Where no one has gone before - First LHC measurements at 13 TeV

Alexander Grohsjean

Université Catholique de Louvain

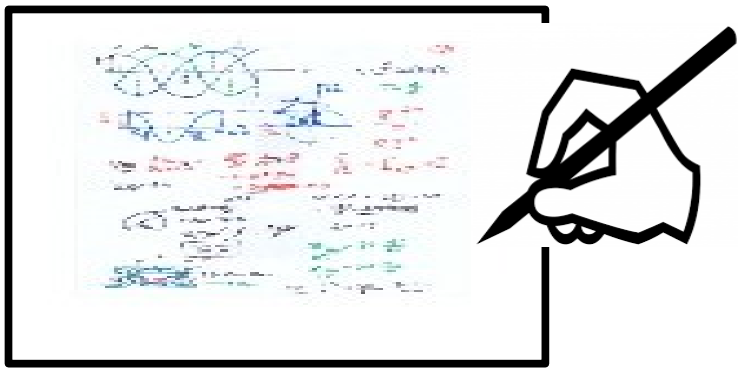
February 3rd, 2016



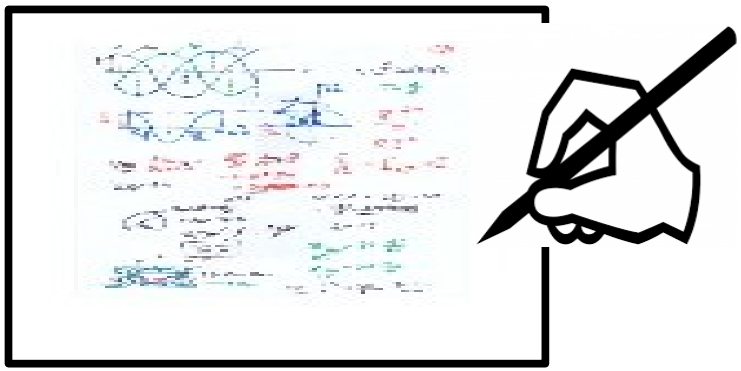


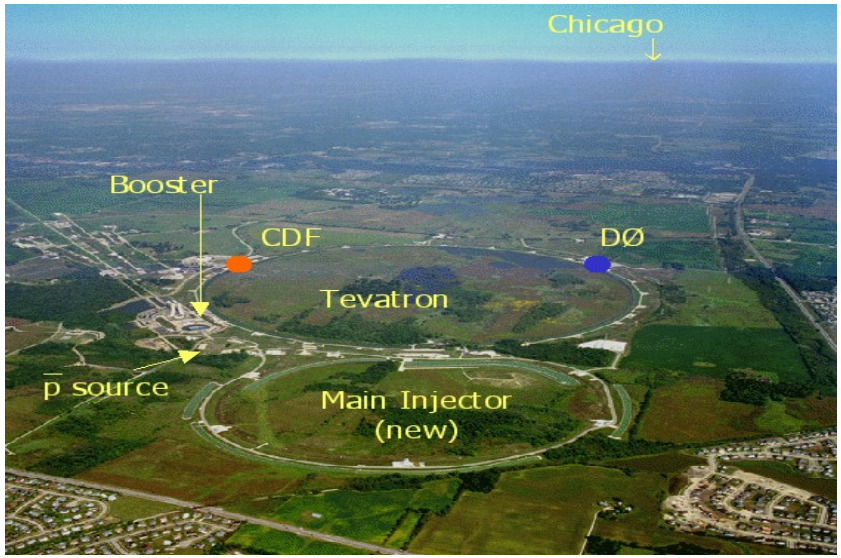
HELMHOLTZ GEMEINSCHAFT

20 Years Ago

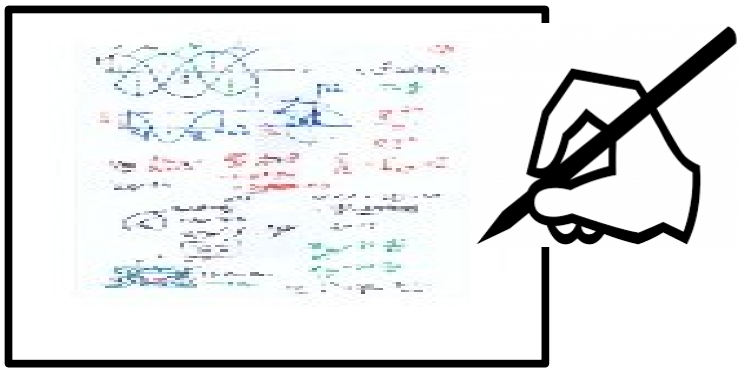


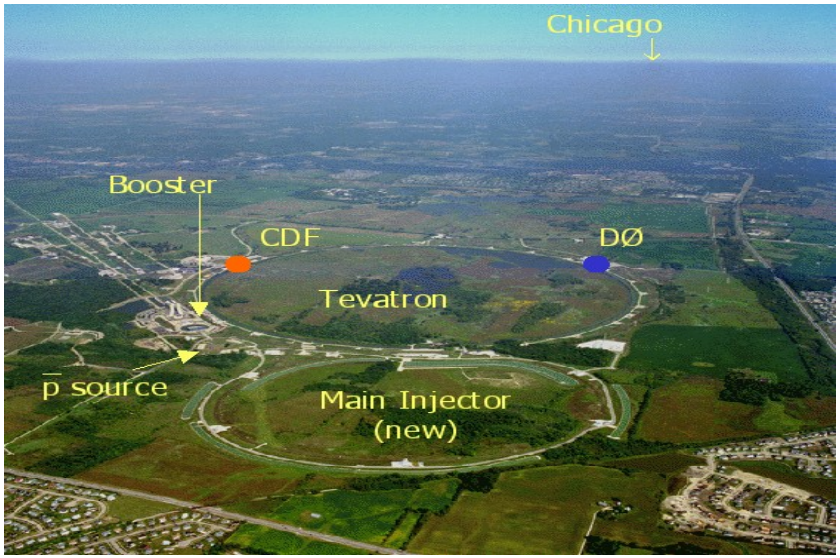
20 Years Ago

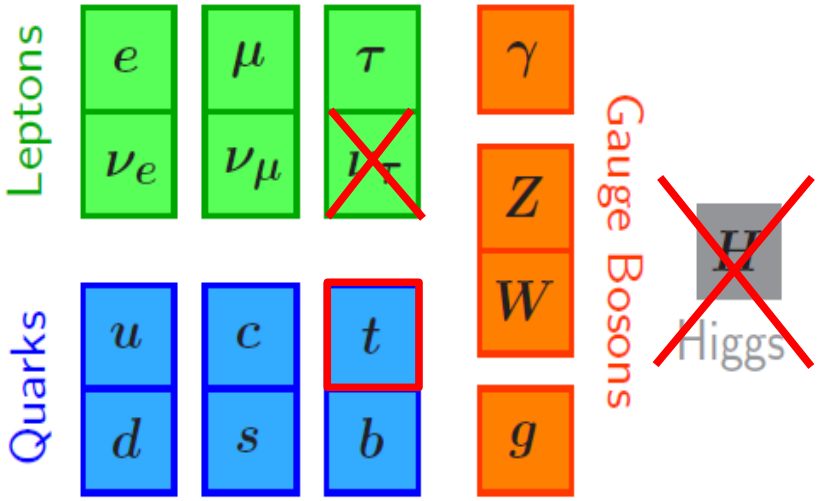




20 Years Ago




Chicago
Booster
CDF
DØ
Tevatron
p source
Main Injector
(new)

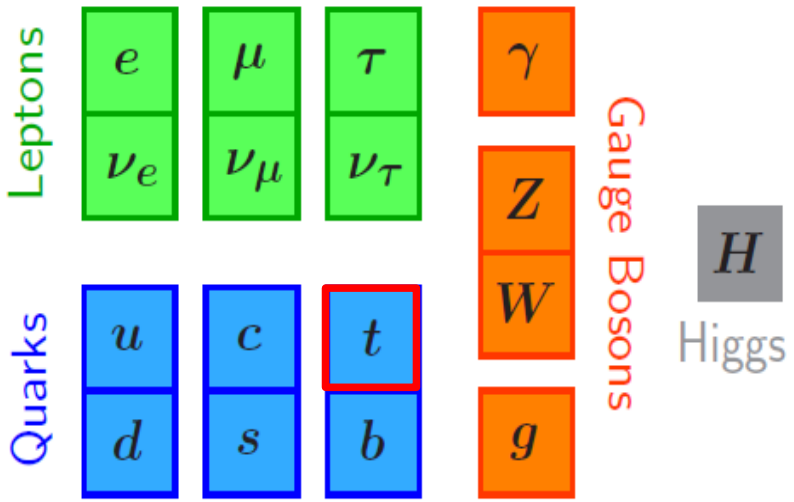

Leptons
e
μ
τ
νe
νμ
ντ
Quarks
u
c
t
d
s
b
γ
Z
W
g
Gauge Bosons
H
Higgs

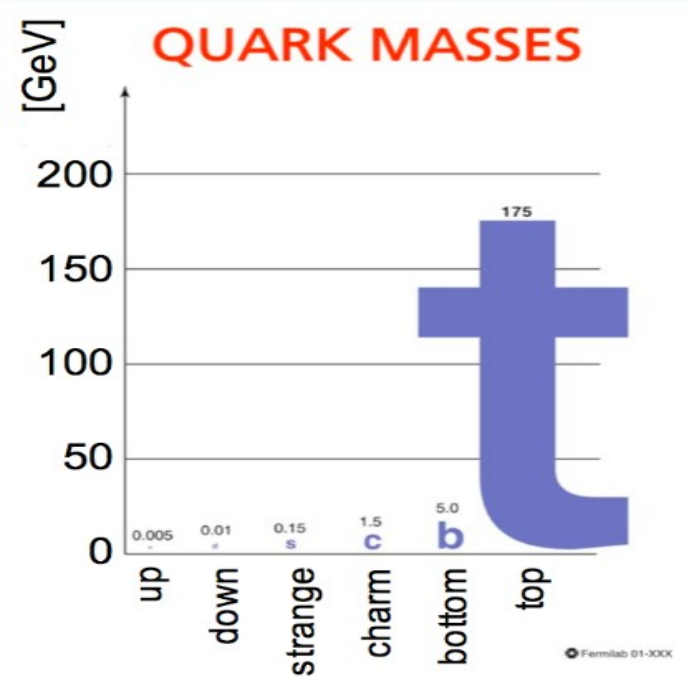
The Top Quark

- short lifetime of $0.5 \cdot 10^{-24}$ s
  → top quarks decay before hadronization
  → observation of a “bare” quark

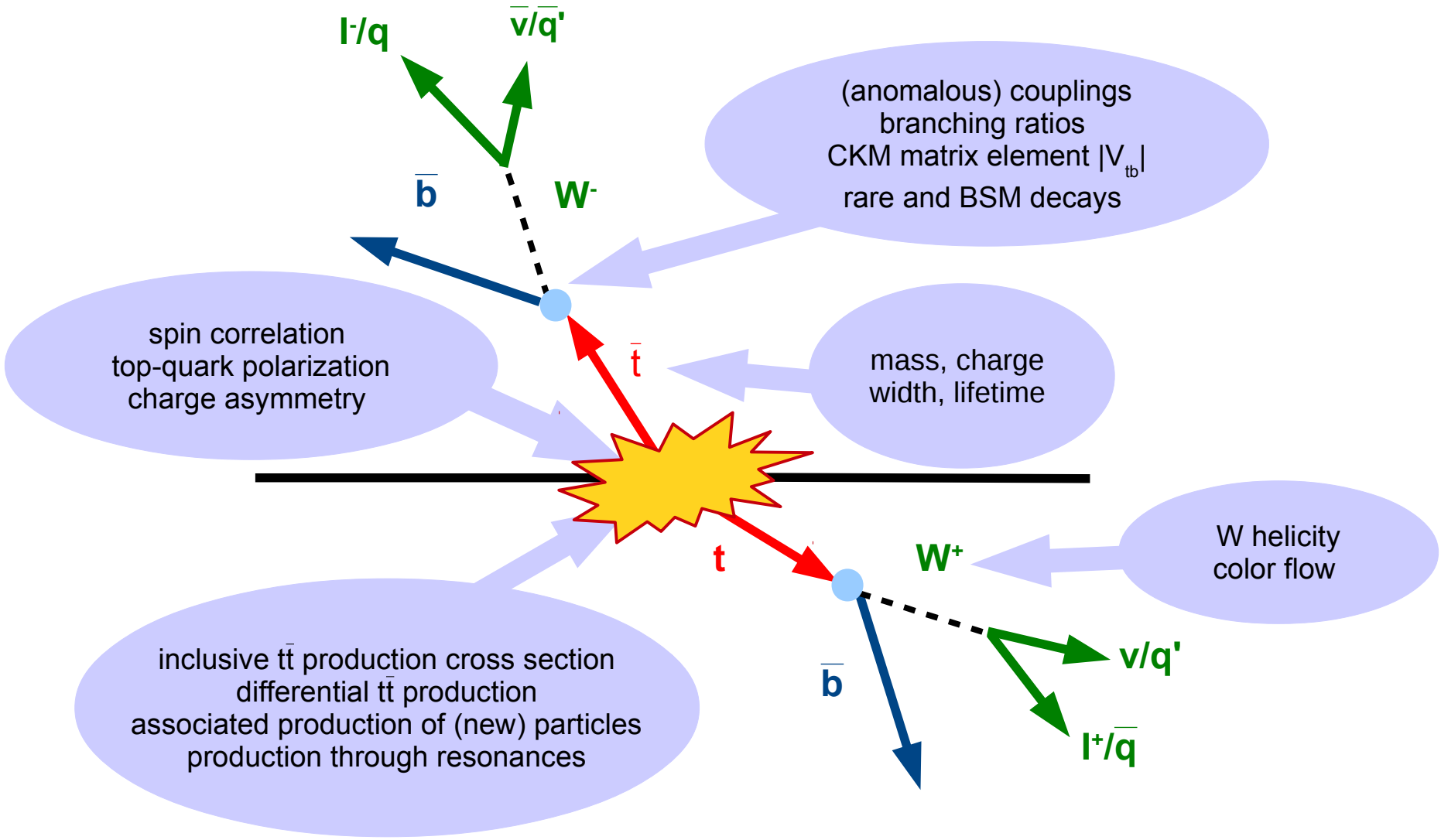
- heaviest SM particle: ~173 GeV

- strongest coupling (~1) to the Higgs field
  → a special role beyond the SM ?

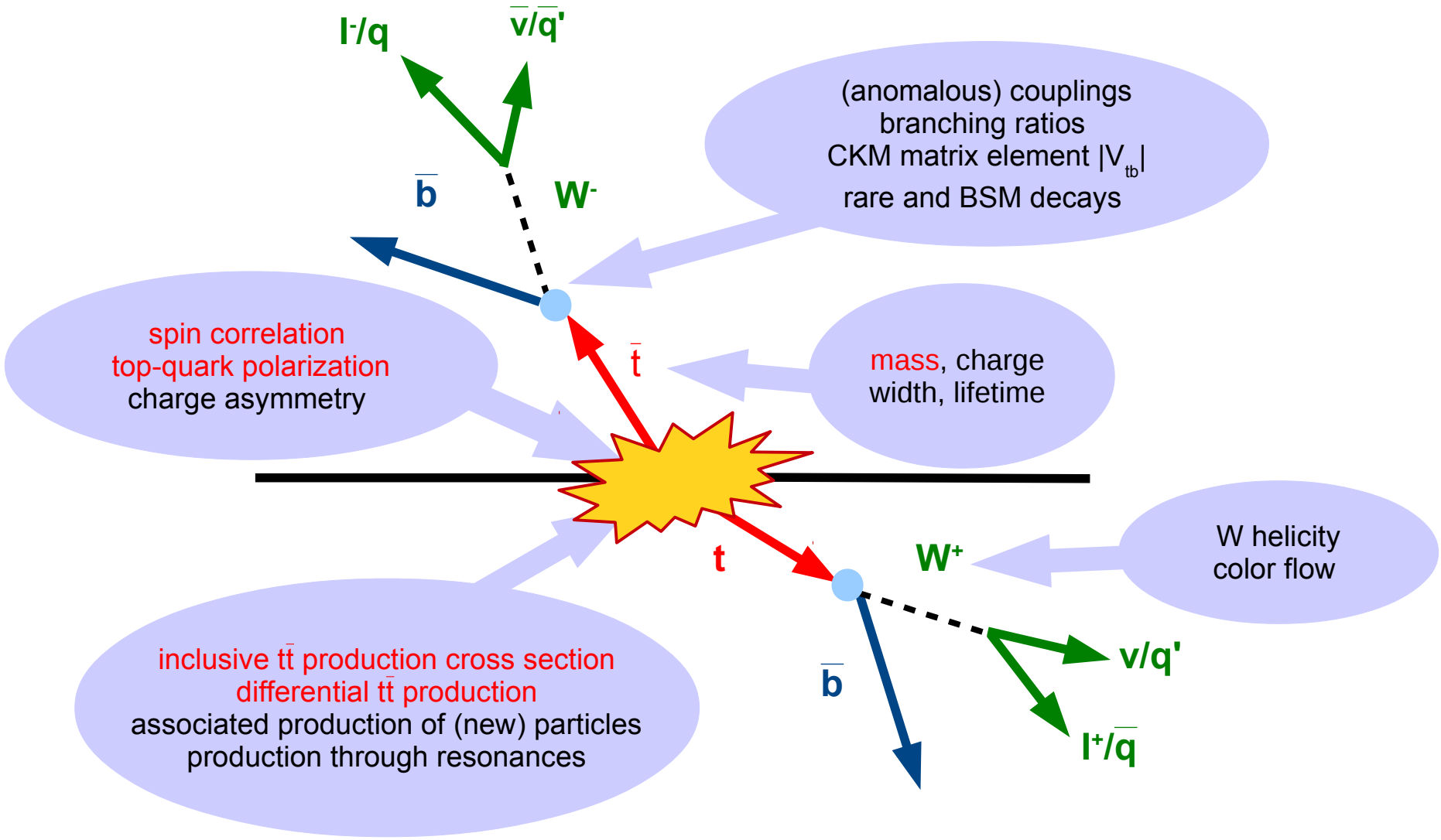




Top Quark Physics



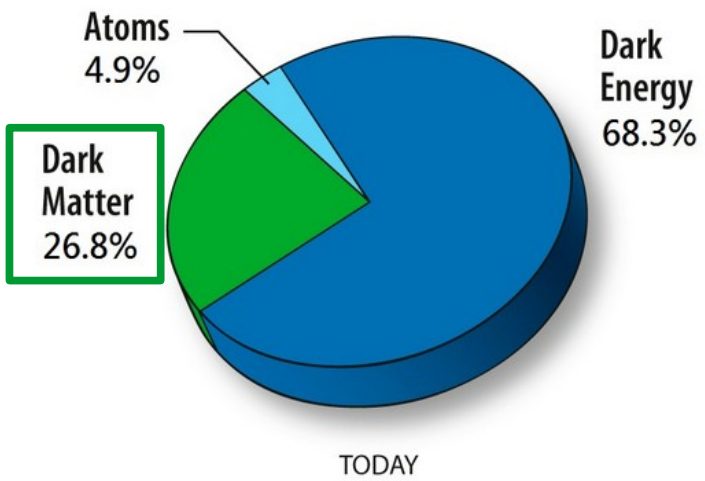
Top Quark Physics



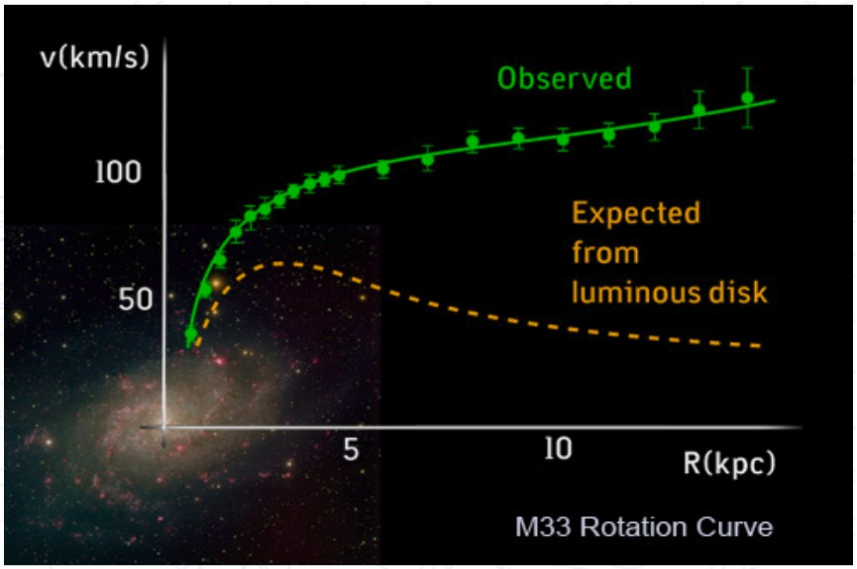
precision measurements → discovery of new physics in the top sector at 13 TeV ?

Extension of the Standard Model

- open question, e.g.:
  - no candidate for dark matter



learner.org/courses/physics/index.html

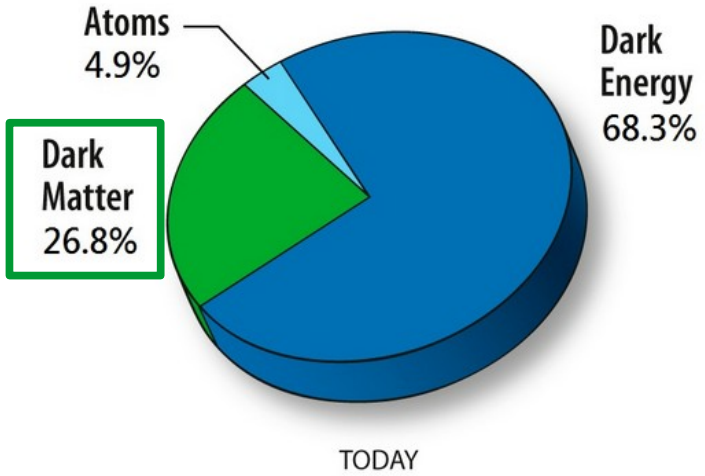


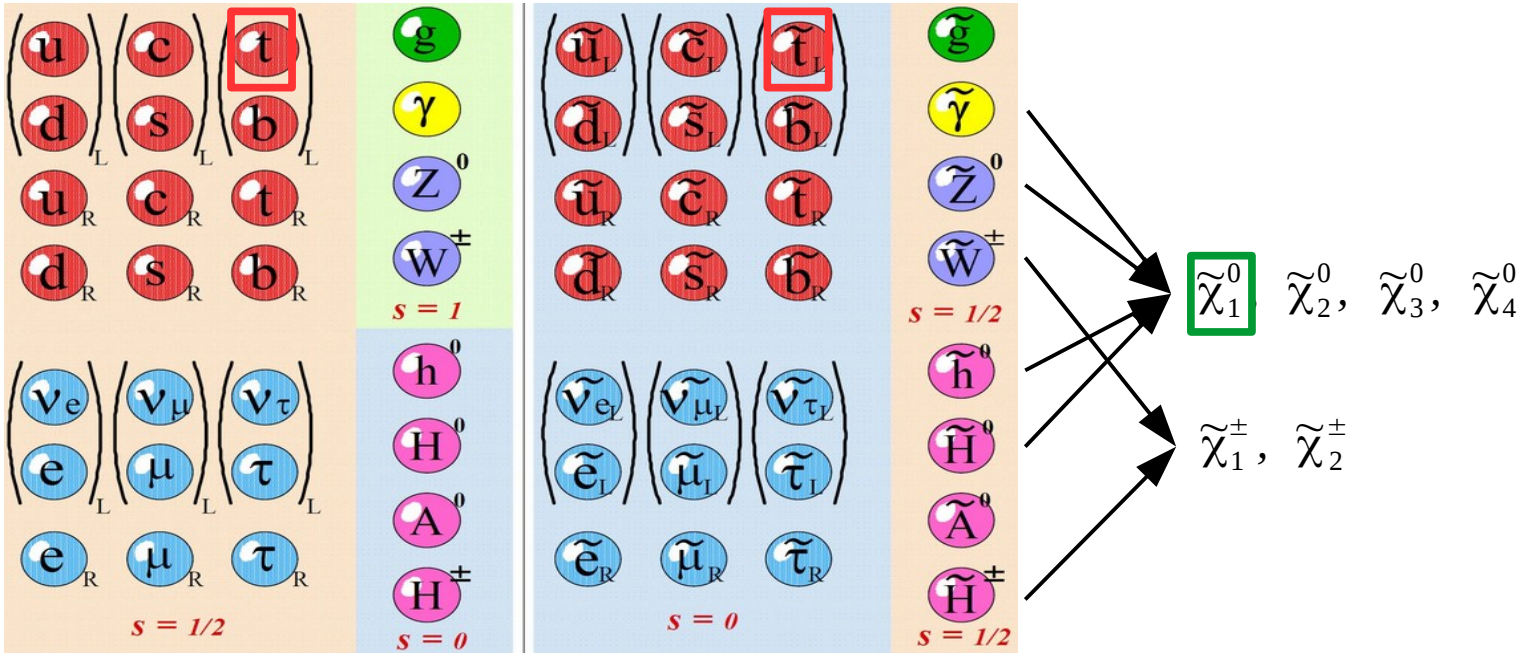
1970^{s} : velocity of hydrogen gas near Andromeda galaxy

Extension of the Standard Model

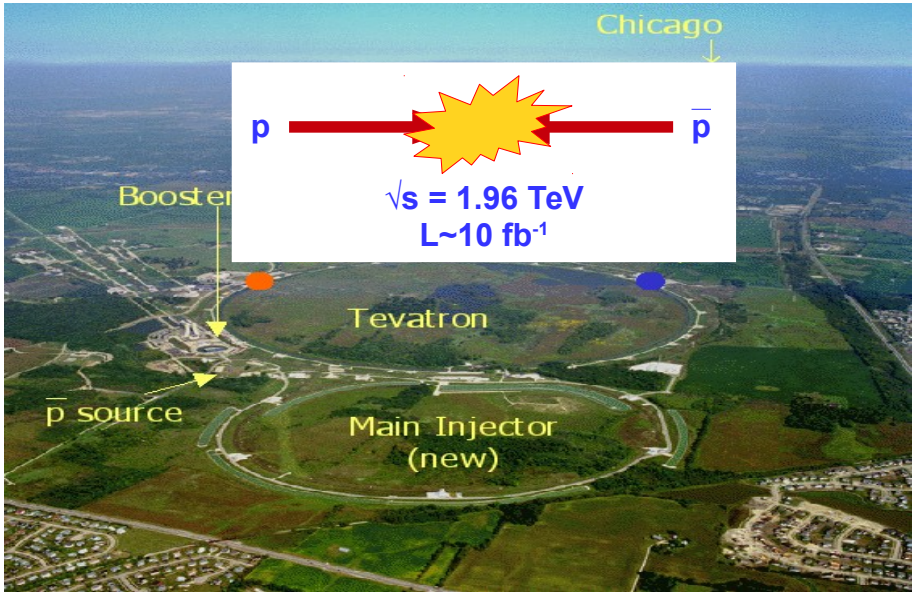
- open question, e.g.:
  - no candidate for dark matter

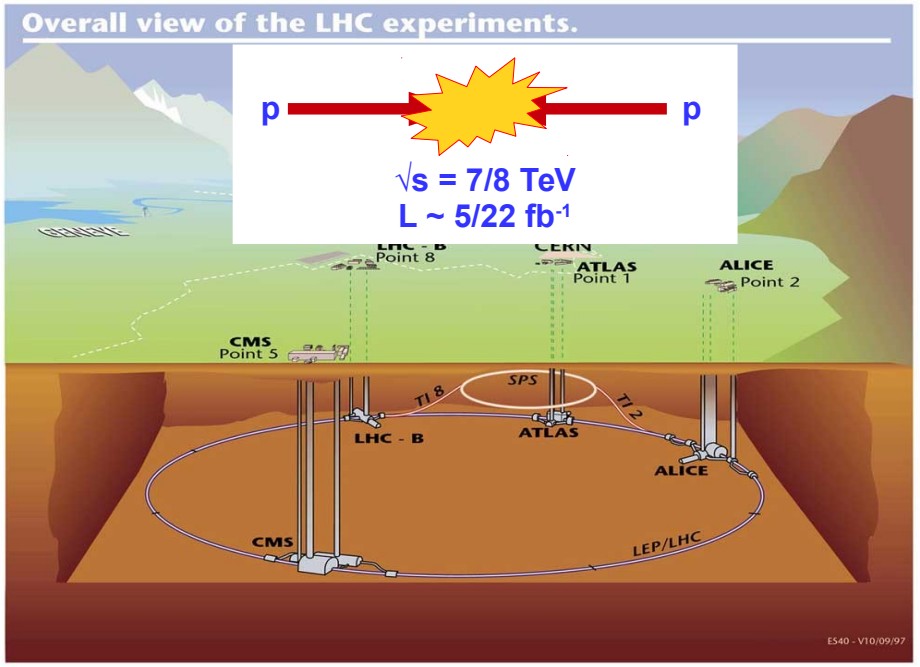
- possible solutions:
  e.g. Supersymmetry (MSSM)
  - extension of the SM by super partners with Spin (SM-½)



