Asymmetries at (Hadron) Colliders

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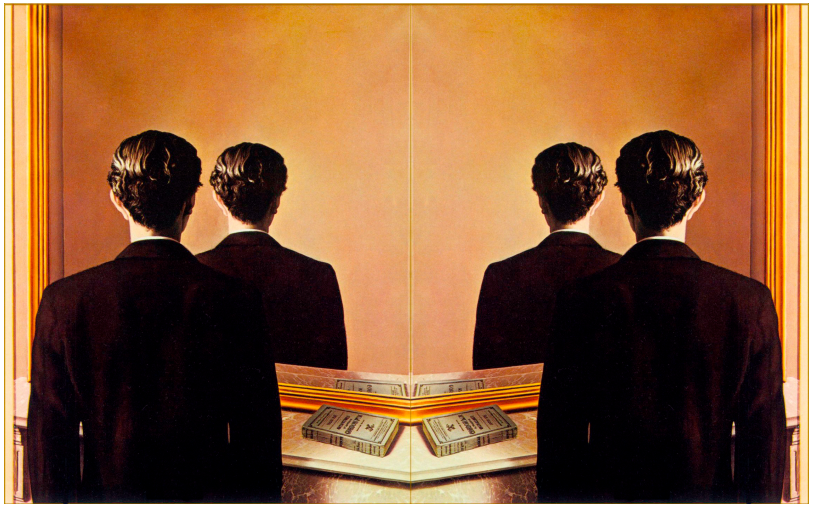
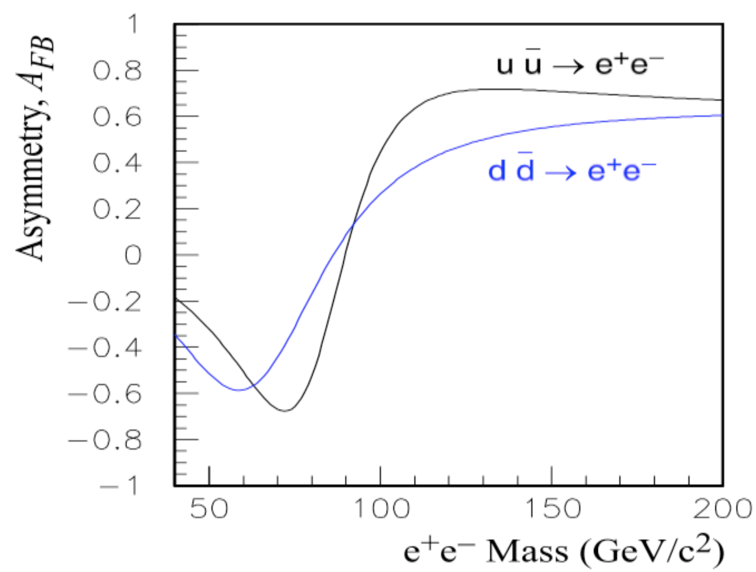


Asymmetry Measurements

- Provide precise tests of the standard model
  - SM makes specific predictions on asymmetries
  - Test higher order QCD predictions (e.g. top quark charge asymmetry)
  - Useful in searches for new particles
- Allow to measure some parameters of the SM and (new) particle properties.
- Identify
  - production mechanisms.
  - Couplings and spin



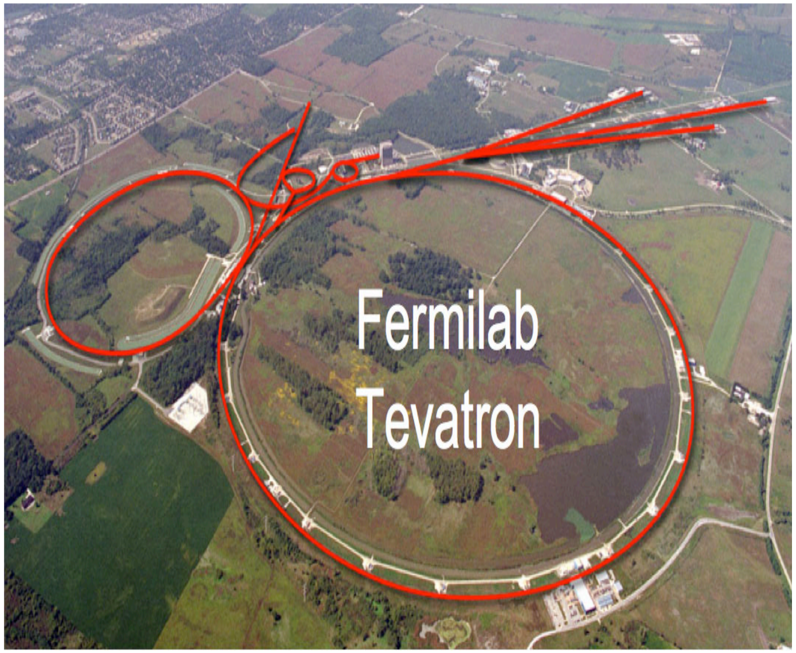
Asymmetries defined in ratios → Free of some of the uncertainties.

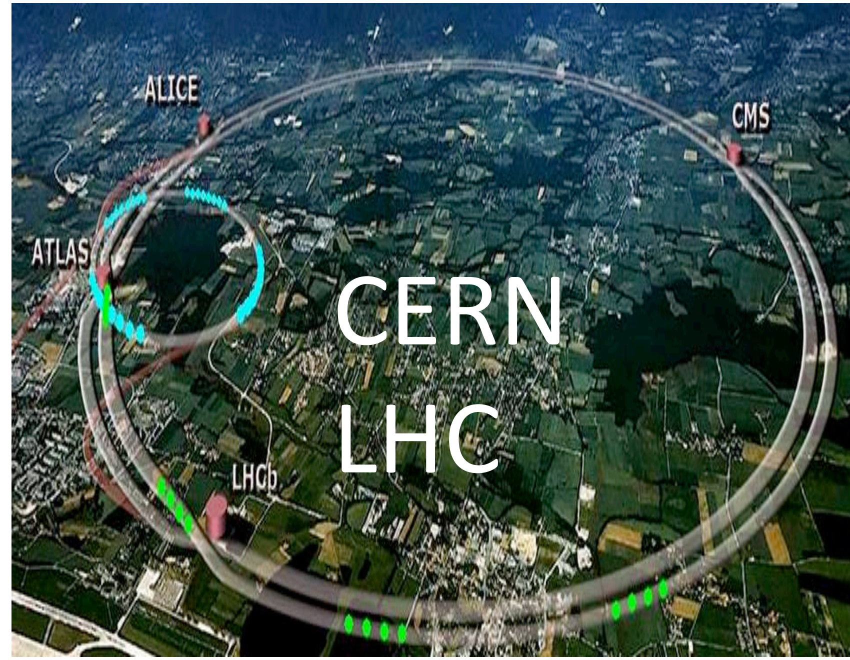
This talk:

→ Asymmetries due to interference/higher-order QCD effects.

→ Asymmetries in direction, charge, and in angles.

Asymmetries at Hadron Colliders





$P\bar{P}$ collider

Parity → changes the direction of proton and anti-proton
Charge → changes the direction of proton and anti-proton

CP symmetric $\sigma_{total} = \bar{\sigma}_{total}$
not C and P symmetric separately

PP collider

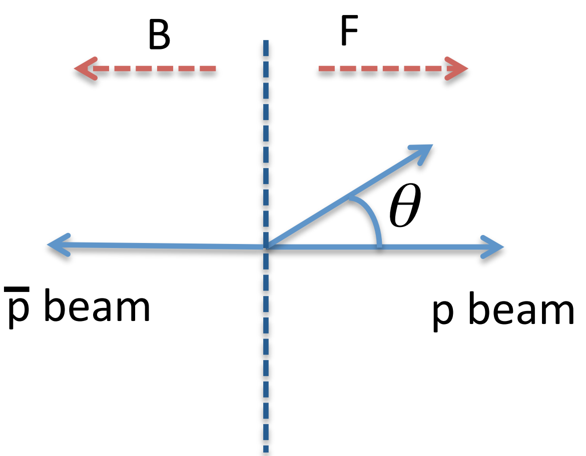
Parity → changes nothing
Charge → Makes LHC an anti-proton collider.

Not CP symmetric $\sigma_{total} \neq \bar{\sigma}_{total}$
not C symmetric but P symmetric.

Asymmetries at Hadron Colliders

$P\bar{P}$ collider (Tevatron)

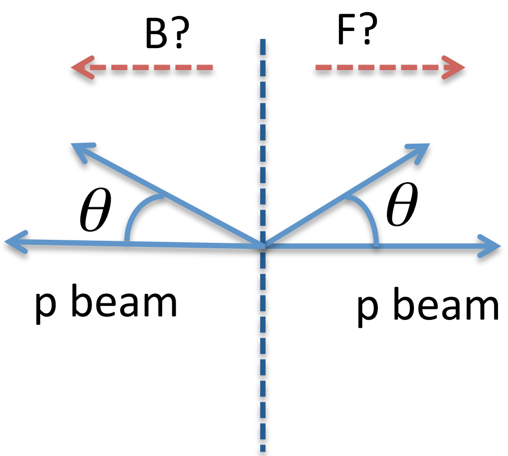
Parity asymmetric



Allows the definition of a forward (backward) hemisphere based on the P direction.

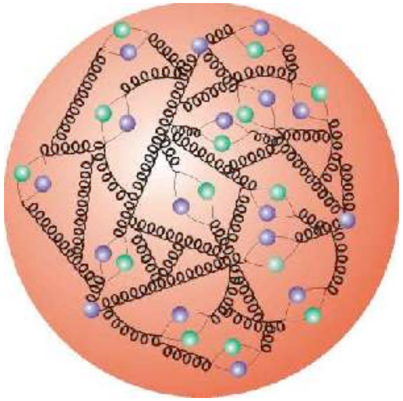
PP collider (LHC)

Parity symmetric



Does not allow the definition of a forward (backward) hemisphere based on the P direction, unless we consider the Parton Distribution Functions (PDFs.)

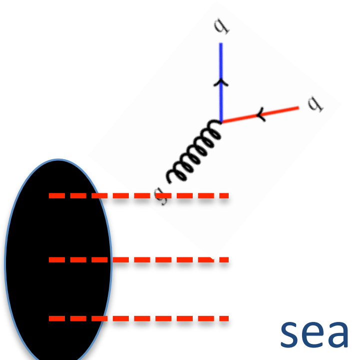
Nucleon Structure



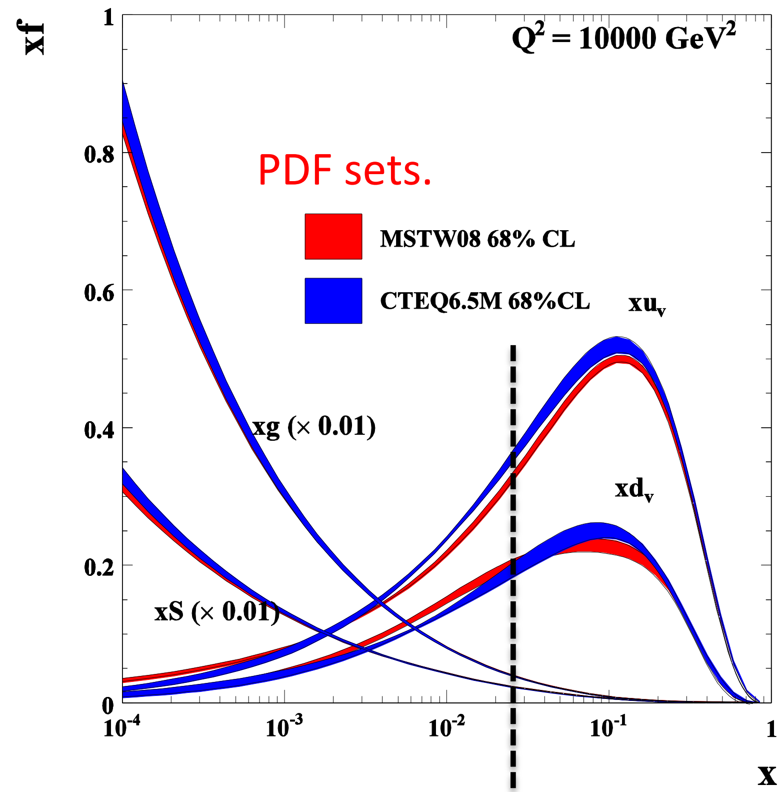
- Hadron collider = parton collider
- $f_i(x,Q^2)$ probability to find a parton to carry the fraction x of the longitudinal hadron momentum at the energy scale Q^2.
  - Intrinsic property of the nucleon → process independent.
  - Parametrized by PDF sets.

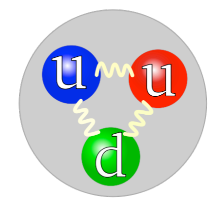
The quark sea:

Valence quarks emit gluons that in turn split into quark-antiquark pairs.



sea quarks dominate.

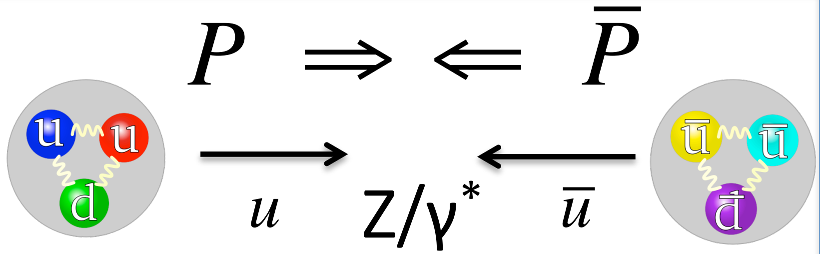




determine the quantum numbers of the hadron.

Valence quarks dominate.

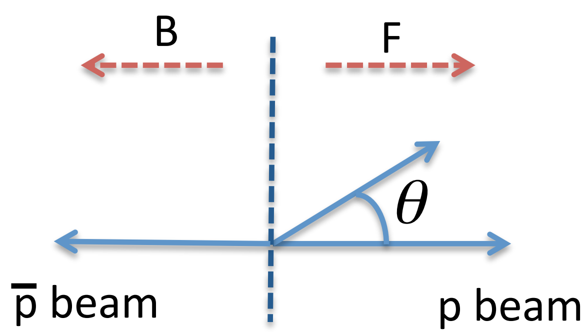
Asymmetry from Interference $A_{FB}^{\ell^+\ell^-}$

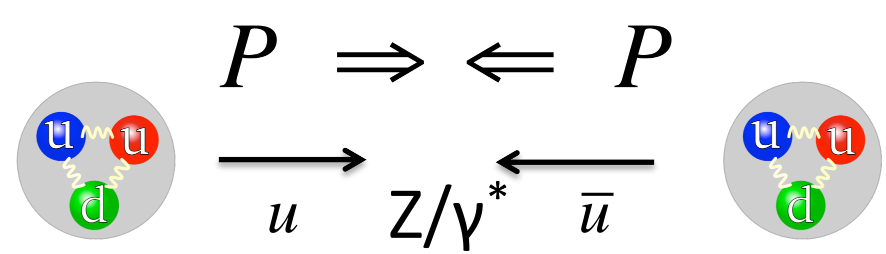


(valence – valence)

Asymmetric due to inteference,
Parity asymmetric, PDF symmetric

quark direction known

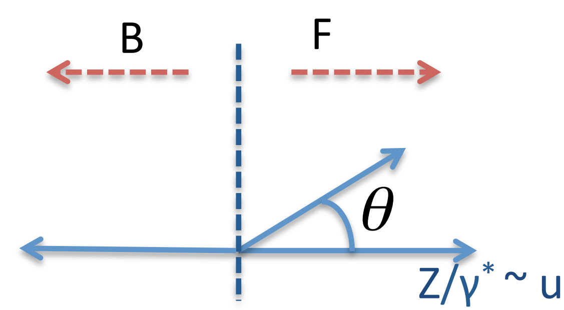




(valence – sea)

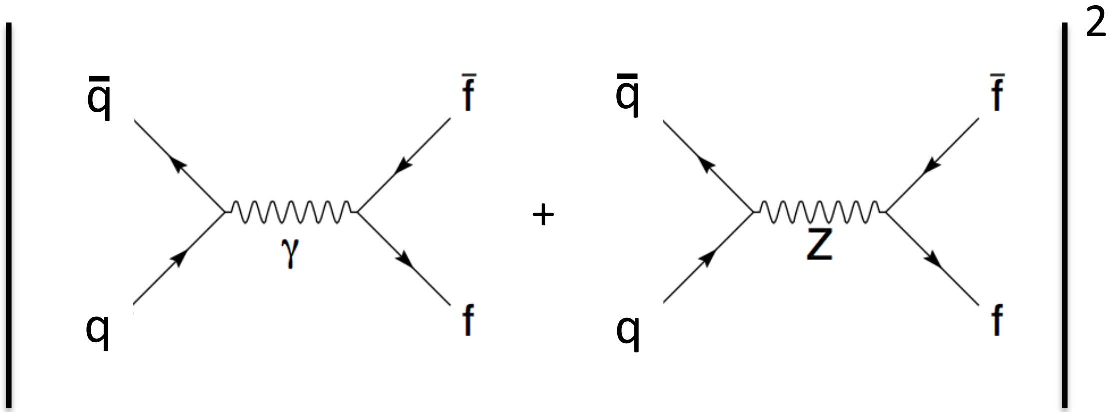
Asymmetric due to interference,
Parity symmetric, PDF asymmetric

u in P is harder than ū from the quark sea.
→ Z/γ* is boosted along u.



