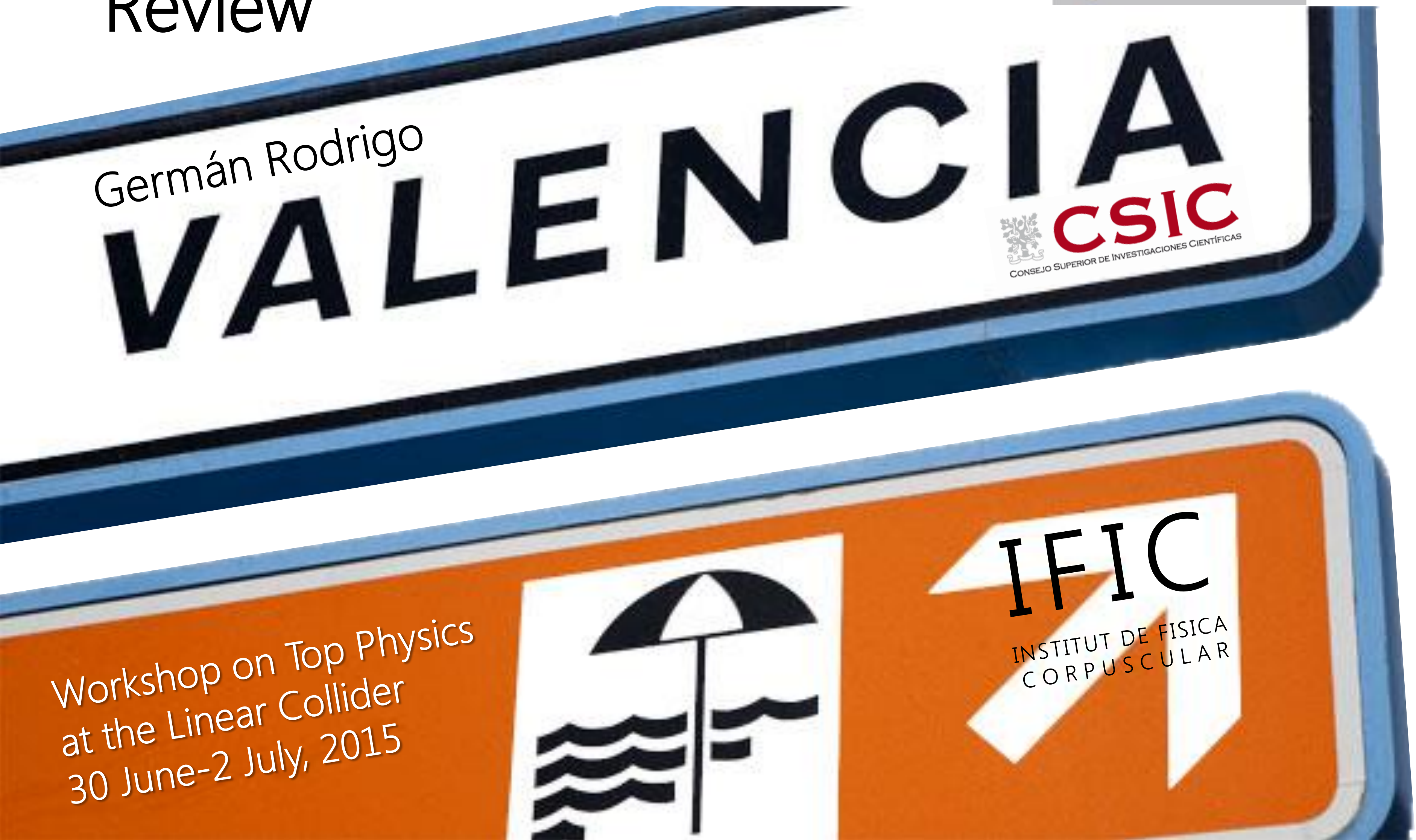
Top-Quark Charge Asymmetry Review

Germán Rodrigo



EXCELENCIA SEVERO OCHOA

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

IFIC
INSTITUT DE FISICA CORPUSCULAR

Workshop on Top Physics
at the Linear Collider
30 June-2 July, 2015

the top quark: the gold(en) particle

- The heaviest known elementary particle
- Yukawa coupling to Higgs boson $y_t = \mathcal{O}(1)$: bridge to EWSB
- Special role in many BSM: a window to new physics that couples preferentially to top quarks
- Decays before hadronizing: the only "naked" quark

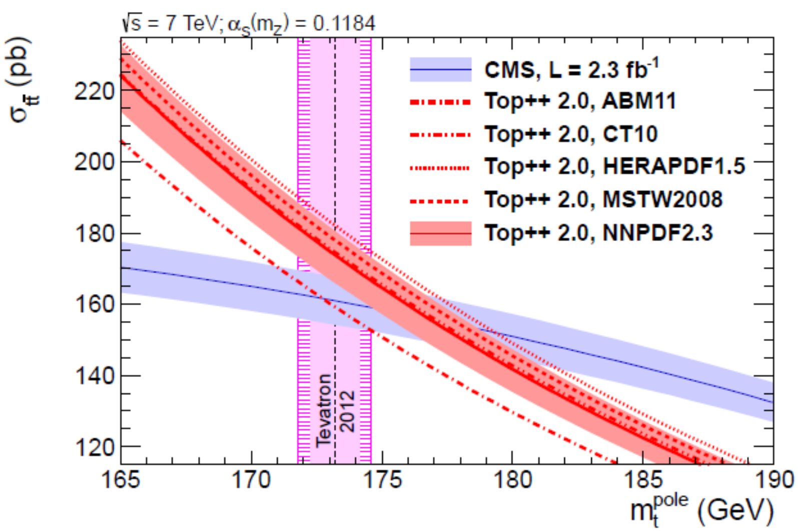
$$\tau_{\rm had} \approx h/\Lambda_{\rm QCD} = 2 \cdot 10^{-24}{\rm s}$$

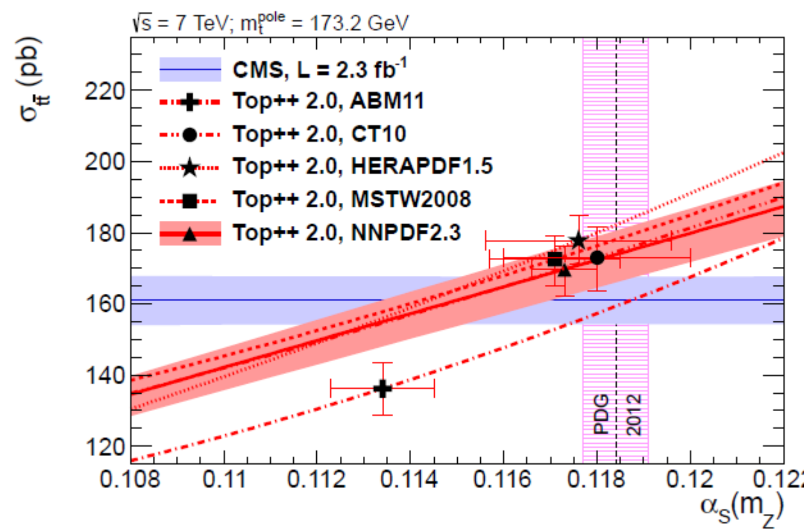
$$\tau_{\rm top} \approx h/\Gamma_{\rm top} = 1/(G_F m_t^3 |V_{tb}|^2/8\pi\sqrt{2}) = 5 \cdot 10^{-25}{\rm s}$$

$$\tau_{\rm bottom} \approx 10^{-12}{\rm s}$$

the top quark entering the precision era

- Total $t\bar{t}$ cross section known at NNLO+NNLL [Mitov, Czakon, Gehrmann, Moch, Bonciani …]
- Use total cross-section for determining the top quark mass and/or α_S [CMS 1307.1907], and to constrain PDFs
- m_t also from $t\bar{t}$+jet [Irles talk]





