

**UIC Physics Colloquium  
September 7, 2005**

# **Are top quarks lonely?**

**Hunting for EW top production at the Tevatron**

# 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

**What is the Universe made of?**

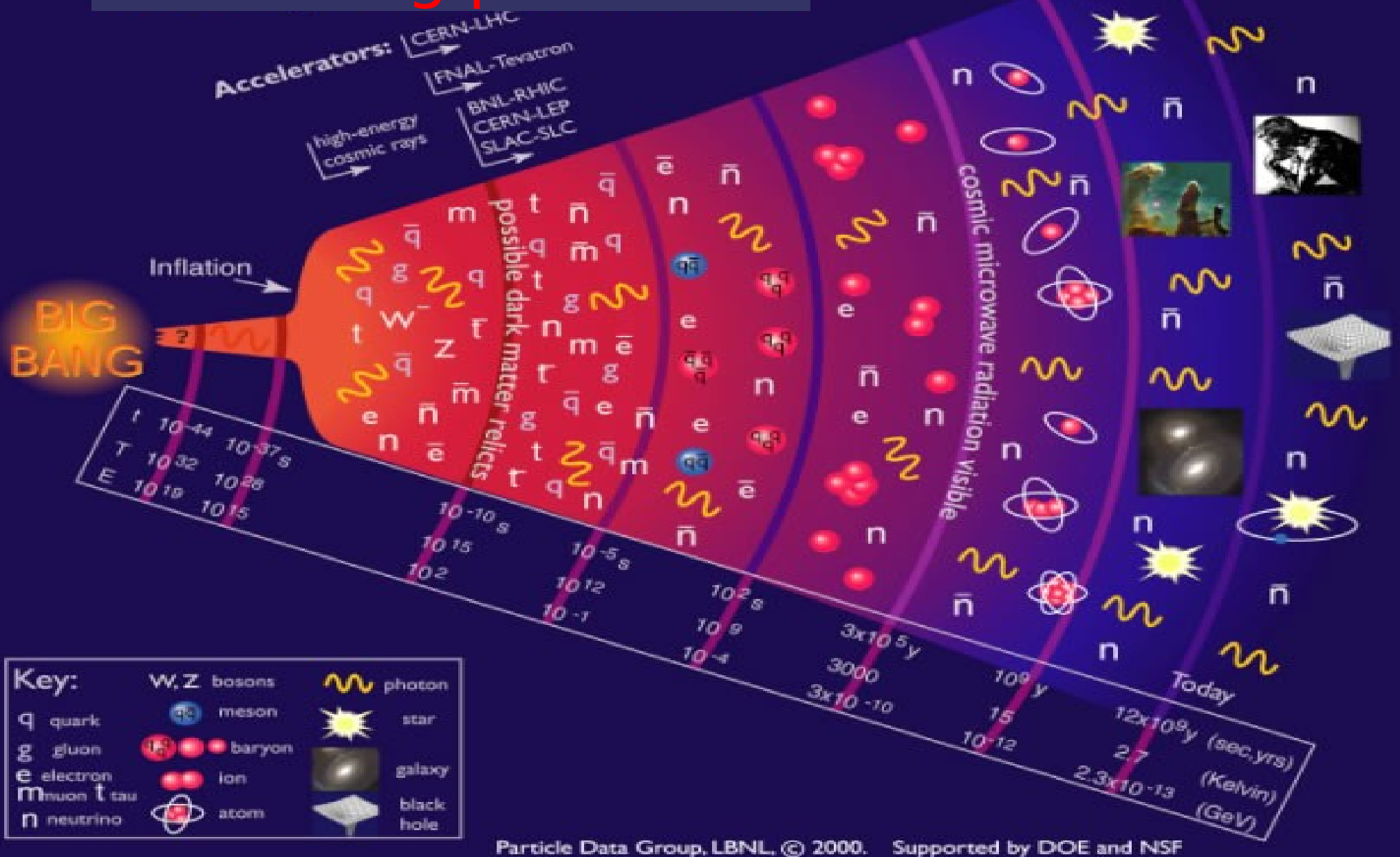
**Cosmology & Astrophysics**

**Atomic Physics**

**Nuclear Physics**

**Particle Physics**

# The big picture



Interconnections:

SM Cosmology  $\leftrightarrow$  SM Particle Physics  $\leftrightarrow$  QF Theory  $\leftrightarrow$  Astrophysics

Arán García-Bellido, UW

# 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- $1/2$  fermions
- ▶ Which interact through the exchange of spin-1 bosons
- ▶ Gauge theory:  $SU(3)_C \times SU(2)_L \times U(1) \Rightarrow$  symmetry, local scale invariance

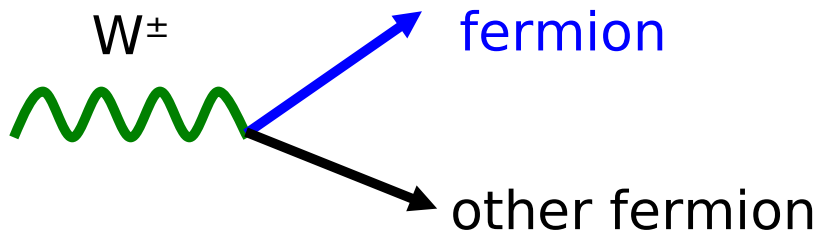


# Interactions

## Electroweak interactions

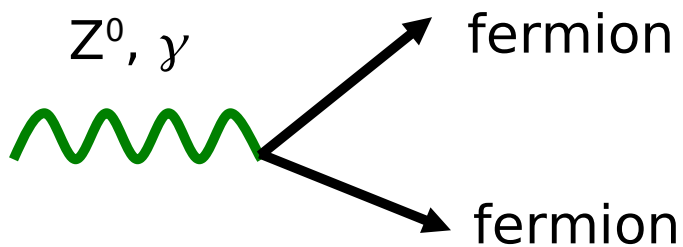
Charged current:

- nuclear beta decay



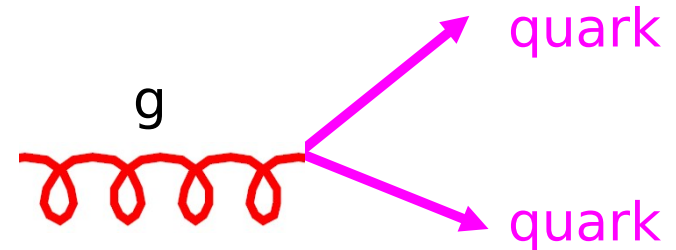
Neutral current:

- electromagnetism



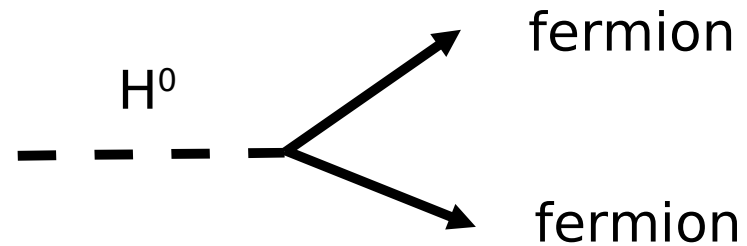
## Strong interaction

- Holds atomic nucleus together



## Yukawa coupling

- Particles acquire mass

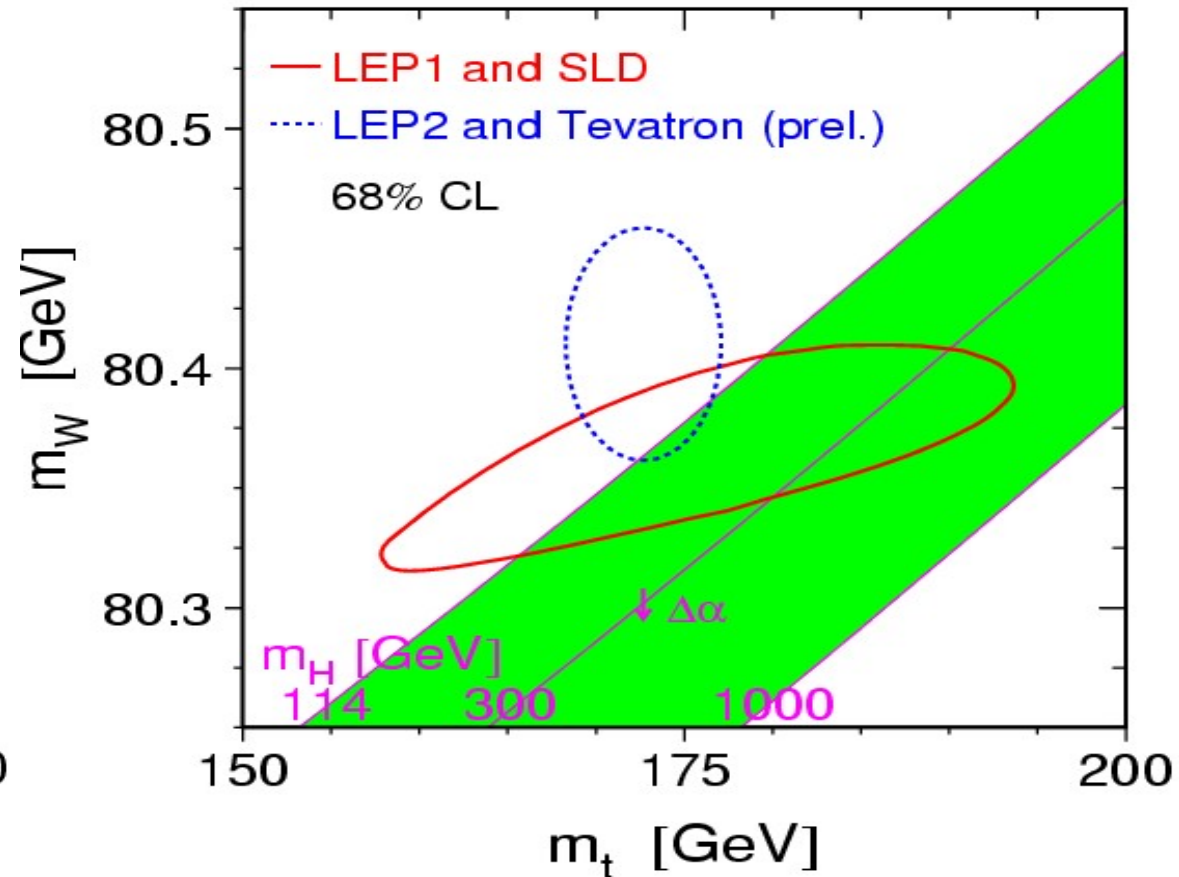
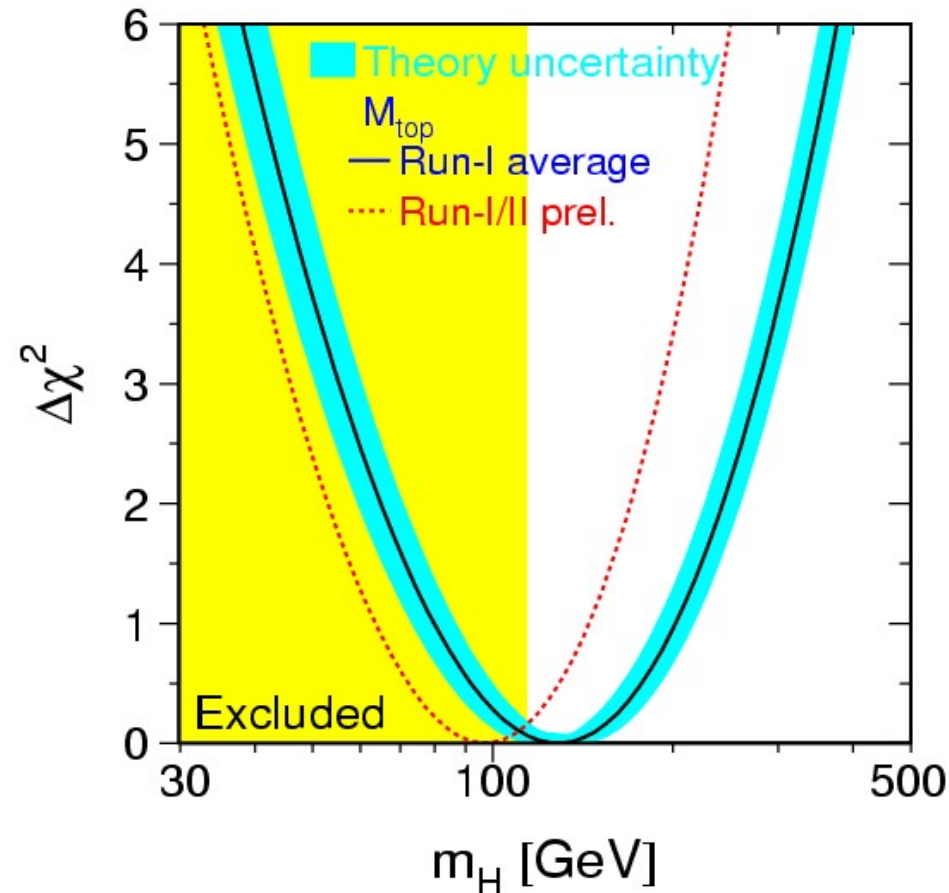
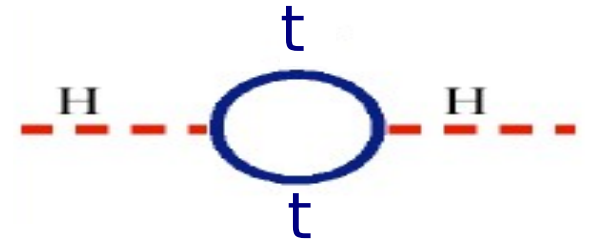
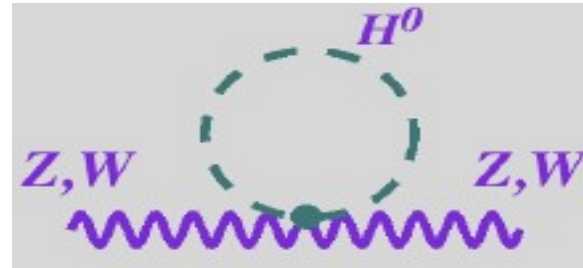
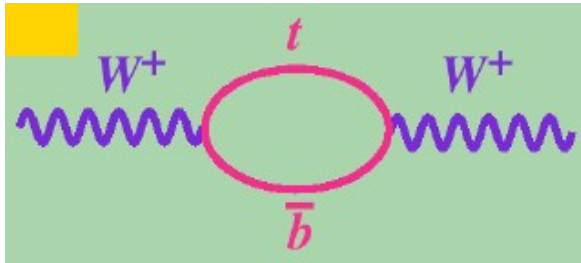






$$W \leftrightarrow t \leftrightarrow H$$

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

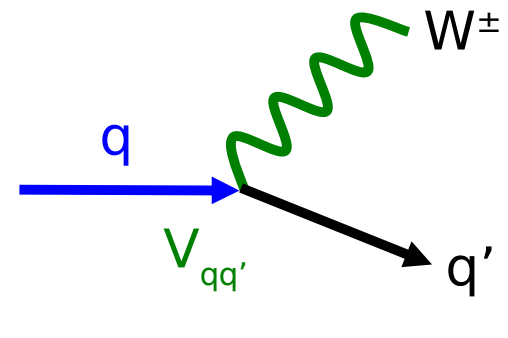


# The SM under attack

- ▶ 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)

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


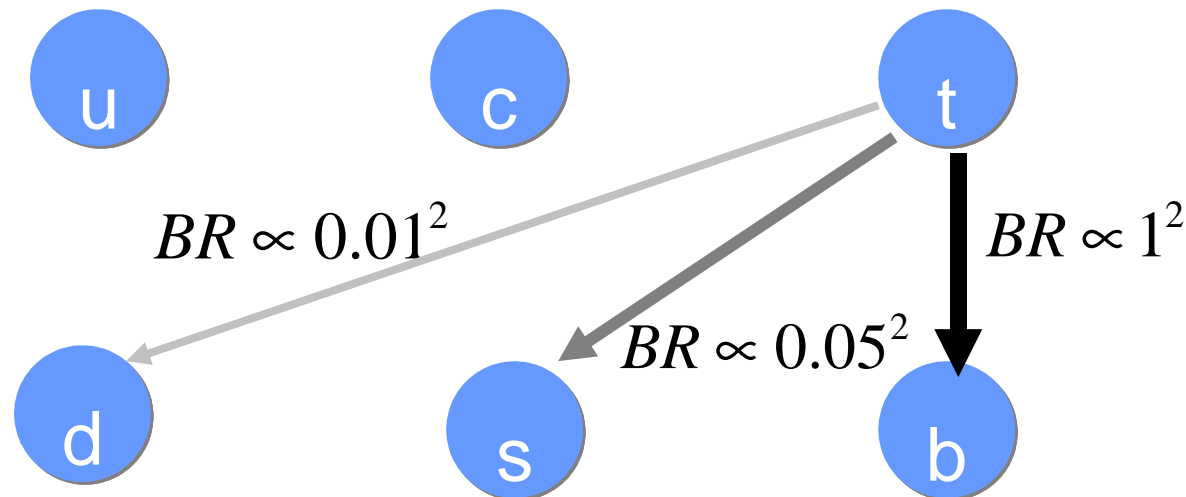
Only element not measured directly yet

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

# Flavor changing interactions

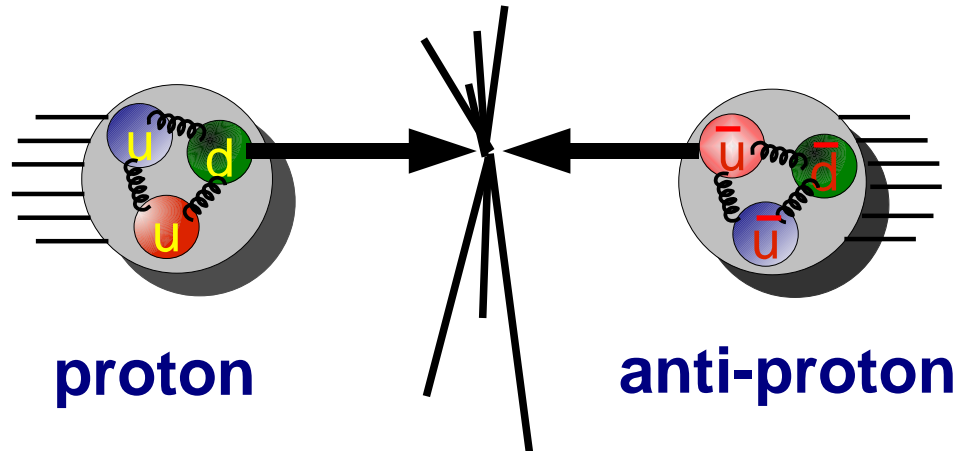
$$\begin{pmatrix} 0.9741 - 0.9756 & 0.219 - 0.226 & 0.002 - 0.005 \\ 0.219 - 0.226 & 0.9732 - 0.9748 & 0.038 - 0.044 \\ 0.004 - 0.014 & 0.037 - 0.044 & 0.9990 - 0.9993 \end{pmatrix}$$

- ▶ 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:  $N[\text{collisions}] = L[\text{pb}^{-1}]\sigma[\text{pb}]$

- ▶ **Picobarns** (pb) are a measure of “cross section” ( $\sigma$ =interaction probability). 1 barn =  $10^{-24}$  cm<sup>2</sup>.
- ▶ **Inverse picobarns** (pb<sup>-1</sup>) are a measure of the “integrated luminosity” (L=collected data)

Example: 100 pb<sup>-1</sup> = sufficient data to observe 100 events of a process having 1 pb cross section

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

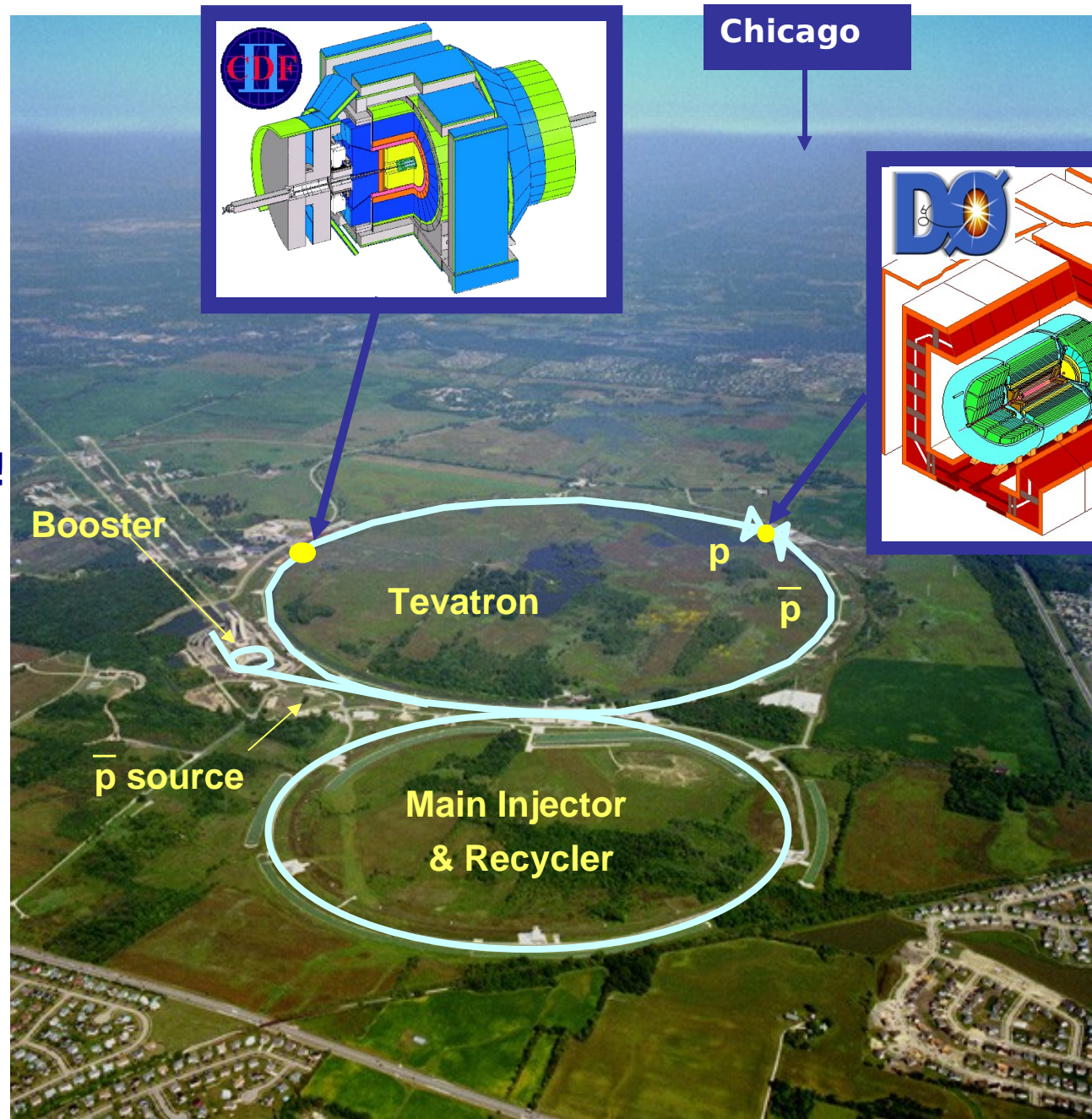
# The Tevatron

The highest energy particle accelerator in the world!

