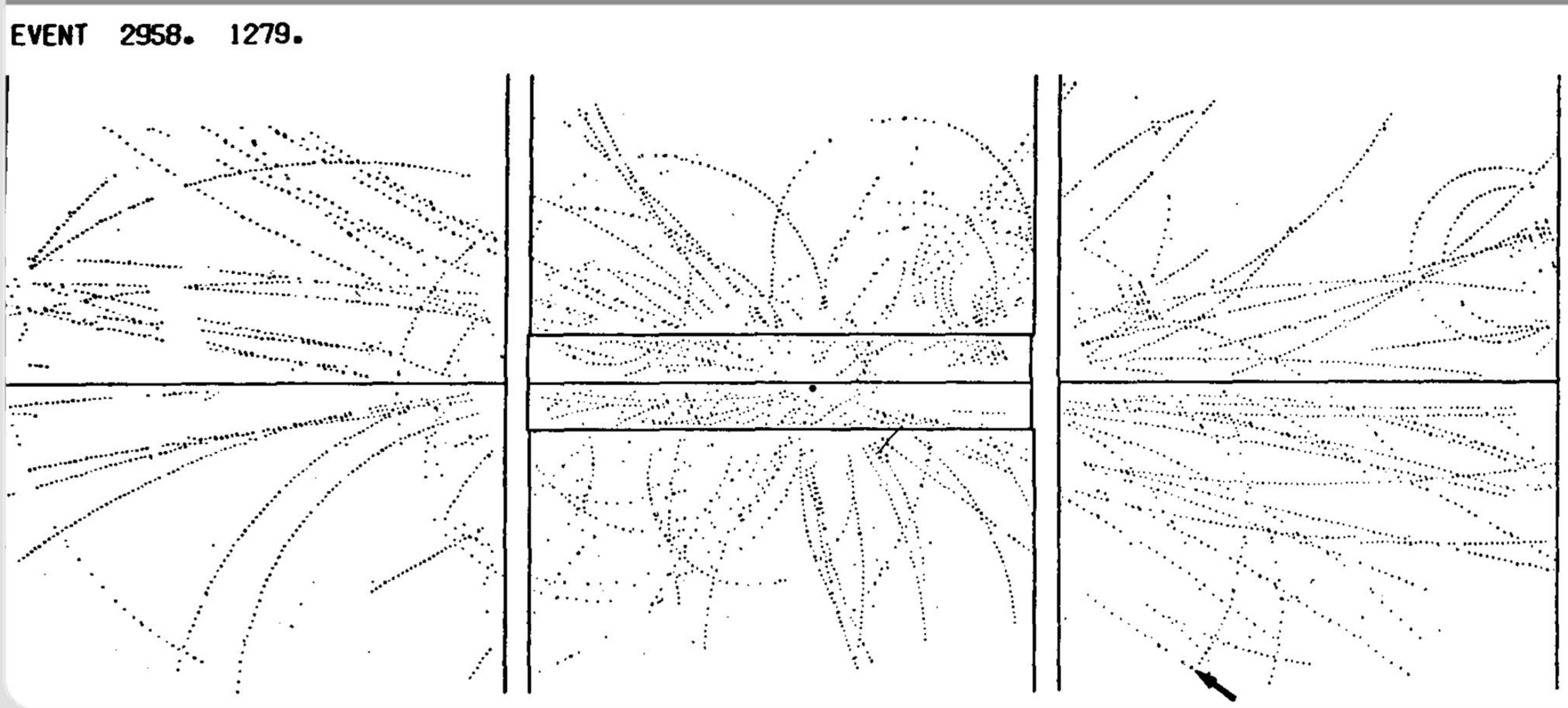
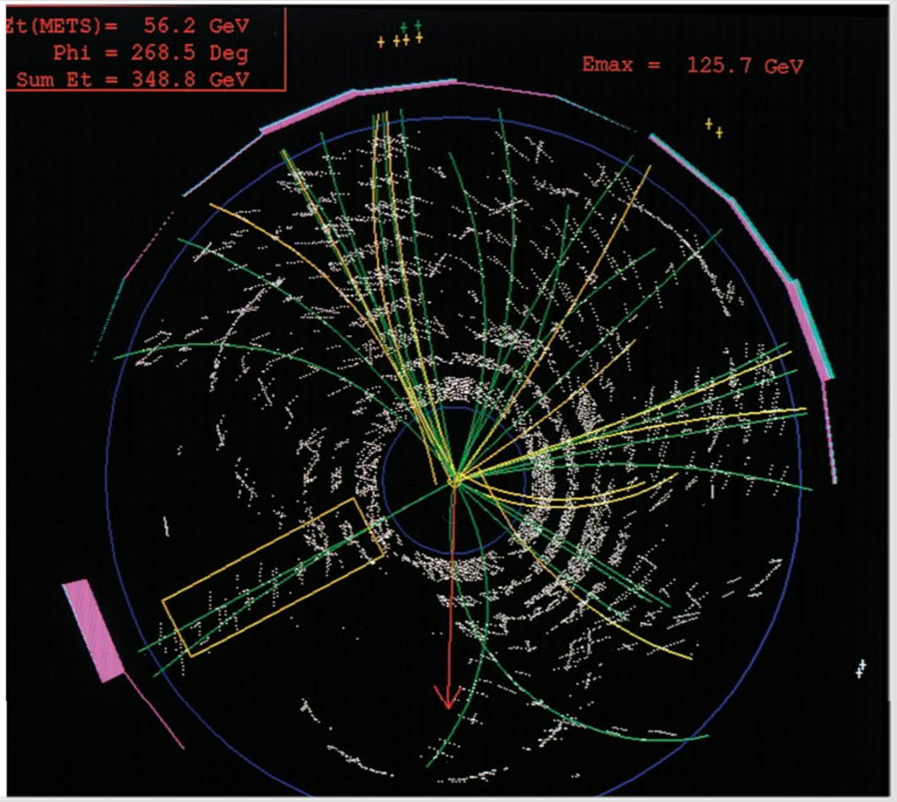
Karlsruher Institut für Technologie

KSETA-Course: Accelelerator-Based Particle Physics

Flavor- and Top physics

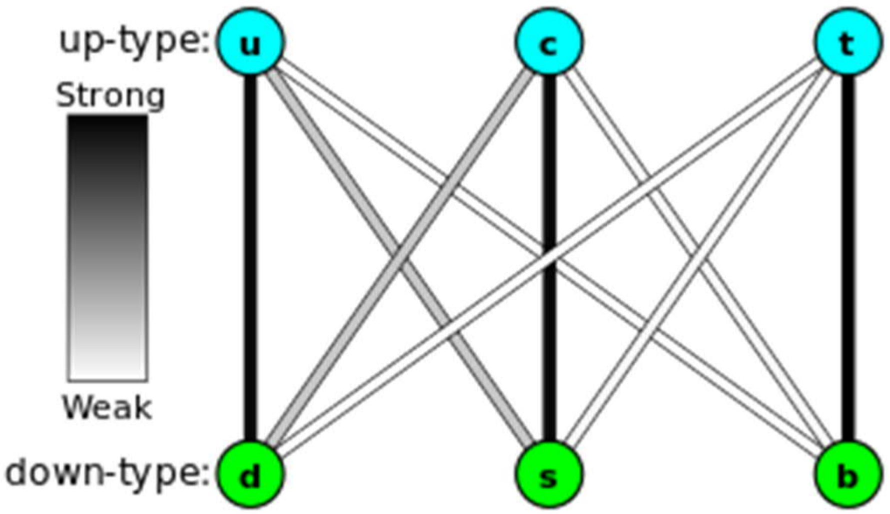
Matthias Mozer, Roger Wolf
Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie





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:

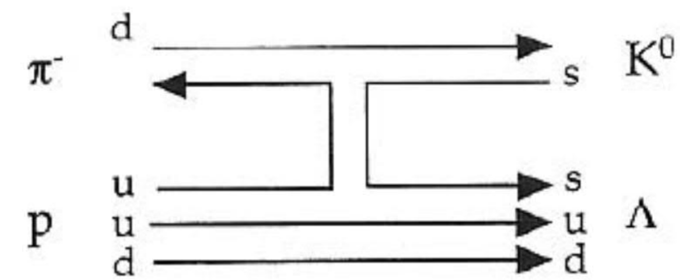
- Explain “strange particles” with new flavor quantum number ***strangeness (S)***
- strangeness conserved in strong and EM interaction changes in weak interaction

