

Top Quark Physics

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HASCO Summer School 2014

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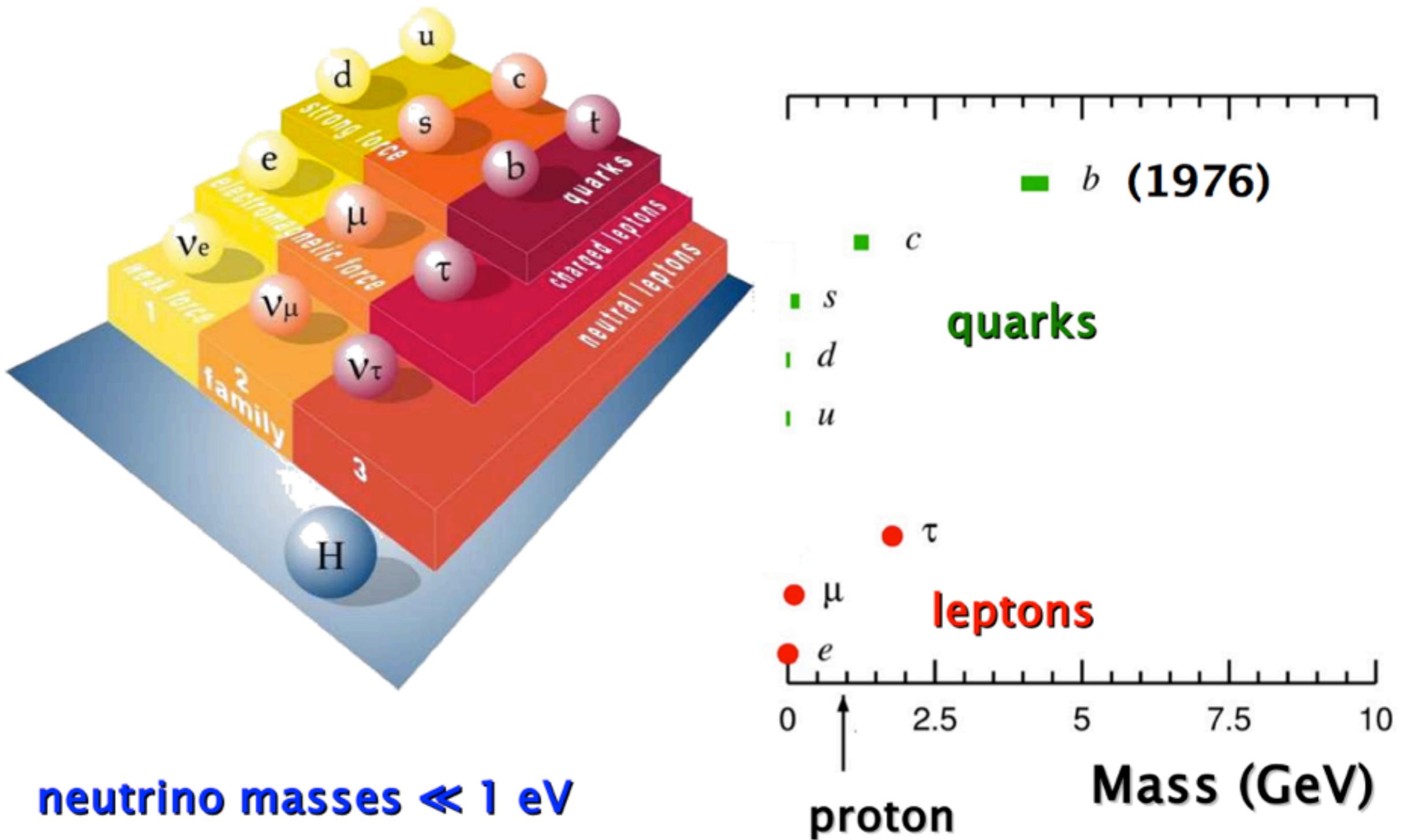
Plan for this Morning

- Top quark physics:
 - Introduction & top quark production - Mark Owen
 - Top quark properties - Efe Yazgan
 - On some top quark physics issues - Stano Tokar

Outline

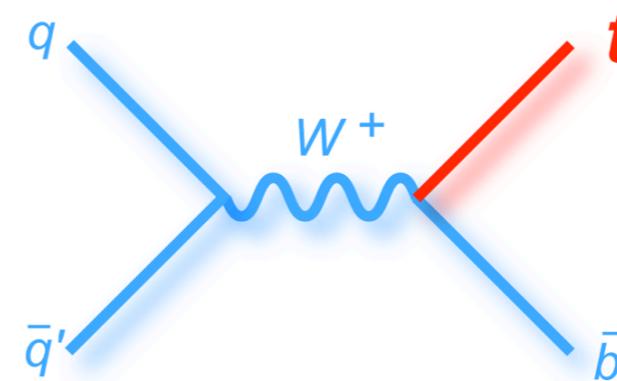
- Introduction & History of Top Quark Search
- Identifying top pair production
- Top Quark Pair Production
 - Inclusive cross section
 - Modelling top quark production
 - Differential cross sections
- Single Top Production
 - Tevatron discovery
 - LHC measurements

Particle Masses



History of Top Quark

- 1976: Discovery of Upsilon (Fermilab) - contains a 5th quark - the b-quark.
- From family structure of SM - expect a 6th quark - race to find it:
- Petra (e+e-) at DESY, Hamburg, $m_t > 23.3$ GeV (1984)
- Tristan (e+e-) in Japan: $m_t > 30.2$ GeV in late 1980s
- UA1@SPS at CERN: $m_t > 44$ GeV (1988)
- LEP (e+e-) at CERN: $m_t > 45.8$ GeV (1990)
- UA2@SPS: $m_t > 69$ GeV
- End of $W \rightarrow tb$ search channel



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Electroweak precision data

$$M_z^2 = M_z^{2\text{ 0.order}} / (1 - \Delta)$$
$$\Delta \approx \dots m_t^2 \dots + \dots \ln m_h \dots$$

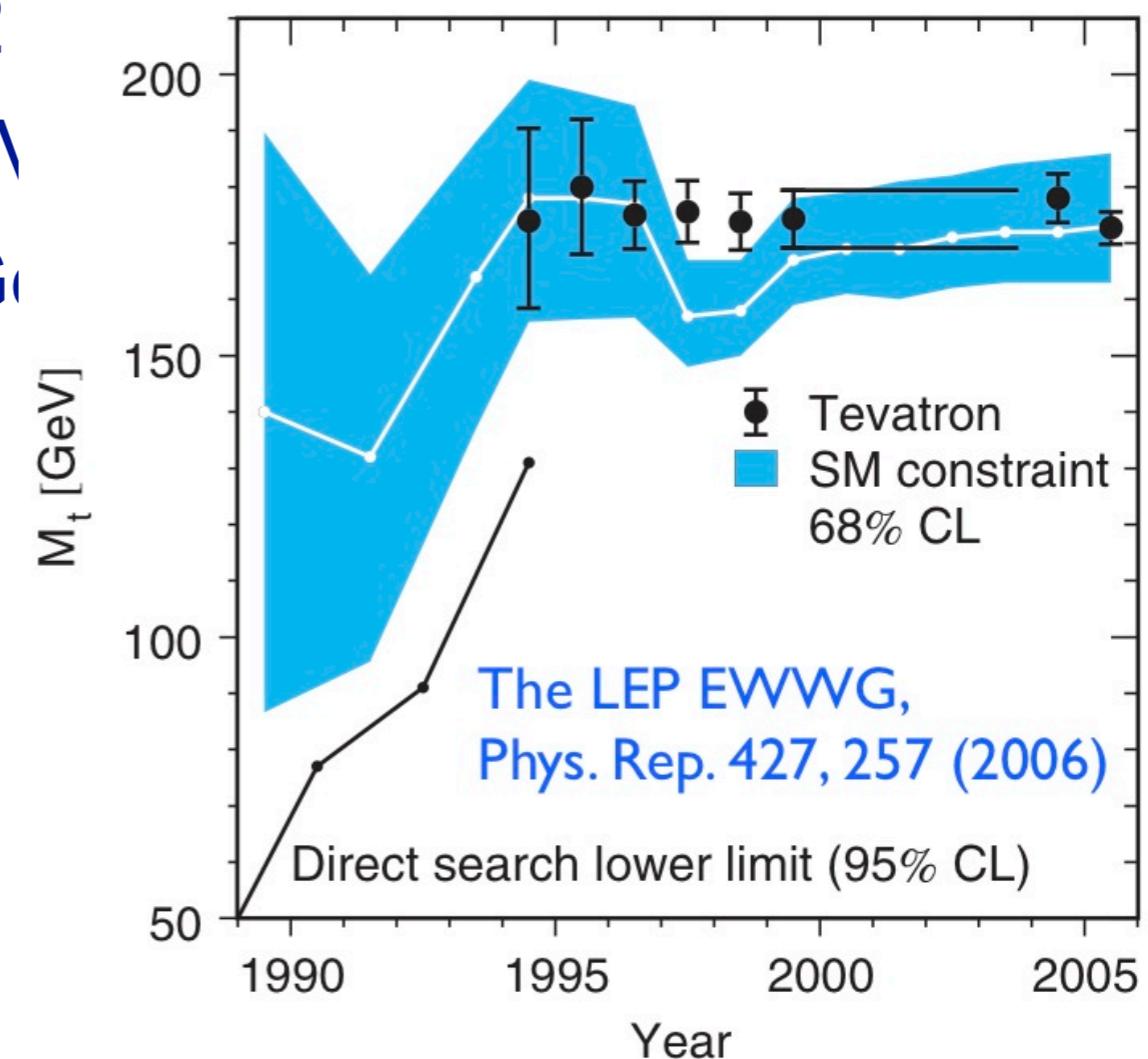
Top is heavy -
should be in
reach of Tevatron
(pp @ 1.8 TeV)

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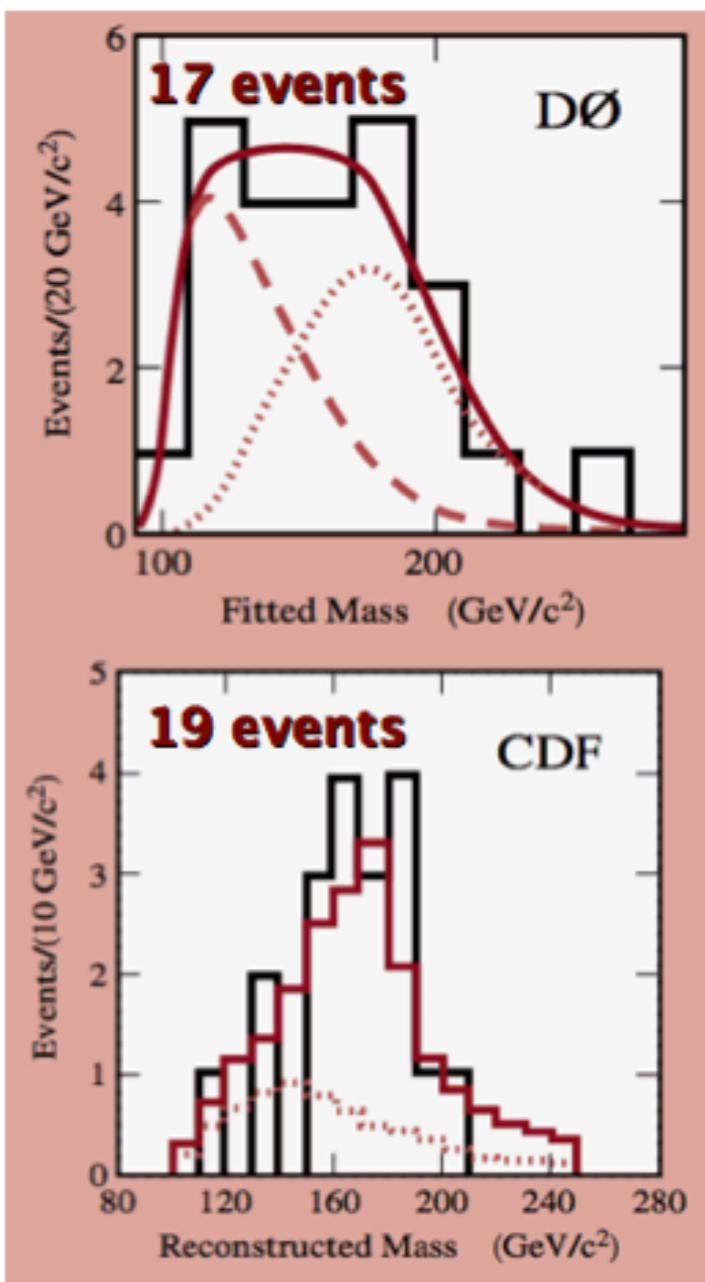
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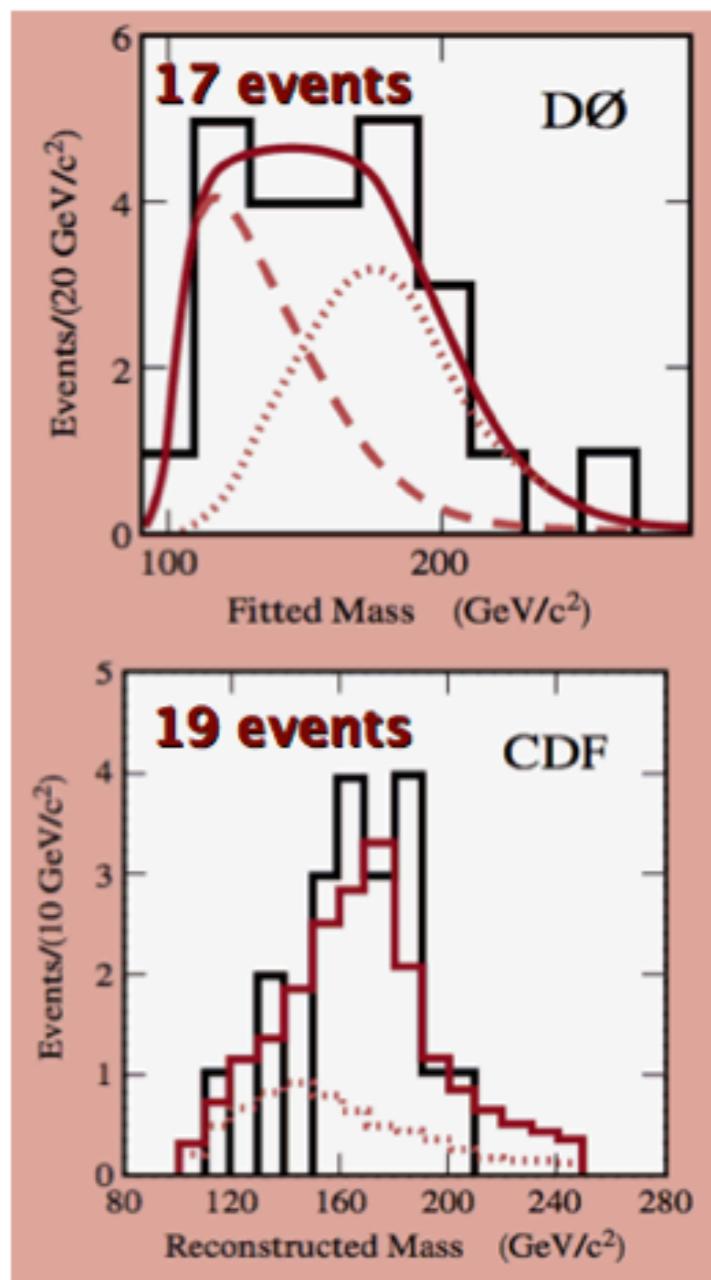
Top Quark Discovery

- 1984/85: Tevatron collider commissioned & dedicated.
- October 1985: First collisions at CDF (D0 still under construction).
- 1987: CDF Run-0
- 1992: First collisions at D0
- 1992-1996: Run 1 Tevatron (1.8 TeV)
- 1995: Discovery of the top quark.

Top Quark Discovery

discoveryPRL 74, 2632 (1995)
PRL 74, 2626 (1995)**1995, CDF and DØ
experiments, Fermilab**

Top Quark Discovery

discoveryPRL 74, 2632 (1995)
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March 2nd, 1995:
First announcement of Top Discovery
in public seminar at Fermilab



Top Quark Discovery

July 4th, 2012: Higgs discovery

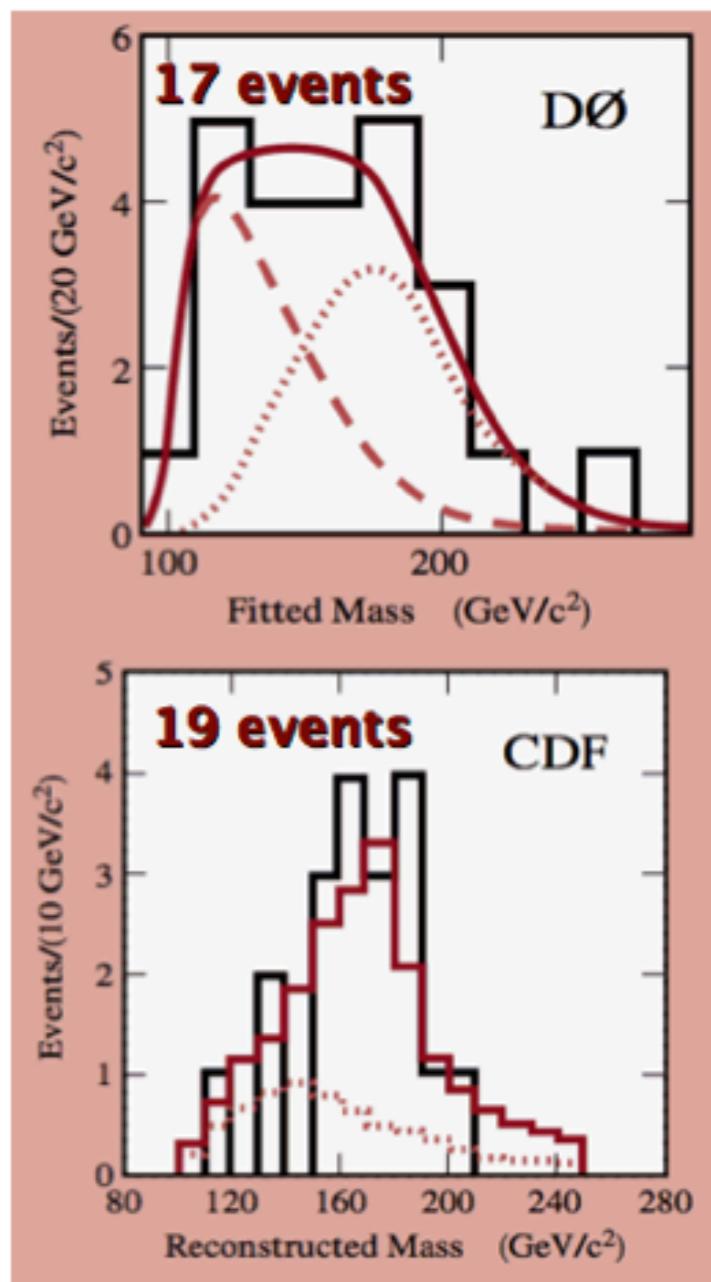


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Top Quark Discovery

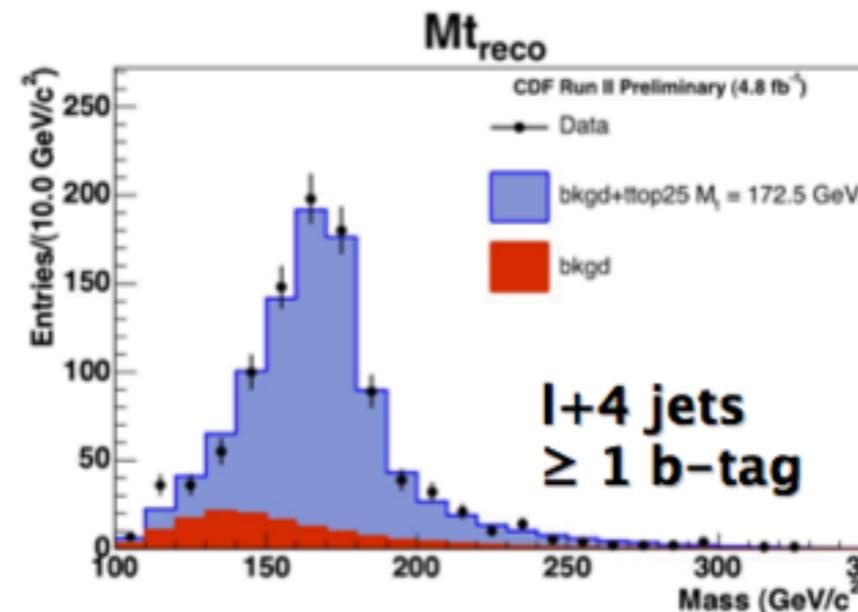
discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)

1995, CDF and DØ
experiments, Fermilab

today

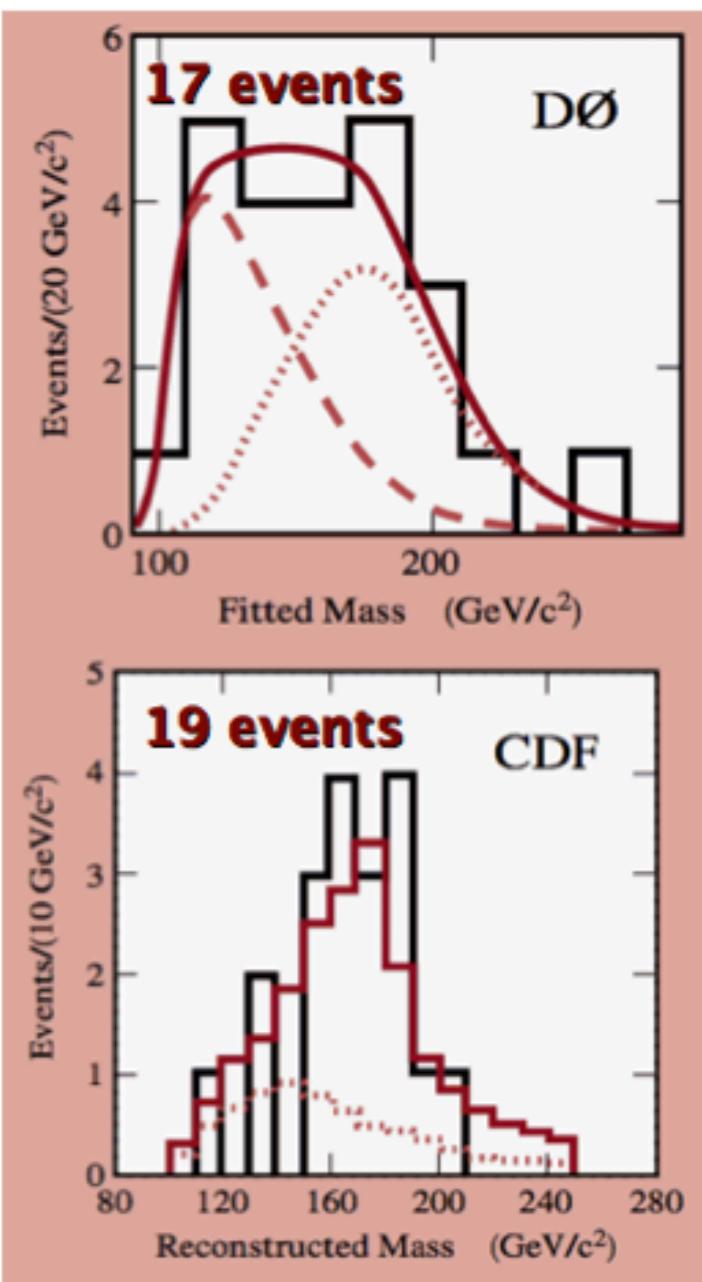
1000s of events



Top Quark Discovery

discovery

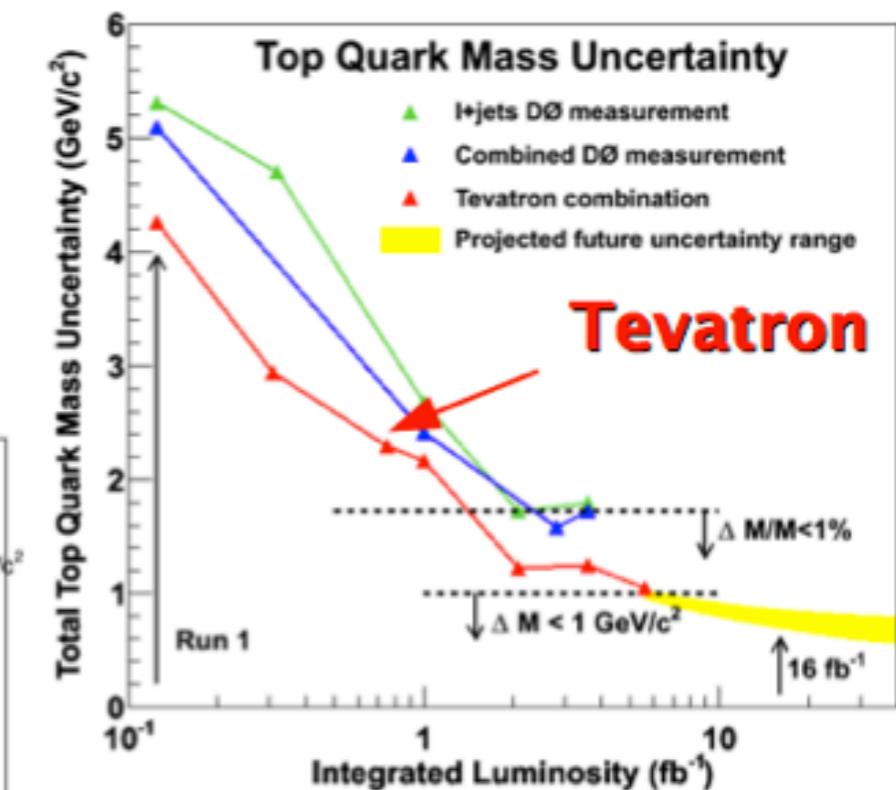
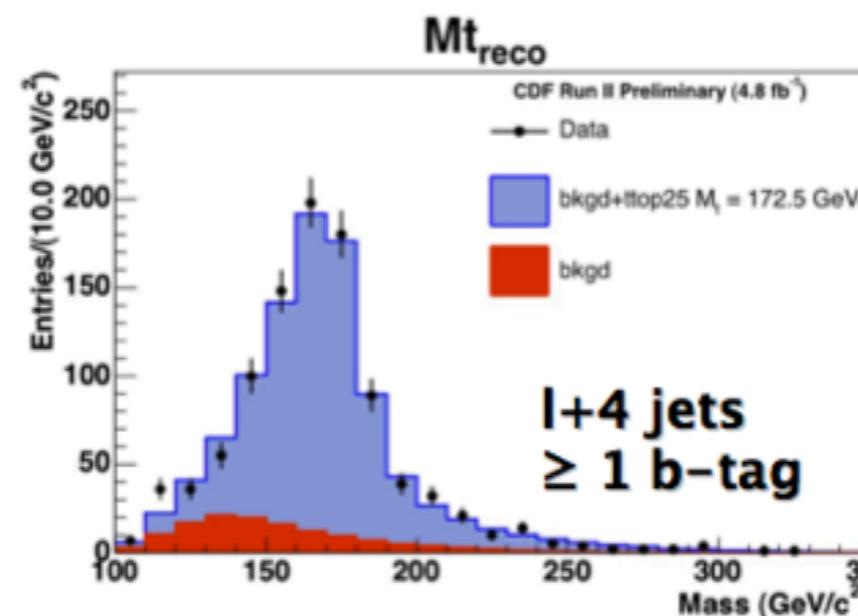
PRL 74, 2632 (1995)
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1995, CDF and DØ experiments, Fermilab

