Top Quark Physics
(at CMS)

Susan Dittmer (University of Illinois at Chicago)
USCMS Undergraduate Internship
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STANDARD MODEL OF ELEMENTARY PARTICLES

QUARKS

UP
mass 2,3 MeV/c²
charge ⅔
spin ½
u

CHARM
1,275 GeV/c²
⅔
½
c

TOP
172.67 GeV/c²
⅔
½
t

DOWN
4,8 MeV/c²
-⅓
½
d

STRANGE
95 MeV/c²
-⅓
½
s

BOTTOM
4,18 GeV/c²
-⅓
½
b

GAUGE BOSONS

GLUON
0
0
1
g

PHOTON
0
0
1
γ

HIGGS BOSON
126 GeV/c²
0
0
H

Z BOSON
91,2 GeV/c²
0
1
Z

W BOSON
80,4 GeV/c²
±1
1
W

LEPTONS

ELECTRON
0,511 MeV/c²
-1
½
e

MUON
105,7 MeV/c²
-1
½
μ

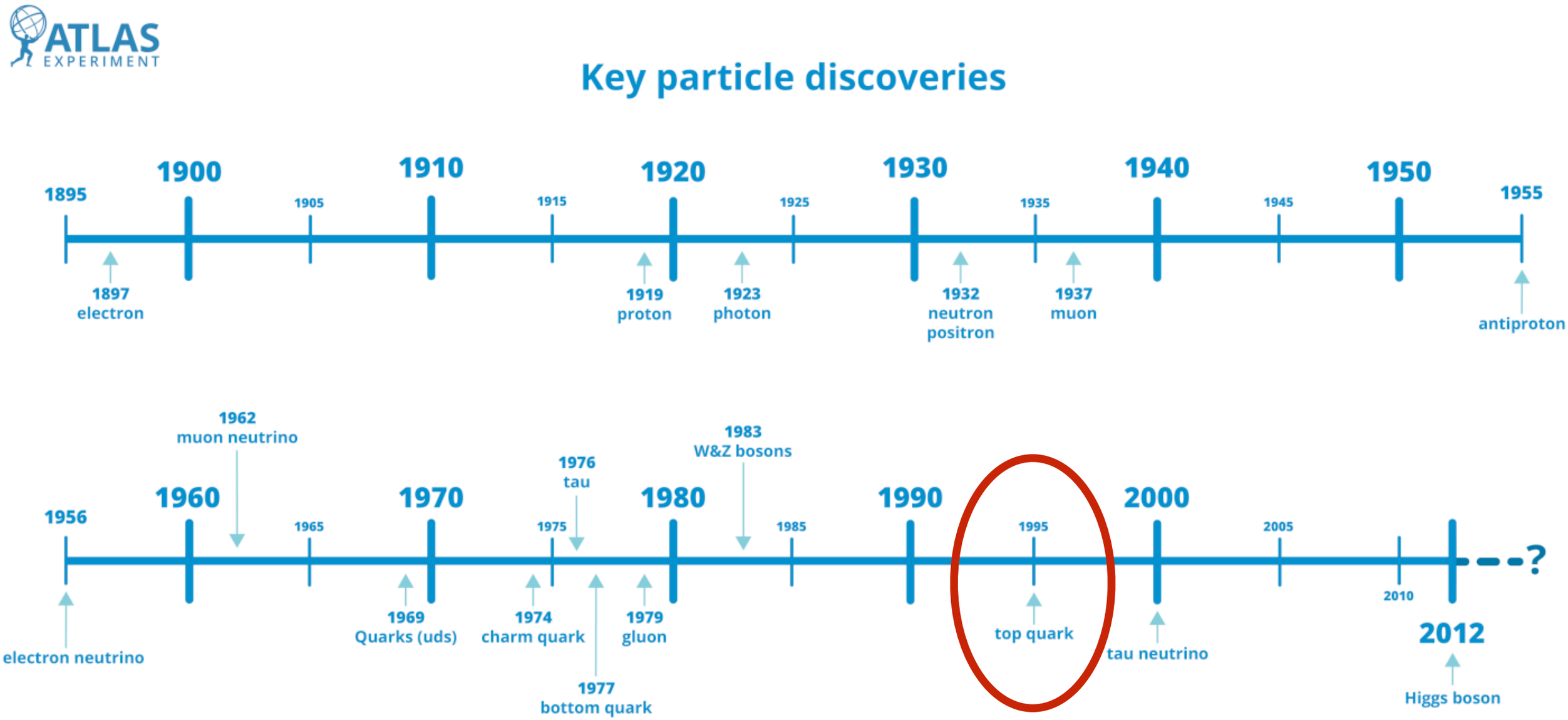
TAU
1,777 GeV/c²
-1
½
τ

ELECTRON NEUTRINO
<2,2 eV/c²
0
½
ν_e

MUON NEUTRINO
<0,17 MeV/c²
0
½
ν_μ

TAU NEUTRINO
<15,5 MeV/c²
0
½
ν_τ

Top Quark Discovery



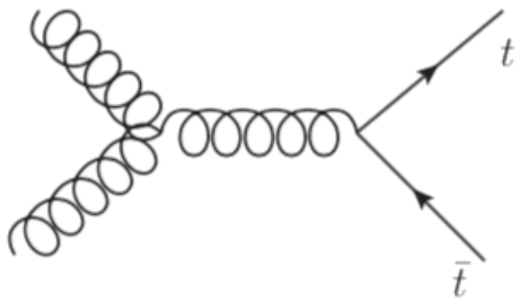
Joint discovery by CDF and D0 experiments at Fermilab Tevatron

Why measure the top quark?

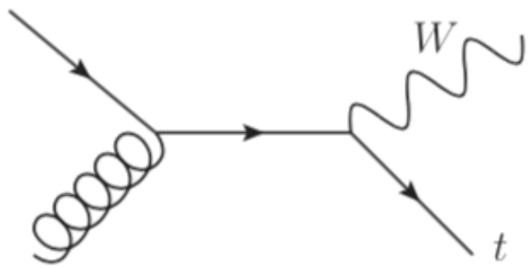
- Special properties of top quark…
  - Heaviest particle in SM — largest Yukawa coupling to Higgs
  - Decays before hadronization — can measure properties of bare top quark
- …make top physics sensitive to SM and new physics
  - Large Yukawa coupling -> sensitive to form of EWK symmetry breaking
  - Precise measurements of QCD, PDFs, EWK through top mass, cross section, properties
  - SUSY, extra dimensions, etc. predict heavy resonances decaying to pair of tops

Top Quark Production (at LHC)

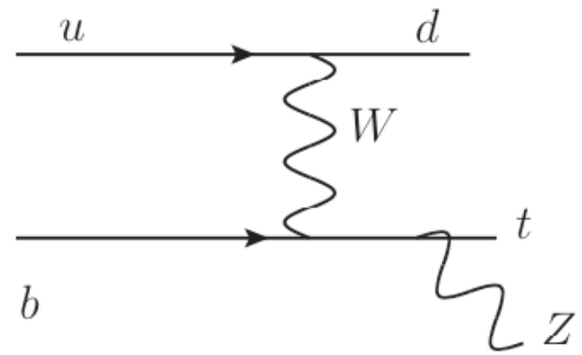
Top quark pair



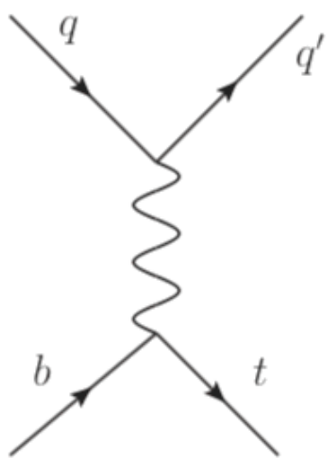
tW



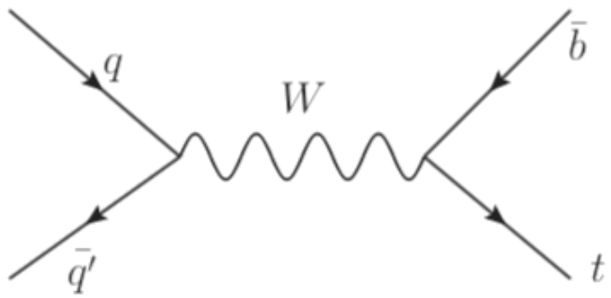
tZ



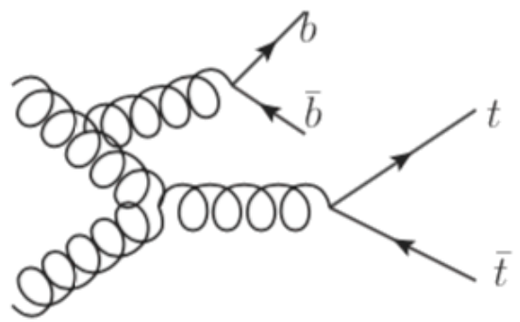
Single top (t-channel)