Proton-antiproton collider

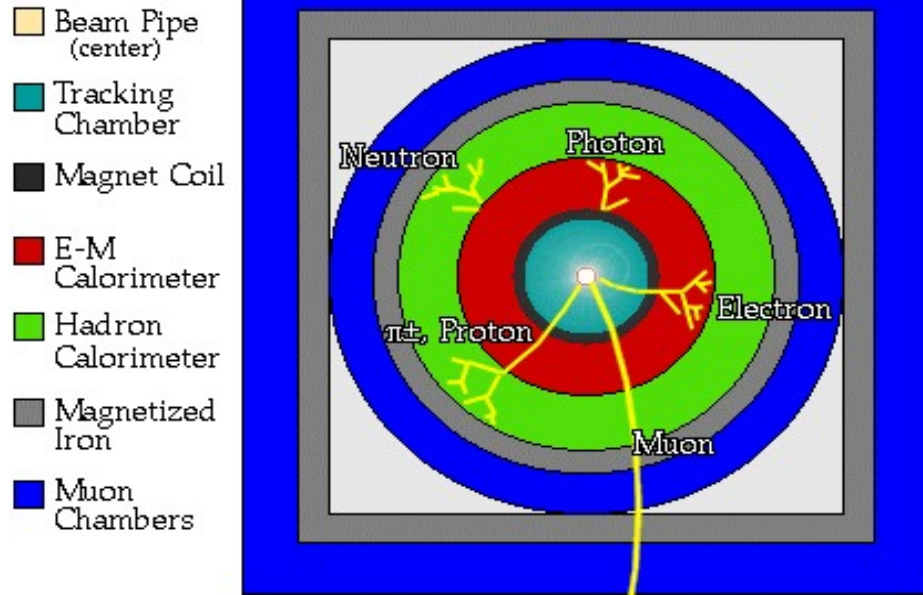
**Run I 1992-1995**  
Top quark discovered!

**Run II 2001-09(?)**  
 $\sqrt{s} = 1.96 \text{ TeV}$   
 $\Delta t = 396 \text{ ns}$   
1fb<sup>-1</sup> delivered  
Peak Lumi:  $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$



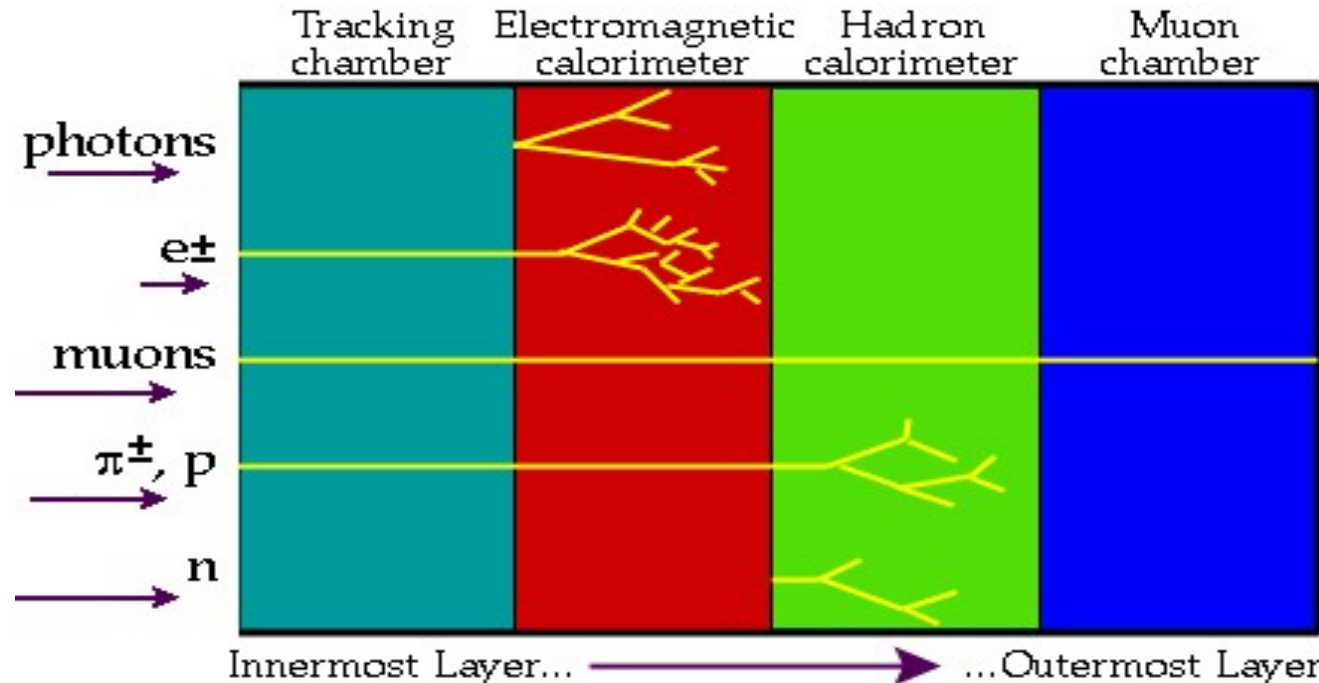
# General detector and particle ID

A detector cross-section, showing particle paths

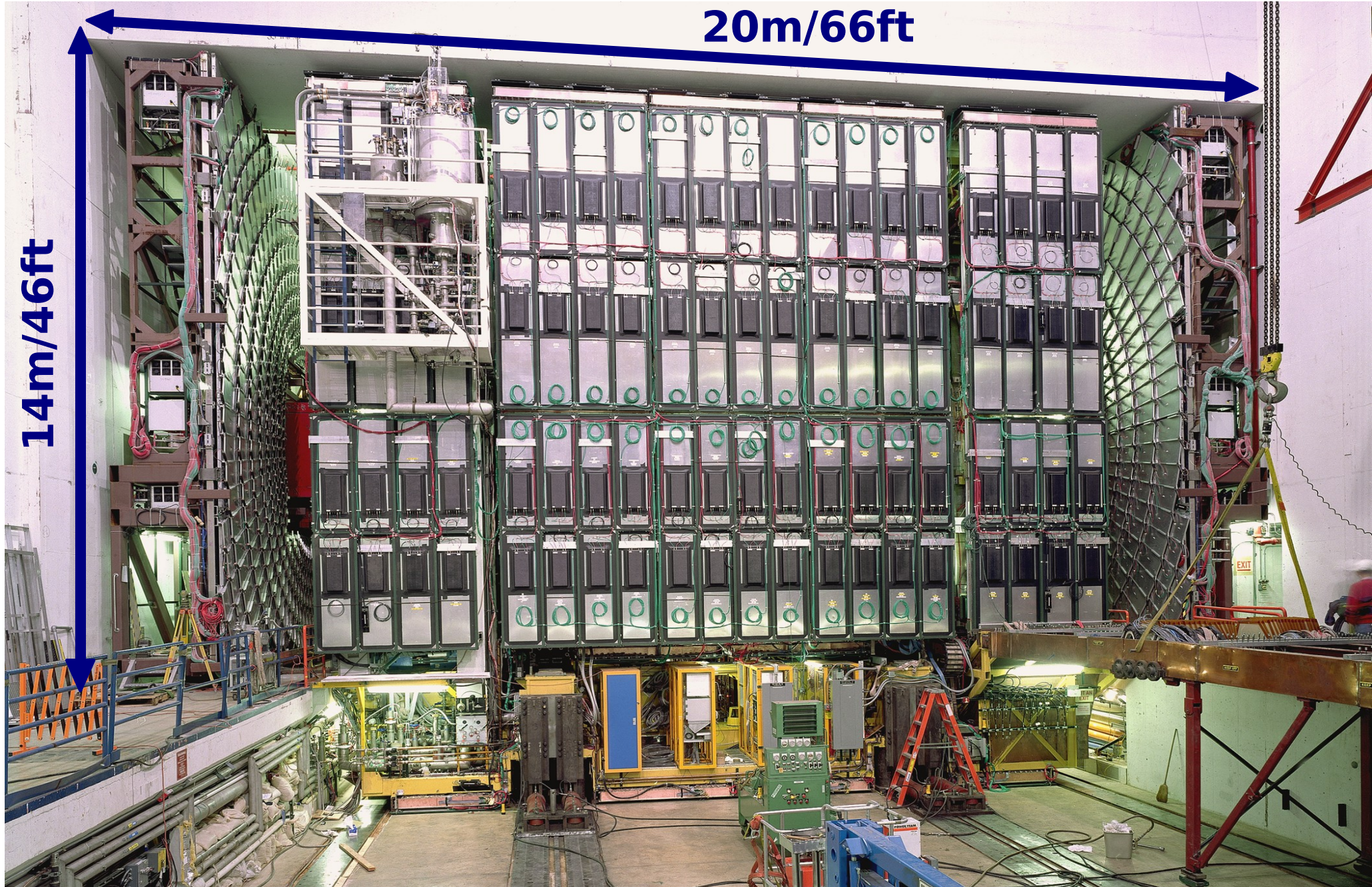


We detect particles by the EM and strong interaction fingerprints they leave behind

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

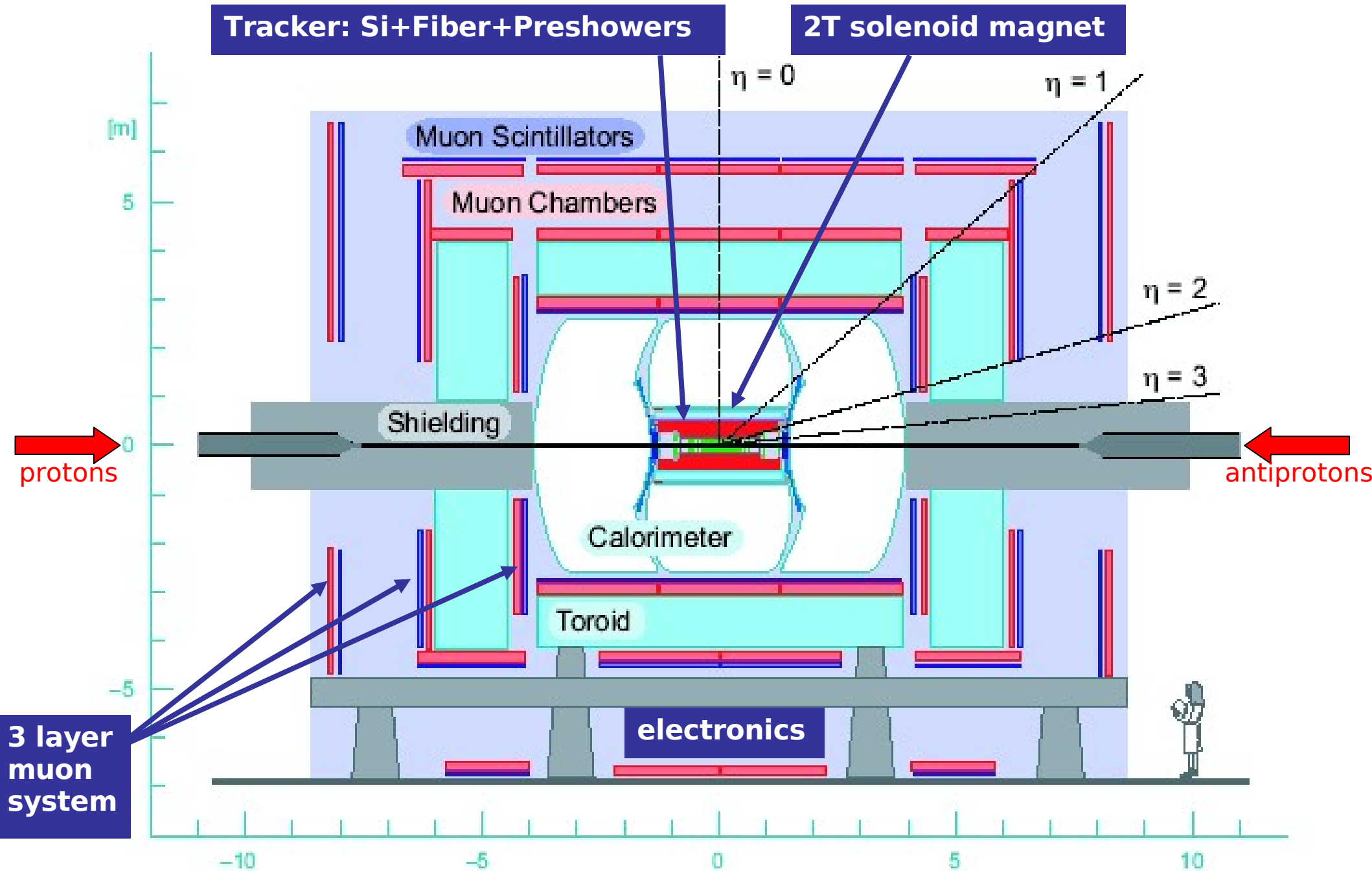


# The real thing: the DØ detector





# DØ for Run II



# 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 that what you are doing is sensible and deserves to be published!

Fermilab-Pub-08/207-E

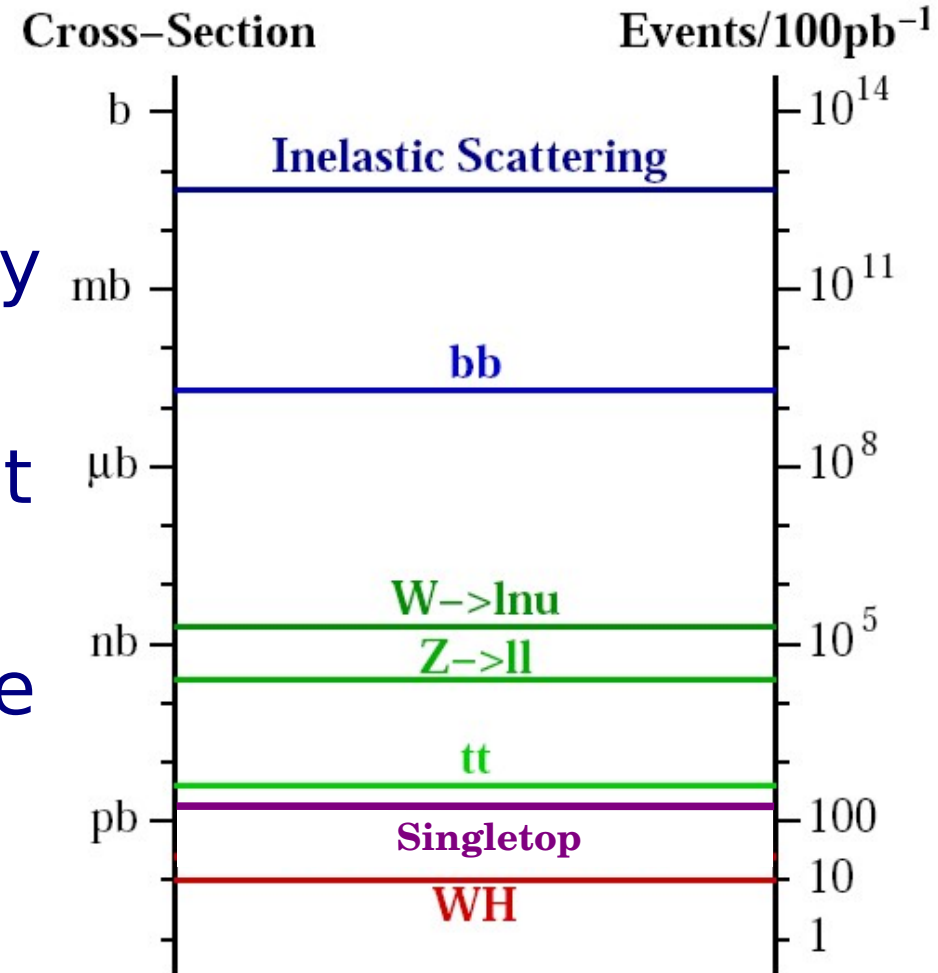
Search for single top quark production in  $pp$  collisions at  $\sqrt{s}=1.96$  TeV