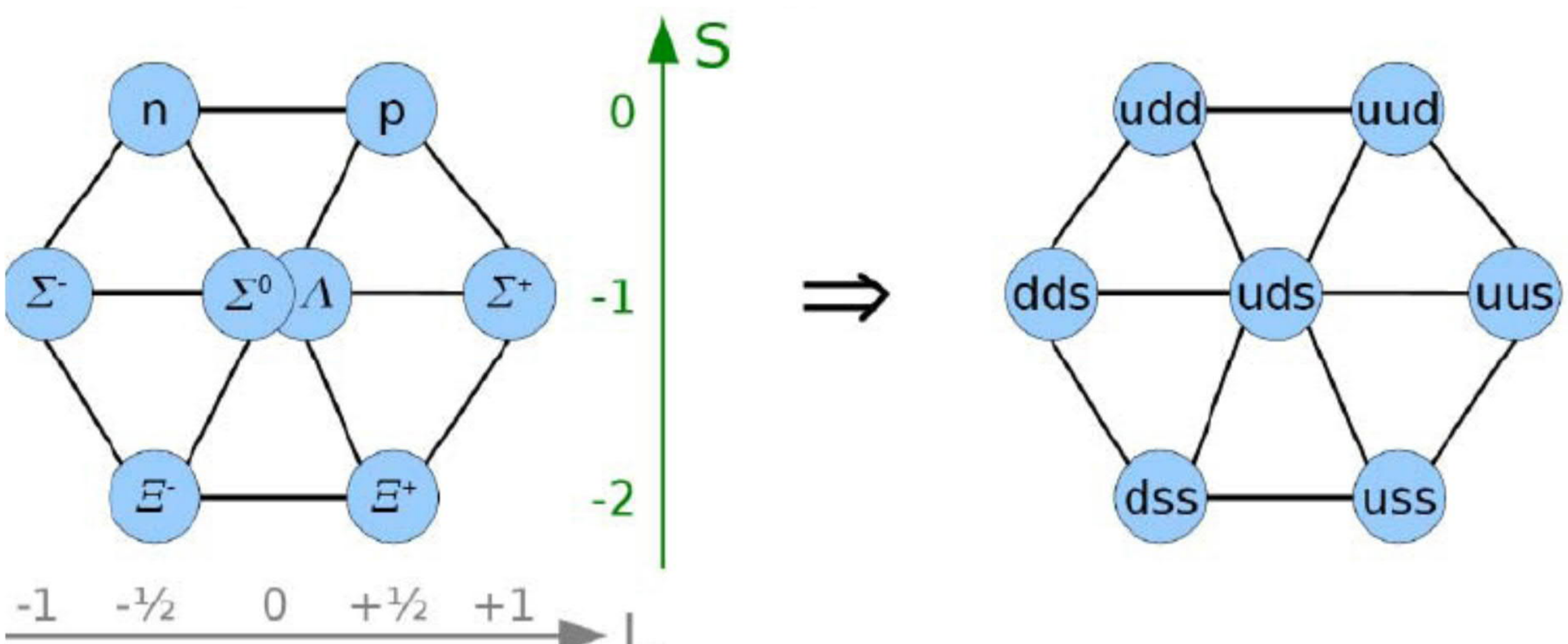
Murray Gell-Mann

Nobel price 1969

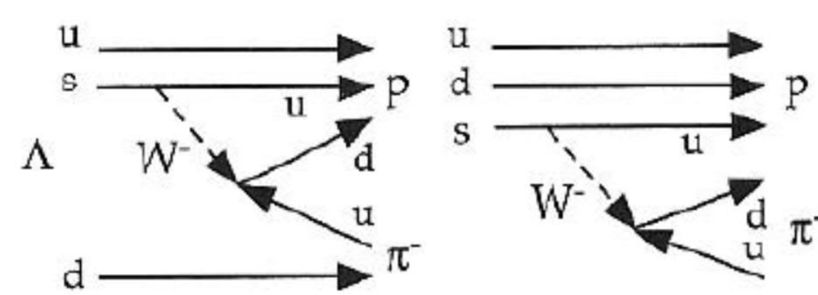
1964: Gell-Mann

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





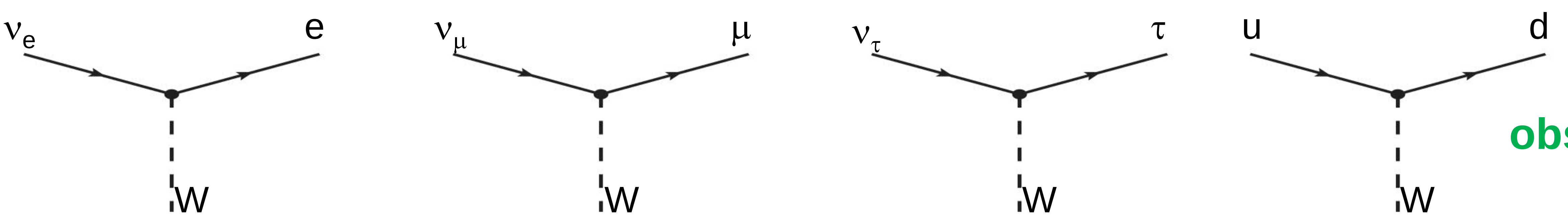
$$Q = I_3 + \frac{B+S}{2}$$



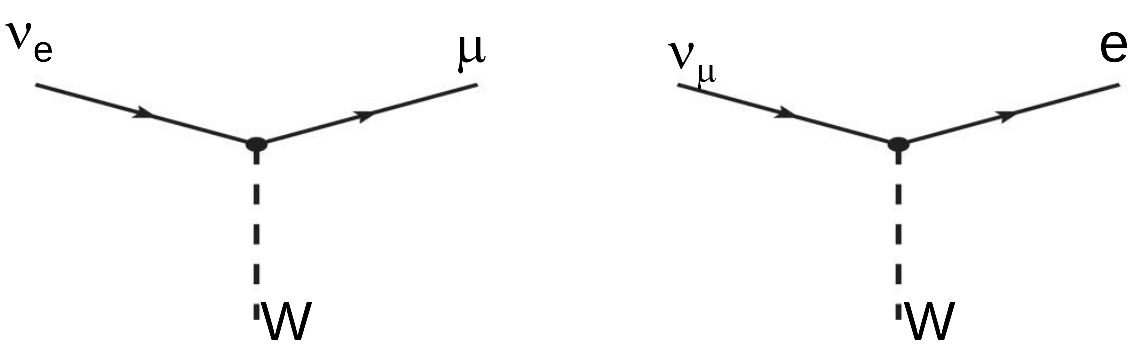
Weak interaction of quarks

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

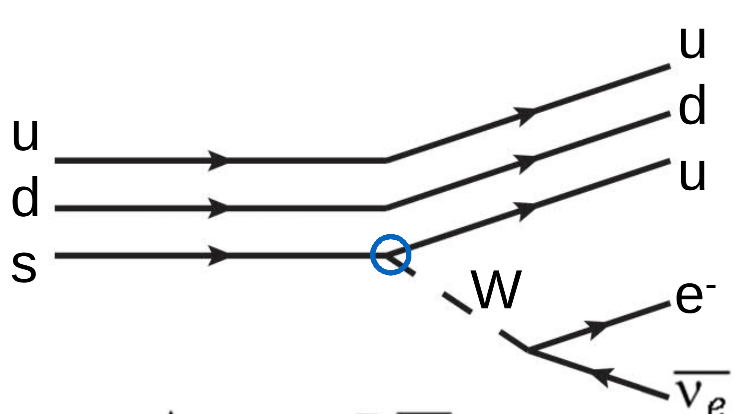
observations:



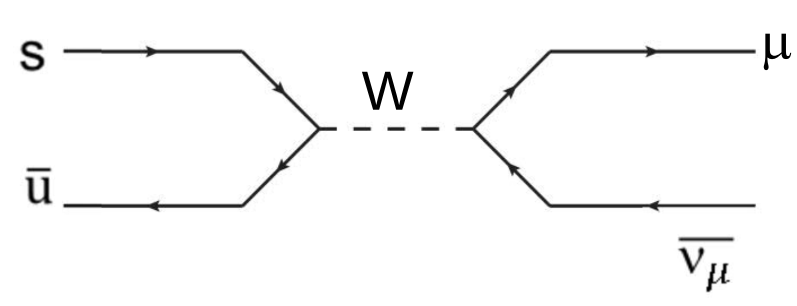
observed



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 $\rightarrow$ mass-eigenstates $\neq$ flavor-eigenstates

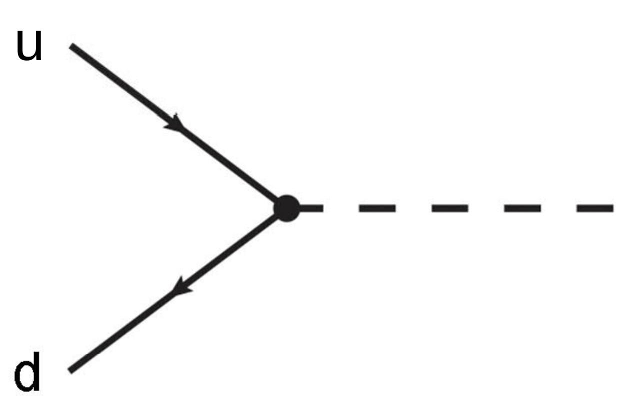
$$\begin{pmatrix} u \\ d' \end{pmatrix} = \begin{pmatrix} u \\ d \cdot \cos\vartheta_C + s \cdot \sin\vartheta_C \end{pmatrix}$$

weak isospin doublet

convention

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

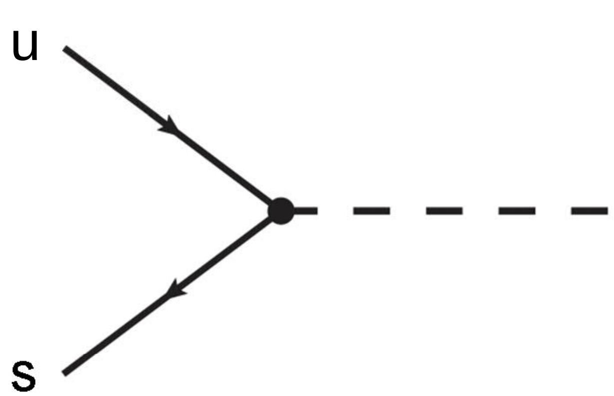
$\Rightarrow$



$\propto \frac{g}{\sqrt{2}} \cos\vartheta_C$

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

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



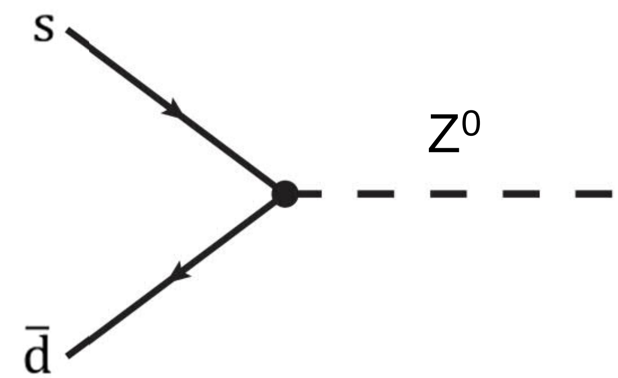
$\propto \frac{g}{\sqrt{2}} \sin\vartheta_C$

ϑ_C : Cabibbo-angle

$\vartheta_C = 12.9°$

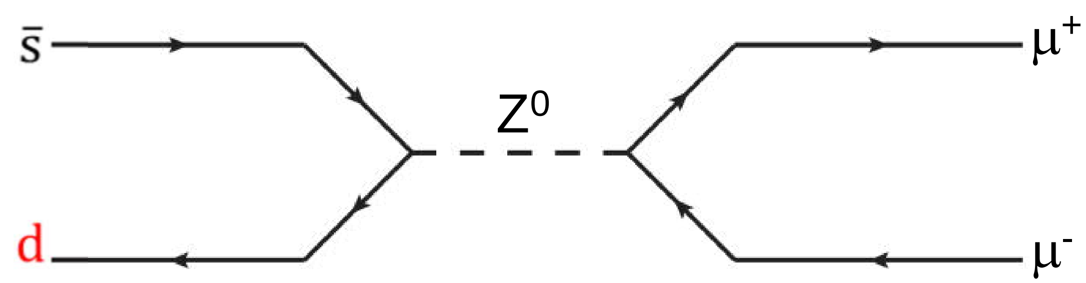
GIM Mechanism

Expected transitions:



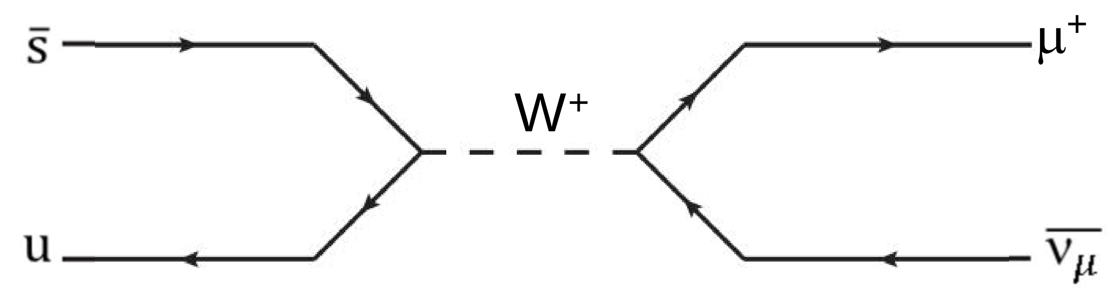
flavor-changing neutral currents (FCNC)

i.e. decays like:



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

analogous to observed decays:



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

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

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

proposal by GIM (1970): additional weak doublet

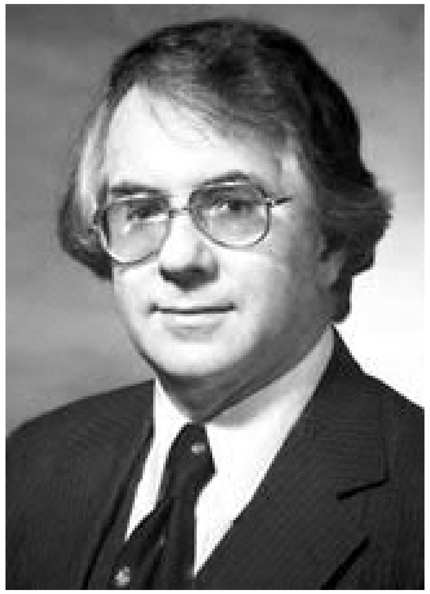
(Glashow, Illiopoulos, Maiani)

=> c-quark prediction (observed 1970)

$$\binom{c}{s'} = \binom{c}{s\cdot\cos\vartheta_C - d\cdot\sin\vartheta_C}$$

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

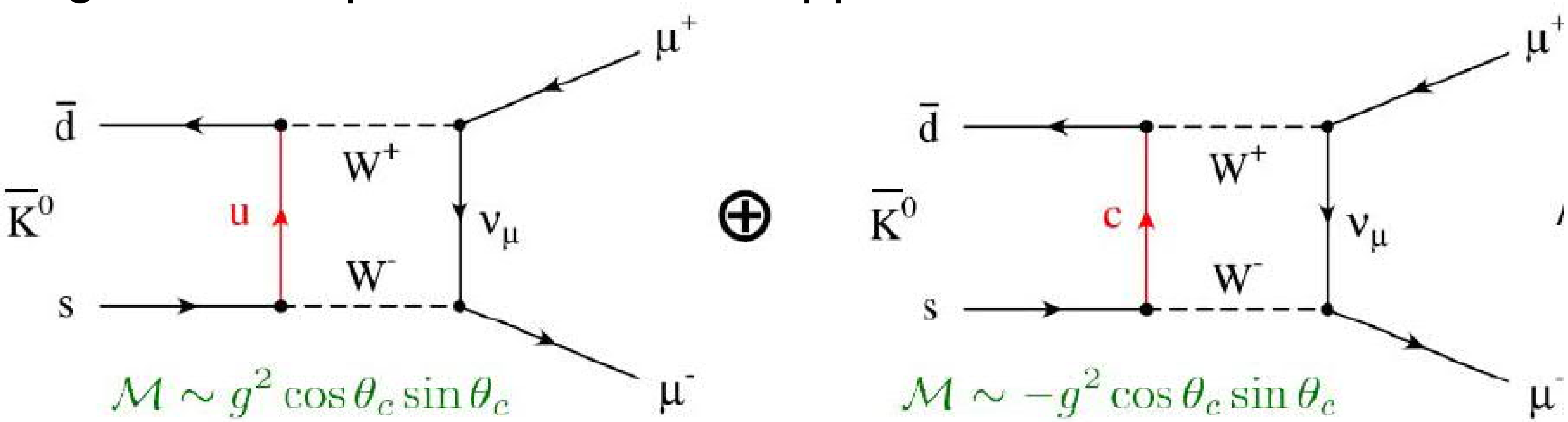
Interference cancels mixed terms (d→s) in the Lagrangian.
Only flavor-conserving neutral currents remain:

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

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)

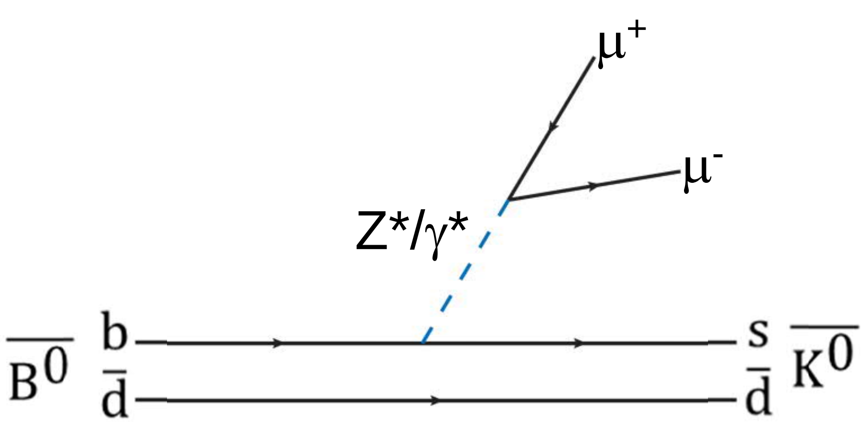
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = M_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