Asymmetry from Interference $A_{FB}^{\ell^+\ell^-}$

- Interference between virtual photon and Z exchange.



$$\sigma \propto \left|A_{EM} + A_{weak}\right|^2 = \left|A_{EM}\right|^2 + \left|A_{weak}\right|^2 + 2\mathrm{Re}\left(A_{EM} A^*_{weak}\right)$$

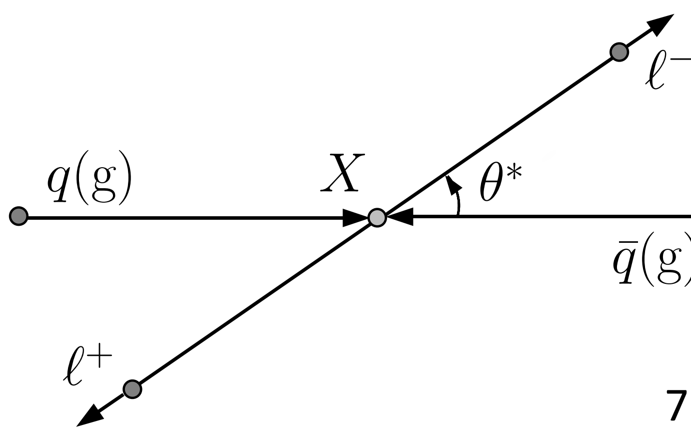
Lowest order differential cross-section:

parity violating term

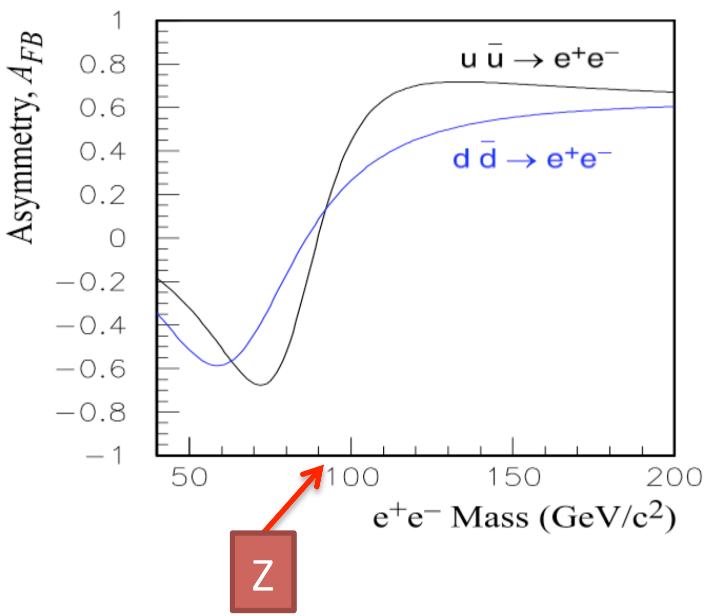
$$\frac{d\sigma(s)}{d\cos\theta^*} = \sigma(s)\left[\frac{3}{8}\left(1+\cos^2\theta^*\right) + A_{FB}(s)\cos\theta^*\right]$$

→ Forward-backward asymmetry

$$A_{FB} = \frac{N\left(\cos\theta^* > 0\right) - N\left(\cos\theta^* < 0\right)}{N\left(\cos\theta^* > 0\right) + N\left(\cos\theta^* < 0\right)} = \frac{N_F - N_B}{N_F + N_B}$$

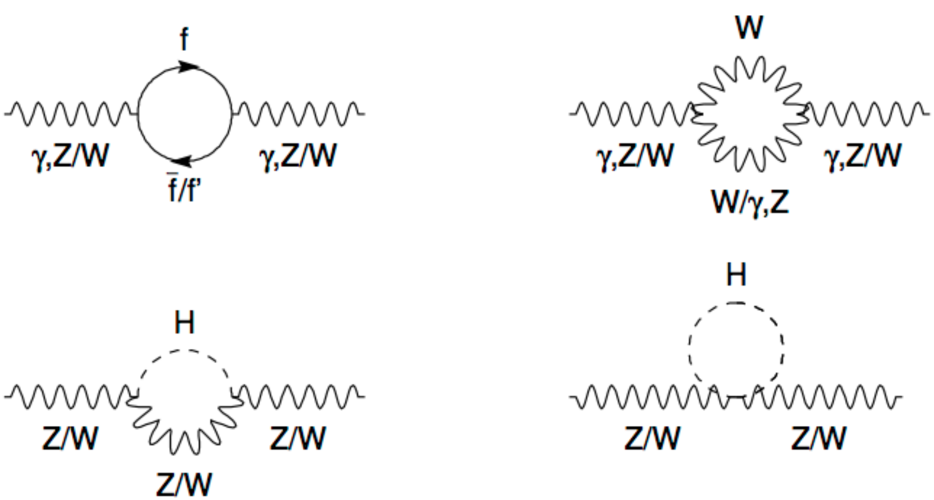


Asymmetry from Interference $A_{FB}^{\ell^+\ell^-}$



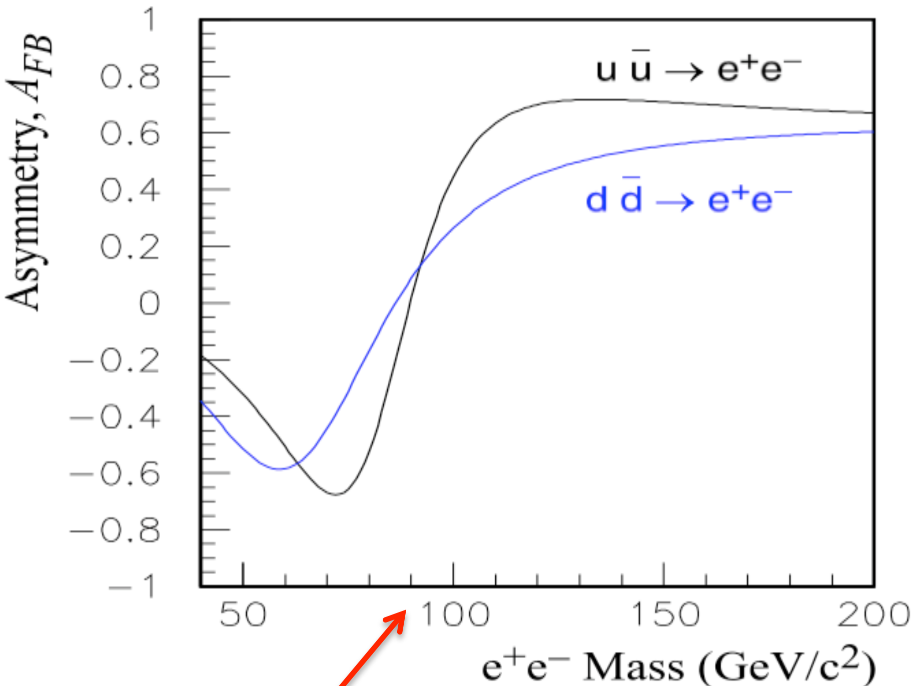
- A_{FB} depends on √s = M, weak mixing angle, couplings.
- Near the Z peak

$$A_{FB} \propto \sin^2\theta_{eff}^{\ell}$$



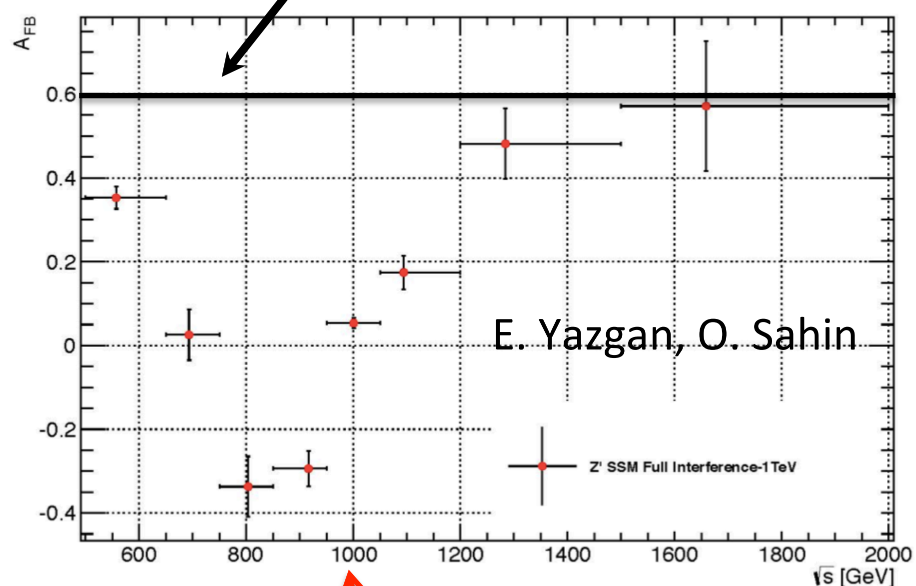
$$\sin^2\theta_{eff}^{\ell} = \frac{1}{4}\left(1 - \frac{g_{V\ell}}{g_{A\ell}}\right)$$

Asymmetry from Interference $A_{FB}^{\ell^+\ell^-}$



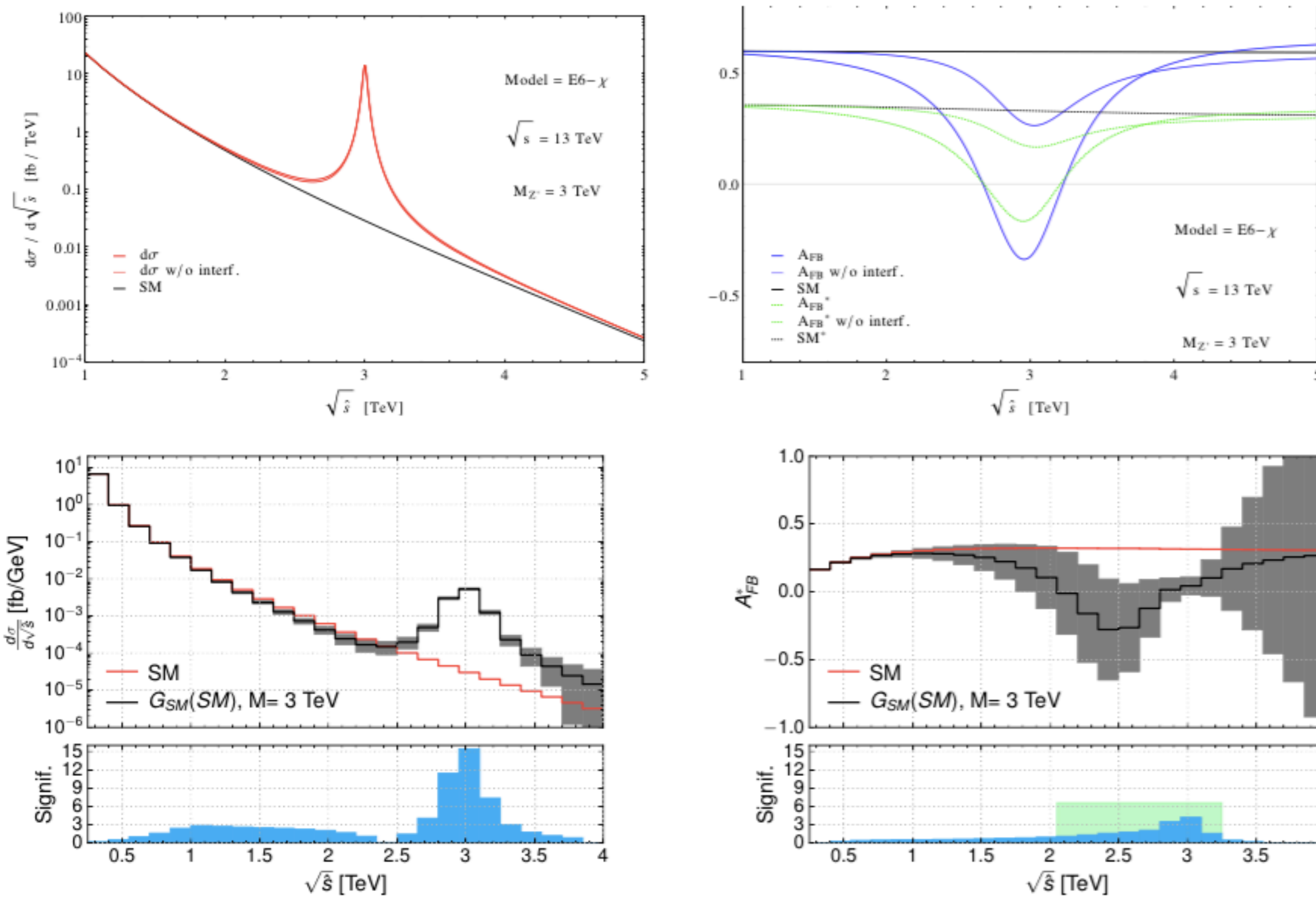
Z

A_{FB}(SM) = 0.6 for ~>150 GeV



Z'(1 TeV)

- A_{FB} constant for M>>M_Z (← effectively γ=Z).
- At high dilepton mass, deviations from the SM prediction may indicate the existence of neutral BSM particles (e.g. Z').
- A_{FB} might be more effective in identifying a broad resonance than using dilepton mass spectrum.

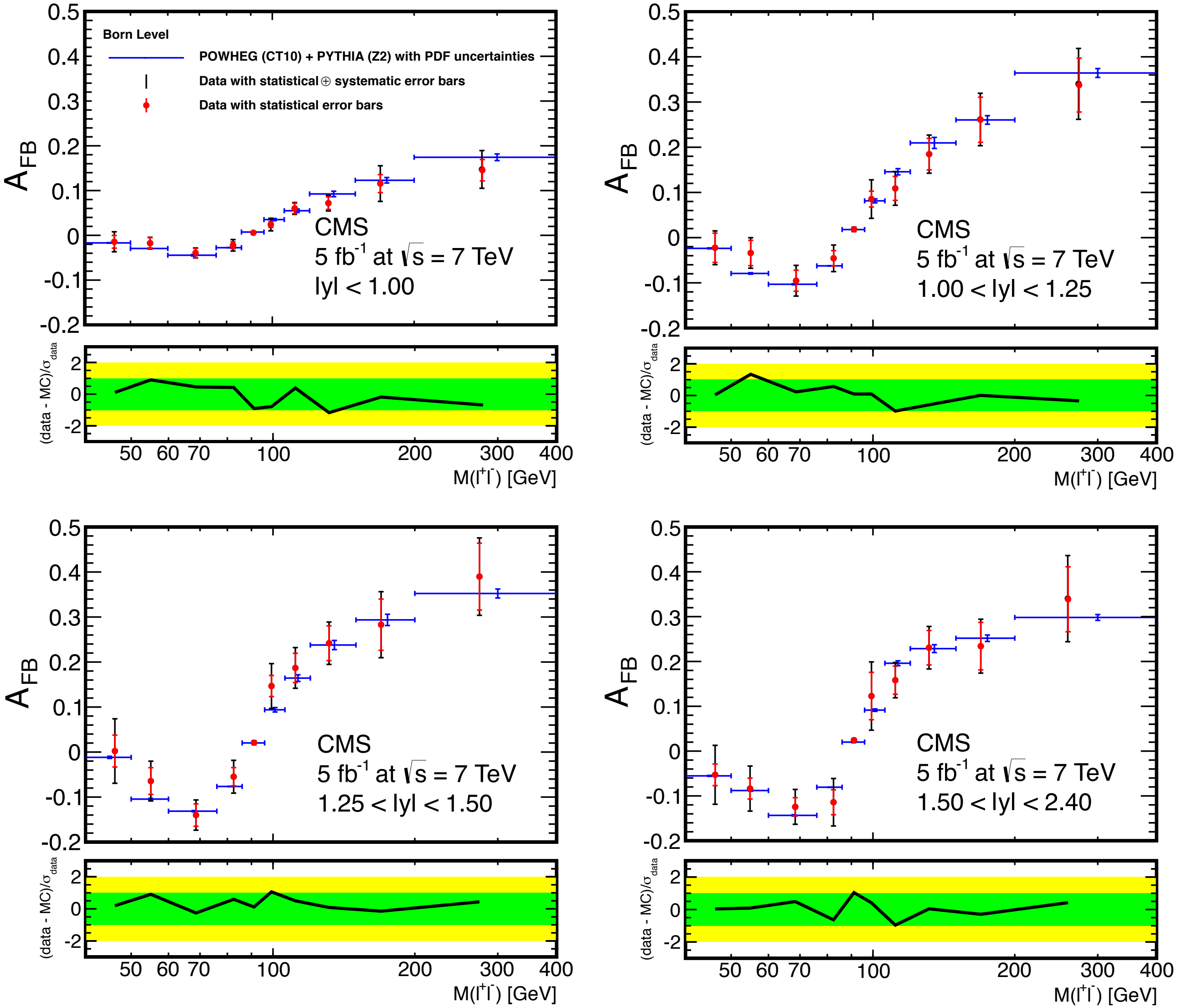


A paper from today! Accomando et al., arXiv:1503.02672

300 fb^{-1}

- AFB → comparable sensitivity to narrow resonance searches using invariant mass spectrum.

