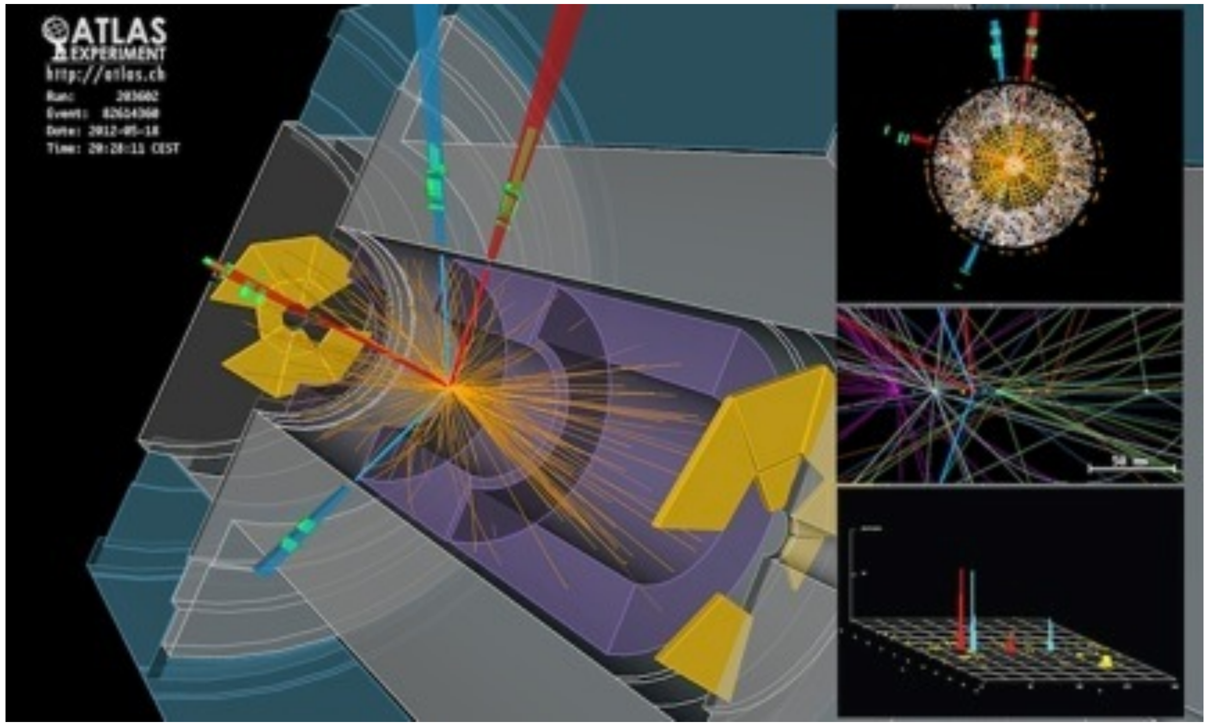
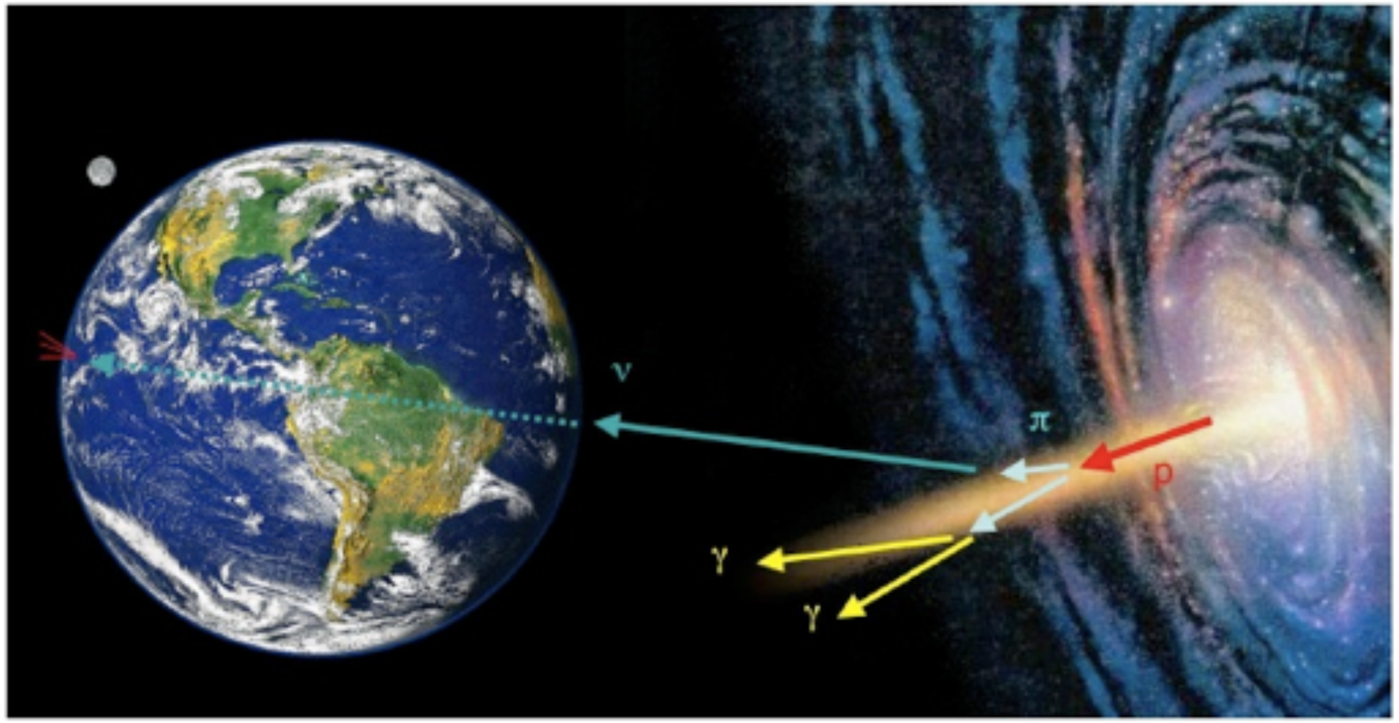
Particle Physics with Accelerators and Natural Sources





12. Physics with Flavor: Top & Bottom

22.07.2019

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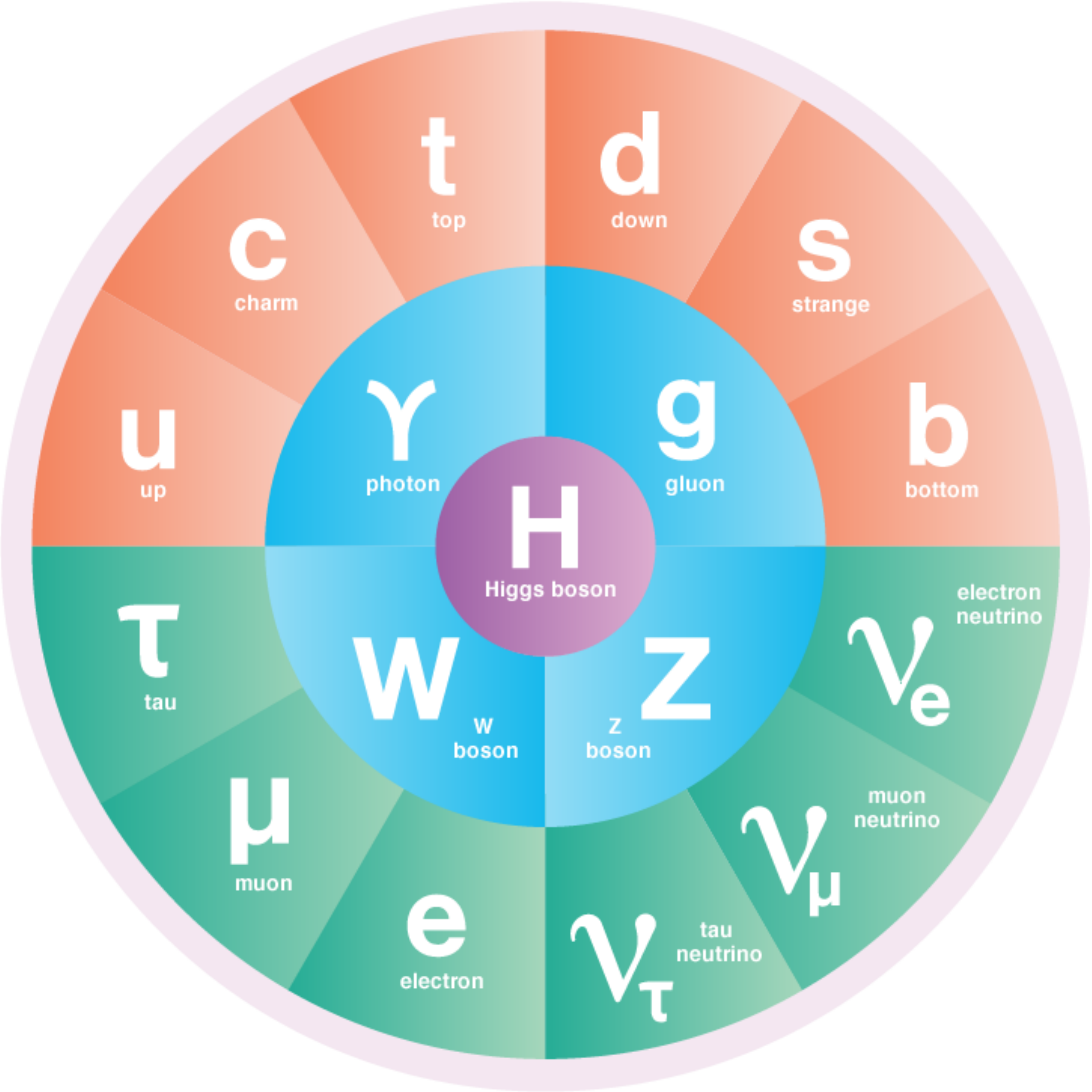
Dr. Bela Majorovits

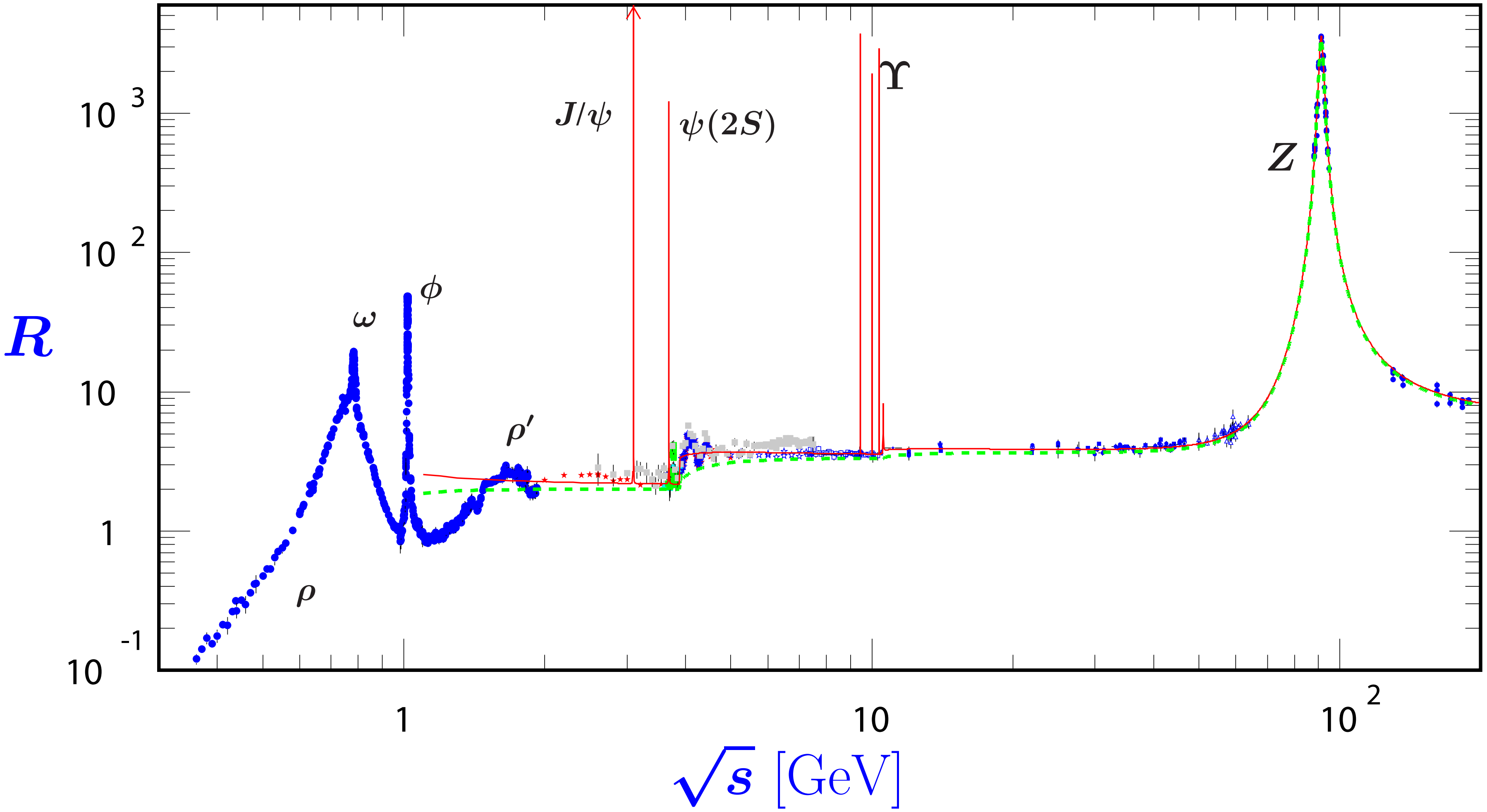
Flavor in the Standard Model



- Flavor physics: A wide range of topics connected to different particle types (“flavour”)
    - There are six flavors of leptons, and six flavors of quarks: A rich part of particle physics!

Historical Perspective - Discovering the 3. Family

- After the discovery of the τ a third quark family was basically obvious (it was already predicted based on the observation of CP violation at a time when only three quarks were known):
  - Renormalizability of the SM requires equal number of lepton and quark families
- The discovery of the b quark in 1977 directly implied the existence of the t quark since no flavor-changing neutral currents were observed (in the SM: Due to cancellations of t and b contributions) (analogous to the GIM mechanism, which predicted the c quark)
- The precise measurement of the cross-section in e^+e^- - Kollisionen above the b threshold gives the charge of the b: -1/3 => The top has to be + 2/3



A Word of Warning

- I am mixing two topics here:
  - The **top quark** typically does not run under “flavor physics” - due to its very high mass, the primary interest here is in **electroweak physics**
  - The **bottom quark** is the front runner in **flavor physics** - the main subject of study in the context of CP violation and various other studies

Today: Sketching a few topics and questions - no chance to go much in depth

B Quark Physics

Physics with Heavy Quarks

- Mixing in the quark sector: the CKM Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

specifies the mismatch of quantum states of quarks when they propagate freely (***mass eigenstates***) or interact strongly and when they take part in the weak interaction (***weak eigenstates***)

- Can be parametrized by 3 mixing angles and 1 complex phase (see discussion on neutrino mixing)

$$\begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta'} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta'} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The complex phase generates CP violation

The CKM Matrix

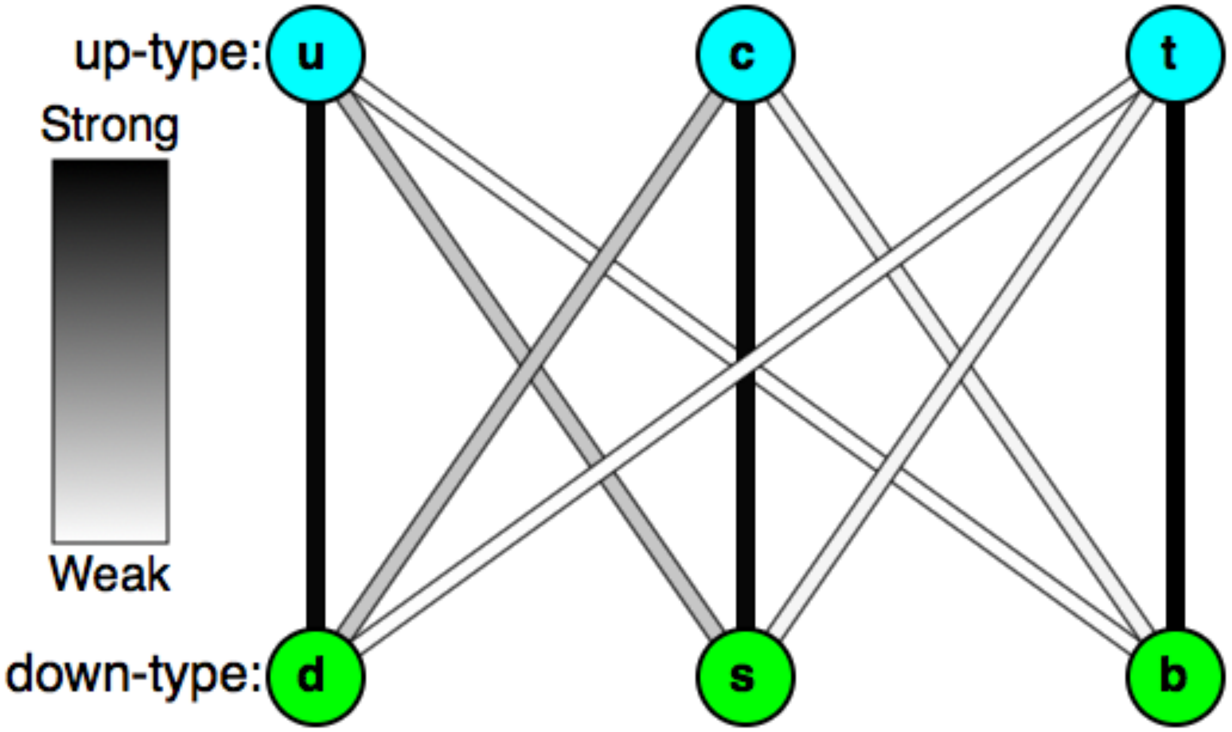
- Alternative parametrization: Wolfenstein parametrization, takes into account observed values of matrix elements:

$$A\lambda^2 = \sin\phi_{23} \quad \text{and} \quad A\lambda^3(\rho - i\eta) = \sin\phi_{13} e^{-i\delta'} \qquad \lambda = \sin\phi_{12} \approx 0.22.$$

(the Cabbibo angle)

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

graphical representation of transition probability

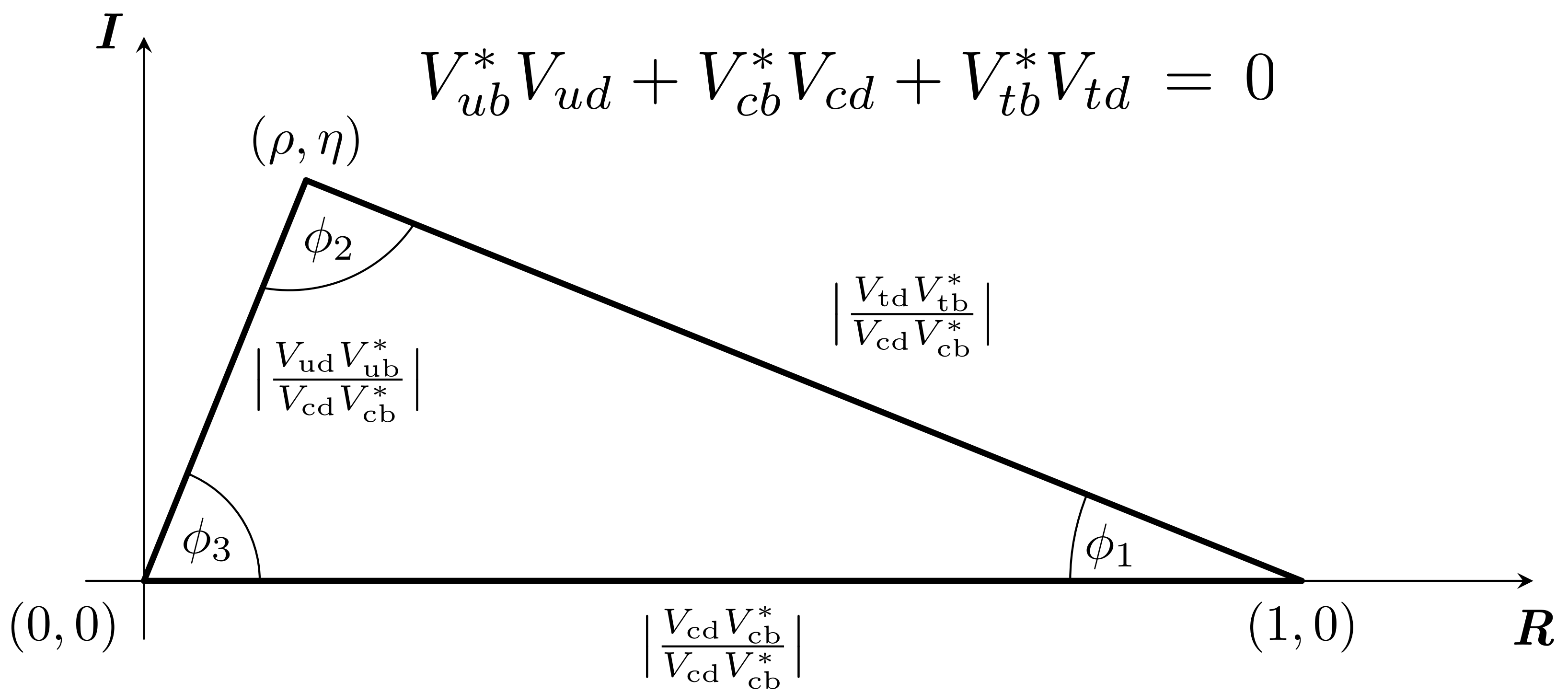


Why Study CP Violation with b Quarks?