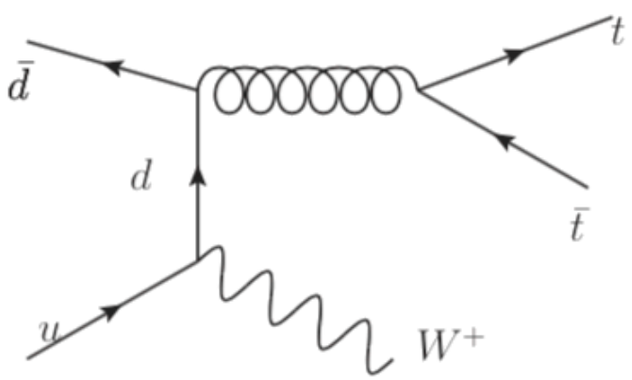
Single top (s-channel)



ttbb



ttW



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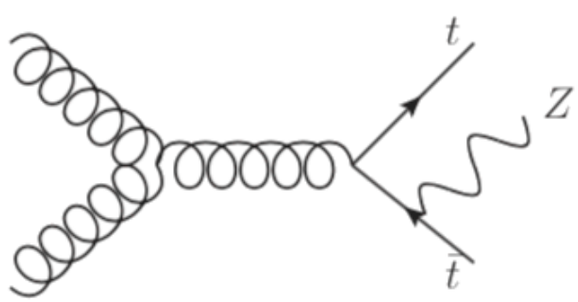
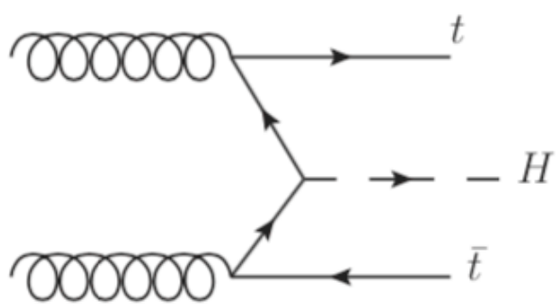