V.M. Abazov,<sup>21</sup> B. Abbott,<sup>22</sup> M. Abolmali,<sup>23</sup> B.S. Acharya,<sup>24</sup> M. Adams,<sup>25</sup> T. Adams,<sup>26</sup> J.-L. Agram,<sup>27</sup> S.H. Ahn,<sup>28</sup> M. Akhmetov,<sup>29</sup> G.D. Alexeev,<sup>30</sup> G. Alkhazov,<sup>31</sup> A. Alton,<sup>32</sup> G. Alverson,<sup>33</sup> G.A. Alves,<sup>34</sup> M. Amato,<sup>35</sup> T. Andeen,<sup>36</sup> S. Anderson,<sup>37</sup> B. Androic,<sup>38</sup> Y. Aranda,<sup>39</sup> A. Askew,<sup>40</sup> B. Aouf,<sup>41</sup> A.C.S. Assis-Junior,<sup>42</sup> O. Atanunovic,<sup>43</sup> C. Avila,<sup>44</sup> F. Badauer,<sup>45</sup> A. Baden,<sup>46</sup> B. Baidin,<sup>47</sup> P.W. Baldwin,<sup>48</sup> S. Banerjee,<sup>49</sup> E. Banerji,<sup>50</sup> P. Banerjee,<sup>51</sup> B. Banerjee,<sup>52</sup> C. Banerjee,<sup>53</sup> J. Barco,<sup>54</sup> J.F. Barletta,<sup>55</sup> U. Baur,<sup>56</sup> D. Bauer,<sup>57</sup> A. Beau,<sup>58</sup> S. Becher,<sup>59</sup> M. Begel,<sup>60</sup> M. Begel,<sup>61</sup> A. Bellave,<sup>62</sup> S.B. Beri,<sup>63</sup> G. Bernabini,<sup>64</sup> R. Bernhard,<sup>65</sup> I. Bertram,<sup>66</sup> M. Besana,<sup>67</sup> R. Beuselinck,<sup>68</sup> V.A. Bezrukov,<sup>69</sup> P.C. Bhat,<sup>70</sup> M. Bhat,<sup>71</sup> M. Bhat,<sup>72</sup> C. Biscarat,<sup>73</sup> K.M. Black,<sup>74</sup> I. Black,<sup>75</sup> G. Blazynski,<sup>76</sup> P. Blackburn,<sup>77</sup> S. Blessing,<sup>78</sup> D. Block,<sup>79</sup> U. Blumenschein,<sup>80</sup> A. Bobasik,<sup>81</sup> O. Bobrov,<sup>82</sup> T.A. Bobrov,<sup>83</sup> F. Bockelée-Brugnot,<sup>84</sup> G. Boerner,<sup>85</sup> K. Boer,<sup>86</sup> E.E. Boos,<sup>87</sup> T. Bose,<sup>88</sup> A. Brandi,<sup>89</sup> R. Brock,<sup>90</sup> G. Broojmans,<sup>91</sup> A. Bruch,<sup>92</sup> N.J. Buttar,<sup>93</sup> D. Burchini,<sup>94</sup> M. Busch,<sup>95</sup> V. Buscher,<sup>96</sup> J. Buscher,<sup>97</sup> S. Bardin,<sup>98</sup> S. Baur,<sup>99</sup> S. Baur,<sup>100</sup> S.P. Barzanti,<sup>101</sup> C.F. Beaulieu,<sup>102</sup> J.M. Butler,<sup>103</sup> J. Camargo,<sup>104</sup> S. Caron,<sup>105</sup> W. Carvalho,<sup>106</sup> B.C.K. Casey,<sup>107</sup> N.M. Cason,<sup>108</sup> H. Castilla-Vidal,<sup>109</sup> S. Chakraborty,<sup>110</sup> K.M. Chan,<sup>111</sup> A. Chandra,<sup>112</sup> D. Chapiro,<sup>113</sup> F. Charles,<sup>114</sup> E. Ches,<sup>115</sup> D.K. Cho,<sup>116</sup> S. Choi,<sup>117</sup> B. Choudhury,<sup>118</sup> T. Christianova,<sup>119</sup> L. Christoffel,<sup>120</sup> D. Cioba,<sup>121</sup> B. Clément,<sup>122</sup> C. Clément,<sup>123</sup> Y. Coadou,<sup>124</sup> M. Cooke,<sup>125</sup> W.E. Cooper,<sup>126</sup> D. Coppiga,<sup>127</sup> M. Cormier,<sup>128</sup> A. Cottrill,<sup>129</sup> M.-C. Coucouin,<sup>130</sup> B. Cox,<sup>131</sup> S. Csepel-Benešová,<sup>132</sup> D. Cutts,<sup>133</sup> H. de Maria,<sup>134</sup> M. Das,<sup>135</sup> B. Davids,<sup>136</sup> G. Davies,<sup>137</sup> A.K. De,<sup>138</sup> P. de Jong,<sup>139</sup> S.J. de Jong,<sup>140</sup> E. De La Cruz-Becerra,<sup>141</sup> C. De Oliveira Martins,<sup>142</sup> S. Dean,<sup>143</sup> J.D. DeGroot,<sup>144</sup> F. DiLisi,<sup>145</sup> M. Dimentiev,<sup>146</sup> R. Dima,<sup>147</sup> P. Dima,<sup>148</sup> D. Dima,<sup>149</sup> S.P. Denisov,<sup>150</sup> S. Desai,<sup>151</sup> H.T. Doshi,<sup>152</sup> M. Drees,<sup>153</sup> M. Drees,<sup>154</sup> H. Dang,<sup>155</sup> S. Dasu,<sup>156</sup> L.V. Daul,<sup>157</sup> L. Daul,<sup>158</sup> S.R. Dugad,<sup>159</sup> A. Dapunta,<sup>160</sup> J. Dey,<sup>161</sup> A. Dey,<sup>162</sup> M. Eidi,<sup>163</sup> D. DiMauro,<sup>164</sup> T. Edwards,<sup>165</sup> J. Ellison,<sup>166</sup> J. Elmsheier,<sup>167</sup> V.D. Elvira,<sup>168</sup> S. Emery,<sup>169</sup> P. Emili,<sup>170</sup> G.V. Erskine,<sup>171</sup> J. Erskine,<sup>172</sup> H. Evans,<sup>173</sup> A. Evdokimov,<sup>174</sup> V.N. Evdokimov,<sup>175</sup> J. Fan,<sup>176</sup> S.N. Fazio,<sup>177</sup> L. Fajstovc,<sup>178</sup> A.V. Farberov,<sup>179</sup> T. Fardipour,<sup>180</sup> F. Fiedler,<sup>181</sup> F. Filthaut,<sup>182</sup> W. Fisher,<sup>183</sup> H.E. Fisk,<sup>184</sup> I. Fleck,<sup>185</sup> M. Fueter,<sup>186</sup> H. Fox,<sup>187</sup> S. Fu,<sup>188</sup> S. Fu,<sup>189</sup> Z.F. Gales,<sup>190</sup> E. Gallas,<sup>191</sup> E. Gallas,<sup>192</sup> G. Garcia,<sup>193</sup> A. Garcia-Bellido,<sup>194</sup> J. Garbino,<sup>195</sup> V. Gavrilov,<sup>196</sup> A. Gay,<sup>197</sup> P. Gay,<sup>198</sup> D. Gold,<sup>199</sup> R. Golubov,<sup>200</sup> K. Genser,<sup>201</sup> C.E. Gerber,<sup>202</sup> Y. Gershon,<sup>203</sup> D. Gillberg,<sup>204</sup> G. Gindler,<sup>205</sup> T. Golling,<sup>206</sup> N. Golub,<sup>207</sup> B. Gómez,<sup>208</sup> K. González,<sup>209</sup> A. González,<sup>210</sup> P.D. González,<sup>211</sup> S. Gouder,<sup>212</sup> H. Goussard,<sup>213</sup> Z.D. Greenwood,<sup>214</sup> E.M. Gregoire,<sup>215</sup> Ph. Grenier,<sup>216</sup> J.-F. Grunz,<sup>217</sup> L. Grunz,<sup>218</sup> S. Grunwald,<sup>219</sup> M.W. Grunwald,<sup>220</sup> S.N. Gunther,<sup>221</sup> G. Gutierrez,<sup>222</sup> G. Gutierrez,<sup>223</sup> A. Haas,<sup>224</sup> N.J. Haefliger,<sup>225</sup> S. Haggopian,<sup>226</sup> J. Hall,<sup>227</sup> R.E. Hall,<sup>228</sup> C. Han,<sup>229</sup> L. Han,<sup>230</sup> H. Hasegaki,<sup>231</sup> K. Hara,<sup>232</sup> A. Harel,<sup>233</sup> B. Harland-angus,<sup>234</sup> J.M. Hargreaves,<sup>235</sup> B. Hase,<sup>236</sup> J. Hays,<sup>237</sup> T. Heldt,<sup>238</sup> D. Heller,<sup>239</sup> J.M. Heintzberger,<sup>240</sup> A.P. Heinson,<sup>241</sup> U. Heintz,<sup>242</sup> C. Heiser,<sup>243</sup> G. Helber,<sup>244</sup> M.D. Hilditch,<sup>245</sup> R. Hirose,<sup>246</sup> J.D. Hobbs,<sup>247</sup> B. Hosenstein,<sup>248</sup> M. Hohlkiel,<sup>249</sup> S.J. Hong,<sup>250</sup> R. Hooper,<sup>251</sup> P. Hoenen,<sup>252</sup> Y. Hu,<sup>253</sup> J. Huang,<sup>254</sup> V.D. Hrynkiw,<sup>255</sup> I. Iashvili,<sup>256</sup> R. Iliesiu,<sup>257</sup> A.S. Ito,<sup>258</sup> S. Itoh,<sup>259</sup> M. Jafari,<sup>260</sup> S. Jain,<sup>261</sup> V. Jain,<sup>262</sup> H. K. Jakobs,<sup>263</sup> A. Jankina,<sup>264</sup> R. Jankov,<sup>265</sup> K. Jaska,<sup>266</sup> M. Johnson,<sup>267</sup> A. Jurek,<sup>268</sup> P. Jovanovic,<sup>269</sup> A. Juste,<sup>270</sup> D. Kifer,<sup>271</sup> S. Klein,<sup>272</sup> E. Klyachko,<sup>273</sup> A.M. Klok,<sup>274</sup> J. Klok,<sup>275</sup> D. Krummenov,<sup>276</sup> J. Kueper,<sup>277</sup> D. Kuz,<sup>278</sup> R. Kuz,<sup>279</sup> R. Kuz,<sup>280</sup> S. Kuznetsov,<sup>281</sup> S. Kuznetsov,<sup>282</sup> A. Kuznetsov,<sup>283</sup> A. Kuznetsov,<sup>284</sup> Y.M. Kuznetsov,<sup>285</sup> H. Kim,<sup>286</sup> T.I. Kim,<sup>287</sup> B. Klima,<sup>288</sup> J.M. Klotz,<sup>289</sup> J.-P. Kolarik,<sup>290</sup> M. Kopal,<sup>291</sup> Y.M. Kovalenko,<sup>292</sup> J. Kotchouk,<sup>293</sup> B. Kottar,<sup>294</sup> A. Kotlyarskiy,<sup>295</sup> A.V. Kovalov,<sup>296</sup> J. Kozminski,<sup>297</sup> A. Kopylov,<sup>298</sup> S. Kopylov,<sup>299</sup> V. Kork,<sup>300</sup> A. Krasn,<sup>301</sup> S. Kuznetsov,<sup>302</sup> A. Kuznetsov,<sup>303</sup> T. Kure,<sup>304</sup> J. Kure,<sup>305</sup> S. Kure,<sup>306</sup> S. Kure,<sup>307</sup> S. Kure,<sup>308</sup> S. Kure,<sup>309</sup> S. Kure,<sup>310</sup> S. Kure,<sup>311</sup> S. Kure,<sup>312</sup> S. Kure,<sup>313</sup> S. Kure,<sup>314</sup> S. Kure,<sup>315</sup> S. Kure,<sup>316</sup> S. Kure,<sup>317</sup> S. Kure,<sup>318</sup> S. Kure,<sup>319</sup> S. Kure,<sup>320</sup> S. Kure,<sup>321</sup> S. Kure,<sup>322</sup> S. Kure,<sup>323</sup> S. Kure,<sup>324</sup> S. Kure,<sup>325</sup> S. Kure,<sup>326</sup> S. Kure,<sup>327</sup> S. Kure,<sup>328</sup> S. Kure,<sup>329</sup> S. Kure,<sup>330</sup> S. Kure,<sup>331</sup> S. Kure,<sup>332</sup> S. 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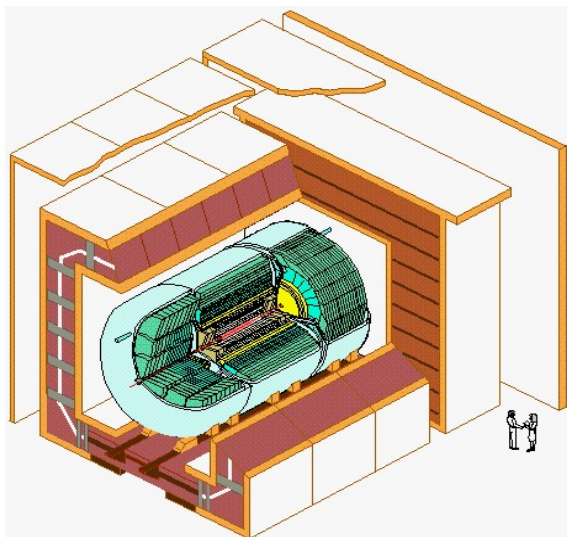
# Physics at a hadron collider is like... drinking from a fire hose



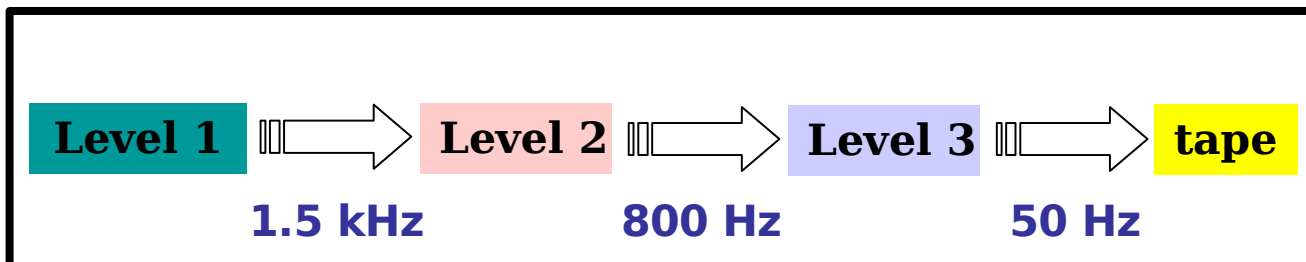
- ▶ Collision rate is huge  
Every 396 ns  $\rightarrow$   $\sim 1.7$  MHz (live crossings)
- ▶ Total cross section  $\sim 0.1$  b  
2-3 interactions per collision at  $L=10^{32}$
- ▶ W, Z, top, Higgs are relatively rare
- ▶ Need trigger system to select “interesting” events
- ▶ Only store a manageable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



# DØ data acquisition system



1.7 MHz

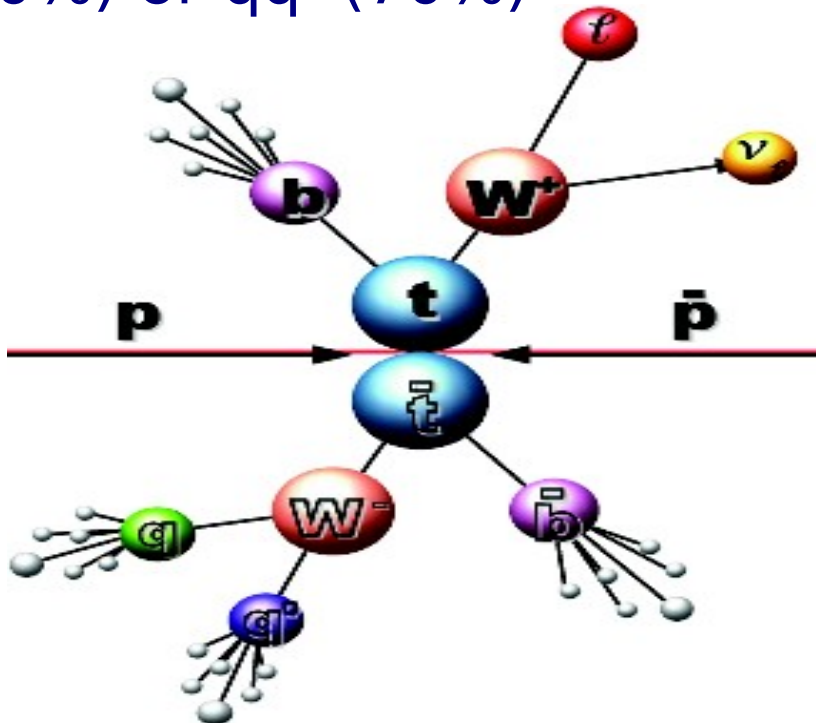
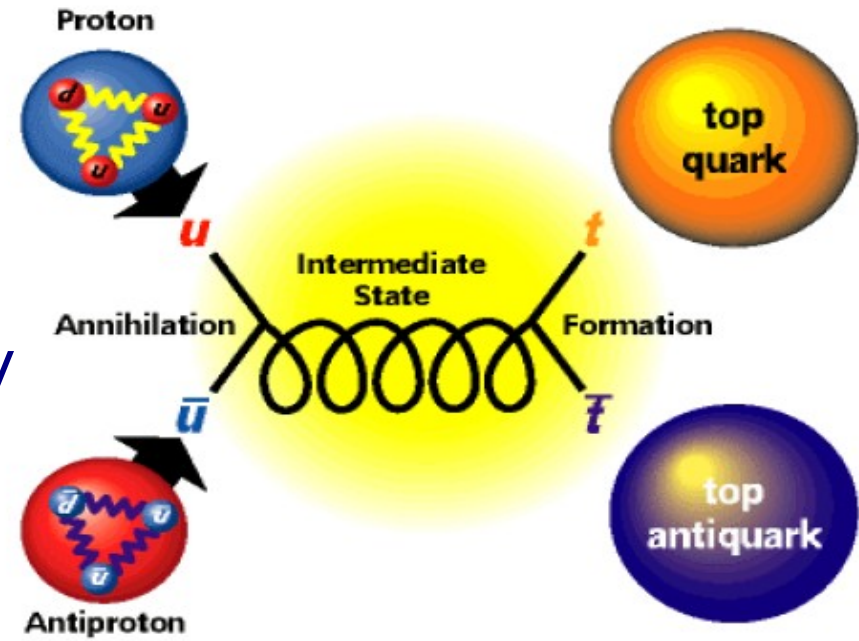


- ▶ Three level trigger
- ▶ Selects events containing high energy final state objects ( $e$ ,  $\mu$ , jets)
- ▶ Algorithms implemented in hardware/firmware at L1 & L2, software at L3
- ▶ Increasing level of sophistication, increasing time per decision, decreasing event accept rate



# Close encounters of the 3<sup>rd</sup> 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%)

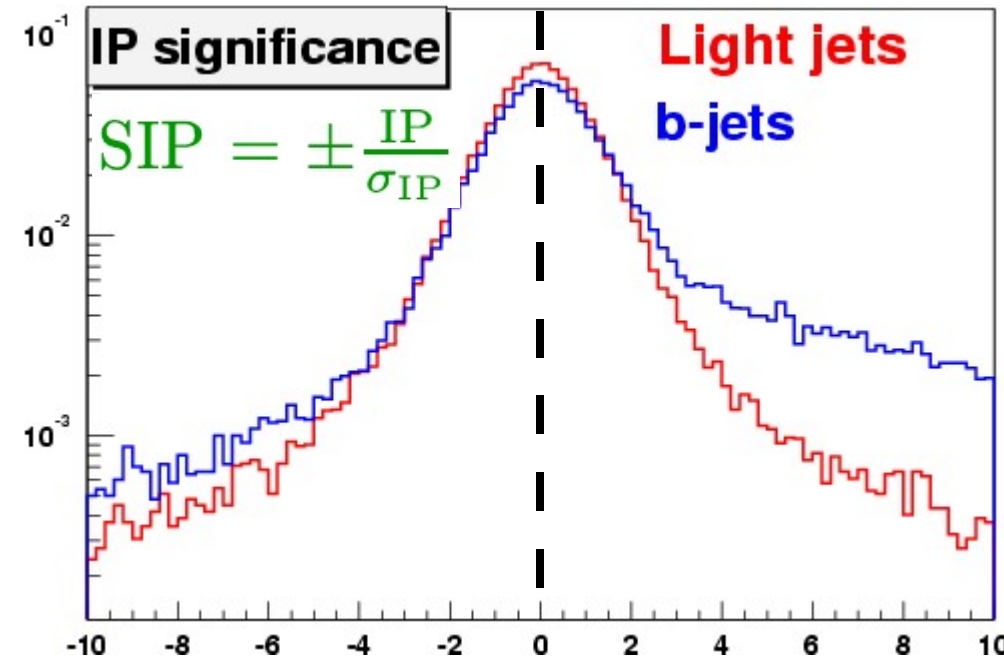
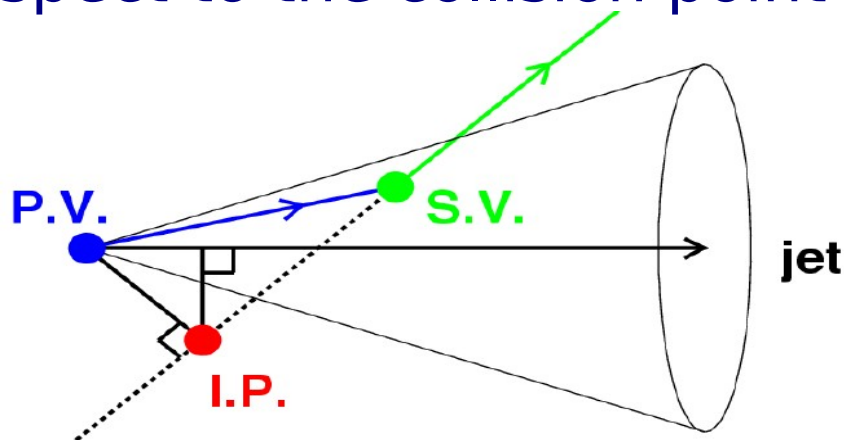
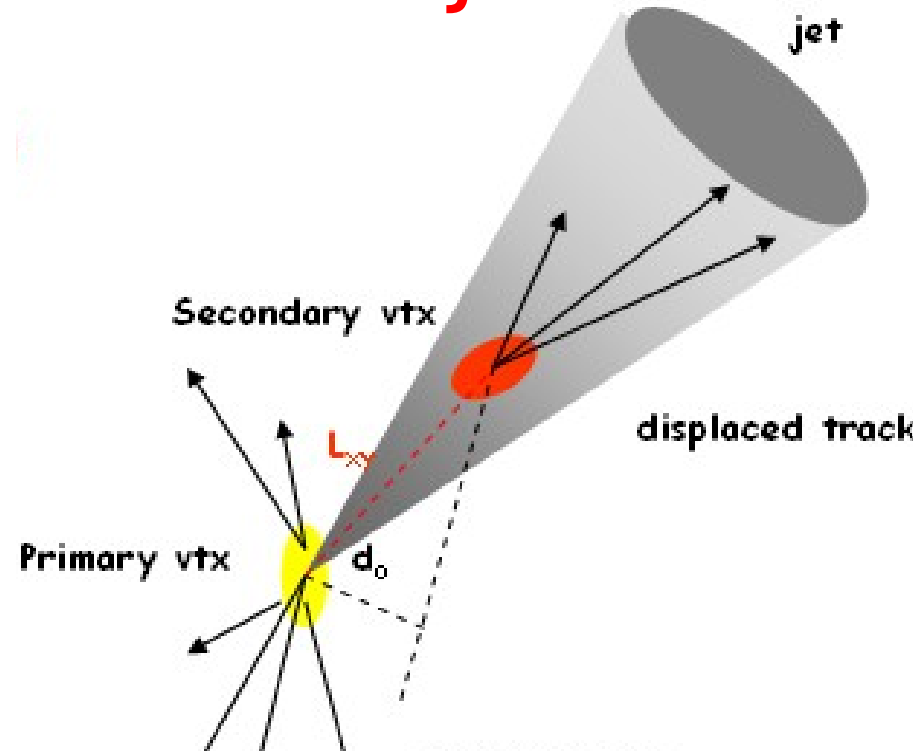


Final objects (if  $W_1 \rightarrow \ell\nu$  and  $W_2 \rightarrow qq'$ )

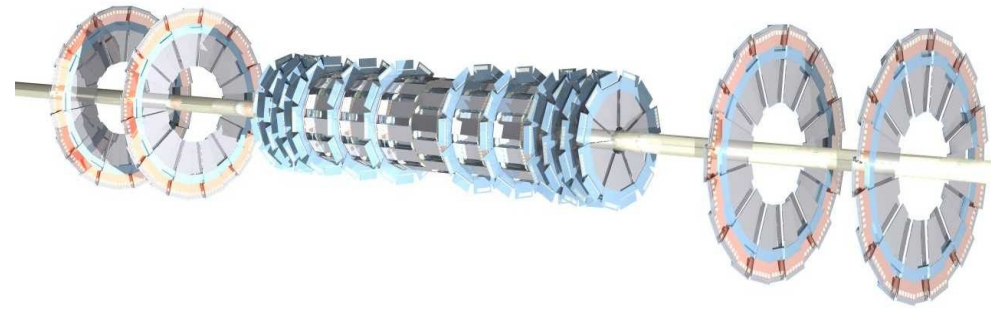
- ▶ 4jets (2 of them b)
- ▶ lepton
- ▶ neutrino (missing energy)

# Did you see that bottom jet?

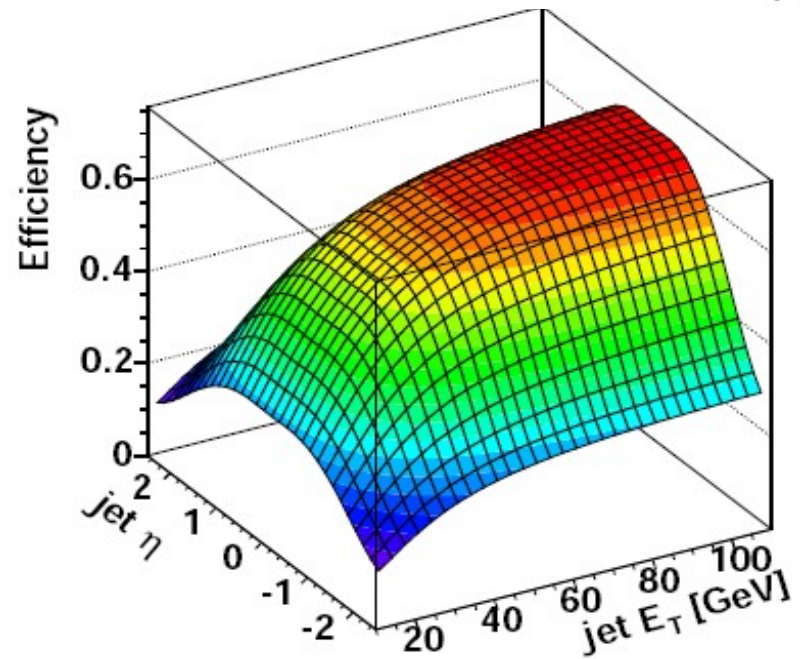
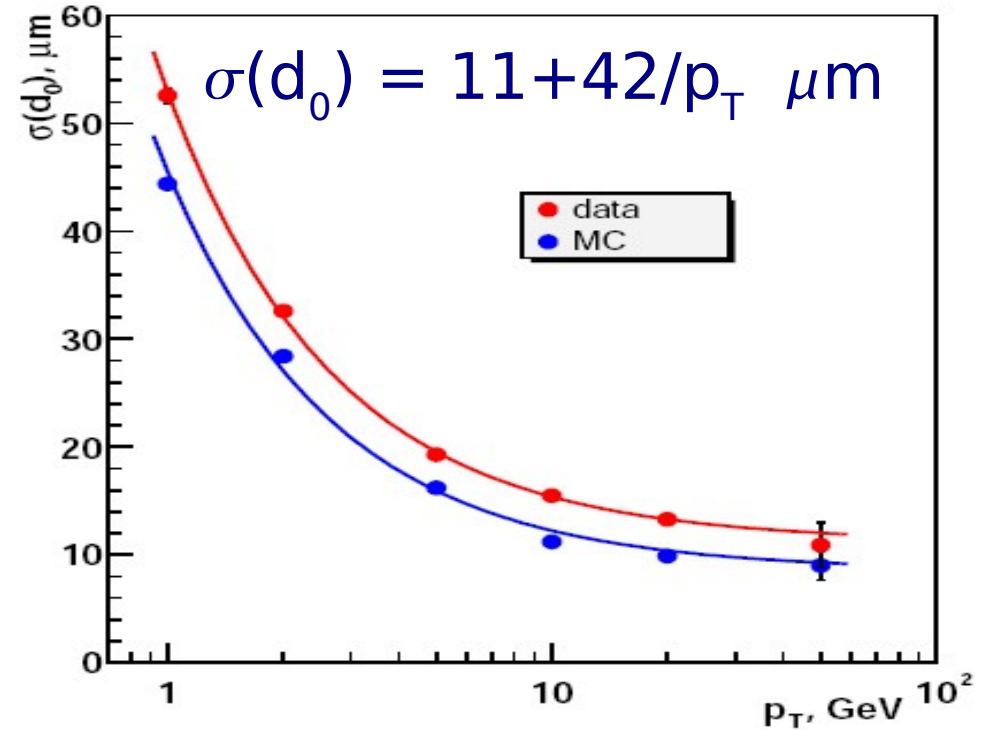
- ▶ Top quarks decay into b quarks  
→ can we tell the difference between a b jet and any other jet originated from u, d, s or a gluon?
- ▶ b-quarks have a lifetime  $\sim 10^{-12}$ s  
→ they travel  $\sim 500\mu\text{m}$  before decaying
- ▶ Look for tracks coming from a common vertex displaced from the original pp collision
- ▶ These tracks have a positive signed impact parameter with respect to the collision point