$$m_t^{\rm pole} = 176.7^{+3.0}_{-2.8}\ \text{GeV}$$

$$\alpha_S(m_Z) = 0.1151^{+0.0028}_{-0.0027}$$

Charge asymmetry = particle-antiparticle asymmetry

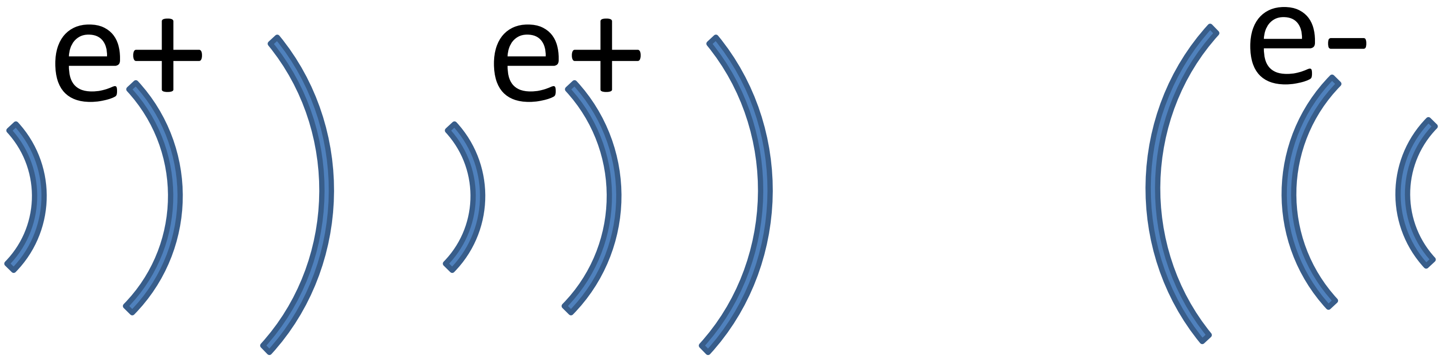
A difference in the angular distribution of **top quarks** with respect to **top antiquarks** at Tevatron or the LHC

A qualitative picture

QED: $e^+ e^- \rightarrow \mu^+ \mu^-$

A qualitative picture

QED: $e^+ e^- \to \mu^+ \mu^-$



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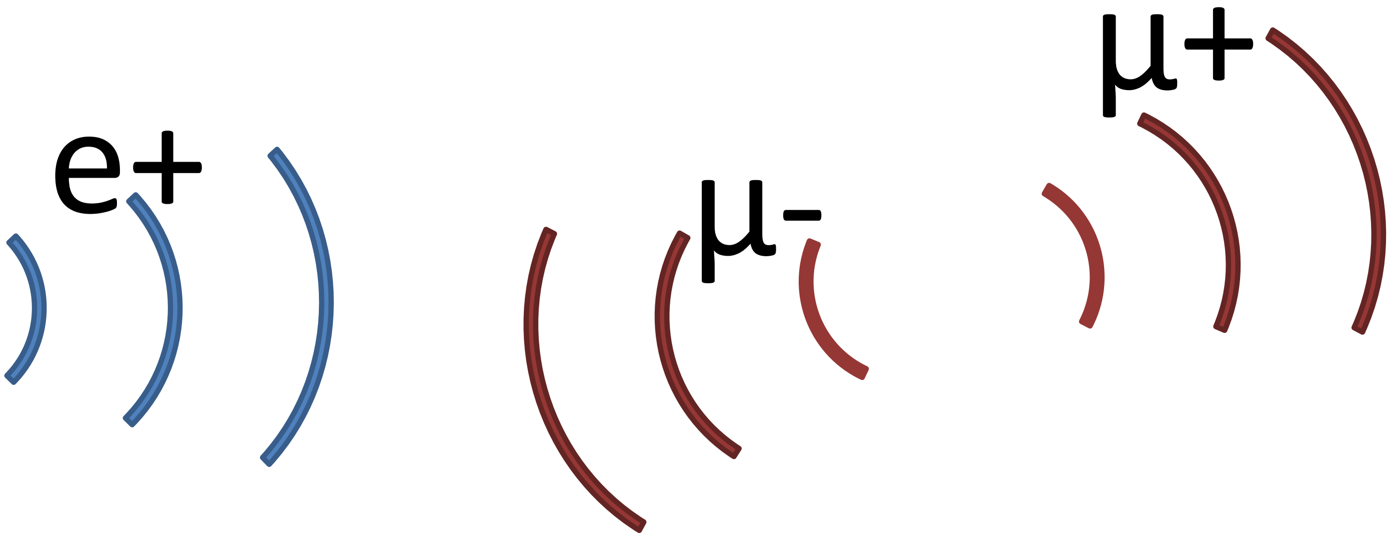
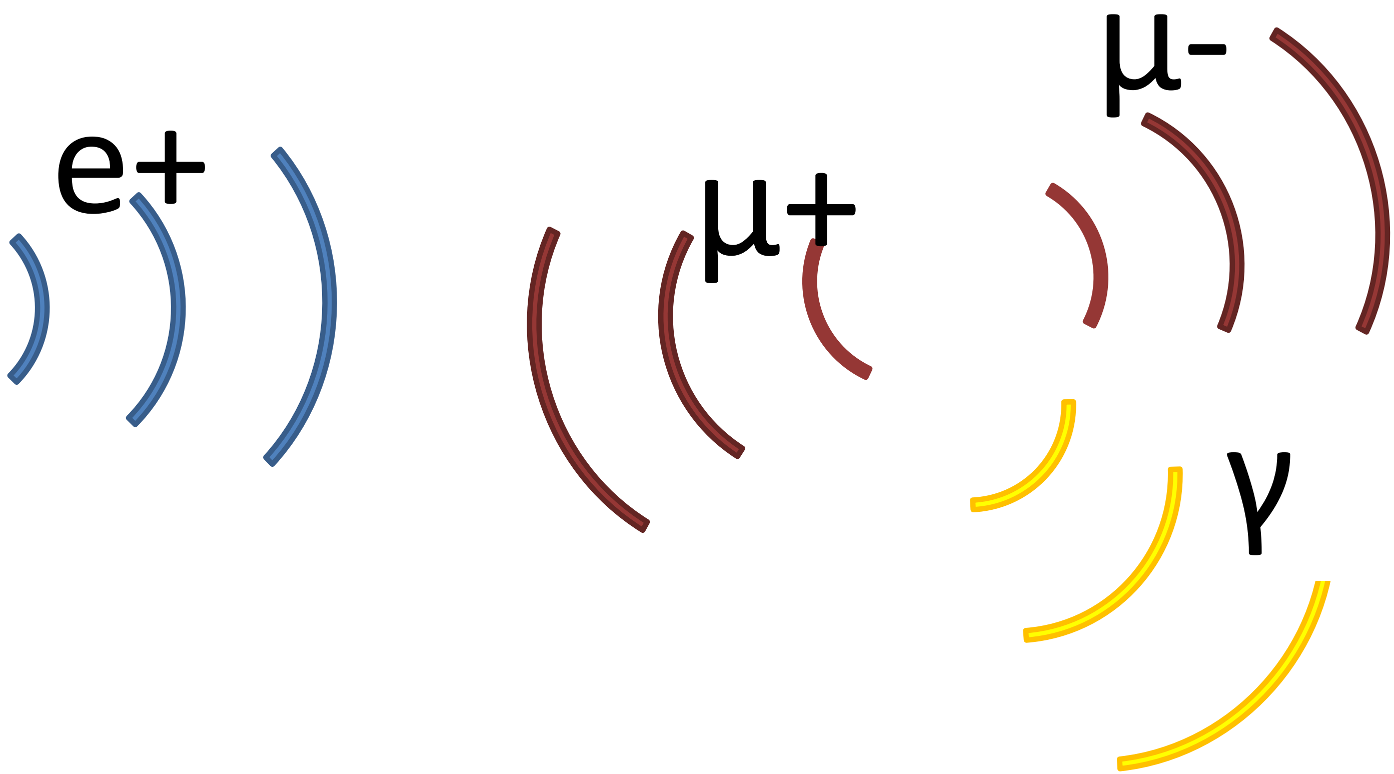