$A_{FB}^{\ell^+\ell^-}$ Measurement in CMS



PLB 718 (2013) 752

- A_{FB} vs M shows the photon Z Boson interference predicted by the SM.
- No new particles at high mass. At LHC Run II, we will probe much higher invariant mass values.

$$y = rapidity = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

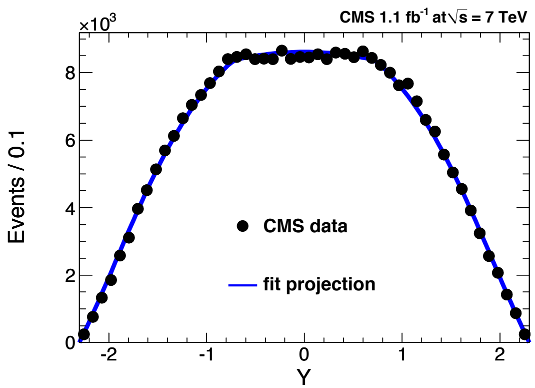
$$\eta = pseudo\ rapidity$$

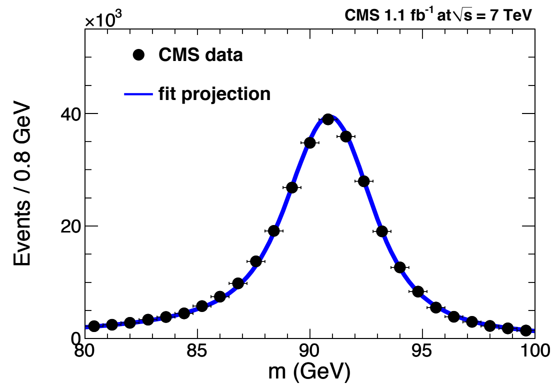
$$= -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Effective Weak Mixing Angle

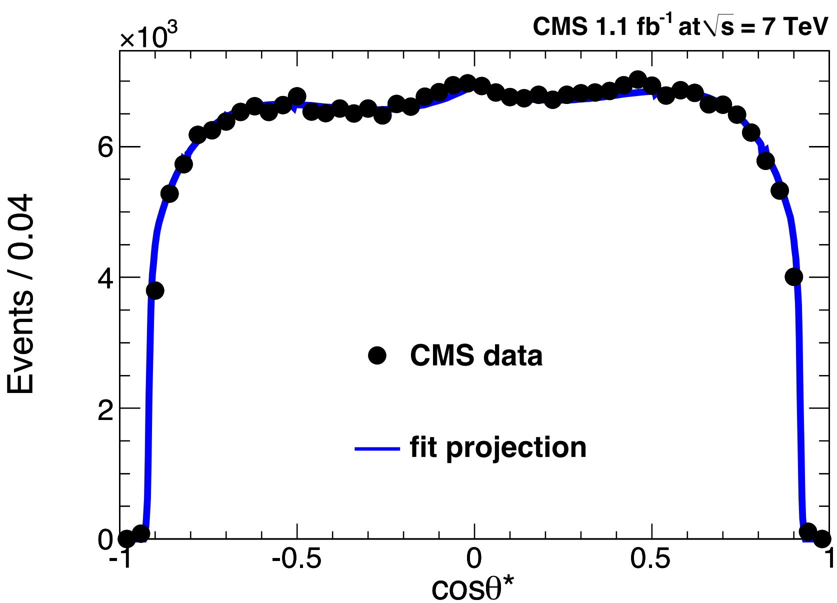
$$pp \rightarrow u\bar{u}, d\bar{d} \rightarrow Z/\gamma^* \rightarrow \mu^+\mu^-$$

PRD 84 (2011) 112002





- Matrix element method
  - Compare data to LO analytical model (LO EWK + PDFs)
  - Likelihood fit using the full event information.
  - Allow only θ_{eff} and M to be unconstrained.



$$\mathcal{P}_{\mathrm{sig}}(Y, \hat{s}, \cos\theta^*; \theta_{\mathrm{eff}}) = \mathcal{G}(Y, \hat{s}, \cos\theta^*) \times \int_{-\infty}^{+\infty} dx \mathcal{R}(x) \mathcal{P}_{\mathrm{ideal}}(Y, \hat{s} - x, \cos\theta^*; \theta_{\mathrm{eff}}).$$

$$\sin^2\theta_{eff}^{\ell} = 0.2287 \pm 0.0020(stat.) \pm 0.0025(sys.)$$

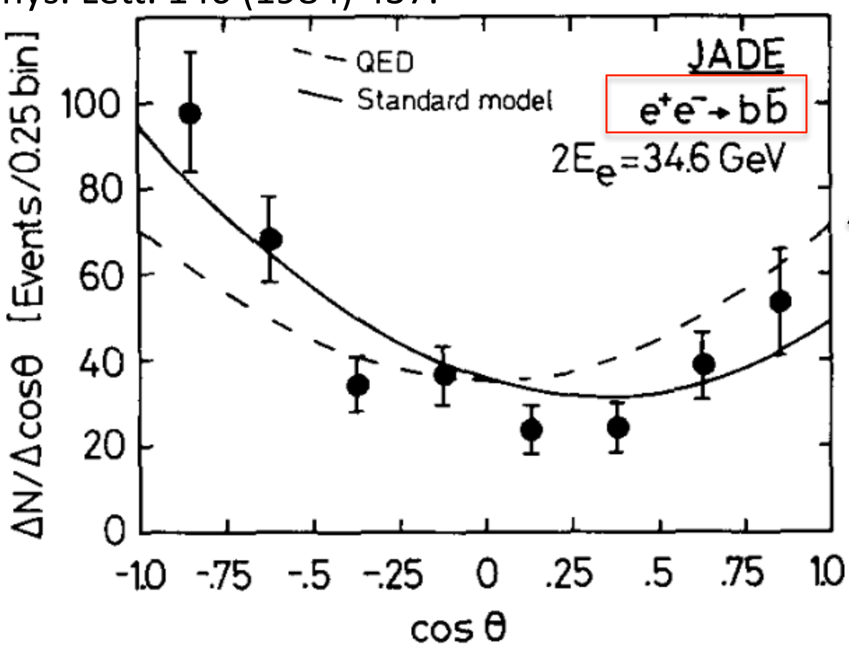
$\sin^2\theta_{eff}$ vs M_W → important in testing the consistency of the SM including the Higgs boson.

Asymmetry from Interference $A_{FB}^{b\bar{b}}$

- A_{FB} depends on √s = M, weak mixing angle, couplings.
  - And through couplings, it depends on the weak isospin, I_3.

$$g_v = \frac{I_3 - 2Q\sin^2\theta_W}{2\sin\theta_W\cos\theta_W}, \quad g_A = \frac{I_3}{2\sin\theta_W\cos\theta_W}$$

JADE Collaboration,
Phys. Lett. 146 (1984) 437.



$1 + \cos^2\theta \ (QED)$ No interference→ No asymmetry.

$$N\left[\frac{3}{8}\left(1+\cos^2\theta\right) + A_{FB}\cos\theta\right] \ (SM)$$

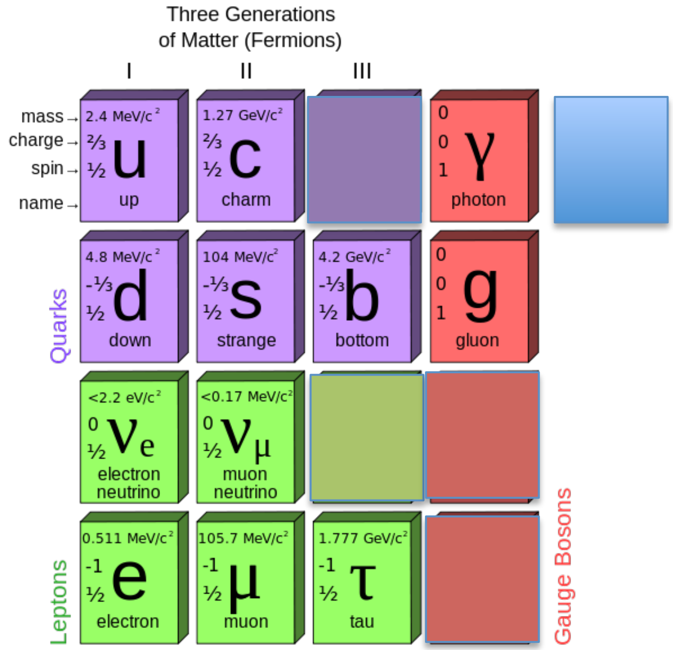
$$A_{FB} = -22.8 \pm 6.0 \pm 2.5\% \ \left(fit\right)$$

$$A_{FB} = 25\% \ \left(SM \ \ with \ I_3^{b-quark} = -1/2\right)$$

The first extraction of the weak isospin of the b-quark.

Asymmetry from Interference $A_{FB}^{b\bar{b}}$

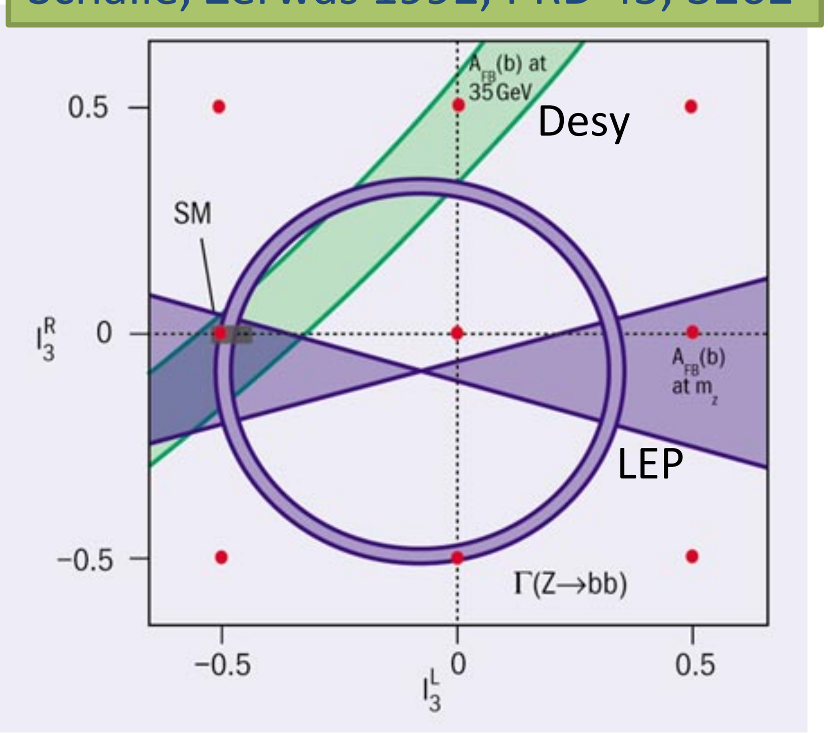
SM in 1978



- b-quark discovered and its iso-spin is measured.
- To complete the third generation, find the weak isospin partner of the b-quark.
- Top quark already predicted Kobayashi and Maskawa in 1973 for CP violation in the SM.

Schaile, Zerwas 1992, PRD 45, 3262

(right handed b-quark)



(left handed b-quark)

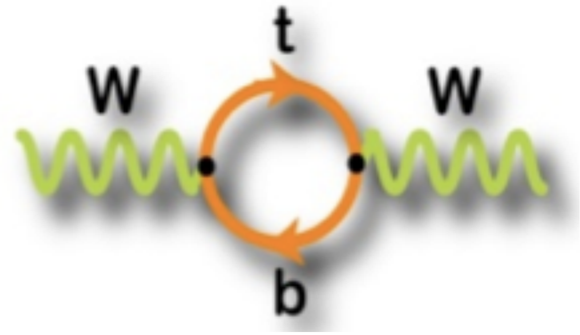
A_{FB} to determine the property of an already discovered particle and to indirectly show the existence of another particle.

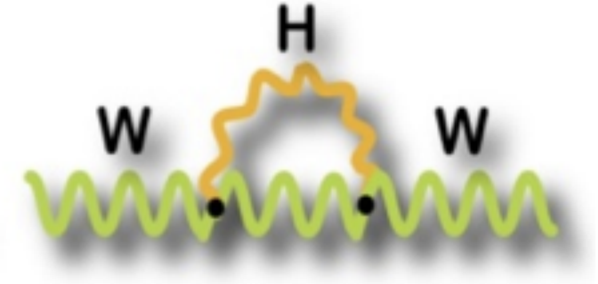
Heavy Particle Masses and Asymmetries

Top and Higgs modify tree level SM processes through radiative corrections → Constraints on m_t & m_H.

e.g. virtual loops contributing to the W mass

$$M_W^2 = \rho\left(M_W^{tree-level}\right)^2$$





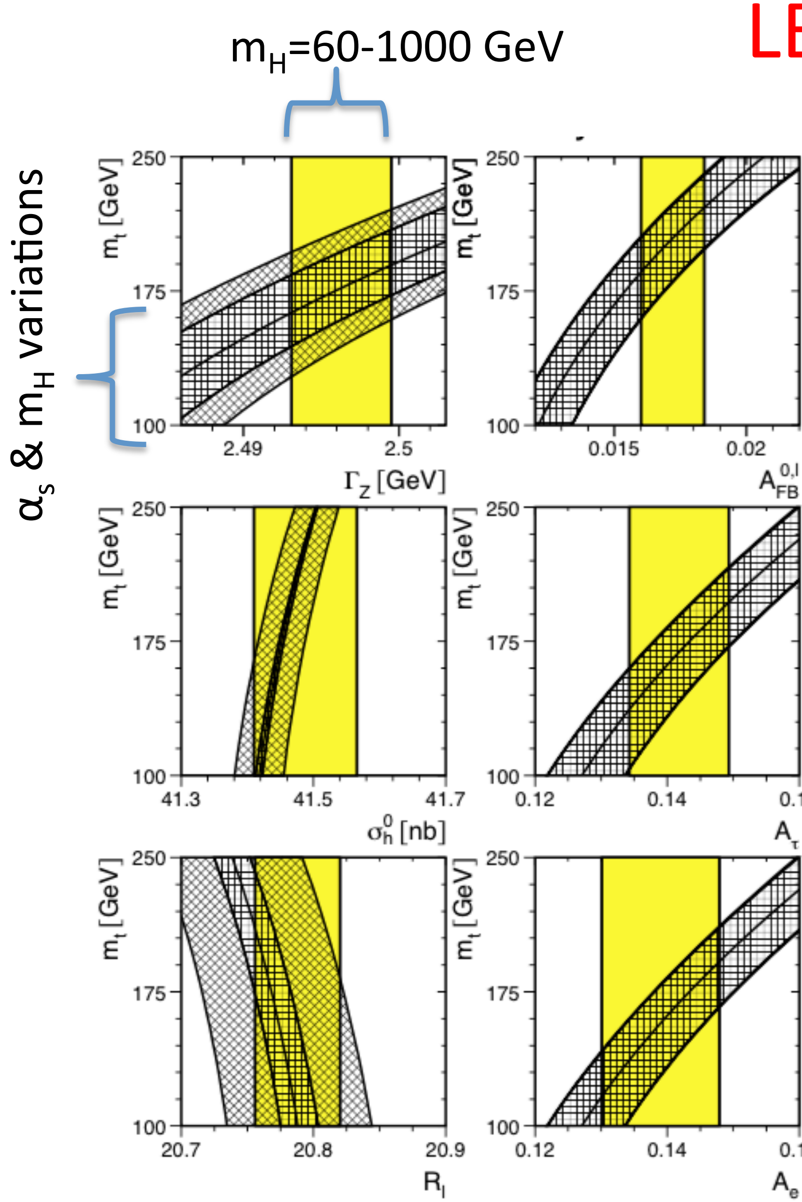
$$\Delta\rho \propto m_t^2$$

$$\Delta\rho \propto \ln\left(m_H\right)$$

Propagator for fermions (Dirac equation)

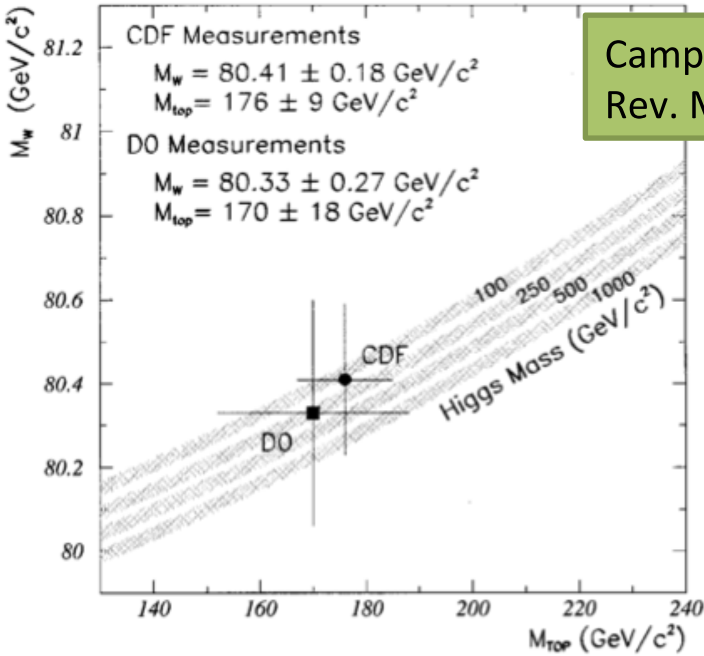
Propagator for bosons (Klein-Gordon equation)

LEP (1995) vs SM predictions



LEP Collaborations
CERN-PPE/95-172

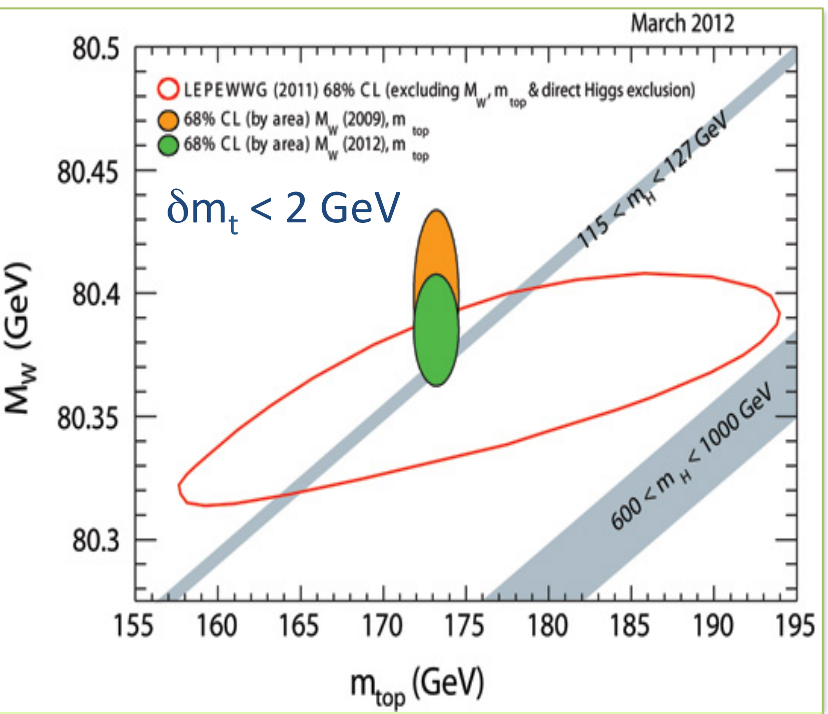
- Z line shape and asymmetries compared to SM measurements vs top mass.
- Precursors of the top discovery!

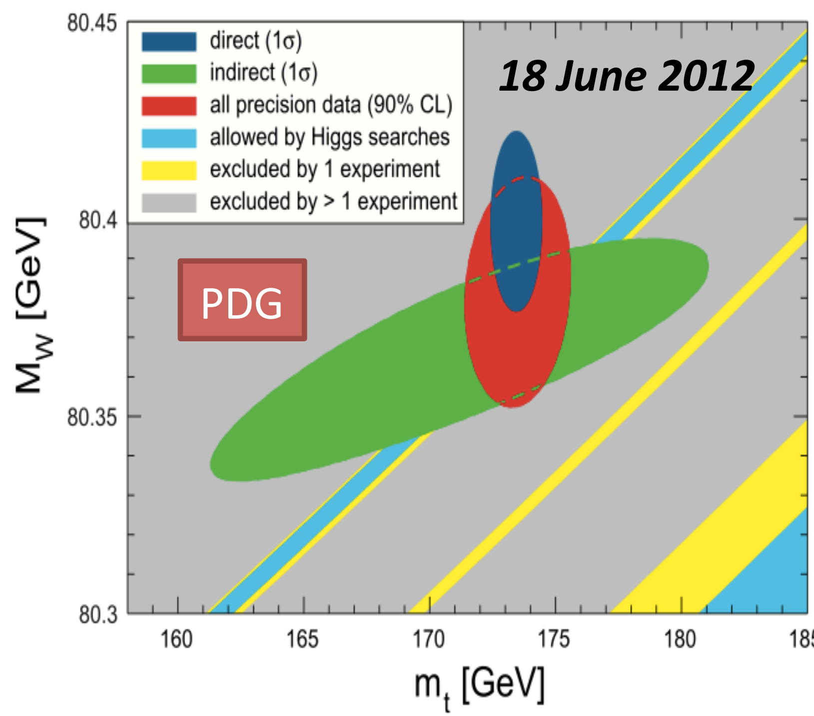


Campagnari & Franklin
Rev. Mod. Phys. 69, 1 (1997)

~15 years to
δM_W~0.2% → ~0.03%
δM_t~5% → ~0.8%

Precursors of the Higgs discovery!