- The CKM Matrix is ***unitary***

$$V^\dagger V = \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Graphically represented by ***Unitarity Triangles*** in the complex plane

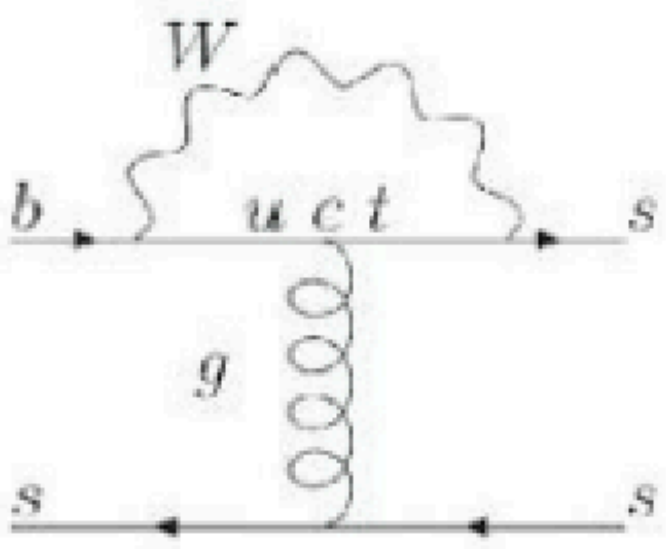


$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

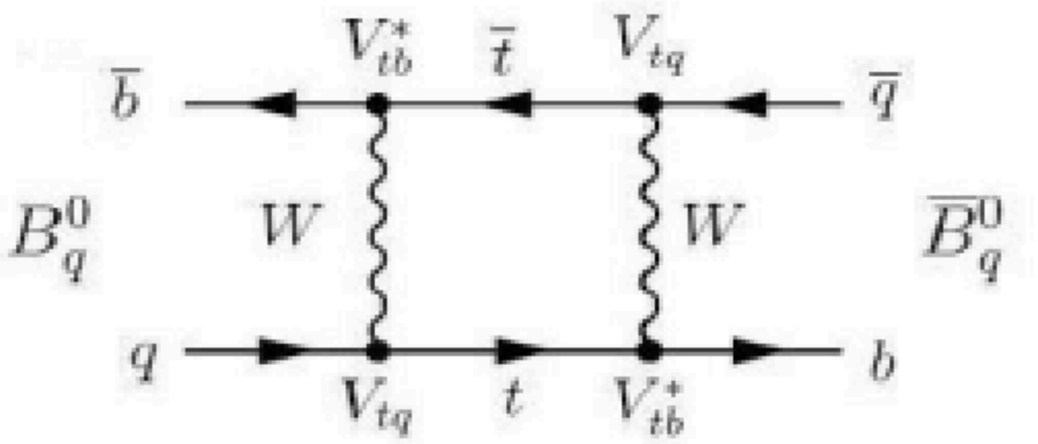
- Special feature for B^0 mesons (b and u quark bound states): Comparable length of all three sides - large effects from CP violation

The Processes in B Physics

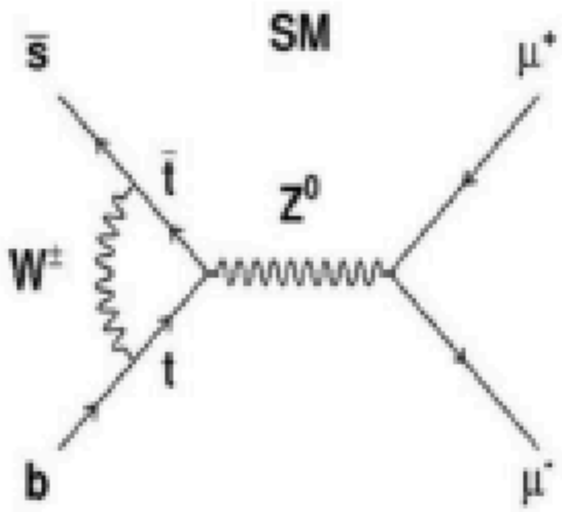
- Main goals of measurements: Measure and overconstrain the parameters of the CKM matrix (fundamental parameters of the SM) -> “non-closure” of unitarity triangles would indicate physics beyond the SM
- Processes dominated by loops are particularly sensitive



“Penguins”
rare decays

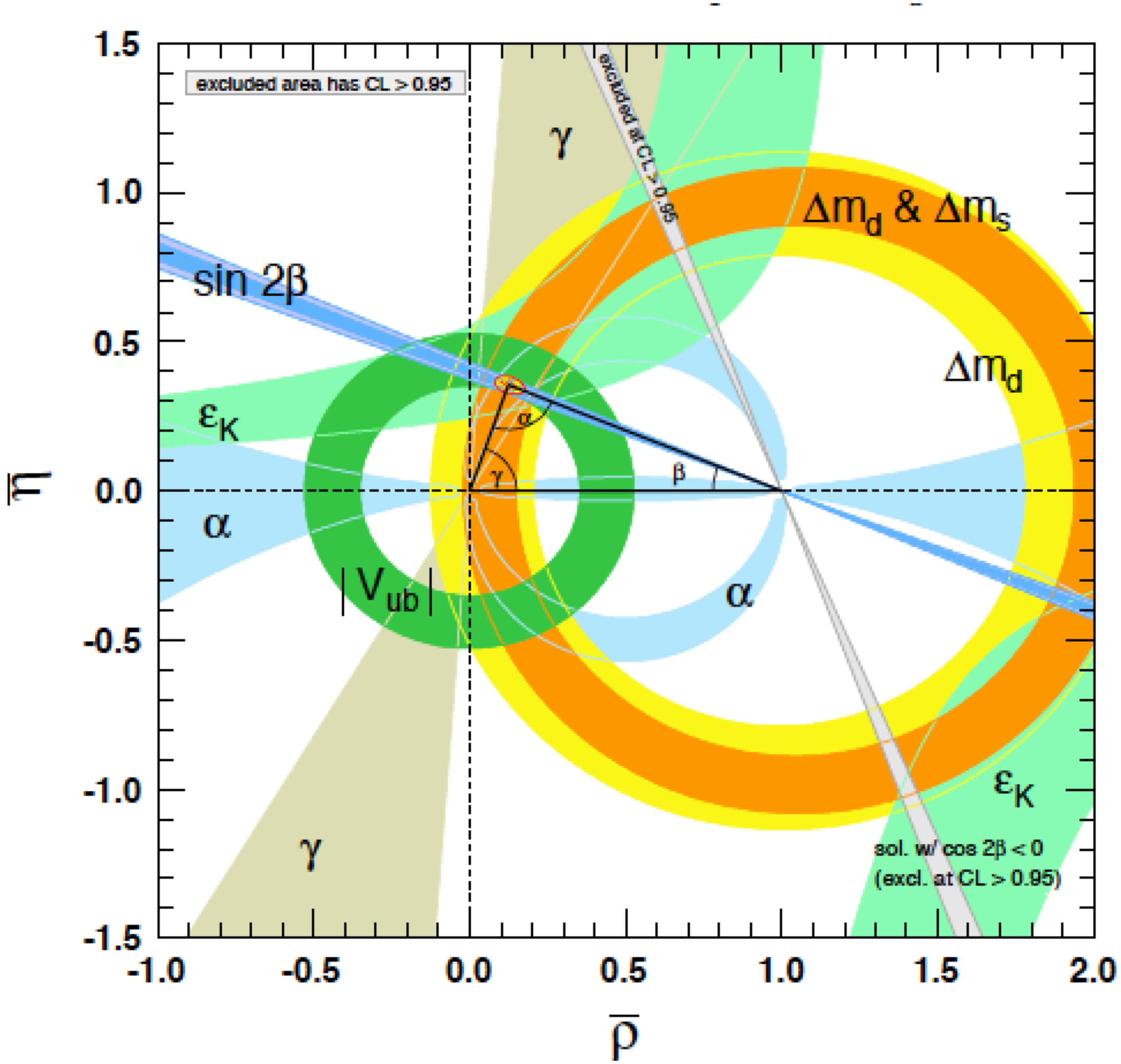


“box diagrams”
mixing of neutral mesons



rare decays

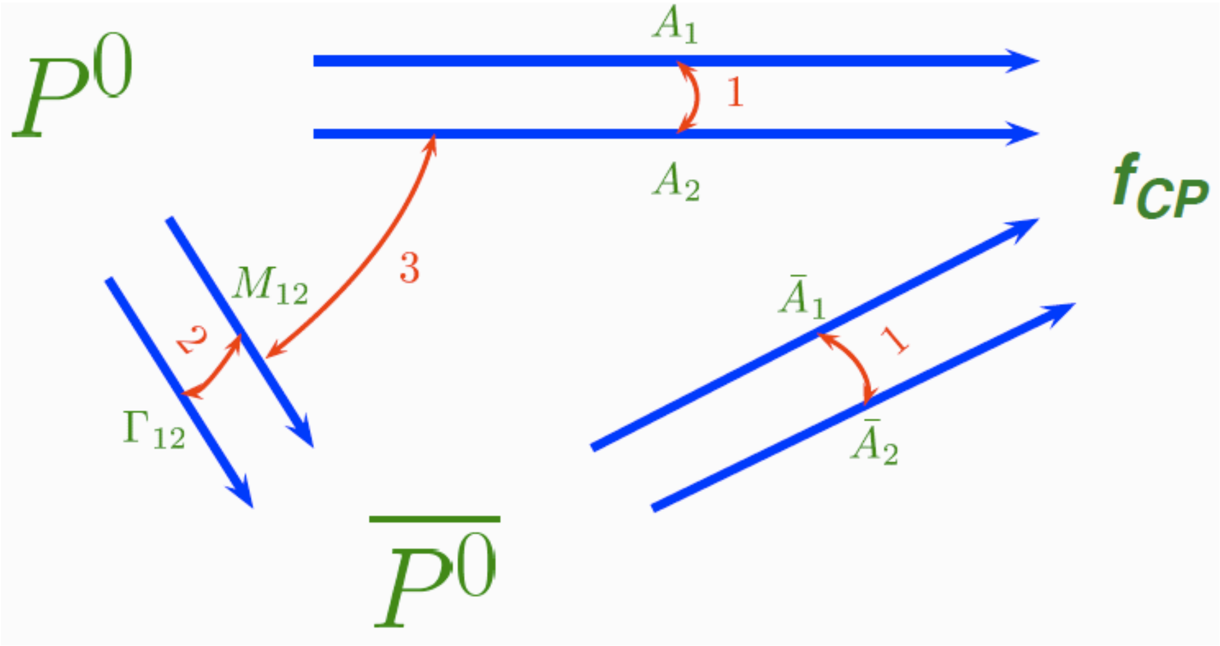
The CKM Matrix - The Status



$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{pmatrix}$$

Studying CP Violation with B Mesons

- A complex interplay of mixing and decay of neutral mesons

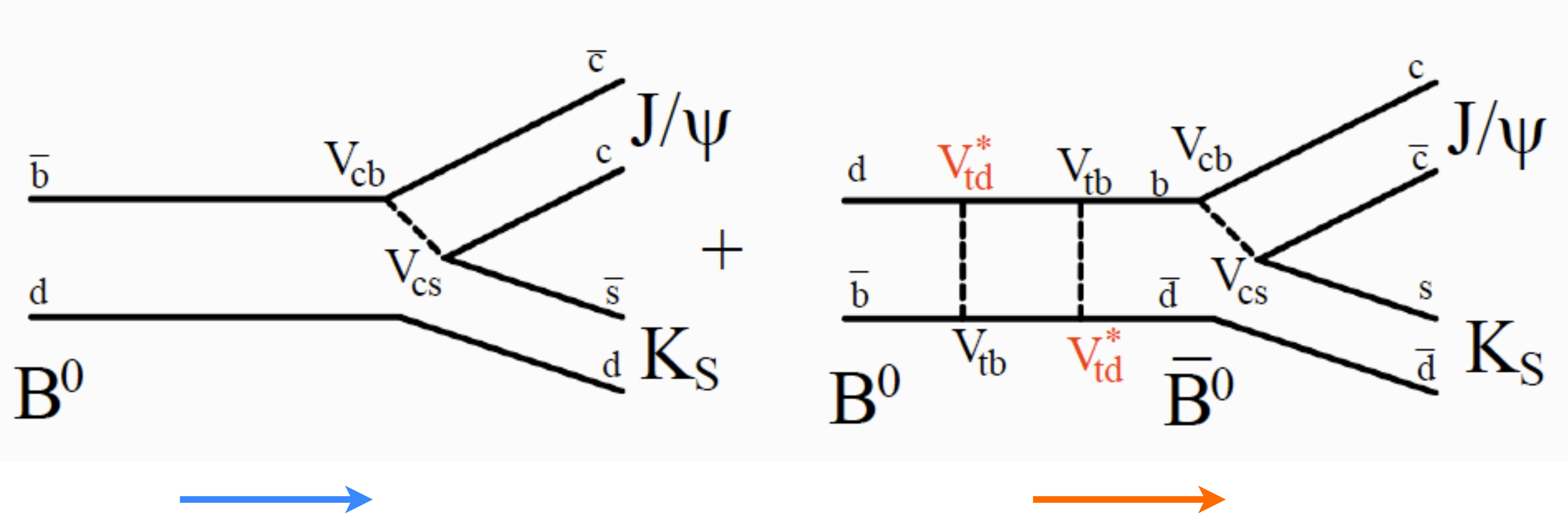


- General principle: Studying decays to CP Eigenstates - comparing particle and anti-particle in the initial state

- CP violation can manifest itself in three ways
  - Direct CP violation in the decay: Difference in amplitude for particle and anti-particle. (1)
  - In particle - anti-particle oscillations (2)
  - In the interference of decay and oscillation (3)

One Example for the Interference Case

$$\begin{tikzcd} B^0 \arrow[rr] \arrow[dr] & & f_{CP} & \neq & \bar{B}^0 \arrow[rr] \arrow[dr] & & f_{CP} \\ & \bar{B}^0 \arrow[ur] & & & & B^0 \arrow[ur] & \end{tikzcd}$$



The “golden” channel in “***B Factories***”

Ingredients needed for the Measurement

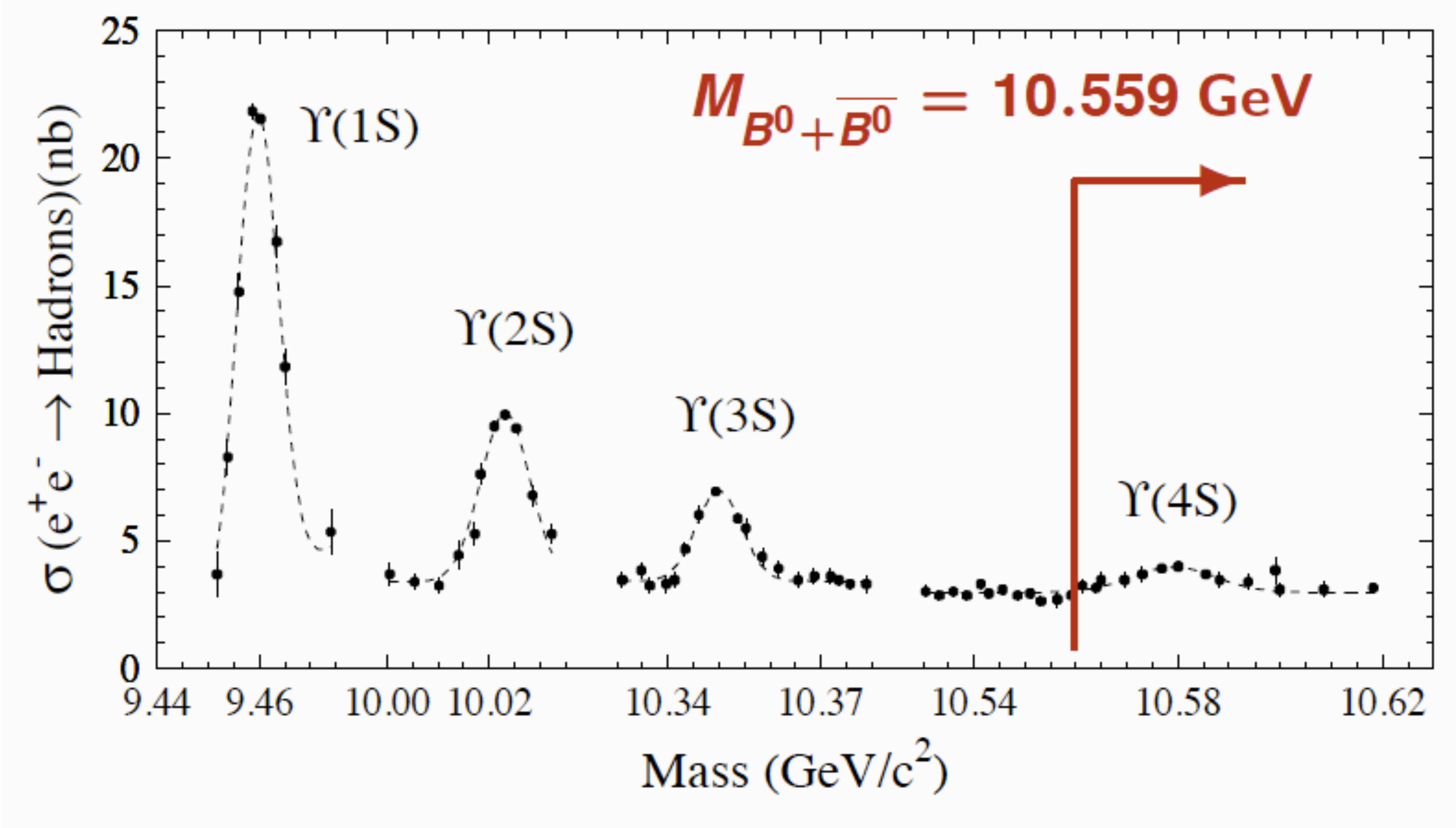
- Interference of oscillation and decay results in a time-dependent asymmetry, where the amplitude provides one parameter in the unitarity triangle, and the frequency is given by the mass difference of the B^0 mass eigenstates:
  - 330 μeV, corresponds to 0.5 ps^{-1}, a full oscillation takes ~ 12 ps (B^0 lifetime ~ 1.5 ps)

- Need to measure:
  - Time since creation of B meson
  - B meson flavor at the time of the decay
  - Full reconstruction of decay channle

- This is tough: short times < 1 ps, small branching ratios (~ 10^{-4}), oscillating flavors