- **Inclusive:** the system is less perturbed if **the outgoing positive electric charge field (colour field of the top)** flows in the direction of **the incoming positive electric charge field (colour field of the incoming quark)**

A qualitative picture

QED: $e^+ e^- \rightarrow \mu^+\mu^-$

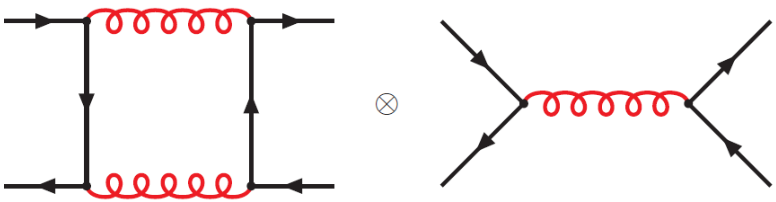


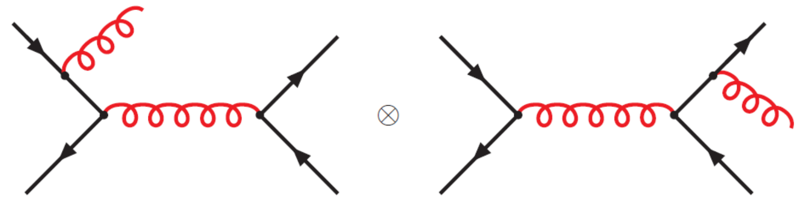
- $\boldsymbol{\mu^+\mu^-\gamma/t\bar{t}g}$ final state, emission of **extra radiation** requires to **decelerate** the electric (colour) charges: negative charge asymmetry

Charge asymmetry in QCD [Kühn, GR, 1998]

At $O(\alpha_S^2)$: top and antitop quarks have identical angular distributions

However, a charge asymmetry arises at $O(\alpha_S^3)$





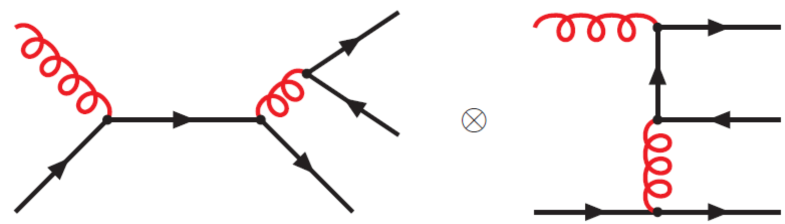
Interference of **box diagrams** with Born **(+soft)**
positive contribution to $t\bar{t}$ +0 jet

>

Interference of **ISR with FSR**
LO for $t\bar{t}$+jet
negative contribution to $t\bar{t}$ +1 jet

- color factor d_{abc}^2 : top pair in color singlet, interference of C=+ with C=-
- Loop (+soft) contribution larger than tree level

top quarks are preferentially emitted in the direction of the incoming quark



Flavor excitation (qg channel) much smaller

SM charge asymmetry (aka FB) at Tevatron

Charge conjugation symmetry* ($N_{\bar{t}}(y) = N_t(-y)$) ⇨ equivalent to forward-backward [Kühn, GR,1998; 2011]

$$A_{\rm lab} = \frac{N(y_t > 0) - N(y_{\bar{t}} > 0)}{N(y_t > 0) + N(y_{\bar{t}} > 0)} = 0.056(7)$$

laboratory frame

$$A_{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} = 0.087(10)$$

$$\Delta y = y_t - y_{\bar{t}}$$

- $A_{\rm lab}$ needs to reconstruct either y_t or $y_{\bar{t}}$
- only $A_{\rm lab}$ is a "true" forward-backward
- $A_{t\bar{t}}$ requires both top and antitop, or Δy
- Different systematics

- $A_{t\bar{t}}$ is equivalent to evaluate the asymmetry in the $t\bar{t}$ rest frame because Δy is invariant under boost, but

$$A_{\rm lab} < A_{t\bar{t}}$$

Not a change in the SM prediction !!!!

* CP violation arising from electric or chromoelectric dipole moments does not contribute to the asymmetry

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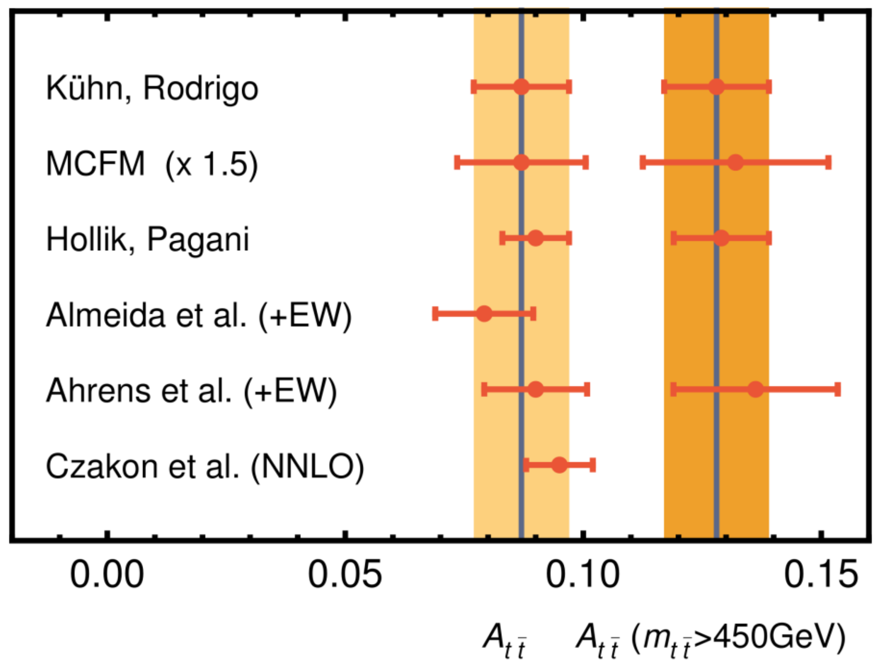
$$A_{t\bar t} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} = 0.087(10) \qquad \Delta y = y_t - y_{\bar t}$$

equivalent to $t\bar{t}$ rest frame
Δy is invariant under boost
but $A_{\rm lab} < A_{t\bar t}$

- mixed QCD-EW interference included: factor 1.2 x QCD [Kühn, GR / Hollik, Pagani]
  Weak Sudakov logs [Manohar, Trott] at most 0.02-0.03
- first contribution to the antisymmetric cross-section is a loop effect, first contribution to the symmetric x-section is tree level: asymmetry normalized to LO cross-section (otherwise a factor 1.3 lower)
- stable to threshold resummation: per mille shift of central value, and less sensitive to normalization [Almeida et al., Ahrens et al., Melnikov&Schulze]
- NNLO [Czakon et al., Gehrmann et al.] in agreement with NLO

