Karlsruher Institut für Technologie

KSETA-Course: Accelelerator-Based Particle Physics

Flavor- and Top physics

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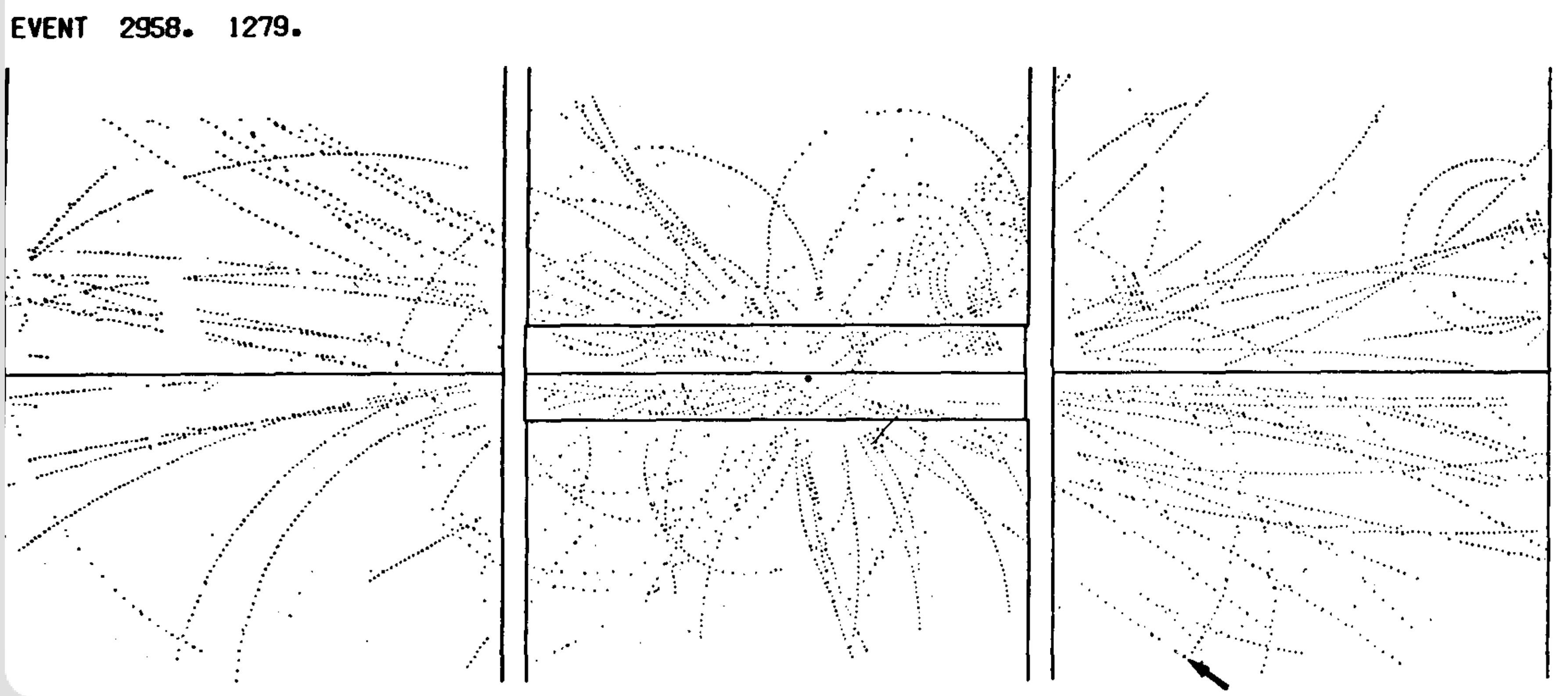
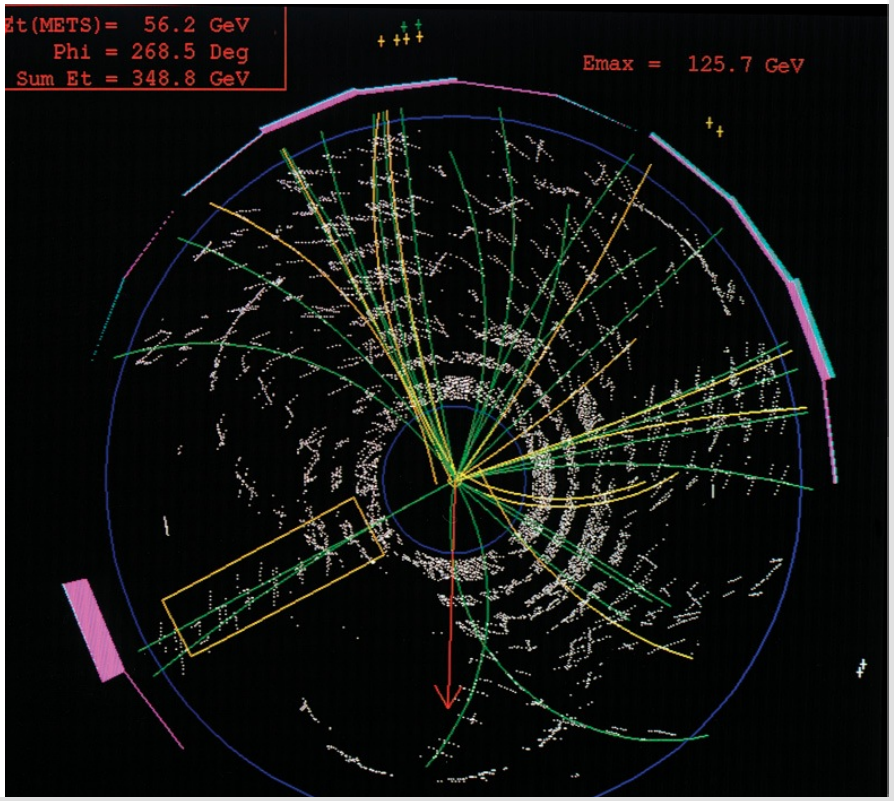
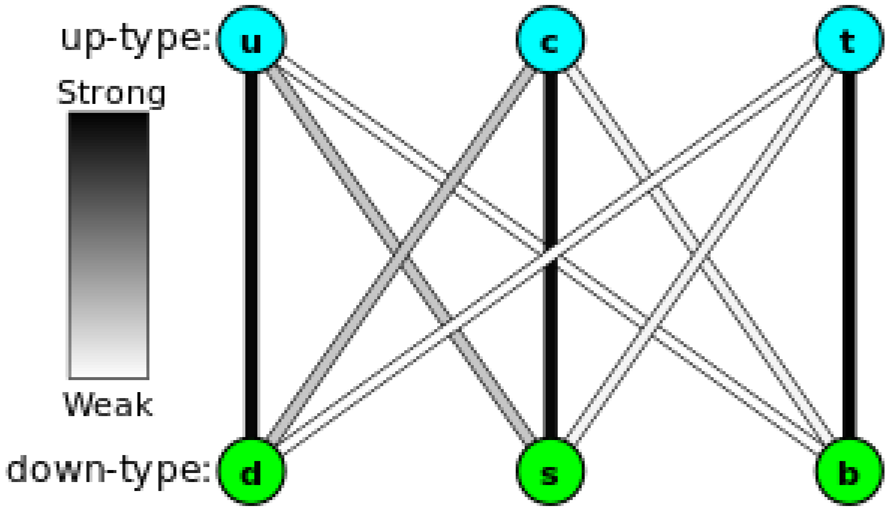




Reminder: what is flavor?



- Quarks and quantum numbers
  - six different flavors
    → six different quantum numbers
  - conserved in strong and EM interaction
  - can change in weak interaction
  - three up-type (charge 2/3)
    three down-type (charge -1/3)
- Why flavor physics?
  - classic flavor physics:
    hadrons with s,c,b quarks
  - top quark too unstable to form hadrons
    → mostly considered ist own field

Reminder: History

1953: Gell-Mann and Nishijima:

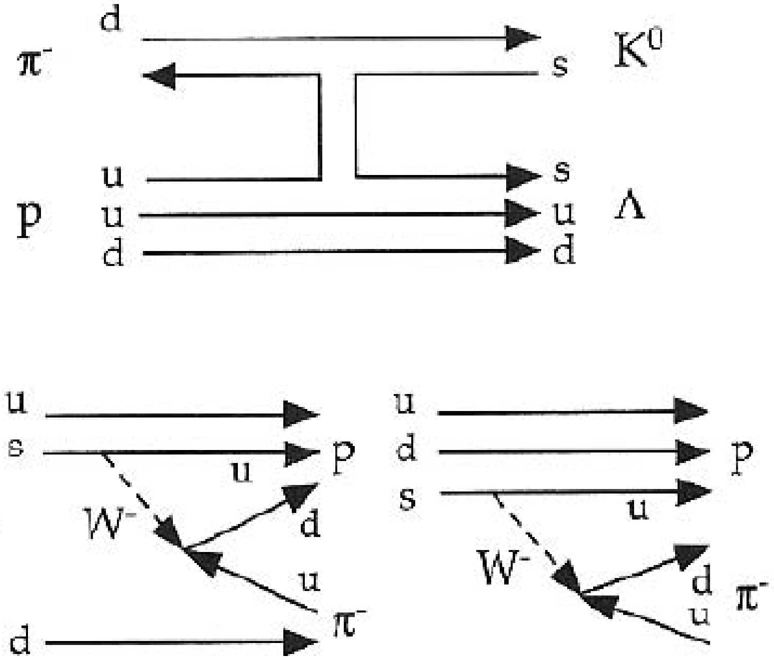
- Explain “strange particles” with new flavor quantum number ***strangeness (S)***
- strangeness conserved in strong and EM interaction changes in weak interaction

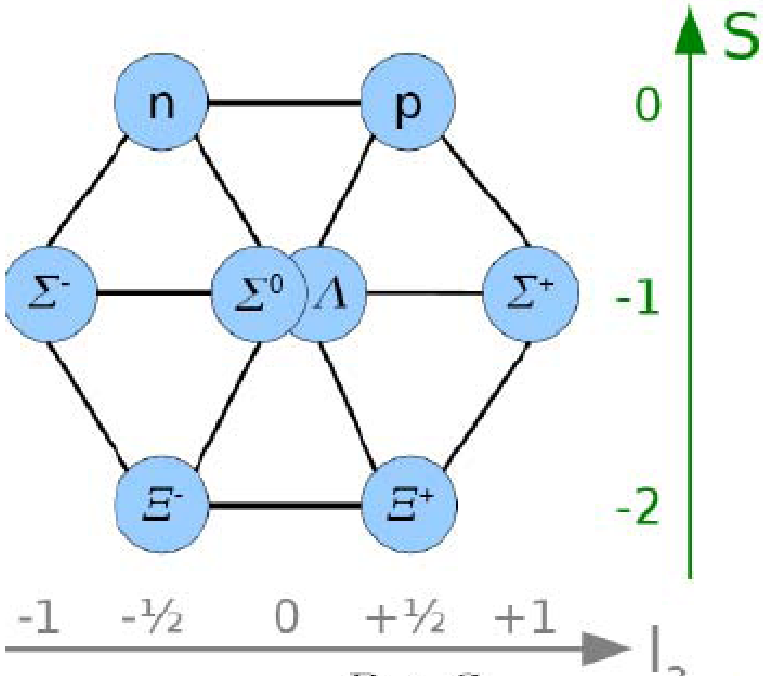
Murray Gell-Mann

Nobel price 1969

1964: Gell-Mann

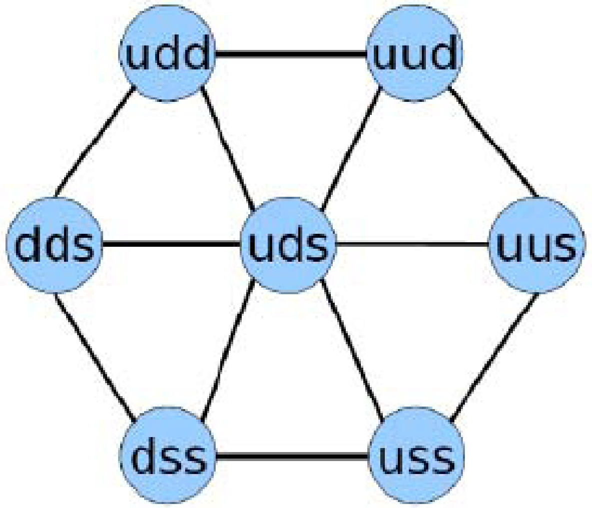
- particle zoo (hadrons) explained in the quark model (using u,d,s quarks)





$$Q = I_3 + \frac{B+S}{2}$$

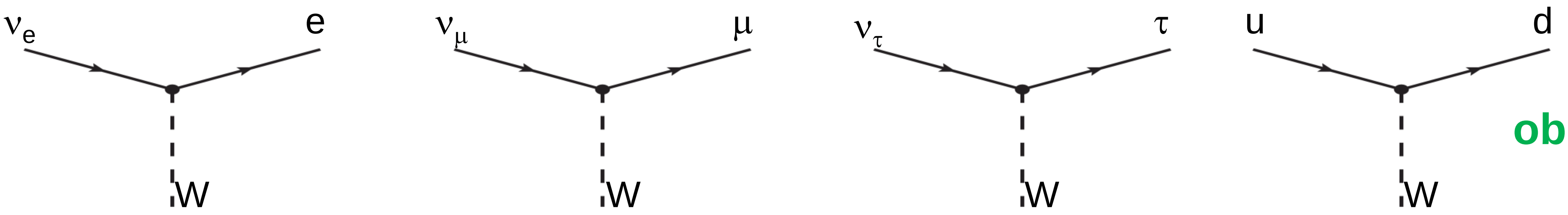
⇒



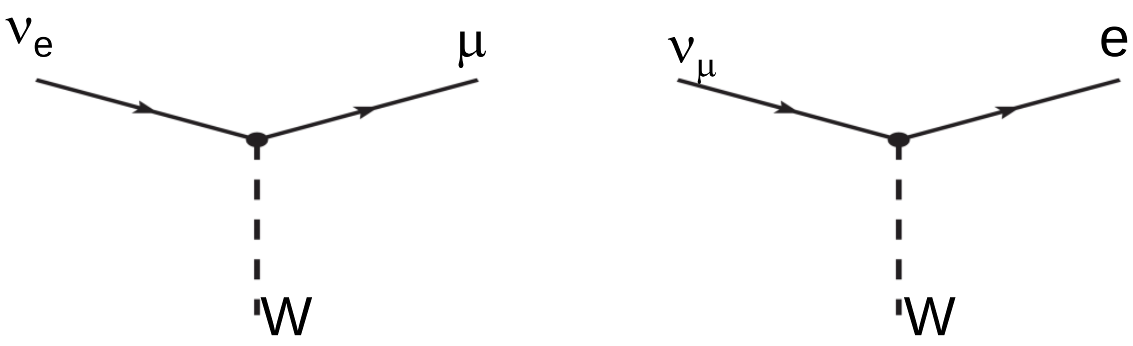
Weak interaction of quarks

Nucl. β-decays, meson- decays, νN-scattering:
→ universal coupling of weak interaction to leptons and quarks

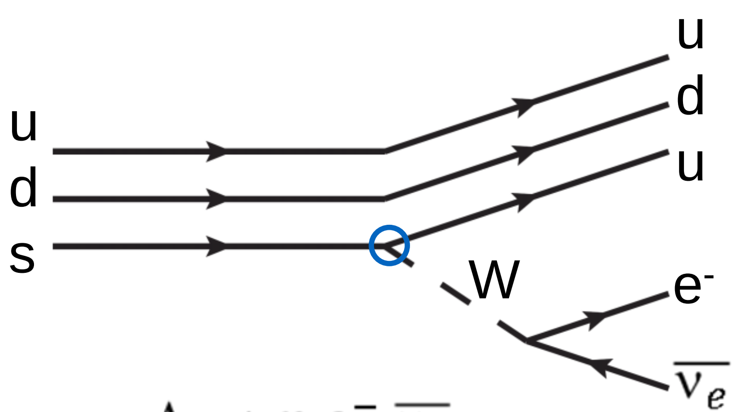
observations:



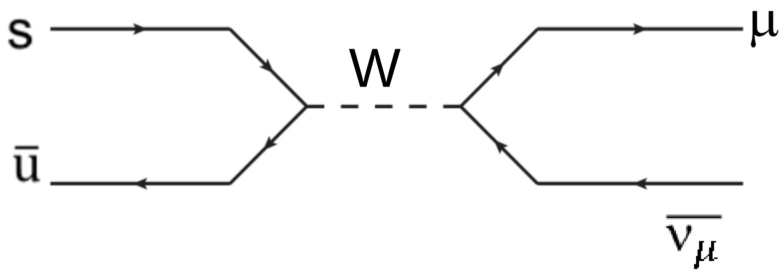
observed



not observed



$\Lambda \to p\, e^- \overline{\nu_e}$



$K^- \to \mu^- \overline{\nu_\mu}$

observed

i.e. quarks
change family

Cabibbo theory

Observation from n, μ decays GF(n)/GF(μ) = 0.98 $\neq$ 1

Nicola Cabibbo: quarks mix → mass-eigenstates $\neq$ flavor-eigenstates

$$\begin{pmatrix} u \\ d' \end{pmatrix} = \begin{pmatrix} u \\ d\cdot\cos\vartheta_C + s\cdot\sin\vartheta_C \end{pmatrix}$$

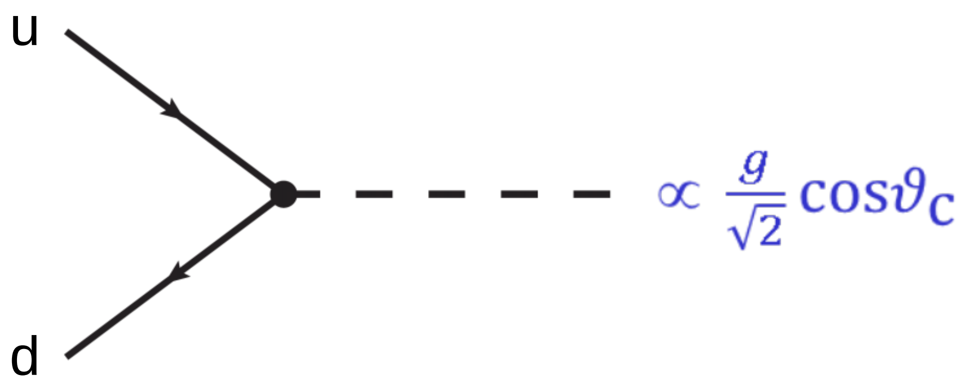
convention

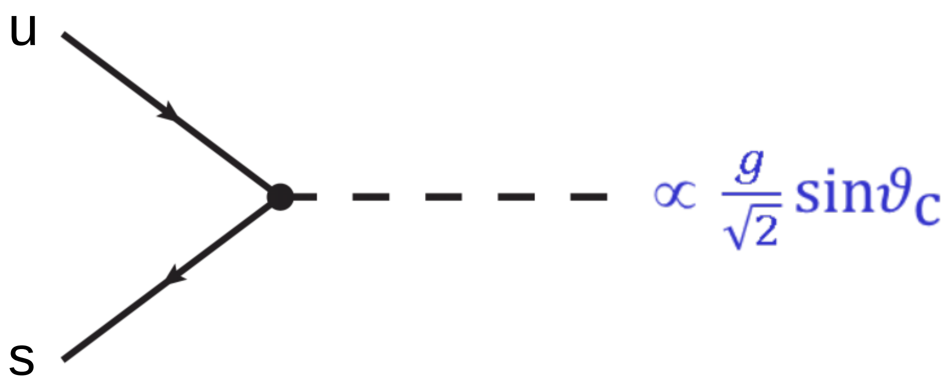
weak isospin doublet

mass eigenstates d,s,b u,c,t

flavor-eigenstates d',s',b' u,c,t

$\Rightarrow$





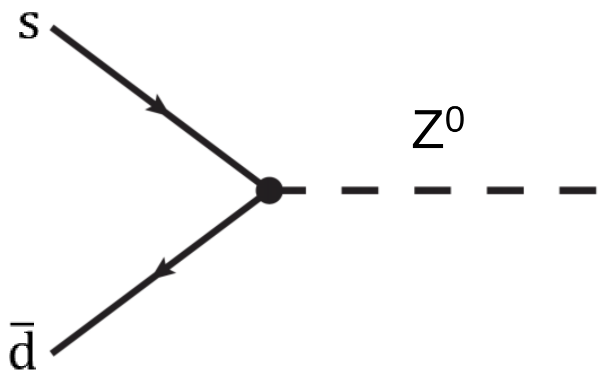
→ $G_F(n)/G_F(\mu) = \cos\vartheta_c = 0.98$