today

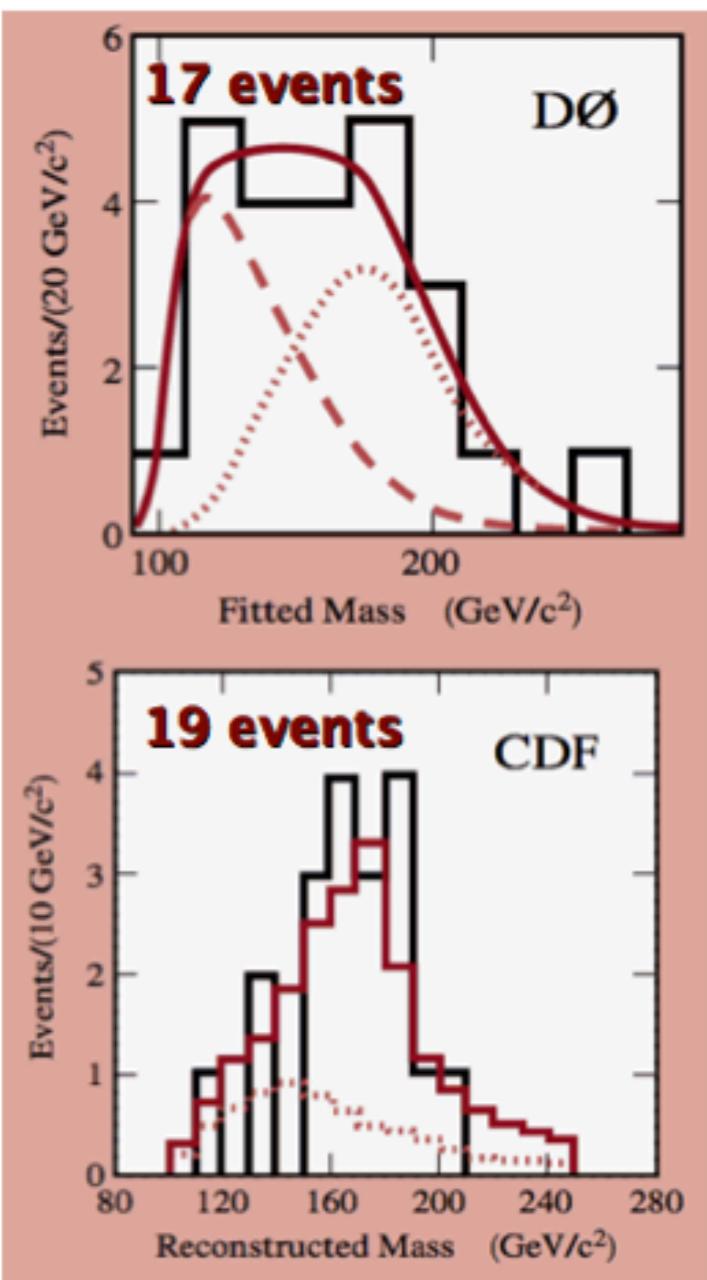
1000s of events



Top Quark Discovery

discovery

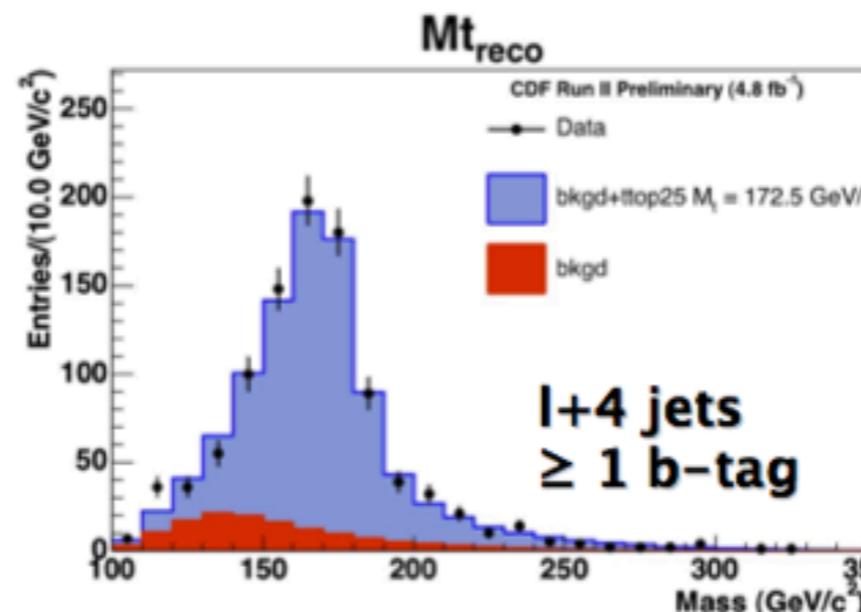
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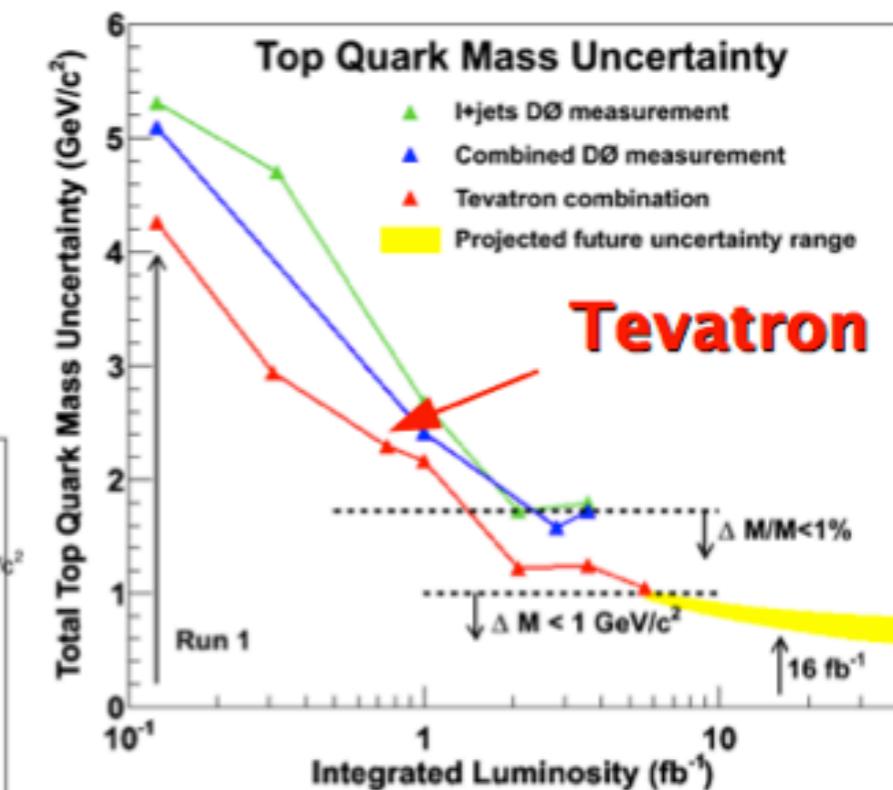
1995, CDF and DØ experiments, Fermilab

today

1000s of events



precision



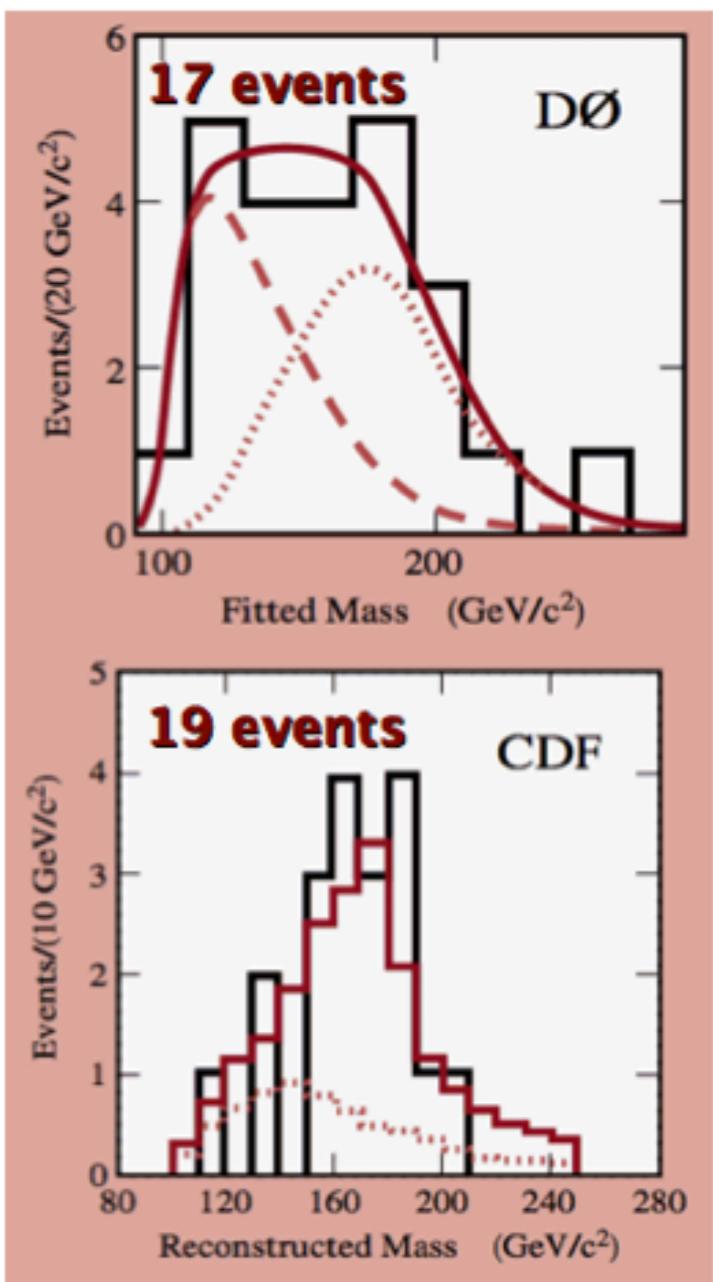
searches



Top Quark Discovery

discovery

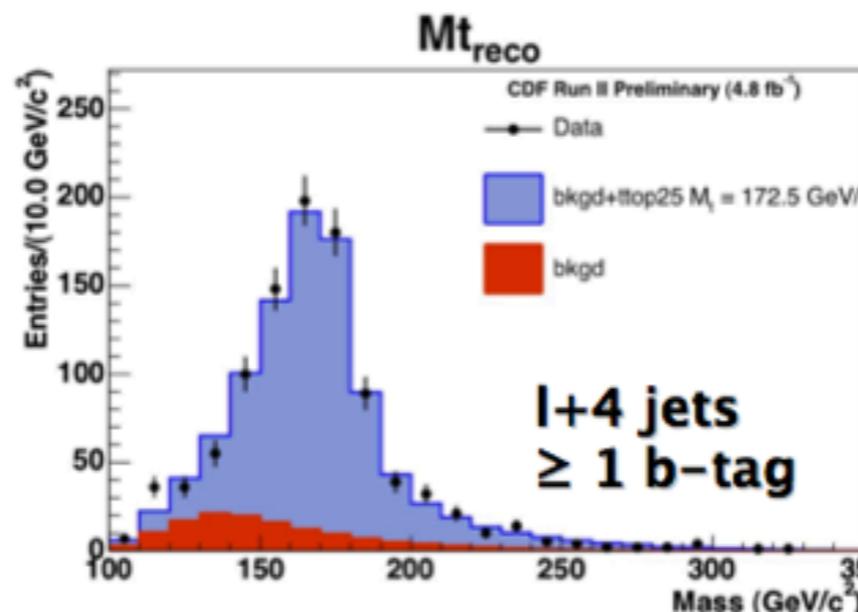
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1995, CDF and DØ experiments, Fermilab

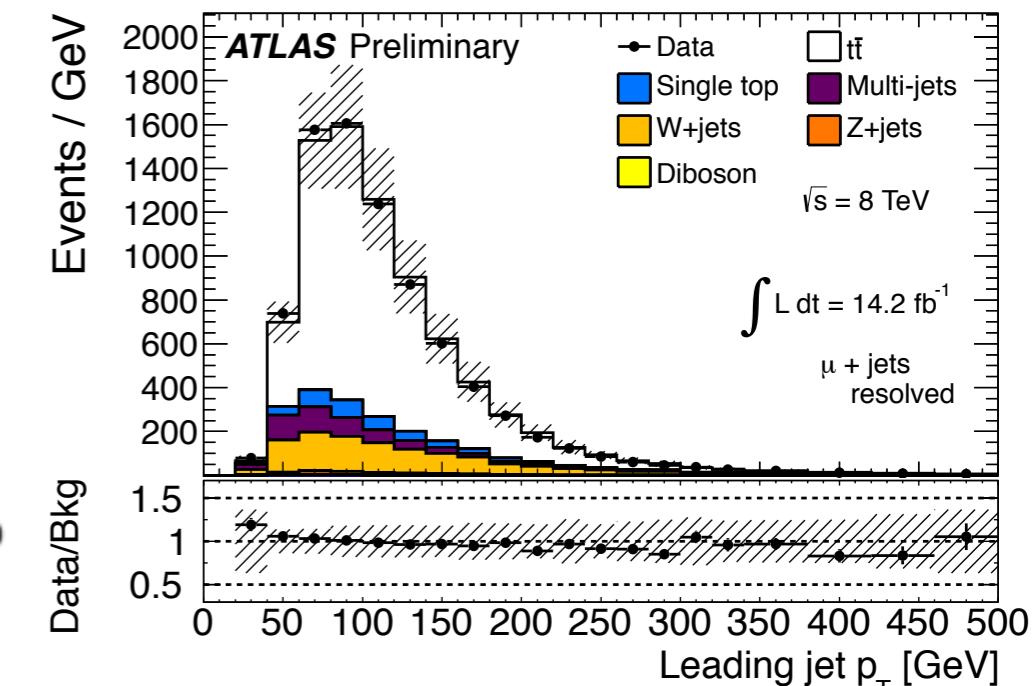
today

1000s of events

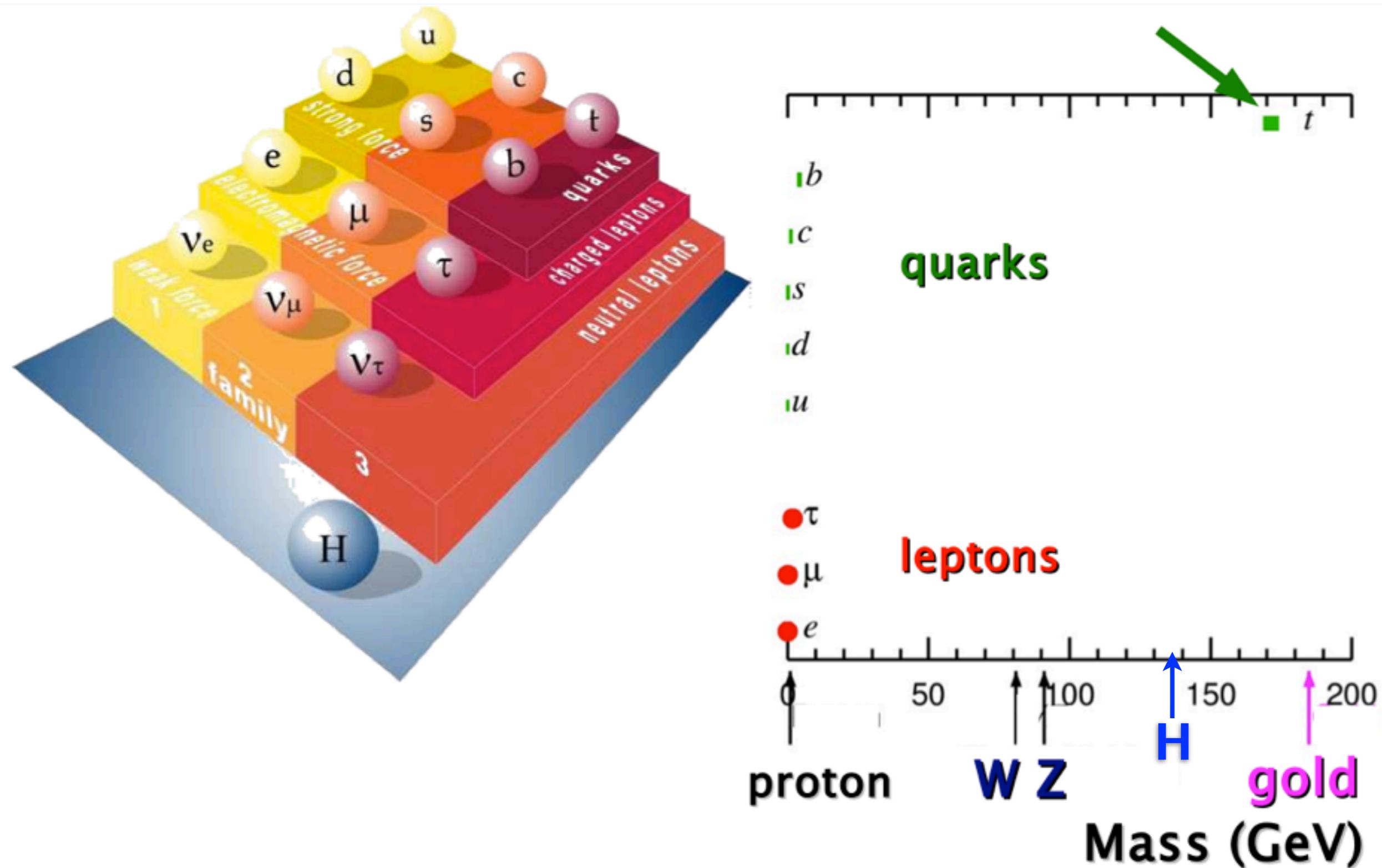


**LHC:
top quark
factory**

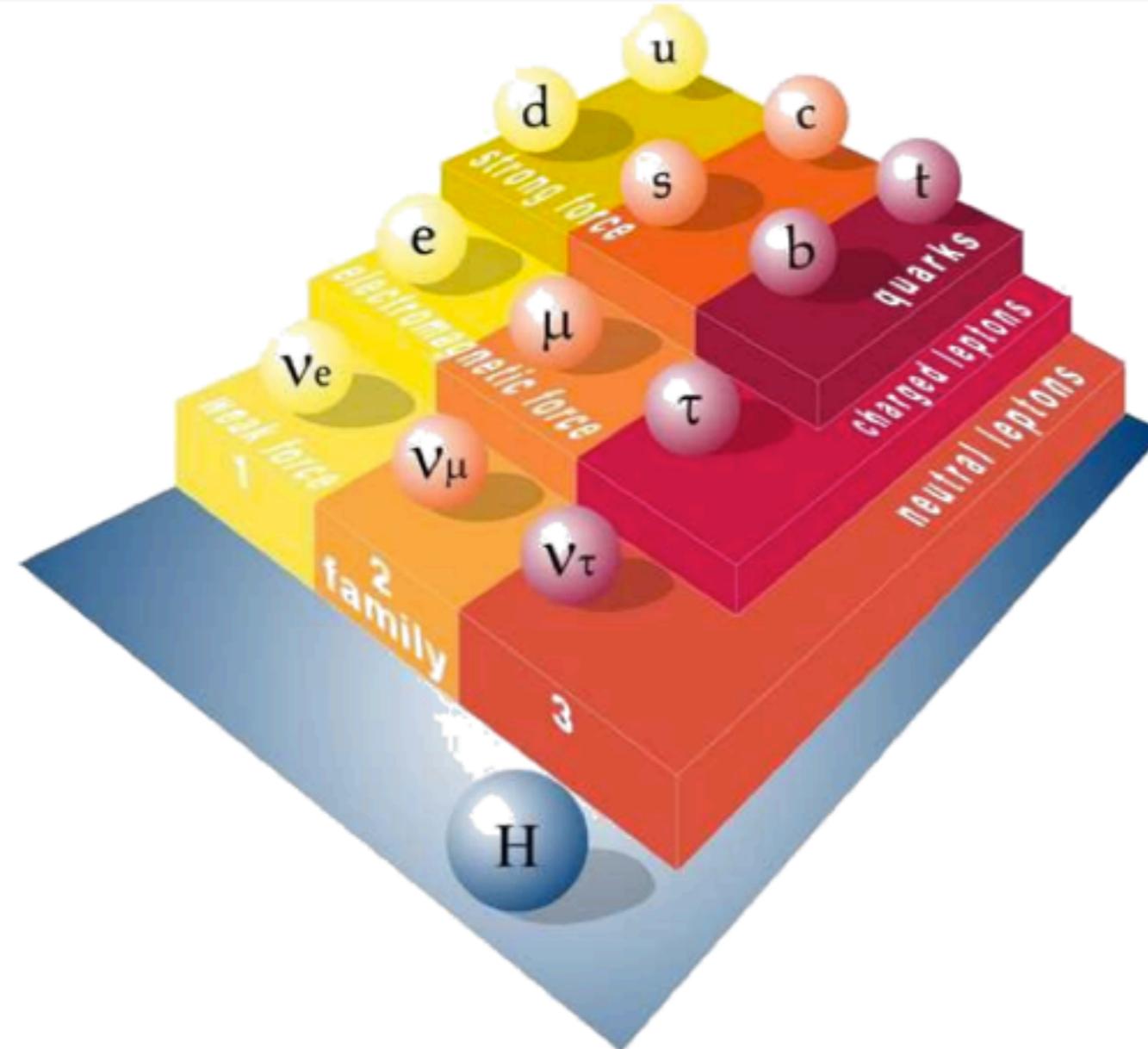
100000s of events



The Top Quark



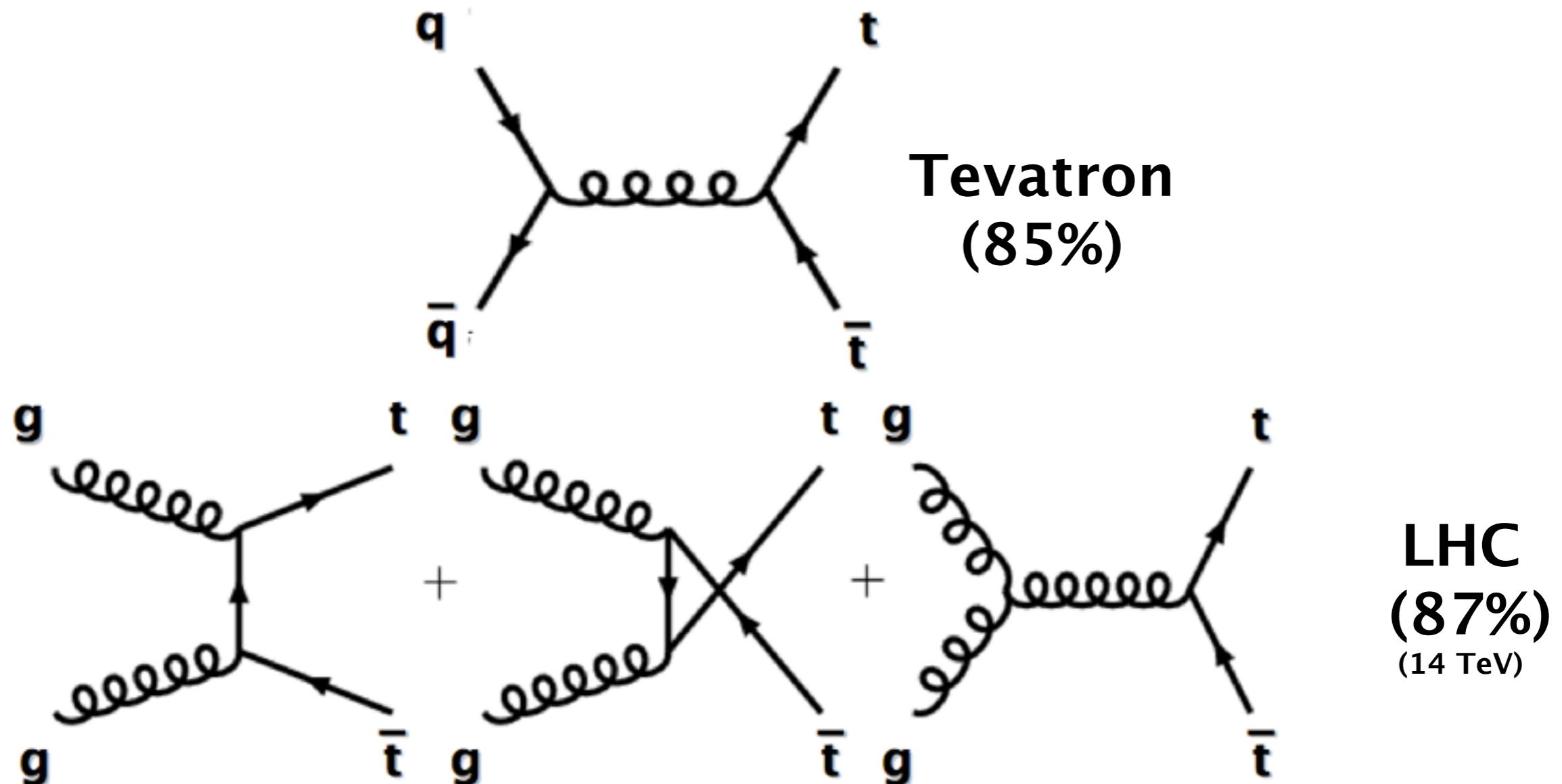
Why The Top Quark

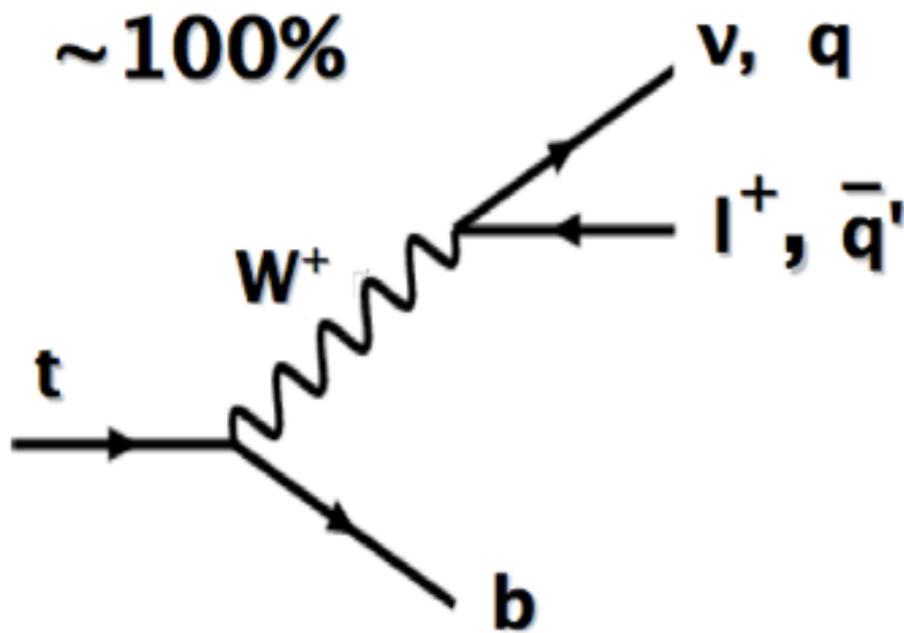


- In the SM it's the only quark:
 1. With a natural mass:
$$m_{top} = y_t v / \sqrt{2} \approx 173 \text{ GeV} \Rightarrow y_t \approx 1$$
 2. That decays before hadronizing:
$$\tau_{had} \approx 2 \times 10^{-24} \text{ s}$$
$$\tau_{top} \approx 5 \times 10^{-25} \text{ s}$$
 - Top is a unique window on QCD & EW physics.