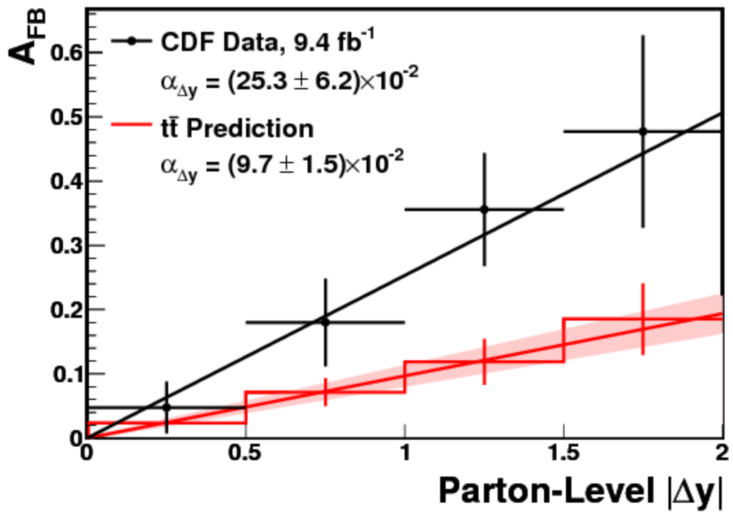


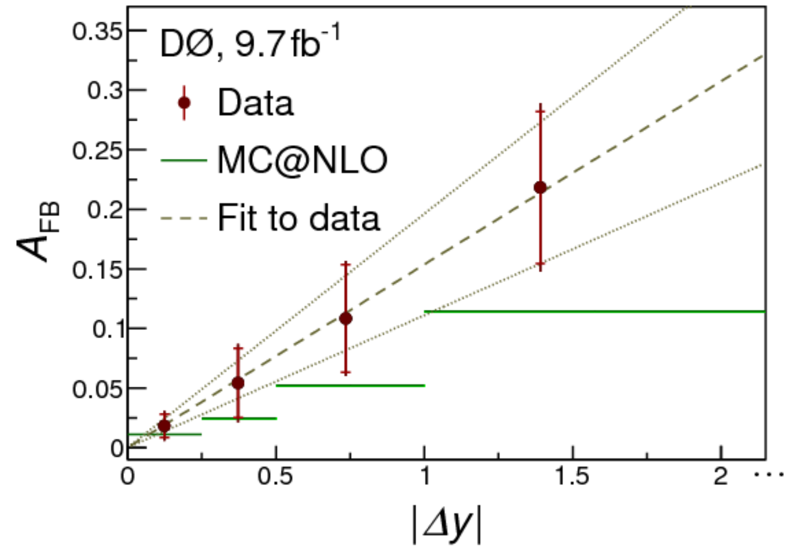
▶ Main difference among theoretical predictions due to renormalization scale choice, asymmetry proportional to the strong coupling [BLM scale choice could increase the asymmetry]

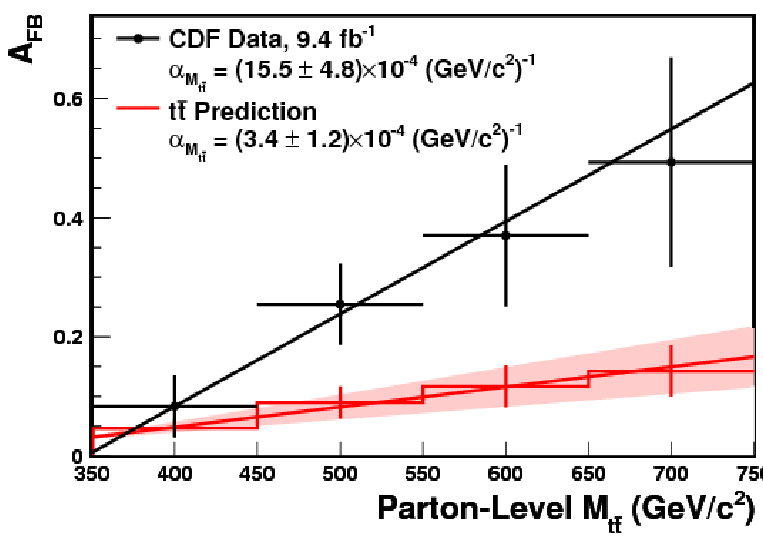
▶ small dependence on PDFs / top quark mass: it´s a ratio

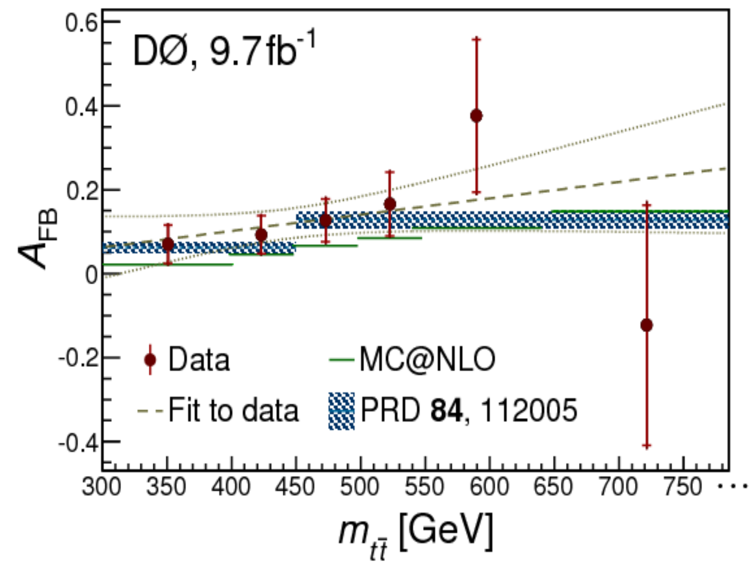
CDF arXiv:1211.1003
Inclusive asymmetry
A_{FB} = 0.164 (47)   1.6σ

D0 arXiv:1405.0421
Inclusive asymmetry
A_{FB} = 0.106 (30)   0.6σ









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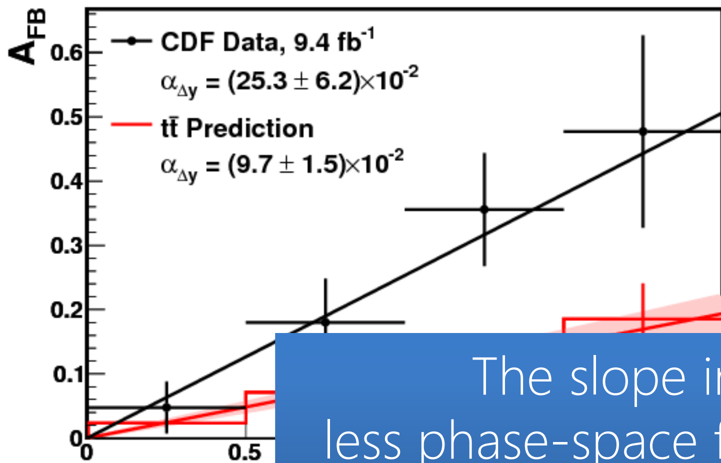
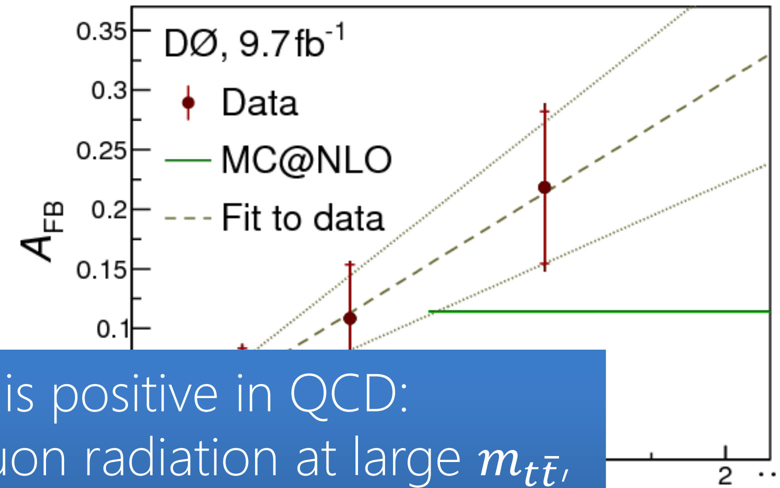
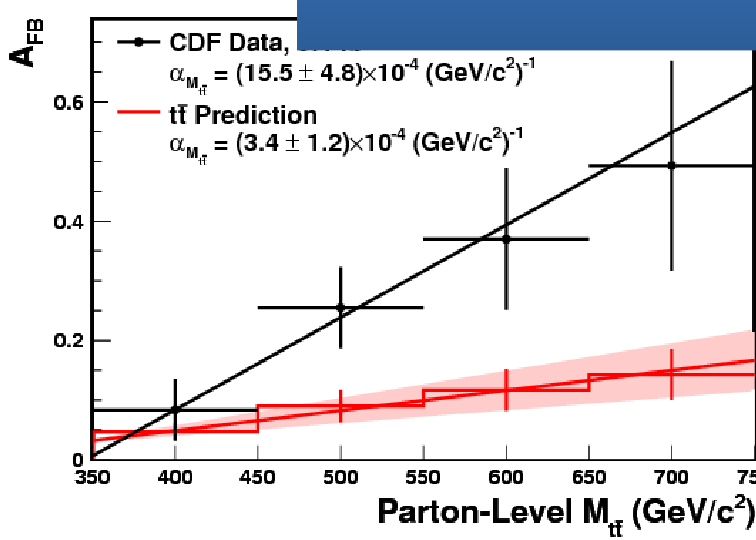
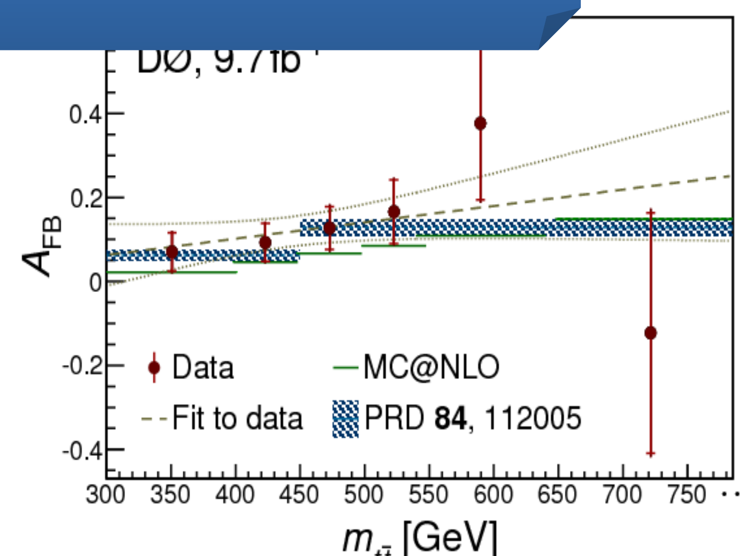