# You better have good tracking



- ▶ The Silicon Microstrip Tracker allows resolutions of  $\sim 10 \mu\text{m}$
- ▶ Inner radius: 2.6cm away from the interaction point
- ▶ Efficiency to identify a b-quark jet  $\sim 55\%$
- ▶ Mistag-rate  $\sim 0.5\%$

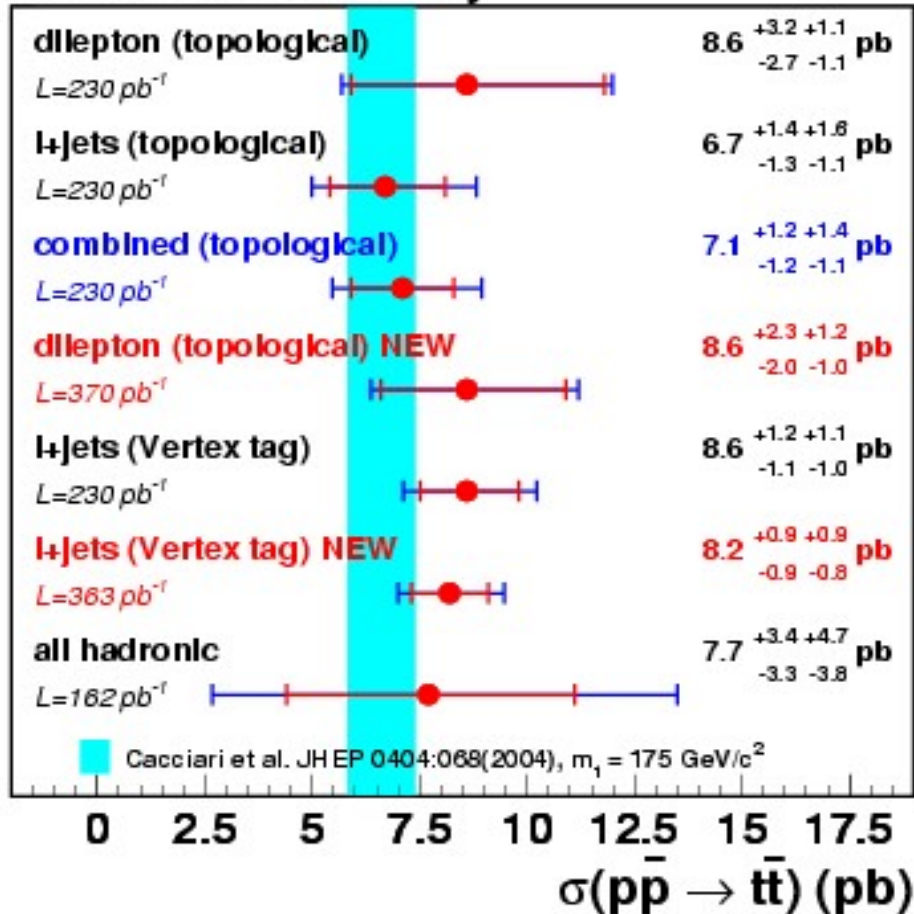




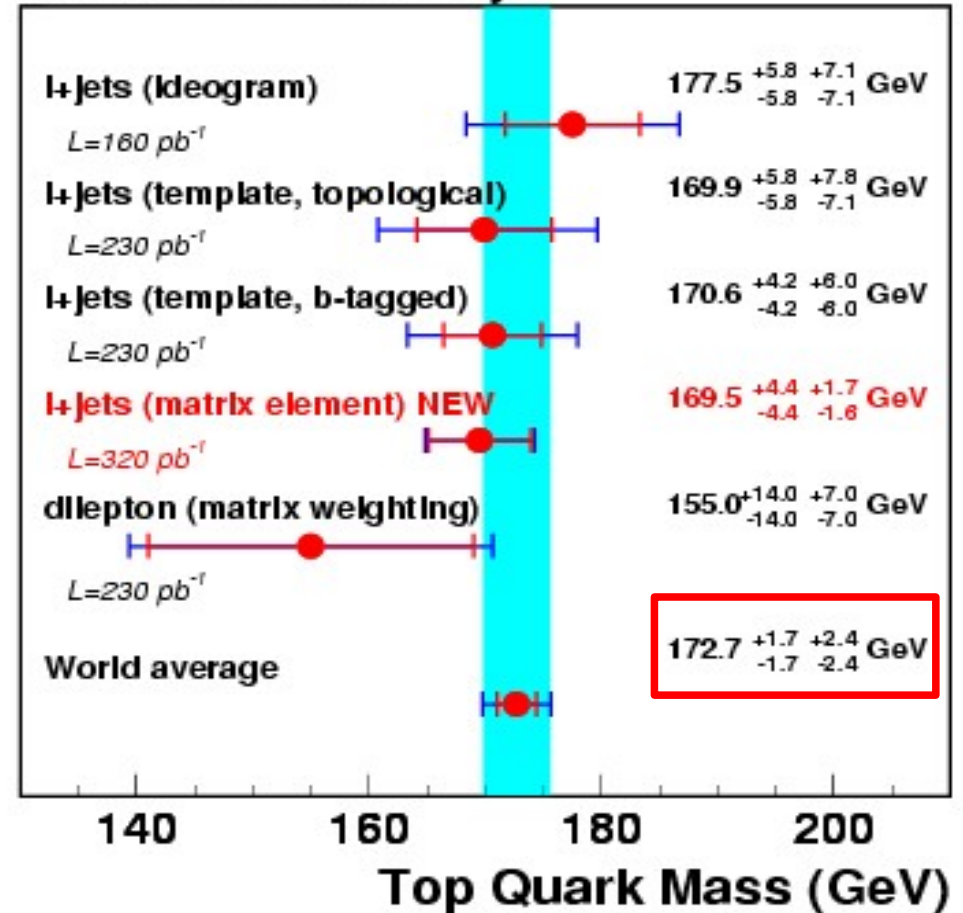
# Top quarks deconstructed

We know the pair production cross section and its mass

DØ Run II Preliminary



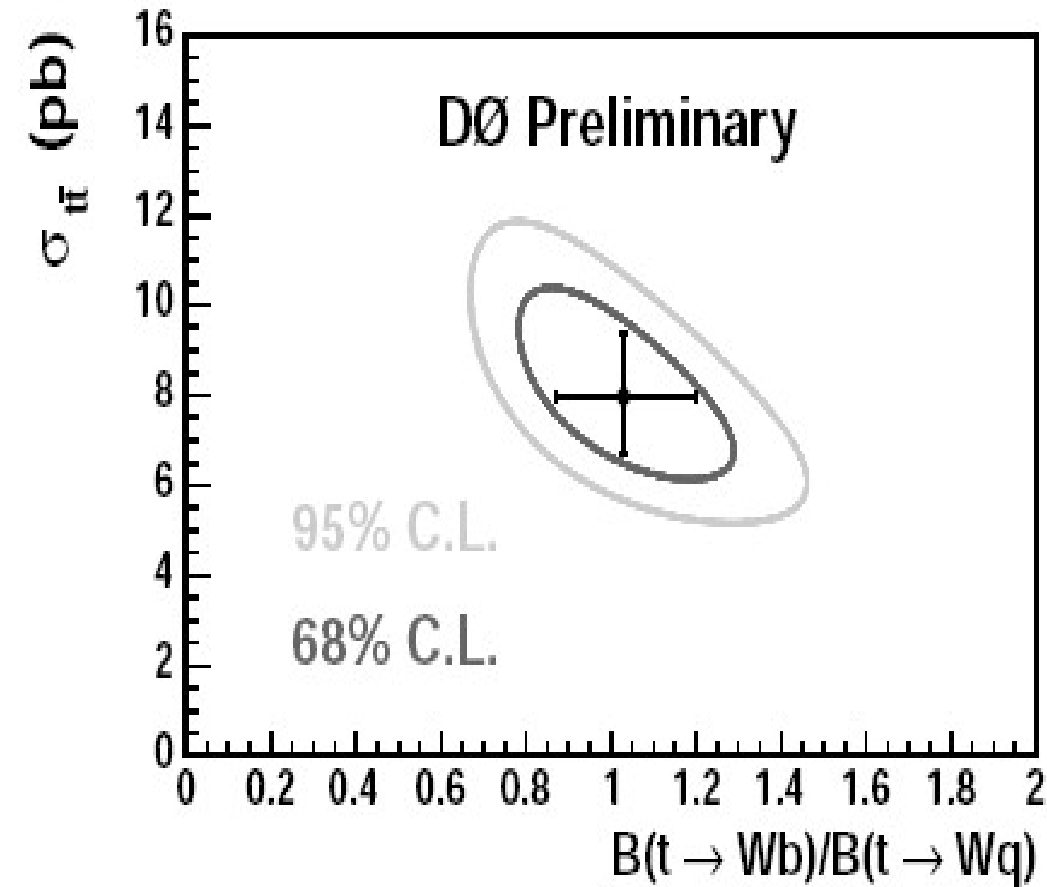
DØ Run II Preliminary



$$\sigma(tt) \sim 7 \text{ pb}$$

$$m_t \sim 175 \text{ GeV}$$

# Other properties...



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

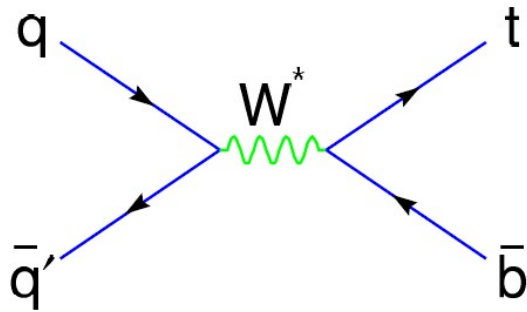
- ...But there are still many things we don't know about top quarks:
- ▶ Charge?
  - ▶ Spin?
  - ▶ Width?
  - ▶ Couplings?

Can they be produced alone?

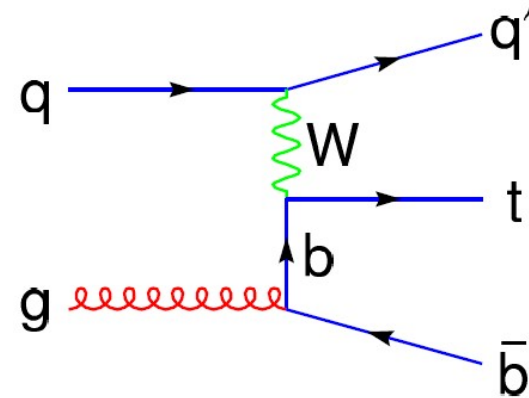
# Yes! Top quarks can be lonely!

## Electroweak production of single top quarks

Two main production modes at the Tevatron:



s-channel  $\sigma_s \sim 1\text{pb}$



t-channel  $\sigma_t \sim 2\text{pb}$

- ▶ 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

Arán García-Bellido, UW

# Single top search status

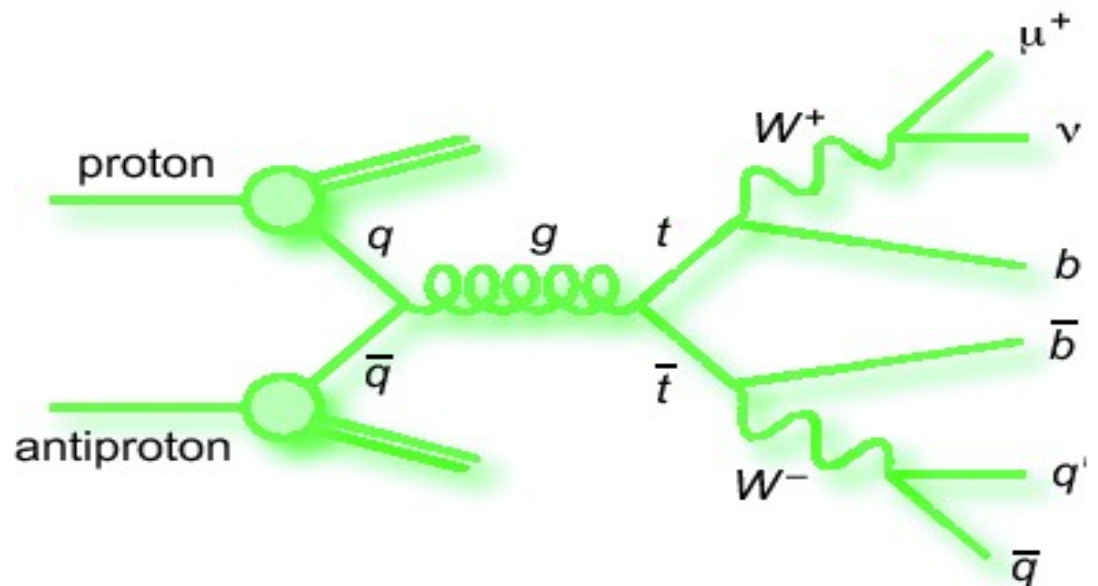
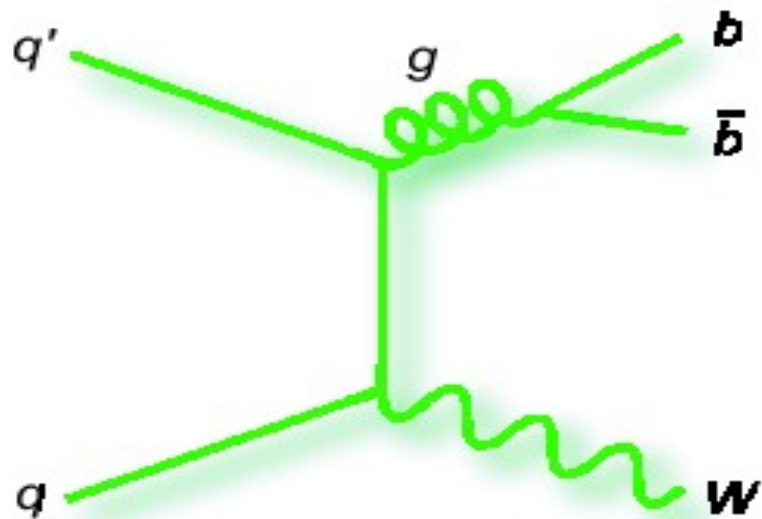
Cross section limits at 95% confidence level:

	s-channel	t-channel	combined
DØ Run I:	$\sigma_s < 17\text{pb}$	$\sigma_t < 22\text{pb}$	
CDF Run I:	$\sigma_s < 18\text{pb}$	$\sigma_t < 13\text{pb}$	$\sigma_{s+t} < 14\text{pb}$
CDF Run II:	$\sigma_s < 14\text{pb}$	$\sigma_t < 10\text{pb}$	$\sigma_{s+t} < 18\text{pb}$
DØ Run II:	<b><math>\sigma_s &lt; 6.4\text{pb}</math></b>	<b><math>\sigma_t &lt; 5.0\text{pb}</math></b>	

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

# How do we find single tops?

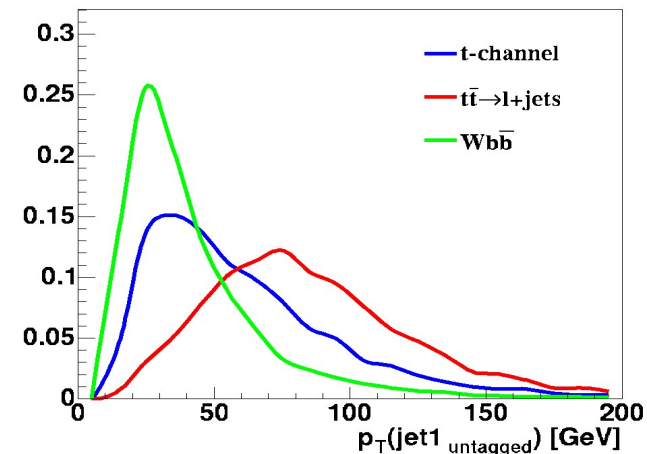
- ▶ It's not easy!
- ▶ Out of  $\sim 10$  million recorded events we are looking for  $\sim 100$  signal events
- ▶ But there are many other processes that mimic single top events:  $W$ +jets,  $t\bar{t}$ , multijets
- ▶ Our final state consists of 2, 3, or 4 jets (with at least one of them  $b$ ) +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



# Analysis strategy

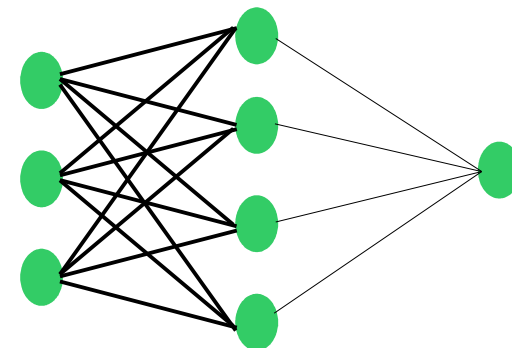
## 1) Event selection

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



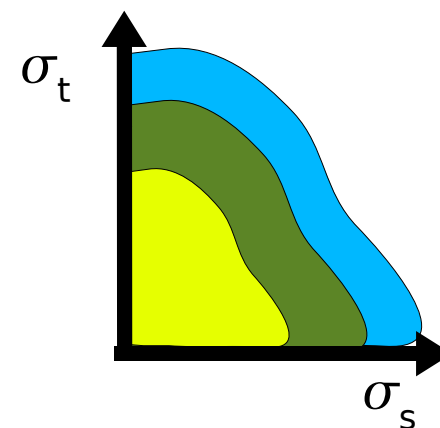
## 2) Separate signals from backgrounds

- ▶ Find discriminating variables
- ▶ Multivariate analysis



## 3) Determine cross section

- ▶ Use shape information
- ▶ Bayesian statistical analysis



# 1) Event Selection

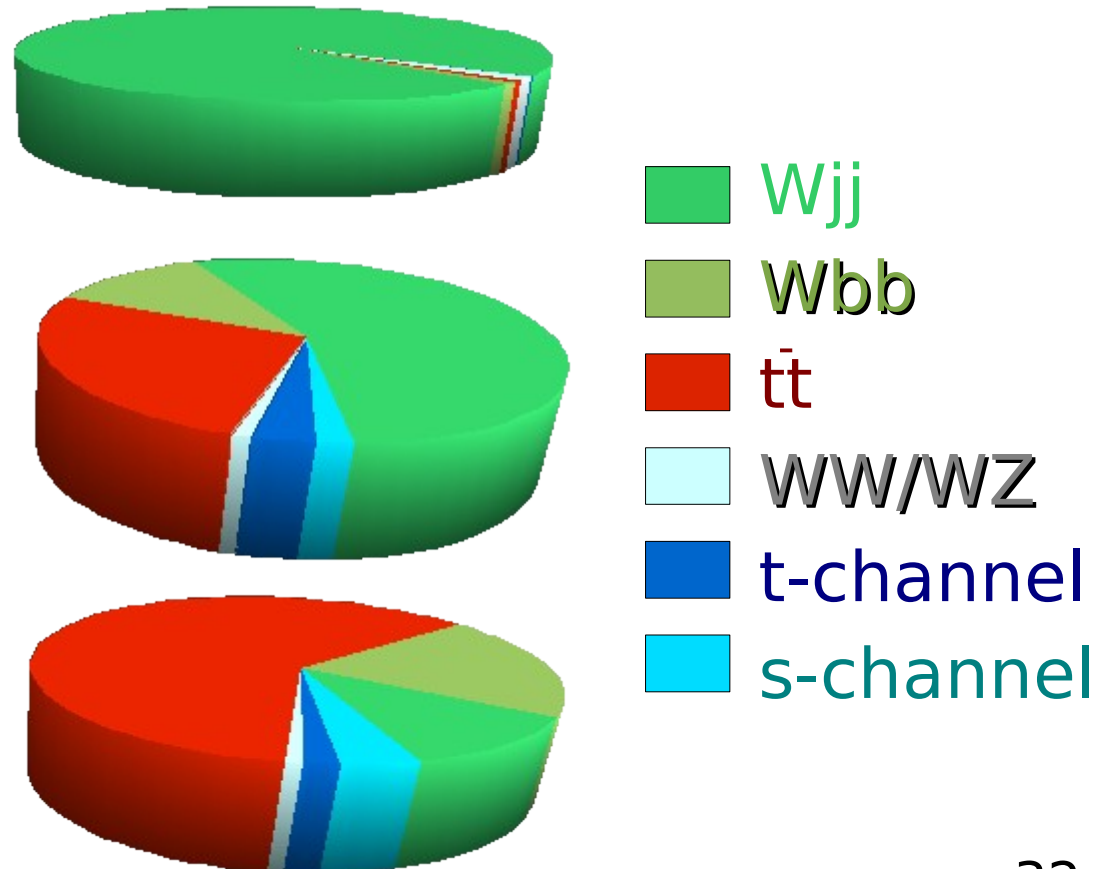
- ▶  $2 \leq N_{\text{jets}} \leq 4$ ,  $p_{\text{T}} > 15$  GeV
- ▶ 1 lepton  $p_{\text{T}} > 15$  GeV
- ▶  $\text{MET} > 15$  GeV

