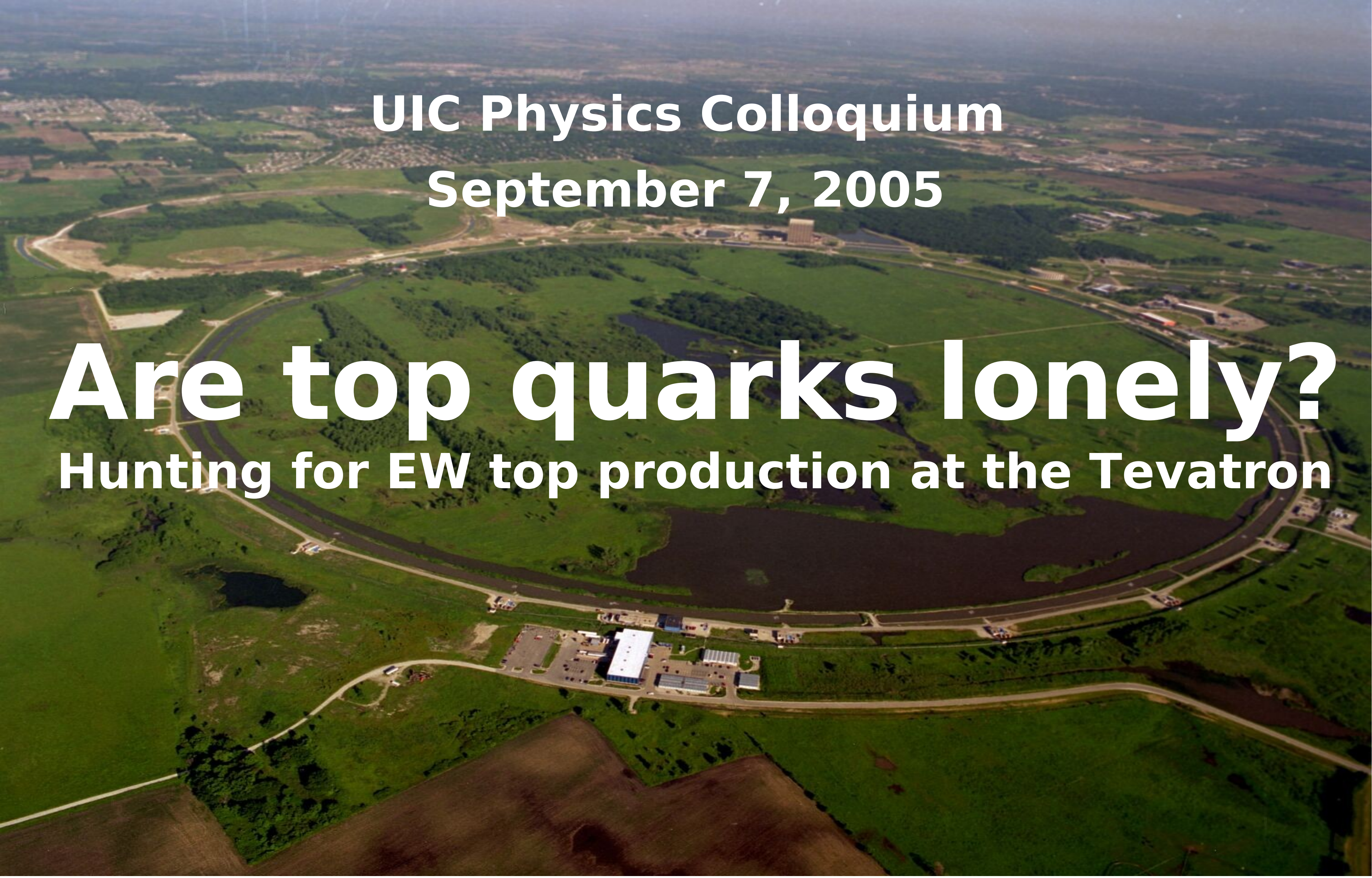


UIC Physics Colloquium

September 7, 2005

Are top quarks lonely?

Hunting for EW top production at the Tevatron

UNIVERSITY OF WASHINGTON

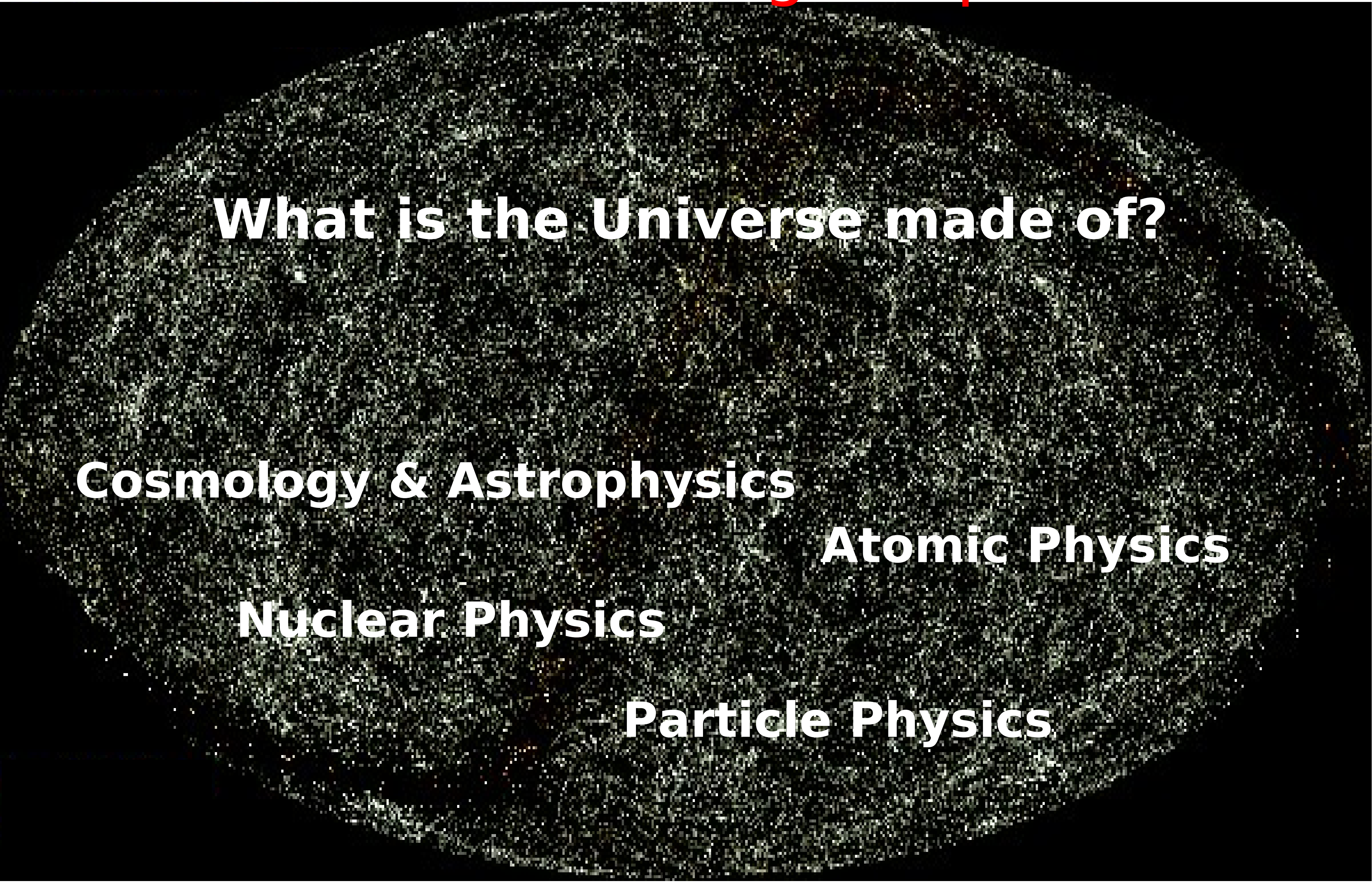
Arán García-Bellido

DØ

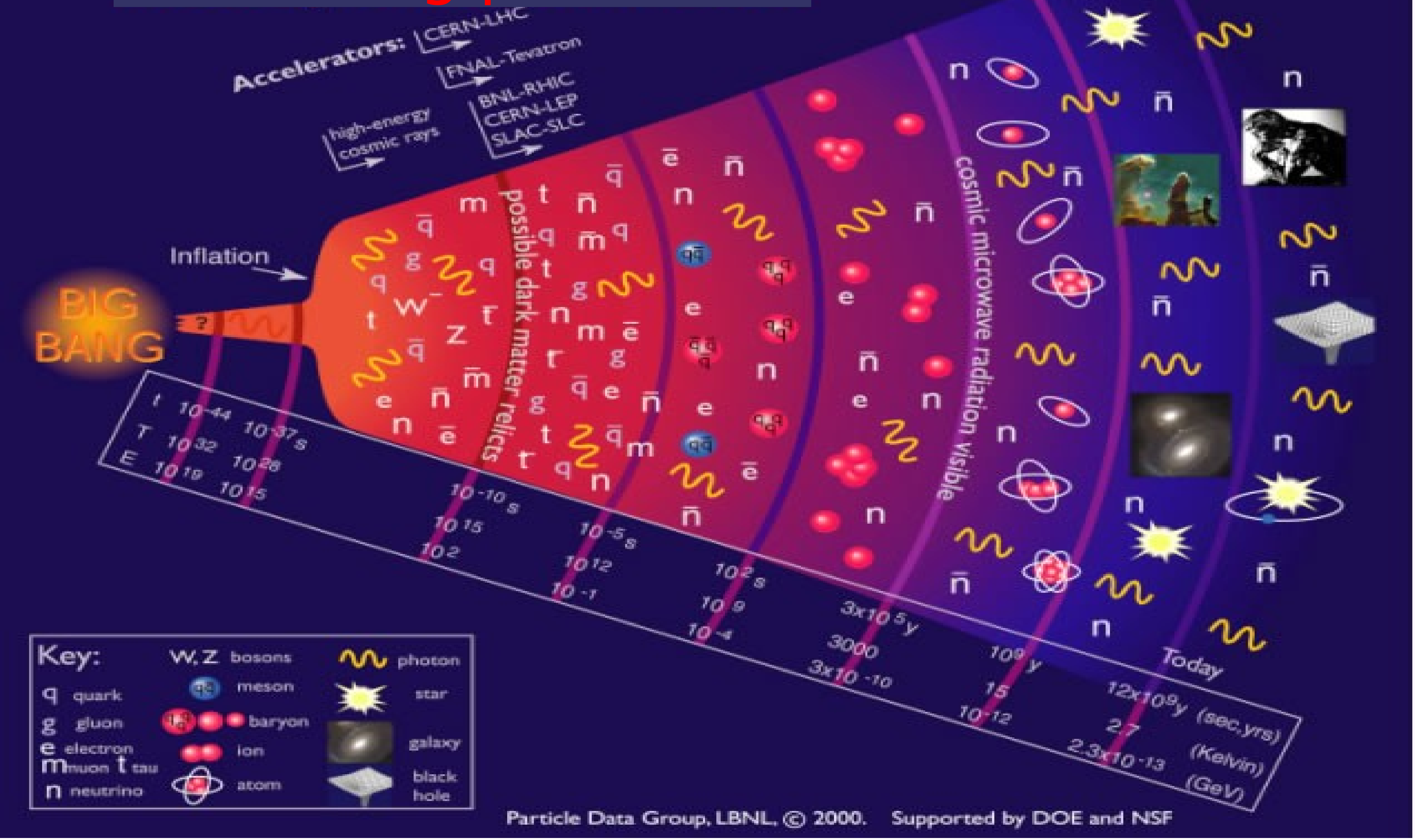
Outline

- The big picture and Particle Physics
- The Standard Model ... under attack
- Colliders and detectors
- Top quark physics
- The search for single top
- Latest results and outlook
- Conclusions

The Universe through experiment



The big picture



Interconnections:

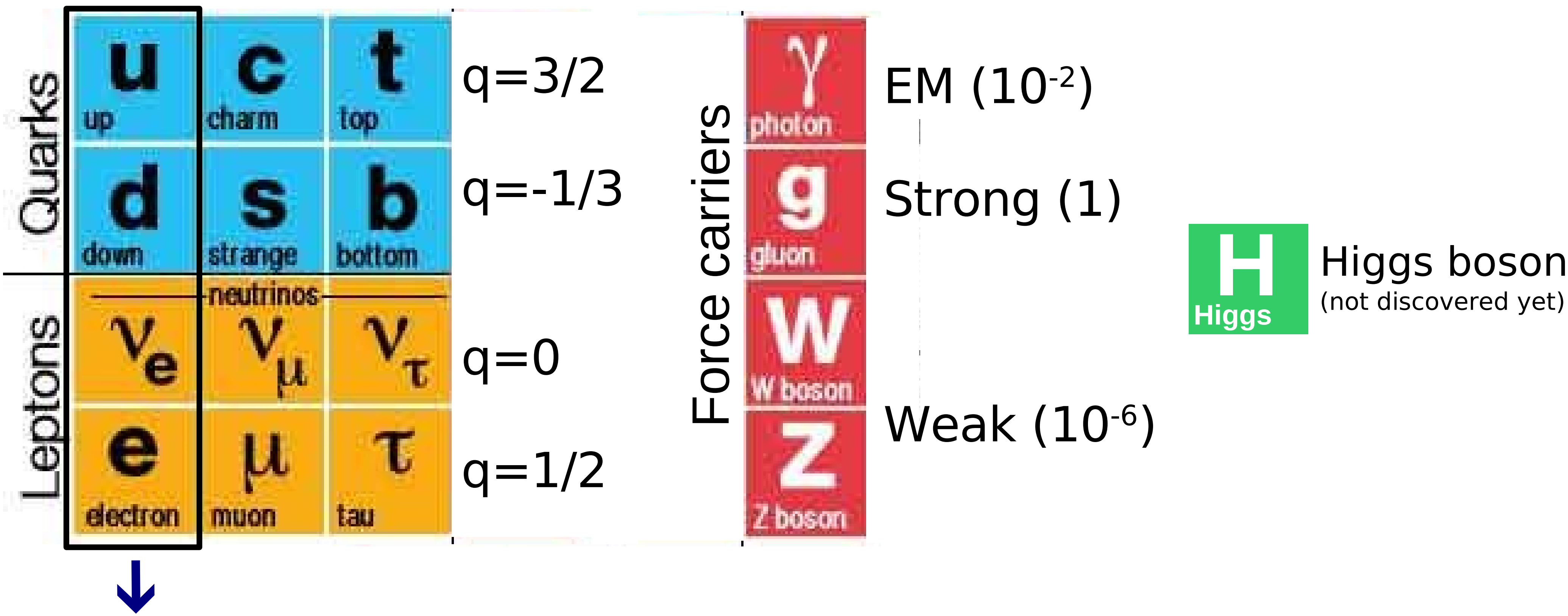
SM Cosmology ↔ SM Particle Physics ↔ QF Theory ↔ Astrophysics

Particle Physics

- The quest for the nature of matter
- Questions we are trying to answer:
  - What is matter made of?
  - How do the constituents interact?
  - Are fundamental particles really fundamental?
  - What is the origin of mass?
  - Why is there more matter than antimatter in the Universe?
  - What is dark matter?
- So what do we know so far?

The Standard ~~Model~~ Theory

- Three families of spin-½ fermions
- Which interact through the exchange of spin-1 bosons
- Gauge theory: $SU(3)_C x SU(2)_L x U(1)$ ⇨ symmetry, local scale invariance



1st family: every day matter

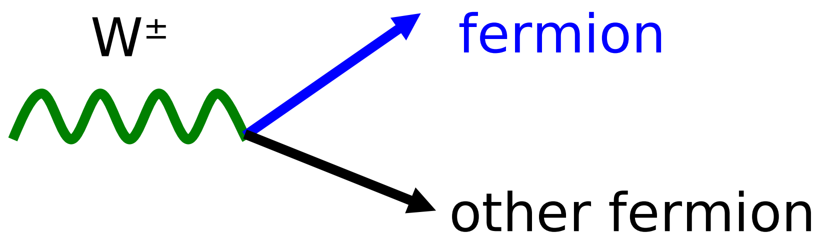
Gravity (10^{-40})

Interactions

Electroweak interactions

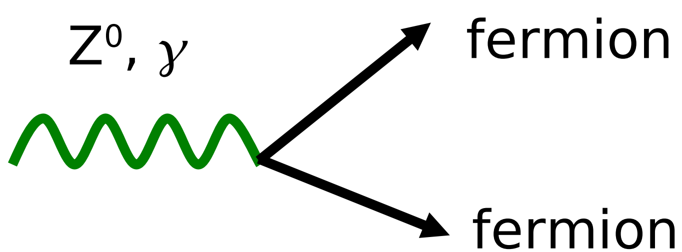
Charged current:

- nuclear beta decay



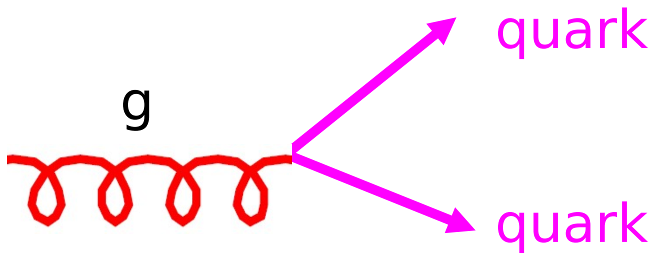
Neutral current:

- electromagnetism



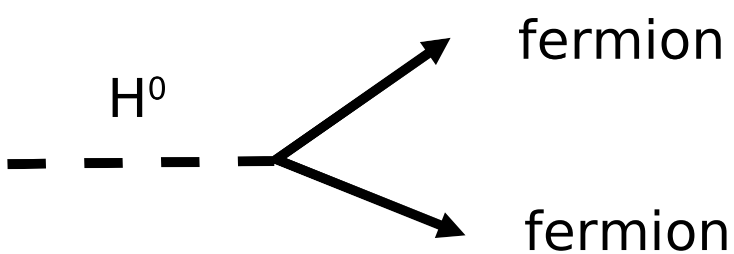
Strong interaction

- Holds atomic nucleus together

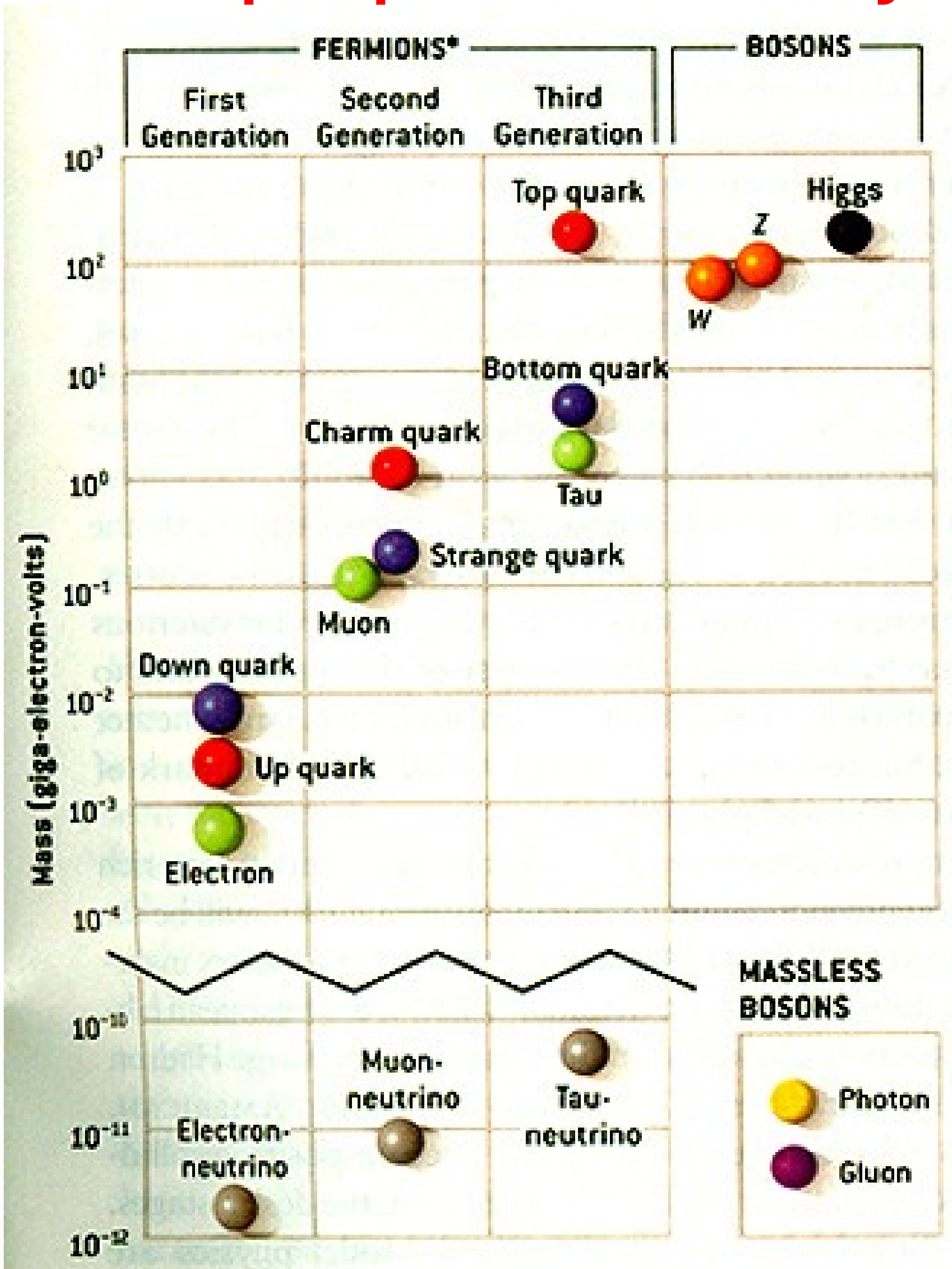


Yukawa coupling

- Particles acquire mass



Top quark: not just the sixth quark



- Discovered in 1995 at CDF and DØ
- Heaviest known particle

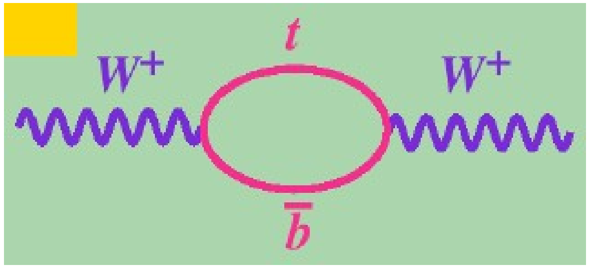
  40 times heavier than b (~Au atom)
- Only quark that decays before hadronization

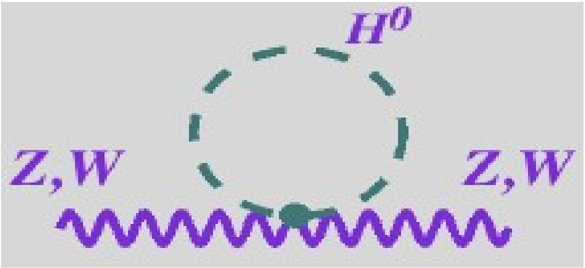
  $t \rightarrow Wb$ in $\sim 10^{-25}$s
- Couples strongly to Higgs boson