ϑ_C : Cabibbo-angle

$\vartheta_C = 12.9°$

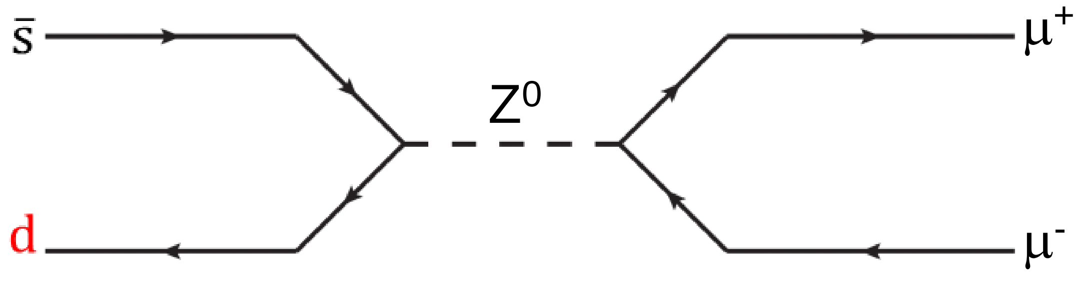
GIM Mechanism

Expected transitions:



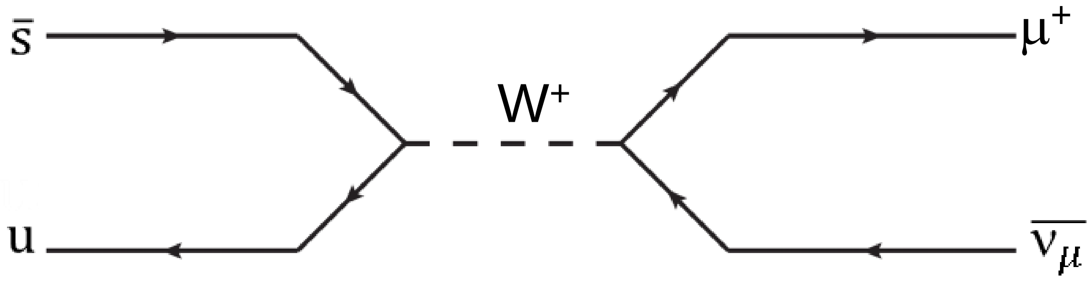
flavor-changing neutral currents (FCNC)

i.e. decays like:



$K^0 \rightarrow \mu^+\mu^-$

analogous to observed decays:



$K^+ \rightarrow \mu^+\bar{\nu}_\mu$

Observation: BR($K^0 \rightarrow \mu^+\mu^-$) $= 7 \cdot 10^{-9}$

BR($K^+ \rightarrow \mu^+\nu_\mu$) = 64%

proposal by GIM (1970): additional weak doublet

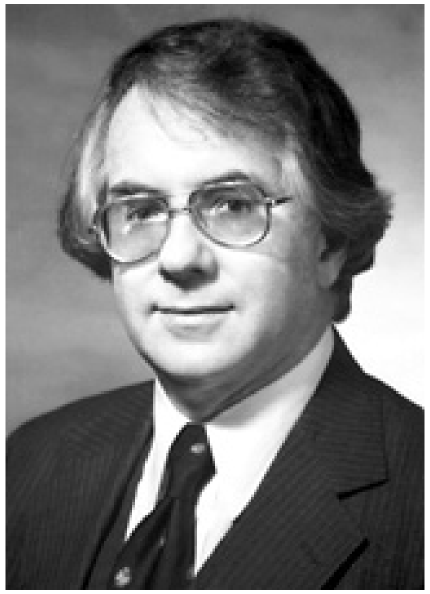
(Glashow, Illiopoulos, Maiani)

=> c-quark prediction
(observed 1970)

$$\begin{pmatrix} c \\ s' \end{pmatrix} = \begin{pmatrix} c \\ s \cdot \cos\vartheta_C - d \cdot \sin\vartheta_C \end{pmatrix}$$

Sheldon L. Glashow

Nobel price 1979



GIM Mechanism

Mixing matrix: $\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\vartheta_c & \sin\vartheta_c \\ -\sin\vartheta_c & \cos\vartheta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$

mass eigenstates

electroweak
eigenstates

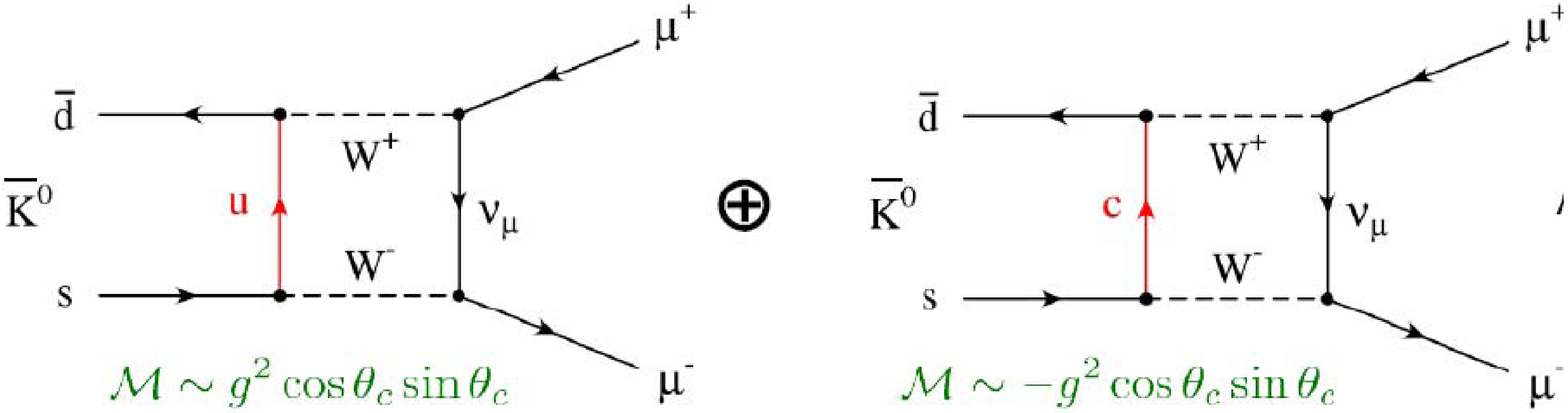
Interference cancels mixed terms (d→s) in the Lagrangian.
Only flavor-conserving neutral currents remain:

$$\bar{d}'d' + \bar{s}'s' + \bar{u}u + \bar{c}c = \cdots = \bar{d}d + \bar{s}s + \bar{u}u + \bar{c}c$$

no mixed terms $\bar{d}s$
→ no FCNC

short for $\bar{u}\gamma_\mu(c_v - c_A\gamma^5)u$

higher order processes also suppressed



Σ=0 if m_u=m_c

⇒ amplitude ≠0
due to different
quark masses

3-Doublet Extension

Today: 3 flavor-families with CKM-matrix
(Cabibbo-Kobayashi-Maskawa)

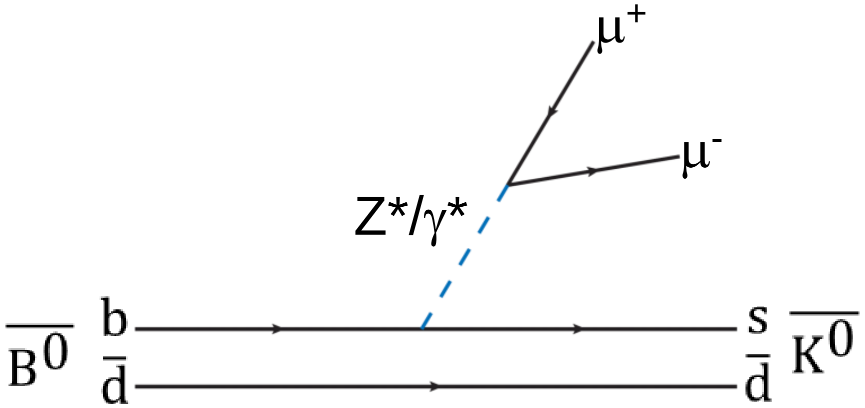
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = M_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

M_{CKM}:
unitary 3x3
matrix

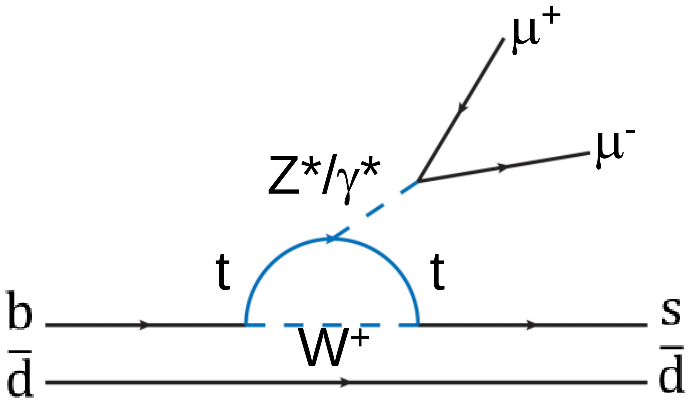
$$M_{CKM} = \begin{pmatrix} \boxed{c_1}\ \approx 1 & c_3 s_1 \qquad \approx 1 & s_1 s_3 \\ -c_2 s_1 & \boxed{c_1 c_2 c_3 - s_2 s_3 e^{i\delta}} & c_1 c_2 s_3 + c_3 s_3 e^{i\delta} \\ -s_1 s_2 & c_1 c_3 s_2 + c_2 s_3 e^{i\delta} & \boxed{c_1 s_2 s_3 - c_2 c_3 e^{i\delta}} \\ & & \approx 1 \end{pmatrix}$$

with:
$c_i = \cos\theta_i$ $s_i = \sin\theta_i$
$e^{i\delta}$: phase
→ CP-violation

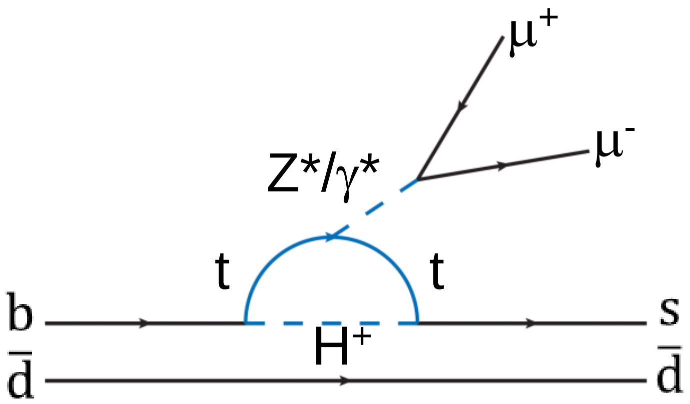
Test the SM: search for FCNC
example: $B^0 \to \mu^+\mu^- K^0$ (SM: BR = $5\cdot10^{-7}$), $B^0 \to \mu^+\mu^- K^{0*}$ (SM: BR = $5\cdot10^{-6}$)



Not allowed in SM
(FCNC)



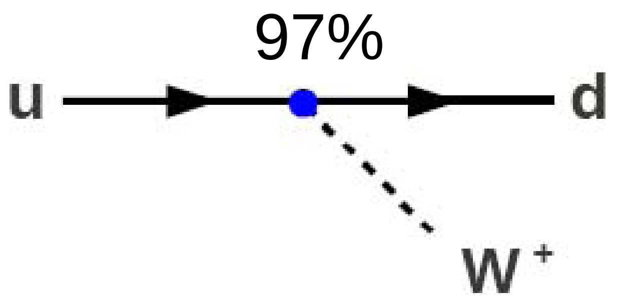
allowed in SM
("penguin")

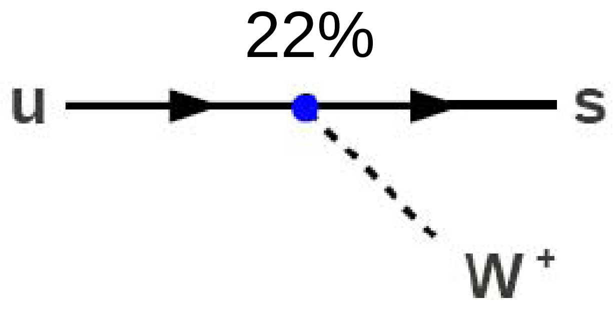


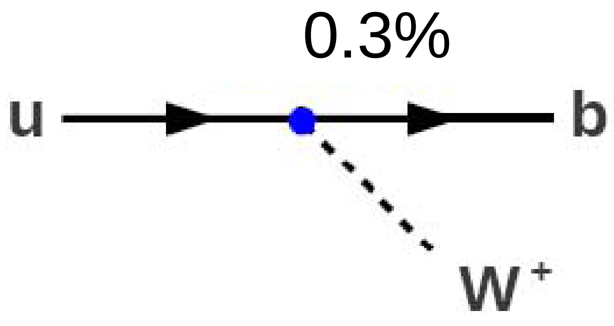
test the SM:
possible new particles (i.e SUSY)

CKM Matrix

- change of quark flavor only via W-boson exchange
- W-boson couples to mixture of quark generations







$$M_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- complex elements
  → 18 parameters
- Unitarity: $(MM^{\dagger}=1)$
  + quark phases

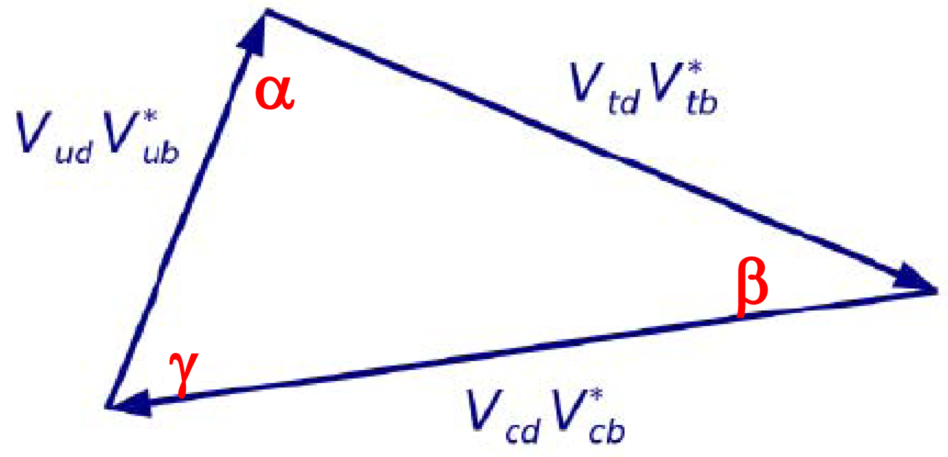
→ 4 free parameters
3 angles +
1 phase (~~CP~~)

Unitarity Triangle

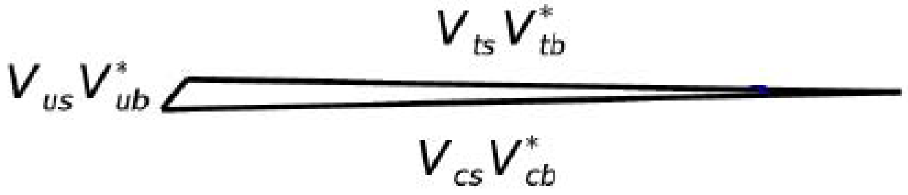
- N>4 observables for 4 paramters
  ⇒ overconstrained system
  ⇒ test the SM
- Graphical representation in „unitarity triangle“
  ⇒ unitaritiy condition $\sum_i V_{ij} V^*_{jk} = \delta_{jk}$

$$\begin{aligned}
(V^\dagger V)_{21} &: \quad V^*_{us}V_{ud} + V^*_{cs}V_{cd} + V^*_{ts}V_{td} = 0 \\
(V^\dagger V)_{31} &: \quad V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0 \\
(V^\dagger V)_{32} &: \quad V^*_{ub}V_{us} + V^*_{cb}V_{cs} + V^*_{tb}V_{ts} = 0.
\end{aligned}$$

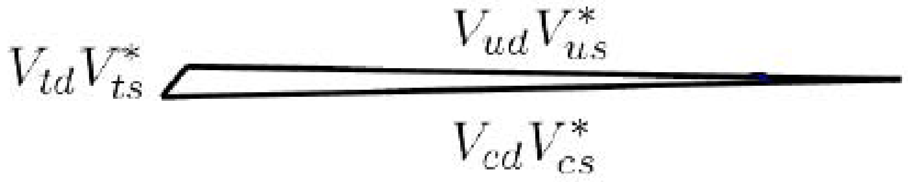
$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$



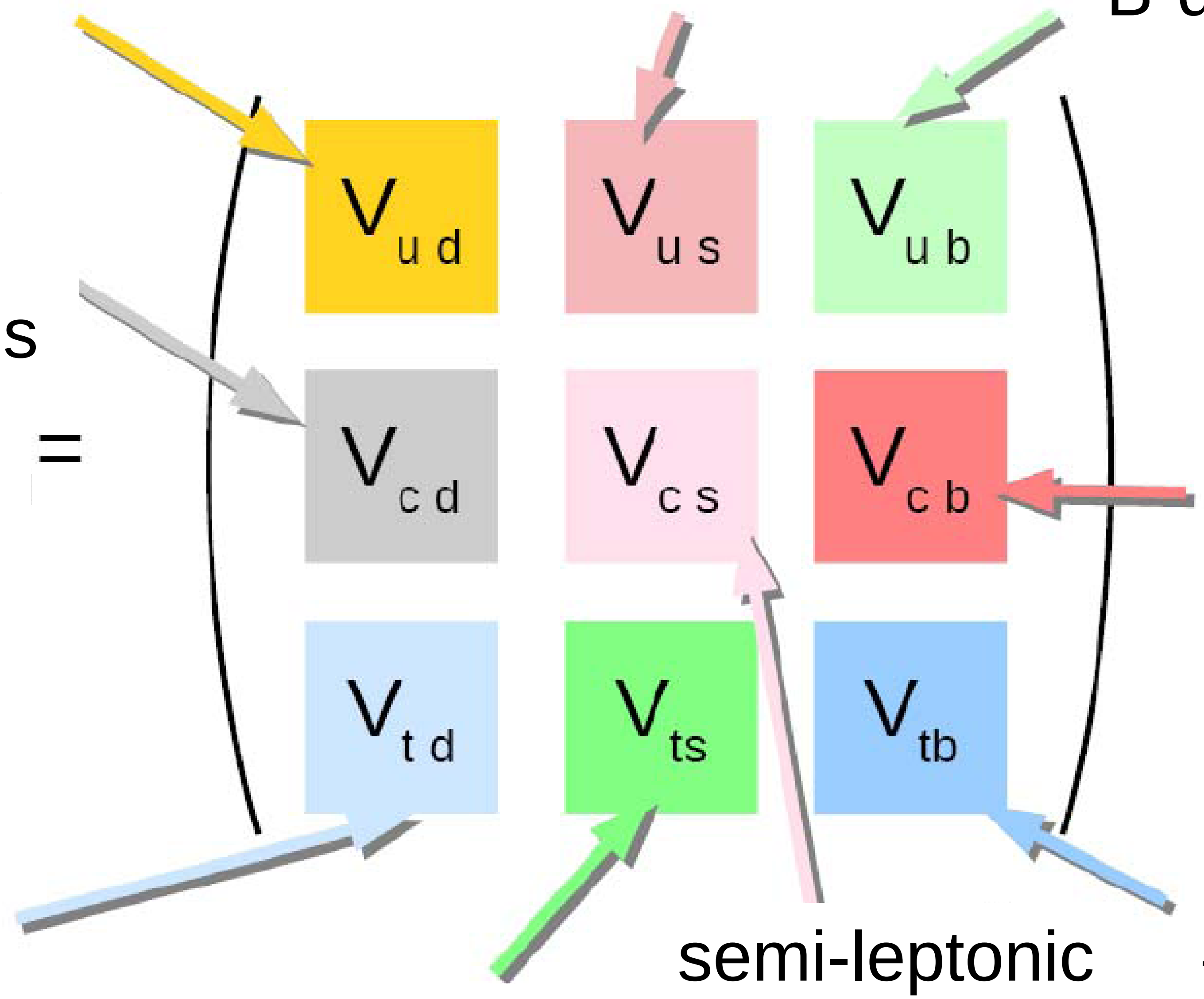
$$V_{us}V^*_{ub} + V_{cs}V^*_{cb} + V_{ts}V^*_{tb} = 0$$