ttH



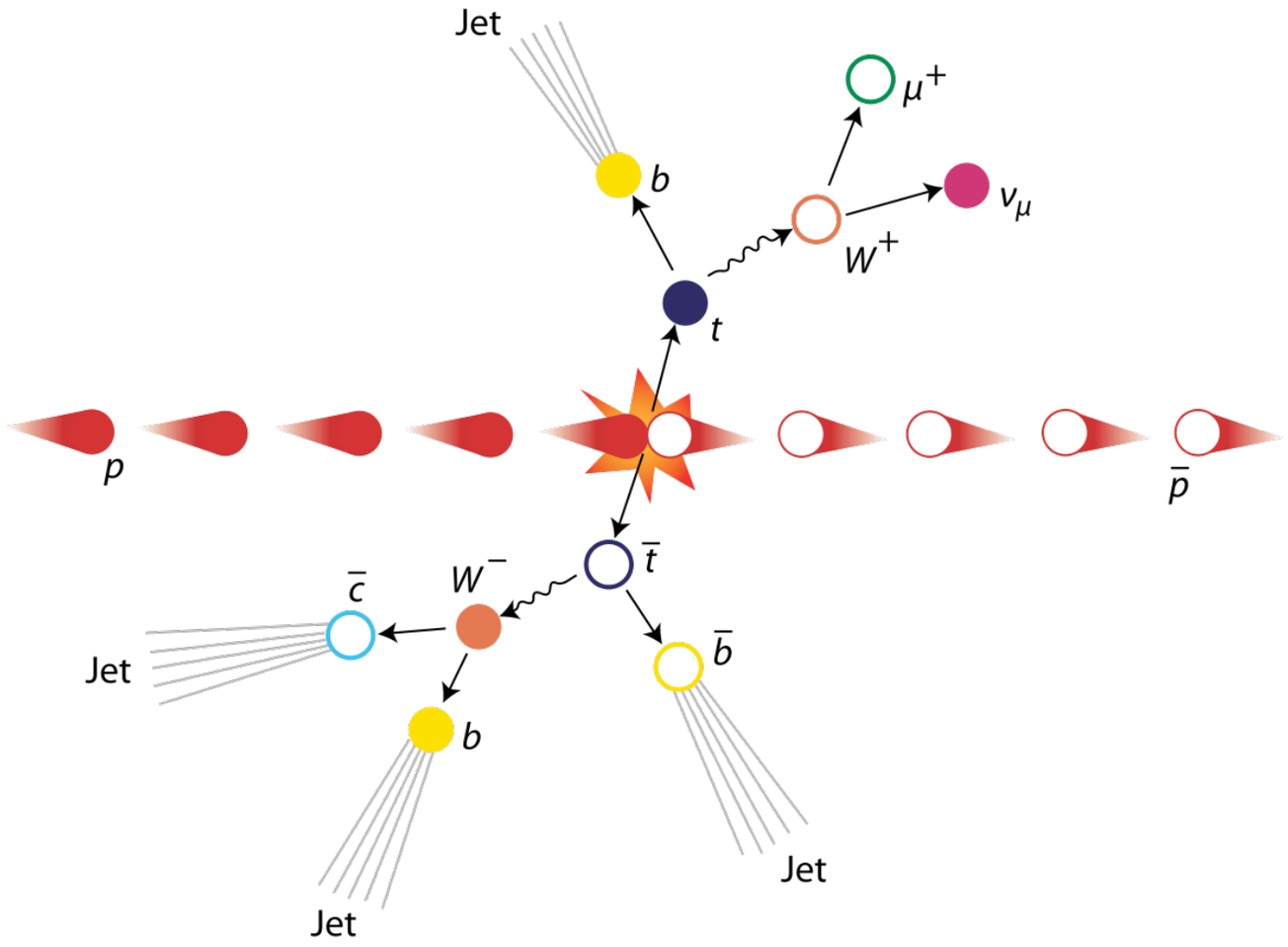
Top Quark Decay

- Short top quark lifetime means top quark decays before it can hadronize

- Top quark always (>99%) decays to Wb

  - b quark hadronizes to produce b hadron jet

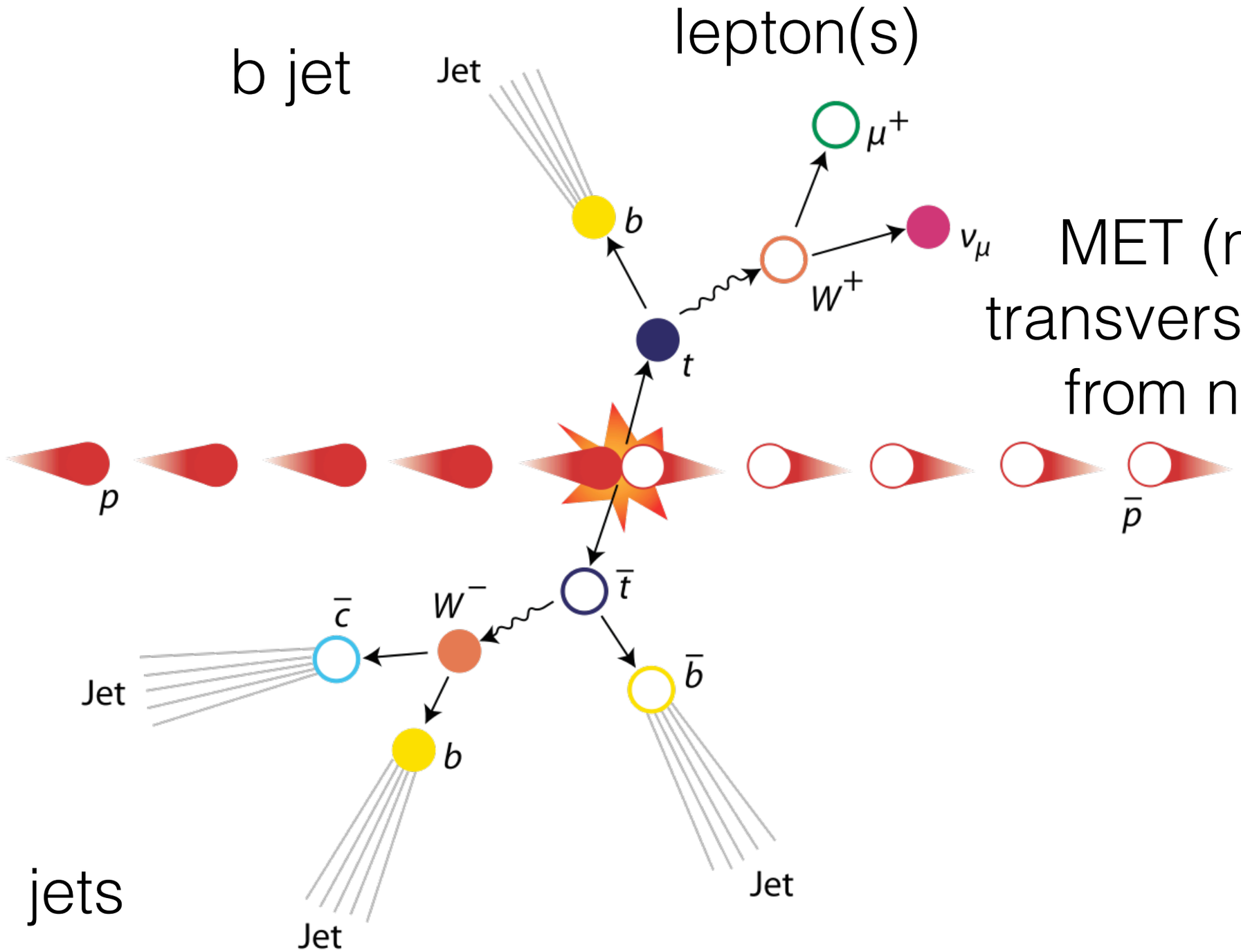
  - W decays to qq (66%) or lv (33%)



Reconstructing a Top Quark

b jet

lepton(s)



MET (missing transverse energy) from neutrino

jets

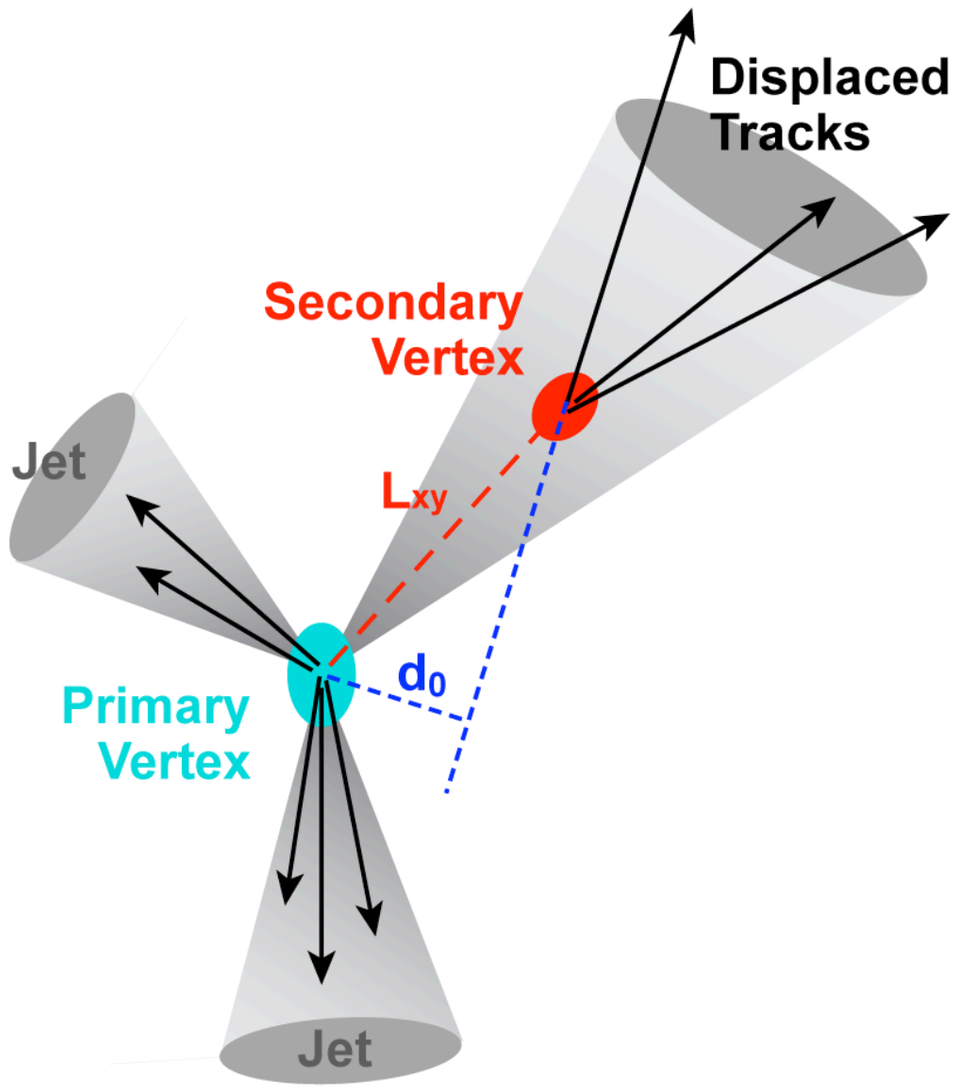
b Jet Identification

- b jet has long lifetime —> travels perceptible distance before decaying

- Identify b jet by reconstructing secondary decay vertex, containing tracks which do not point back to primary vertex

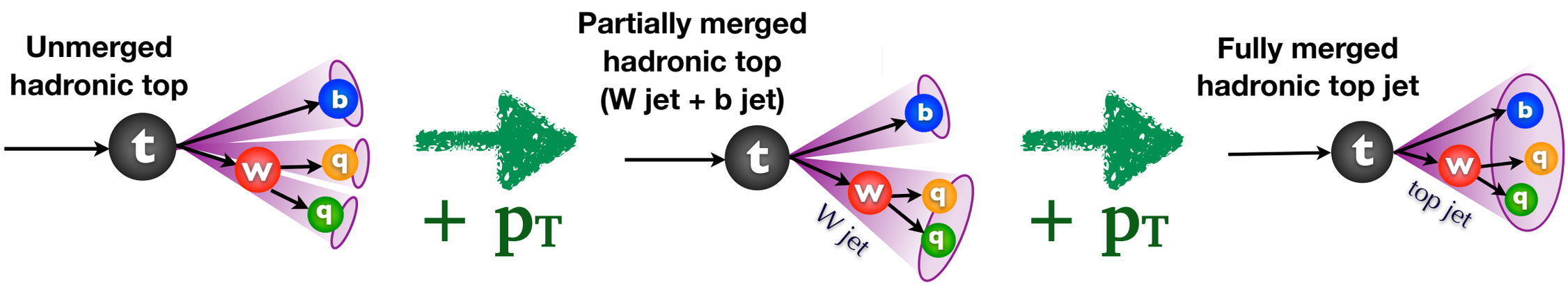
- Currently rely on machine learning for ID