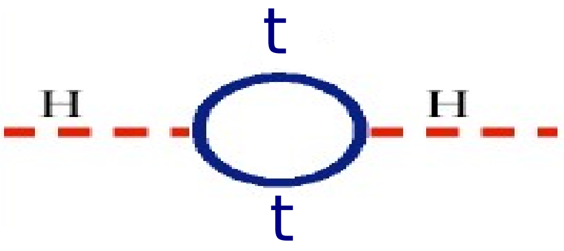
  Related to the origin of mass?
- Unique laboratory to study the SM and beyond

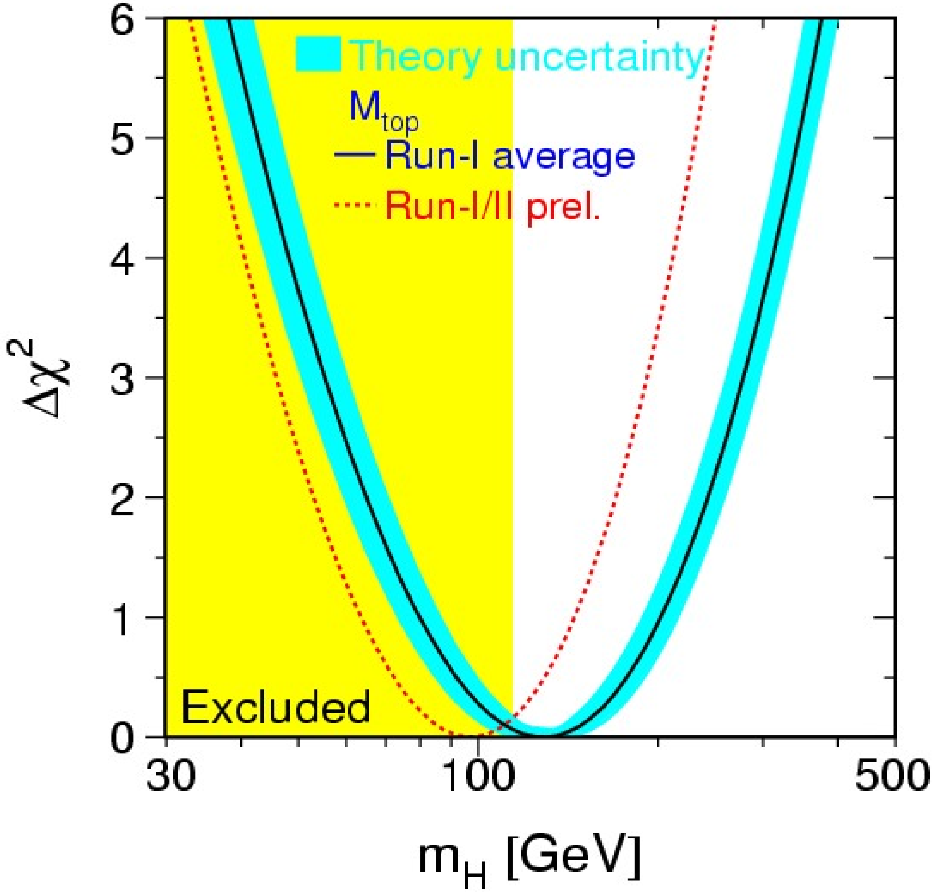
W ⇔ t ⇔ H

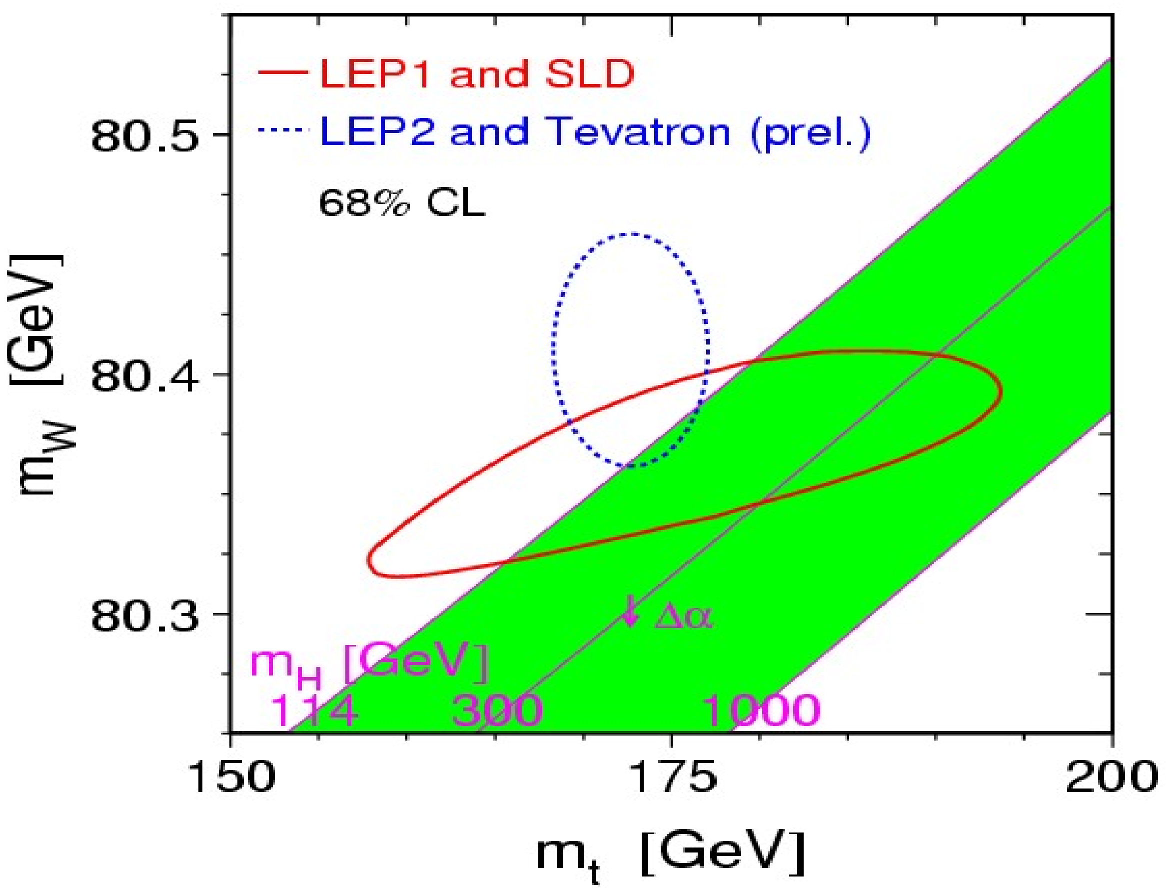
The SM is a quantum field theory: boson propagators and virtual bubbles (loops) play an important role











The SM under attack

- The SM is a fantastic success: not a single break over many years of extremely precise measurements
- But recently: Neutrino masses, dark matter
- So we know it is not a complete description of Nature
- Many unanswered questions:
  - Why three generations?
  - Is the Higgs mechanism actually responsible for the particles' masses?
  - Why that hierarchy of masses?
  - What's with so many free parameters?
  - Gravity is not in the picture
  - Unification of three couplings is not possible

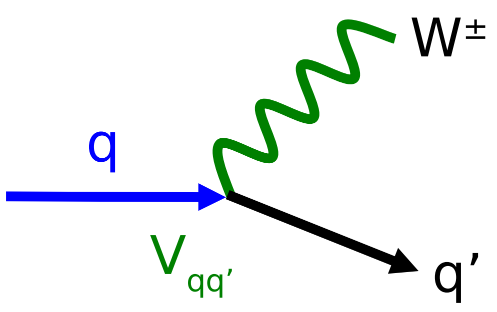
It's all dubbya's fault

- Studying the electroweak sector is crucial to test the SM... and understand the asymmetry of matter and antimatter in the Universe

- Weak interactions treat matter and antimatter differently ...only possible because there are three families!

- Weak interaction and mass eigenstates aren't the same ➔ **Mixing** (Cabibbo-Kowayashi-Maskawa matrix)

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



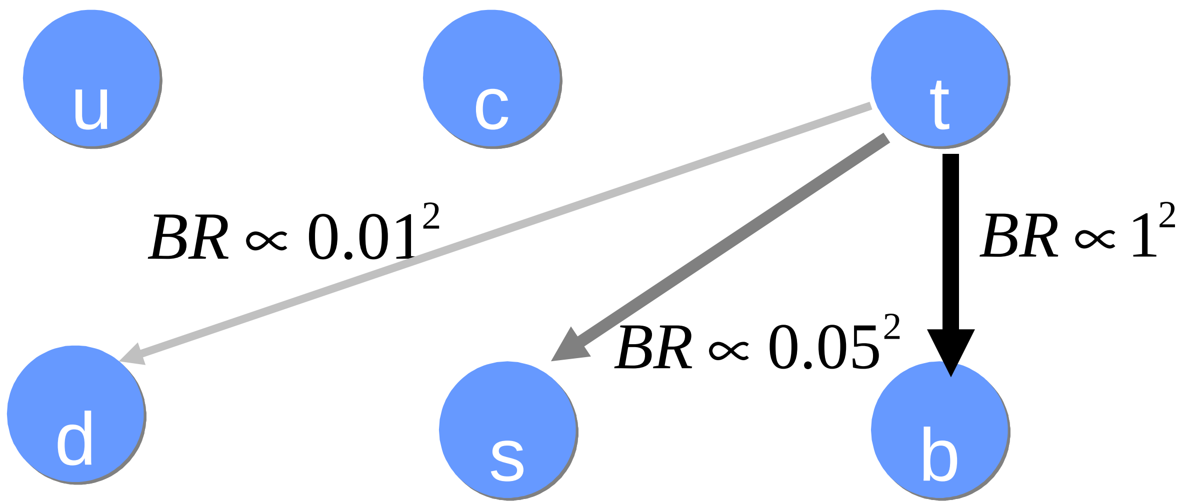
Only element not measured directly yet

- The CKM matrix is being scrutinized from many different angles: B-factories, Tevatron, nuclear experiments...

Flavor changing interactions

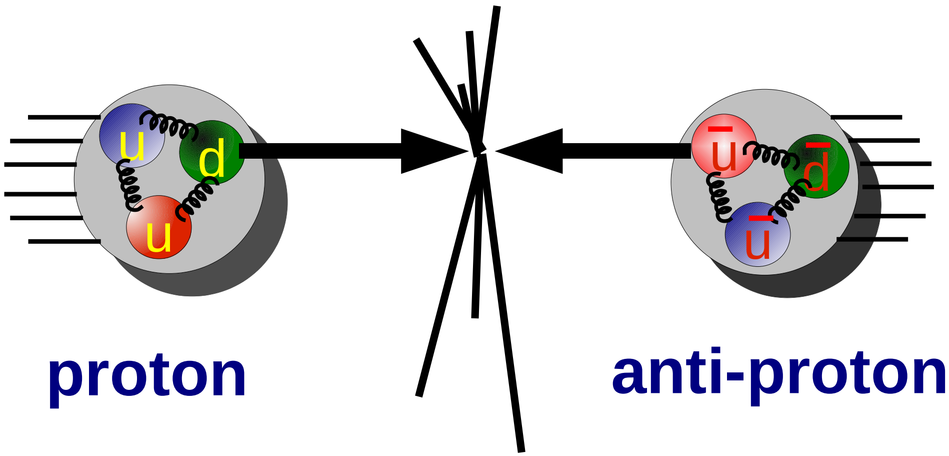
$$\begin{pmatrix} 0.9741-0.9756 & 0.219\ \ -0.226 & 0.002\ \ -0.005 \\ 0.219\ \ -0.226 & 0.9732-0.9748 & 0.038\ \ -0.044 \\ 0.004\ \ -0.014 & 0.037\ \ -0.044 & 0.9990-0.9993 \end{pmatrix}$$

- Observe hierarchy in flavor-changing transitions
- Probability of transition (branching ratio) within one family is the largest
- Transitions between families are suppressed:



Tools of the trade

- Particle physicists use high energy colliders to probe physics at small distances



Note on units: N[collisions]=L[pb^{-1}]σ[pb]

- **Picobarns** (pb) are a measure of "cross section" (σ=interaction probability). 1 barn = 10^{-24} cm^2.

- **Inverse picobarns** (pb) are a measure of the "integrated luminosity" (L=collected data)

Example: 100 pb^{-1} = sufficient data to observe 100 events of a process having 1 pb cross section

- **GeV** are used interchangeably for mass, energy and momentum

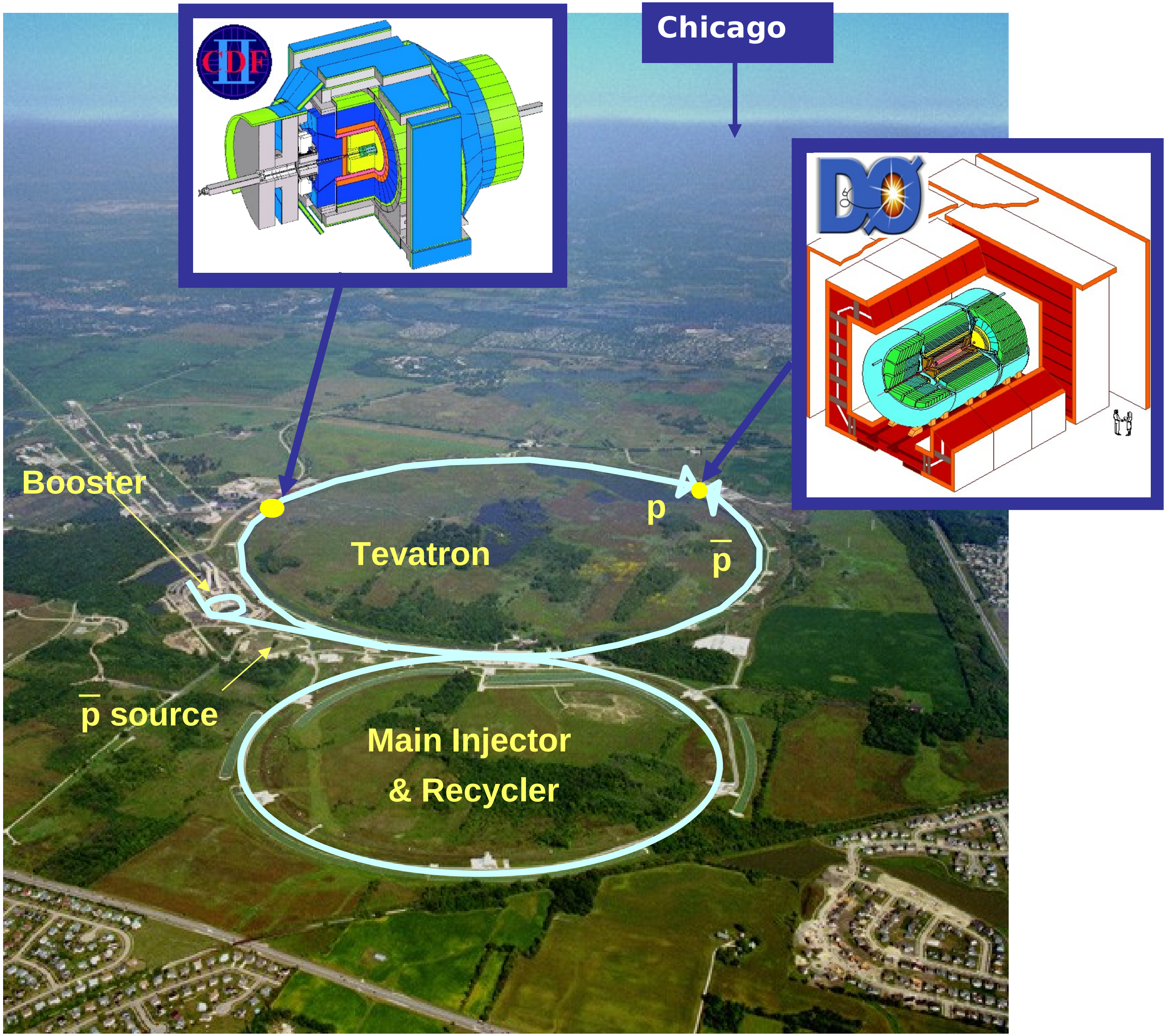
The Tevatron

The highest energy particle accelerator in the world!

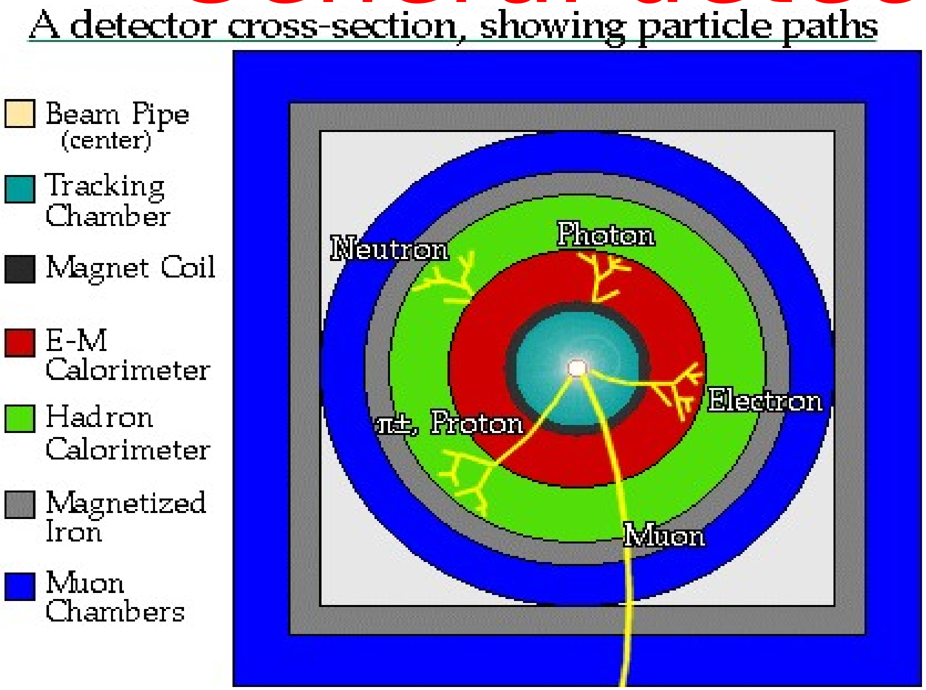
Proton-antiproton collider

Run I 1992-1995
Top quark discovered!

Run II 2001-09(?)
$\sqrt{s}$ = 1.96 TeV
Δt = 396ns
1fb^{-1} delivered
Peak Lumi: $10^{32}cm^{-2}s^{-1}$

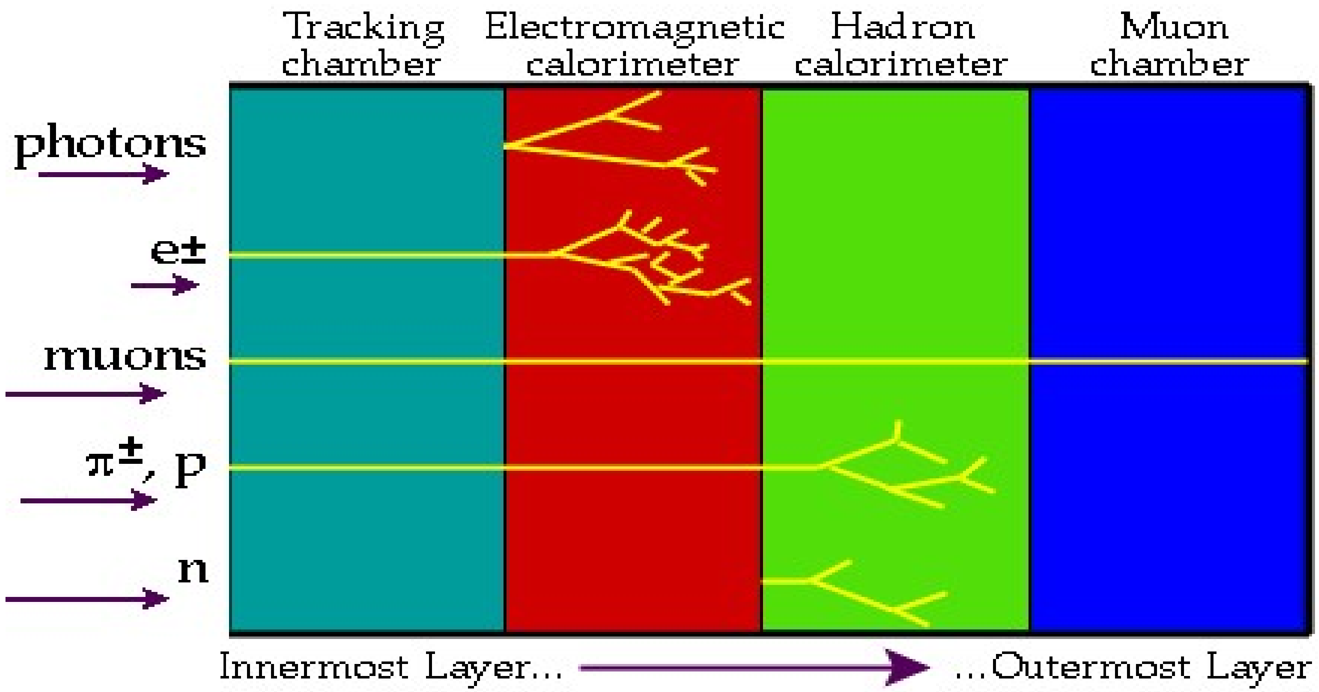


General detector and particle ID

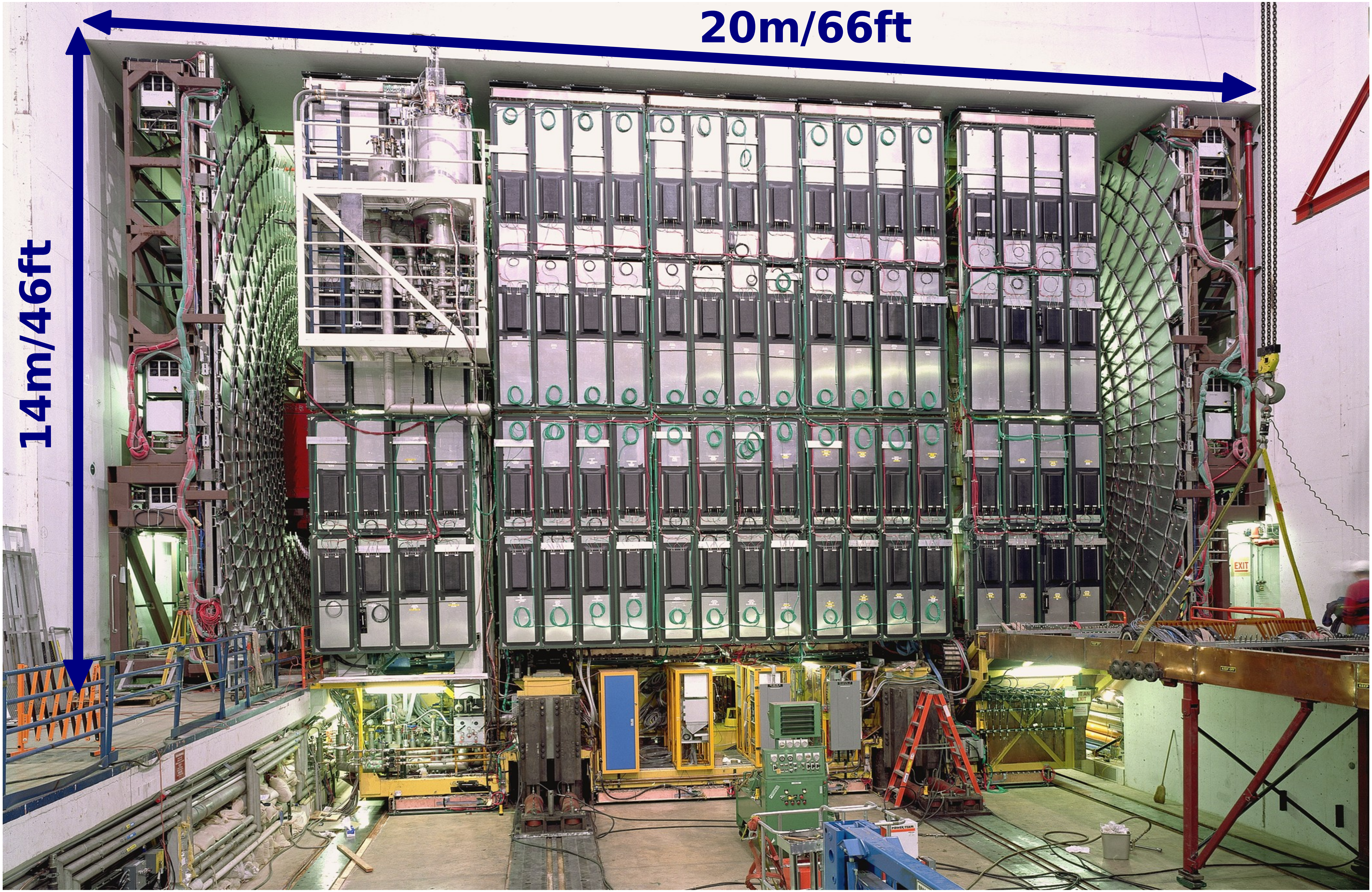


We detect particles by the EM and strong interaction fingerprints they leave behind