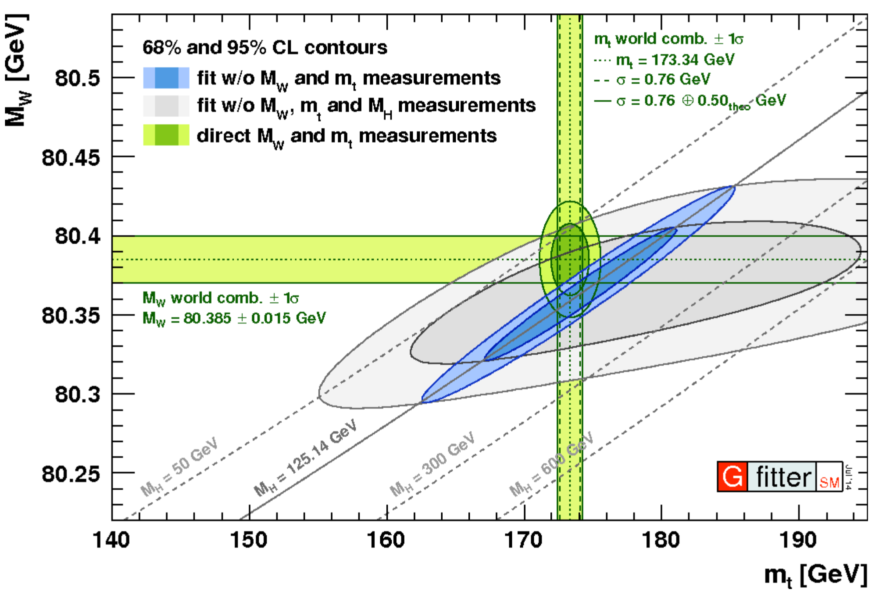


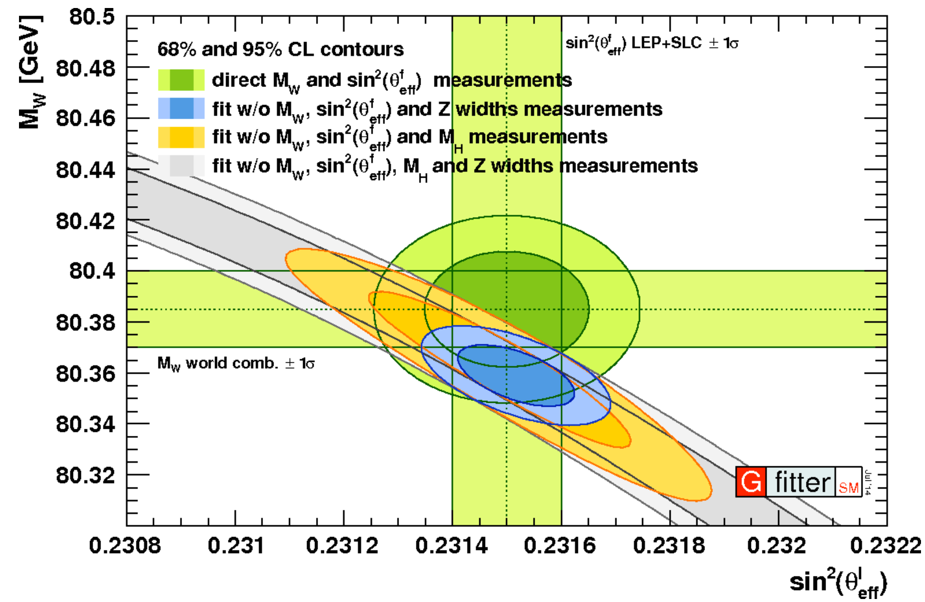
Electroweak fit before Higgs discovery: $m_H = 94^{+25}_{-22}\, GeV$ consistent with measured m_H within 1.3σ.

$$m_H^{CMS-Run\ I} = 125.02^{+0.26}_{-0.27}(stat)^{+0.14}_{-0.15}(sys.)\ GeV$$

arXiv:1412.8662

The Gfitter Group, M. Baak et al., EPJC 72, 2205 (2012)



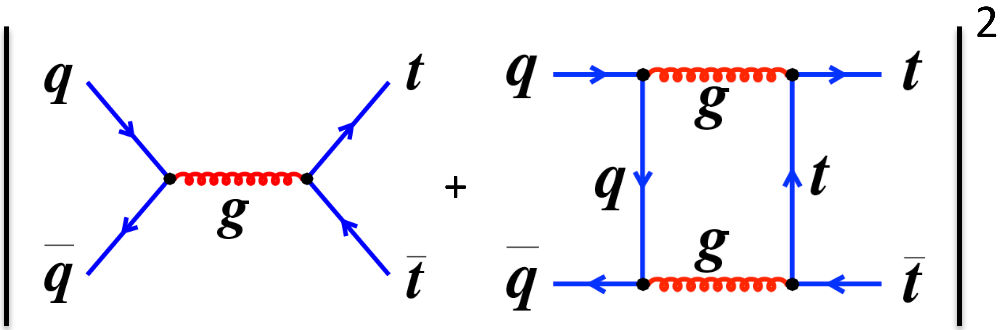


Analysis assumes that the SM is the fundamental theory with nothing beyond.

→ One of the most critical tests of the standard model!

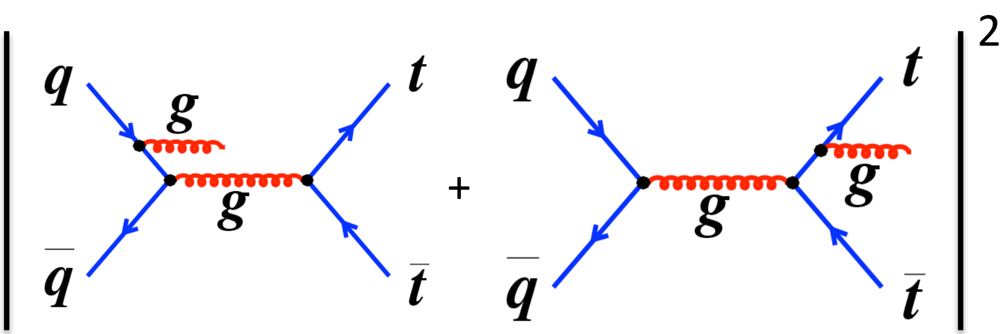
Asymmetry from Interference - $t\bar{t}$

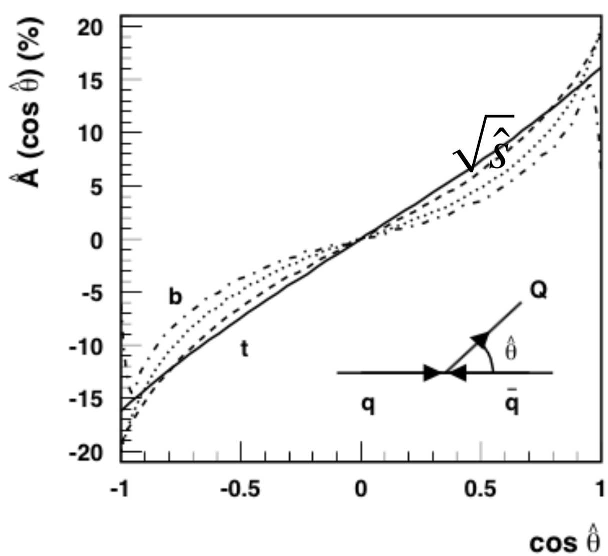
Interference: tree-level + box diagrams
(positive asymmetry)



- No asymmetry at LO
- No asymmetry from gluon fusion
- At NLO: Interferences between $q\bar{q}$ diagrams

Kühn & Rodrigo PRL 81 (1998) 49

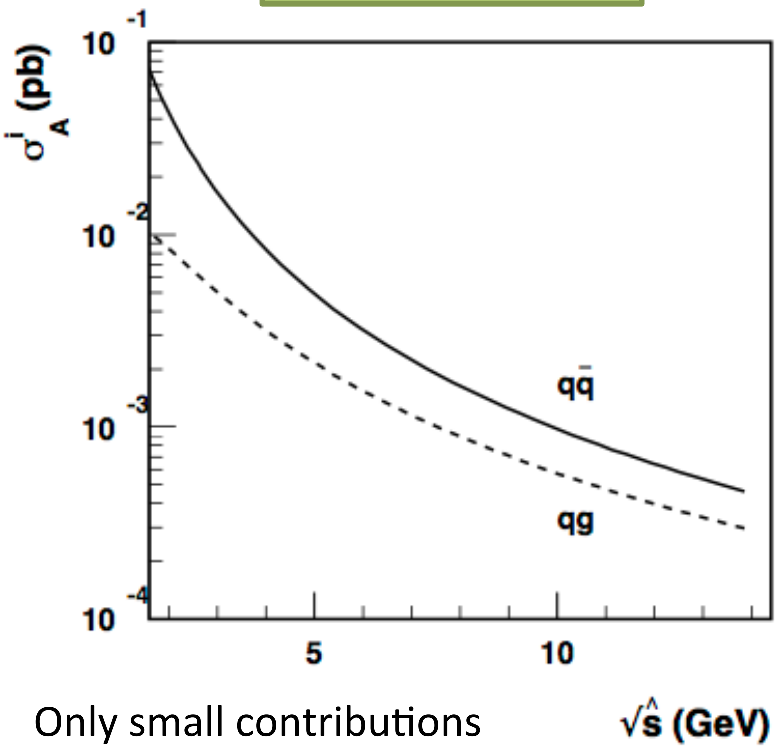




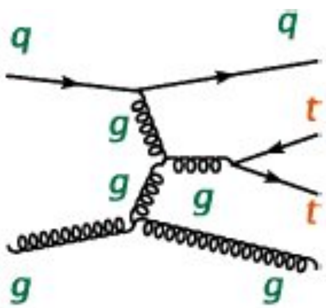
Interference: ISR+FSR
(negative asymmetry)

Asymmetry from Interference - $t\bar{t}$

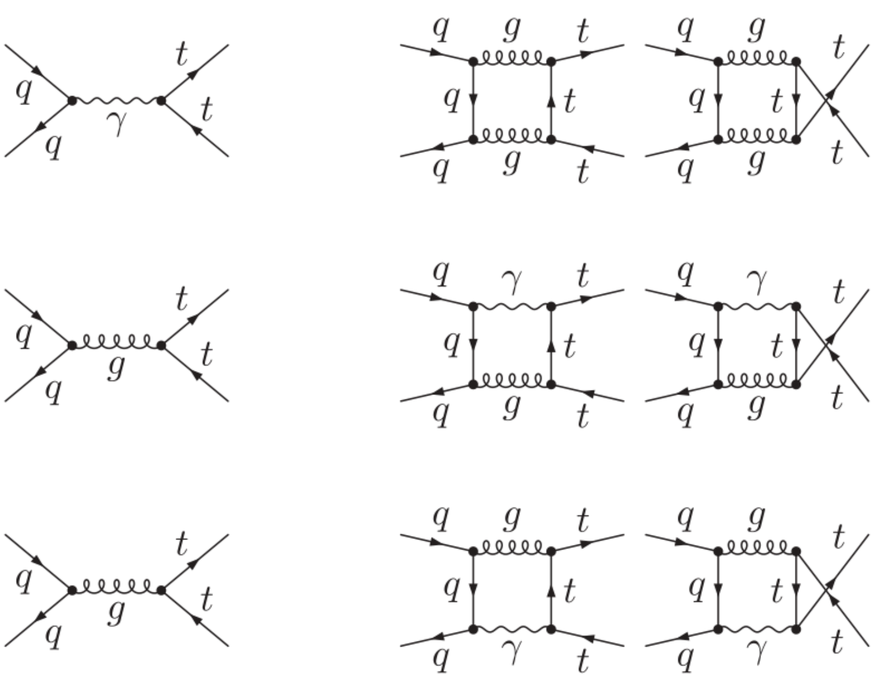
Kuhn & Rodrigo,
PRD 59 (1999) 054017



- Only small contributions from quark-gluon scattering



Hollik & Pagani
PRD 84 (2011) 093003

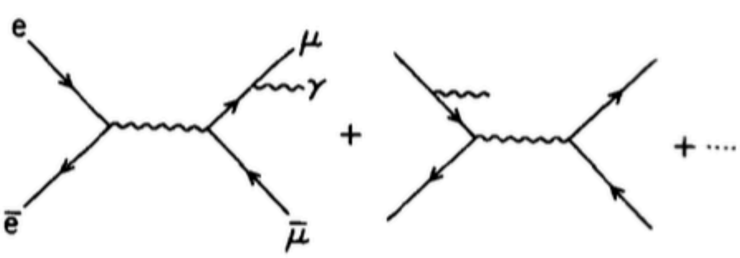


- Significant (~25%) contributions from QCD-electroweak interference terms.

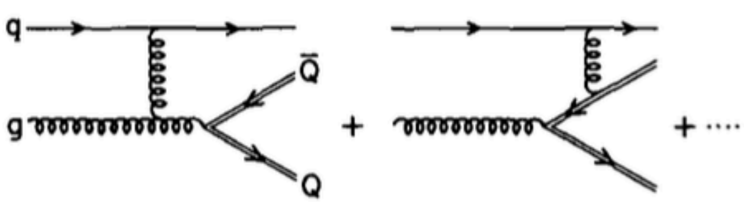
Asymmetry from Interference - $t\bar{t}$

- First calculation of asymmetry by Halzen et al. 1987 (PLB 195, 74) for m_t = 45 GeV!
- Making analogy to QED.
- But considered only real gluon emission.

$$q\bar{q} \rightarrow Q\bar{Q}g$$

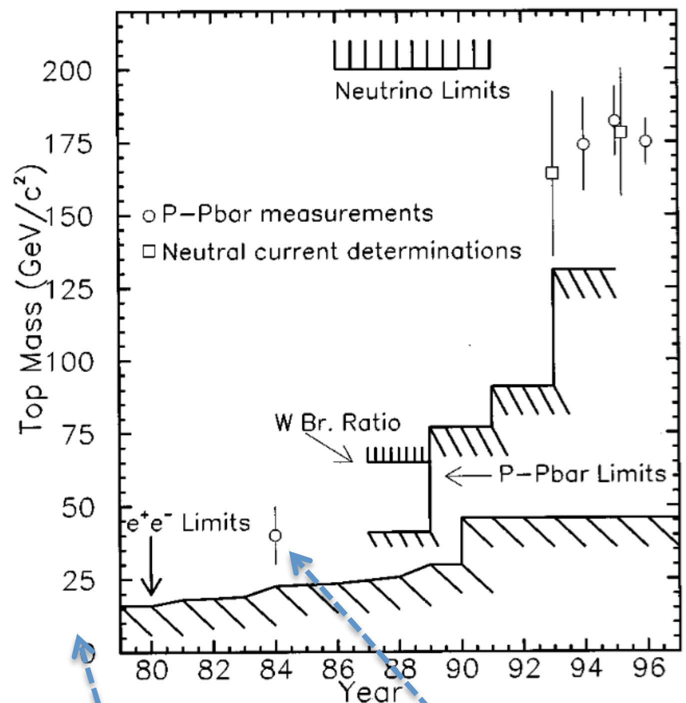


(a)



(b)

$$qg \rightarrow Q\bar{Q}q$$

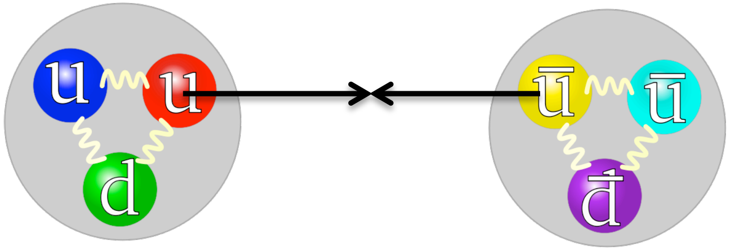


Campagnari & Franklin
Rev. Mod. Phys. 69, 137 (1997)

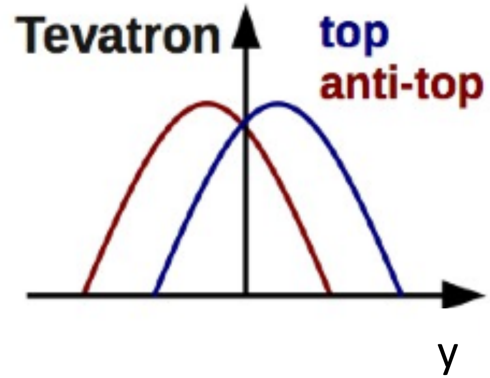
Example predictions of m_t:
→ **5-65 GeV**
(J. Ellis, et. al. NPB 131 (1977) 285)
→ **16-19 GeV**
(T. Yanagida, PRD 20 (1979) 2986)
→ **~148 GeV**
(H. Terazawa, PRD 22 (1980) 2921)

1984 UA1 measurement
m_t = 40+/-10 GeV.

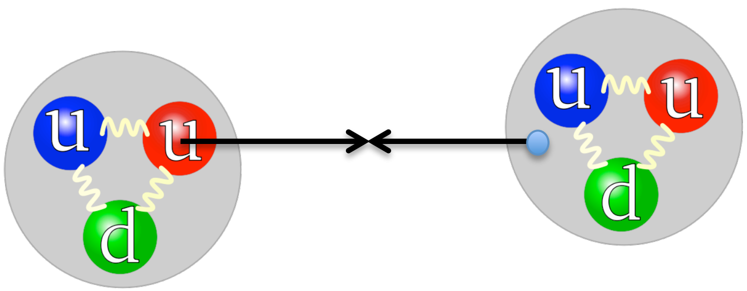
Asymmetry from Interference - $t\bar{t}$



Tevatron: annihilation of two valence quarks (PDF symmetric).

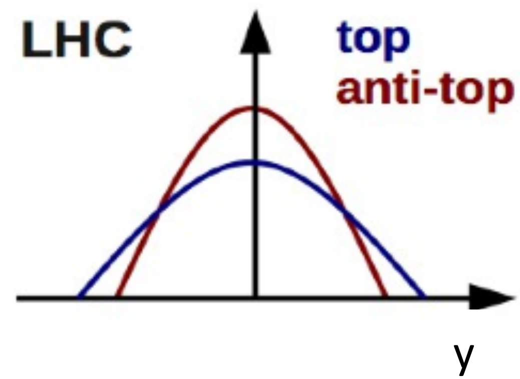


Forward-backward asymmetry (A_{FB})



LHC: annihilation of one valence and a sea anti-quark (PDF asymmetric) and moreover gluon fusion dominates.