Tricks for the Measurement

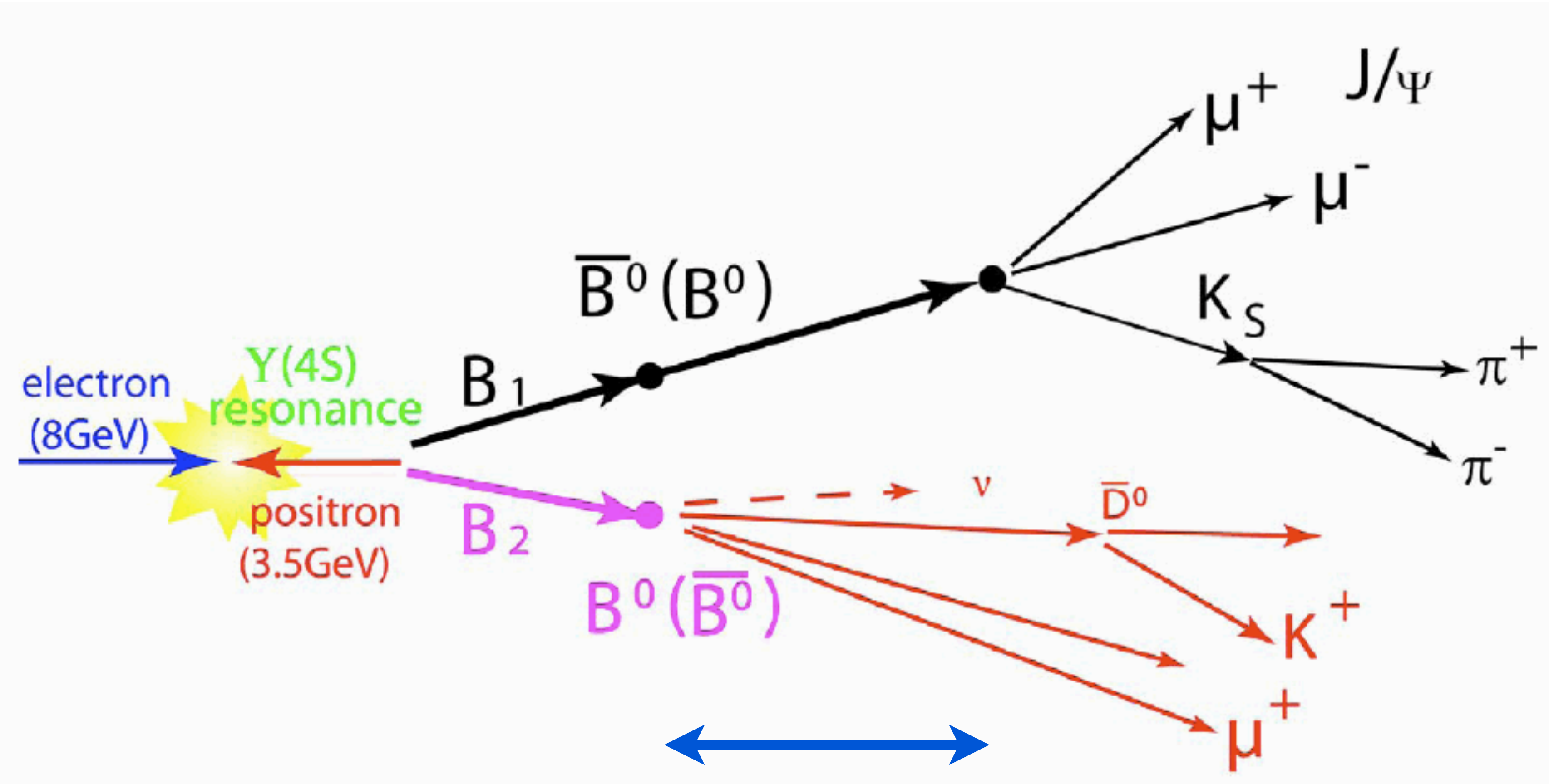
- Use quantum mechanically entangled mesons: Flavor of one can be determined by observing flavor of the other



Production of Y(4S) resonance in e^+e^- collisions

Tricks for the Measurement

- Measuring decay times via distance: Asymmetric energy in collision trades time vs space: 1 ps ~ 300 μm at speed of light



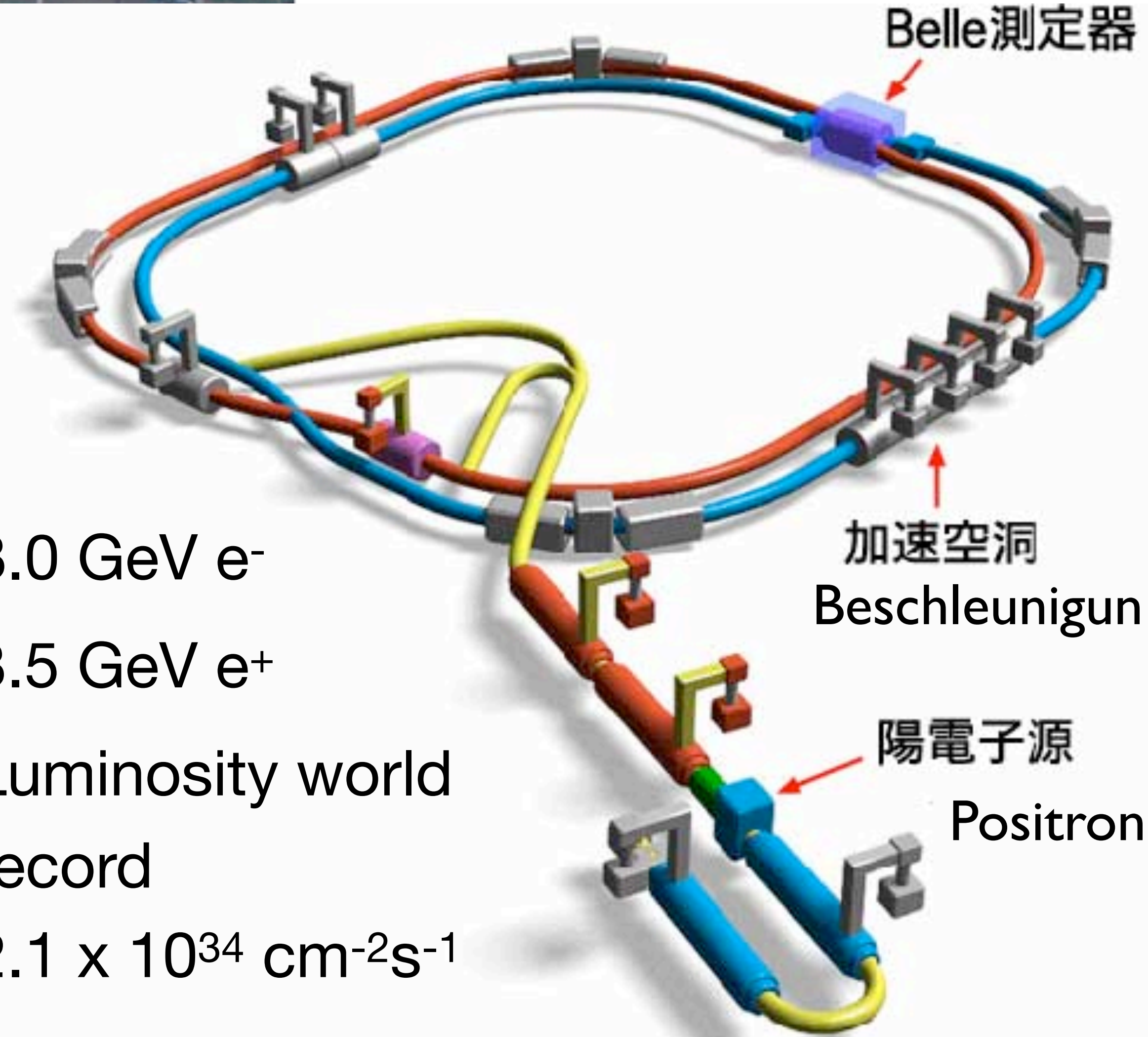
Δz ~ 200 μm
=> Δt

- Flavor tagging of B decaying into CP eigenstate by other B (“tag side”), where a flavor-specific decay is used (charge of lepton gives B flavor)

B - Factories

- Running until 2010

KEKB / Belle



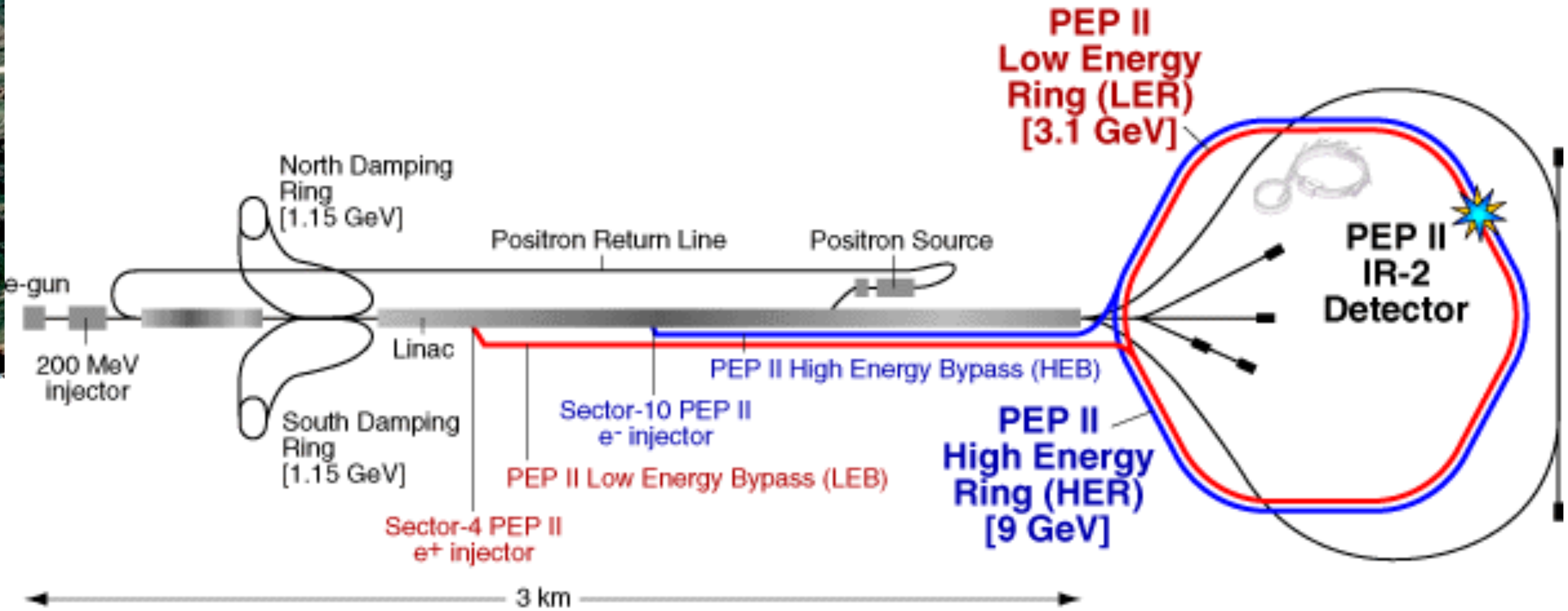
- 8.0 GeV e^-
- 3.5 GeV e^+
- Luminosity world record
  $2.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $> 1\ \mathrm{fb}^{-1}$ per day

B - Factories

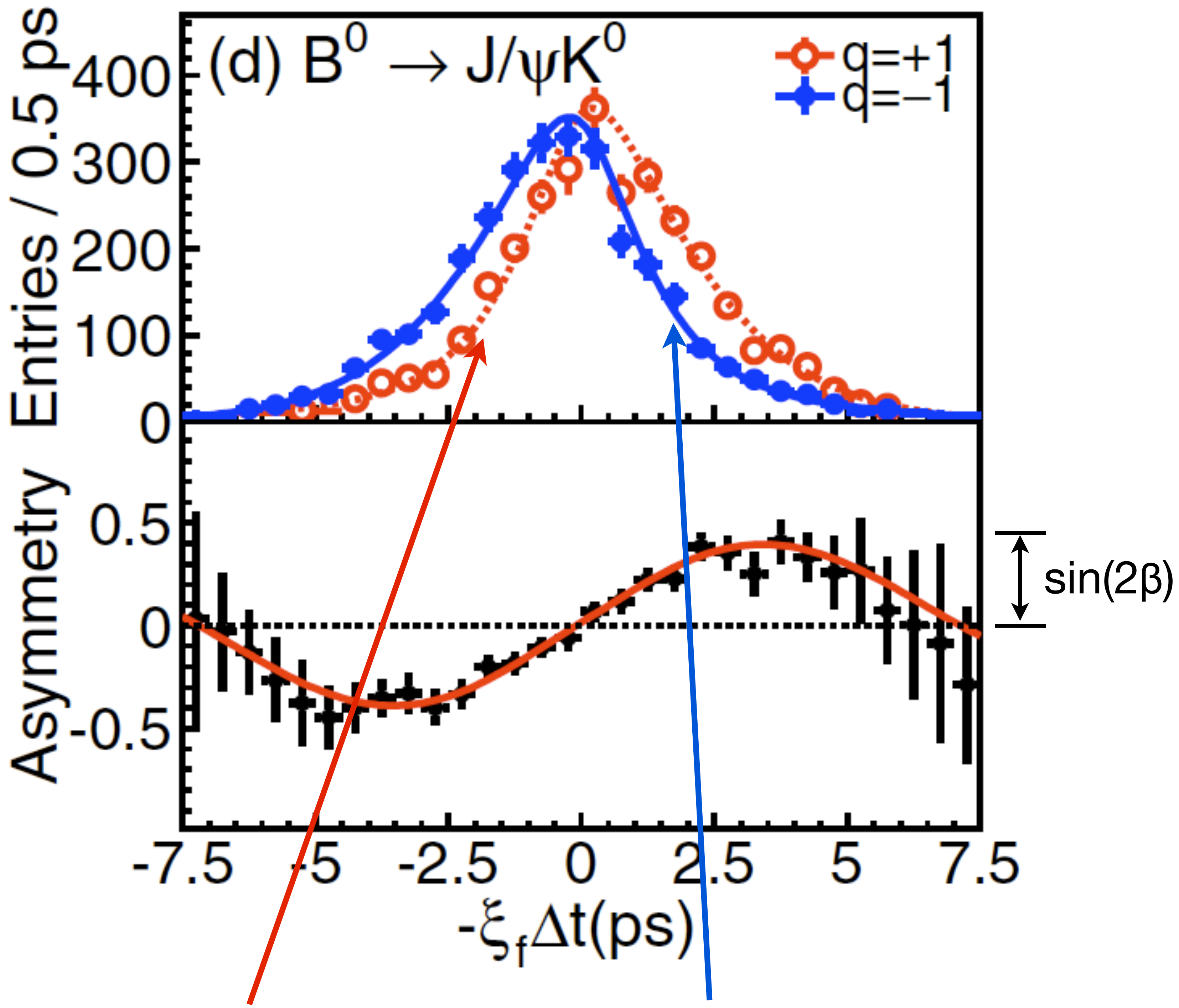
- Running until 2008

SLAC PEP II / BaBar

- 9.0 GeV e^-
- 3.1 GeV e^+
- Luminosity 1.2×10^{34} $cm^{-2}s^{-1}$



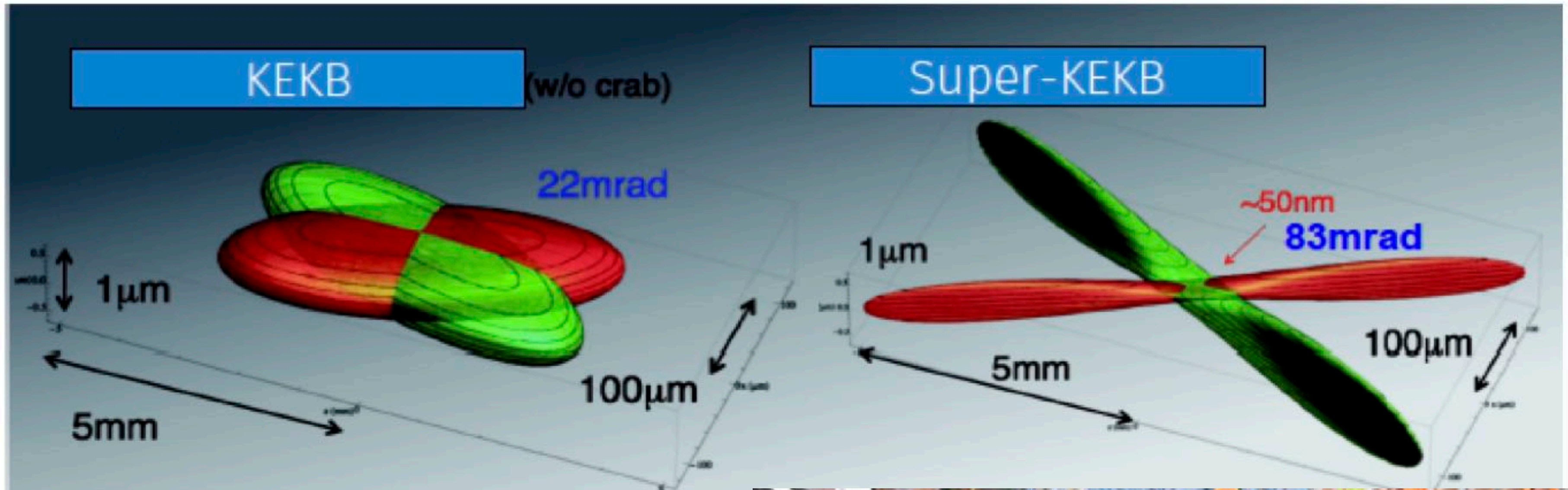
The Measurement



$\bar{B}^0 \rightarrow J/\psi K^0_S$ $B^0 \rightarrow J/\psi K^0_S$

Now coming on line: Belle II & SuperKEKB

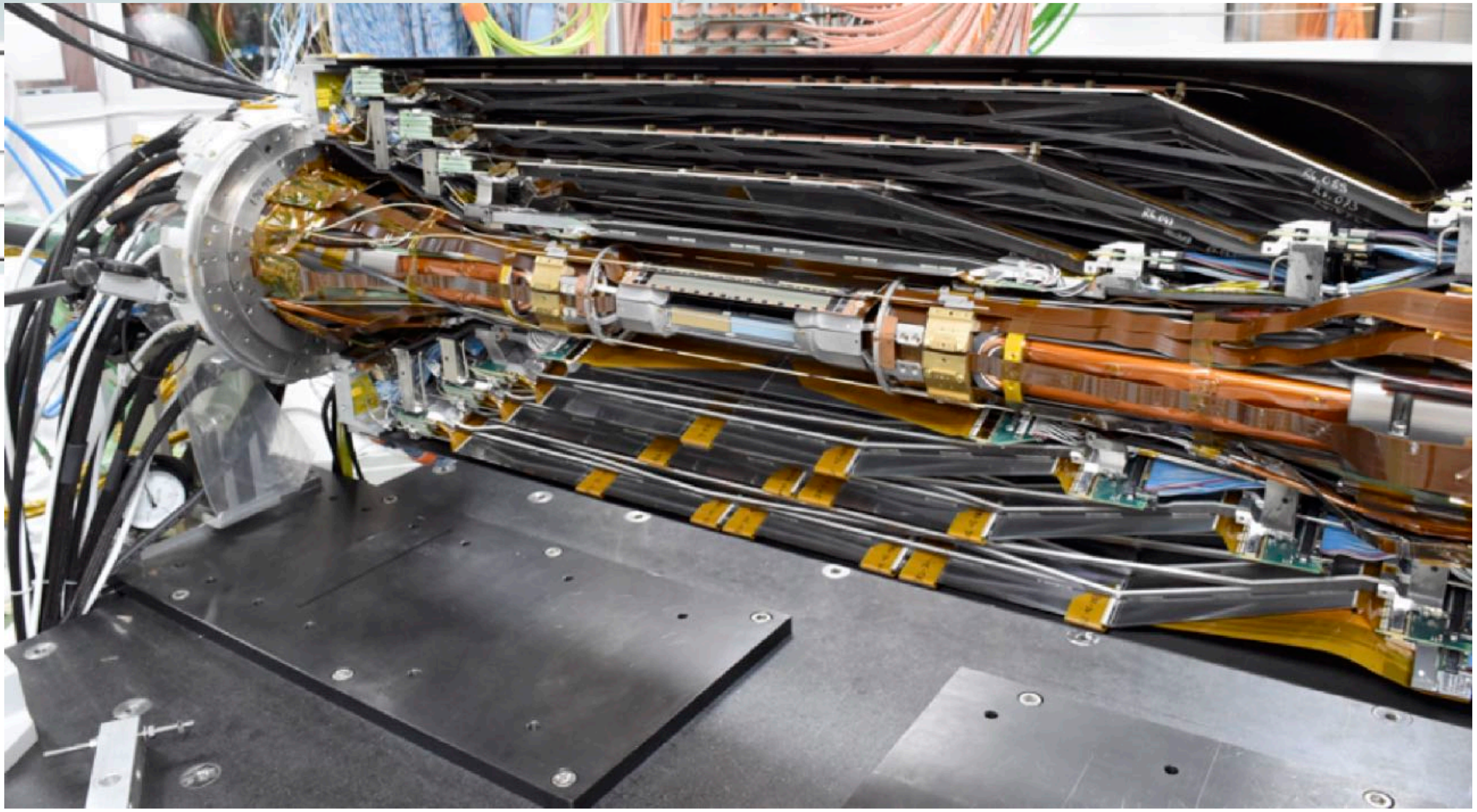
- Increase of Luminosity by up to x 40



	E (GeV) LER/HER	β^*_y (mm) LER/HER
KEKB	3.5/8.0	5.9/5.9
SuperKEKB	4.0/7.0	0.27/0.30