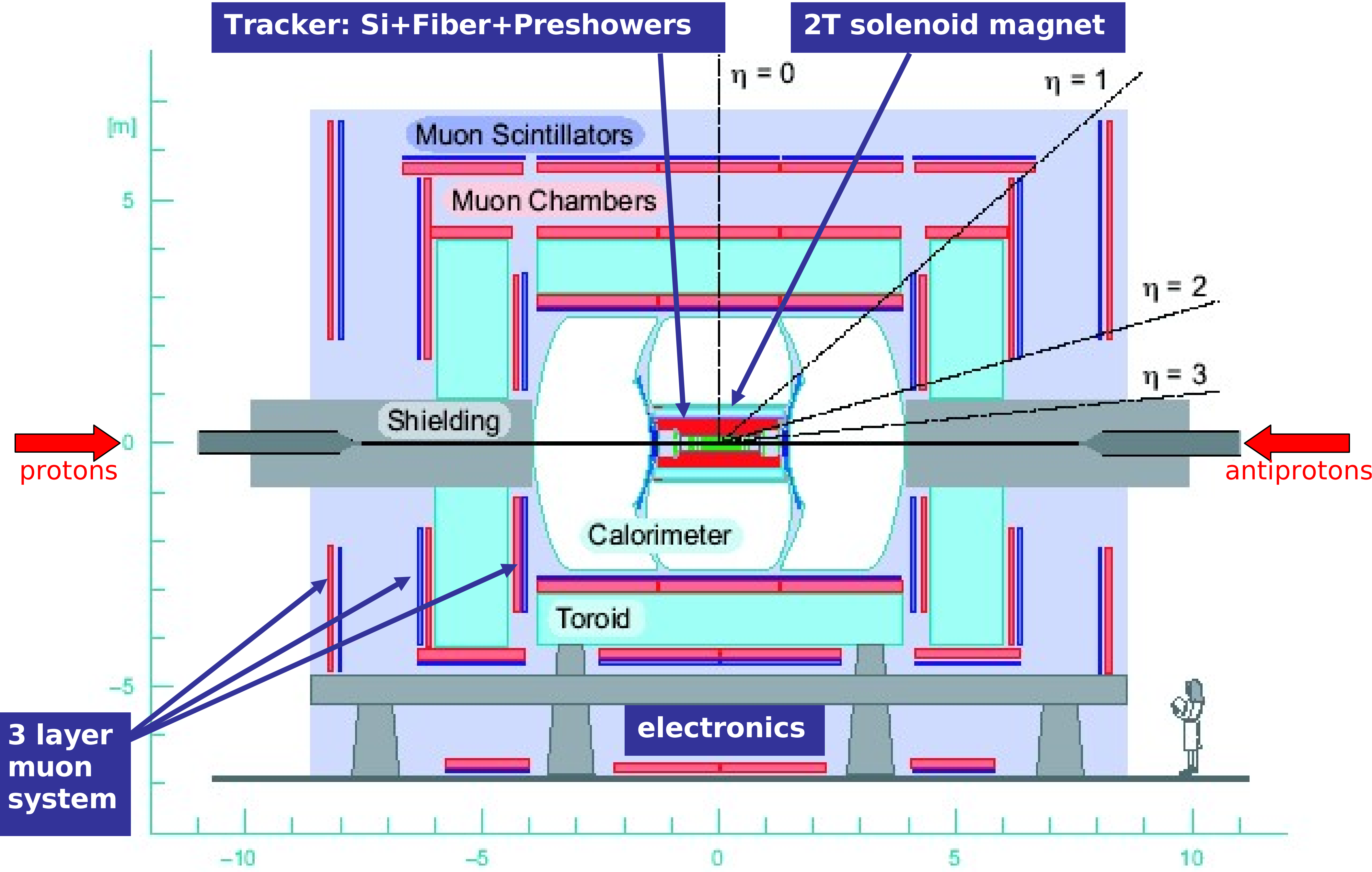
- Tracking is first (measure p_T)
- Calorimetry (EM and hadronic)
- Muons
- All the rest is neutrinos



The real thing: the DØ detector



DØ for Run II


Tracker: Si+Fiber+Preshowers
2T solenoid magnet
η = 0
η = 1
η = 2
η = 3
[m]
5
0
−5
Muon Scintillators
Muon Chambers
Shielding
Calorimeter
Toroid
protons
antiprotons
electronics
3 layer muon system
−10
−5
0
5
10

Many, many people running it

19 countries, 80 institutions, 670 physicists

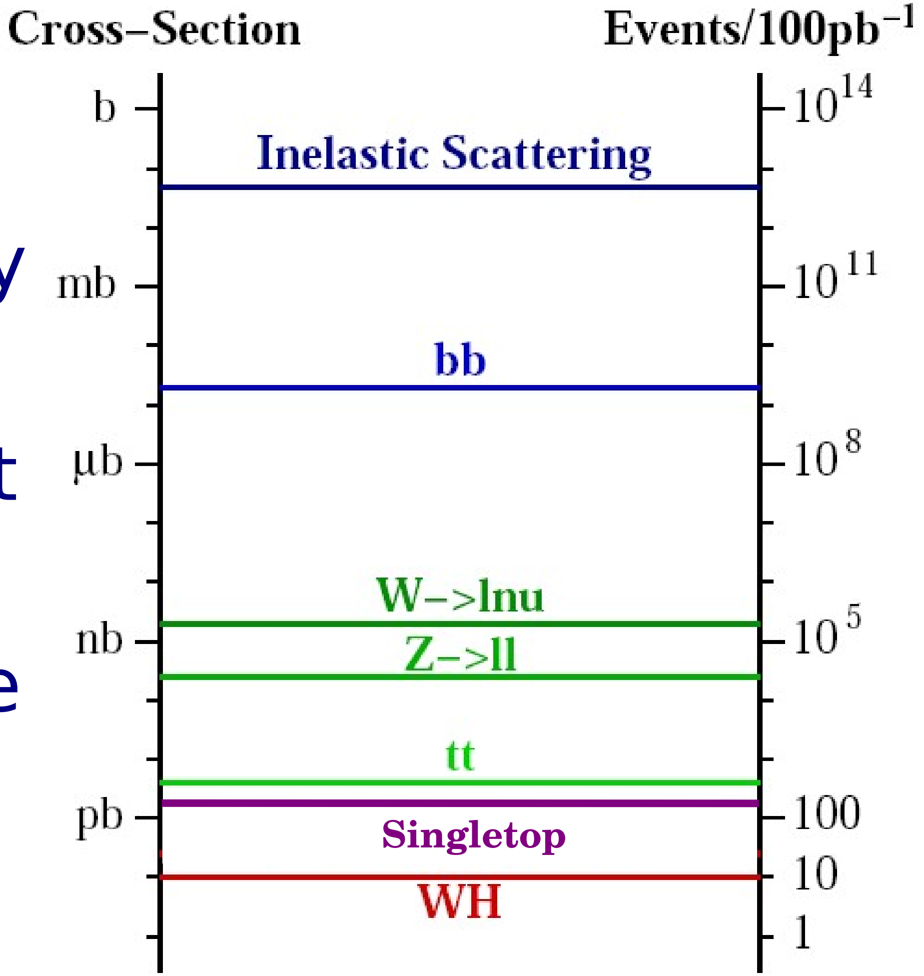
DØ Collaboration Meeting, Vancouver Canada, June 2005

A lot of convincing to do...

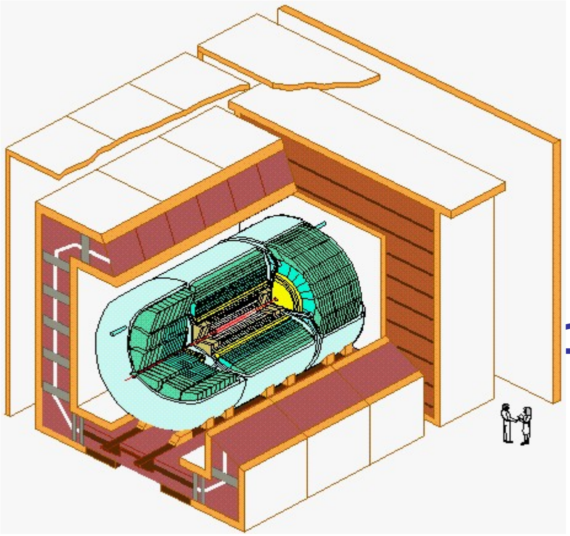
Since we are all signing the papers together you have to convince them all that what you are doing is sensible and deserves to be published!

Physics at a hadron collider is like… drinking from a fire hose

- Collision rate is huge
  Every 396 ns → ~1.7 MHz (live crossings)
- Total cross section ~0.1b
  2-3 interactions per collision at L=10^{32}
- W, Z, top, Higgs are relatively rare
- Need trigger system to select "interesting" events
- Only store a manageable size in tape ~13MB/s



DØ data acquisition system

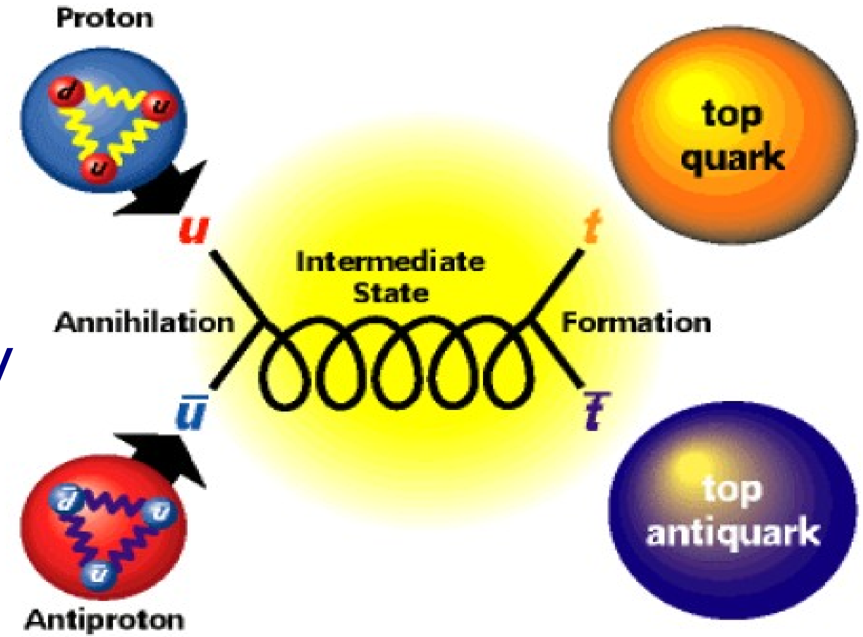


1.7 MHz → Level 1 → 1.5 kHz → Level 2 → 800 Hz → Level 3 → 50 Hz → tape

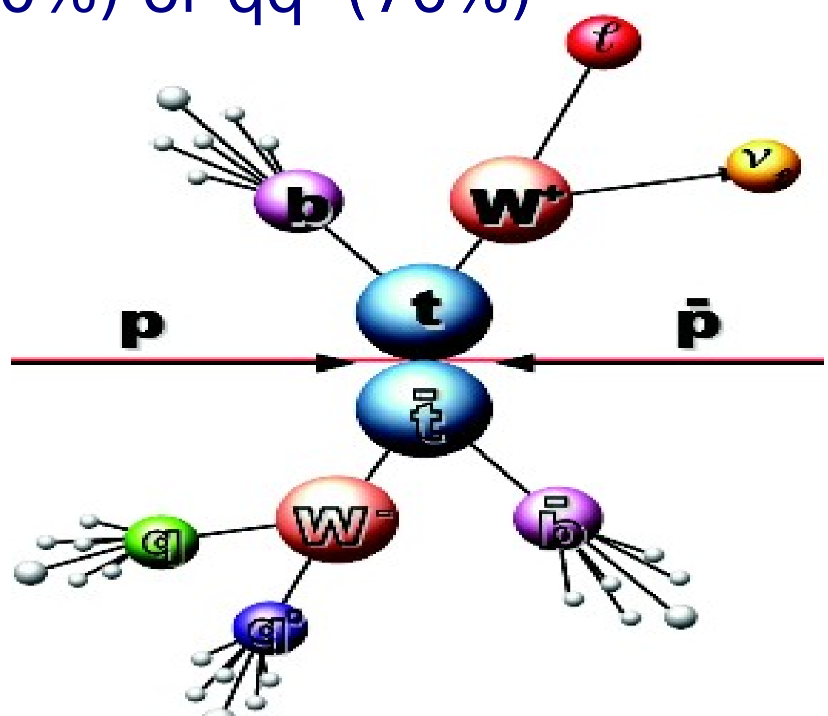
- Three level trigger
- Selects events containing high energy final state objects (e, μ, jets)
- Algorithms implemented in hardware/firmware at L1 & L2, software at L3
- Increasing level of sophistication, increasing time per decision, decreasing event accept rate

Close encounters of the 3rd generation

- Top quarks have only been seen so far produced in pairs of top and anti-top



- Then each top quark decays quickly into a W boson and a b-quark
- The W can then decay into $\ell\nu$ (30%) or qq' (70%)

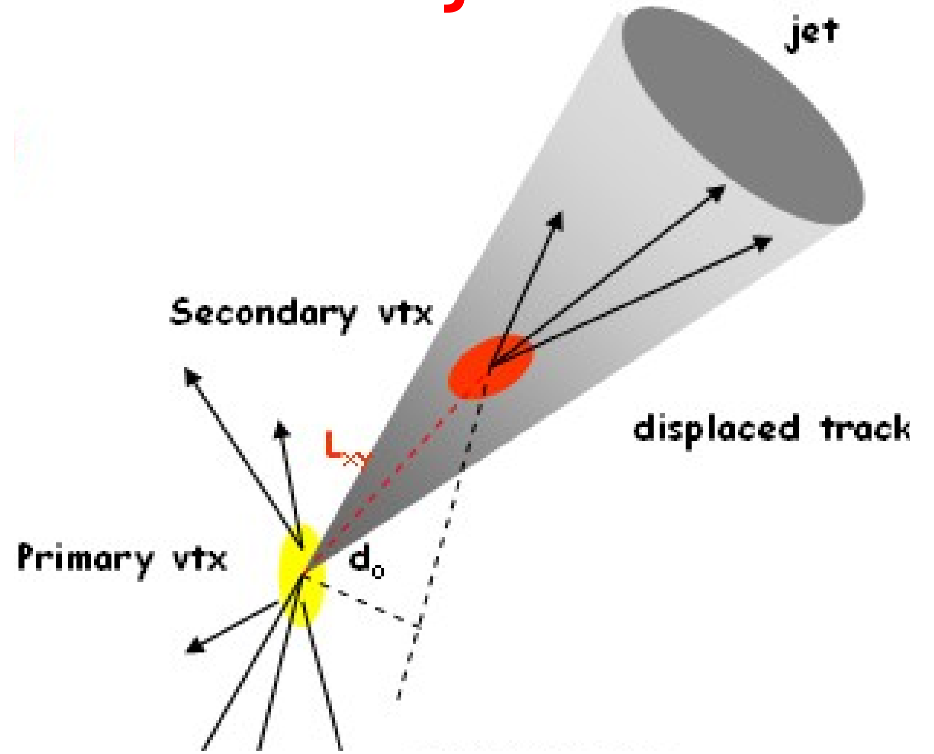


Final objects (if $W_1 \rightarrow \ell\nu$ and $W_2 \rightarrow qq'$)

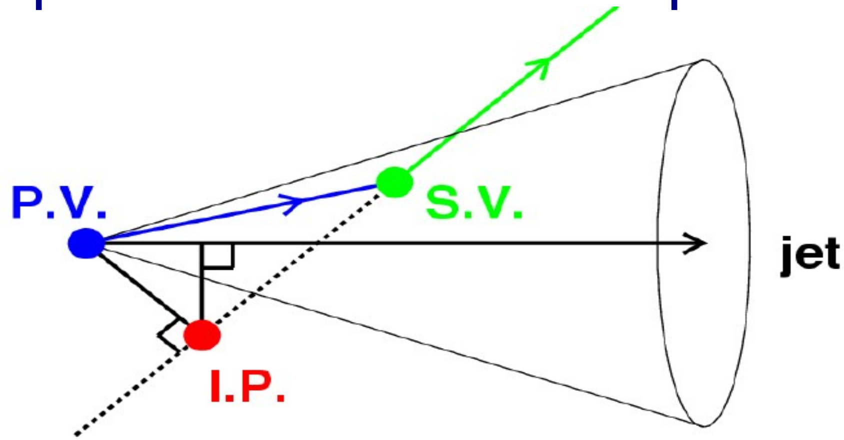
- 4jets (2 of them b)
- lepton
- neutrino (missing energy)

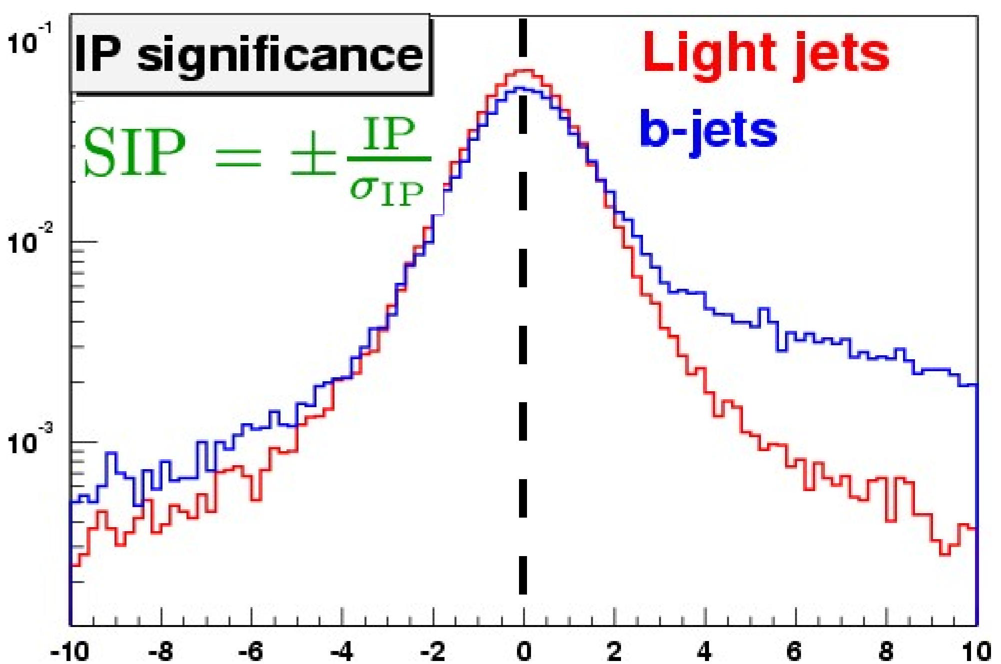
Did you see that bottom jet?

- Top quarks decay into b quarks
  → can we tell the difference between a b jet and any other jet originated from u, d, s or a gluon?