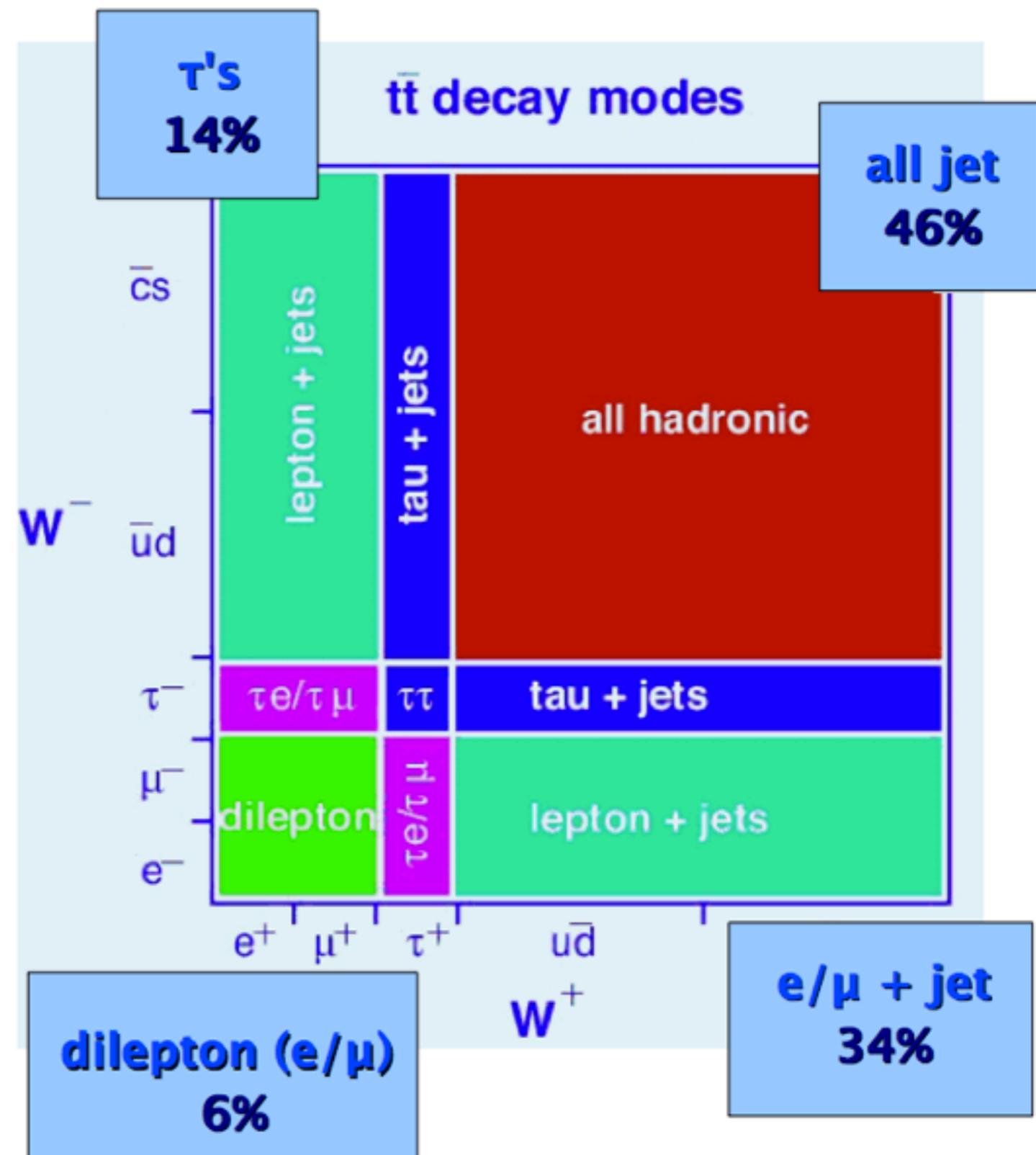
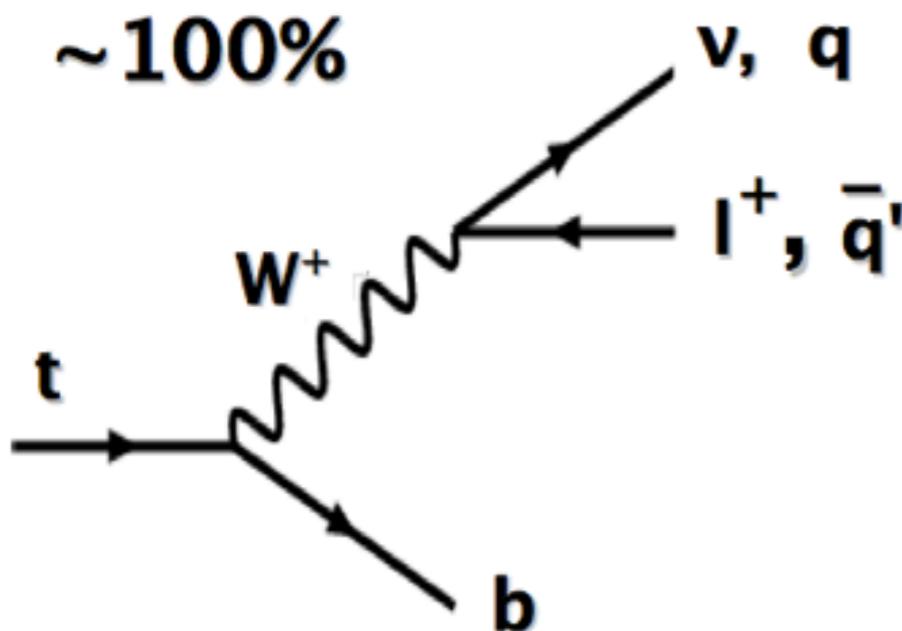
Top Quark Production & Decay

Top Quark Pair Production

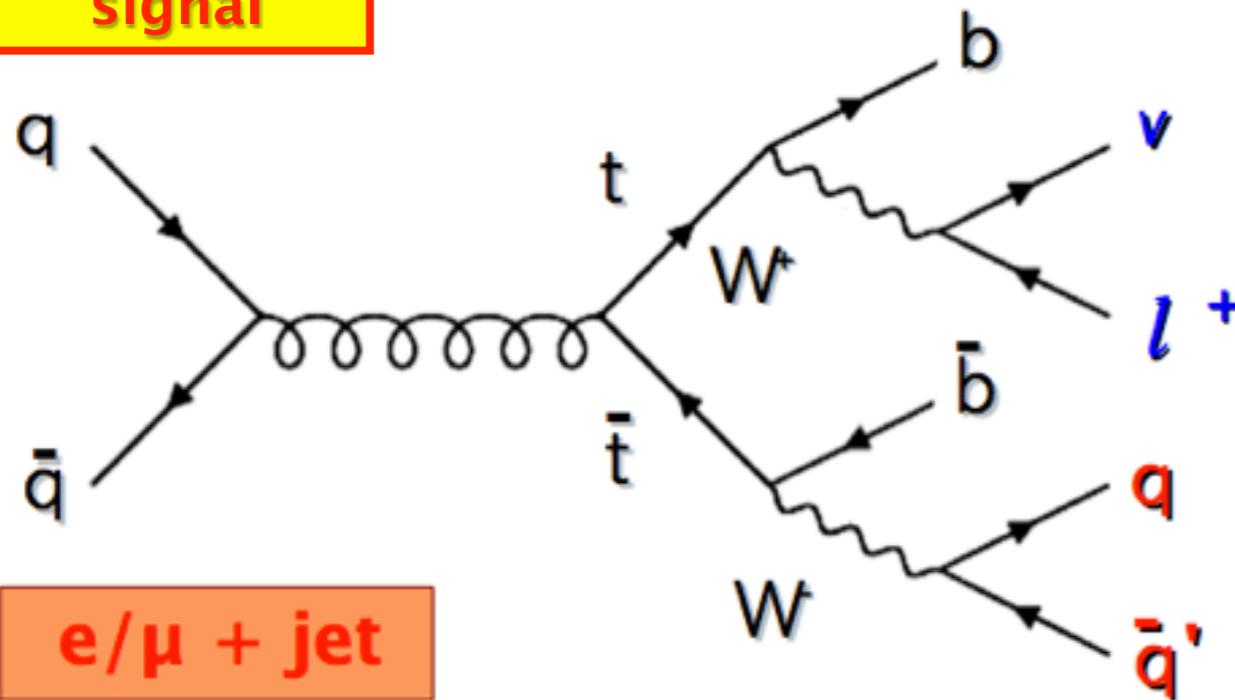


top decay:

Top Quark Signatures

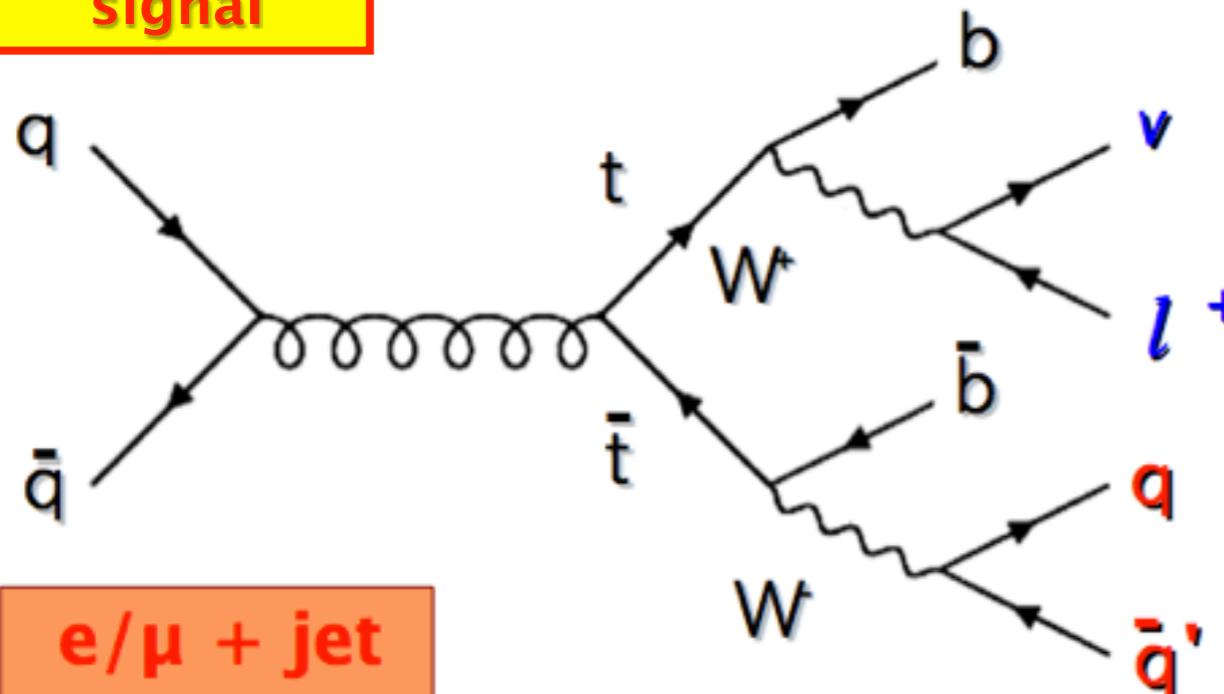
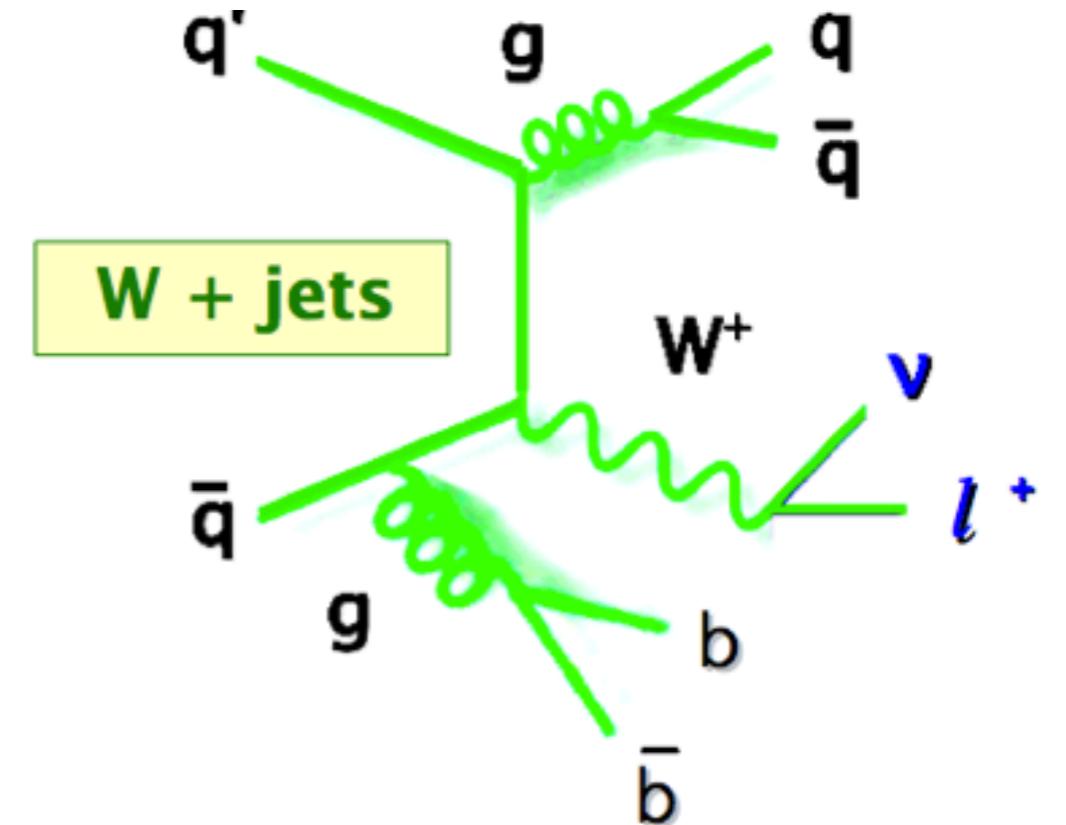
top decay:

Lepton + Jets Signature

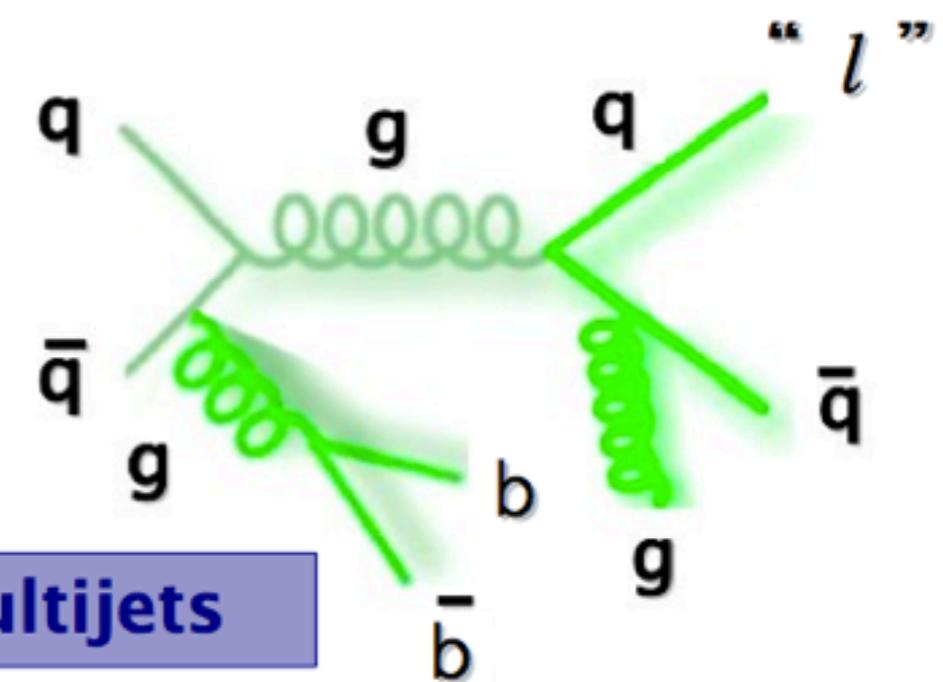
signal**e/ μ + jet**

- High pT lepton
- Missing transverse momentum
- Four high pT jets
- Two jets from b-decays.
- B hadron lifetime ~ 1 ps,
decay length ~ 3 mm

Lepton + Jets Signature

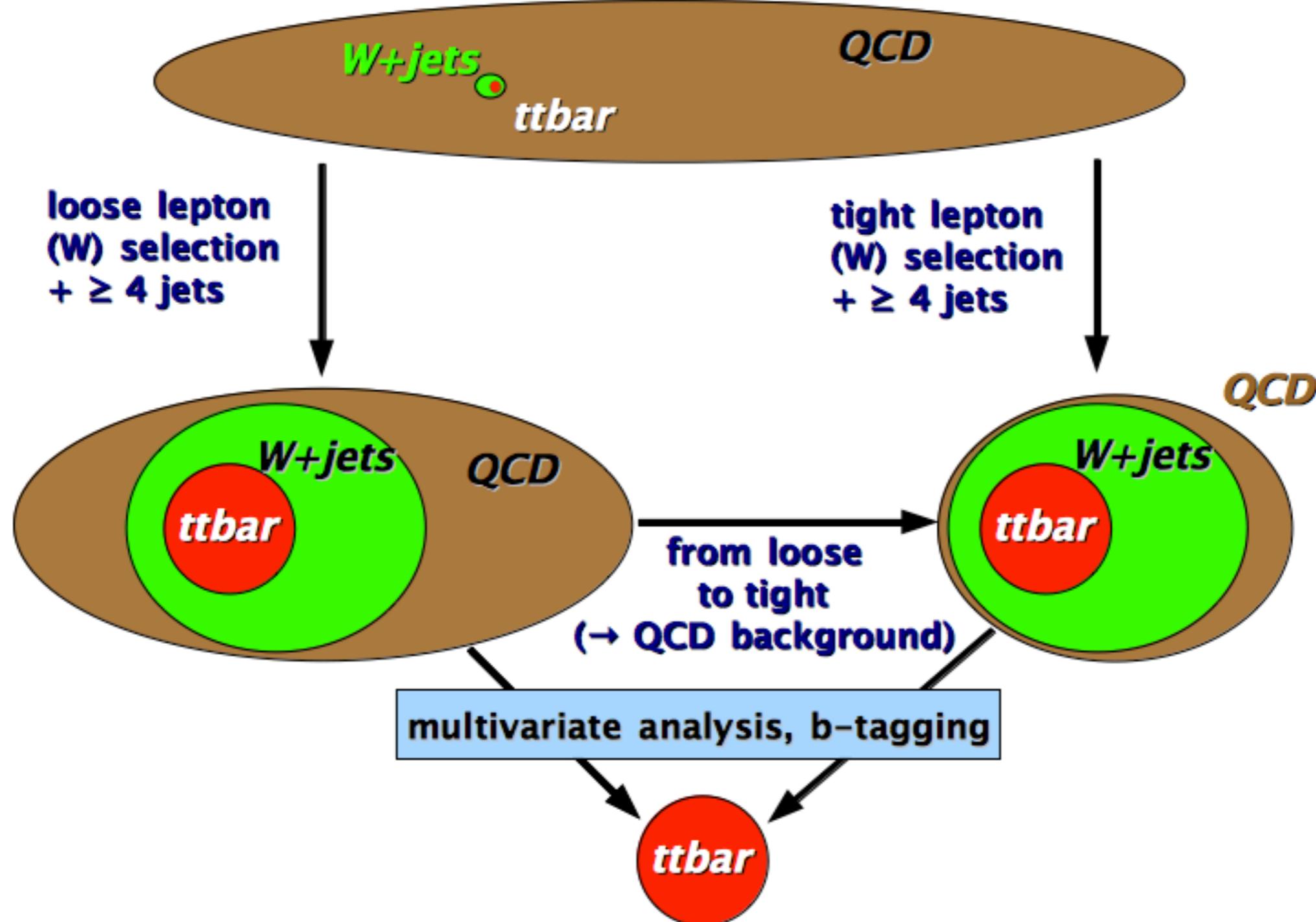
signal**background****e/mu + jet**

- High pT lepton
- Missing transverse momentum
- Four high pT jets
- Two jets from b-decays.
- B hadron lifetime ~ 1 ps,
decay length $\sim 3\text{mm}$