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

↓  
 Pretagged  
 7100 events

↓  
 =1 b-tagged jet  
 252 events

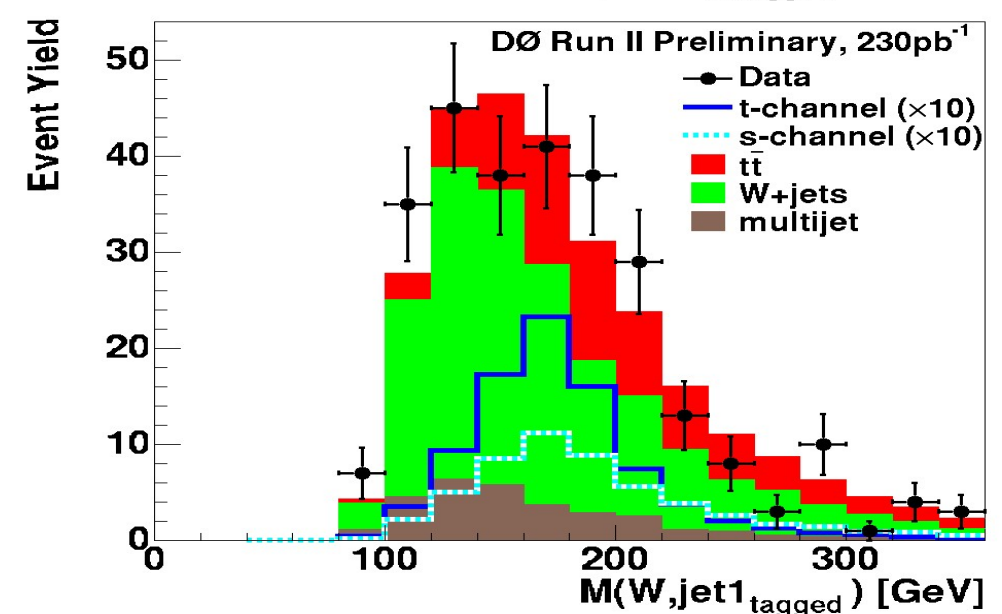
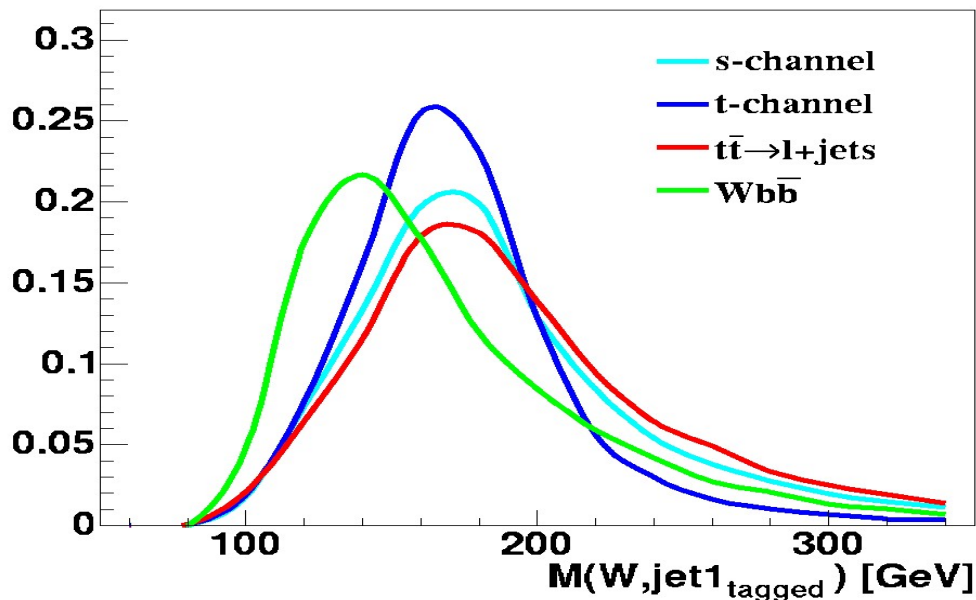
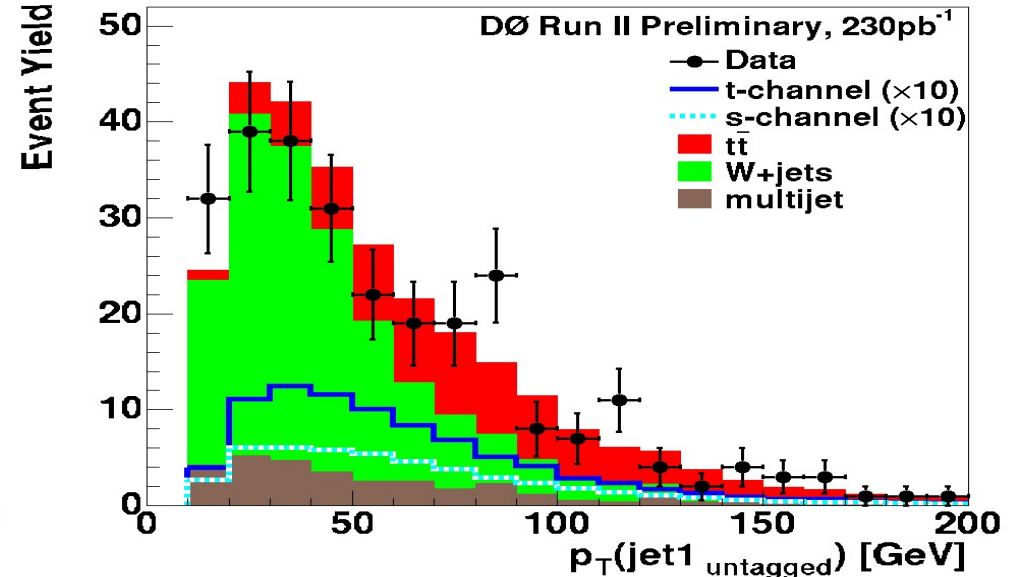
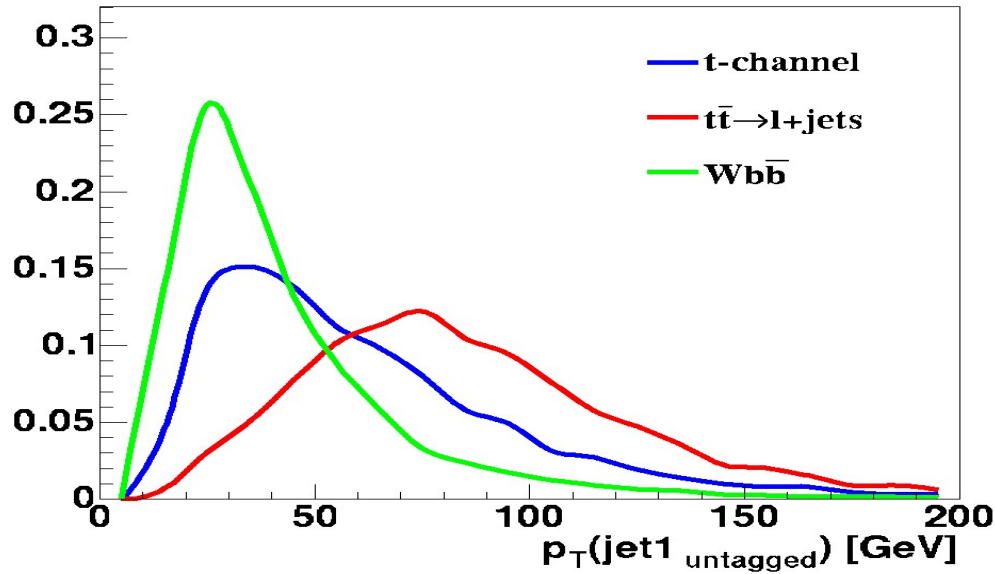
↓  
 $\geq 2$  b-tagged jets  
 31 events





# 2) Separate signals from backgrounds

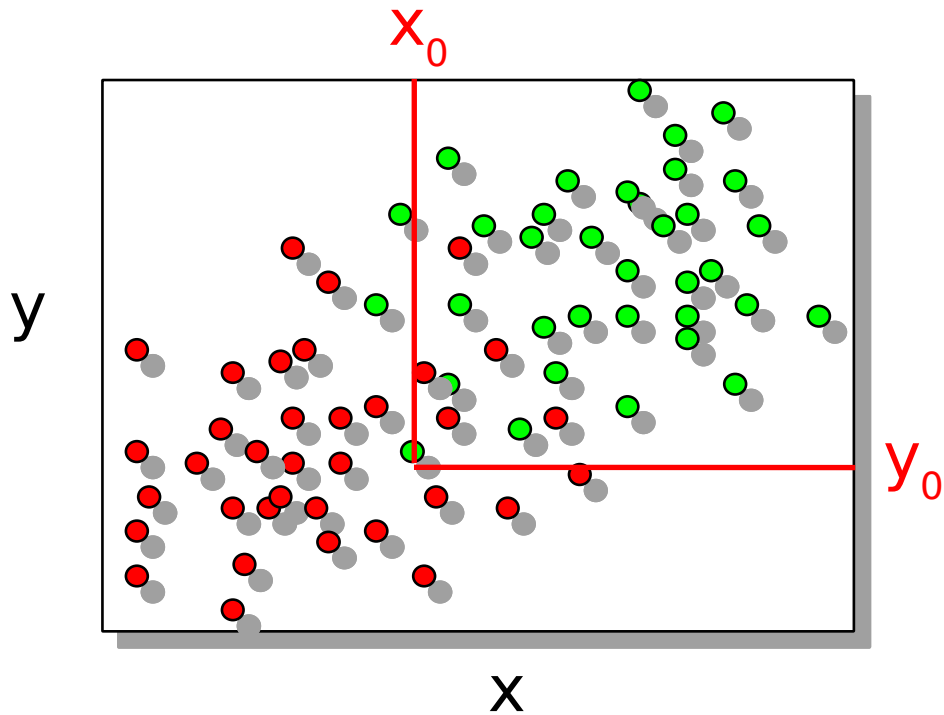
- ▶ Make sure your data agrees well with your prediction (i.e.: you know what you are doing)
- ▶ Choose variables that show good discrimination



# Optimal separation

Signal = ● Background = ●

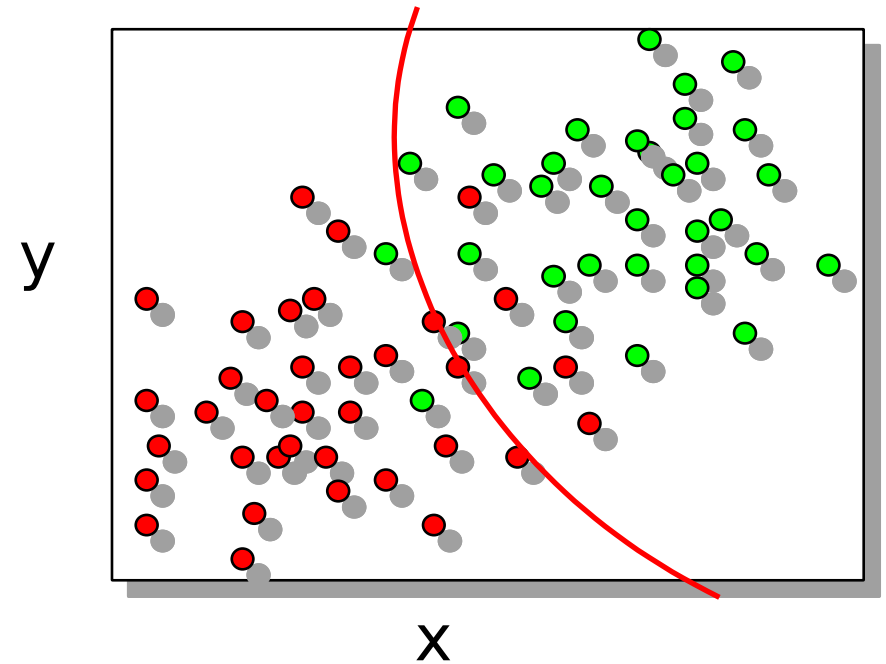
Conventional cuts



$$x > x_0$$

$$y > y_0$$

Multivariate technique

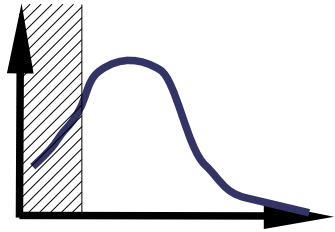


$$r(x, y) = \frac{P(x, y|S)P(S)}{P(x, y|B)P(B)}$$

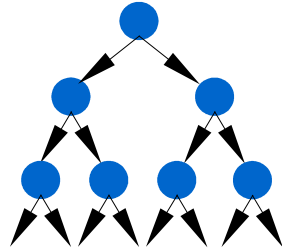
# Analysis methods

DØ has implemented four analysis methods:

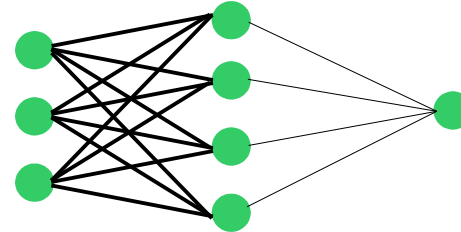
Cut-based



Decision Trees



Neural Networks



Likelihoods

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

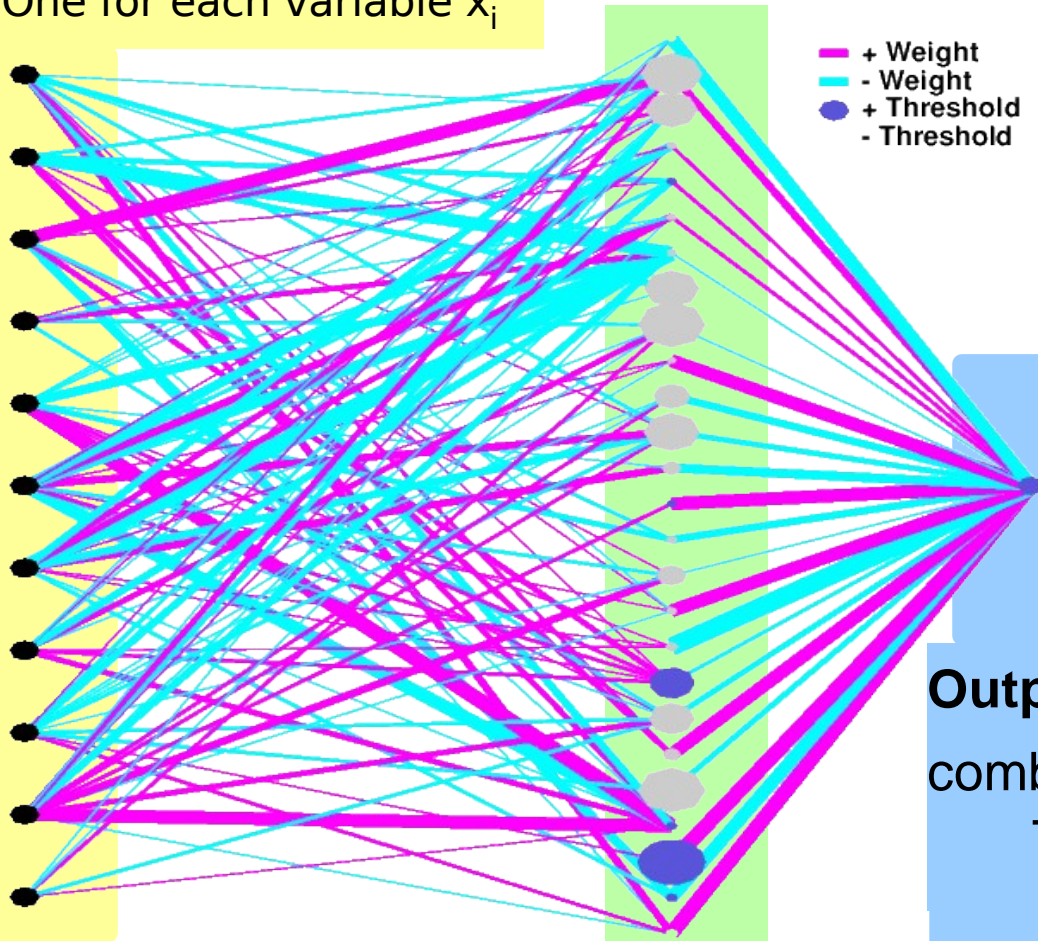
I will describe only neural networks

- ▶ 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 →  $\ell$  + jets, tqb-Wbb & tqb-tt →  $\ell$  + jets (for e and  $\mu$ )

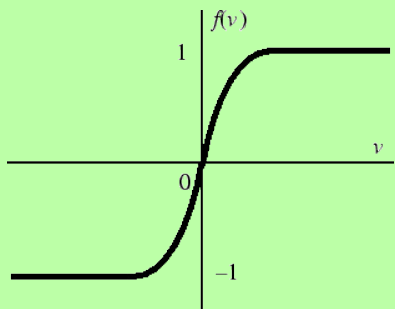
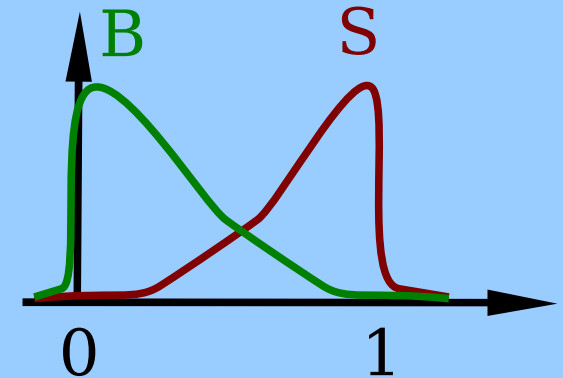
# Neural Networks

**Input Nodes:** One for each variable  $x_i$

- $M_T(\text{jet1, jet2})$
- $M(\text{alljets})$
- $p_T(\text{jet1, jet2})$
- $p_T(\text{notbest2})$
- $p_T(\text{notbest1})$
- $\cos(\angle, Q(l) \times z)_{\text{besttop}}$
- $M(W, \text{best})$
- $M(W, \text{tag1})$
- $\Delta R(\text{jet1, jet2})$
- $\sqrt{s}$
- $p_T(\text{tag1})$



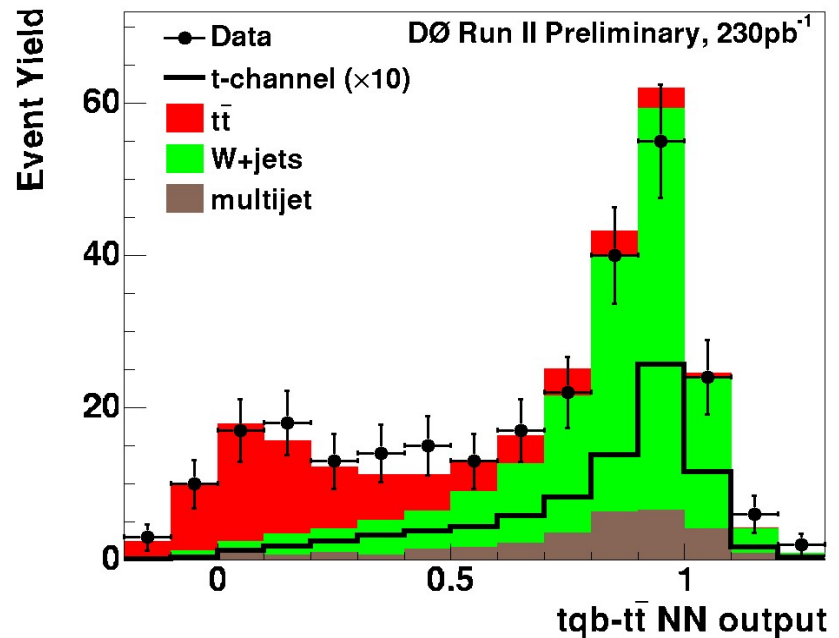
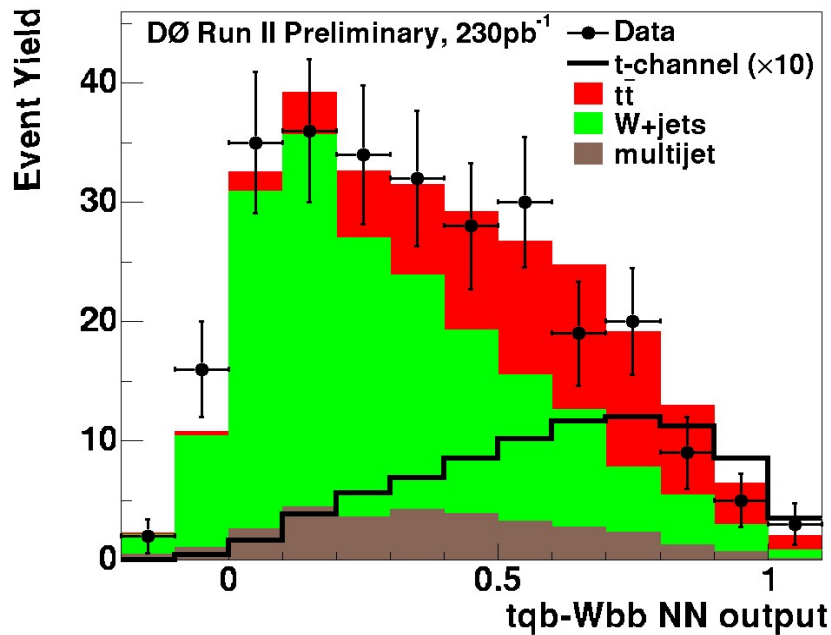
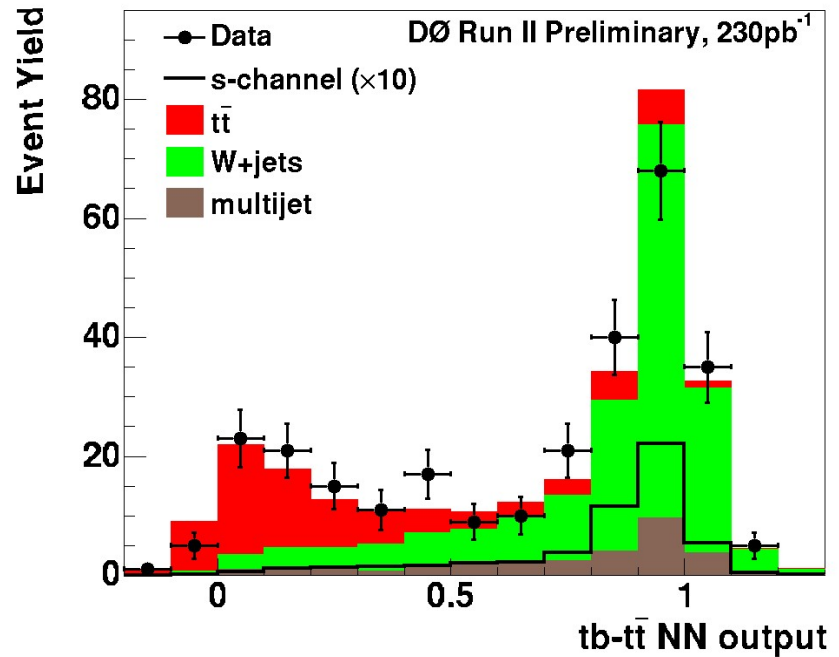
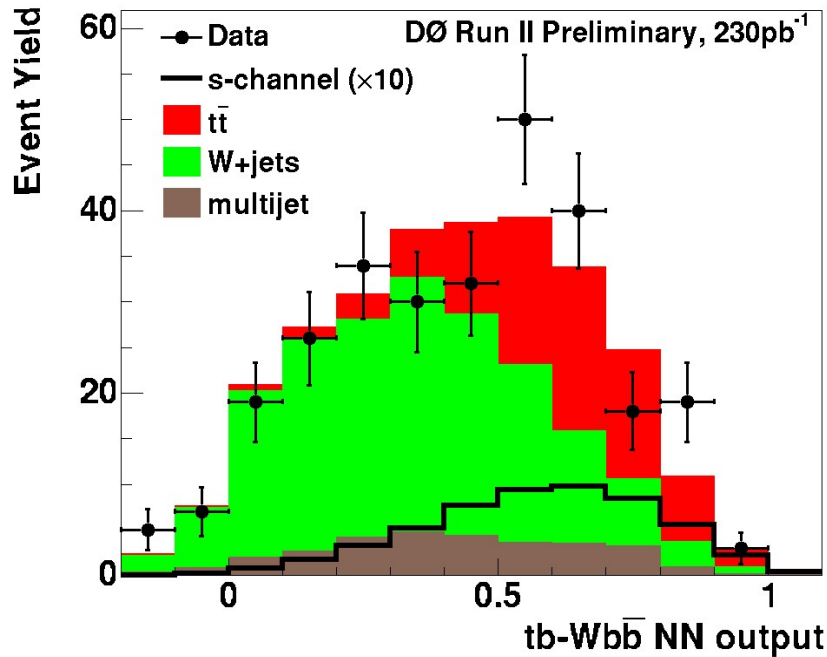
**Output Node:** linear combination of hidden nodes  
 $f(\vec{X}) = w'_k n_k(\vec{X}, \vec{w}_k)$