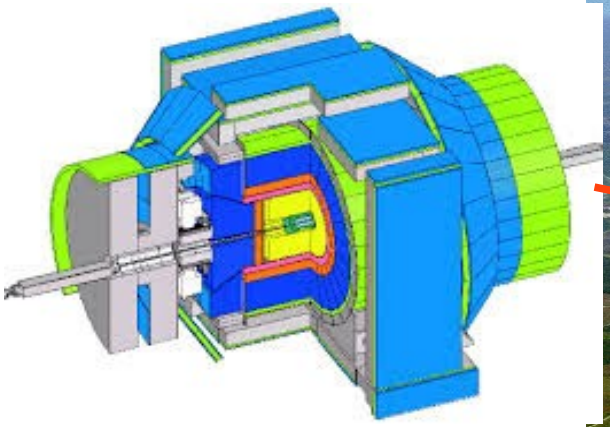


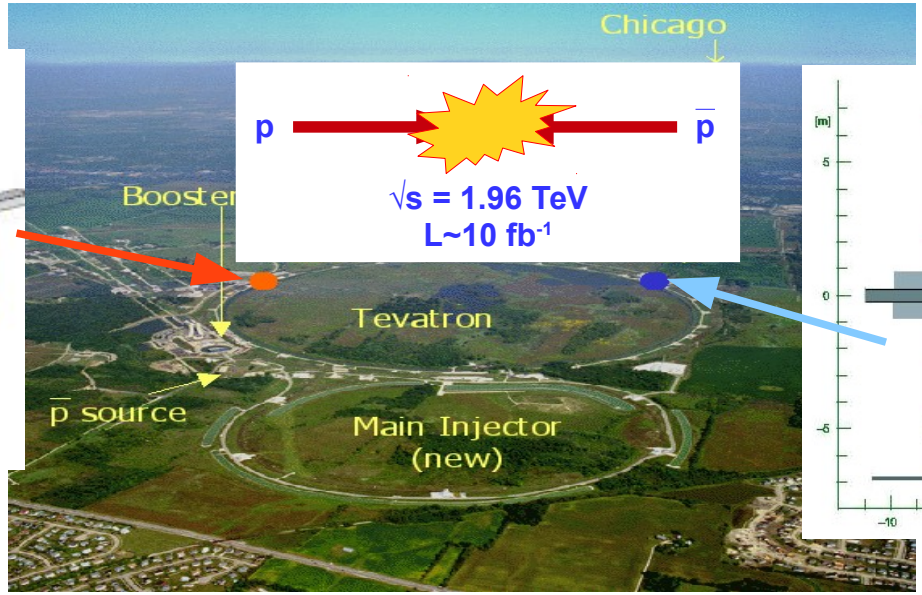
From Tevatron to LHC

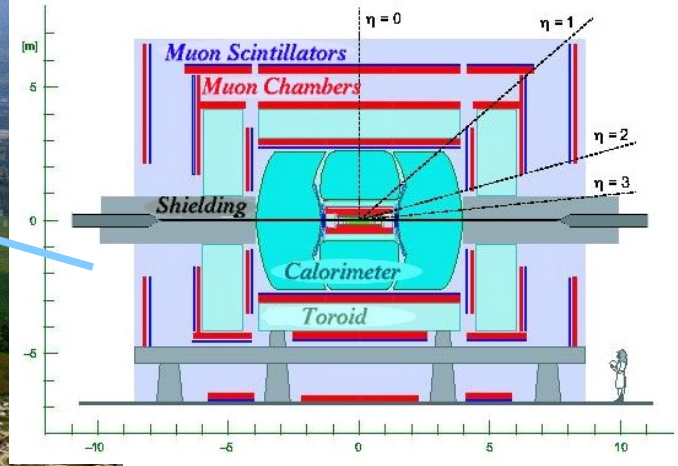


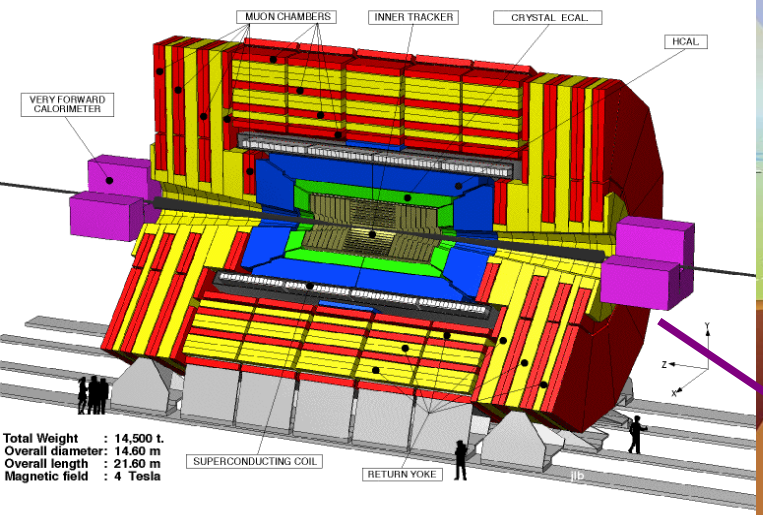


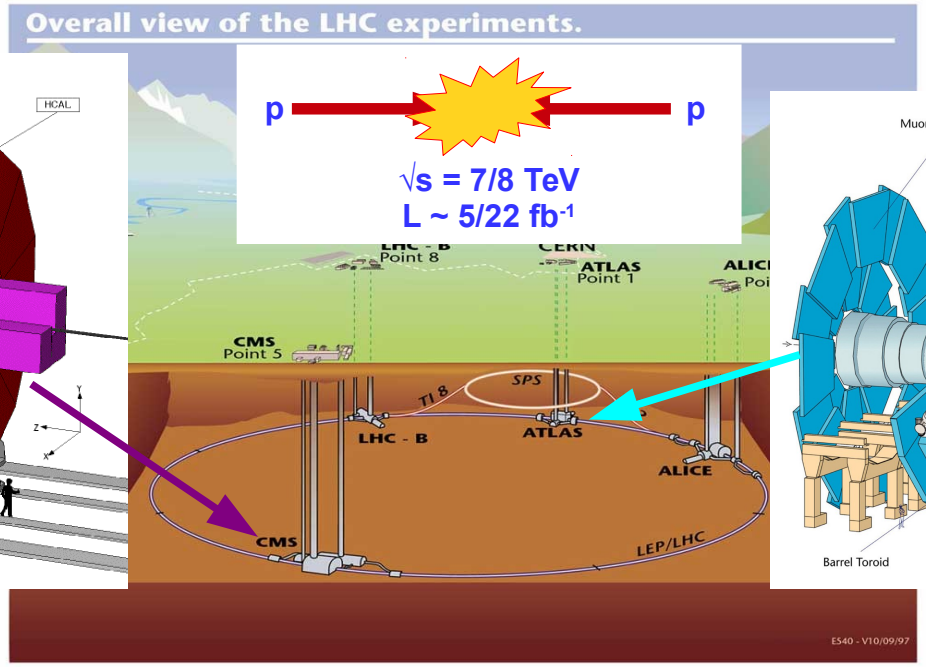
From Tevatron to LHC

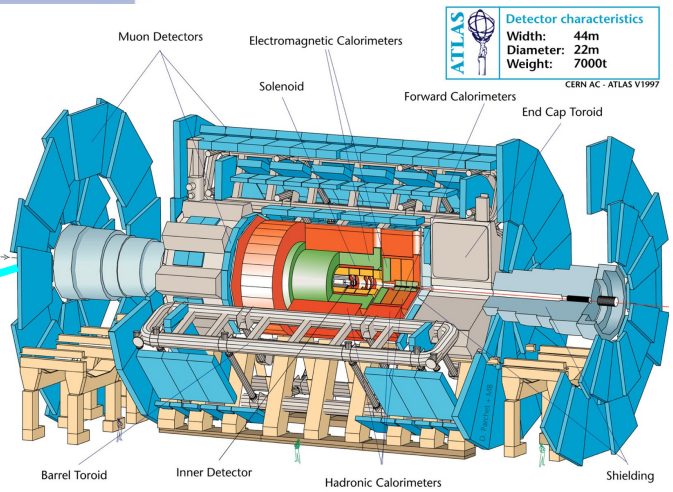




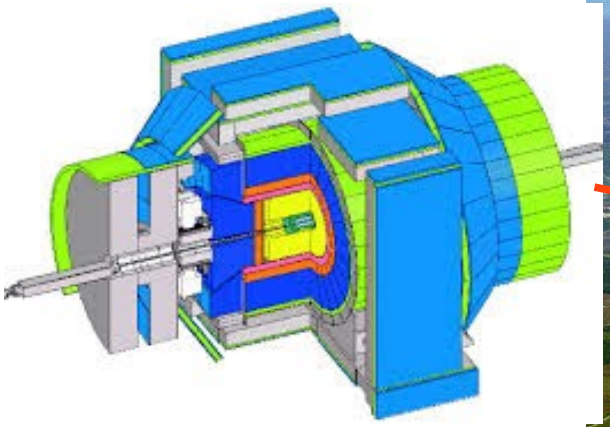


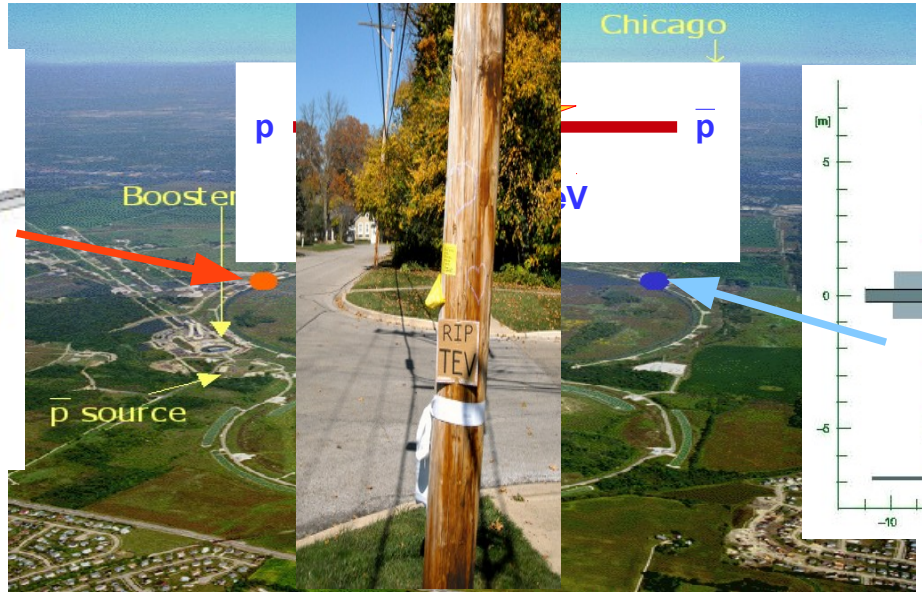


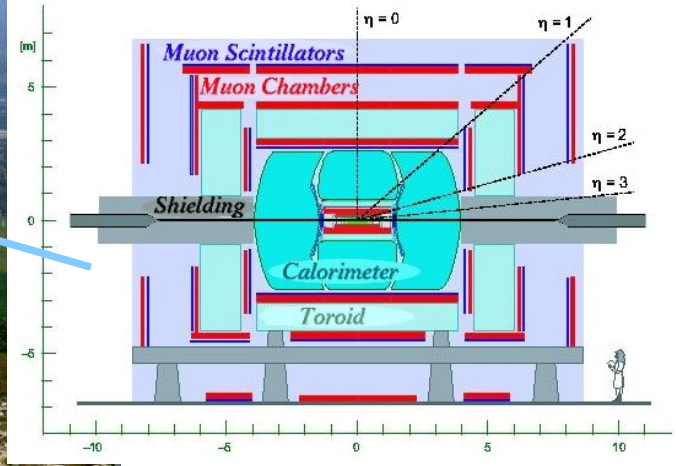


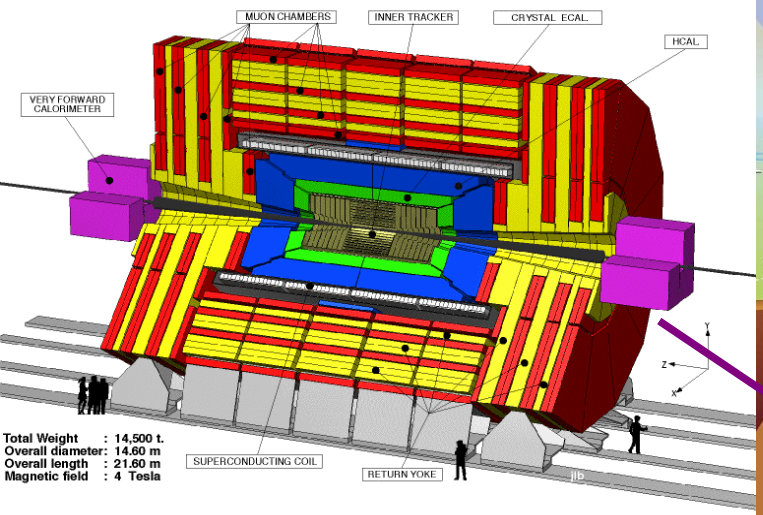


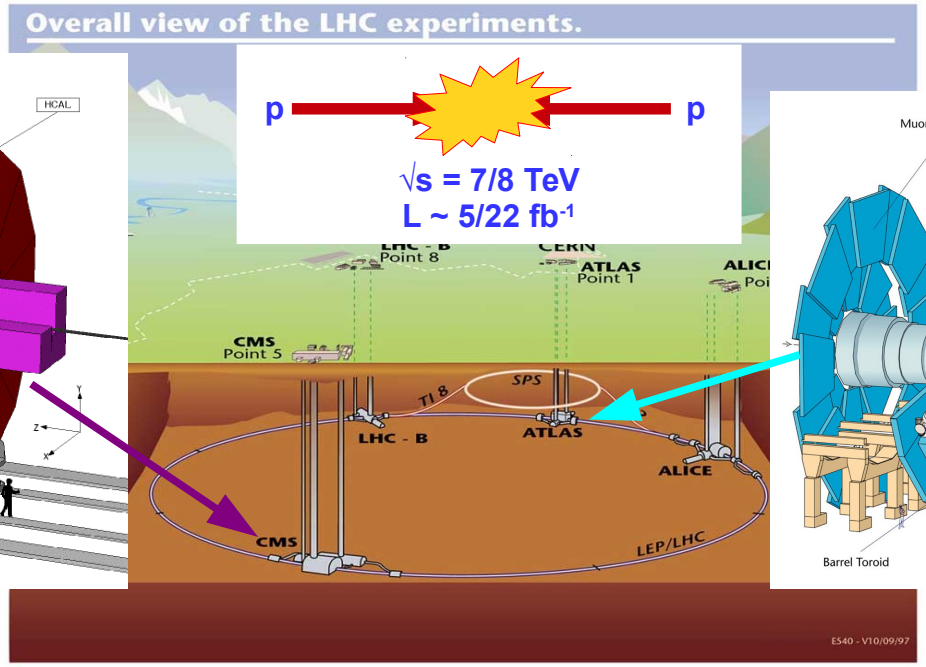
From Tevatron to LHC

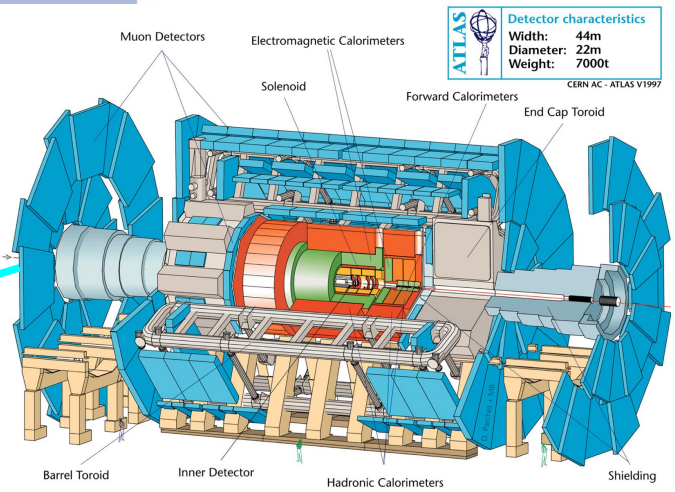




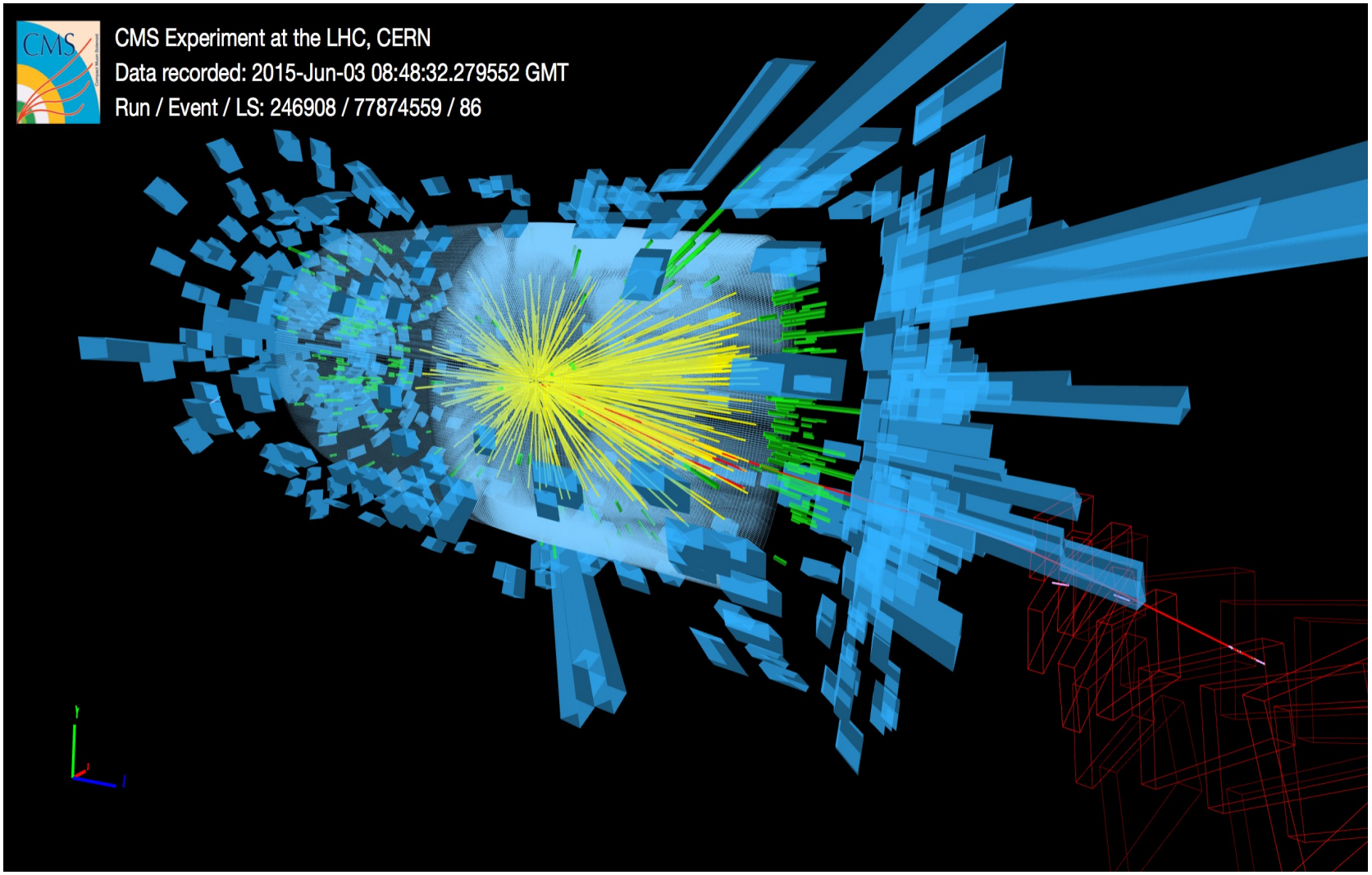




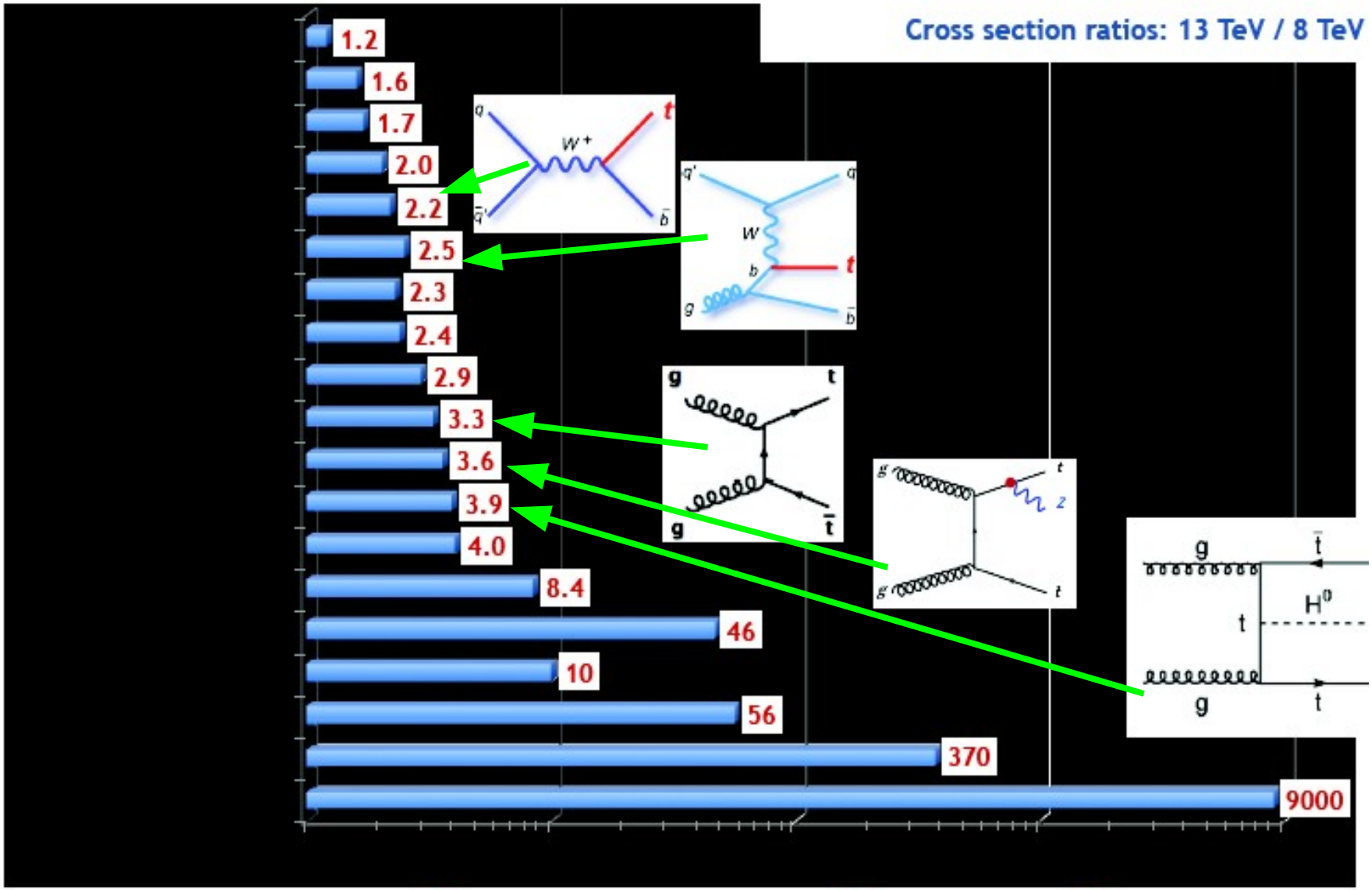




June 3rd, 2015: First collisions at 13 TeV

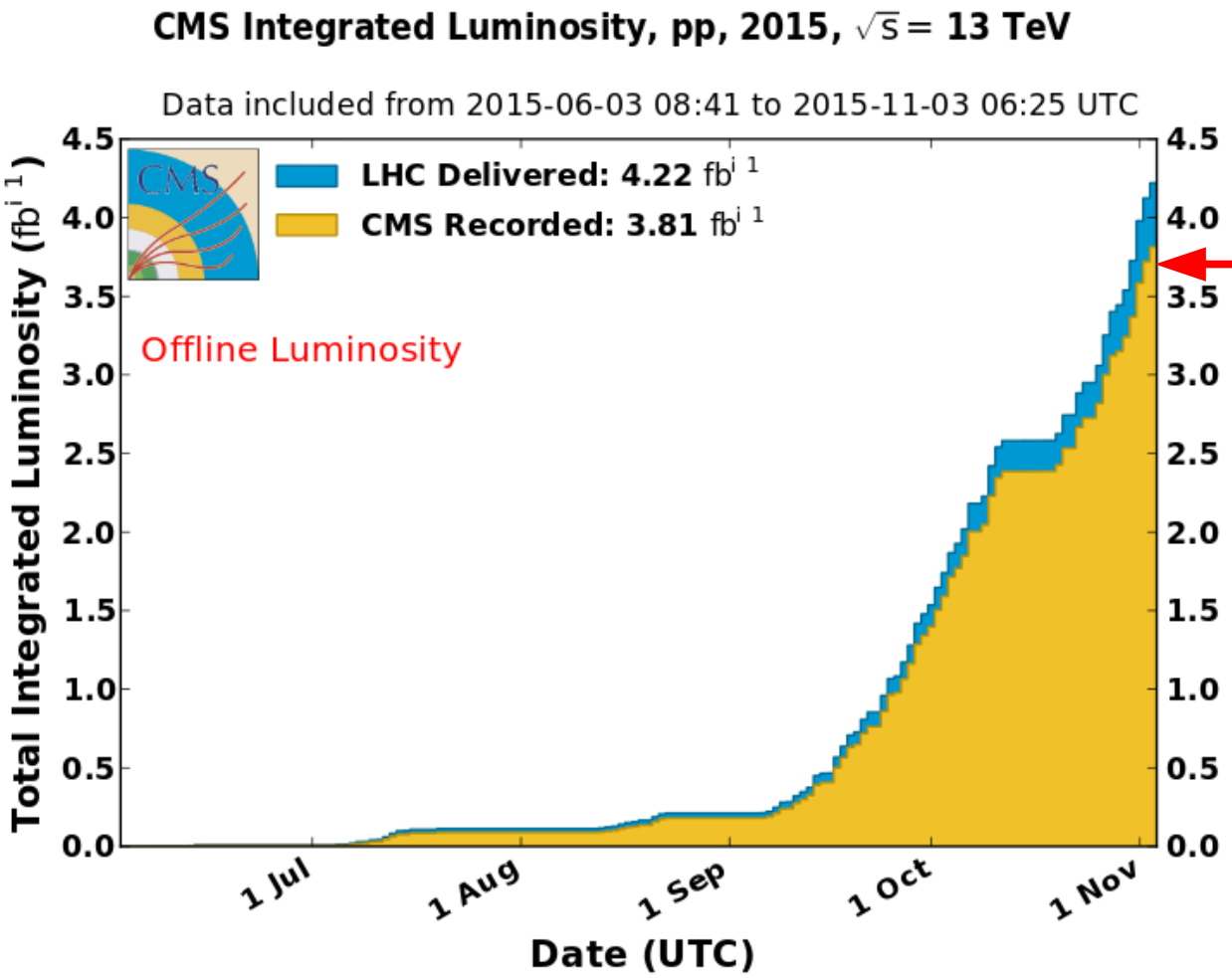


13TeV Prospects



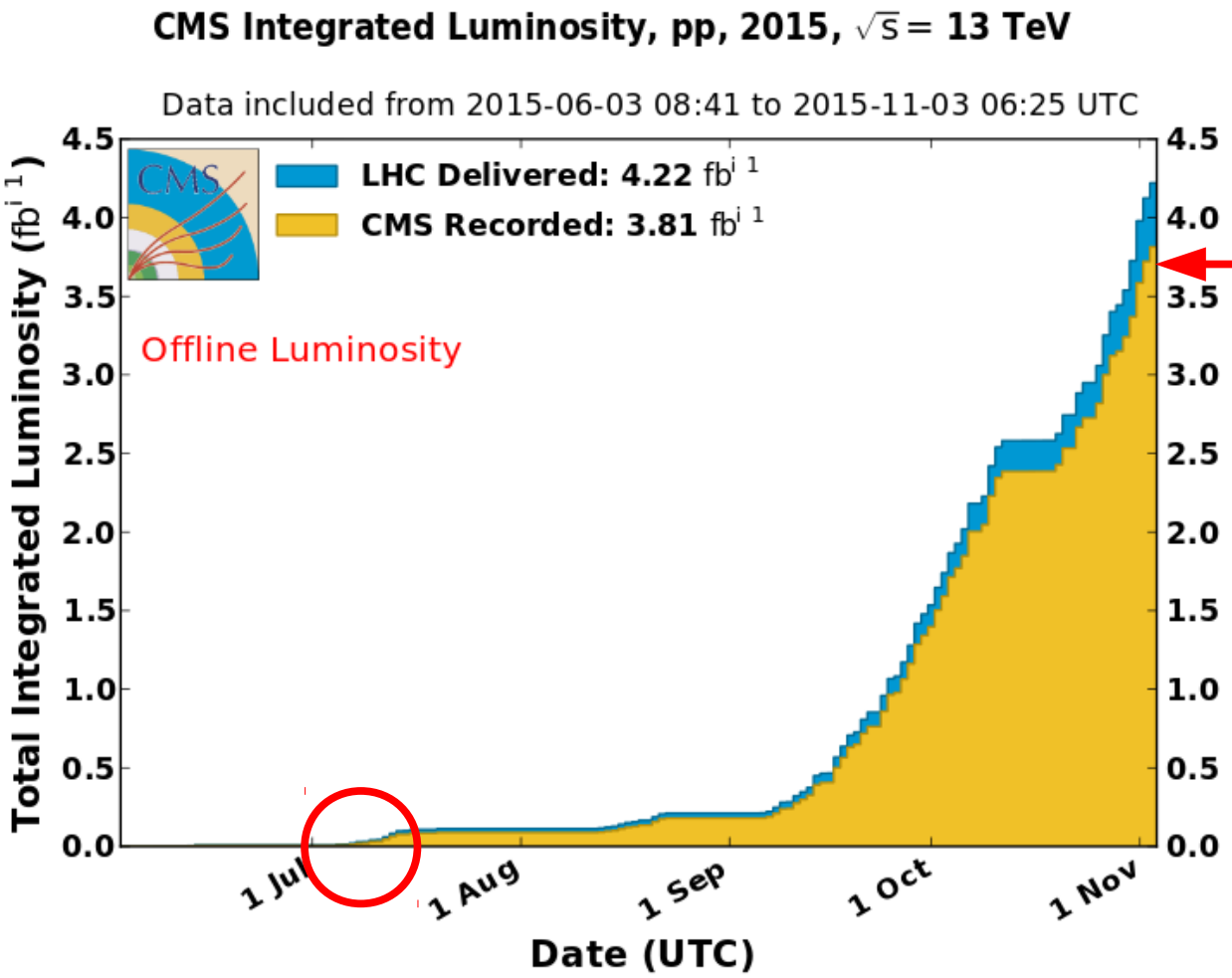
excellent prospects for top quark physics !

13 TeV Run Performance



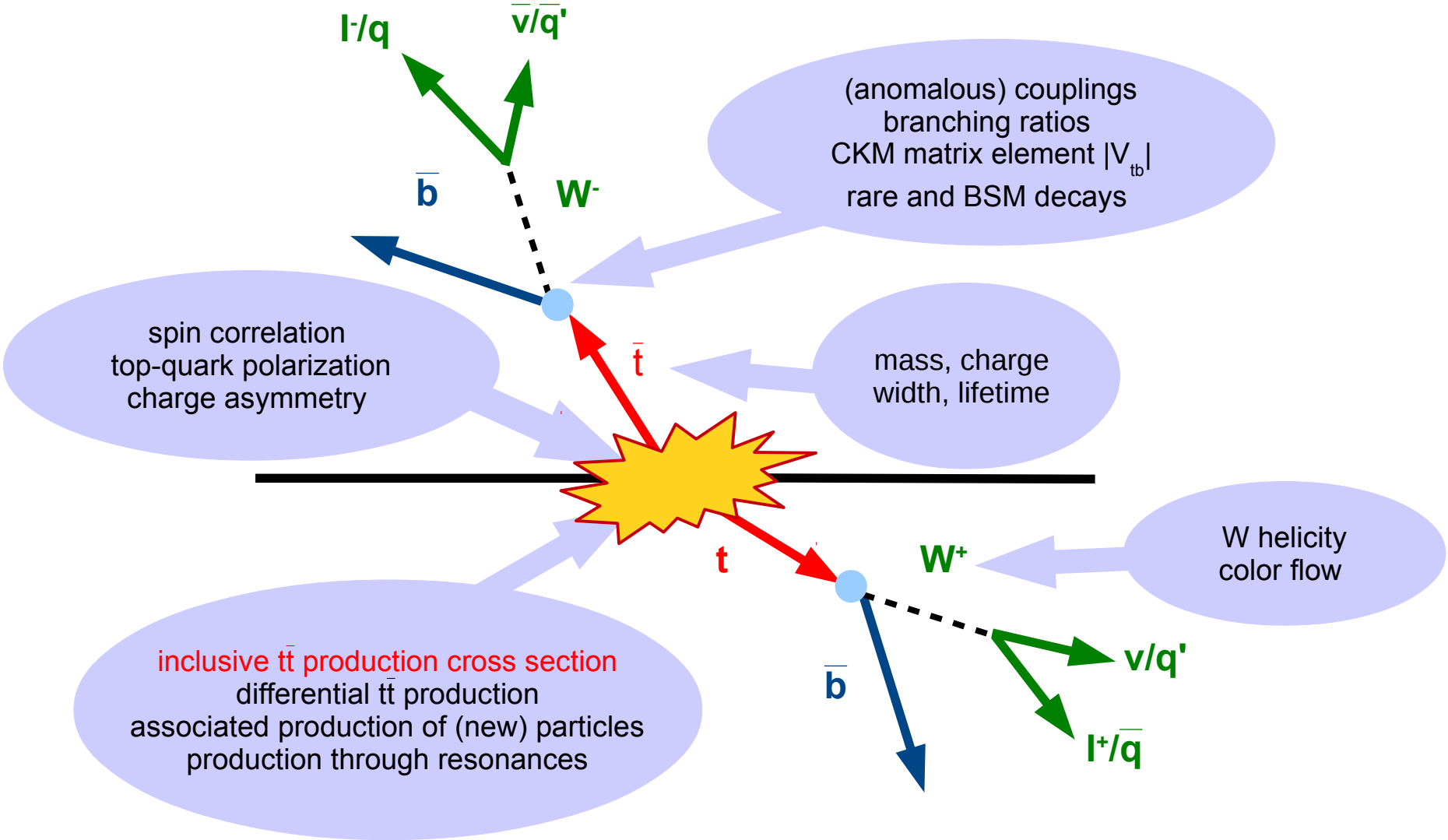
already half of the 7 & 8 TeV $t\bar{t}$ data

13 TeV Run Performance

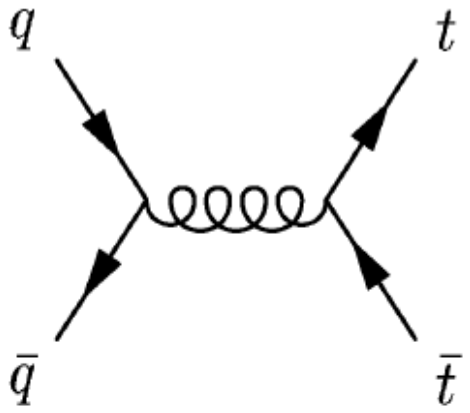


already half of the 7 & 8 TeV $t\bar{t}$ data

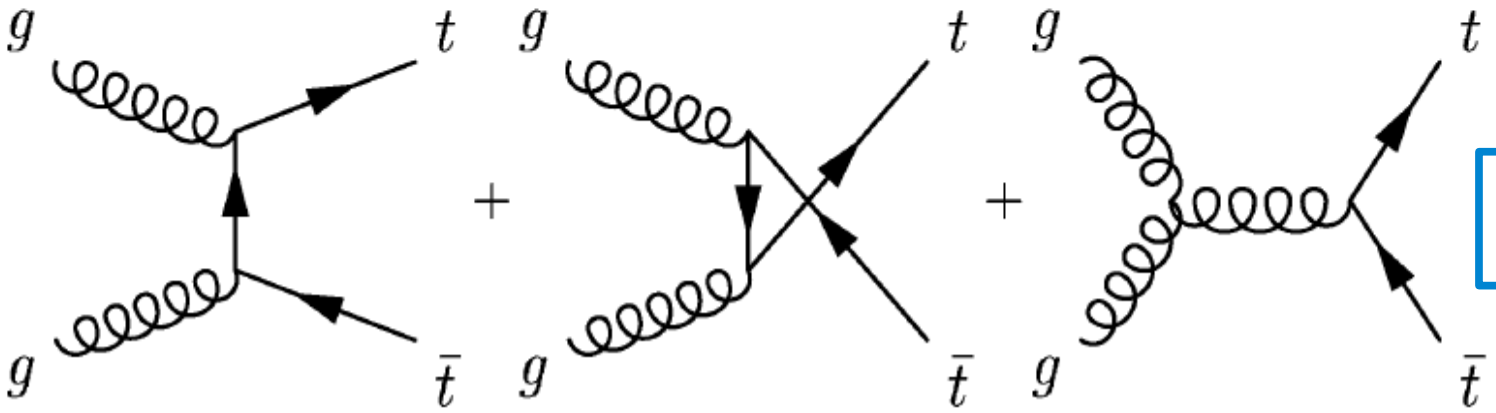
first glimpse at 13 TeV regime


l-/q
v̄/q̄'
b̄
W-
(anomalous) couplings
branching ratios
CKM matrix element |Vtb|
rare and BSM decays
spin correlation
top-quark polarization
charge asymmetry
t̄
mass, charge
width, lifetime
t
W+
W helicity
color flow
inclusive tt̄ production cross section
differential tt̄ production
associated production of (new) particles
production through resonances
b̄
v/q'
l+/q̄

Leading Order $t\bar{t}$ Production



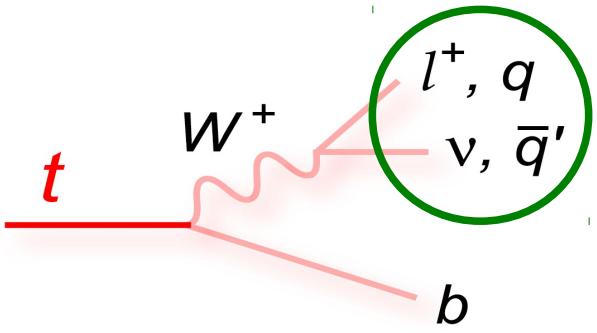
Tevatron:
~85%



LHC:
~90% @ 13 TeV

Top Quark Decays

BR(t→Wb) ≅ 100% → final state classification according to W boson decay



ττ/τ+X
14 %

Top Pair Decay Channels

all-hadronic
46%

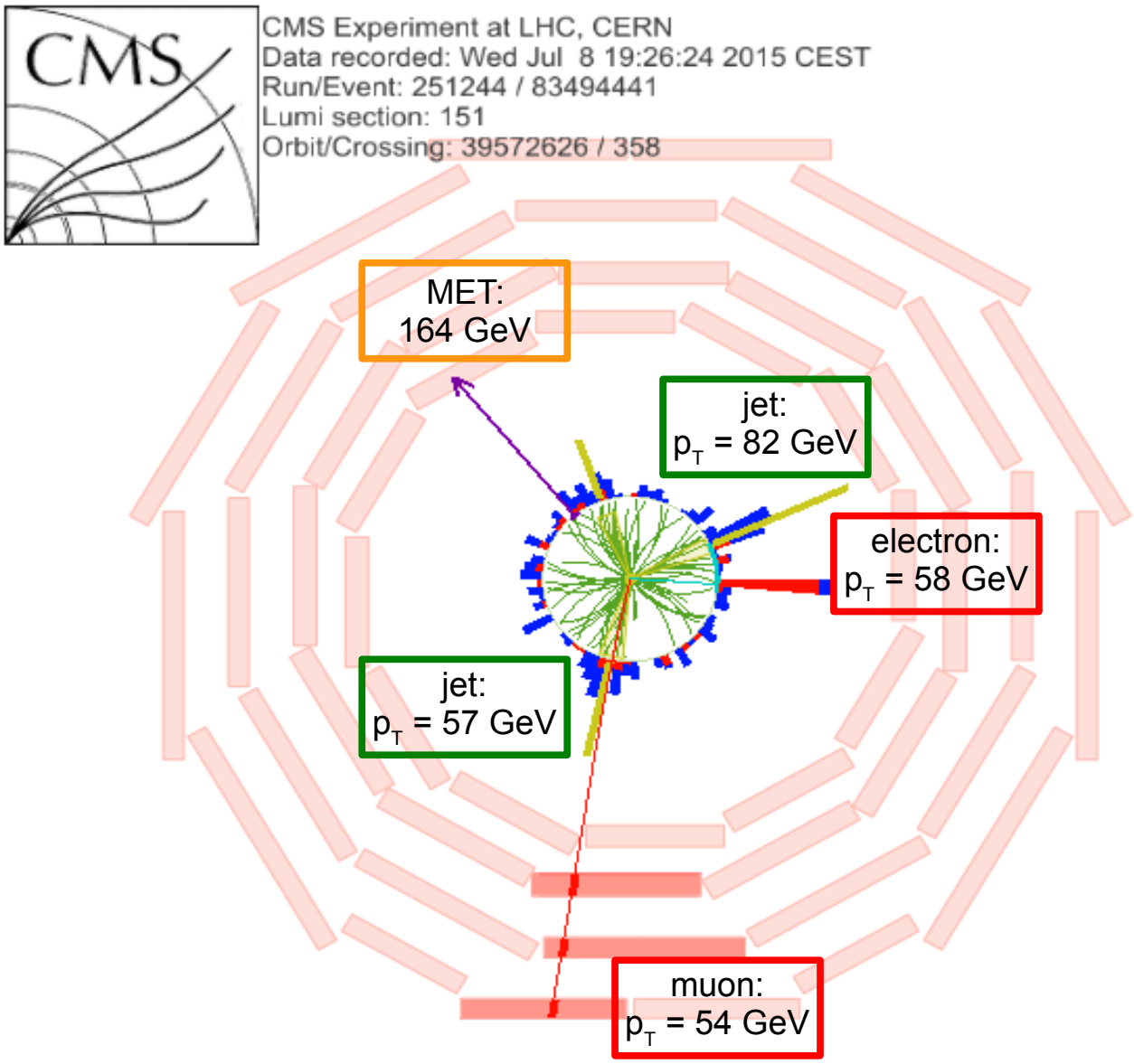
W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$					
τ^-	eτ	μτ	ττ	tau+jets	
μ^-	eμ	μμ	μτ	muon+jets	
e^-	ee	eμ	eτ	electron+jets	

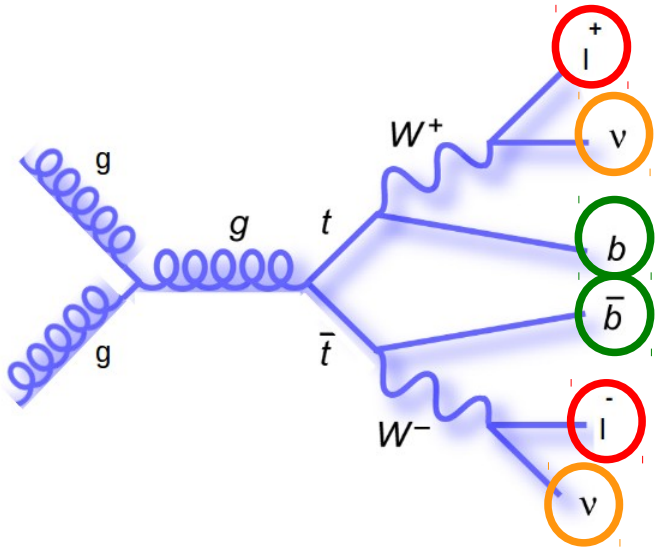
dileptons

dileptonic (ee/eμ/μμ)
6%

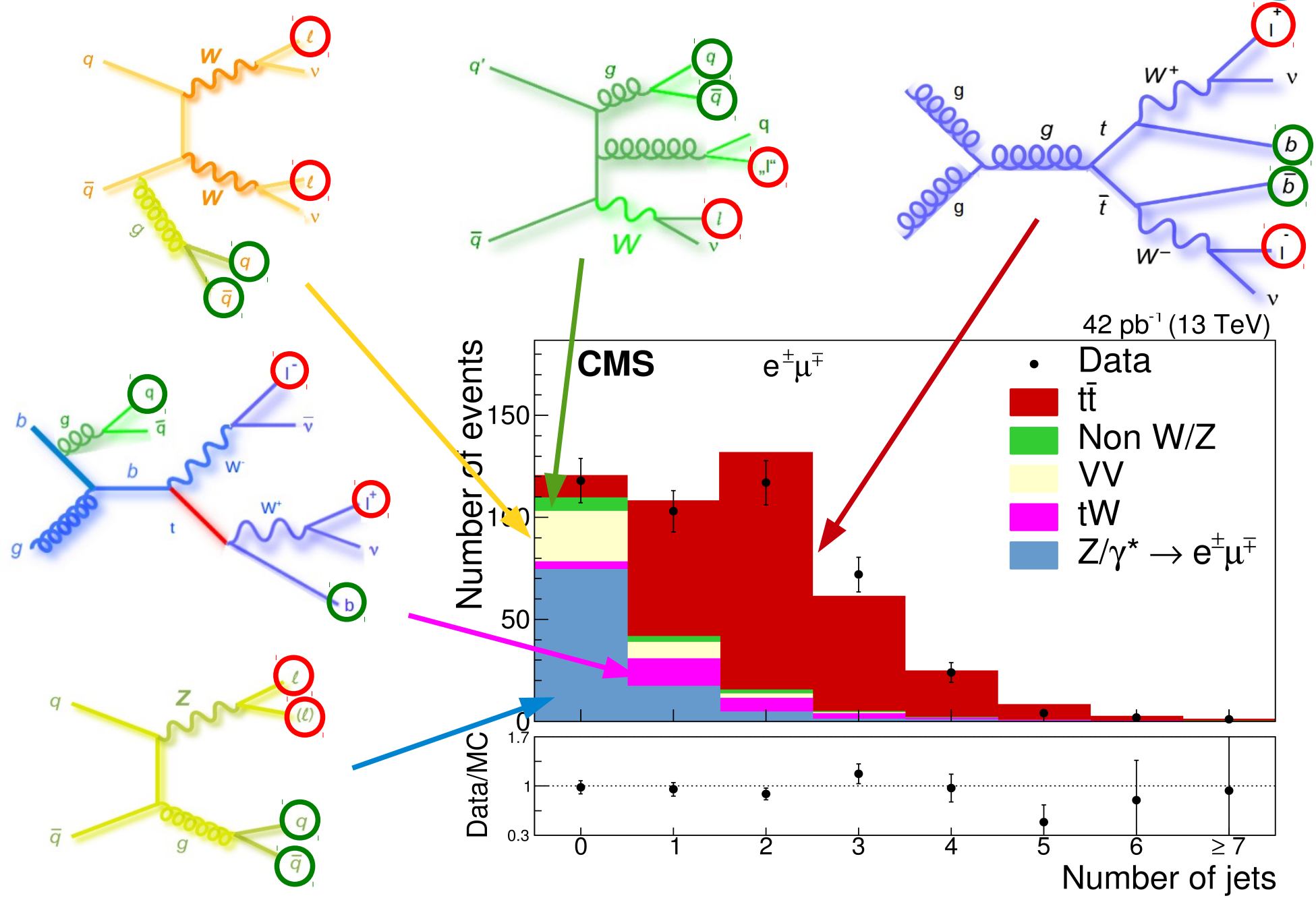
semileptonic (e/μ+jets)
34%

Dilepton Signature



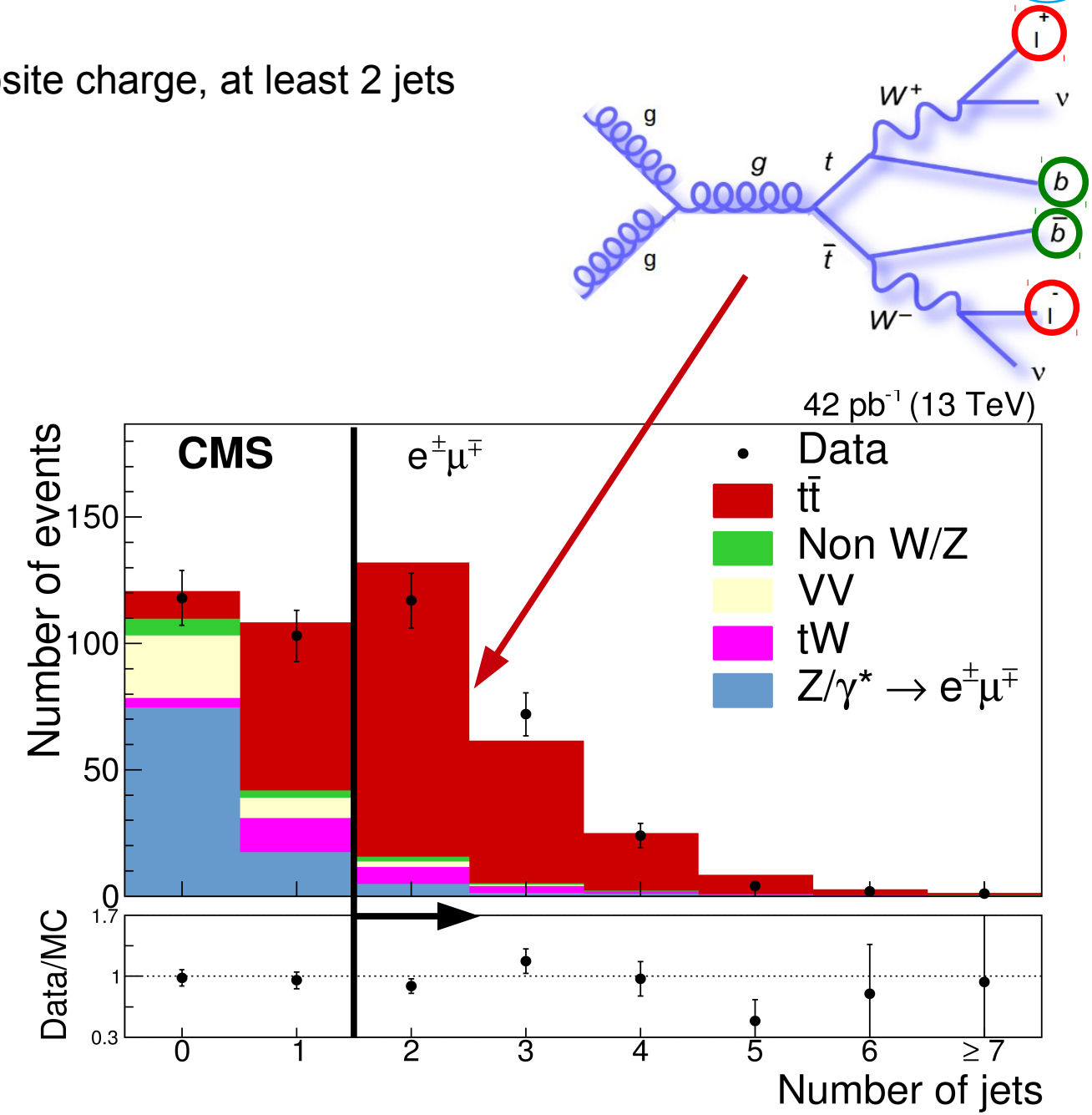


Dilepton Events



$t\bar{t}$ Cross Section at 13 TeV

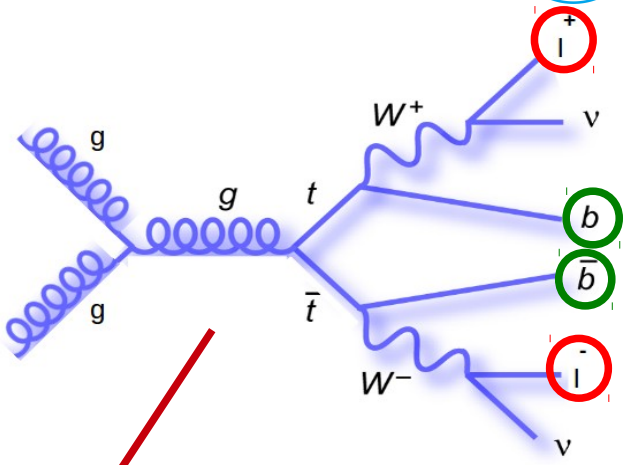
- one isolated eμ pair of opposite charge, at least 2 jets



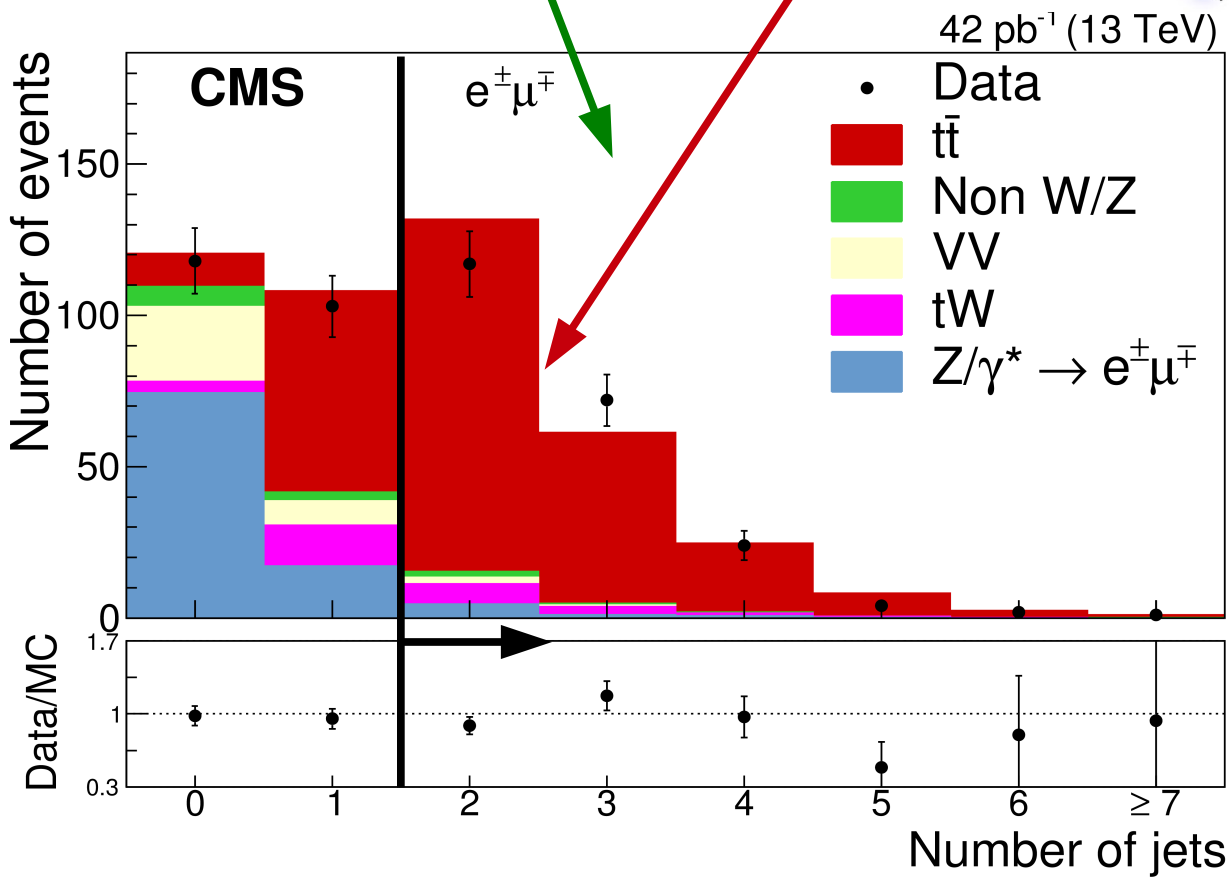
$t\bar{t}$ Cross Section at 13 TeV

- one isolated eμ pair of opposite charge, at least 2 jets
- pure counting

$$\sigma = \frac{N_{data} - N_{bkg}}{\epsilon \cdot A \cdot BR(t\bar{t} \to ll) \cdot \int L\,dt}$$



basically background free



$t\bar{t}$ Cross Section at 13 TeV

- one isolated eμ pair of opposite charge, at least 2 jets
- pure counting

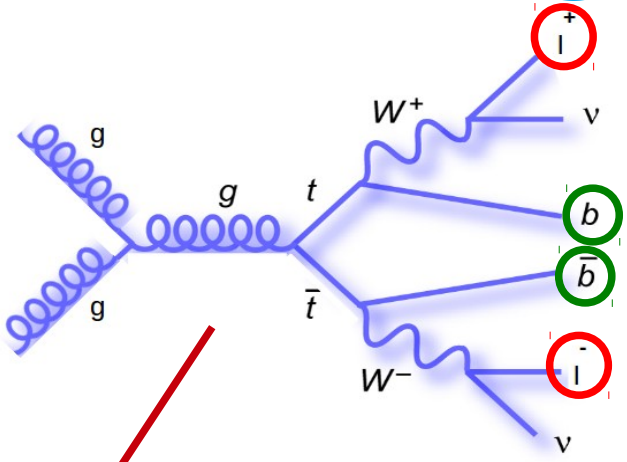
data events

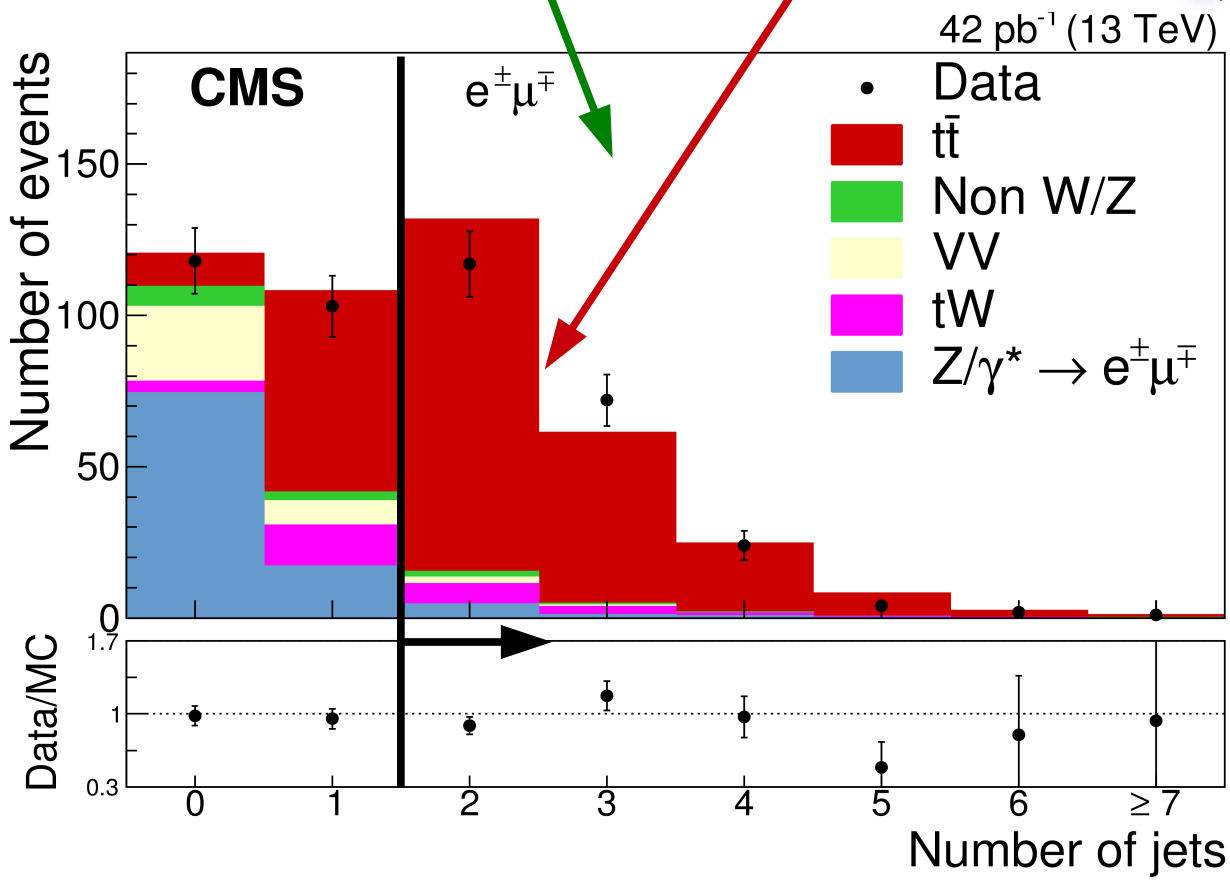
background events

basically background free

$$\sigma = \frac{N_{data} - N_{bkg}}{\epsilon \cdot A \cdot BR(t\bar{t} \to ll) \cdot \int L\,dt}$$

selection efficiency (trigger, lepton identification, isolation)





$t\bar{t}$ Cross Section at 13 TeV

- one isolated eμ pair of opposite charge, at least 2 jets
- pure counting

data events

background events

basically background free

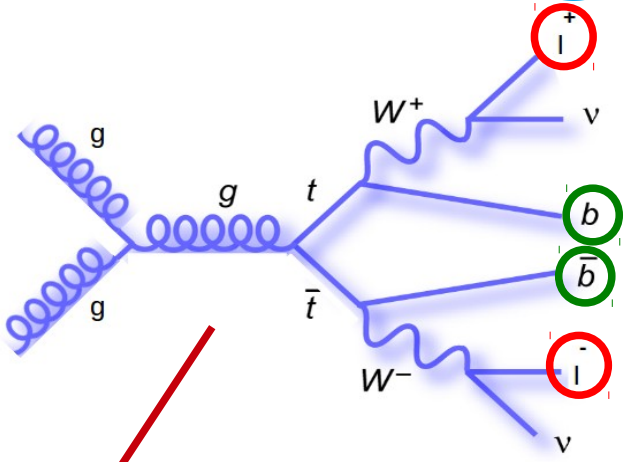
$$\sigma = \frac{N_{data} - N_{bkg}}{\epsilon \cdot A \cdot BR(t\bar{t} \to ll) \cdot \int L\,dt}$$

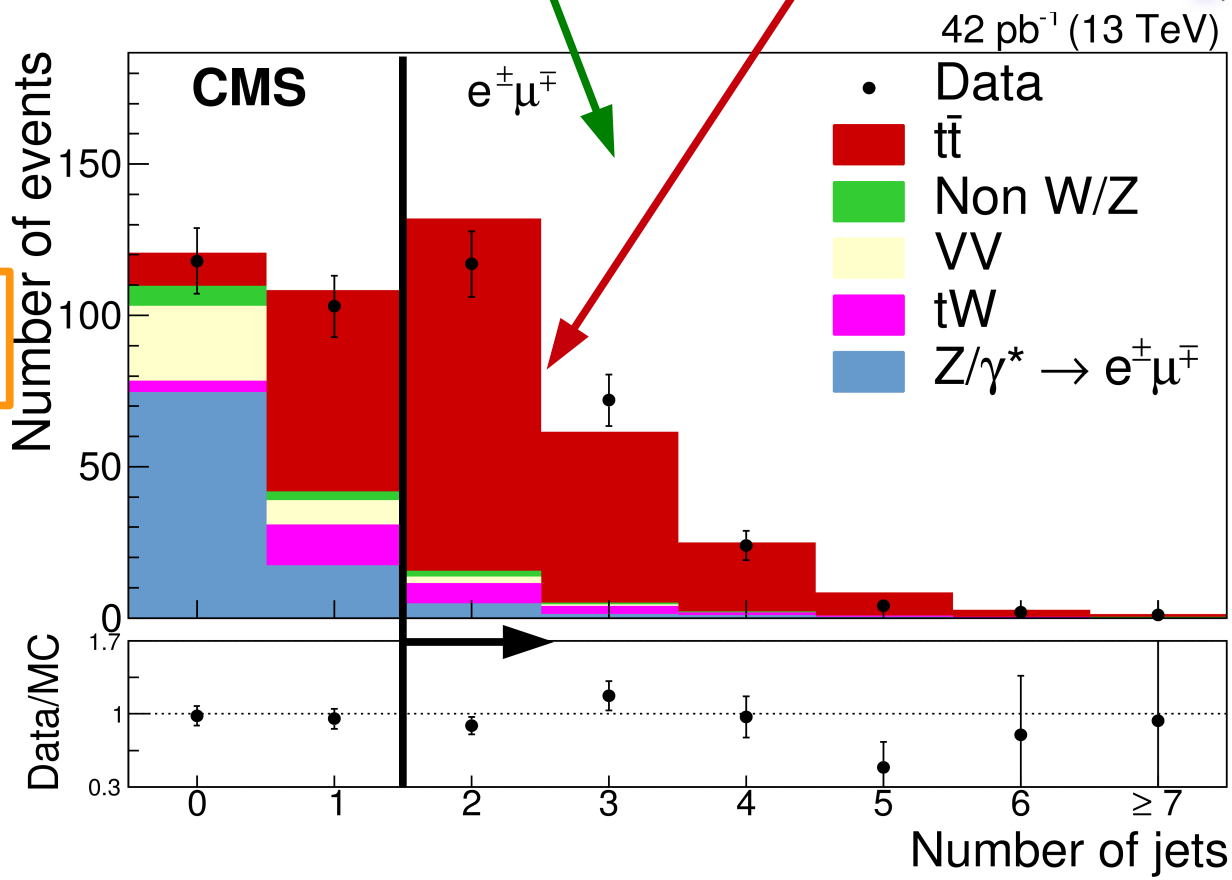
efficiency

detector acceptance

branching ratio

integrated luminosity





$t\bar{t}$ Cross Section at 13 TeV

- one isolated eμ pair of opposite charge, at least 2 jets
- pure counting

data events

background events

basically background free

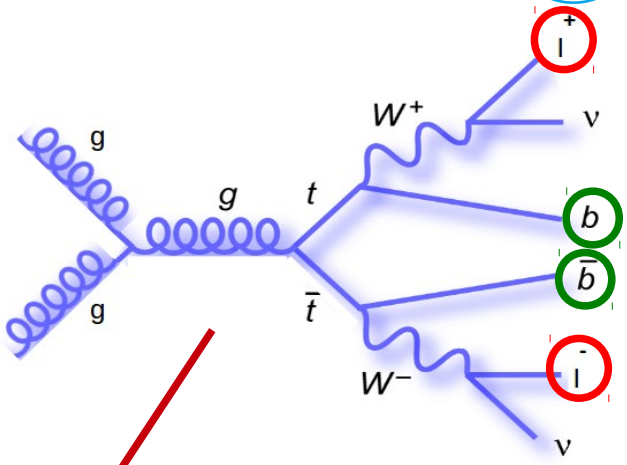
$$\sigma = \frac{N_{data} - N_{bkg}}{\epsilon \cdot A \cdot BR(t\bar{t} \to ll) \cdot \int L\,dt}$$