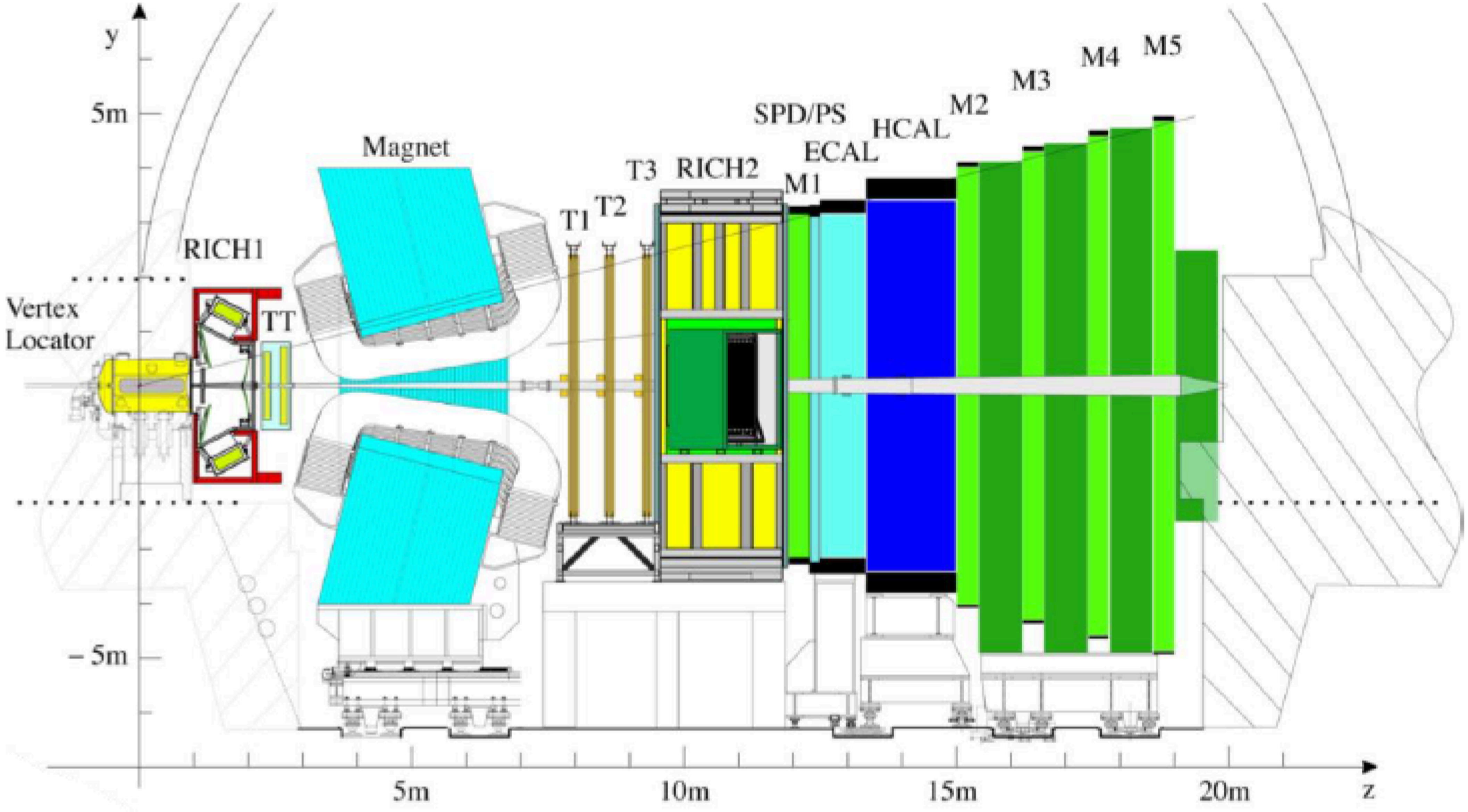
factor 20

- And a new detector
  - One highlight: The vertex detector, with key contributions from MPP, also from TUM, LMU



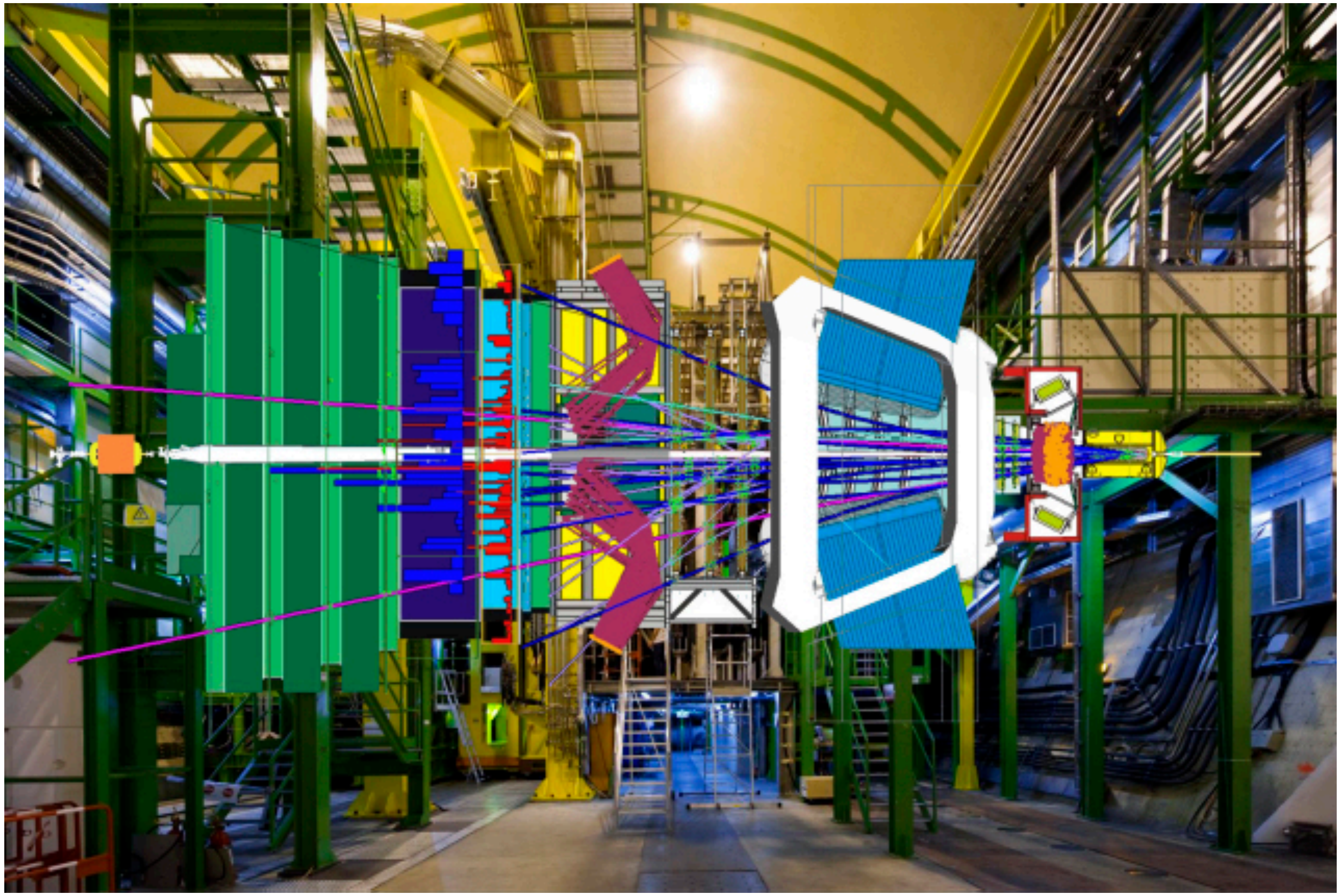
Flavor Physics at LHC: LHCb

- A forward spectrometer, exploiting particle boost



Flavor Physics at LHC: LHCb

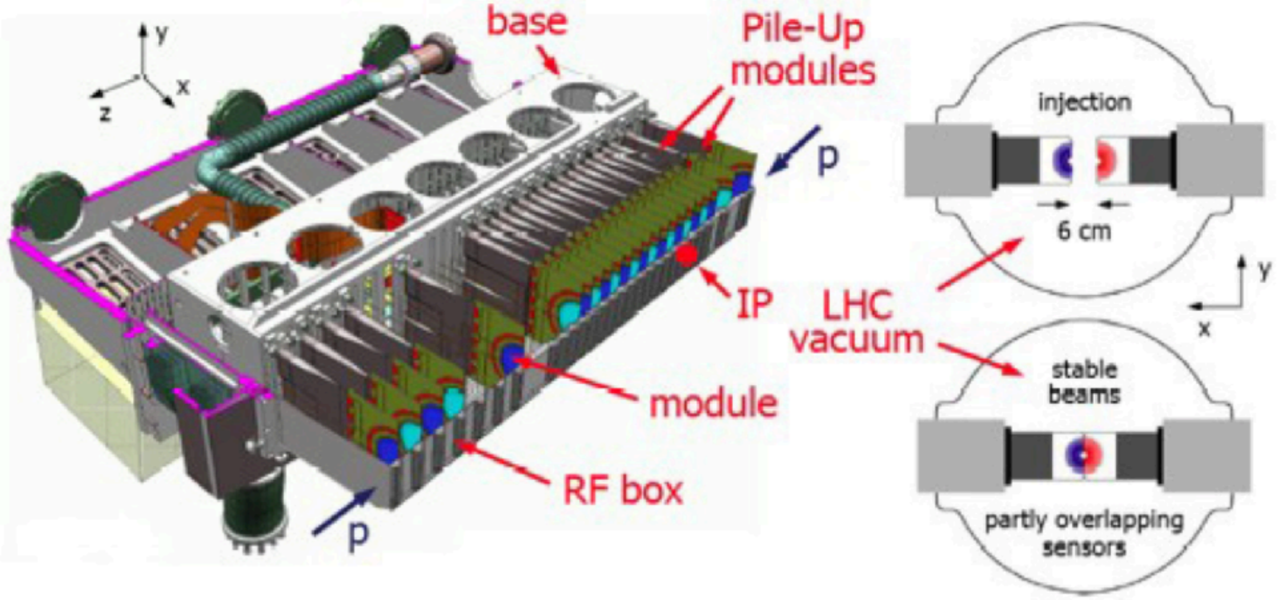
- A forward spectrometer, exploiting particle boost

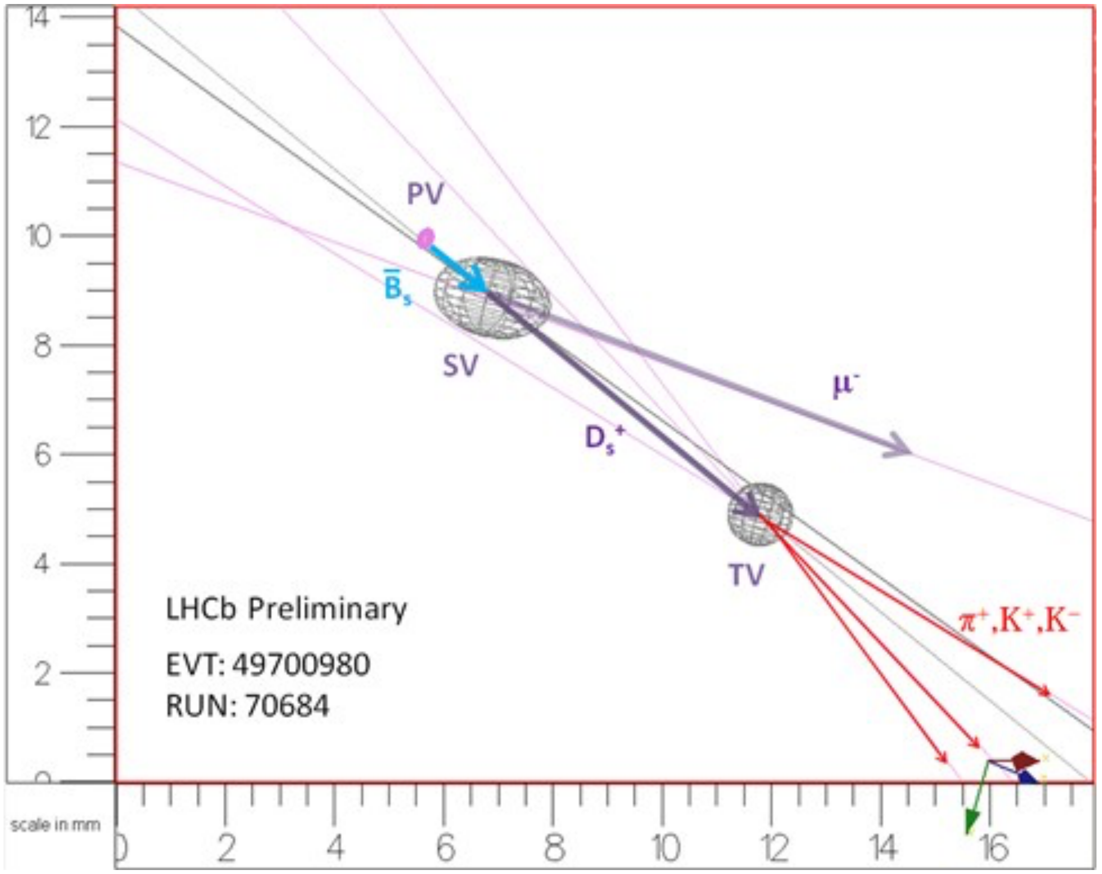


A key LHCb Element: Vertex Reconstruction

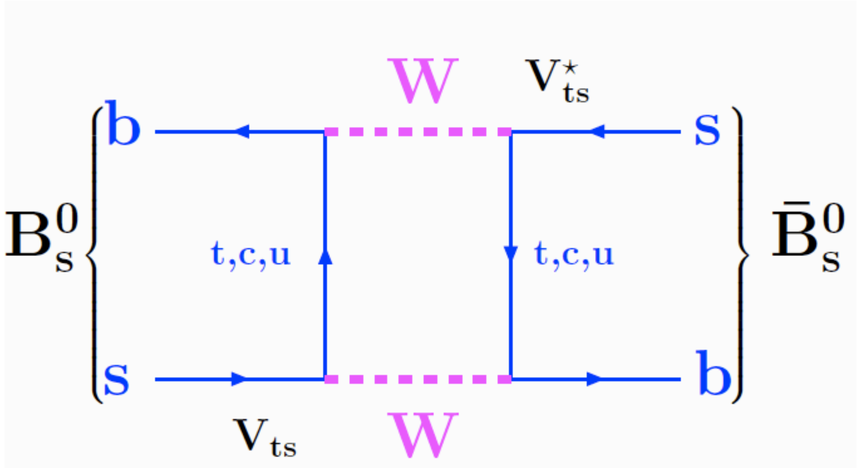
- The vertex locator VELO

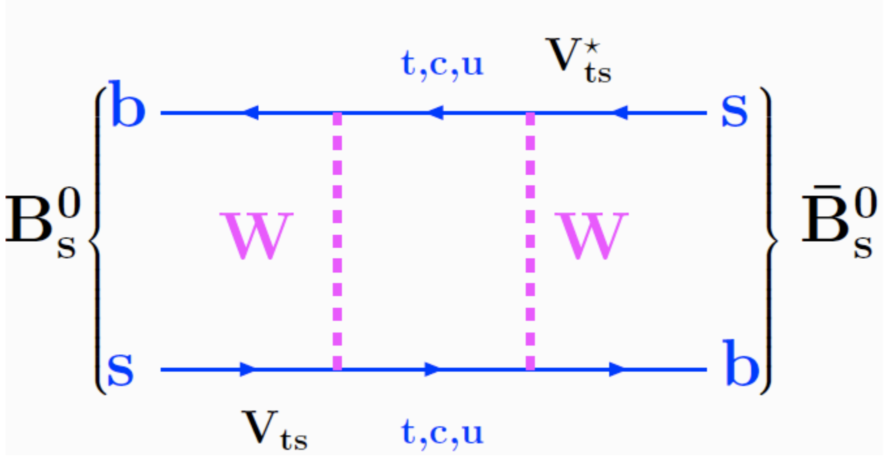
- 42 silicon detector elements inside the beam pipe vacuum to get as close as possible to the interaction point
  - Localisation of B hadron decays with 10 µm precision

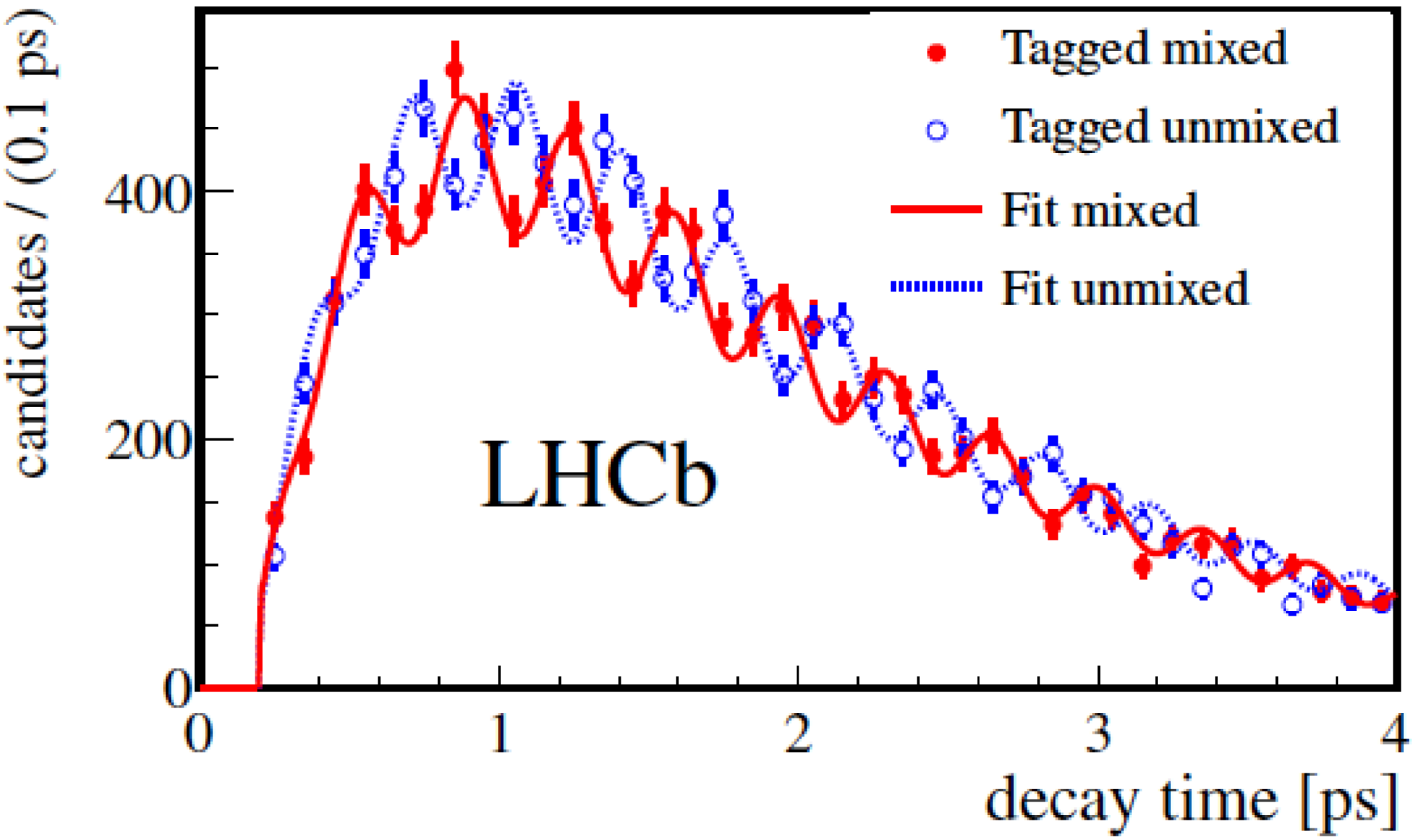




At Hadron Colliders: Measurements of B_s





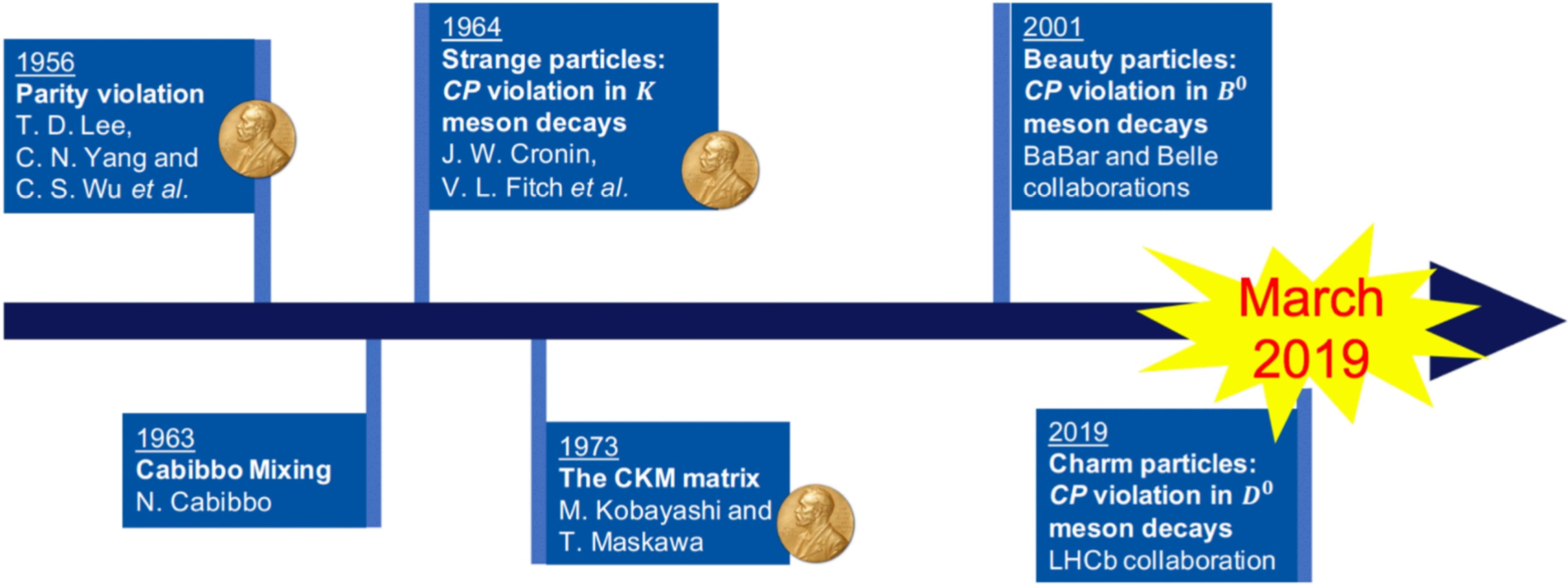


- Larger mass difference: Much faster oscillation

A long list of other measurements

- … which we cannot cover here, some intriguing observations connected to leptons in the final state, but nothing conclusive so far