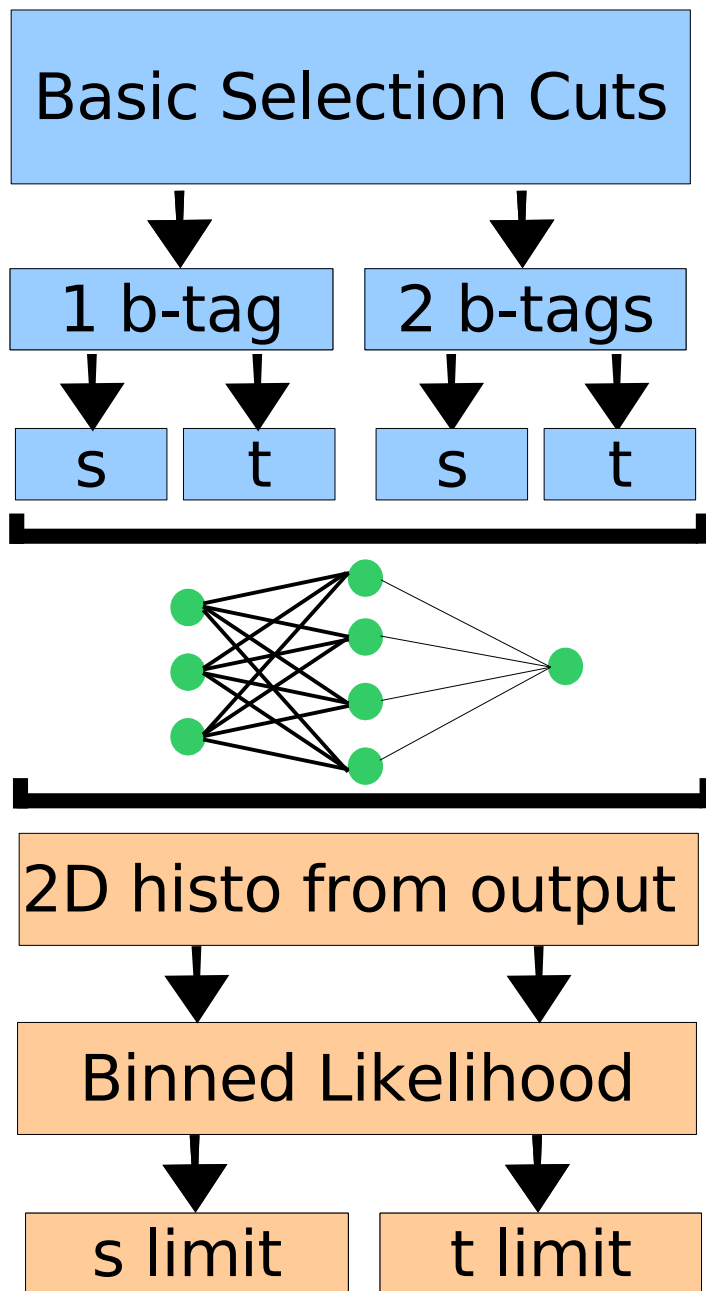
**Hidden Nodes:** Each is a sigmoid dependent on the input variables

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

# Neural Networks output



# Analysis flow revisited



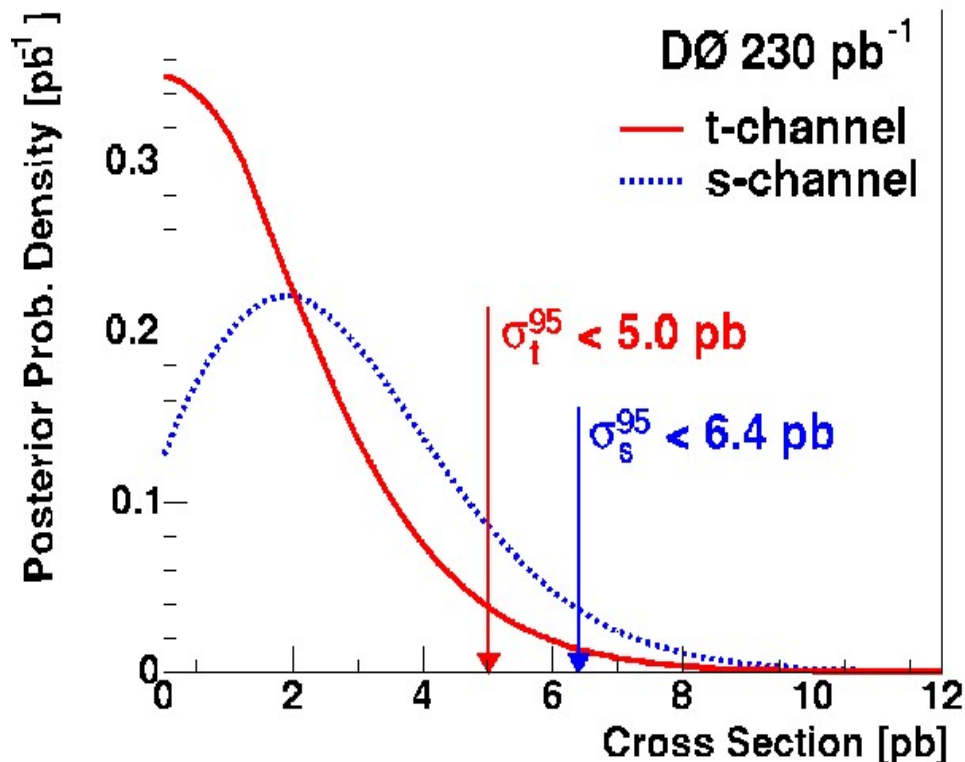
1) Separate s- and t-channel in electron or muon and 1 or 2 b-tags

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	<b>6.4</b>	4.5
t-channel	<b>5.0</b>	5.8

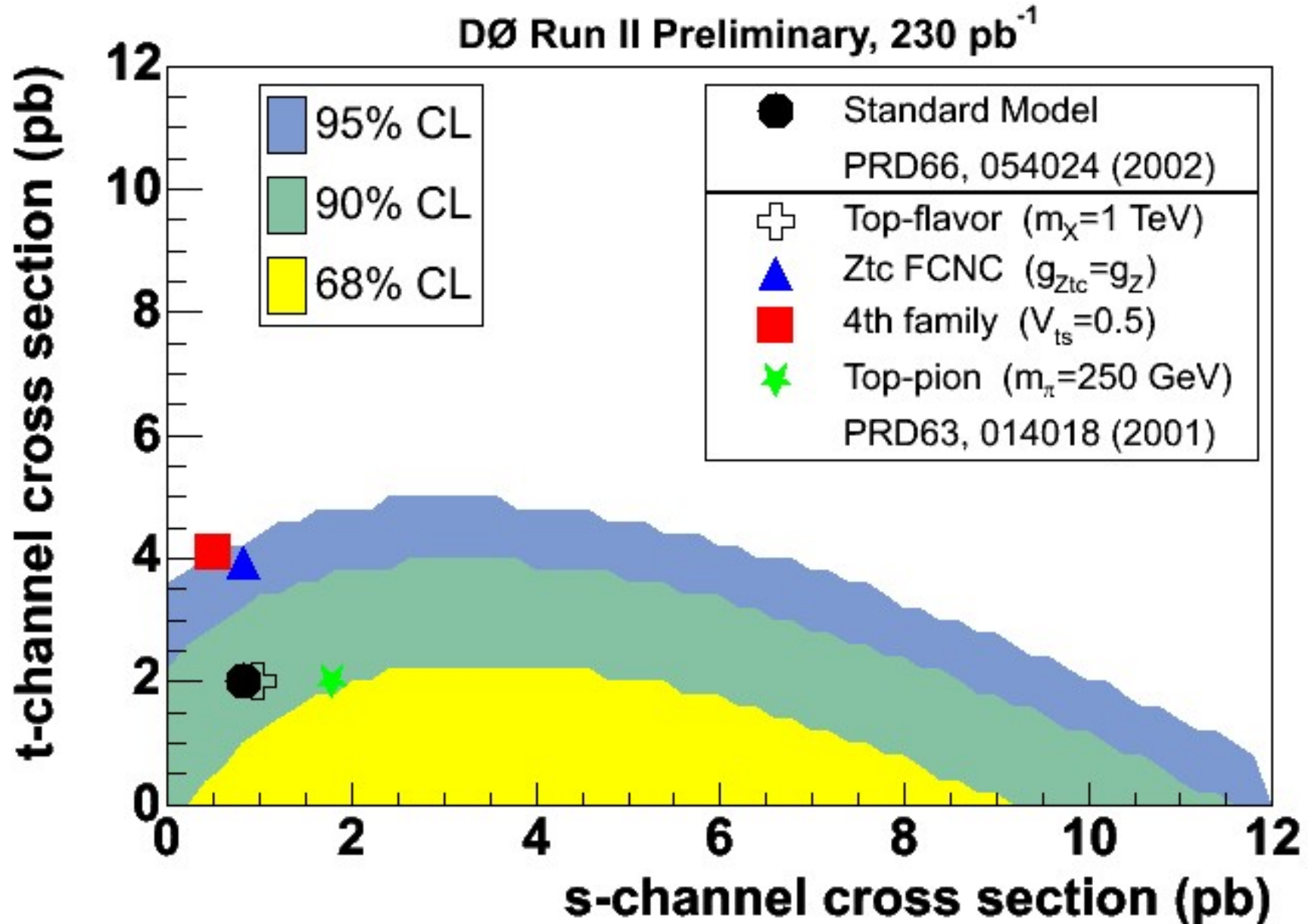
## Likelihoods (370pb-1)

	Observed	Expected
s-channel	<b>5.0</b>	3.3
t-channel	<b>4.4</b>	4.3

- ▶ Use Bayesian approach to combine channels (e,  $\mu$  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**

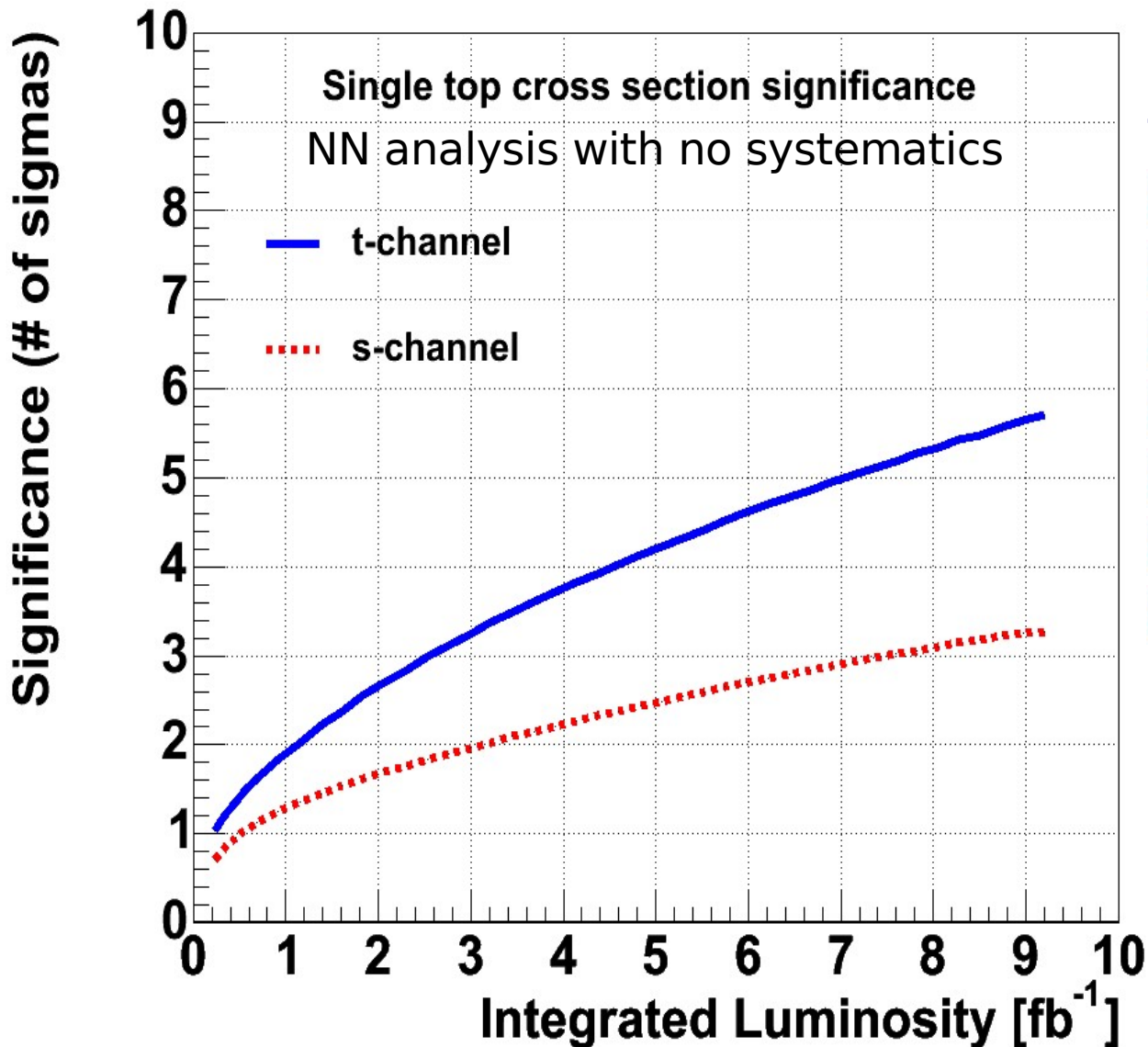
# Model independent limits





# Sensitivity

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



Need to work on many fronts to improve:

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

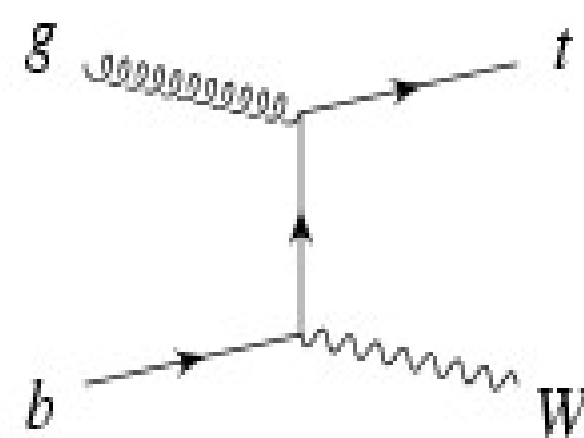
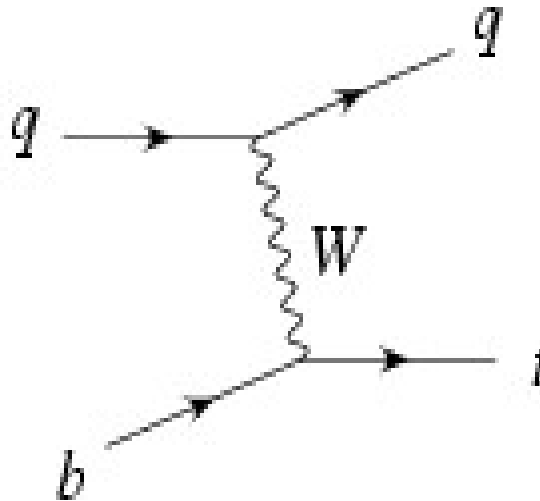
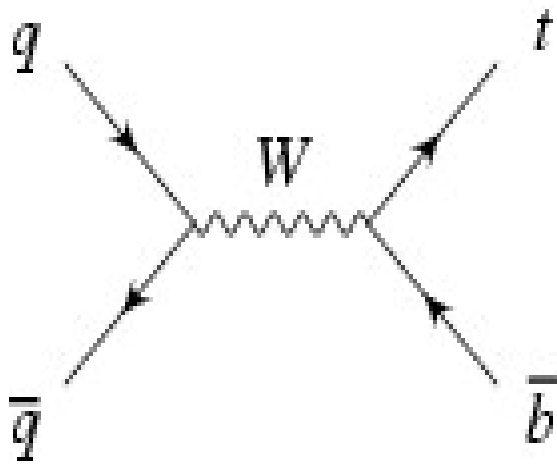
# Single top in a couple of years

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

$$\sigma_s = 10.6 \pm 1.1 \text{ pb}$$

$$\sigma_t = 246.6 \pm 0.25 \text{ pb}$$

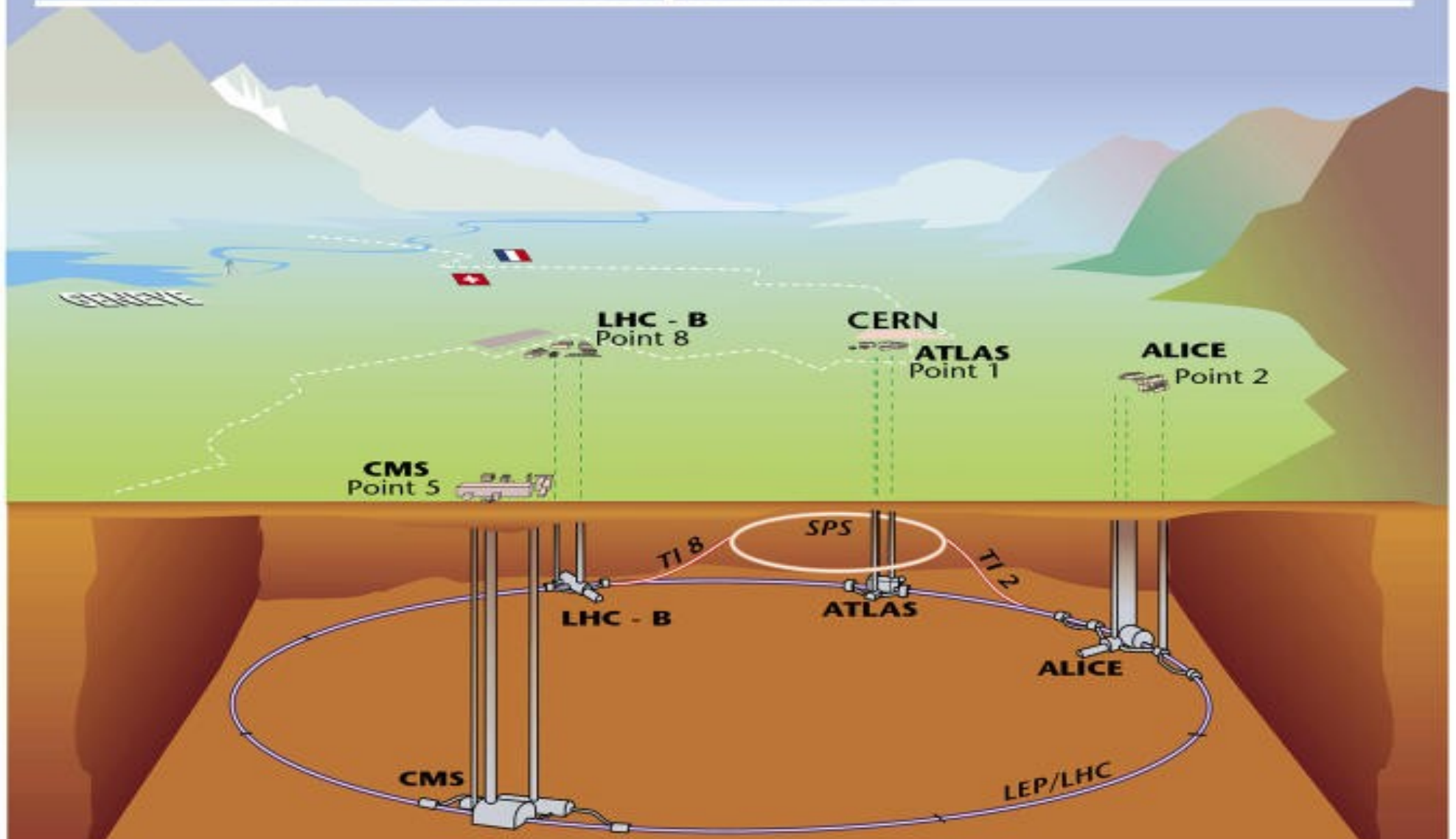
$$\sigma_{tW} = 62.0^{+16.6}_{-3.6} \text{ pb}$$