multijets

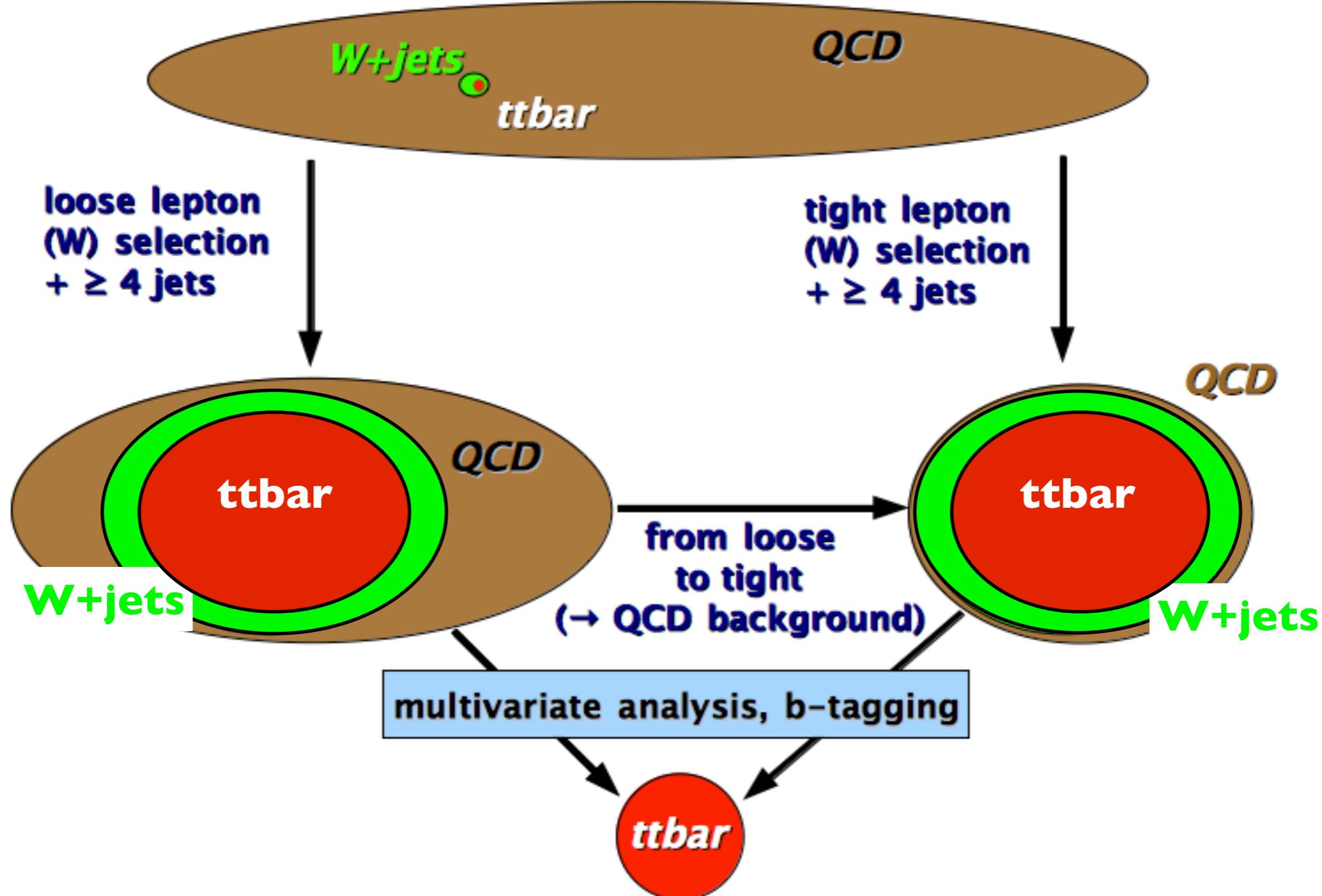
Lepton + Jets Signature

Tevatron



Lepton + Jets Signature

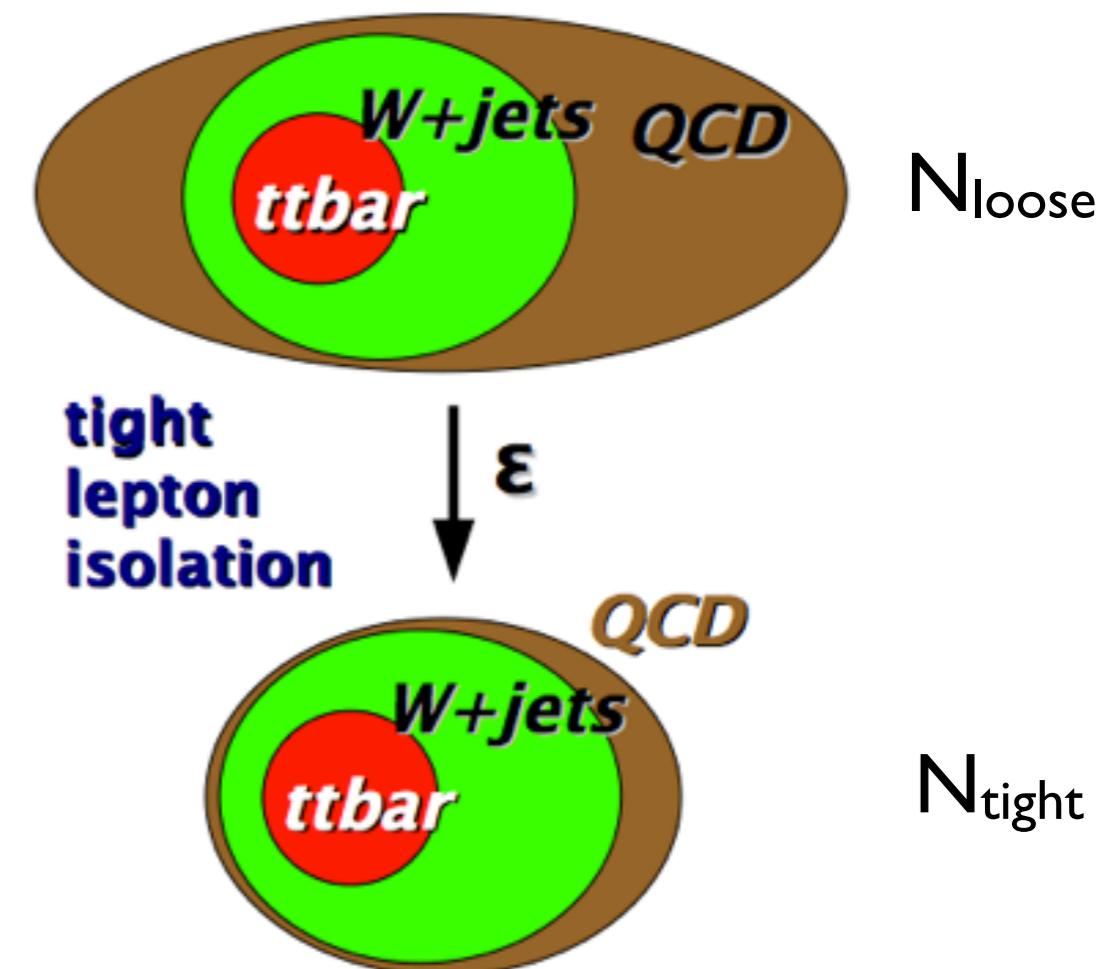
LHC



Multijet Background

lepton+jets

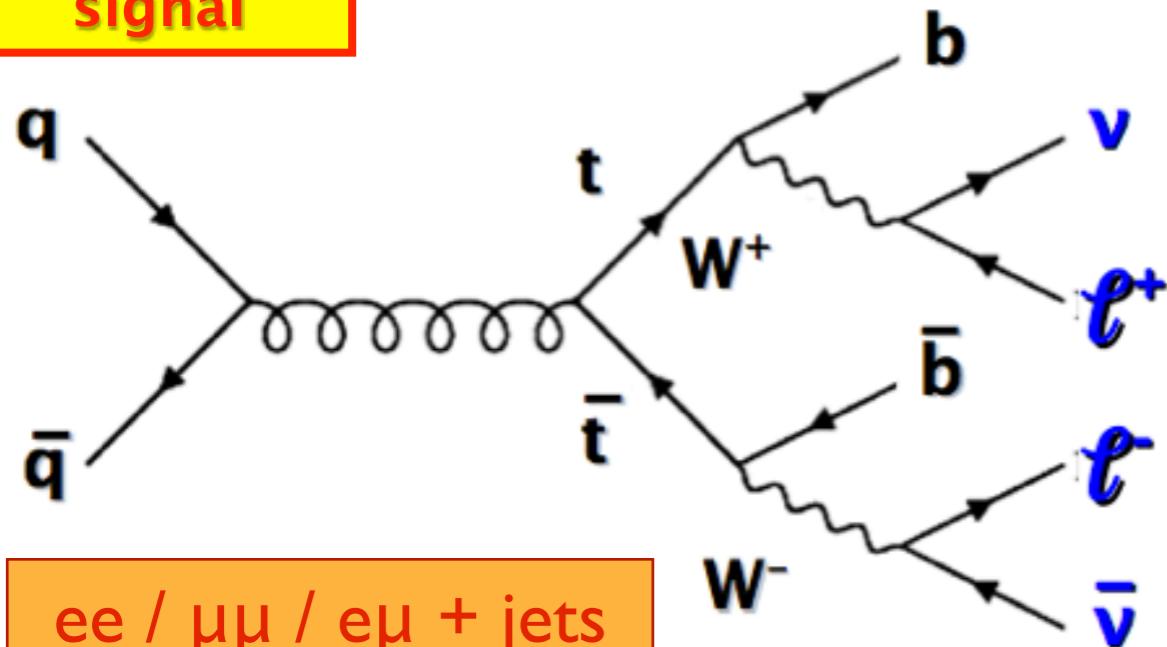
$$\begin{aligned}
 N_{\text{loose}} &= N_{\text{QCD}} + N_{W+\text{ttbar}} \\
 \downarrow \varepsilon &\quad \downarrow \varepsilon_{\text{QCD}} \quad \downarrow \varepsilon_{W+\text{ttbar}} \\
 N_{\text{tight}} &= \varepsilon_{\text{QCD}} * N_{\text{QCD}} + \varepsilon_{W+\text{ttbar}} * N_{W+\text{ttbar}}
 \end{aligned}$$



- ε_{QCD} : independent multijet (QCD) data set (e.g. small \mathbf{E}_T)
- $\varepsilon_{W+\text{ttbar}}$: W+jets Monte Carlo simulation
(normalization to data)

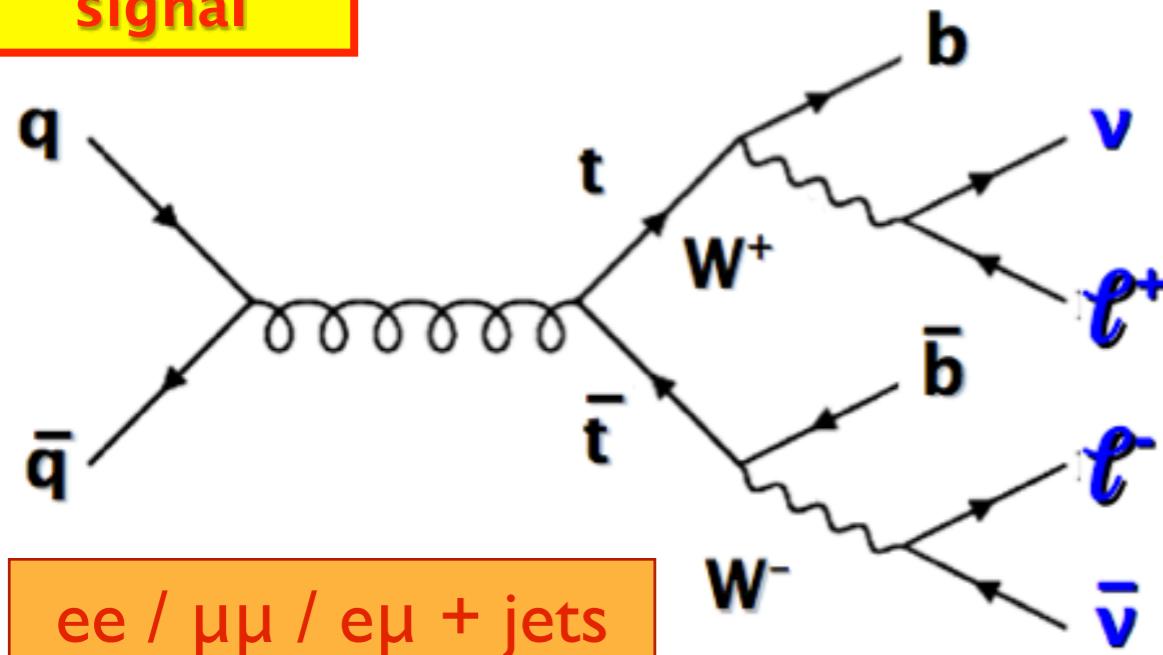
- solve equations for N_{QCD} Try it!
- determine multijet (QCD) background entirely from data

Dilepton Signature

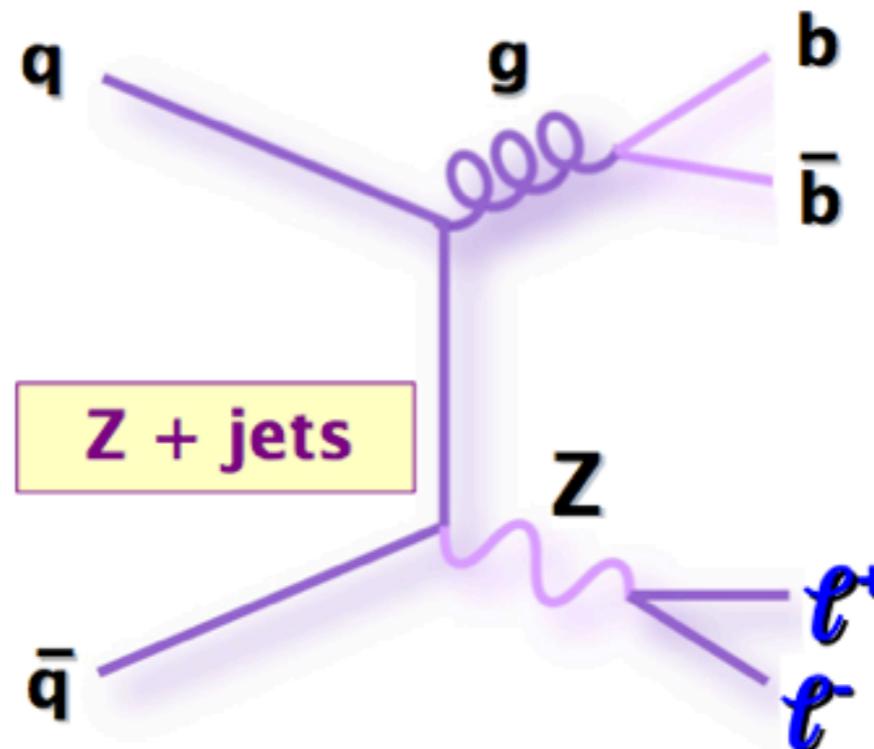
signal**ee / $\mu\mu$ / $e\mu$ + jets**

- 2 High pT leptons
- Missing transverse momentum
- Two jets from b-decays.

Dilepton Signature

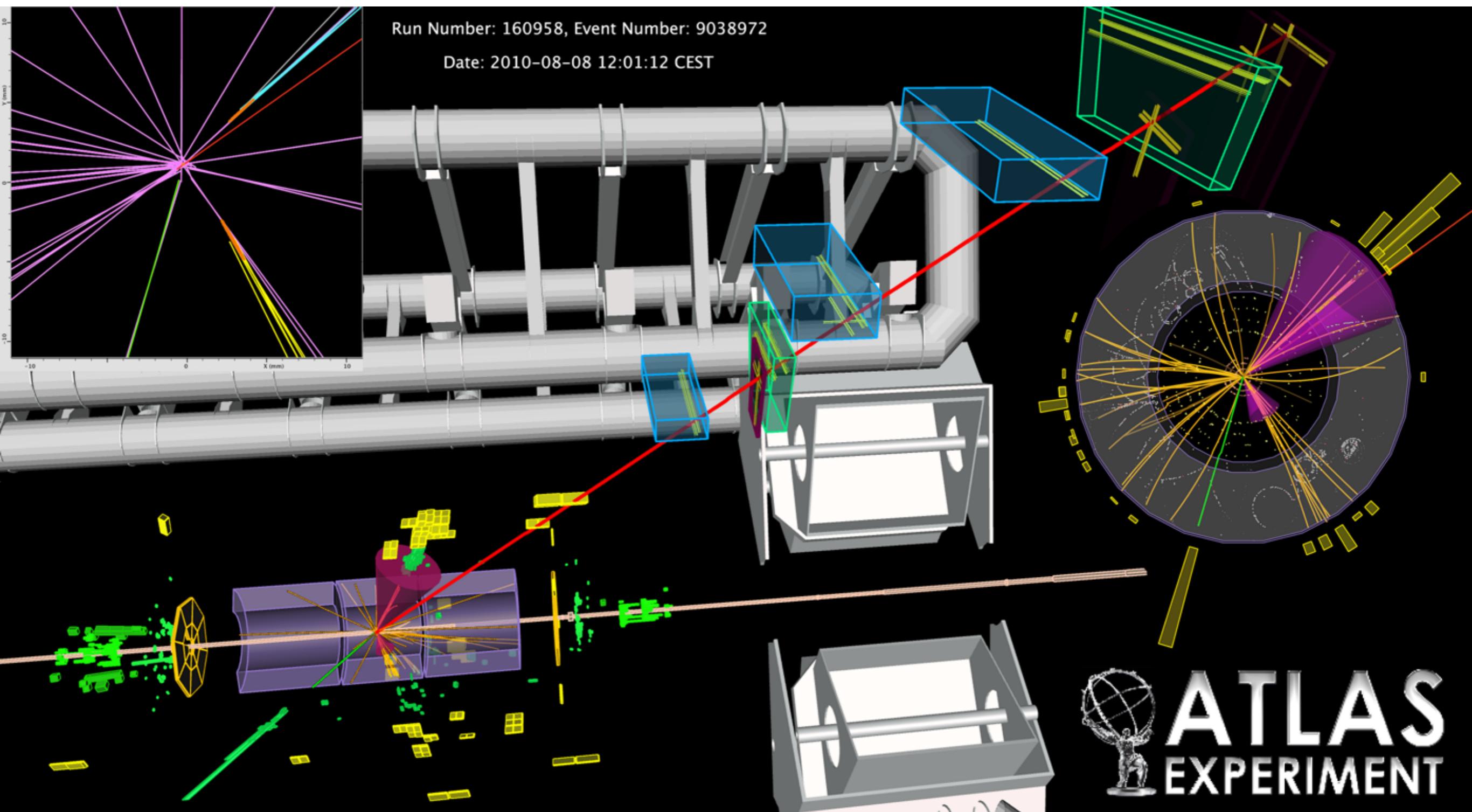
signal**ee / $\mu\mu$ / $e\mu + \text{jets}$**

- 2 High pT leptons
- Missing transverse momentum
- Two jets from b-decays.

background **$Z + \text{jets}$**

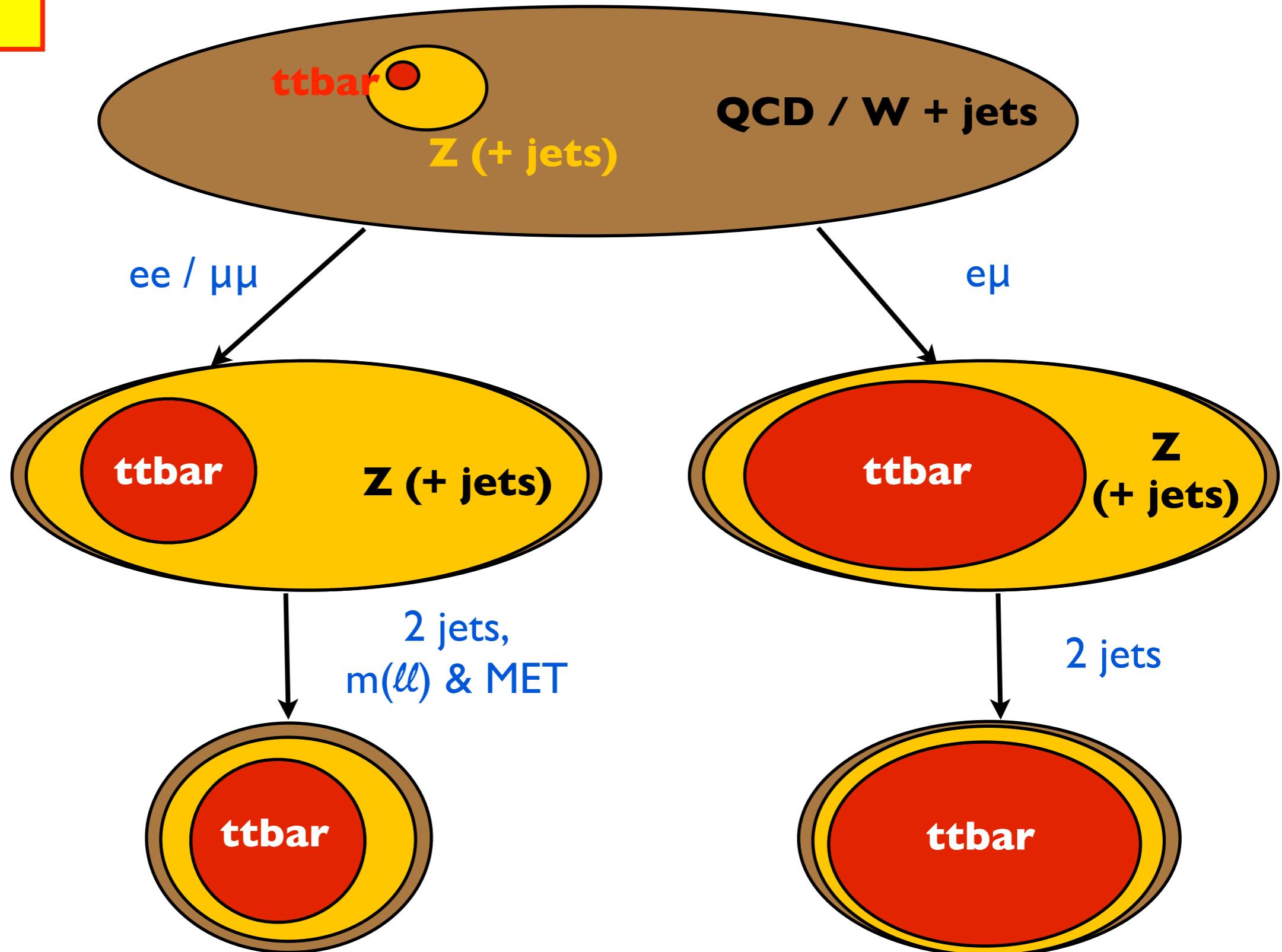
- **less statistics**
- **less background**

Dilepton Signature



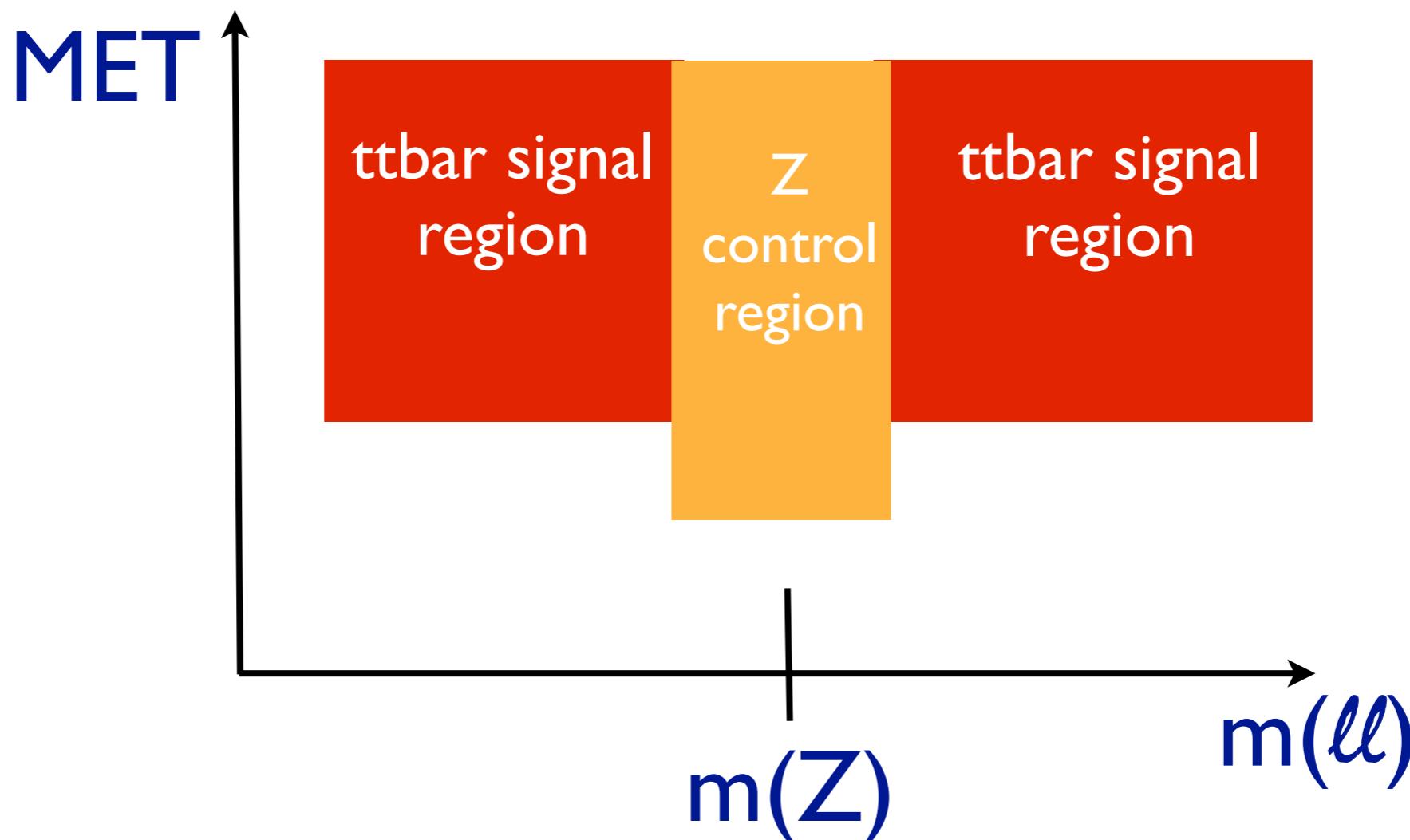
Dilepton Signature

LHC



Z+jets Background

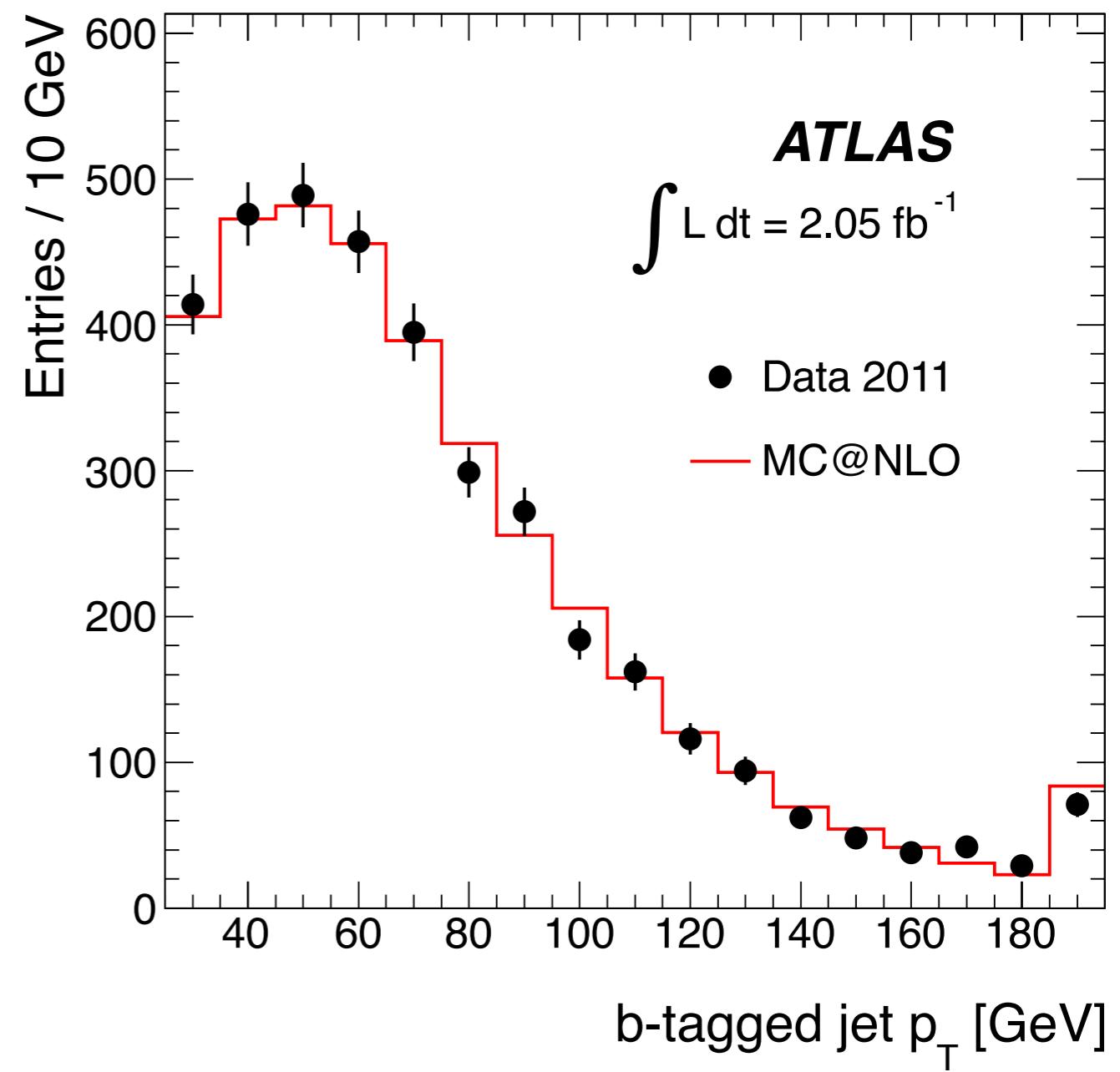
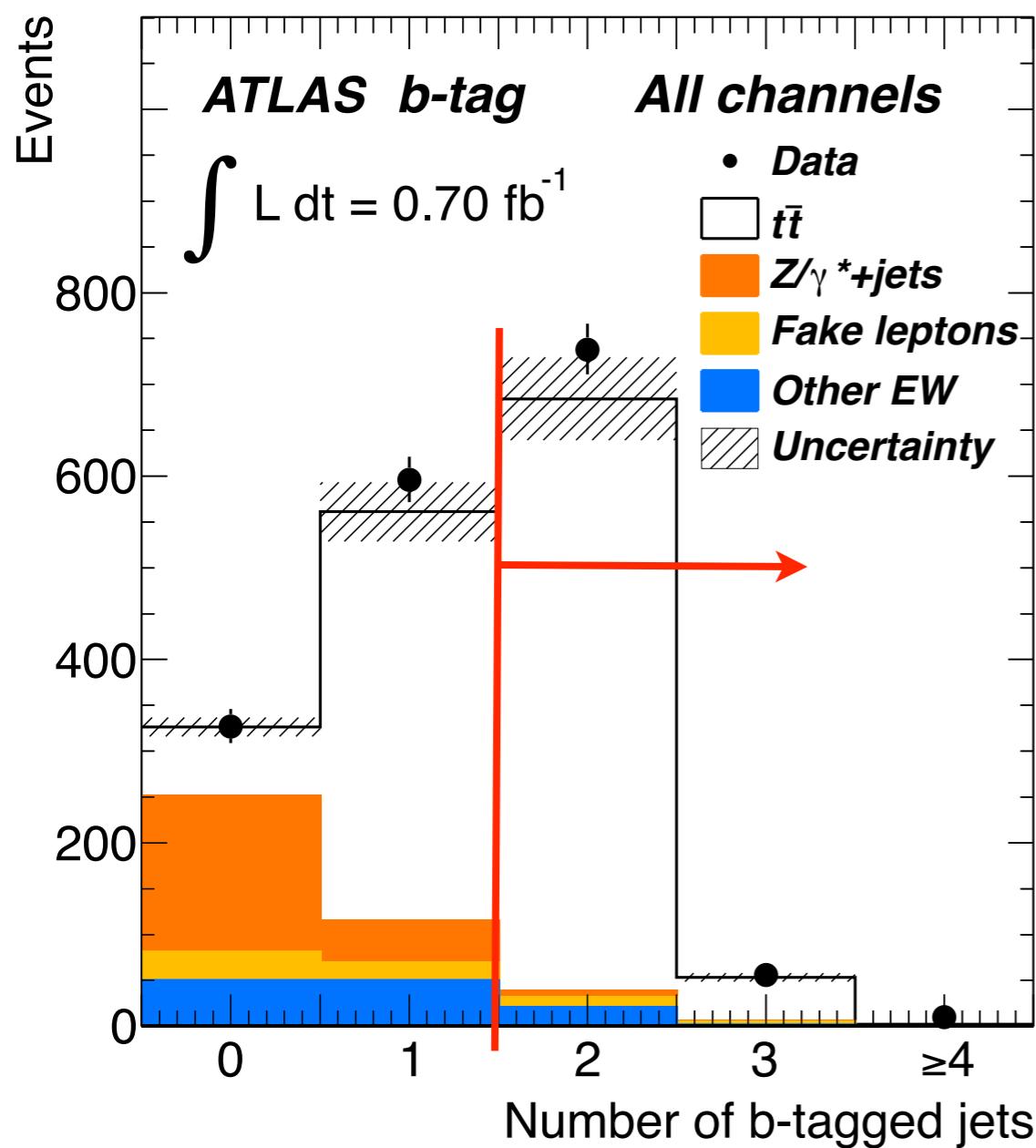
- Z events peak in $m(\ell\ell)$ at Z mass - use this to constrain the background in the signal region.



