	$9.72\%$	8.93%	$8.31\%$	$p\bar p$ tot	$6.42\%$	$5.92\%$	$5.43\%$	
		$0.35 \Gamma$				$0.35 \Gamma$			
		$\mid 0.3 \mid$		$\pm\sigma$		0.3		$\pm\sigma$	
				$\pm 2\sigma$				$\pm 2\sigma$	
		$\mid 0.25 \mid$		$mt/2<\mu<2mt$ (theory)		$\vert 0.25 \vert$		$mt/2<\mu<2mt$ (theory)	a) at $1\sigma$ b)inside $2\sigma$
		$\vert 0.2 \vert$				$\vert 0.2 \vert$			
						$\vert 0.1 \vert$			
		0.05				$\boxed{0.05}$			
		$0^{\perp}$							
		(a) $A_{FB}^{t\bar{t}}$				(b) $A_{FB}^{p\bar{p}}$			

 $\begin{CD} \mathcal{L} & \mathcal{L}^T \mathcal{L$ 

 $\frac{p\bar{p}}{FB}\big) EW$ 

 $\frac{(AP\bar{p})}{(A_{FB}^{p\bar{p}})^{QCD}} = (0.186, 0.218, 0.243)$ 

 $\frac{(A_{FB}^{t\bar{t}})^{EW}}{(\bar{t}^t_B)^{QCD}} = (0.190, 0.220, 0.254) \qquad \frac{(A_{FI}^{p\bar{p}})^{U}}{(A_{FE}^{p\bar{p}})^{U}}$ 

$$
\frac{0.59\%}{0.90\%}
$$
  $R_{QED}^{u\bar{u}} = (0.192, 0.214, 0.237)$   
\n $R_{QED}^{u\bar{u}} = (0.006, 0.107, 0.110)$ 

(a)  $A_{FB}^{t\bar{t}}(M_{t\bar{t}} > 450 \text{ GeV})$  (b)  $A_{FB}^{t\bar{t}}(|\Delta$ (a)  $A_{FB}(m_{tt} > 400 \text{ GeV})$ (a)  $A_{FB}^{t\bar{t}}(M_{t\bar{t}}>450\,\,\mathrm{GeV})$ 

(b)  $A_{FB}^{tt}$  (  $\cdot$  1) (b)  $At\bar{t}$  ( $\Delta$   $\Delta t$ )  $\begin{bmatrix} \n\langle \nu \rangle \n\end{bmatrix} \begin{bmatrix} \n\Delta y \mid \Delta z \n\end{bmatrix}$ (b)  $A_{FB}^{t\bar{t}}(|\Delta y| > 1)$ 

![](_page_28_Picture_1682.jpeg)

![](_page_28_Figure_3.jpeg)