Recent anomalies in processes with heavy quarks

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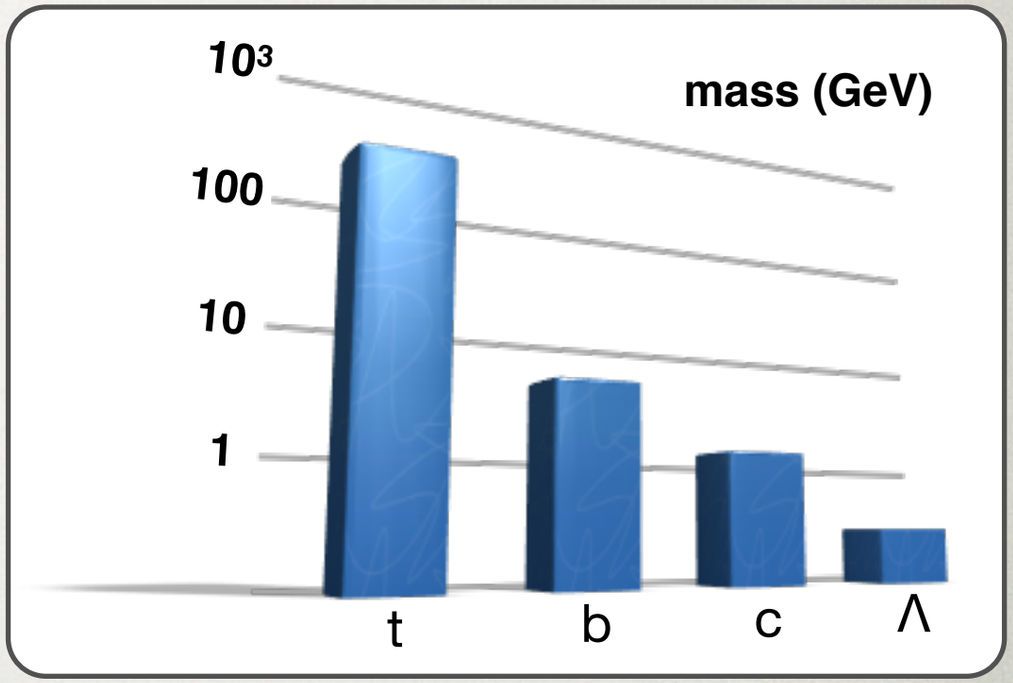
Theory colloquium, June 27 2012, CERN

HEAVY QUARKS

- heavy quarks:
  - mass above Λ_{QCD}
    - top: $y_t \sim 1$
    - b quark: $y_b \sim 0.03 \times tan\beta$
    - charm: $y_c \sim 0.01$
- for each of them a surprising experimental result



THREE ANOMALIES

- top quark
  - $A_{FB}{}^{tt}$ at Tevatron
- charm quark
  - CP asymmetry in $D \to K^+K^-, \pi^+\pi^-$
- b quark
  - lepton flavor universality violation in $B^{(*)} \to D\tau\upsilon, B \to \tau\upsilon$

THE AIMS

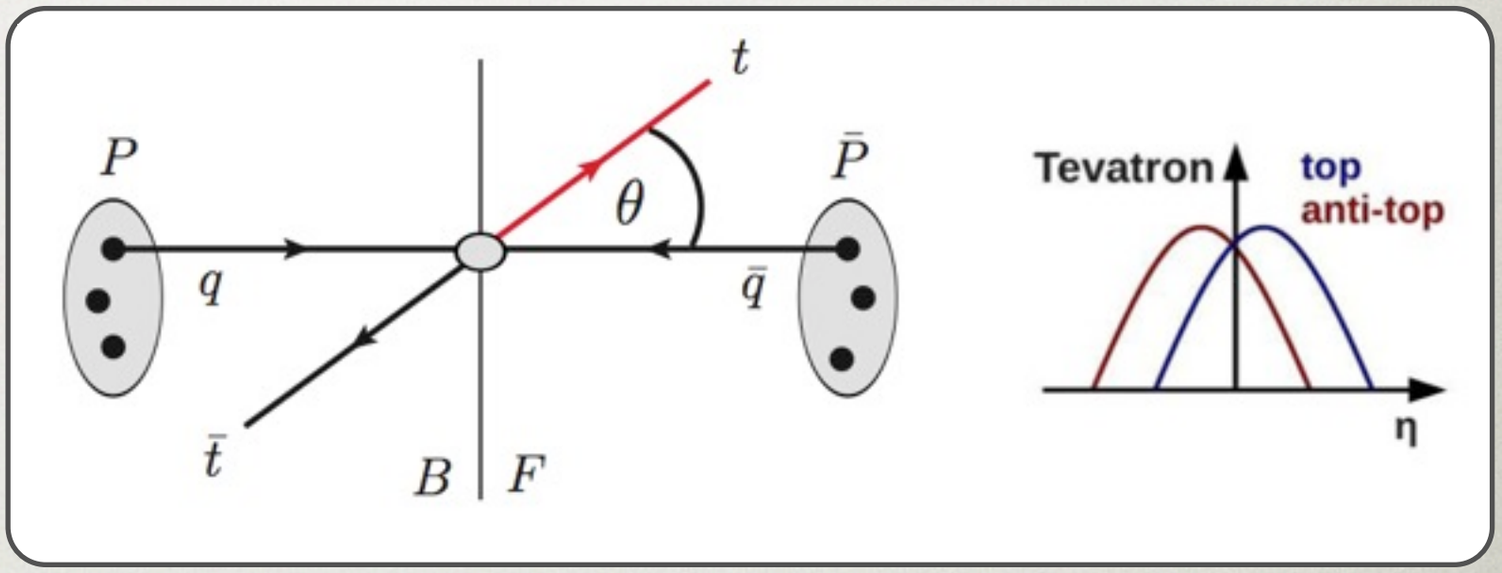
- for each of the anomalies:
  - experimental status
  - could it be due to standard model?
  - could it be due to new physics?
    - what kind of NP?

NP IN TTBAR PRODUCTION?

THE PROBLEM

- indications that $A_{FB}{}^{tt}$ at Tevatron is anomalously large

$$A_{FB}^{t\bar{t}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



- the top cross section agrees with predictions

THE PROBLEM

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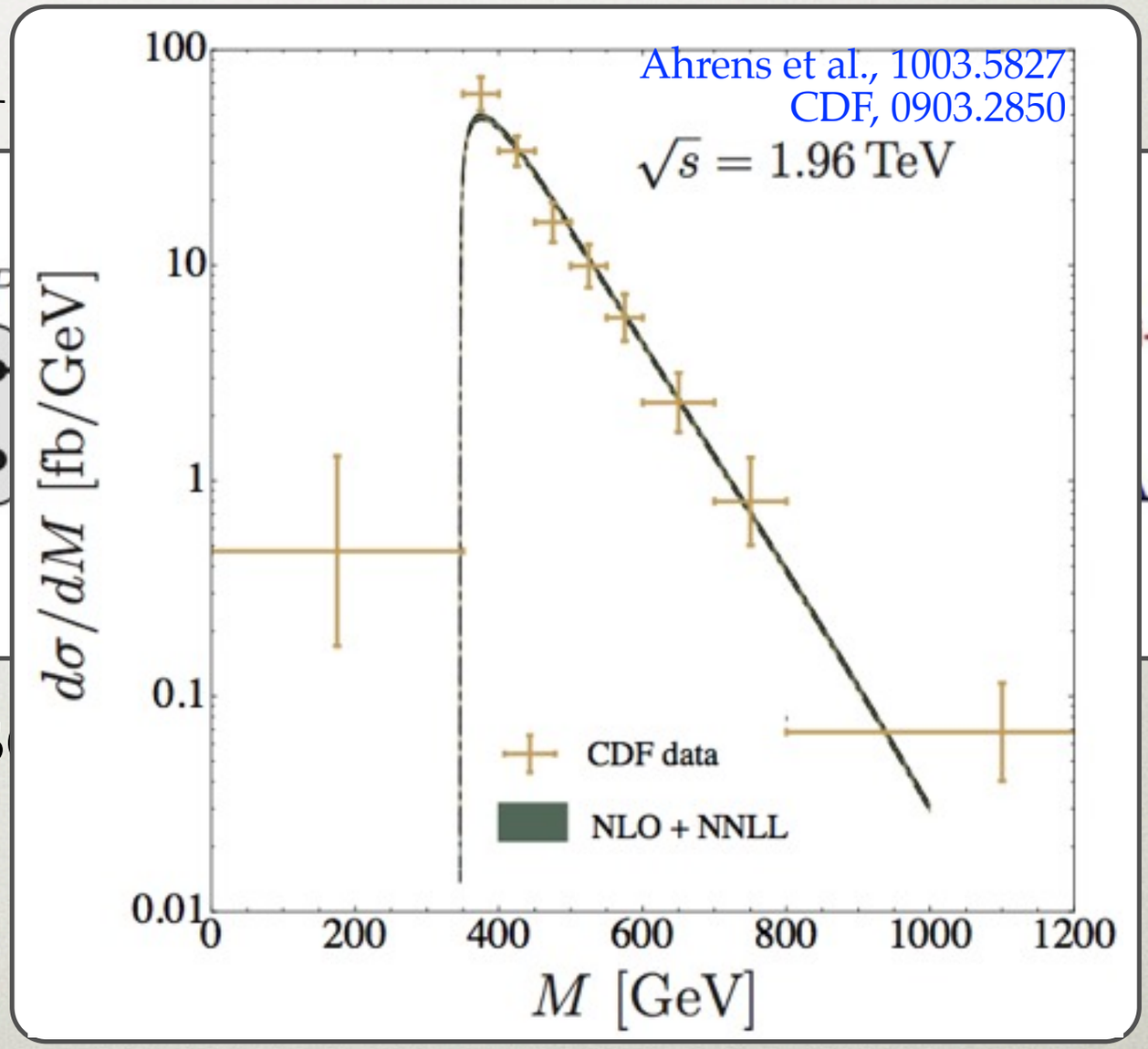


- the top cross s
  predictions

SM origin of the asymmetries

- nonzero A_{FB} from $(\hat{u}\text{-}\hat{t})$-odd contributions

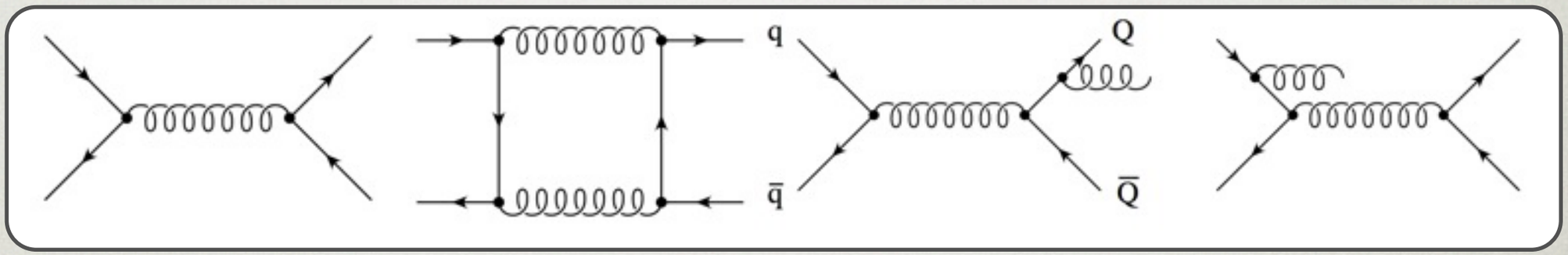
$$\hat{t}, \hat{u} = m_t^2 - \frac{\hat{s}}{2}[1 \mp \beta_t \cos\theta]$$

$$\beta_t = \sqrt{1 - \frac{4m_t^2}{\hat{s}}}$$

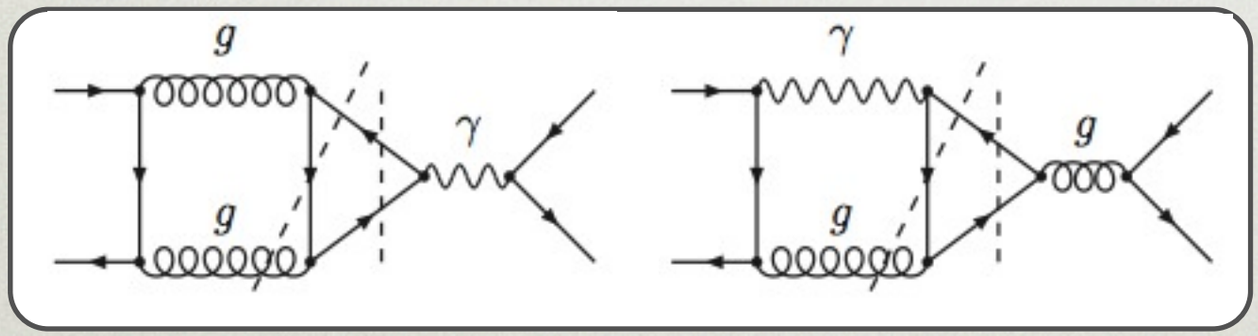
Kuhn, Rodrigo hep-ph/9802268; hep-ph/9807420

- in QCD at $O(\alpha_S^3)$

Ahrens et al, 1106.6051



- additional EW contribs.



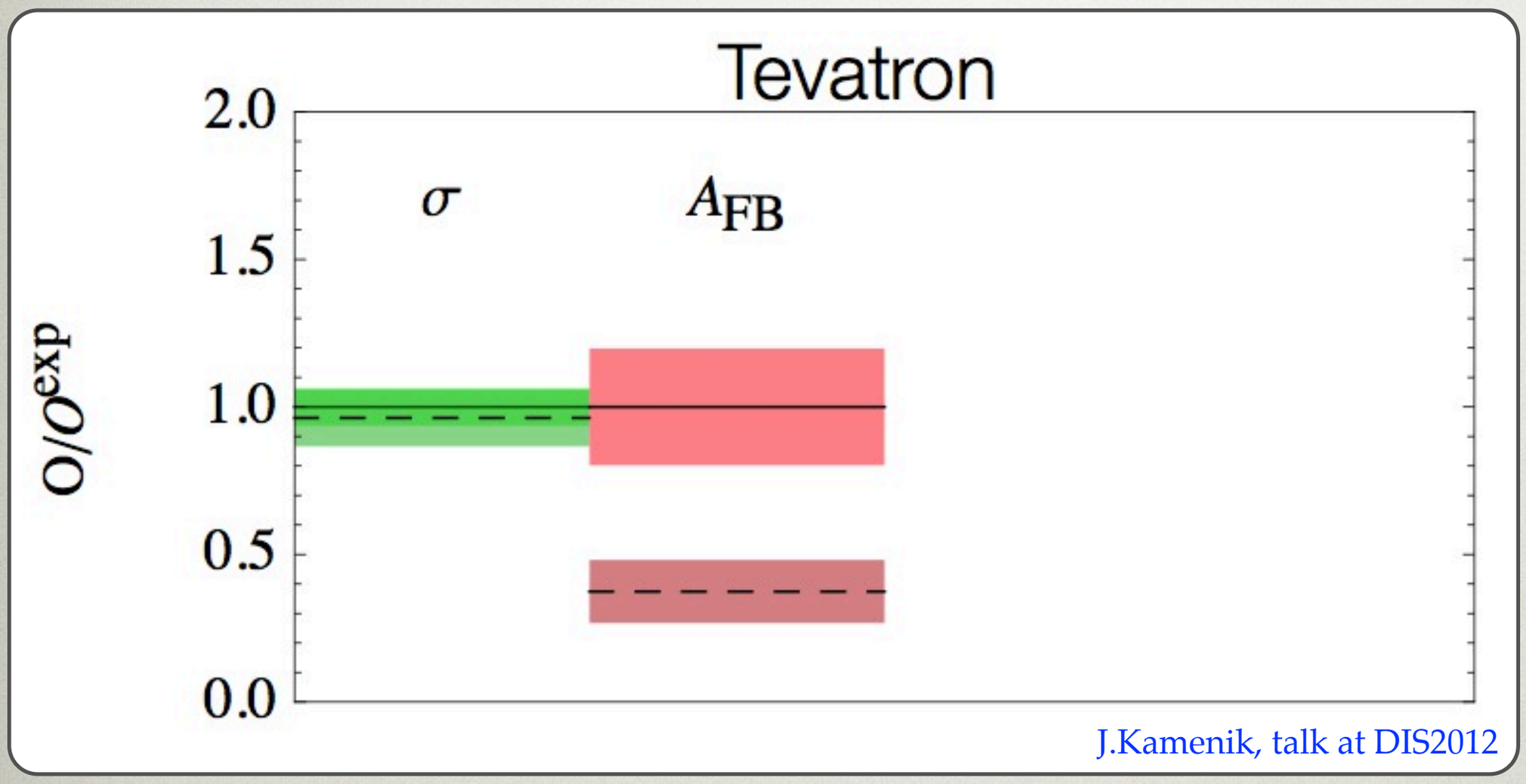
Hollik, Pagani, 1107.2606
Kuhn, Rodrigo, 1109.6830
Manohar, Trott, 1201.3926