M_{CKM}:
unitary 3x3
matrix

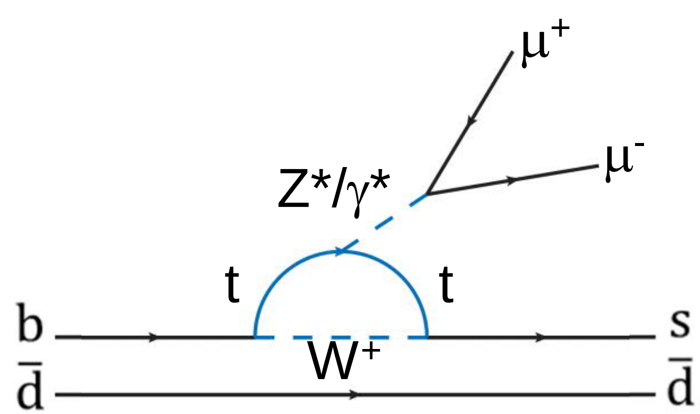
$$M_{CKM} = \begin{pmatrix} \boxed{c_1} \ {\color{red}\approx 1} & c_3 s_1 & s_1 s_3 \\ -c_2 s_1 & \boxed{c_1 c_2 c_3 - s_2 s_3 e^{i\delta}} \ {\color{red}\approx 1} & c_1 c_2 s_3 + c_3 s_3 e^{i\delta} \\ -s_1 s_2 & c_1 c_3 s_2 + c_2 s_3 e^{i\delta} & \boxed{c_1 s_2 s_3 - c_2 c_3 e^{i\delta}} \ {\color{red}\approx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

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

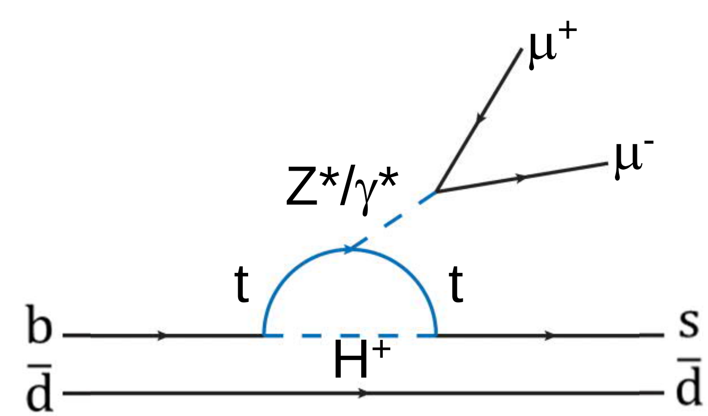
Test the SM: search for FCNC
example: $B^0 \rightarrow \mu^+\mu^- K^0$ (SM: BR = $5{\cdot}10^{-7}$), $B^0 \rightarrow \mu^+\mu^- K^{0*}$ (SM: BR = $5{\cdot}10^{-6}$)



Not allowed in SM
(FCNC)



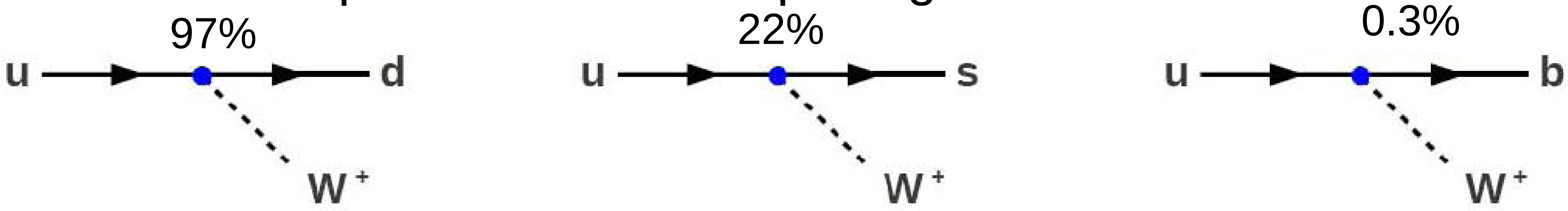
allowed in SM
("penguin")



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~~)

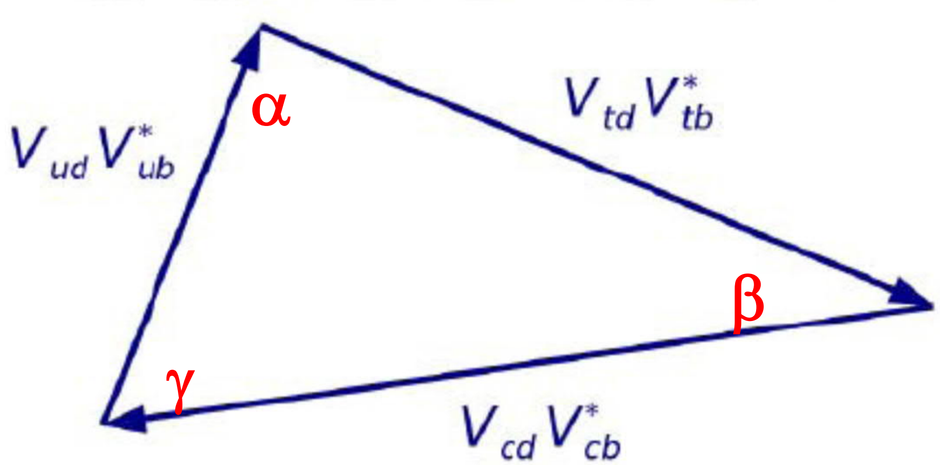
Unitarity Triangle

- N>4 observables for 4 paramters
  $\Rightarrow$ overconstrained system
  $\Rightarrow$ test the SM

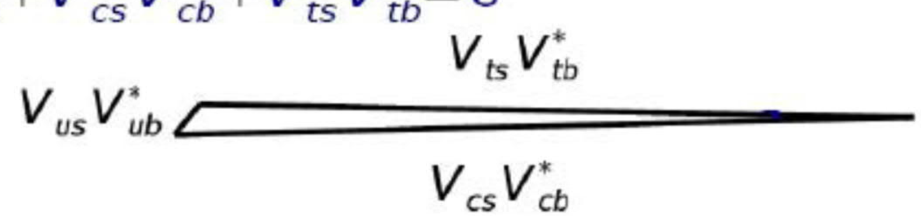
- Graphical representation in „unitarity triangle“
  $\Rightarrow$ unitaritiy condition $\sum_i V_{ij} V_{jk}^* = \delta_{jk}$

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

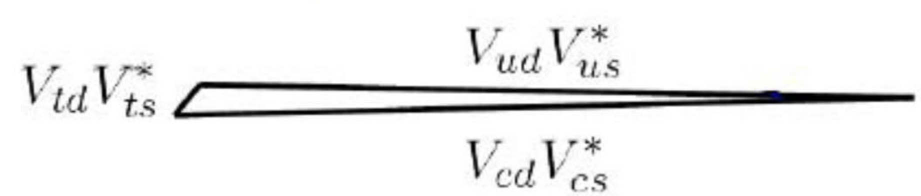
$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$



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

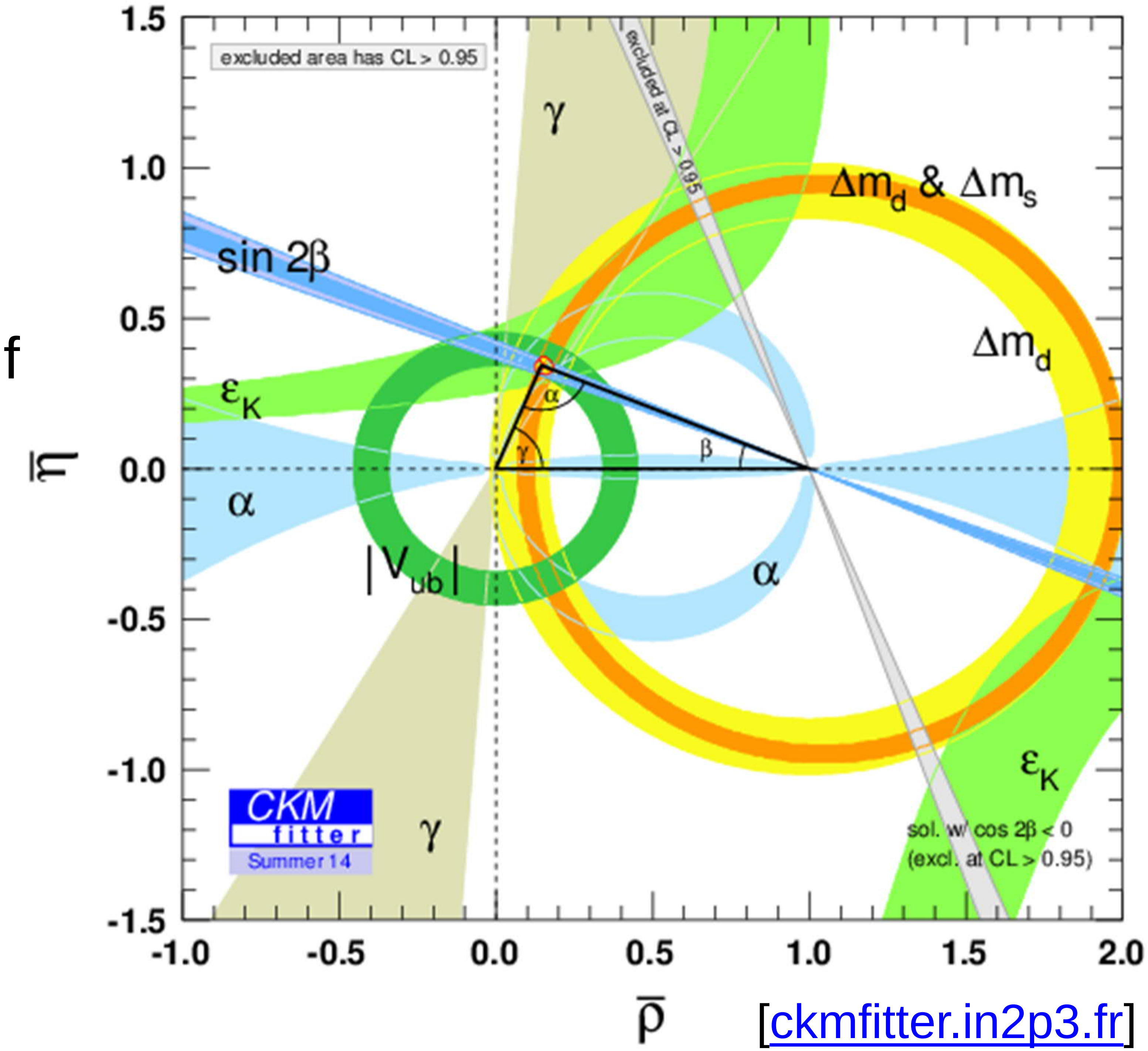


$$V_{ud} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* = 0$$



Unitarity Triangle

- 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
  $\rightarrow$ eigenstates of the strong interaction

- Not necessarily eigenstates of the weak interaction

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

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

widely studied particle-anti-particle systems with oscillations

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

Time Evolution

Calculation equivalent to neutrino-oszillations

Difference: Mesons are unstable, additional oszillations caused by difference in decay width

transition probabilities:

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

decay

oscillation from width difference

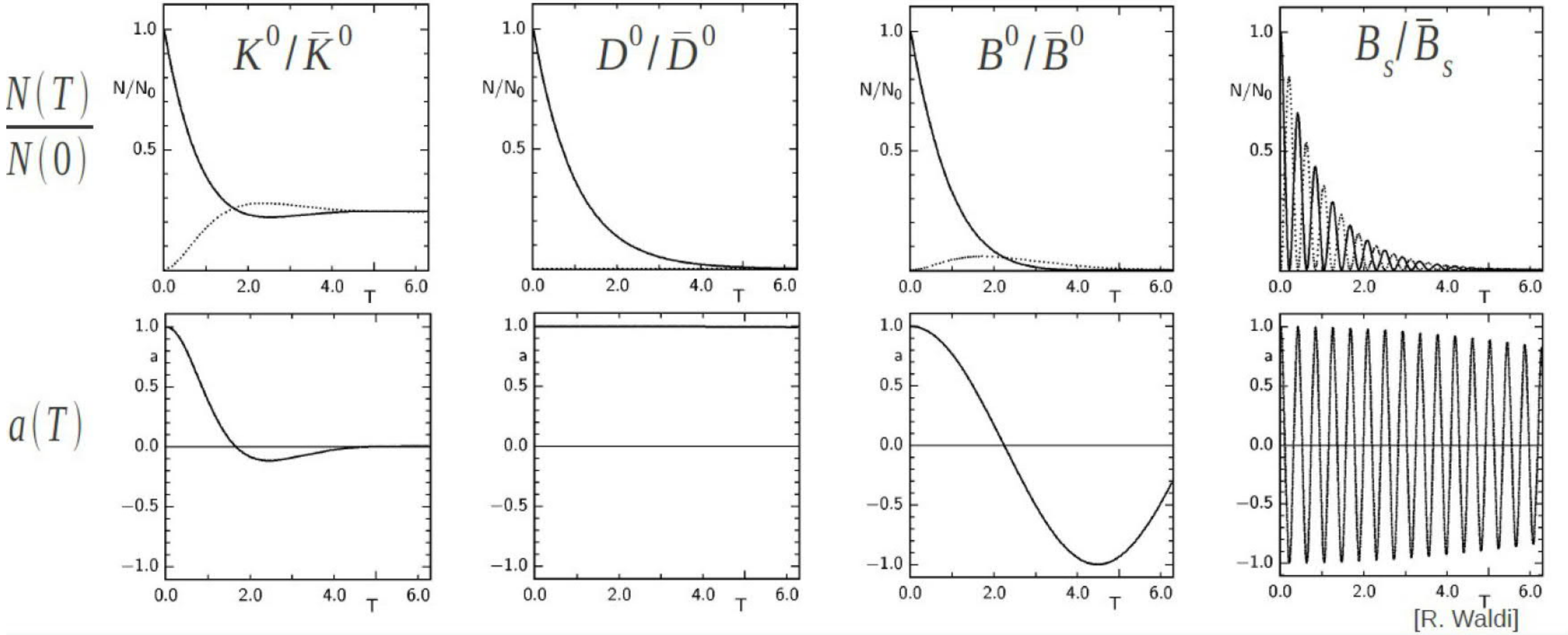
oscillation from mass difference

Different Oscillating Systems

Mass difference and decay widths

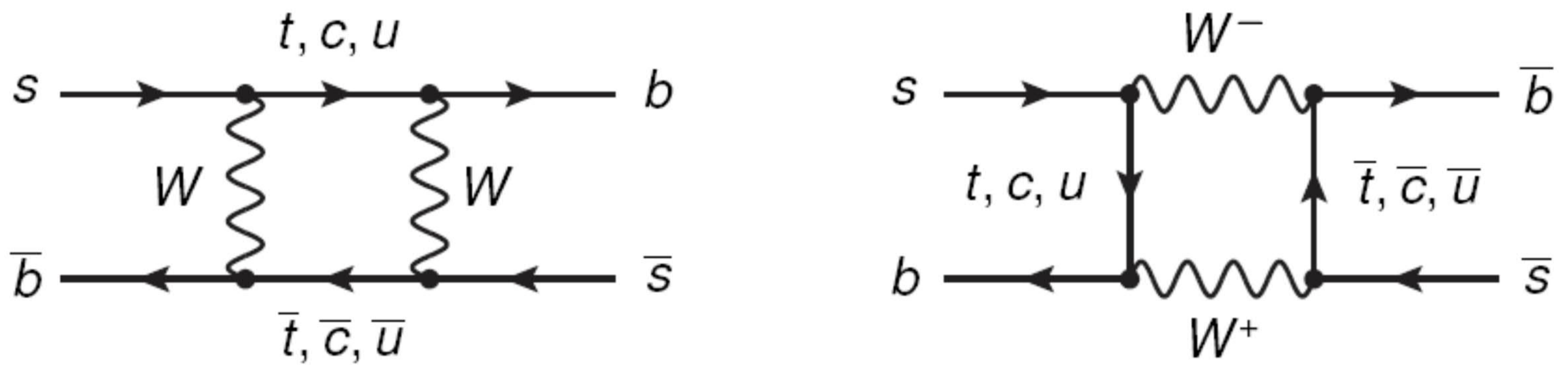
	$K^0/\bar{K}^0$	$D^0/\bar{D}^0$	$B^0/\bar{B}^0$	$B_s/\bar{B}_s$
τ [ps]*	89 51700	0.4	1.6	1.5
Γ [ps^{-1}]	5.6×10^{-3}	2.4	0.64	0.62
y=$\frac{\Delta\Gamma}{2\Gamma}$	-0.997	0.01	|y|<0.01	0.03±0.03
Δm [ps^{-1}]	5.3×10^{-3}	0.02	0.5	17.8
x=$\frac{\Delta m}{\Gamma}$	0.95	0.01	0.8	26

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



Learning from Oscillations

Compute mass differences from box diagrams

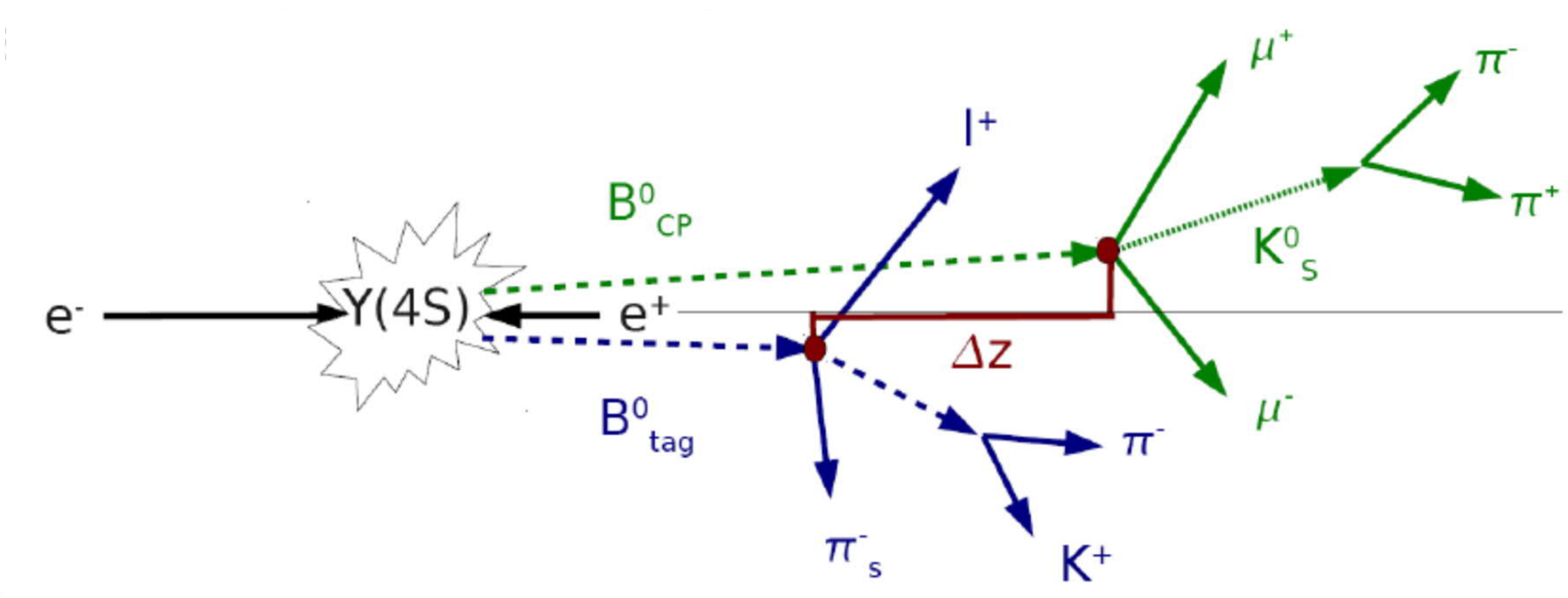


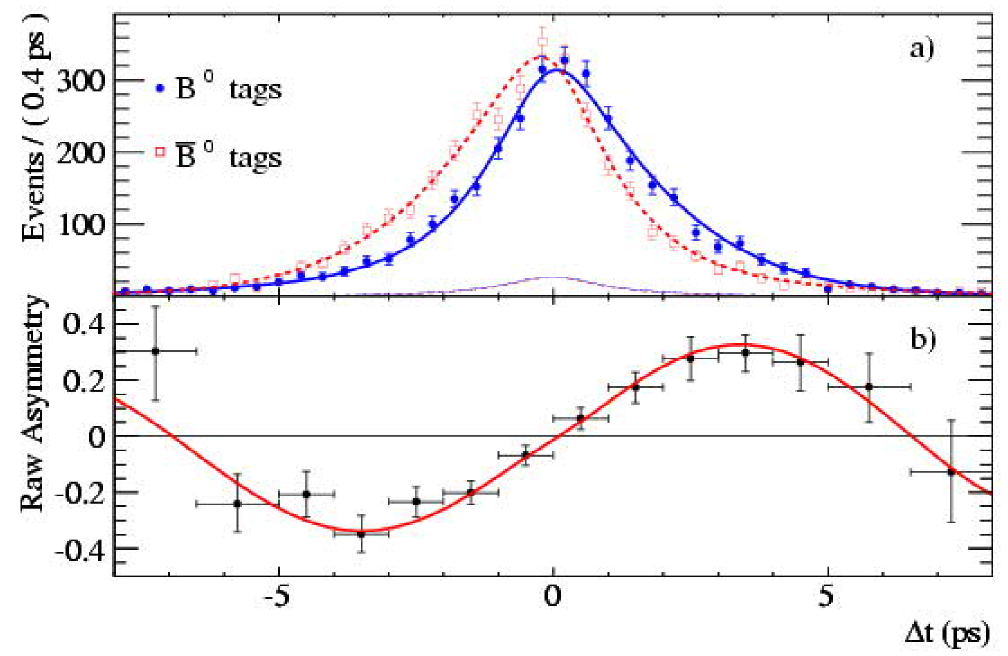
- approximations: m_t only relevant quark mass, $V_{tb} \approx 1$
- Result: $\Delta m_{d,s} \approx 2|M_{12}| \sim G_F^2 m_W^2 S\left(\frac{m_t^2}{m_W^2}\right)\left(V_{td,ts}^* V_{tb}\right)^2$
- Measurement of $|V_{td}|$ and $|V_{ts}|$ from oscillation frequency
- First results in B_d at ARGUS (DESY)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

Oscillations Measurements

B-factories: electron positron colliders with asymmetric beam energy

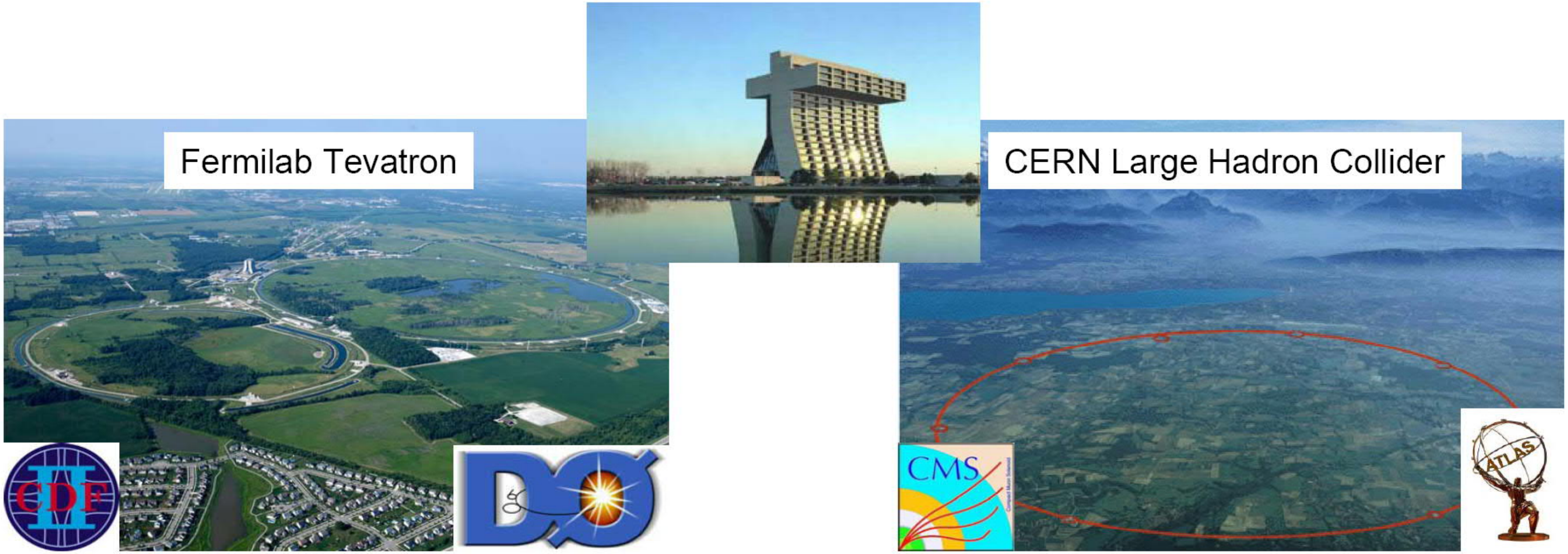
- tuned to Υ(4S) resonance: $B\bar{B}$ pairs ~ at rest in e⁺e⁻ system
- $B\bar{B}$ system moving relative to laboratory frame
  → better measurement of decay length
- $B\bar{B}$ system is an entangled quantum system
  → first decay as B or $\bar{B}$ determines second decay
- Measure flavor as function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





Where to find top quarks

Karlsruher Institut für Technologie



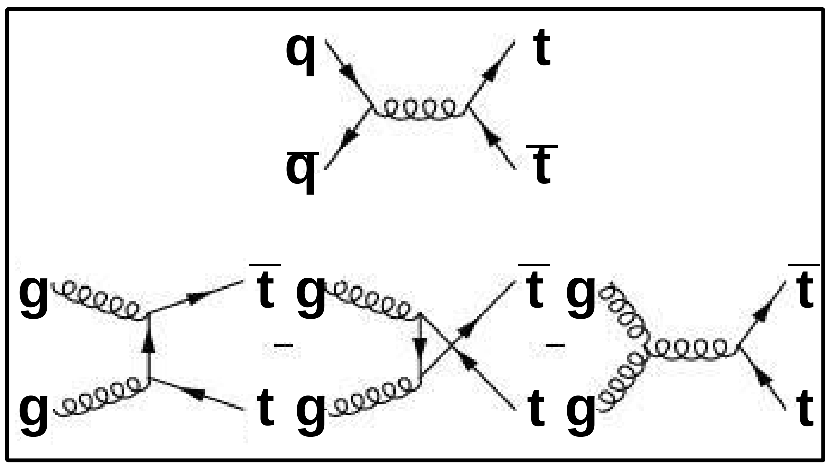
Tevatron:

- 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:

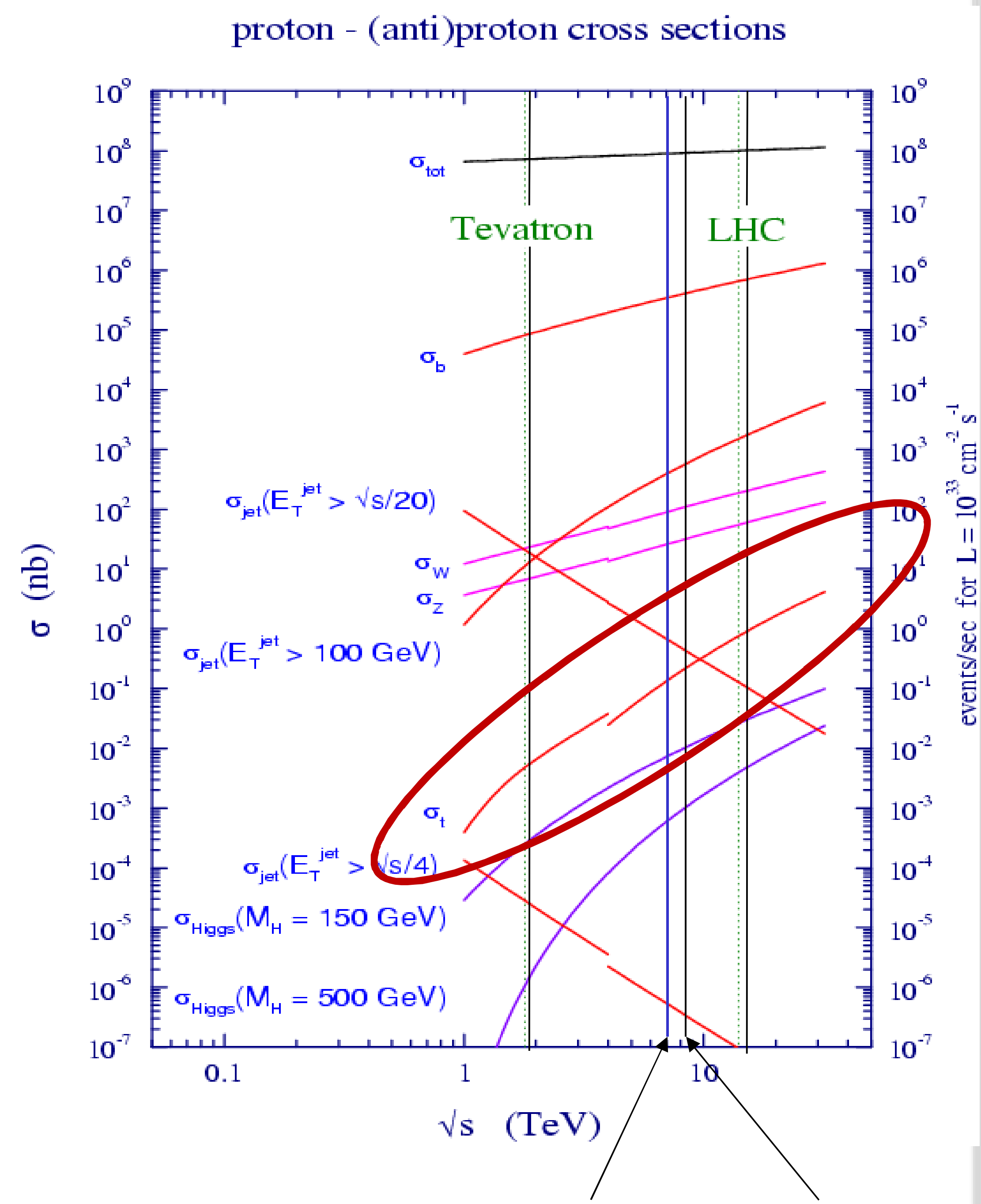
- $\sqrt{s}$ = 7 TeV (2010-2011)
  5 fb^{-1}: 1M top pairs produced ~60k reco
  re-establish top quark
- $\sqrt{s}$=8 TeV(2012)
  20 fb^{-1} precision top physics
  statistical uncertainties become irrelevant
- $\sqrt{s}$=13 TeV(2015-…)
  >20 fb^{-1}more precision studies
  very rare processes

Producing top quarks



← ~15%

← ~85%



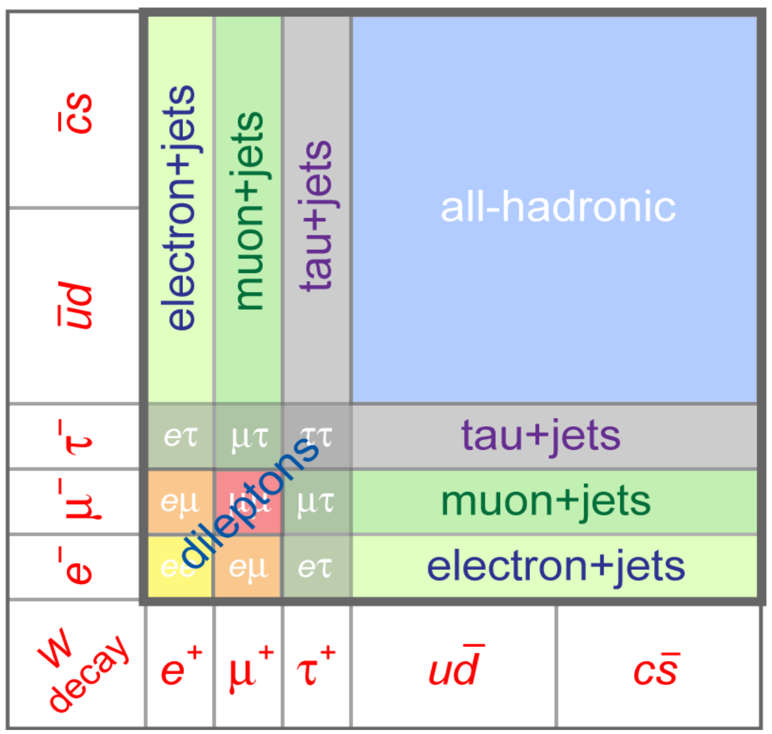
7 TeV 8 TeV

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

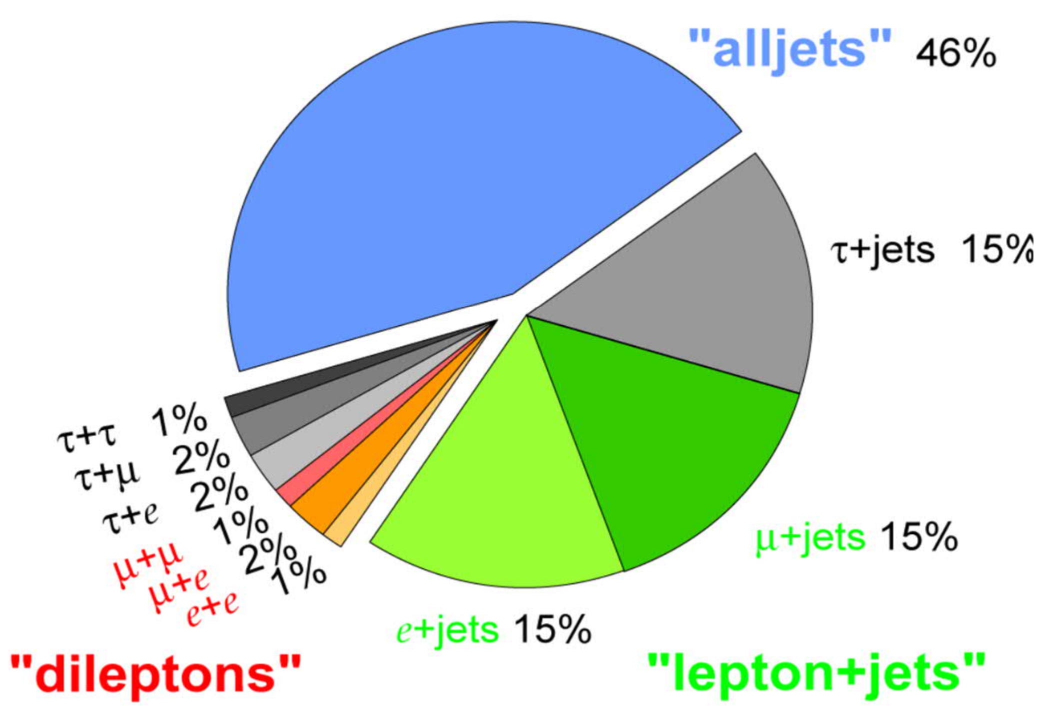
Top quark decays

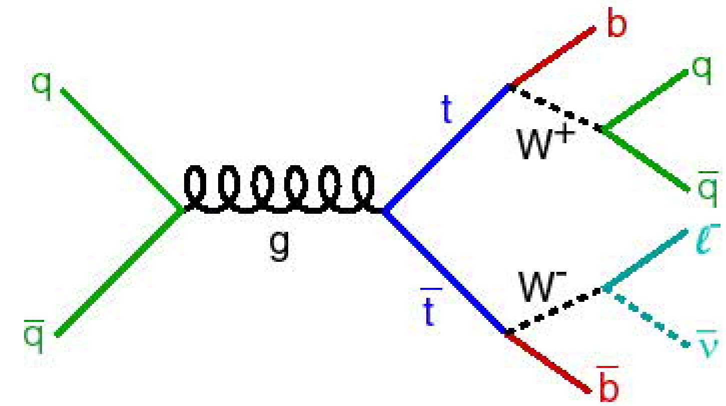
Karlsruher Institut für Technologie

Top Pair Decay Channels



Top Pair Branching Fractions

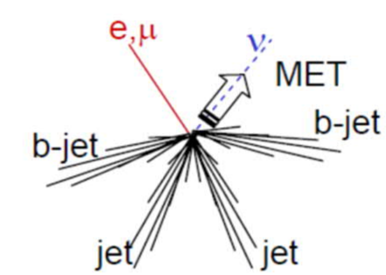




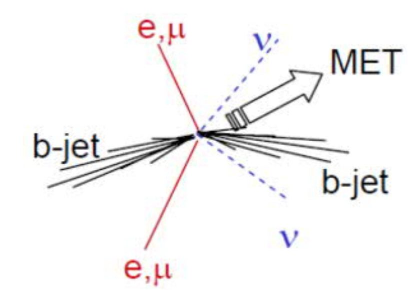
$t \to Wb$ ~100%

classify by W decay

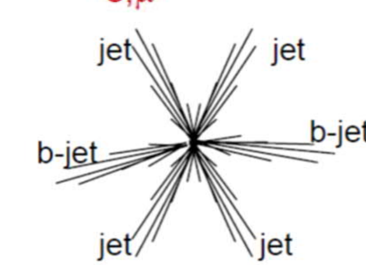
- "Lepton [e,μ] + jets" (34%)
  $tt \to bl\nu bqq'$



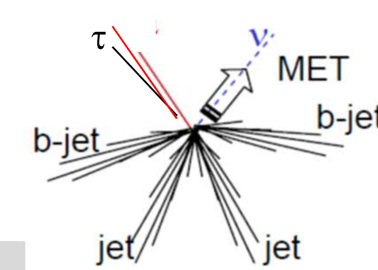
- "Dilepton [e,μ]" (6%)
  $tt \to bl\nu bl\nu$