  - DeepCSV, DeepJet



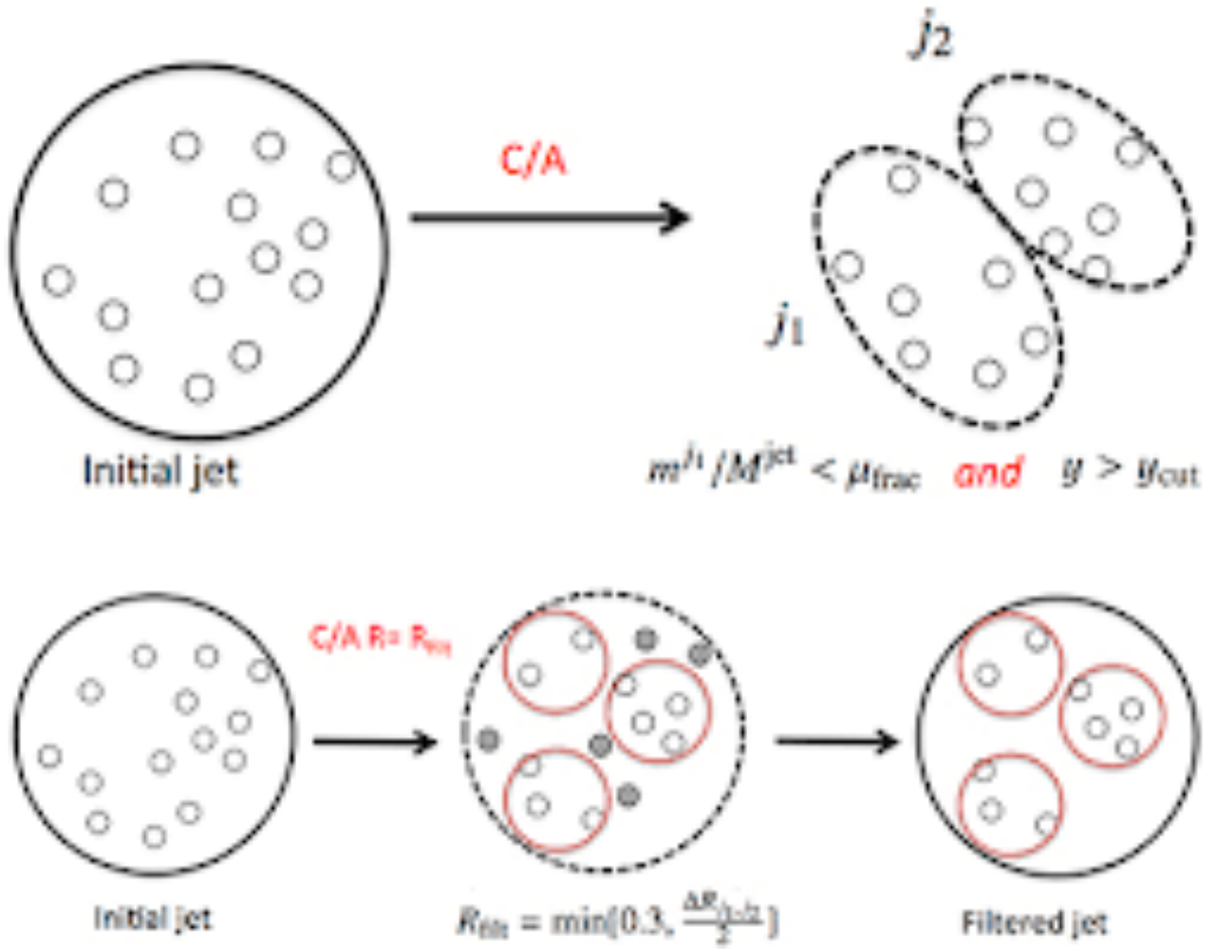
Reconstructing a Boosted Top Quark

- Want to be able to measure top production at all energy scales
  - Tails of differential distributions
  - New high-mass particles decaying to top quarks
- When top quark has high momentum, decay products are boosted
  - Hadronic top decay products merge into single jet



Identifying Boosted Tops

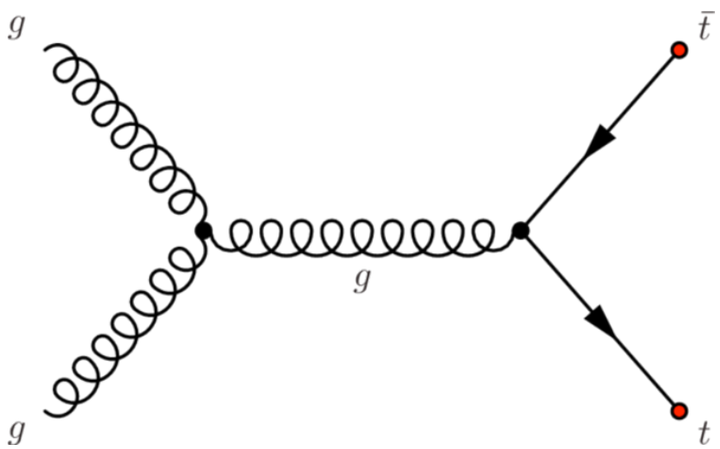
- Merged jets can be identified using substructure (‘bumpiness’ of jet)
- Prune jet (drop constituent particles with low momenta) then look for clumps / axes within the remaining particles
- Number of subjets indicates type of merged jet (e.g. 2 subjets for W, 3 for top)