- SM predictions
  - Tevatron: $(A_{FB})^{SM} \sim 7\text{-}9\%$ ($\bar{q}q$ init. state dominates)

MEASUREMENTS

- precisely measured inclusive observables

Ahrens et al. 1003.5827; 1103.0550
Kidonakis, 1009.4935; 1105.3481
Beneke et al., 1109.1536
Barnreuther et al., 1204.5201



J.Kamenik, talk at DIS2012

- $\sigma=(7.50\pm0.48)$pb $A_{FB}=0.187\pm0.037$*

CDF, Public Notes 9913, 10398, 10807
D0, 1107.4995

*naive average of CDF&D0

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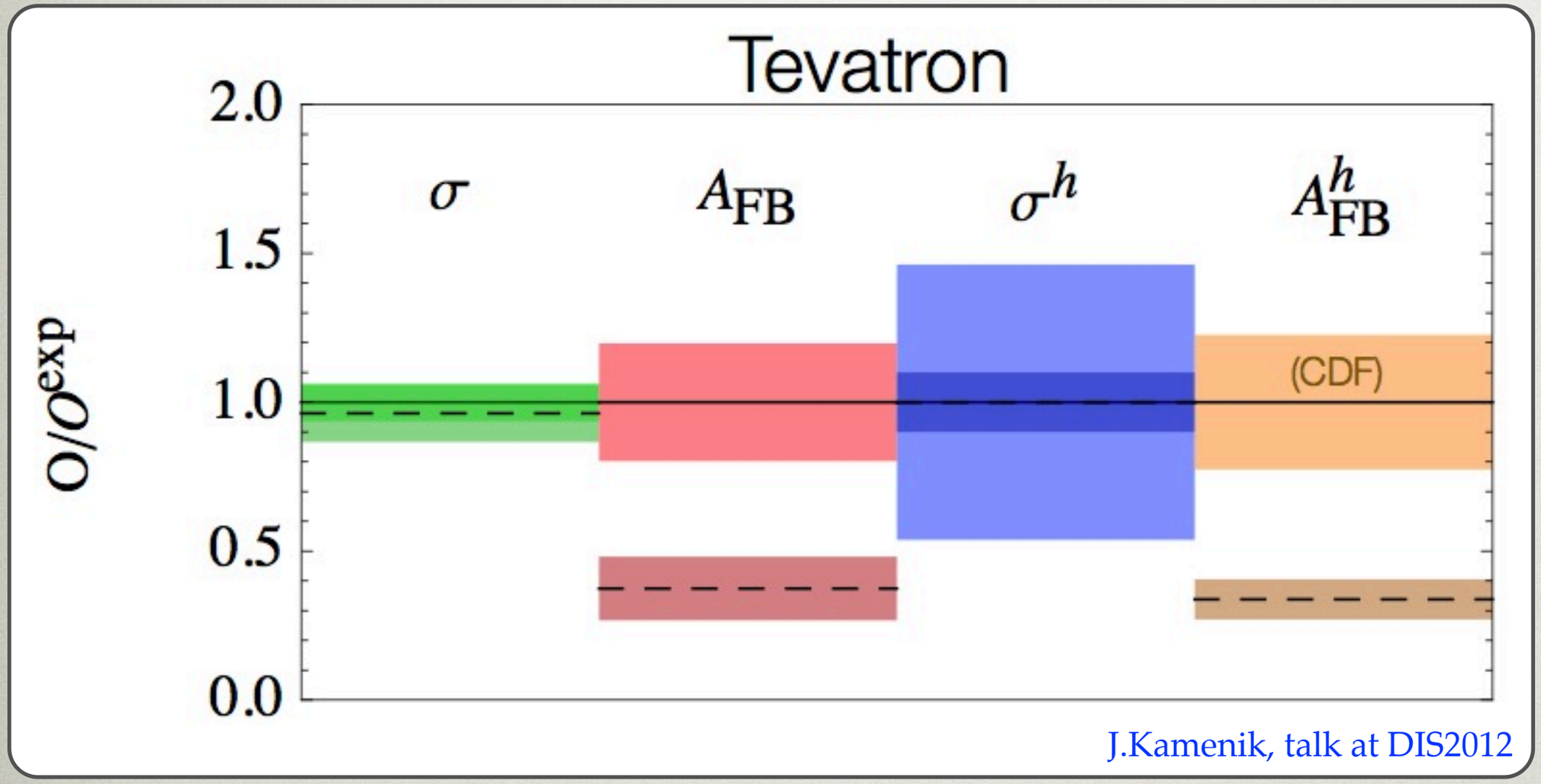

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- exclusive m_{tt} observables sensitive to NP
  - $\sigma^h=\sigma(700\text{GeV}<m_{tt}<800\text{GeV})$ $\quad A_{FB}{}^h=A_{FB}(m_{tt}>450\text{GeV})$

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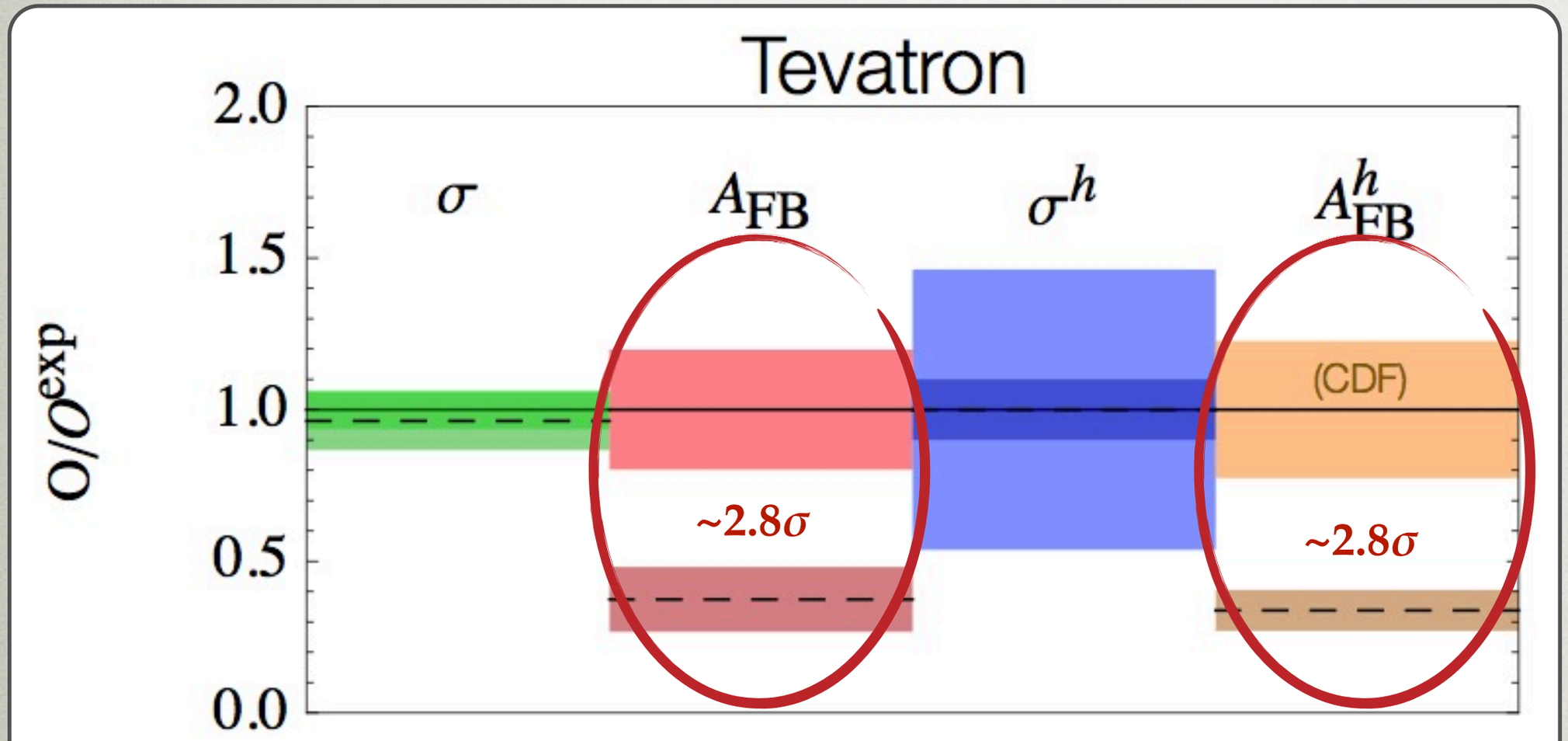

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D0, 1107.4995
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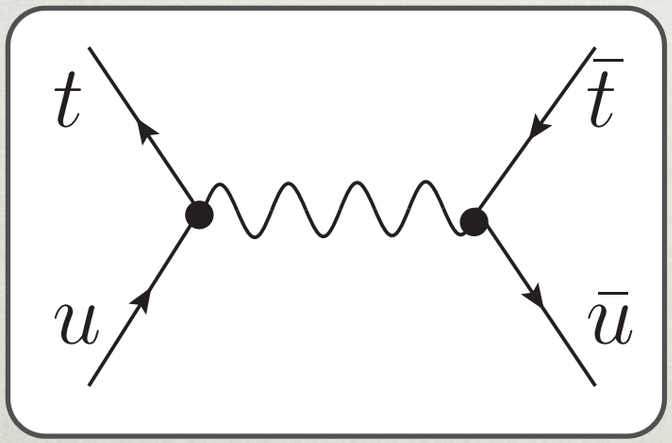
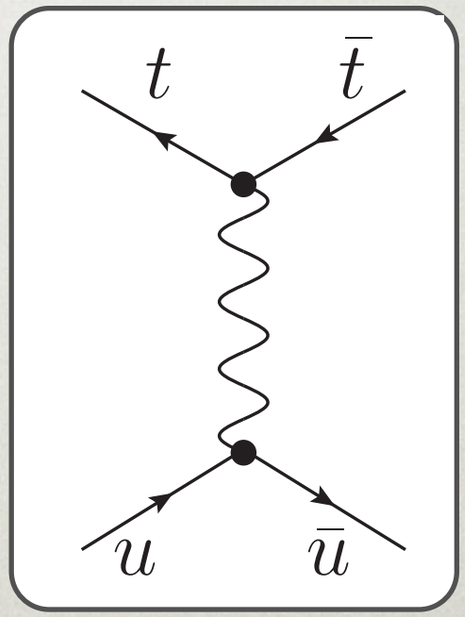
COULD IT BE NEW PHYSICS?

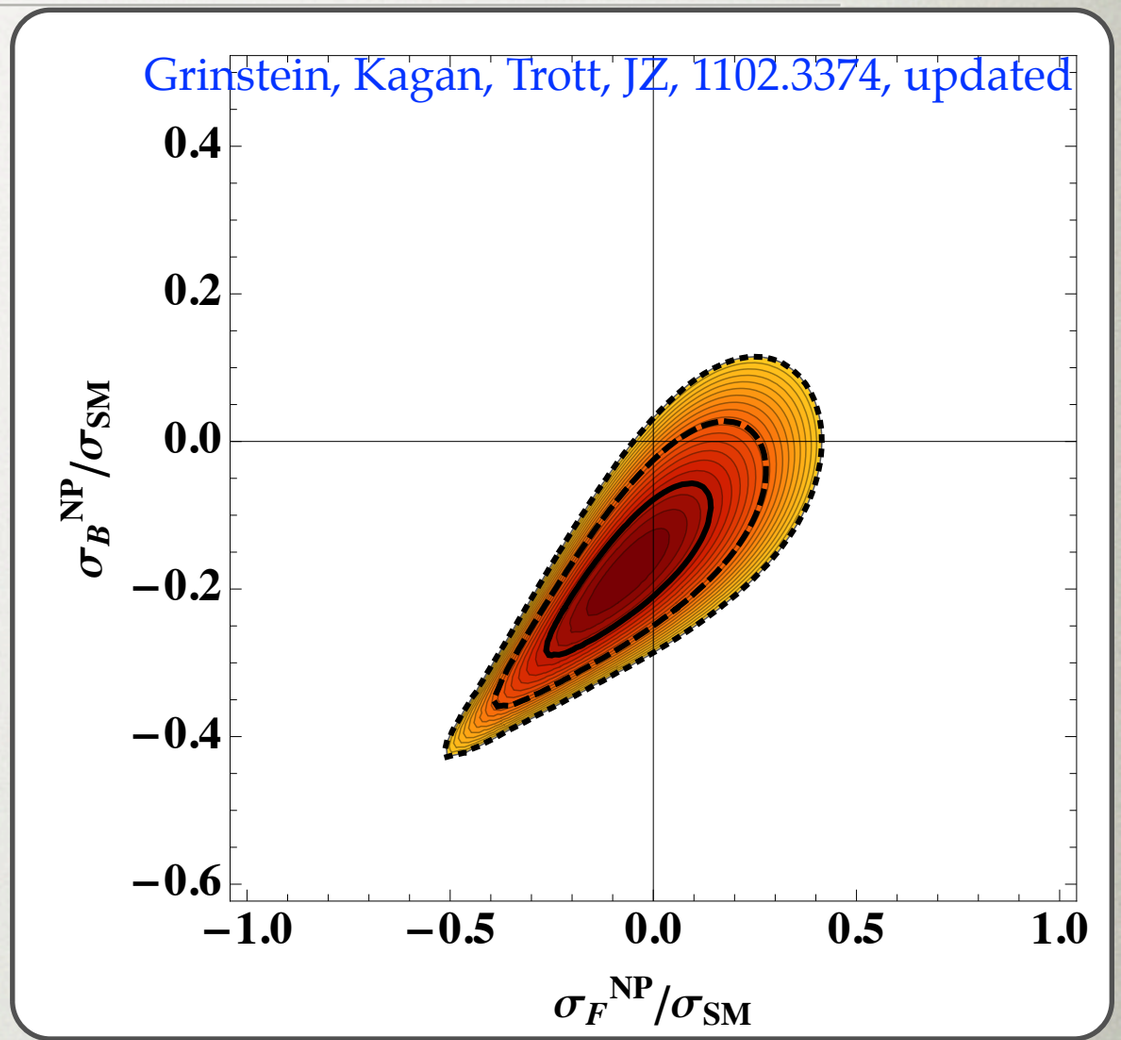
- if A_{FB} is due to New Physics
  - the effects are large ⇒ tree level
  - t-(u-)channel? s-channel?