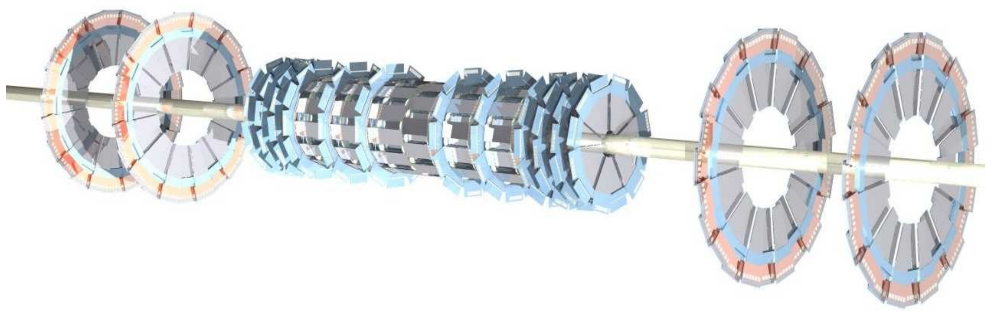
- b-quarks have a lifetime ~10^{-12}s
  → they travel ~500μm before decaying
- Look for tracks coming from a common vertex displaced from the original pp collision
- These tracks have a positive signed impact parameter with respect to the collision point

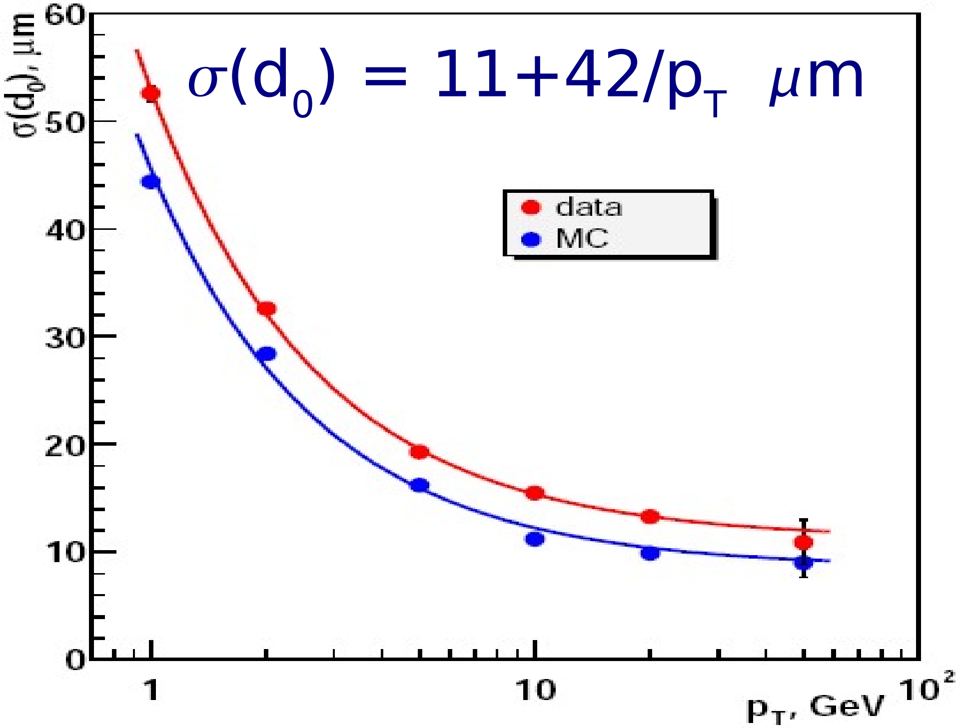




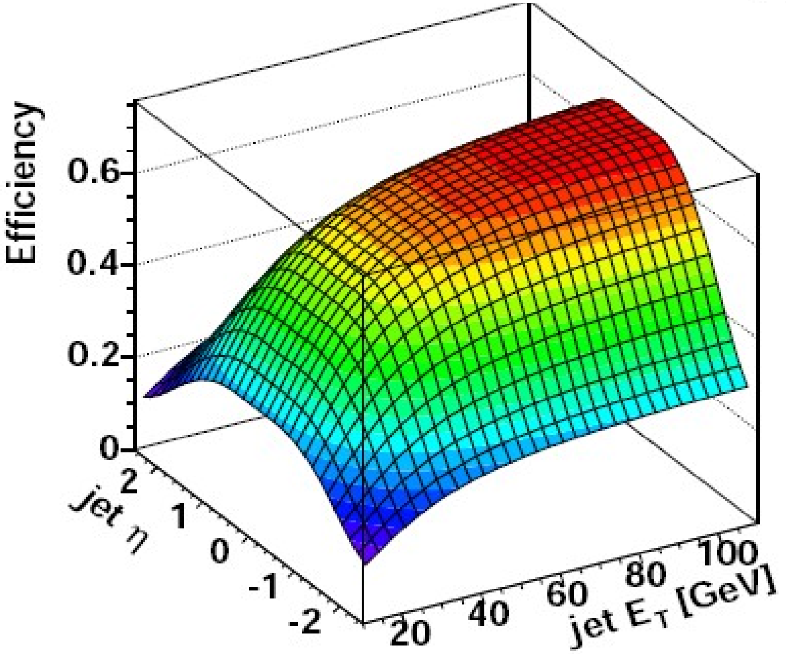
Arán

You better have good tracking



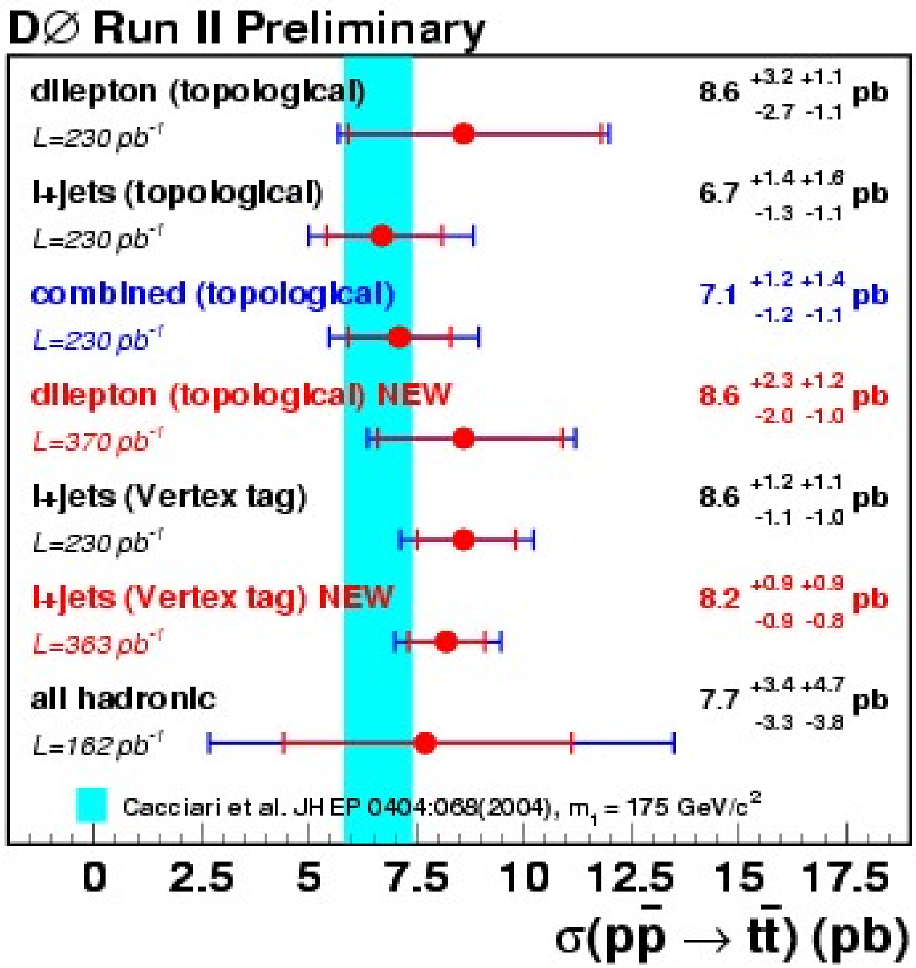


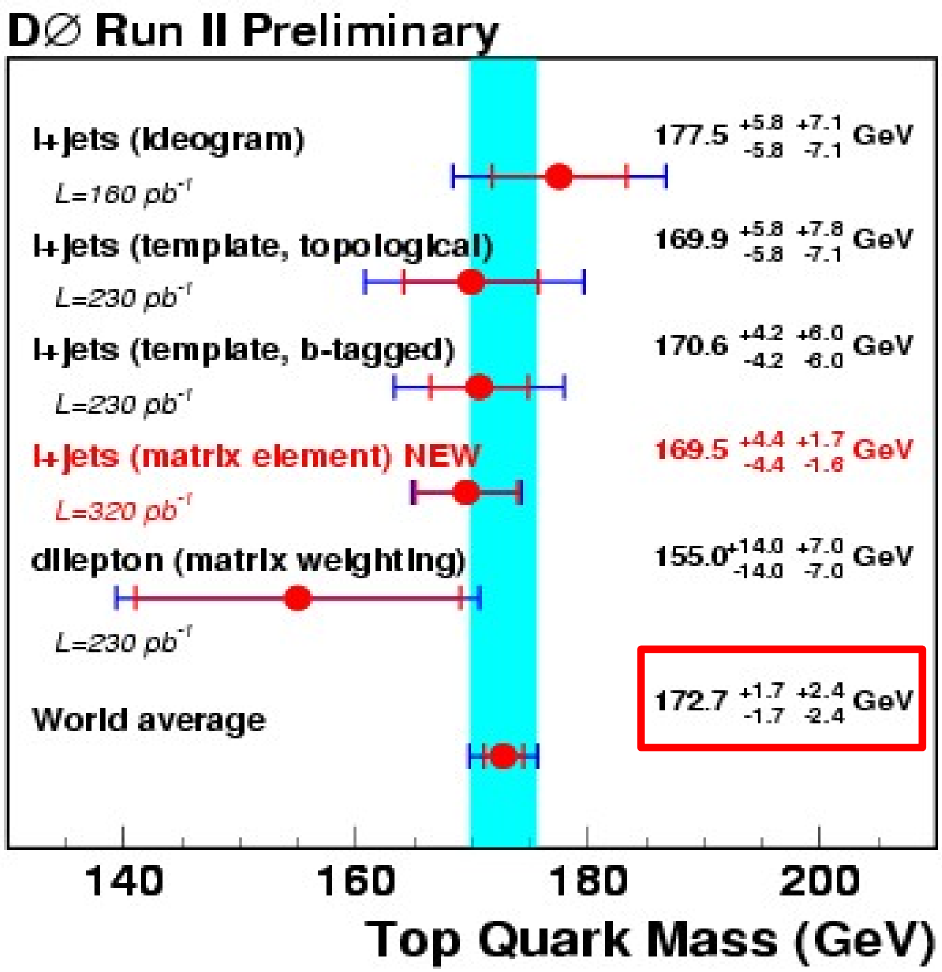
- The Silicon Microstrip Tracker allows resolutions of ~10 μm
- Inner radius: 2.6cm away from the interaction point
- Efficiency to identify a b-quark jet ~55%
- Mistag-rate ~0.5%



Top quarks deconstructed

We know the pair production cross section and its mass

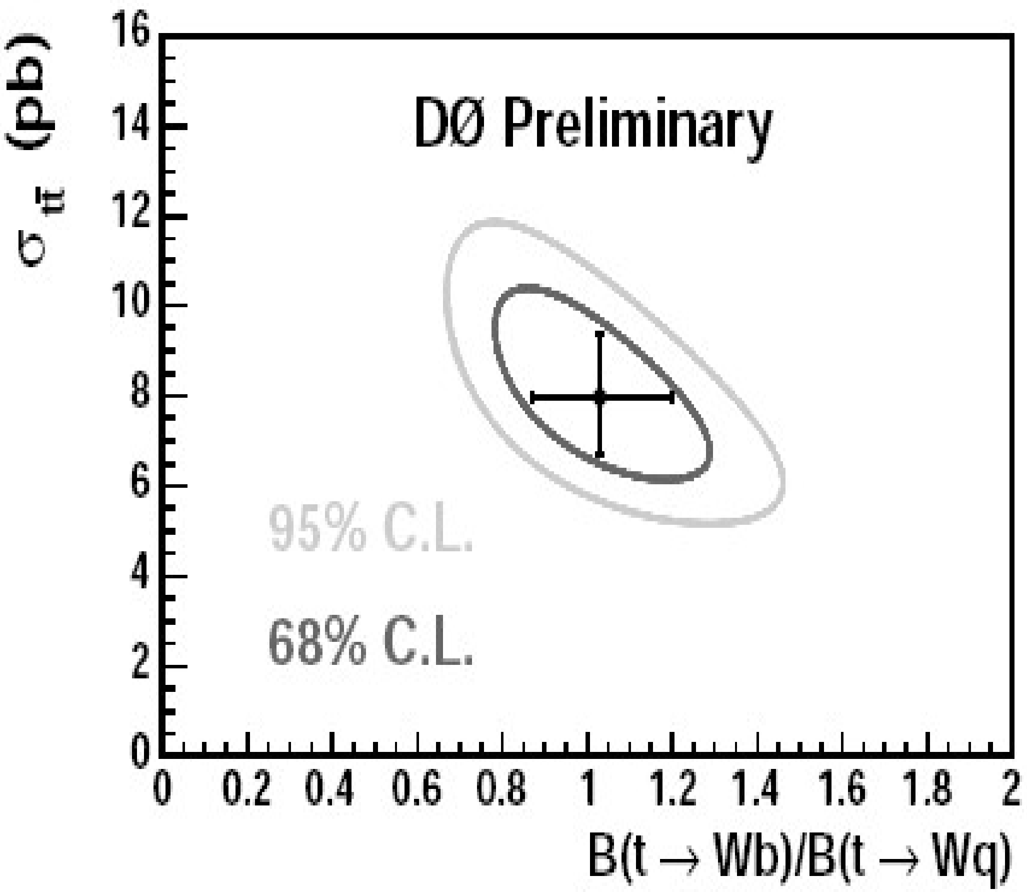




$\sigma(tt) \sim 7$ pb

$m_t \sim 175$ GeV

Other properties…



$$R = 1.03^{+0.19}_{-0.17} \Rightarrow V_{tb} > 0.80$$

…But there are still many things we don't know about top quarks:

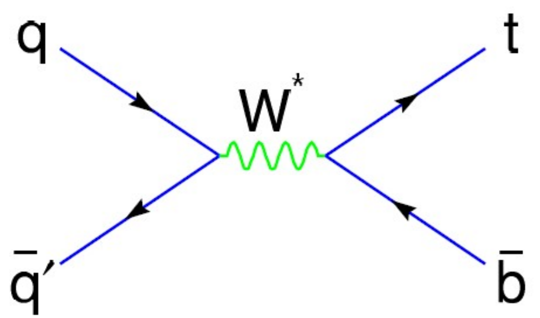
- Charge?
- Spin?
- Width?
- Couplings?

Can they be produced alone?

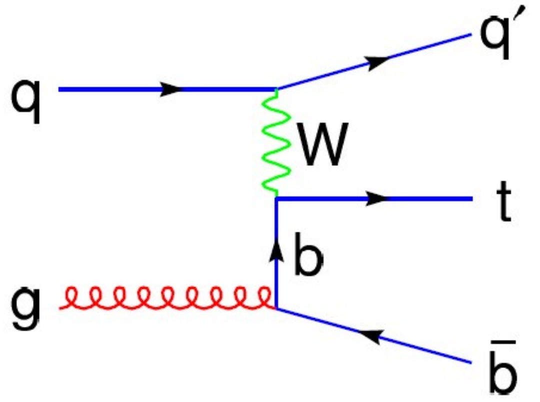
Yes! Top quarks can be lonely!

Electroweak production of single top quarks

Two main production modes at the Tevatron:



s-channel $\sigma_s \sim 1$pb



t-channel $\sigma_t \sim 2$pb

- Not seen yet!
- Challenging signature!
- Probe V_{tb} at production
- Sensitive to new physics

Goals for RunII:

- Observe SM single top production
- Measure production cross section
- First direct measurement of V_{tb}
- Study top quark spin
- Look for new physics!

We are looking at V_{tb} from different angles

Animation from Reinhard Schwienhorst

Single top search status

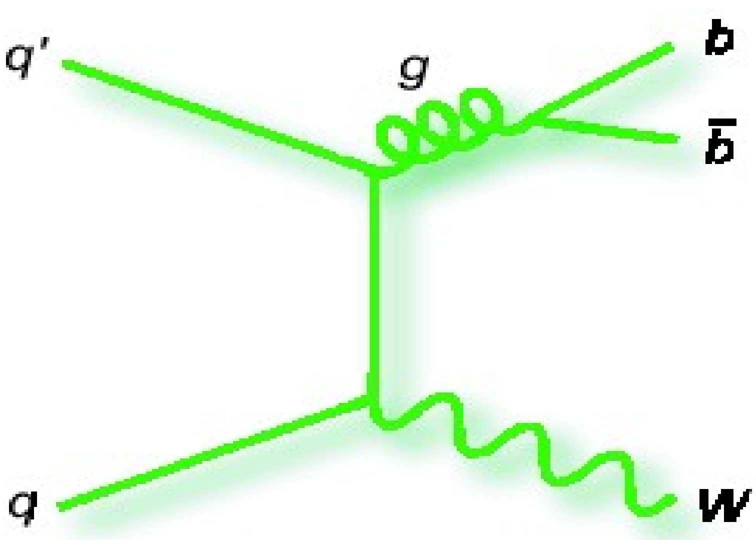
Cross section limits at 95% confidence level:

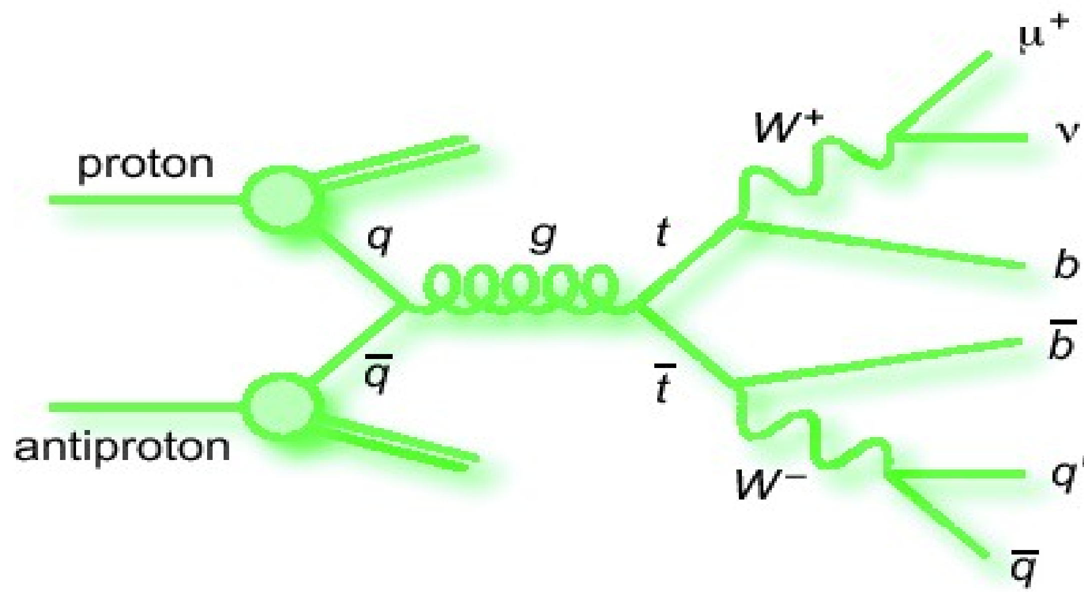
	s-channel	t-channel	combined
DØ Run I:	σ_s<17pb	σ_t<22pb	
CDF Run I:	σ_s<18pb	σ_t<13pb	σ_{s+t}<14pb
CDF Run II:	σ_s<14pb	σ_t<10pb	σ_{s+t}<18pb
DØ Run II:	**σ_s<6.4pb**	**σ_t<5.0pb**	

I will present here the highlighted result
and a new preliminary result

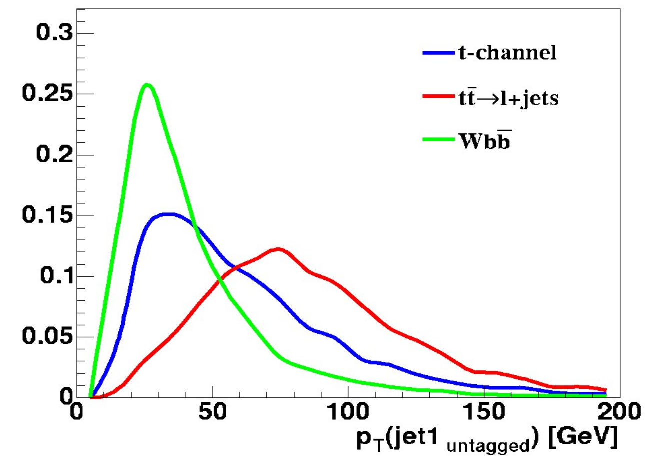
How do we find single tops?

- It's not easy!
- Out of ~10 million recorded events we are looking for ~100 signal events
- But there are many other processes that mimic single top events: W+jets, tt, multijets
- Our final state consists of 2, 3, or 4 jets (with at least one of them b) + lepton + neutrino (missing E_T)





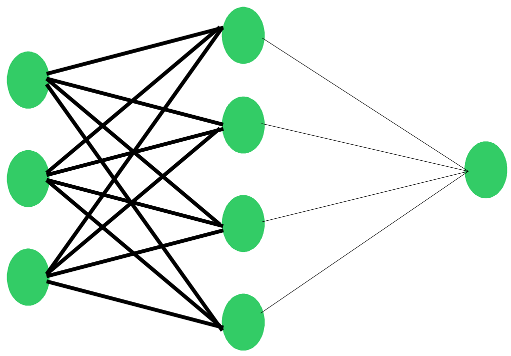
Analysis strategy



1) Event selection

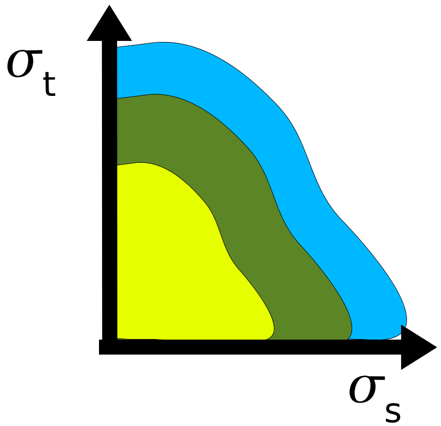
- Select W like events
- Maximize acceptance
- Model backgrounds well