$$V_{ud}V^*_{us} + V_{cd}V^*_{cs} + V_{td}V^*_{ts} = 0$$



Unitarity Triangle



$$M_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Nuclear β-decay

semi-leptonic
K-decays

charm-less
B-decays

charm production
and neutrino reactions

semi-leptonic
B-decays

BB-Mixing

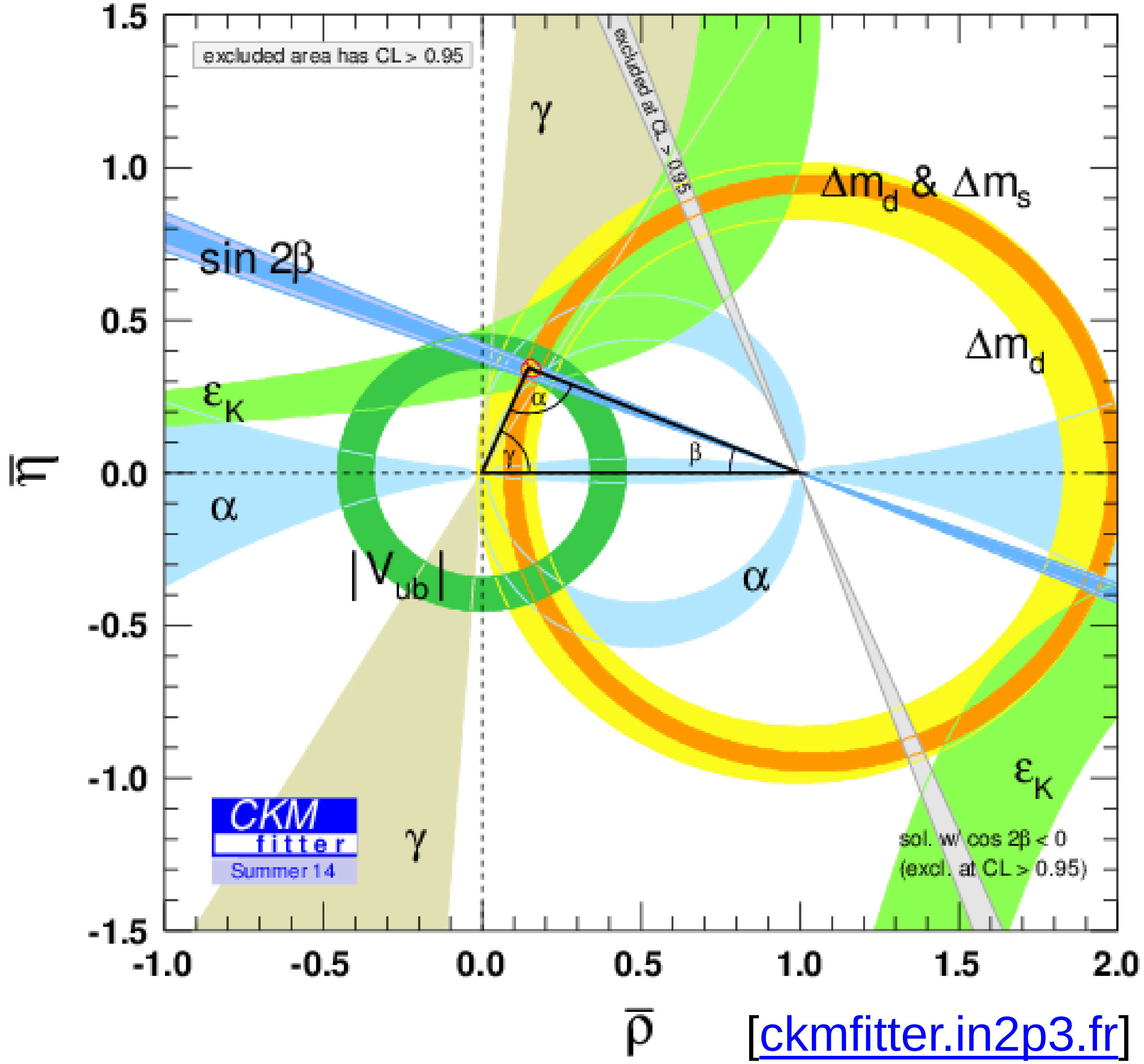
B-decays via
EM penguin
diagrams

semi-leptonic
D-decays

BB-mixing
top production

Unitarity Triangle

- Idea: overconstrain with many independent measurements
  → consistency check
- Could see non-unitarity if
  → quarks mix with additional generations
  → quarks couple to additional bosons
  → …
- so far consistent



[ckmfitter.in2p3.fr]

Flavor Oscillations

Quantum numbers of hadrons

- hadrons produced in strong interactions
  → eigenstates of the strong interaction

- Not necessarily eigenstates of the weak interaction

- Flavor-changing process in neutral mesons:
  transition between particles and anti-particles
  → flavor oscillations (also called: flavor mixing)

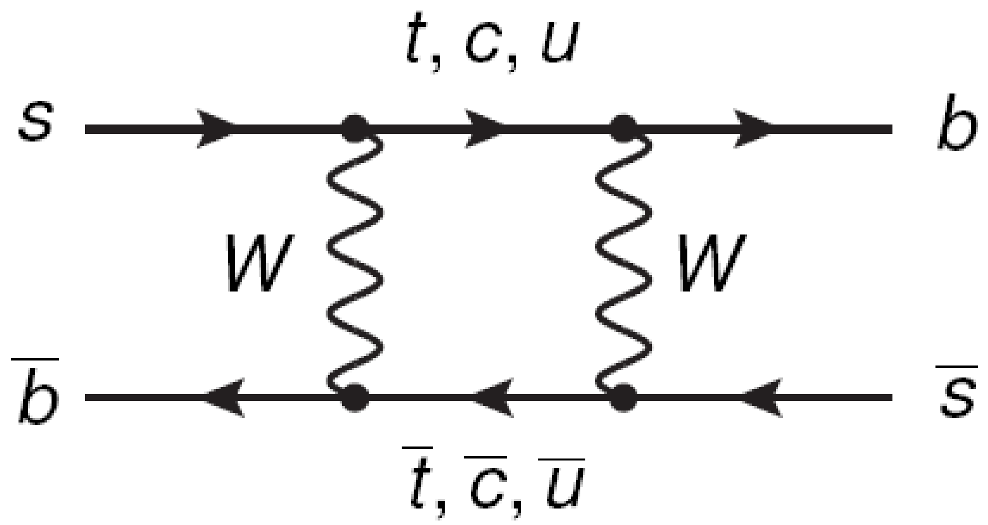
$$|P\rangle \leftrightarrow |\bar{P}\rangle$$

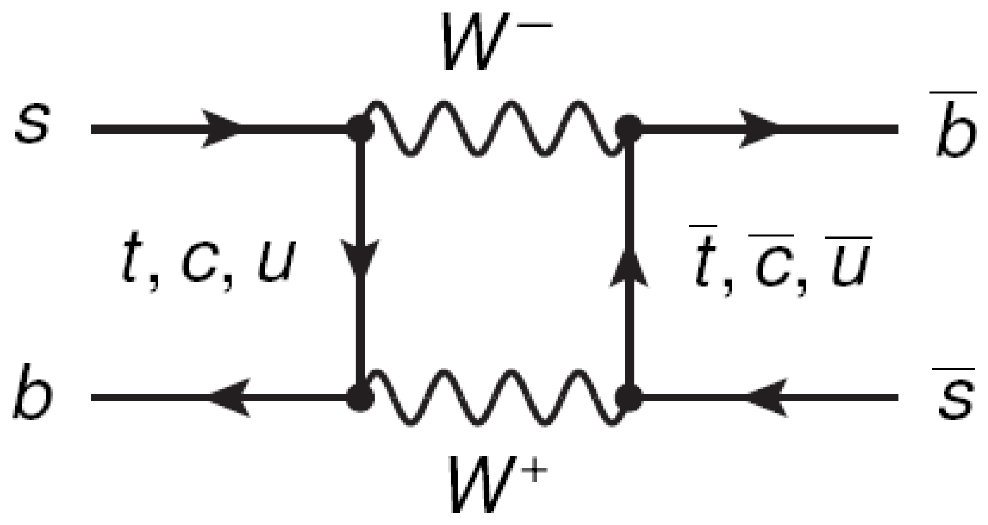
widely studied particle-anti-particle systems with oscillations

neutral Kaons:	$|K^0\rangle = |\bar{s}d\rangle \quad \leftrightarrow \quad |\bar{K}^0\rangle = |s\bar{d}\rangle$
neutral B-mesons:	$|B_d^0\rangle = |\bar{b}d\rangle \quad \leftrightarrow \quad |\bar{B}_d^0\rangle = |b\bar{d}\rangle$ $|B_s^0\rangle = |\bar{b}s\rangle \quad \leftrightarrow \quad |\bar{B}_s^0\rangle = |b\bar{s}\rangle$

Example: B-Oscillations

Dominant standard model contribution: box diagrams





Time evolution

- start with a pure state $|P\rangle$ or $|\bar{P}\rangle$
- After a time-interval Δt: mixture of $|P\rangle$ and $|\bar{P}\rangle$, or decay
- phaenomenologic description of time-evolution:
  Schrödinger-equation with „effective Hamilton operator“ Σ

Time Evolution

Formalism for time evolution: Schrödinger equation:

$$i\,\frac{\mathrm{d}}{\mathrm{dt}}\begin{pmatrix}|P(t)\rangle\\|\bar{P}(t)\rangle\end{pmatrix} = \Sigma\begin{pmatrix}|P(t)\rangle\\|\bar{P}(t)\rangle\end{pmatrix} = \left(M - i\,\frac{\Gamma}{2}\right)\begin{pmatrix}|P(t)\rangle\\|\bar{P}(t)\rangle\end{pmatrix} \quad \text{with } M^{\dagger} = M, \Gamma^{\dagger} = \Gamma$$

mass matrix

decay width matrix

Effective Hamilton operator:

$$\Sigma = \begin{pmatrix} M_{11} - i\Gamma_{11}/2 & M_{12} - i\Gamma_{12}/2 \\ M_{12} - i\Gamma_{12}^{*}/2 & M_{22} - i\Gamma_{22}/2 \end{pmatrix}$$

- M_{11}, M_{22}: quark masses and binding energies (strong interaction) → no oscillation
- Γ_{11}, Γ_{22}, M_{12}, Γ_{12}: oscillations and decay by weak interaction
- CPT-symmetry: particles and anti-partcles have the same mass and decay width → $M_{12} = M_{22} = m$, $\Gamma_{11} = \Gamma_{22}, = \Gamma$

Time Evolution

Diagonalize $\Sigma \rightarrow$ massses and widths of physical particles

- Ansatz: linear combinations of $|P\rangle$ and $|\bar{P}\rangle$

  $$|P_L\rangle = p|P\rangle + \mathrm{q}|\bar{P}\rangle, \qquad |P_H\rangle = p|P\rangle - \mathrm{q}|\bar{P}\rangle$$

  with $|P_L\rangle$ "light" and $|P_H\rangle$ "heavy" mass eigenstate
  p,q complex coefficients with norm $|p|^2 + |q|^2=1$

- Time evolution of the physical particles $|P_L\rangle$ and $|P_H\rangle$

  $$|P_{L,H}(t)\rangle = \exp\left[-iM_{L,H}t - \frac{\Gamma_{L,H}}{2}t\right]|P_{L,H}\rangle$$

- Time evolution of the flavor eigenstates $|P\rangle$ and $|\bar{P}\rangle$
  transform with matrix of eigenvectors (p,q) and (p.-q)

$$\begin{pmatrix} |P(t)\rangle \\ |\bar{P}(t)\rangle \end{pmatrix} = \begin{pmatrix} p & p \\ q & -q \end{pmatrix} \begin{pmatrix} \exp\left[-iM_L t - \frac{\Gamma_L}{2}t\right] & 0 \\ 0 & \exp\left[-iM_H t - \frac{\Gamma_H}{2}t\right] \end{pmatrix} \begin{pmatrix} p & p \\ q & -q \end{pmatrix}^{-1} \begin{pmatrix} |P\rangle \\ |\bar{P}\rangle \end{pmatrix}$$

Time Evolution

Multiply matrices:

$$\begin{pmatrix} |P(t)\rangle \\ |\bar{P}(t)\rangle \end{pmatrix} = \begin{pmatrix} g_+(t) & \frac{p}{q} g_-(t) \\ \frac{q}{p} g_-(t) & g_+(t) \end{pmatrix} \begin{pmatrix} |P\rangle \\ |\bar{P}\rangle \end{pmatrix}$$

with: $g_\pm(t) = \frac{1}{2}\left(\exp\left[-iM_L t - \frac{\Gamma_L}{2} t\right] \pm \exp\left[-iM_H t - \frac{\Gamma_H}{2} t\right]\right)$

Interpretation as transition amplitudes:

- $|g_+(t)|^2$: probability that $|P\rangle$ ($|\bar{P}\rangle$) remains in this state
- $|q/p|^2 |g_-(t)|^2$: probability for $|P\rangle$ to oscillate to $|\bar{P}\rangle$
- $|p/q|^2 |g_-(t)|^2$: probability for $|\bar{P}\rangle$ to oscillate to $|P\rangle$

Observe direct CP violation if $p \neq q$

Time Evolution

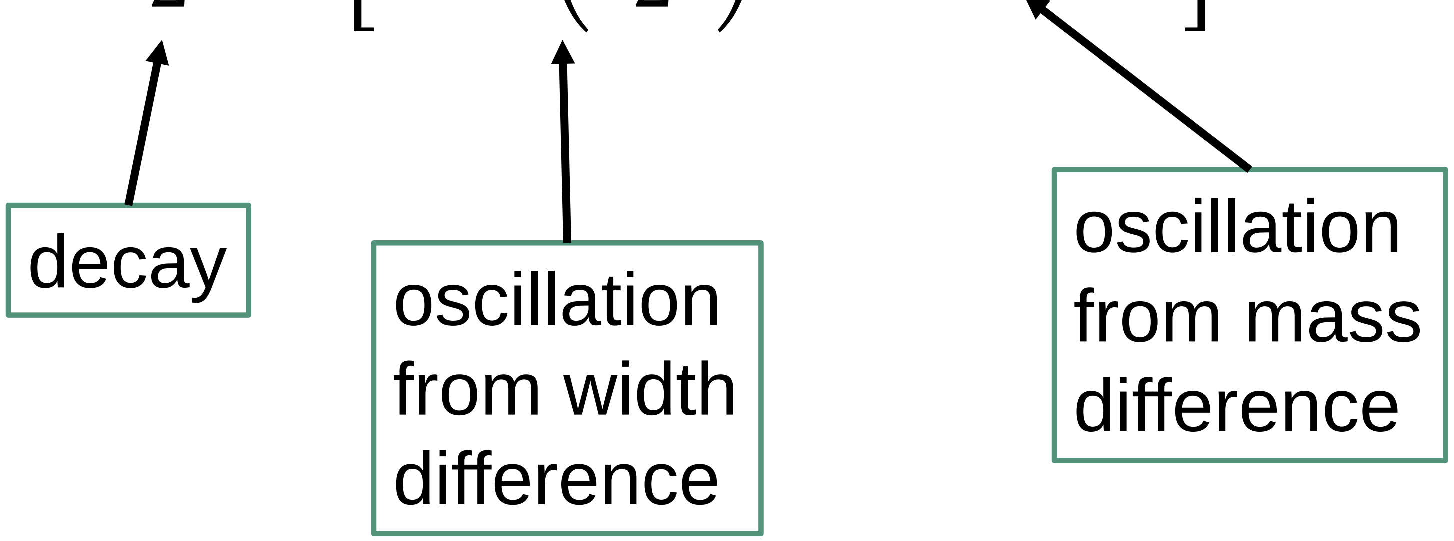
Convention: replace mass and width of light/heavy particle by average and difference

$$m = M_{11} = M_{22} = \frac{1}{2}(M_H + M_L) \qquad \Gamma = \Gamma_{11} = \Gamma_{22} = \frac{1}{2}(\Gamma_L + \Gamma_H)$$

$$\Delta m = M_H - M_L \qquad \Delta\Gamma = \Gamma_L - \Gamma_H$$

transition probabilities:

$$|g_\pm(t)|^2 = \frac{\exp(-\Gamma t)}{2}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) \pm \cos(\Delta m t)\right]$$



decay

oscillation from width difference

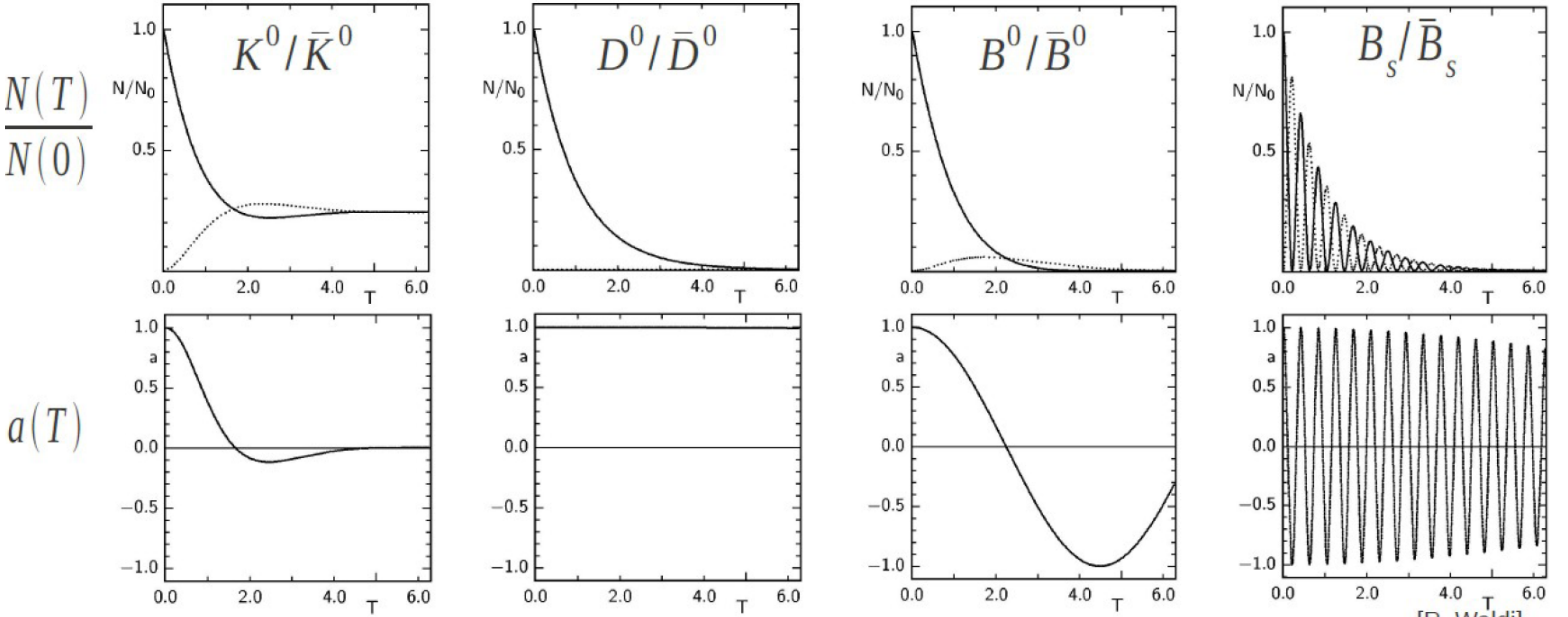
oscillation from mass difference

Different Oscillating Systems

Mass difference and decay widths

	$K^0/\bar{K}^0$	$D^0/\bar{D}^0$	$B^0/\bar{B}^0$	$B_s/\bar{B}_s$
τ [ps]*	89	0.4	1.6	1.5
	51700			
Γ [ps^{-1}]	5.6×10^{-3}	2.4	0.64	0.62
$y=\frac{\Delta\Gamma}{2\Gamma}$	-0.997	0.01	$\lvert y\rvert<0.01$	0.03 ± 0.03
Δm [ps^{-1}]	5.3×10^{-3}	0.02	0.5	17.8
$x=\frac{\Delta m}{\Gamma}$	0.95	0.01	0.8	26

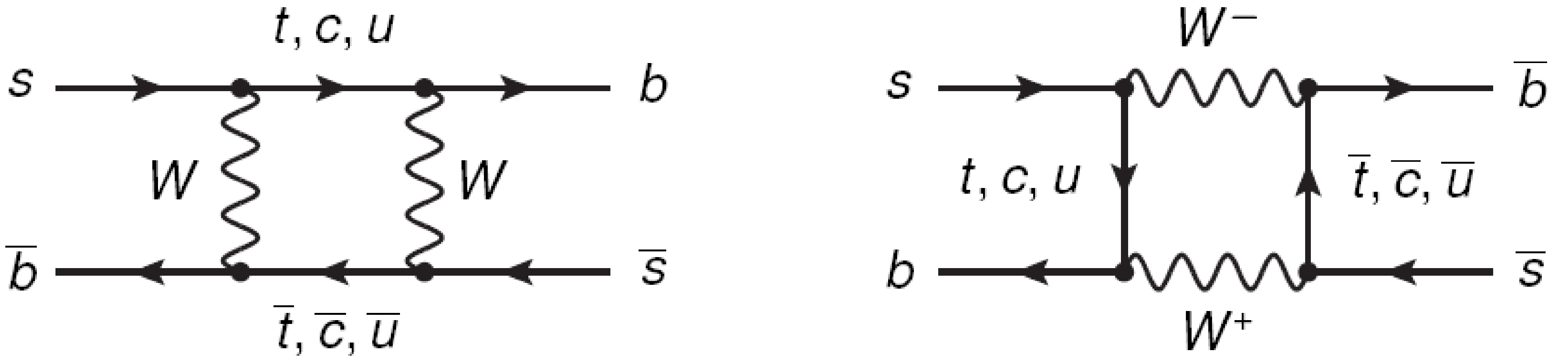
*) at LHCb energies lifetime in ps ~ decay length in cm