INTERFERENCE

- NP has to interfere with the SM
- if *s*-channel resonance:
  - to interfere with one-gluon exchange has to be color-octet
  - "axigluon"
- this does not fix *t*-channel quantum numbers



$$\sigma_{F,B}^{\rm NP} \equiv \sigma_{F,B} - \sigma_{F,B}^{\rm SM}$$

NEW PHYSICS MODELS

- light NP (~300-400 GeV) models

for review see Kamenik, Shu, JZ,1107.5257

Jung, Murayama, Pierce, Wells, 0907.4112 Cheung, Keung, Yuan, 0908.2589

  - t-channel vectors: Z' : $\bar{u}u \to \bar{t}t$, W': $\bar{d}d \to \bar{t}t$; scalar: H': $\bar{u}u \to \bar{t}t$; colored and flavor multiplet variants

Blum, Hochberg, Nir, 1107.4350

Grinstein, Kagan, Trott, JZ, 1102.3374;1108.4027

  - u-channel scalars: color triplet, sextet diquarks: $\bar{u}u \to \bar{t}t$

Shu, Tait, Wang, 0911.3237; Arhrib, Benbrik, Chen, 0911.4875; Ligeti, Tavares, Schmaltz,1103.2757;. Dorsner, Fajfer, Kamenik, Kosnik, 0912.0972; Cao,McKeen, Rosner, Shaughnessy, Wagner , 1003.3461

  - s-channel axigluon: $\bar{u}u \to \bar{t}t$ and $\bar{d}d \to \bar{t}t$

Tavares, Schmaltz, 1107.0978; Aguilar-Saavedra, Perez-Victoria, 1107.2120

- heavy NP (~2TeV)

Ferrario ,Rodrigo, 0906.5541; Frampton, Shu,Wang, 0911.2955

  - can apply EFT

Blum, Delaunay, Gedalia, Hochberg, Lee, Nir, Perez, Soreq,1102.3133; Delaunay, Gedalia, Hochberg, Perez, Soreq,1103.2297;

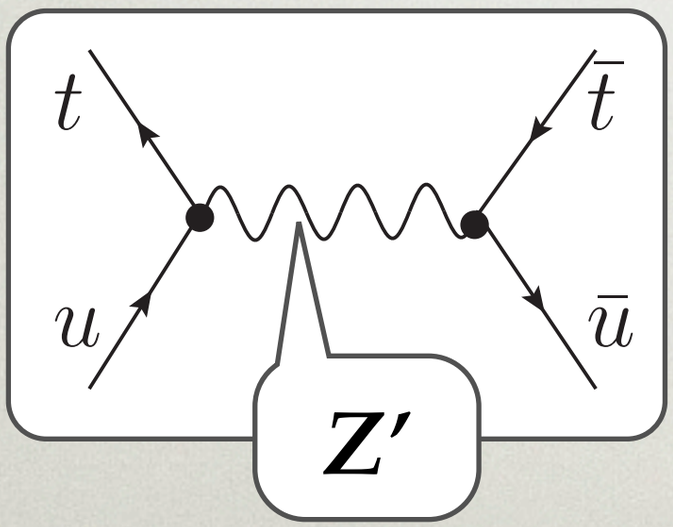
  - perturbative bounds at ~10TeV

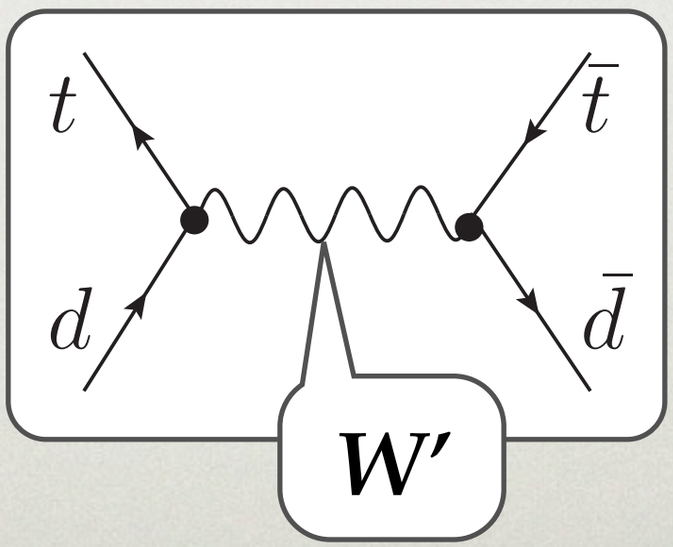
Aguilar-Saavedra, Perez-Victoria,1103.2765

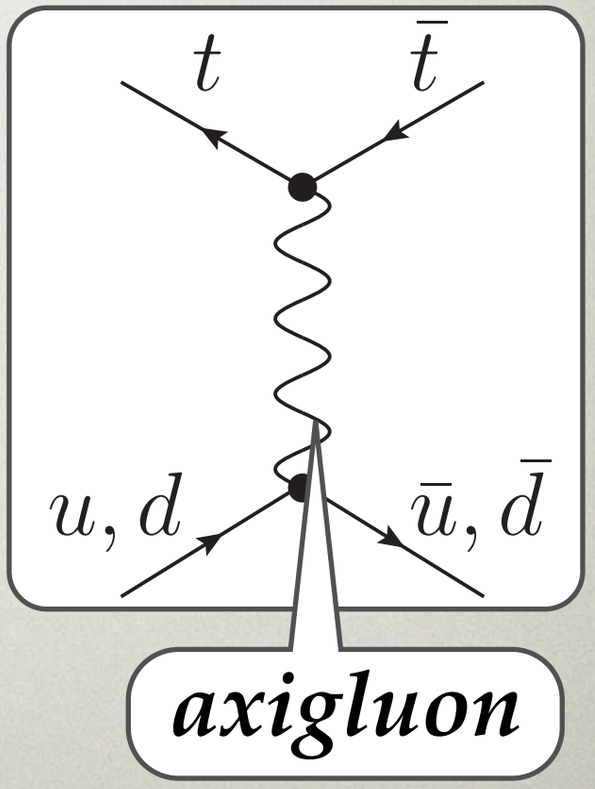
  - realizations: some type of axigluon (e.g., KK-gluon in RS)

THREE EXAMPLES

- all models are "effective"
  - assumed that at low eng. dominated by a single resonance
- three examples







NONTRIVIAL MODELS

- Models have to be nontrivial
  - no significant effect in $d\sigma/dM_{tt}$
  - large A_{FB}, but small A_C
  - constraints from dijets
  - same sign tops
  - atomic parity constraints
  - single top production
  - flavor constraints

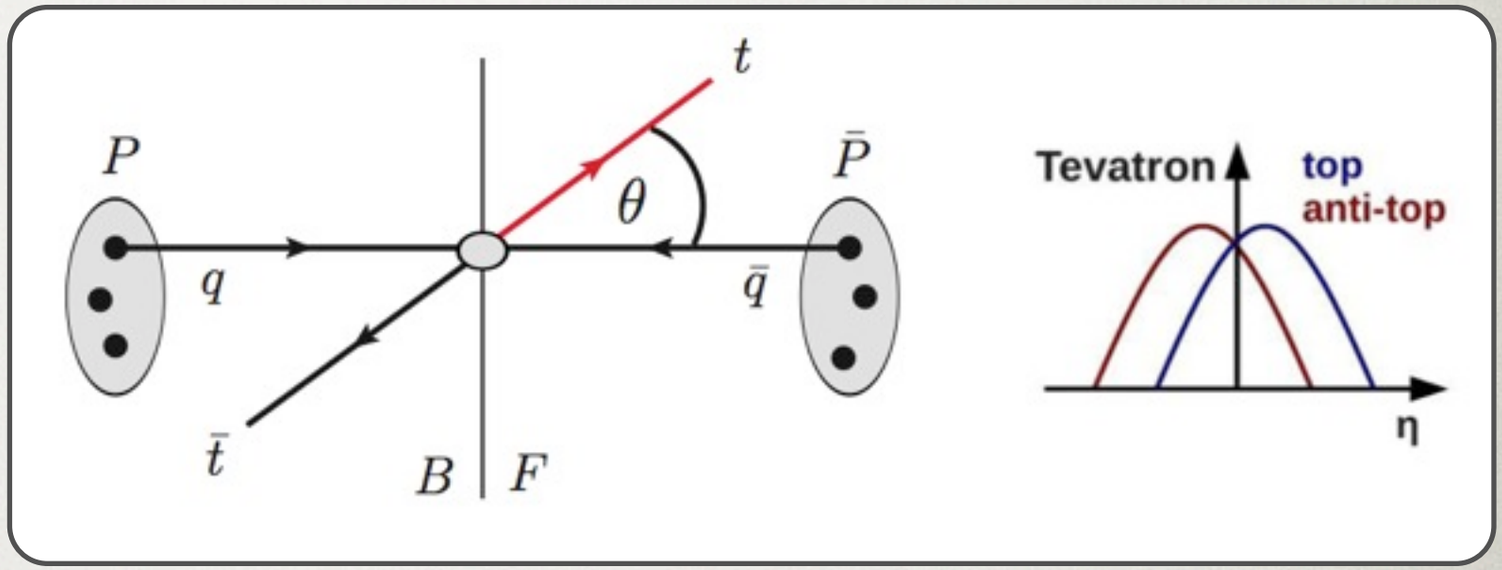
SEARCHING FOR NP

- how can we find out, if NP?
  - should see a deviation in one of the above observables
  - cannot hide completely: one needs to couple to quarks
- little additional info to be expected from Tevatron
- need to use LHC data
  - one major difference to Tevatron: *ttbar* production dominated by *gg* initial state
- let me single out one observable: A_C

A_{FB} vs. A_C

- A_{FB} at Tevatron

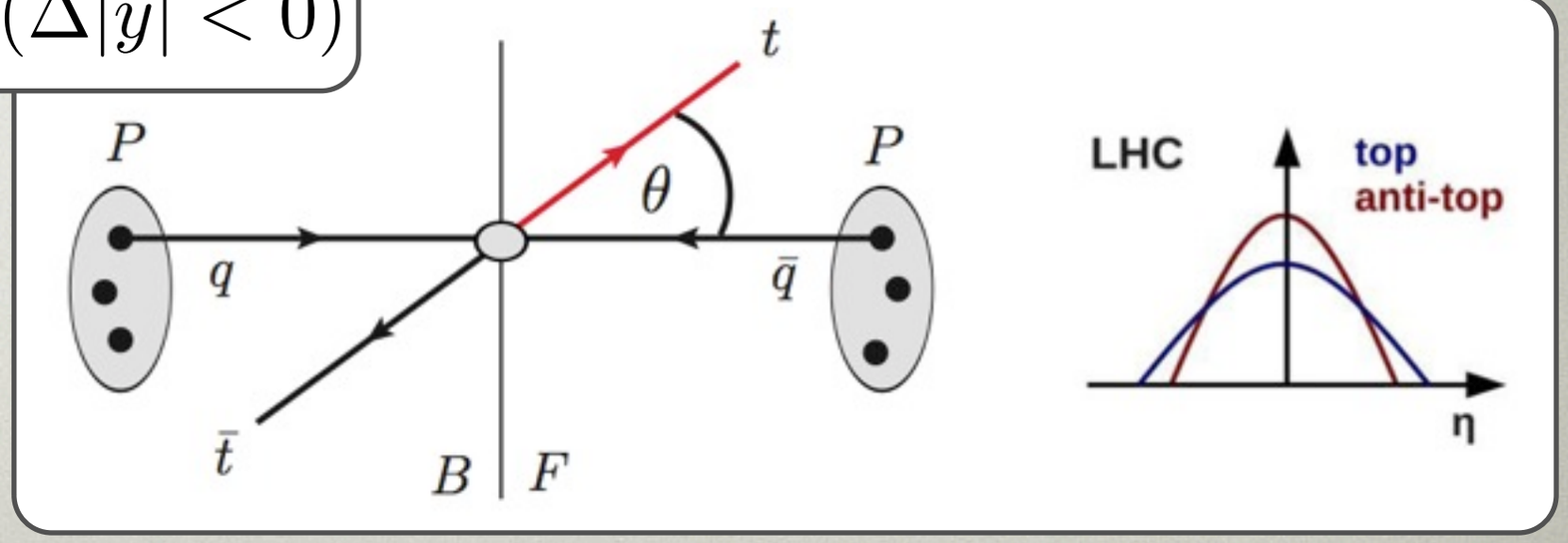
$$A_{FB}^{t\bar{t}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



- A_C at the LHC

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

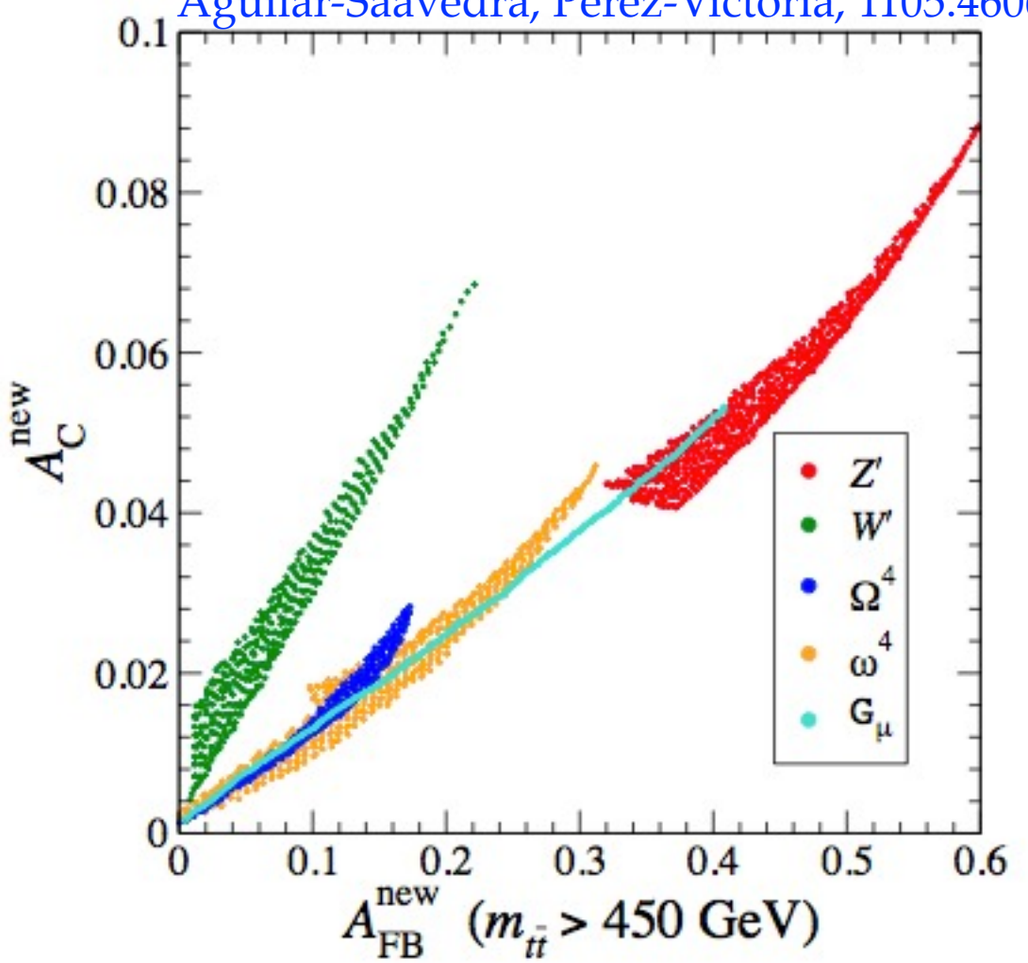
$$\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$



A_{FB} vs. A_C

- A_C and A_{FB} both arise in charge asymmetric part of $\sigma(q\bar{q}\to t\bar{t})\propto ...+...(\hat{u}-\hat{t})$
- rigid positive correlation of A_{FB} and A_C
  - if NP dominated by only u or d in initial state
- no deviations seen at the LHC!
  - $A_C=0.001\pm0.014$