2) Separate signals from backgrounds



- Find discriminating variables
- Multivariate analysis

3) Determine cross section



- Use shape information
- Bayesian statistical analysis

1) Event Selection

- $2 \leq$ Njets ≤ 4, $p_T>15$ GeV
- 1 lepton $p_T>15$ GeV
- MET>15 GeV

↓

Pretagged
7100 events

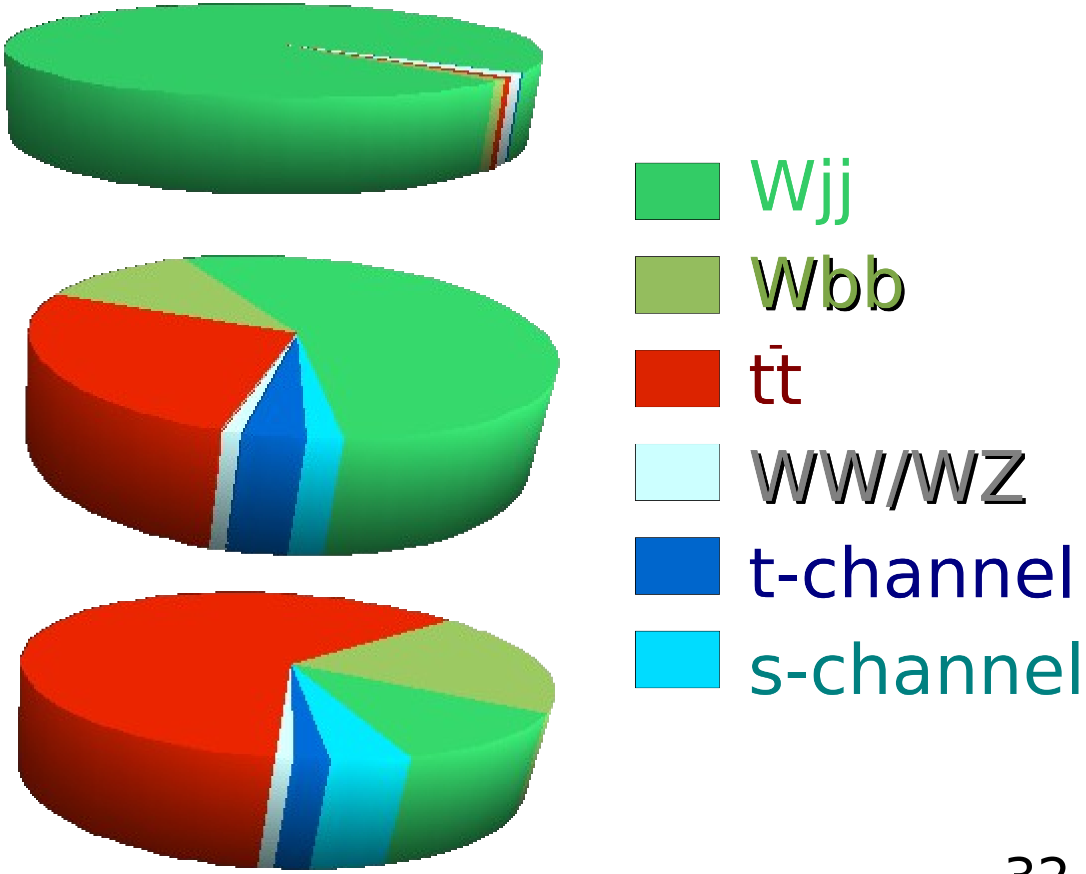
↓

=1 b-tagged jet
252 events

↓

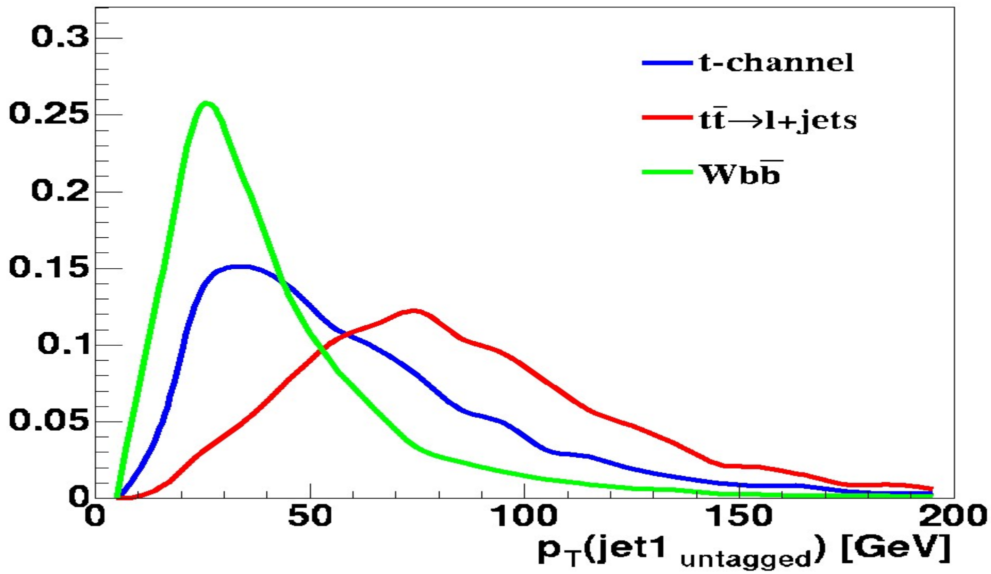
≥2 b-tagged jets
31 events

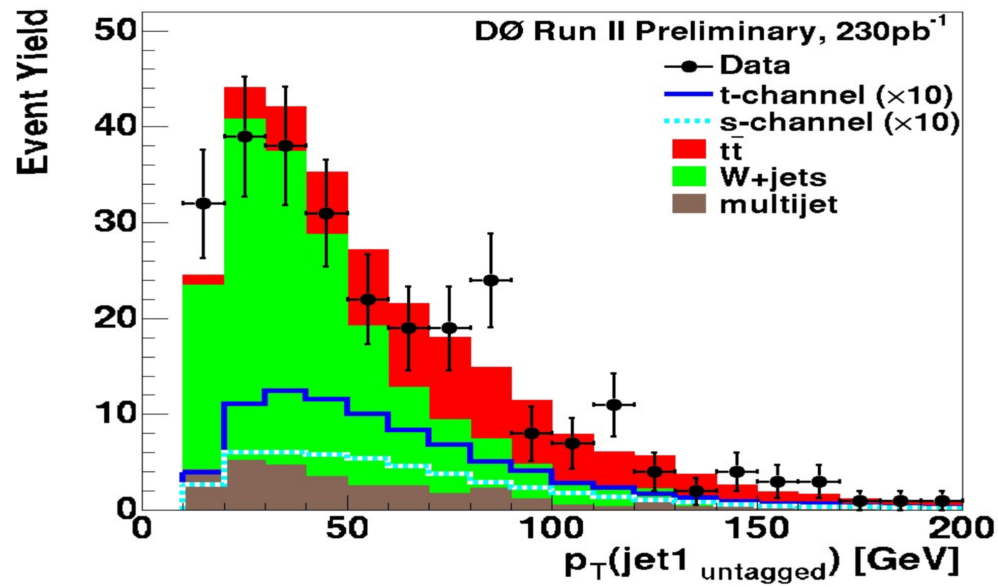
Source	s-channel search	t-channel search
tb	5.5 ± 1.2	4.7 ± 1.0
tqb	8.6 ± 1.9	8.5 ± 1.9
W+jets	169.1 ± 19.2	163.9 ± 17.8
$t\bar{t}$	78.3 ± 17.6	75.9 ± 17.0
Multijet	31.4 ± 3.3	31.3 ± 3.2
Total background	287.4 ± 31.4	275.8 ± 31.5
Observed events	283	271

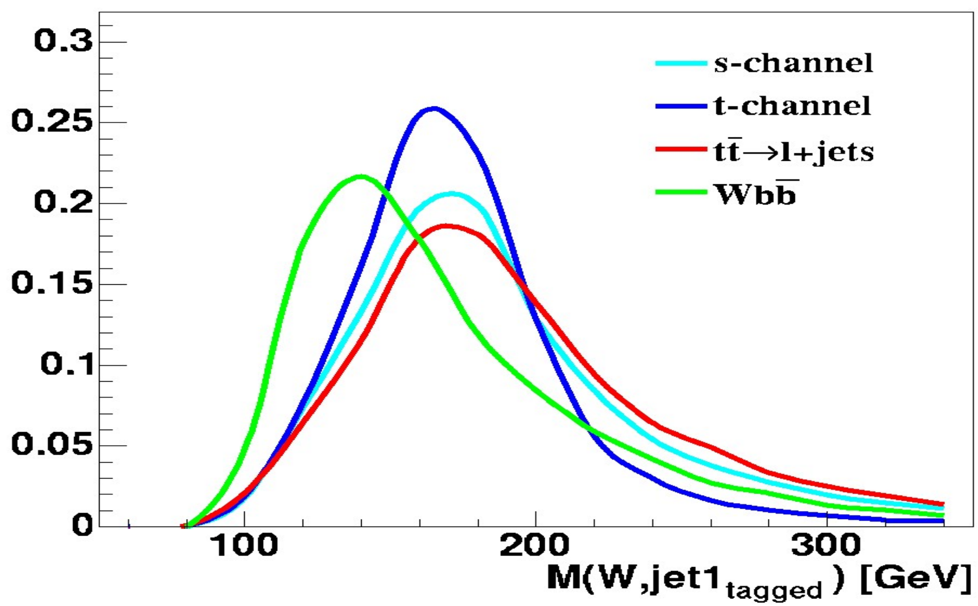


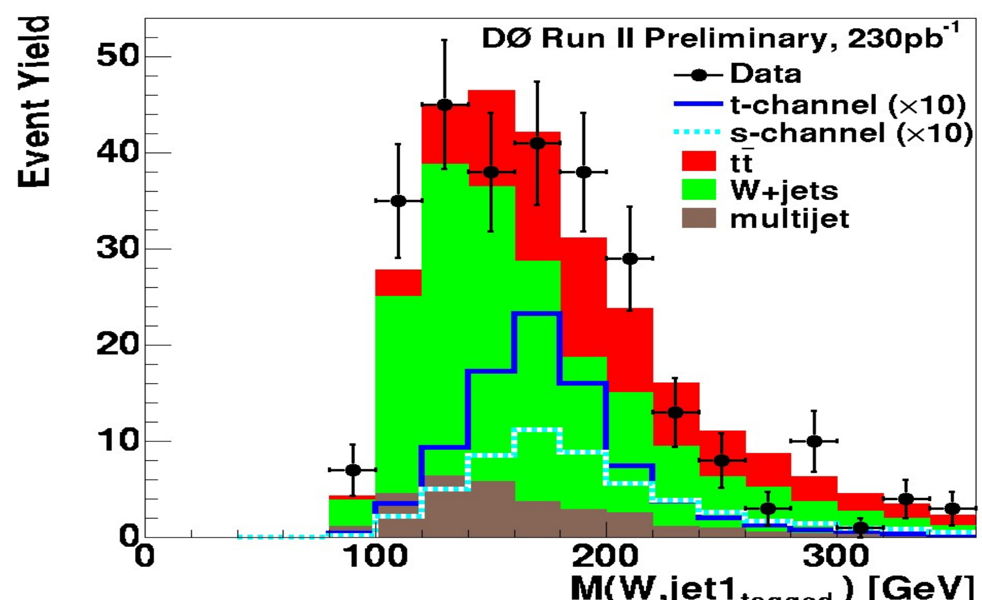
2) Separate signals from backgrounds

- Make sure your data agrees well with your prediction (i.e.: you know what you are doing)
- Choose variables that show good discrimination





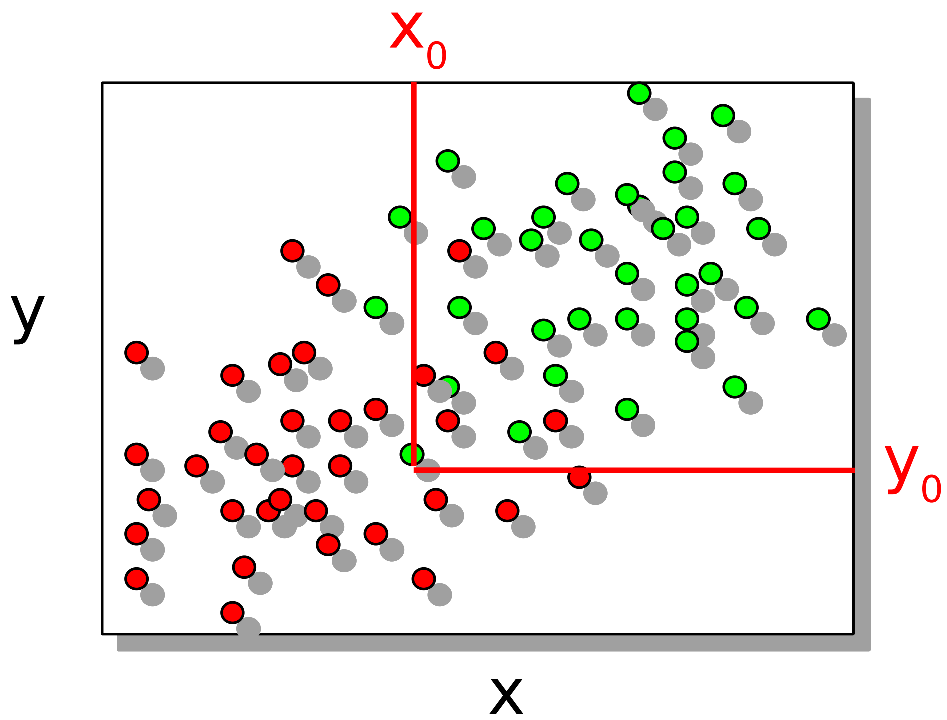




Optimal separation

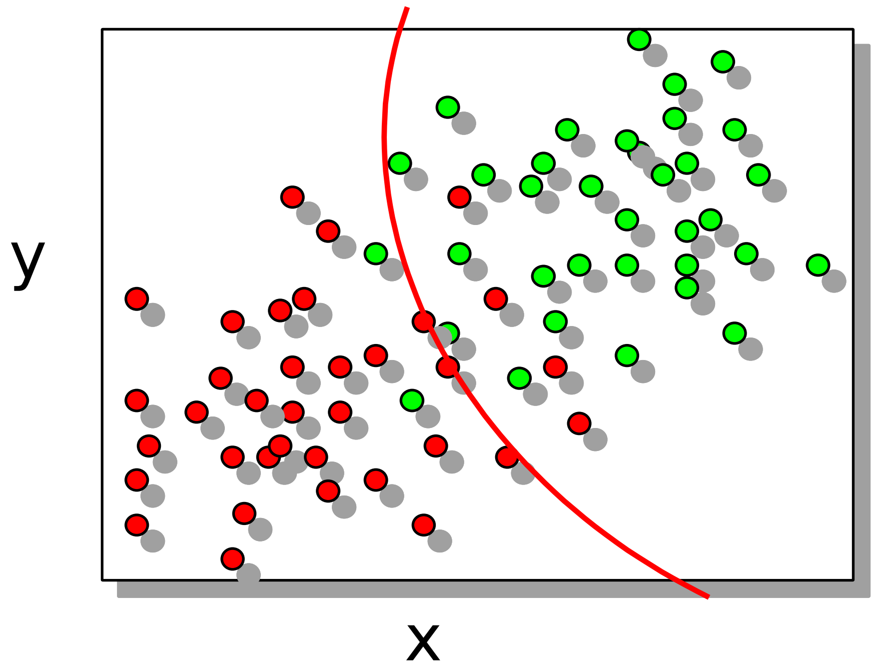
Signal = 🟢 Background = 🔴

Conventional cuts



$$x > x_0$$
$$y > y_0$$

Multivariate technique

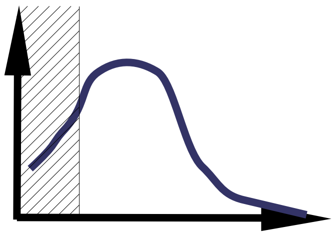


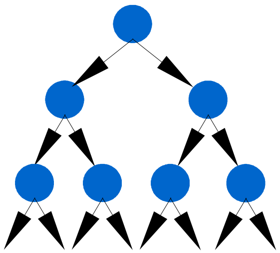
$$r(x,y) = \frac{P(x,y|S)\,P(S)}{P(x,y|B)\,P(B)}$$

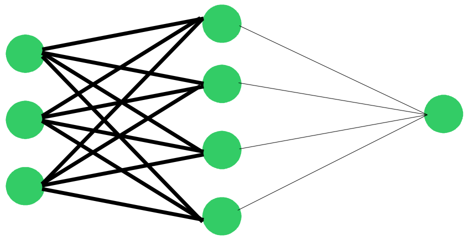
Analysis methods

DØ has implemented four analysis methods:

Cut-based | Decision Trees | Neural Networks | Likelihoods







$$L = \frac{P(S)}{P(S)+P(B)}$$

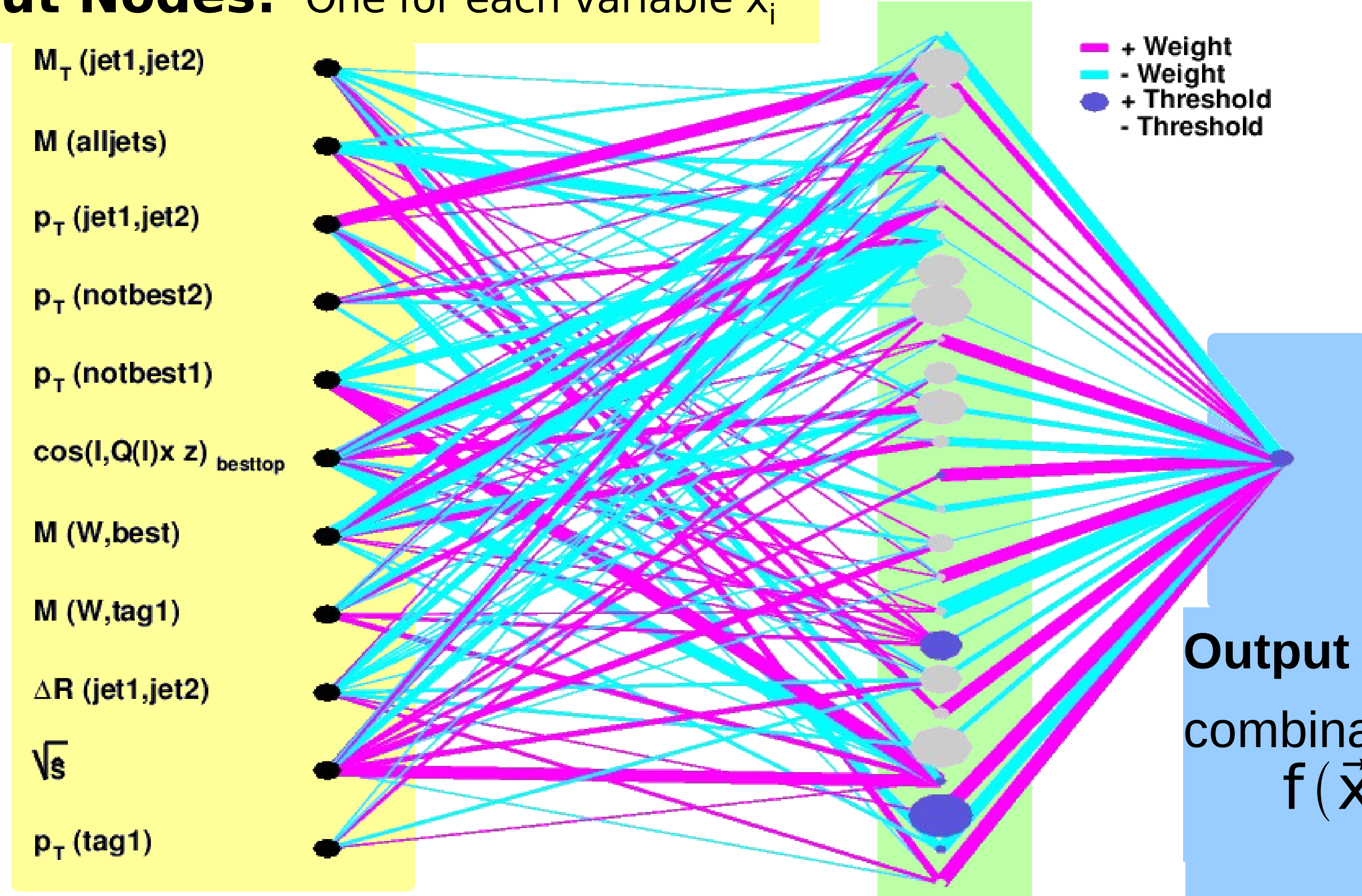
I will describe only neural networks

- Use same pool of discriminating variables for all 4 analyses
- Optimize separately for s-channel and t-channel
- Focus on two dominant backgrounds: Wbb and tt
- A total of 8 sets of cuts/trees/networks/likelihoods:

  tb-Wbb, tb-tt→ℓ+jets, tqb-Wbb & tqb-tt→ℓ+jets (for e and μ)

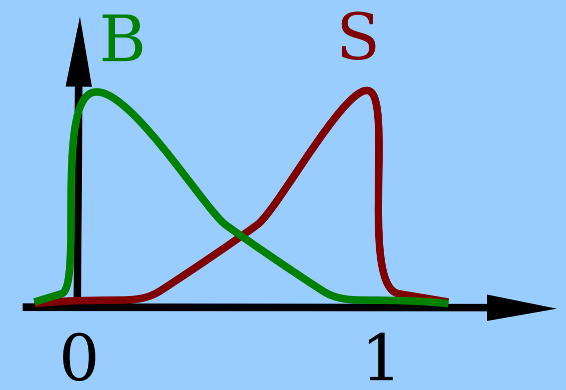
Neural Networks

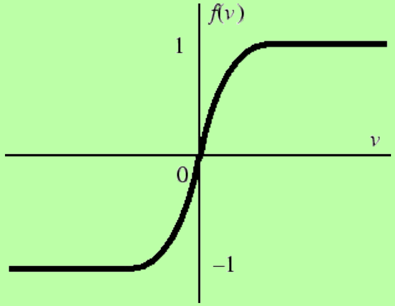
Input Nodes: One for each variable x_i



Output Node: linear combination of hidden nodes

$$f(\vec{x}) = w'_k \, n_k(\vec{x}, \vec{w}_k)$$

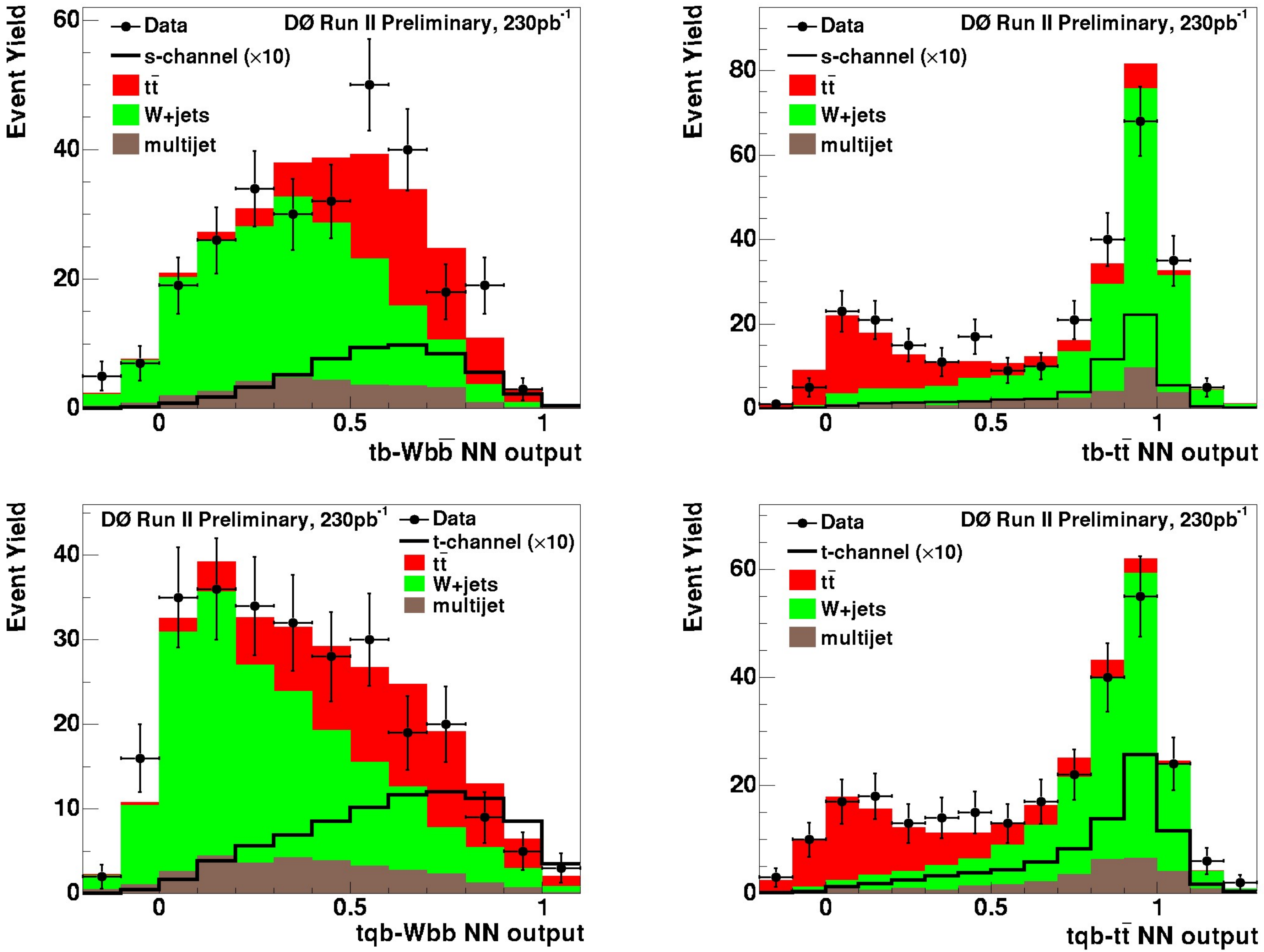




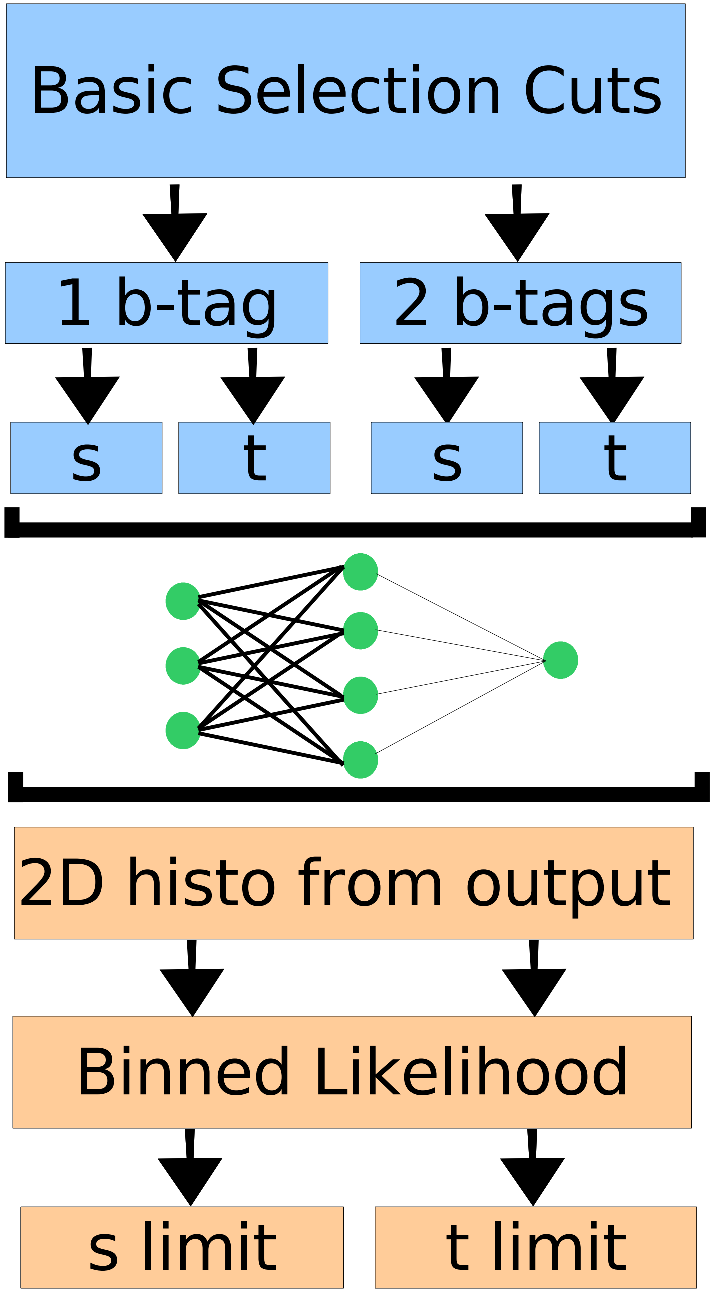
Hidden Nodes: Each is a sigmoid dependent on the input variables