[R. Waldi]

Learning from Oscillations

Compute mass differences from box diagrams

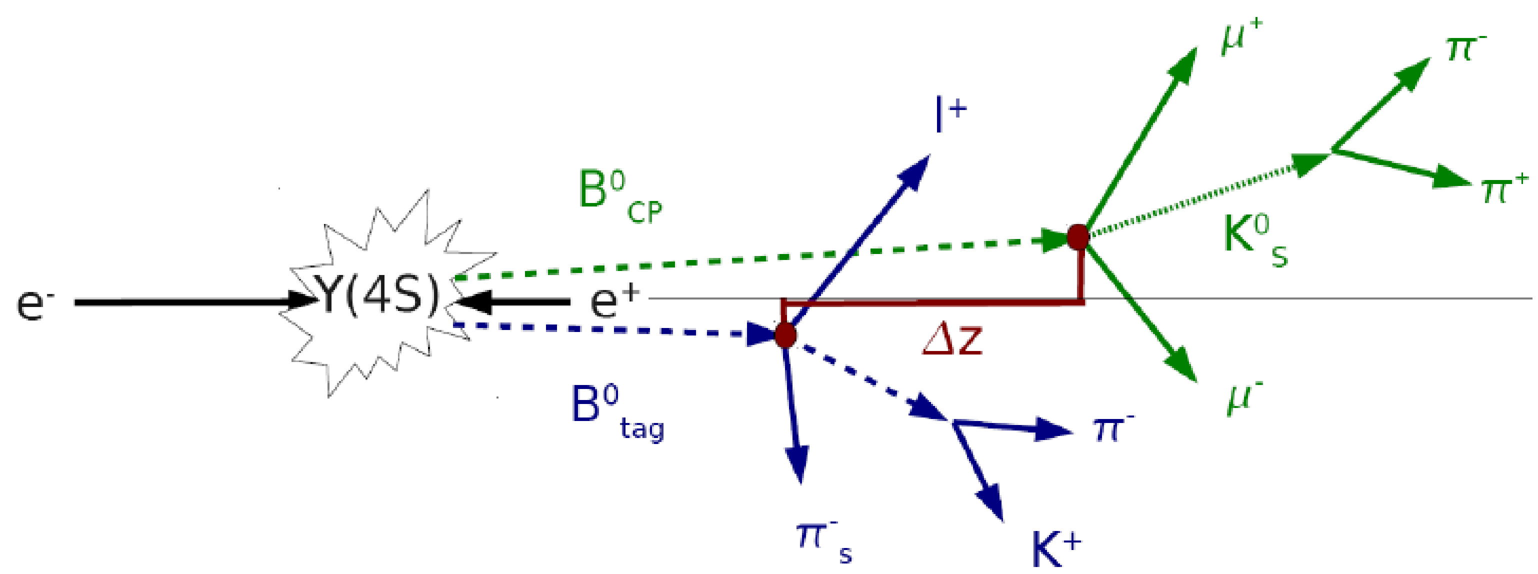


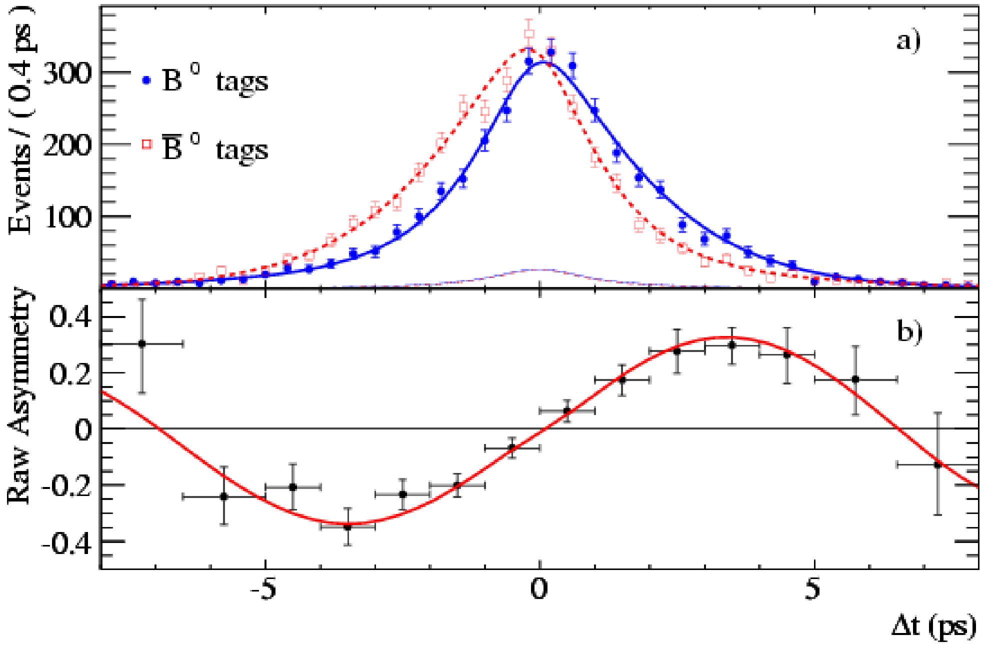
- approximations: m_t only relevant quark mass, $V_{tb} \approx 1$
- Result: $\Delta m_{d,s} \approx 2|M_{12}| \sim G_F^2 m_W^2 S\left(\frac{m_t^2}{m_W^2}\right)\left(V_{td,ts}^* V_{tb}\right)^2$
- Measurement of $|V_{td}|$ and $|V_{ts}|$ from oscillation frequency
- First results in B_d at ARGUS (DESY) and UA1 (CERN) 1987
  → large Δm_d hints at high top quark mass

Oscillations Measurements

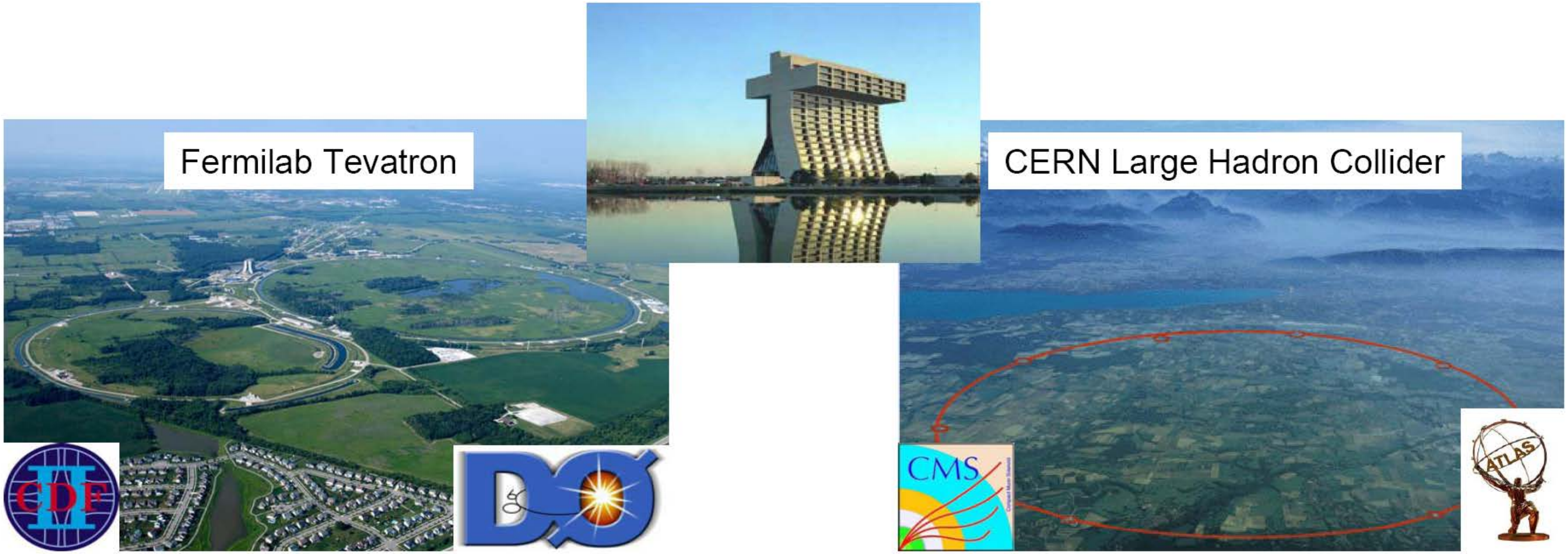
B-factories: electron positron colliders with asymmetric beam energy

- tuned to Y(4S) resonance: $B\bar{B}$ pairs ~ at rest in e^+e^- system
- $B\bar{B}$ system moving relative to laboratory frame
  → better measurement of decay length
- $B\bar{B}$ system is an entangled quantum system
  → first decay as B or $\bar{B}$ determines second decay
- Measure flavor as function in difference of decay length





Where to find top quarks



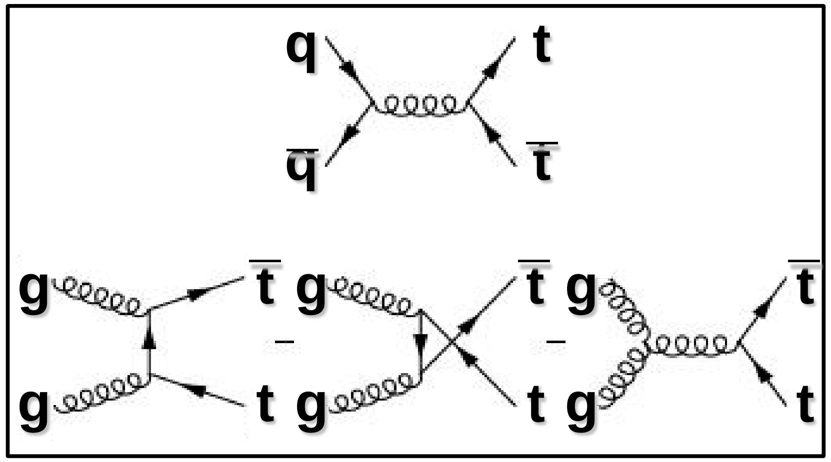
Tevatron:

- Run 1: $\sqrt{s}$ = 1.8 TeV (1992-1996)
  65 pb^{-1}: top quark discovered
  (~20 events per experiment)
- Run 2: $\sqrt{s}$=1.96 TeV(2001-2011)
  12 fb^{-1} first precision top physics

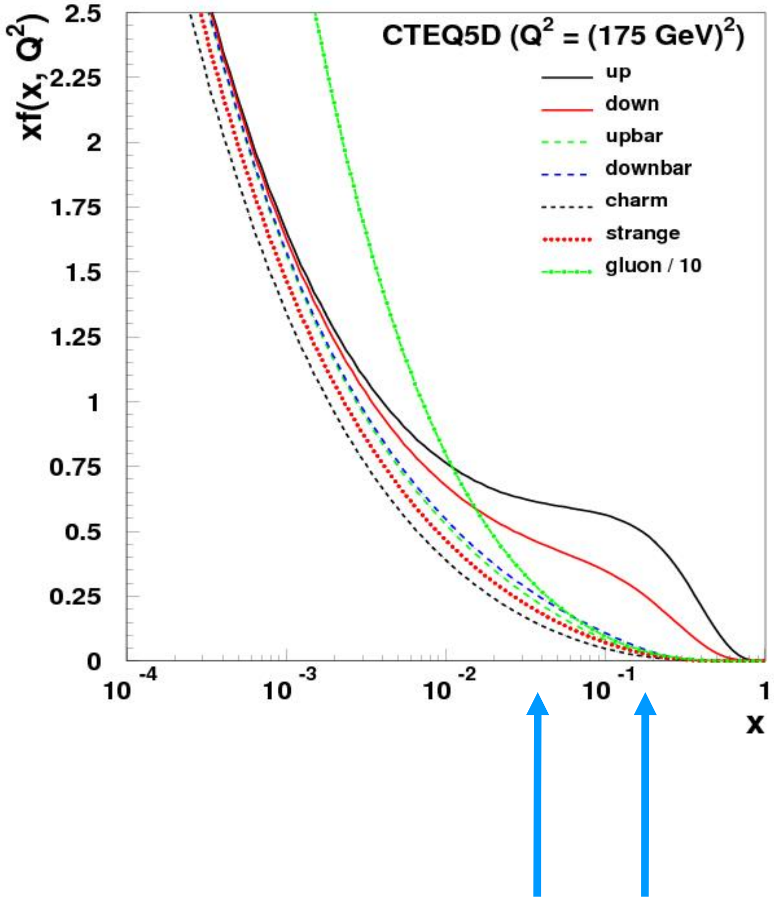
LHC:

- $\sqrt{s}$ = 7 TeV (2010-2011)
  5 fb^{-1}: 1M top pairs produced ~60k reco
  re-establish top quark
- $\sqrt{s}$=8 TeV(2012)
  20 fb^{-1} precision top physics
  statistical uncertainties become irrelevant
- $\sqrt{s}$=13 TeV(2015-…)
  >20 fb^{-1}more precision studies
  very rare processes

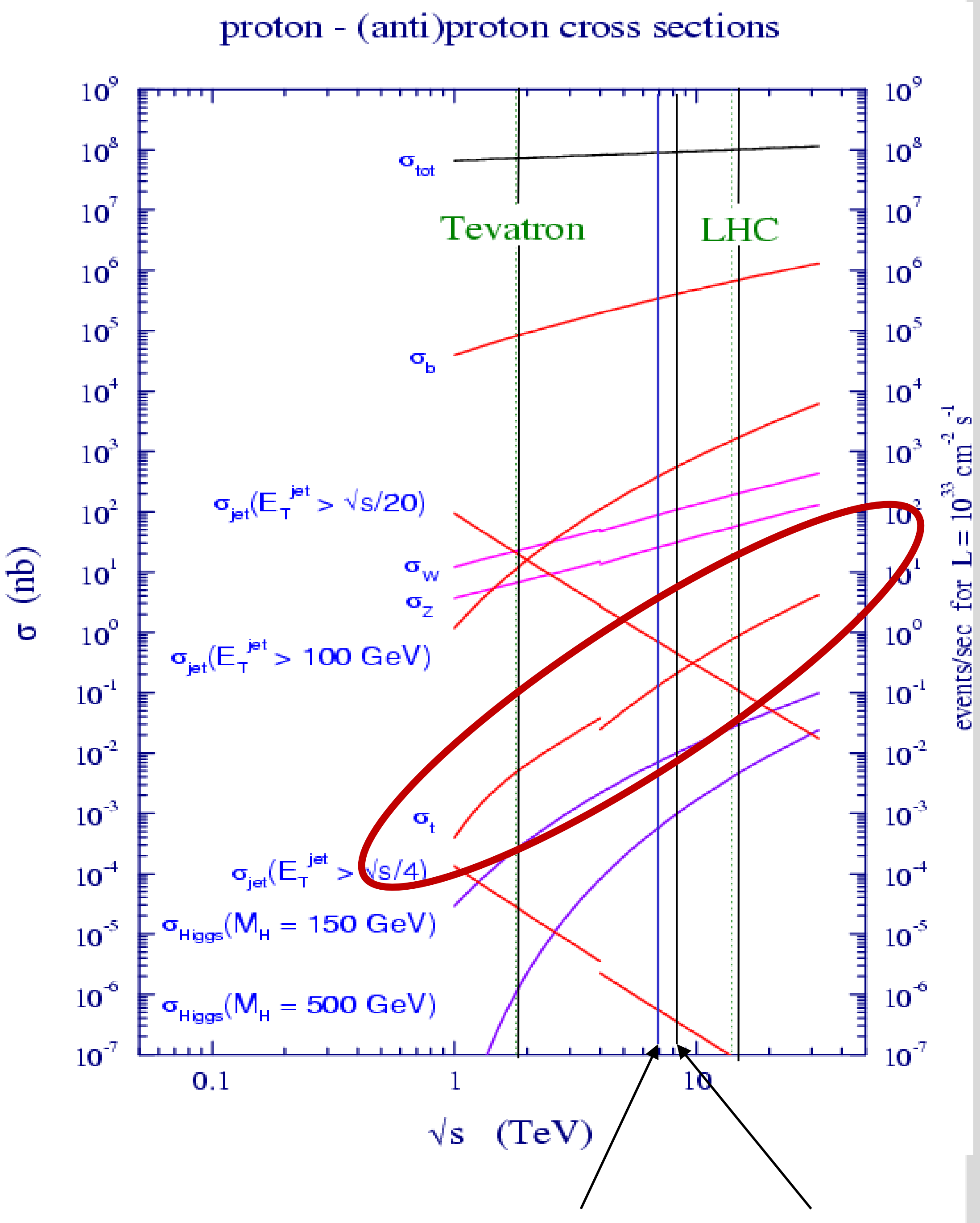
Producing top quarks



	TEV	LHC
←	~85%	~15%
←	~15%	~85%



LHC **Tevatron**



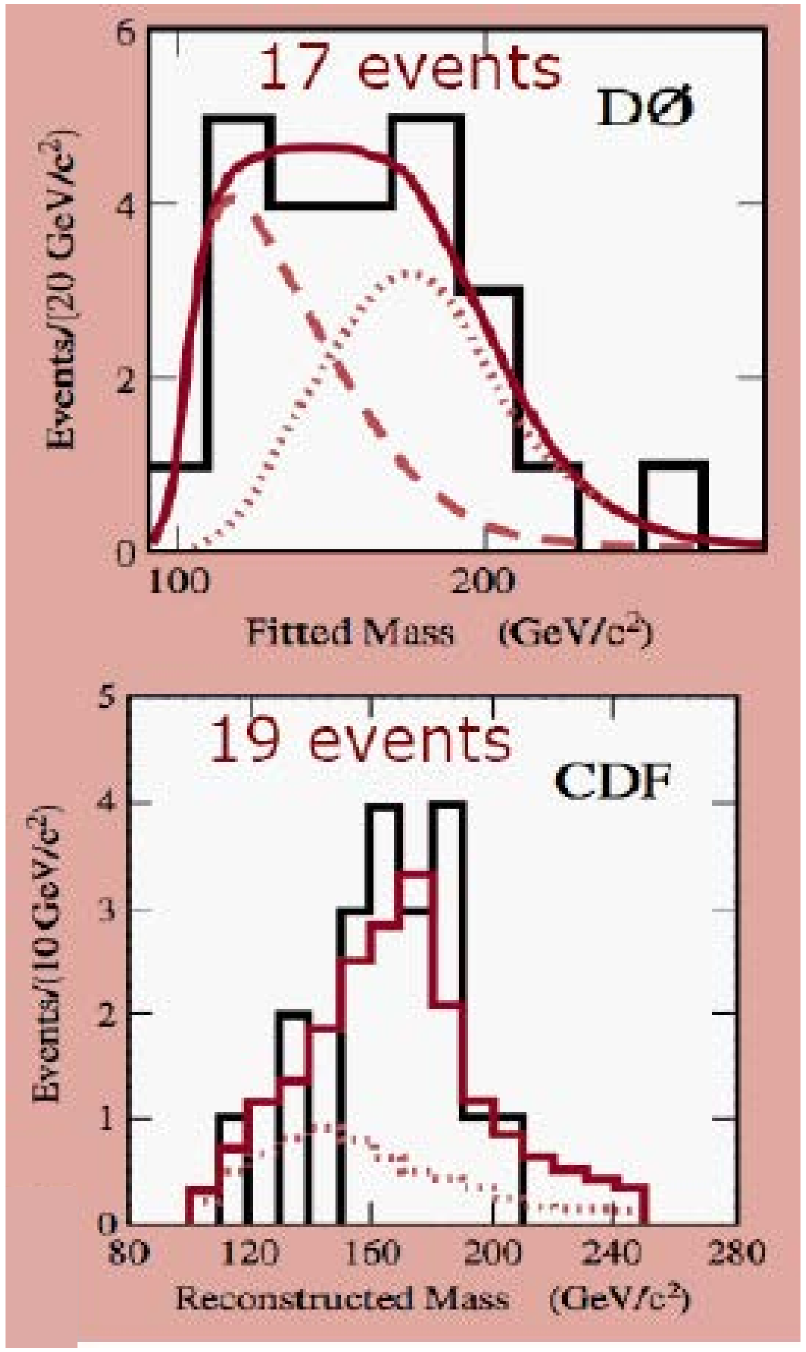
7 TeV 8 TeV

History: Top discovery

- 24.02.1995:
  Two simultaneous publications
  by CDF and DØ

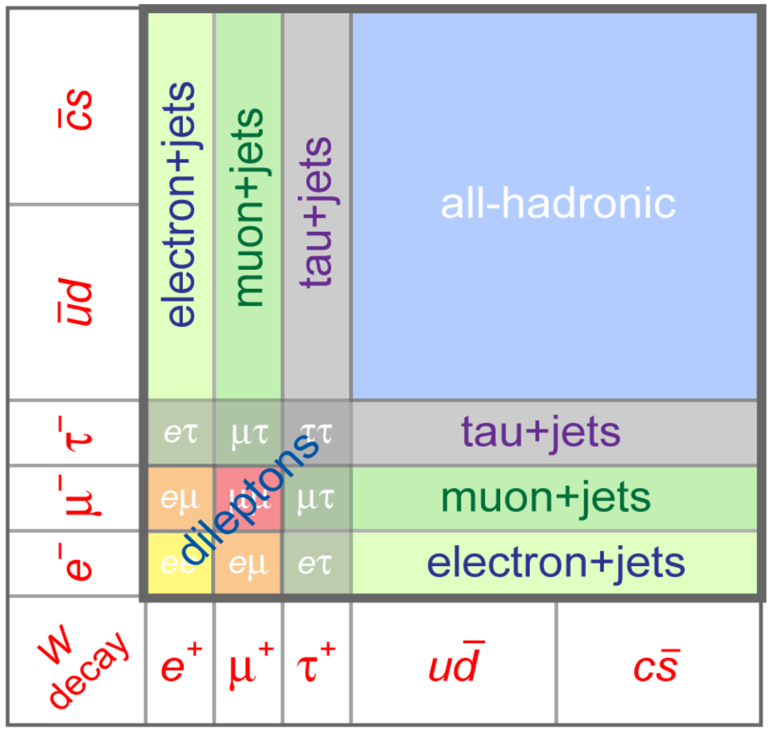
- DØ: 50 pb^{-1}
  signifikance 4,6σ
  $m_t = 199 \pm 30$ GeV
  $\sigma_{t\bar{t}} = 6.4 \pm 2.2$ pb