Aguilar-Saavedra, Perez-Victoria, 1105.4606



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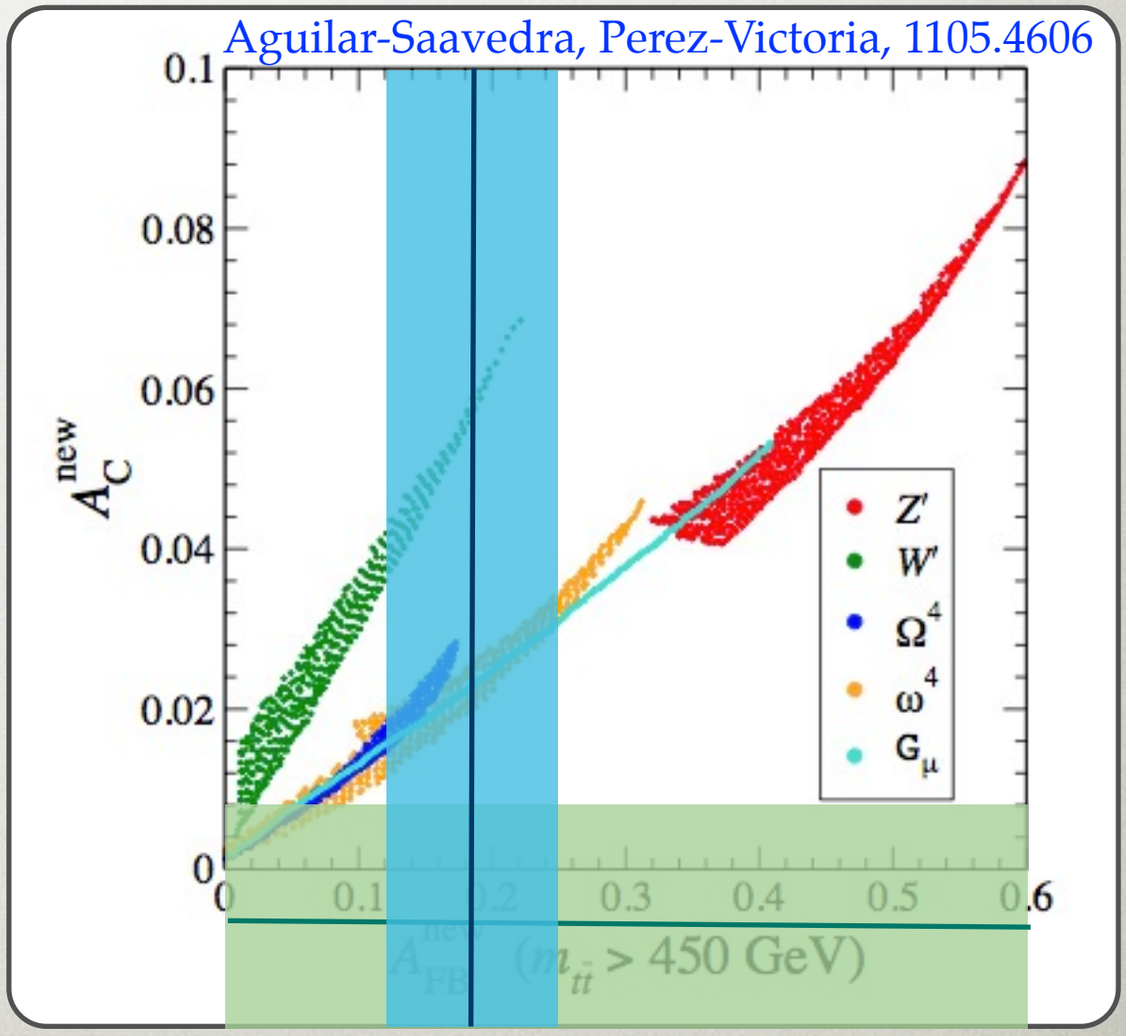
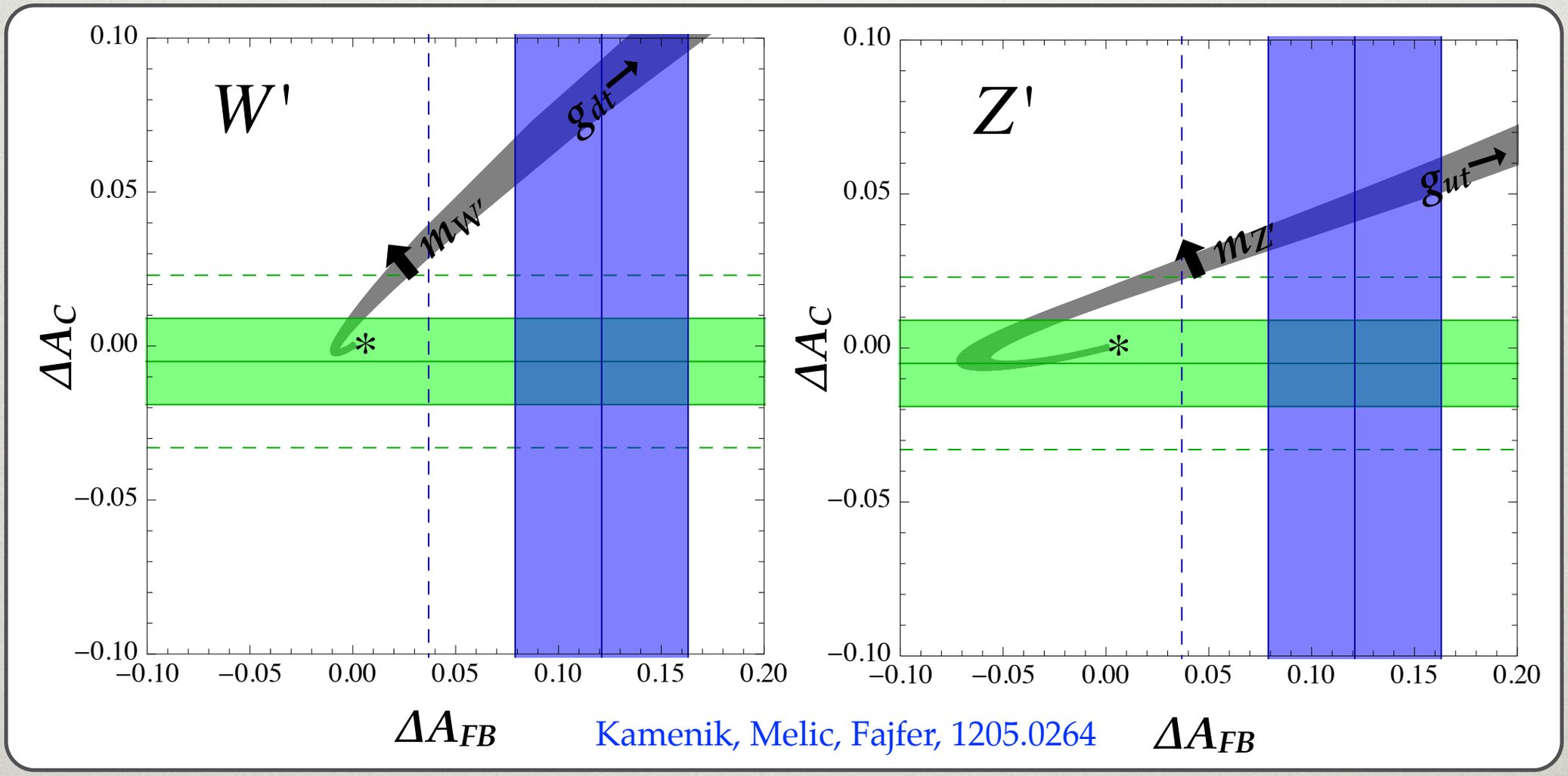


A_C constraints

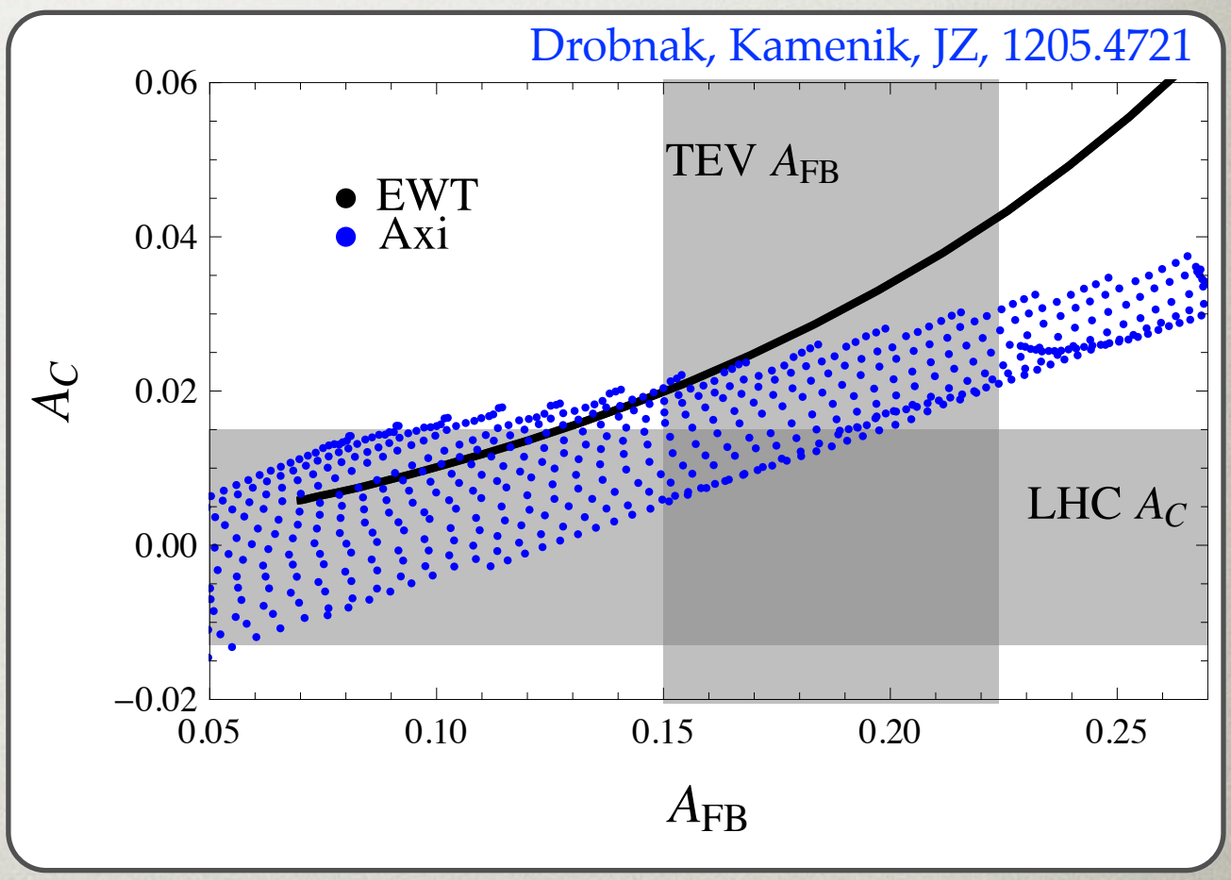
- LHC measurements of A_C have an impact
  - Z' and W' are incompatible with A_{FB}



Kamenik, Melic, Fajfer, 1205.0264

A_{FB} vs. A_C

- does this mean all NP models are dead?
- No!
  - strict correlation for A_{FB} vs. A_C lost if NP couples to both u and d
  - can be a simple extension of existing models
    - e.g. the light axigluon $SU(3)_L x SU(3)_R$ model
      - relax parity inv. in the new fermionic sector



SUMMARY OF A_{FB}

- tight constraints on the models that can explain A_{FB}
- most models are dead = provide an improvement over SM < 1σ in global picture
- preferred model is axigluon
  - light axigluon needs large decay width, $\Gamma \sim 0.2m$
  - heavy axigluon needs $g_u \ll g_t$
  - could be our first sign of strongly coupled EWSB sector or just a mirage...

direct CP violation in charm

THE PROBLEM

- the topic of the talk

$$\Delta A_{CP} = A_{CP}(D \to K^+K^-) - A_{CP}(D \to \pi^+\pi^-)$$

  - experiment (WA): $\Delta A_{CP} = (-0.67 \pm 0.16)\%$

Di Canto, La Thuile 2012

- could it be New Physics?
- could it be Standard Model?
- could we have anticipated such a large value?
  - how large is the SU(3) breaking in charm?

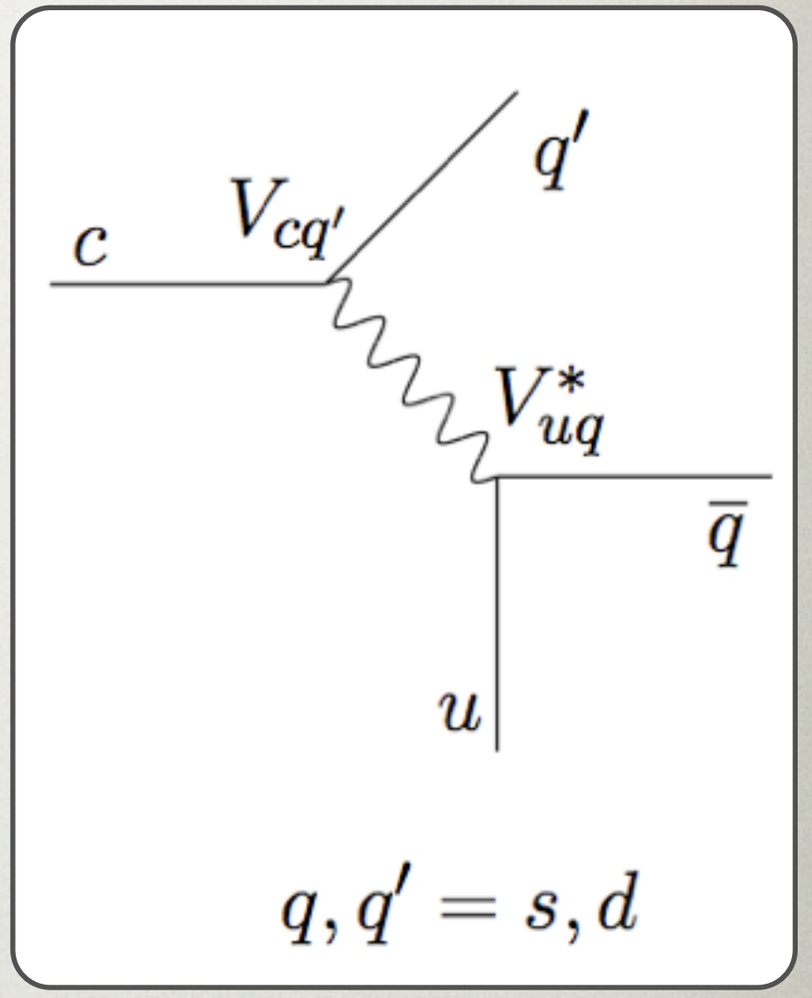
SETTING UP THE STAGE

- three classes of D decays
  - Cabibbo allowed
    - example: $D^0 \to K^- \pi^+$ $(c \to s u \bar{d})$

      $A_T \sim V_{cs}\, V_{ud} \sim 1$
  - singly Cabibbo suppressed (SCS)
    - example: $D^0 \to K^- K^+$, $D^0 \to \pi^- \pi^+$ $(c \to s u \bar{s},\ d u \bar{d})$

      $A_T \sim V_{cd}\, V_{ud},\ V_{cs}\, V_{us} \sim \lambda$
  - doubly Cabibbo suppressed
    - example: $D^0 \to \pi^- K^+$ $(c \to d u \bar{s})$

      $A_T \sim V_{cd}\, V_{us} \sim \lambda^2$



$D^0 \sim c\bar{u}$

$K^- \sim s\bar{u}$

$\pi^+ \sim u\bar{d}$

DIRECT CPV

- focus on SCS D decays in the SM

$$A_f(D \to f) = A_f^T[1 + r_f e^{i(\delta_f - \gamma)}],$$
$$\overline{A}_{\bar{f}}(\bar{D} \to \bar{f}) = A_f^T[1 + r_f e^{i(\delta_f + \gamma)}],$$