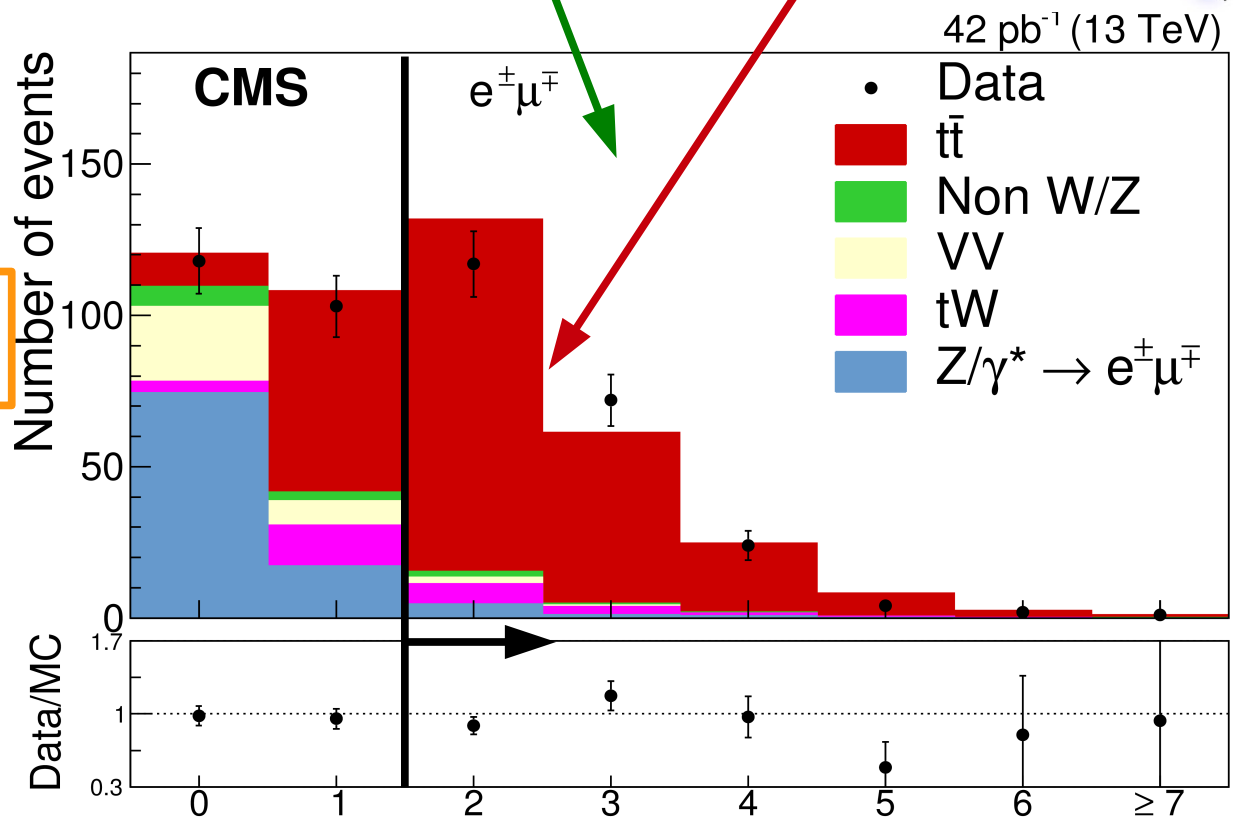
efficiency

detector acceptance

branching ratio

integrated luminosity



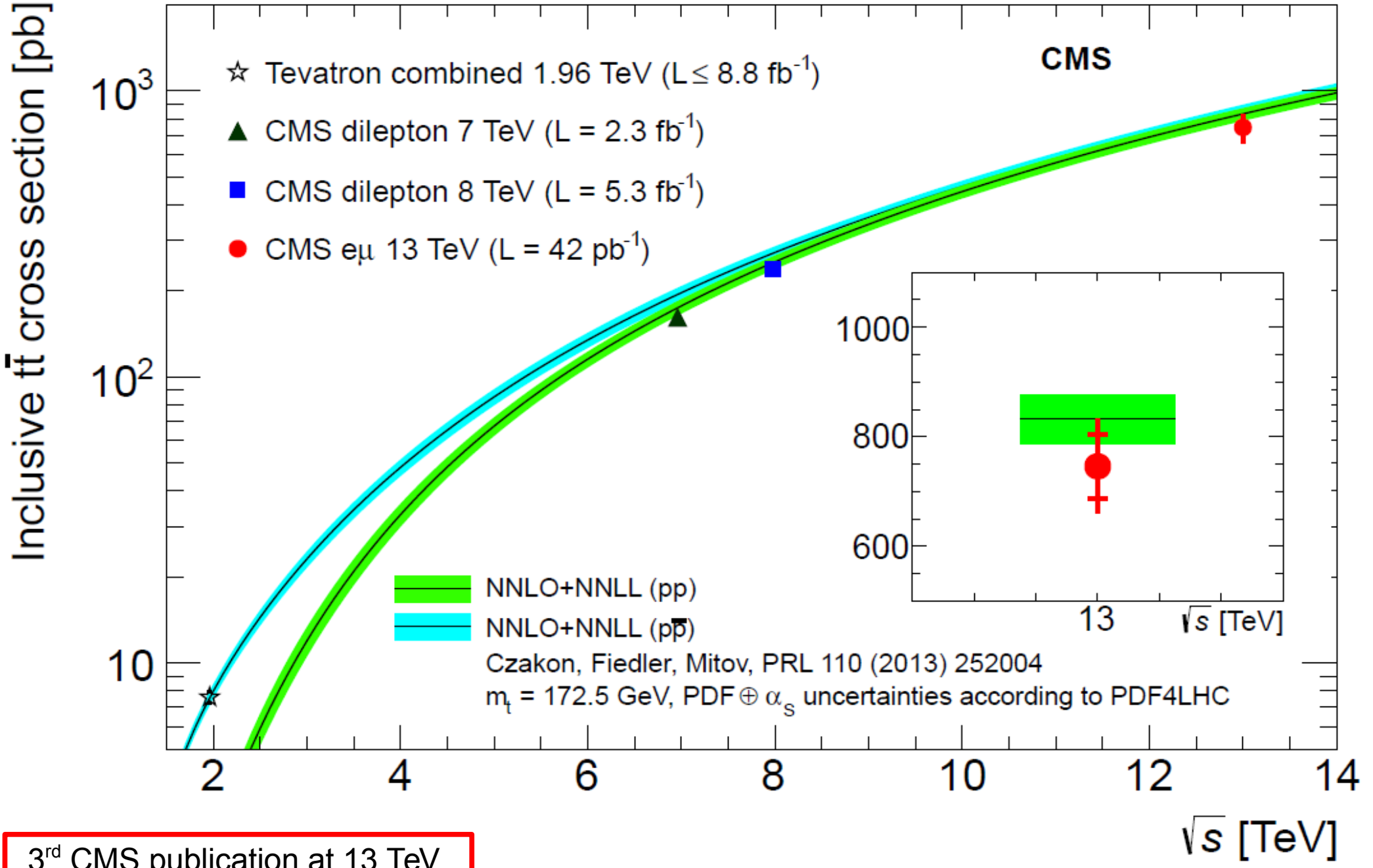


$\sigma_{t\bar{t}}$ = 769 ± 123 pb (± 16%)
60 (stat) ± 55 (syst) ± 92 (lumi) pb

13 TeV cross section consistent with SM prediction: 832 pb

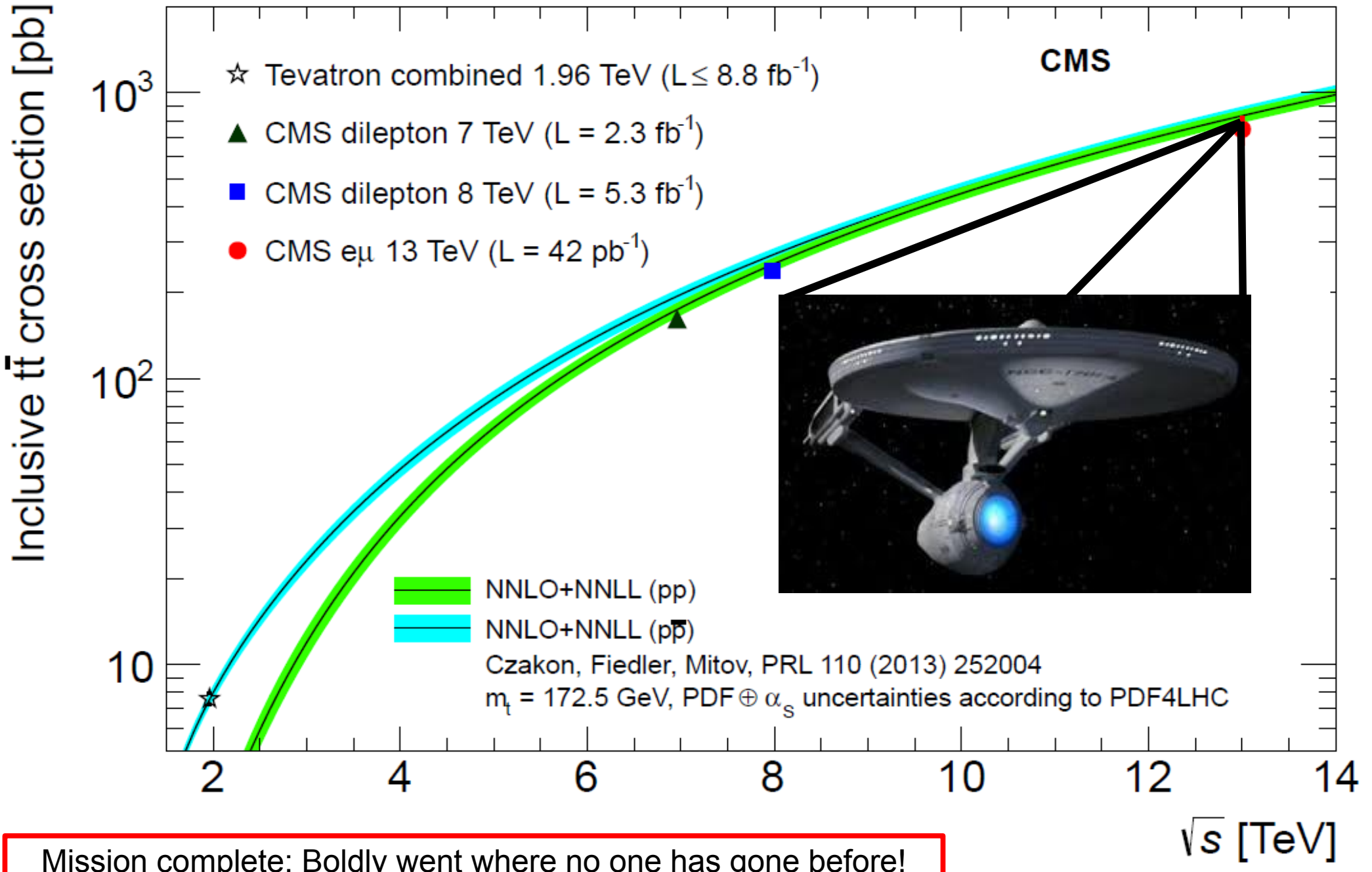
CMS-PAS-TOP-13-004

From 2 to 13 TeV



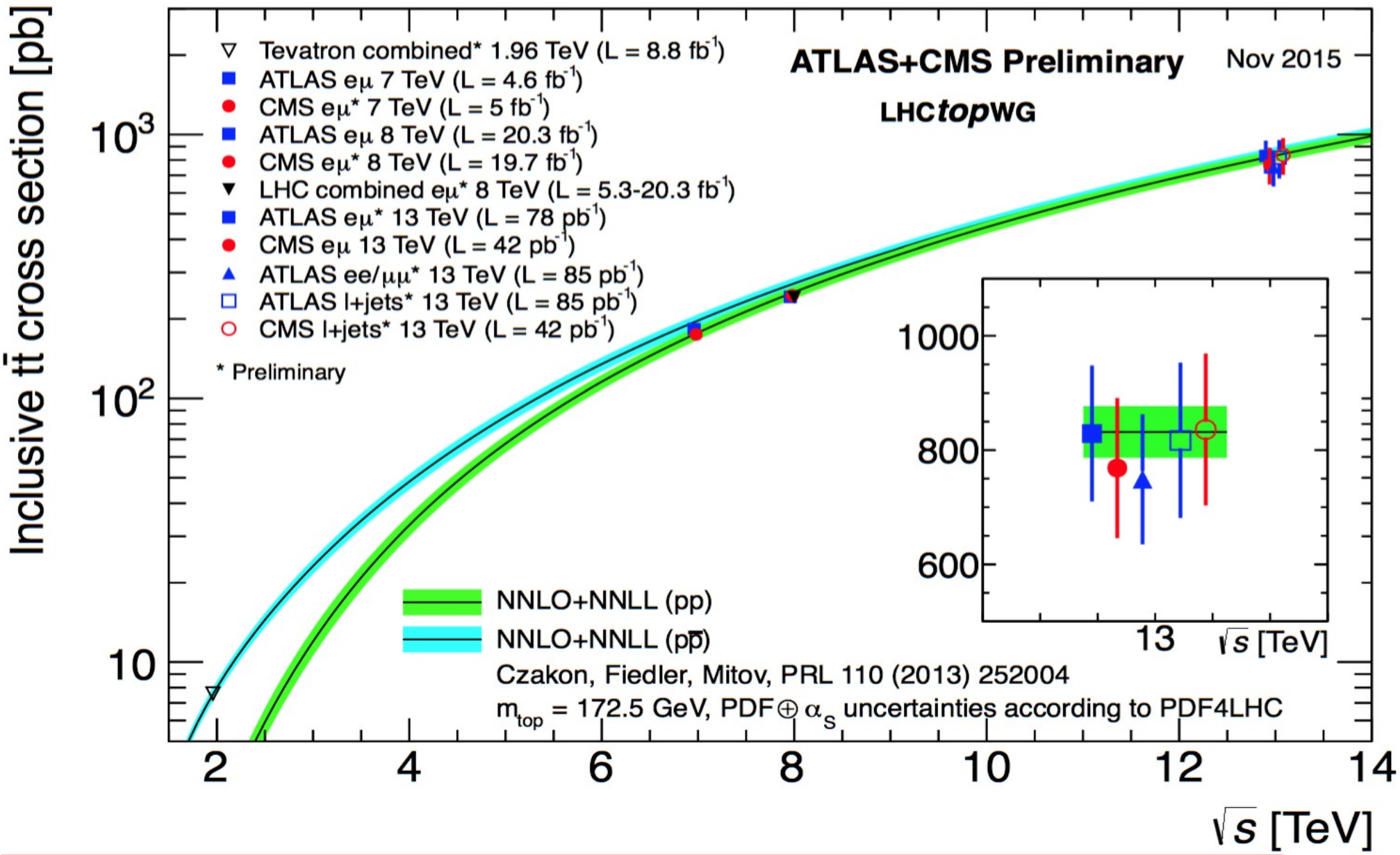
3rd CMS publication at 13 TeV

From 2 to 13 TeV



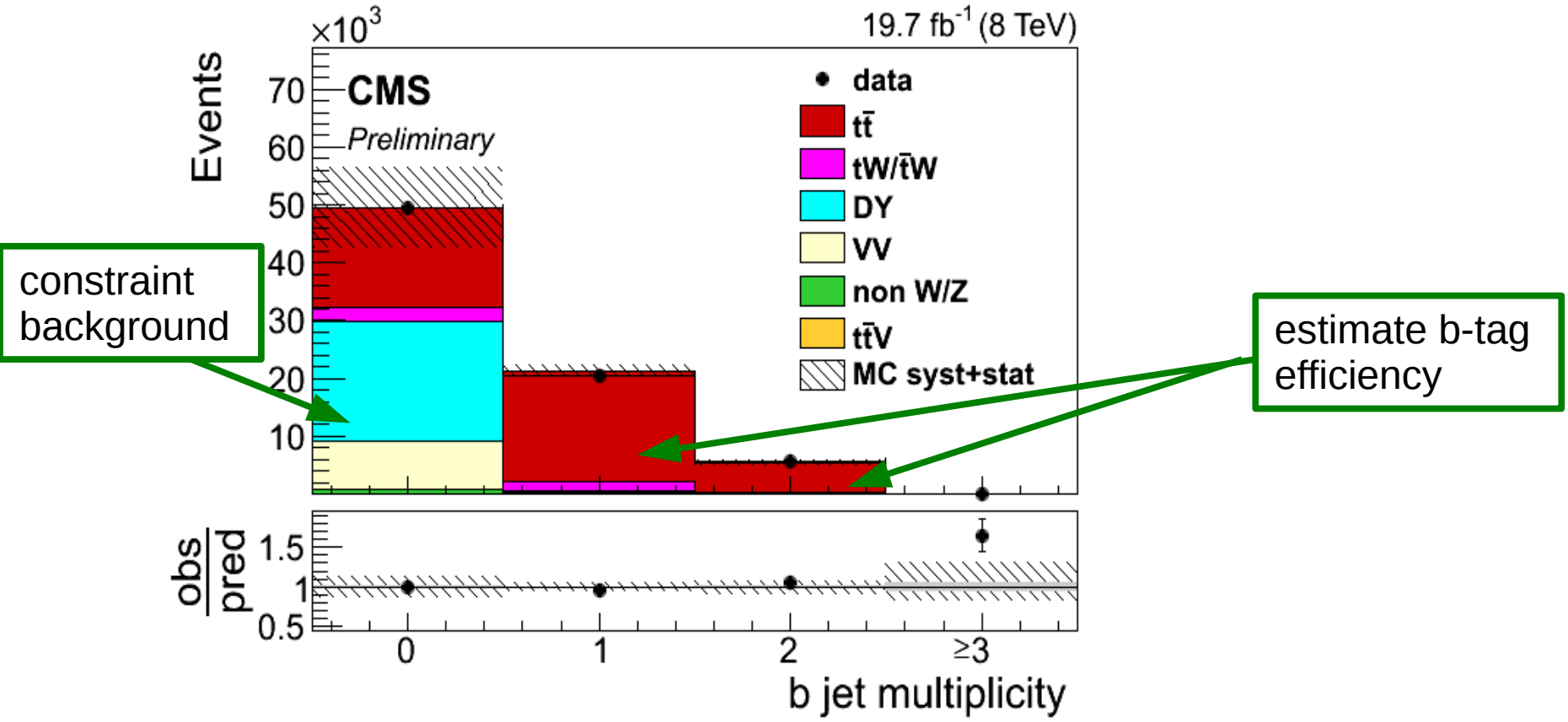
Mission complete: Boldly went where no one has gone before!

From 2 to 13 TeV



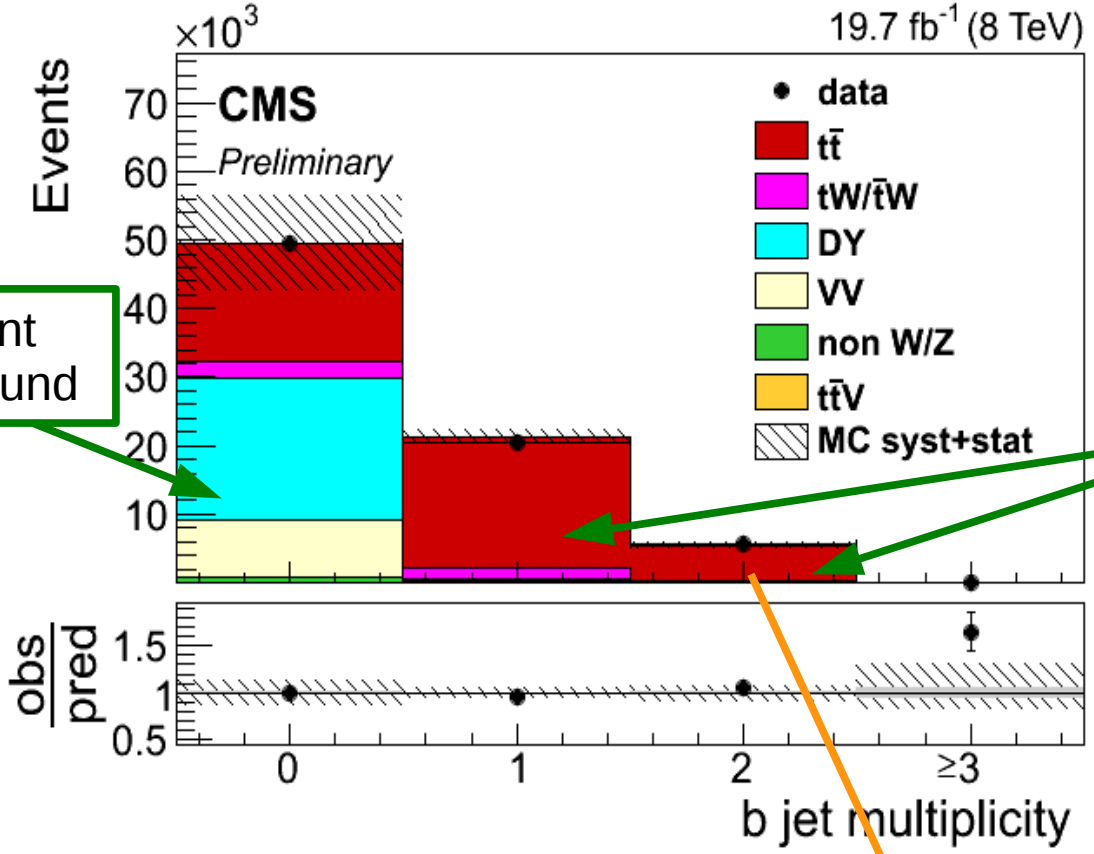
excellent agreement from 2 to 13 TeV and between different channels and experiments

Precision Cross Sections at 7 and 8 TeV



- simultaneous template fit to 7 and 8 TeV

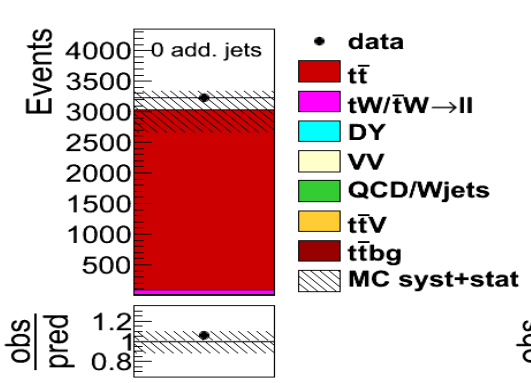
Precision Cross Sections at 7 and 8 TeV

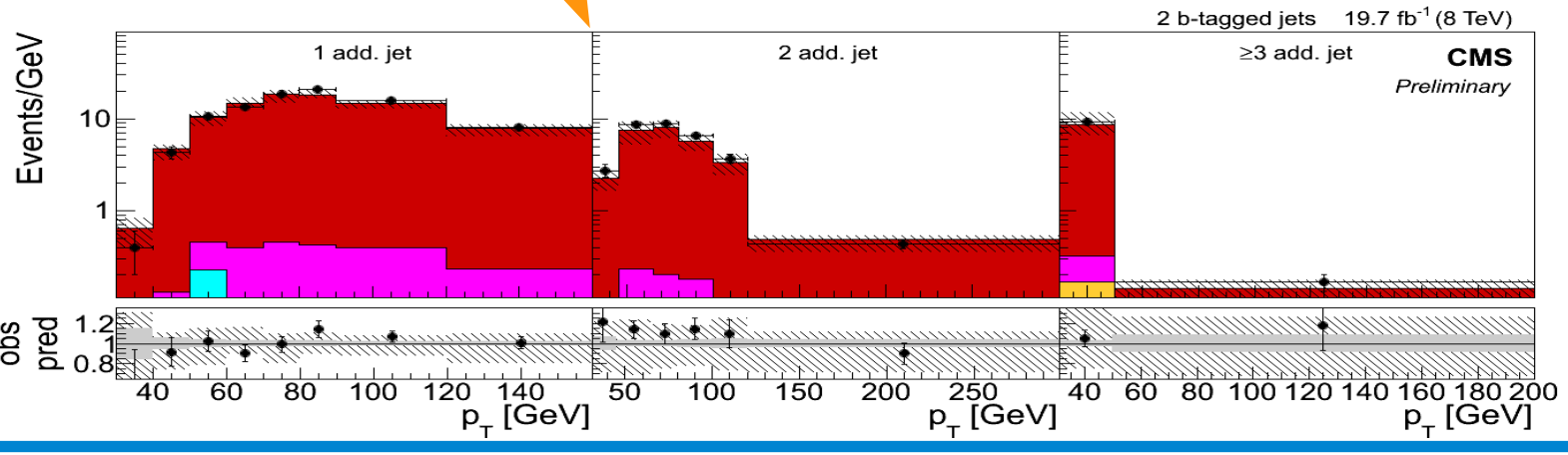


constraint background

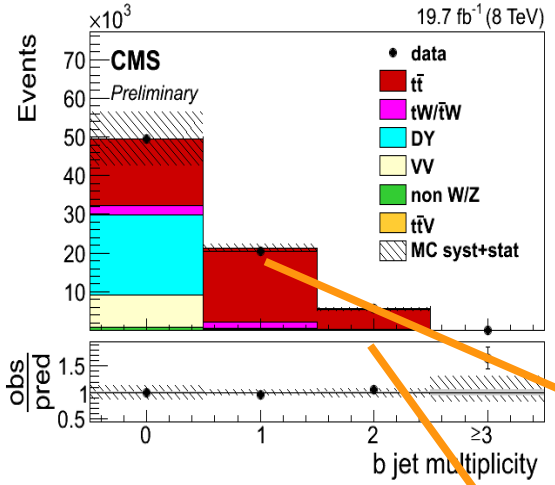
estimate b-tag efficiency

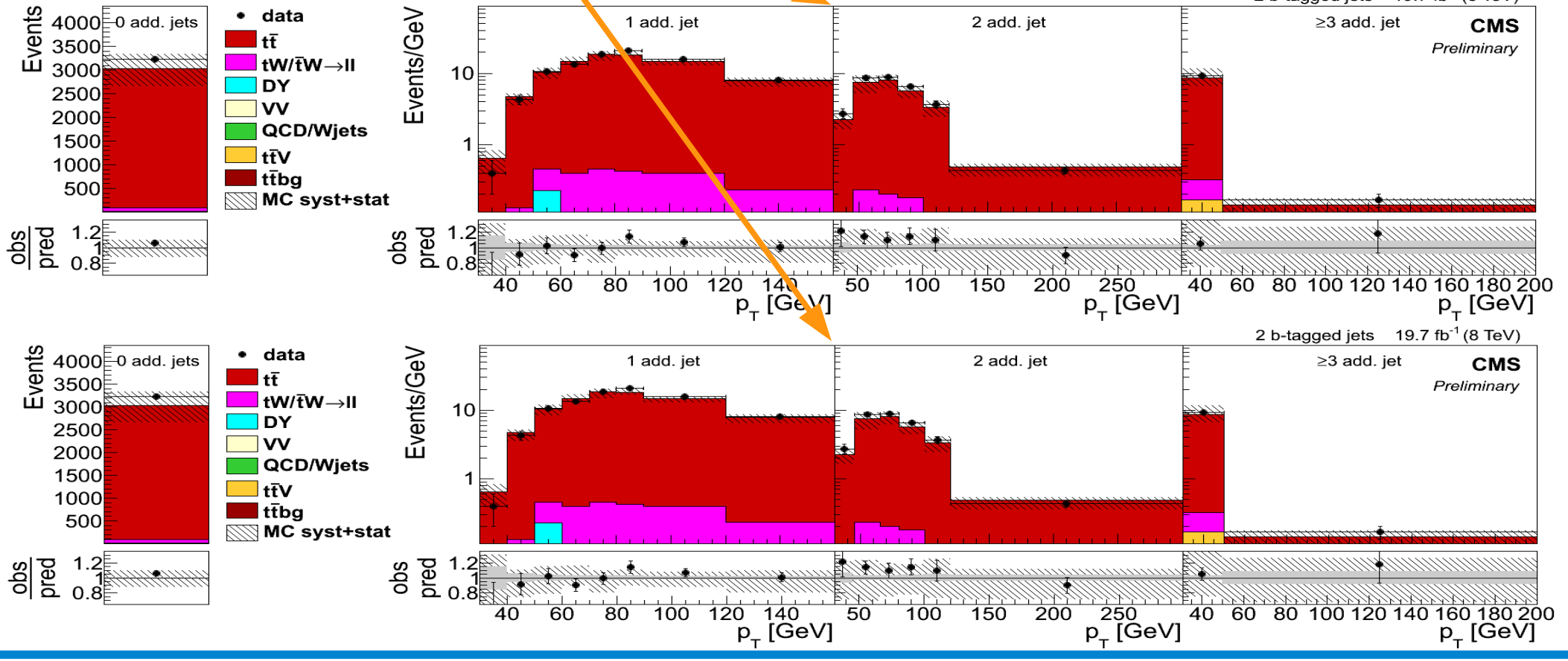
constraint jet energy scale, tt̄ modeling (e.g. scale, matching ME and PS)



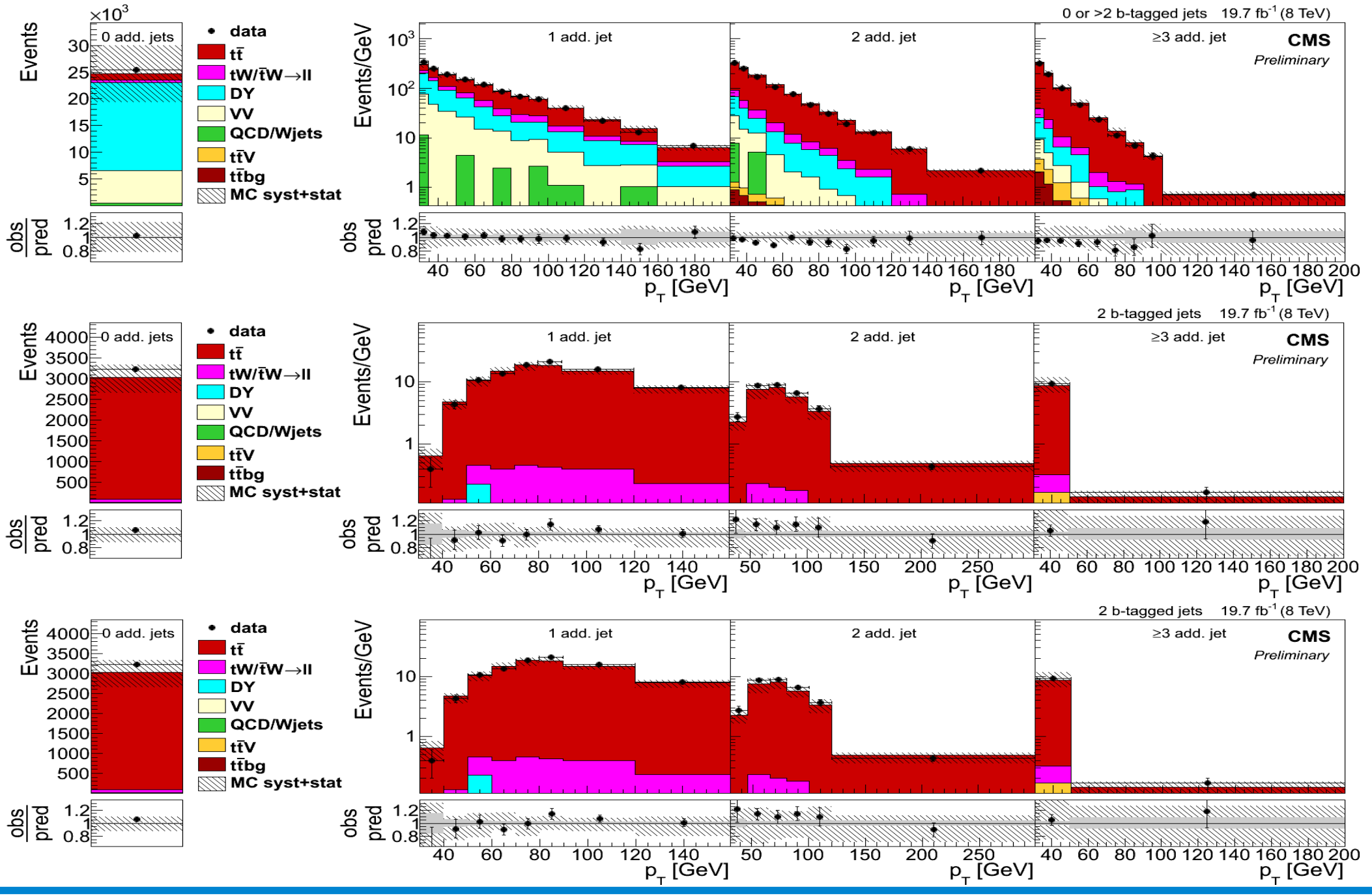


Precision Cross Sections at 7 and 8 TeV

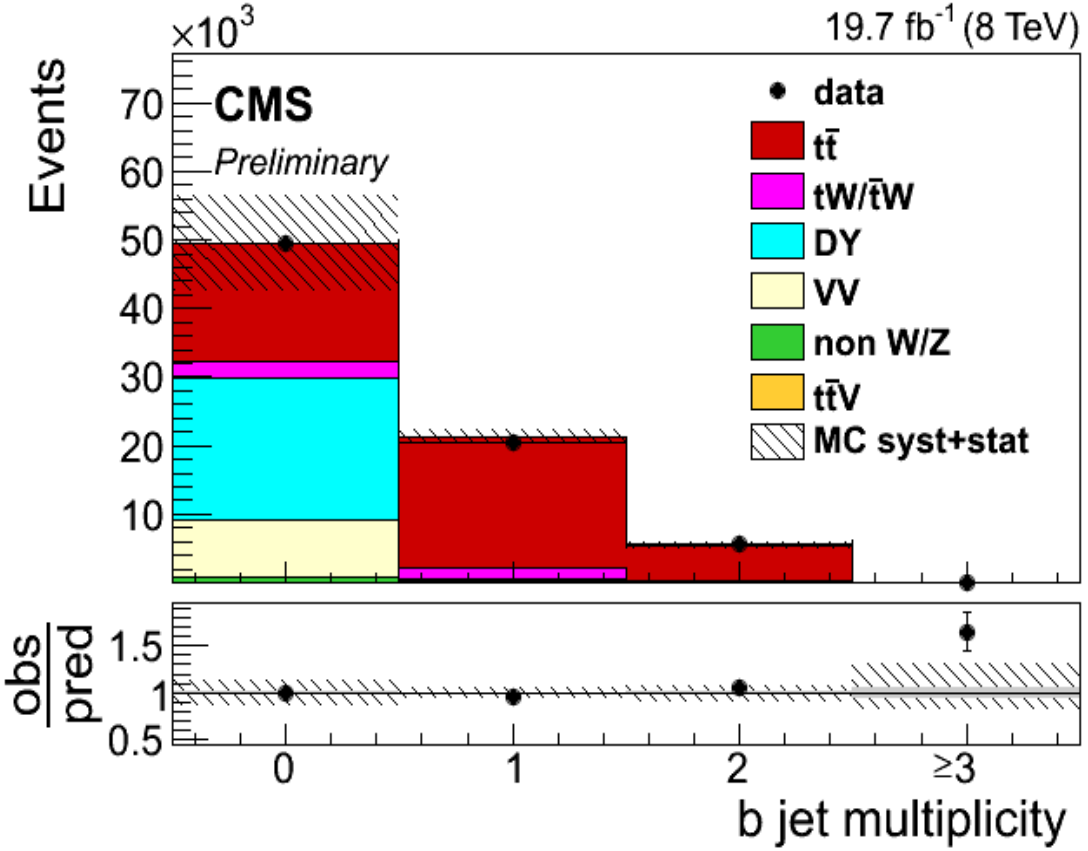




Precision Cross Sections at 7 and 8 TeV



Precision Cross Sections at 7 and 8 TeV



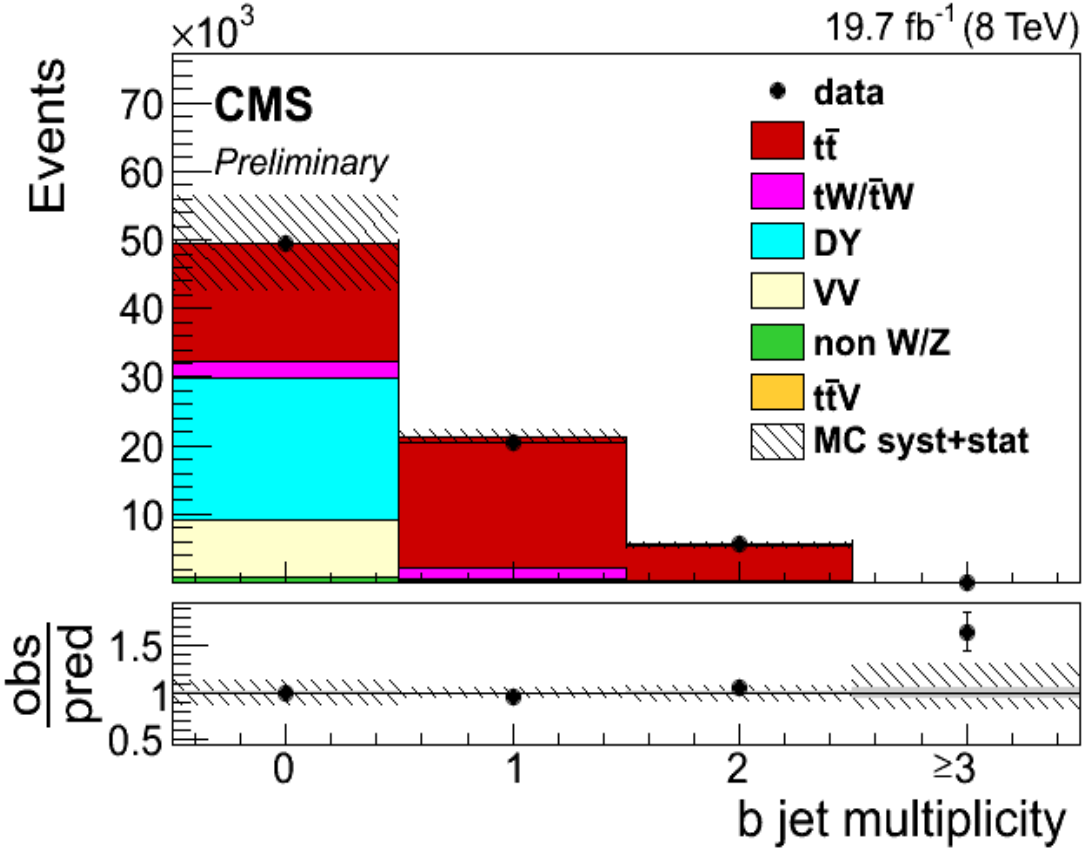
- simultaneous template fit to 7 and 8 TeV

$\sigma_{t\bar{t}}$ = 174.5 ± 6.3 pb (± 3.6%) : 2.1 (stat) ± 4.5 (syst) ± 3.8 (lumi) pb

$\sigma_{t\bar{t}}$ = 245.6 ± 9.3 pb (± 3.8%) : 1.3 (stat) ± 6.6 (syst) ± 6.5 (lumi) pb

- systematic uncertainties included as nuissance parameter
  - largest variations trigger (1.2%), lepton id./iso. (1.5%), Drell-Yan (1.2%)

Precision Cross Sections at 7 and 8 TeV



NNLO+NNLL (arXiv: 1303.6254) :

$\sigma_{t\bar{t}}$ = 172.0 ± 7.5 pb (± 4.3%)

$\sigma_{t\bar{t}}$ = 245.8 ± 10.5 pb (± 4.3%)

- simultaneous template fit to 7 and 8 TeV

$\sigma_{t\bar{t}}$ = 174.5 ± 6.3 pb (± 3.6%) : 2.1 (stat) ± 4.5 (syst) ± 3.8 (lumi) pb

$\sigma_{t\bar{t}}$ = 245.6 ± 9.3 pb (± 3.8%) : 1.3 (stat) ± 6.6 (syst) ± 6.5 (lumi) pb

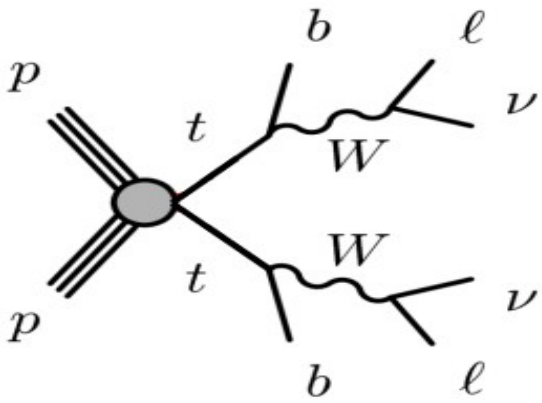
- systematic uncertainties included as nuissance parameter
  - largest variations trigger (1.2%), lepton id./iso. (1.5%), Drell-Yan (1.2%)

most precise $t\bar{t}$ cross section measurement → challenging predictions!