$$N_{\text{sig}}^Z = \frac{N_{\text{control}}^{Z\text{data}}}{N_{\text{control}}^{ZMC}} N_{\text{sig}}^{ZMC}$$

B-tagging in dilepton

- Can have almost pure ttbar sample with two b-tags in dilepton events:

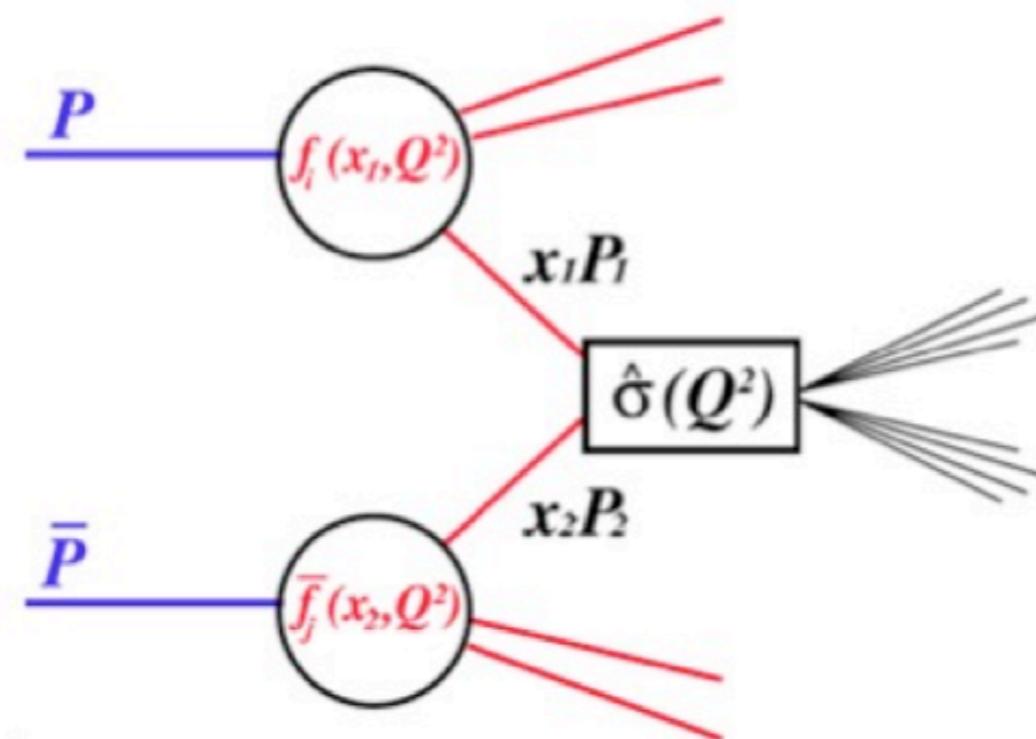


Top Quark Pair Production:

Inclusive cross section

Modelling top quark production

Differential cross section



$$\sigma = \sum_{i,j=q,\bar{q},g} \int dx_1 dx_2 f_i(x_1, Q^2) \cdot \bar{f}_j(x_2, Q^2) \cdot \hat{\sigma}(Q^2)$$

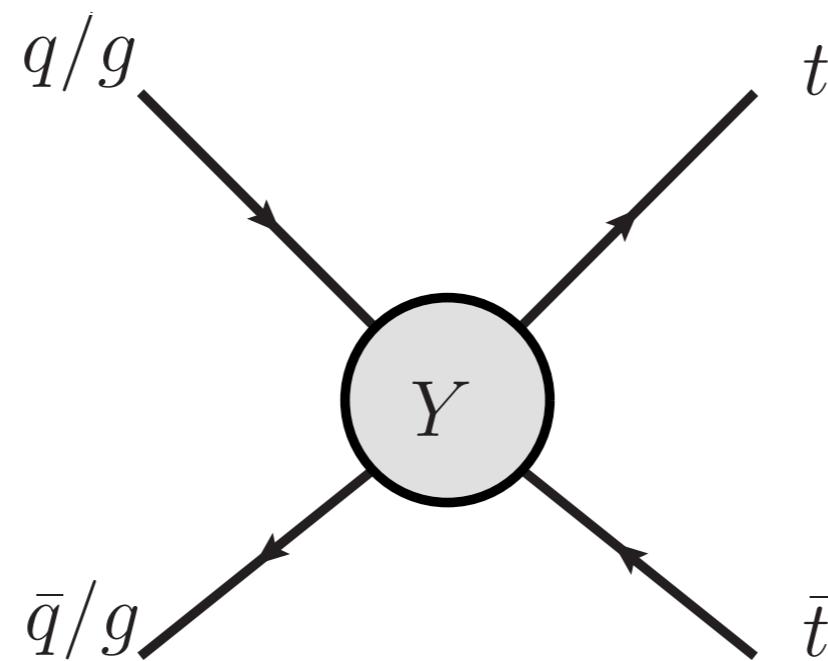
Sum over incoming
partons i, j

Momentum fraction
for incoming parton

PDF for incoming
parton i

"partonic" cross
section

- Partonic cross section:



- In principle calculate all allowed processes that could go into Y.
 - Use perturbation theory to expand Y in terms of strong coupling constant.
 - Feynman diagrams used to represent allowed sub-processes.

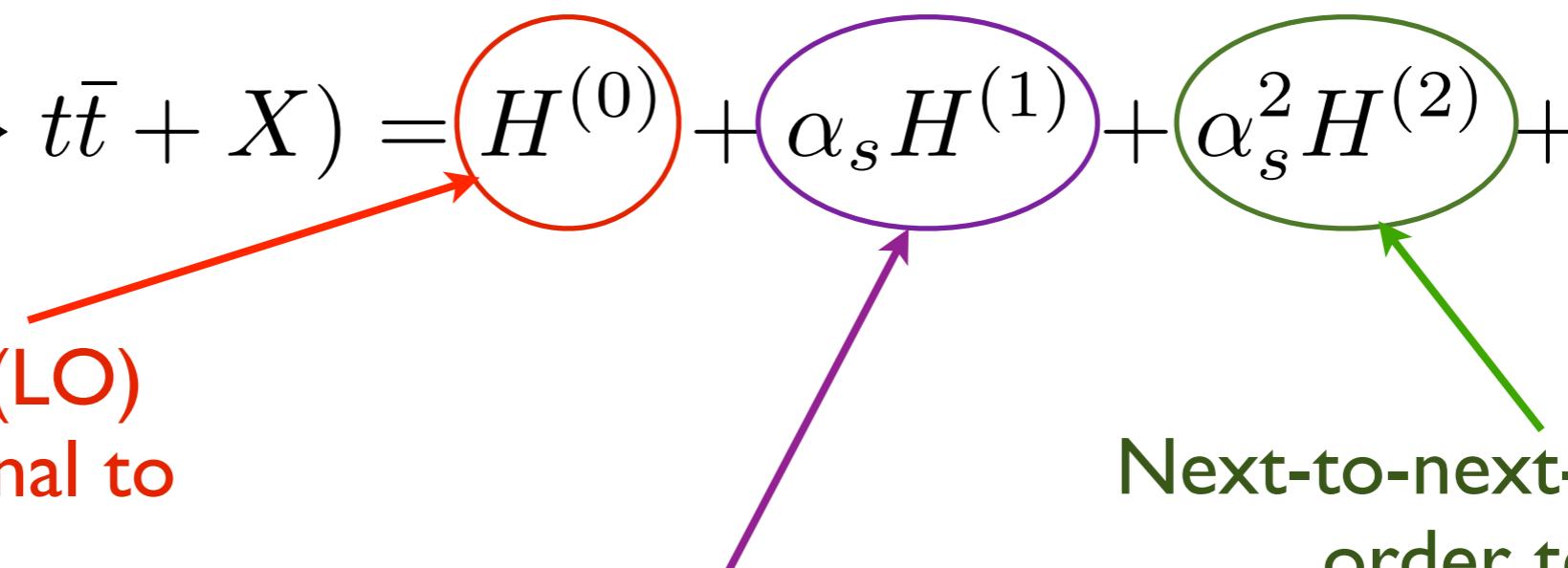
- Use perturbation theory and expand σ in terms of the strong coupling constant, α_s .

$$\sigma (q\bar{q}/gg \rightarrow t\bar{t} + X) = H^{(0)} + \alpha_s H^{(1)} + \alpha_s^2 H^{(2)} + \dots$$

Leading order (LO)
term, proportional to
 αs^2

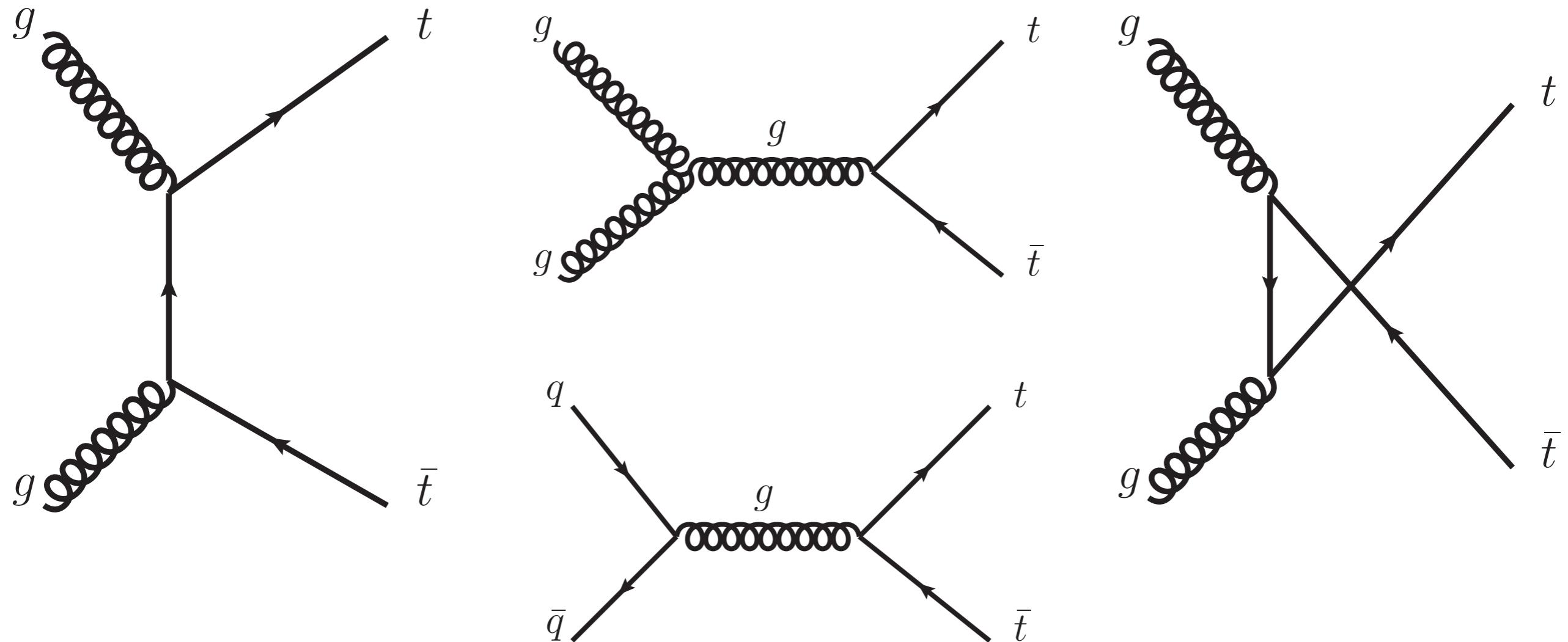
Next-to-leading order
(NLO) term,
proportional to αs^3

Next-to-next-to-leading
order term,
proportional to αs^4

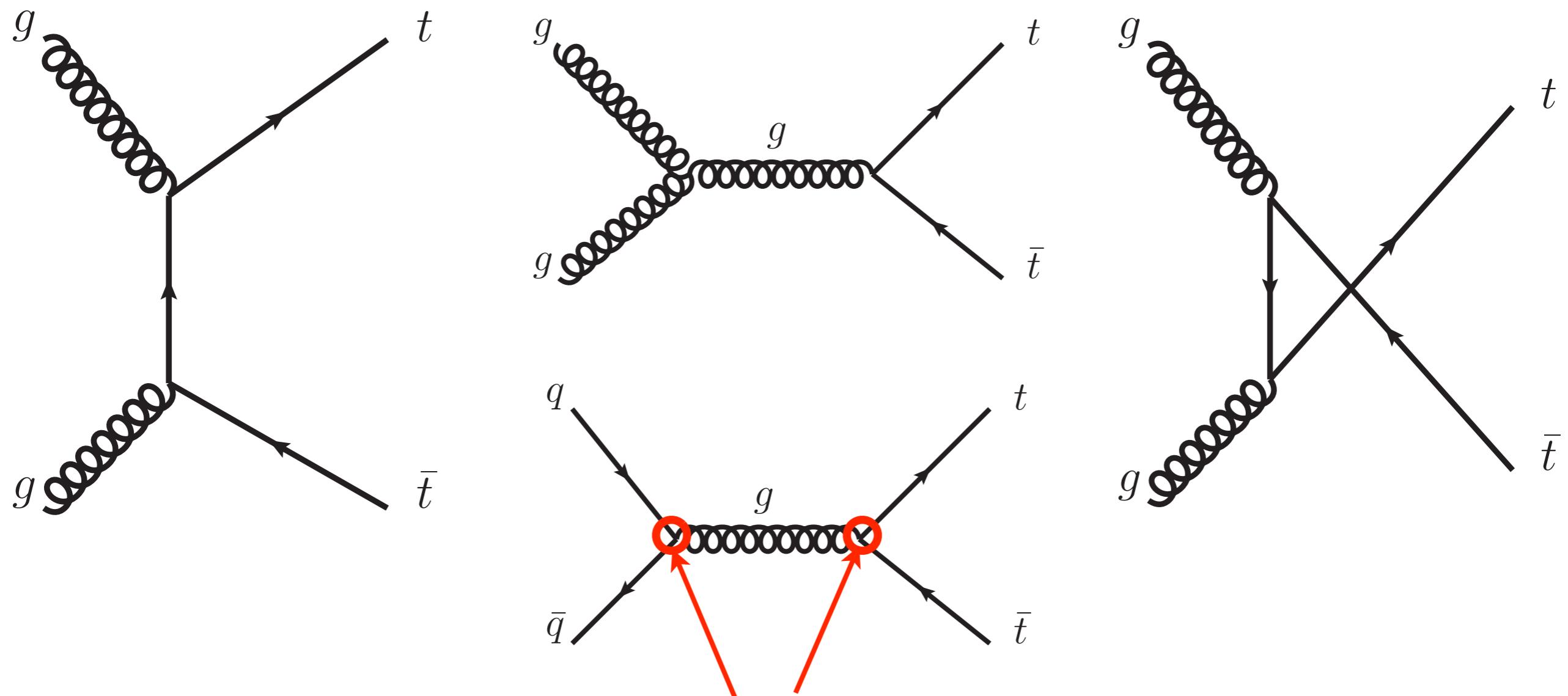


- $\alpha_s \sim 0.1$ - series should converge.

- Simplest production of top pairs:



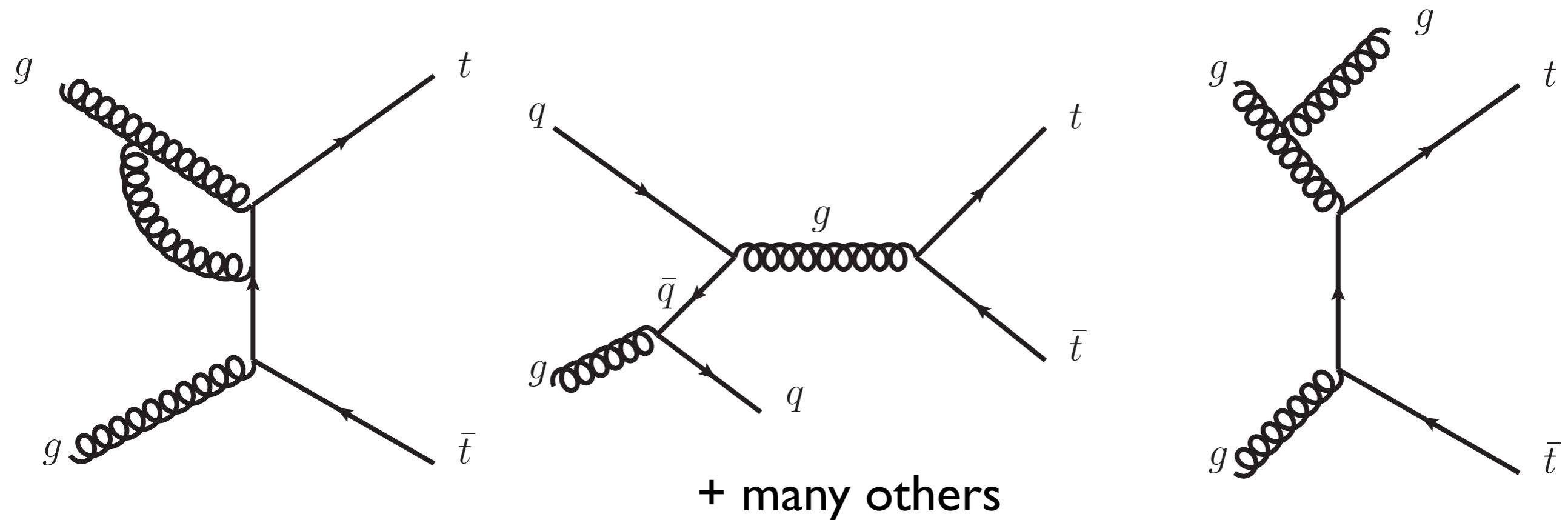
- Simplest production of top pairs:



Each vertex contributes $\sqrt{\alpha_s}$

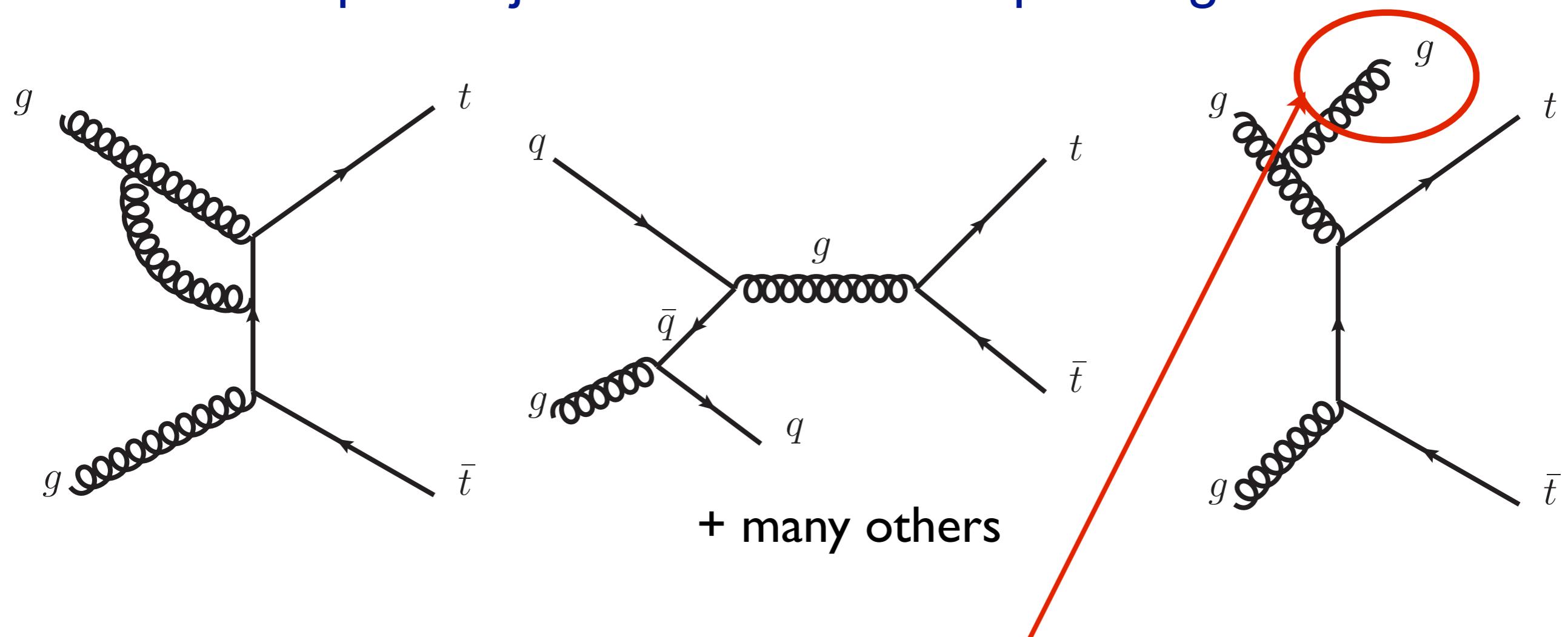
α_s = strong force (QCD) coupling constant

- Next simplest - just add one more quark / gluon line:



Partonic Cross Section

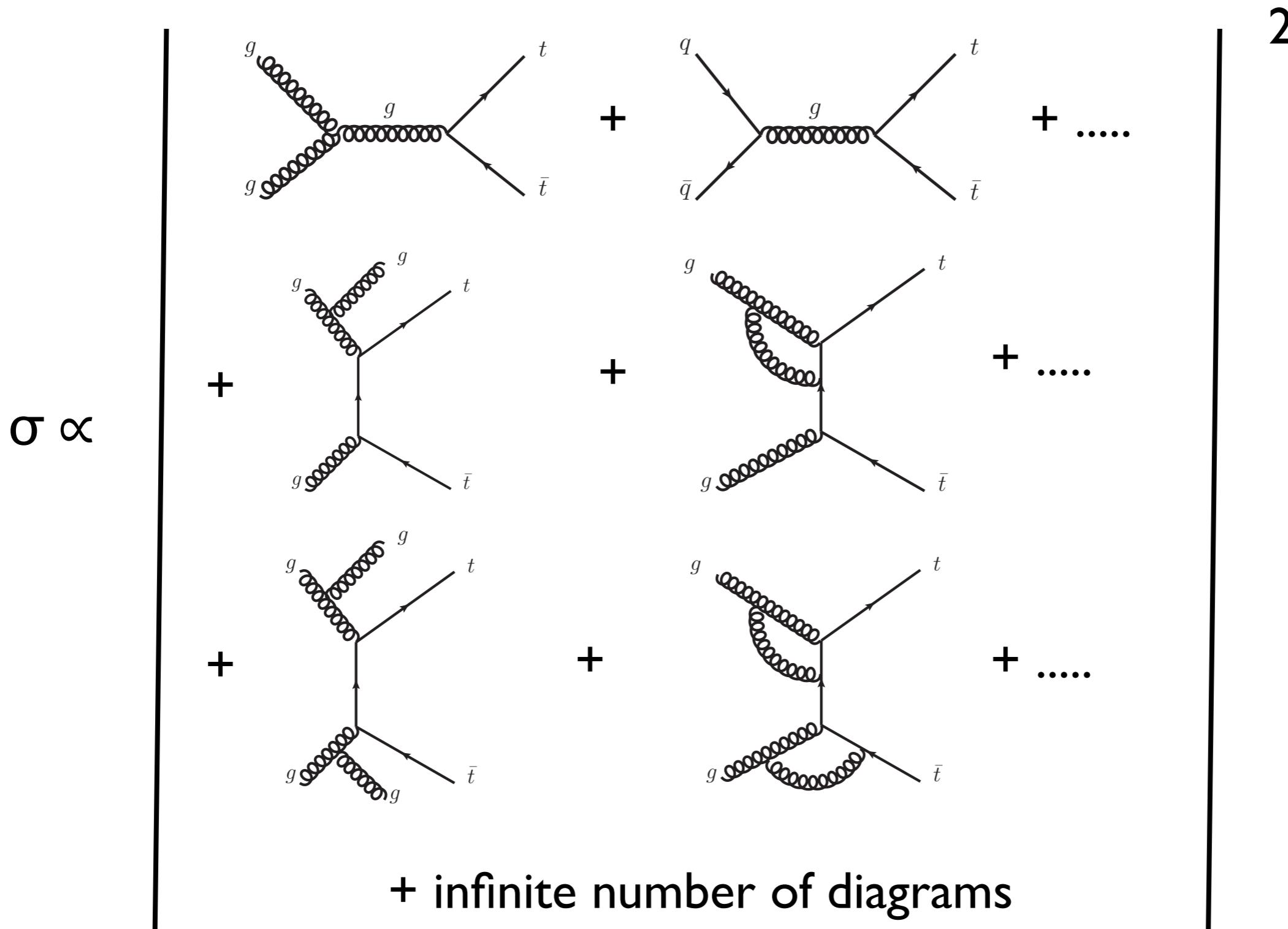
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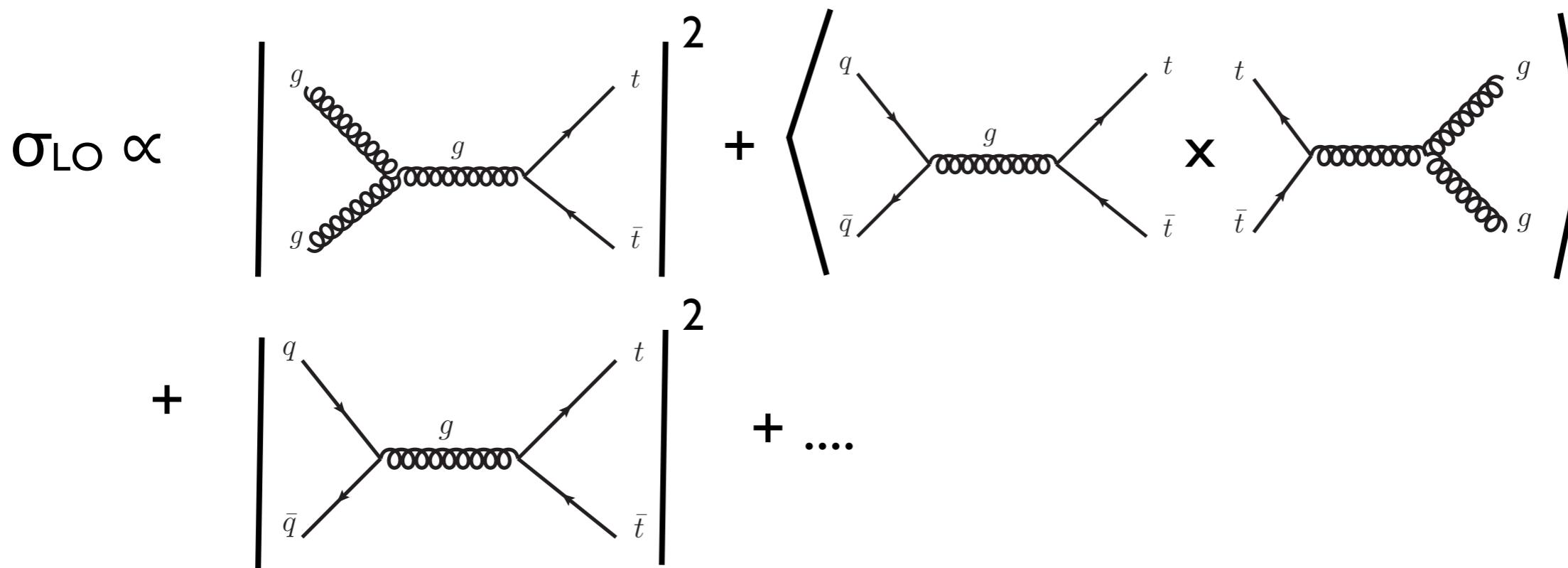
Extra gluon - results in extra jet of hadrons in detector (more later)

Partonic Cross Section

- Calculate all allowed processes:



- Leading-order cross section contains all terms proportional to α_s^2



- Next-to-leading-order cross section contains all terms proportional to α_s^2 and α_s^3 :

$$\sigma_{\text{NLO}} \propto \sigma_{\text{LO}} +$$

The diagram shows the expansion of the next-to-leading order (NLO) cross-section. It starts with the leading order (LO) cross-section, represented by a vertical line on the left. This is followed by a plus sign and two diagrams representing corrections. The first correction diagram shows a gluon-gluon fusion process where two gluons (g) interact to produce a top quark (t) and an anti-top quark (bar{t}). The second correction diagram shows a gluon-gluon fusion process where two gluons (g) interact via a loop to produce a top quark (t) and an anti-top quark (bar{t}). A third correction diagram is shown below, involving three gluons (g) and a top-anti-top pair (t-bar{t}), multiplied by a factor of x. The entire series is followed by a plus sign and an ellipsis.

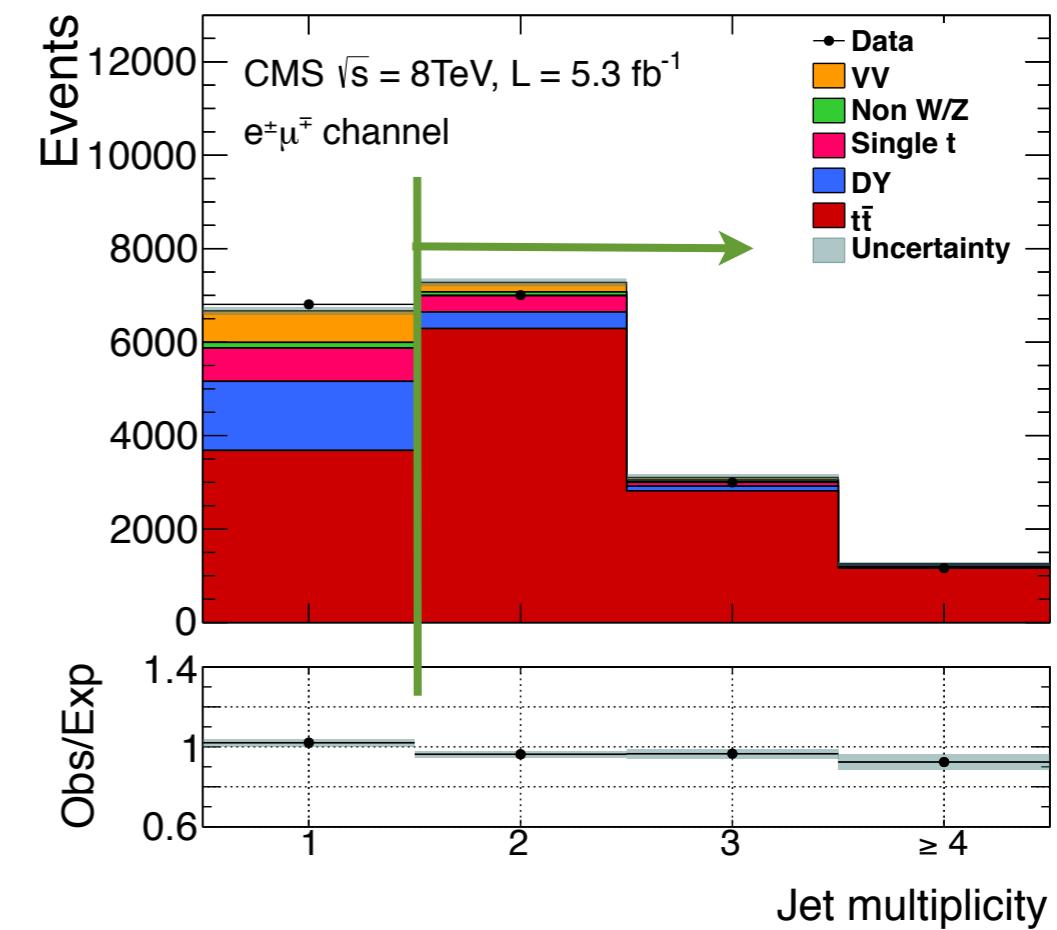
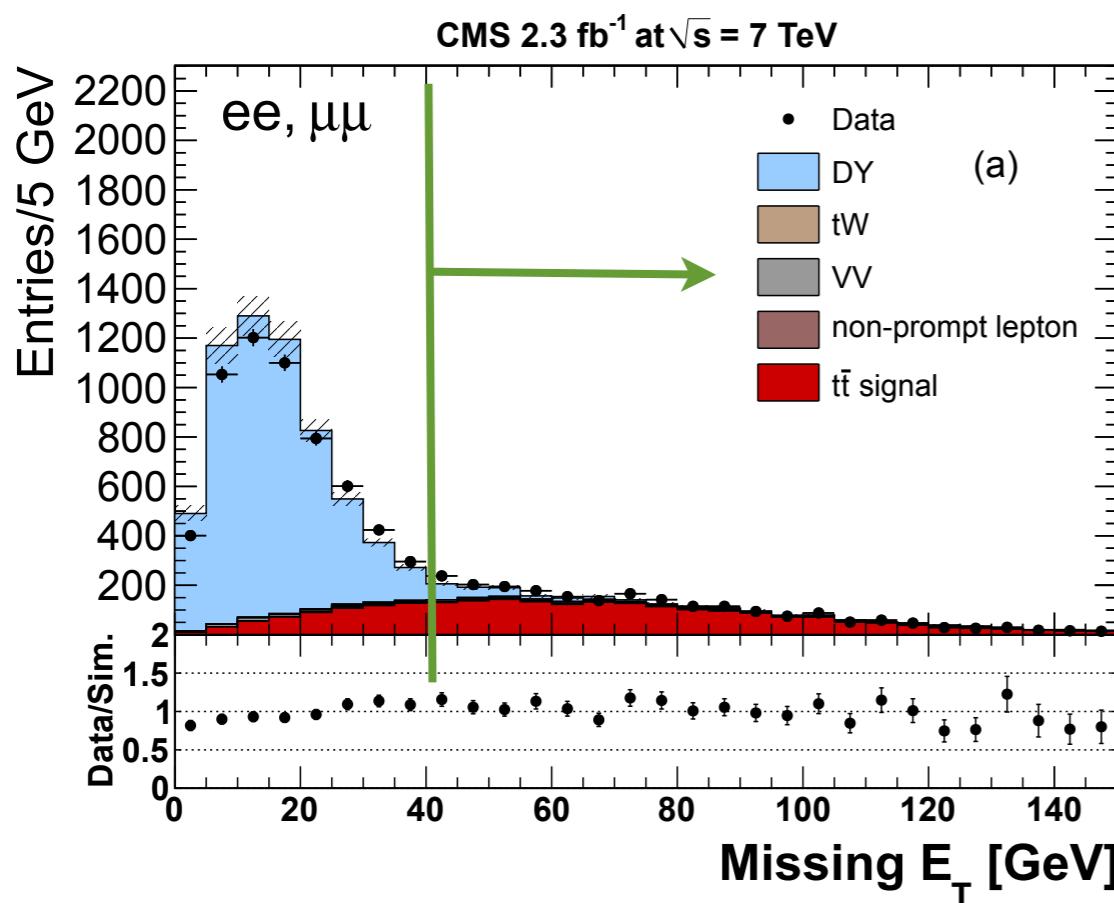
- State-of-the-art theoretical calculation calculates the inclusive ttbar cross section to NNLO.
- Theoretical precision ~5%!

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) -0.200(2.8%)	+0.169(2.4%) -0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) -5.8(3.4%)	+4.7(2.7%) -4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) -8.4(3.4%)	+6.2(2.5%) -6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) -33.9(3.6%)	+16.2(1.7%) -17.8(1.9%)

- Should test with experimental measurements.

Dilepton Cross Section

- Exploit clean signature of dilepton events:
 - Simple selection of events with two high pT leptons and two jets.
 - Use $m(\ell\ell)$ & MET to remove Z events.



- Extract cross-section by counting events:

$$\sigma = \frac{N_{obs} - N_b}{\epsilon L} = 239 \text{ pb}$$

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Systematic uncertainties are key

Dilepton Cross Section

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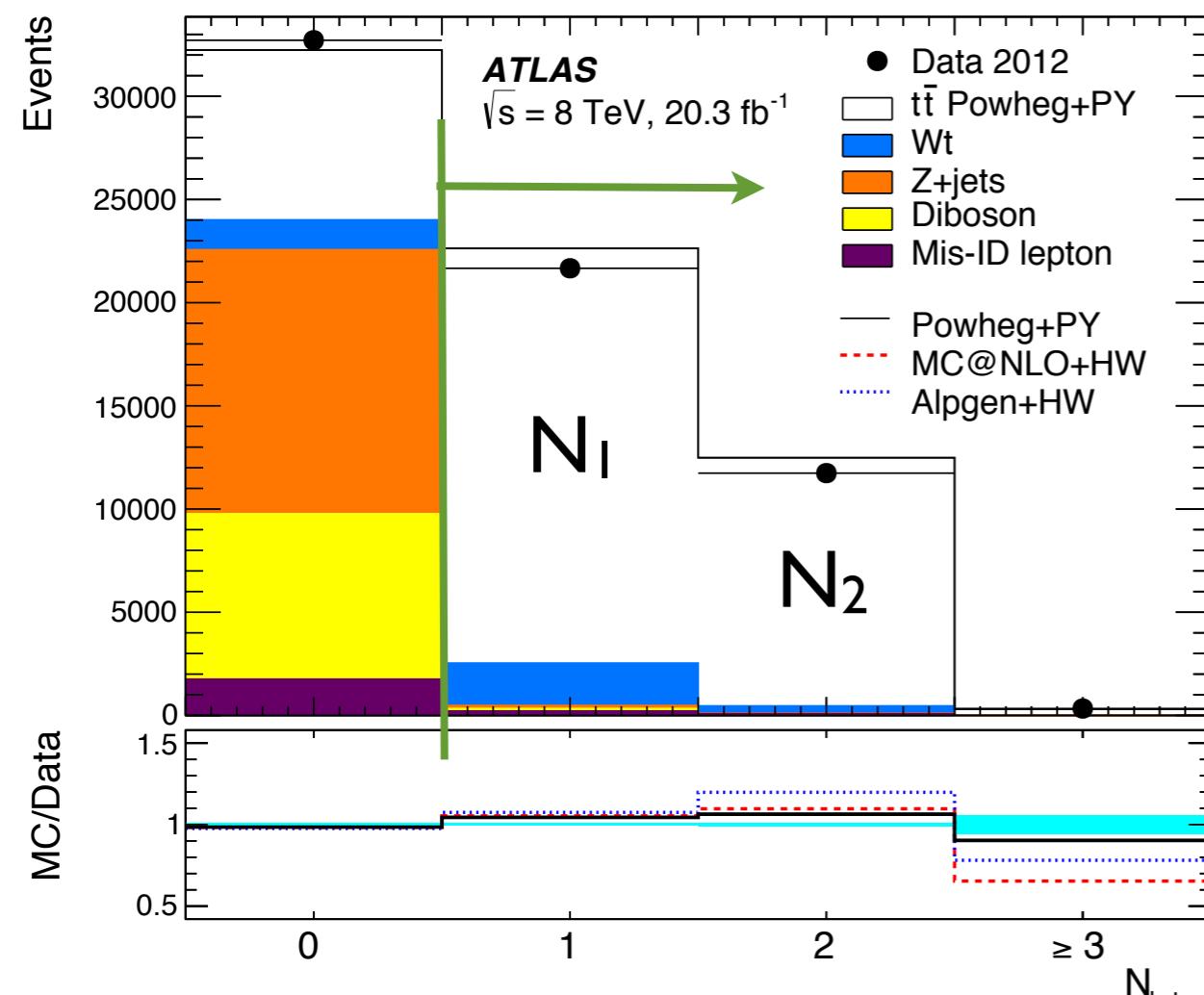
$$\sigma = \frac{N_{obs} - N_b}{\epsilon L} = 239 \text{ pb}$$

Systematic uncertainties are key

Source	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Trigger efficiencies	4.1	3.0	3.6
Lepton efficiencies	5.8	5.6	4.0
Lepton energy scale	0.6	0.3	0.2
Jet energy scale	10.3	10.8	5.2
Jet energy resolution	3.2	4.0	3.0
b-jet tagging	1.9	1.9	1.7
Pileup	1.7	1.5	2.0
Scale (μ_F and μ_R)	5.7	5.5	5.6
Matching partons to showers	3.9	3.8	3.8
Single top quark	2.6	2.4	2.3
VV	0.7	0.7	0.5
Drell–Yan	10.8	10.3	1.5
Non-W/Z leptons	0.9	3.2	1.9
Total systematic	18.6	18.6	11.4
Integrated luminosity	6.4	6.1	6.2
Statistical	5.2	4.5	2.6

Dilepton Cross Section

- Can improve the precision by measuring some of the efficiency in the data:

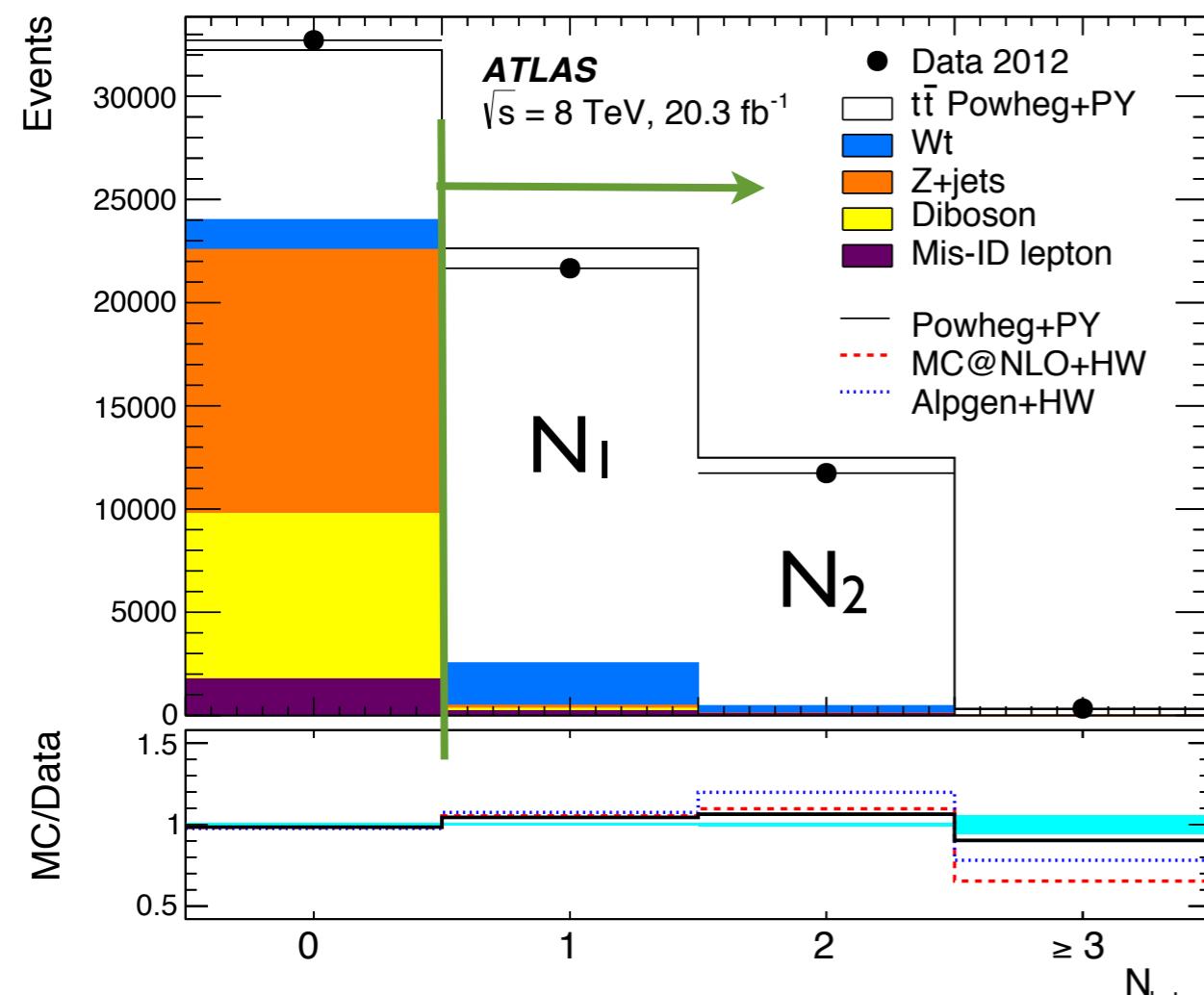


$$t\bar{t} \rightarrow e\mu\nu\bar{\nu} b\bar{b}$$

$$N_2 = L\sigma \epsilon_{e\mu} \epsilon_b^2 C_b + N_{b2}$$

Dilepton Cross Section

- Can improve the precision by measuring some of the efficiency in the data:

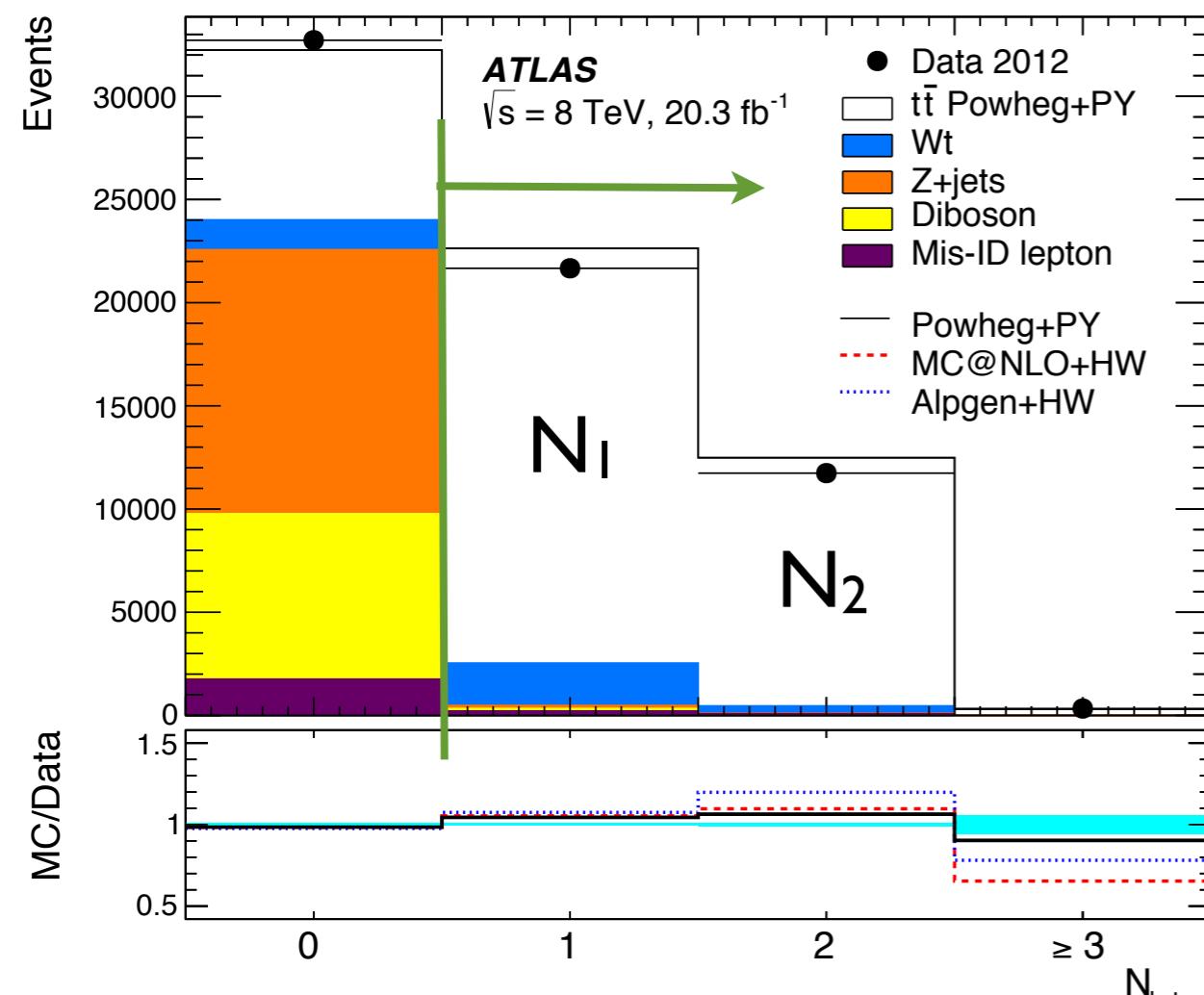


$$N_2 = L\sigma \epsilon_{e\mu} \epsilon_b^2 C_b + N_{b2}$$

$\epsilon_{e\mu} =$ Efficiency for leptons to be in the detector & reconstructed by ATLAS