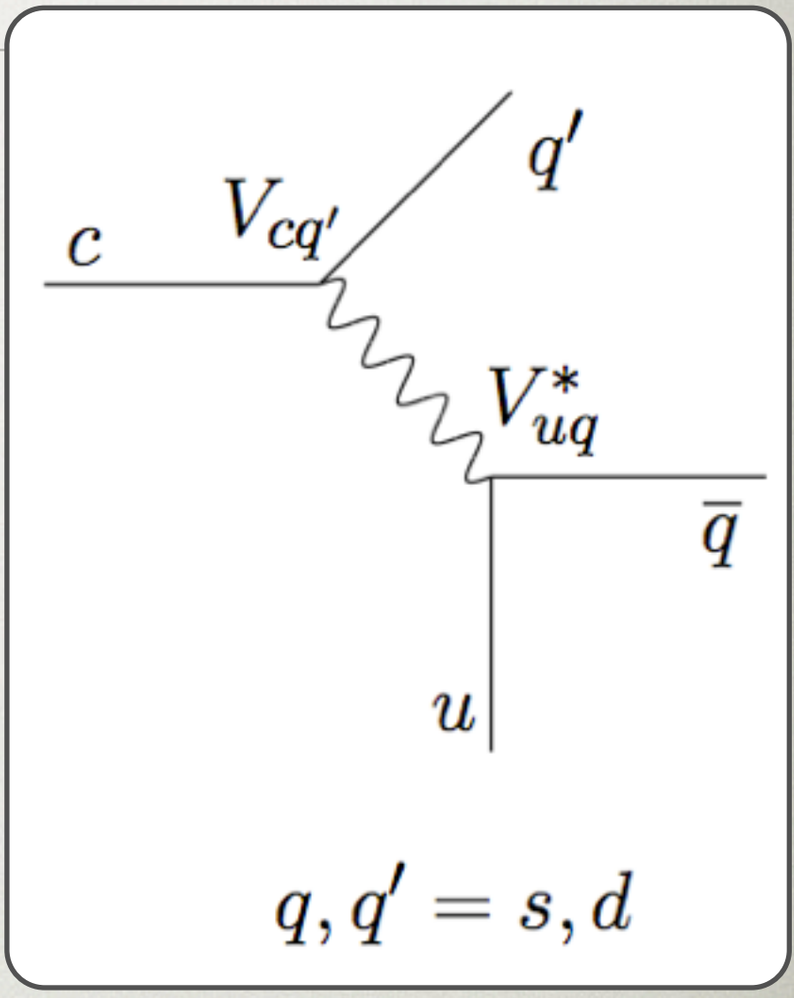
- A_f^T - tree ampl., r_f - relative "penguin" contrib., δ_f - strong phase

- direct CP asymmetry

$$\mathcal{A}_f^{\rm dir} \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2} = 2r_f \sin\gamma \sin\delta_f$$

- sinγ~0.9, so for δ_f~$O(1)$

$$\mathcal{A}_f^{\rm dir} \sim 2r_f$$



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- $\sin\gamma \sim 0.9$, so for $\delta_f \sim O(1)$

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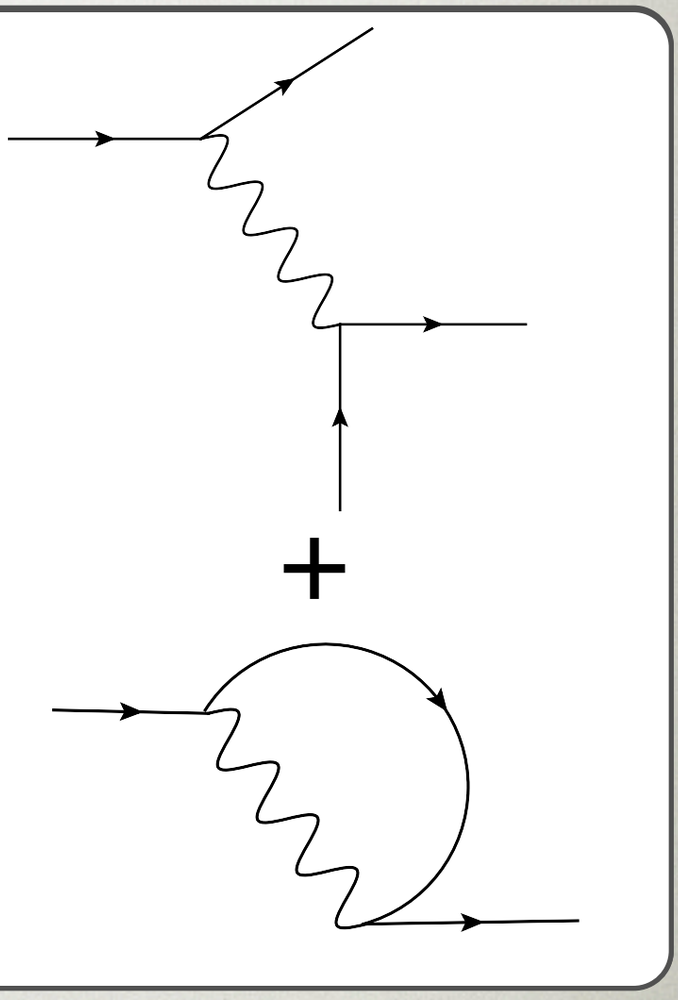
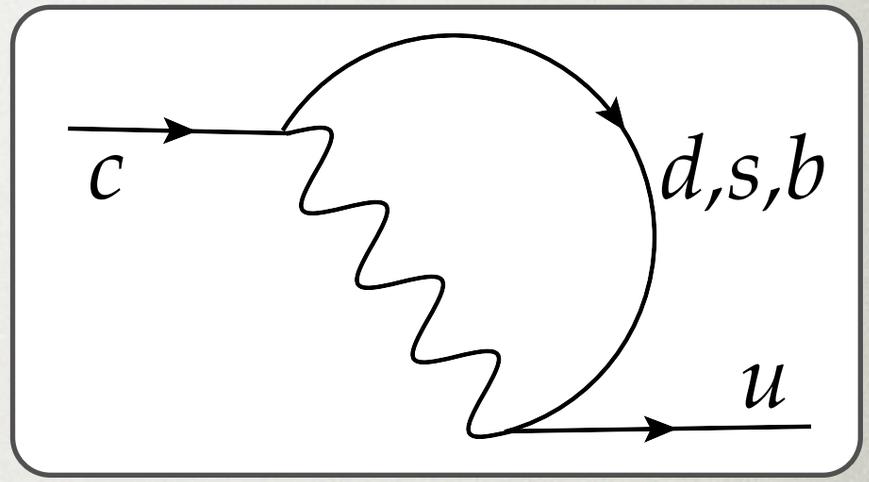


SCS: $c \to s\bar{u}\bar{s}$, $du\bar{d}$

CP VIOLATION IN CHARM

- in charm physics the first 2 gen. dominate
  - $\Rightarrow$ CP conserving to a good approximation in the SM



- CPV is parametrically suppressed
  - in mixing it enters as $\mathcal{O}\left(V_{cb}V_{ub}/V_{cs}V_{us}\right) \sim 10^{-3}$
  - direct CPV in SCS as $\mathcal{O}([V_{cb}V_{ub}/V_{cs}V_{us}]\alpha_s/\pi) \sim 10^{-4}$
- is it possible that it is significantly larger?

Size of P/T needed

- expect. that A_{KK} and $A_{\pi\pi}$ add up in ΔA_{CP}
  - since $V_{cs}V_{us} \simeq -V_{cd}V_{ud}$
- for O(1) strong phases then

$$\Delta \mathcal{A}_{CP} \sim 4 r_f$$

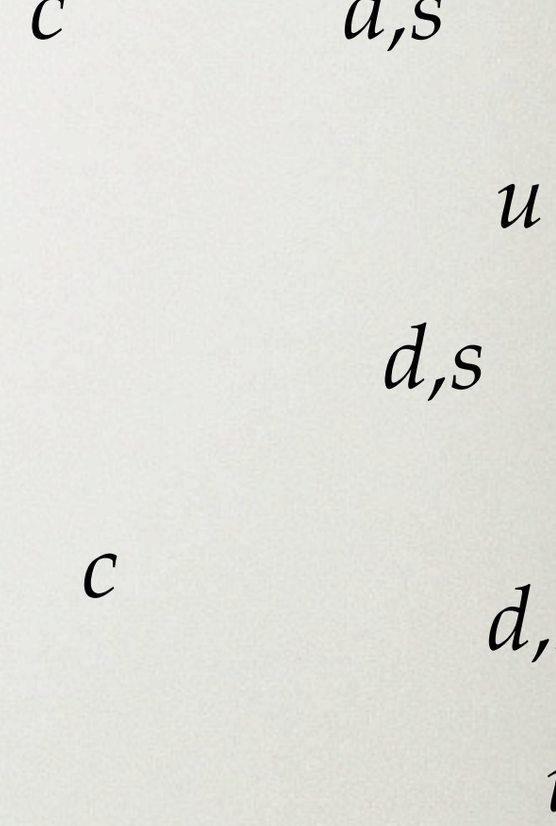
- from experiment thus required

$$r_f \sim 0.15\%$$

- naive estimate

$$r_f \sim \mathcal{O}([V_{cb}V_{ub}/V_{cs}V_{us}]\alpha_s/\pi) \sim 0.01\%$$

- an order of magnitude enhancement over naive estimate required



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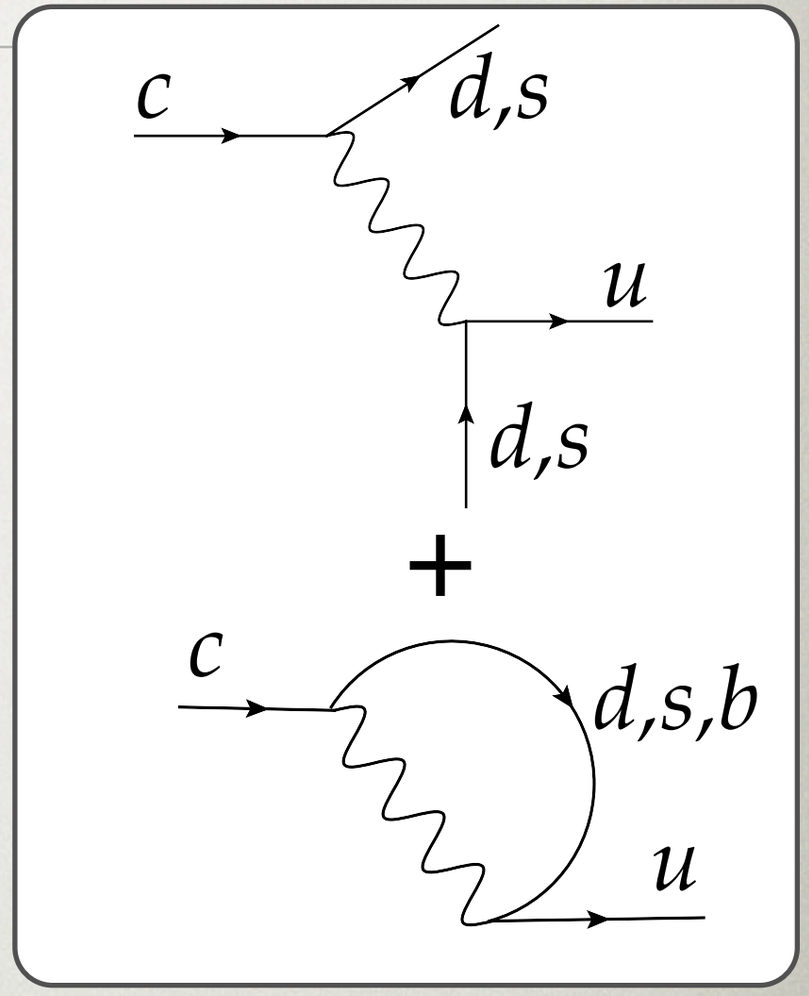


COULD IT BE NEW PHYSICS?

NEW PHYSICS?

- could it be NP?
- "reasonable" models of NP can do it
  - model independent NP ops. analysis
    Isidori, Kamenik, Ligeti, Perez, 1111.4987
  - supersymmetric examples Grossman, Kagan, Nir, hep-ph/0609178
    Giudice, Isidori, Paradisi, 1201.6204
    Hiller, Hochber, Nir, 1204.1046
  - tree level exchanges
    Hochberg, Nir, 1112.5268
    Altmannshofer, Primulando, Yu, Yu, 1202.2866
  - partial compositeness models
    Keren-Zur et al., 1205.5803
    Delaunay, talk at LHCb workshop, Apr 18 2012

SUSY?