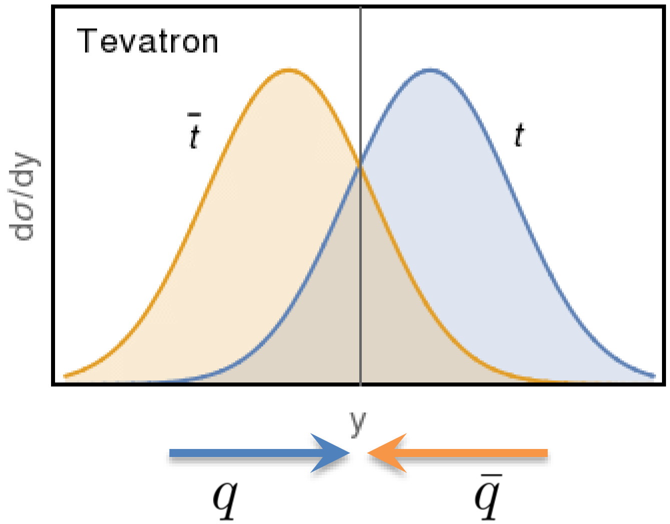


The slope in $m_{t\bar{t}}$ is positive in QCD:
less phase-space for gluon radiation at large $m_{t\bar{t}}$,
less negative $t\bar{t}$+jet contribution at large $m_{t\bar{t}}$





From Tevatron to the LHC



- **At Tevatron:** valence quarks and valence antiquarks of similar momenta collide, still $A_{\rm lab} < A_{t\bar{t}}$

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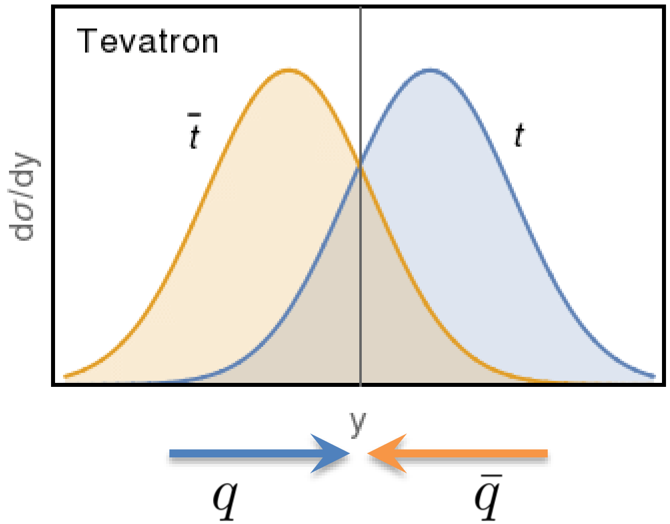
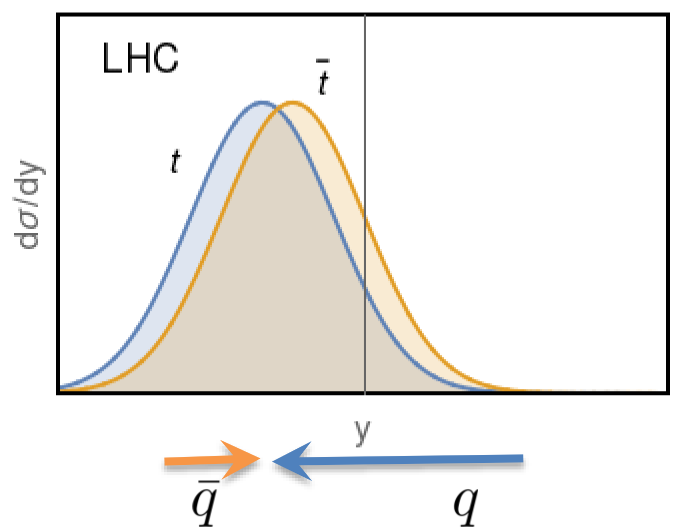
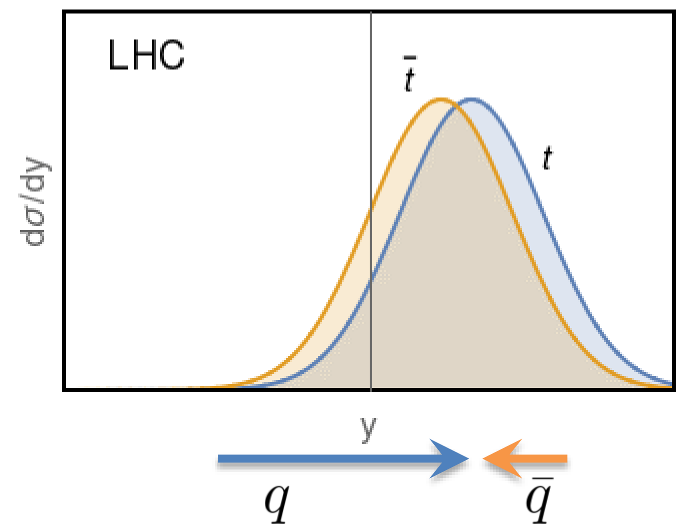


- At Tevatron: valence quarks and valence antiquarks of similar momenta collide, still $A_{\mathrm{lab}} < A_{t\bar{t}}$

- LHC is symmetric ► no forward-backward, but same charge asymmetry
- valence quarks collide with sea antiquarks, which carry less momenta
- excess of tops quarks in the forward and backward regions