$$n_k(\vec{x}, \vec{w}_k) = \frac{1}{1 + e^{-w_{ik} x_i}}$$

Neural Networks output



Analysis flow revisited



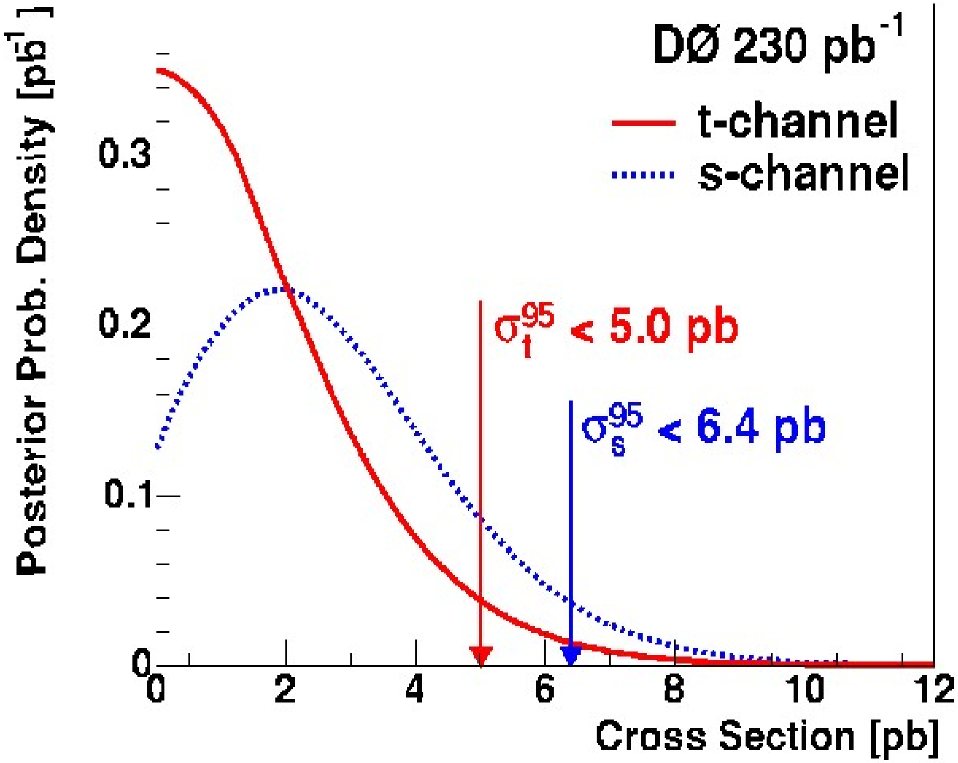
1) Separate s- and t-channel in electron or muon and 1 or 2 b-tags

2) Apply discrimination method

3) Take the Wbb and tt NN outputs and make a 2D histogram Construct a binned likelihood and evaluate signal hypothesis based on shape information

3) Results

- Cannot claim discovery yet
- Can set cross section upper limits at 95% CL:



Neural Networks (230pb-1)

	Observed	Expected
s-channel	**6.4**	4.5
t-channel	**5.0**	5.8

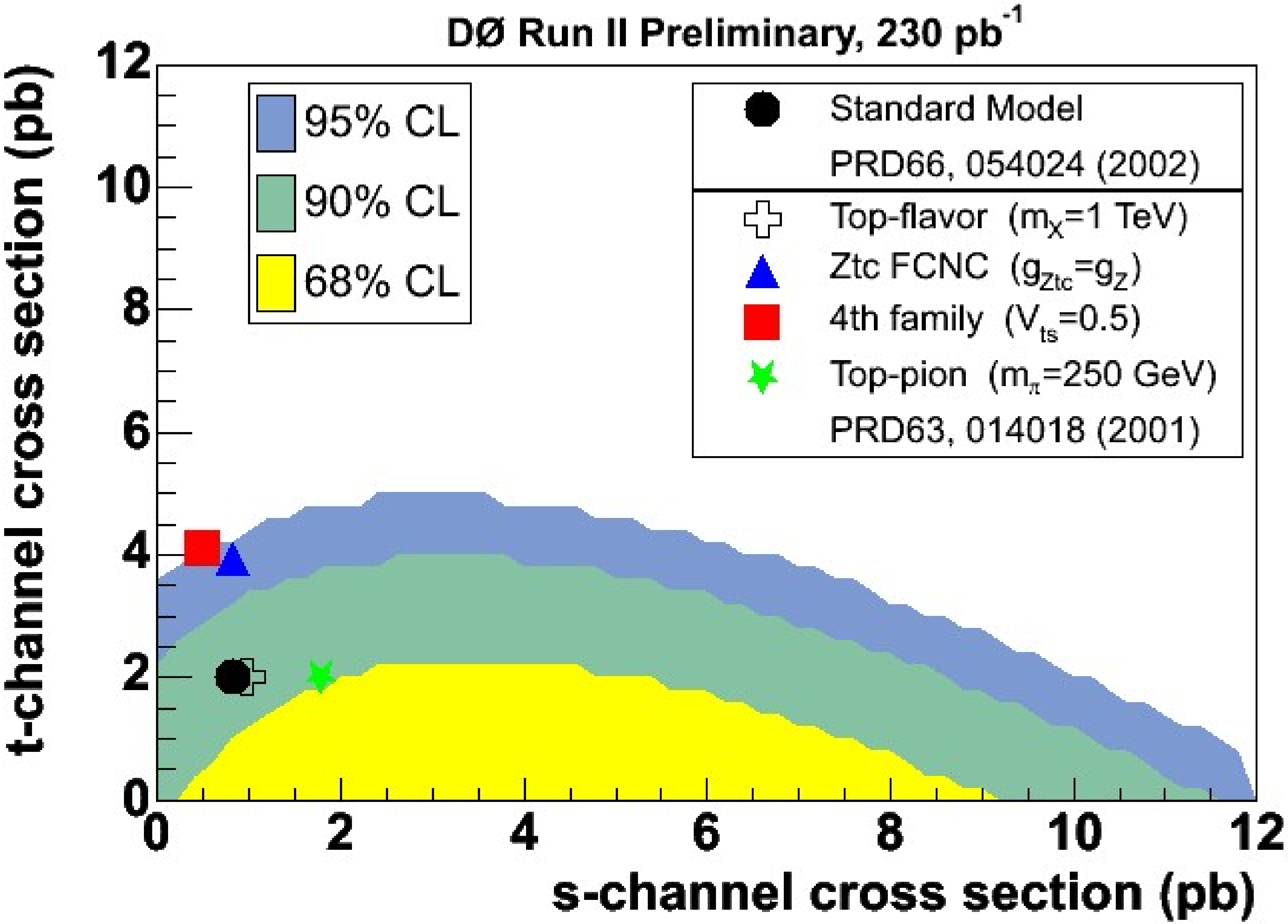
Likelihoods (370pb-1)

	Observed	Expected
s-channel	**5.0**	3.3
t-channel	**4.4**	4.3

- Use Bayesian approach to combine channels (e, μ and 1 tag, 2 tags)
- Take systematics and correlations into account
- Decision Trees/Neural Networks/Likelihoods have ~ sensitivity
- Multivariate analysis + shape information from output:

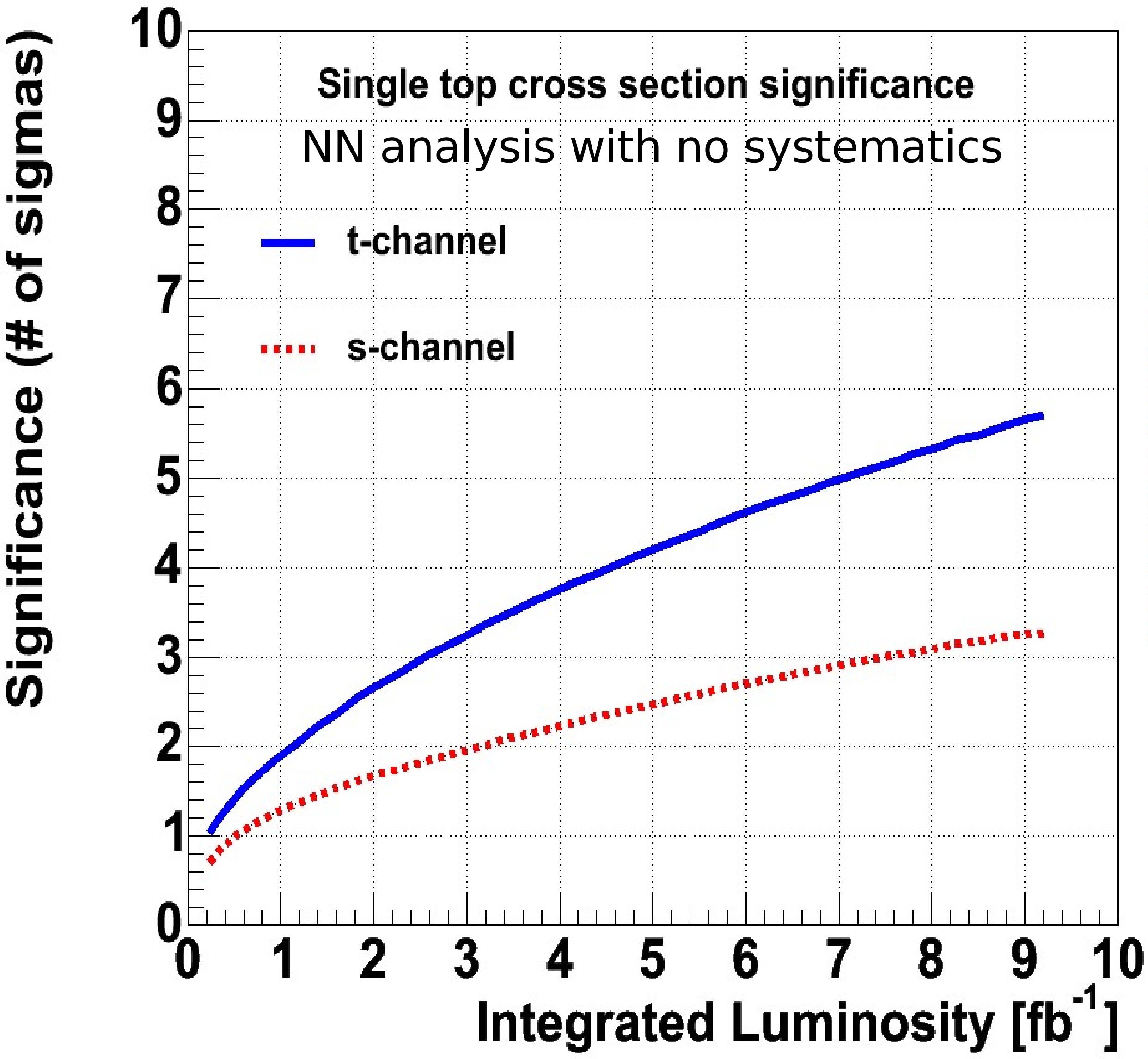
→ **factor 2 better than simple cuts**

Model independent limits



Sensitivity

With current analysis, we would need several fb^{-1} for an observation of SM single top



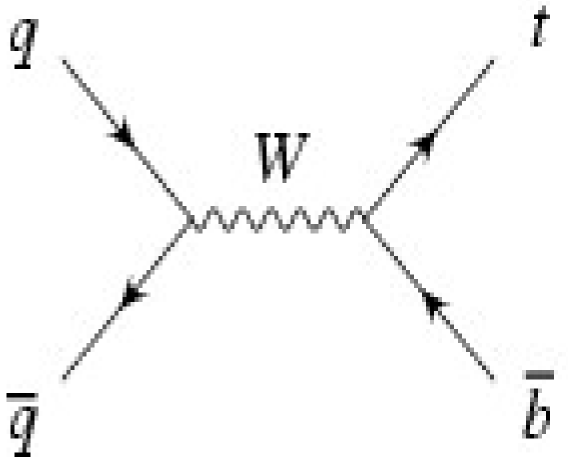
Need to work on many fronts to improve:

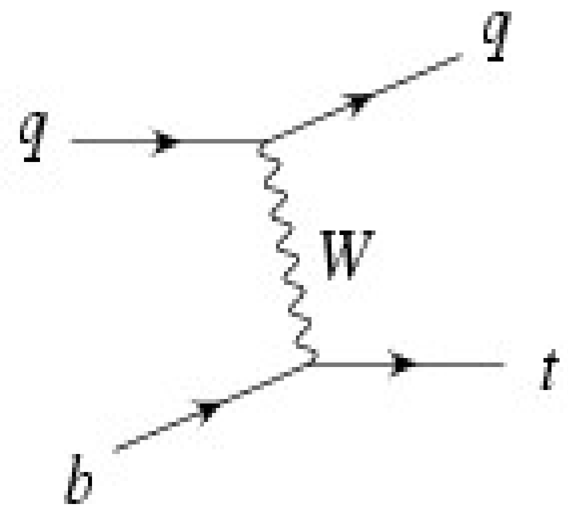
- Trigger efficiency
- Object ID: e, μ, jet, b
- Jets resolution
- Add more channels
- Background estimation
- Reduction of systematics
- Bkgnd-signal separation

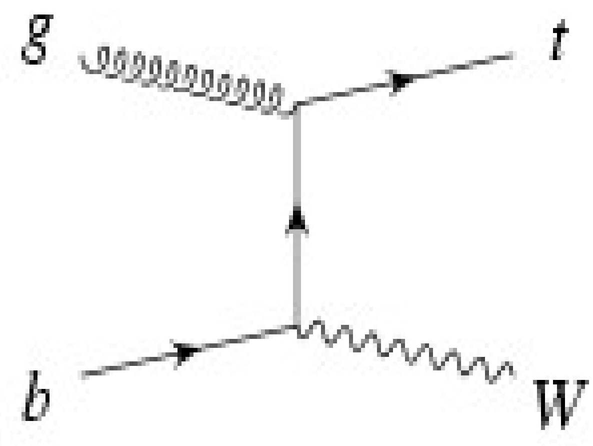
Single top in a couple of years

- By 2007 we will have observed single top and measured its cross section to ~10% at the Tevatron
- Then the LHC will start with huge production rates:

σ_s=10.6±1.1 pb σ_t=246.6±0.25 pb $\sigma_{tW}=62.0^{+16.6}_{-3.6}$ pb

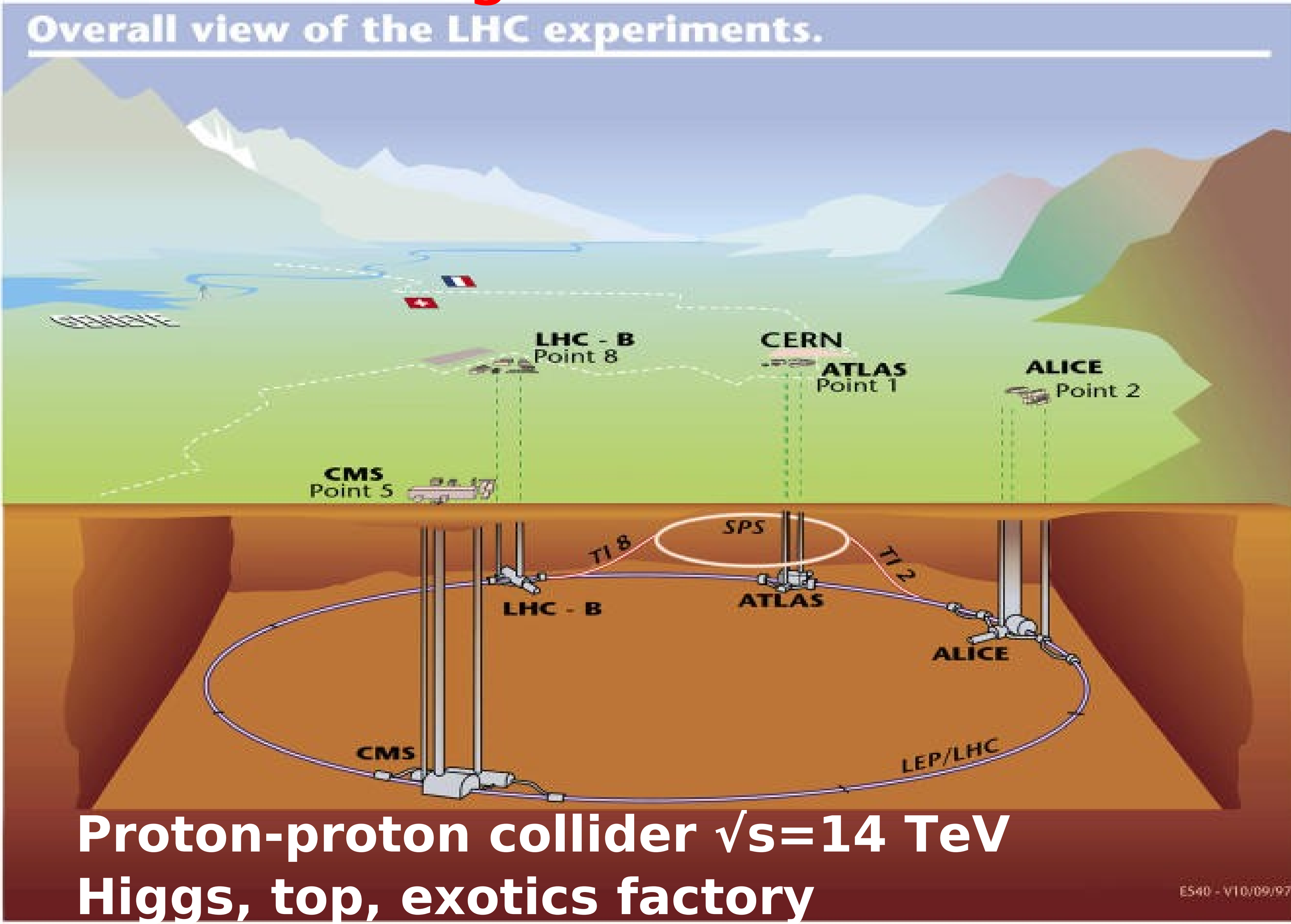






- Observe all three channels
- Measure V_{tb} to a few %
- Large samples: study properties