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

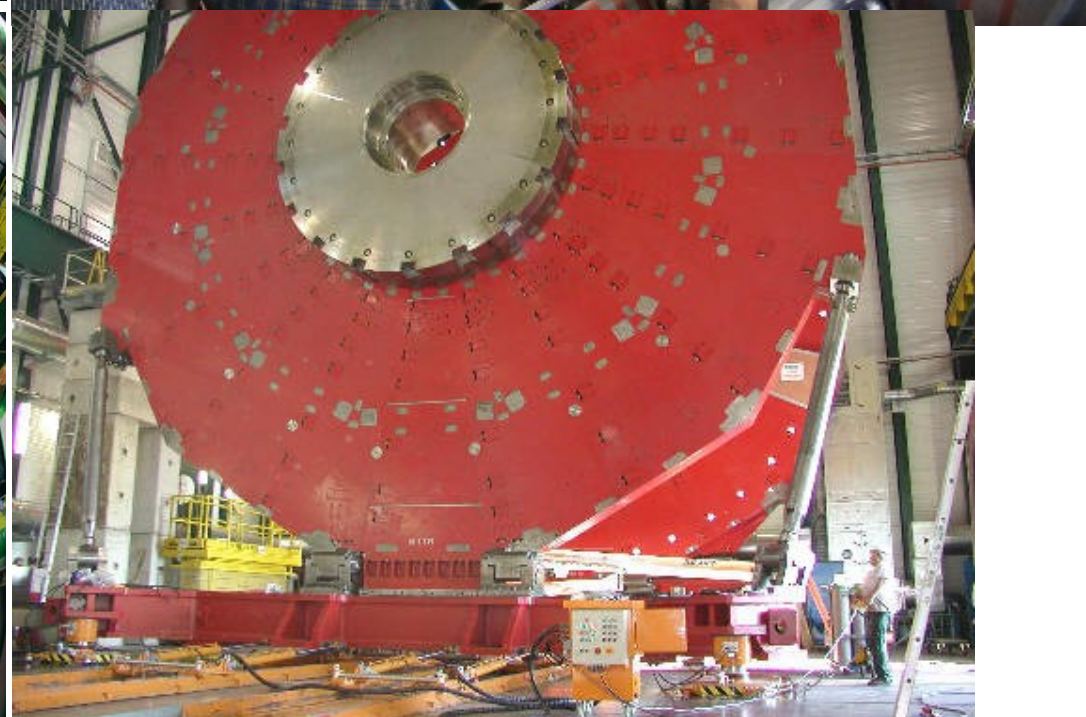
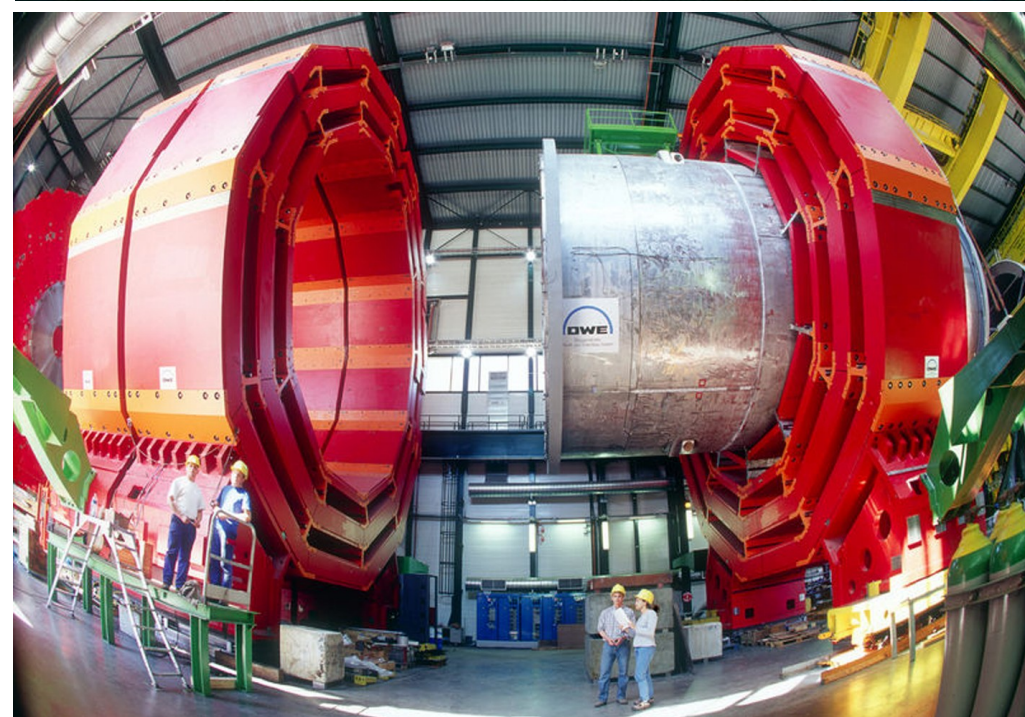
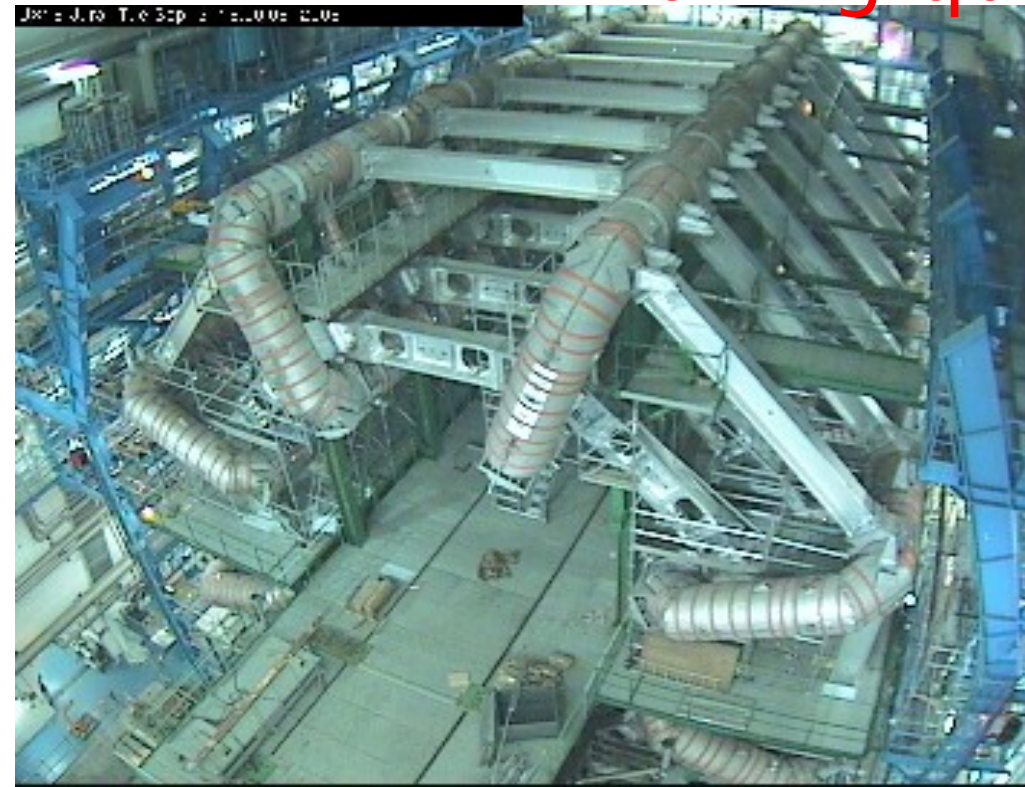
# The Large Hadron Collider

Overall view of the LHC experiments.



**Proton-proton collider  $\sqrt{s}=14$  TeV**  
**Higgs, top, exotics factory**

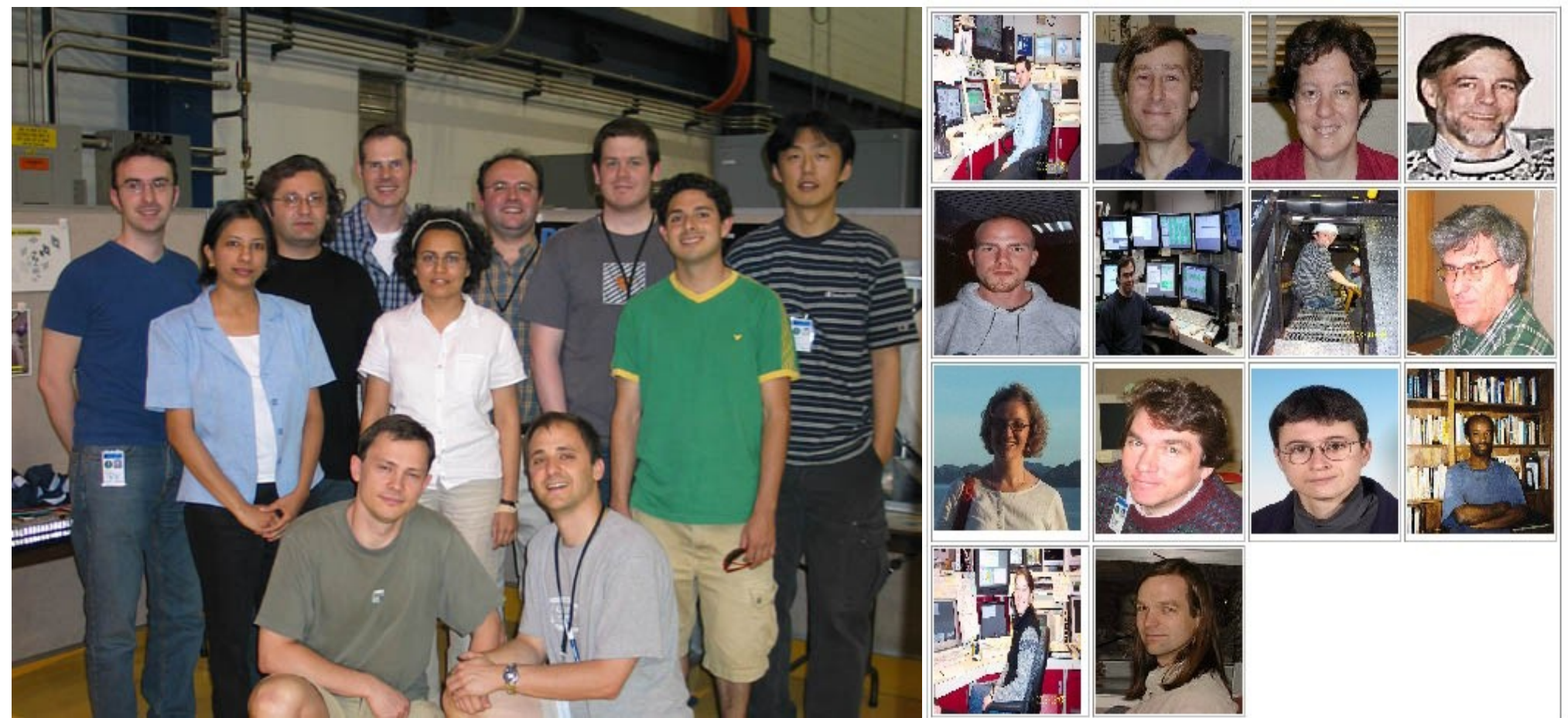
# Making quick progress



# Conclusions

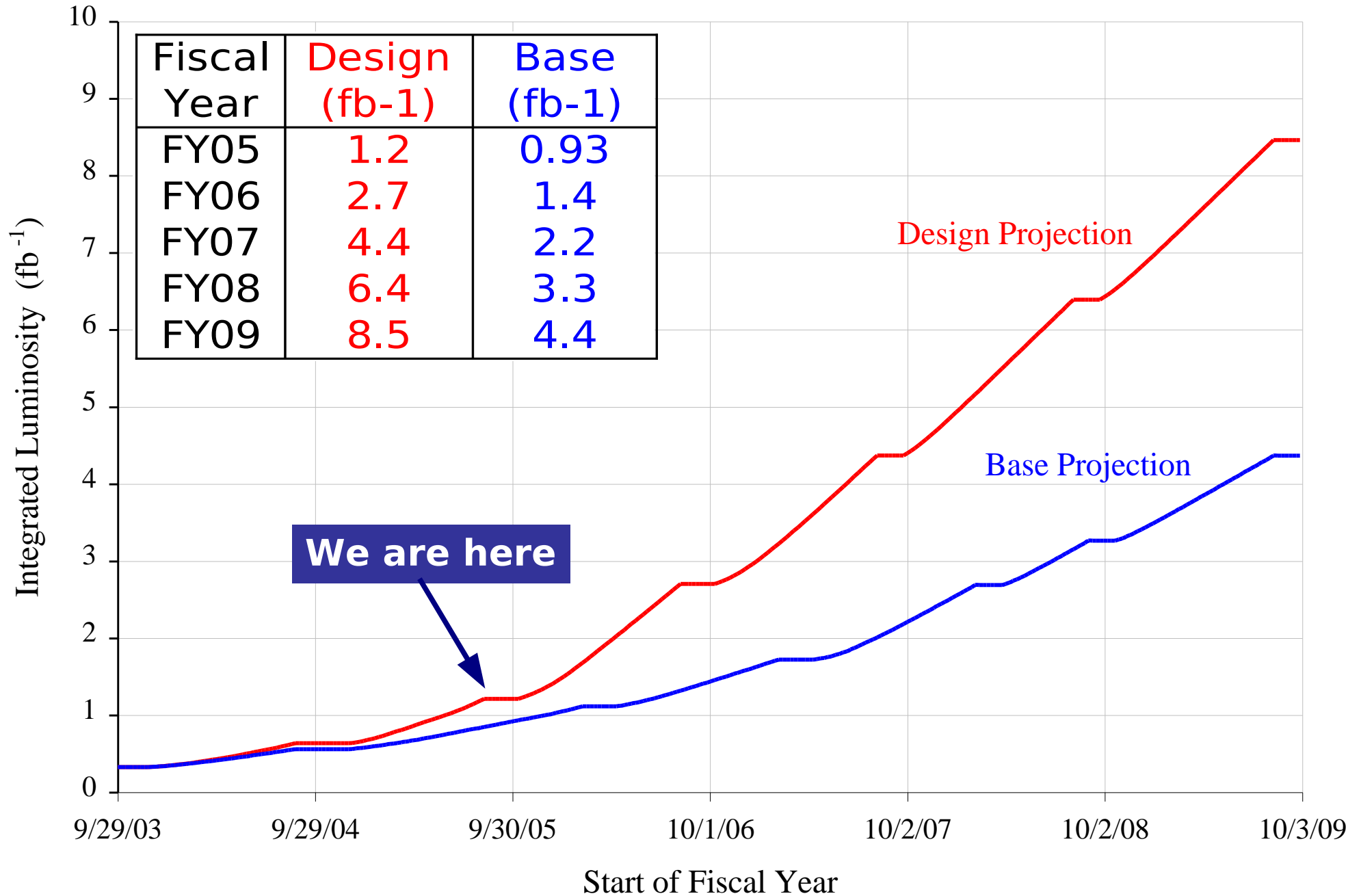
- ▶ The Standard Model is a tremendous achievement
- ▶ Still many puzzles: Origin of mass, hierarchies, dark matter, matter-antimatter asymmetry, supersymmetry, gravity...
- ▶ Top quarks offer a vantage point to test the SM
- ▶ The Tevatron is at the energy frontier (it is the place to be!)
- ▶ Data 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:  
 $\sigma_s < 5.0 \text{ pb}$     $\sigma_t < 4.4 \text{ pb}$  (SM predicts  $\sim 1 \text{ pb}$  and  $2 \text{ pb}$ )
- ▶ 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



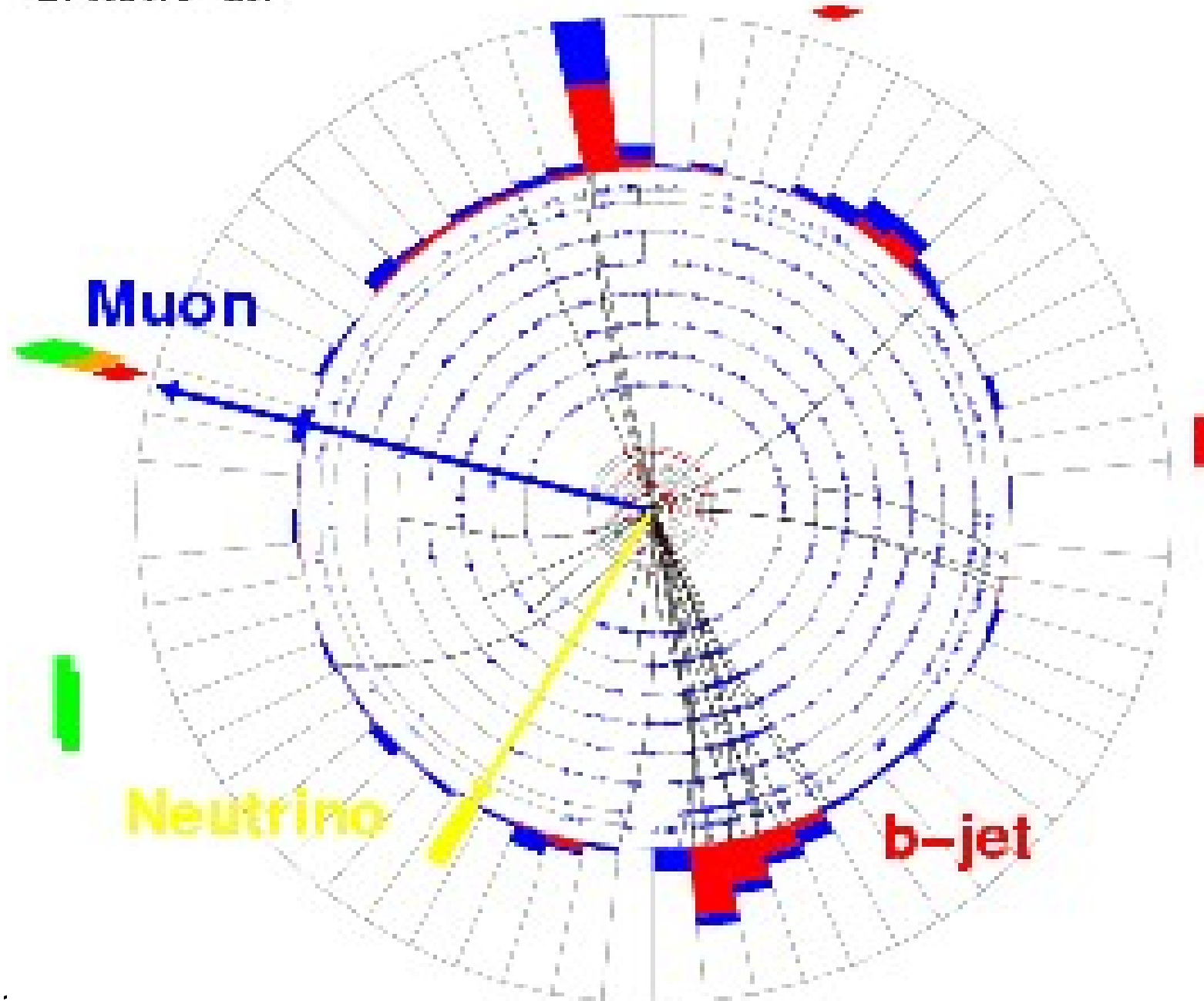
# Extra slides



# Candidate event

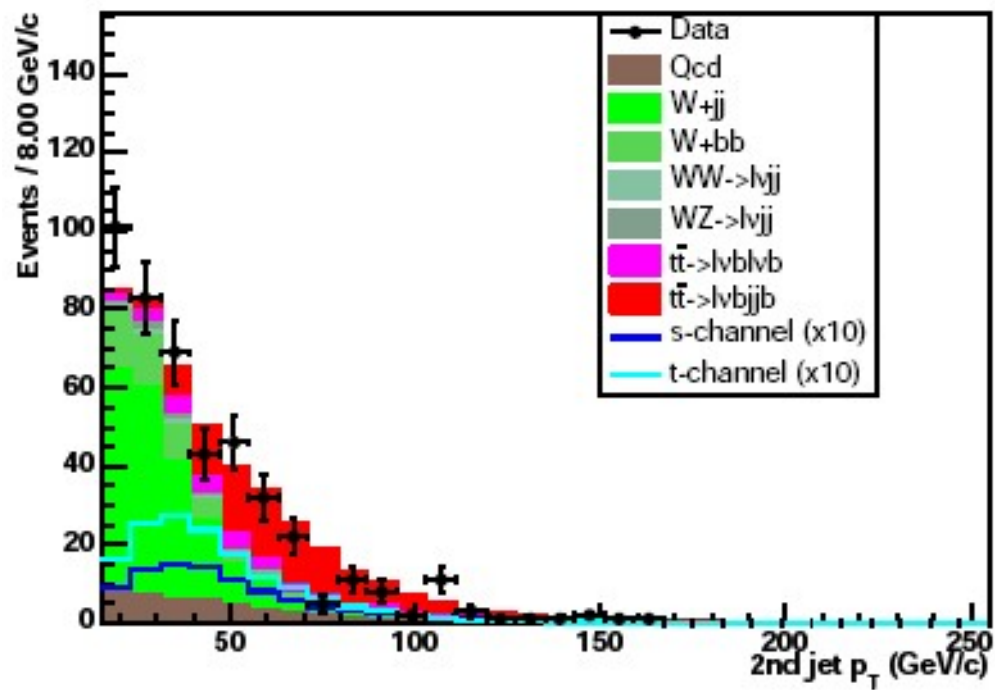
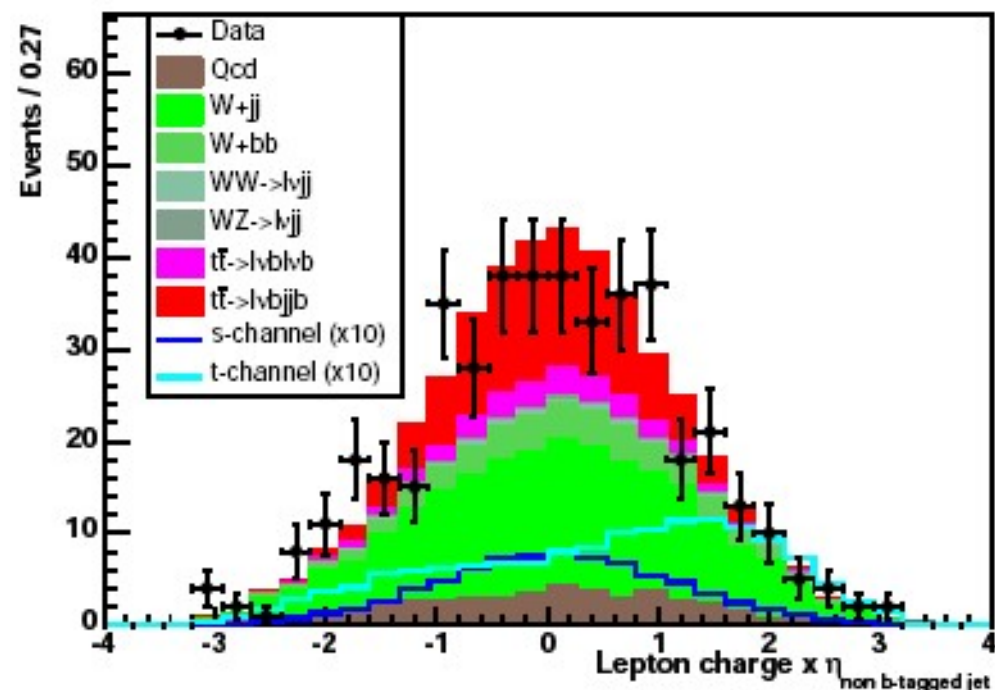
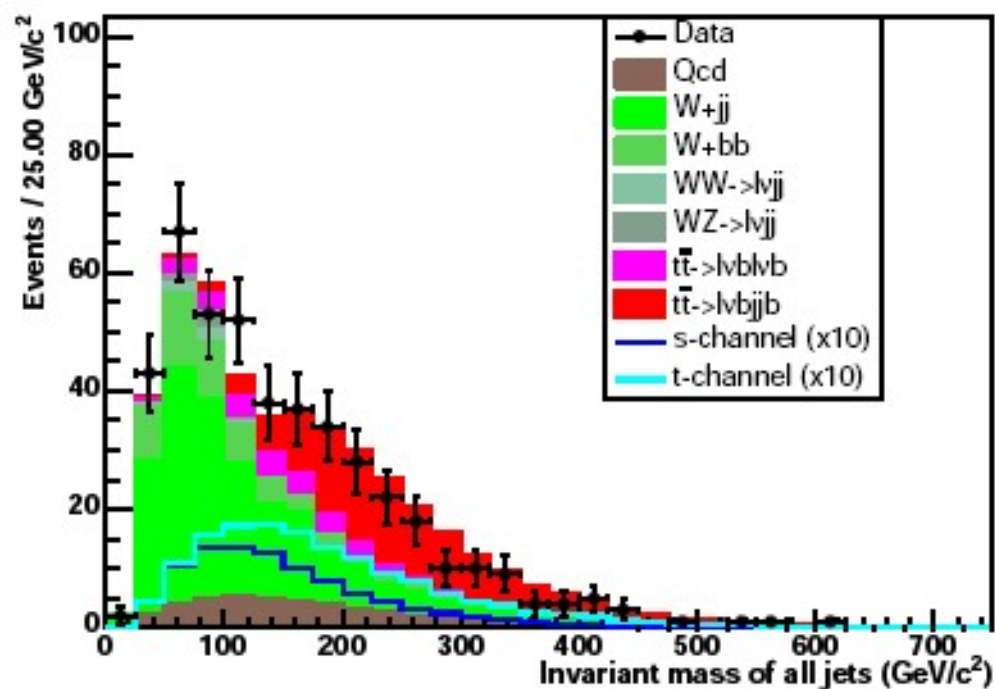
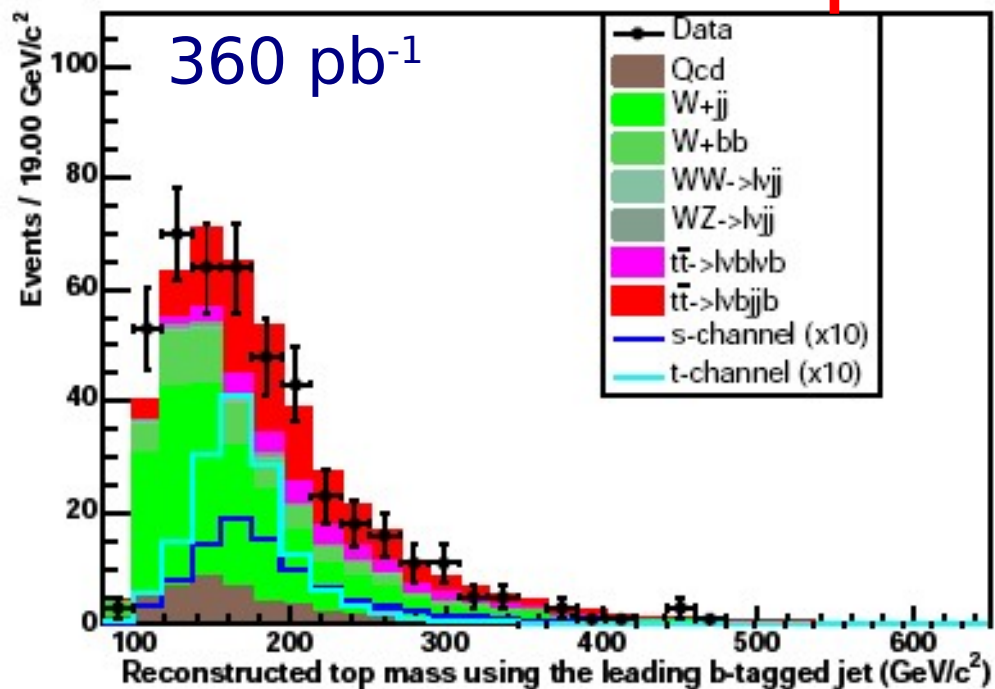
Run 181059 Lx:43000433 Sca: 9a 9 11:15:43 2004