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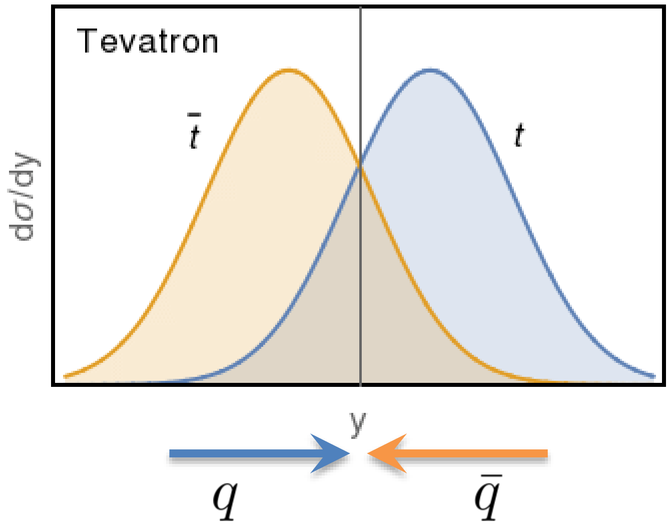

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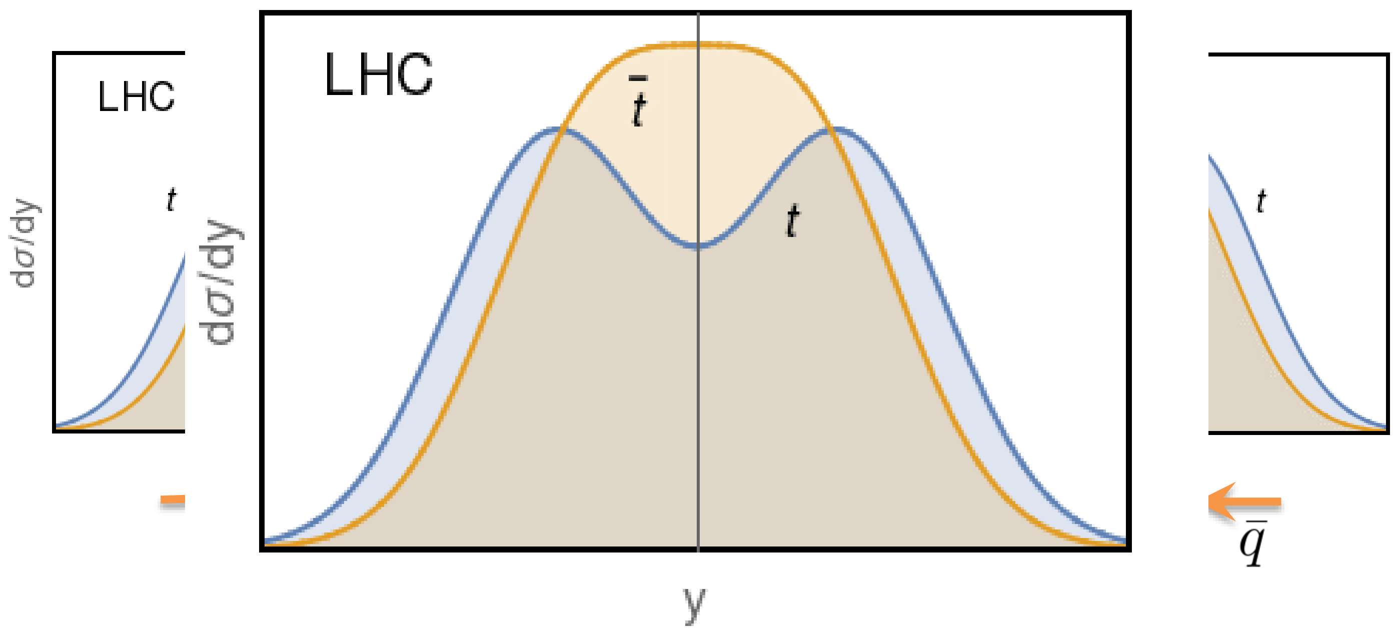
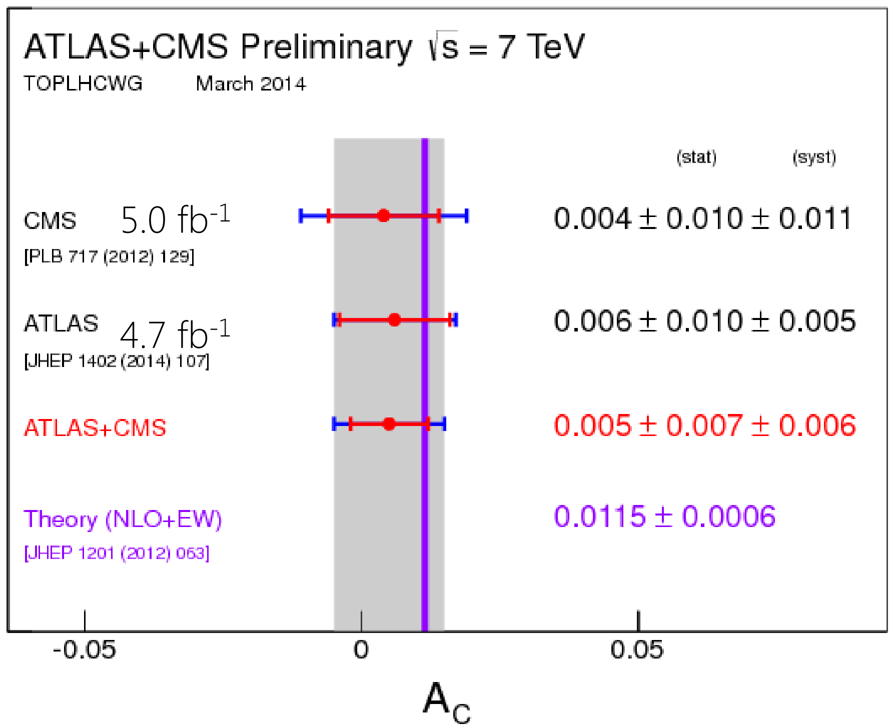


Charge asymmetry at the LHC

$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|>0)}{N(\Delta|y|>0) + N(\Delta|y|<0)} = \begin{cases} 0.0115(6)@7\text{TeV} \\ 0.0102(5)@8\text{TeV} \\ 0.0059(3)@14\text{TeV} \end{cases}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}| > 0 \quad \text{if} \quad (y_t + y_{\bar{t}})\Delta y > 0$$



- Expected statistical error down by 1/2 with the 8 TeV sample (ongoing measurements at ATLAS and CMS)
- much better at Run II although asymmetry by 1/2 @ 13-14 TeV

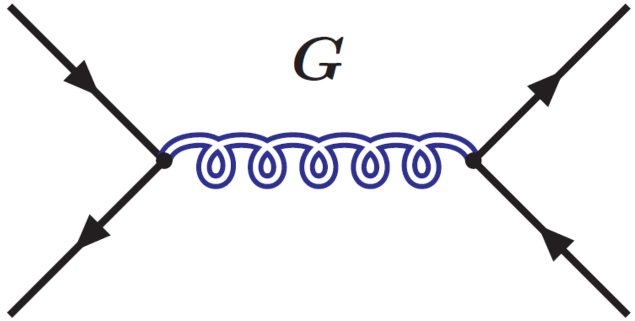
Charge asymmetry at the LHC

- The LHC is gg dominated (symmetric): asymmetry is diluted
- in this sense Tevatron, which is a $q\bar{q}$ collider was a unique place to probe the asymmetry (no more data)
- introduce cuts to enrich the $q\bar{q}$ sample
  - large $m_{t\bar{t}}$: gg dominate at small x, also closer to BSM
  - large rapidities: gg more central
  - tag quark events with initial state $W^{\pm}$ [Maltoni et al., 1406.3262]

	Order	$t\bar{t}W^{\pm}$	$t\bar{t}W^{+}$	$t\bar{t}W^{-}$
σ(fb)	LO	$140.5^{+27\%}_{-20\%}$	$98.3^{+27\%}_{-20\%}$	$42.2^{+27\%}_{-20\%}$
	NLO	$210^{+11\%}_{-11\%}$	$146^{+11\%}_{-11\%}$	$63.6^{+11\%}_{-11\%}$
A_c^t (%)	NLO	$2.49^{+0.75}_{-0.34}$	$2.73^{+0.74}_{-0.42}$	$2.03^{+0.81}_{-0.19}$
	NLO+PS	$2.37^{+0.56}_{-0.38}$	$2.51^{+0.62}_{-0.42}$	$1.90^{+0.51}_{-0.35}$