A brief history of CP Violation measurement & theory



1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
CP violation in K meson decays
J. W. Cronin,
V. L. Fitch *et al.*

1973
The CKM matrix
M. Kobayashi and
T. Maskawa

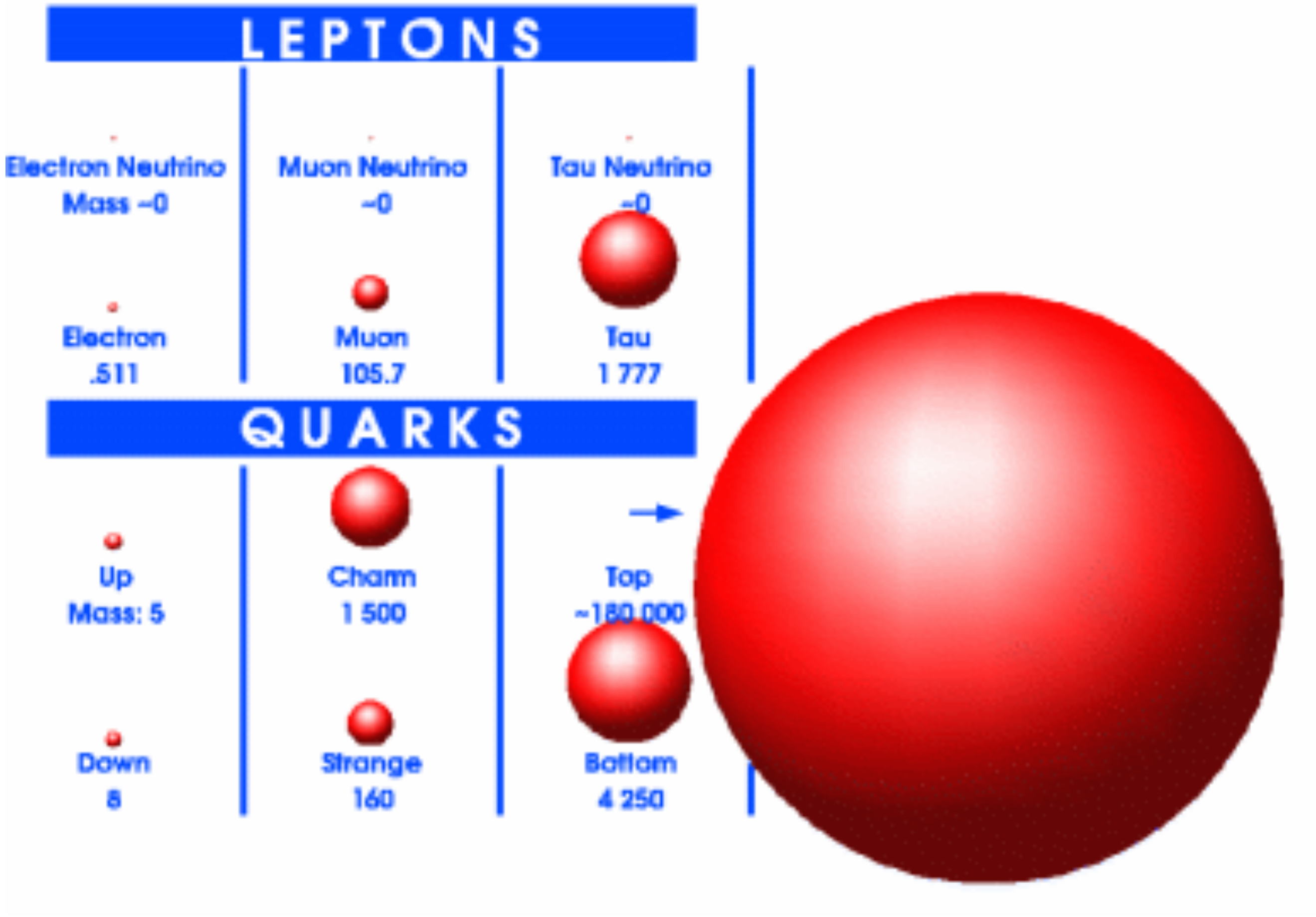
2001
Beauty particles:
CP violation in B^0 meson decays
BaBar and Belle collaborations

2019
Charm particles:
CP violation in D^0 meson decays
LHCb collaboration

Top Quark Physics

Why are we so interested in the Top Quark?

- The Top quark has a special role in the Standard Model
  - It is the heaviest particle, and by far the heaviest Fermion
  - Its mass is comparable to the electroweak scale - The top quark could be a window to new physics!
  - Its life time is shorter than the hadronization time - it does not form bound states



The Questions:

- How are top quarks produced?
- How do they decay?
  - both compared to the SM expectation
- What is the mass of the top quark?

The Top Quark in The Standard Model

- Remember lecture 5: Precision measurements of boson gauge boson (and other) properties, together with the assumptions of the Standard Model can provide indirect constraints on unobserved particles
  - These “loop corrections” typically increase with particle mass: Most relevant for top quark loops

In the Standard Model:

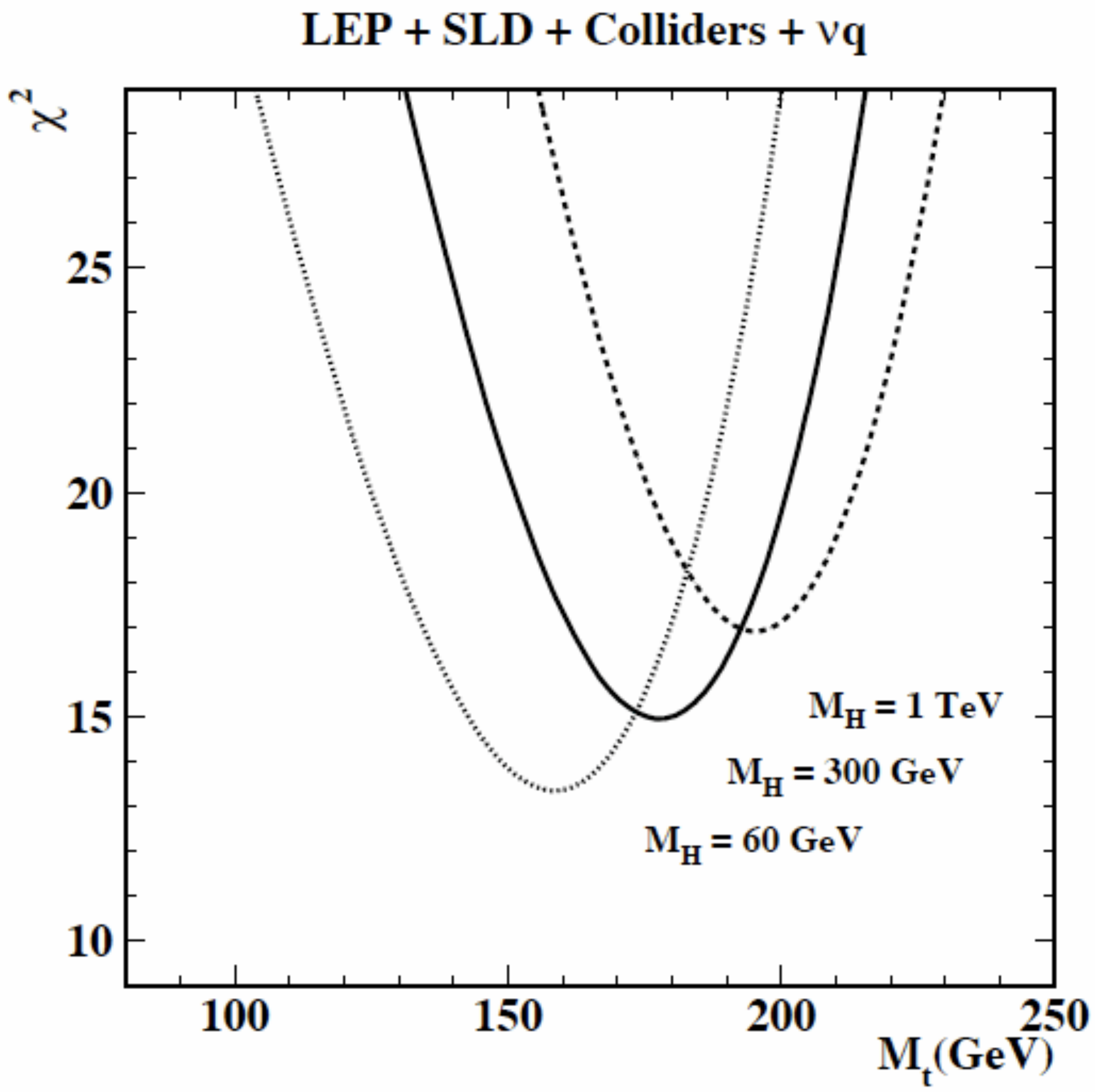
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F}\frac{1}{sin^2\theta_W(1-\Delta r)}$$ with $$\frac{m_W^2}{m_Z^2} = 1 - sin^2\theta_W$$

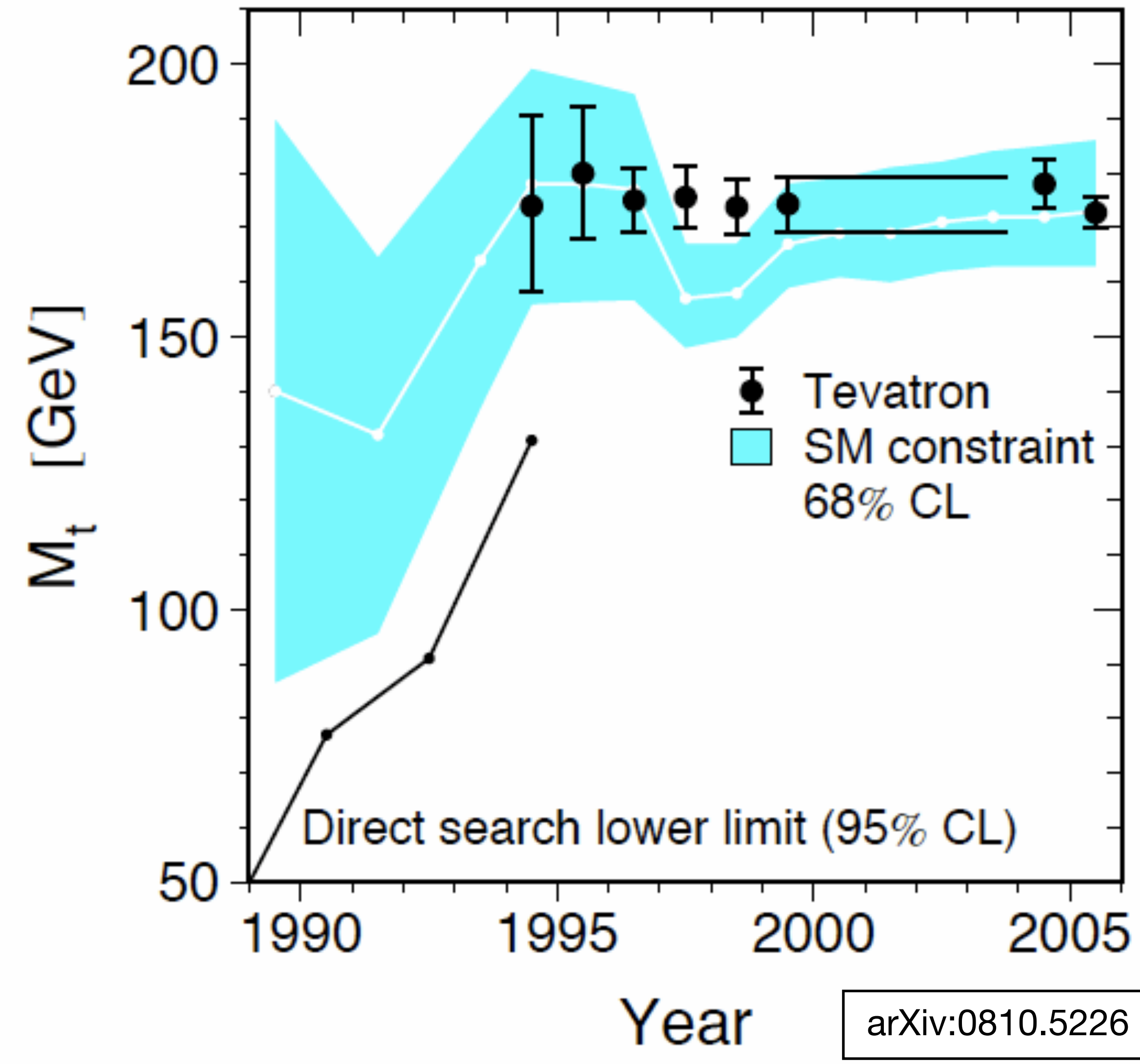
The influence of single top loops:

$$\Delta r^{top} = -\frac{3\sqrt{2}G_F cot^2\theta_W}{16\pi^2}m_t^2$$ for $m_t \gg m_b$

NB: Corrections quadratic in m_t, there are also Higgs-induced corrections, which depend logarithmically on m_H: Need to know the top well to constrain H

Predicting the Top Quark Mass





arXiv:0810.5226 [hep-ex]

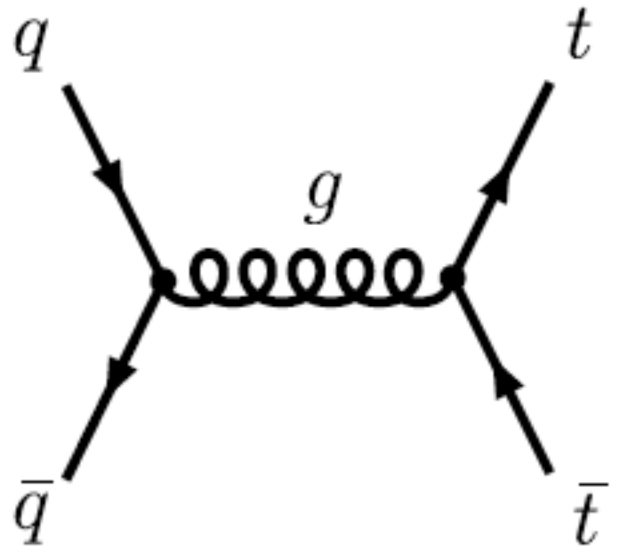
- Improvement of electroweak precision measurements led to a constant improvement of the prediction of the top quark mass -> early on it was clear the top is heavy!

➯ Discovery of the top quark in 1995 at the Tevatron, 18 years after the b

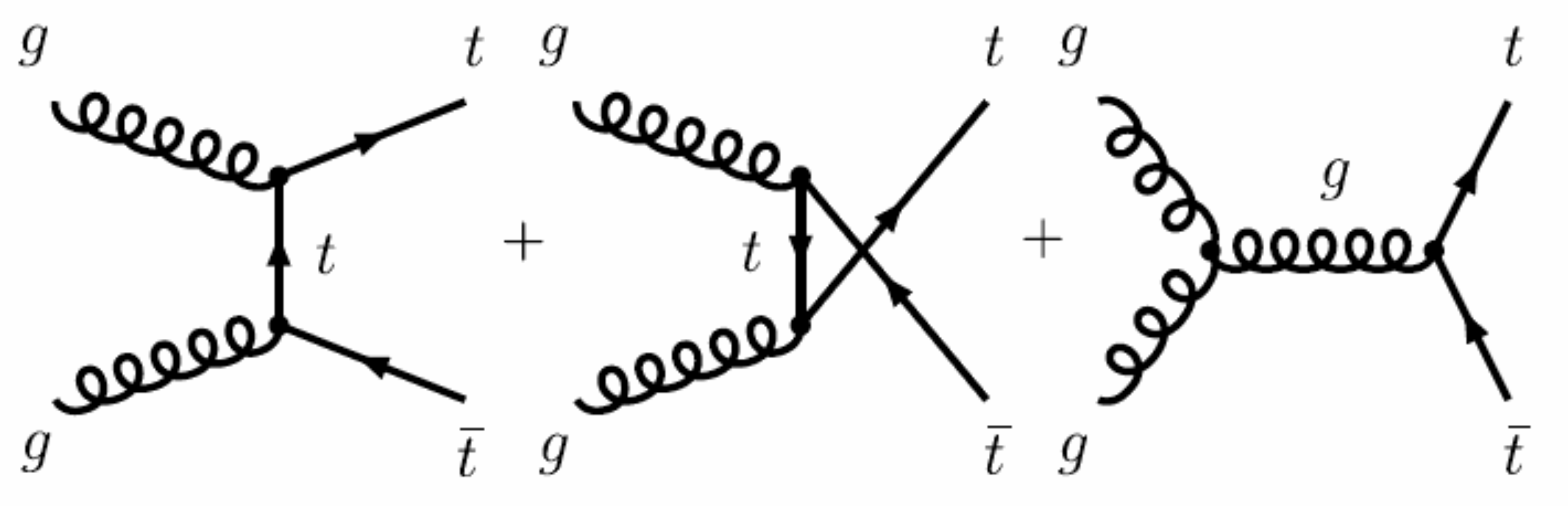
Top Quark Pair Production

- Two important production mechanisms via the strong interaction

Quark-AntiQuark annihilation:



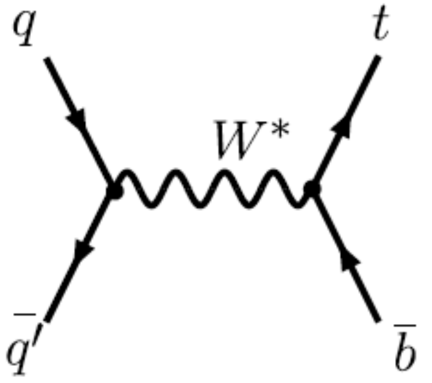
Gluon-Gluon fusion:



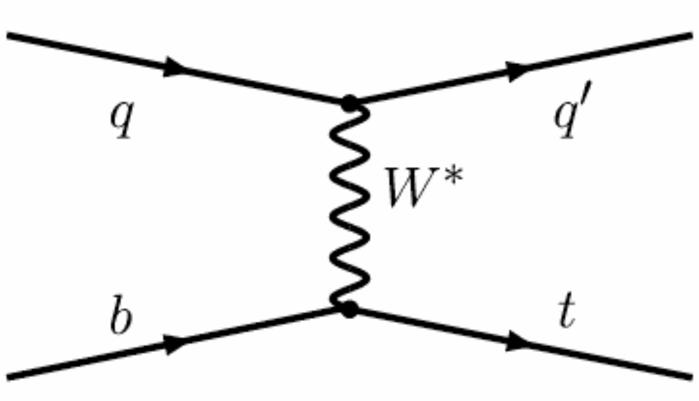
Production of Single Top Quarks

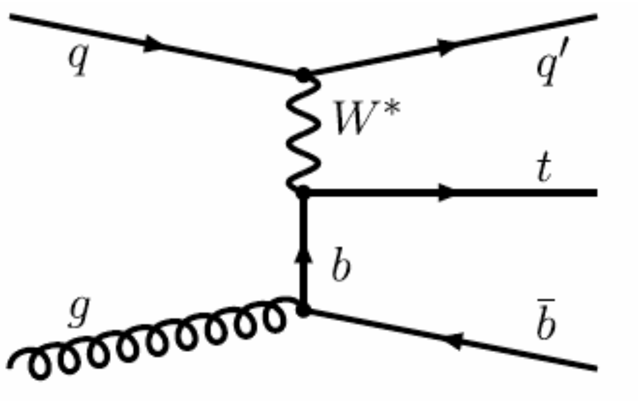
- Production of single top quarks via the weak interaction:

s-channel production via W exchange

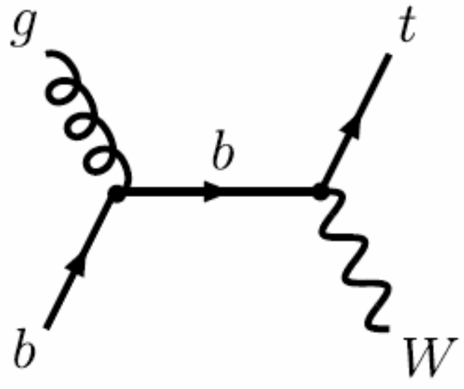


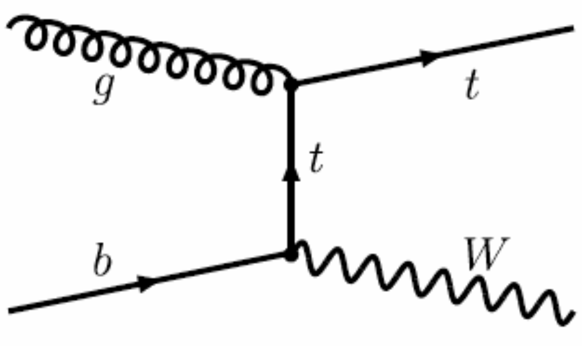
t-channel production





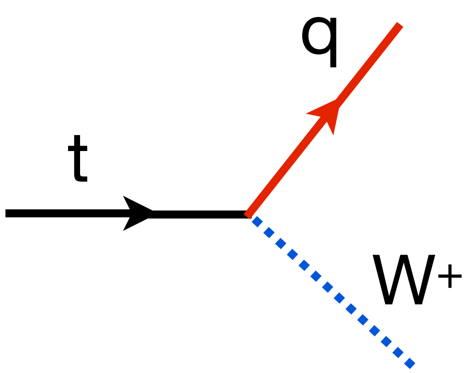
associated production of
W and t quark





Top Quark Decay

- Decay via the weak interaction:



$$R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

Currently (assuming 3 generations and unitarity):

$$|V_{td}| = 0.00874^{+0.00026}_{-0.00037}$$

$$|V_{ts}| = 0.00407 \pm 0.0010$$

$$|V_{tb}| = 0.999133^{+0.000044}_{-0.000043}$$

➯ Top quarks decay almost exclusively into a W boson and a b quark

Top Quark: Width / Lifetime

- In the Standard Modell the width of the top is given by:

$$\Gamma_t = |V_{tb}|^2 \frac{G_F\, m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{m_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]$$

- For a mass of ~ 170 GeV this gives a width of ~ 1.3 GeV
  - Corresponds to a lifetime of ~ 5 x 10^{-25} s
  - Much shorter than the hadronization time:

$$\tau_{had} = \Lambda_{QCD}^{-1} \approx (0.2\,\mathrm{GeV})^{-1} \approx 3 \times 10^{-24}\,\mathrm{s}$$

➩ Top quarks do not form bound states, they decay as free quarks

(Still there are influences from the strong interaction, for example via the interaction of the t quarks with the proton remnants in hadron collisions (effects increase with energy), interactions of the decay products from the two quarks in pair production, ...)

arXiv:0810.5226 [hep-ex]

Top Decays: Classified by Decay of W Bosons

- W decay via the weak interaction:
  "Universality" of the weak interaction, maximal parity violation

- couples to left-handed fermions, right-handed anti-fermions, always with the same strength
  - Quarks have a three-fold weight: 3 colors!
  - Example W^+:

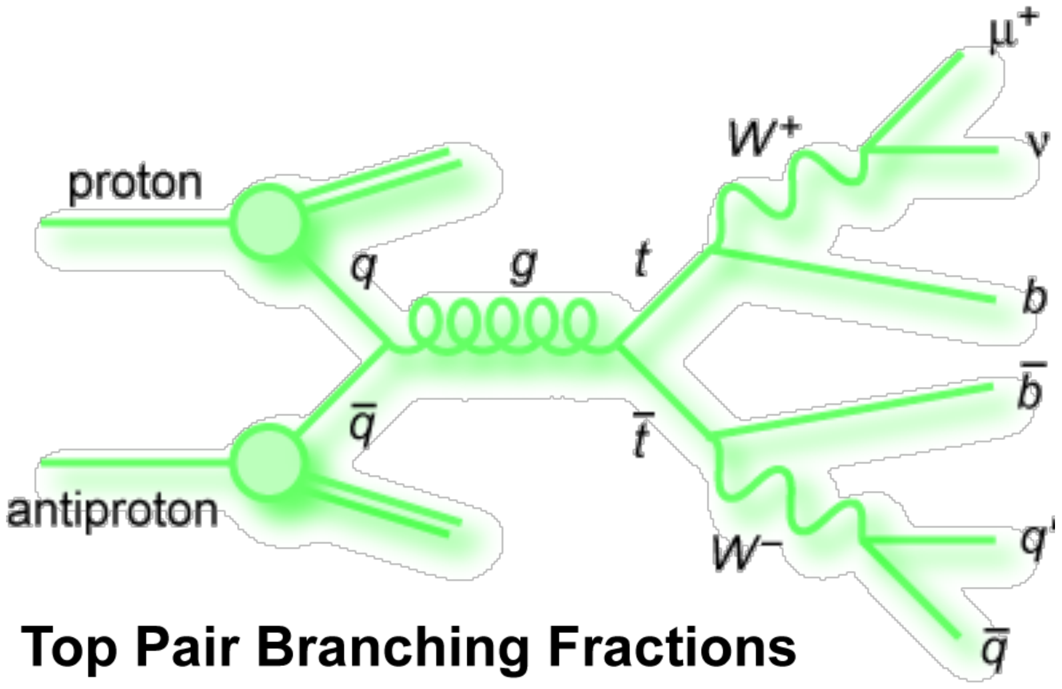
$$W^+ \rightarrow e^+\nu_e : \mu^+\nu_\mu : \tau^+\nu_\tau : u\bar{d}' : c\bar{s}'$$

$$1 : 1 : 1 : 3 : 3$$

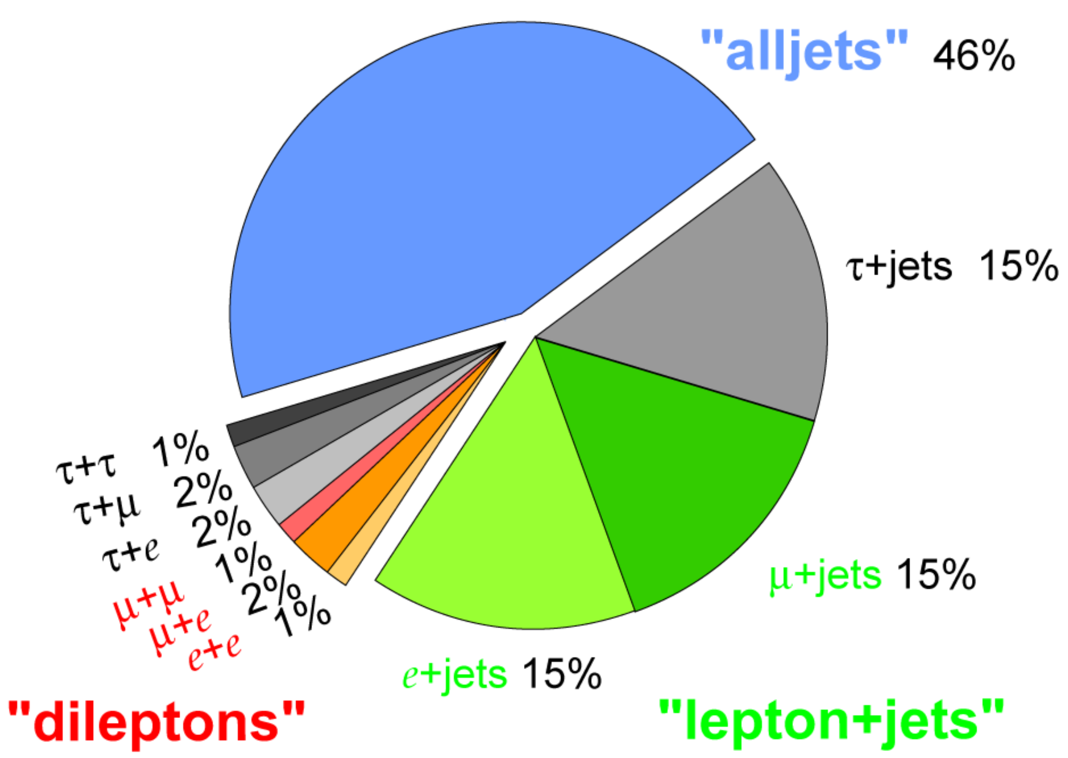
- The types of the W decay determine the different top decay signatures

Top Quark Pair Decays - Classification

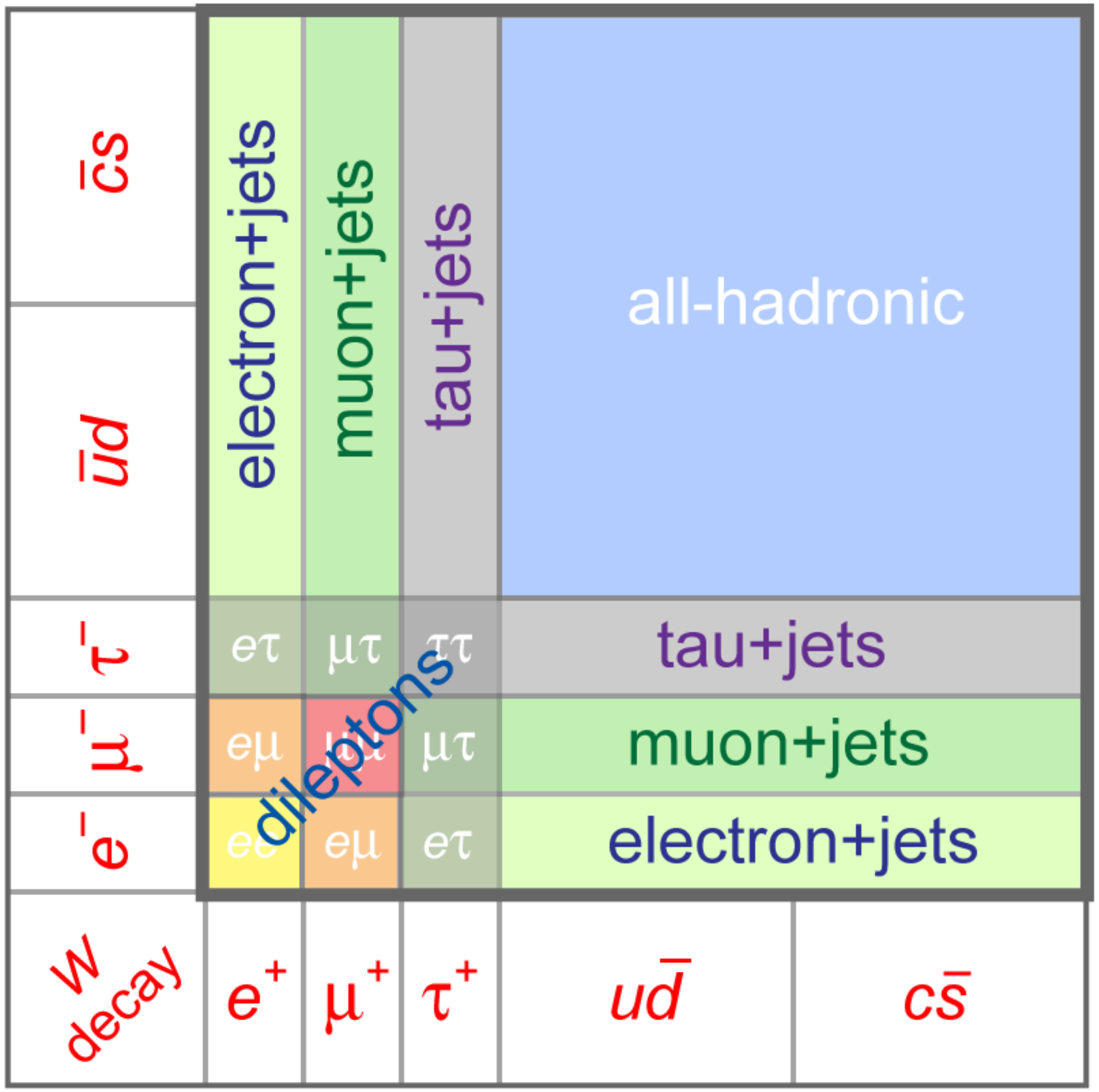
- Classified according to W decay (since basically 100% t → bW)



Top Pair Branching Fractions



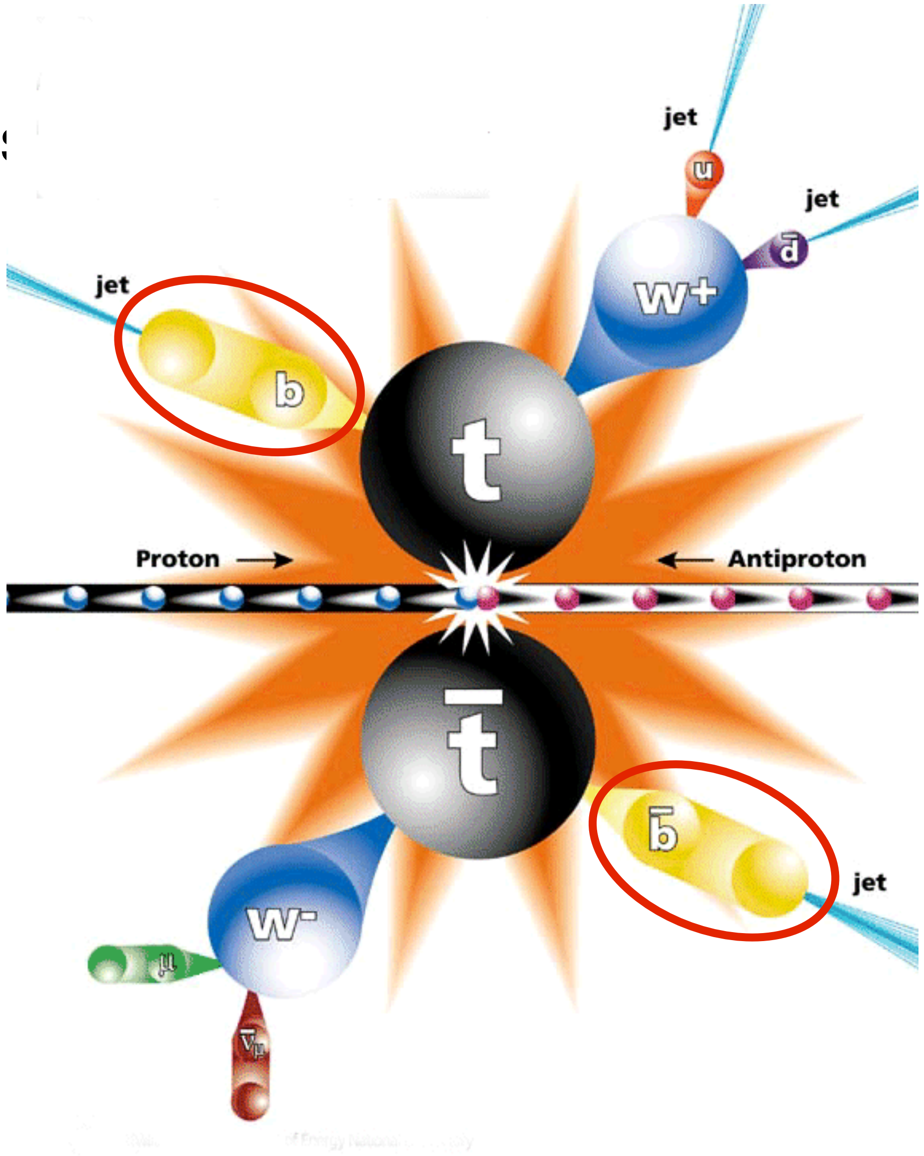
Top Pair Decay Channels



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

Detection of Top Events

- Classification of the events based on their characteristic signatures, then a specialized analysis for each decay mode
  - Di-Lepton Events: Two isolated, highly energetic leptons (e, μ) from W decay
  - Lepton + Jets: One isolated lepton (e, μ) from W decay, jets from W decay and from b quarks
  - All-Hadronic: Jets from both Ws, jets from b quark Tagging crucial - quite difficult at hadron colliders

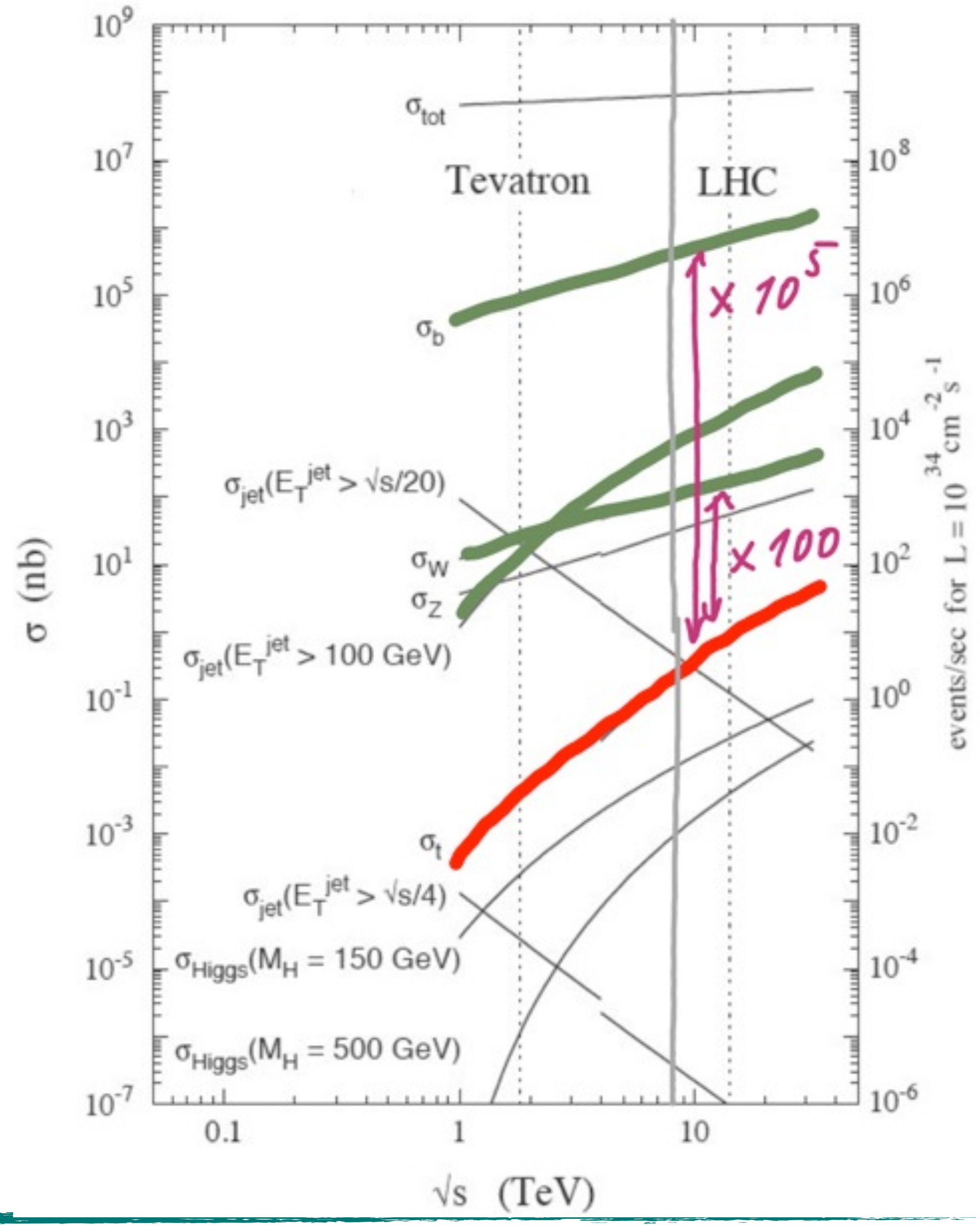


Reminder: b quark identification

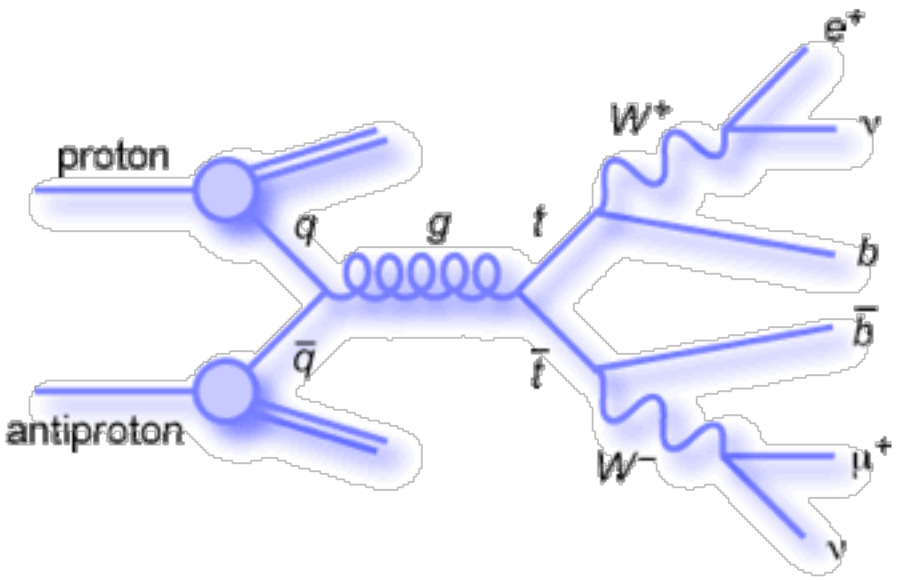
- Relatively long life time of mesons containing b quarks ($c\tau$ (B^0) ~ 460 μm, $c\tau$ ($B^\pm$) ~ 490 μm)
- ‣ Identification of a displaced secondary vertex in a jet
  - ‣ Jet is “tagged” as a b jet