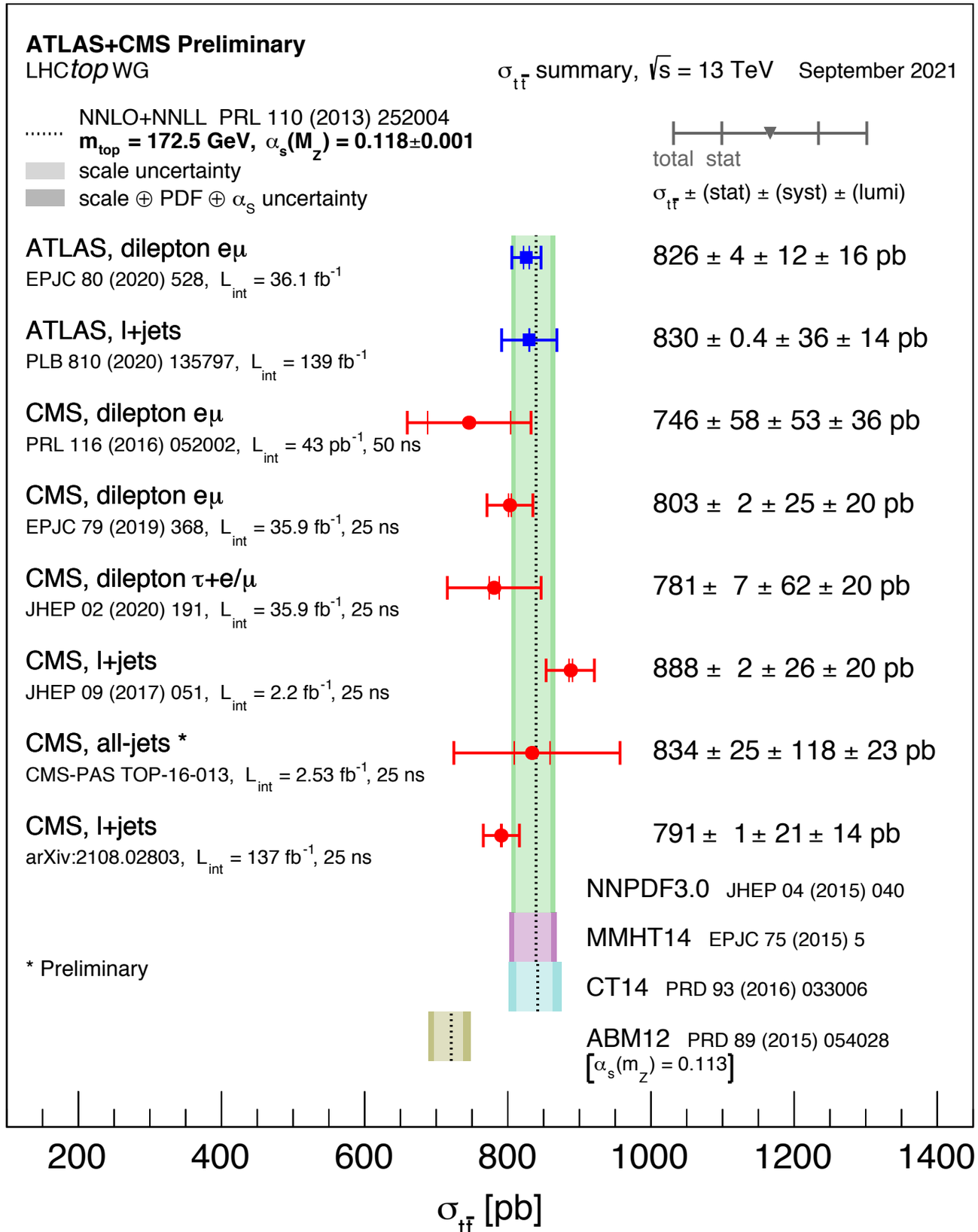


Measurements

tt Cross Section - Inclusive

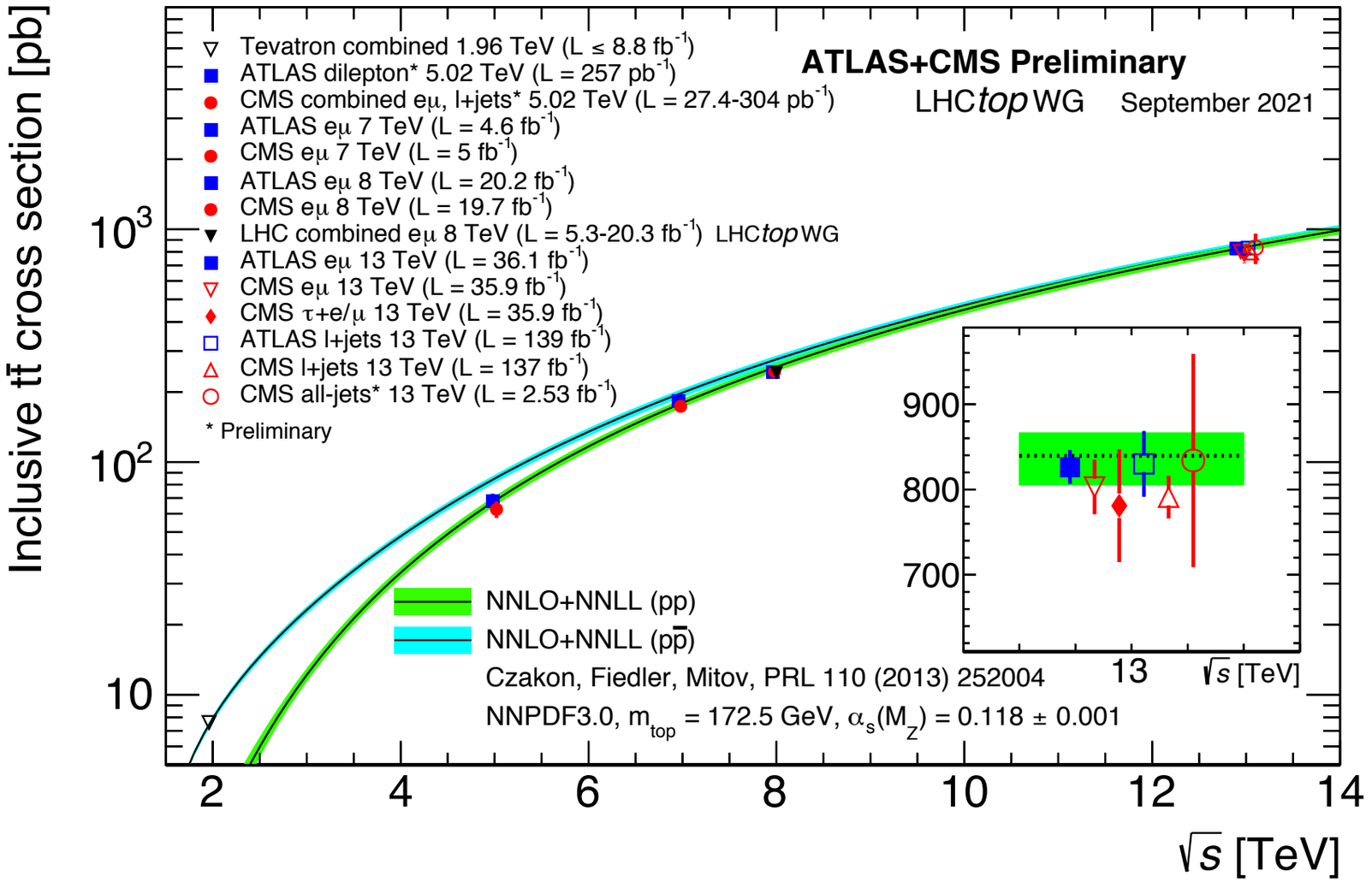
- Pair production is most common way to produce top quarks at LHC
- High statistics —> precision test of SM