- The price, statistics, is not a problem

New physics in the s-channel: Axigluons or KK gluons



Color-octet resonances

$$\mathcal{L} = g_S\, T^a\, \bar{q}_i\, \gamma^\mu (g_V^{q_i} + g_A^{q_i}\gamma_5)\, G_\mu^a\, q_i$$

might produce a charge asymmetry through the interference with the LO SM amplitude

But this asymmetry is **negative** because it is proportional to

$$(\hat{s} - m_G^2)\, g_A^q\, g_A^t$$

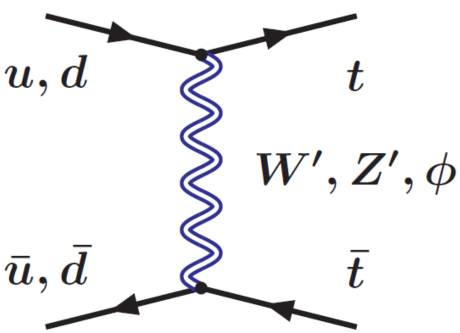
A **positive** asymmetry can be generated if

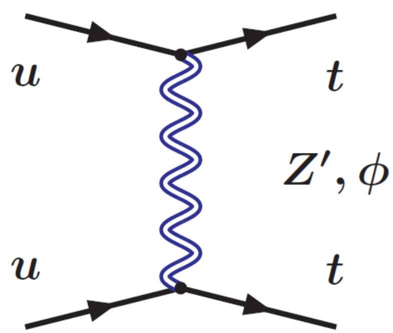
- very light axigluon: but would be visible in $m_{t\bar{t}}$: new decay channels to enlarge the width [Marques Tavares, Schmalz]
- vector-axial couplings of opposite sign: $\mathrm{sign}(g_A{}^q) = -\mathrm{sign}(g_A{}^t)$ [Ferrario, GR, Frampton, Shu, Wang ...]
- the square of the BSM amplitude dominates, which is proportional to $g_V{}^q g_V{}^t g_A{}^q g_A{}^t$: large vector couplings [Ferrario, GR]
- Heavy Stealth gluons: $G \to Q\bar{q}$ with Q a quark excitation decaying like the top quark [Barcelo, Carmona, Masip, Santiago]

Very constrained by dijet and $t\bar{t}$ diff cross-section at LHC

New physics in the t-channel

[Jung, Murayama, Pierce, Wells / Cheung, Keung,Yuan / Cao, Heng, Wu,Yang / Barger, Keung, Yu / Cao, McKeen, Rosner, Saughnessy, Wagner / Berger, Cao, Chen, Li, Zhang / Bhattacherjee, Biswal, Ghosh/ Zhou, Wang, Zhu / Aguilar-Saavedra, Perez-Victoria/ Buckley, Hooper, Kopp, Neil / Rajaraman, Surujon, Tait/ Duraisamy, Rashed, Datta, Shu, Tait,Wang / Cao,Heng,Wu,Yang / Dorsner, Faifer, Kamenik, Kosnik / Jung, Ko,Lee,Nam/ Patel, Sharma / Ligeti, Marques Tavares, Schmalz, ...]





- Because of color algebra a Z' (SM Z) in the s-channel does not interfere with the LO QCD amplitude
- (coloured) scalars do not generate an asymmetry in the s-channel

- A sizeable asymmetry requires large flavour violating couplings [Jung,Murayama,Pierce,Wells]
- Relatively light Z´ and/or W´: O(200-700 GeV), or O(1TeV) colored scalars
- like sign $tt + \bar{t}\bar{t}$ very constrained at Tevatron and the LHC: Z' soon excluded
- Also new resonances in strongly interacting theories [Brod et al.]

Are the Tevatron and LHC asymmetries correlated ?

- **YES**, in the SM (QCD): an excess at Tevatron predicts and excess at the LHC

Are the Tevatron and LHC asymmetries correlated ?

- **YES**, in the SM (QCD): an excess at Tevatron predicts and excess at the LHC

- **BUT**, at Tevatron the ratio of $u\bar{u}$ wrt $d\bar{d}$ events is 4:1
- at the LHC is 2:1
- if the flavour asymmetries have opposite sign the cancellation is different at Tevatron and the LHC

  - EW corrections at Tevatron > LHC (weak almost cancel), but are too small
  - Sizeable in BSM models [Drobnak, Kamenik, Zupan]

The asymmetry through the decay products

[Godbole, Rao, Rindani,Singh / Jung, Ko, Lee/ Choudhury, Godbole, Rindani, Saha/ Cao, Wu, Yang / Melnikov, Schulze / Bernreuther, Si/ Krohn, Liu, Shelton, Wang / Bai, Han/ Baumgart, Tweedie, ...]

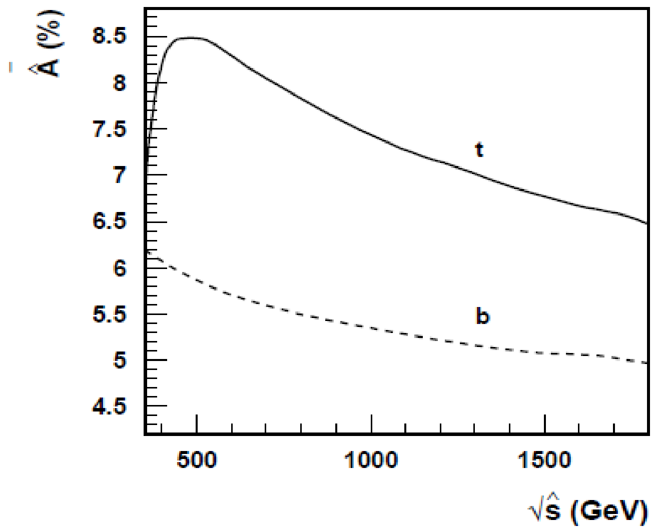
■ Direction of the lepton (antilepton) correlated with the direction of the top quark (antitop quark), particularly for very boosted tops: same asymmetries

$$y_t \to y_\ell \;, \Delta y \to \Delta y_\ell \;, \Delta|y| \to \Delta|y_\ell|$$

☑ leptons are well measured
☒ the asymmetry is diluted by a factor 2 (approx.)

■ Top quarks are almost unpolarised in the SM
☑ BSM might polarize top quarks, and they decay before hadronizing:
lepton asymmetries are sensible to BSM polarization (angular distribution of the lepton wrt the parent top) and spin correlations

Bottom quark asymmetry



* Partonic asymmetry: ratio of antisymmetric to symmetric $q\bar{q}$ cross-sections [Kühn, GR, 98]

Same effect for bottom production, but much more supressed by gluon fusion, even at Tevatron: inclusive asymmetry almost vanishes