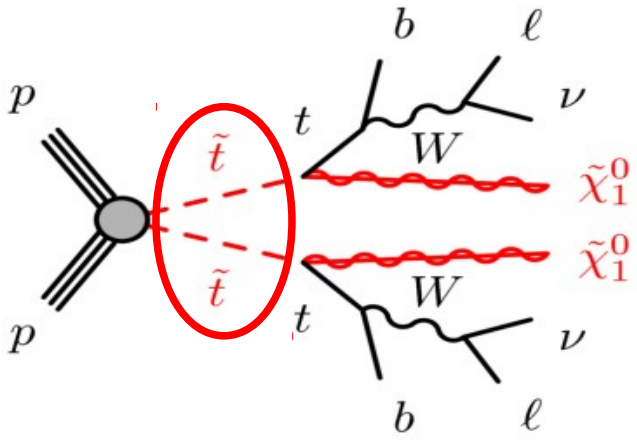
CMS-PAS-TOP-13-004

Turning into a Search for New Physics

- additional top squarks → increased $t\bar{t}$ prodction rate



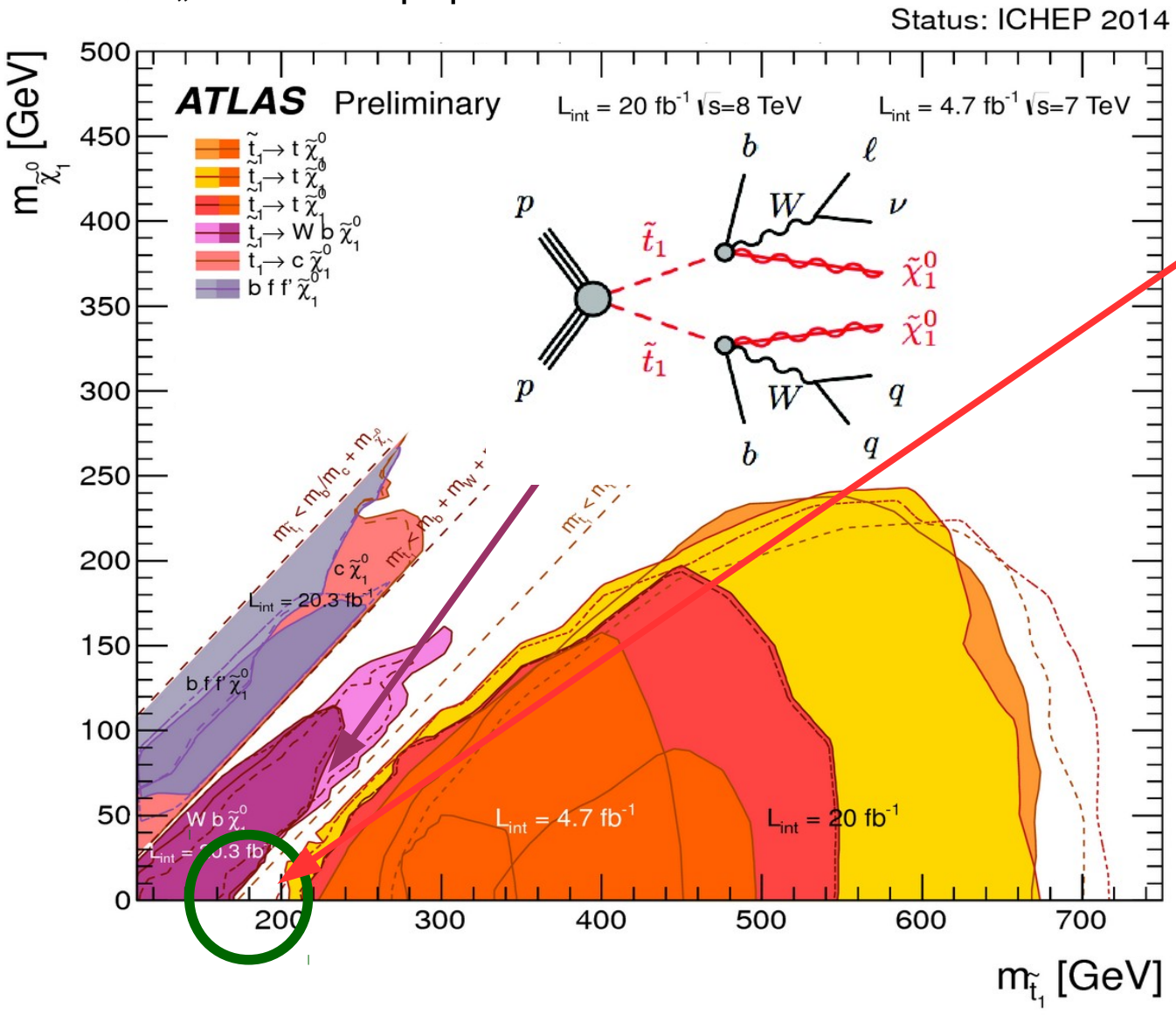
SM production

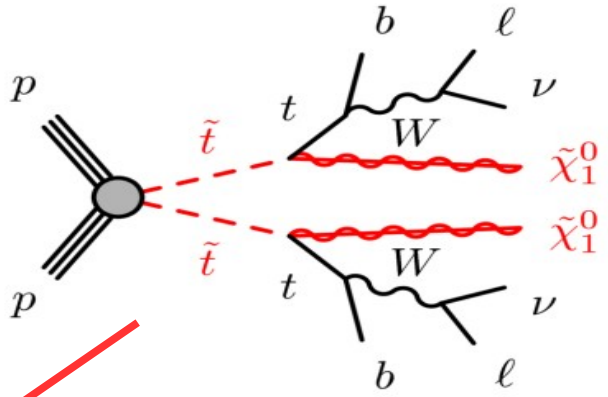


SUSY contributions

Stealthy Top Squarks I

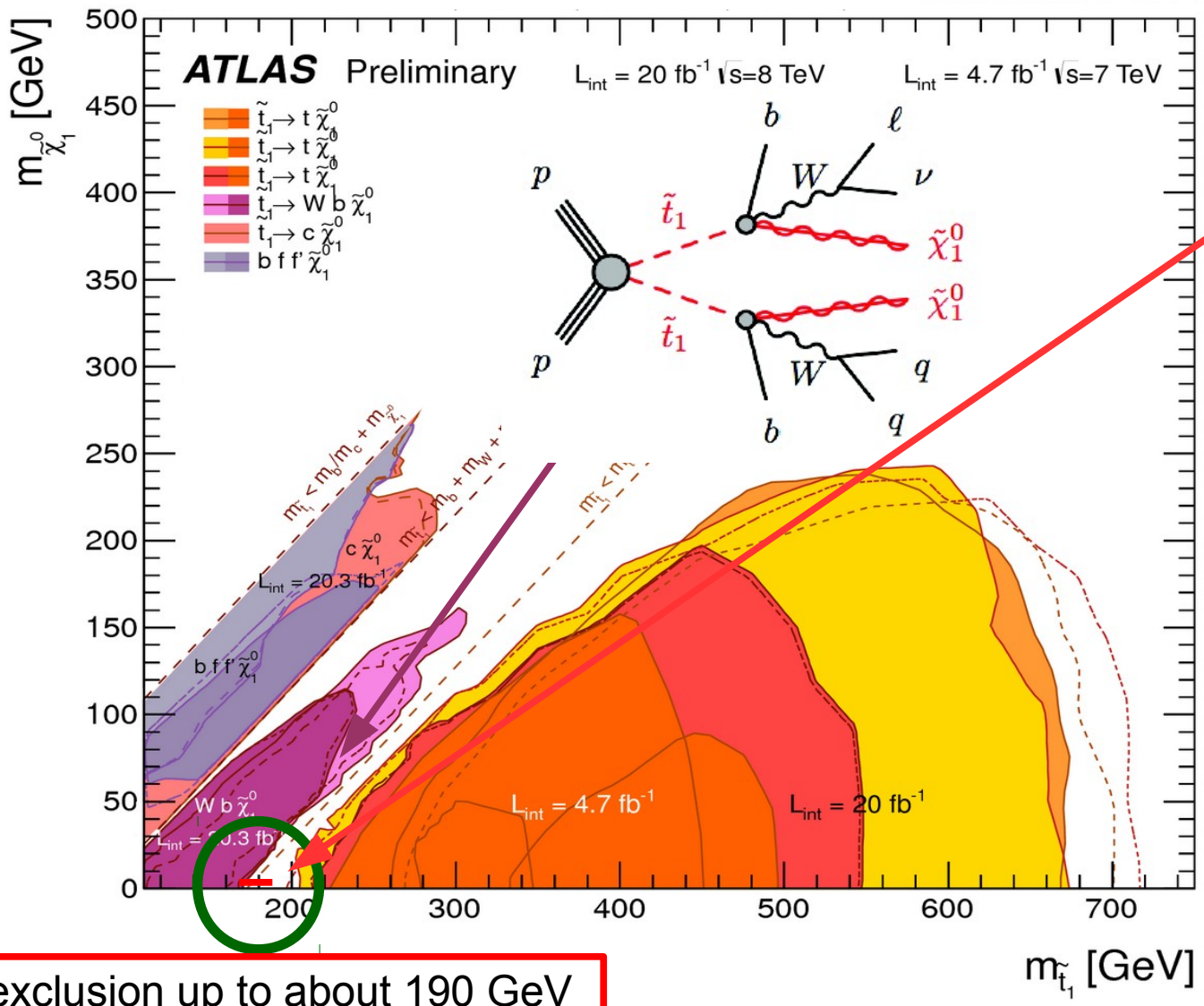
- probes interesting and unexplored region of „natural“ stop quark masses

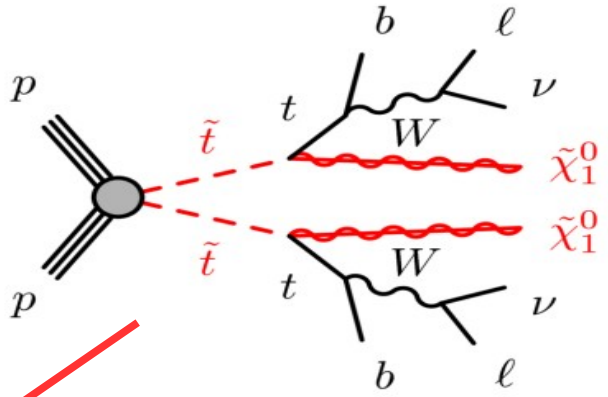




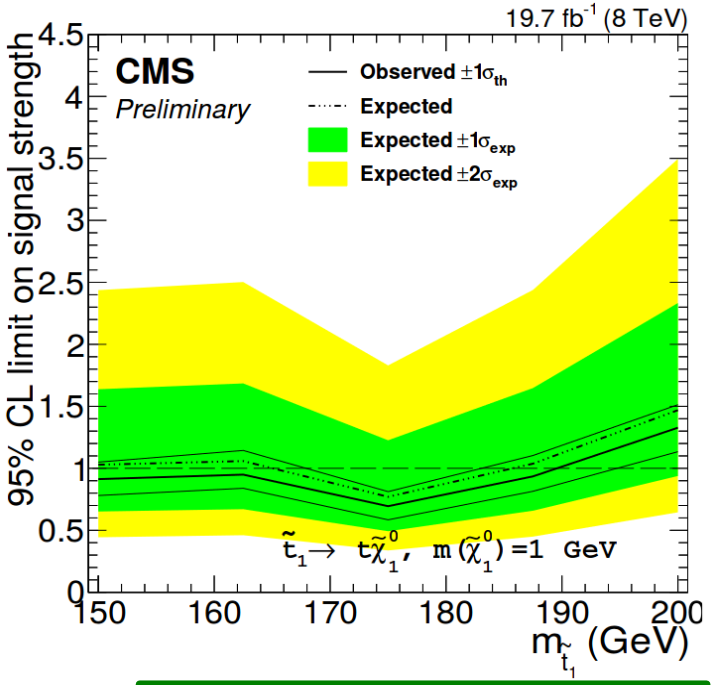
Stealthy Top Squarks I

- probes interesting and unexplored region of „natural“ stop quark masses



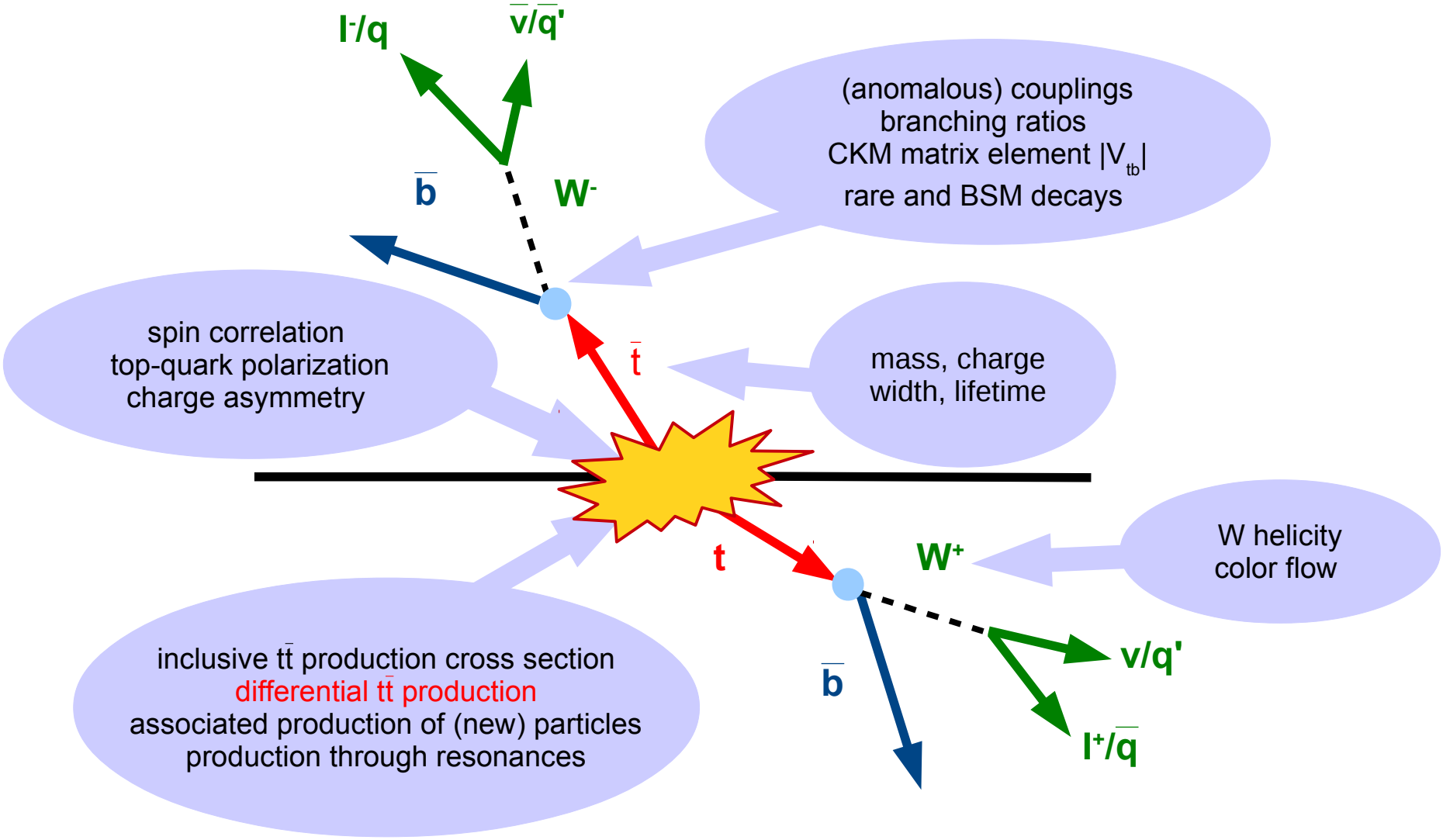


BR($\tilde{t} \rightarrow t\tilde{\chi}_1^0$) = 100%
$\tilde{t}$: right-handedly polarized

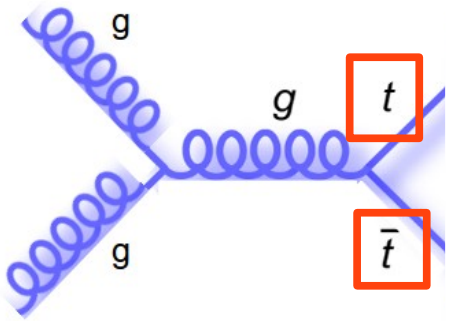


exclusion up to about 190 GeV

CMS-PAS-TOP-13-004


l⁻/q
ν̄/q̄'
b̄
W⁻
(anomalous) couplings
branching ratios
CKM matrix element |V_tb|
rare and BSM decays
spin correlation
top-quark polarization
charge asymmetry
t̄
mass, charge
width, lifetime
t
W⁺
W helicity
color flow
inclusive tt̄ production cross section
differential tt̄ production
associated production of (new) particles
production through resonances
b̄
ν/q'
l⁺/q̄

Differential Measurements

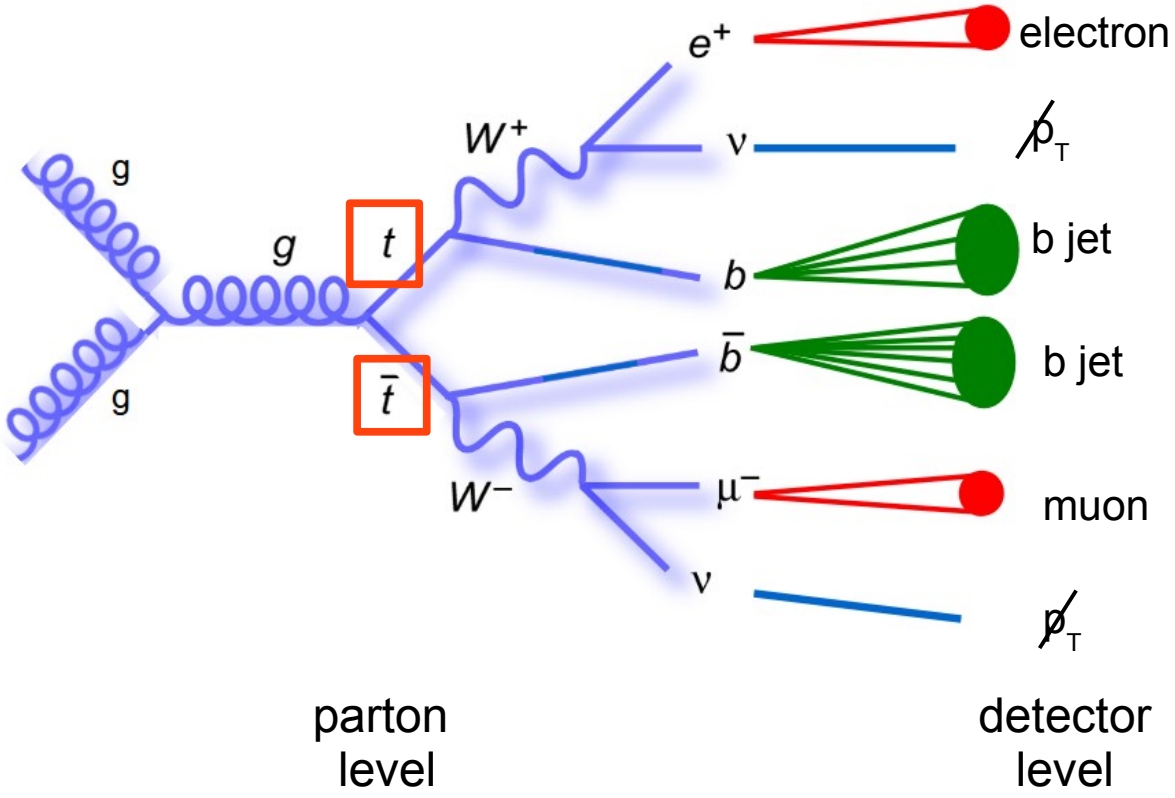


parton level



G. Cowan, „Statistical Data Analysis“

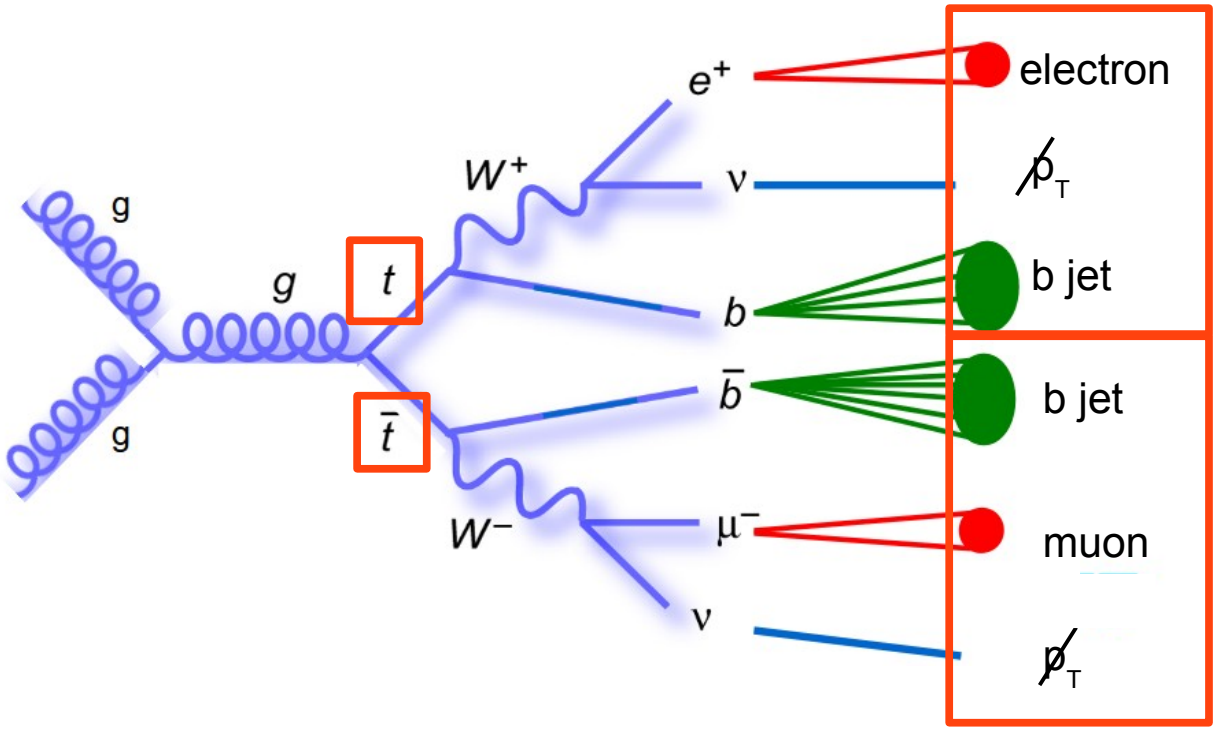
Differential Measurements





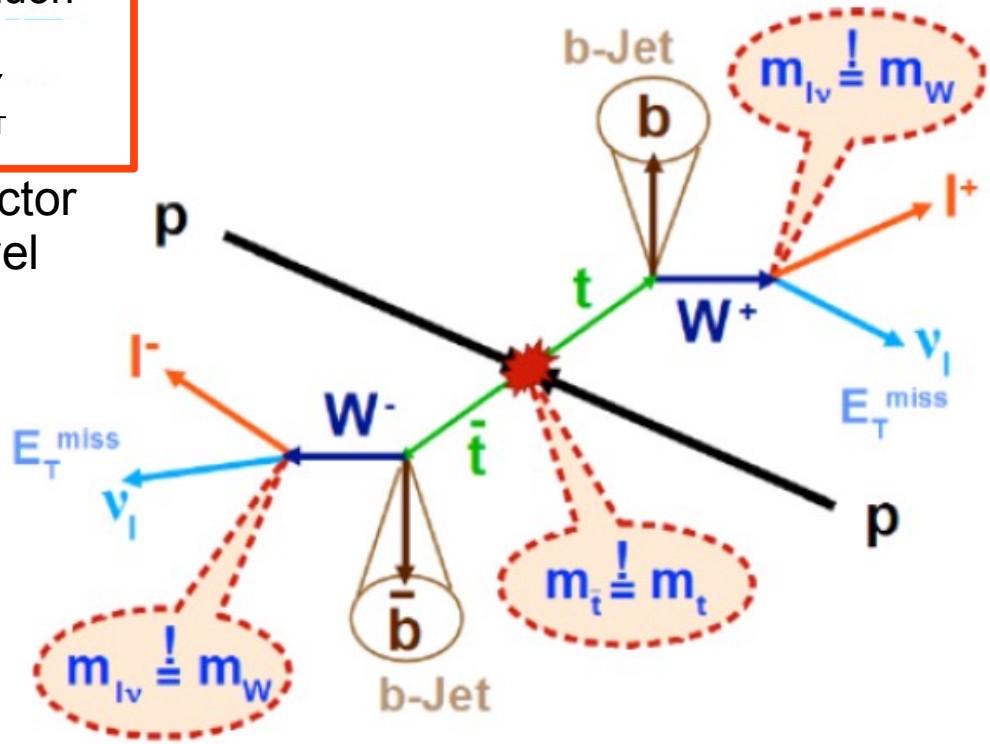
G. Cowan, „Statistical Data Analysis“

Differential Measurements

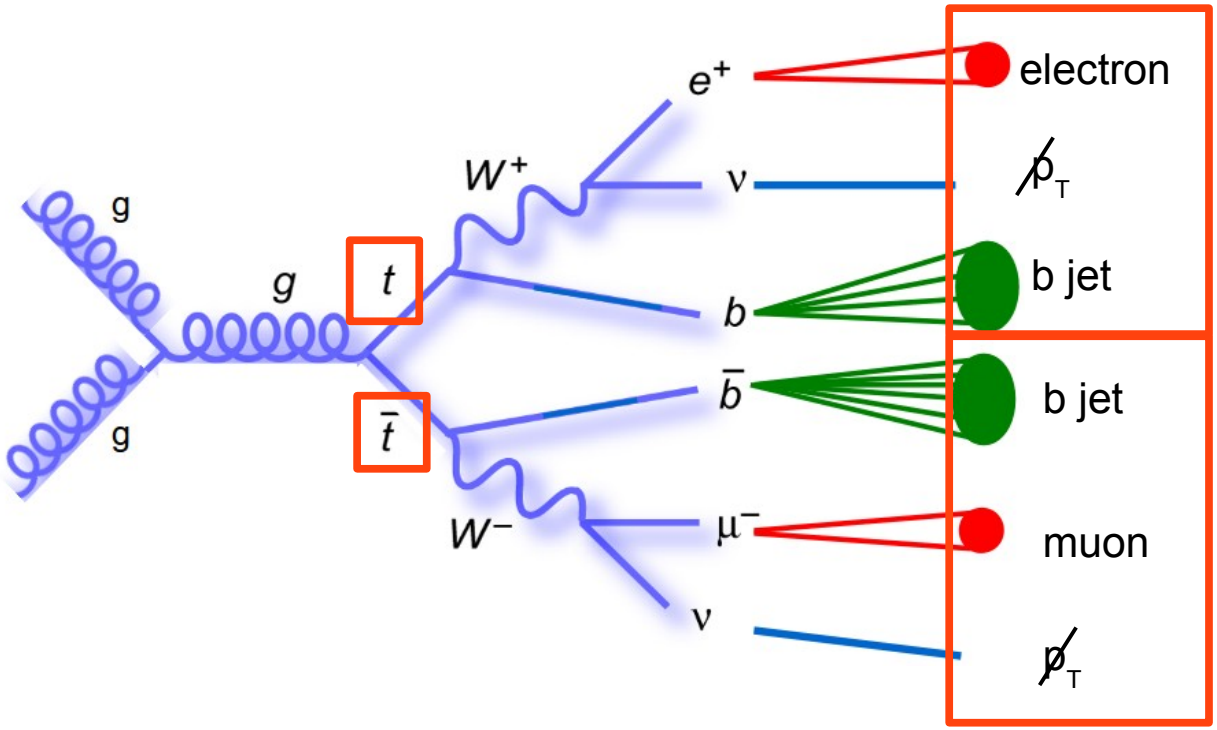


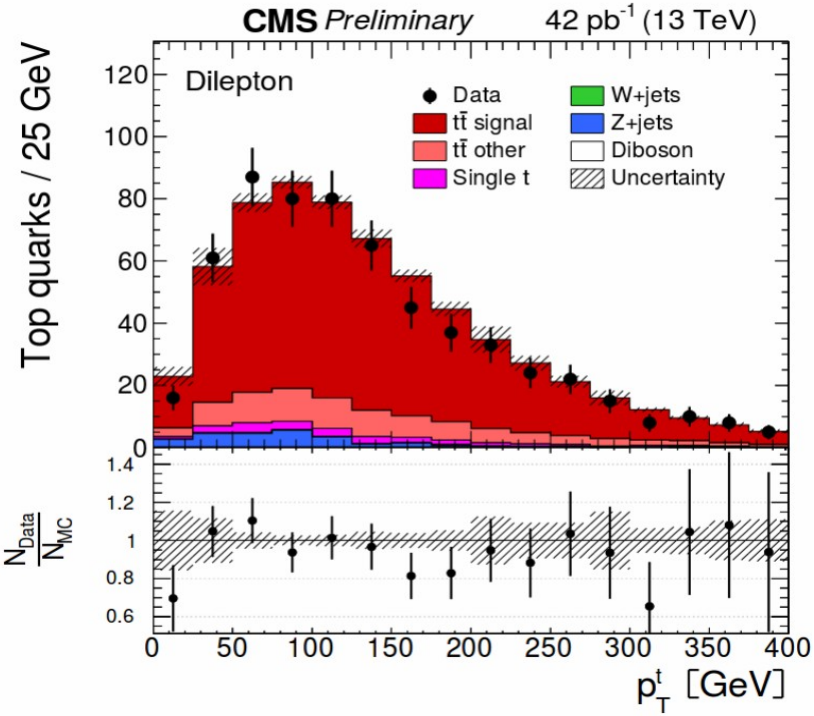


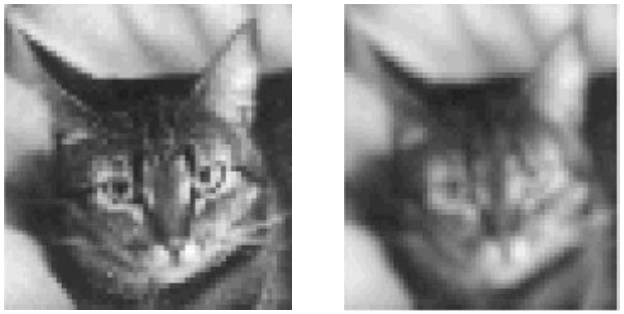
G. Cowan, „Statistical Data Analysis“



Differential Measurements

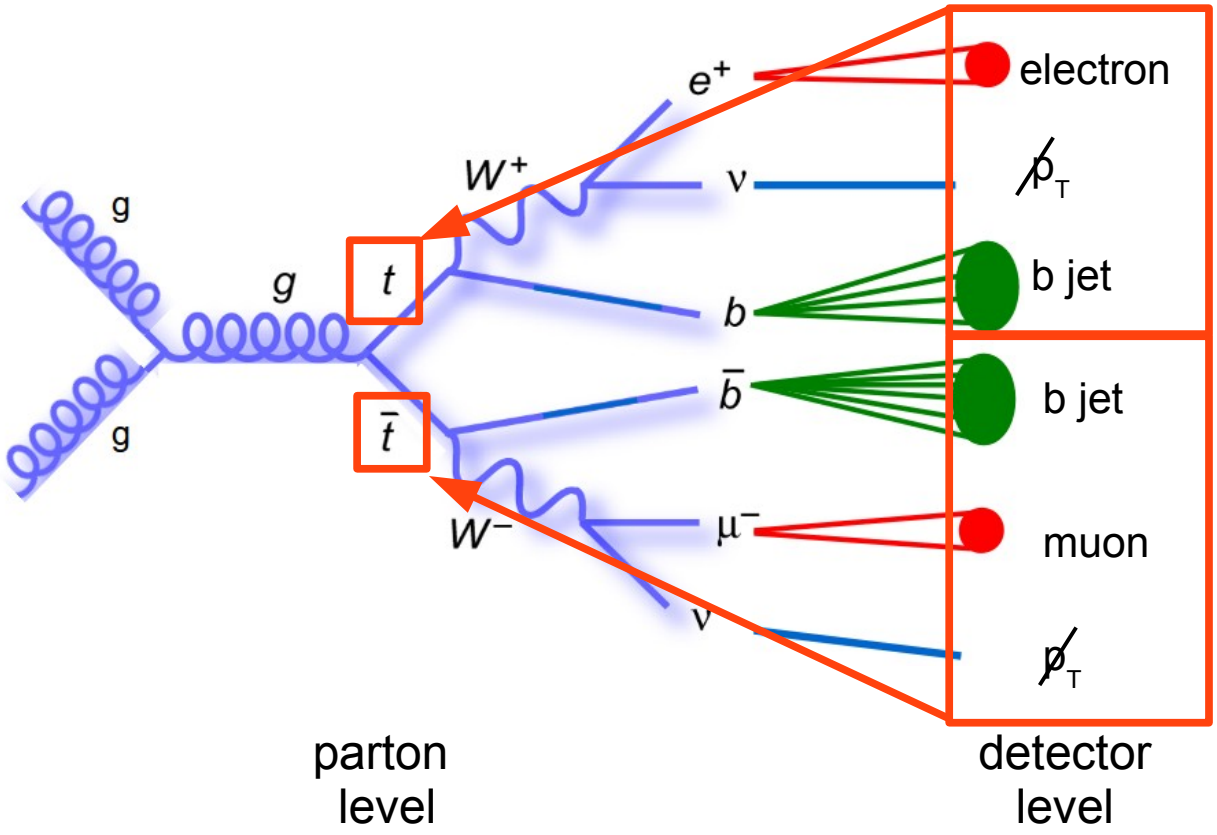


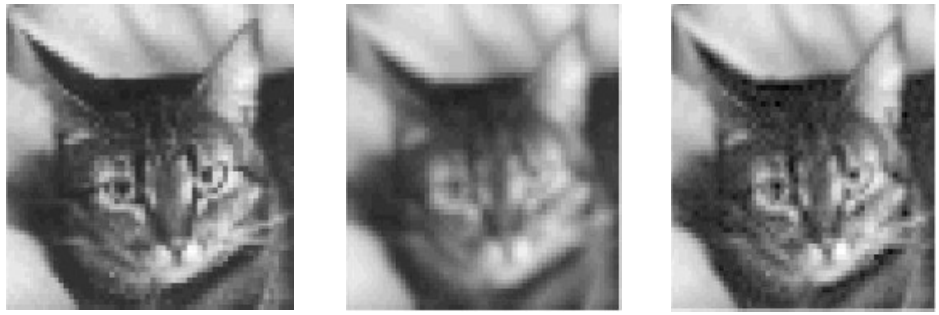




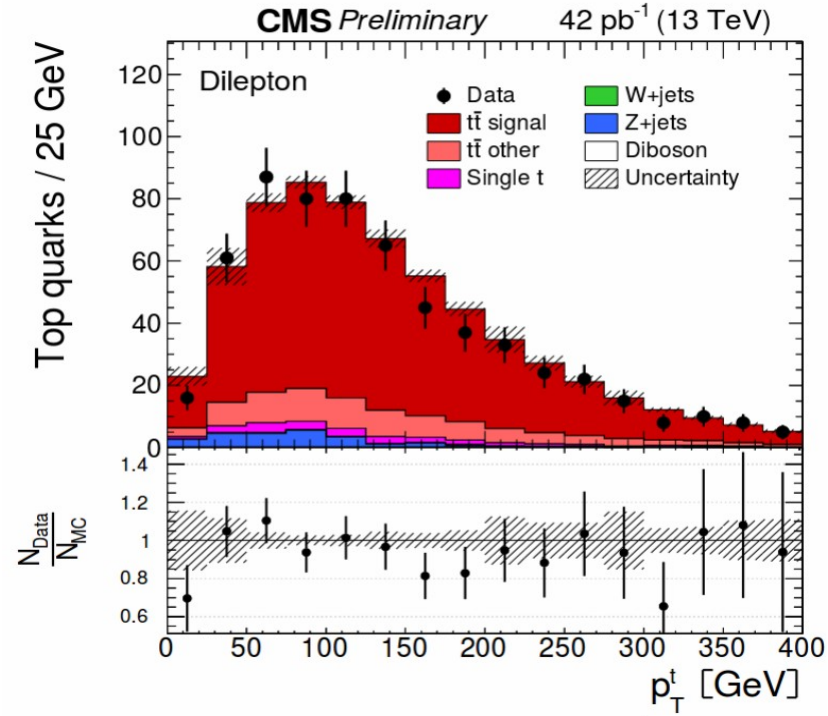
G. Cowan, „Statistical Data Analysis“

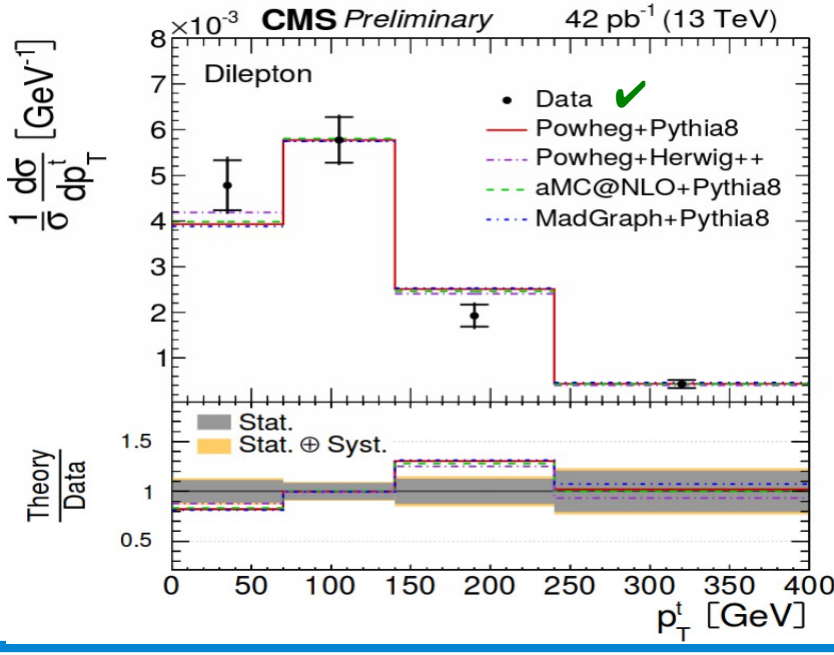
Differential Measurements



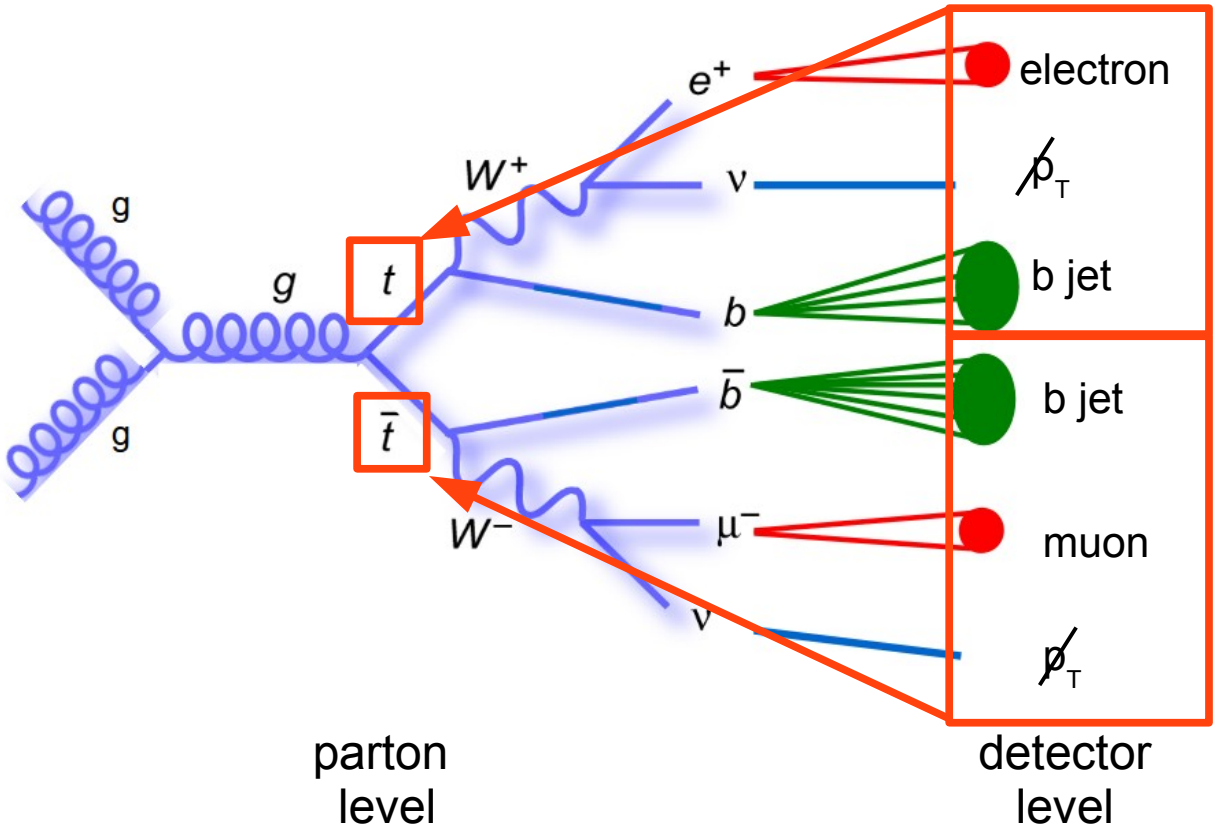


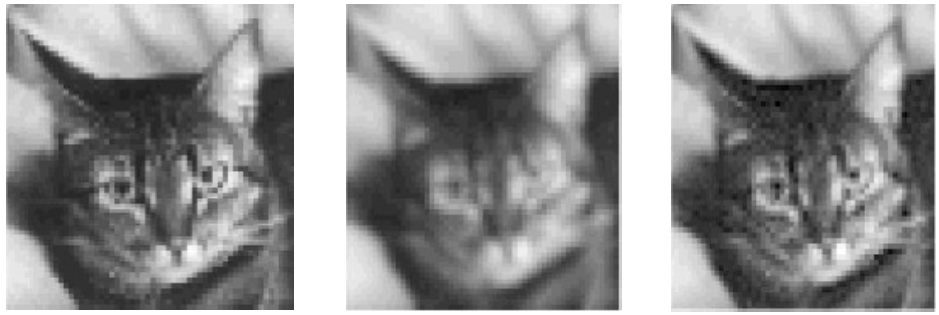
G. Cowan, „Statistical Data Analysis“



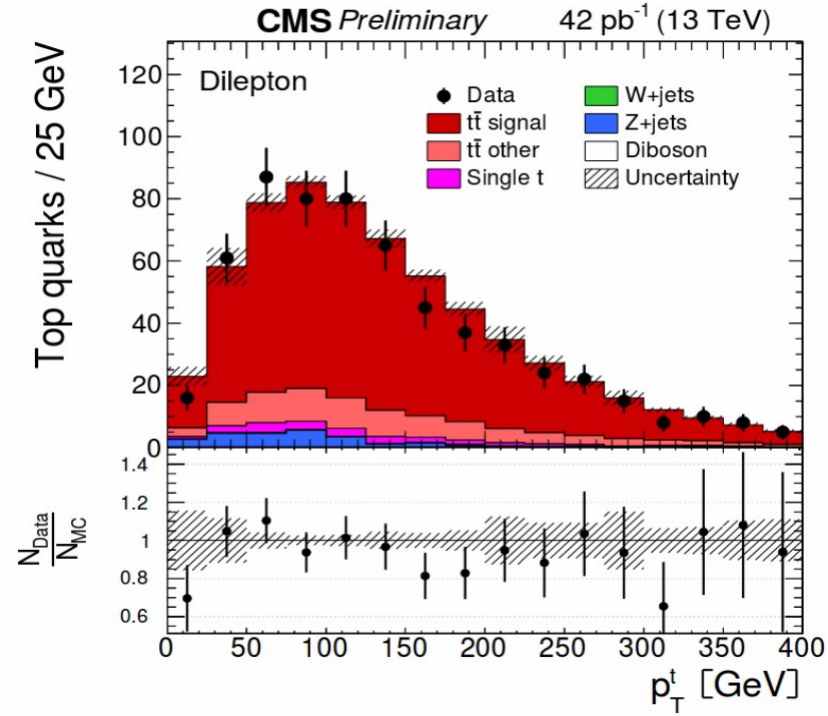


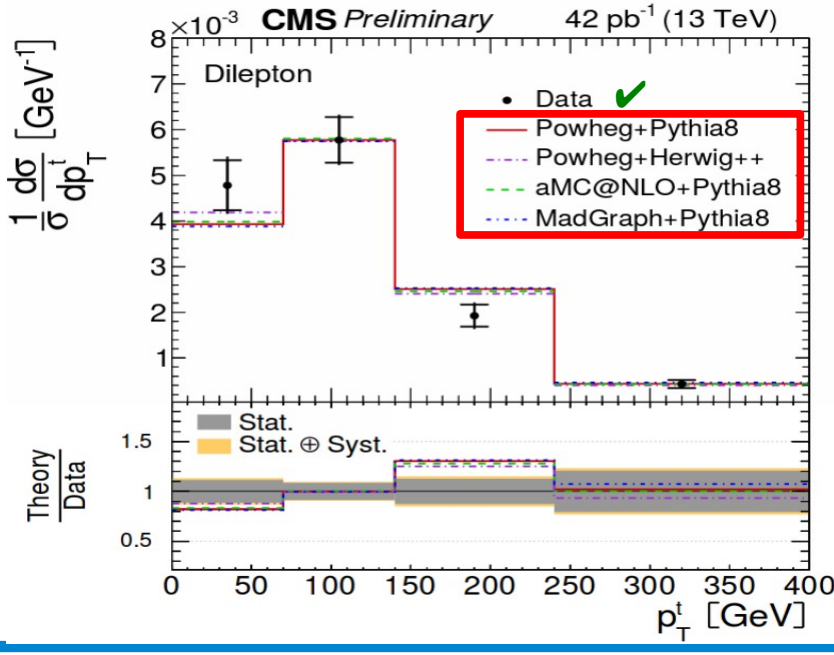
Differential Measurements





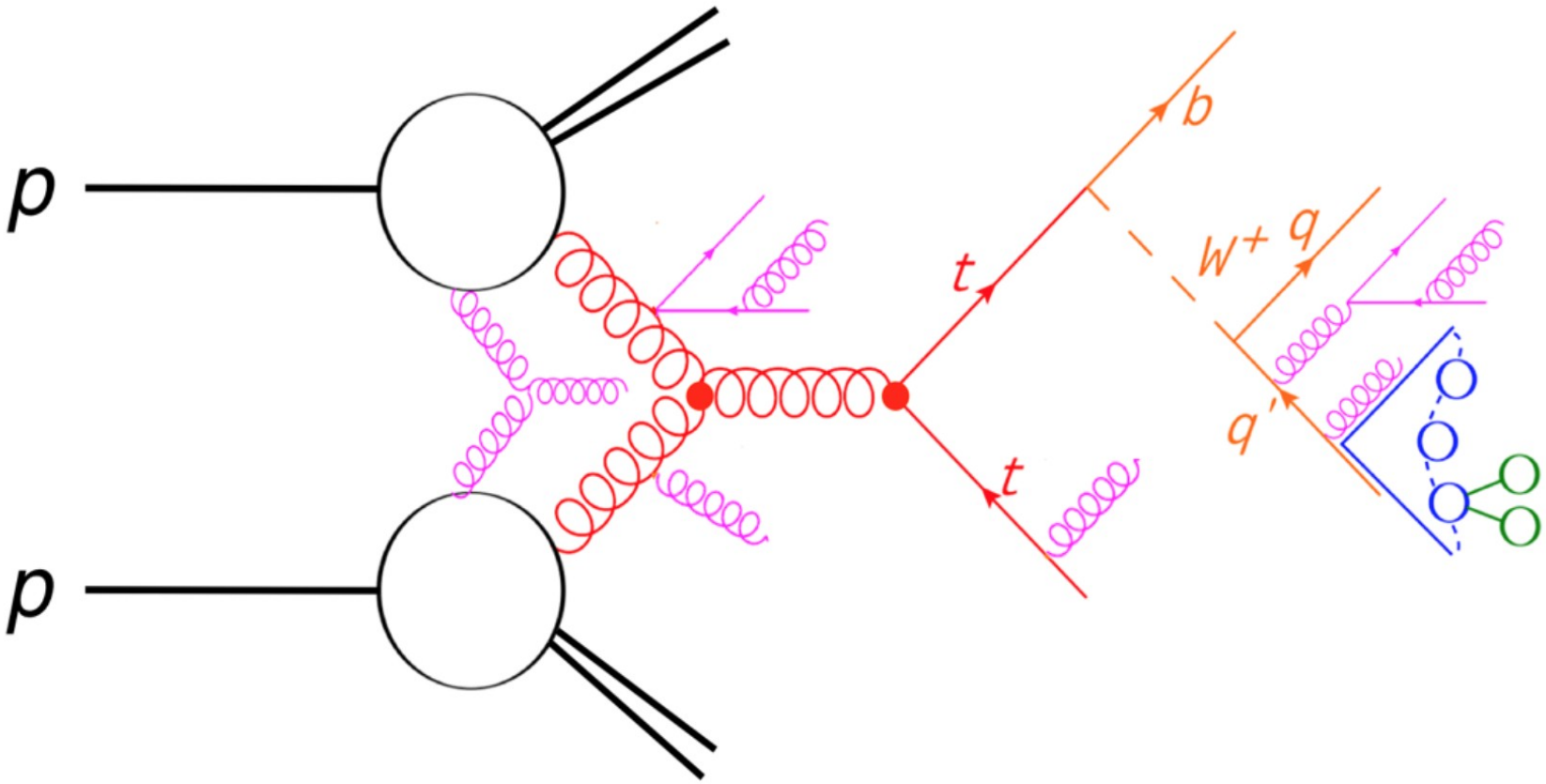
G. Cowan, „Statistical Data Analysis“





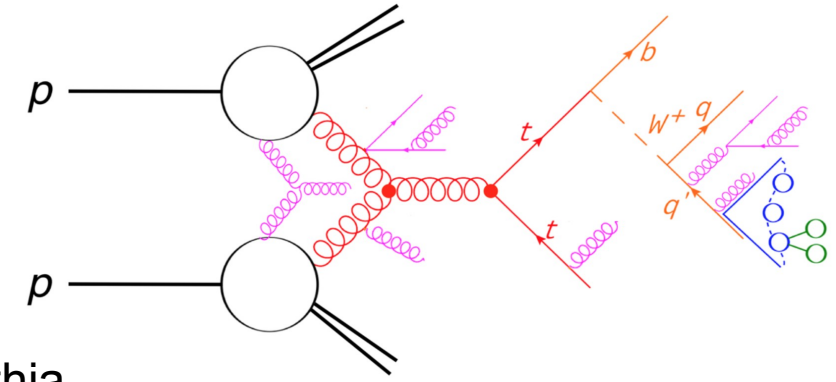
A Phenomenological Revolution

- LO QCD + parton shower generators:
  Pythia, Herwig, ...

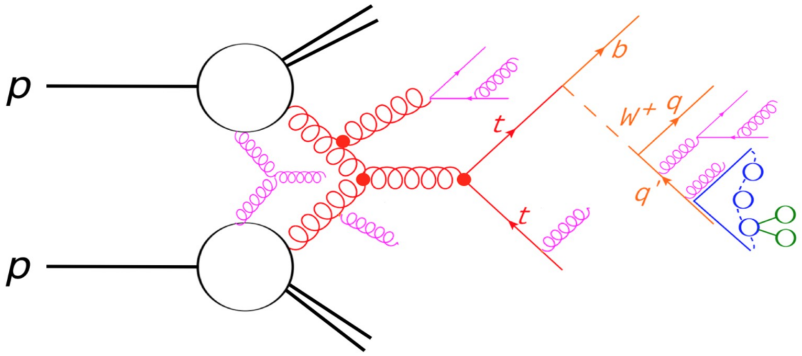


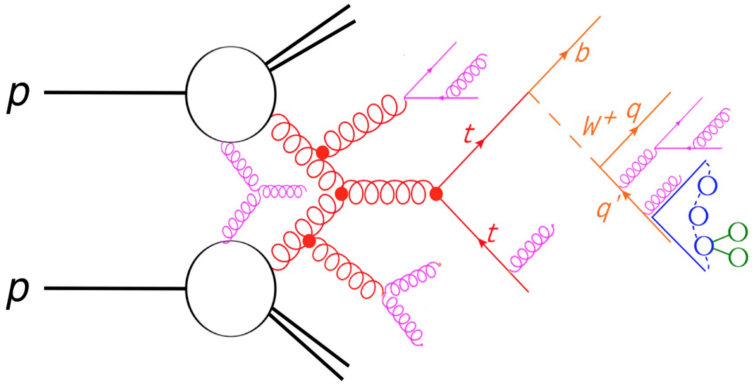
A Phenomenological Revolution

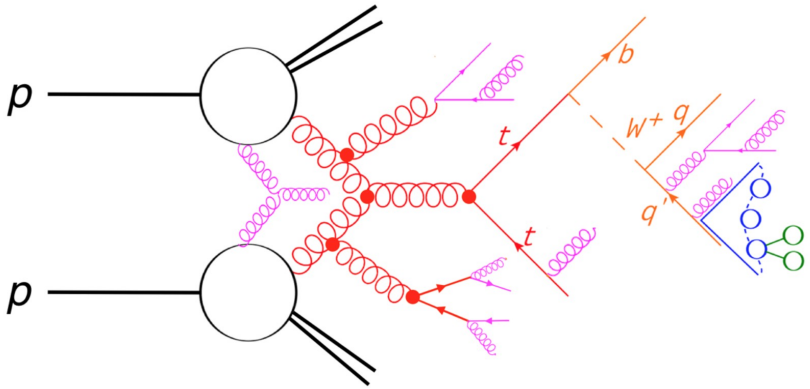
- LO QCD + parton shower generators:
  Pythia, Herwig, ...



- LO multileg generators matched with parton shower:
  Alpgen+Pythia, Alpgen+Herwig, Madgraph+Pythia,...