- CDF: 67 pb^{-1}
  signifikance 4,8σ
  $m_t = 176 \pm 13$ GeV
  $\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}$ pb



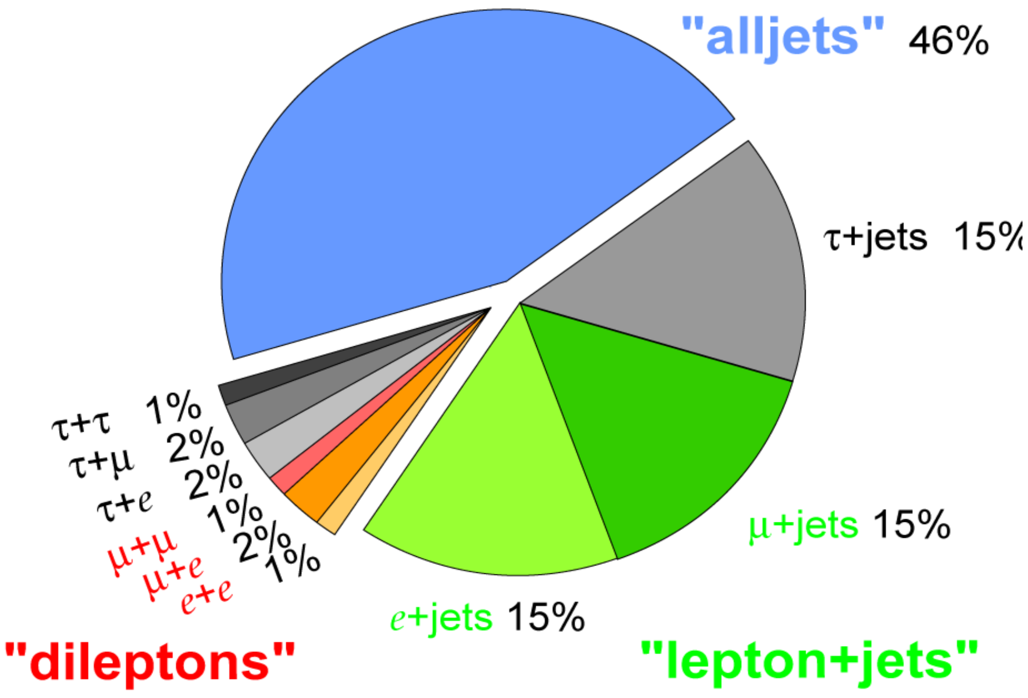
Top quark decays

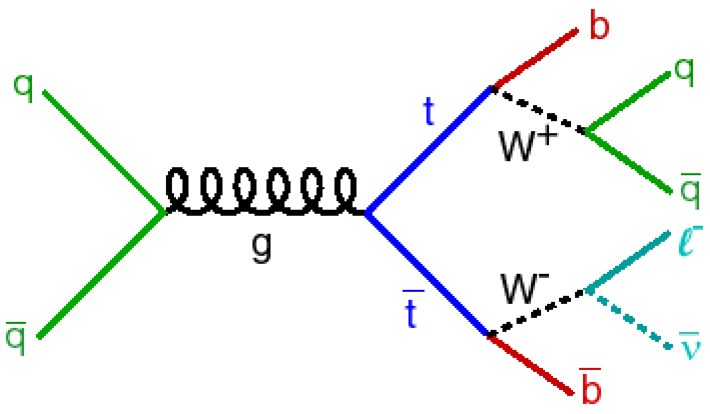
Top Pair Decay Channels



$c\bar{s}$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$	electron+jets	muon+jets	tau+jets	all-hadronic	
τ^-	eτ	μτ	ττ	tau+jets	
μ^-	eμ	μμ	μτ	muon+jets	
e^-	ee	eμ	eτ	electron+jets	
W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$

Top Pair Branching Fractions

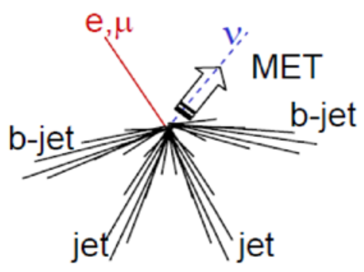




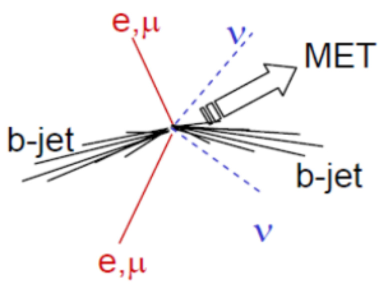
$t \rightarrow Wb$ ~100%

classify by W decay

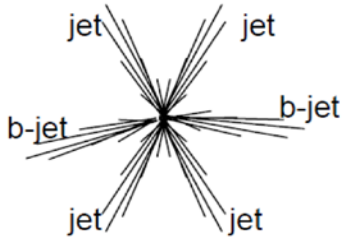
- "Lepton [e,μ] + jets" (34%)
  $t\bar{t} \rightarrow bl\nu bqq'$



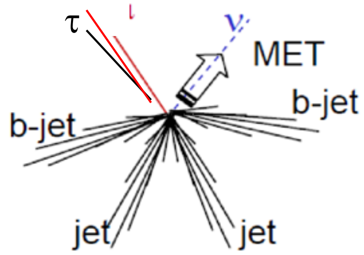
- "Dilepton [e,μ]" (6%)
  $t\bar{t} \rightarrow bl\nu bl\nu$



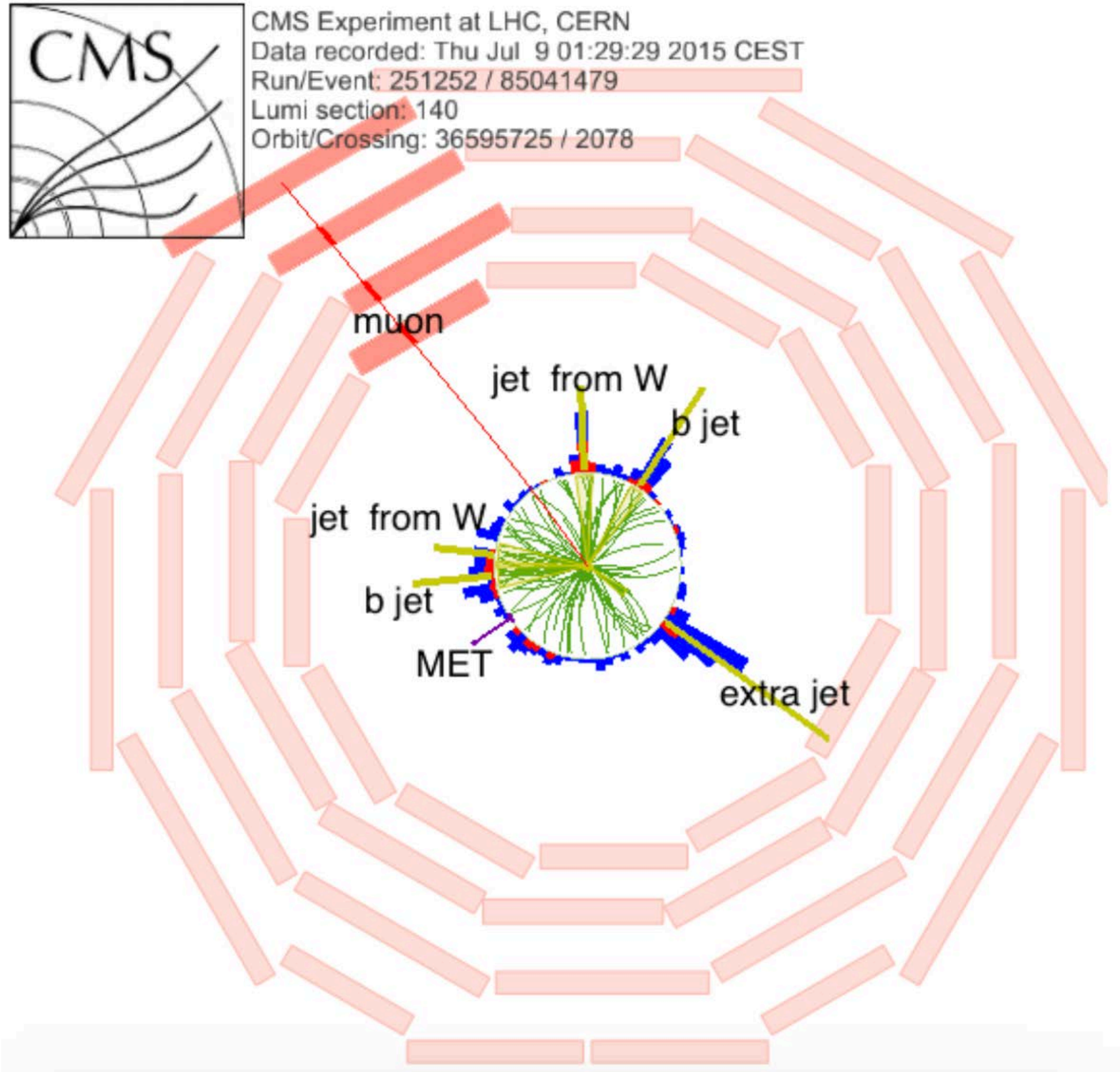
- "All jets" (46%)
  $t\bar{t} \rightarrow bqq'bqq'$



- "Tau + jets" (15%)
  $t\bar{t} \rightarrow b\tau\nu bqq'$



Detector View

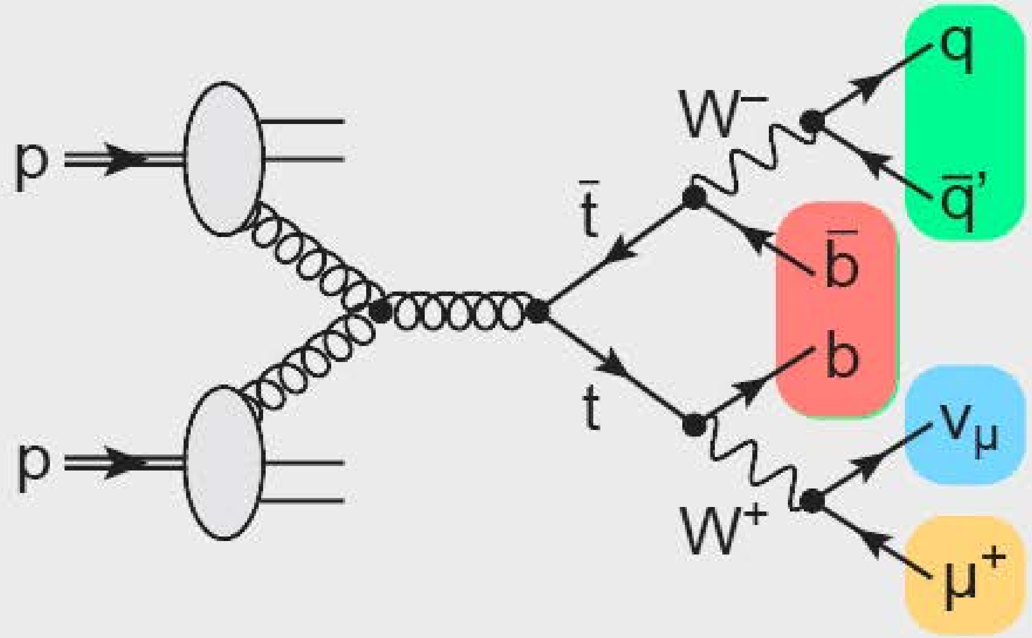


Selecting Top events

- Event selection:
  → enrich signal over backgrounds
  → simplest method: „cuts“

- Optimize selection :
  → Signal to backgground N^{sig}/N^{bkg}
  → signal significance $N^{sig}/\sqrt{N^{sig}+N^{bkg}}$
  → optimized on simulation to avoid bias

Example: lepton + jets channel



Lepton with p_T > 20-30 GeV

Neutrino: MET > 30GeV

4 Jets with p_T > 40GeV

2 jets from B-decays (b-tag)

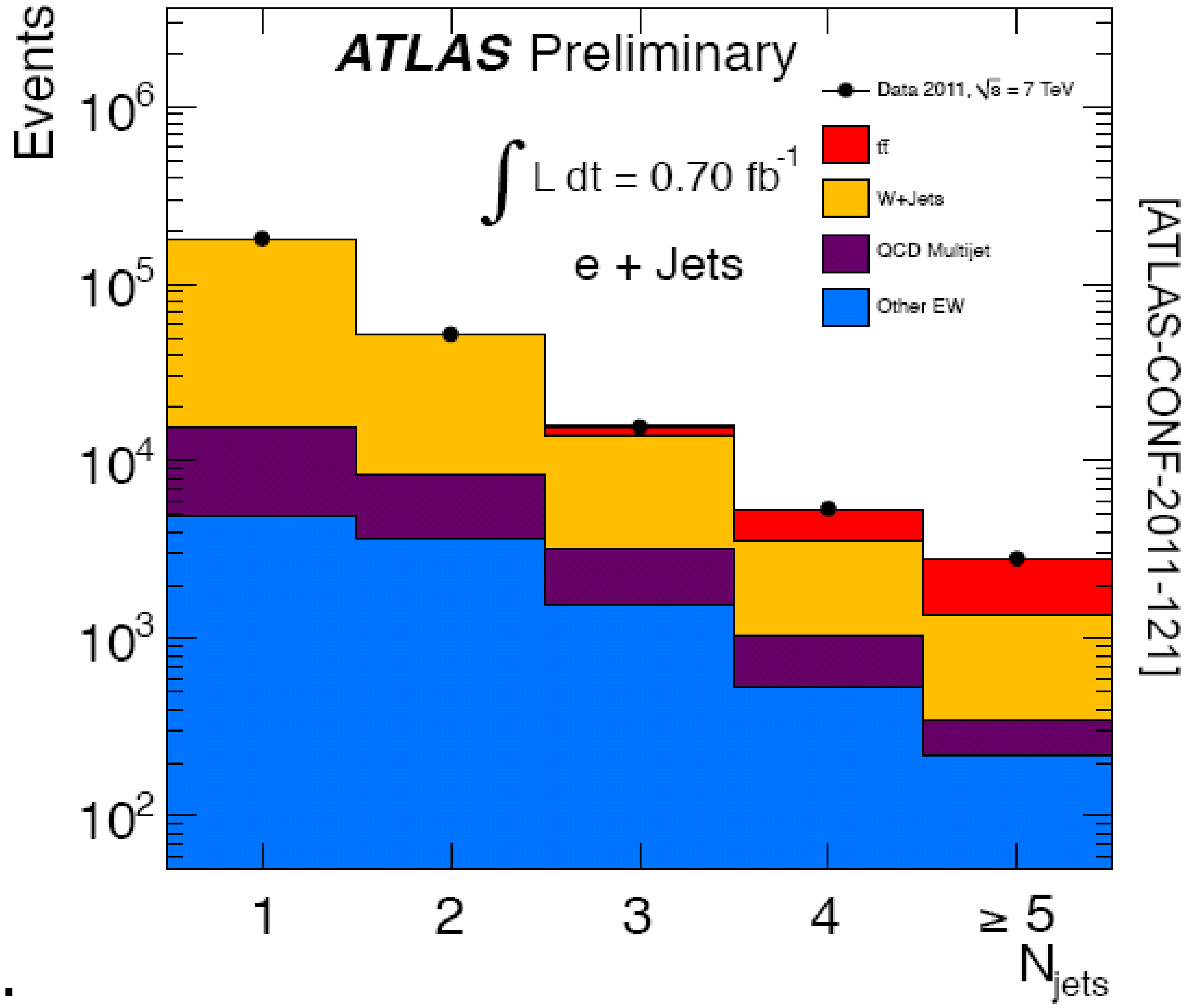
Backgrounds

- Which backgrounds are distinguishable from signal
  → reducible backgrounds

- Instrumental background
  → detector noise
  → misidentifications („fakes“)
  e.g. jet fakes an electron

- Important backgrounds for top
  → lepton + jets: W-boson production in assotiation with jets (W+ jetes)
  → Di-lepton: Z+ jets
  → also: multijets, single-top, …

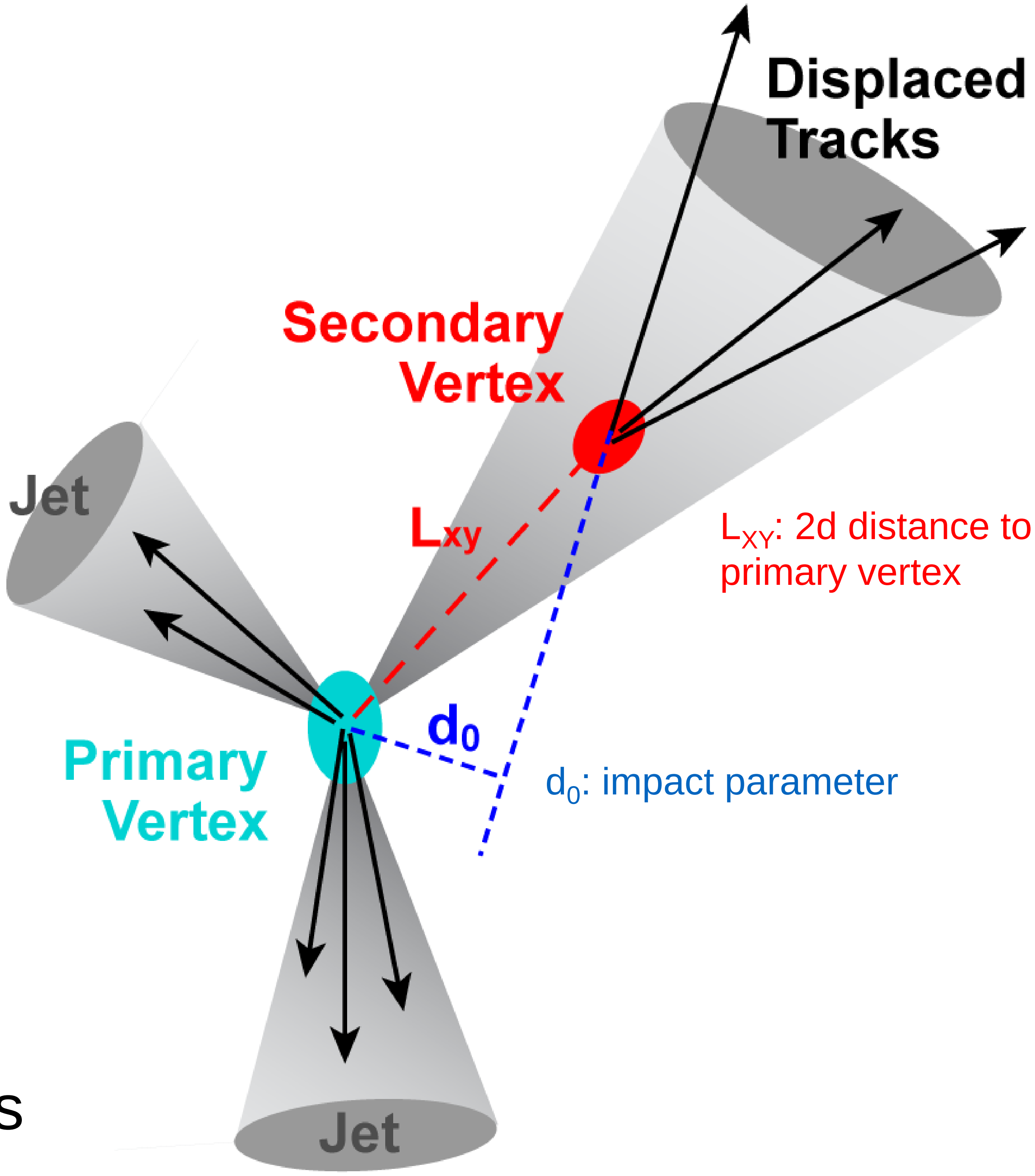
Jet multiplicity in e+jets events



[ATLAS-CONF-2011-121]