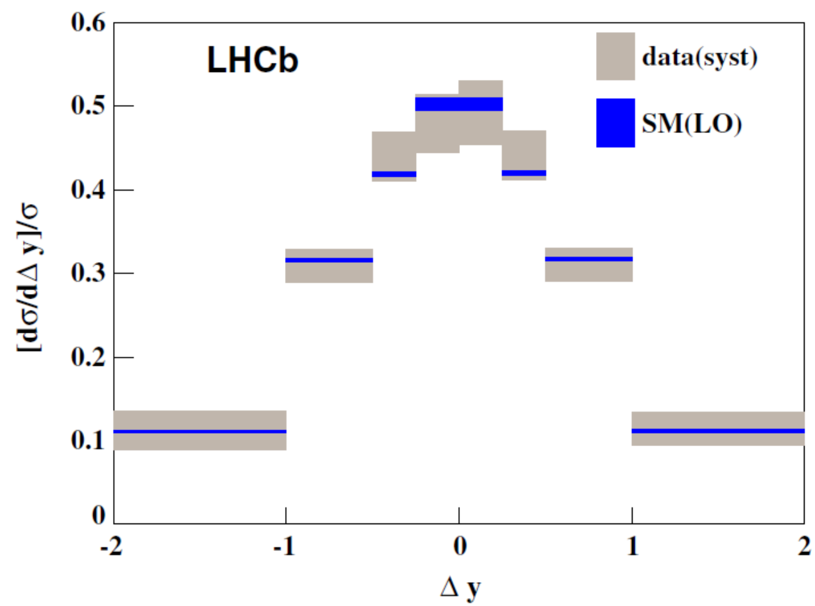
A_{lab}=4.3%-5.1% for $m_{b\bar{b}} > 300$ GeV |cos θ|<0.9 Tevatron [Hogan et. al., D0]

$$A_C^{b\bar{b}}(40,75) = 0.4 \pm 0.4(\text{stat}) \pm 0.3(\text{syst})\%$$

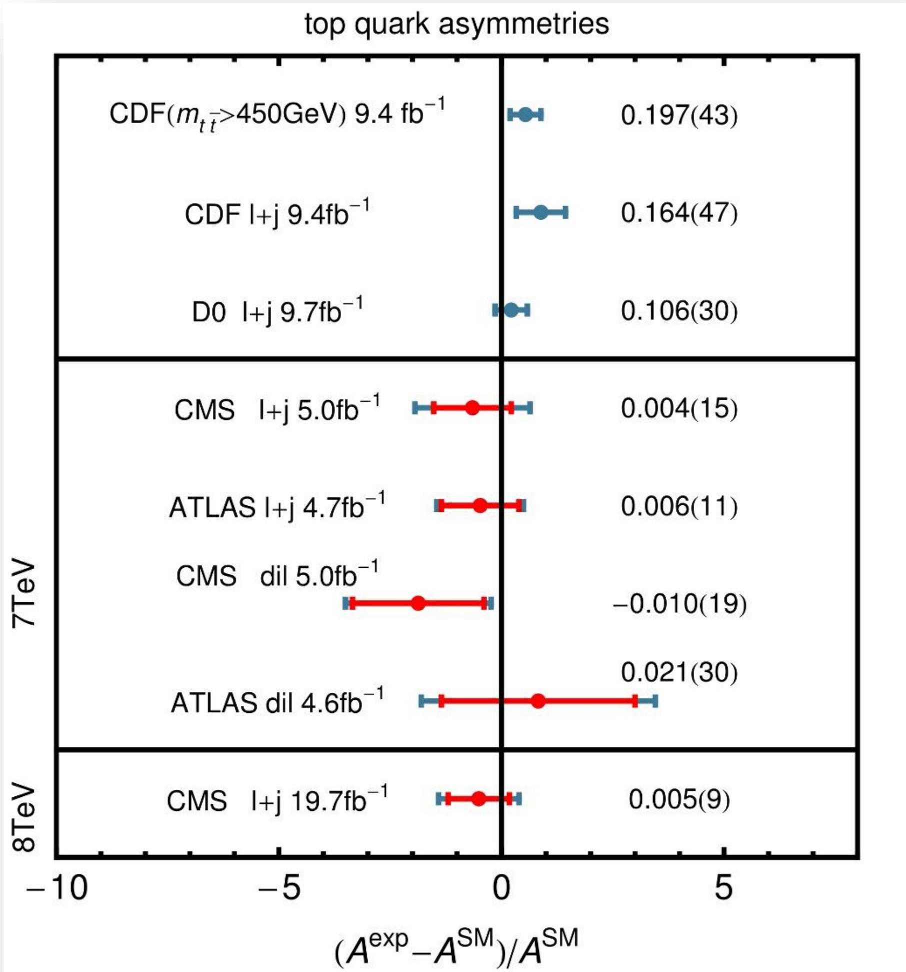
$$A_C^{b\bar{b}}(75,105) = 2.0 \pm 0.9(\text{stat}) \pm 0.6(\text{syst})\%$$

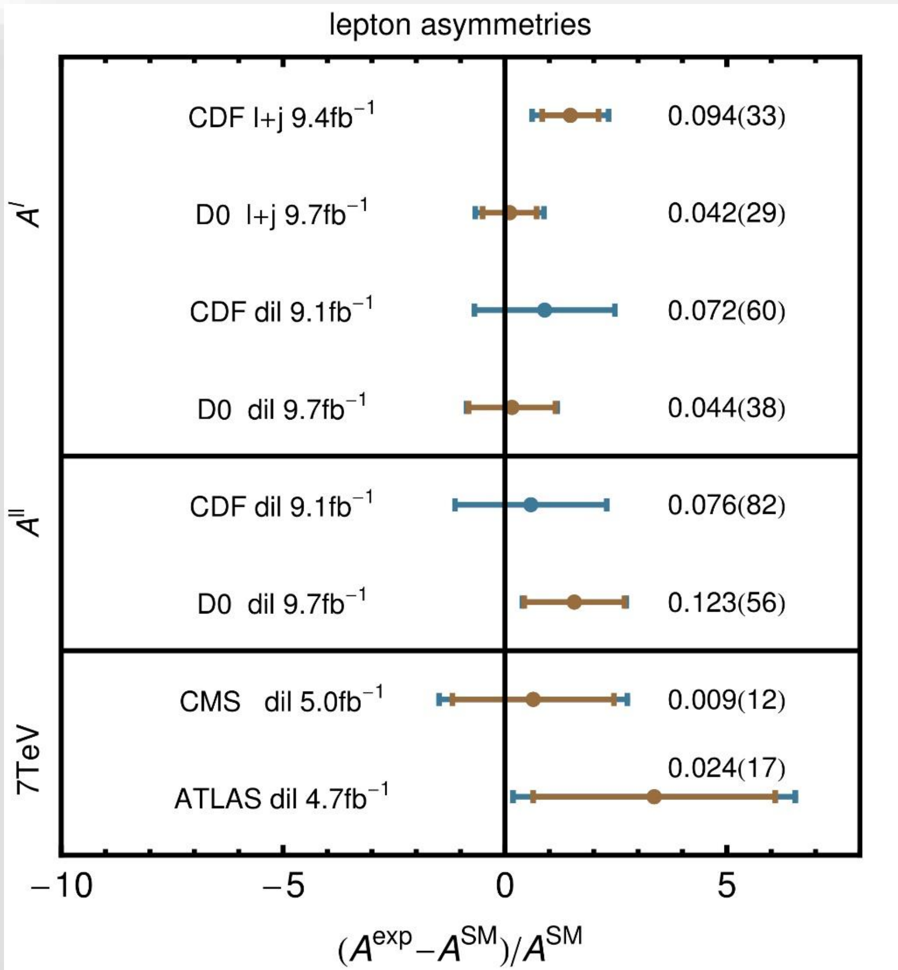
$$A_C^{b\bar{b}}(>105) = 1.6 \pm 1.7(\text{stat}) \pm 0.6(\text{syst})\%$$

- Compatible with SM = 1%
- Measurement close to the Z pole, it is the asymmetry generated by the SM Z in the s-channel, not (yet) the QCD asymmetry



My (preliminary) summary





Summary

- **NNLO** results confirm the stability of SM prediction to higher orders (already anticipated from resummed calculations).
- Better agreement with the SM is not due to a change in the theory prediction but to a lower value of latest D0 measurement, moreover CDF anomaly milder than before.
- **Tevatron anomalies** have boosted a better understanding of the properties of the top quark in recent years, both for BSM model building and precision physics.
- Plenty of room for further analysis of the top quark / lepton / and bottom asymmetries at the next run of the **LHC**.
- Linear Collider: large EW asymmetry from Z exchange at tree-level / probe of complementary BSM.

THE PHYSICS OF THE TOP QUARK IS

BSEMYQOCND

SCHRÖDINGER'S CAT IS

ADLEAVDE