- SUSY contribs. to QCD penguin particularly interesting

Grossman, Kagan, Nir, hep-ph/0609178

  - LR mixing in squark matrices

$$Q_8 = \frac{m_c}{4\pi^2}\bar{u}_L\sigma_{\mu\nu}T^a g_s G_a^{\mu\nu} c_R$$

$$\frac{m_c}{m_W^2} \to \frac{v}{\tilde{m}^2}$$

$$Q_8 = \frac{1}{4\pi^2}(\bar{Q}_L H)\sigma_{\mu\nu}T^a g_s G_a^{\mu\nu} c_R$$

  - for $v \sim m_{susy}$ the op. Q_8 is secretly dim=5

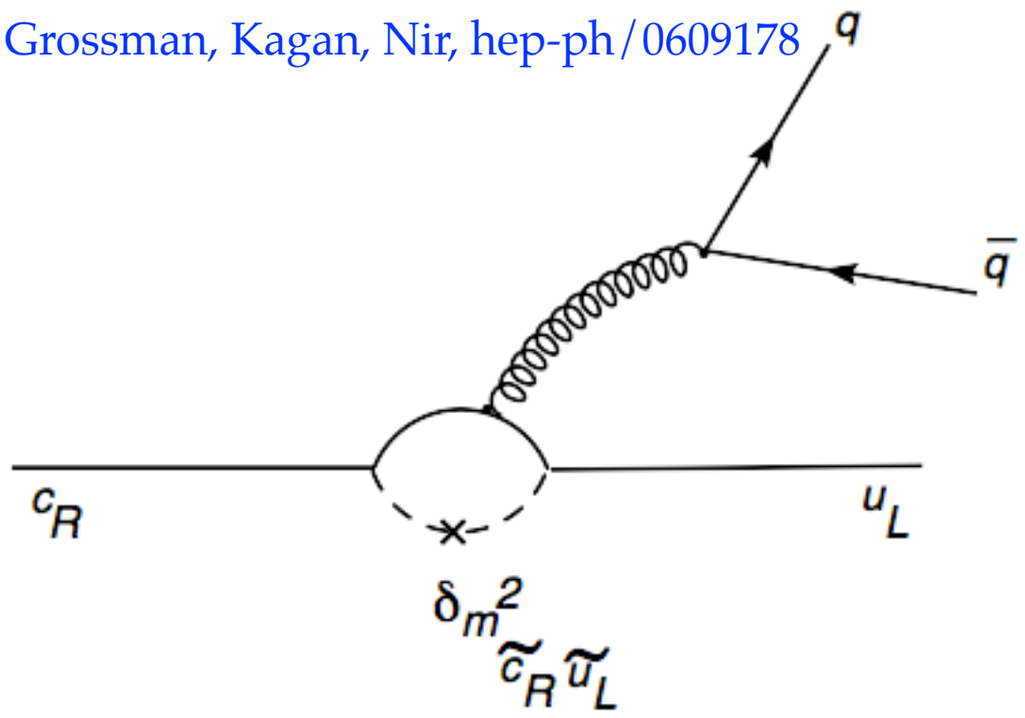
- *D-Dbar* mixing operators are dim=6

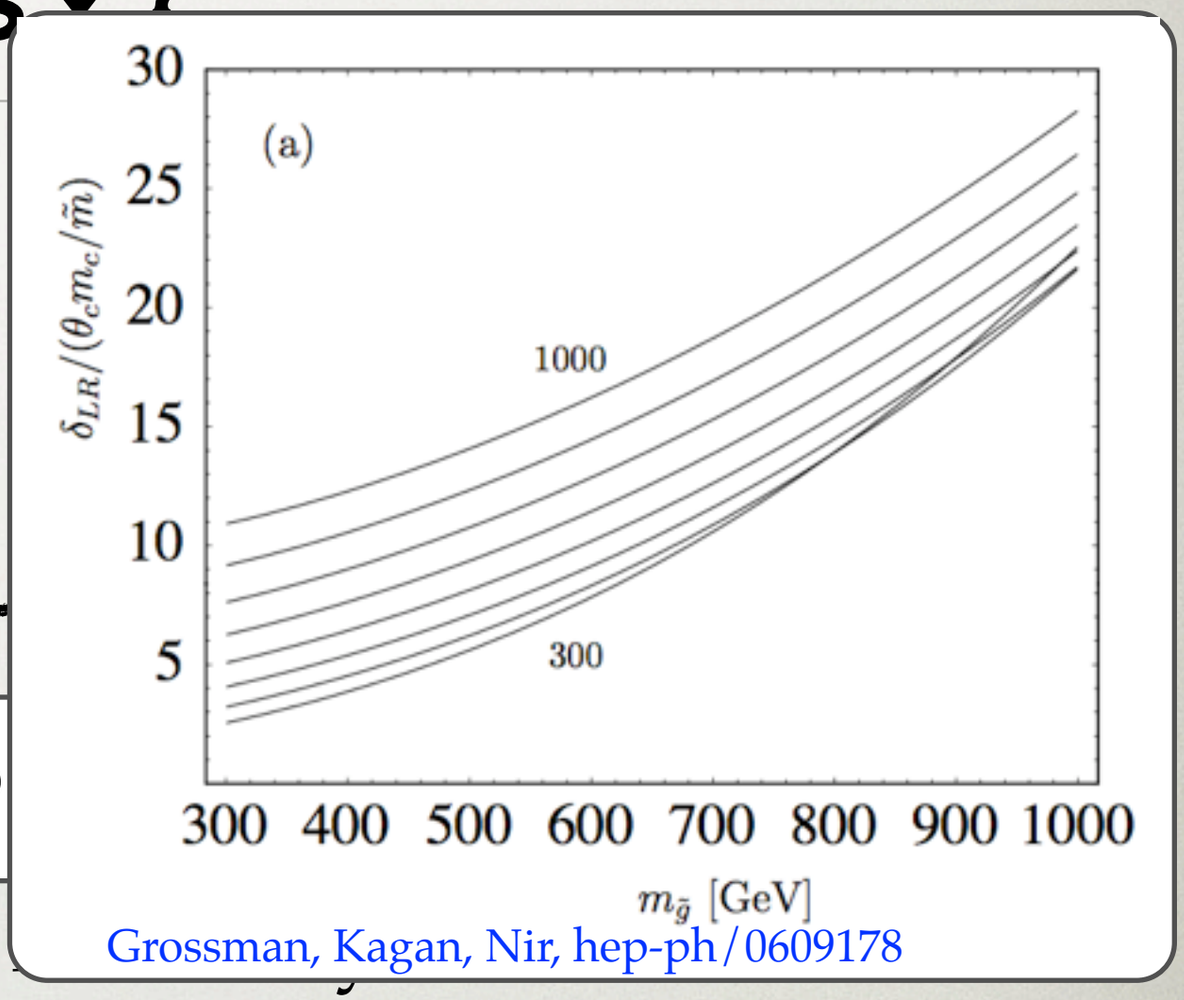
$$Q_2^{cu} = \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta$$

  - SUSY contributions are parametrically smaller

susy?

Grossman, Kagan, Nir, hep-ph/0609178





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- SUSY contributions are parametrically smaller

NEW PHYSICS UPSHOT

- it can be new physics
- but does it have to be?

A REMINDER

- for O(1) strong phases

$$\Delta\mathcal{A}_{CP} \sim 4r_f$$

- size of P/T needed

$$r_f \sim 0.15\%$$

- naive estimate

$$r_f \sim \mathcal{O}([V_{cb}V_{ub}/V_{cs}V_{us}]\alpha_s/\pi) \sim 0.01\%$$

- an order of magnitude enhancement over naive estimate required

INDICATION IN FAVOR OF SM

- long standing puzzle J. Brod, Y. Grossman, A. Kagan, JZ, 1203.6659
  - $Br(D\to K^+K^-)=2.8\ Br(D\to\pi^+\pi^-)$
  - should be the same in flavor SU(3) limit
- with large SM penguin a consistent picture
  - *Br*'s changed by $P_{break}=\varepsilon_{SU(3)}P\sim T$
  - the fit to four *Br* confirms $P_{break}\sim T$
- using $P\sim P_{break}/\varepsilon$ one predicts (for $\varepsilon=0.3$)

$$r_f = \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{P}{T} \sim \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{1}{\epsilon} \sim 0.2\%$$

  - exactly the required size for ΔA_{CP}

INDICATION IN FAVOR OF

$$H_{\rm eff}^{\Delta C=1} = \frac{G_F}{\sqrt{2}}\Big(V_{cs}^* V_{us} \sum_{i=1,2} C_i \left(Q_i^s - Q_i^d\right) - V_{cb}^* V_{ub} \Big[\sum_{i=1,2} C_i \left(Q_i^d - Q_i^s\right)/2$$

$$+ \sum_{i=1,2} C_i \left(Q_i^s + Q_i^d\right)/2 + \sum_{i=3}^{6} C_i Q_i + C_{8g} Q_{8g} \Big]\Big) + \text{h.c.},$$

- $Br(D \to K^+K^-)=2.$ $Br(D$
- should same i
- with large SM penguin

P

P_{break}

$$T_{KK} = T_{KK}^s + P_{KK}^{T,s} - P_{KK}^{T,d},$$

$$T_{\pi\pi} = -T_{\pi\pi}^d + P_{\pi\pi}^{T,s} - P_{\pi\pi}^{T,d},$$

$$A_f^P = -V_{cb}^* V_{ub} \left(P_f + [P_f^{T,s} + P_f^{T,d}]/2 + [P_f^{E,s} + P_f^{E,d}]/2\right)$$

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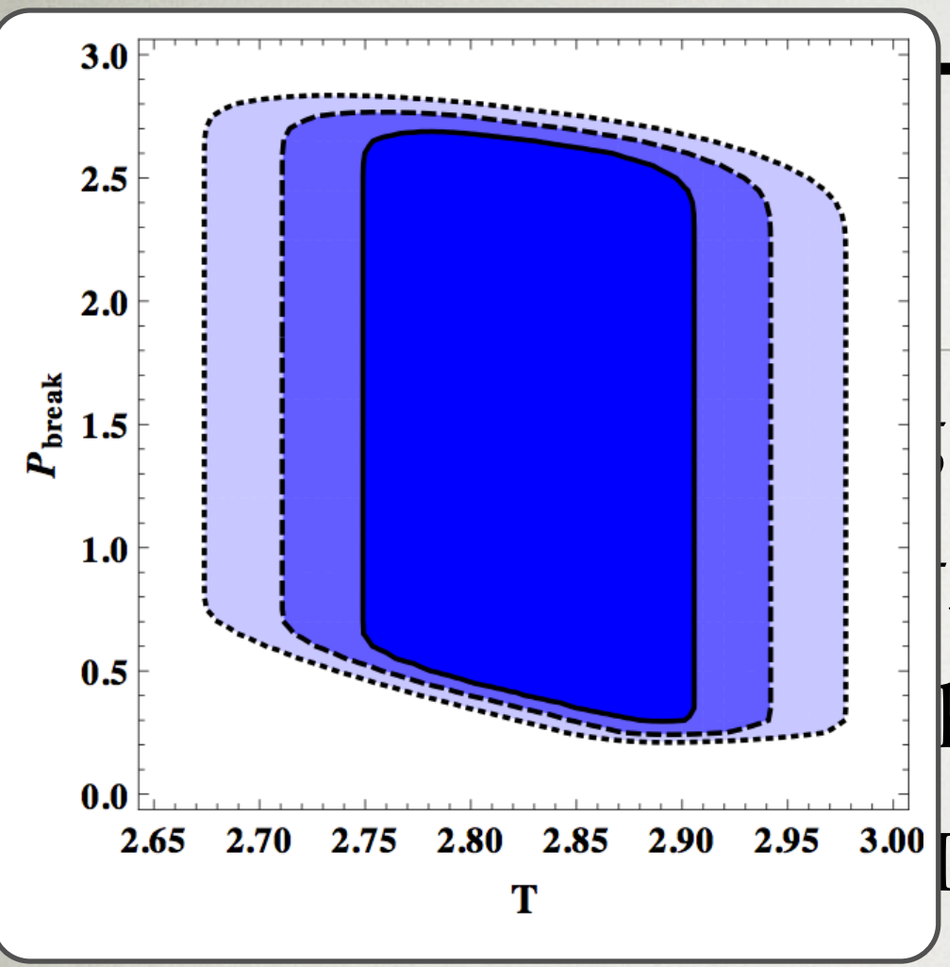

TION IN FAVOR OF SM

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J. Brod, Y. Grossman, A. Kagan, JZ, 1203.6659

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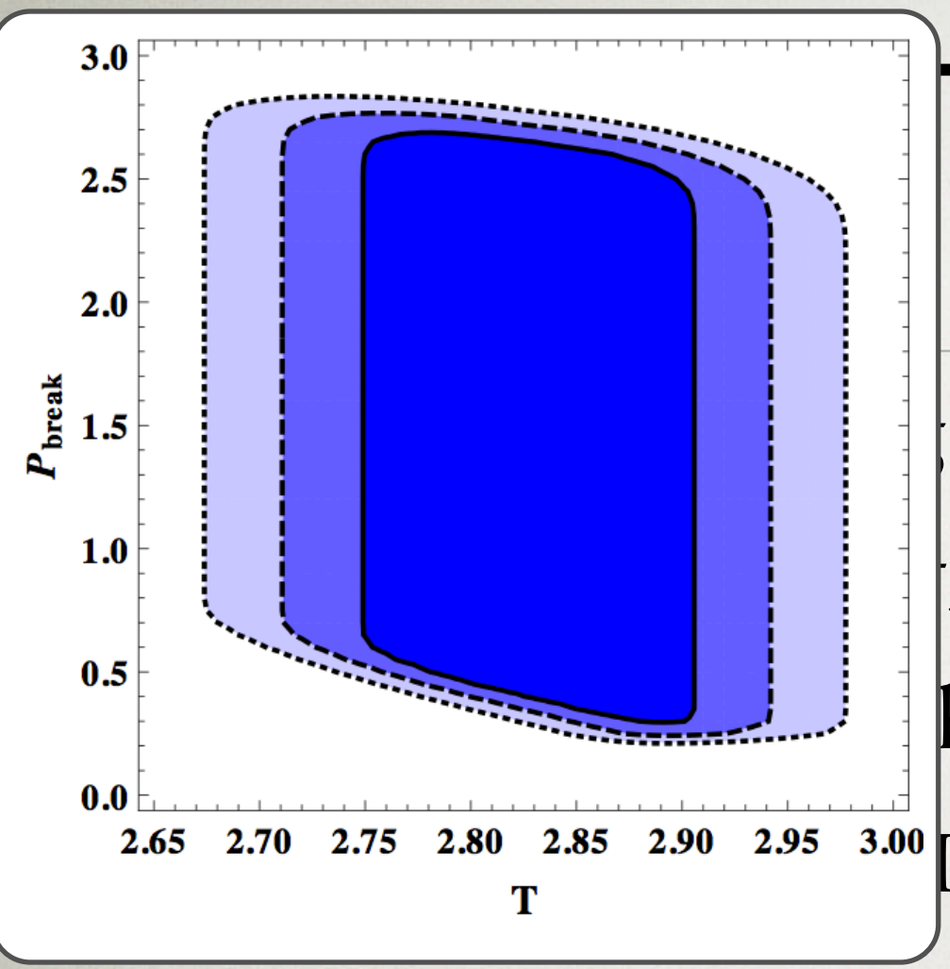

TION IN F SM

puzzle

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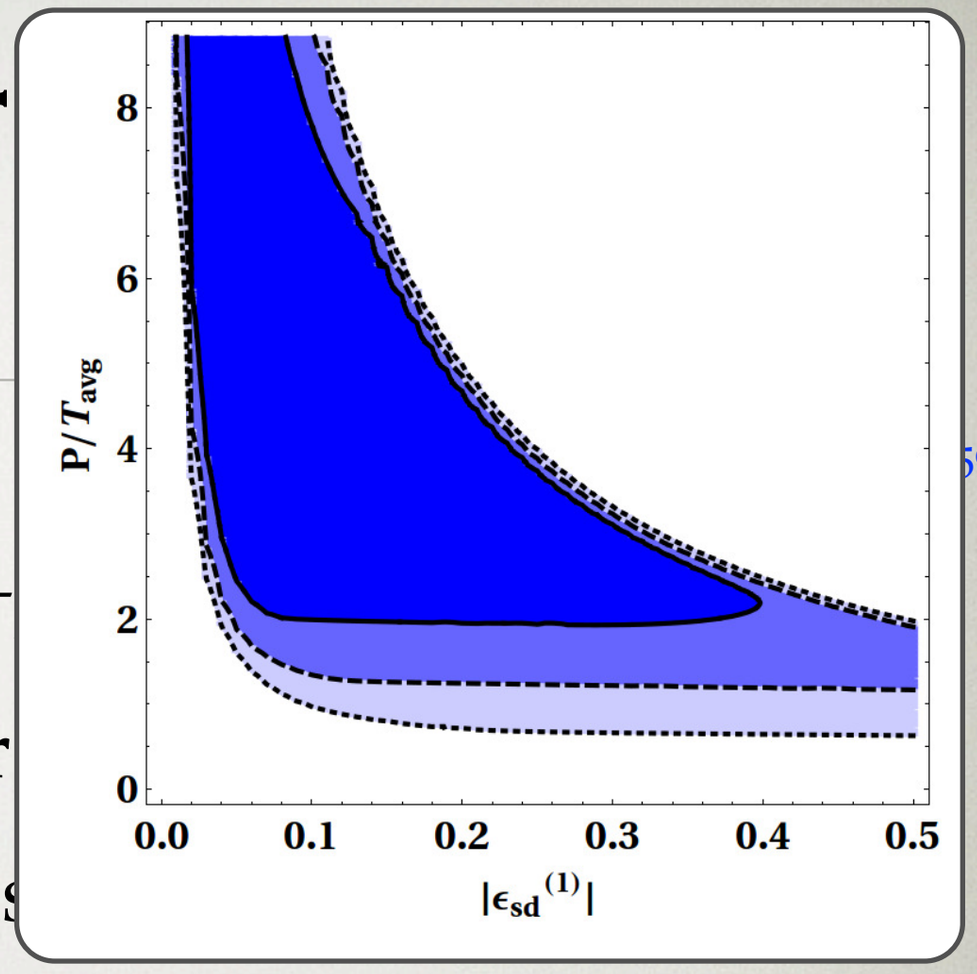
I penguin a consis



59

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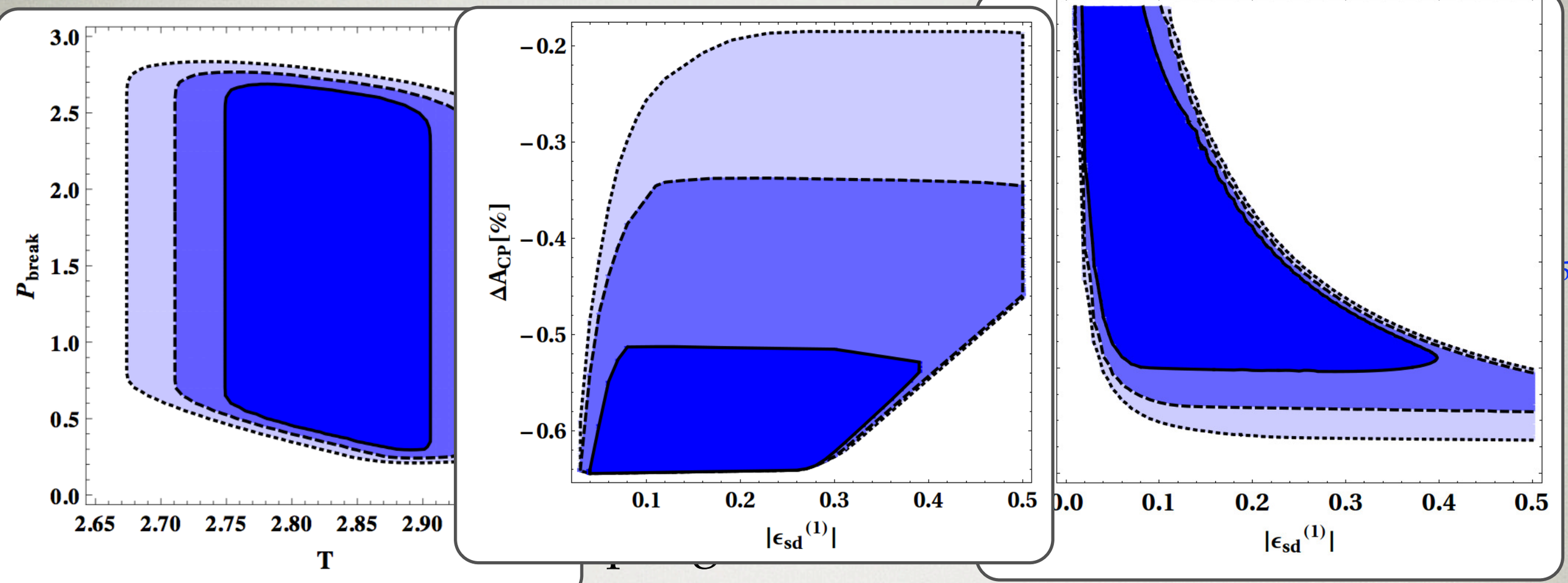