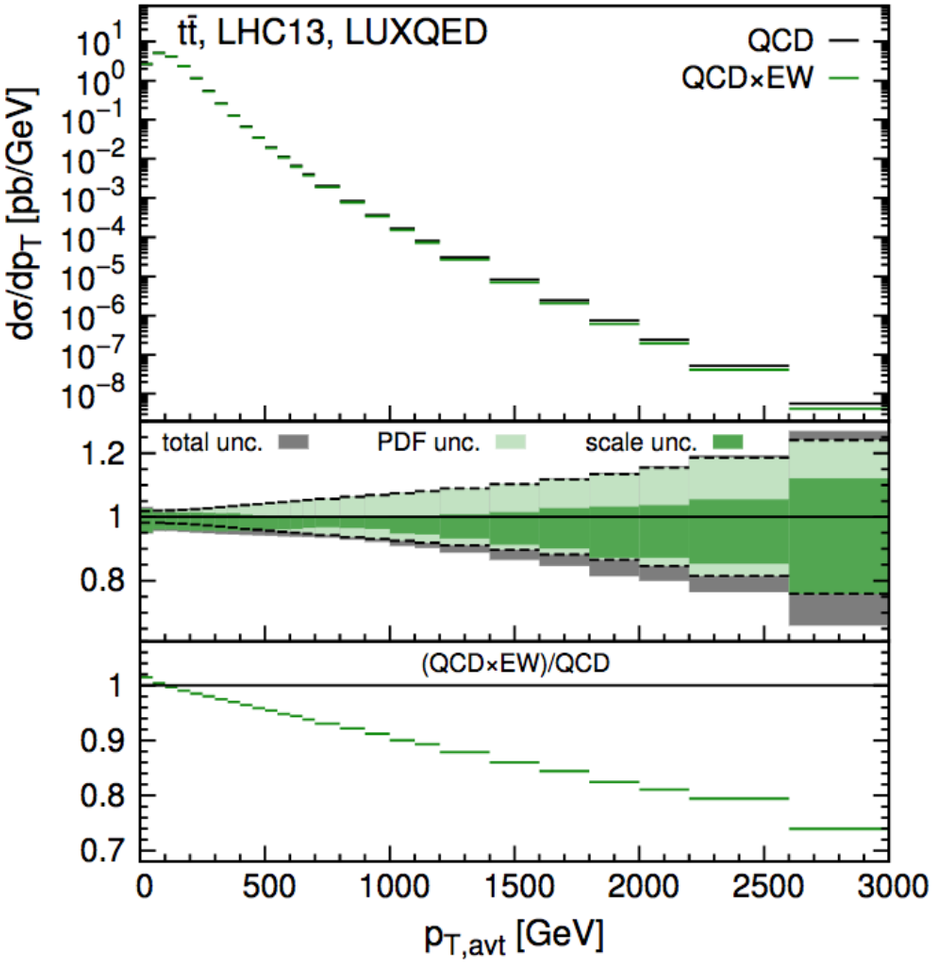


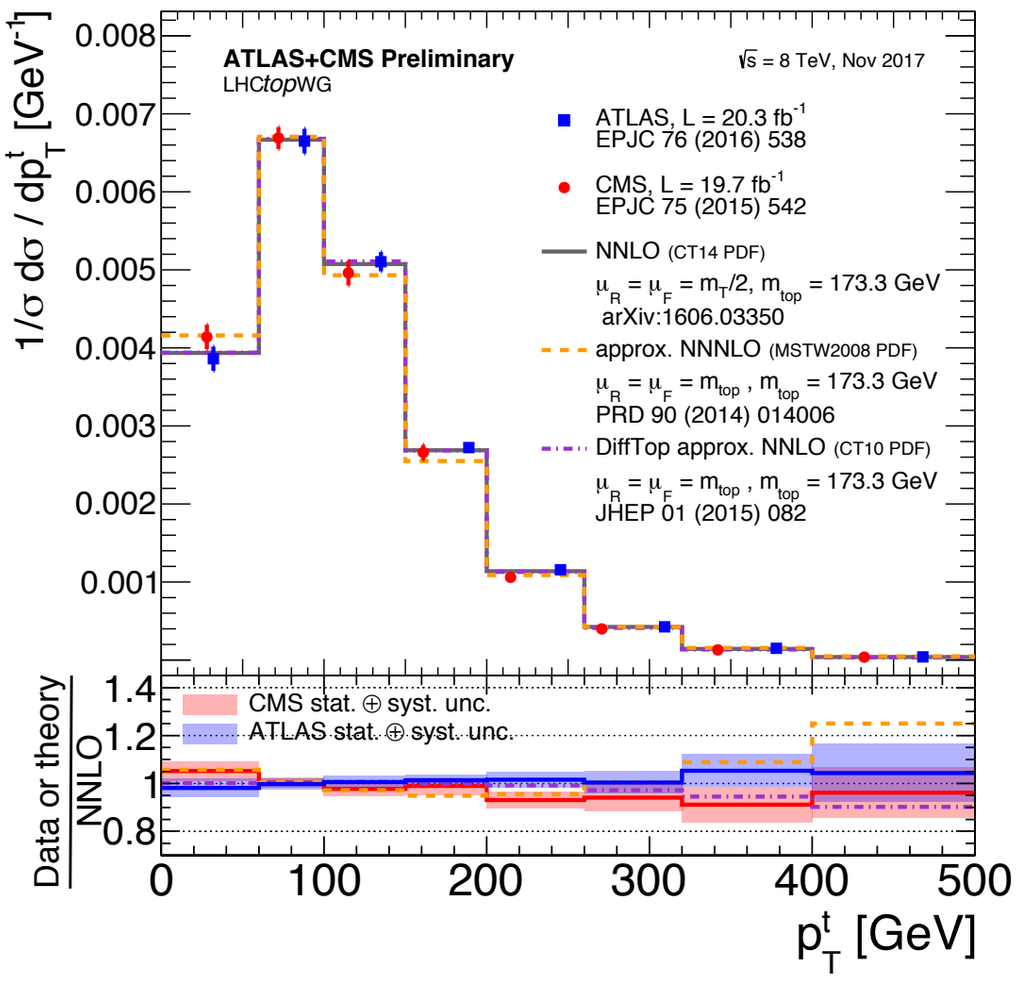
tt Cross Section - Inclusive

- Cross section varies with center-of-mass energy —> combine measurements at different energies to improve precision



$t\bar{t}$ Cross Section - Differential



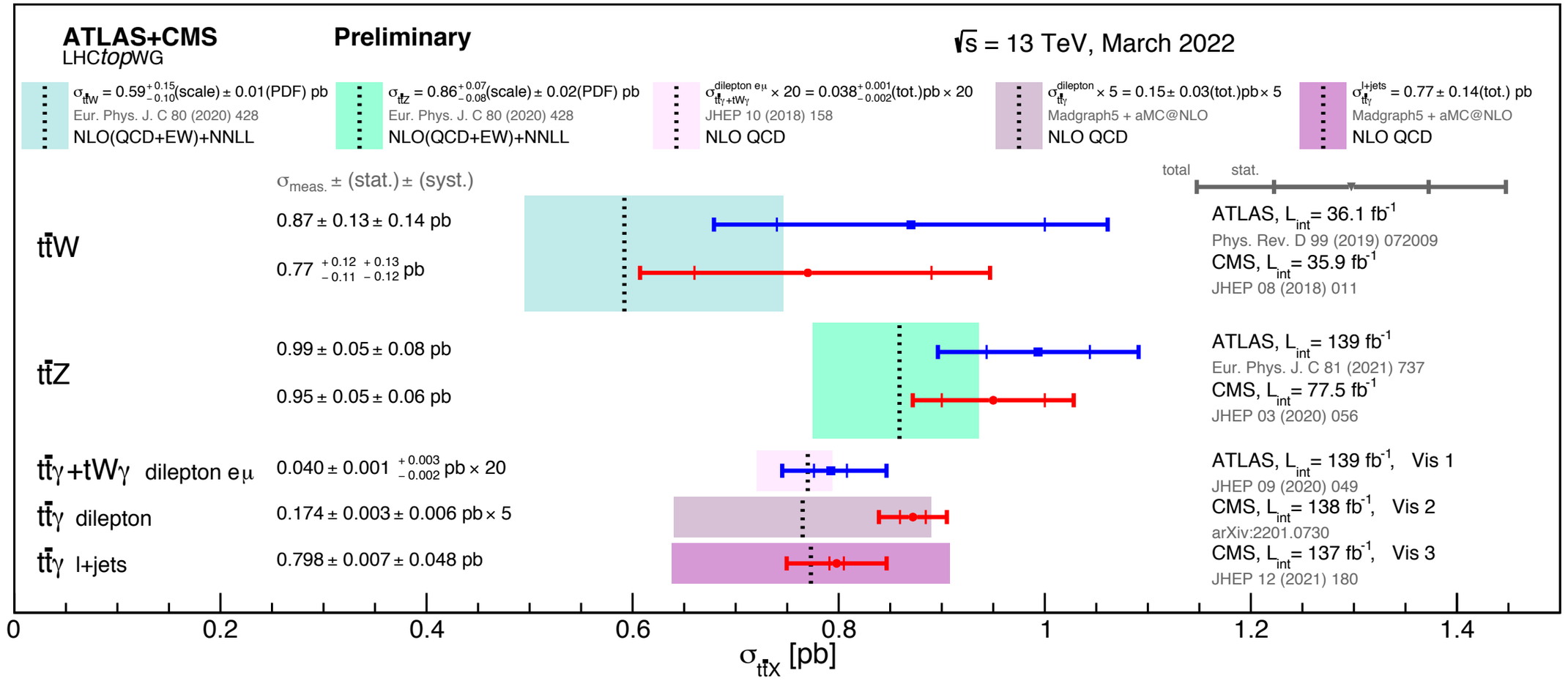


- Differential cross section = cross section as a function of kinematic variable (top pT, mass of ttbar pair, etc.)