B-tagging

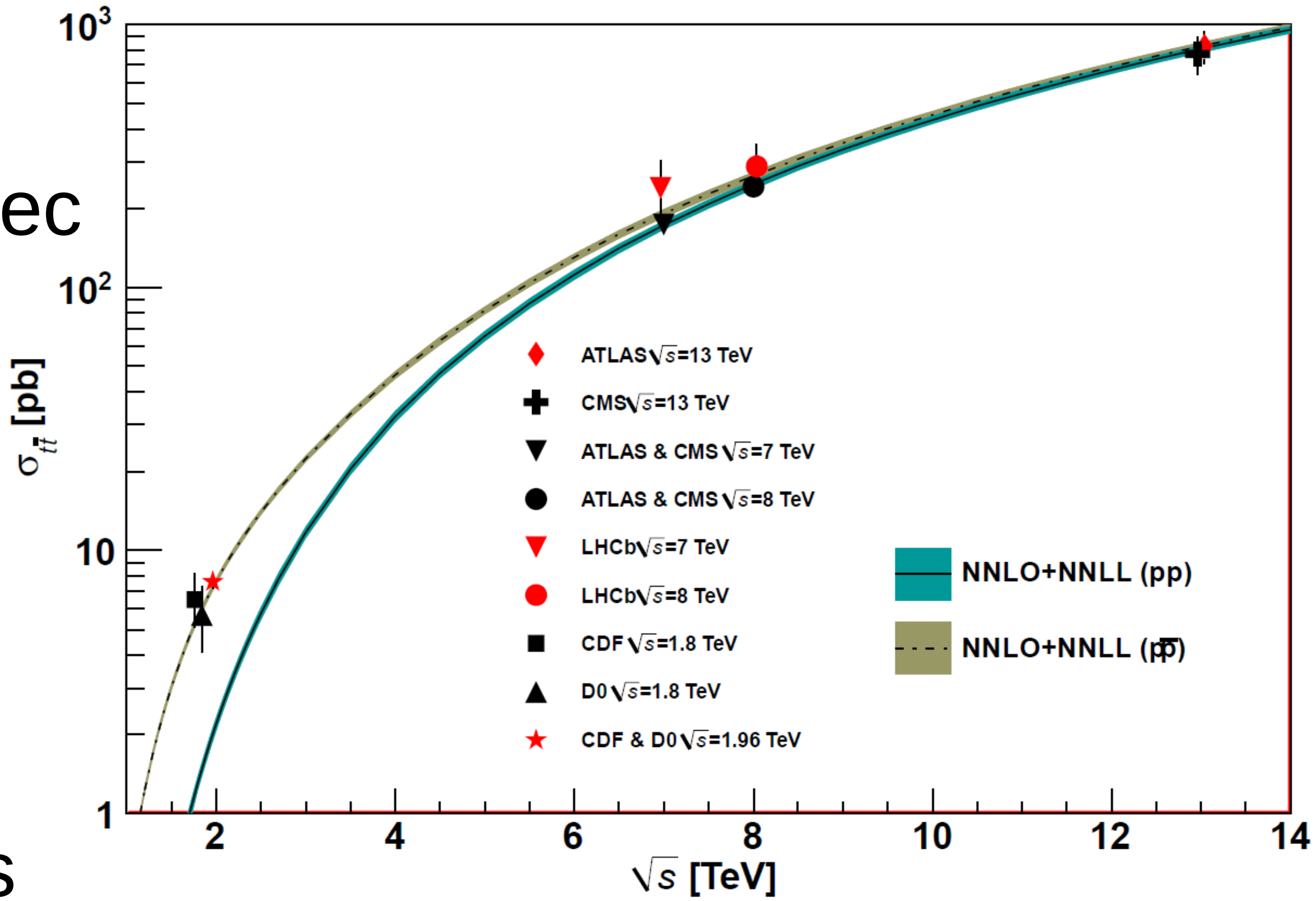
- Many interesting process with b-quarks
  - ⇒ H→bb, tt→WbWb
  - ⇒ identify jets with B-hadrons
- B-tag I (hadrons)
  B-mesons are massive and long lived (cτ~0.5mm)
  - ⇒ B-mesons are massive large impact parameter tracks
  - ⇒ displaced massive vertex
- B-tag II (leptons)
  look for semi-leptonic B decays
  - ⇒ soft leptons



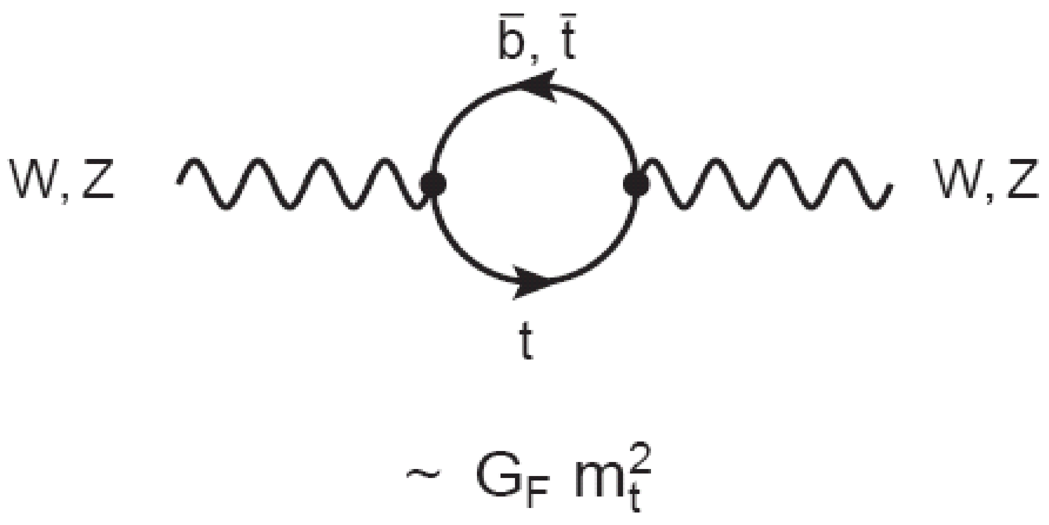
Top Cross Section

- Theory for top-pairs (2015)
  NNLO + NNLL
  ⇒ few % uncertainty

- Compare Tevatron ↔ LHC
  ⇒ LHC: 20-100 x tevatron xsec
  ⇒ Tevatron: large difference between pp and p-anti-p tops produced from valence-quarks
  ⇒ LHC: small difference between pp and p-anti-p tops produced from gluons and sea-quarks
  → skip complicated antiproton generation



Top Quark Mass



- Reminder: M_W, m_t, M_H connected via loop diagrams

- How to define the top mass?
  → usual defintion: pole-mass
  = mass term in the propagator

$$\frac{1}{p^2 - m_t^2 - i\Gamma_t m_t}$$

→ Problem: non-perturbative effects for color charged particles of $O(\Lambda_{QCD})$
→ Experimentally: use mass-parameter of Monte-Carlo-Simulation ⇒ roughly equal to pole mass (within unc.)
→ Theoretically cleaner: scale-dependent „running mass“
⇒ well defined within a given calculation schem (e.q MS-bar)

$$m_t^{\overline{\mathrm{MS}}}(m_t) = \frac{m_t}{1 + 4\alpha_s(m_t)/3}$$

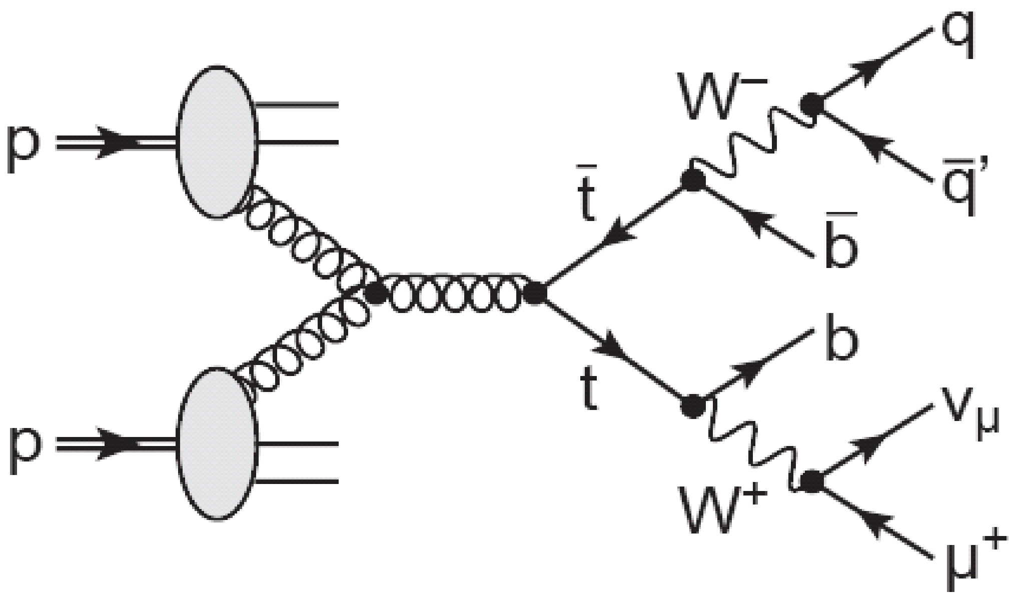
Measuring the Top Mass

- Direct measurement of top mass
  use event kinematics

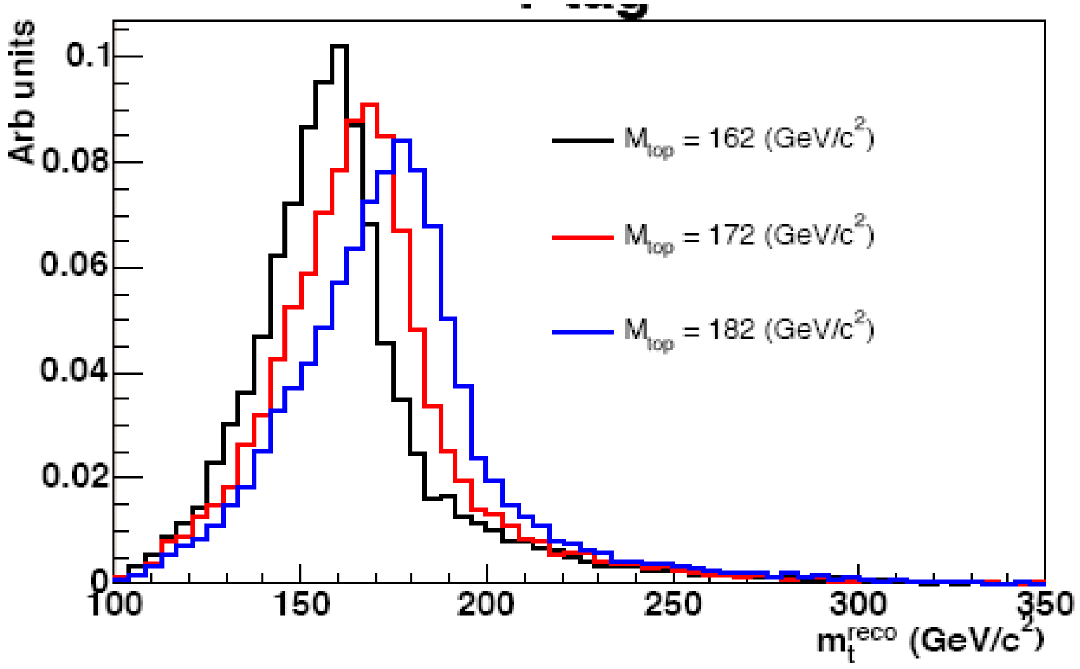
- Lepton + Jets: kinematics
  overconstrained
  → one unknown: neutrino pz
  → possible constraints:
  W-mass, $m_t = m_{anti\text{-}t}$

- Combinatorics: associate jets
  to partons (4 jets ⇒ 24 combinations)
  → find „best“ combination

- Measurement method
  at Tevatron and LHC
  → template fit (like W-mass)
  → matrix-element methods



Schablonen für drei Top-Massen



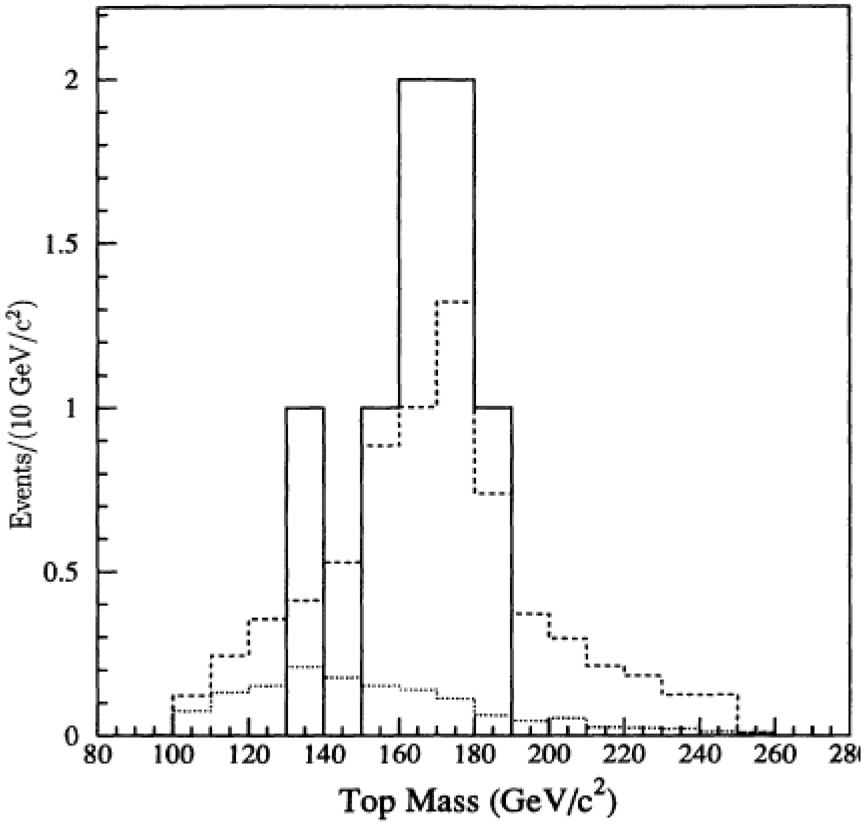
[http://www-cdf.fnal.gov/physics/new/top/2010/mass/TMT_p28_public/]

Top Quark Mass

first measurement

(CDF, 1994, 7 events)

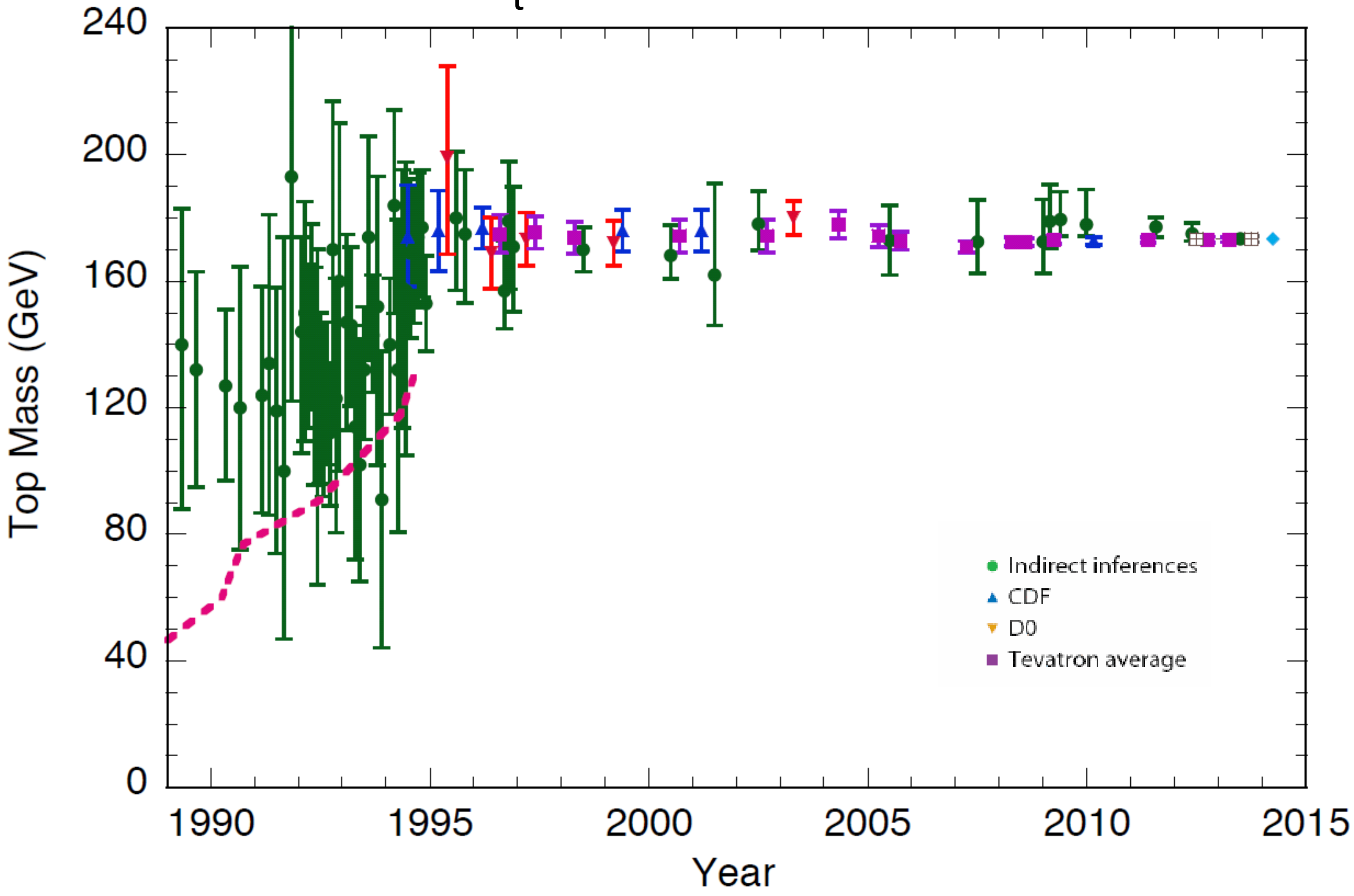
$M_t=170\pm10^{+13}_{-12}$GeV



now

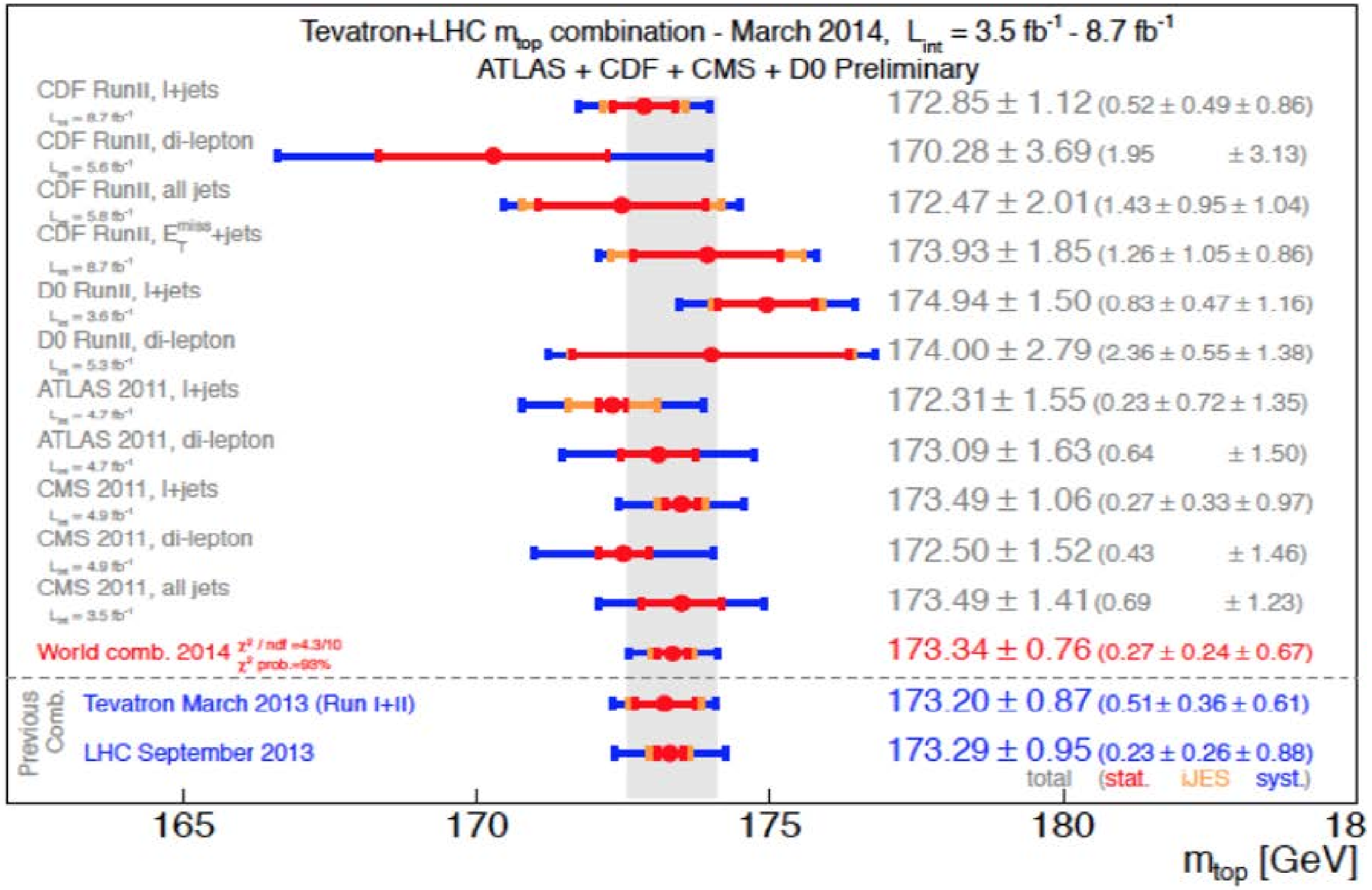
(world average 2014)