59

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- exactly the required size for ΔA_{CP}

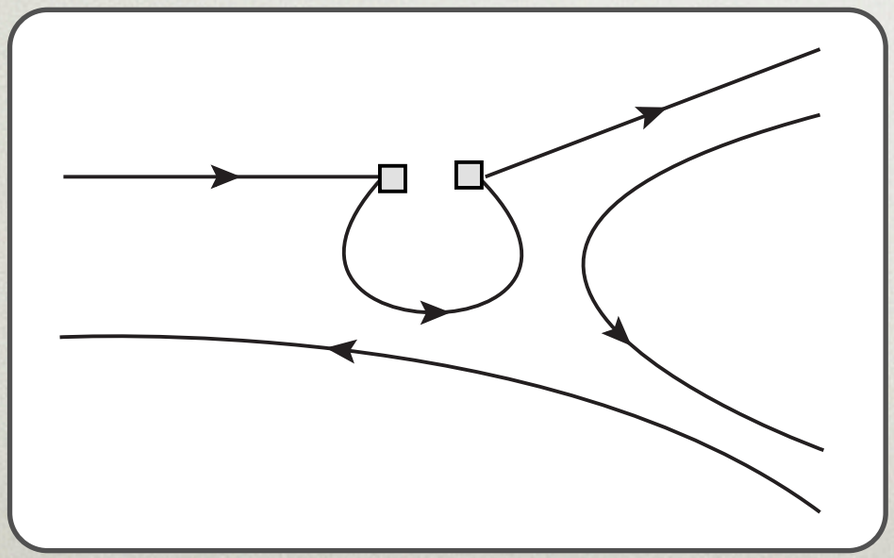
IS IT SM?

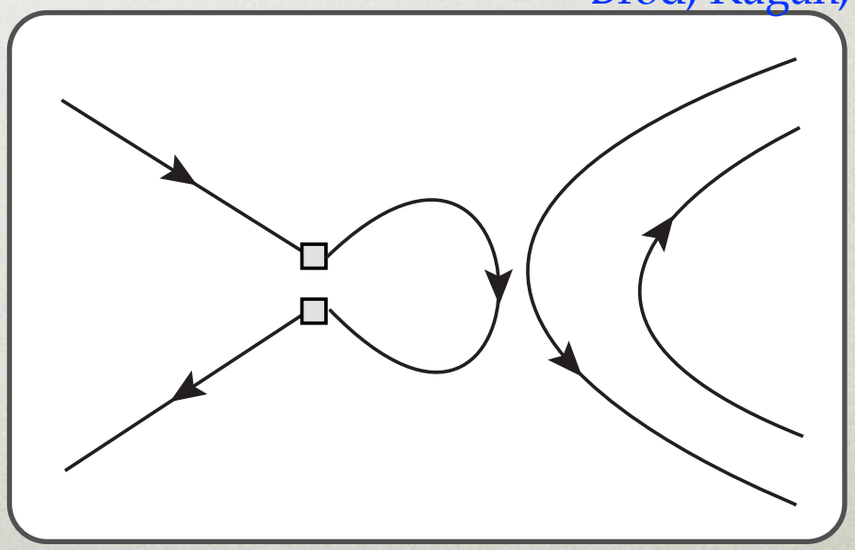
- in principle we could have anticipated the size of ΔA_{CP} from $Br(D \to KK, \pi\pi)$
- now it is post-diction
- any way to check?

see also Hansen, Sharpe, 1204.0826

- on the lattice: are penguin contractions large?
  - it could be the origin of large "broken" penguins

Brod, Kagan, JZ, 1111.5000



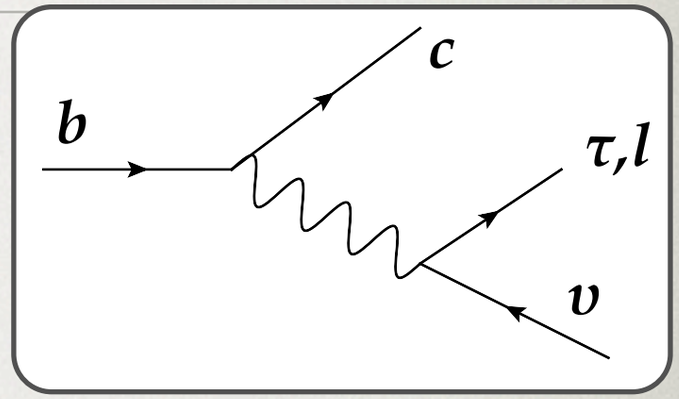


NP or SM?

- it could be NP or SM
- how to distinguish between the two?
- by building NP models
  - search for other signatures (collider or otherwise)
- also using <u>just charm data</u>
  - possible to write isospin sum rules that would be violated if NP Grossman, Kagan, JZ, 1204.3557
  - from $D \to V\gamma$ search for enhanced Q_{8G} Isidori, Kamenik, 1205.3164

FLAVOR UNIVERSALITY VIOLATIONS

THE MEASUREMENT



- the topic of this section
  - recent measurement of $b\to c\tau\nu/b\to cl\nu$

BaBar collaboration, 1205.5442

- flavor universality violated at 3.4σ

$$\mathcal{R}^*_{\tau/\ell} \equiv \frac{\mathcal{B}(B\to D^*\tau\nu)}{\mathcal{B}(B\to D^*\ell\nu)} = 0.332 \pm 0.030\,,$$
$$\mathcal{R}_{\tau/\ell} \equiv \frac{\mathcal{B}(B\to D\tau\nu)}{\mathcal{B}(B\to D\ell\nu)} = 0.440 \pm 0.072\,,$$

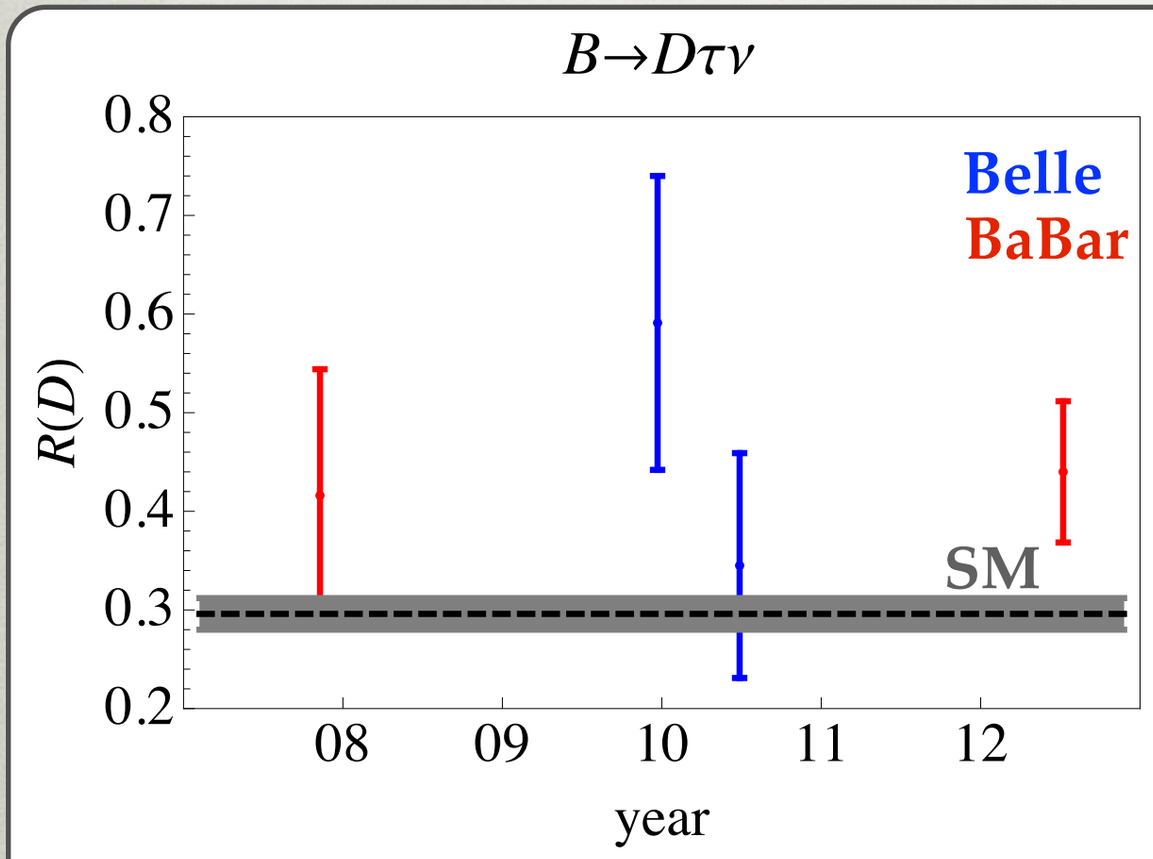
$$\mathcal{R}^{*,\mathrm{SM}}_{\tau/\ell} = 0.252(3)$$
$$\mathcal{R}^{\mathrm{SM}}_{\tau/\ell} = 0.296(16)$$

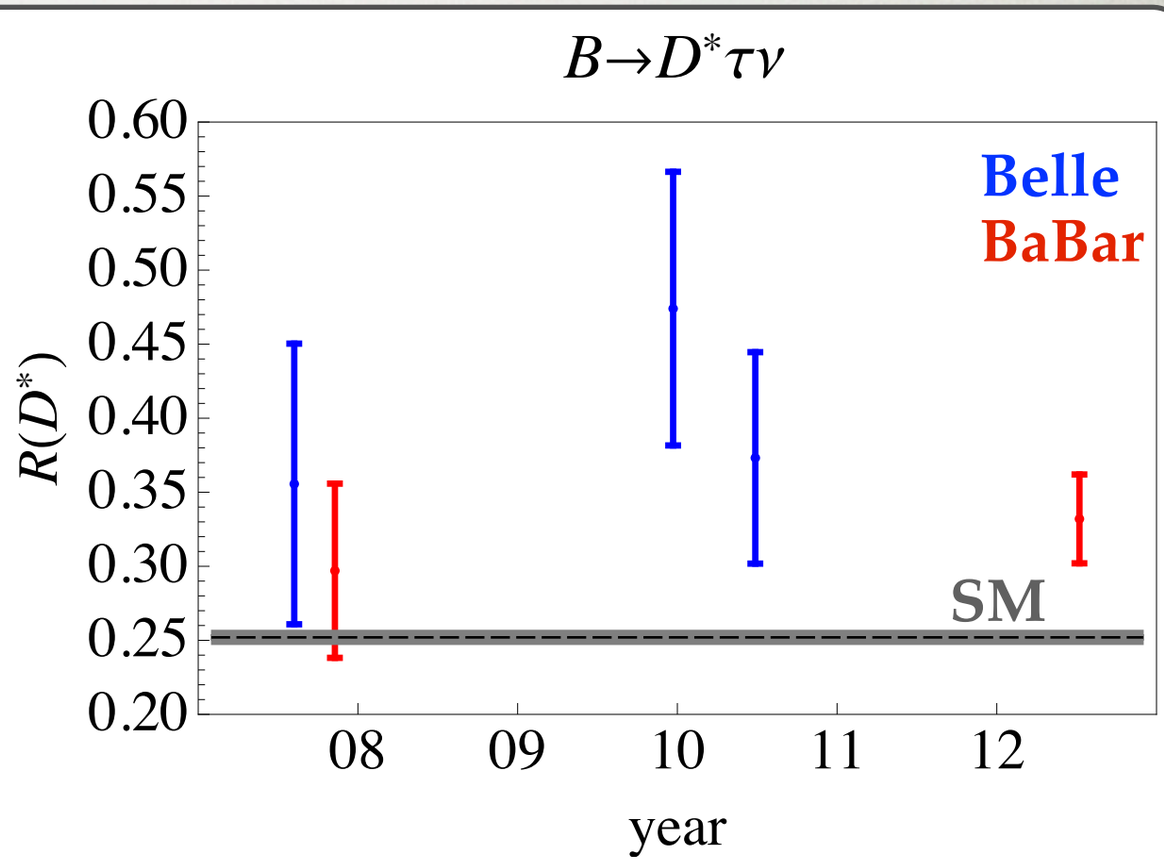
Fajfer, Kamenik, Nisandzic,1203.2654
Kamenik, Mescia, 0802.3790

see also Becirevic, Kosnik, Tayduganov, 1206.4977; Bailey et al., 1206.4992

COMPARISON TO PREVIOUS MEASUREMENTS

- both Belle and BaBar had previous measurmnts.
- new measurements agree with the old
- Belle also two methods (uncorrelated)





BaBar 0709.1698, 1205.5442 Belle 0706.4429, 0910.4310, 1005.2302

LEPTON FLAVOR UNIVERSALITY

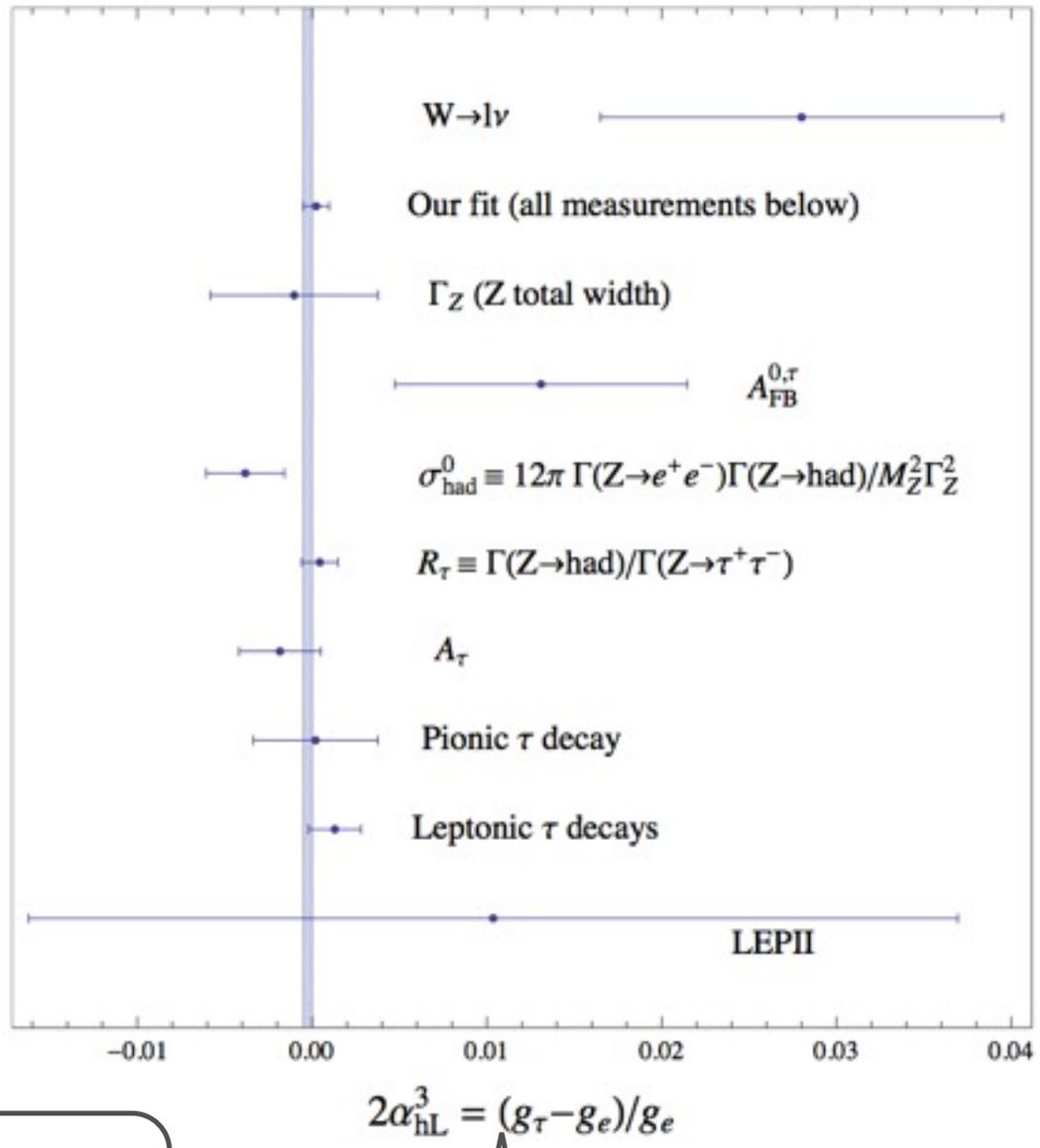
Filipuzzi, Portoles, Gonzalez-Alonso, 1203.2092