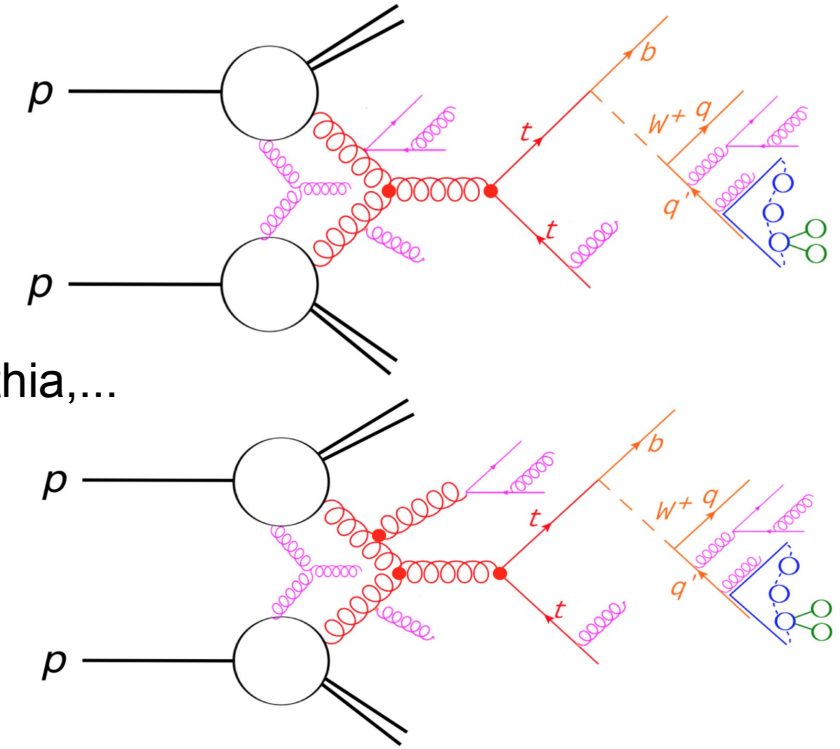


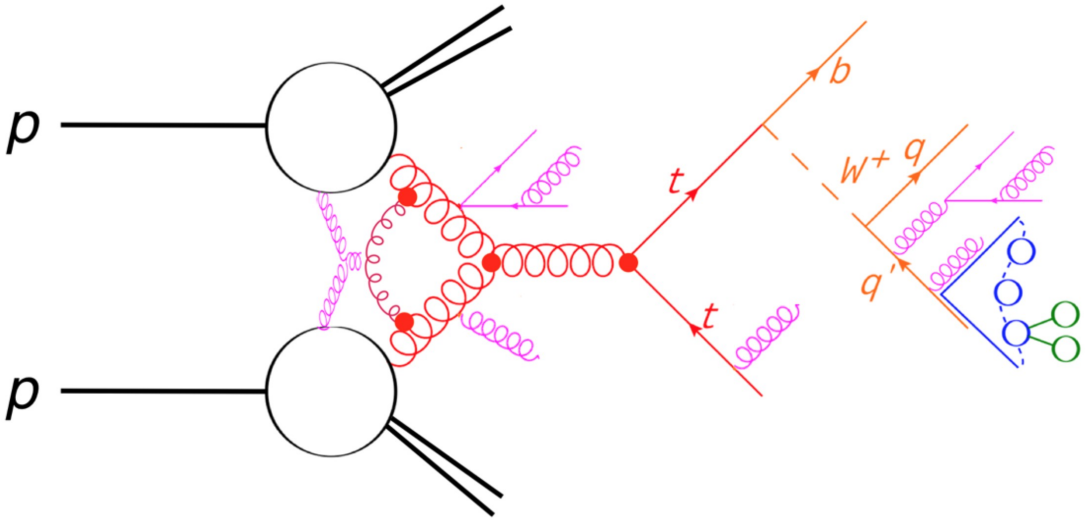


...

A Phenomenological Revolution

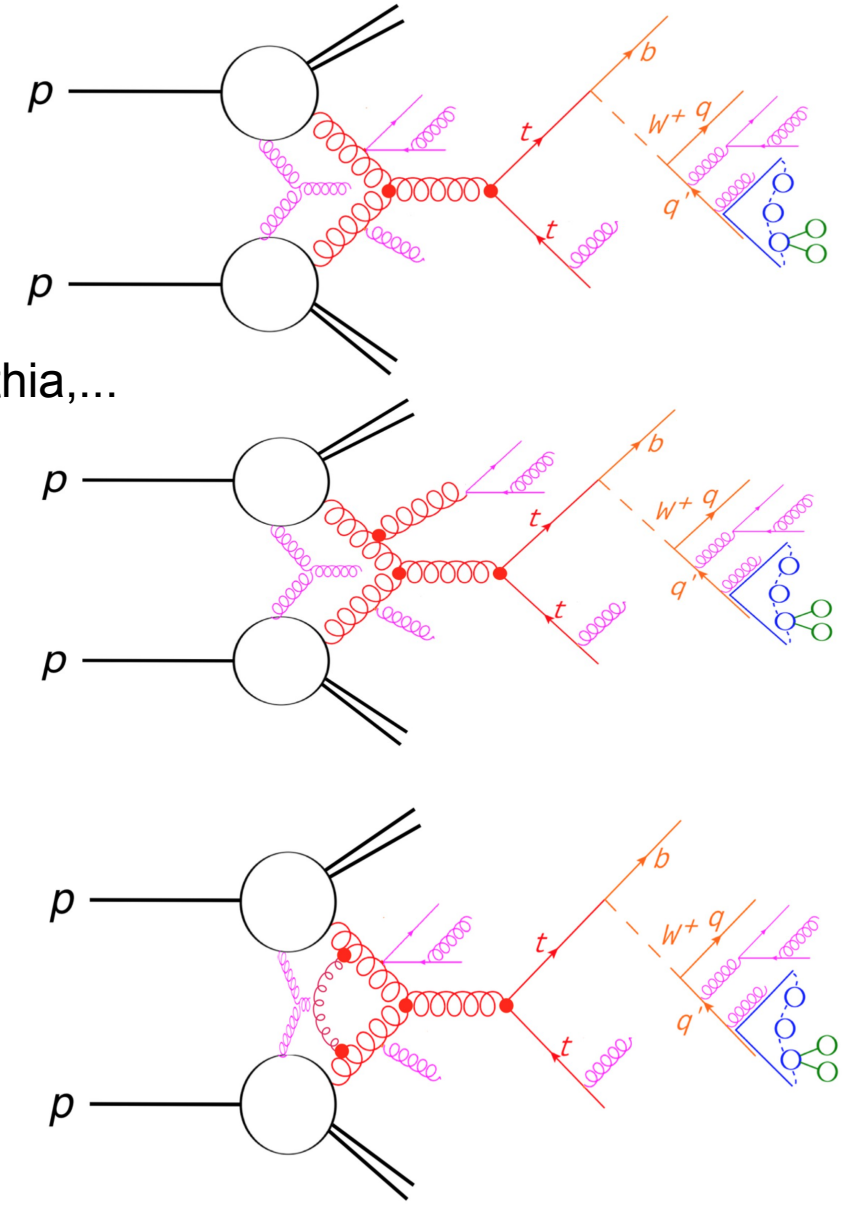
- LO QCD + parton shower generators:
  Pythia, Herwig, ...
- LO multileg generators matched with parton shower:
  Alpgen+Pythia, Alpgen+Herwig, Madgraph+Pythia,...
- NLO + parton shower generators:
  Powheg+Pythia, MC@NLO+Herwig





A Phenomenological Revolution

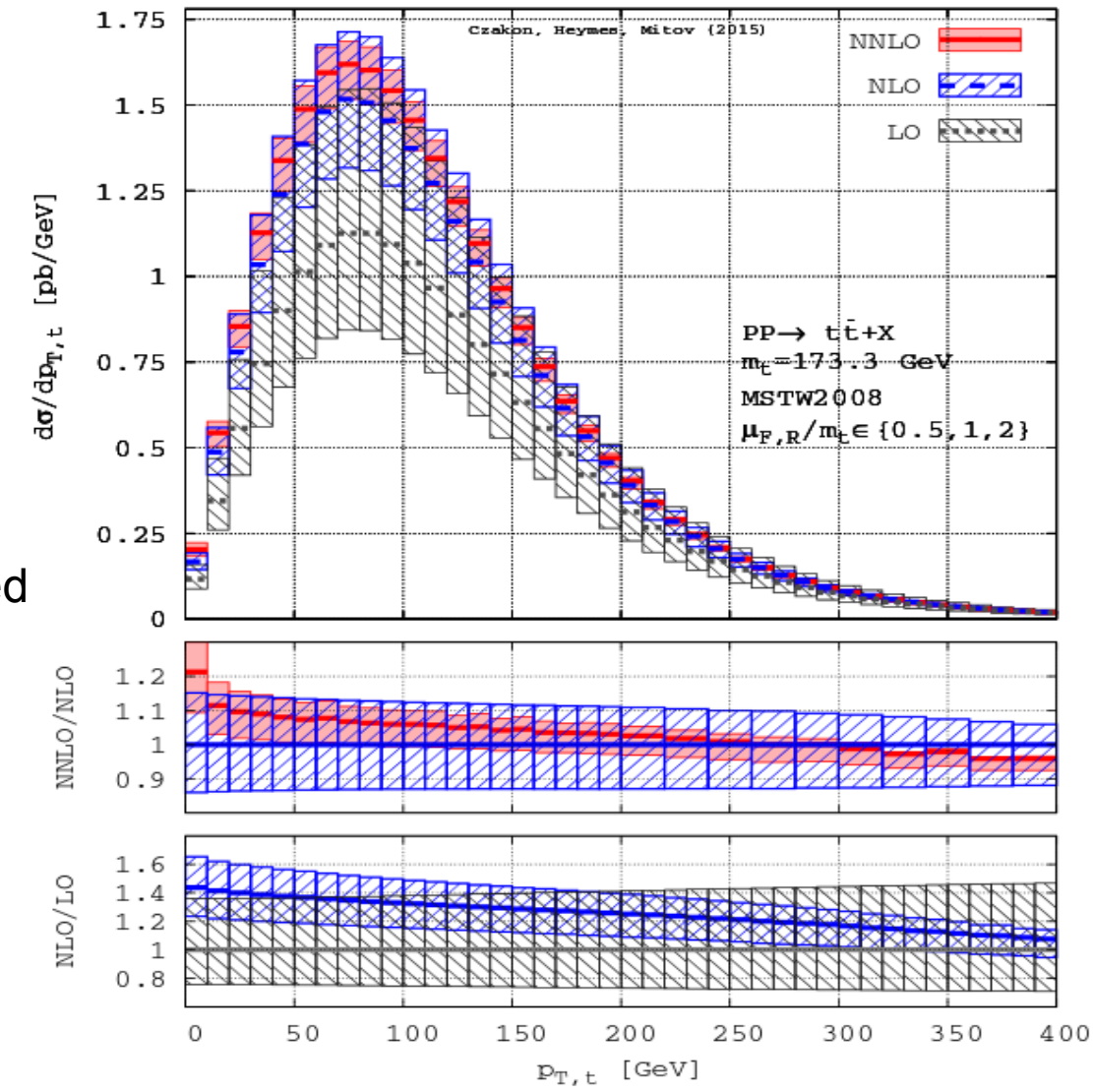
- LO QCD + parton shower generators:
  Pythia, Herwig, ...
- LO multileg generators matched with parton shower:
  Alpgen+Pythia, Alpgen+Herwig, Madgraph+Pythia,...
- NLO + parton shower generators:
  Powheg+Pythia, MC@NLO+Herwig
- NLO + LO multileg generators matched with parton showers: Sherpa, ...



A Phenomenological Revolution

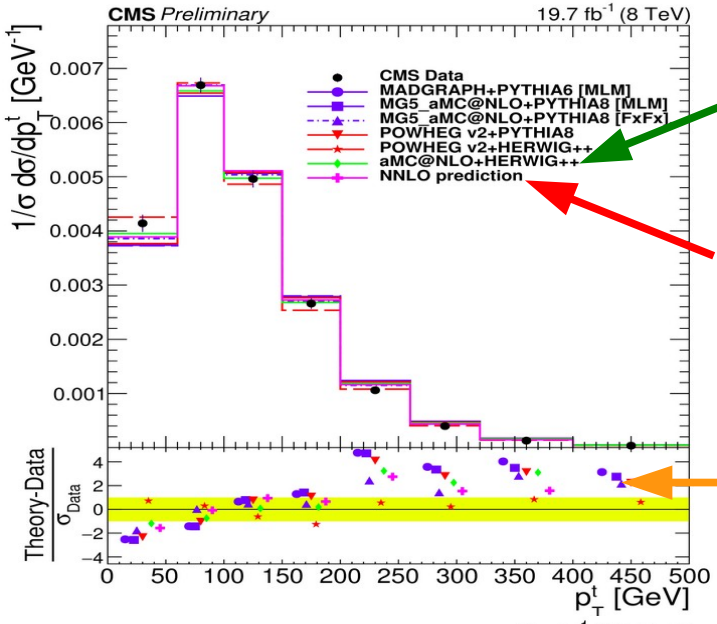
- LO QCD + parton shower generators: Pythia, Herwig, ...
- LO multileg generators matched with parton shower: Alpgen+Pythia, Alpgen+Herwig.
- NLO + parton shower generators: Powheg+Pythia, MC@NLO+Herwig
- NLO + LO multileg generators matched with parton showers: Sherpa, ...
- NNLO QCD calculations

arXiv:151.00549



exciting perspectives for precision differential measurements

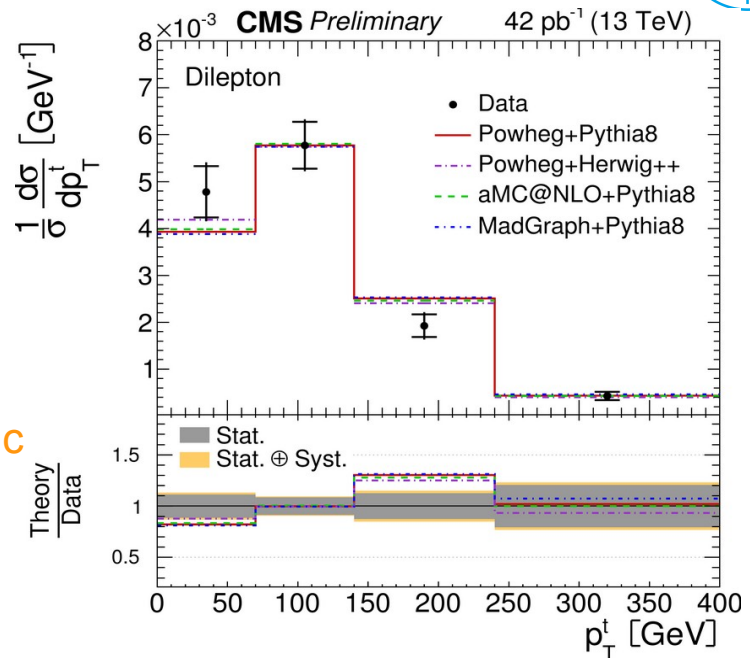
Differential Distributions: Top p_T

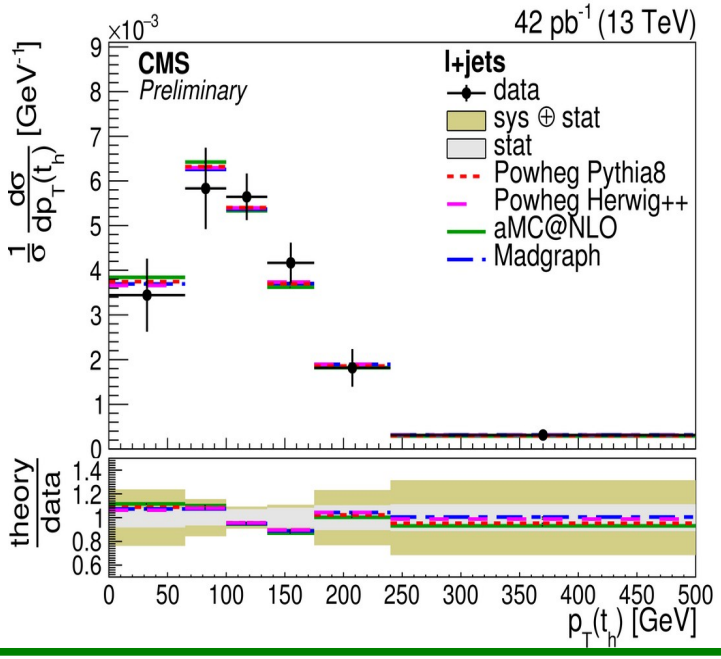


best performance

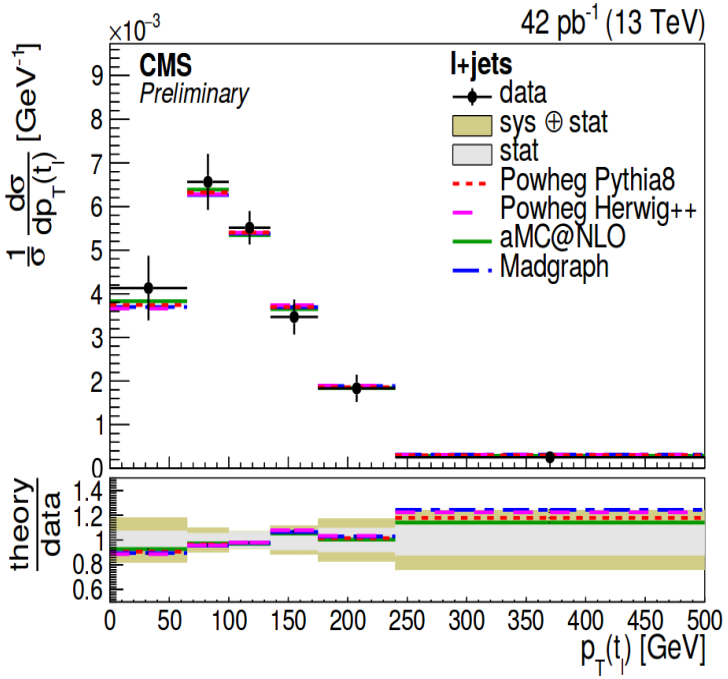
good agreement

slope in both dileptonic and semileptonic channel



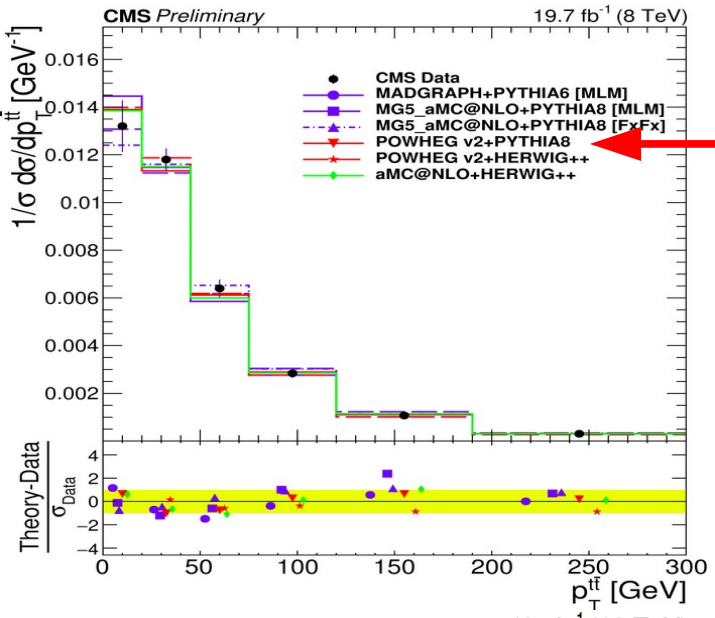


first 13 TeV results

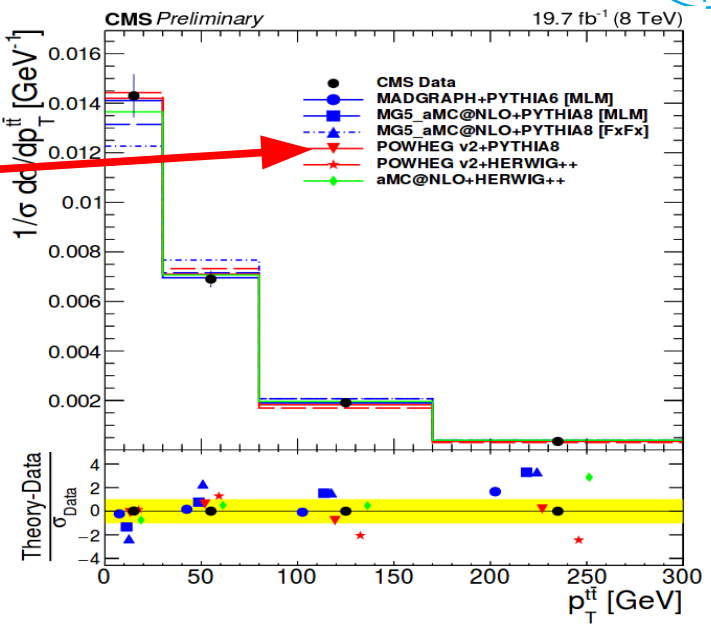


CMS-PAS-Top-15-011, 15-005, 15-010

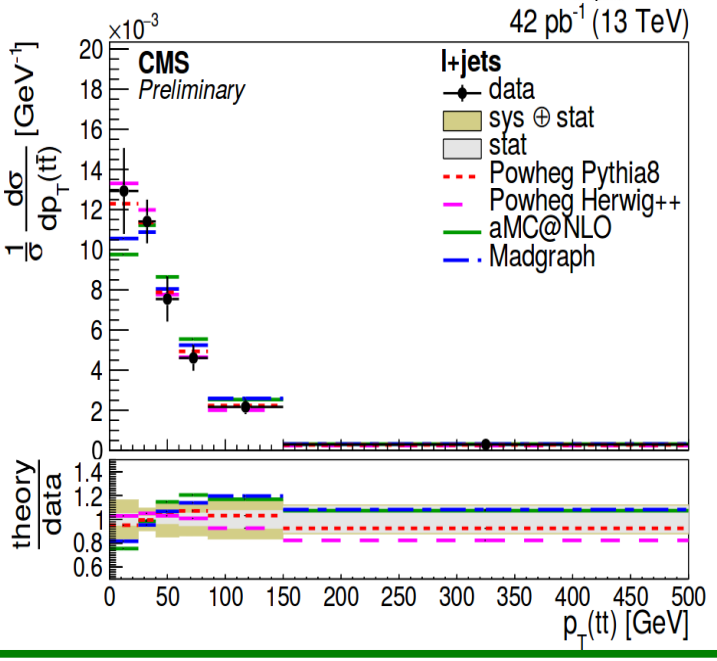
Differential Distributions: $t\bar{t}$ p_T



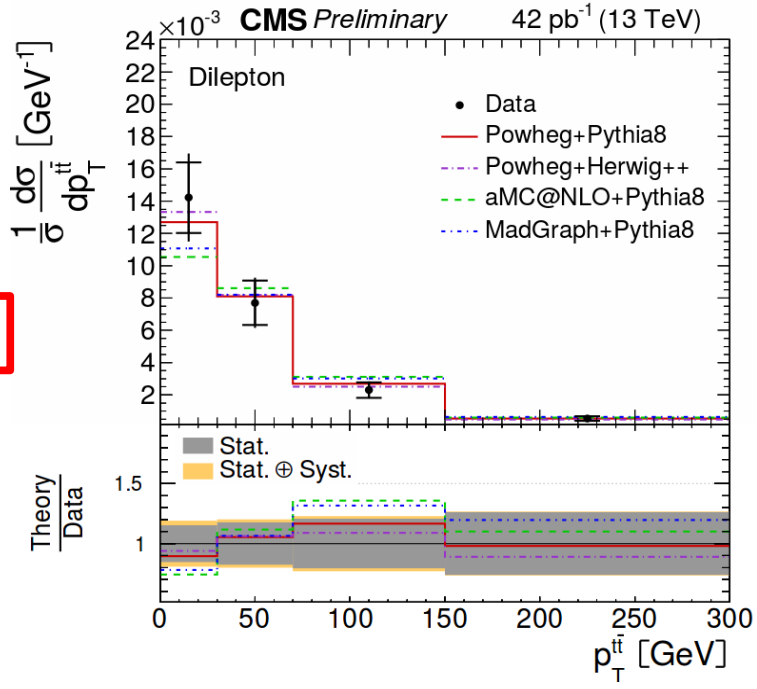
best performance



differences between dileptonic and semileptonic channels for high p_T

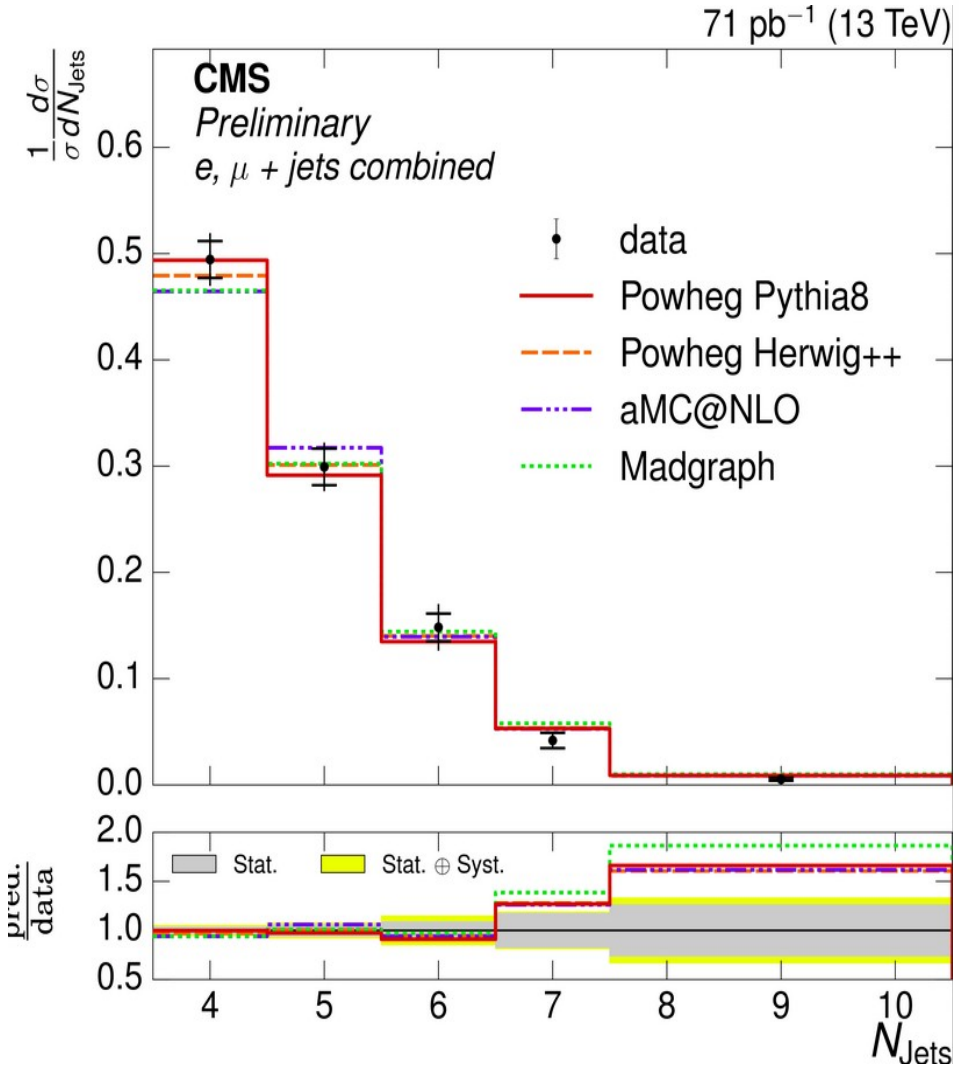


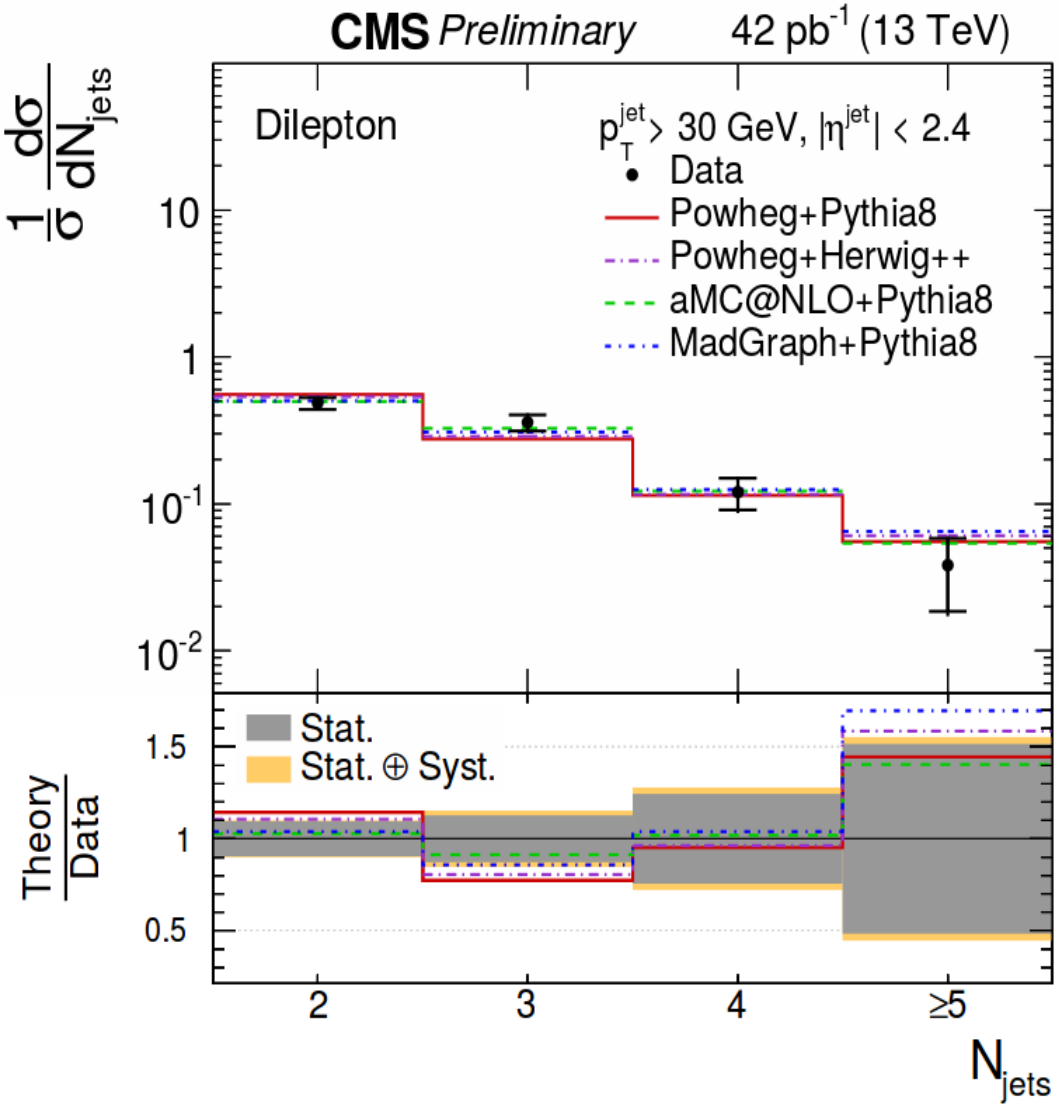
first 13 TeV results



CMS-PAS-Top-15-011, 15-005, 15-010

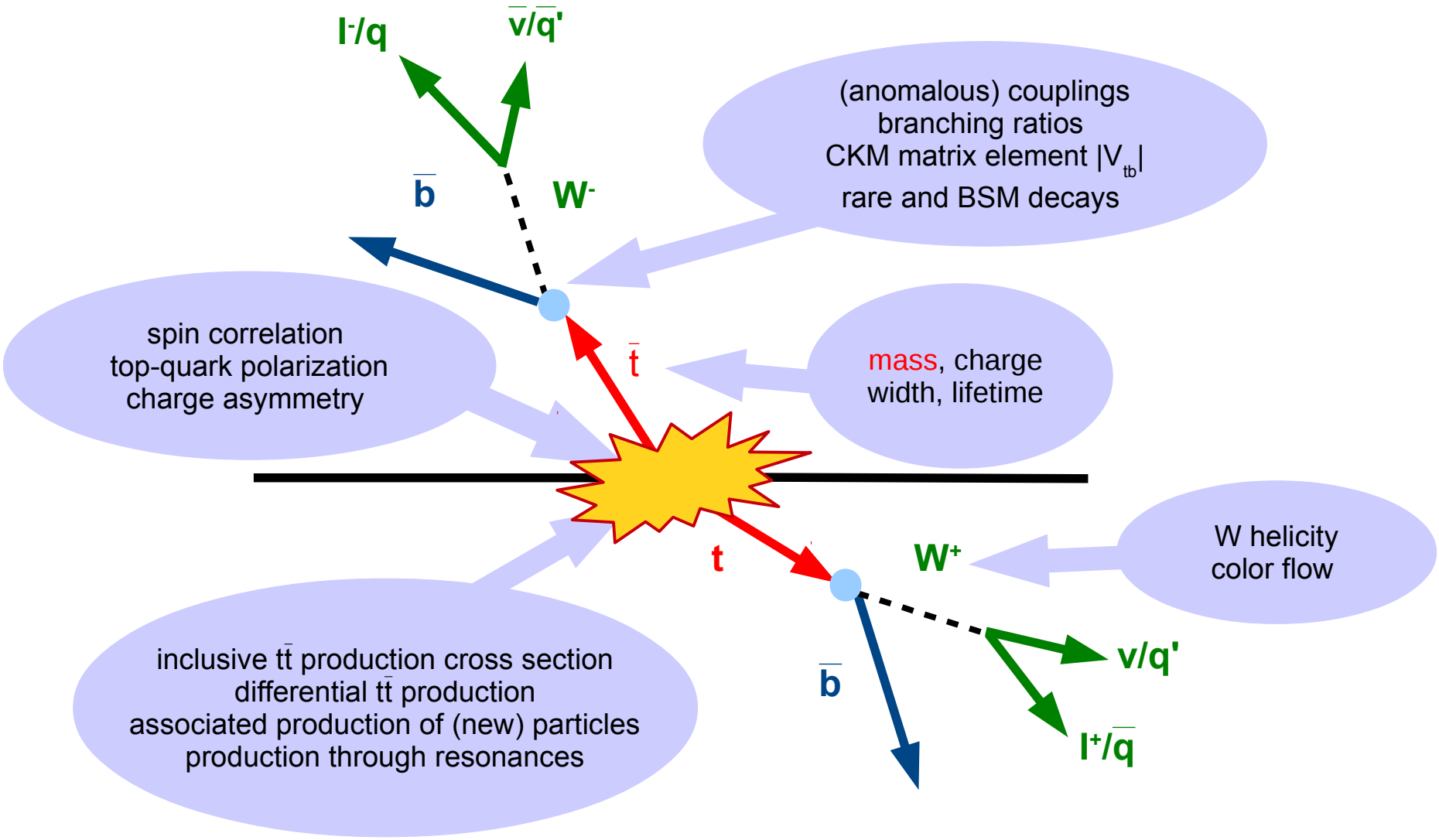
Differential Distributions: Jet Multiplicity





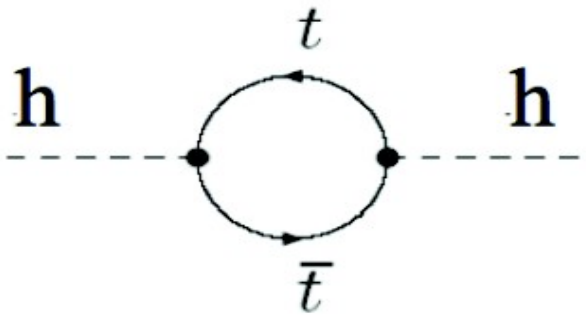
high jet multiplicity bins overestimated in MC

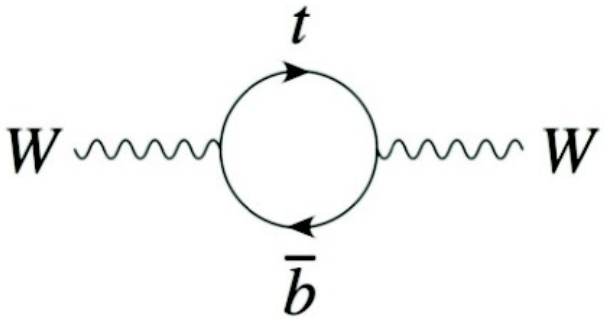
CMS-PAS-Top-15-011, 15-005, 15-010

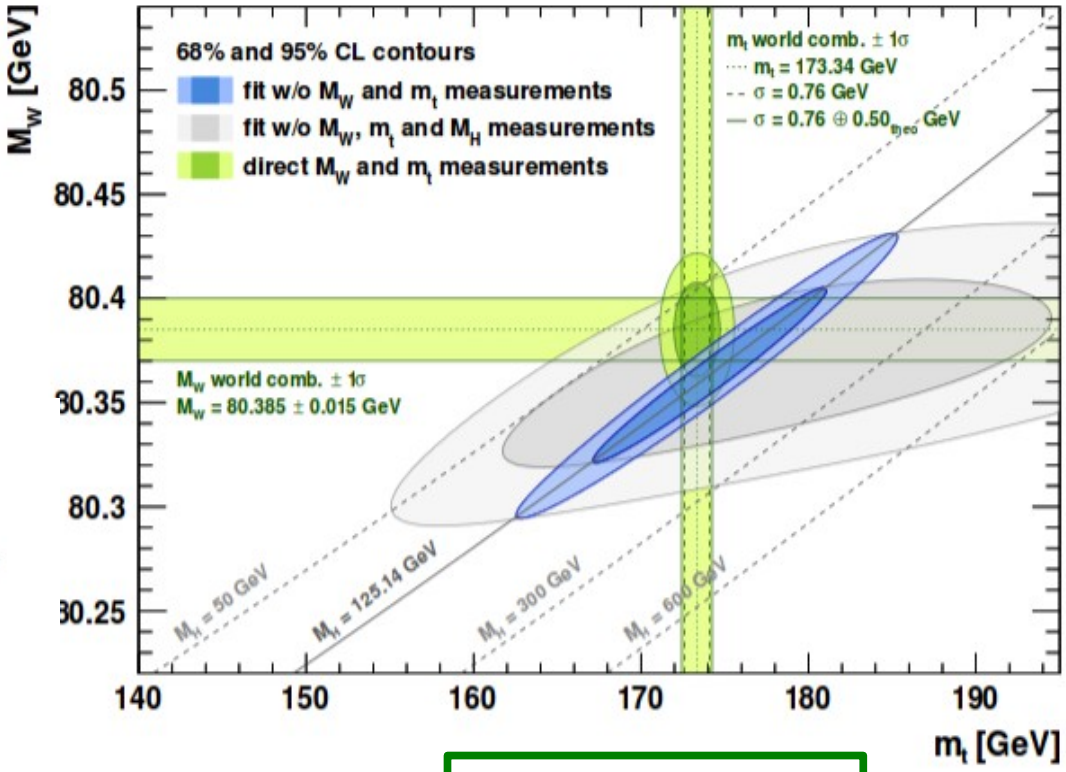

l⁻/q
ν̄/q̄'
b̄
W⁻
(anomalous) couplings
branching ratios
CKM matrix element |V_tb|
rare and BSM decays
spin correlation
top-quark polarization
charge asymmetry
t̄
mass, charge
width, lifetime
t
W⁺
W helicity
color flow
inclusive tt̄ production cross section
differential tt̄ production
associated production of (new) particles
production through resonances
b̄
ν/q'
l⁺/q̄

The Top Quark Mass

- in combination with W and Higgs mass: self-consistency of the SM



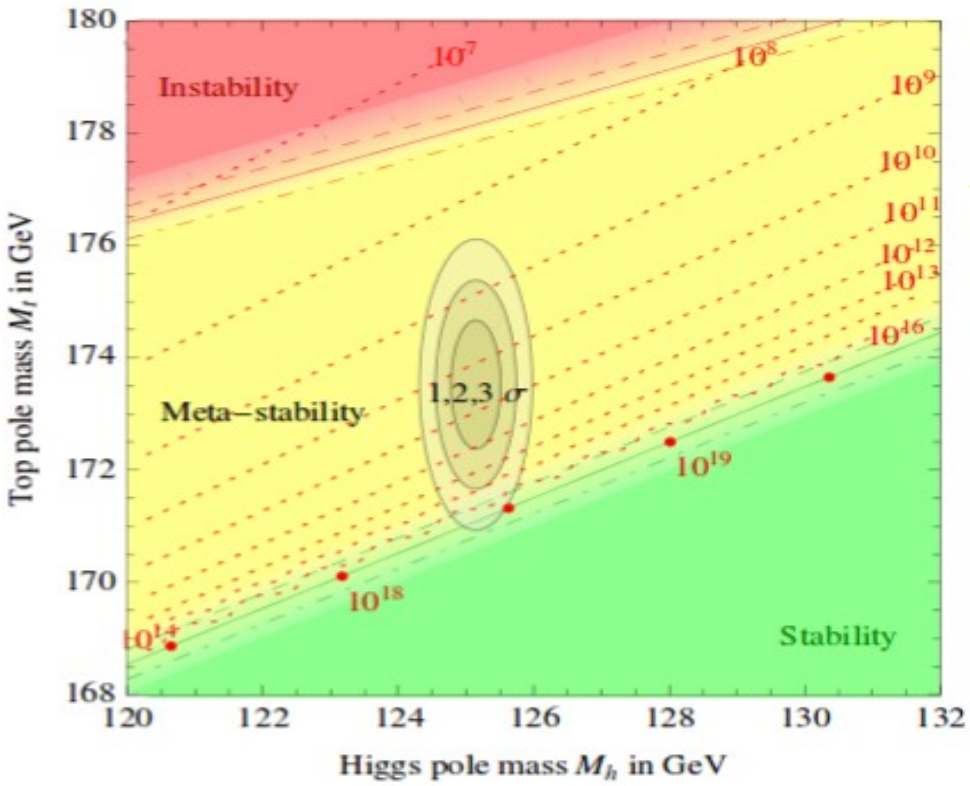


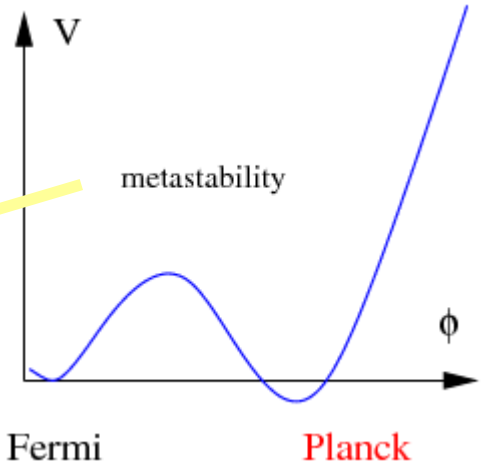


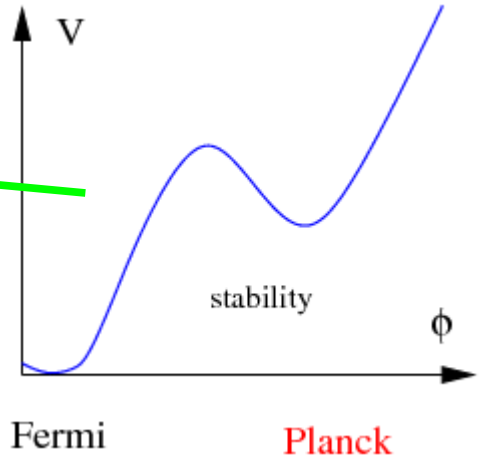
arXiv:1407.3792

The Top Quark Mass

- in combination with W and Higgs mass: self-consistency of the SM
- stability of the Higgs potential



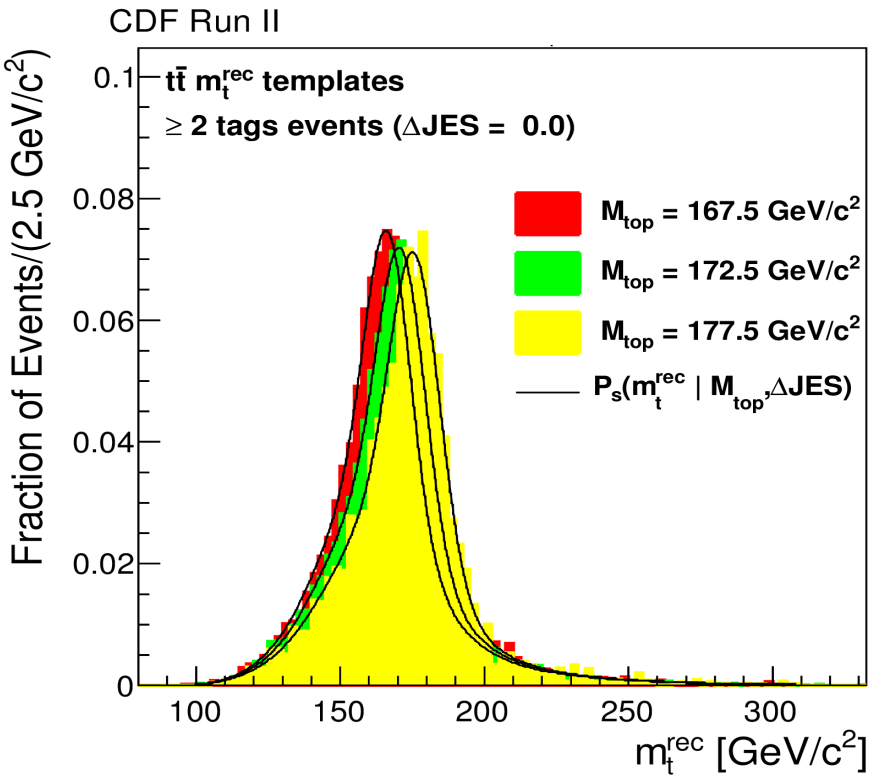




arXiv:1307.3536

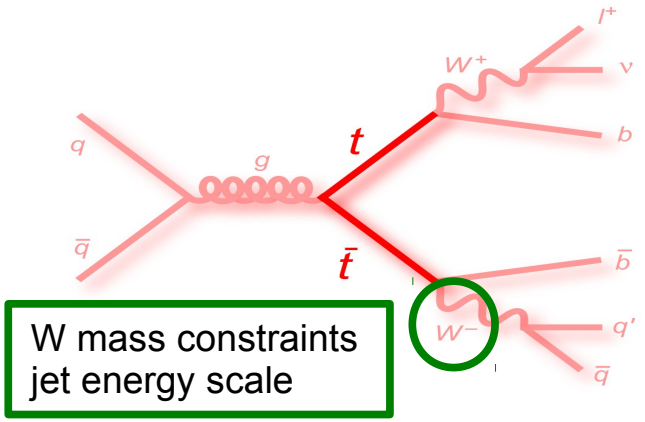
Measurement Techniques

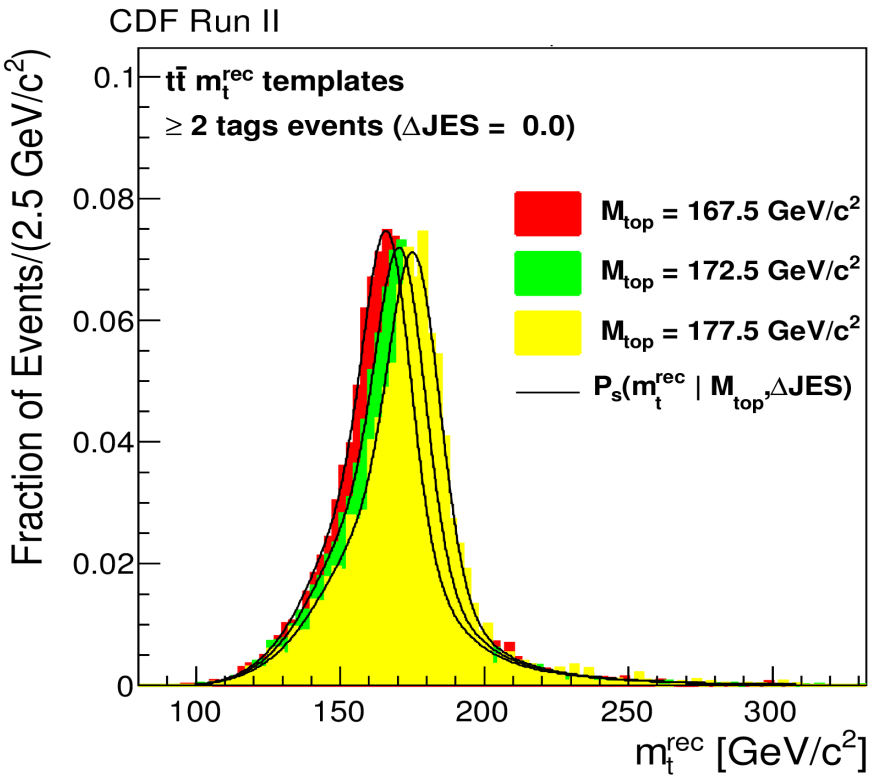
- use variables strongly correlated with m_t
- compare data to MC with different top mass hypotheses