→ much smaller asymmetry.

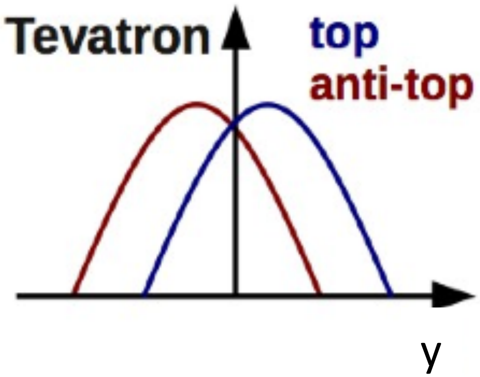


Charge asymmetry (A_C)

On average, P(valence quark) > P(sea anti-quark)
→ top quark rapidity broader than the anti-quark rapidity

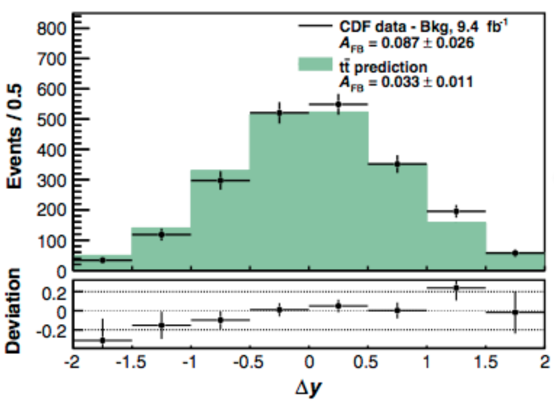
→ any large asymmetry will indicate the existence of new physics.

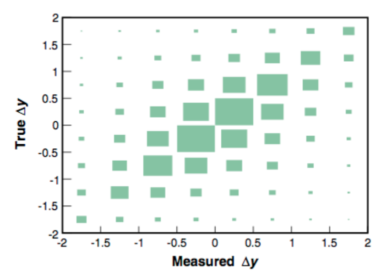
$t\bar{t}$ Asymmetry at the Tevatron

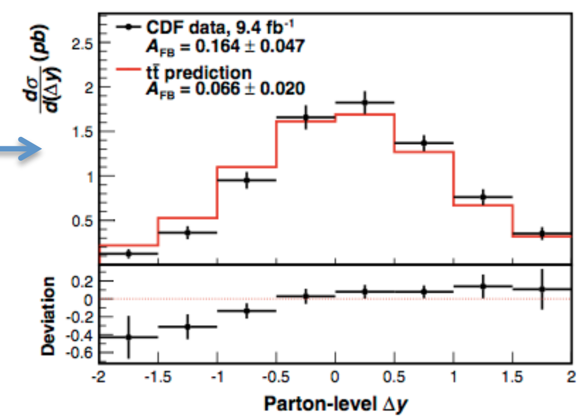


← Requires reconstruction of the top quarks.

arXiv:1211.1003
PRD 87, 092002 (2013)

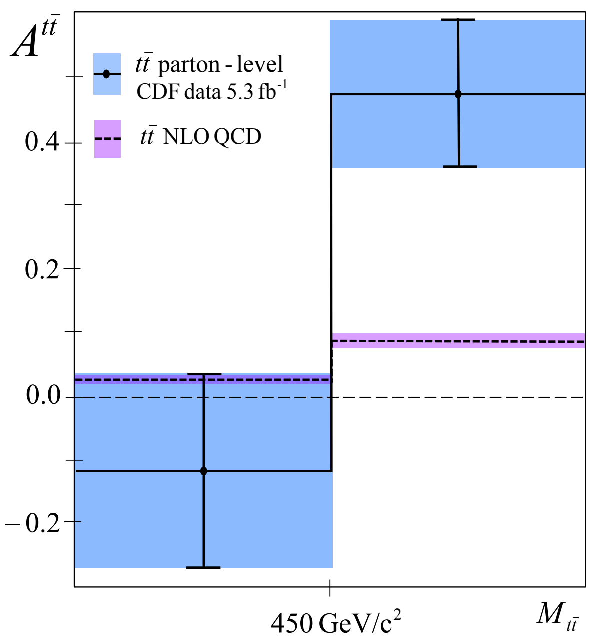




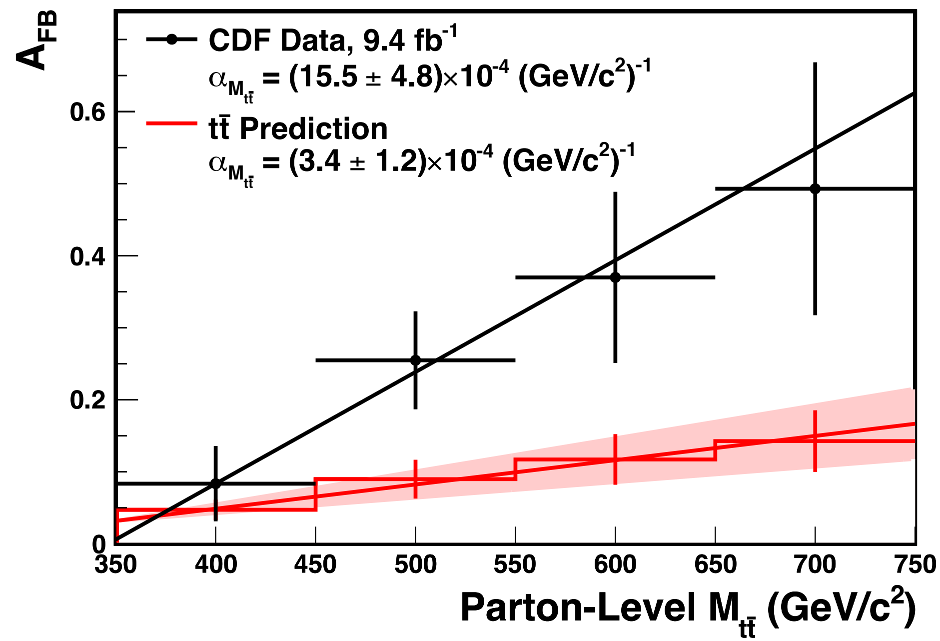


Unfolding to correct for detector and acceptance effects.

$t\bar{t}$ Asymmetry at the Tevatron



PRL, 83 (2011) 112003



arXiv:1211.1003
PRD 87, 092002 (2013)

Inclusive A_{FB}: ~2σ deviation

$A_{FB}(m_{tt}>450$ GeV): ~3σ

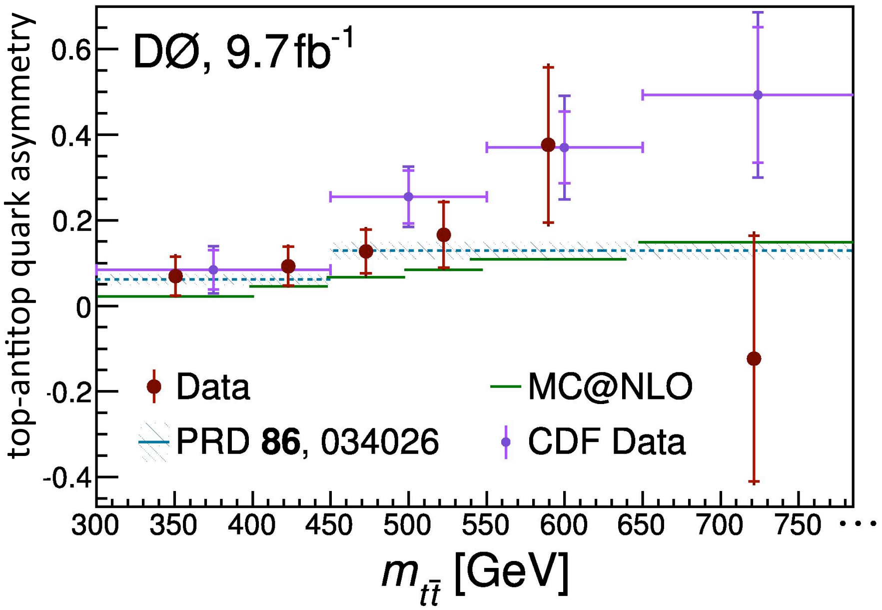
D0 measured somewhat higher asymmetry than NLO predictions.

PRD 84 (2011) 112005

- Statistical fluctuation?
  - results dominated by statistical uncertainties
- Missing theory effect?
  - calculations only at the lowest order
- Analysis method?
- Missing uncertainties?

➔ If none, may be new physics, *but even so, no precursor (contrary to W, Z, Top, Higgs, ... discoveries)*

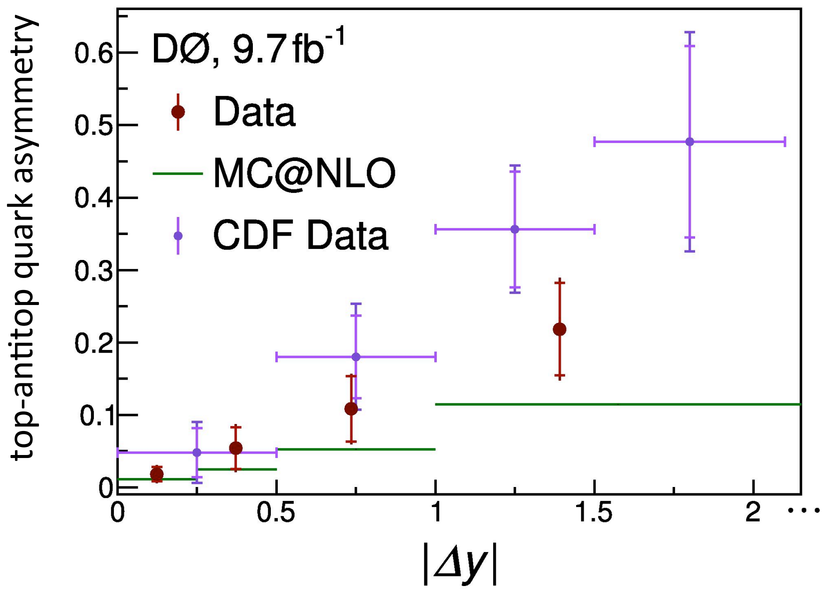
New $t\bar{t}$ Asymmetry Results



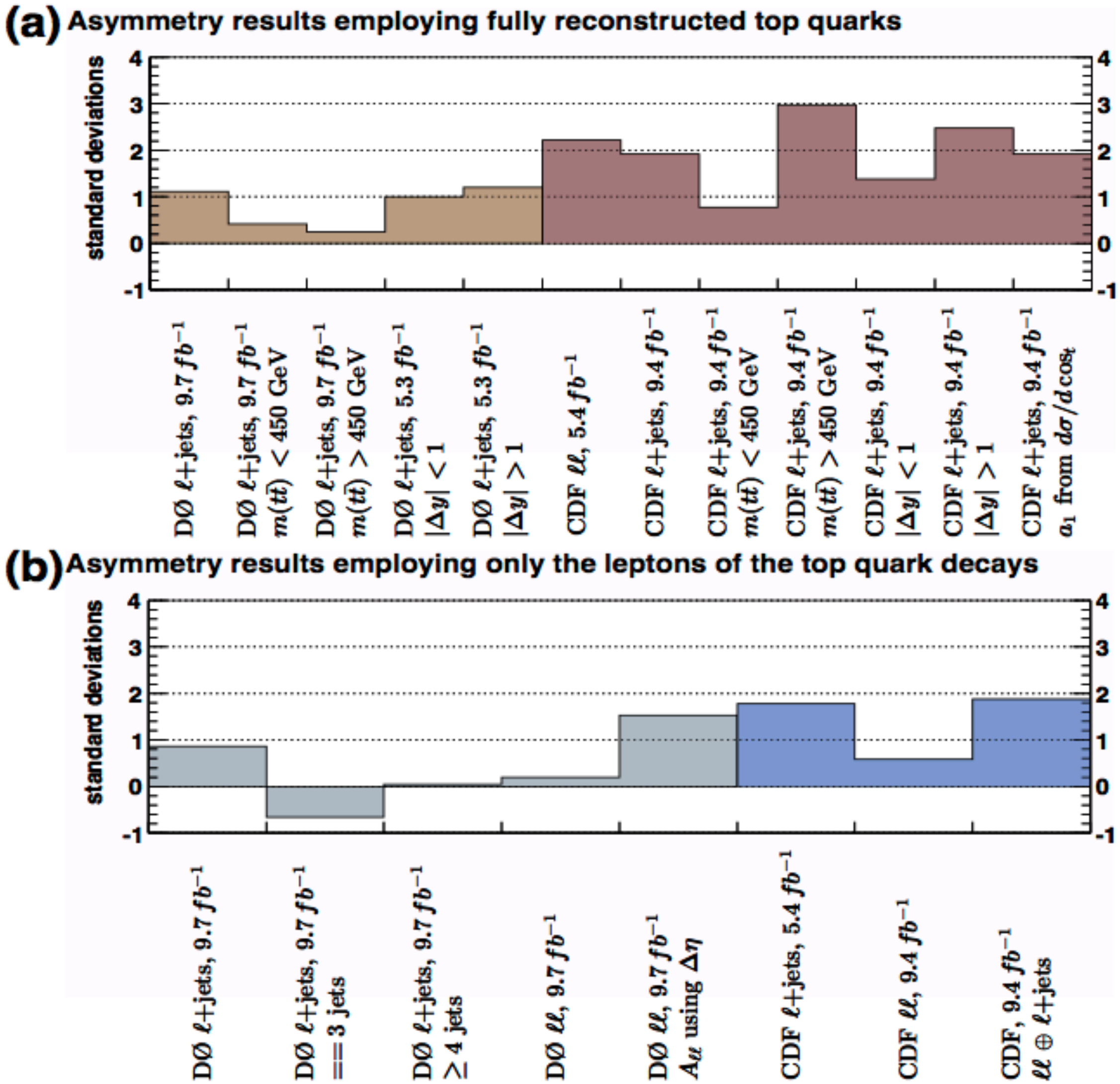
Fermilab-Pub-14-116-E

arXiv:1405:0421

- D0 data is consistent with SM and CDF.
- CDF data in agreement with SM within ~2σ.



Summary of A_{FB} Measurements at the Tevatron

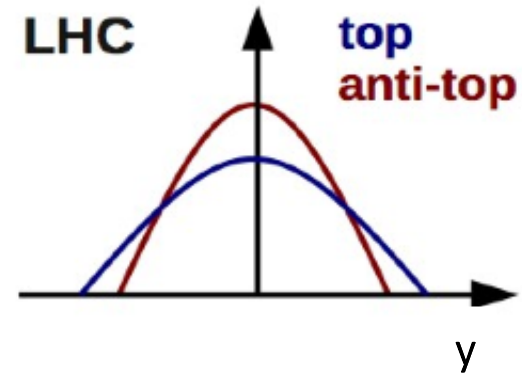


A. Jung, arXiv:1404.1842

Standard deviations w.r.t. NLO calculation including EWK corrections.

Bernreuther & Si, PRD 86 (2012) 034026

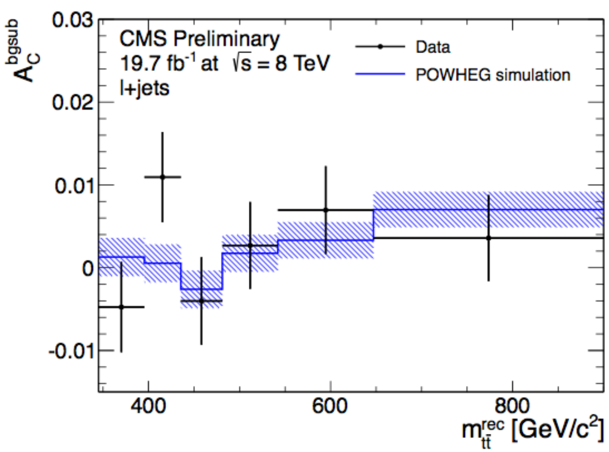
A_C at the LHC



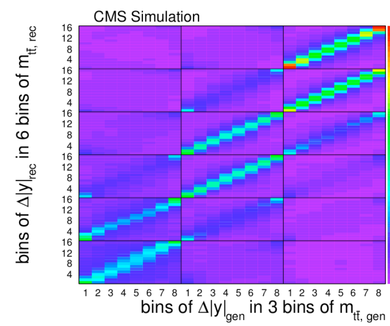
Charge asymmetry (A_C)

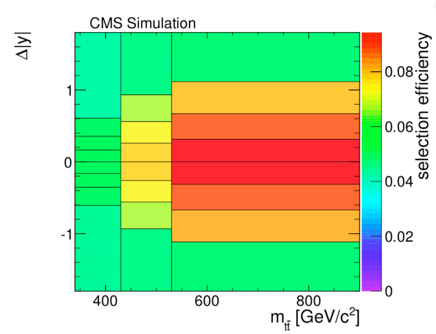
- Inclusive and differential measurements of A_C
  - vs $Y(t\bar{t})$, $p_T(t\bar{t})$, $m(t\bar{t})$
- All measurements consistent with SM predictions.
  - *true for leptonic A_C as well (not covered).*

Requiring no top quark reconstruction

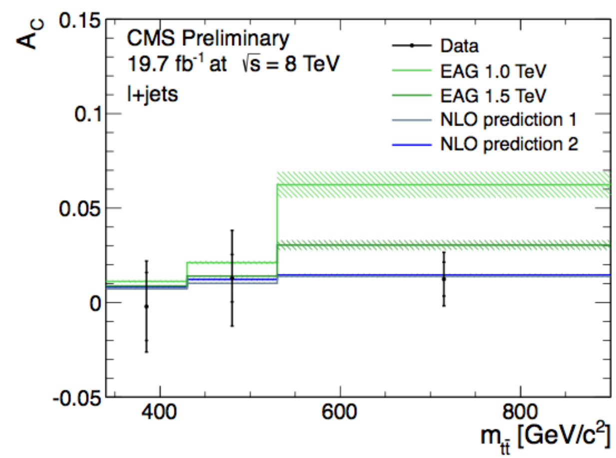


CMS-PAS-TOP-12-033

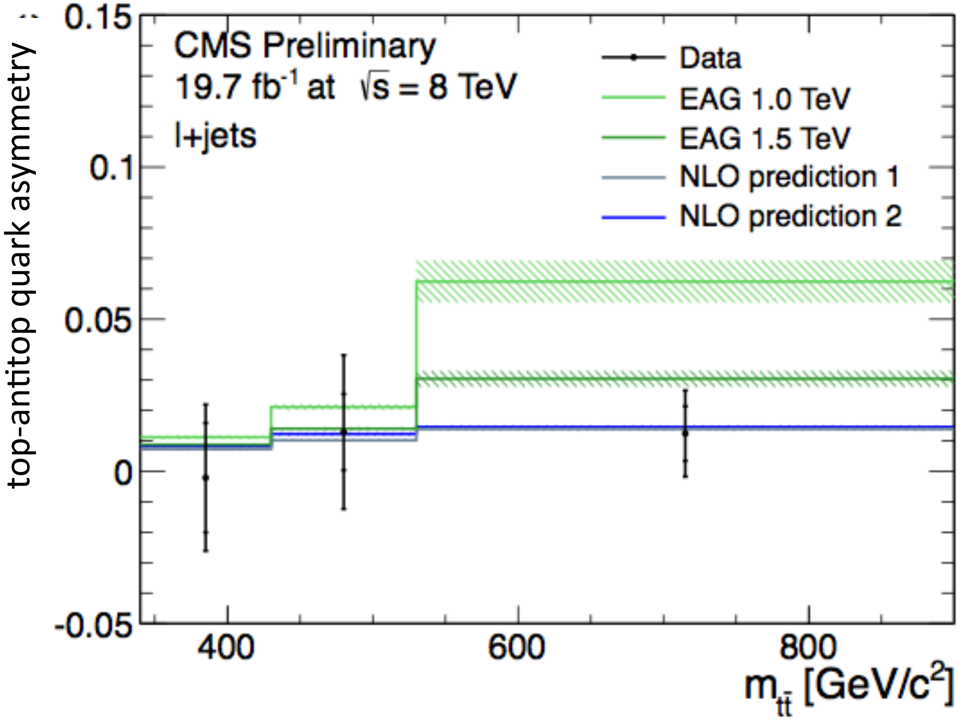




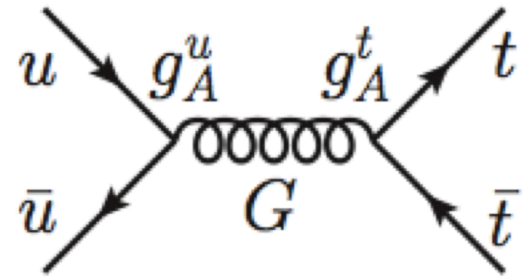
EAG: effective axial-vector coupling to gluons.