- Differential cross section more sensitive to QCD effects (α_S), PDF

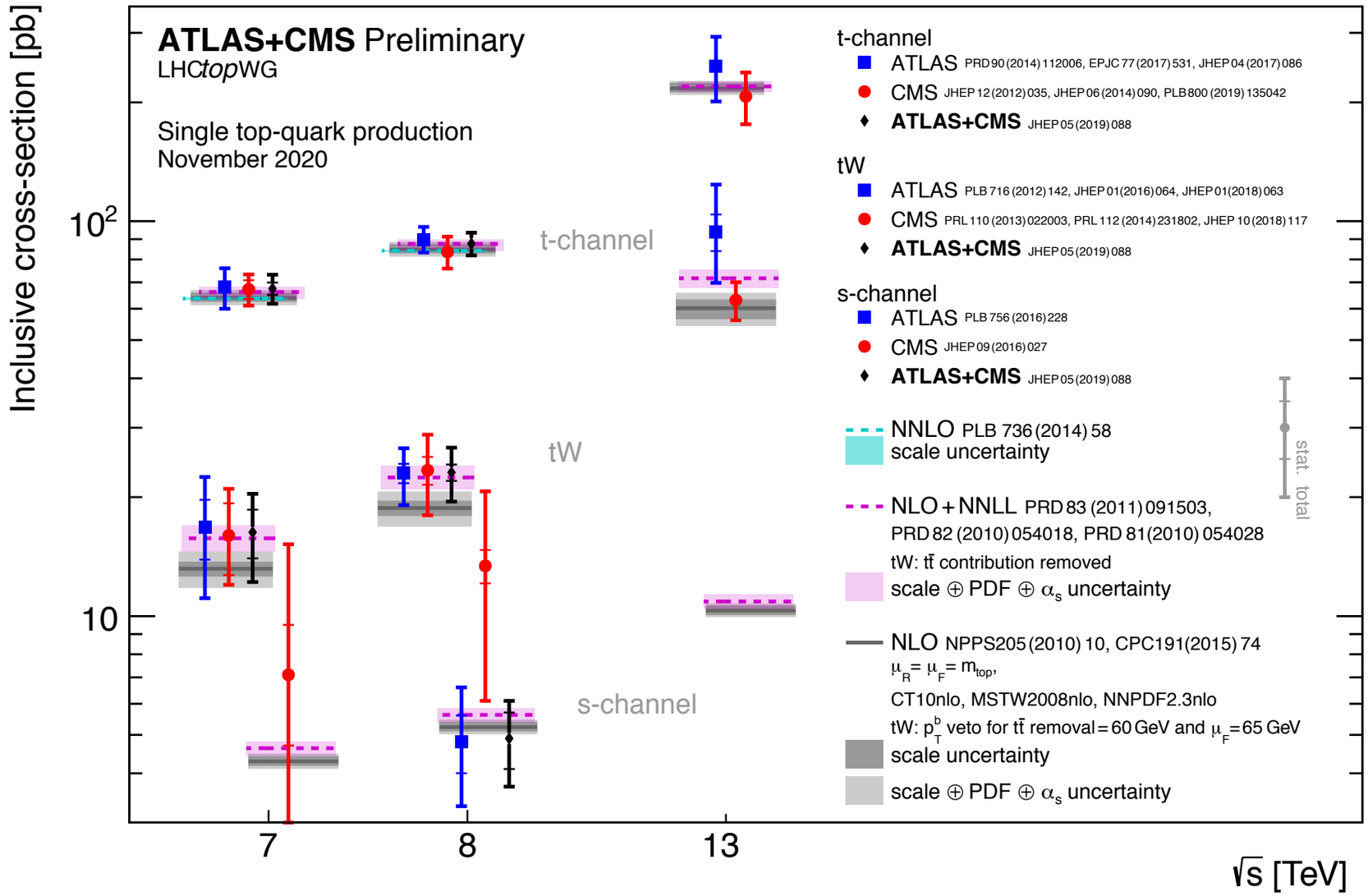
tt+X Cross Section

- Top quark pairs can also be produced in association with other bosons (W, Z, photon)
  - Cross section dependent on coupling between top quark and associated boson



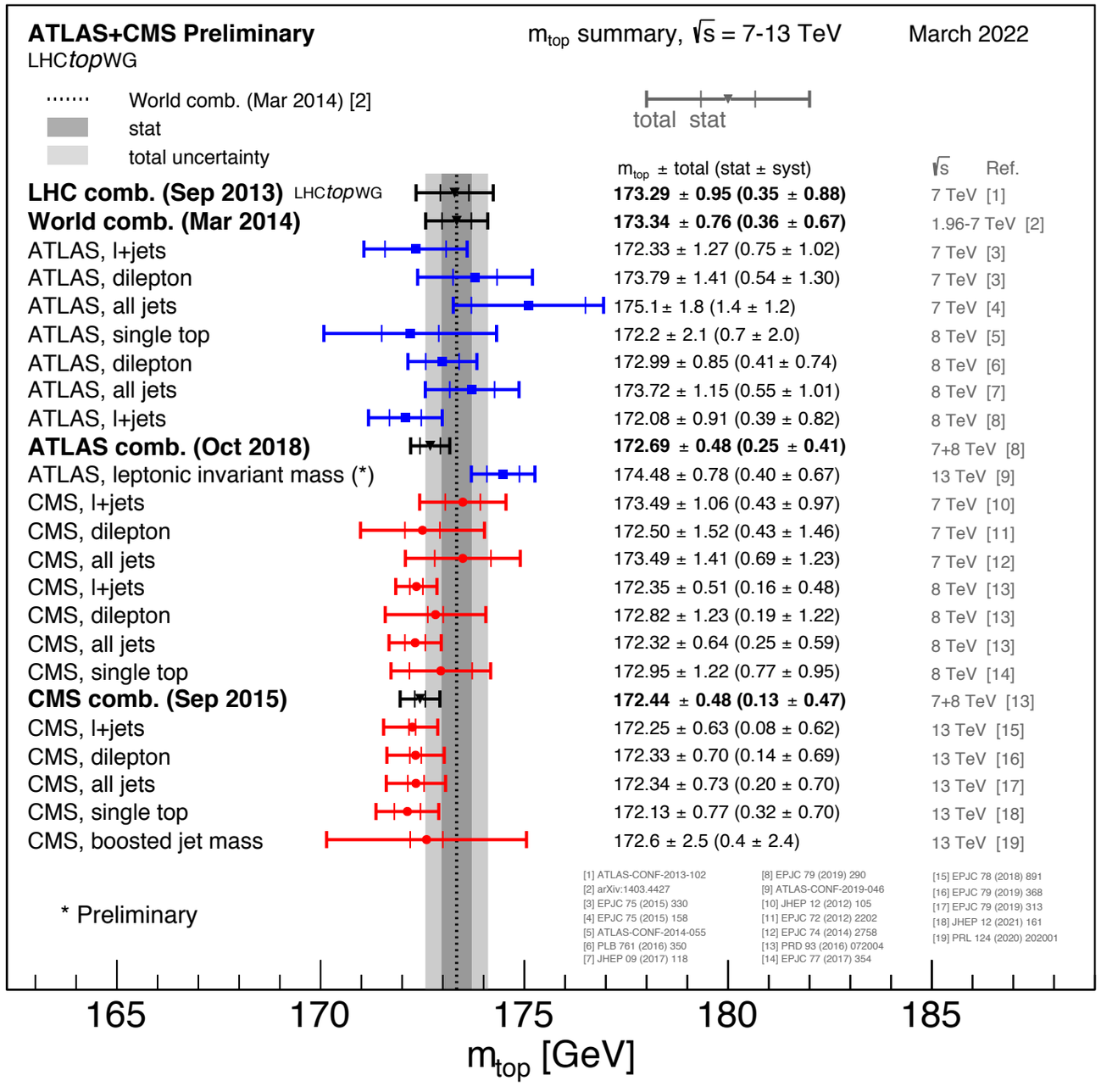
Single Top Cross Section

- Single top quark production is less common, but still measurable at the LHC



Top Quark Mass

- Top quark mass gives direct pope of Yuakawa coupling
  - Very sensitive to modifications fo EWSB
- Difficult to measure top quark mass directly
  - Leptonic W decay produces neutrino in final state —> missing information
  - Hadronic W decay yields many jets in final state —> difficult to correctly associate jets to tops



Top EFT

- Effective Field Theory gives ‘generic’ description of high-energy new physics at low energies
  - No new particles, just new interactions among existing particles
  - New interactions parametrized through new operators in SM Lagrangian
- Complete basis of SM EFT has 59 operators at lowest order
  - Difficult to explore these simultaneously — look for information from many different types of measurements
  - Top measurements give best performance in investigating operators modifying top couplings