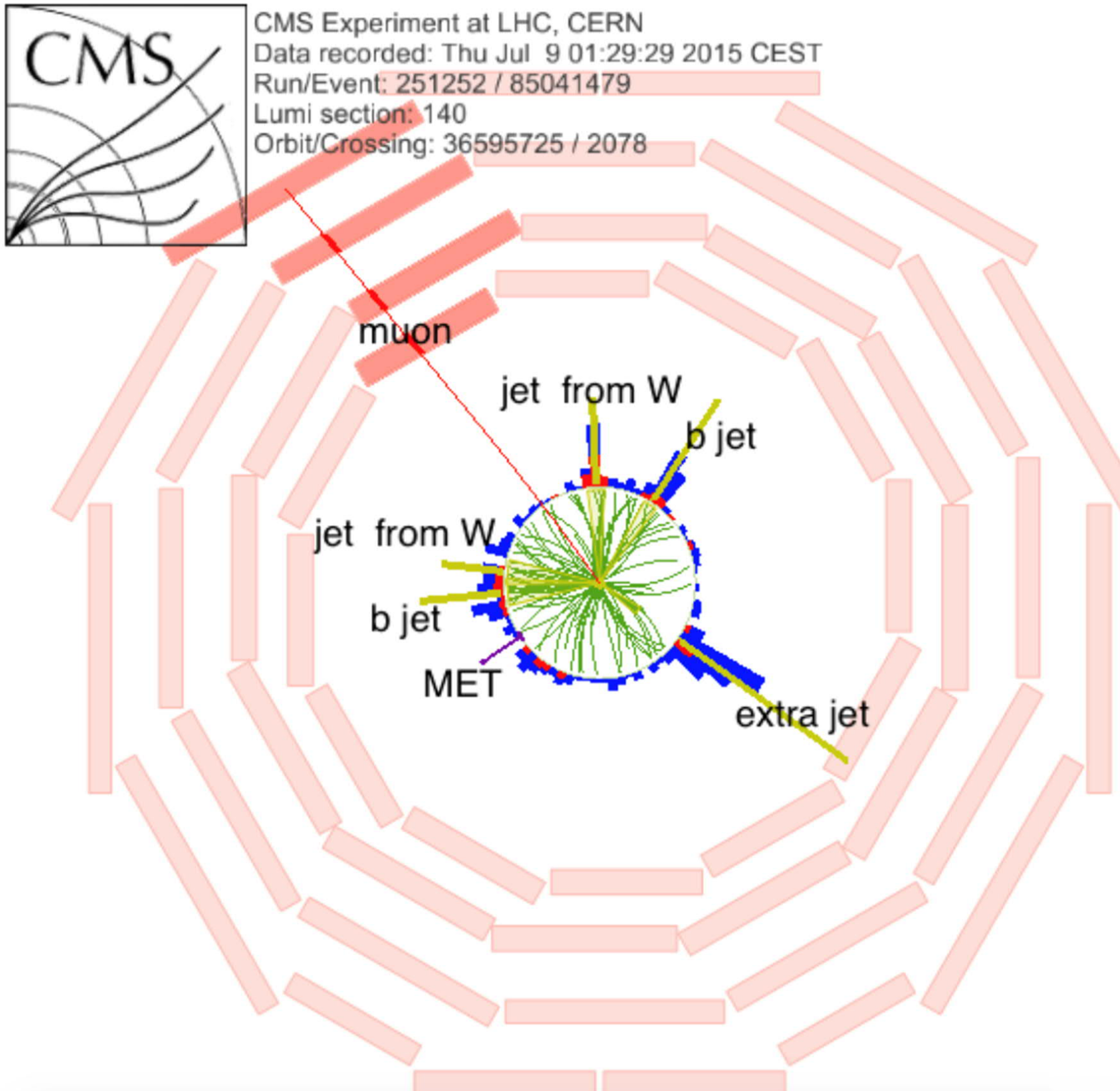
- "All jets" (46%)
  $tt \to bqq'bqq'$



- "Tau + jets" (15%)
  $tt \to b\tau\nu bqq'$



Detector View

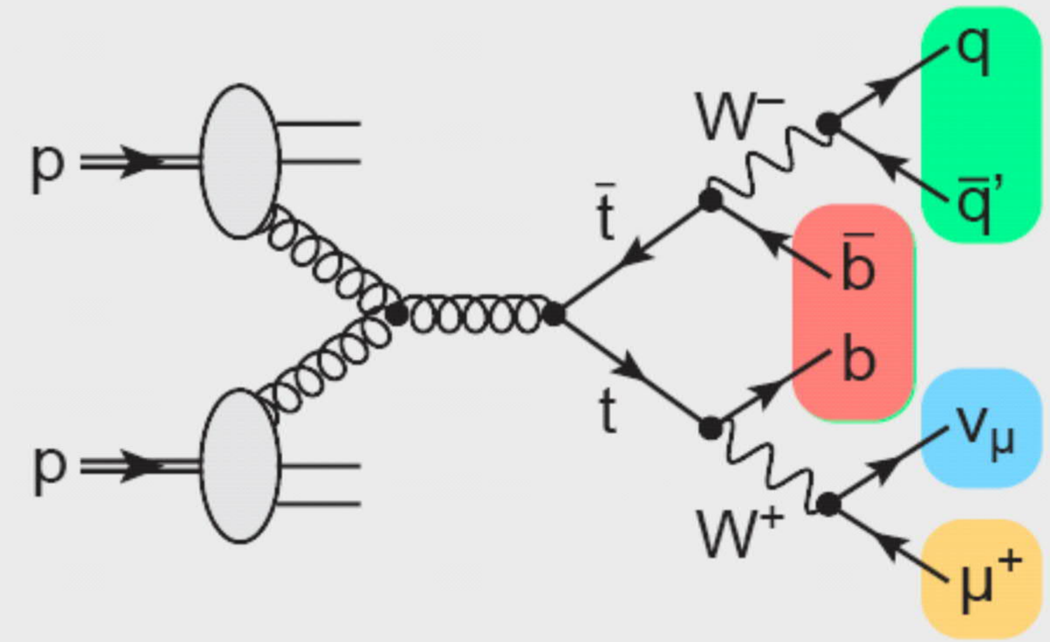


Selecting Top events

- 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)

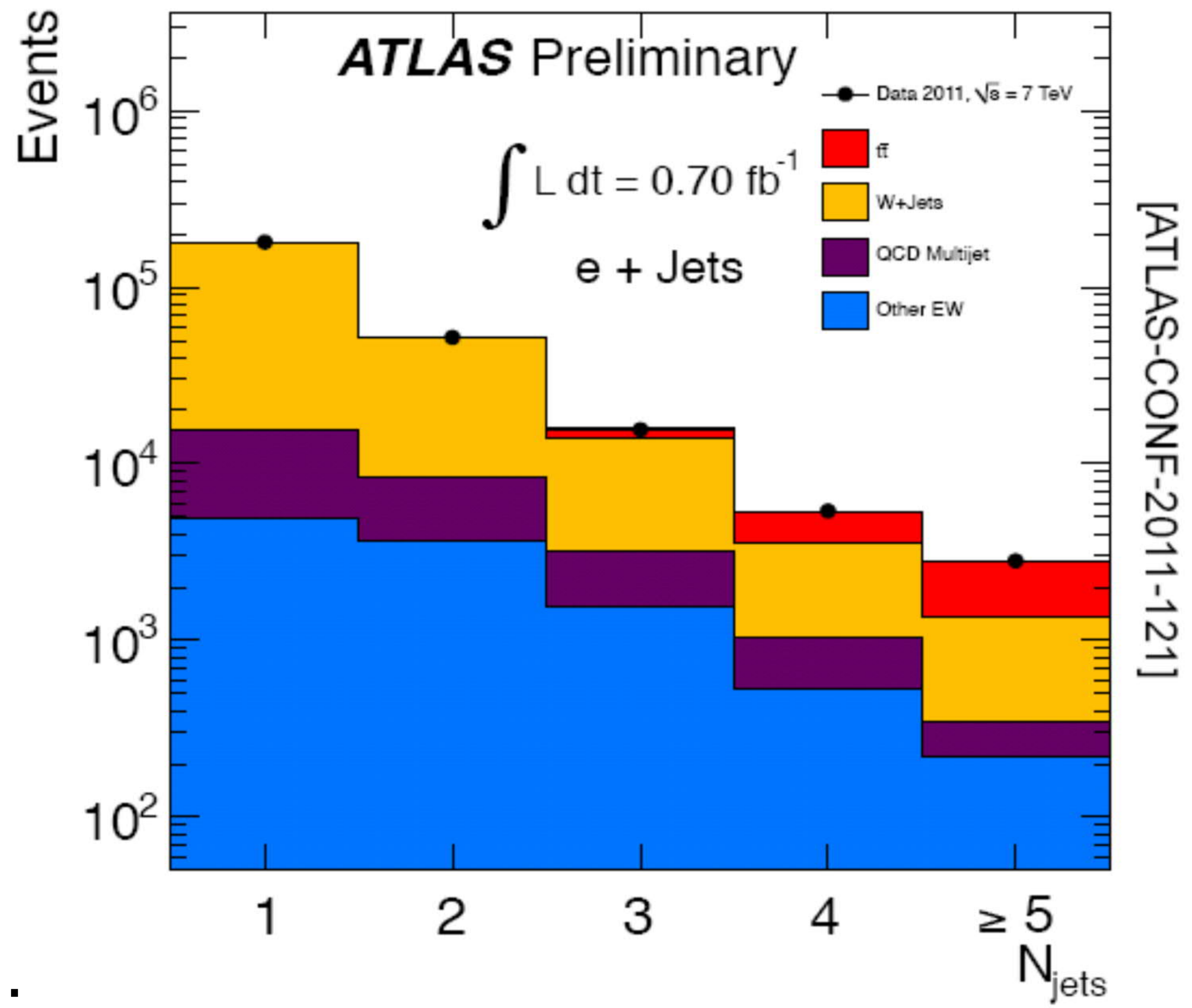
Backgrounds

- 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

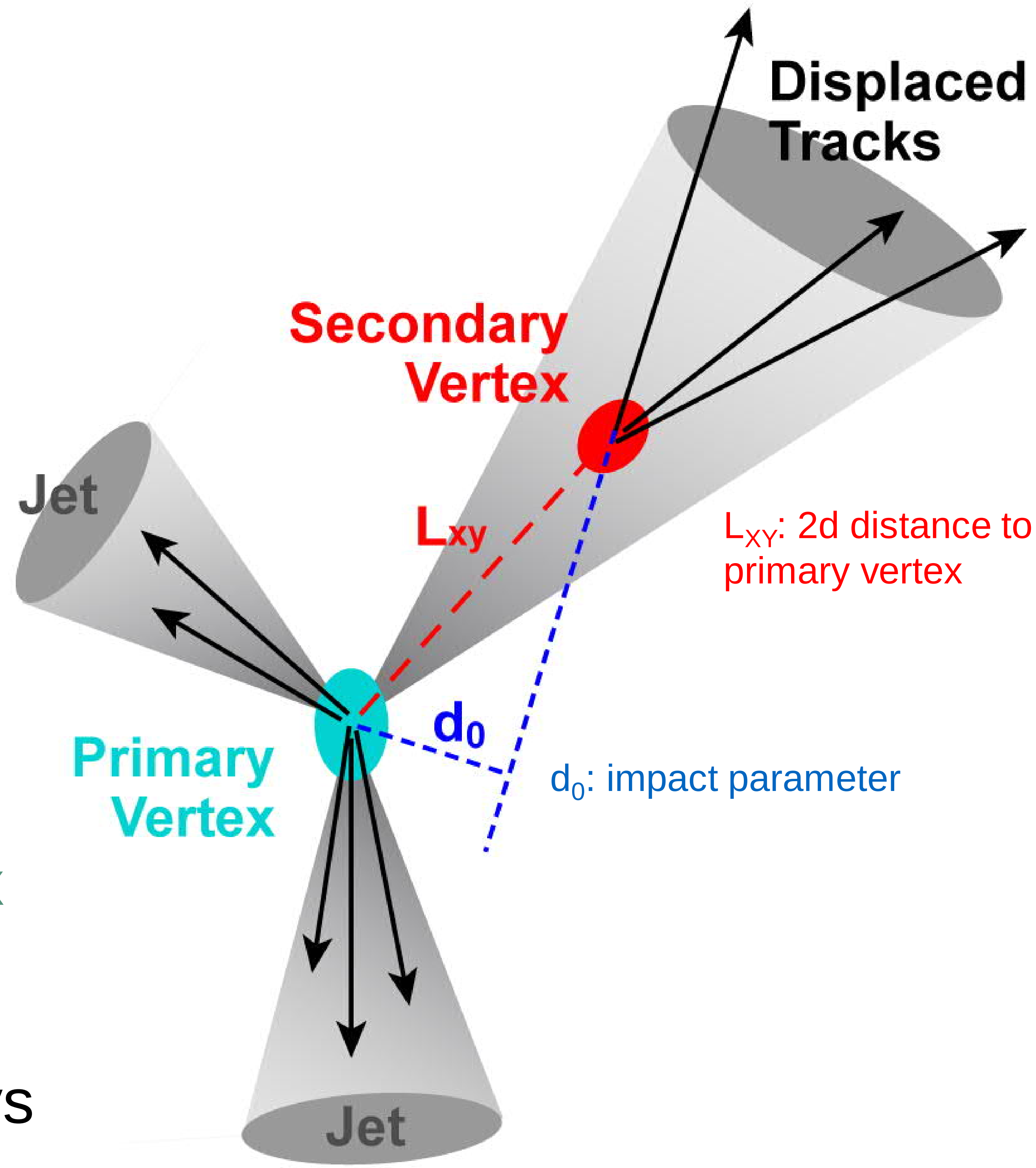


B-tagging

- 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 ($c\tau \sim 0.5$mm)
  - ⇒ B-mesons are massive large impact parameter tracks
  - ⇒ displaced massive vertex