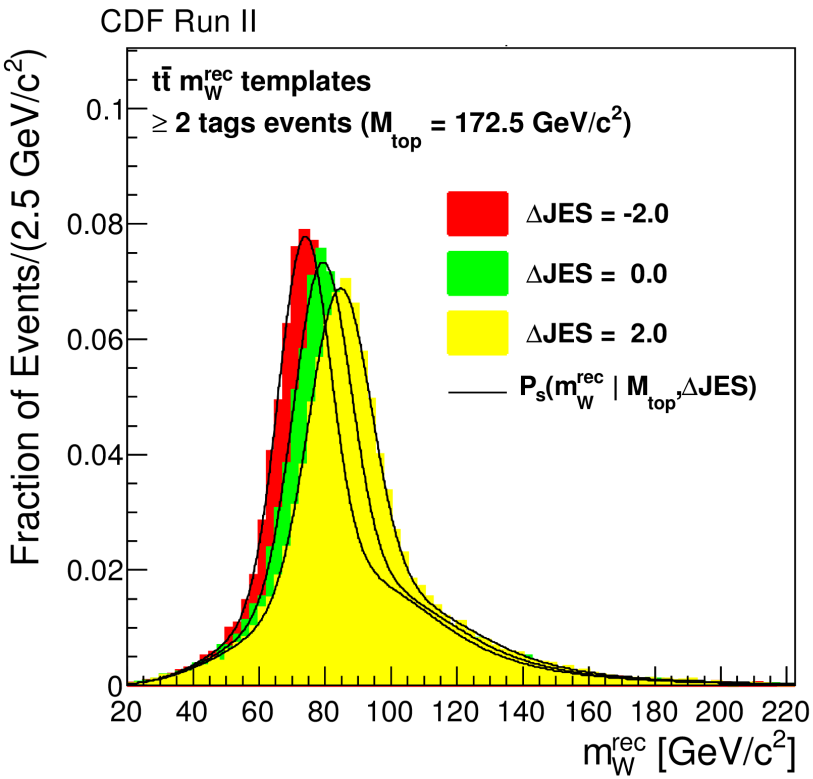


Measurement Techniques

- use variables strongly correlated with m_t
- compare data to MC with different top mass hypotheses

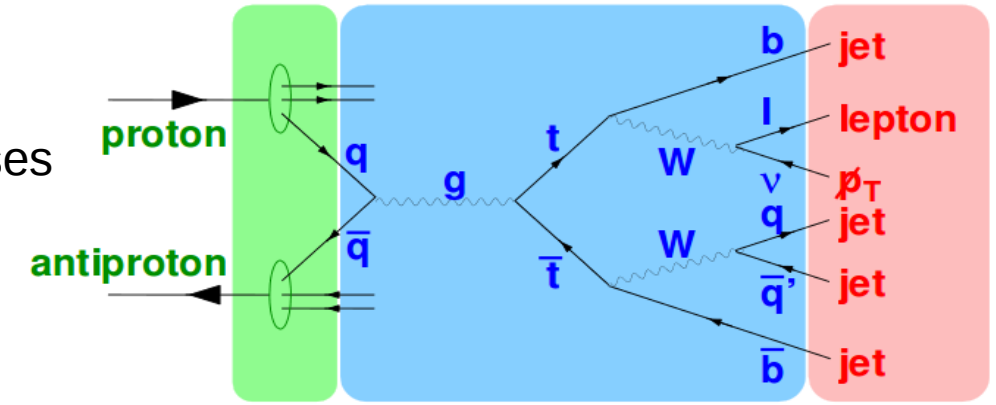






Matrix Element Method

- optimized usage of kinematic and topological information
- LO $t\bar{t}$ matrix element:
  - depending on (m_t,JES,...) hypotheses
  - PDFs and detector resolution

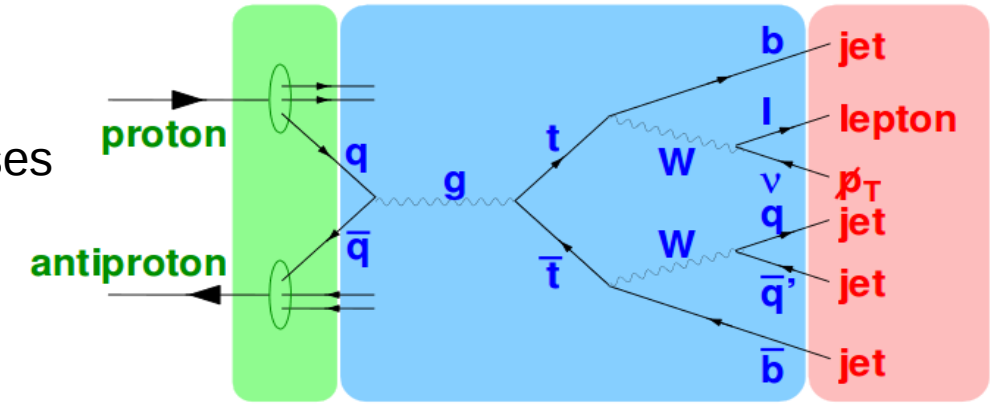


f_{PDF}: Partonverteilung ; $M(y; m_t, JES)$: LO ME fuer Partonen y
$W(x, y)$: Detektoraufloseung$(y \rightarrow x)$; w_{btag}: $b-Tagging-Gewicht$

$$P_{t\bar{t}}(x; m_t, JES) \propto \sum_{i=1}^{24} w_{btag,i} \int d\epsilon_1 d\epsilon_2 f_{PDF}(\epsilon_1) f_{PDF}(\epsilon_2) \frac{|M(y; m_t, JES)|^2}{\epsilon_1 \epsilon_2 s} W(x, y) d\varphi_6$$

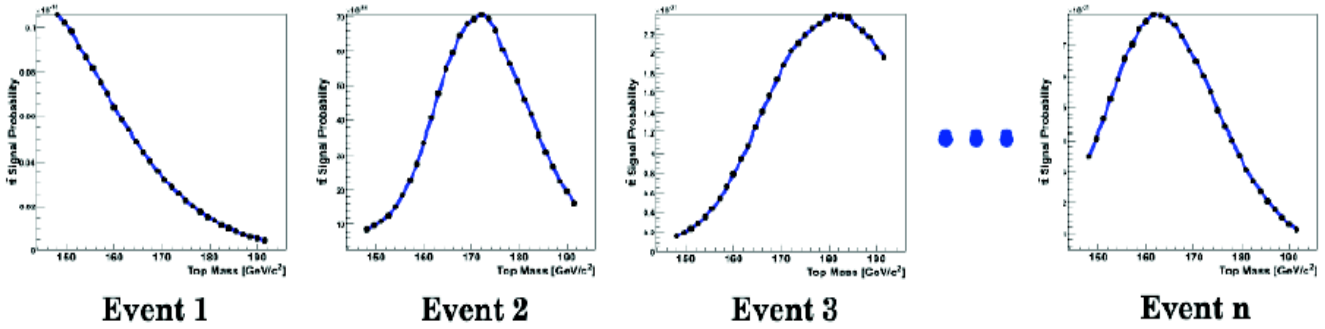
Matrix Element Method

- optimized usage of kinematic and topological information
- LO $t\bar{t}$ matrix element
  - depending on (m_t,JES,...) hypotheses
  - PDFs and detector resolution



- combination of signal and background probabilities:

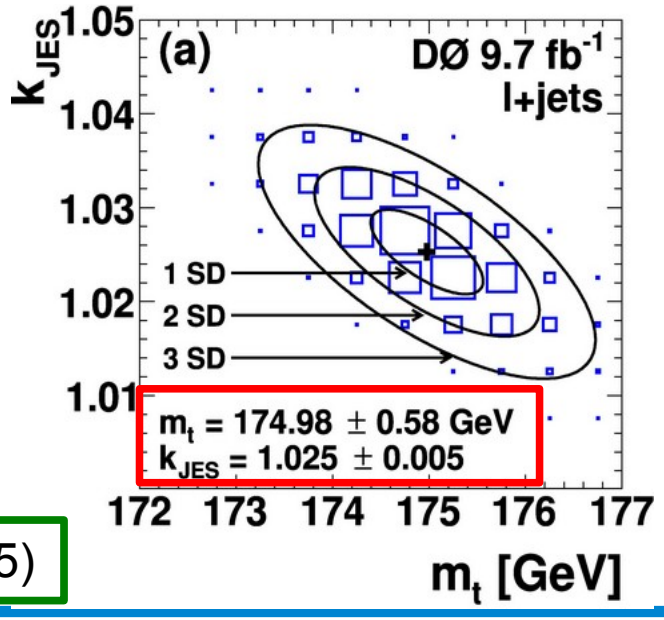
$$P_{evt}(x;m_t,JES)=f_{t\bar{t}}\,P_{t\bar{t}}(x;m_t,JES)+(1-f_{sgn})\,P_{bkg}(x;JES)$$



Top Mass at the Tevatron

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections	+0.15
Initial/final state radiation	±0.09
Hadronization and UE	+0.26
Color reconnection	+0.10
Multiple $p\bar{p}$ interactions	−0.06
Heavy flavor scale factor	±0.06
b-jet modeling	+0.09
PDF uncertainty	±0.11
Detector modeling:	
Residual jet energy scale	±0.21
Flavor-dependent response to jets	±0.16
b tagging	±0.10
Trigger	±0.01
Lepton momentum scale	±0.01
Jet energy resolution	±0.07
Jet ID efficiency	−0.01
Method:	
Modeling of multijet events	+0.04
Signal fraction	±0.08
MC calibration	±0.07
Total systematic uncertainty	±0.49

± 0.43 %

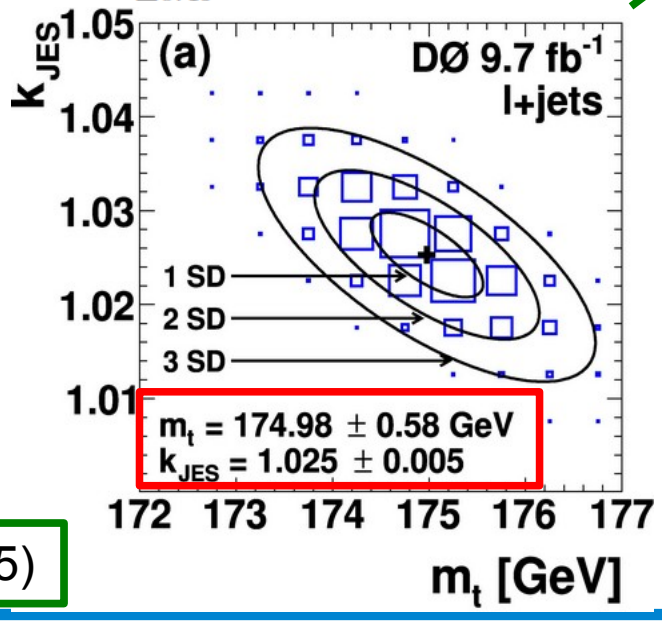


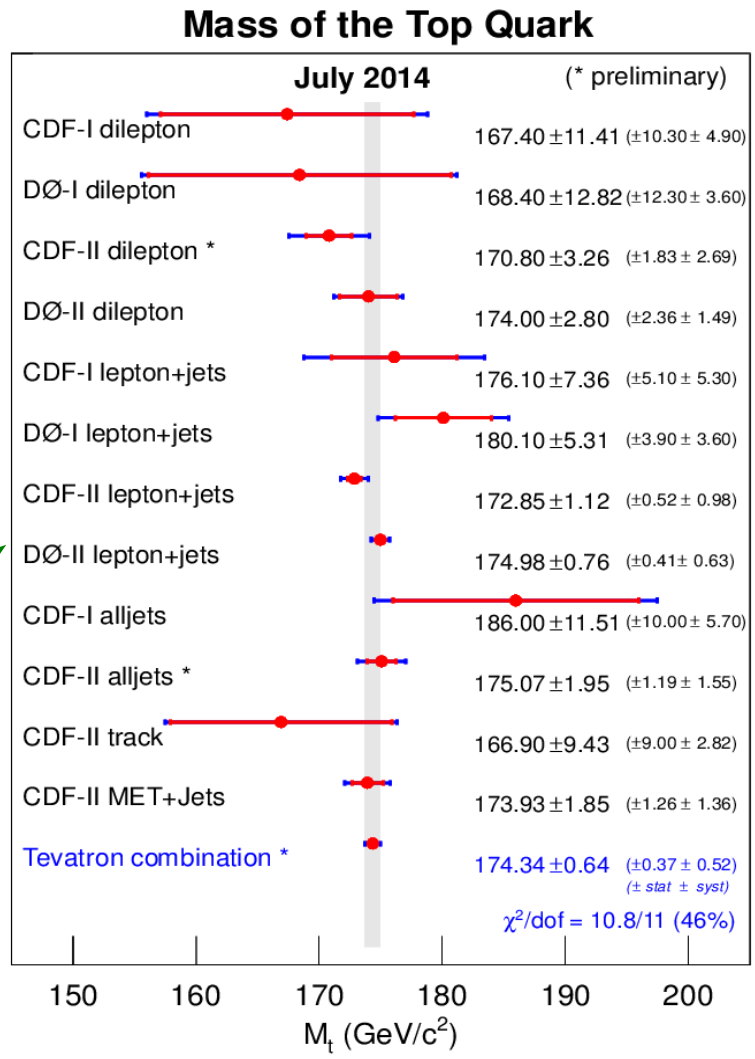
PRD 91, 112003 (2015)

Top Mass at the Tevatron

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections	+0.15
Initial/final state radiation	±0.09
Hadronization and UE	+0.26
Color reconnection	+0.10
Multiple $p\bar{p}$ interactions	−0.06
Heavy flavor scale factor	±0.06
b-jet modeling	+0.09
PDF uncertainty	±0.11
Detector modeling:	
Residual jet energy scale	±0.21
Flavor-dependent response to jets	±0.16
b tagging	±0.10
Trigger	±0.01
Lepton momentum scale	±0.01
Jet energy resolution	±0.07
Jet ID efficiency	−0.01
Method:	
Modeling of multijet events	+0.04
Signal fraction	±0.08
MC calibration	±0.07
Total systematic uncertainty	±0.49

± 0.43 %

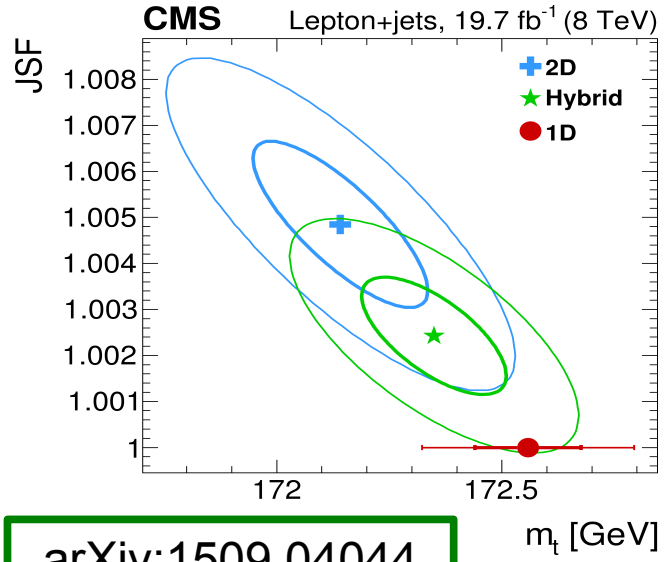




PRD 91, 112003 (2015)

good agreement between all channels

Top Mass at the LHC



± 0.29 %

most precise!

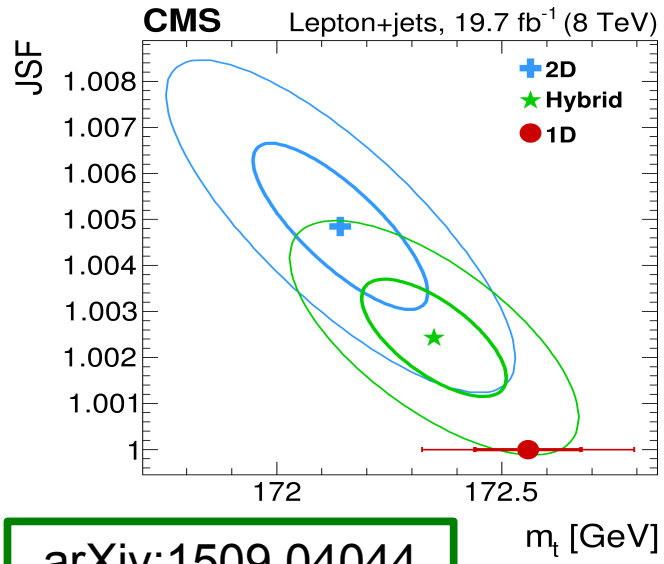
arXiv:1509.04044

m_t = 172.35 ± 0.16 (stat+JSF) ± 0.48 (syst) GeV

Modeling of perturbative QCD	
PDF	0.09
Ren. and fact. scales	$+0.17 \pm 0.0$
ME-PS matching threshold	$+0.11 \pm 0.09$
ME generator	-0.07 ± 0.11
Top quark p_T	+0.16
Modeling of soft QCD	
Underlying event	$+0.15 \pm 0.15$
Color reconnection modeling	$+0.11 \pm 0.13$
Total systematic	0.59
Statistical	0.20
Total	0.62

top event modeling crucial !

Top Mass at the LHC



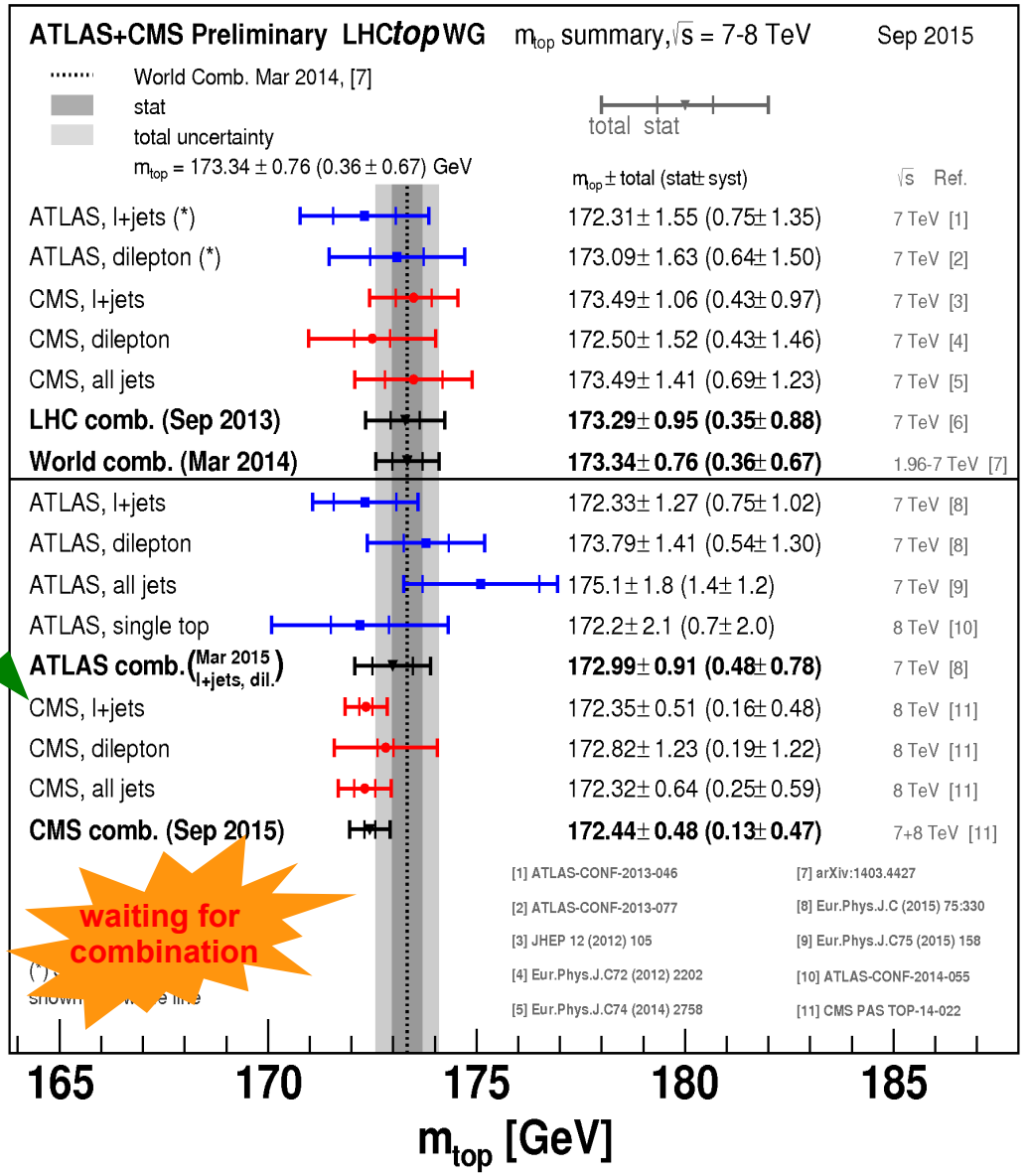
arXiv:1509.04044

m_t = 172.35 ± 0.16 (stat+JSF) ± 0.48 (syst) GeV

± 0.29 %

most precise!

Modeling of perturbative QCD	
PDF	0.09
Ren. and fact. scales	$+0.17 \pm 0.0$
ME-PS matching threshold	$+0.11 \pm 0.09$
ME generator	-0.07 ± 0.11
Top quark p_T	+0.16
Modeling of soft QCD	
Underlying event	$+0.15 \pm 0.15$
Color reconnection modeling	$+0.11 \pm 0.13$
Total systematic	0.59
Statistical	0.20
Total	0.62

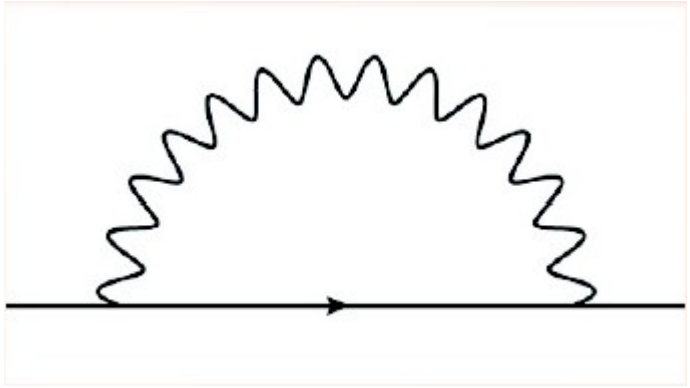


top event modeling crucial !

Definition of the Top Quark Mass

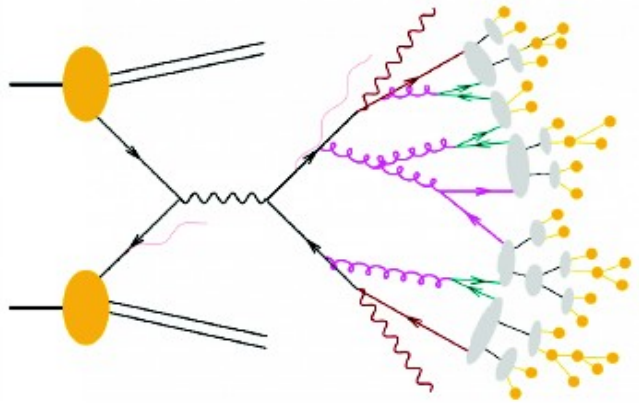
- beyond leading order: self-energy corrections

$$\frac{i}{\not p - m_0} \rightarrow \frac{i}{\not p - m_0 - \sum_{dive} - \sum_{fin}}$$

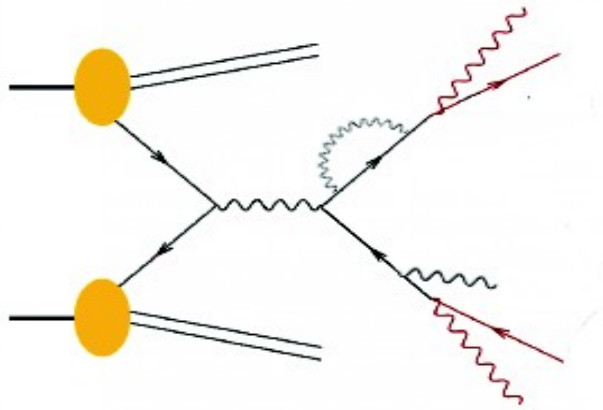


- m_t becomes renormalization scheme dependent:
  - pole mass, running masses e.g. $\overline{\text{MS}}$

- most precise measurement rely on MC mass (calibration):
  - difference to pole mass assumed to be ~ 1 GeV (e.g. arXiv:1101.2599)





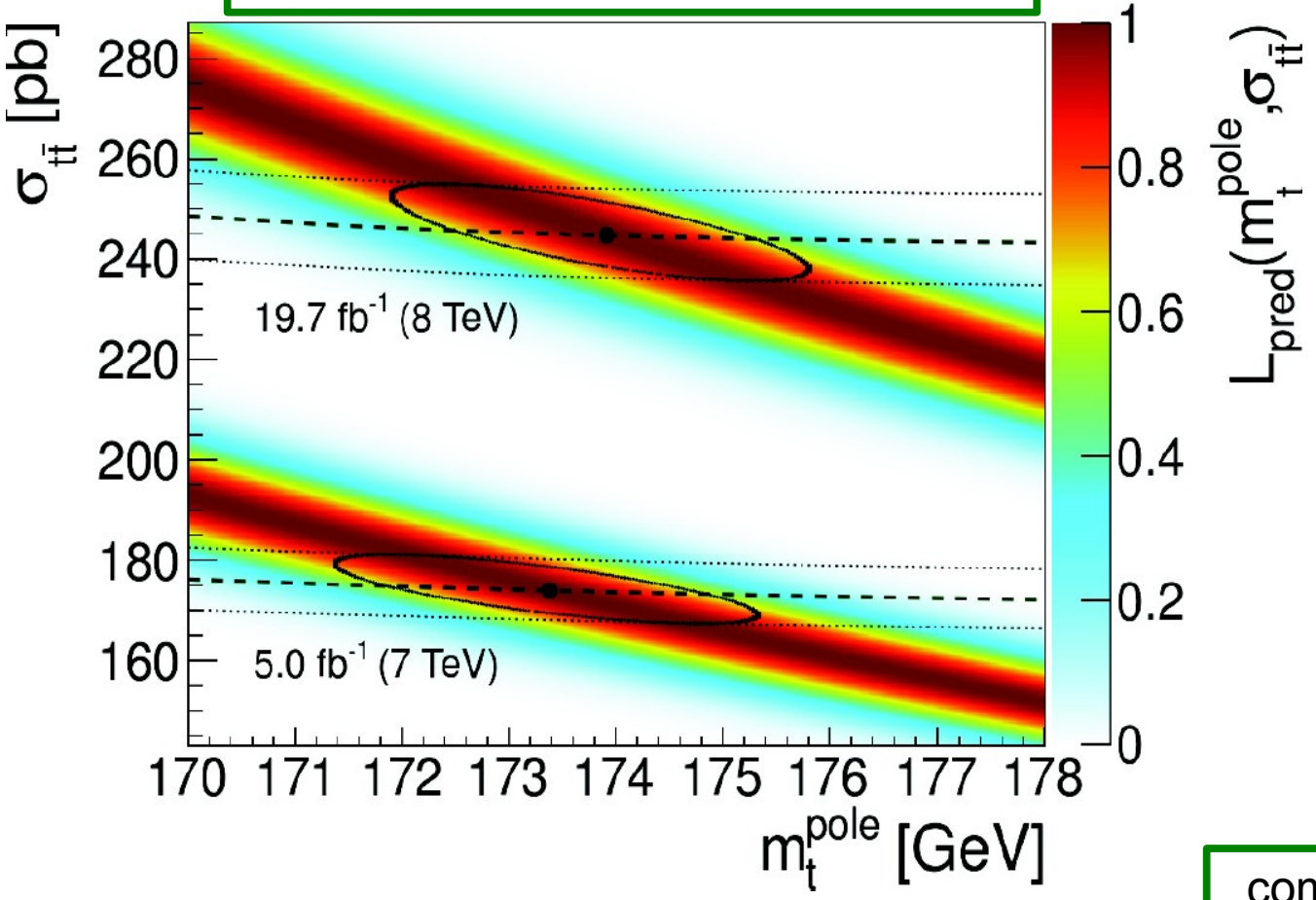


$m_{t,MC}$ = 173.34 ± 0.76 GeV

$m_{t,pole}$ = ??? GeV

Top Quark Mass from Cross Section

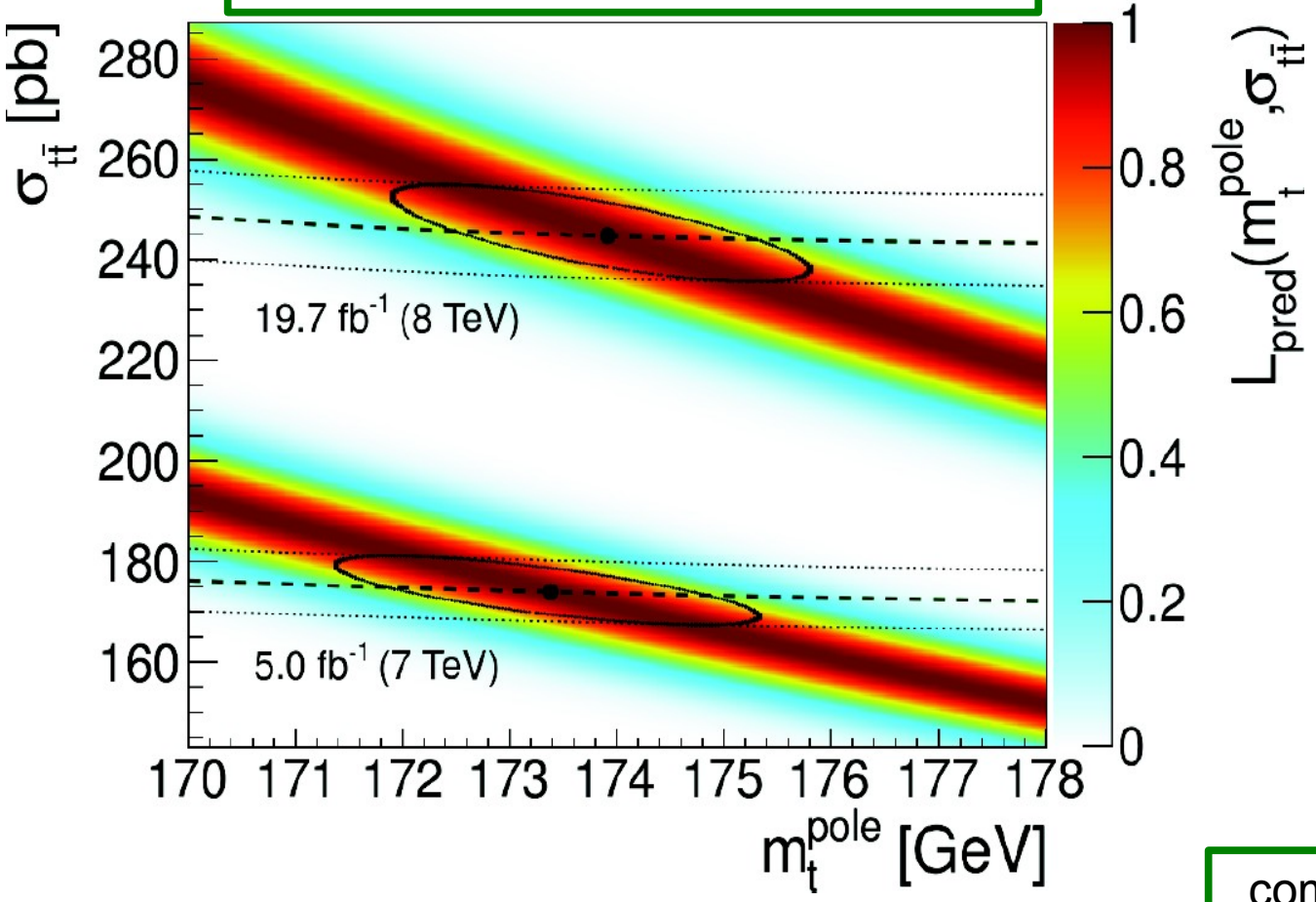
J. Kieseler, DESY-Thesis-2015-054



comparison to NNLO+NNLL
arXiv:1303.6254

Top Quark Mass from Cross Section

J. Kieseler, DESY-Thesis-2015-054

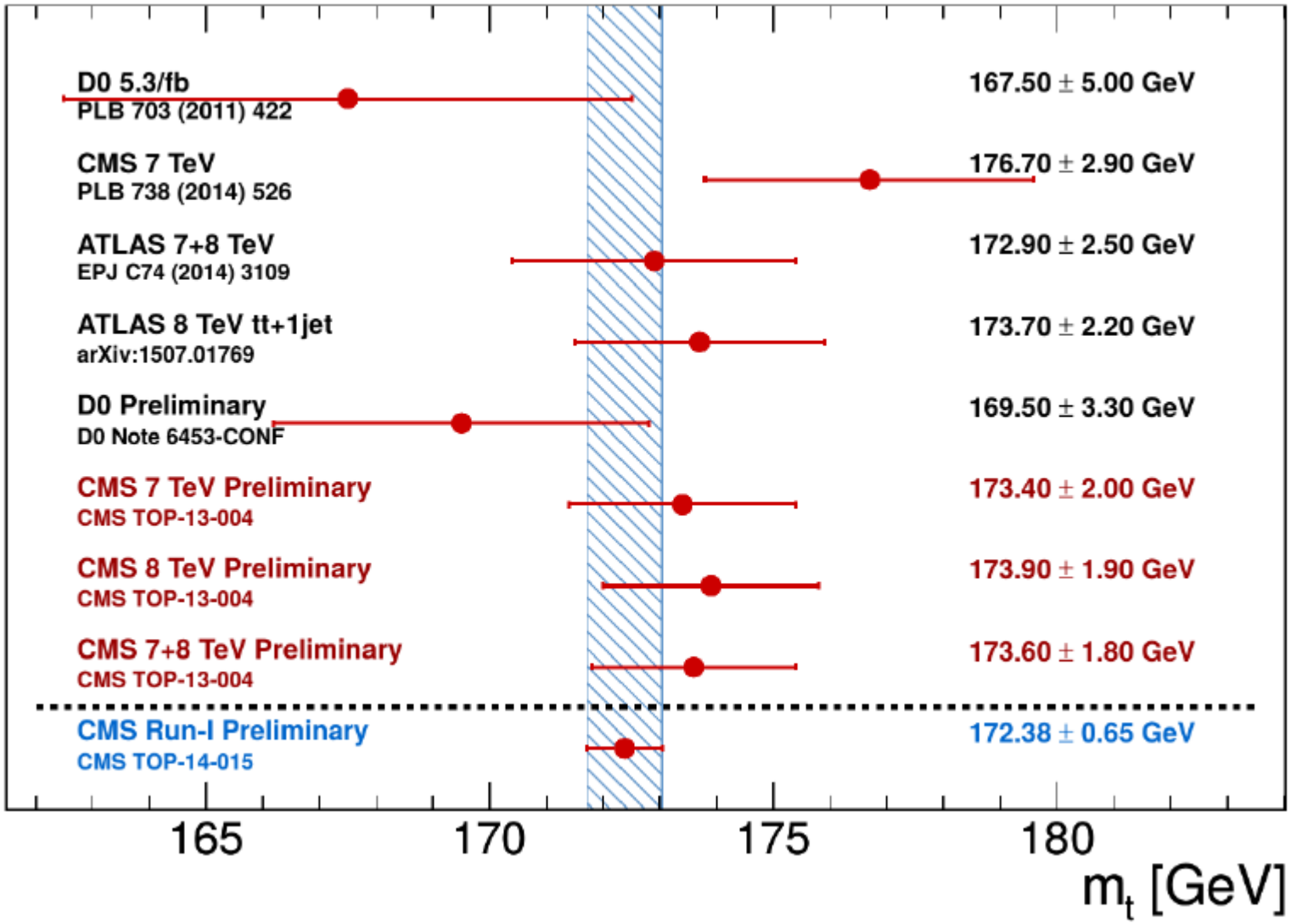


m_t = 173.6 ± 1.8 GeV
for NNPDF 3.0

comparison to NNLO+NNLL
arXiv:1303.6254

most precise measurement of top quark pole mass

Summary – Top Quark Pole Mass



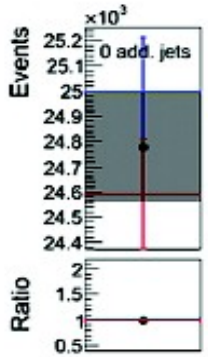
good agreement between different experiments: still large uncertainties of ~ 2 GeV

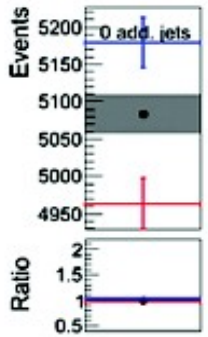
Connecting MC and Pole Mass

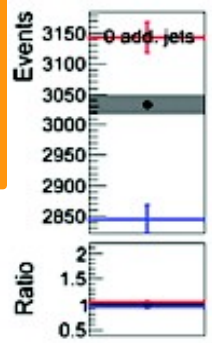
$m_t^{\mathrm{MC}} = 172.5\,\mathrm{GeV}$

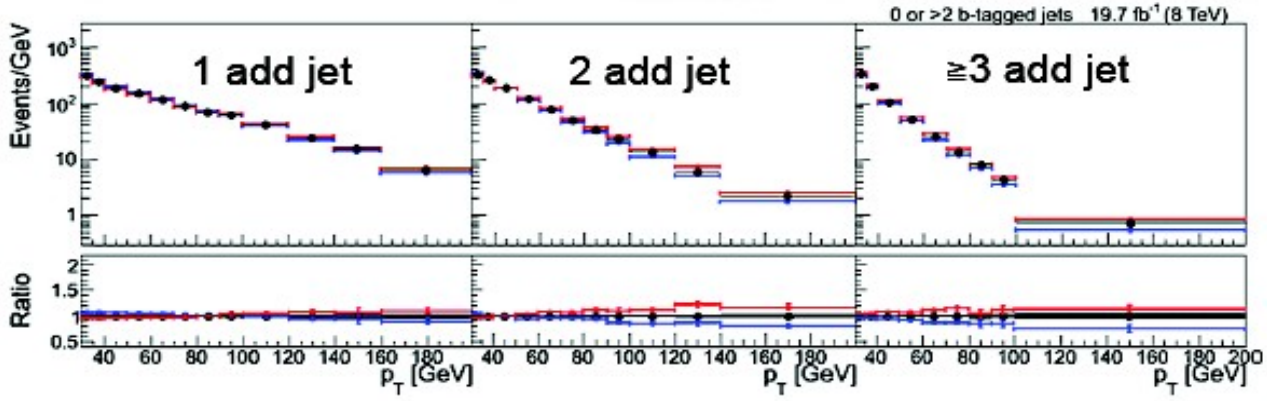
$m_t^{\mathrm{MC}} = 178.5\,\mathrm{GeV}$

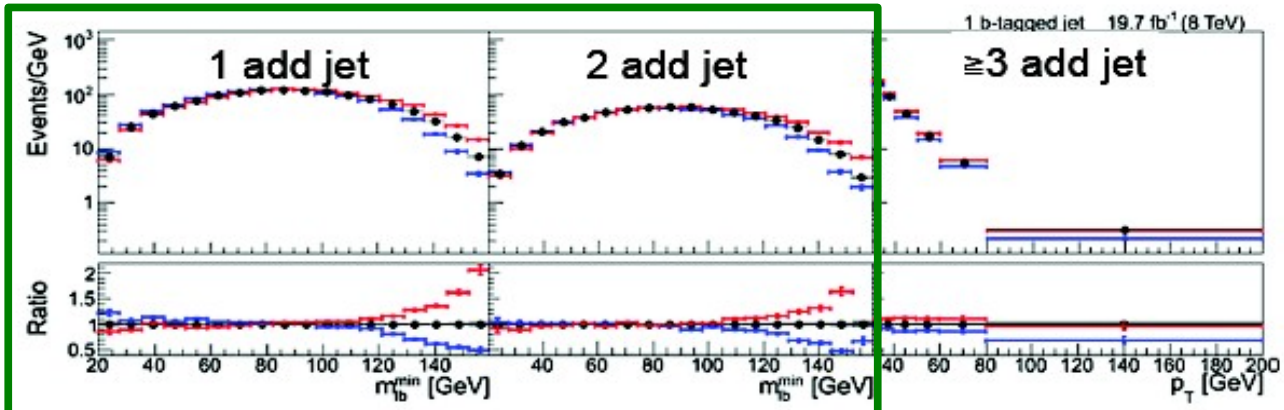
$m_t^{\mathrm{MC}} = 166.5\,\mathrm{GeV}$

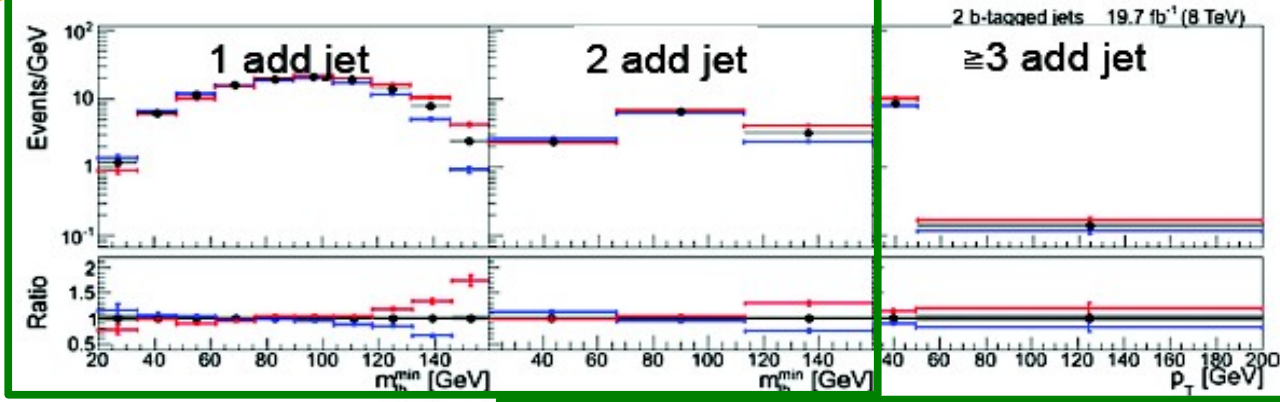










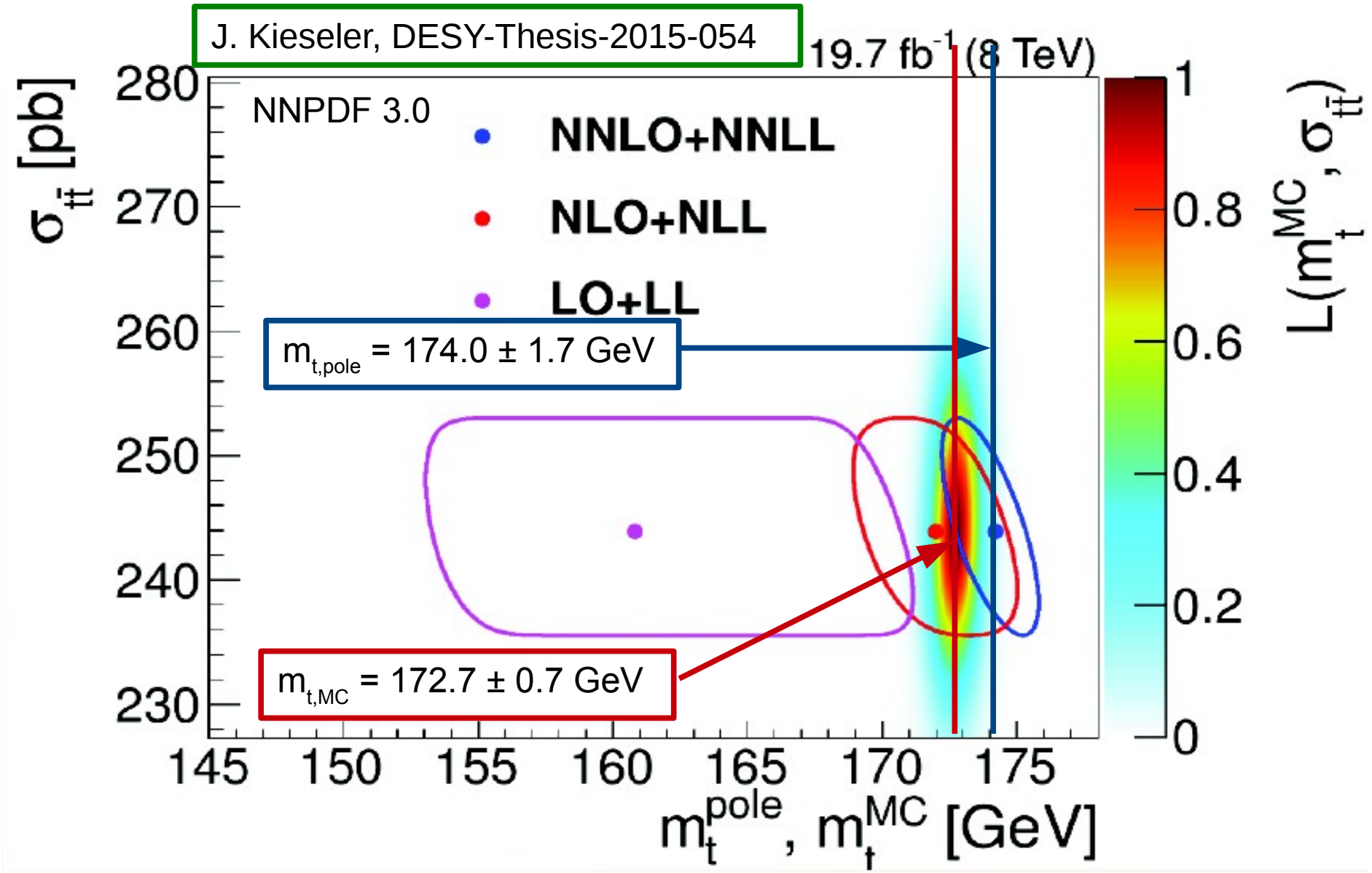


invariant lepton + b-quark mass: independent of production mechanism

simultaneous fit of $\sigma_{t\bar{t}}$ and $m_{t,MC}$

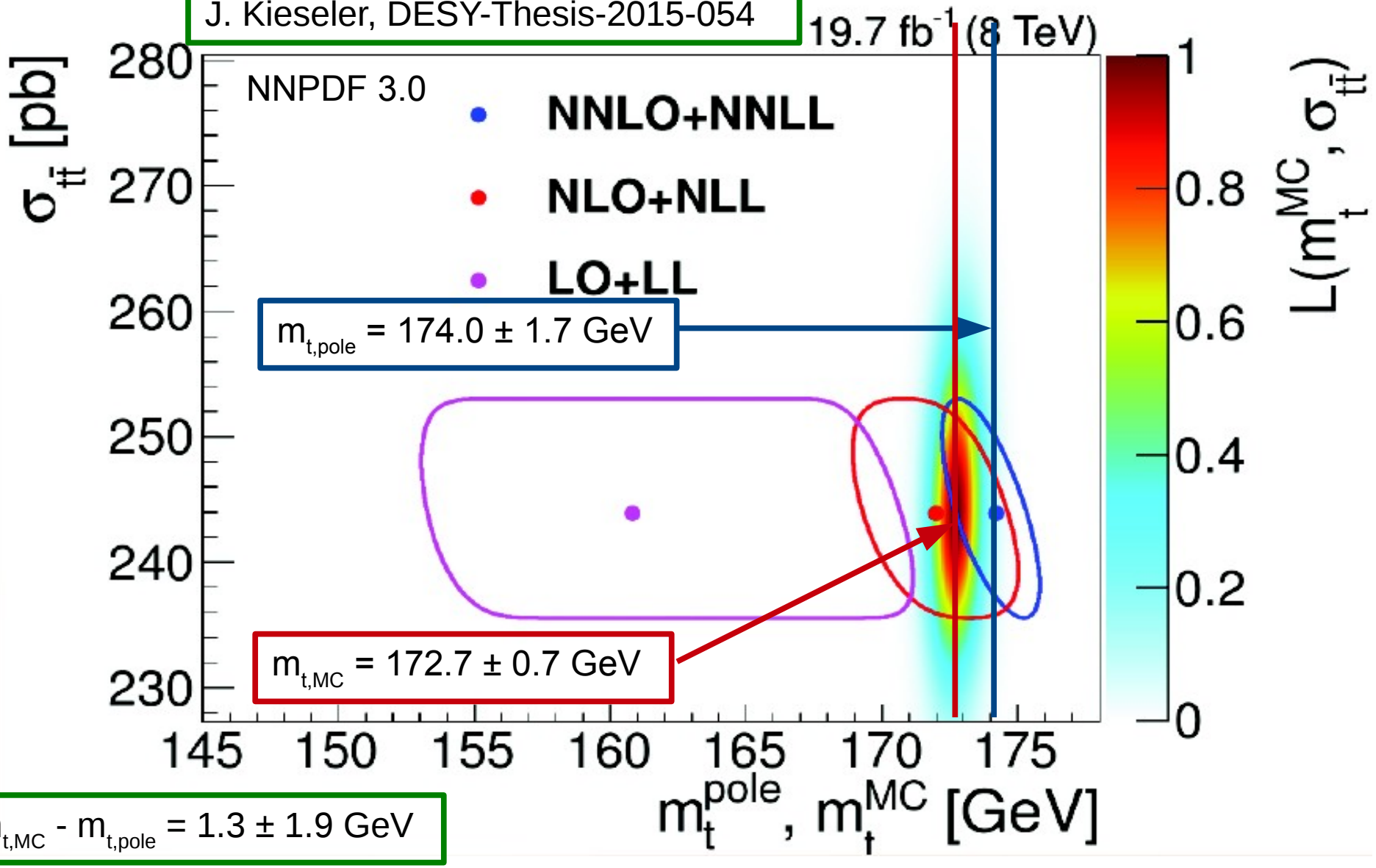
J. Kieseler, DESY-Thesis-2015-054

Connecting MC and Pole Mass



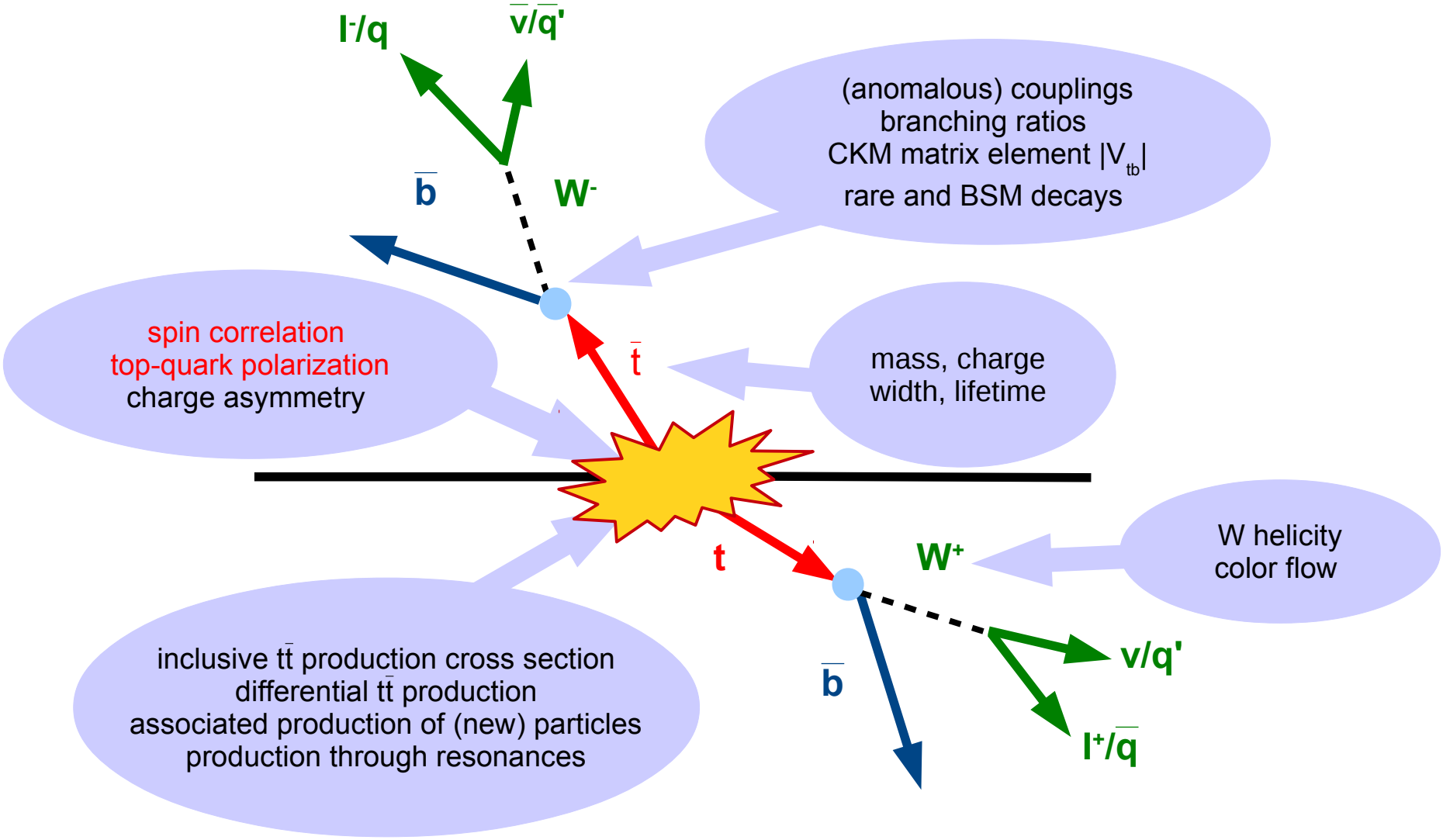
Connecting MC and Pole Mass

J. Kieseler, DESY-Thesis-2015-054



$m_{t,MC} - m_{t,pole}$ = 1.3 ± 1.9 GeV

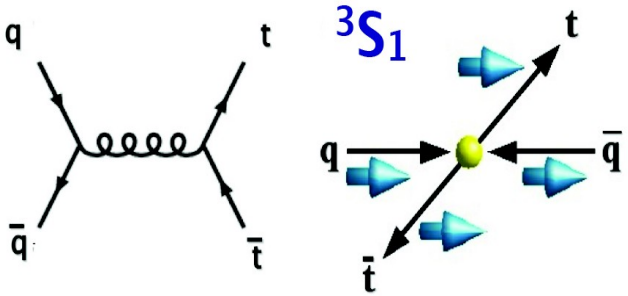
first experimental calibration of $m_{t,MC}$: compatible with assumption of 1 GeV


l-/q
ν̄/q̄'
b̄
W-
(anomalous) couplings
branching ratios
CKM matrix element |Vtb|
rare and BSM decays
spin correlation
top-quark polarization
charge asymmetry
t̄
mass, charge
width, lifetime
t
W+
W helicity
color flow
inclusive tt̄ production cross section
differential tt̄ production
associated production of (new) particles
production through resonances
b̄
ν/q'
l+/q̄