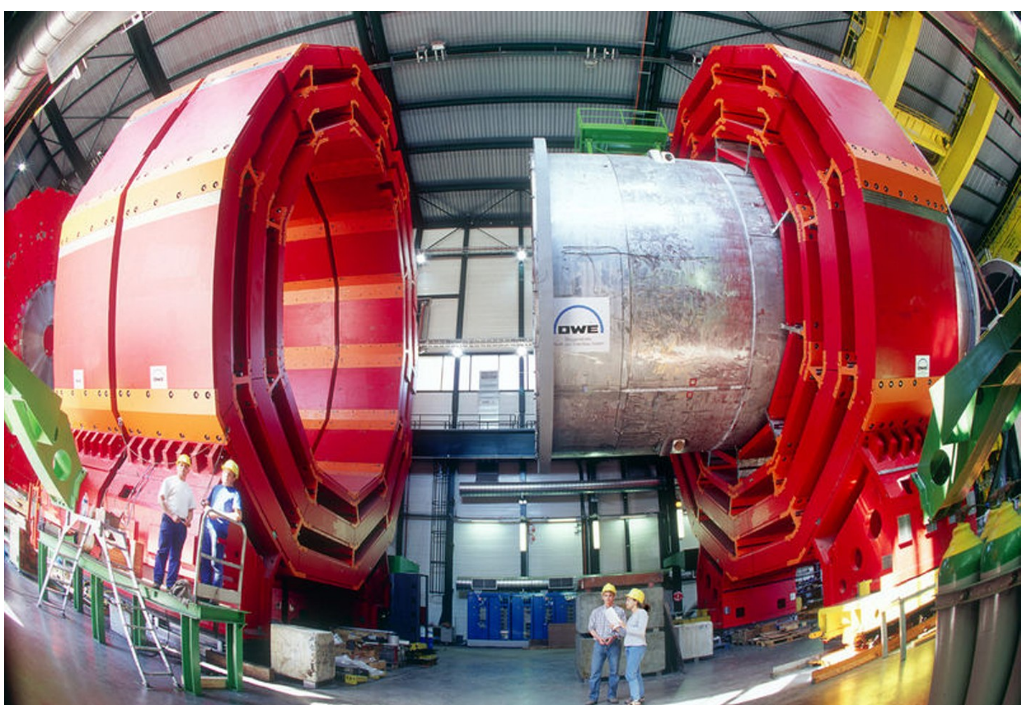
The Large Hadron Collider



Proton-proton collider $\sqrt{s}$=14 TeV

Higgs, top, exotics factory

Making quick progress



Conclusions

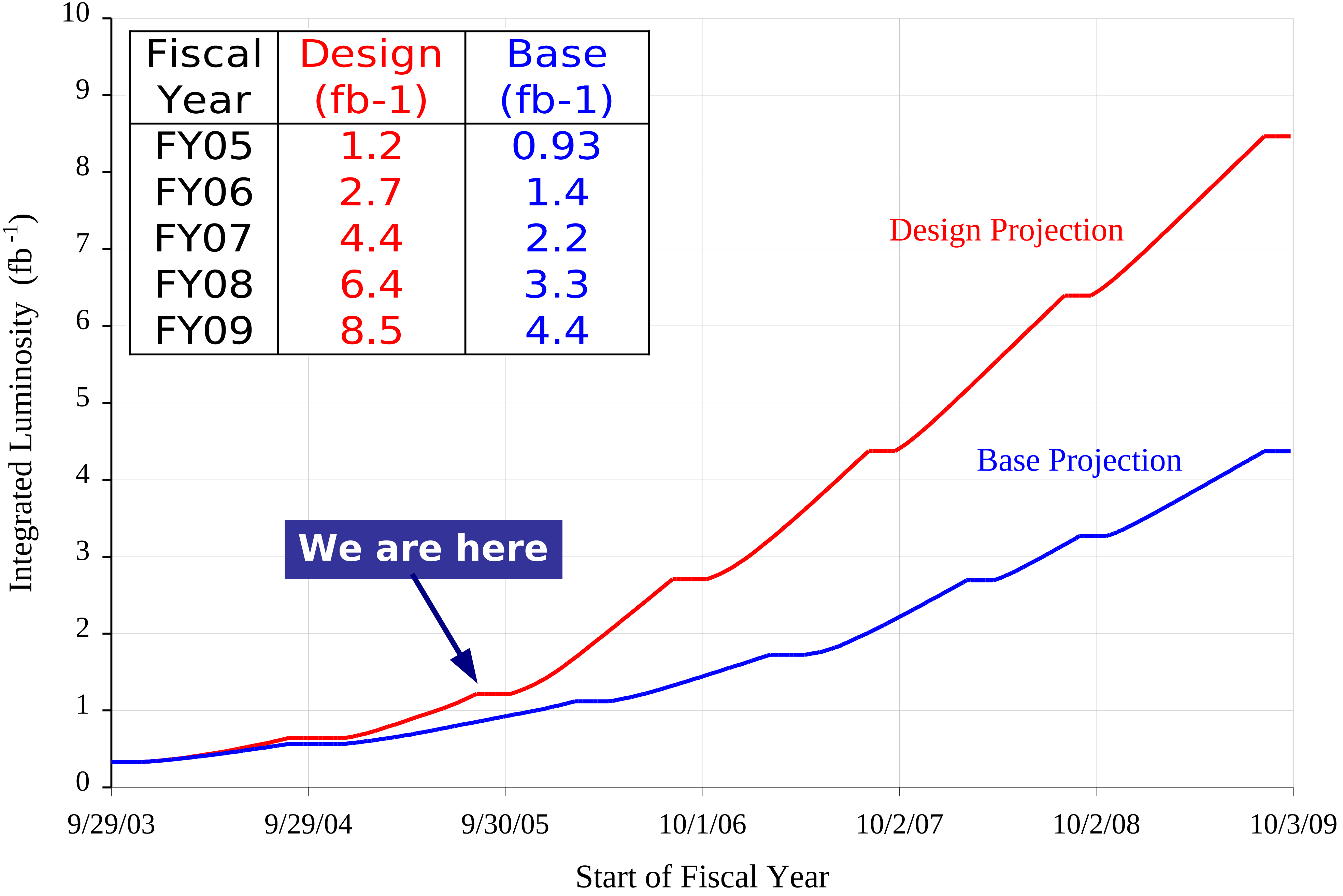
- The Standard Model is a tremendous achievement
- Still many puzzles: Origin of mass, hierarchies, dark matter, matter-antimatter asymmetry, supersymmetry, gravity...
- Top quarks offer a vantage point to test the SM
- The Tevatron is at the energy frontier (it is the place to be!)
- Data is pouring in and we have finely tuned detectors
- The race for single top observation is on! (W-t-b vertex)
- Currently, 95% CL cross section limits:

  σ_s<5.0 pb σ_t<4.4 pb (SM predicts ~1pb and 2pb)
- Will observe it soon!
- The LHC will then push the energy frontier x10

All possible by the work of many

And special thanks to Gordon Watts, Reinhard Schwienhorst, and others for a lot of the material for this presentation

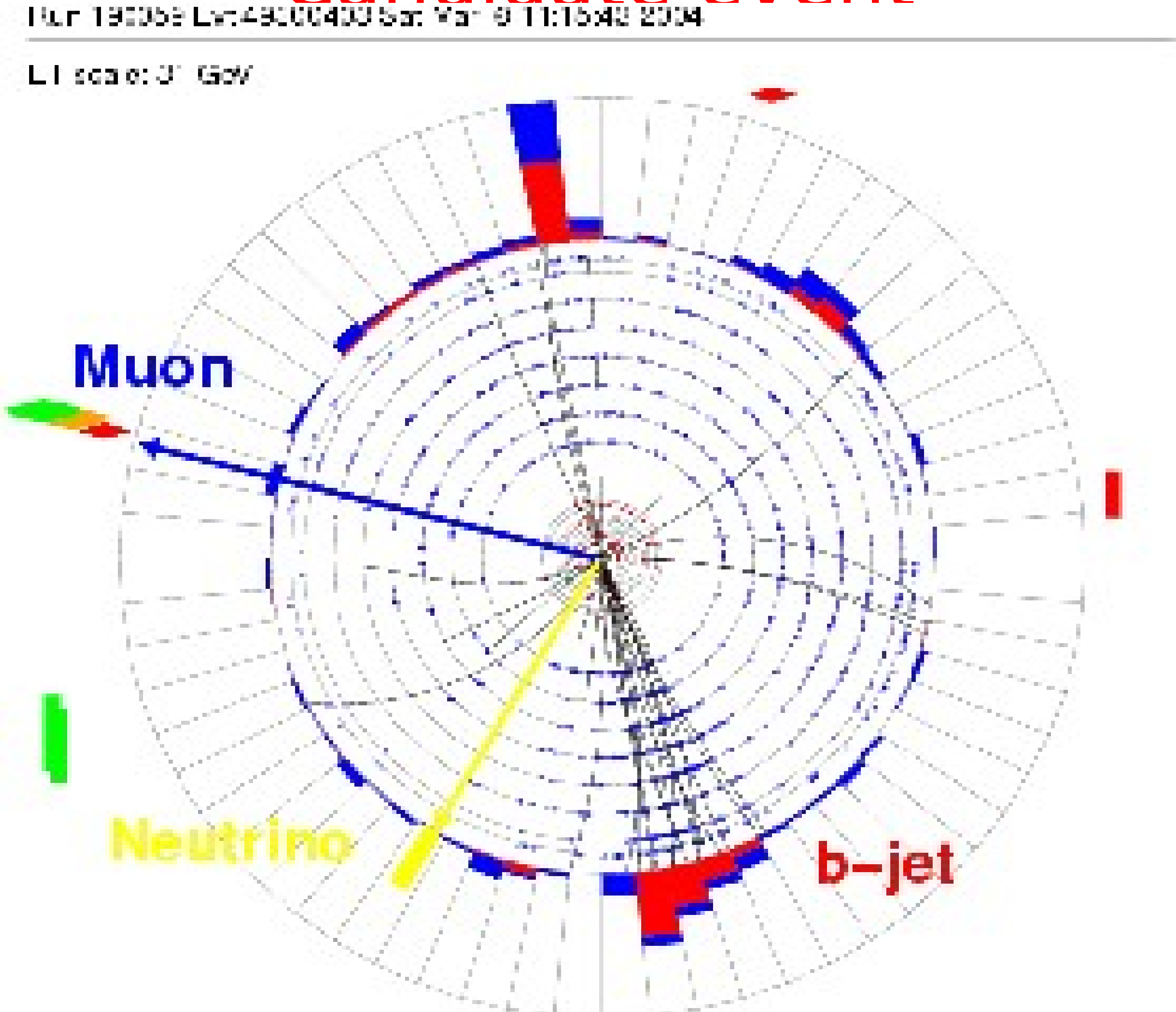
Tevatron luminosity prospects



Fiscal Year	Design (fb-1)	Base (fb-1)
FY05	1.2	0.93
FY06	2.7	1.4
FY07	4.4	2.2
FY08	6.4	3.3
FY09	8.5	4.4

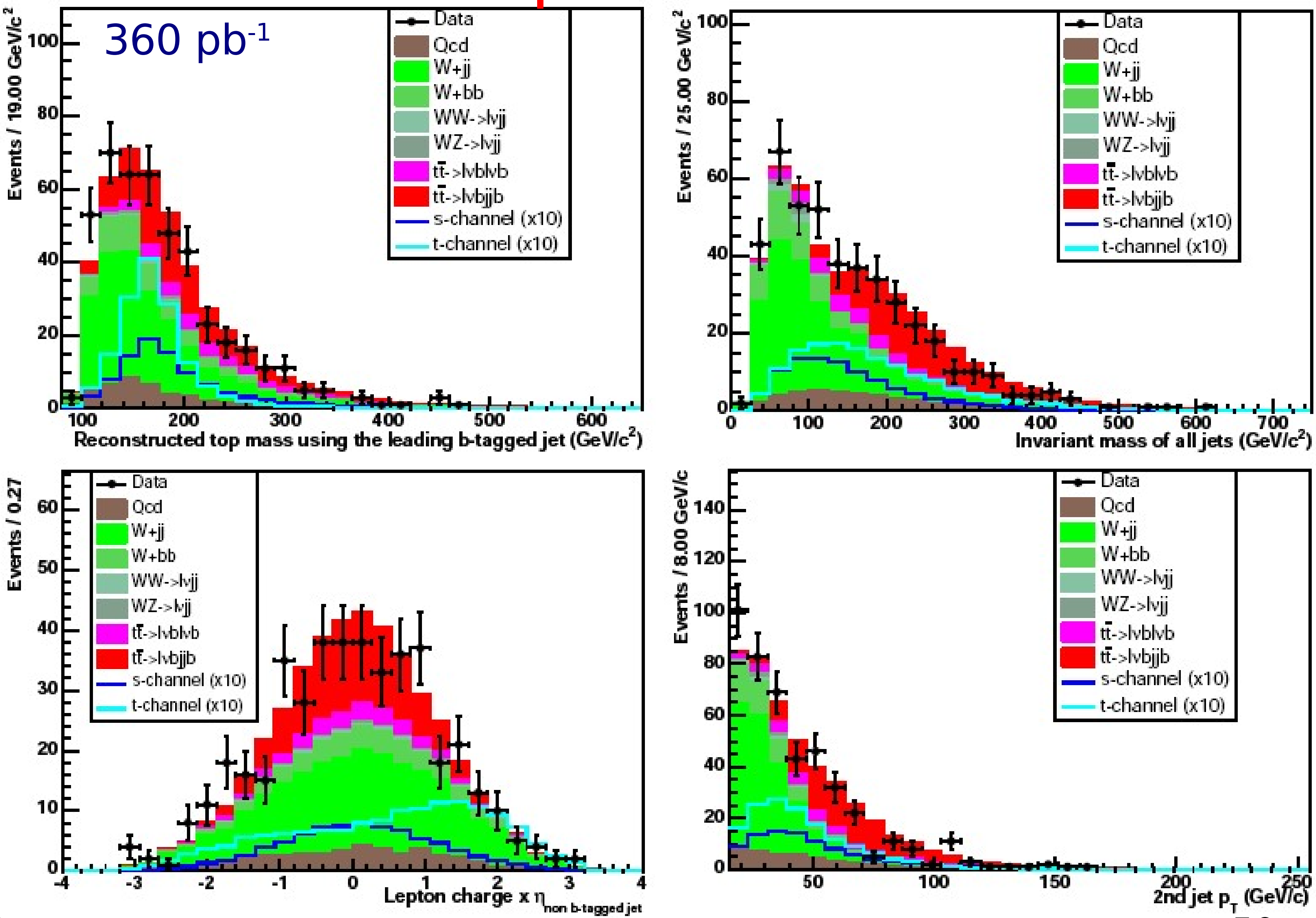
Extra slides

Candidate event



Input variables

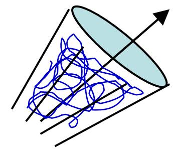
e+μ =1tag+2tag



Discriminating variables

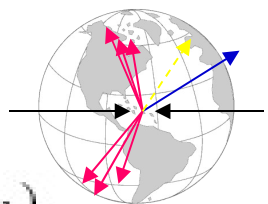
Individual object kinematics

- $p_T(\text{jet1}_{\text{tagged}})$
- $p_T(\text{jet1}_{\text{untagged}})$
- $p_T(\text{jet2}_{\text{untagged}})$
- $p_T(\text{jet1}_{\text{nonbest}})$
- $p_T(\text{jet2}_{\text{nonbest}})$



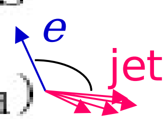
Global event kinematics

- $M_T(\text{jet1},\text{jet2})$
- $p_T(\text{jet1},\text{jet2})$
- $M(\text{alljets})$
- $H_T(\text{alljets})$
- $M(\text{alljets} - \text{jet1}_{\text{tagged}})$
- $H(\text{alljets} - \text{jet1}_{\text{tagged}})$
- $H_T(\text{alljets} - \text{jet1}_{\text{tagged}})$
- $p_T(\text{alljets} - \text{jet1}_{\text{tagged}})$
- $M(\text{alljets} - \text{jet}_{\text{best}})$
- $H(\text{alljets} - \text{jet}_{\text{best}})$
- $H_T(\text{alljets} - \text{jet}_{\text{best}})$
- $M(\text{top}_{\text{tagged}}) = M(W,\text{jet1}_{\text{tagged}})$
- $M(\text{top}_{\text{best}}) = M(W,\text{jet}_{\text{best}})$
- $\sqrt{\hat{s}}$



Angular variables

- $\Delta R(\text{jet1},\text{jet2})$
- $Q(\text{lepton}) \times \eta(\text{jet1}_{\text{untagged}})$
- $\cos(\text{lepton}, Q(\text{lepton}) \times z)_{\text{top}_{\text{best}}}$
- $\cos(\text{lepton}, \text{jet1}_{\text{untagged}})_{\text{top}_{\text{tagged}}}$
- $\cos(\text{alljets}, \text{jet1}_{\text{tagged}})_{\text{alljets}}$
- $\cos(\text{alljets}, \text{jet}_{\text{nonbest}})_{\text{all jets}}$



This is where our phenomenology friends come so handy!

Three broad categories:

- Object kinematics
- Global event kinematics
- Angular correlations

Reconstruct W: from ℓ and

To reconstruct the top quark:

- s-channel: “best” jet algorithm

Chose the jet that gives m_t closest to 175GeV

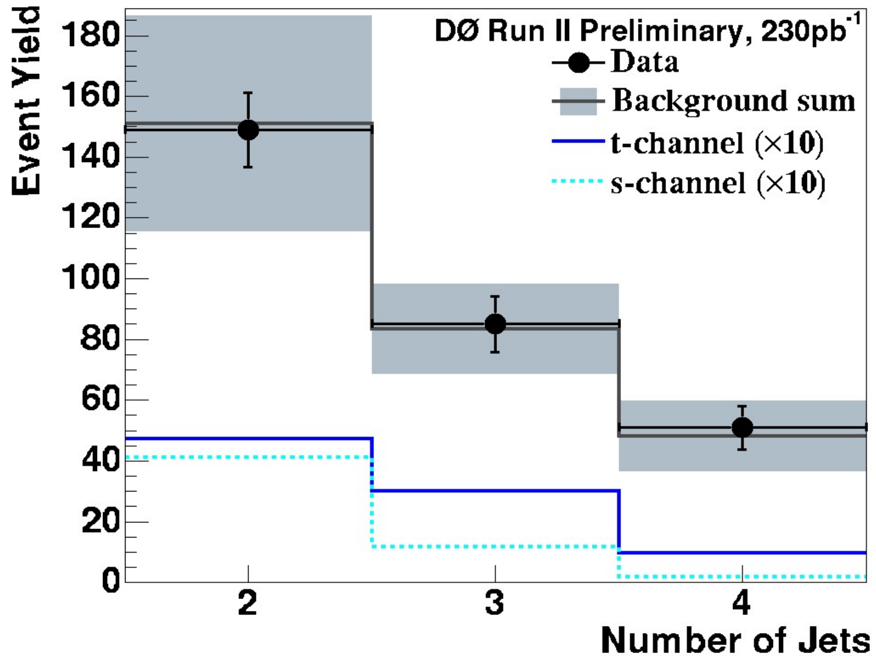
- t-channel: lead b-tagged jet + W

Reconstruct q': lead untagged jet

- **s-channel search only**
- **t-channel search only**
- **used in both**

Systematic Uncertainites

Monte Carlo Systematic Uncertainties	
Theory cross sections	15 %
SVT modeling, single (double) tag	10 %(20 %)
Jet Energy Scale	10 %
Trigger Modeling	6 %
Jet Fragmentation	6 %
Jet ID	5 %
ℓ ID	5 %



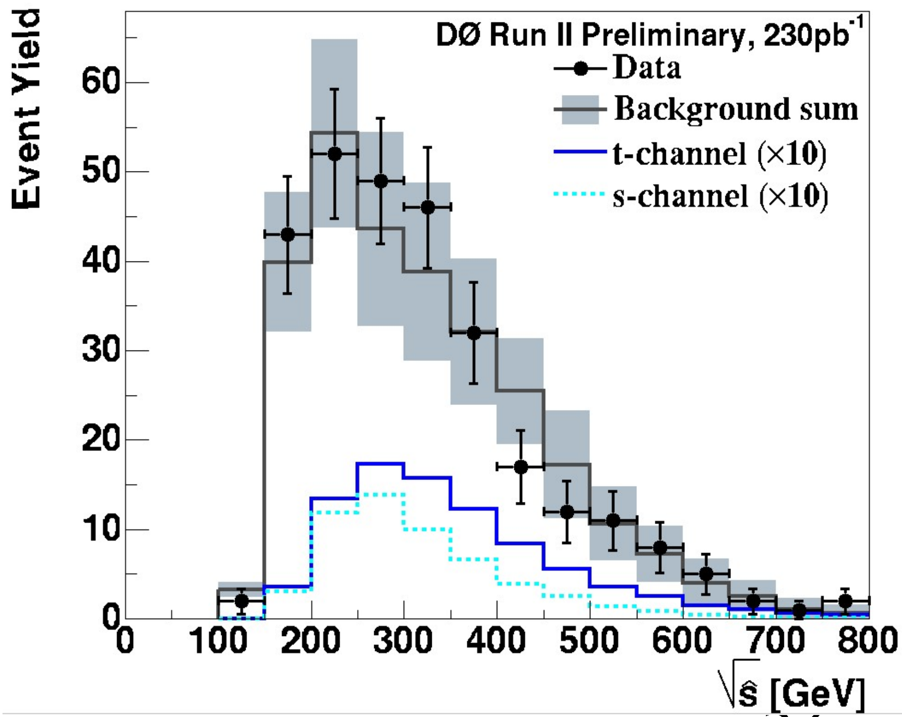
- Some systematic uncertainties also affect shape:

  JES, b-tag and trigger modeling

- Total uncertainty:

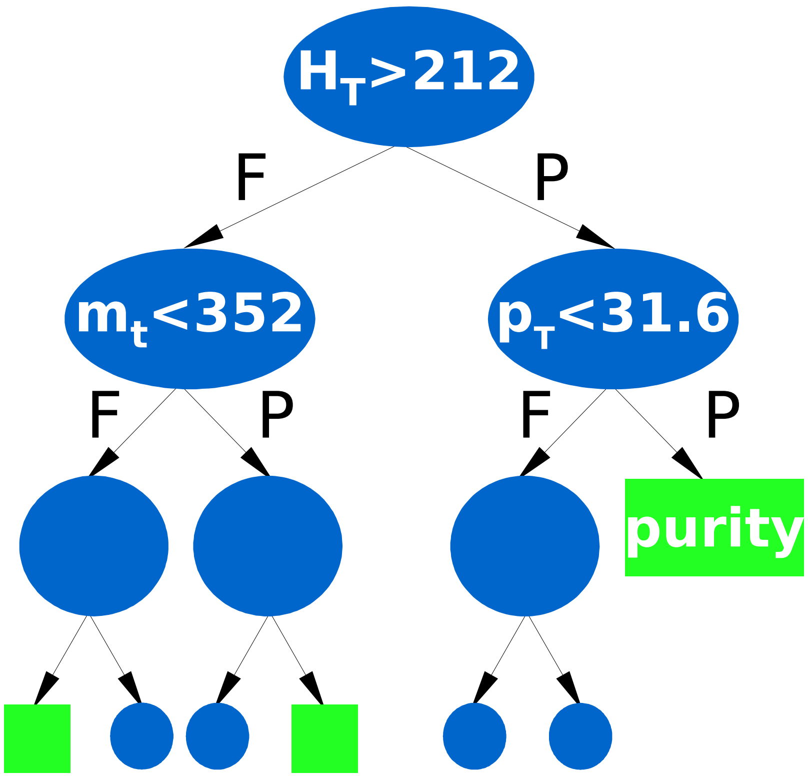
	1 tag	2 tags
Signal acceptance	15%	25%
Background sum	10%	26%

- Result is statistics limited

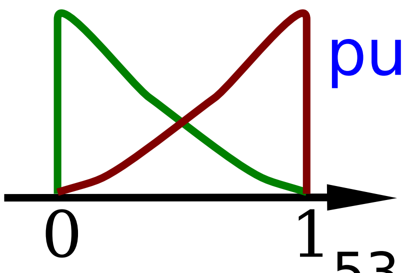


Decision Trees

Multivariate technique widely used in social sciences
Recently applied to HEP: MiniBooNE (object ID), GLAST
Gives probability for an event to be signal



- Send each event down the tree
- Each node corresponds to a cut
  - Pass cut (P): right branch
  - Fail cut (F): left branch
- A leaf corresponds to a node without branches
- Define purity= $N_S/(N_S+N_B)$
- Training: optimize Gini improvement
  - Gini=2 $N_S N_B / (N_S + N_B)$
- Output: purity for each event



Crash course in Bayesian probability

Bayes' theorem expresses the degree of belief in a hypothesis A, given another B. "Conditional" probability P(A|B):

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

In HEP: $B \rightarrow N_{observed}$, $A \rightarrow n_{predicted} = n_{signal} + n_{bkgd}$, $n_s = Acc*L*\sigma$

P(B|A): "model" density, or likelihood: $L(N_{observed}|n_{predicted}) = n^N e^{-n}/N!$

P(A): "prior" probability density $\prod(n_{pred}) = \prod(Acc*L, n_b)\prod(\sigma)$