$M_t=173.34\pm0.76$ GeV

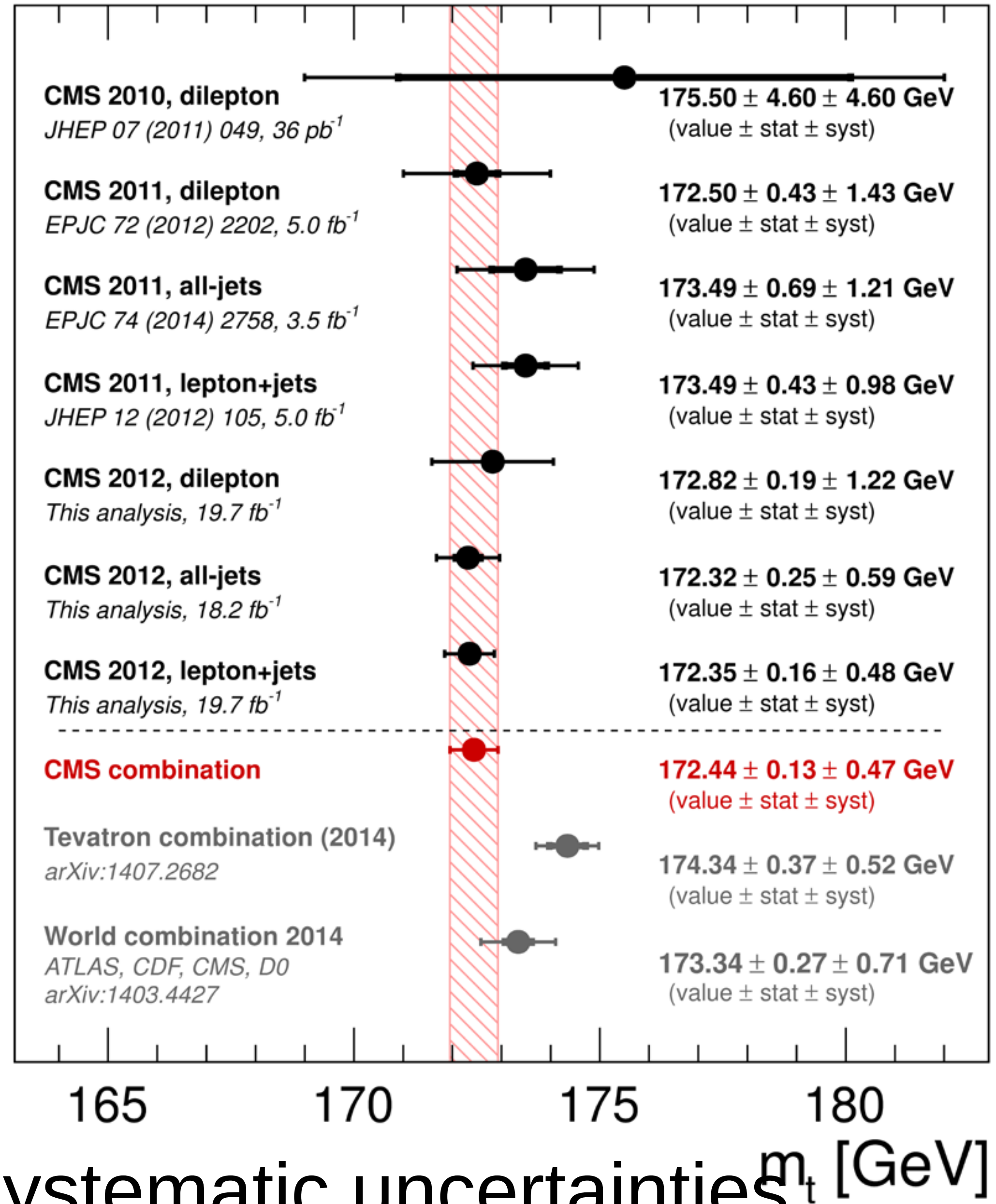


Measuring the Top Mass

World Combination



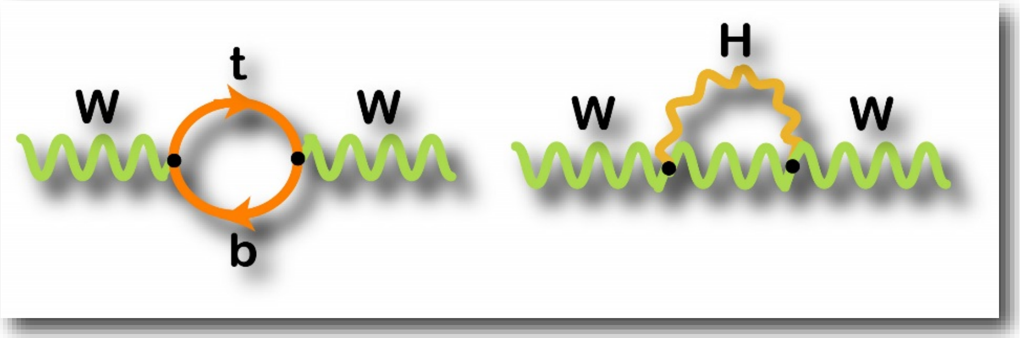
CMS by channel



- uncertainties < 1%
- newer LHC measurements limited by systematic uncertainties
- Visible tension between tevatron and LHC

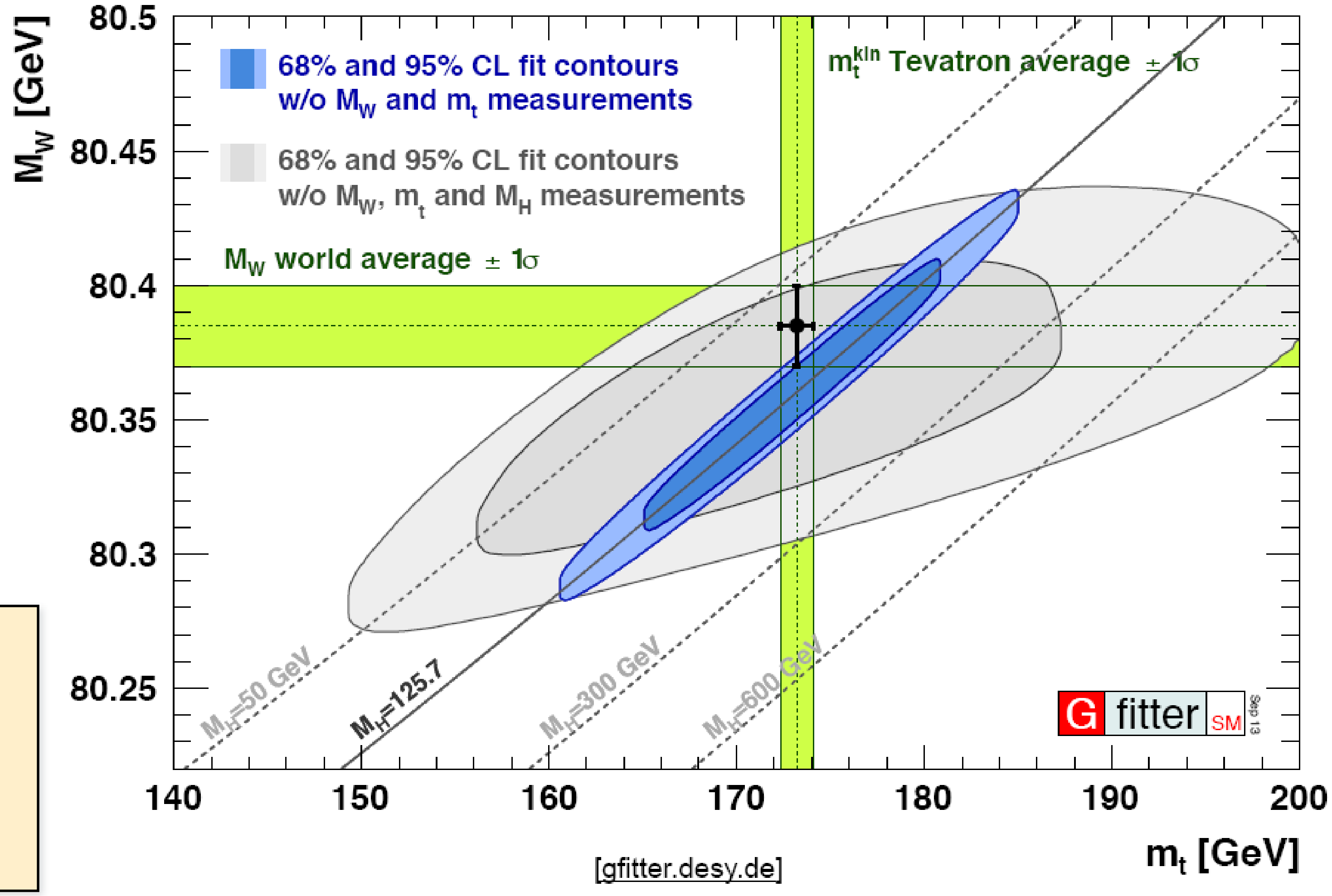
Measuring the Top Mass

M_W, M_t, M_H intermixed at loop level



~M_t^2 ~ln(m_H)

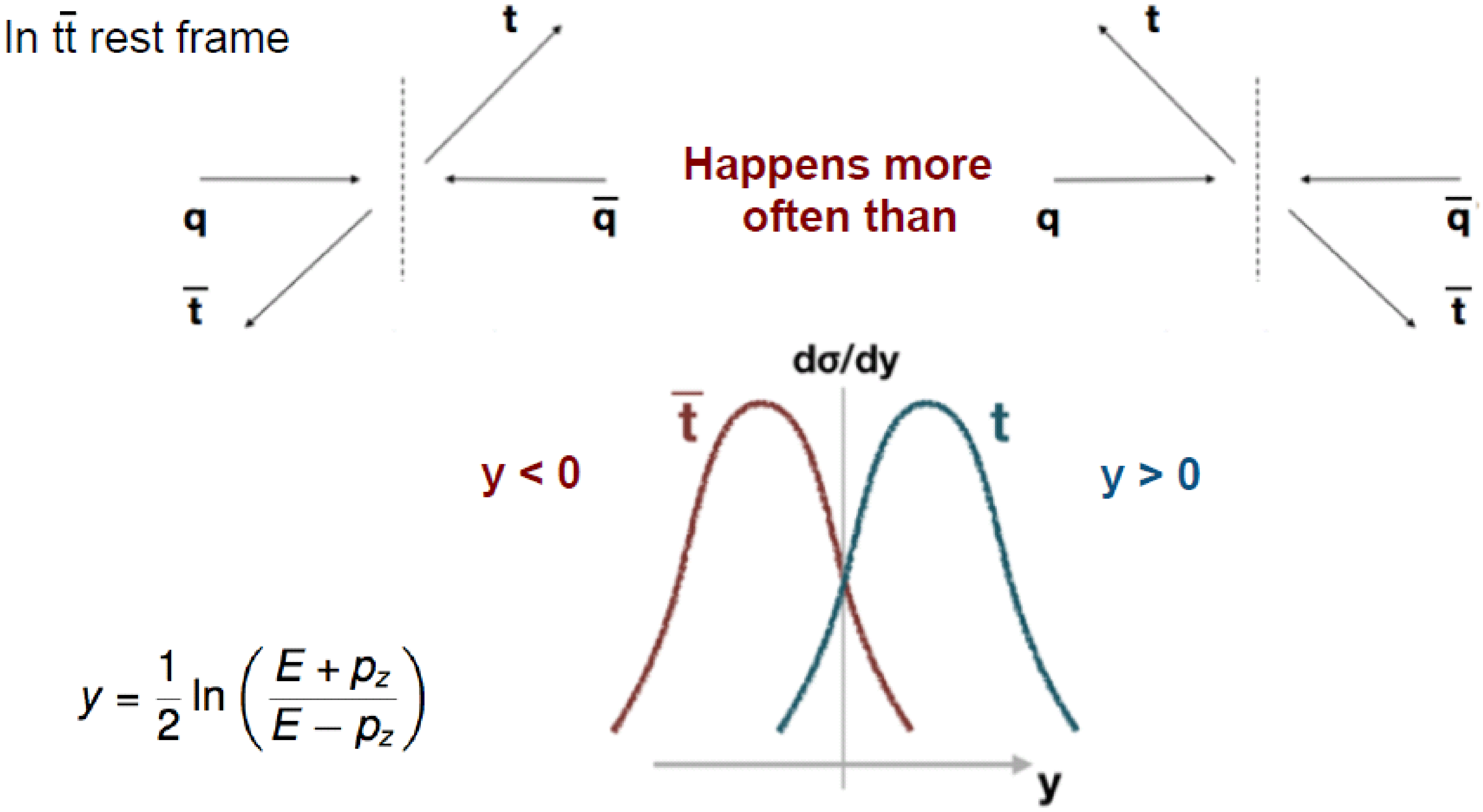
expect from EWK data :
$M_H = 90\ ^{+36}_{-27}$ GeV
$M_H < 152$ GeV @ 95 % CL



- Measured M_W, M_H, M_t consistent with SM
- constrain exotic models (i.e. SUSY) instead

Top Pair Asymmetry

- Similar idea as A_{FB} at LEP
- Gluon has pure vector coupling ⇒ nailvey no asymmetry expected (small interference in SM caused by interference effects)
- Some asymmetry seen at Tevatron
  ⇒ new axial-vector particle interfereng with SM graphs?



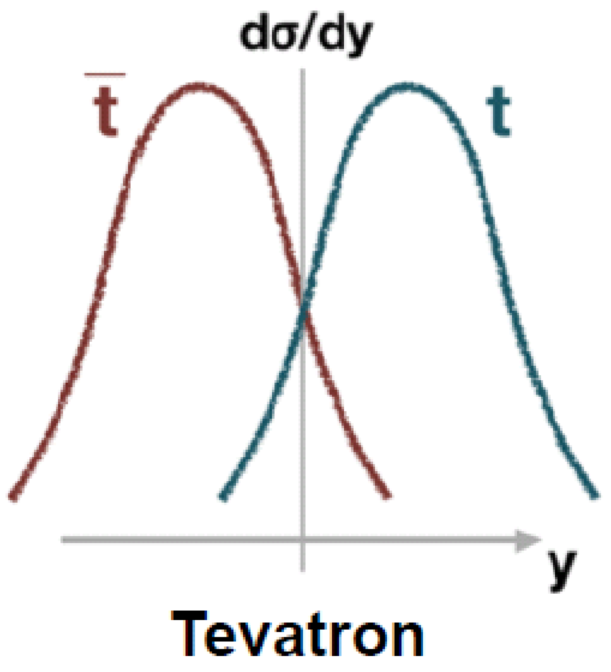
$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

Top Pair Asymmetry

- Tevatron: $p\bar{p}$ is CP eigenstate → pp (LHC) is not
  → different way to measure the effect at Tevatron and LHC
- LHC: Quarks valence quarks, antiquark always from the sea
  → antitop less boosted and more central than top in case of asymmetry
- LHC: Measure charge asymmetry