A_C at the LHC



CMS-PAS-TOP-12-033



$$g_A \propto m_{t\bar{t}}^2 / \Lambda^2$$

$$at \quad high \quad m_{t\bar{t}} \quad with \quad m_{t\bar{t}} \le \Lambda$$

EAG = Effective Axial-Vector coupling of the Gluon.

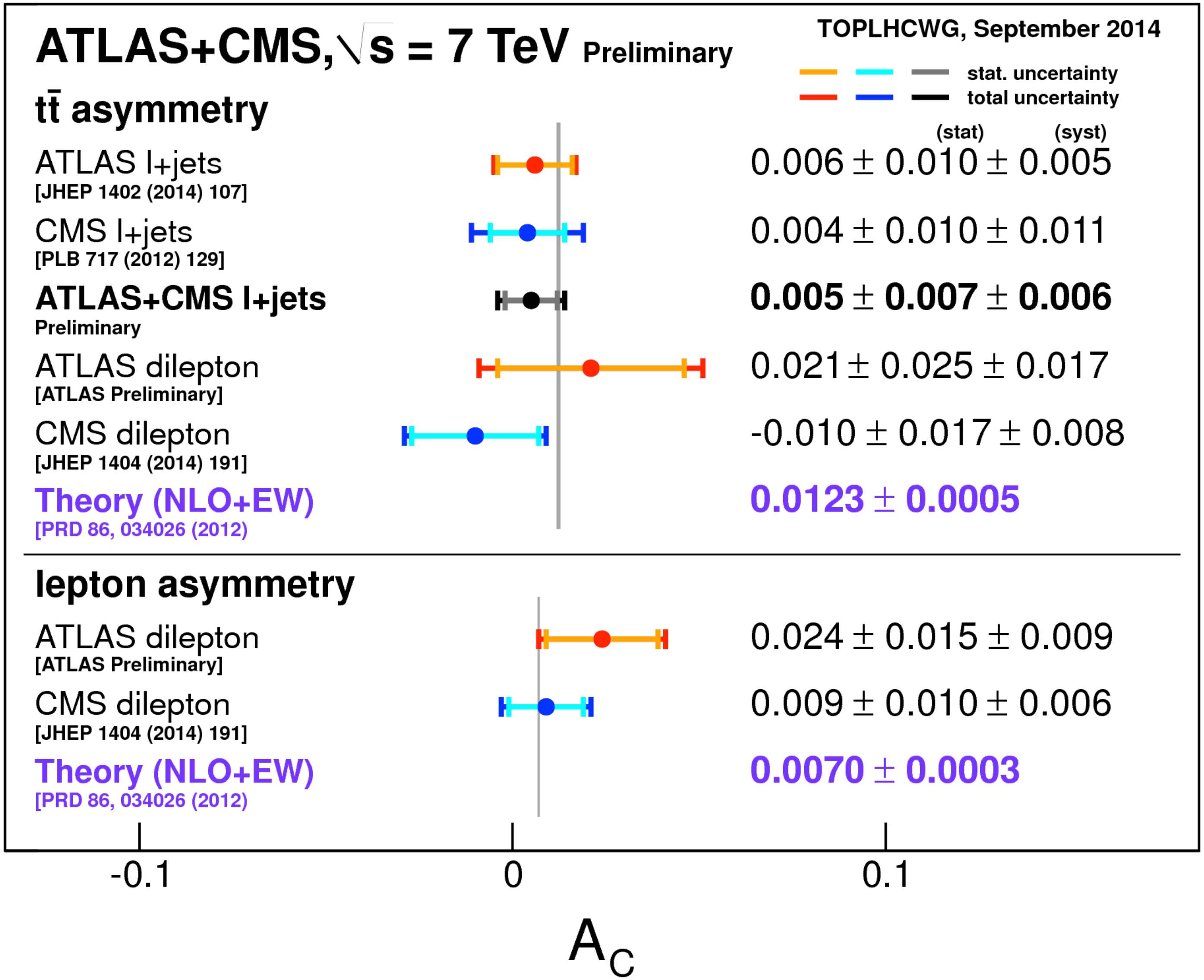
→ g_V strongly constrained by $\sigma(q\bar{q} \to t\bar{t})$

→ When new physics scale ~ 1.3 TeV EAG can explain Tevatron results.

E. Gabrielli, A. Giammanco, A. Racioppi, M. Raidal arXiv:1203.1488 [hep-ph]

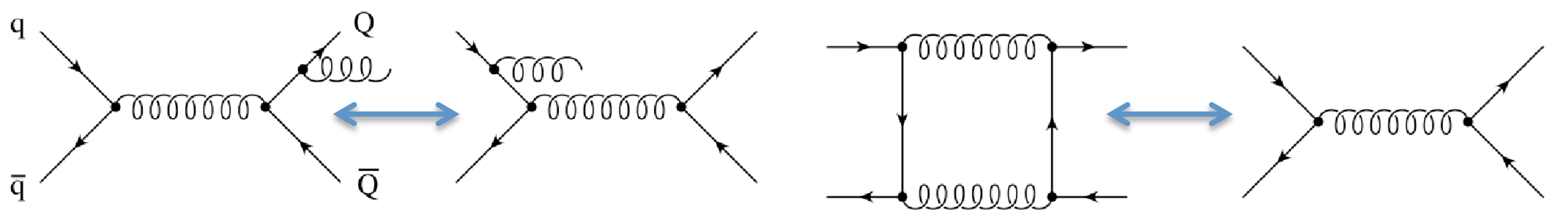
- No deviation from SM predictions at the LHC.
- Not enough events to eliminate physics models with typical scales > 1.5 TeV.

A_C – LHC Combination



$A_{FB/C}(b\bar{b})$

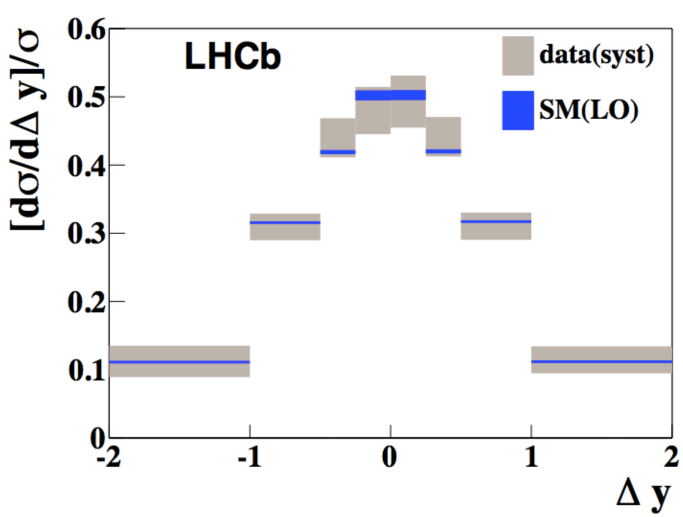
- *Validate $q\bar{q}$ asymmetry at low $M(q\bar{q})$.* → *i.e.* Validate the analysis method for top quark pair asymmetries using low mass particles where you expect no new physics.



LHCb

$$A_C^{b\bar{b}} \equiv \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)}$$

$$\Delta y \equiv |y_b| - |y_{\bar{b}}|$$



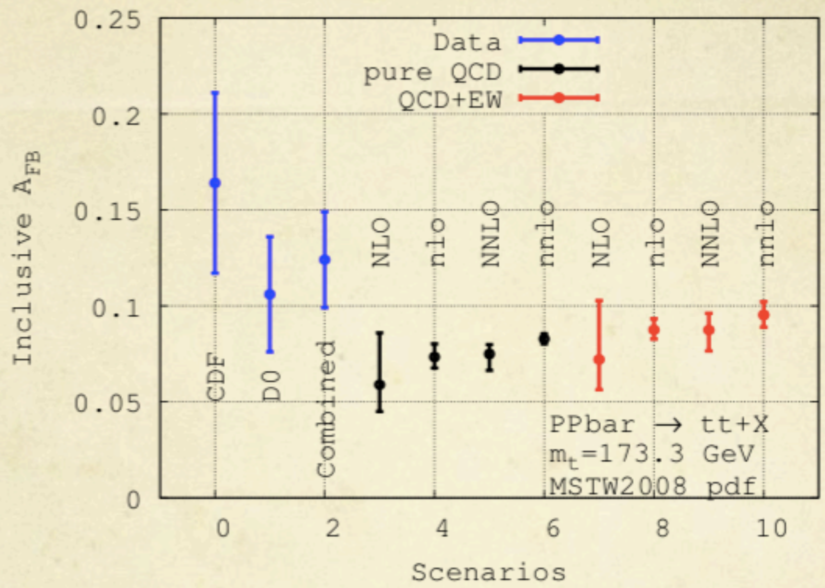
Also measured in three $M_{b\bar{b}}$ ranges.
Measured at D0, and CDF as well.

All results consistent with SM predictions.

→ Analysis method used for $A_{FB}(t\bar{t})$ can be considered successfully validated.

arXiv:1406.4789

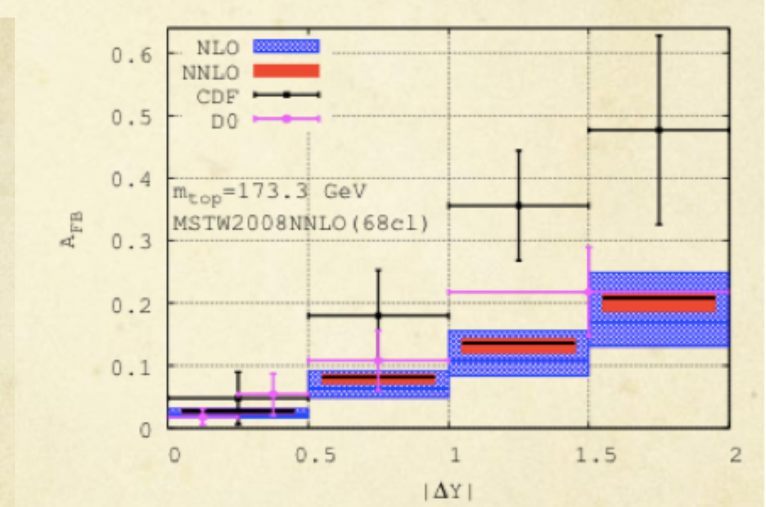
Improved Calculations

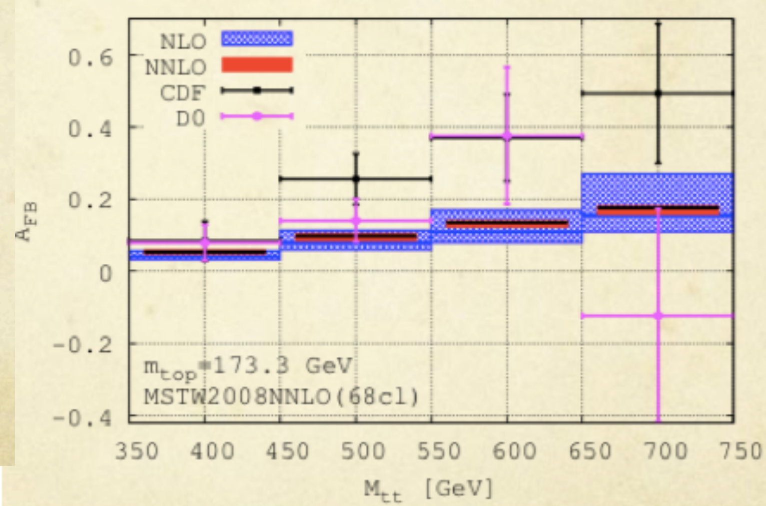


Mitov CERN TOPLHCWG Open Meeting 12 Jan 2015

How to read the above plot:

- *NLO, NNLO* : exact numerator and denominator (see previous slide)
- *nlo, nnlo* : expanded in powers of a_S





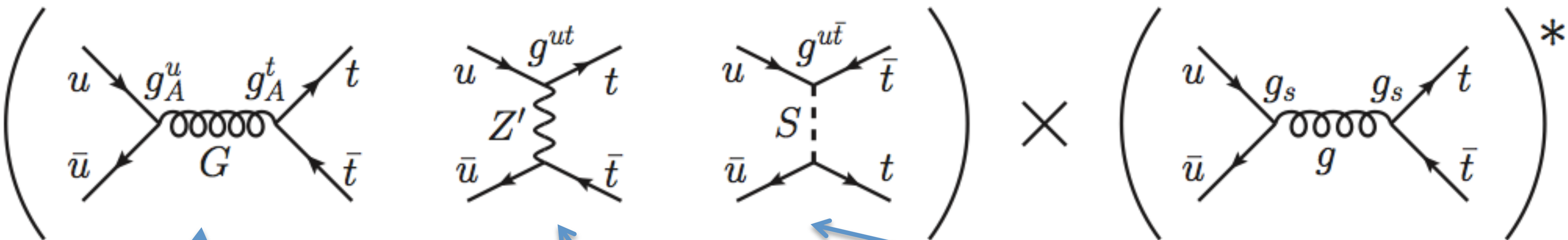
- Agreement between NNLO and Tevatron asymmetry measurements.

- Only scale errors.
- Still ~2σ deviation w.r.t. CDF.
- Perfect agreement with D0

A_{FB} and New Particles

Westhoff, arXiv:1108.3341

- Interference of new particles in s,t or u channels with the SM process.



→ Axi-gluon

→ ...

→ Flavor-changing Z' boson,
ϕ (color-singlet scalar doublet)

→ No same-sign top

→ No discrepancy in $t\bar{t}$ cross-section.

→ W' exchanged in $d\bar{d} \to t\bar{t}$

→ B physics constraints

→ ...

→ Charge 4/3 ω^4, Ω^4

→ constraints from dijet production.

→ ...

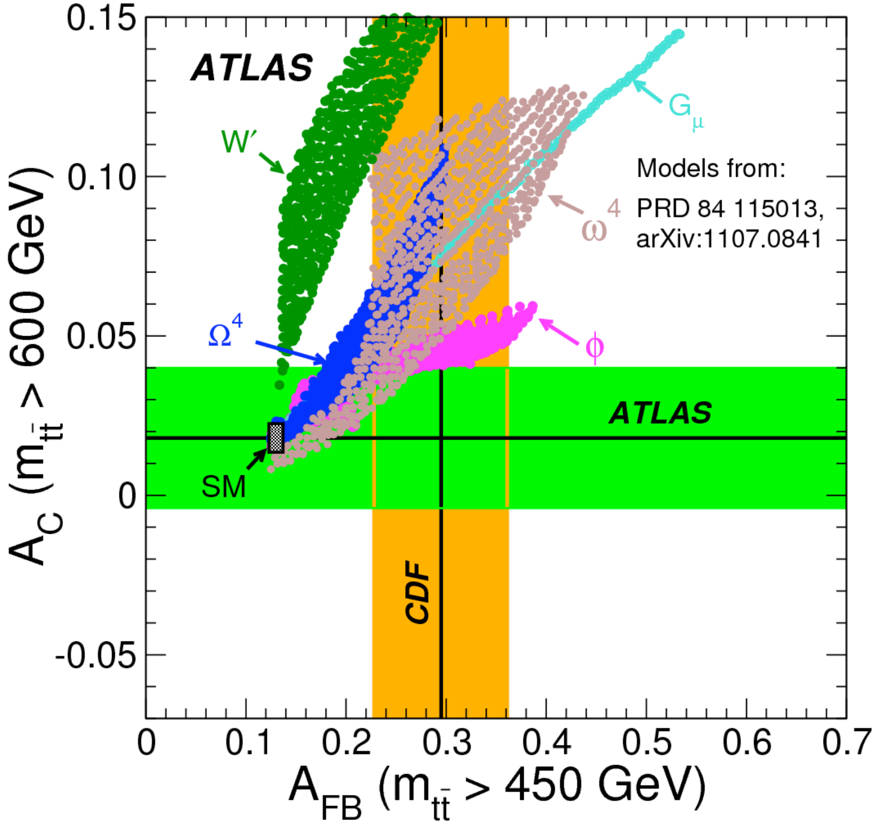
New particles giving rise to large asymmetries with other SM observables remain unaffected.