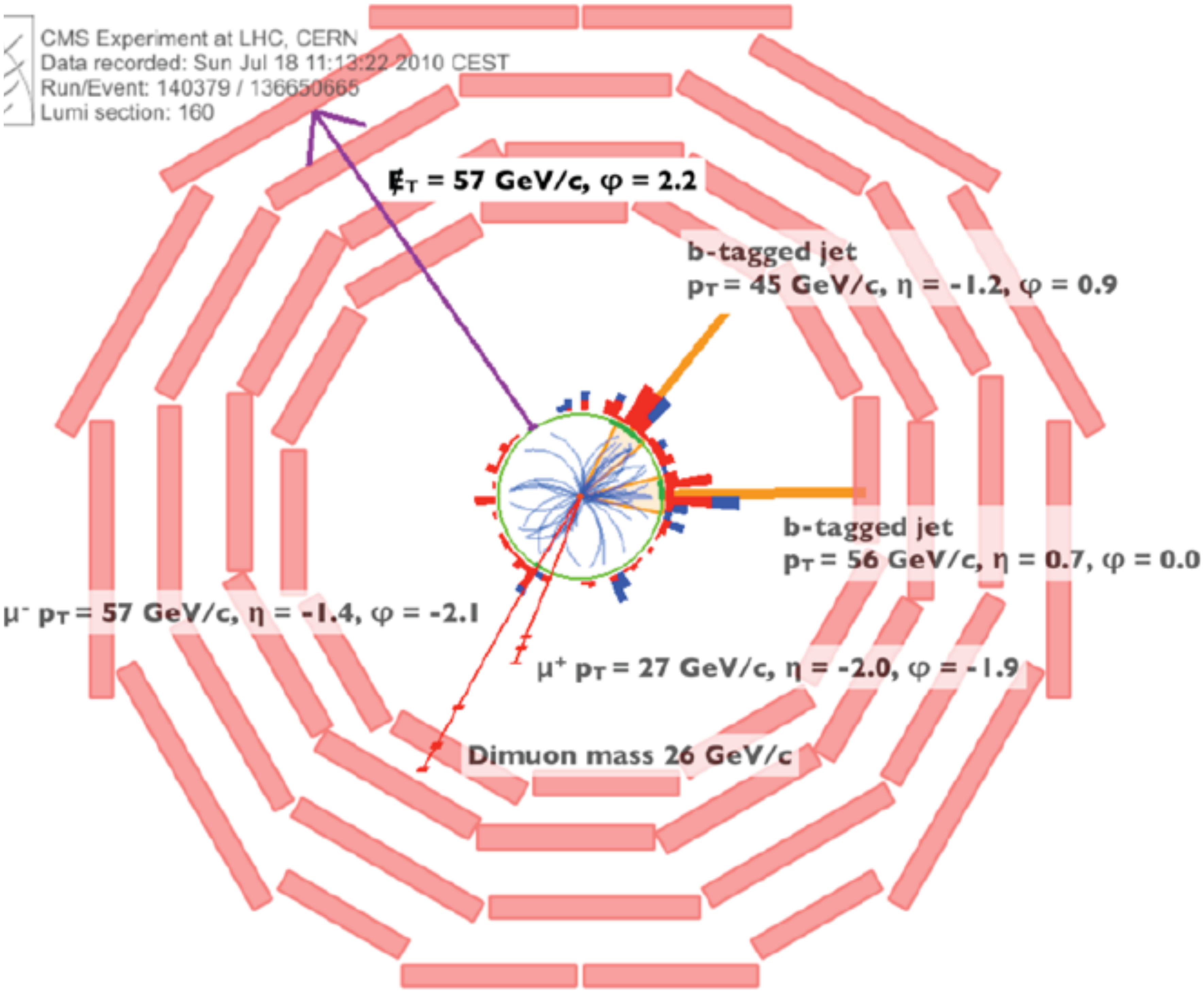
The Challenge: Background

- Top production is only a very small part of the total pp cross section
- High background, in particular for hadronic decays of the W
  - all-hadronic: QCD multi-jet background (very high!)
  - lepton+jets: W + jets and QCD multi-jet background (ok)
  - di-lepton: Z + jets and di-boson background (low)



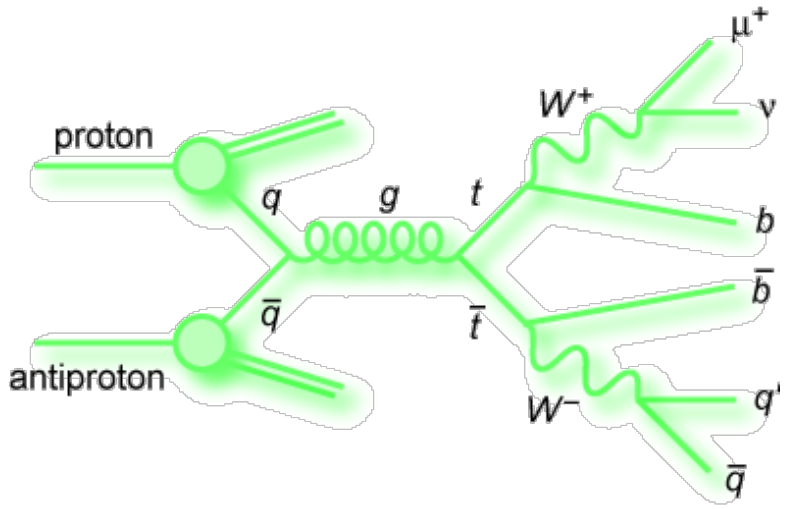
Experimental Detection: Di-Lepton Events



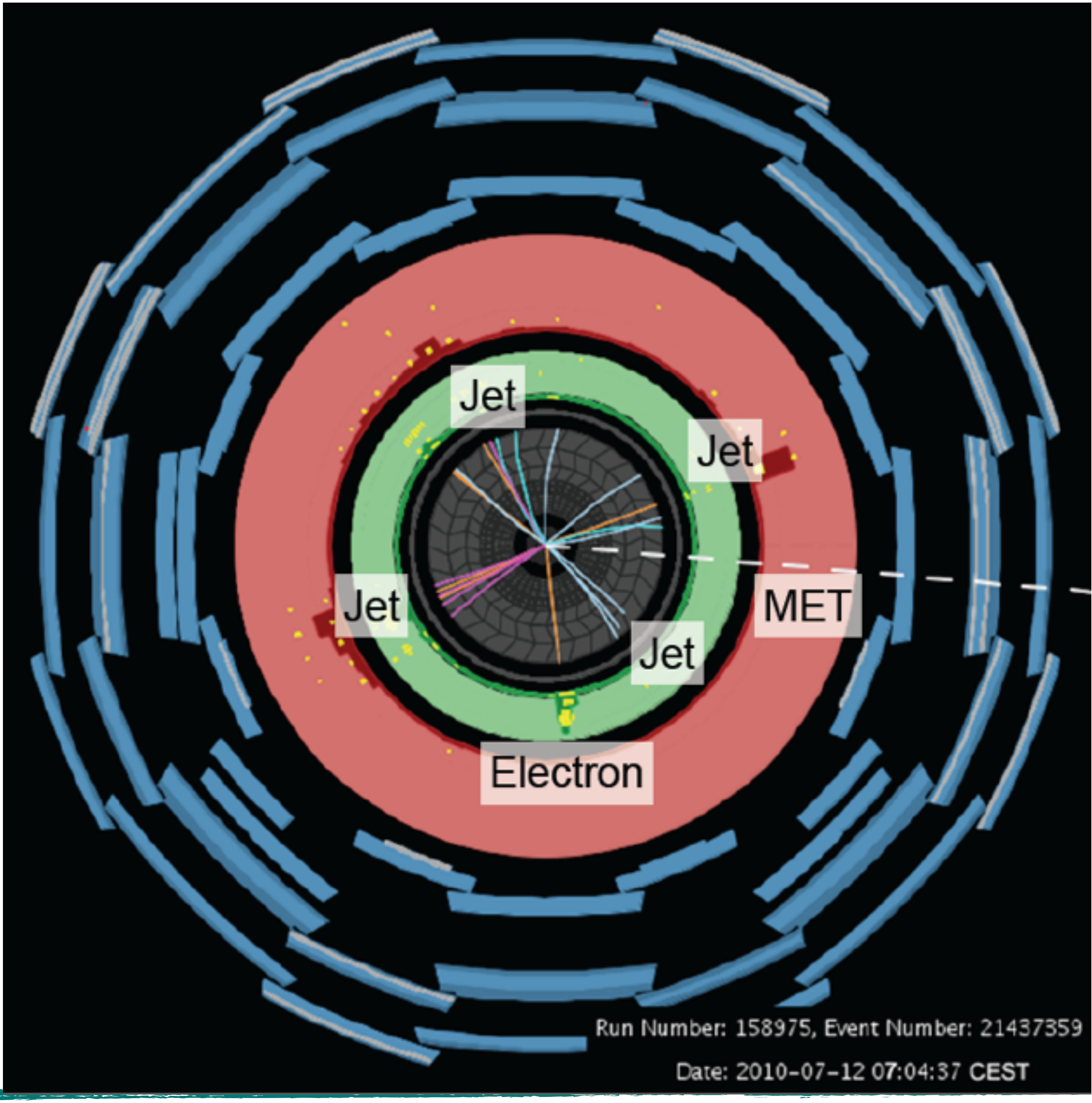


- Clear, clean signature
- missing information from two (undetected) neutrinos
- small branching ratio, low statistics
- Background: mainly W + X

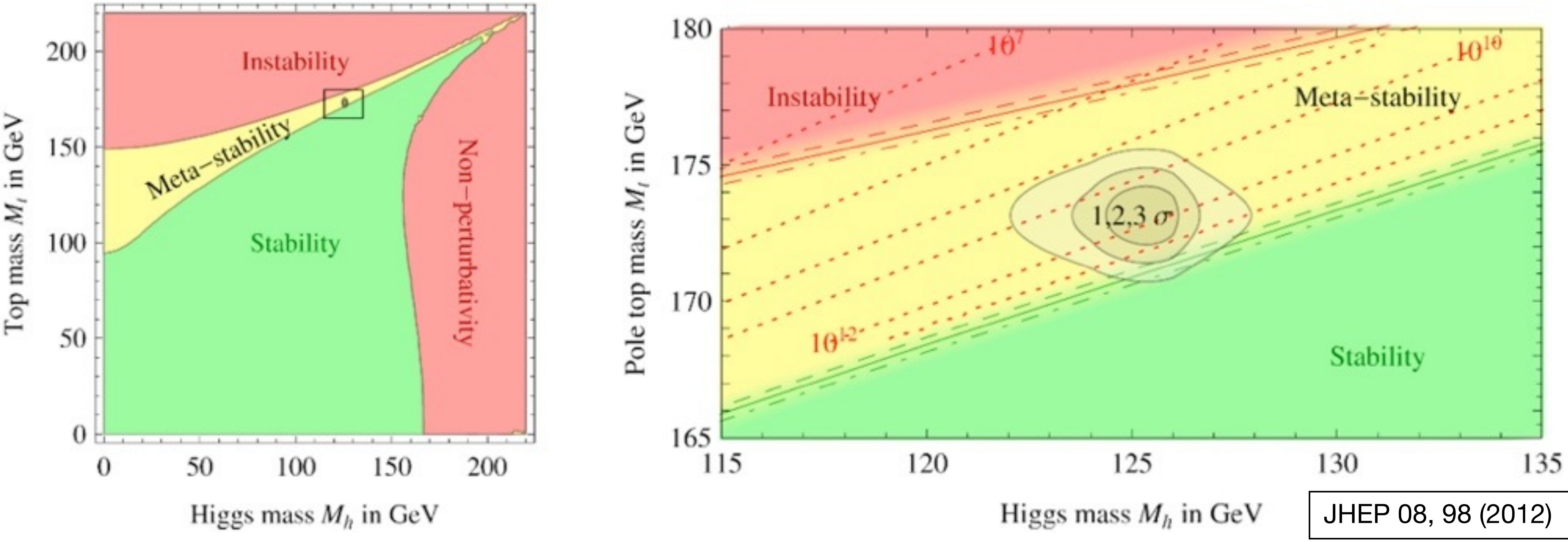
Experimental Detection: Lepton + Jets



- Relatively clean due to the leptonic decay of one W
    - Signature: Isolated lepton, highly energetic jets and missing energy
- missing information from neutrino
- high statistics (BR 30%)
- Background: Mainly W + jets



Interest in Top Mass: The Fate of the Universe



JHEP 08, 98 (2012)

- Top mass, together with Higgs mass and strong coupling, provides key information on the stability of the SM vacuum at higher scales
  - Possible validity of the SM up to the Planck scale?
  - Impact on evolution of the early universe (Higgs inflation models, ...) & physics beyond the SM

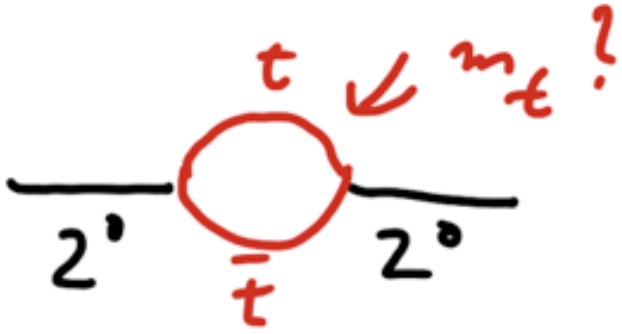
Leading uncertainty: Top Mass!

Measurement of the Mass: General Issues

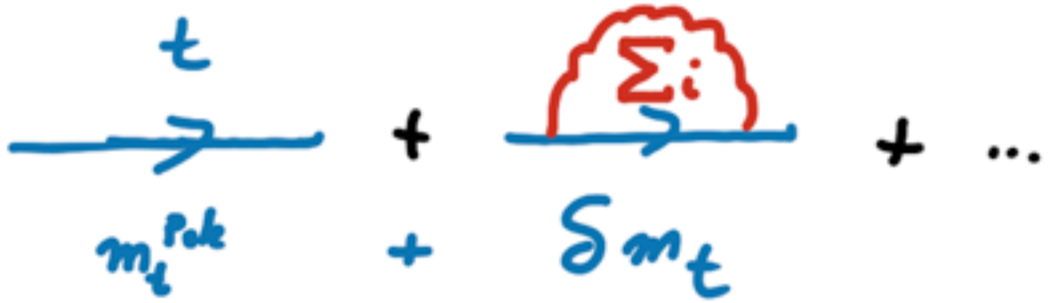
- The mass of the top quark is an important parameter of the standard model - and as such very interesting

The problem: What is a quark mass? - Here the “standard” definitions of theorists and experimentalists are not the same

For **theory**: The mass has to be relevant for precision calculations



Defining the mass of the top is not trivial - it is influenced by QCD corrections at higher orders

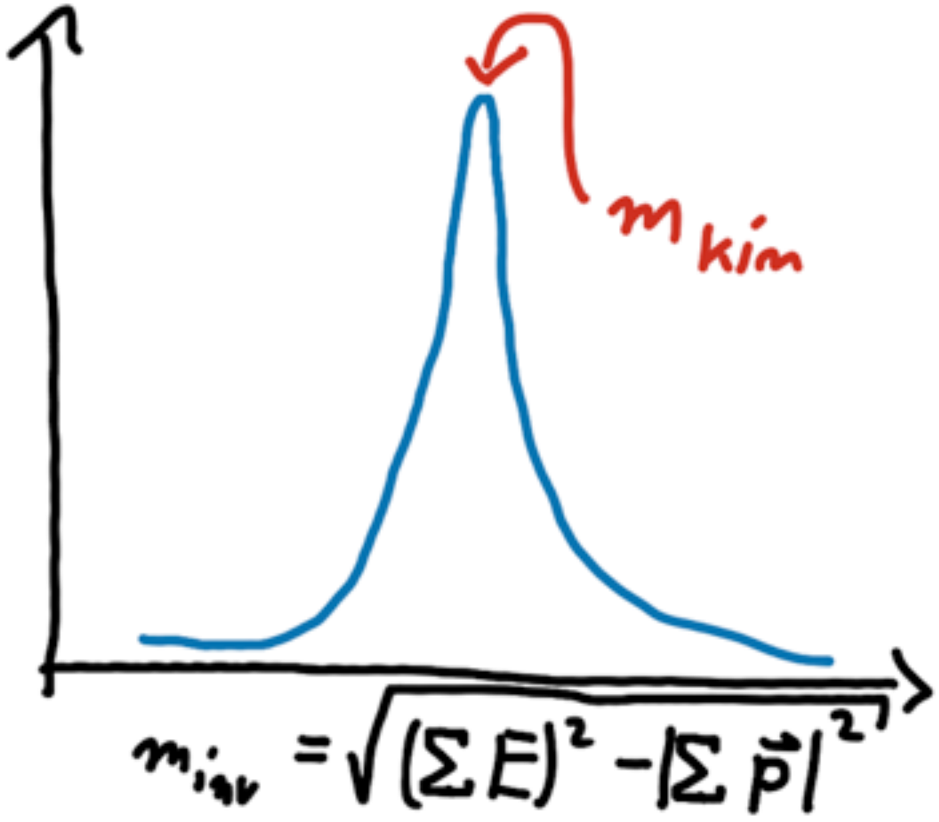


Several definitions exist in theory, depending on the need of the calculations - They can typically be converted with high precision with higher order calculations - Uncertainties on the **100 MeV** level

Measurement of the Mass: General Issues

For **experiment:**

The standard technique to measure a mass is to reconstruct the “invariant mass” of the decay products



The challenge: The connection between the experimentally measured “kinetic mass” and the theoretical definitions is unclear - non-perturbative corrections from the strong interaction
Uncertainties on the **GeV** level - comparable to experimental precision of current experiments, will become critical for future top mass measurements!