LI sca: 0:31 GeV



$e+\mu = 1\text{tag}+2\text{tag}$

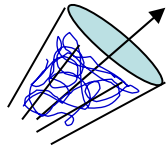
# Input variables



# Discriminating variables

## Individual object kinematics

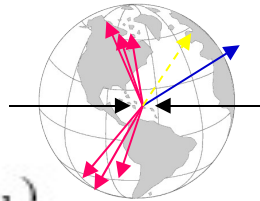
- $p_T(\text{jet1}_{\text{tagged}})$
- $p_T(\text{jet1}_{\text{untagged}})$
- $p_T(\text{jet2}_{\text{untagged}})$
- $p_T(\text{jet1}_{\text{nonbest}})$
- $p_T(\text{jet2}_{\text{nonbest}})$



This is where our phenomenology friends come so handy!

## Global event kinematics

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



Three broad categories:

- ▶ Object kinematics
- ▶ Global event kinematics
- ▶ Angular correlations

Reconstruct  $W$ : from  $\ell$  and

To reconstruct the top quark:

- ▶ s-channel: “best” jet algorithm

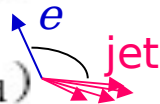
Chose the jet that gives  $m_t$  closest to 175GeV

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

Reconstruct  $q'$ : lead untagged jet

## Angular variables

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

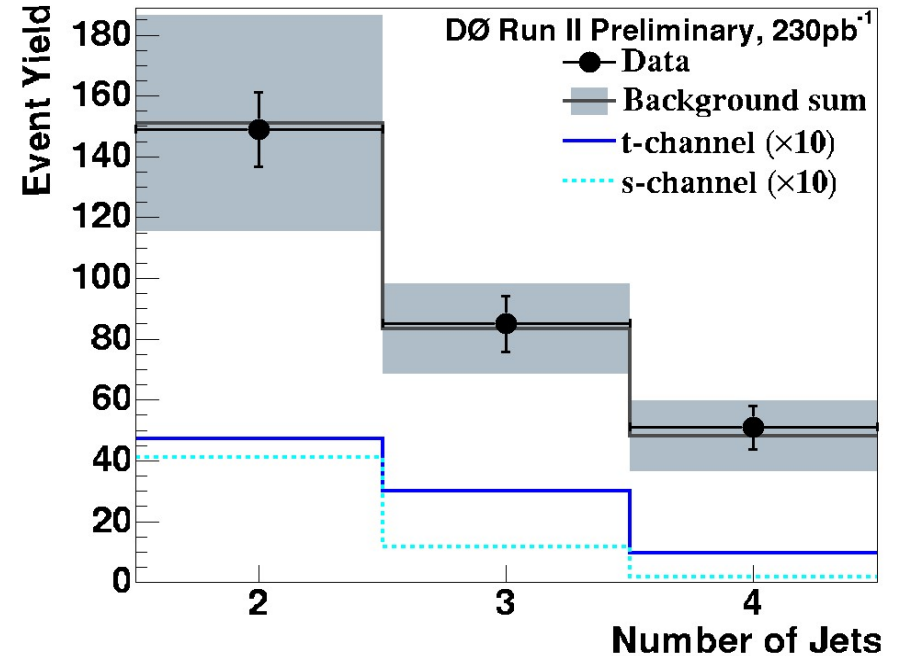


- s-channel search only
- t-channel search only
- used in both

# Systematic Uncertainties

## 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%
$\ell$ ID	5%



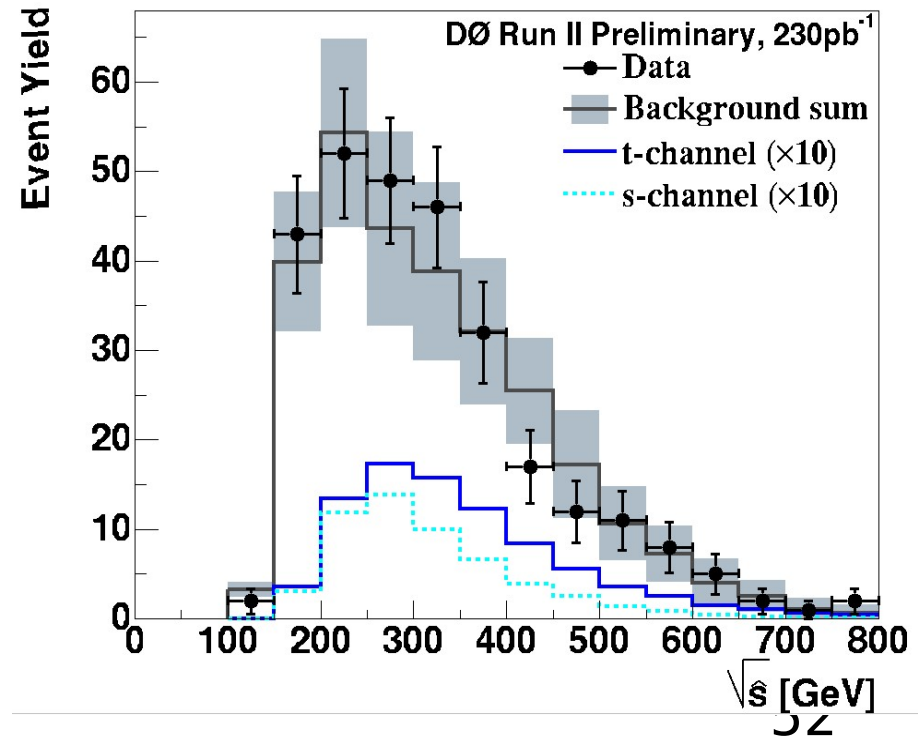
► Some systematic uncertainties also affect shape:

JES, b-tag and trigger modeling

► Total uncertainty:

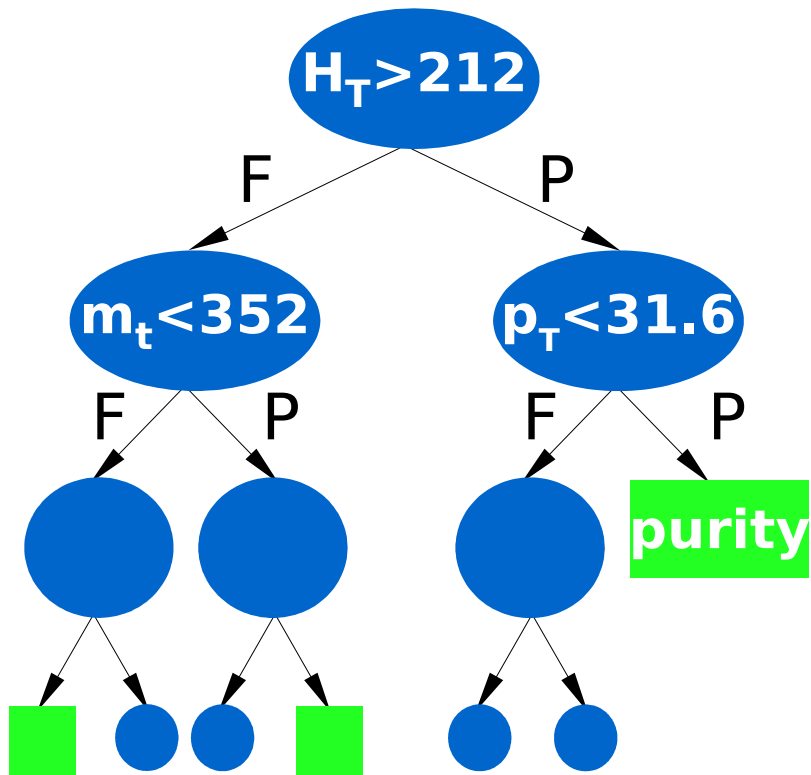
	1 tag	2 tags
Signal acceptance	15%	25%
Background sum	10%	26%

► Result is statistics limited

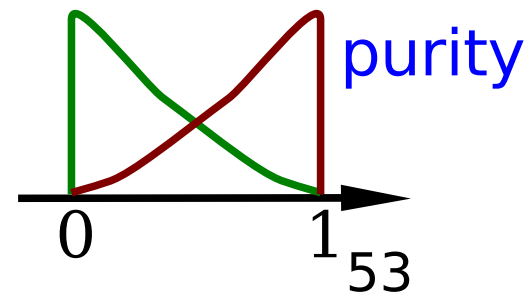


# Decision Trees

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  $\text{purity} = N_S / (N_S + N_B)$
- ▶ Training: optimize Gini improvement  
 $\text{Gini} = 2 N_S N_B / (N_S + N_B)$
- ▶ Output:  
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:  $B \rightarrow N_{\text{observed}}$ ,  $A \rightarrow n_{\text{predicted}} = n_{\text{signal}} + n_{\text{bkgd}}$ ,  $n_s = \text{Acc} * L * \sigma$

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

$P(A)$ : "prior" probability density  $\Pi(n_{\text{pred}}) = \Pi(\text{Acc} * L, n_b) \Pi(\sigma)$   
 $\Pi(n_s, n_b)$  multivariate gaussian ;  $\Pi(\sigma)$  assumed flat

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

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

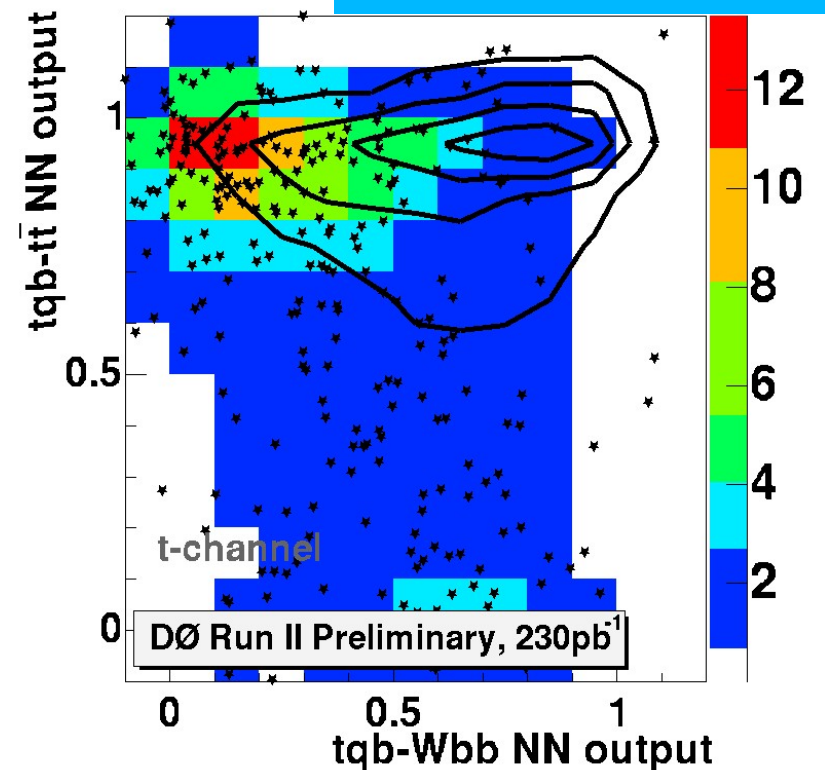
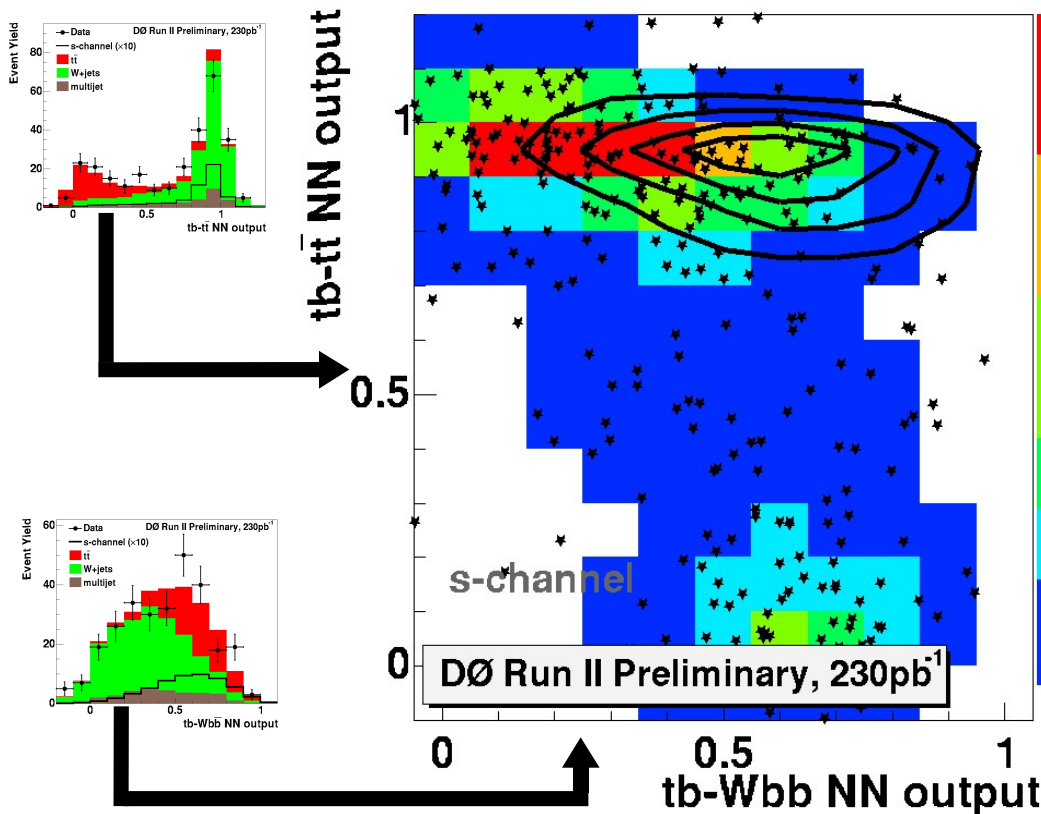
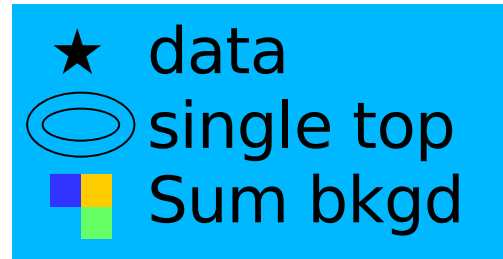
$$P(n_{\text{predicted}} | N_{\text{observed}}) = 1/Z L(N_{\text{observed}} | n_{\text{predicted}}) \Pi(n_{\text{pred}})$$

# 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



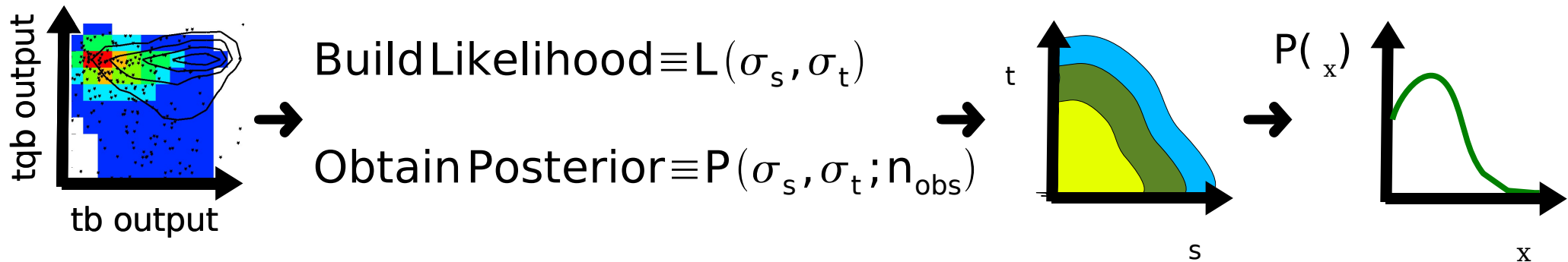
# Full 2D limits

The goal is to obtain  $\sigma_{s'}$ ,  $\sigma_{t'}$  and  $\sigma_{s+t'}$  without any SM assumption

Previously we have used  $\sigma_s^{SM}$  to derive  $\sigma_t$  and vice versa

As before, use likelihood from 2D discriminant output

Float  $\sigma_s$  and  $\sigma_t$  and consider flat priors



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

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

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

- ▶ For the combined limit:  
replace:  $s \rightarrow z-t$  where  $z=s+t$   
at the Likelihood level
- ▶ Additional constraint on priors:  
 $t \leq z \rightarrow$  the prior for  $t$  depends on  $z$

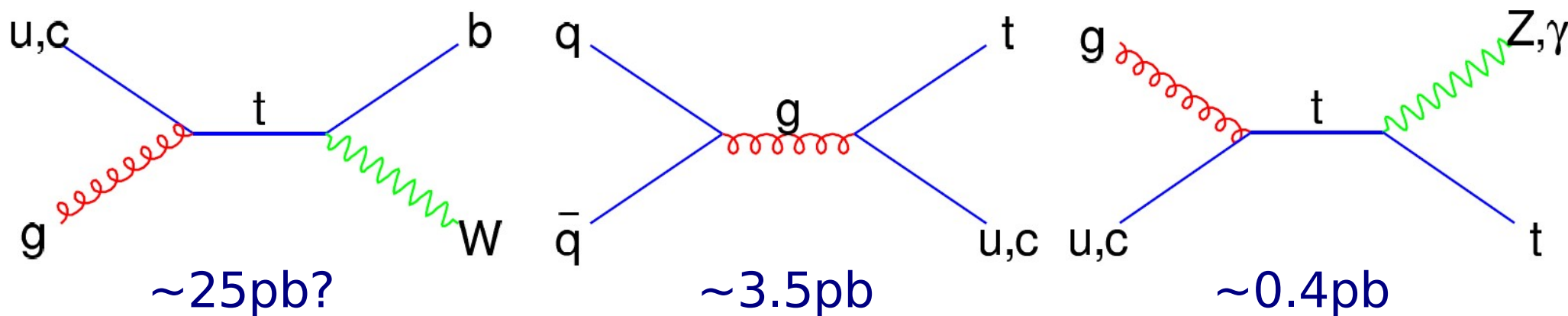
$$\sigma_x^{95} = \int_0^{\sigma_x^{95}} P(\sigma_x; n_{obs}) d\sigma_x$$



# Single top beyond the SM

Plethora of possibilities

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



# Non-SM couplings

Top is a good place to look for deviations from SM:

under control, one dominant decay  $t \rightarrow Wb$ , no top hadrons,...

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

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

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

► Effective single top production cross section:

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

► There are strong bounds on tensor couplings:

from unitarity  $|f_2^L| < 0.6$ , and from  $b \rightarrow s$  :  $|f_2^L| < 0.004$

► But Tevatron can set direct limits

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

► Set limits simultaneously on all four couplings

► Set individual limits