Spin Correlation in Top Quark Events

- detailed probe of top quark spin and production mechanism

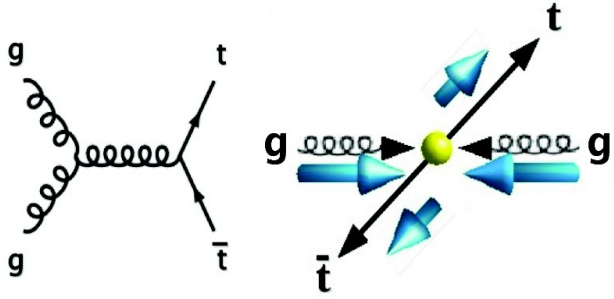
$$C = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\downarrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\downarrow\uparrow} + N_{\uparrow\downarrow}}$$



close to $t\bar{t}$ threshold, small β

Tevatron

- beam basis: C = 0.78 @ NLO



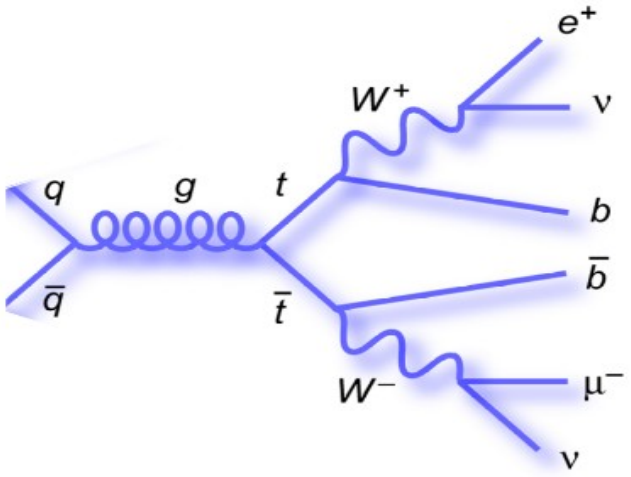
close to $t\bar{t}$ threshold, $\beta \rightarrow 1$

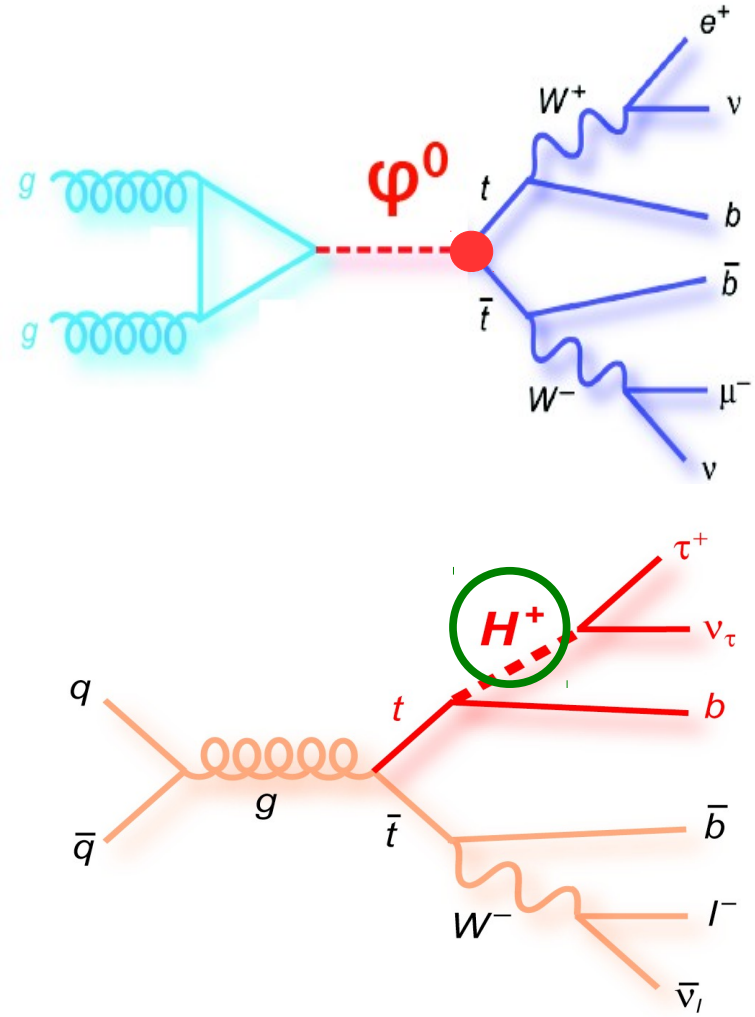
LHC

- helicity basis: C = 0.32 @ NLO

Spin Correlation in Top Quark Events

- detailed probe of top quark spin and production mechanism

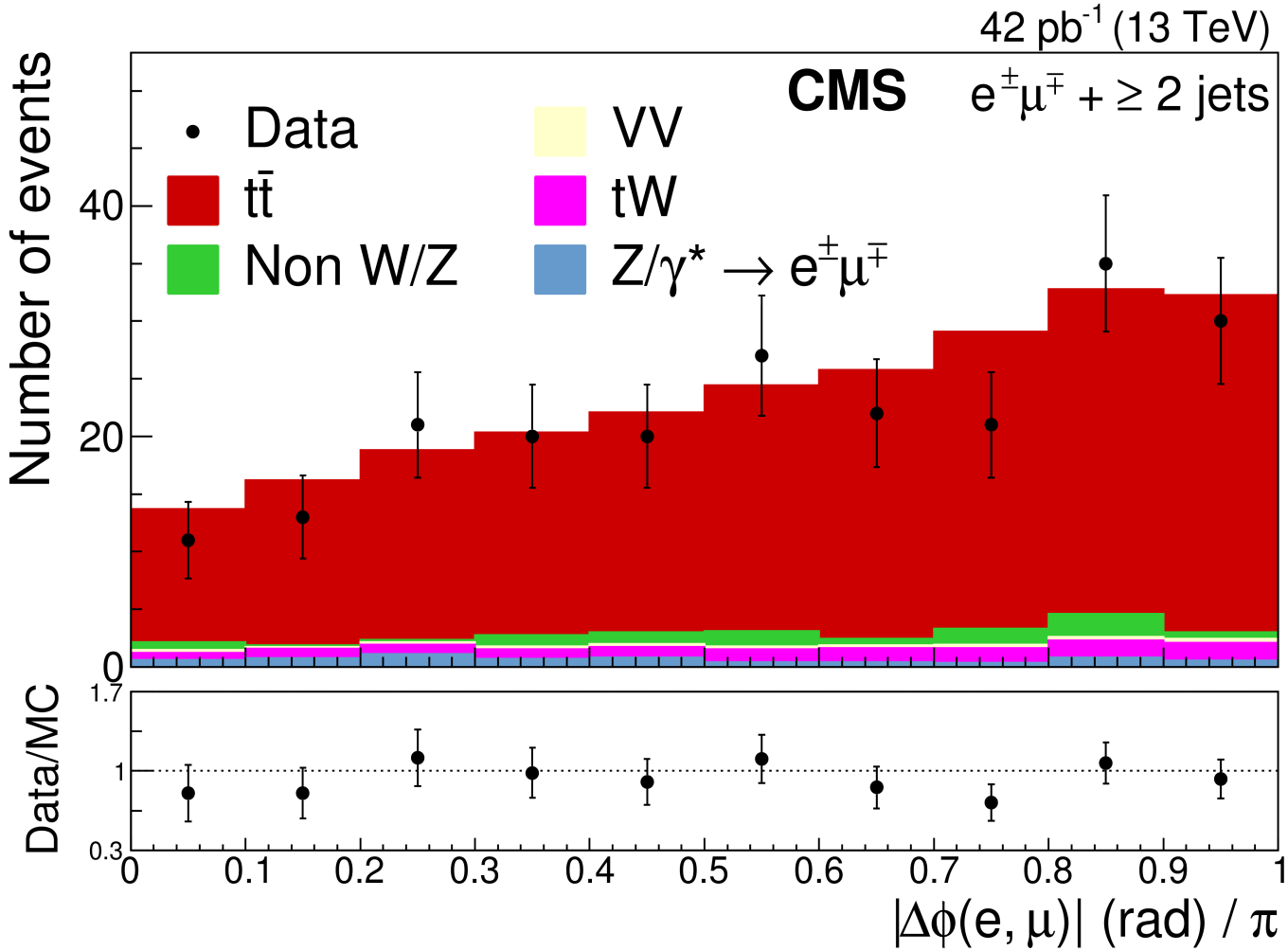




high sensitivity to new physics in production and decay

$t\bar{t}$ Spin Correlation at 13 TeV

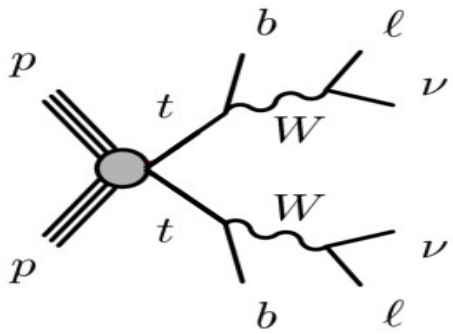
- azimuthal angle between leptons sensitive to $t\bar{t}$ spin correlations at LHC

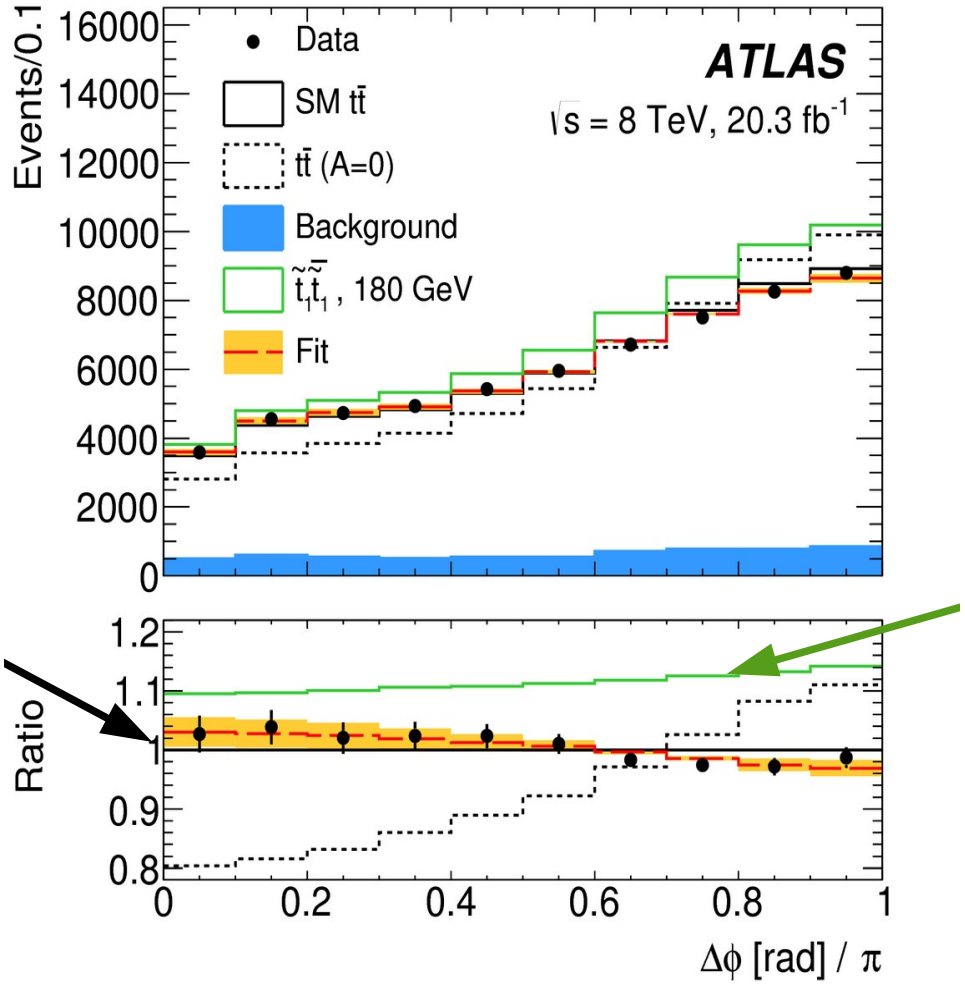


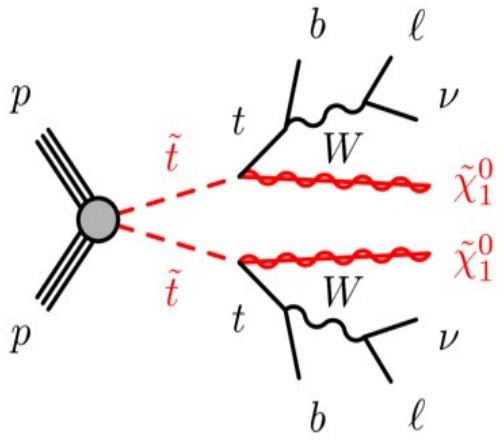
good agreement between data and SM $t\bar{t}$ prediction

Stealthy Top Squarks II

- additional top squarks → vanishing spin correlation

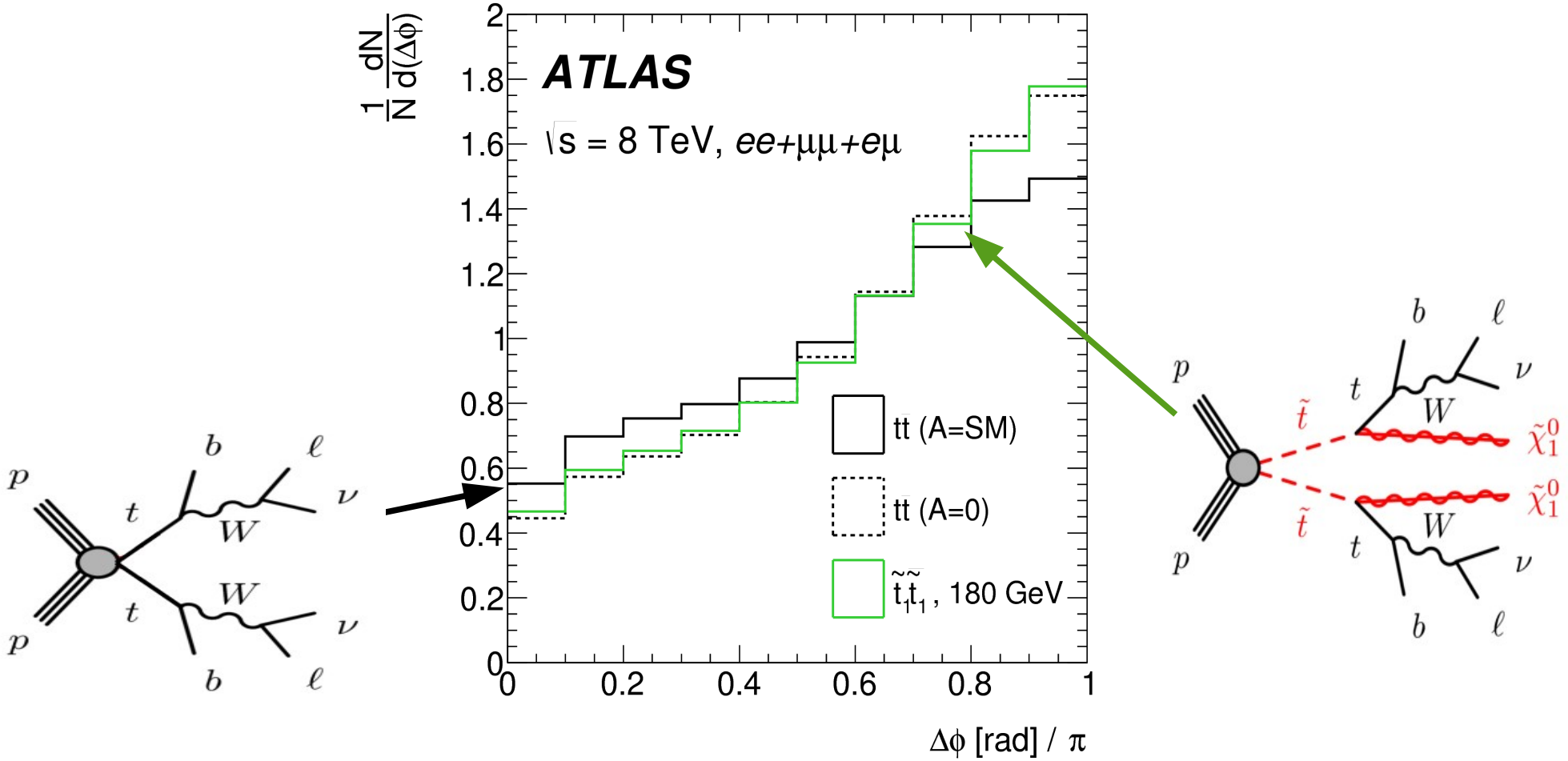




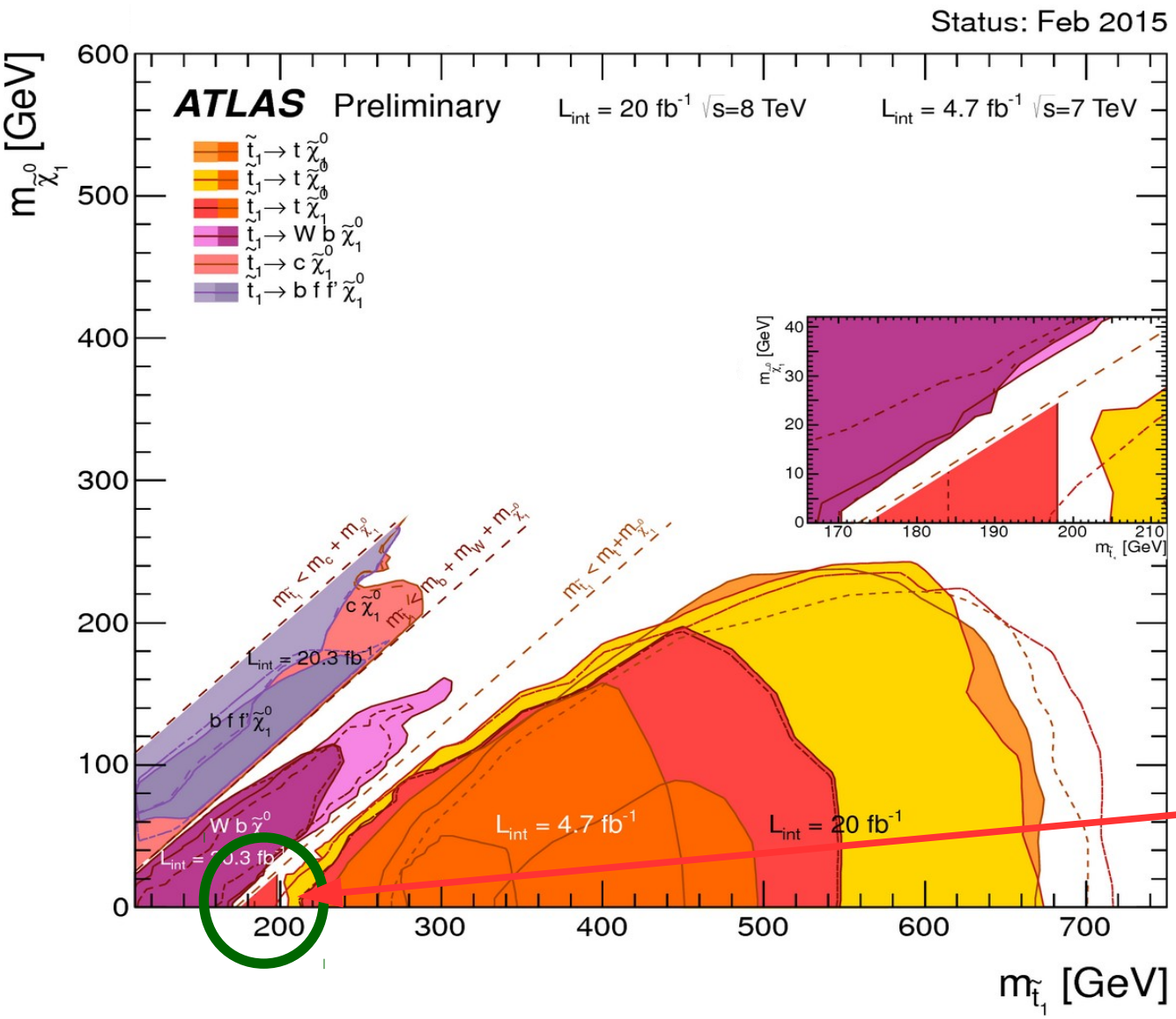


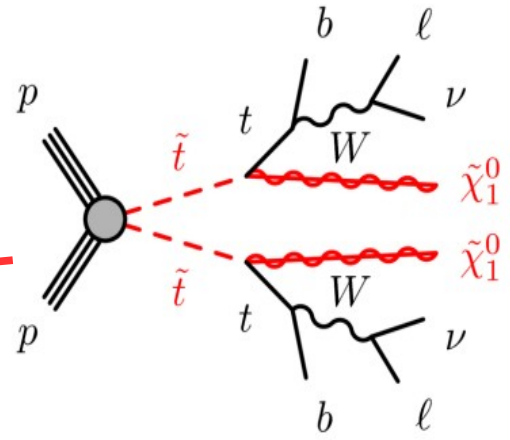
Stealthy Top Squarks II

- additional top squarks → vanishing spin correlation



Stealthy Top Squarks II



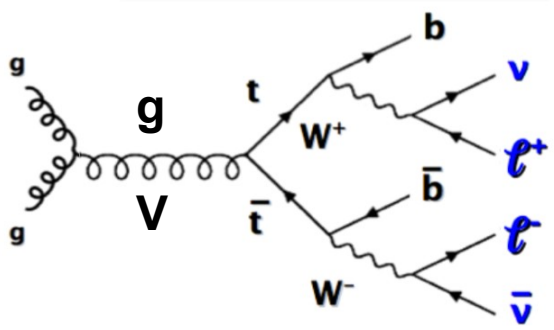


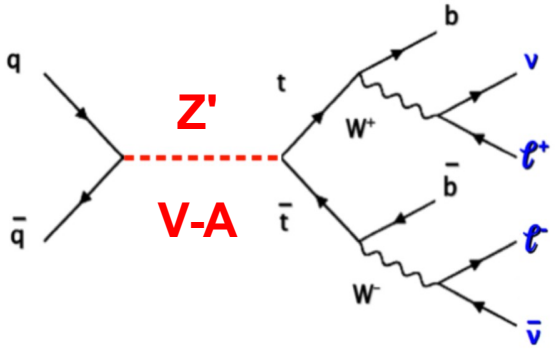
exclusion of top squark pair production up to 198 GeV

Top Quark Polarization

$$P = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$

- strong interaction P-conserving: vanishing top quark polarization in SM

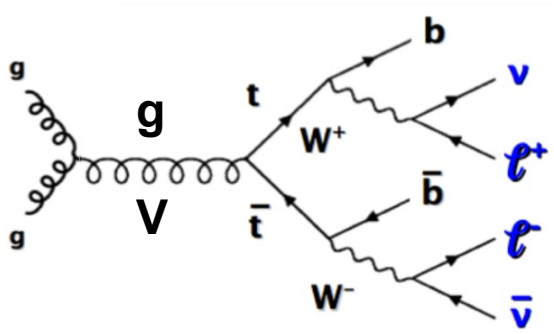


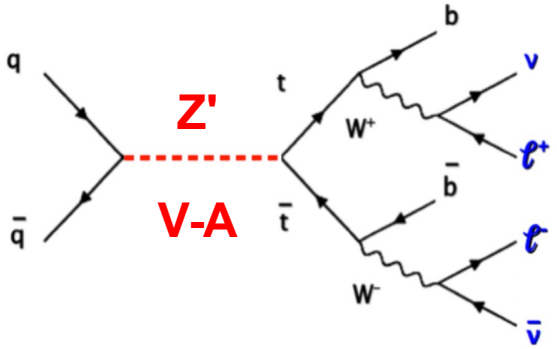


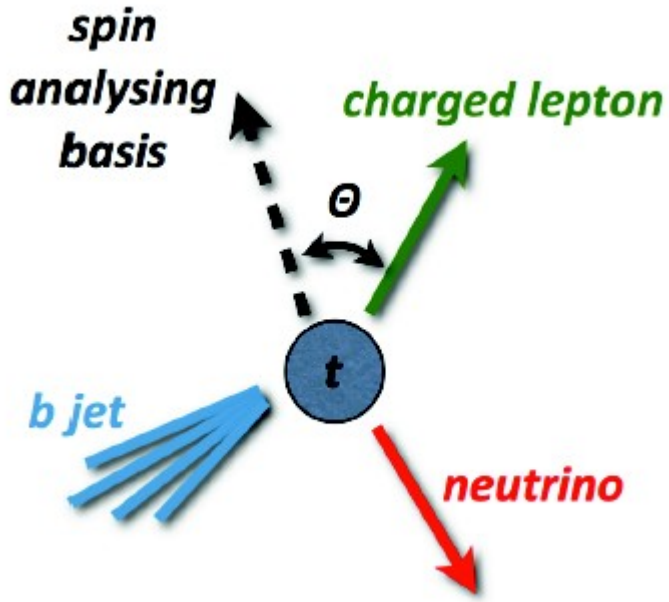
Top Quark Polarization

$$P = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$

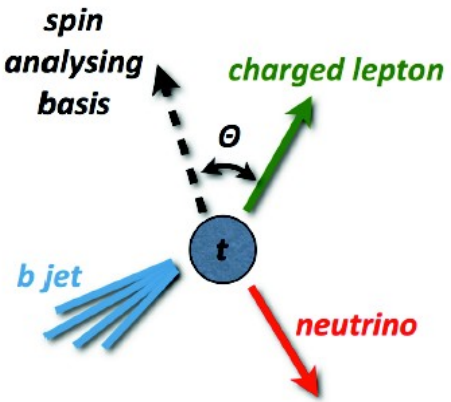
- strong interaction P-conserving: vanishing top quark polarization in SM



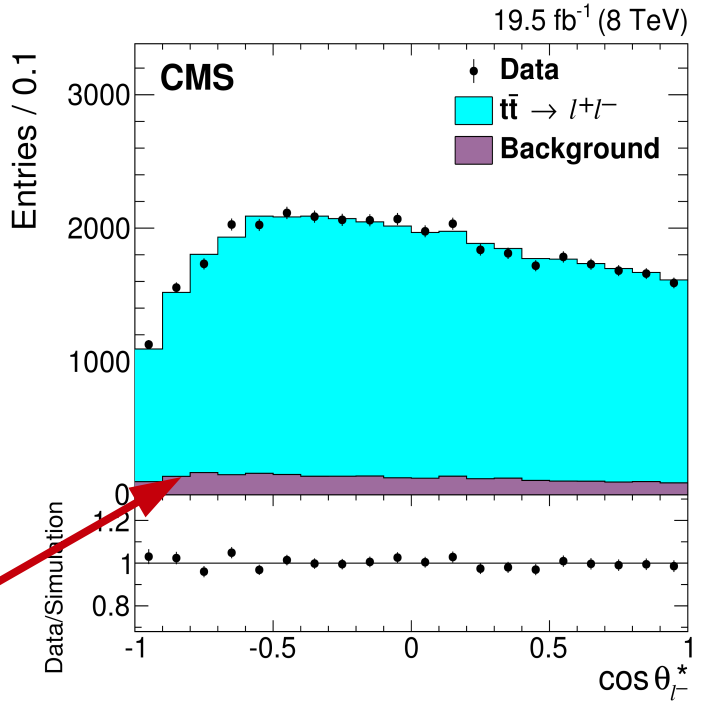


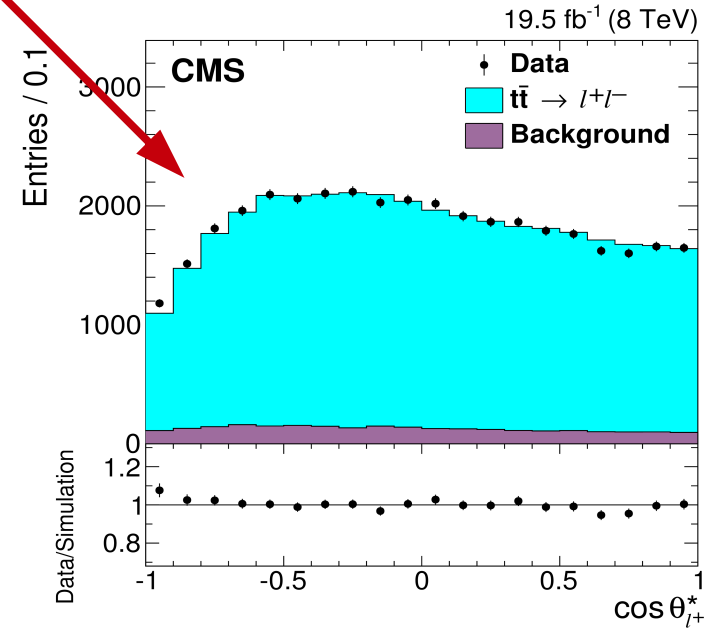


Simultaneous Probe of Spin Correlation and Polarization

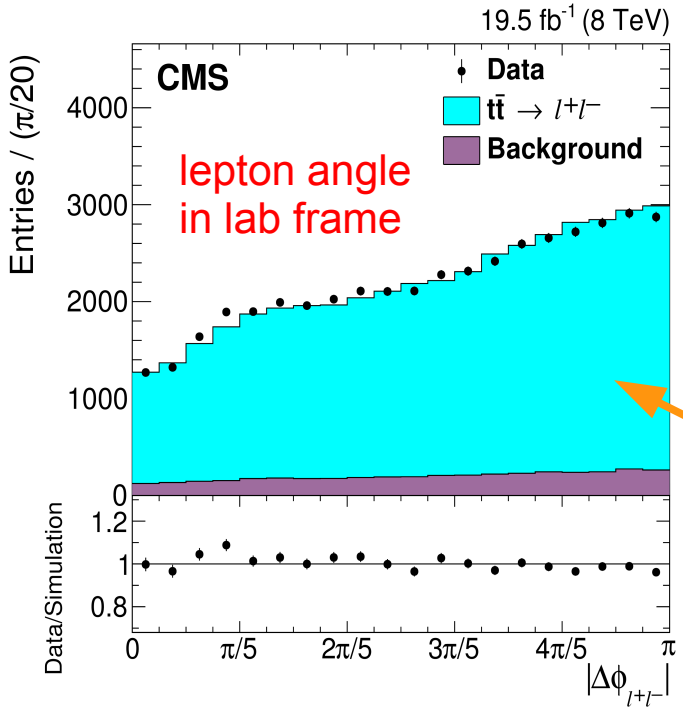


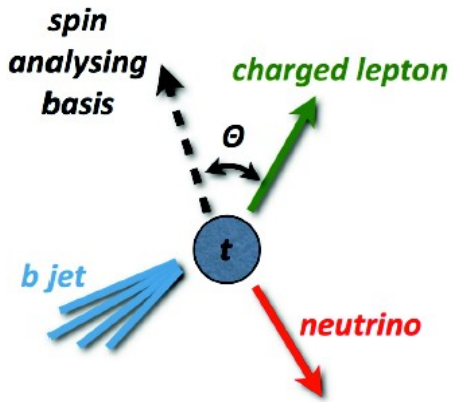
polarization

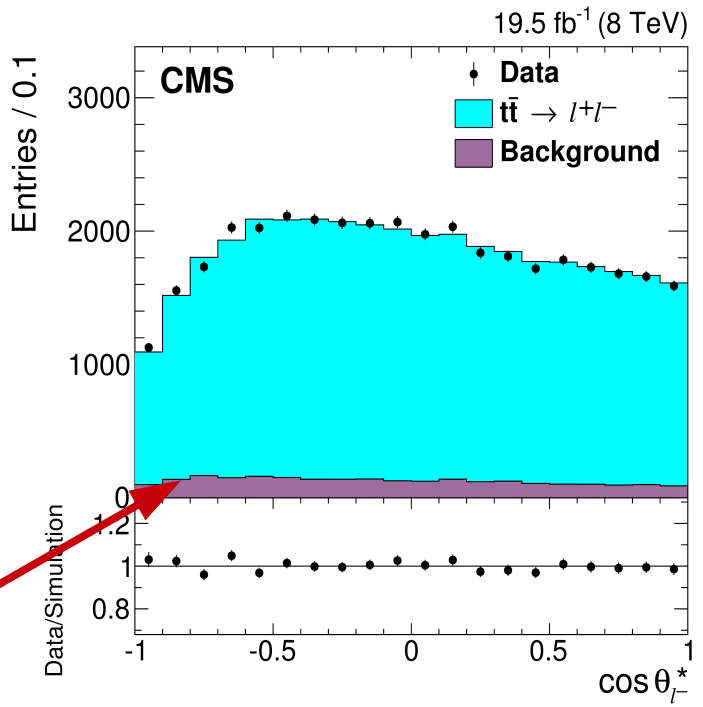




Simultaneous Probe of Spin Correlation and Polarization

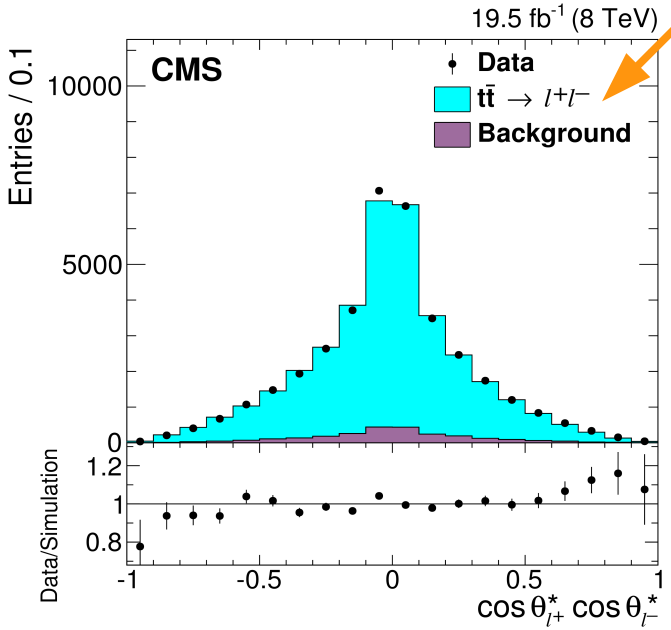


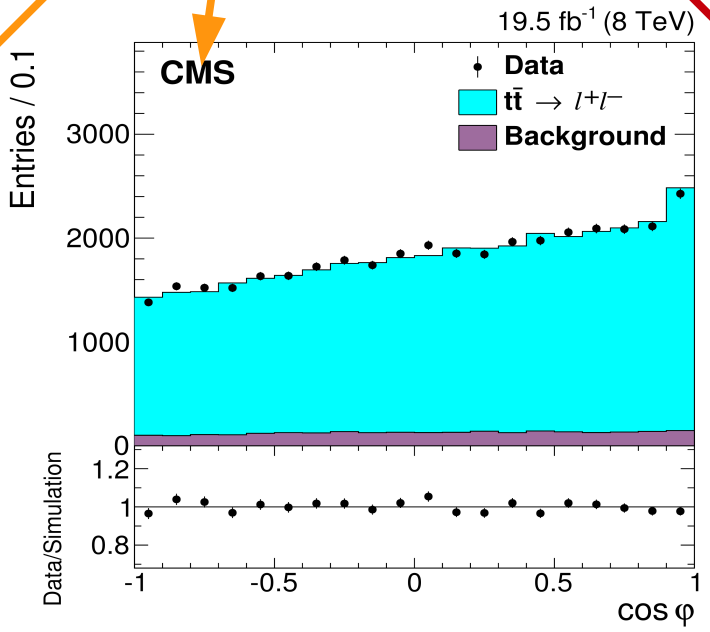


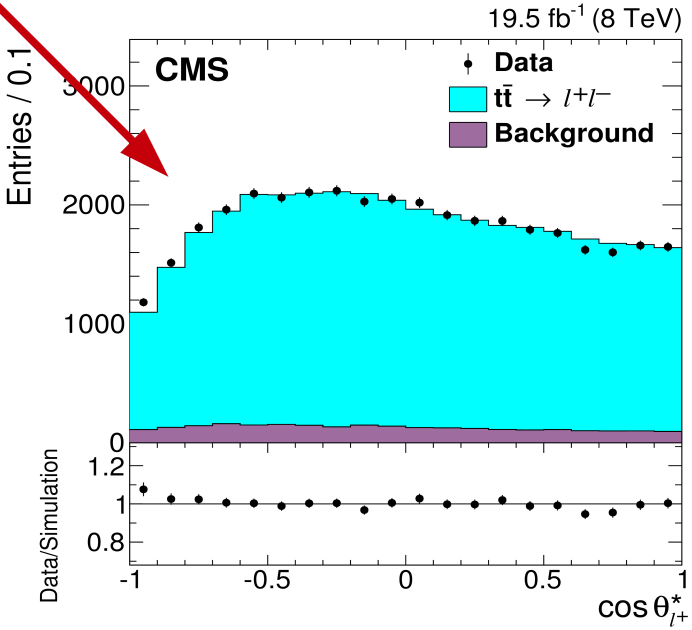


spin correlation

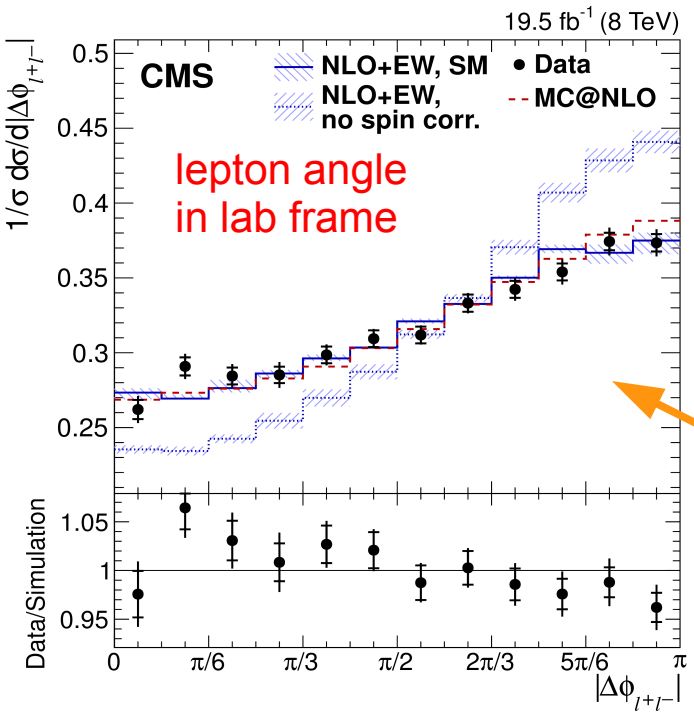
polarization

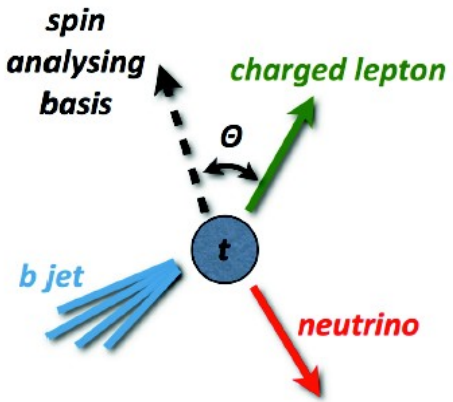






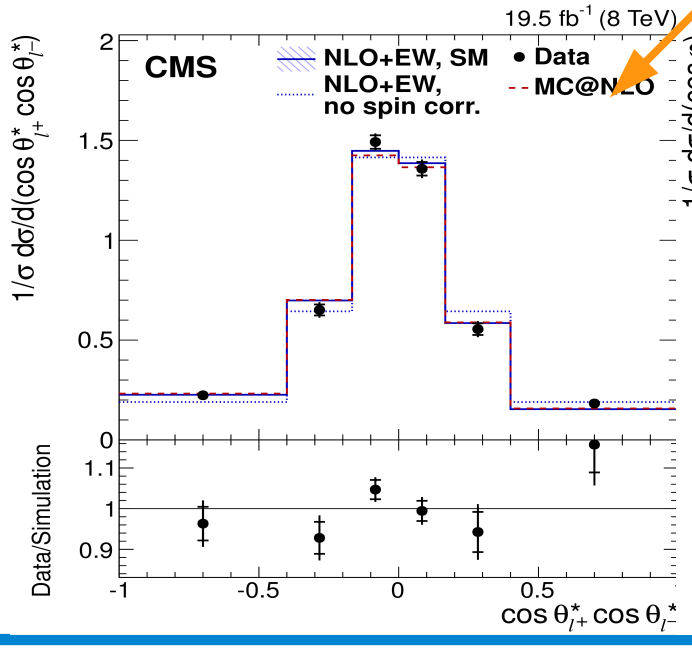
Simultaneous Probe of Spin Correlation and Polarization