- LFU with first two gen. of quarks obeyed at < percent
  - NP effective scale above $O(3\text{-}4\text{TeV})$
- there is a 2.4σ anomaly in $W\to\tau\nu/W\to l\nu$
  - cannot expl. in EFT

see also Dermisek, 0807.2135;Park, hep-ph/0607280

- D_s decays

Filipuzzi, Portoles, Gonzalez-Alonso, 1203.2092

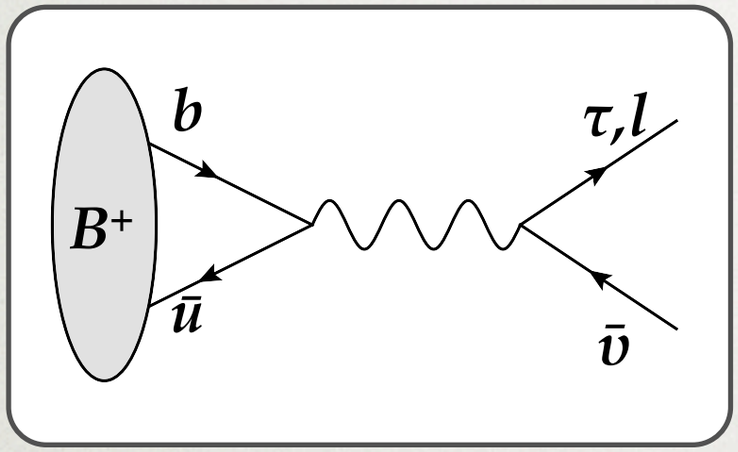


$$\left.\frac{Br(D_s^+\to\tau^+\nu)}{Br(D_s^+\to\mu^+\nu)}\right|_{\rm exp}\Big/\left.\frac{Br(D_s^+\to\tau^+\nu)}{Br(D_s^+\to\mu^+\nu)}\right|_{\rm SM}=0.943\pm0.075$$

$$i(H^\dagger D_\mu\tau^a H)(\bar L\gamma_\mu\tau^a L)$$

IN B DECAYS

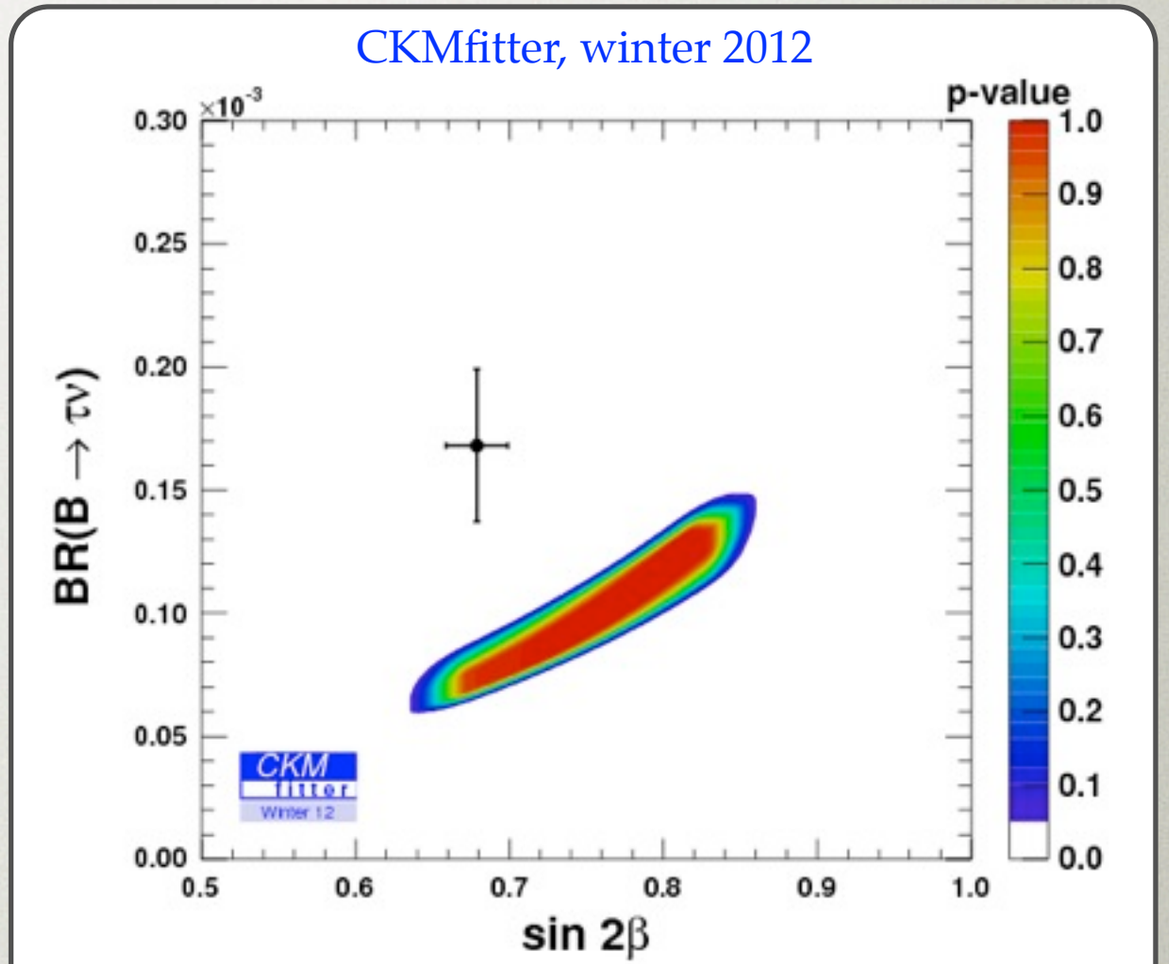
- for a long time now $B \to \tau \nu$ too large



- can define a ratio

$$\mathcal{R}^{\pi}_{\tau/\ell} \equiv \frac{\tau(B^0)}{\tau(B^-)} \frac{\mathcal{B}(B^- \to \tau^- \bar{\nu})}{\mathcal{B}(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu})} = 1.07 \pm 0.20\,.$$

$$\mathcal{R}^{\pi,\mathrm{SM}}_{\tau/\ell} = 0.31(6)$$

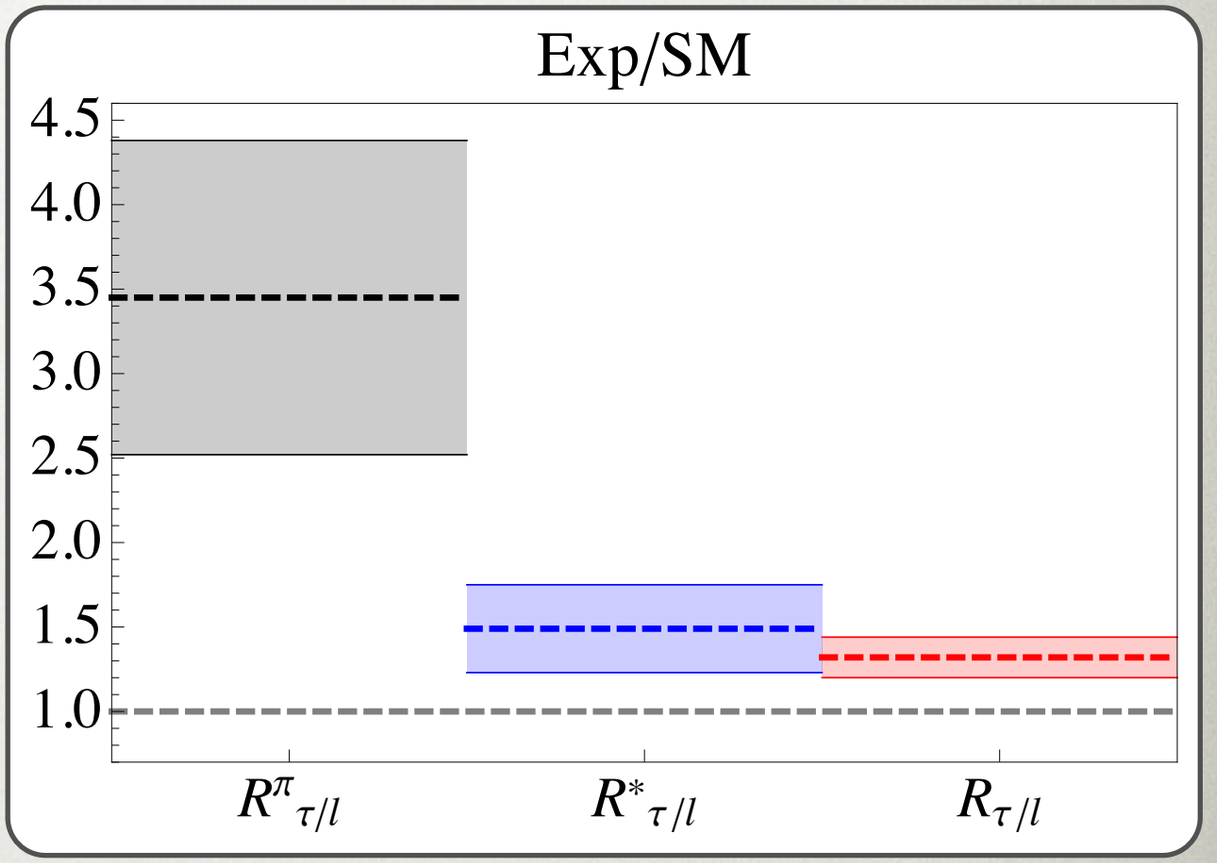


SUMMARY OF EXPERIMENTS

$$\mathcal{R}^{\pi,\mathrm{exp}}_{\tau/\ell}/\mathcal{R}^{\pi,\mathrm{SM}}_{\tau/\ell} = 3.45 \pm 0.93$$

$$\mathcal{R}^{*,\mathrm{exp}}_{\tau/\ell}/\mathcal{R}^{*,\mathrm{SM}}_{\tau/\ell} = 1.32 \pm 0.12$$

$$\mathcal{R}^{\mathrm{exp}}_{\tau/\ell}/\mathcal{R}^{\mathrm{SM}}_{\tau/\ell} = 1.49 \pm 0.26$$



- combined significance of 4.6σ
- including Belle $B\to D^{(*)}\tau\nu$: 4.8σ

preliminary

SM PREDICTIONS

- are the SM prediction reliable?
- the CKM elements cancel in the ratios
- how well do we know hadronic matrix elements?
  - $B \to D\tau\nu$: 1 of 2 FF not fixed from $B \to Dl\nu$
    - from lattice $\Delta(w)=0.46(2)$
    - would need $\Delta(w)=0.63$ for exp. central value
  - $B \to D^*\tau\nu$: 1 of 4 FF not fixed from $B \to D^*l\nu$
    - from HQET $R_0(1)=1.14(11)$
    - would need $R_0(1)=2.45$ for exp. central value

NEW PHYSICS

Nisandzic, Fajfer, Kamenik, JZ, 1206.1872

- assume NP heavier than m_b
  - can do an EFT analysis

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_a \frac{z_a}{\Lambda^{d_a-4}} \mathcal{Q}_i + \text{h.c.}$$

  - 4 operators

$$\mathcal{Q}_L^i = (\bar{u}_L^i \gamma_\mu b_L)(\bar{\tau}\gamma^\mu \nu_\tau)$$
$$\mathcal{Q}_R^i = (\bar{u}_R^i \gamma_\mu b_R)(\tau\gamma^\mu \nu_\tau)$$
$$\mathcal{Q}_{LR}^i = (\bar{u}_L^i b_R)(\tau_R \nu_\tau)$$
$$\mathcal{Q}_{RL}^i = (\bar{u}_R^i b_L)(\tau_R \nu_\tau)$$

  - *i=1,2 (u^1=u, u^2=c)*

SINGLE OPERATOR

Nisandzic, Fajfer, Kamenik, JZ, 1206.1872

- switch on one operator
- if the Wilson coefficients fixed by MFV
  - e.g. $z_L^u/z_L^u = V_{ub}/V_{cb}$,...
  - cannot explain all the three data-points
    - MFV is disfavored as an explanation
- Q_{LR} cannot explain $R^*_{\tau/l}$ and $R_{\tau/l}$ simultaneously
- for generic flavor structure $Q_{L,R,RL}$ ok
  - can get central values
  - scale is *O(100-300 GeV)*, normalizing roughly to CKMs

EXPLICIT MODELS: 2HDM

Nisandzic, Fajfer, Kamenik, JZ, 1206.1872

- right-left operators obvious candidate: 2HDM
  - both Q_{RL} and Q_{LR} generated
- natural flavor conservation: Type I, Type II, "lepton specific" and "flipped"

$$c_{LR} = (2m_b v/m_{H^+}^2)\{\mathrm{ctg}^2\beta, \mathrm{tg}^2\beta, -1, -1\}$$
$$c_{RL}^i = (2m_u^i v/m_{H^+}^2)\{\mathrm{ctg}^2\beta, -1, -1, \mathrm{ctg}^2\beta\}$$

  - no good fit
- general flavor violation
  - good fit possible
  - but tension with D, B_d, B_s mixing
    - need at least an order of magnitude cancellations

EXPLICIT MODELS

- leptoquarks

Nisandzic, Fajfer, Kamenik, JZ, 1206.1872

  - several options, looked at scalar $(3, 3, -1/3)$
    - generates Q_L, not preferred by EWPD
- composite SM fermions
  - contributions to Q_L and Q_R

$$\frac{z_L}{\Lambda^2} \sim \frac{g_\rho^2}{m_\rho^2}[f_3^q][f_i^q][f_3^l]^2\,, \quad \frac{z_R^{u(c)}}{\Lambda^4} \sim \frac{g_\rho^2}{m_\rho^2}\frac{y_3^{Qd} y_{1(2)}^{Qu}}{m_Q^2}[f_3^l]^2$$

  - vector reson. m_ρ, comp. fermions. m_Q
  - fixing $g_\rho=\sqrt{4\pi}$, $m_\rho=1$TeV best fit for (2 solut.)

$$\epsilon_{32} \equiv y_3^{Qd} y_2^{Qu} v^2/m_Q^2 \simeq 0(0.01)$$
$$\epsilon_{31} \equiv y_3^{Qd} y_1^{Qu} v^2/m_Q^2 \simeq -0.01(0.05)$$

CONCLUSIONS

- is A_{FB} due to NP?
  - cannot answer from A_C, but other observables (top polar., bbar A_{FB})
- some indication that ΔA_{CP} due to SM penguin contractions
- interesting flavor universality violation in $b \to c\tau\nu$, $b \to u\tau\nu$
  - MFV disfavored
  - generic FV 2HDM, compositeness

BACKUP SLIDES