Aguilar-Saavedra, Perez-Victoria, arXiv:1107.0841

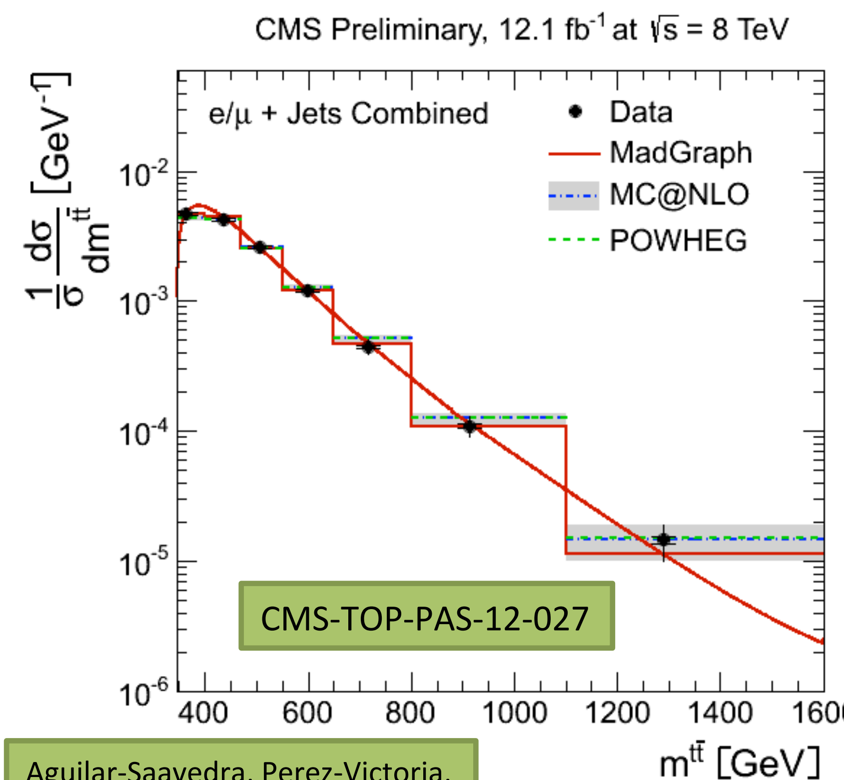
A_{FB} vs A_C

- Tevatron A_{FB} and A_C can be compared in a *model-dependent* way.

JHEP 02 (2014) 107



Some new physics models already disfavored.



CMS-TOP-PAS-12-027

Aguilar-Saavedra, Perez-Victoria, arXiv:1107.0841

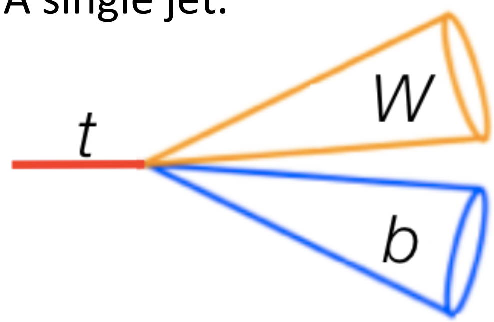
A precise measurement of $m_{t\bar{t}}$ tail would provide significant constraints.

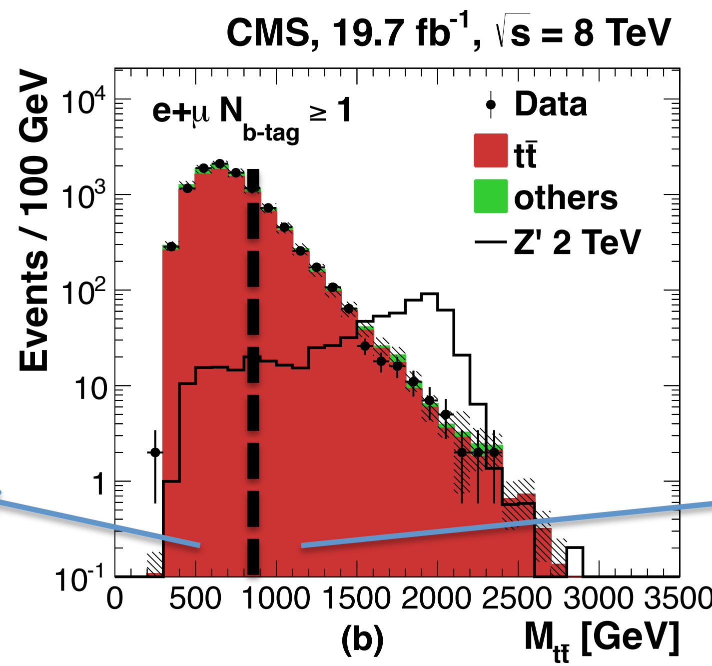
A precise measurement of asymmetry at the tail will show the (in-)existence of a new particle in a model indepenpent way.

New Particles

PRL 111 (2014) 211804

Resolved topology:
Each parton matched to
A single jet.





Boosted topology:
Each top quark is highly
lorentz boosted
→ Decay products collimated

"fat jet"

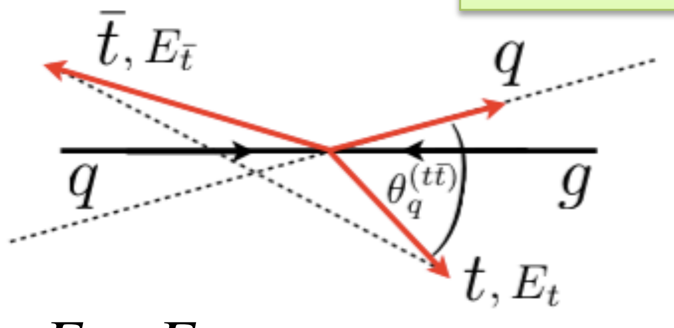
- If the resonance is broad, then the new particle may show itself in A_{FB}.
- Conversely, if a particle is discovered using the mass spectrum, some of its properties can be determined by the asymmetries
  - Same mass range can be scanned using both Drell-Yan and top quark asymmetries.
- *Asymmetries in boosted top quarks haven't been studied in detail yet.*

Asymmetry in $t\bar{t} + jet(s)$

- Huge gluon gluon background in measurements until now.
- At √s = 14 TeV, high parton luminosity for qg production
  - 20% of top pair events are from qg production.
  - Significant asymmetry in $t\bar{t}$ + q-jet

S. Berge, S. Westhoff, JHEP07(2013)179

S. Westhoff, arXiv:1501.07477



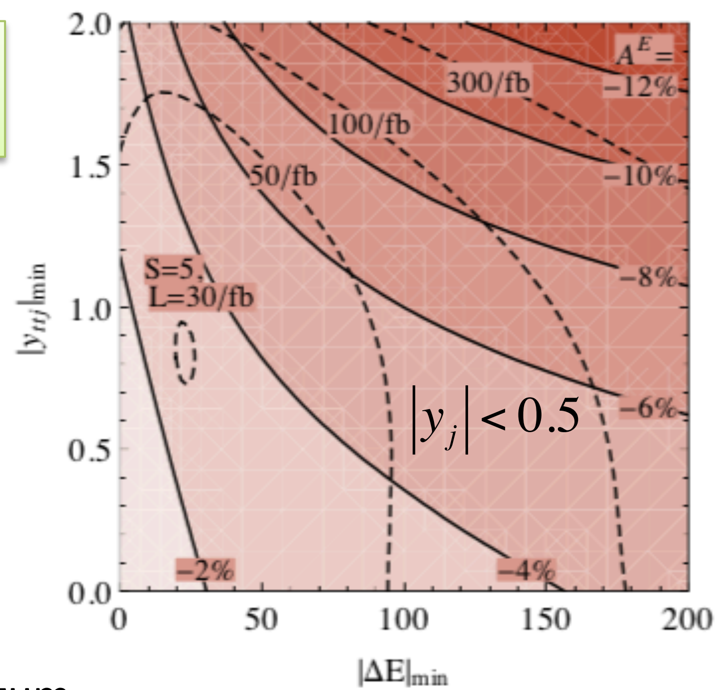
$\Delta E = E_t - E_{\bar{t}}$ in partonic CM frame.

$$A_E = \frac{\sigma_{t\bar{t}}(\Delta E > 0) - \sigma_{t\bar{t}}(\Delta E < 0)}{\sigma_{t\bar{t}}(\Delta E > 0) + \sigma_{t\bar{t}}(\Delta E < 0)}$$

$$\leftrightarrow \frac{\sigma_{t\bar{t}}\left(\cos\theta_q^{(t\bar{t})} < 0\right) - \sigma_{t\bar{t}}\left(\cos\theta_q^{(t\bar{t})} > 0\right)}{\sigma_{t\bar{t}}\left(\cos\theta_q^{(t\bar{t})} < 0\right) + \sigma_{t\bar{t}}\left(\cos\theta_q^{(t\bar{t})} > 0\right)}$$

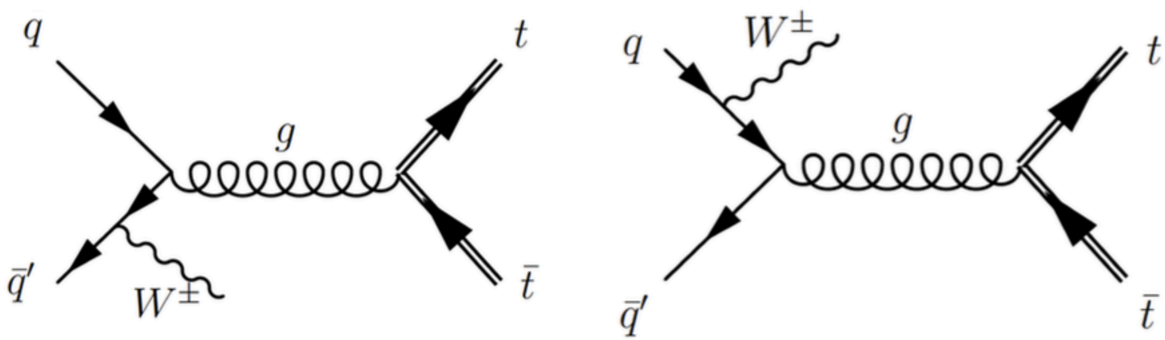
due to momentum Conservation.

A$_{FB}$ of quark-jet in top pair rest frame.



Highest asymmetry for boosted $t\bar{t}j$ events and when the jet is perp. to the beam.

Asymmetry in $t\bar{t} + W$



F. Maltoni et al.
arXiv:1406.3262

- At LO QCD, $t\bar{t}$W production can only occur through $q\bar{q}$ annihilation.
- At NLO → qg scattering.

Gluon fusion only at NNLO

- Asymmetry arises at NLO due to interference but since no gluon fusion, the asymmetry is considerably larger w.r.t. $t\bar{t}$ production. *The observable: rapidity asymmetry*
- Emission of the W boson polarizes the top quarks
  - Decay products asymmetrical in rapidity even at LO. → Also sensitive to new physics.

$t\bar{t} + \gamma$ enchances the asymmetry by increasing the qq/gg fraction.

J. A. Aguilar-Saavedra et al.
arXiv:1402.3598

The Higgs Boson and Asymmetries

- LHC observed a resonance with M~125 GeV
  - Most of its properties are measured but to understand whether it is the SM Higgs boson,
    - measure its properties precisely
      - CP properties and spin
      - Couplings to fermions, gauge bosons
      - and self-couplings

      Two examples for which asymmetries are useful.
    - understand whether the Higgs boson fully unitarizes the longitudinal vector boson scattering.

Asymmetries and Higgs-top Coupling

$$\mathcal{L}_{hf\bar{f}} = -\sum_f \frac{m_f}{v} h\bar{f}(a_f + ib_f\gamma_5)f$$

CP-odd component

SM: Scalar Higgs: a_f=1, b_f=0

Pseudo-scalar Higgs: a_f=1, $b_f \neq 0$

Mixed CP: $a_f \neq 0$, $b_f \neq 0$

F. Boudjema et al., arXiv:1501.03157

Constraints from Higgs boson rates

$|a_t|$ = [-0.6,1.2] (ATLAS, CMS)

No significant constraints on b_t yet.

Asymmetries and Higgs-top Coupling

$$\mathcal{L}_{hf\bar{f}} = -\sum_f \frac{m_f}{v} h\bar{f}(a_f + ib_f\gamma_5)f$$

J. Ellis et al., arXiv:1312.5736

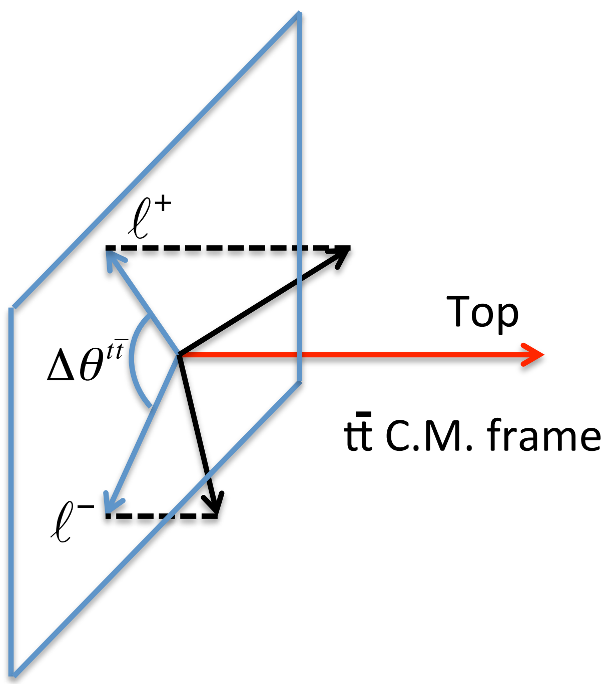
$$A_{t\bar{t}} = \frac{\sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+,\ell^-) > 0) - \sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+,\ell^-) < 0)}{\sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+,\ell^-) > 0) + \sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+,\ell^-) < 0)}$$

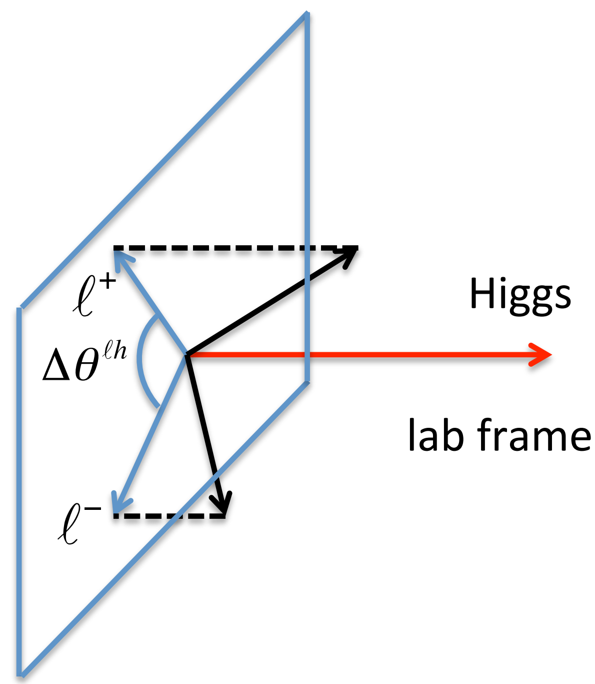
F. Boudjema et al., arXiv:1501.03157

$$A_{\rm lab} = \frac{\sigma(\beta \times \Delta\theta^{\ell h}(\ell^-,\ell^+) > 0) - \sigma(\beta \times \Delta\theta^{\ell h}(\ell^-,\ell^+) < 0)}{\sigma(\beta \times \Delta\theta^{\ell h}(\ell^-,\ell^+) > 0) + \sigma(\beta \times \Delta\theta^{\ell h}(\ell^-,\ell^+) < 0)}$$

Lab frame quantities, no top reconstruction

$$\alpha, \beta \rightarrow CP-odd\ \ observables$$





Asymmetries and Higgs-top Coupling

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J. Ellis et al., arXiv:1312.5736

$$A_{t\bar{t}} = \frac{\sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+,\ell^-) > 0) - \sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+,\ell^-) < 0)}{\sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+,\ell^-) > 0) + \sigma(\alpha \times \Delta\theta^{t\bar{t}}(\ell^+,\ell^-) < 0)}$$

F. Boudjema et al., arXiv:1501.03157

$$A_{\rm lab} = \frac{\sigma(\beta \times \Delta\theta^{\ell h}(\ell^-,\ell^+) > 0) - \sigma(\beta \times \Delta\theta^{\ell h}(\ell^-,\ell^+) < 0)}{\sigma(\beta \times \Delta\theta^{\ell h}(\ell^-,\ell^+) > 0) + \sigma(\beta \times \Delta\theta^{\ell h}(\ell^-,\ell^+) < 0)}$$

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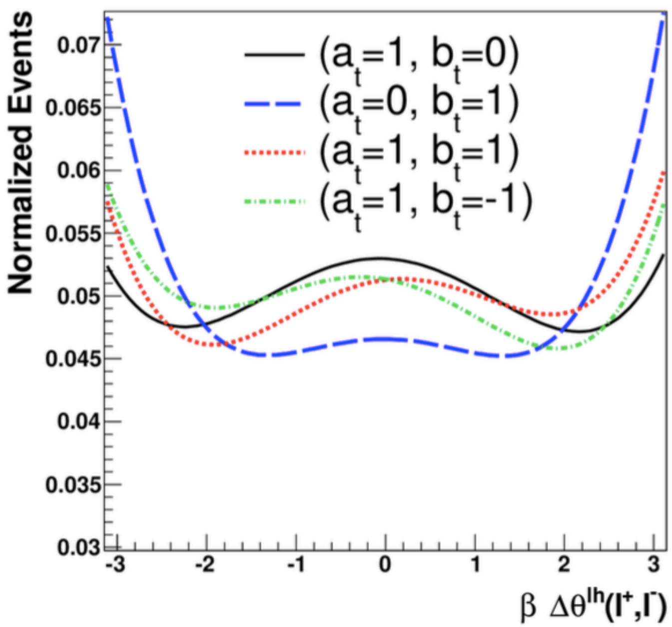
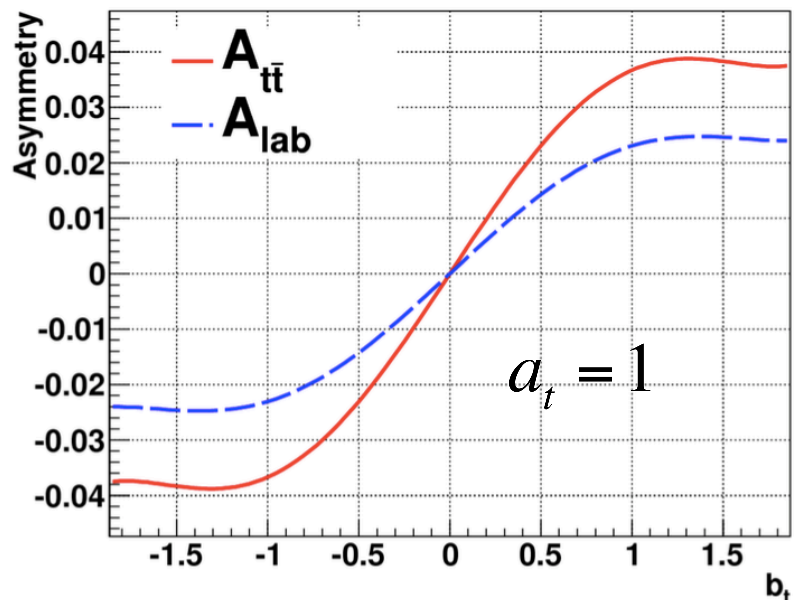