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

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

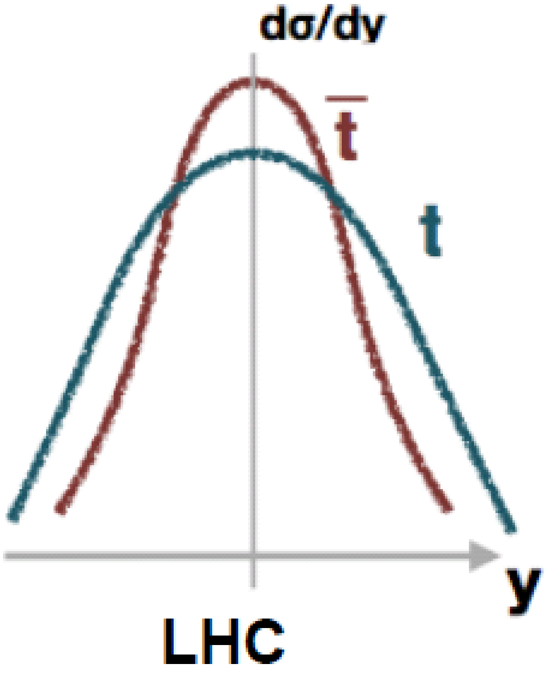


Tevatron

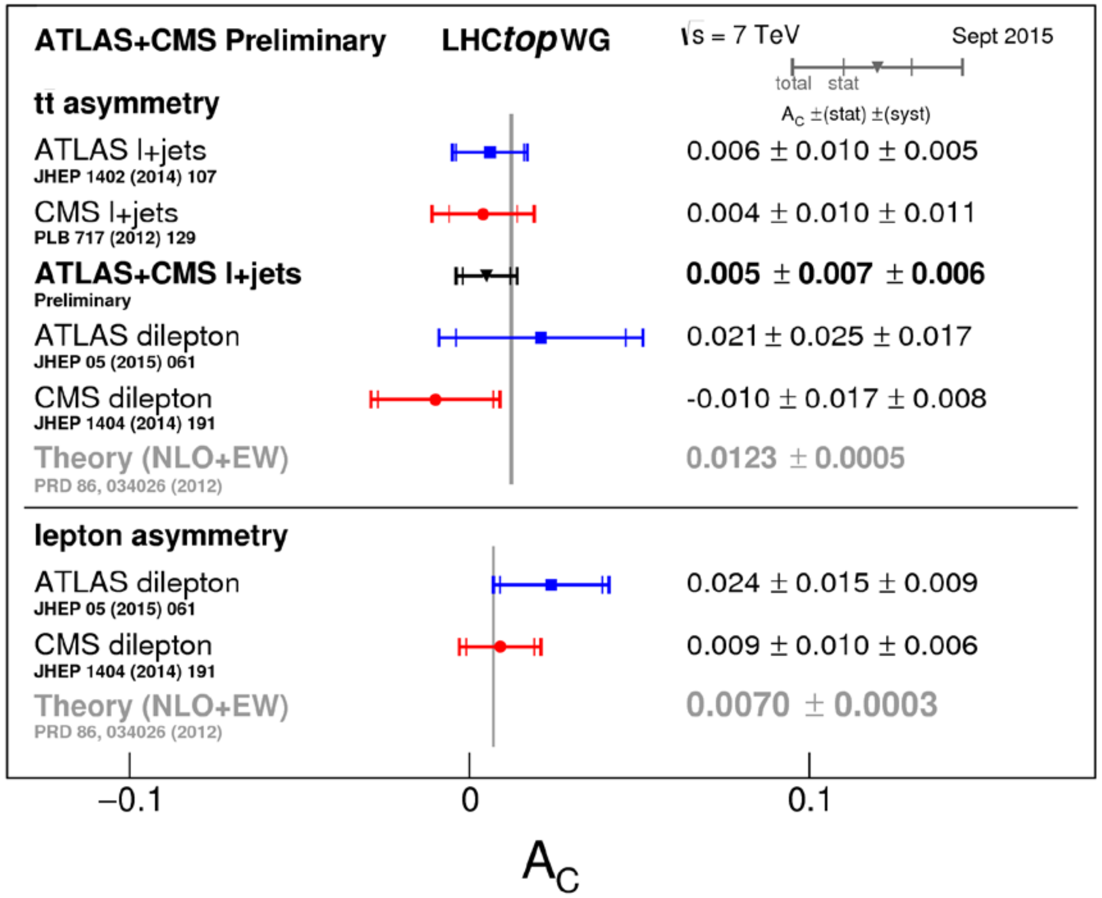
$\Delta y = y_t - y_{\bar{t}}$

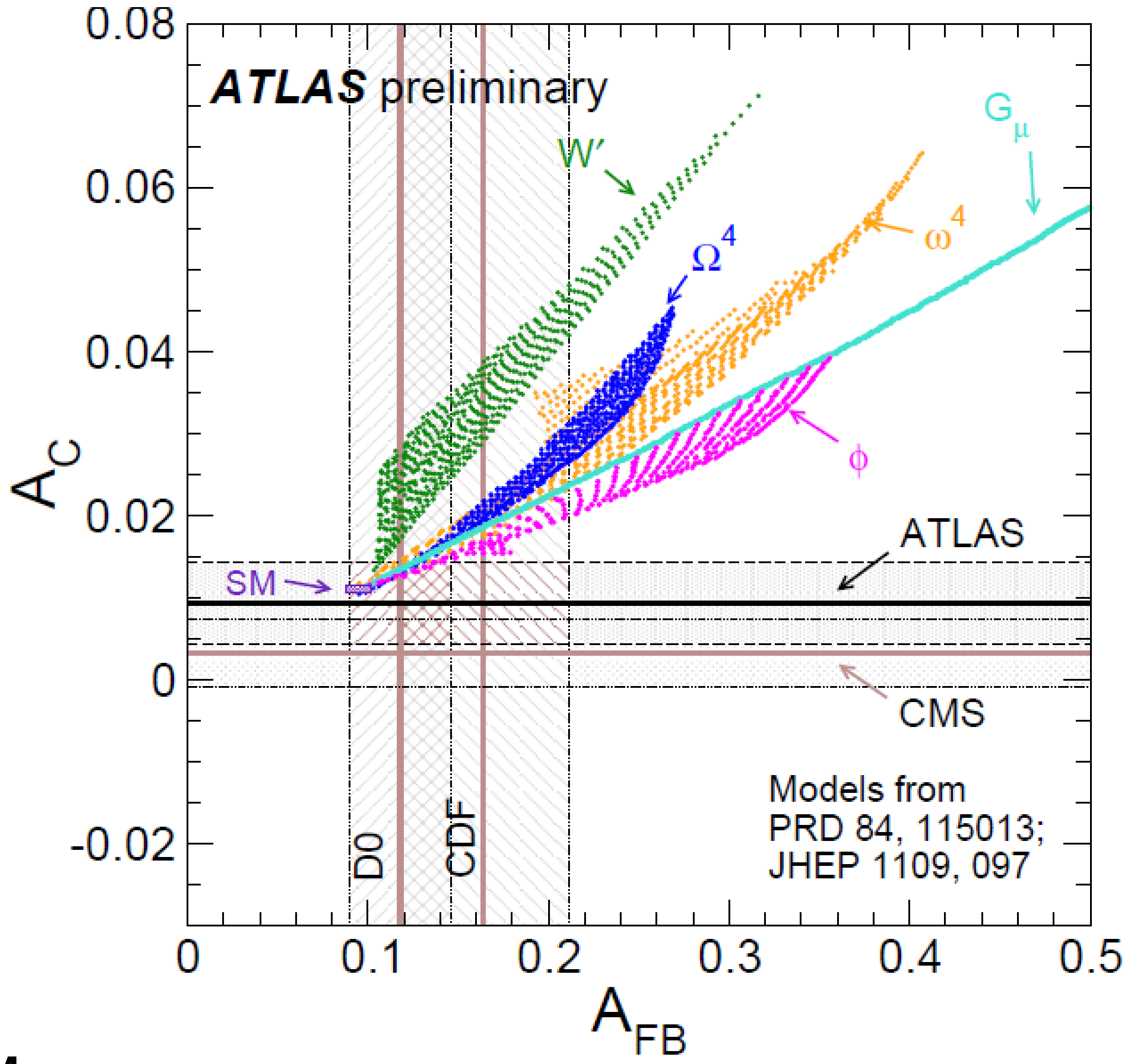
LHC

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



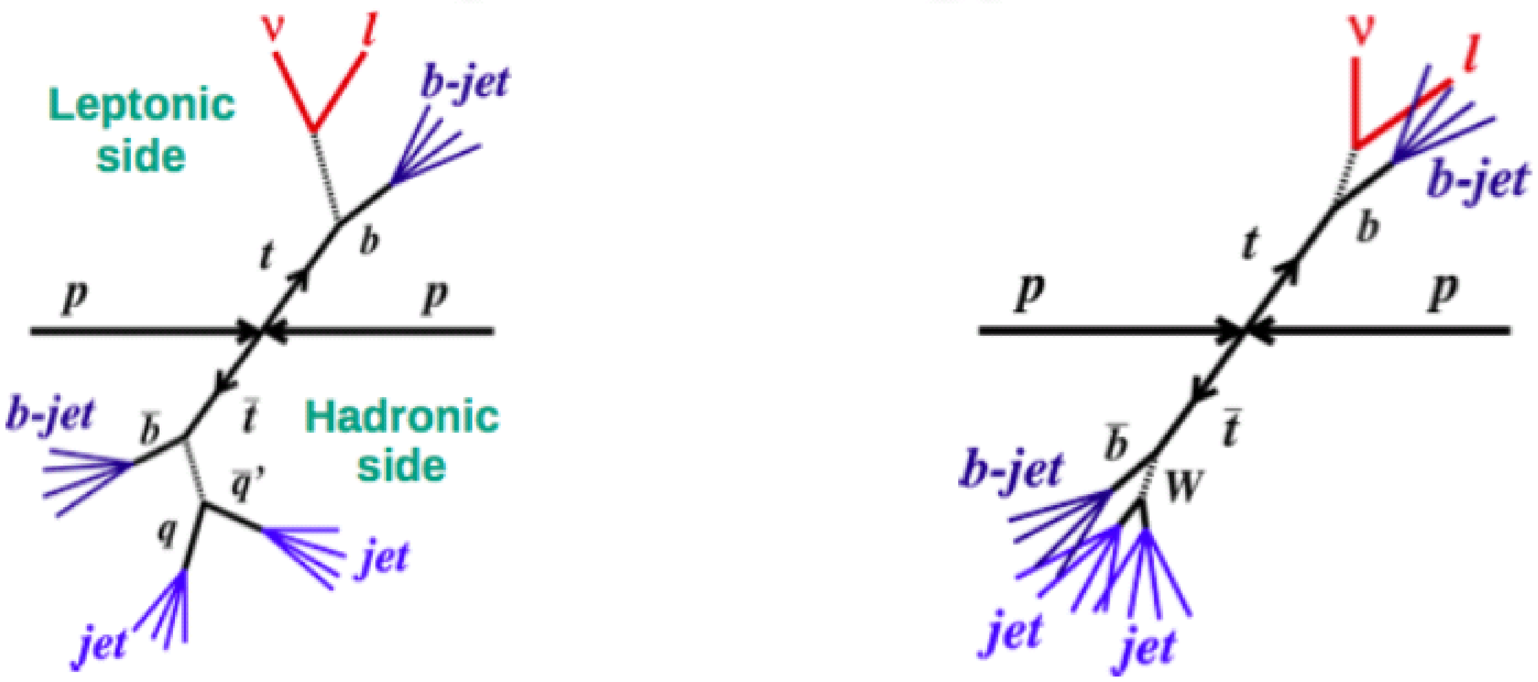
Top Pair Asymmetry



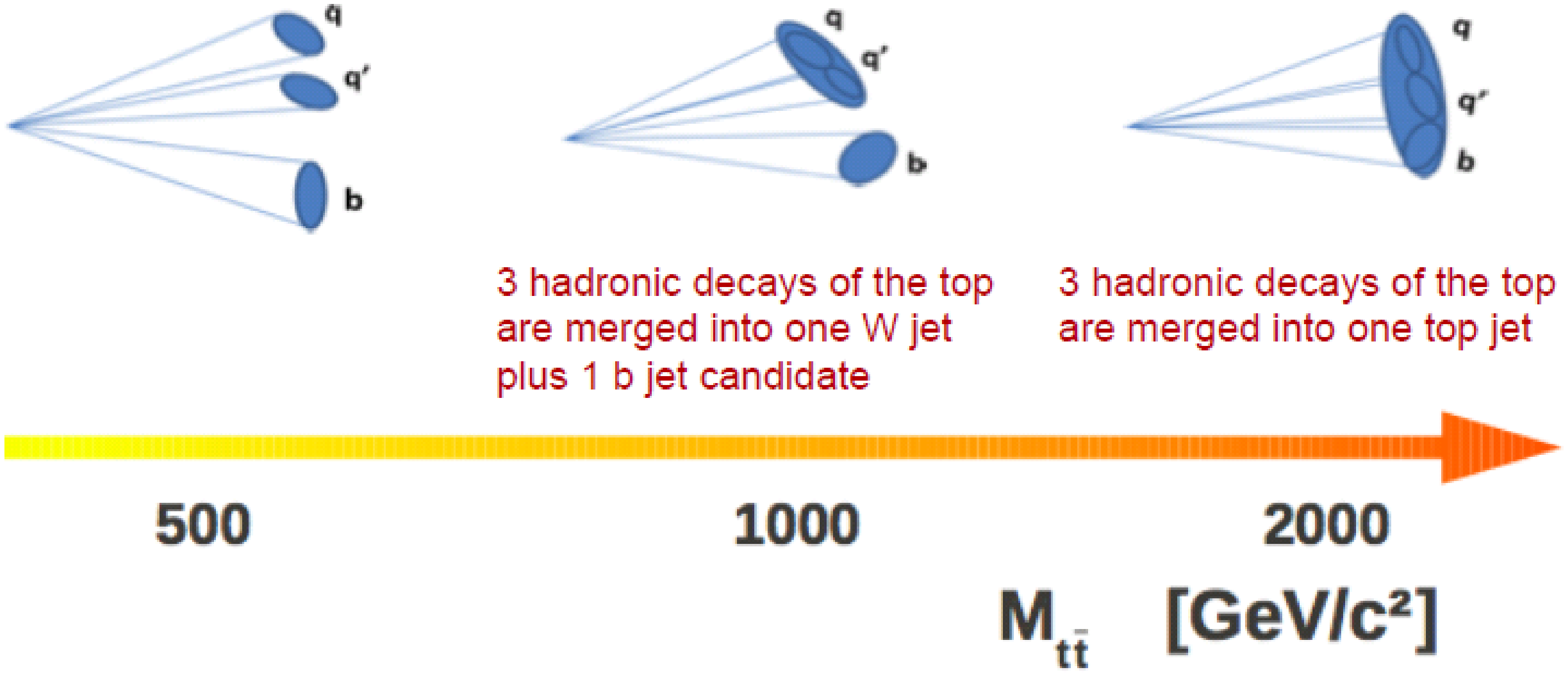


- LHC results compatible with SM
- improved theory calculations ⇒ getting closer to Tevatron

Top Quark Resonances



Hadronic side



3 hadronic decays of the top are merged into one W jet plus 1 b jet candidate

3 hadronic decays of the top are merged into one top jet

The larger the invariant top pair mass $M_{t\bar{t}}$, the more boosted the top quarks and the smaller the angles between the decay products

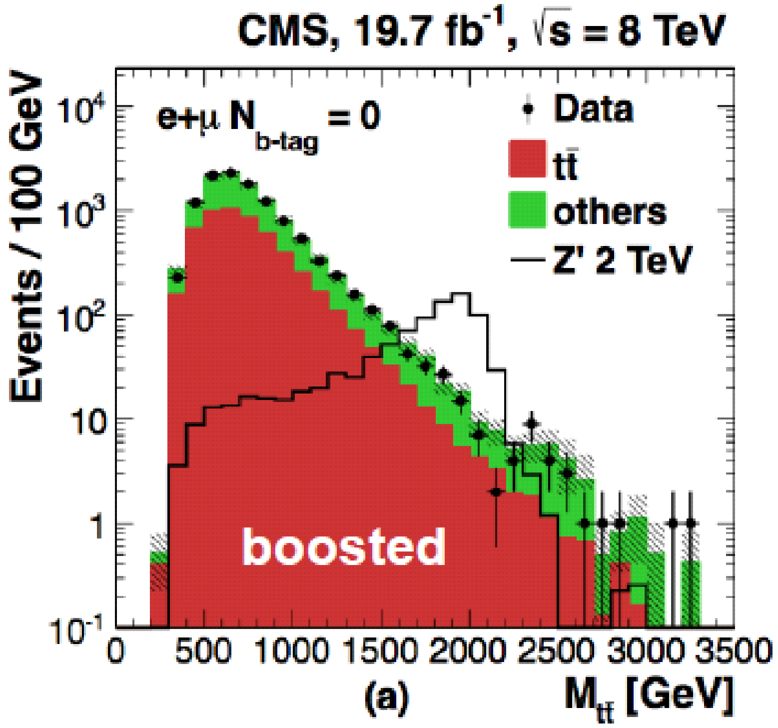
Leptonic side:

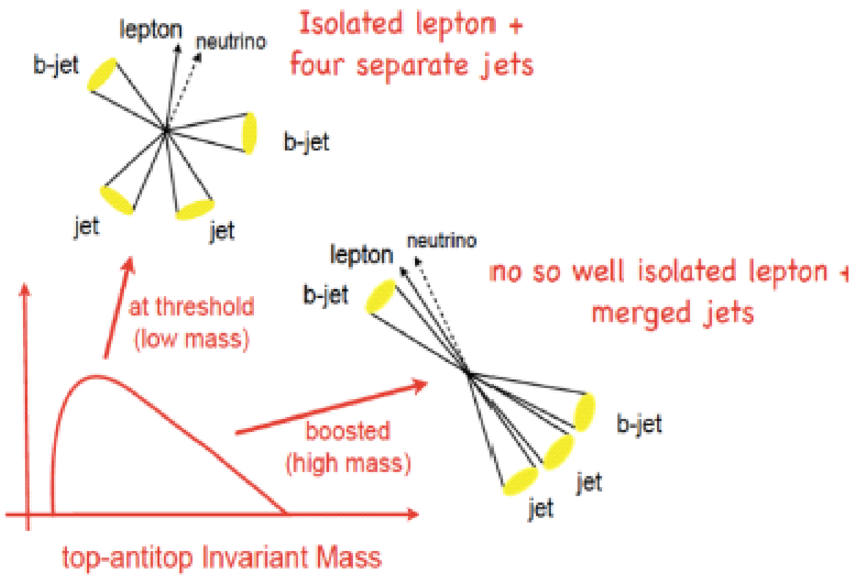
Lepton close to b-jet or in b-jet
(lepton not isolated)

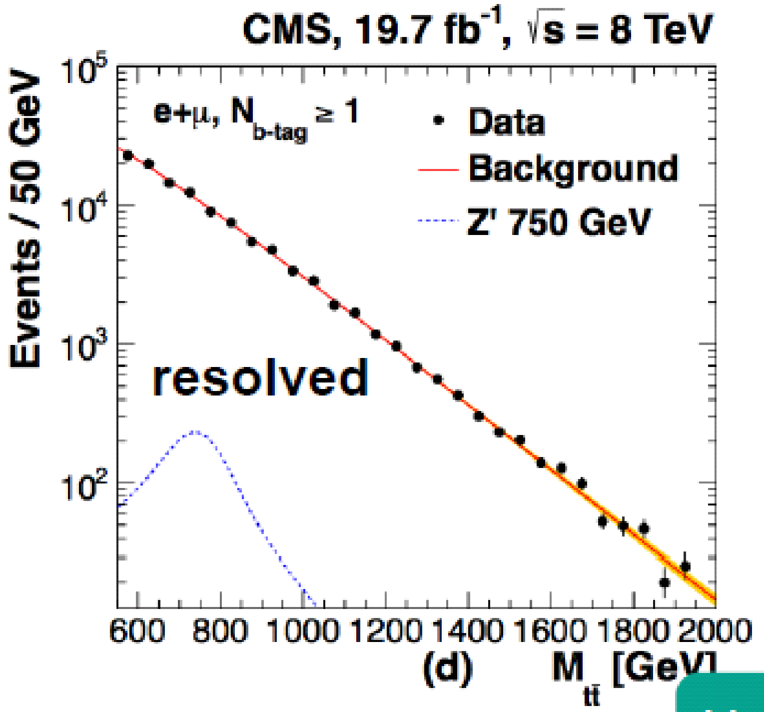
Hadronic side:

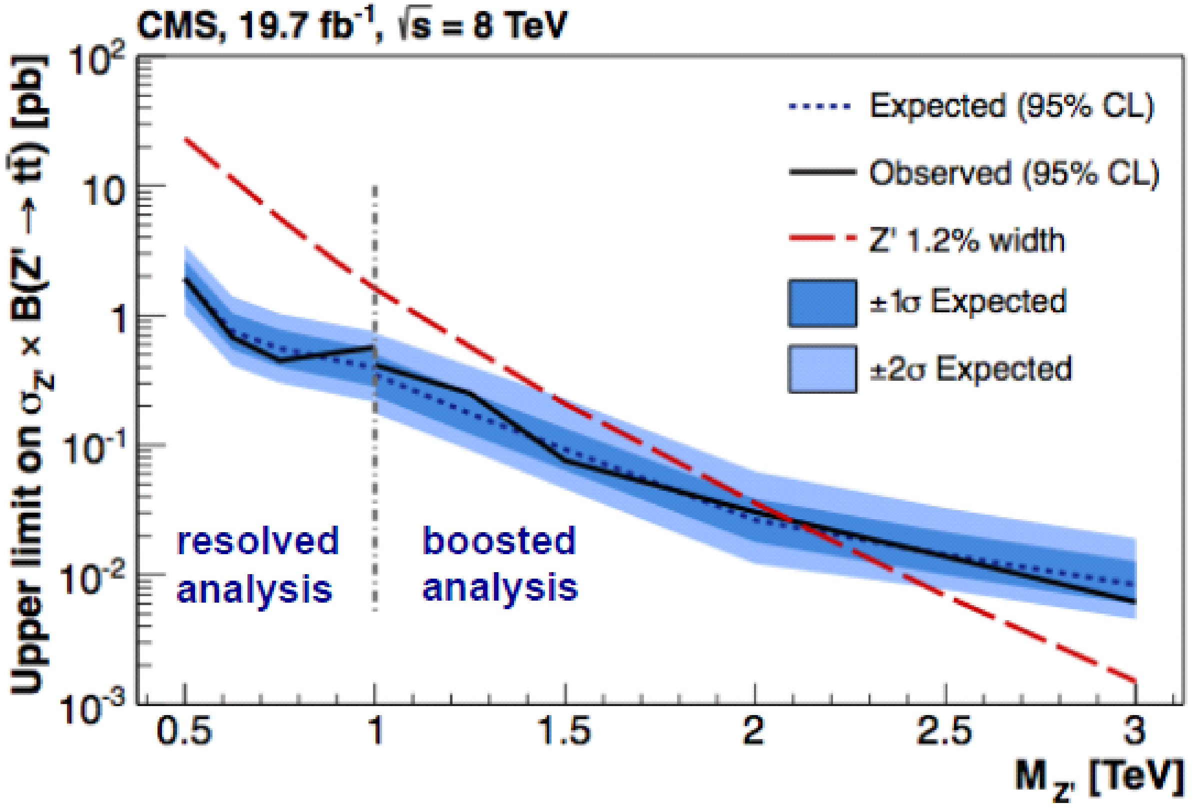
Jets overlap → reconstruction of 1 or 2 jets instead of 3
(jet with substructure)

Top Quark Resonances









PRL 111 (2013) 211804

Heavy resonances excluded up to 2.1 TeV (Z') and 2.5 TeV (KK gluon)

4th generation searches

- →Historically: look for 4th generation decay to tW?
- Out of fashion since 2012
  Higgs cross section too low for additional heavy quarks in loop induced processes
- Immediate switch to „vector-like-quarks“
  - → mass not generated by Higgs mechanism
  - → not constrained by Higgs cross section
  - → Can occur with exotic charges (e.g. 5/3)