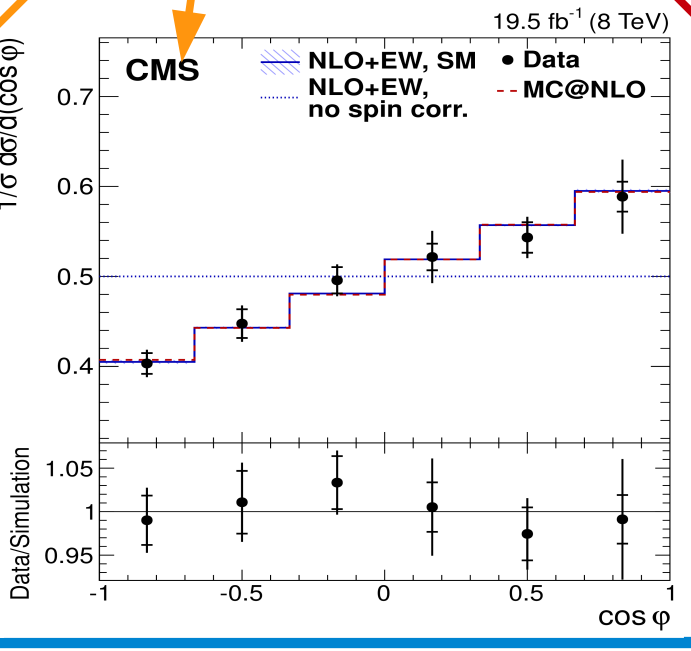


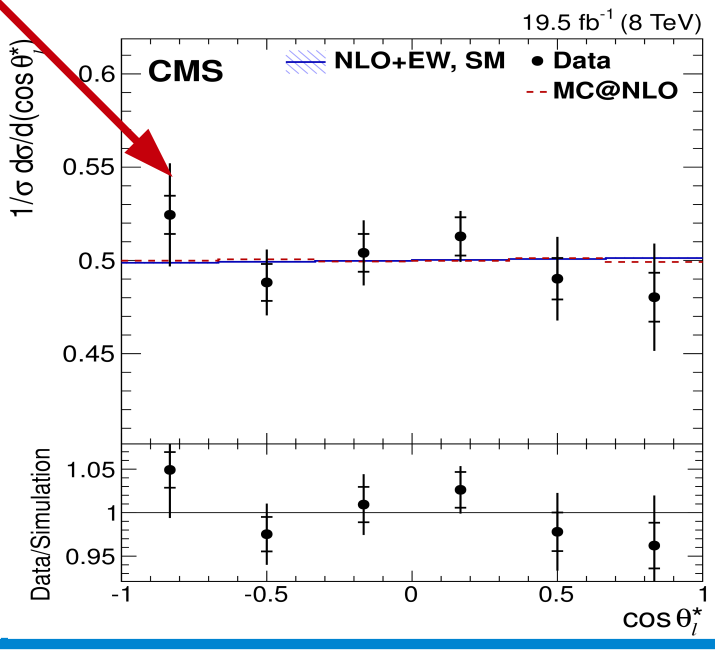


spin correlation

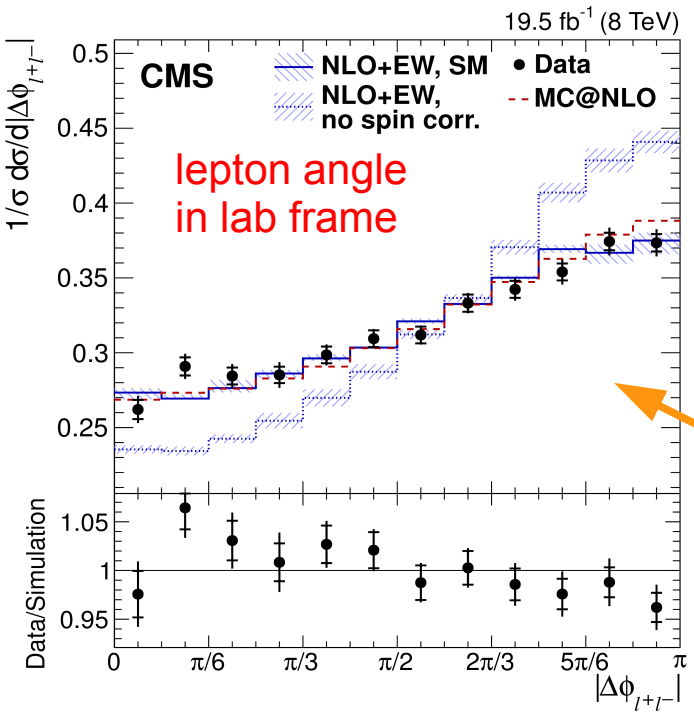
polarization







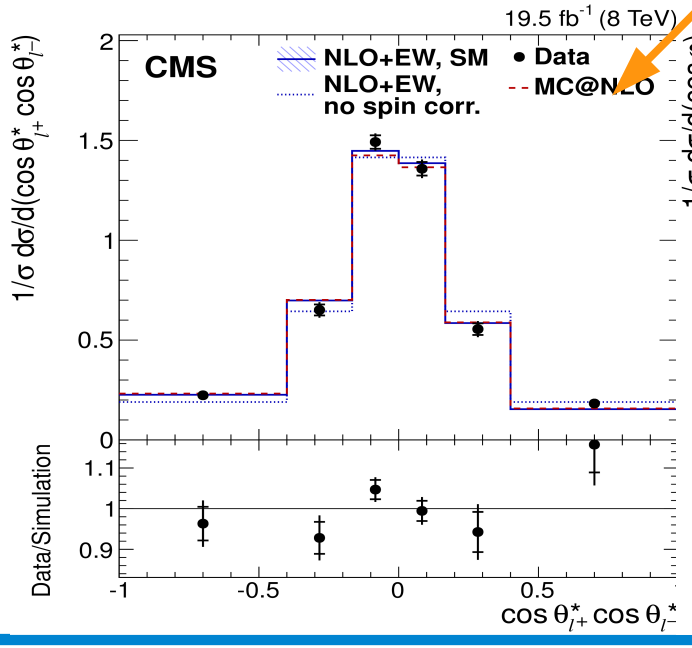
Simultaneous Probe of Spin Correlation and Polarization

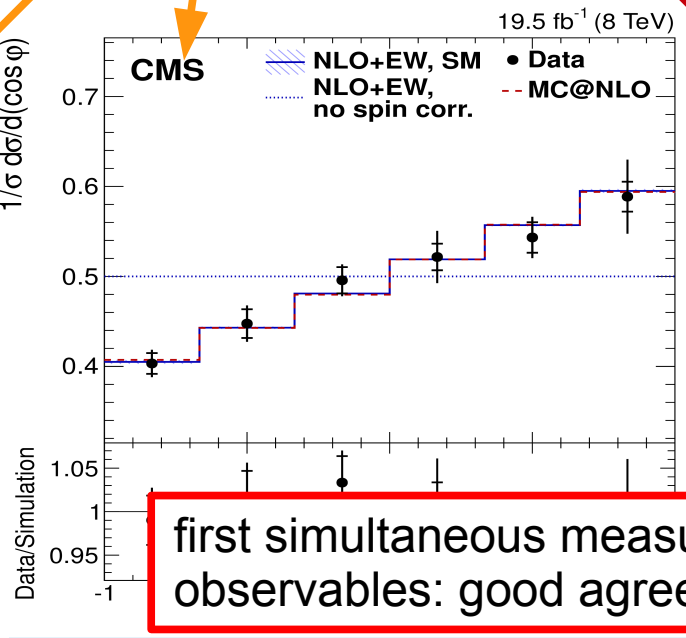


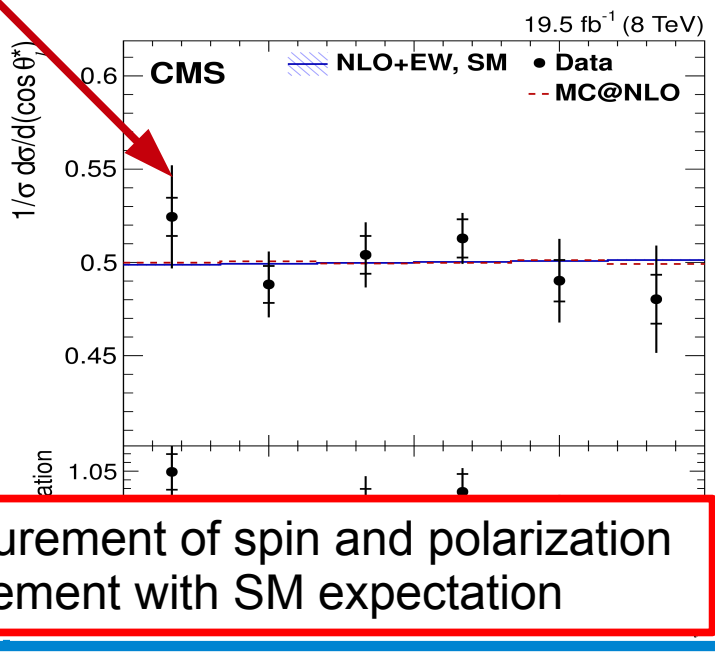
Asymmetry variable	Data (unfolded)	MC@NLO simulation	NLO+EW, SM
$A_{\Delta\phi}$	$0.094 \pm 0.005 \pm 0.012$	0.113 ± 0.001	$0.110\,^{+0.006}_{-0.009}$
$A_{\cos\varphi}$	$0.102 \pm 0.010 \pm 0.012$	0.114 ± 0.001	0.114 ± 0.006
$A_{c_1c_2}$	$-0.069 \pm 0.013 \pm 0.016$	-0.081 ± 0.001	-0.080 ± 0.004
A_P	$-0.011 \pm 0.007 \pm 0.028$	0	0.002 ± 0.001

spin correlation

polarization





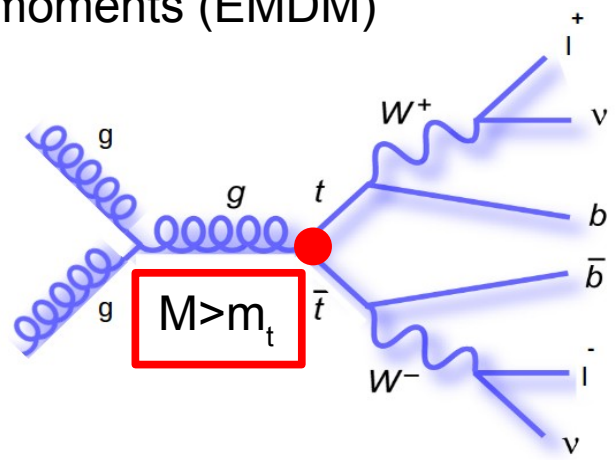


first simultaneous measurement of spin and polarization observables: good agreement with SM expectation

Searching for Top Dipole Moments

- chromo-magnetic (CMDM) and chromo-electric dipole moments (EMDM)

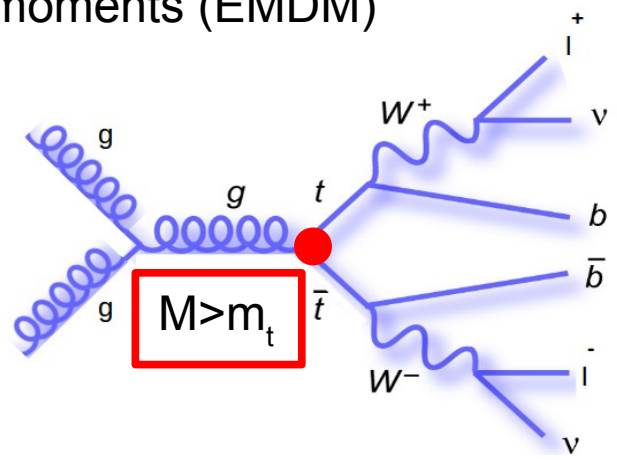
$$L_{eff} = L_{SM} - \frac{\tilde{\mu}_t}{2}\bar{t}\,\sigma^{\mu\nu}T^a t\,G^a_{\mu\nu} - i\frac{\tilde{d}_t}{2}\bar{t}\,\sigma^{\mu\nu}\gamma_5 T^a t\,G^a_{\mu\nu}$$

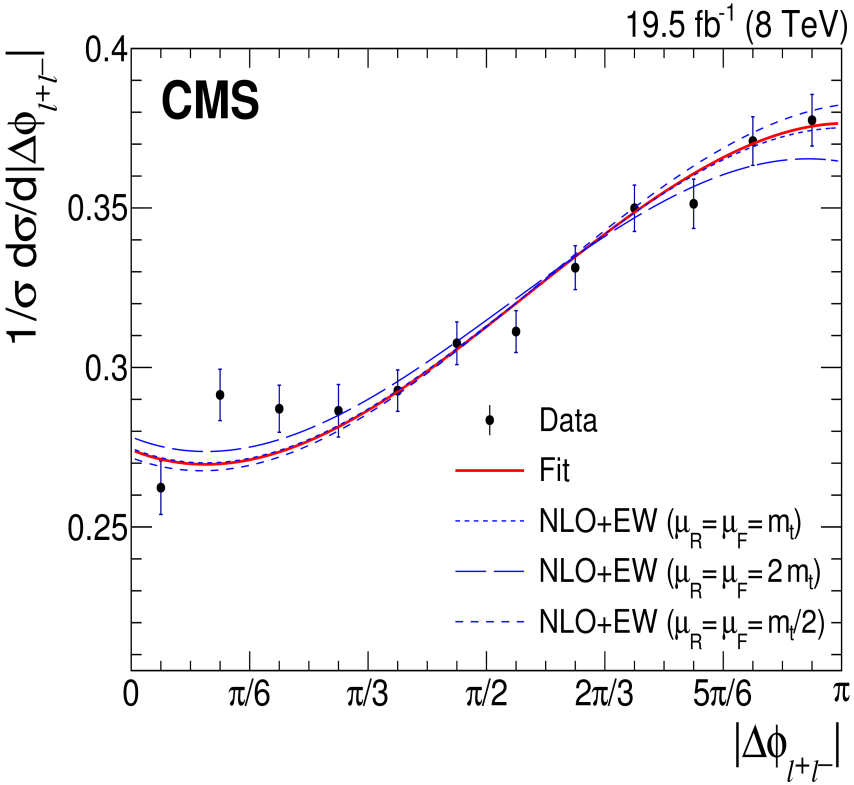


Searching for Top Dipole Moments

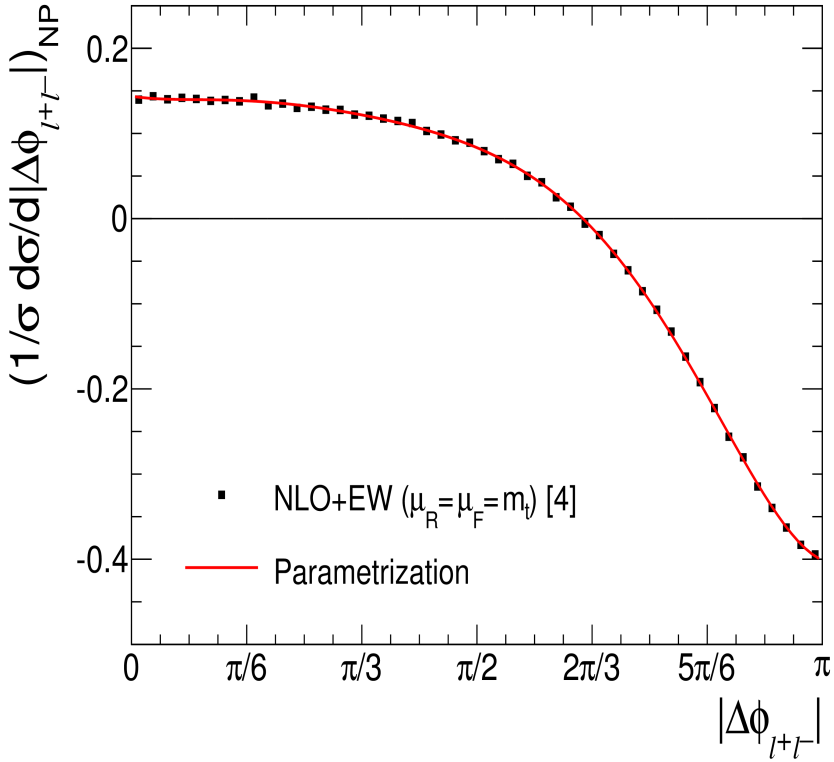
- chromo-magnetic (CMDM) and chromo-electric dipole moments (EMDM)

$$L_{eff} = L_{SM} - \frac{\tilde{\mu}_t}{2}\bar{t}\,\sigma^{\mu\nu}T^a t\,G^a_{\mu\nu} - i\frac{\tilde{d}_t}{2}\bar{t}\,\sigma^{\mu\nu}\gamma_5 T^a t\,G^a_{\mu\nu}$$





+ Re ($m_t \tilde{\mu}_t / g_s$) *

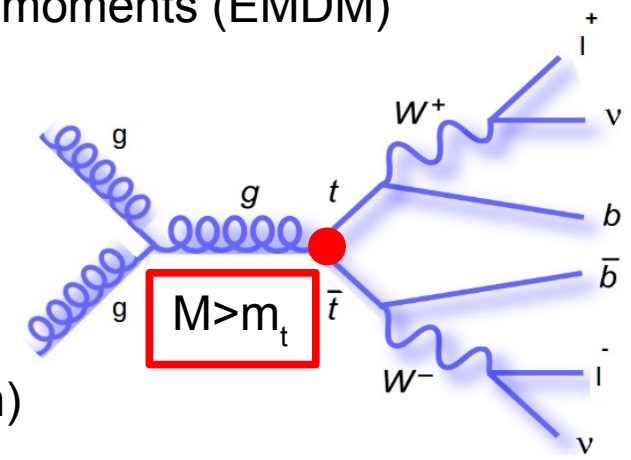


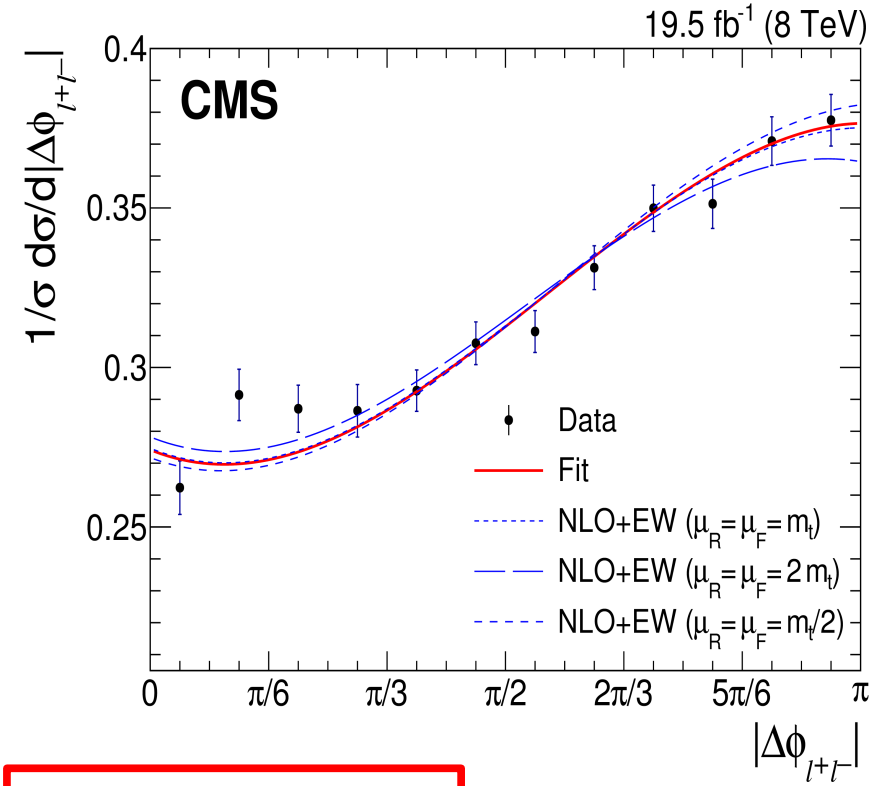
Searching for Top Dipole Moments

- chromo-magnetic (CMDM) and chromo-electric dipole moments (EMDM)

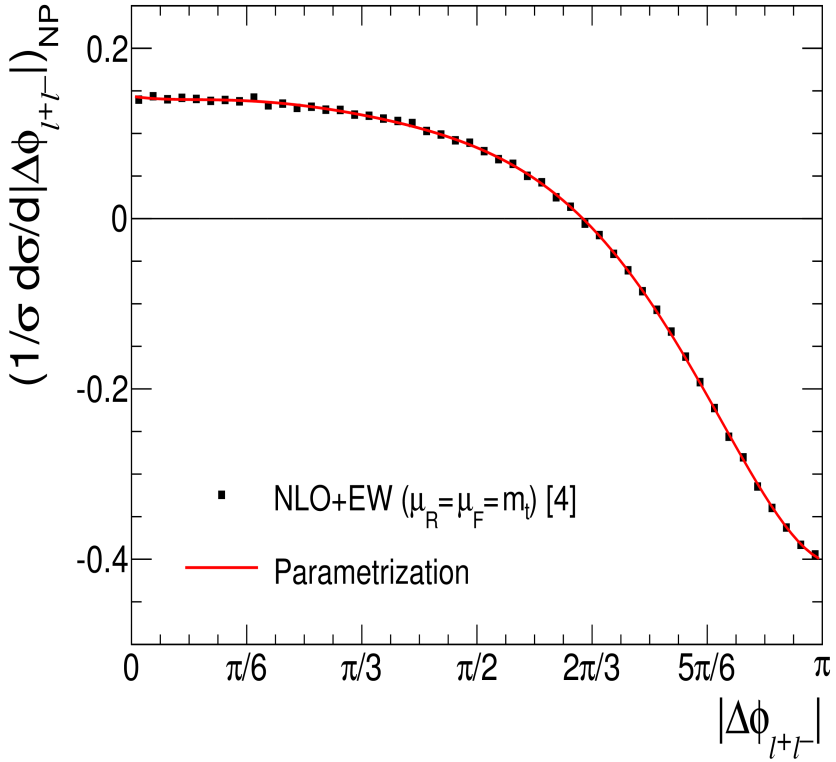
$$L_{eff} = L_{SM} - \frac{\tilde{\mu}_t}{2}\bar{t}\,\sigma^{\mu\nu}T^a t\,G^a_{\mu\nu} - i\frac{\tilde{d}_t}{2}\bar{t}\,\sigma^{\mu\nu}\gamma_5 T^a t\,G^a_{\mu\nu}$$

- excluded at the 95% CL:
  - $-0.053 < \mathrm{Re}\,(m_t\,\tilde{\tilde{\mu}}_t / g_s) < 0.026$ $(\Delta\Phi_{ll})$
  - $-0.068 < \mathrm{Im}\,(m_t\,\tilde{\tilde{d}}_t / g_s) < 0.067$ (CPV polarization)





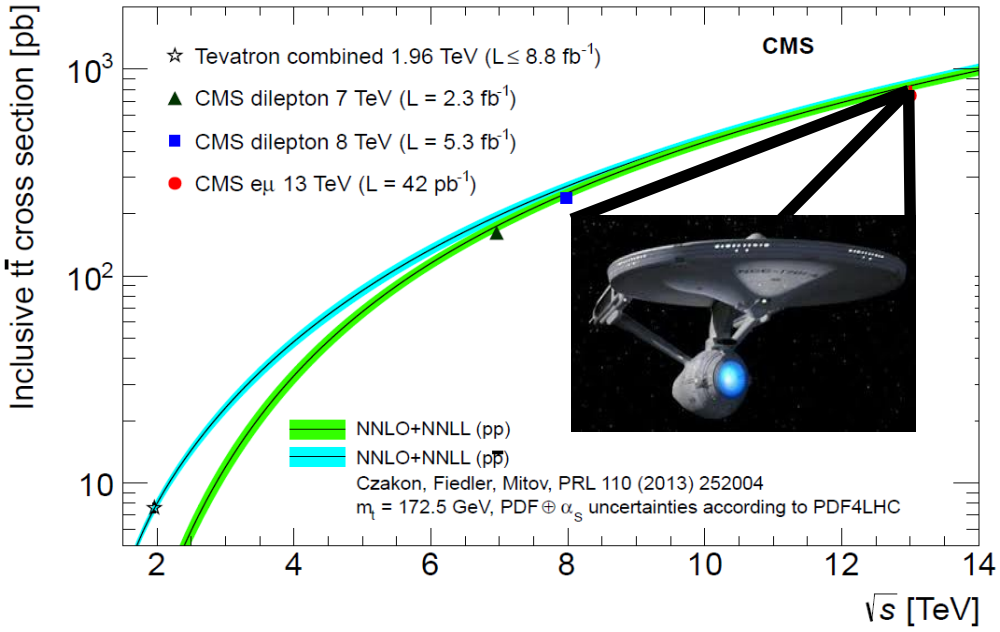
+ Re $(m_t\,\tilde{\tilde{\mu}}_t / g_s)$ *

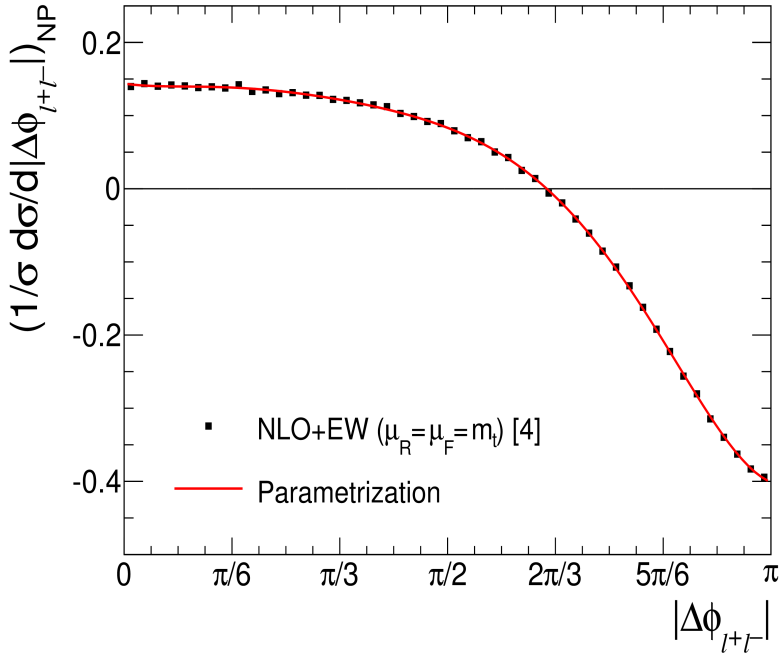


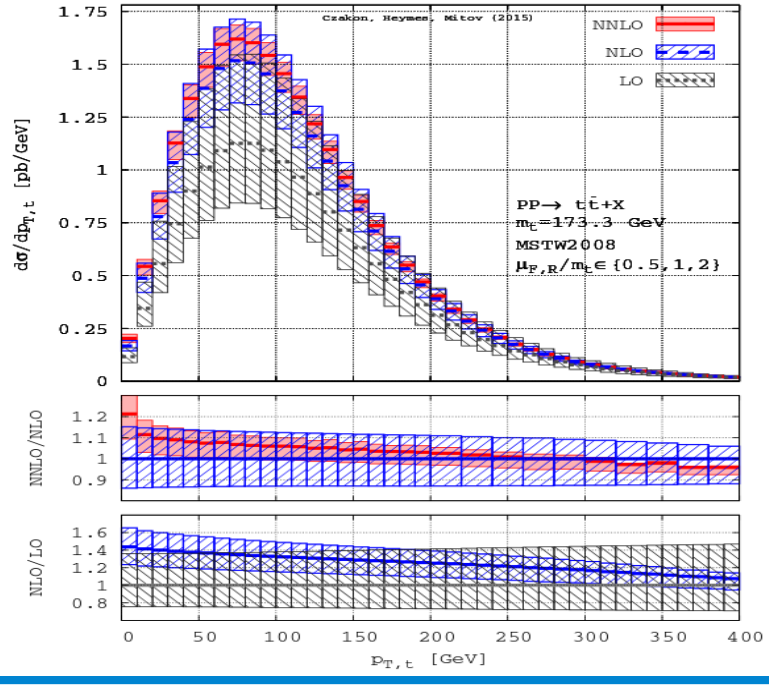
arXiv:1601.01107

Summary

- successfully started exploring the new energy regime at 13 TeV
- phenomenology revolution offers exciting (and demanding) perspectives
- high precision top quark properties
  - effective probe of new physics in the top quark sector

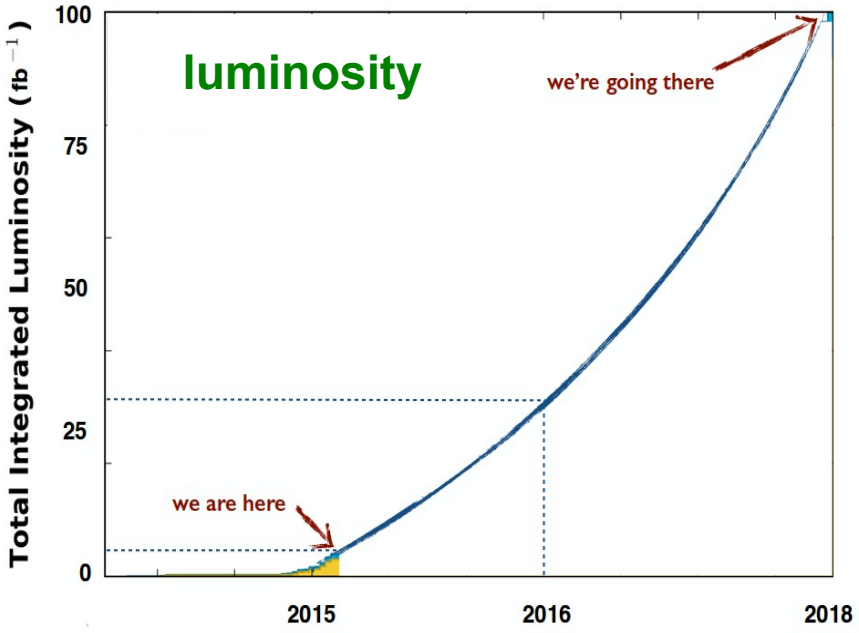






Outlook: Next 3 Years

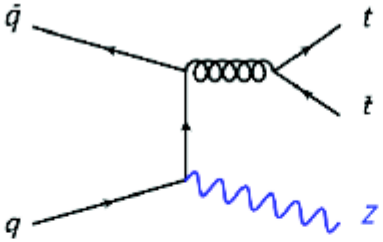


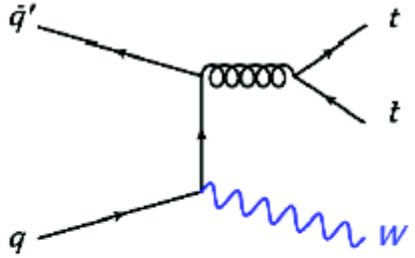


promising perspectives for (new) precision measurements: probe BSM physics at 13 TeV

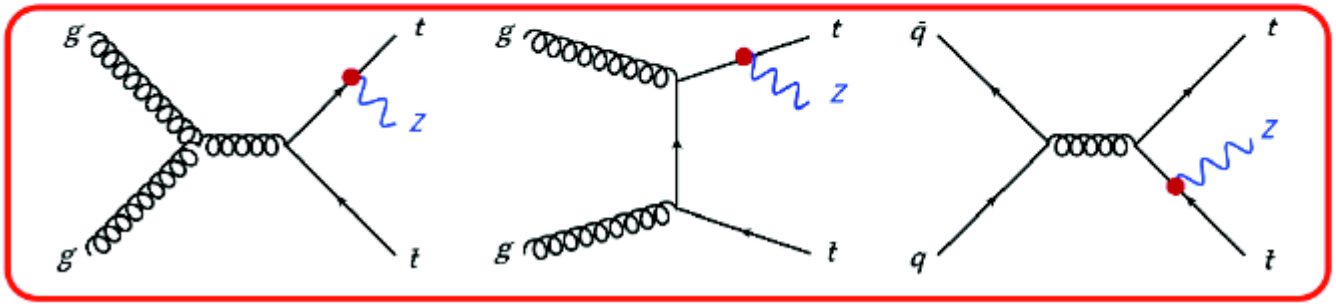
$t\bar{t}Z$ and $t\bar{t}W$

FSR





ISR

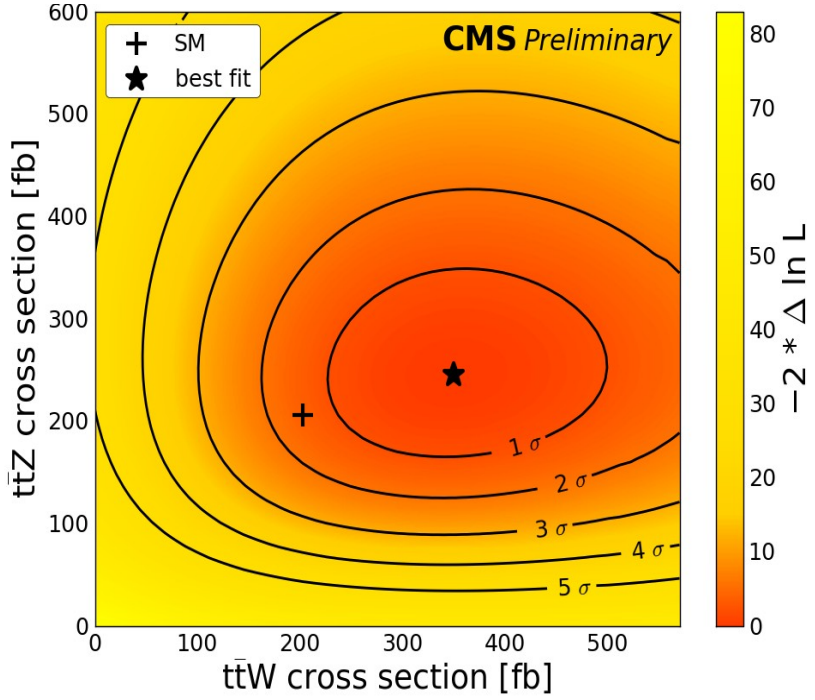


- measure third component of weak isospin

$$-i\frac{e}{\sin\theta_W\cos\theta_W}\left(T_3-\sin^2\theta_W q_t\right)\gamma^\mu$$

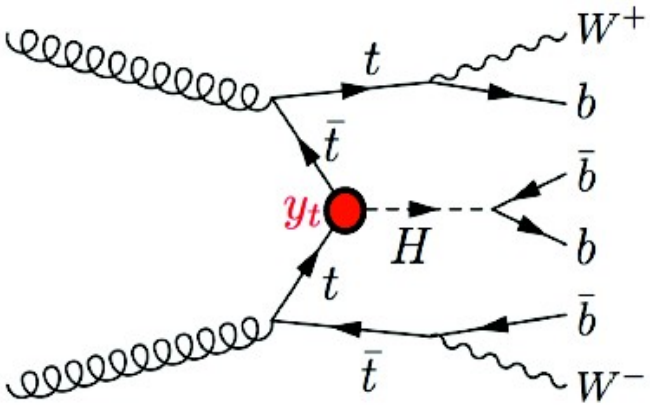
- search for anomalous couplings in $t\bar{t}Z$ vertex (basically unexplored)

$t\bar{t}W$: 3.8 σ (exp) 4.8 σ (obs)
$t\bar{t}Z$: 5.7 σ (exp) 6.4 σ (obs)

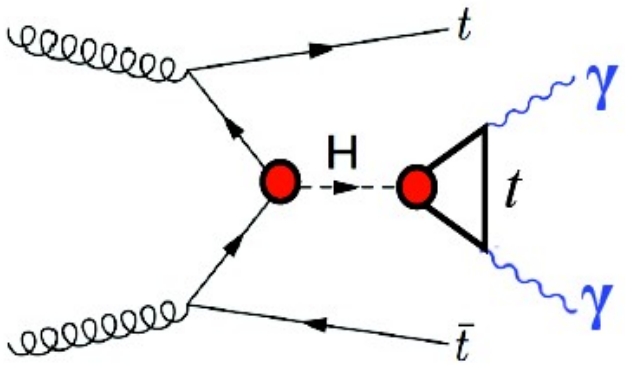


Top Higgs Coupling

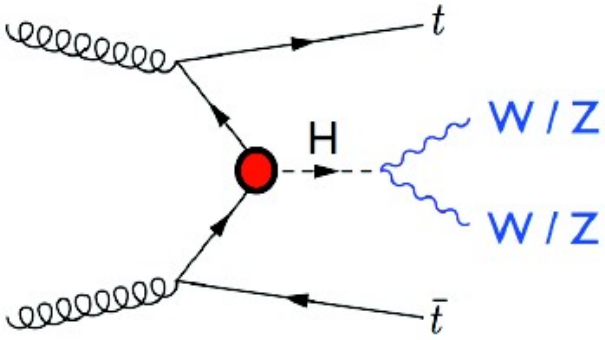
$H \to b\bar{b}$

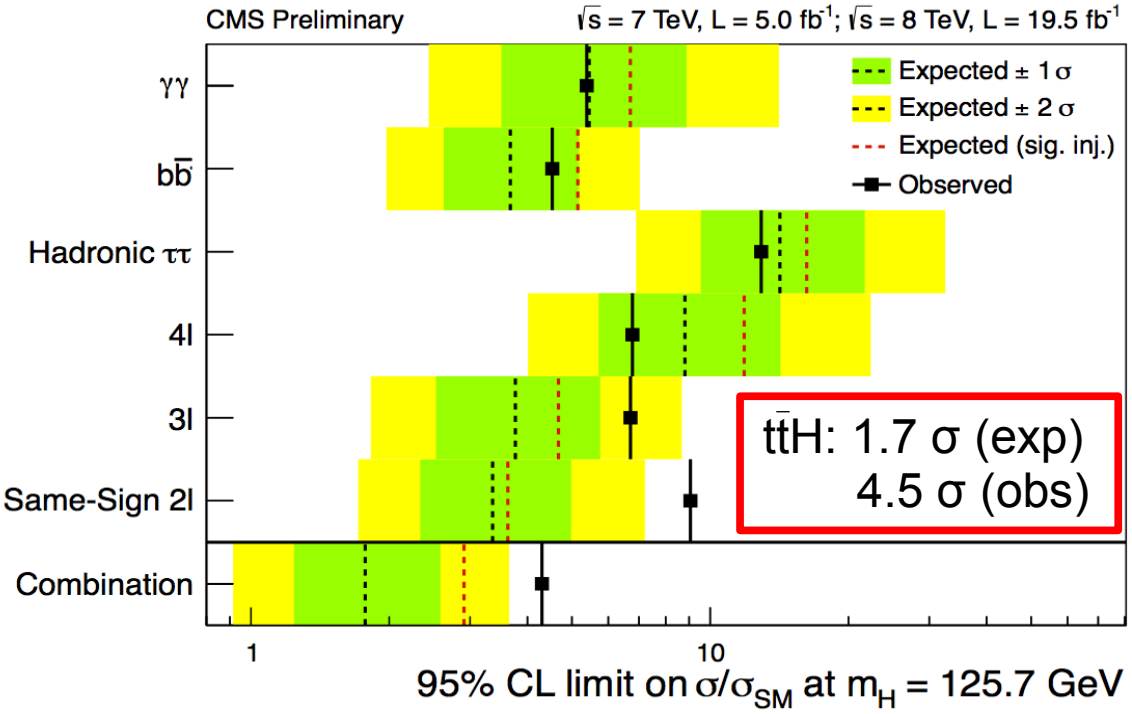


$H \to \gamma\gamma$



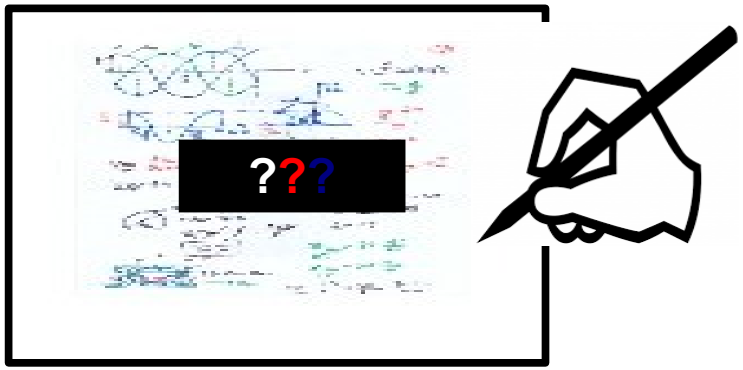
$H \to WW, ZZ$



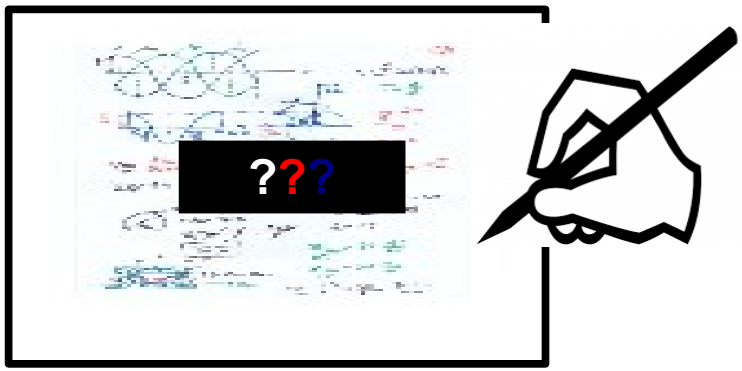


- observation
- measurement of top-Yukawa coupling

In 20 Years

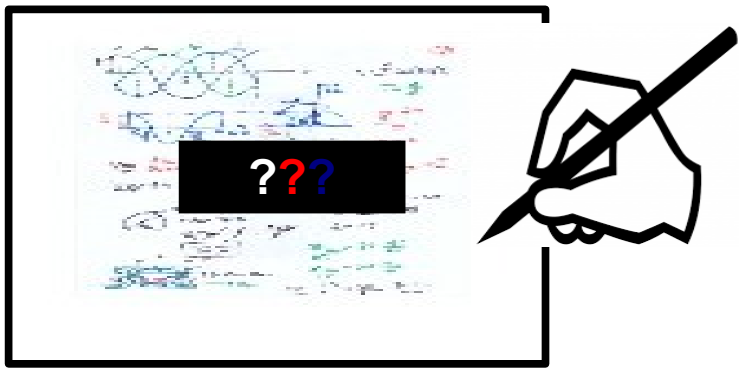


In 20 Years

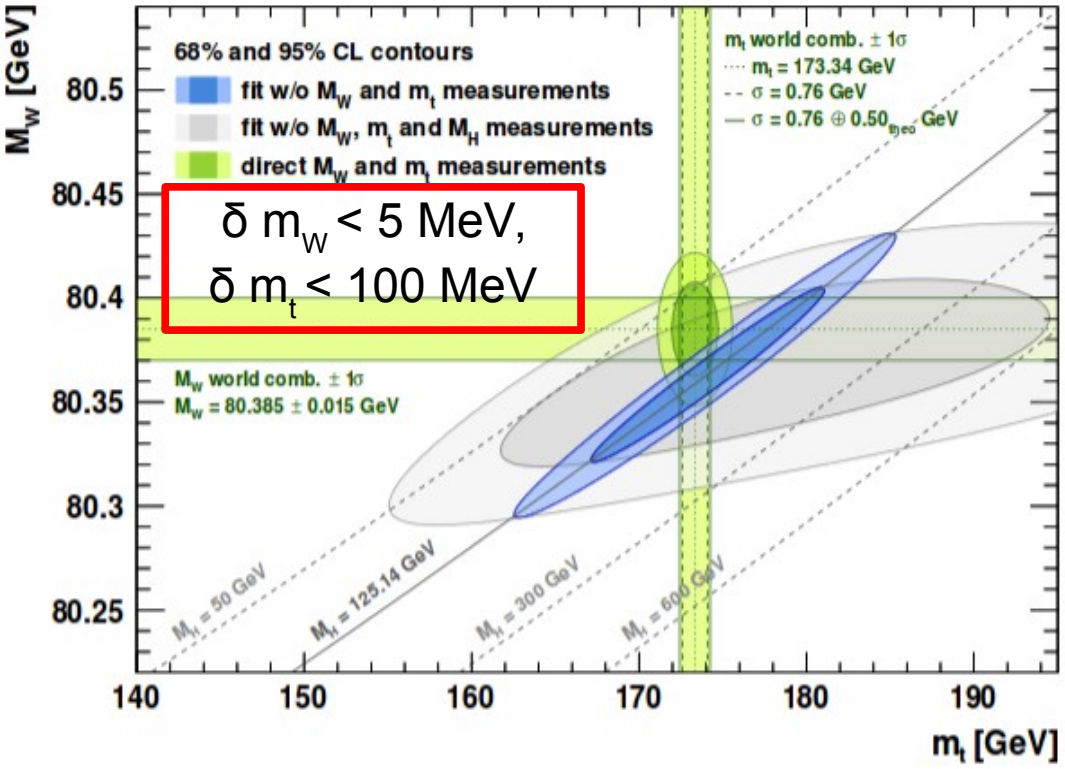




In 20 Years



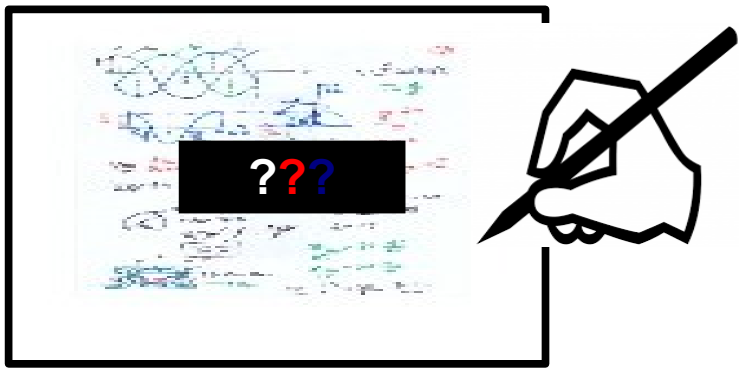




δ m_W < 5 MeV,
δ m_t < 100 MeV

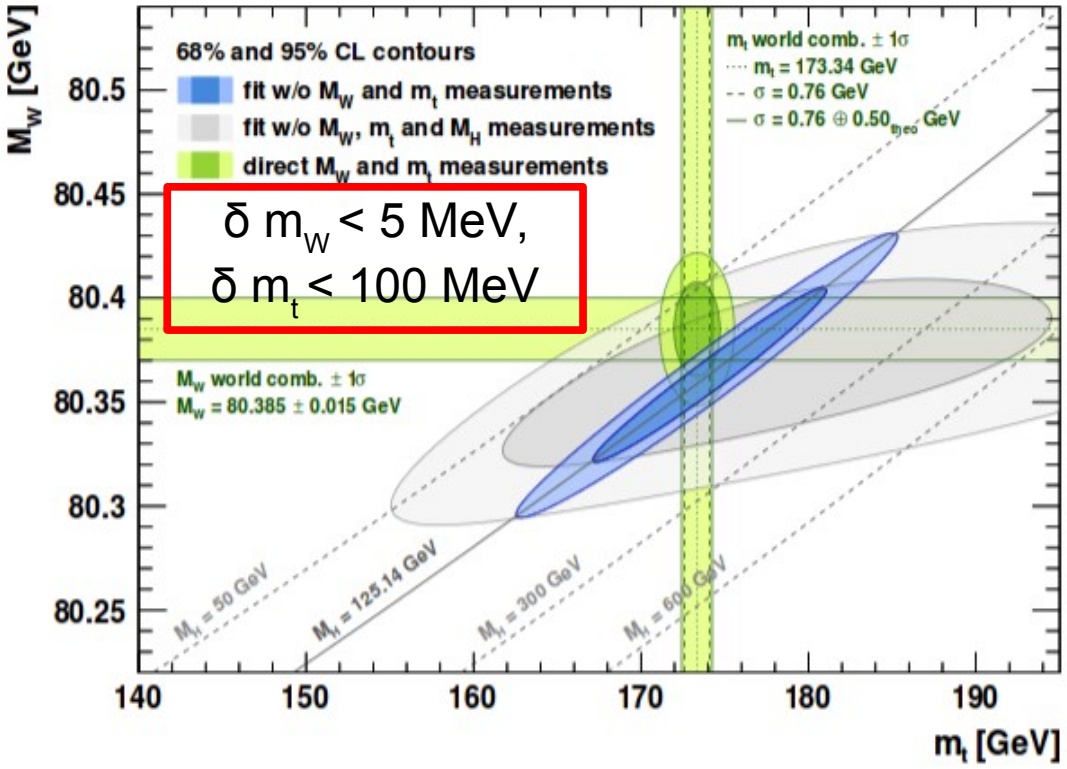
CEPC

In 20 Years





CEPC



δ m_W < 5 MeV,
δ m_t < 100 MeV