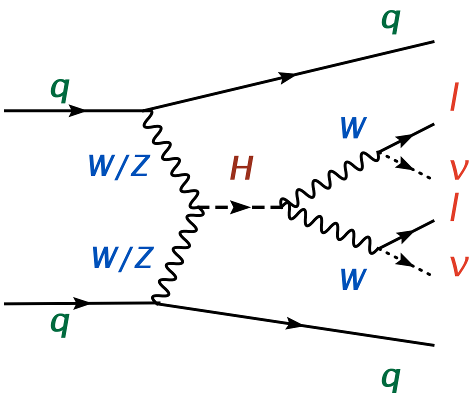


CP-odd component

$t\bar{t}H$, dilepton

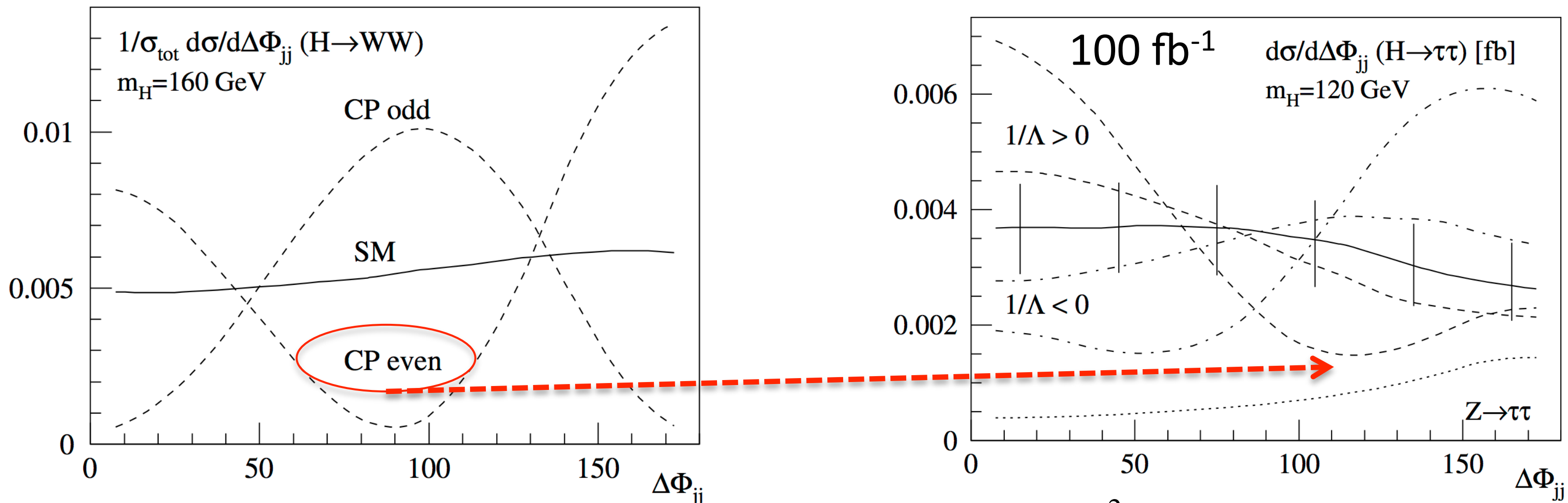
Asymmetries and Higgs-VV Coupling

- deviations in the HVV vertex → study the angle between forward jets in VBF.



Additional CP-even and CP-odd scalars:

$$\mathcal{L}_5 = \frac{1}{\Lambda_{e,5}} H\, W^+_{\mu\nu} W^{-\,\mu\nu} + \frac{1}{\Lambda_{o,5}} H\, \widetilde{W}^+_{\mu\nu} W^{-\,\mu\nu}$$



No interference

$$|\mathrm{M}|^2 = |M_{SM} + M_{e,5}|$$

Interference effects cause an asymmetry →

$$A_\phi = \frac{N(\Delta\phi_{jj} < \pi/2) - N(\Delta\phi_{jj} > \pi/2)}{N(\Delta\phi_{jj} < \pi/2) + N(\Delta\phi_{jj} > \pi/2)}$$

Plehn et al. PRL 88 (2002) 051801

Summary, Conclusions, and Future

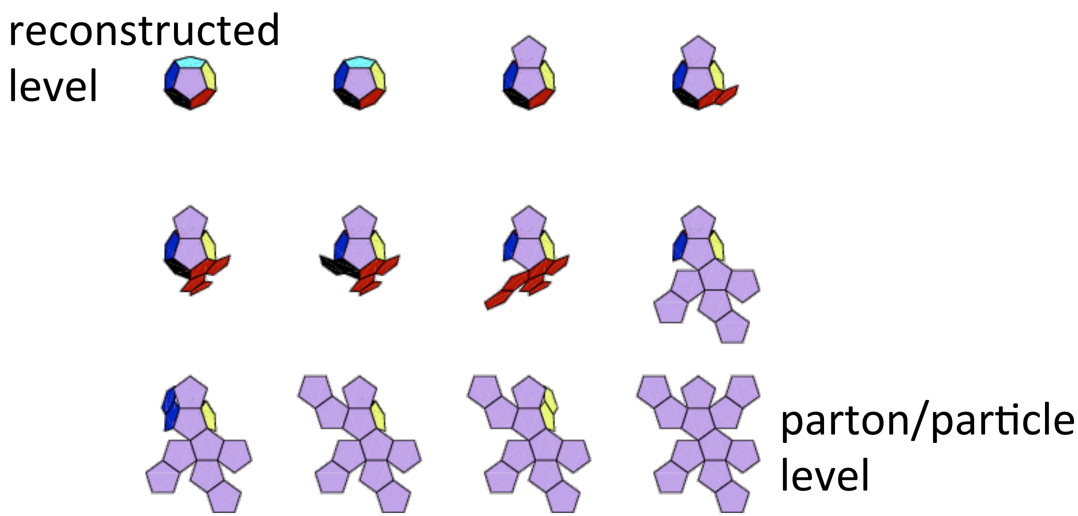
- Asymmetries at Tevatron and LHC providing precision tests of the SM.
  - Asymmetries were highly useful in the construction/testing of the SM and predicting and measuring particle properties.
  - So far all measurements consistent with the SM predictions at the Tevatron (except CDF top pair asymmetry).
    - Tevatron discrepancy →
      - better understanding of top quark properties, improved expertise in asymmetry measurements
      - Measurements pushed for higher order QCD calculations.
  - All measurements consistent with the SM at the LHC including the Higgs boson.

Summary, Conclusions, and Future

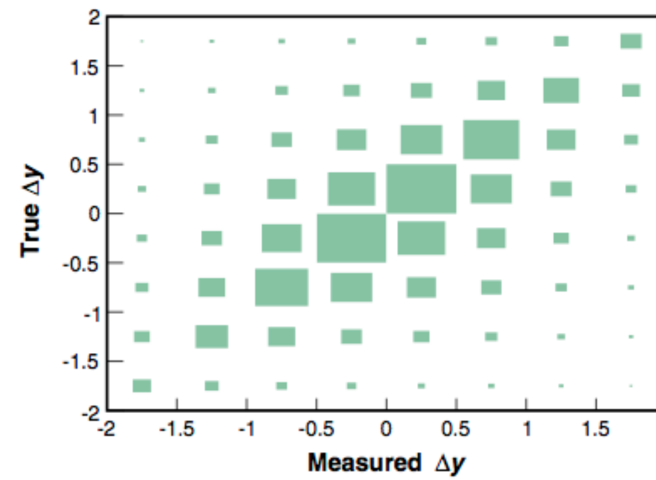
- LHC Run I: SM is “completed” with the Higgs boson discovery
- LHC Run II:
  - Discovery and/or properties measurements through asymmetries.
    - Test SM at high center of mass values (> 1 TeV)
      - Drell-Yan forward-backward asymmetry
      - Top-pair asymmetries
      - Alternative/complementary asymmetry variables to better understand the Tevatron asymmetry and for more through tests of QCD.
      - Asymmetries using boosted objects.
      - Higgs boson properties (Higgs-top couplings, Higgs-Vector boson couplings, CP properties, ..)
  - Improve theory calculations and Monte Carlo generators.

Backup

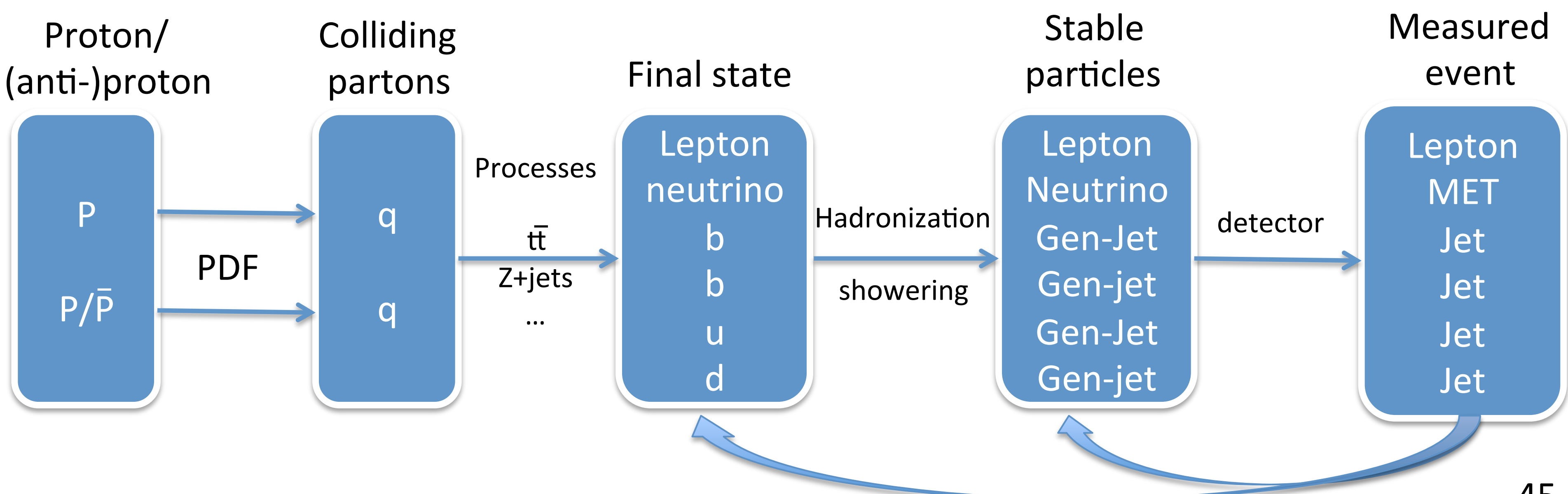
Unfolding



reconstructed
level
parton/particle
level

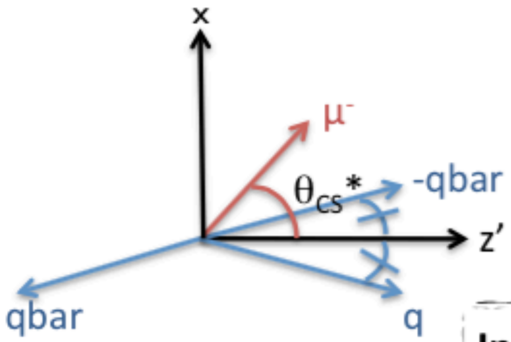


True Δy
Measured Δy
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2



Proton/
(anti-)proton
P
P/P̄
PDF
Colliding
partons
q
q
Processes
tt̄
Z+jets
...
Final state
Lepton
neutrino
b
b
u
d
Hadronization
showering
Stable
particles
Lepton
Neutrino
Gen-Jet
Gen-jet
Gen-Jet
Gen-jet
detector
Measured
event
Lepton
MET
Jet
Jet
Jet
Jet

Defining Forward/Backward: Collins-Soper Frame



Boost into dilepton rest frame.

q is not collinear with q~'s momentum
→ z axis: bisector of q and -q~ directions.

In the Collins-Soper frame
→ The angle θ_{CS}* is measured w.r.t. the axis bisecting the q and -q~ vectors. If there is no pT boost θ_{CS}* in CS frame reduces to θ*.
→ X axis along p_T direction of the dilepton system in the lab frame.

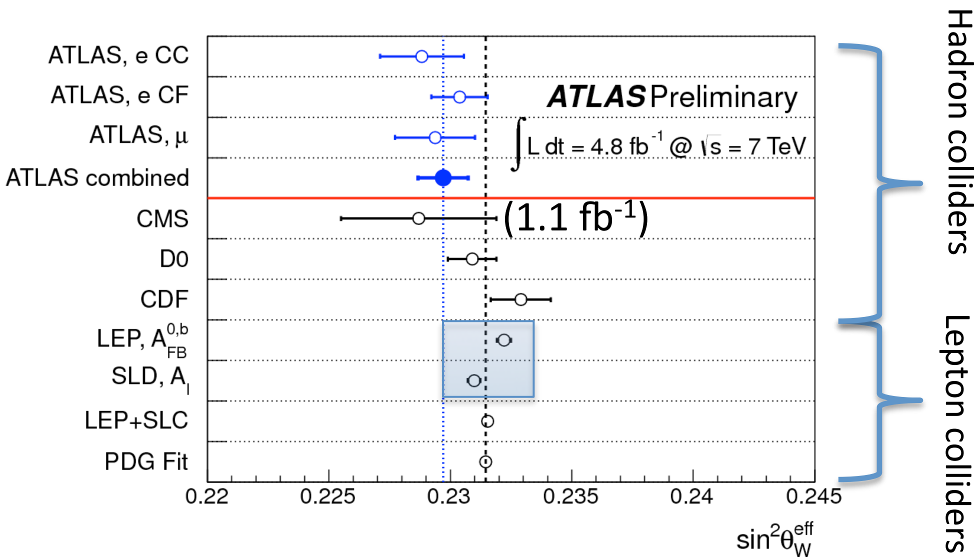
Using the Collins-Soper frame reduces the uncertainties due to the unknown and finite transverse momentum of the incoming quarks.

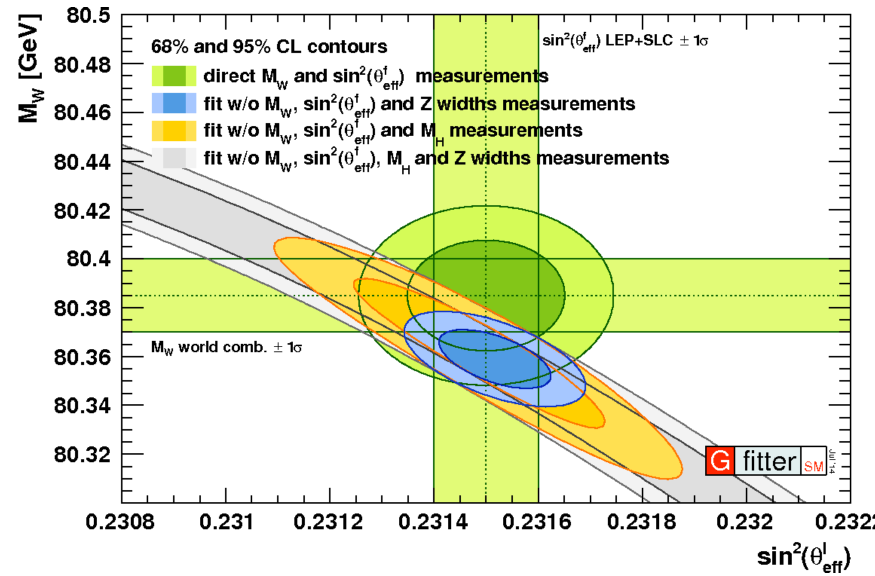
θ* is calculated using lab-frame quantities

$$\cos\theta^*_{CS} = \frac{2\left(P_l^+ P_{\bar{l}}^- - P_l^- P_{\bar{l}}^+\right)}{\sqrt{Q^2\left(Q^2 + Q_T^2\right)}} \qquad P_l^\pm = \left(P_l^0 \pm P_l^3\right)/\sqrt{2}$$

Q: four-momentum of the di-lepton system.
P_l($P_{l\sim}$) represent the 4-momenta of the lepton (anti-lepton).

Summary of the Effective Weak Mixing Angle Measurements





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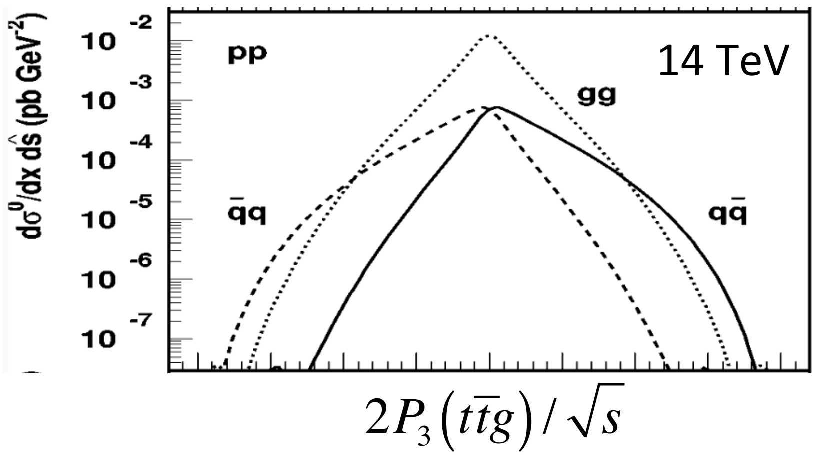
- With ~6x better precision → World average
  - Possible with ~20 fb^{-1} at 14 TeV LHC but also PDF and lepton energy scales need to be improved.
- Full D0+CDF would yield a precision similar to LEP or SLD.
  - Currently (9.7 fb^{-1}) D0= 0.23146+/-0.00047
  - (LEP+SLD = 0.23153+/-0.00016)

arXiv:1408.5016

tt+g Asymmetry



Use the invariant mass of the $t\bar{t}+g$ system and its longitudinal momentum to obtain a preferred direction for the quark-antiquark process.

Kühn & Rodrigo PRL 81 (1998) 49