Techniques to measure the Top Mass

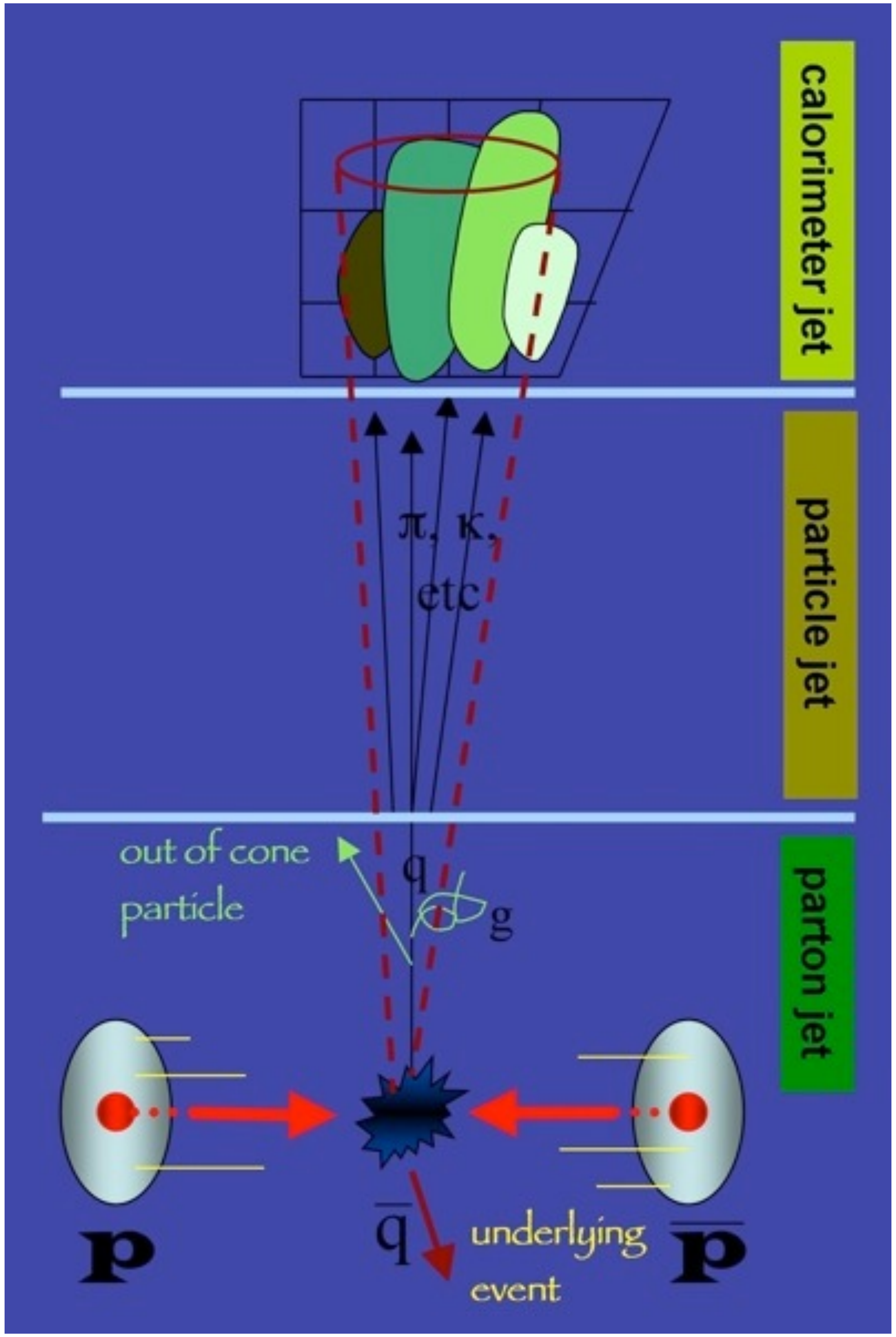
- Measurement in all final states of top pair events:
  Di-Lepton, Lepton+Jets, All Hadronic

- Different methods are used - (almost) all based on kinematic reconstruction:
  - Template-Method: The measured distribution is compared with simulated distributions using different generator top masses as input
  - Matrix-Element-Method: For each event, a probability distribution of the true top mass is calculated based on the reconstructed final state object, probability based on LO matrix elements
    - Combination with Templates: Ideogram - Method
  - ...

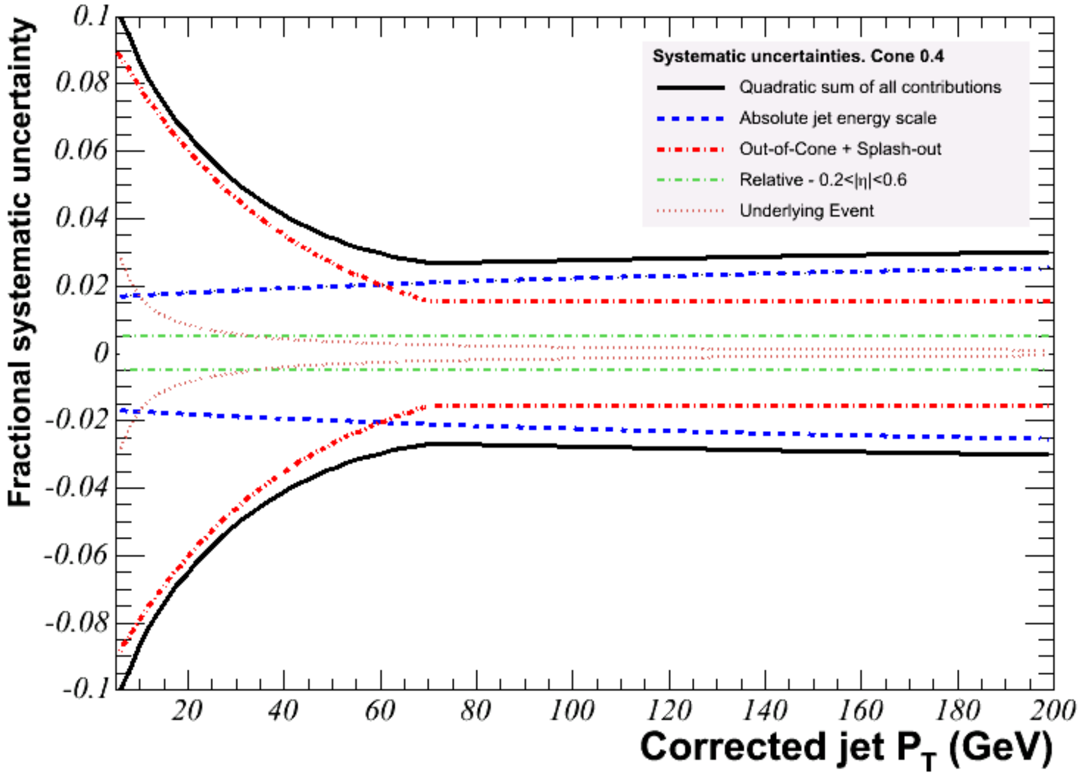
▸ Best accuracy achieved by multi-dimensional fits to reduce systematics

- Most measurements are already limited by systematic uncertainties
  - Important contribution: Jet Energy Scale

Crucial for Mass Measurements: Jet Energy Scale



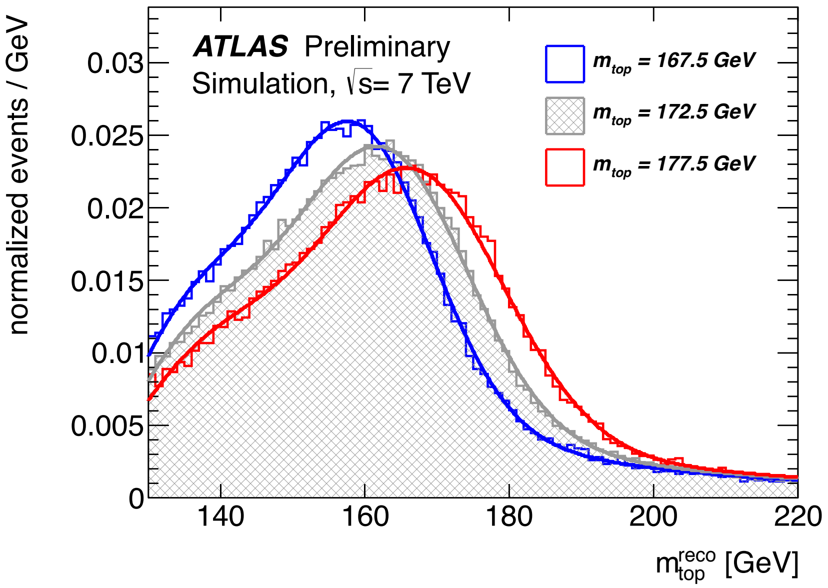
- The measurement of a jet:
  - Energy in a cone with a certain radius (various definitions in use) typically in the calorimeters (more sophisticated approaches also use tracks)
- The physics observable:
  - Energy of the original parton
- The energy scale corrects from the measured jet energy to the energy of the parton
- Uncertainties from energy calibration, jet structure, ...

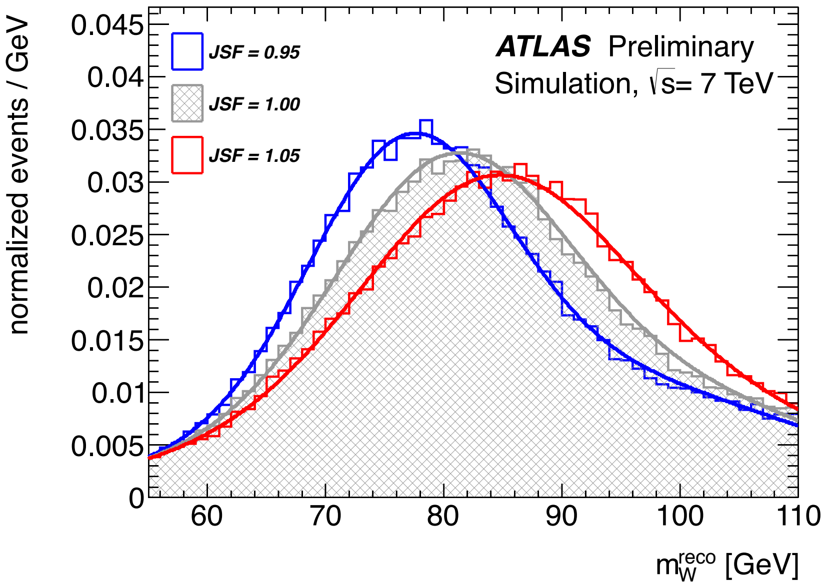


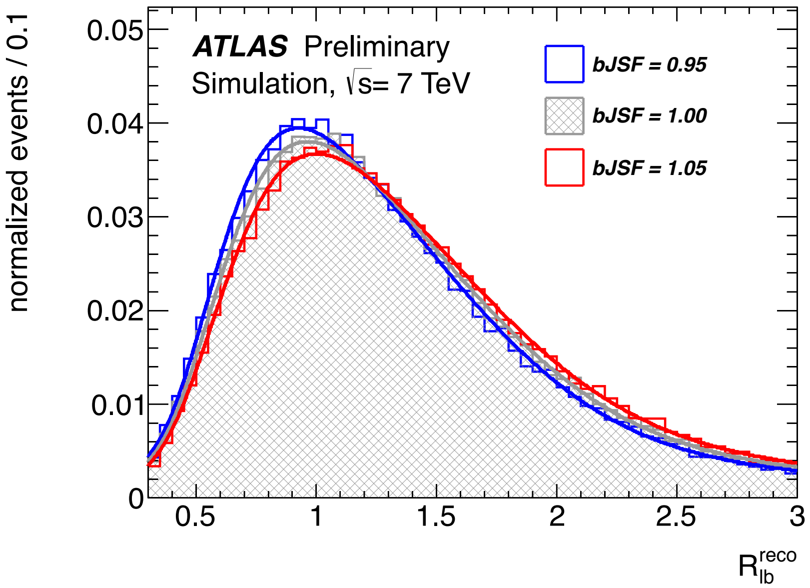
CDF

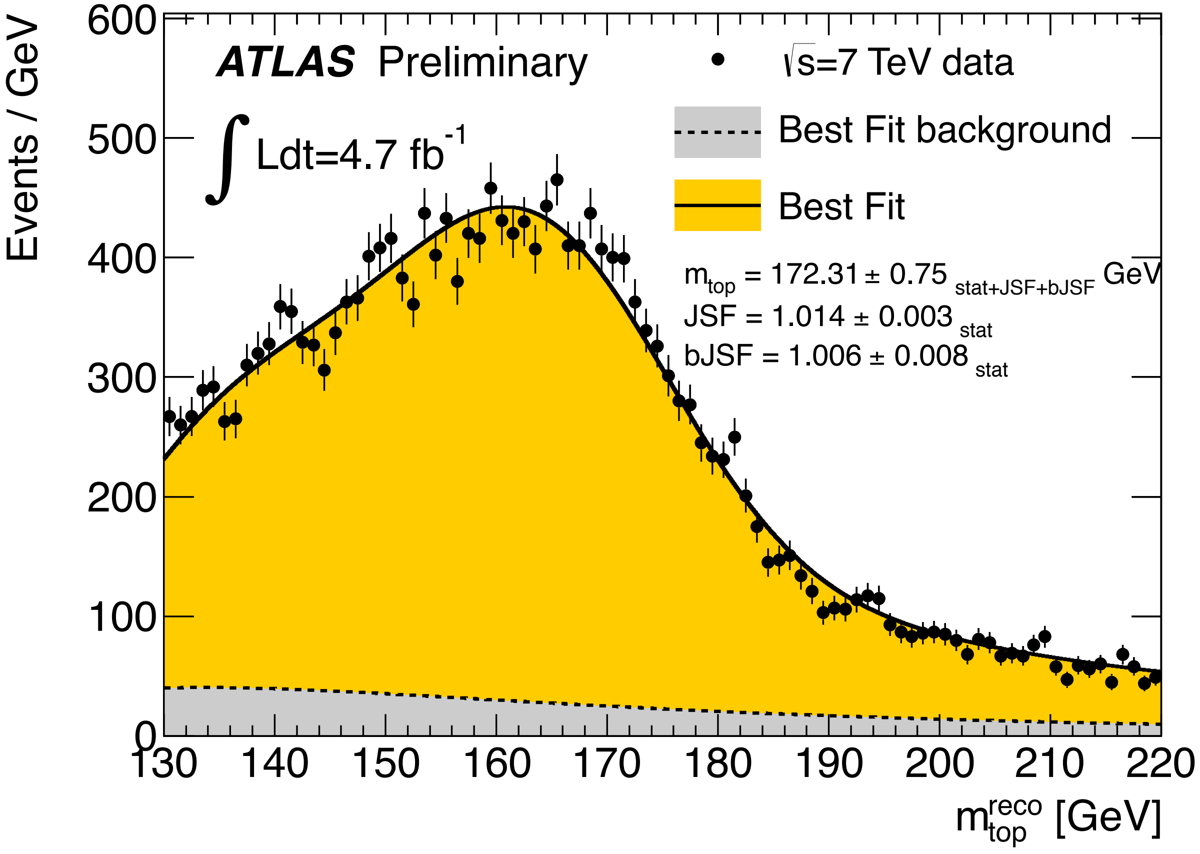
One Example: Lepton + Jets in ATLAS

- 3D Template fit to extract mass, JES and specific b-Jet energy scale







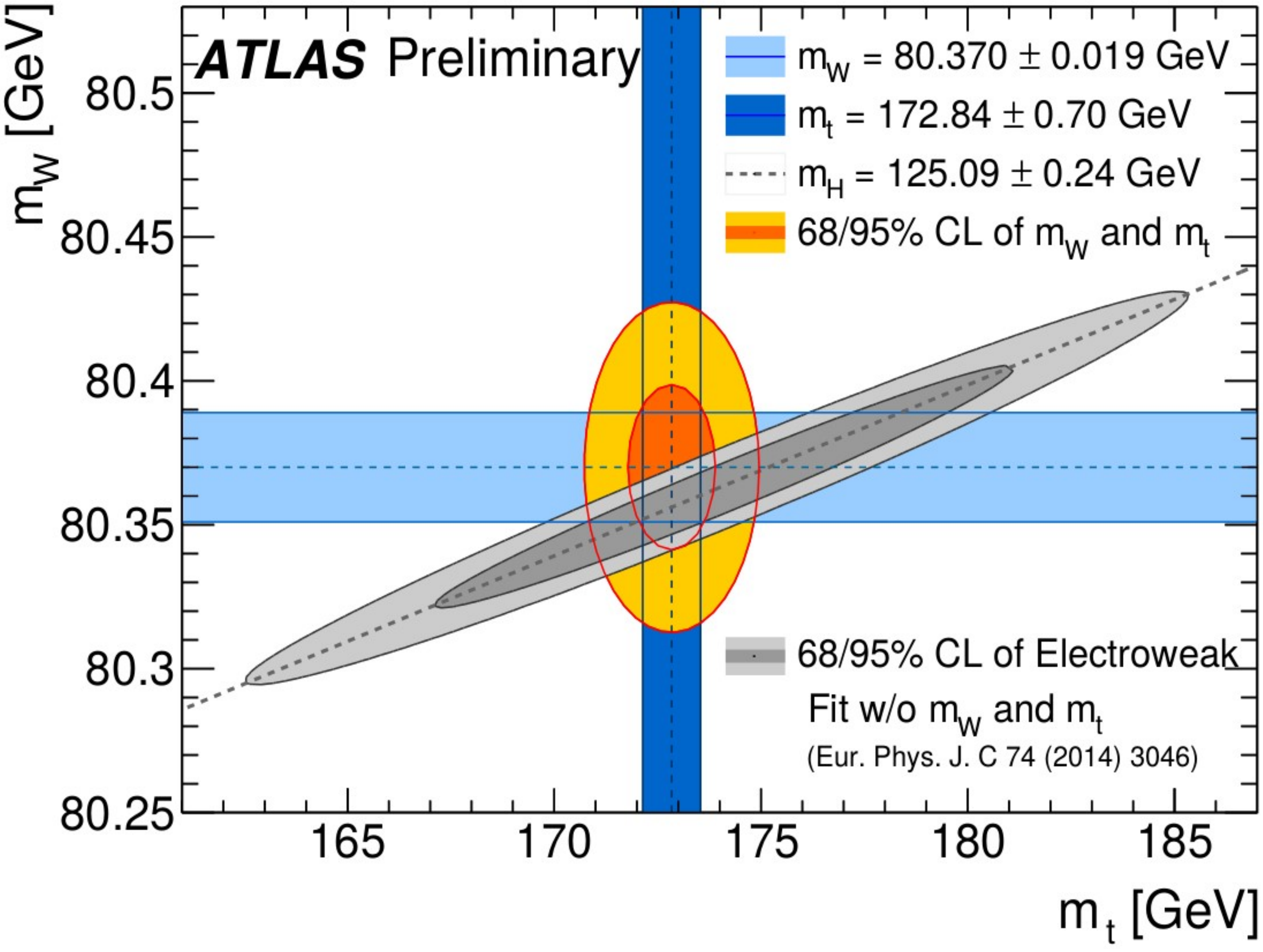


3D fitting substantially reduces systematics (-40% compared to previous technique!)

m_{top} = 172.31 ± 0.23(stat) ± 0.27(JSF) ± 0.67(bJSF) ± 1.35(syst) GeV

Combined with other measurements:
Uncertainty **< 1%**
- By far the best-known quark mass!

SM Closure Test: Now Possible with LHC alone



- Using ATLAS results in an electroweak fit:
  - Top mass
  - Higgs mass
  - W mass

… and a Wealth of other Results

- Measurements of single top production (directly constraining CKM elements)
- Mass measurements in theoretically well-defined mass definitions via the top pair production cross section (larger uncertainties from PDFs)
- First observation of ttH coupling: Direct access to the top Yukawa coupling
- …

Next Semester

- Lecture:
  Particle Physics at Colliders and in the High Energy Universe

- New addition: ***Journal club*** with selected publications on the topics discussed in the lecture

- Announcement to come - expected time slot
  Mondays, 15:00 - 18:00

Lecture Overview

29.04.	Introduction & Recap: Particle Physics & Experiments	*F. Simon*
06.05.	Dark Matter axions and ALPs: Where do they come from?	*B. Majorovits*
13.05.	Axions and ALPs detection	*B. Majorovits*
20.05.	Dark Matter WIMPs - origin and searches	*B. Majorovits*
27.05.	Precision Tests of the Standard Model	*F. Simon*
03.06.	Neutrinos: Freeze out, cosmological implications, structure formation	*B. Majorovits*
	Pentecost	
17.06.	Natural Neutrino Sources: What can we learn from them?	*B. Majorovits*
24.06.	Neutrino Oscillations with Manmade Sources	*F. Simon*
01.07.	Precision Experiments with Low-Energy Accelerators	*F. Simon*
08.07.	Neutrinoless Double Beta Decay	*B. Majorovits*
15.07.	Gravitational Waves	*F. Simon*
22.07.	Physics with Flavor: Top and Bottom	*F. Simon*