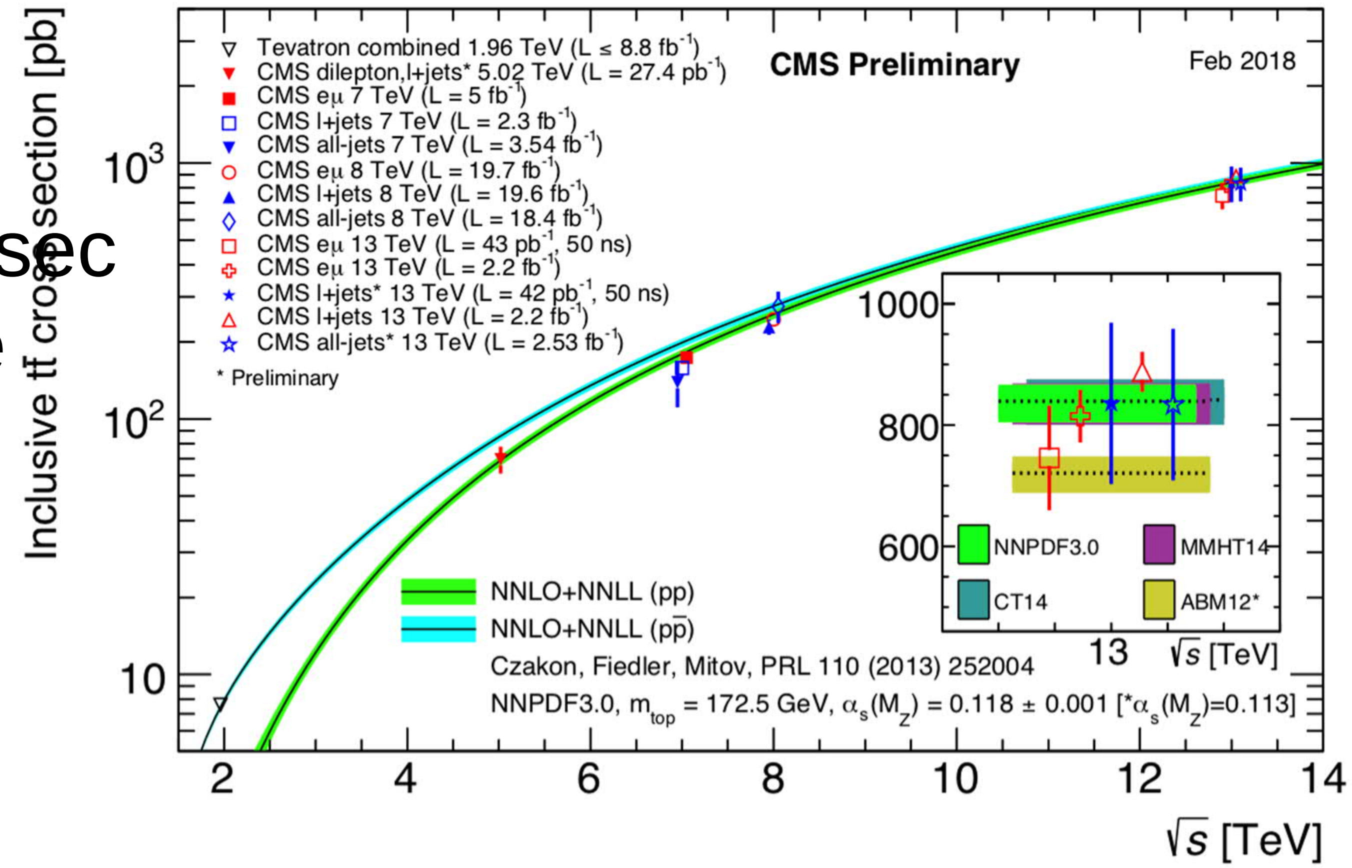
- B-tag II (leptons)
  look for semi-leptonic B decays
  - ⇒ soft leptons



Top Cross Section

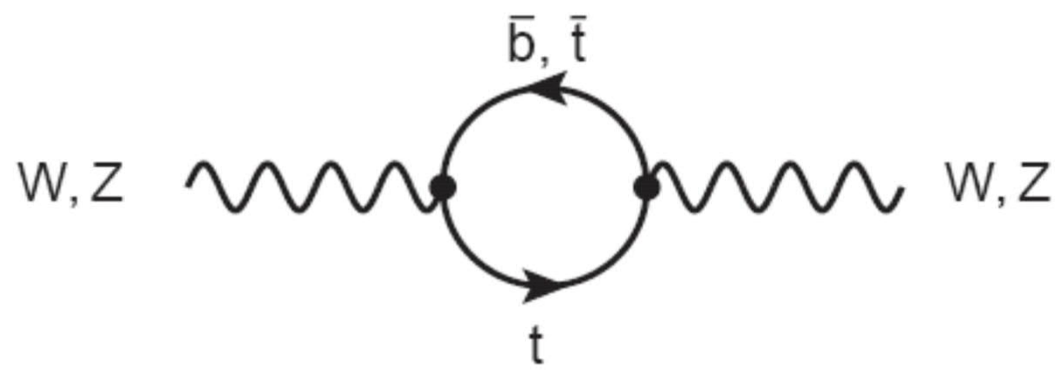
- Theory for top-pairs (2015)
  NNLO + NNLL
  ⇒ few % uncertainty

- 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



$\sim G_F\, m_t^2$

- 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)

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

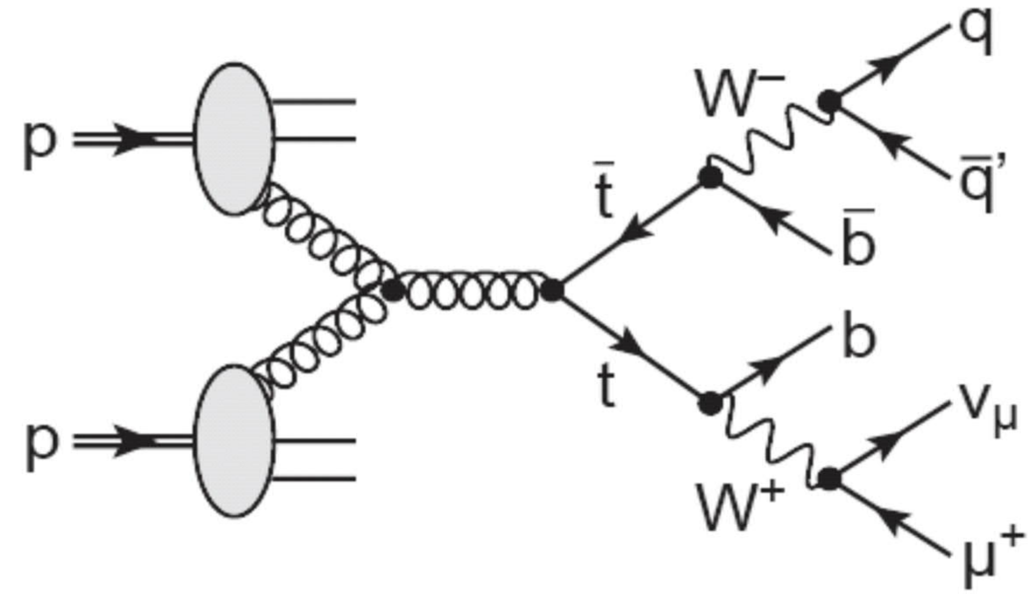
Measuring the Top Mass

- Direct measurement of top mass
  use event kinematics

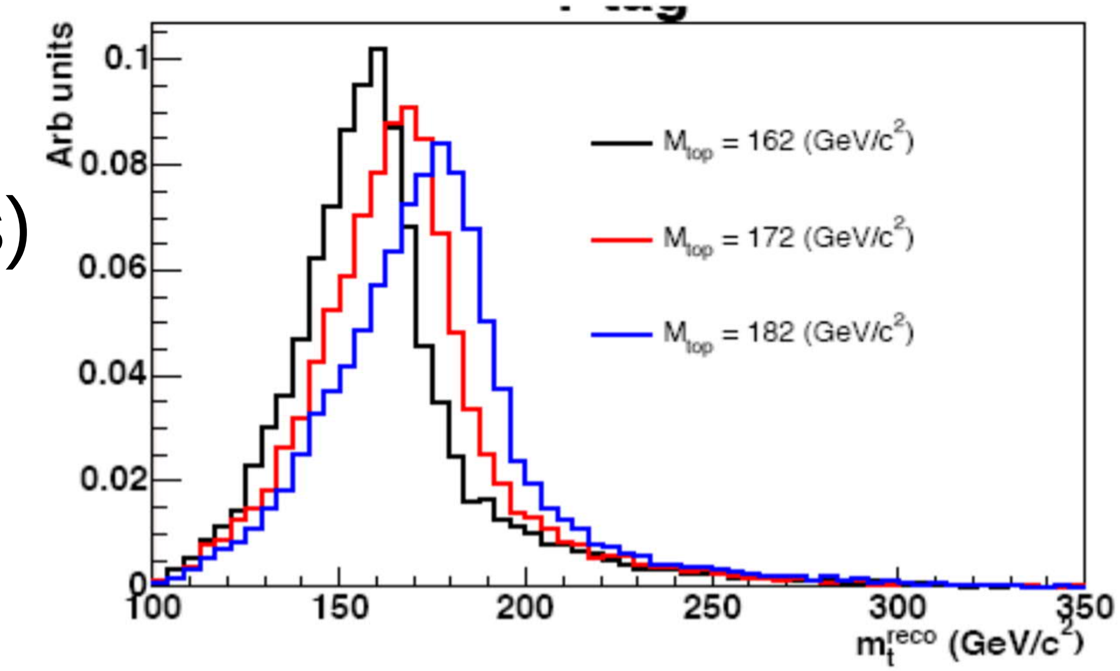
- Lepton + Jets: kinematics
  overconstrained
  → one unknown: neutrino pz
  → possible constraints:
  W-mass, $m_t = m_{anti\text{-}t}$

- 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



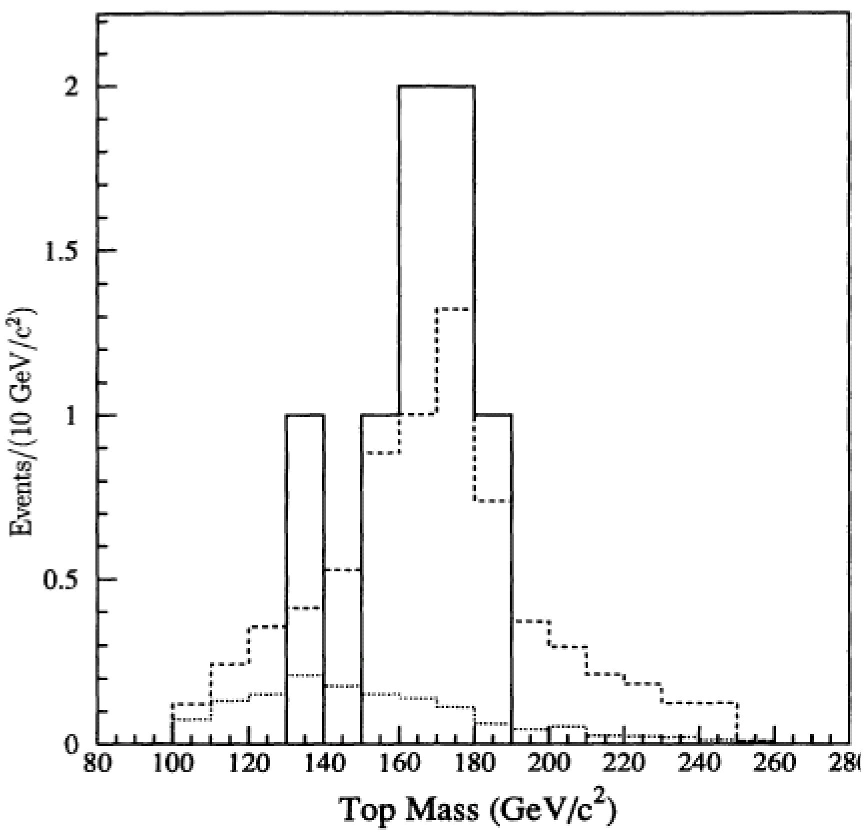
Schablonen für drei Top-Massen



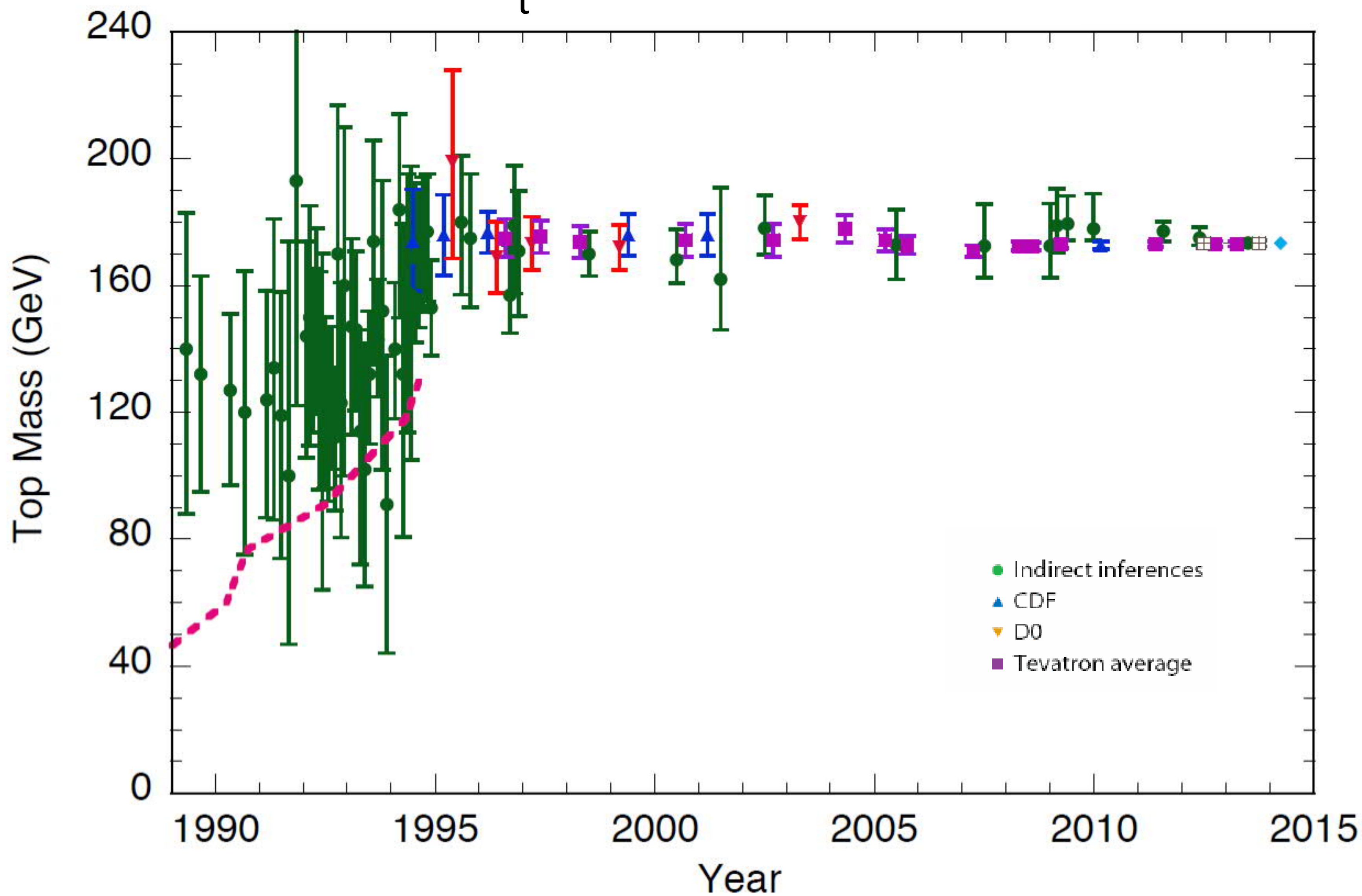
[http://www-cdf.fnal.gov/physics/new/top/2010/mass/TMT_p28_public/]