ATLAS+CMS *Preliminary*

LHC*top*WG

March 2022

(Top) quark - vector boson operators - Individual limits

ATLAS CMS ATLAS+CMS

Following arXiv:1802.07237
Dimension 6 operators

$\tilde{C}_i \equiv C_i/\Lambda^2$ * Preliminary

$\tilde{C}_{tZ}$	CMS, tZq/t$\bar{t}$Z [1]	138 fb^{-1}
	CMS, t$\bar{t}\gamma$* [2]	137 fb^{-1}
	CMS, t$\bar{t}$Z [3]	78 fb^{-1}
	CMS, t$\bar{t}$+Z/W/H, tZq,tHq [4]	42 fb^{-1}
$\tilde{C}^{[I]}_{tZ}$	CMS, t$\bar{t}\gamma$* [2]	137 fb^{-1}
	CMS, t$\bar{t}$Z [3]	78 fb^{-1}
$\tilde{C}_{tB}$	ATLAS, t$\bar{t}$Z [5]	36 fb^{-1}
$\tilde{C}_{tW}$	ATLAS, Top polarization [6]	139 fb^{-1}
	ATLAS, t$\bar{t}$Z [5]	36 fb^{-1}
	ATLAS+CMS, W helicity [7]	20+20 fb^{-1}
	CMS, tZq/t$\bar{t}$Z [1]	138 fb^{-1}
	CMS, t$\bar{t}$ and tW, BSM search [8]	36 fb^{-1}
	CMS, t$\bar{t}$+Z/W/H, tZq,tHq [4]	42 fb^{-1}
$\tilde{C}^{[I]}_{tW}$	ATLAS, Top polarization [6]	139 fb^{-1}
$\tilde{C}_{bW}$	CMS, t$\bar{t}$+Z/W/H, tZq,tHq [4]	42 fb^{-1}
$\tilde{C}_{tG}$ / g_S	ATLAS, t$\bar{t}$ l+jets boosted [9]	139 fb^{-1}
$\tilde{C}_{tG}$	CMS, t$\bar{t}$ and tW, BSM search [8]	36 fb^{-1}
	CMS, t$\bar{t}$ spin correlations [10]	36 fb^{-1}
	CMS, t$\bar{t}$+Z/W/H, tZq,tHq [4]	42 fb^{-1}
$\tilde{C}^{[I]}_{tG}$	CMS, t$\bar{t}$ spin correlations [10]	36 fb^{-1}
$\lvert\tilde{C}^{(32)}_{uW}+\tilde{C}^{(32)}_{uB}\rvert$	ATLAS, FCNC tqγ* [11]	139 fb^{-1}
$\lvert\tilde{C}^{(23)*}_{uW}+\tilde{C}^{(23)*}_{uB}\rvert$	ATLAS, FCNC tqγ* [11]	139 fb^{-1}
$\lvert\tilde{C}^{(31)}_{uW}+\tilde{C}^{(31)}_{uB}\rvert$	ATLAS, FCNC tqγ* [11]	139 fb^{-1}
$\lvert\tilde{C}^{(13)*}_{uW}+\tilde{C}^{(13)*}_{uB}\rvert$	ATLAS, FCNC tqγ* [11]	139 fb^{-1}
$\lvert\tilde{C}^{32}_{uW}\rvert$	ATLAS, FCNC tZq [12]	139 fb^{-1}
$\lvert\tilde{C}^{32}_{uB}\rvert$	ATLAS, FCNC tZq [12]	139 fb^{-1}
$\lvert\tilde{C}^{23}_{uW}*\rvert$	ATLAS, FCNC tZq [12]	139 fb^{-1}
$\lvert\tilde{C}^{23}_{uB}*\rvert$	ATLAS, FCNC tZq [12]	139 fb^{-1}
$\lvert\tilde{C}^{31}_{uW}\rvert$	ATLAS, FCNC tZq [12]	139 fb^{-1}
$\lvert\tilde{C}^{31}_{uB}\rvert$	ATLAS, FCNC tZq [12]	139 fb^{-1}
$\lvert\tilde{C}^{13}_{uW}*\rvert$	ATLAS, FCNC tZq [12]	139 fb^{-1}
$\lvert\tilde{C}^{13}_{uB}*\rvert$	ATLAS, FCNC tZq [12]	139 fb^{-1}
$\lvert\tilde{C}_{uG}\rvert$	ATLAS, FCNC tqg [13]	139 fb^{-1}
	CMS, t$\bar{t}$ and tW, BSM search [8]	36 fb^{-1}
$\lvert\tilde{C}_{cG}\rvert$	ATLAS, FCNC tqg [13]	139 fb^{-1}
	CMS, t$\bar{t}$ and tW, BSM search [8]	36 fb^{-1}

[1] JHEP 12 (2021) 083
[2] arXiv:2201.07301
[3] JHEP 03 (2020) 056
[4] JHEP 03 (2021) 095
[5] PRD 99 (2019) 072009
[6] arXiv:2202.11382
[7] JHEP 08 (2020) 051
[8] EPJC 79 (2019) 886
[9] arXiv:2202.12134
[10] PRD 100 (2019) 072002
[11] ATLAS-CONF-2022-003
[12] ATLAS-CONF-2021-049 *
[13] arXiv:2112.01302

EFT formalism is employed at different levels of experimental analyses

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95% CL limit [TeV^{-2}]

ATLAS+CMS *Preliminary*

LHC*top*WG

March 2022

Four-fermion operators - Individual limits

ATLAS CMS ATLAS+CMS

Following arXiv:1802.07237
Dimension 6 operators

$\tilde{C}_i \equiv C_i/\Lambda^2$ * Preliminary

$\tilde{C}^1_{tt}$	CMS, 4 top quarks [1]	36 fb^{-1}
$\tilde{C}^1_{Qt}$	CMS, 4 top quarks [1]	36 fb^{-1}
$\tilde{C}^1_{QQ}$	CMS, 4 top quarks [1]	36 fb^{-1}
$\tilde{C}^8_{Qt}$	CMS, 4 top quarks [1]	36 fb^{-1}
$\tilde{C}^{3(l)}_{Ql}$	CMS, t$\bar{t}$+Z/W/H, tZq,tHq [2]	42 fb^{-1}
$\tilde{C}^{-(l)}_{Ql}$	CMS, t$\bar{t}$+Z/W/H, tZq,tHq [2]	42 fb^{-1}
$\tilde{C}^{(l)}_{Qe}$	CMS, t$\bar{t}$+Z/W/H, tZq,tHq [2]	42 fb^{-1}
$\tilde{C}^{(l)}_{tl}$	CMS, t$\bar{t}$+Z/W/H, tZq,tHq [2]	42 fb^{-1}
$\tilde{C}^{(l)}_{te}$	CMS, t$\bar{t}$+Z/W/H, tZq,tHq [2]	42 fb^{-1}
$\tilde{C}^{S(l)}_{t}$	CMS, t$\bar{t}$+Z/W/H, tZq,tHq [2]	42 fb^{-1}
$\tilde{C}^{T(l)}_{t}$	CMS, t$\bar{t}$+Z/W/H, tZq,tHq [2]	42 fb^{-1}
$\tilde{C}^{11}_{Qq}$	ATLAS, t$\bar{t}$ energy asymmetry [3]	139 fb^{-1}
$\tilde{C}^{18}_{Qq}$	ATLAS, t$\bar{t}$ all-hadronic boosted* [4]	139 fb^{-1}
	ATLAS, t$\bar{t}$ energy asymmetry [3]	139 fb^{-1}
$\tilde{C}^1_{tq}$	ATLAS, t$\bar{t}$ energy asymmetry [3]	139 fb^{-1}
$\tilde{C}^8_{tq}$	ATLAS, t$\bar{t}$ l+jets boosted [5]	139 fb^{-1}
	ATLAS, t$\bar{t}$ all-hadronic boosted* [4]	139 fb^{-1}
	ATLAS, t$\bar{t}$ energy asymmetry [3]	139 fb^{-1}
$\tilde{C}^1_{tu}$	ATLAS, t$\bar{t}$ energy asymmetry [3]	139 fb^{-1}
$\tilde{C}^8_{tu}$	ATLAS, t$\bar{t}$ all-hadronic boosted* [4]	139 fb^{-1}
	ATLAS, t$\bar{t}$ energy asymmetry [3]	139 fb^{-1}
$\tilde{C}^8_{td}$	ATLAS, t$\bar{t}$ all-hadronic boosted* [4]	139 fb^{-1}
$\tilde{C}^8_{Qd}$	ATLAS, t$\bar{t}$ all-hadronic boosted* [4]	139 fb^{-1}
$\tilde{C}^8_{Qu}$	ATLAS, t$\bar{t}$ all-hadronic boosted* [4]	139 fb^{-1}
$\tilde{C}^{38}_{Qq}$	ATLAS, t$\bar{t}$ all-hadronic boosted* [4]	139 fb^{-1}

[1] JHEP 11 (2019) 082
[2] JHEP 03 (2021) 095
[3] arXiv:2110.05453
[4] ATLAS-CONF-2021-050 *
[5] arXiv:2202.12134

EFT formalism is employed at different levels of experimental analyses

−10 −5 0 5 10

95% CL limit [TeV^{-2}]

Summary

- Many interesting measurements of top quark since discovery in 1995

- LHC is top quark factory — opportunity to perform precision measurements of cross sections, properties

- New physics likely to couple strongly to top —> top measurements give interesting probe to new physics

- Interesting to see where the future takes us!