$\prod(n_s, n_b)$ multivariate gaussian ; $\prod(\sigma)$ assumed flat

P(B): normalization constant Z: $P(N_{observed})$

P(A|B): "posterior" probability density $P(n_{predicted}|N_{observed})$

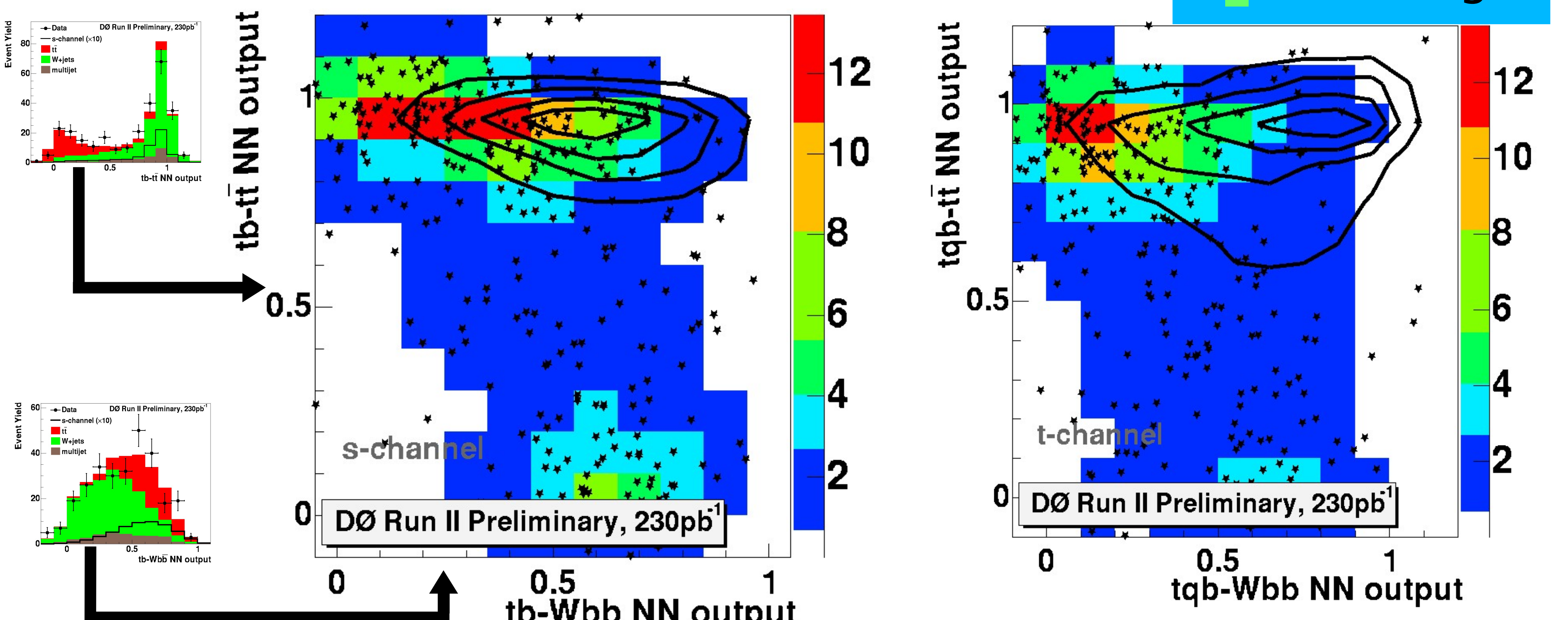
$$P(n_{predicted}|N_{observed}) = 1/Z \; L(N_{observed}|n_{predicted})\prod(n_{pred})$$

Limits from binned likelihood

- No evidence for single top signal
- Set 95% CL upper cross section limit with Bayesian approach
- Use 2D histograms as input for binned likelihood
- Including bin-by-bin systematics and correlations

Used for DT and NN analyses
Cut-based analysis uses likelihood from event count

★ data
single top
Sum bkgd



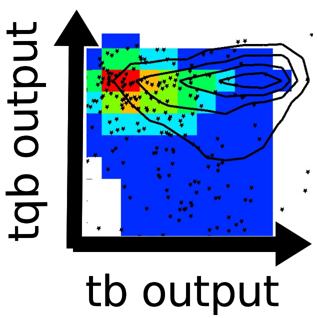
Full 2D limits

The goal is to obtain $_s$, $_t$, and $_{s+t}$, without any SM assumption

Previously we have used $_s^{SM}$ to derive $_t$ and vice versa

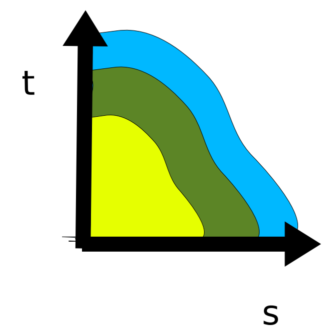
As before, use likelihood from 2D discriminant output

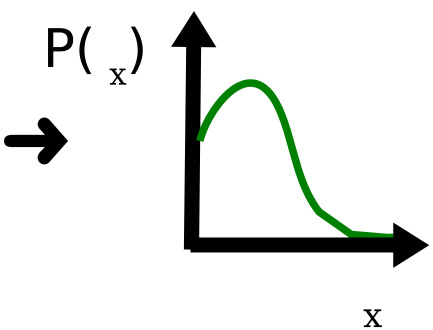
Float $_s$ and $_t$ and consider flat priors



$$\text{Build Likelihood} \equiv L(\sigma_s, \sigma_t)$$

$$\text{Obtain Posterior} \equiv P(\sigma_s, \sigma_t; n_{obs})$$





$$P(\sigma_s; n_{obs}) = \int P(\sigma_s, \sigma_t; n_{obs})\, d\sigma_t$$

$$P(\sigma_t; n_{obs}) = \int P(\sigma_s, \sigma_t; n_{obs})\, d\sigma_s$$

$$P(\sigma_{z=s+t}; n_{obs}) = \frac{1}{\sigma_z} \int P(\sigma_z, \sigma_t; n_{obs})\, d\sigma_t$$

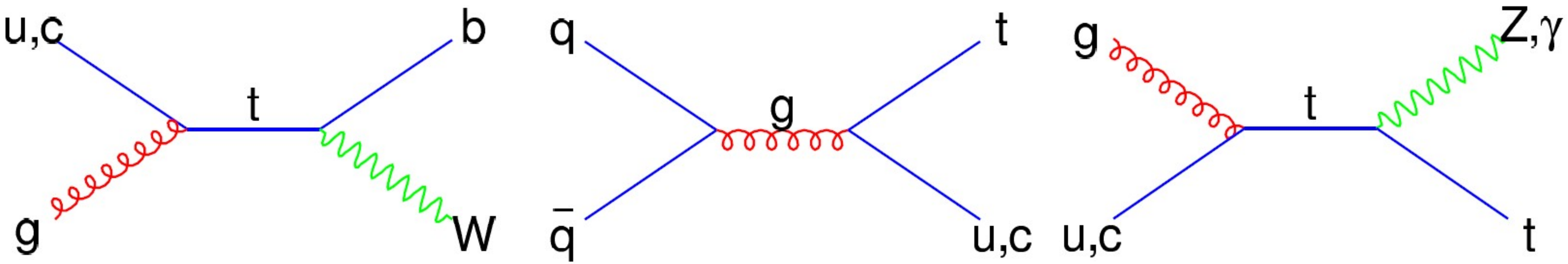
$$\sigma_x^{95} = \int_0^{\sigma^{95}} P(\sigma_x; n_{obs})\, d\sigma_x$$

- For the combined limit: replace: s →z-t where z=s+t at the Likelihood level
- Additional constraint on priors: t≤z →the prior for t depends on z

Single top beyond the SM

Plethora of possibilites

- Wtb interaction: anomalous couplings, “beautiful mirrors”, top see-saw (little Higgs)
- New particles: 4th generation *q*, W', H$^{\pm}$, SUSY, technicolor
- FCNC: probe *tgu* coupling (extends LEP limits because involves a *g*)
- Extra SU(2), Universal Extra Dimensions



~25pb? ~3.5pb ~0.4pb

Non-SM couplings

Top is a good place to look for deviations from SM:
under control, one dominant decay t→Wb, no top hadrons,...

- Generalized Lagrangian for the Wtb interaction (hep-ph/0503040):

$$\mathcal{L}_{tbW} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t + h.c.$$

f1: “vector”-like
f2: “tensor”-like
$P_{R(L)}=(1\pm\gamma_5)/2$
In SM: $f_1^L=V_{tb}\sim1$; $f_1^R=f_2^L=f_2^R=0$

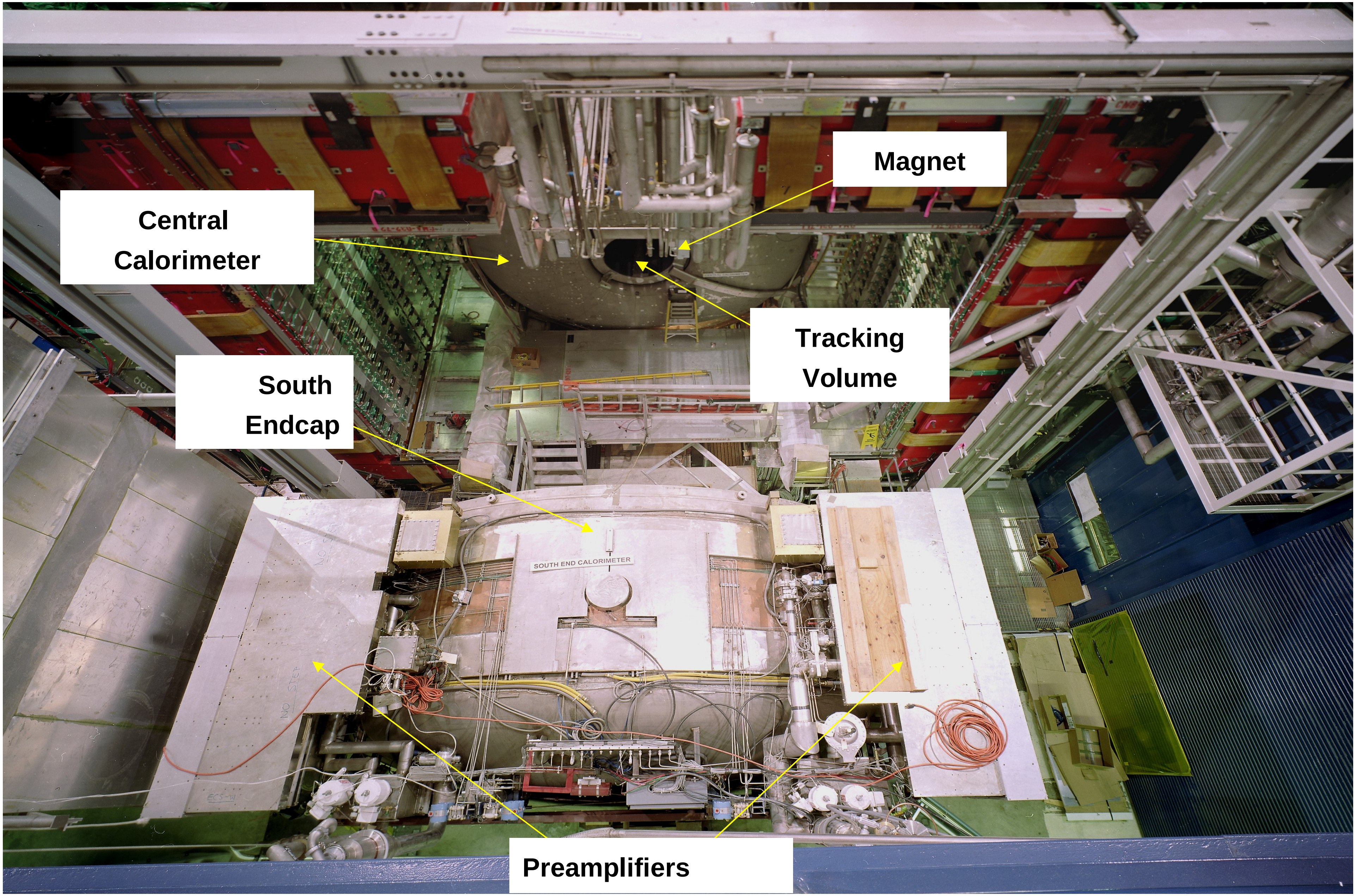
- Effective single top production cross section:

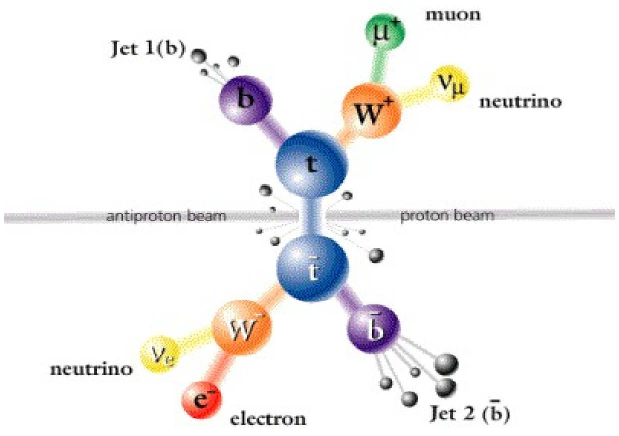
$$\sigma = A(f_1^L)^2 + B(f_1^R)^2 + C(f_1^L+f_2^R)^2 + D(f_2^L+f_1^R)^2$$

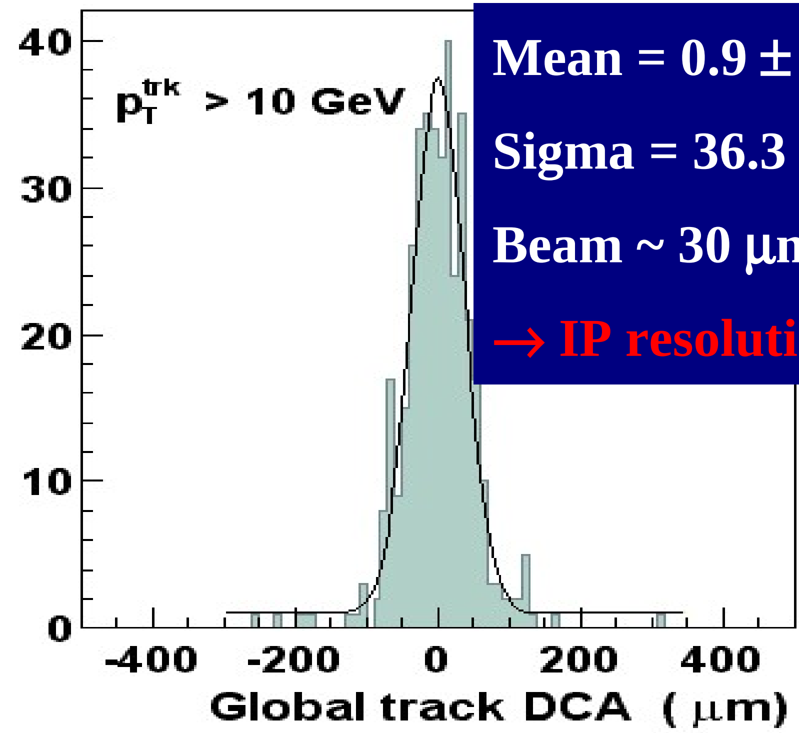
- There are strong bounds on tensor couplings:
  from unitarity $|f_2|<0.6$, and from b→sγ : $|f_2^L|<0.004$
- But Tevatron can set direct limits

Using the analysis on 230pb^{-1} and NN, the goal is:

- Set limits simultaneously on all four couplings
- Set individual limits


Magnet
Central Calorimeter
Tracking Volume
South Endcap
SOUTH END CALORIMETER
Preamplifiers



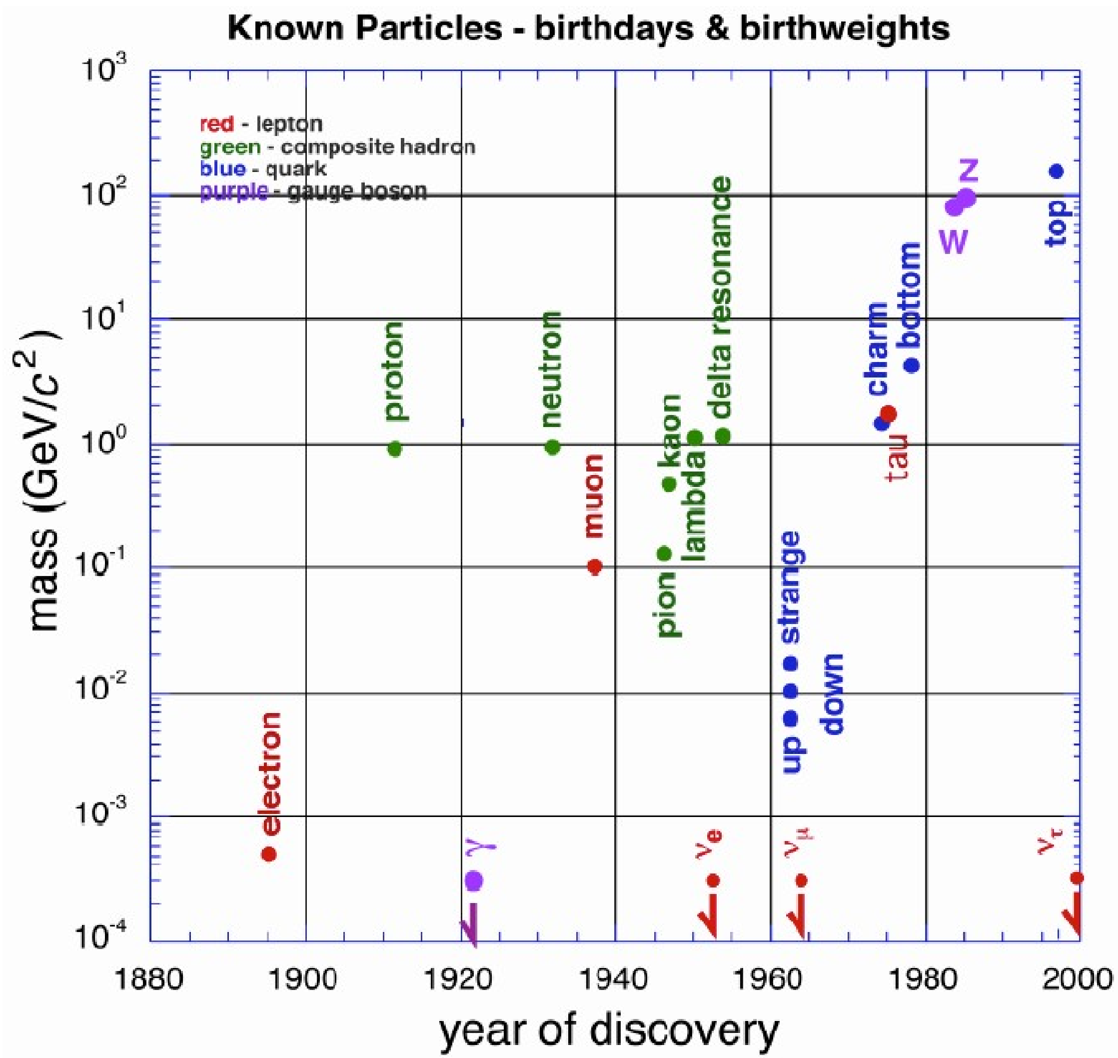


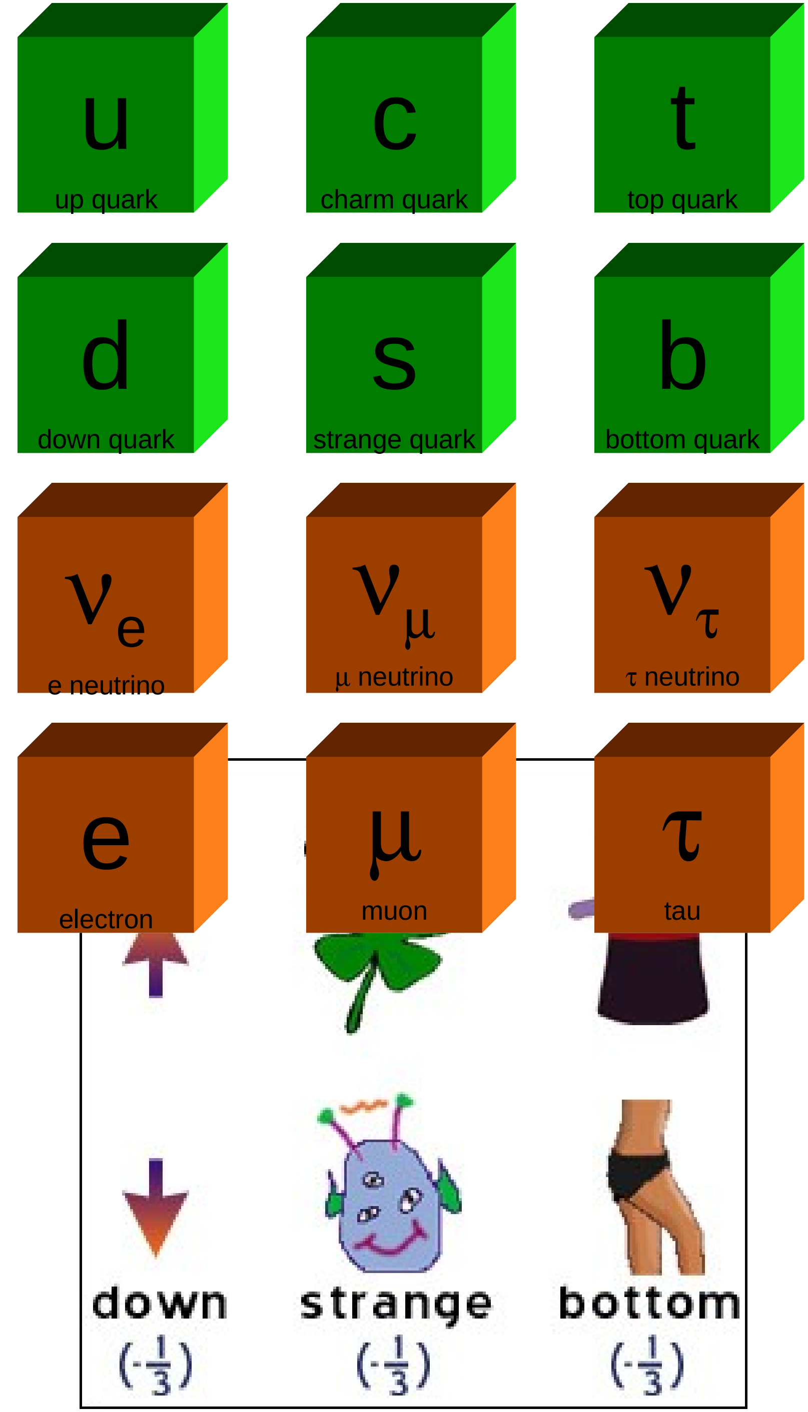
Mean = 0.9 ± 2.2 μm

Sigma = 36.3 ± 1.8 μm

Beam ~ 30 μm

→ IP resolution ~ 20 μm


Known Particles - birthdays & birthweights
red - lepton
green - composite hadron
blue - quark
purple - gauge boson
mass (GeV/c²)
year of discovery
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
1880
1900
1920
1940
1960
1980
2000
electron
γ
proton
neutron
muon
pion
kaon
lambda
delta resonance
νe
up
down
strange
νμ
charm
tau
bottom
W
Z
top
ντ


u
up quark
c
charm quark
t
top quark
d
down quark
s
strange quark
b
bottom quark
νe
e neutrino
νμ
μ neutrino
ντ
τ neutrino
e
electron
μ
muon
τ
tau
down
(-1/3)
strange
(-1/3)
bottom
(-1/3)