Top Quark Mass

first measurement
(CDF, 1994, 7 events)
$M_t = 170 \pm 10^{+13}_{-12}$ GeV

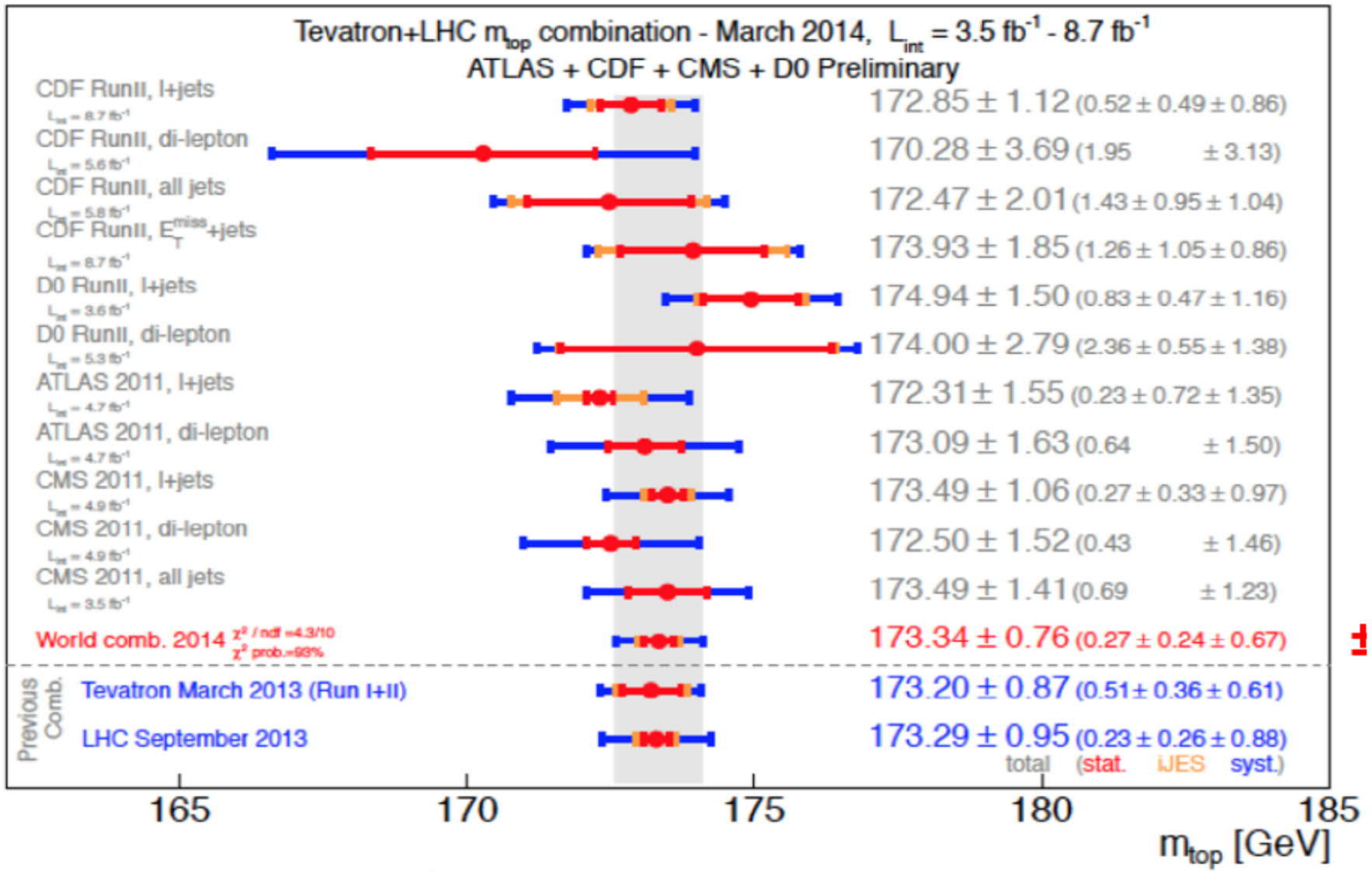


now
(world average 2014)
$M_t = 173.34 \pm 0.76$ GeV

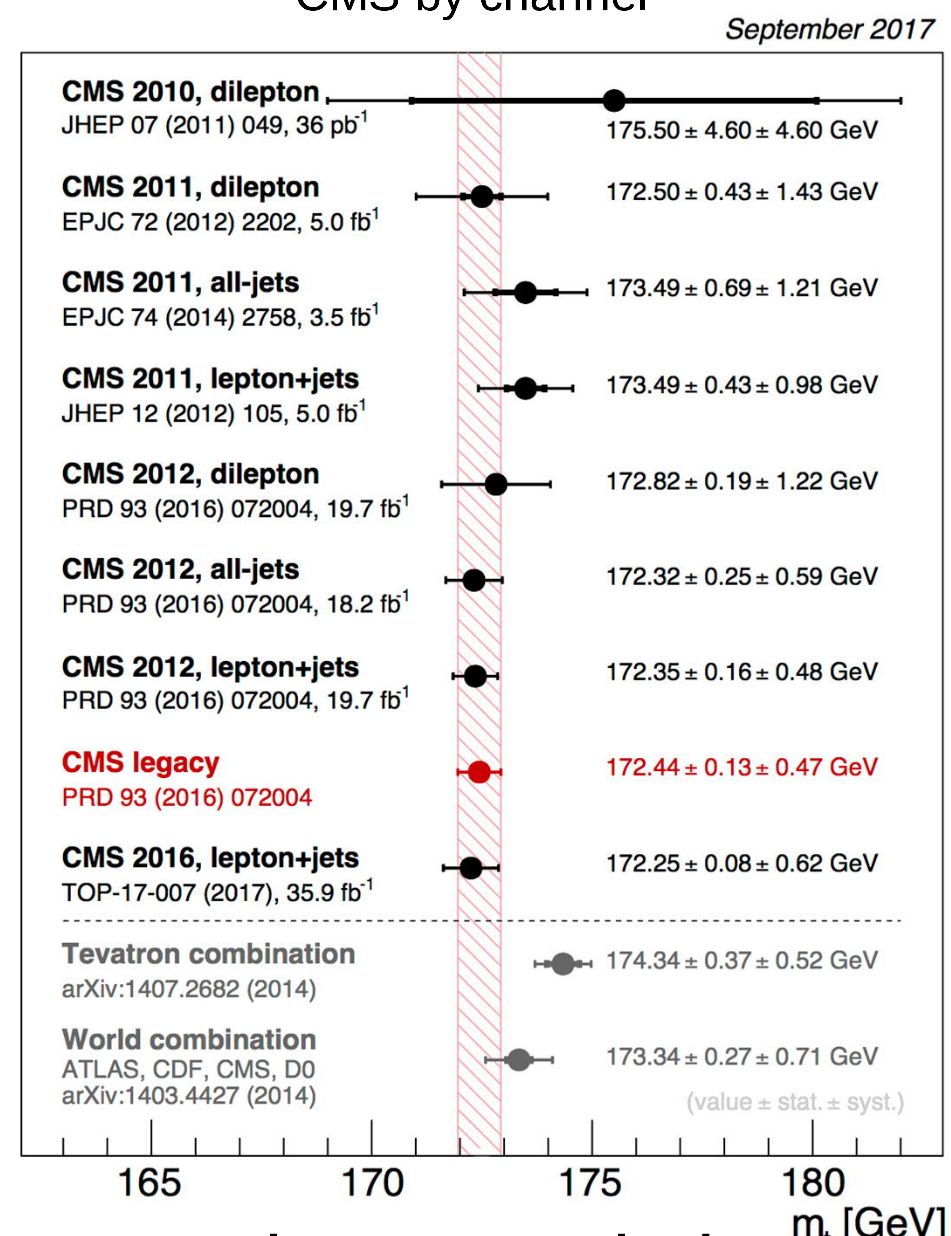


Measuring the Top Mass

World Combination



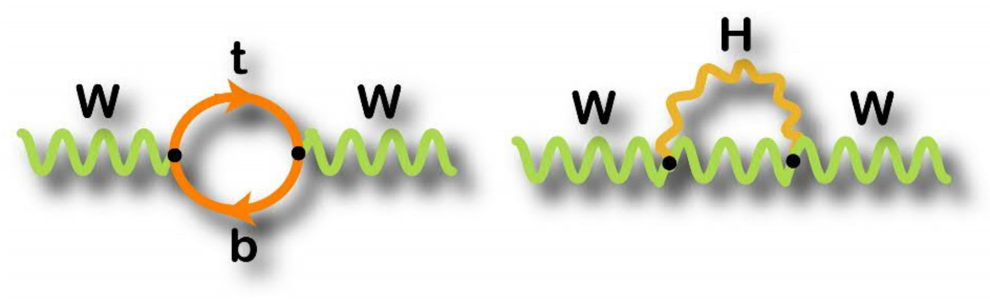
CMS by channel



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

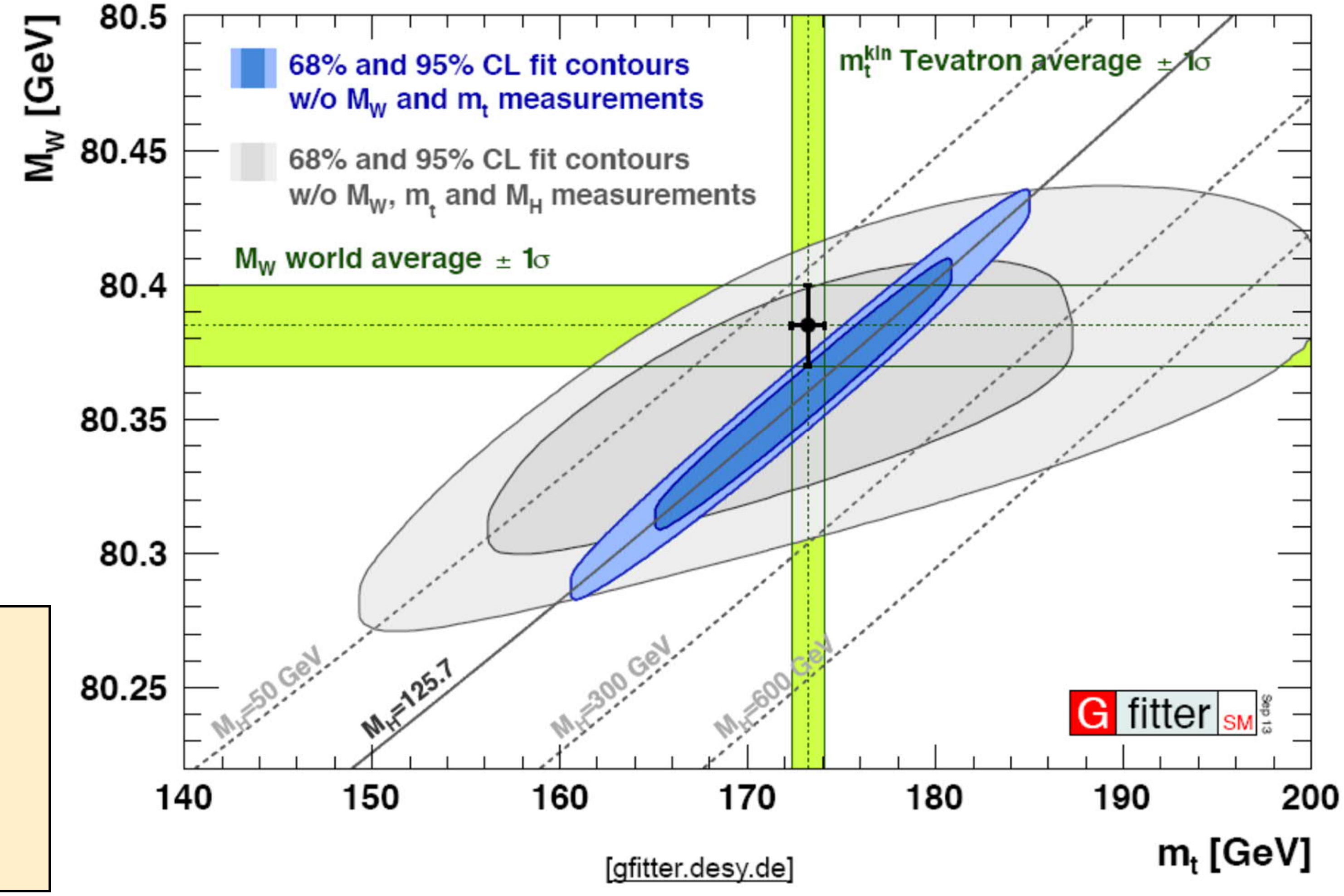
Measuring the Top Mass

M_W, M_t, M_H intermixed at loop level



$\sim M_t^2$ $\sim \ln(m_H)$

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