Dilepton Cross Section

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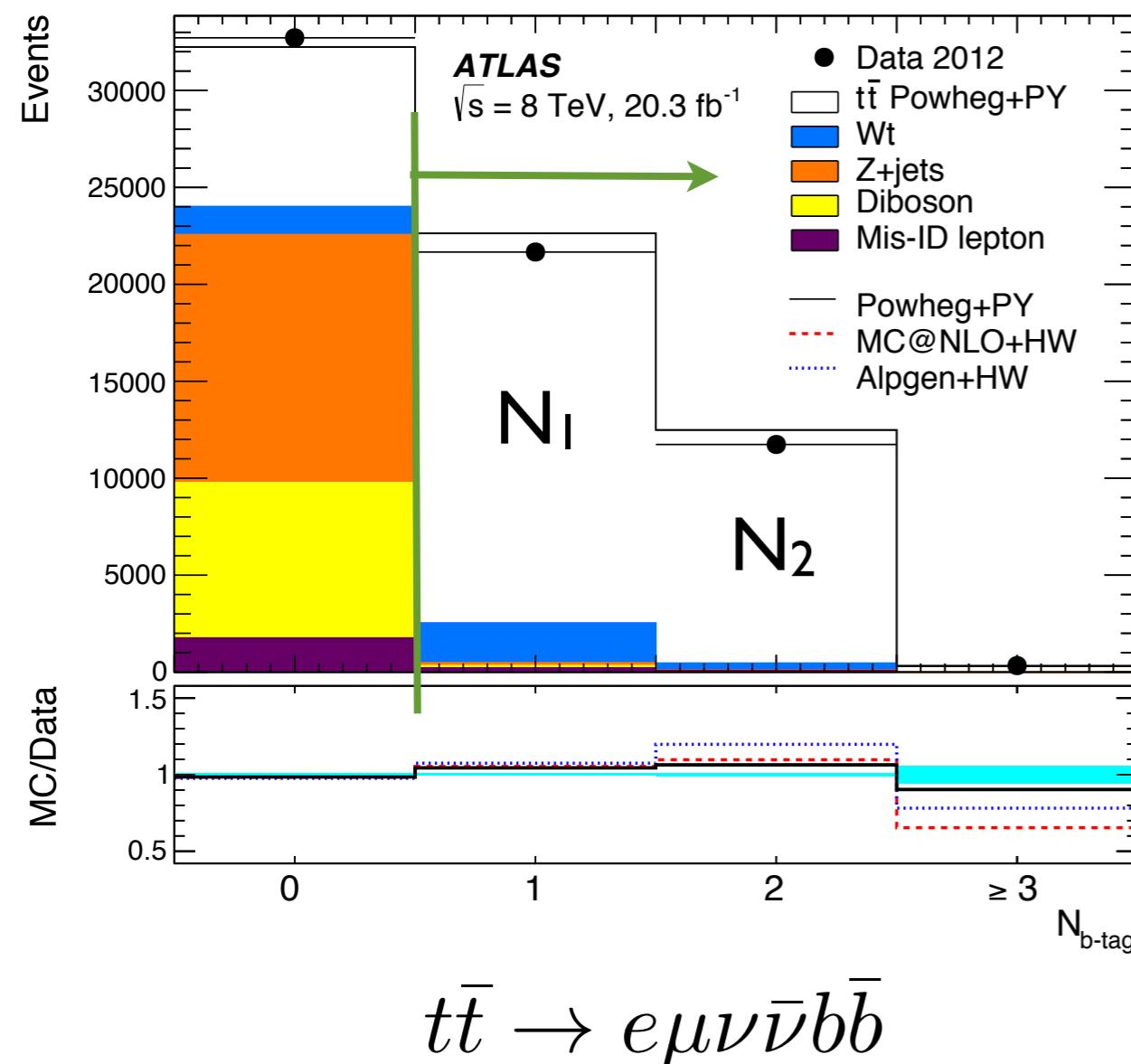
$$N_2 = L\sigma \epsilon_{e\mu} \epsilon_b^2 C_b + N_{b2}$$

$\epsilon_{e\mu}$ = Efficiency for leptons to be in the detector & reconstructed by ATLAS

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Dilepton Cross Section

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$$N_2 = L\sigma \epsilon_{e\mu} \epsilon_b^2 C_b + N_{b2}$$

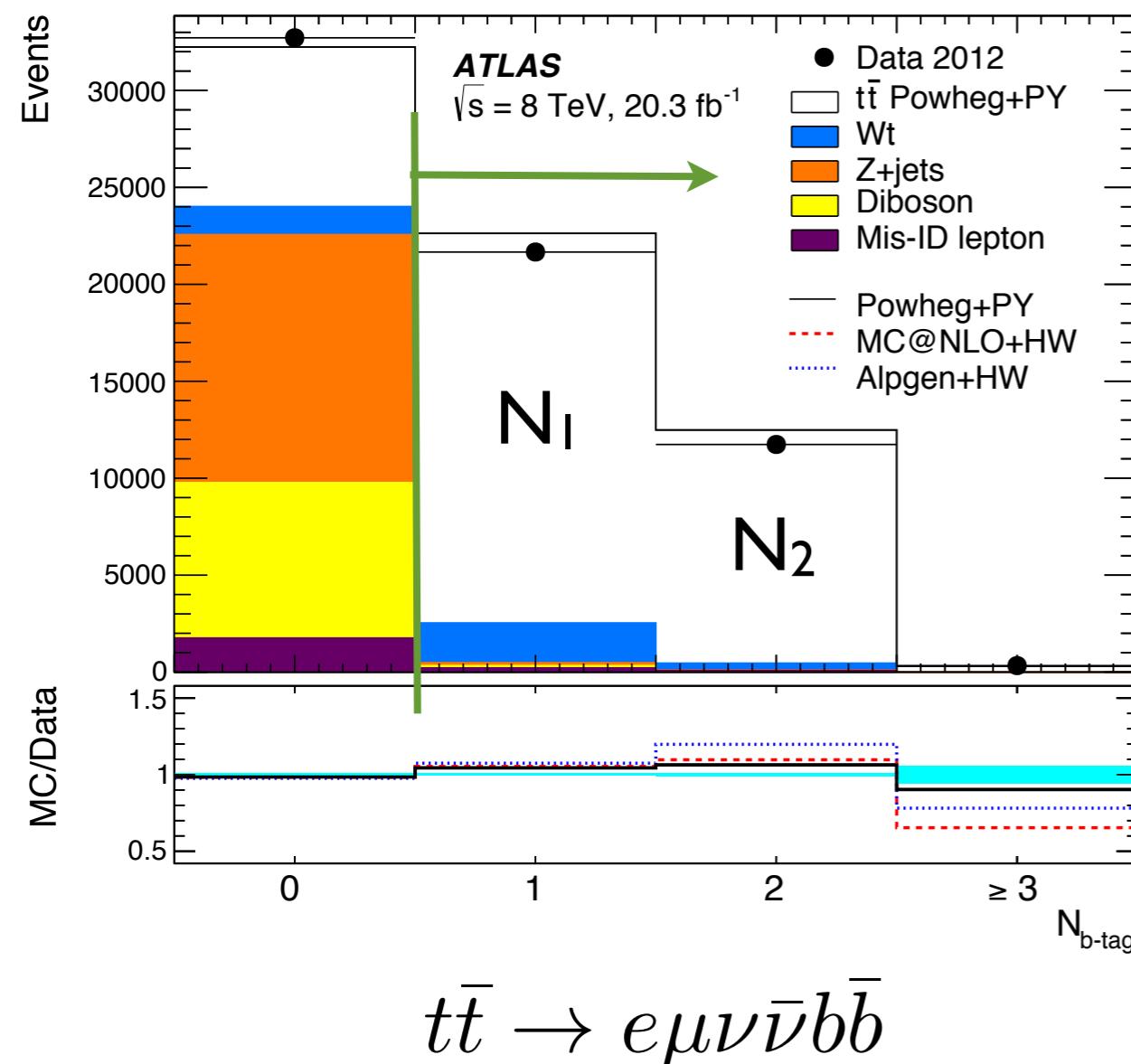
$\epsilon_{e\mu} =$ Efficiency for leptons to be in the detector & reconstructed by ATLAS

$\epsilon_b =$ Efficiency for b-jet from top quark to be in the detector & reconstructed by ATLAS

$C_b =$ Term to account for correlations between the two b-jets

Dilepton Cross Section

- Can improve the precision by measuring some of the efficiency in the data:



$$N_1 = L\sigma\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_{b1}$$

$$N_2 = L\sigma\epsilon_{e\mu}\epsilon_b^2C_b + N_{b2}$$

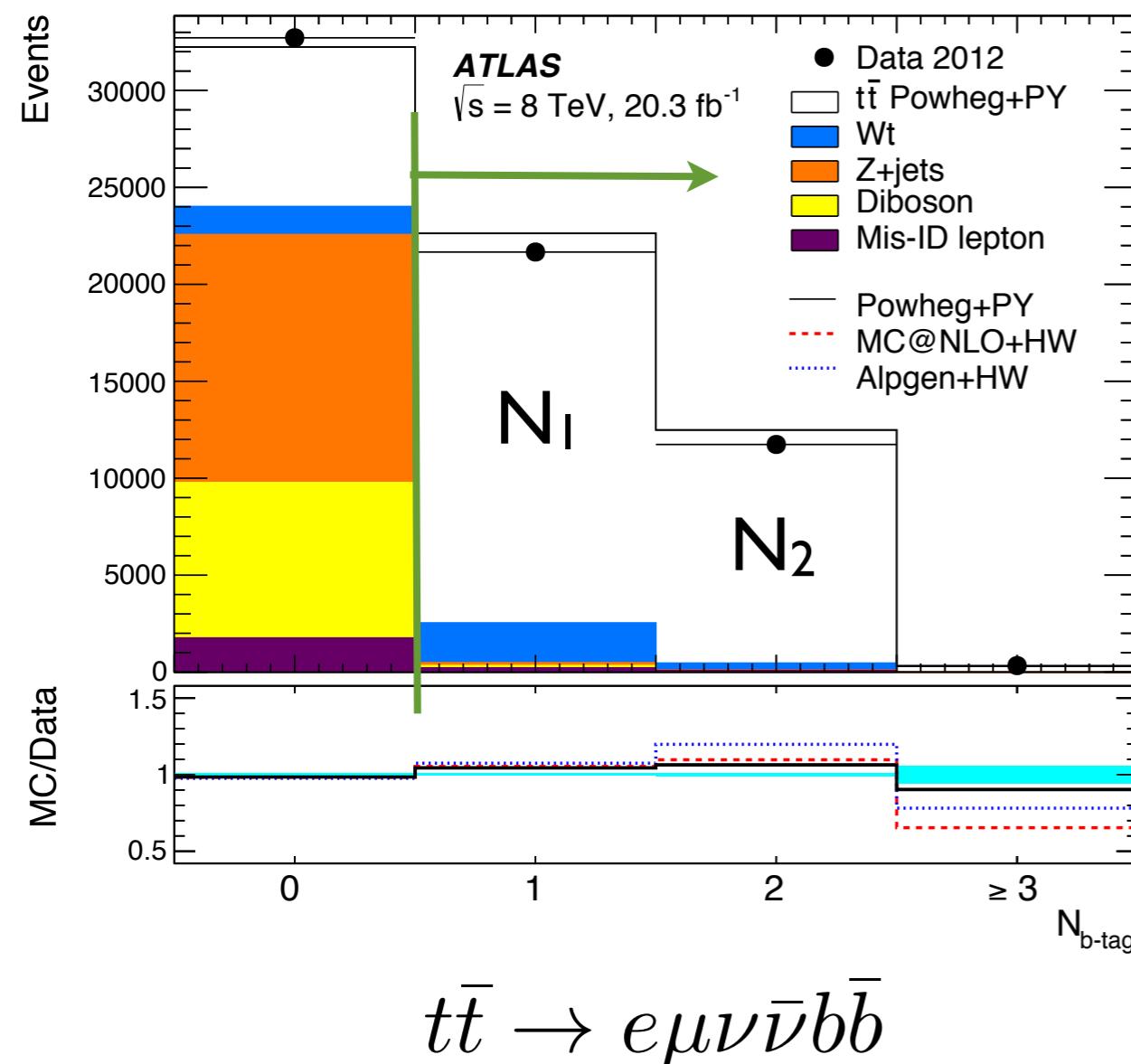
$\epsilon_{e\mu}$ = Efficiency for leptons to be in the detector & reconstructed by ATLAS

ϵ_b = Efficiency for b-jet from top quark to be in the detector & reconstructed by ATLAS

C_b = Term to account for correlations between the two b-jets

Dilepton Cross Section

- Can improve the precision by measuring some of the efficiency in the data:



$$N_1 = L\sigma\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_{b1}$$

$$N_2 = L\sigma\epsilon_{e\mu}\epsilon_b^2C_b + N_{b2}$$

$\epsilon_{e\mu}$ = Efficiency for leptons to be in the detector & reconstructed by ATLAS

ϵ_b = Efficiency for b-jet from top quark to be in the detector & reconstructed by ATLAS

C_b = Term to account for correlations between the two b-jets

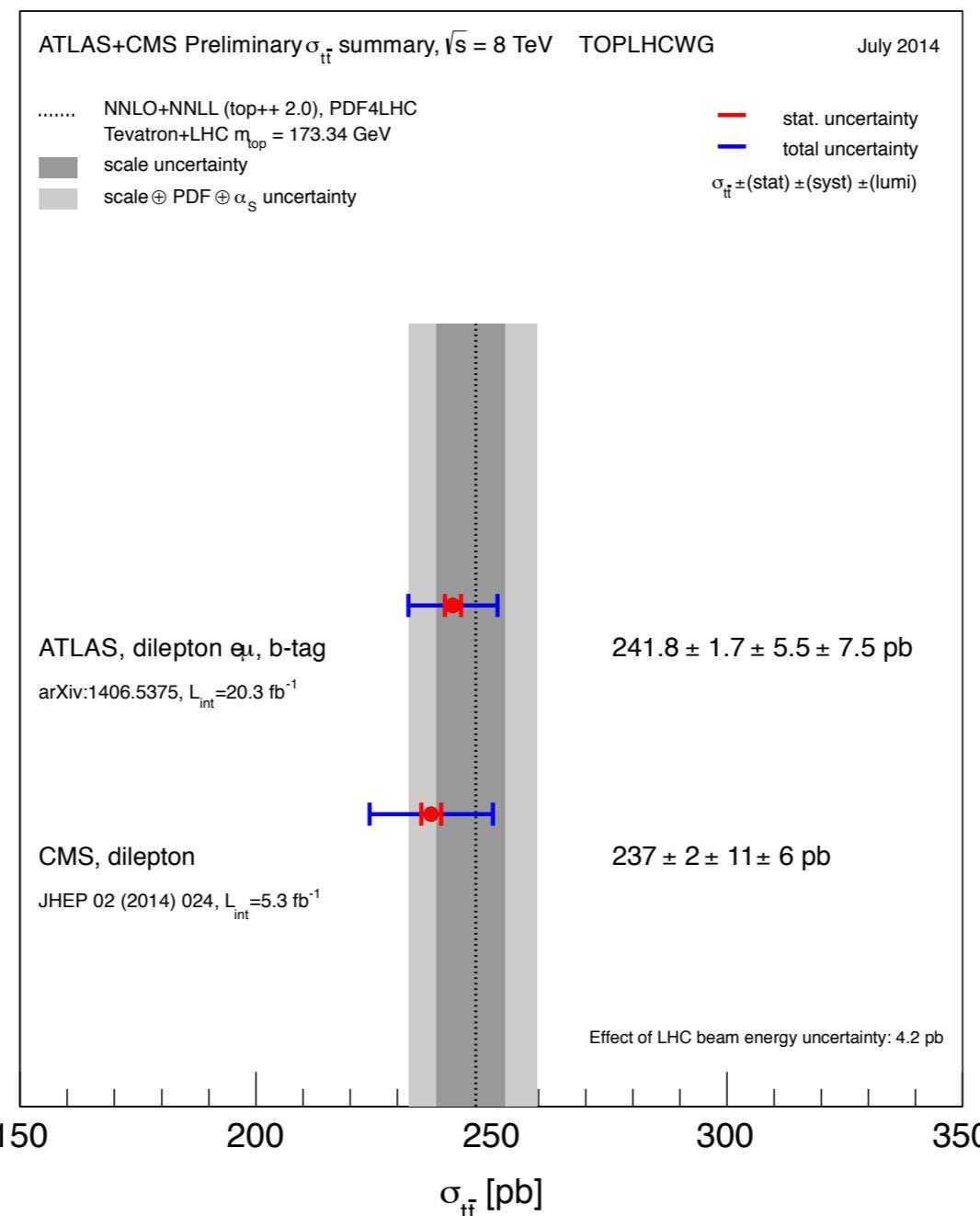
Measure N_1 and $N_2 \rightarrow$ extract ϵ_b and σ

- Systematic uncertainties due to jets go down:

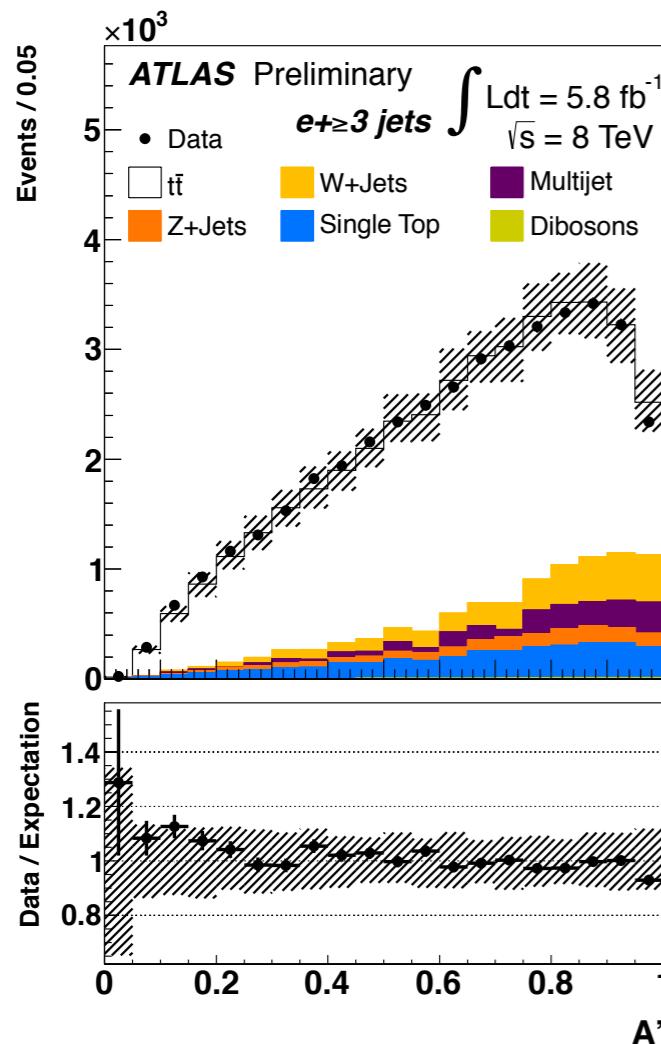
\sqrt{s} Uncertainty (inclusive $\sigma_{t\bar{t}}$)	$\Delta \epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	7 TeV $\Delta C_b/C_b$ (%)	7 TeV $\Delta \sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	8 TeV $\Delta \epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	8 TeV $\Delta C_b/C_b$ (%)	8 TeV $\Delta \sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics			1.69			0.71
$t\bar{t}$ modelling	0.71	-0.72	1.43	0.65	-0.57	1.22
Parton distribution functions	1.03	-	1.04	1.12	-	1.13
QCD scale choice	0.30	-	0.30	0.30	-	0.30
Single-top modelling	-	-	0.34	-	-	0.42
Single-top/ $t\bar{t}$ interference	-	-	0.22	-	-	0.15
Single-top Wt cross-section	-	-	0.72	-	-	0.69
Diboson modelling	-	-	0.12	-	-	0.13
Diboson cross-sections	-	-	0.03	-	-	0.03
$Z+jets$ extrapolation	-	-	0.05	-	-	0.02
Electron energy scale/resolution	0.19	-0.00	0.22	0.46	0.02	0.51
Electron identification	0.12	0.00	0.13	0.36	0.00	0.41
Muon momentum scale/resolution	0.12	0.00	0.14	0.01	0.01	0.02
Muon identification	0.27	0.00	0.30	0.38	0.00	0.42
Lepton isolation	0.74	-	0.74	0.37	-	0.37
Lepton trigger	0.15	-0.02	0.19	0.15	0.00	0.16
Jet energy scale	0.22	0.06	0.27	0.47	0.07	0.52
Jet energy resolution	0.16	0.08	0.30	0.36	0.05	0.51
Jet reconstruction/vertex fraction	0.00	0.00	0.06	0.01	0.01	0.03
b -tagging	-	0.18	0.41	-	0.14	0.40
Misidentified leptons	-	-	0.41	-	-	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	1.56	0.75	2.27	1.66	0.59	2.26
Integrated luminosity	-	-	1.98	-	-	3.10
LHC beam energy	-	-	1.79	-	-	1.72
Total uncertainty ($\sigma_{t\bar{t}}$)	1.56	0.75	3.89	1.66	0.59	4.27

Dilepton Cross Section

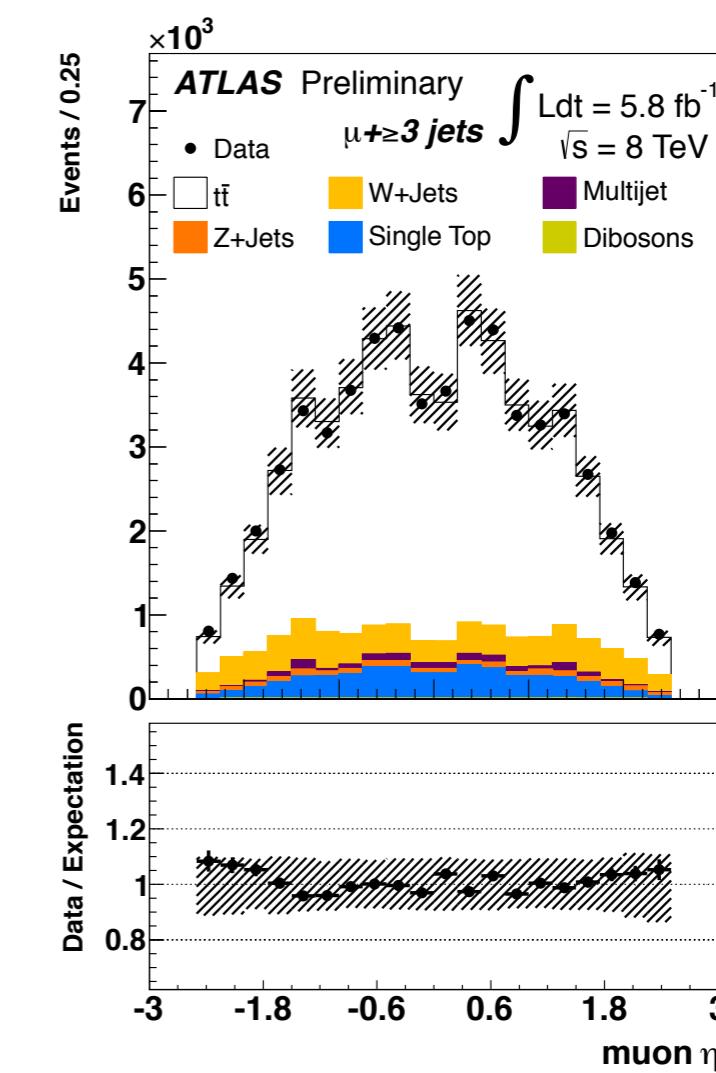
- Good agreement between measurements and NNLO theory.
- Precision of measurement limited by systematic uncertainties.



- ATLAS first measurement with 8 TeV data:
- Select events with high pT lepton, at least three jets, at least one b-tag.
- Separate ttbar from W + jets background with likelihood:

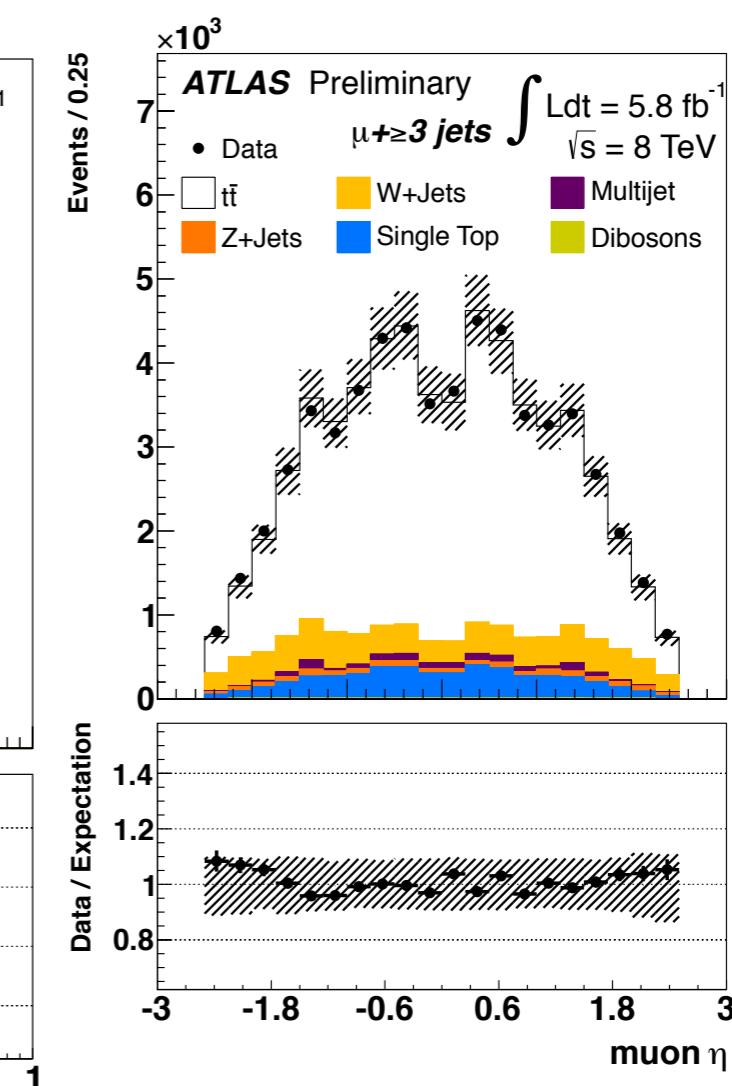
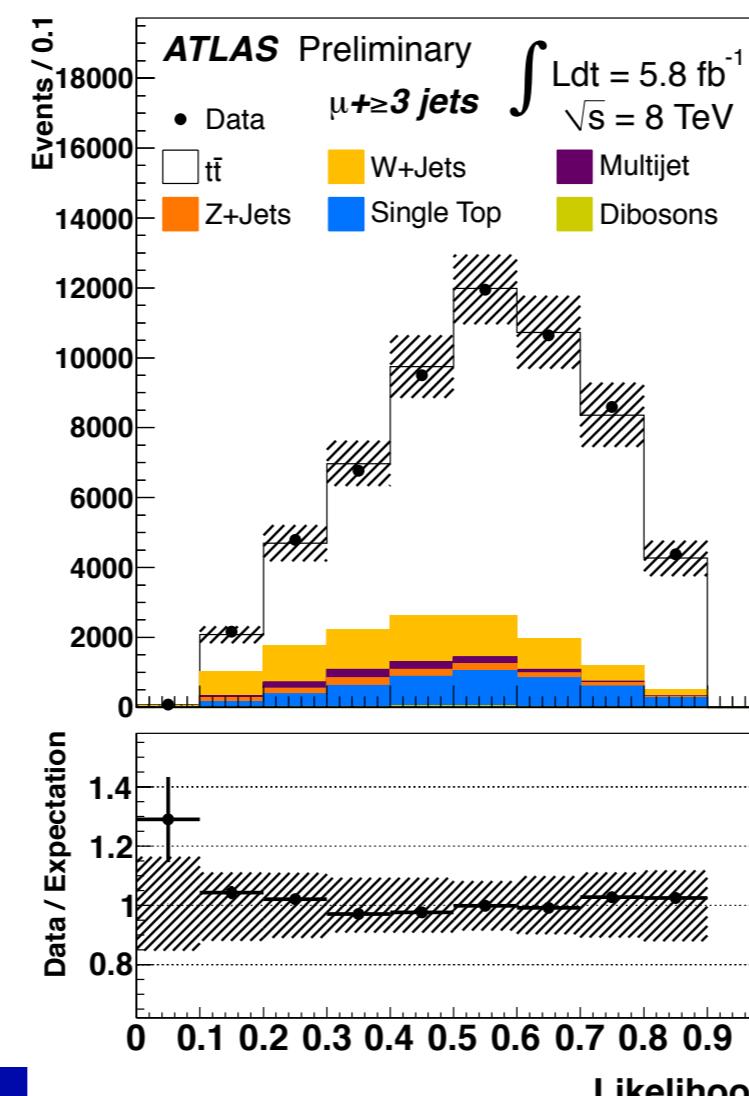
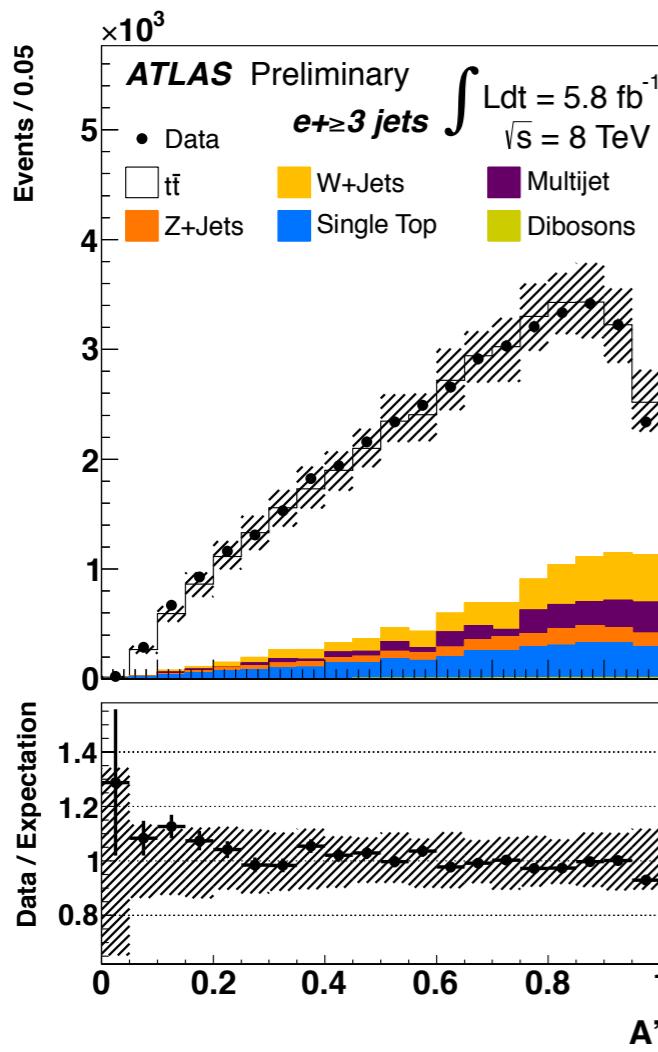


$$D_i = \frac{L_i^S}{(L_i^S + L_i^B)}$$



Lepton + Jets Cross Section

- ATLAS first measurement with 8 TeV data:
- Select events with high pT lepton, at least three jets, at least one b-tag.
- Separate ttbar from W + jets background with likelihood:



- Fit likelihood distribution for ttbar cross section and W + jets normalization:

$$\sigma_{t\bar{t}} = 241 \pm 2 \text{ (stat.)} \pm 31 \text{ (syst.)} \pm 9 \text{ (lumi.) pb.}$$

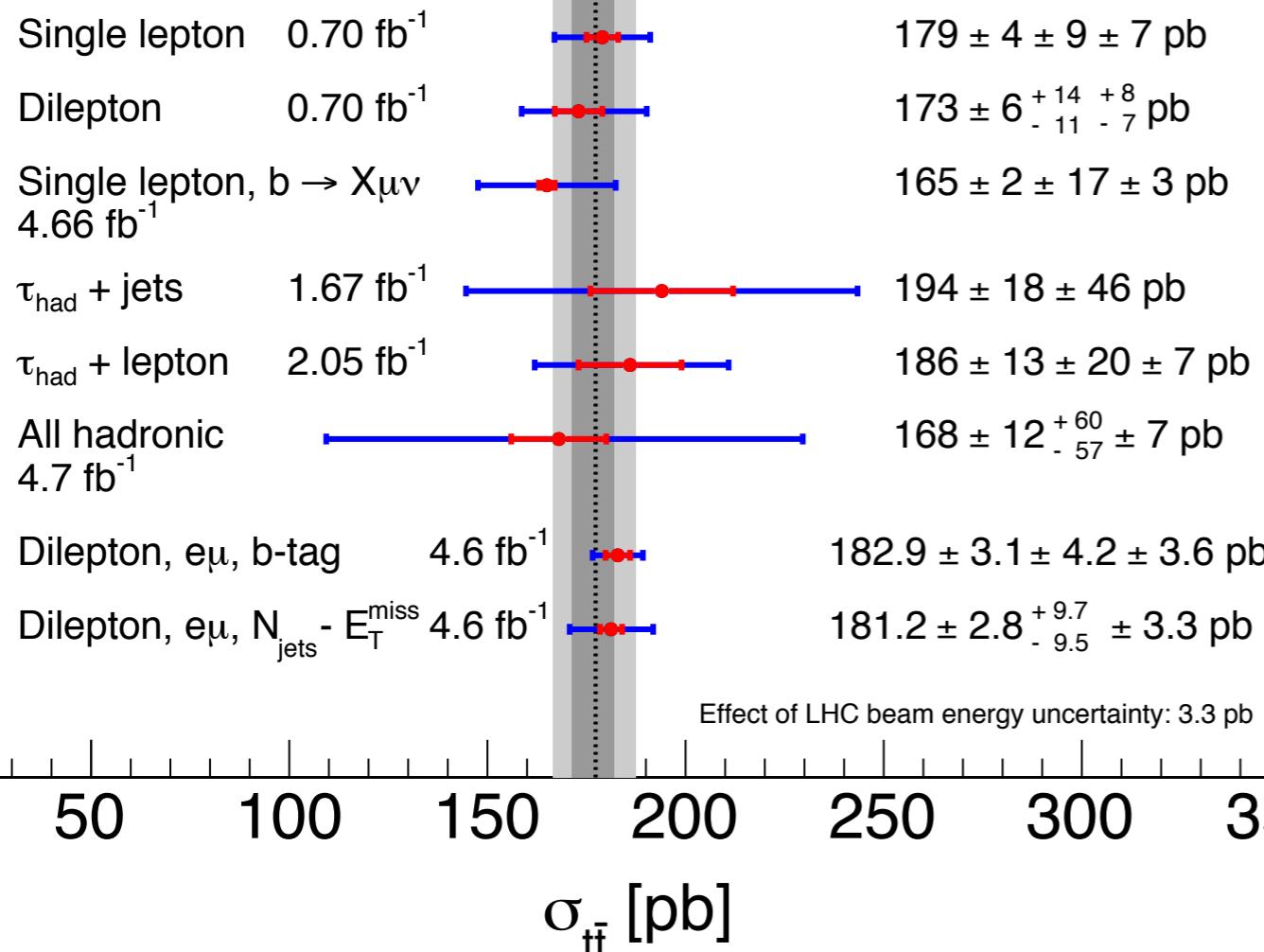
Source	$e^+ \geq 3$ jets	$\mu^+ \geq 3$ jets	combined
Jet/MET reconstruction, calibration	6.7, -6.3	5.4, -4.6	5.9, -5.2
Lepton trigger, identification and reconstruction	2.4, -2.7	4.7, -4.2	2.7, -2.8
Background normalization and composition	1.9, -2.2	1.6, -1.5	1.8, -1.9
b-tagging efficiency	1.7, -1.3	1.9, -1.1	1.8, -1.2
MC modelling of the signal	± 12	± 11	± 11
Total	± 14	± 13	± 13

- Work ongoing to reduce systematic uncertainties.

Top Pair Production LHC

ATLAS PreliminaryData 2011, $\sqrt{s} = 7$ TeV

Channel & Luminosity

**CMS Preliminary, σ_{tt} summary, $\sqrt{s} = 7$ TeV**CMS e/ μ +jetsPLB 720 (2013) 83
($L=2.2\text{-}2.3/\text{fb}$)CMS dilepton (ee, $\mu\mu$, e μ)JHEP 11 (2012) 067 ($L=2.3/\text{fb}$)CMS dilepton (e/ μ + τ_{had})PRD 85 (2012) 112007
($L=2.2/\text{fb}$)CMS $\tau_{\text{had}} + \text{jets}$ EPJC 73 (2013) 2386 ($L=3.9/\text{fb}$)

CMS all jets

JHEP 05 (2013) 065 ($L=3.5/\text{fb}$)NNLO+NNLL (top++ 2.0), PDF4LHC, $m_{\text{top}} = 172.5 \text{ GeV}$

Czakon et al., PRL 110 (2013) 252004, arXiv:1112.5675 (2013)

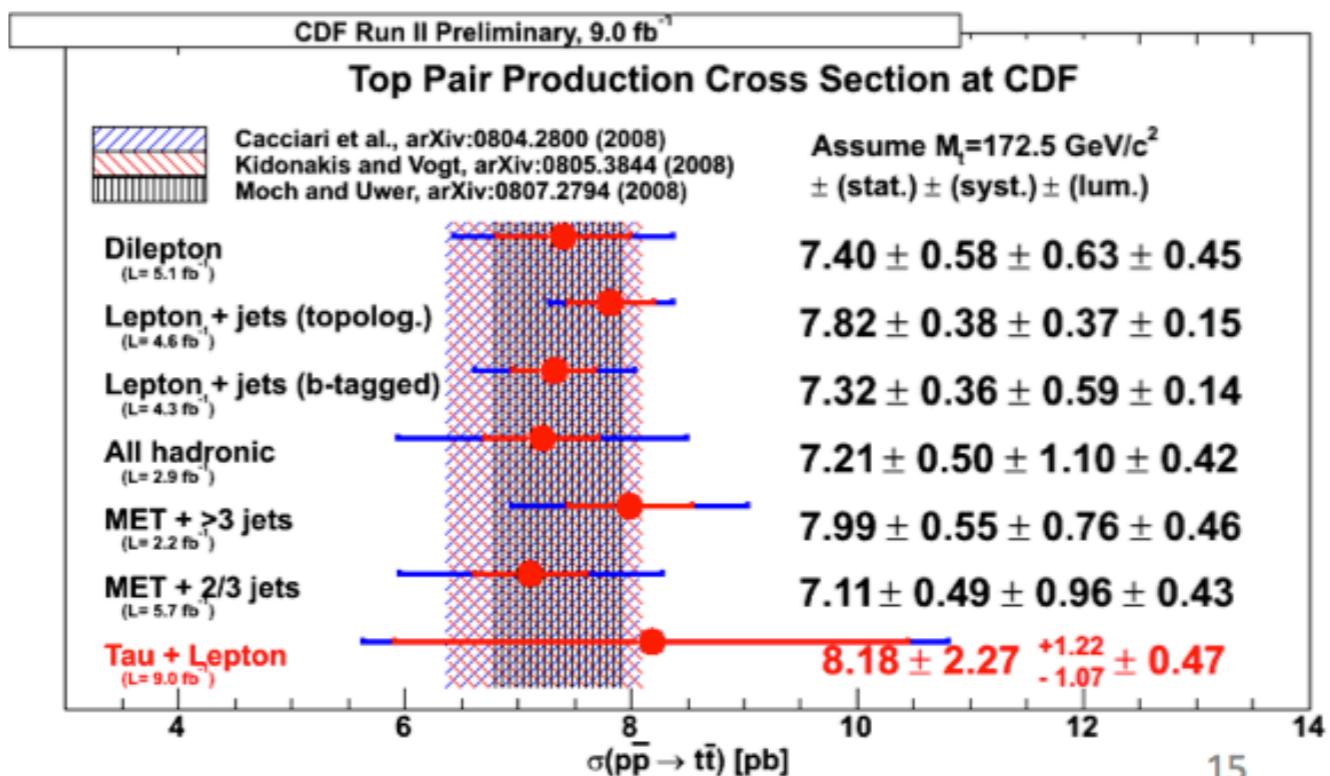
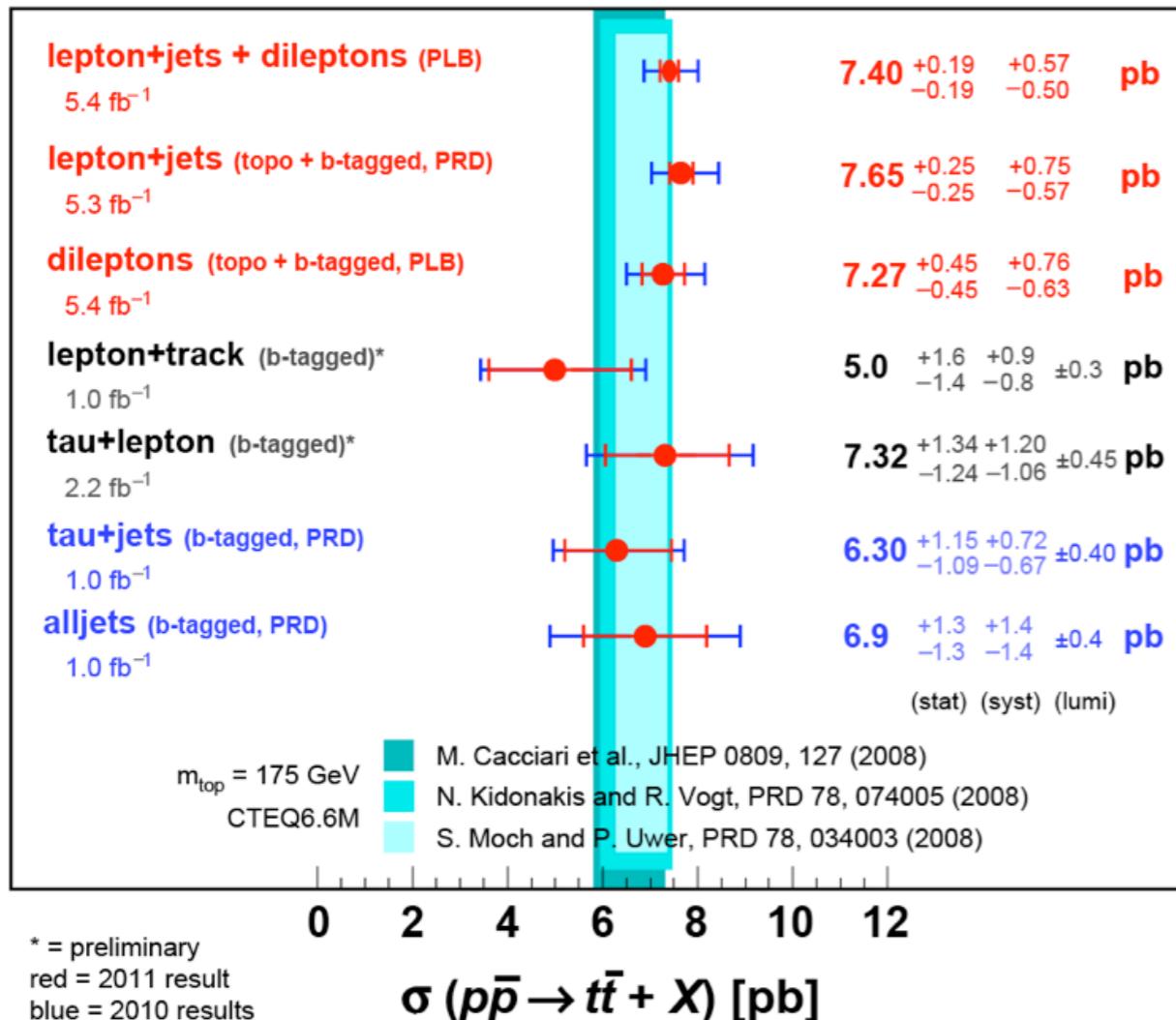
scale uncertainty

scale \oplus PDF $\oplus \alpha_s$ uncertainty**Good agreement with SM in all channels**

Top Pair Production Tevatron

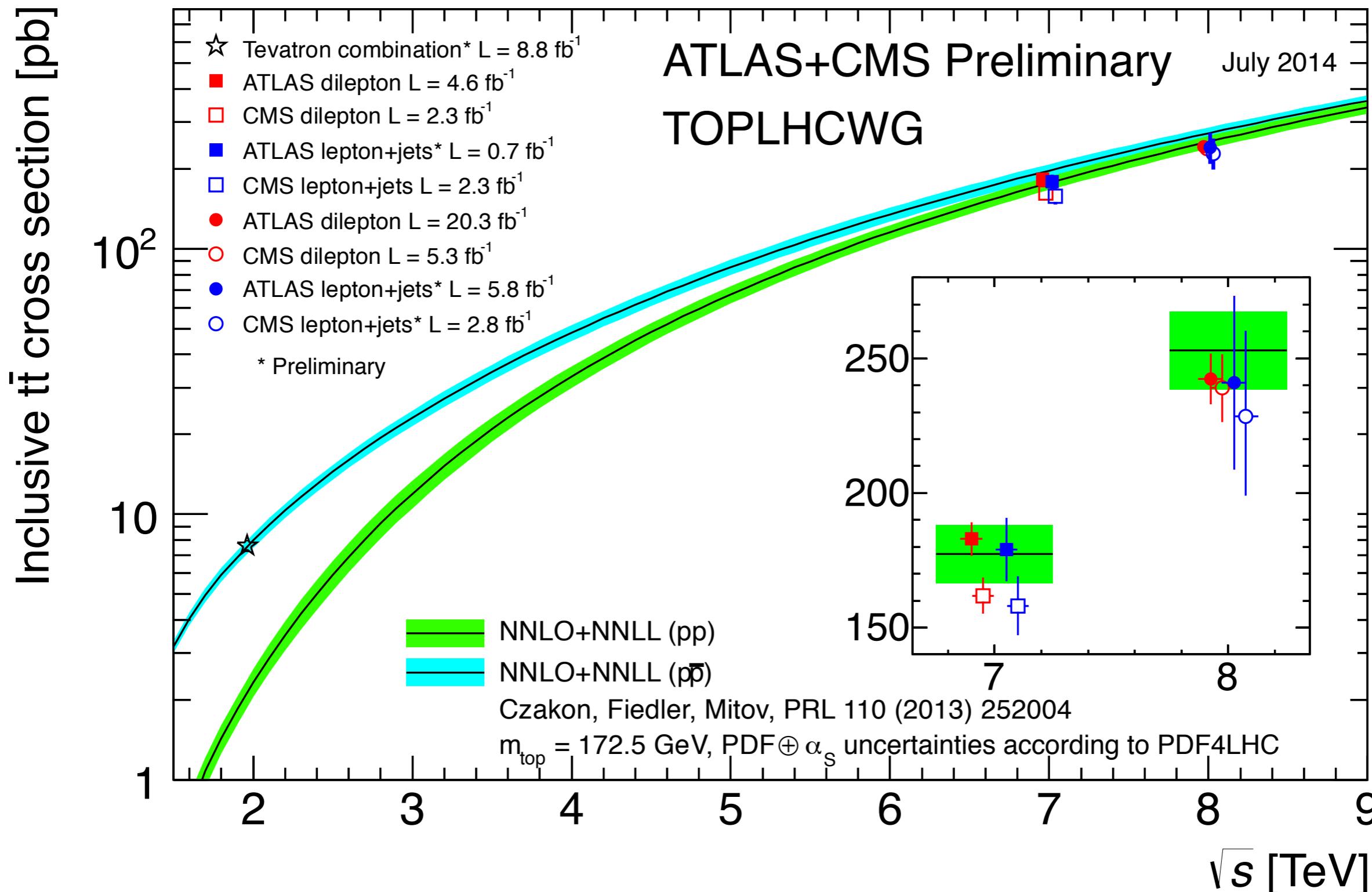
DØ Run II

July 2011



Good agreement with SM in all channels

Top Pair Production



Top Quark Pair Production:

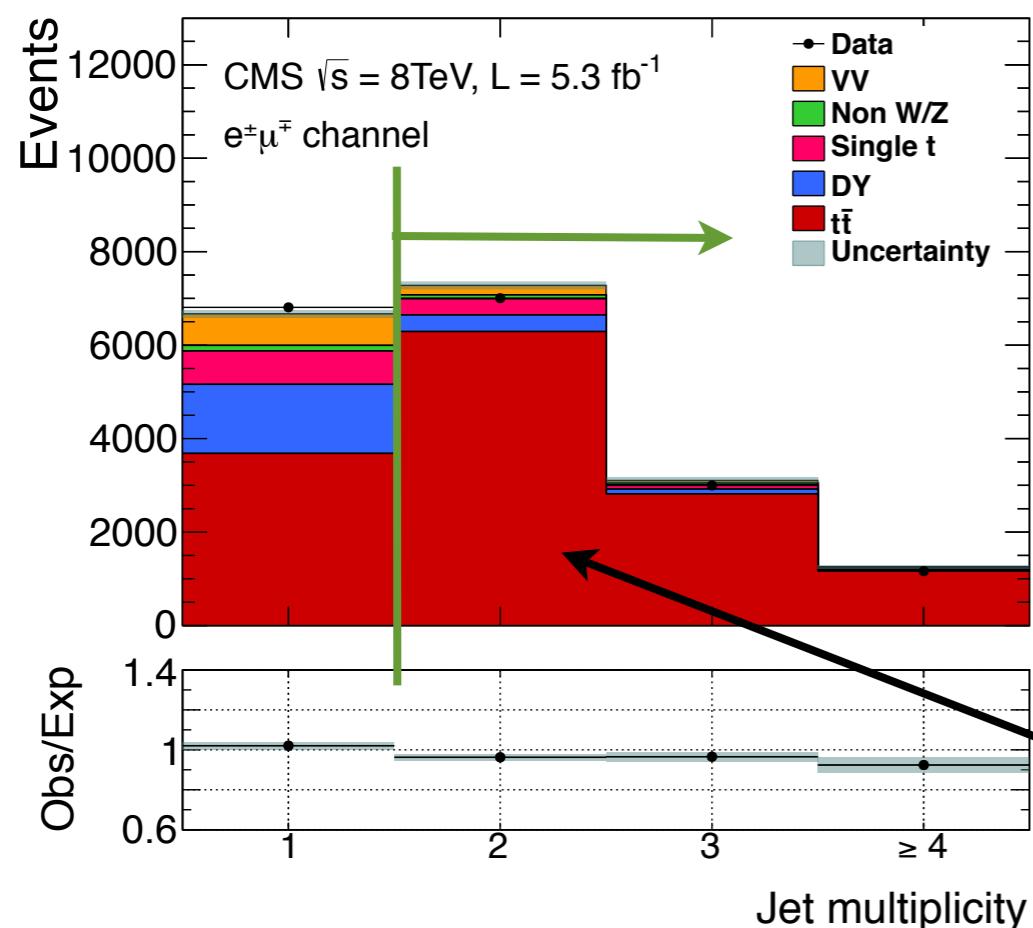
Inclusive cross section

Modelling top quark production

Differential cross section

Simulating Top Quarks

- Often rely on the Monte Carlo (MC) simulation of top pair production in the experimental analyses:



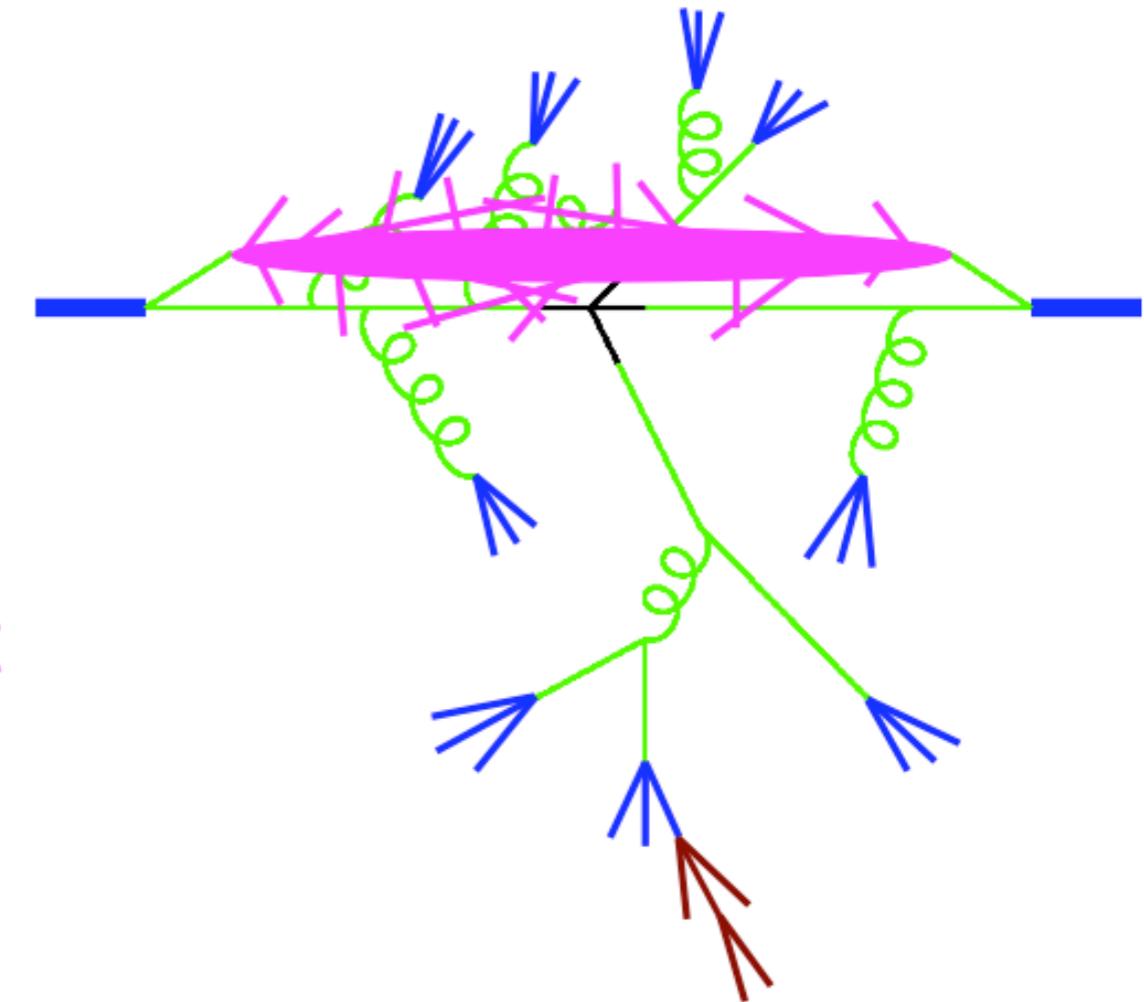
- Extract cross-section by counting events:

$$\sigma = \frac{N_{obs} - N_b}{\epsilon L}$$

Selection efficiency evaluated using MC simulation.

Monte Carlo

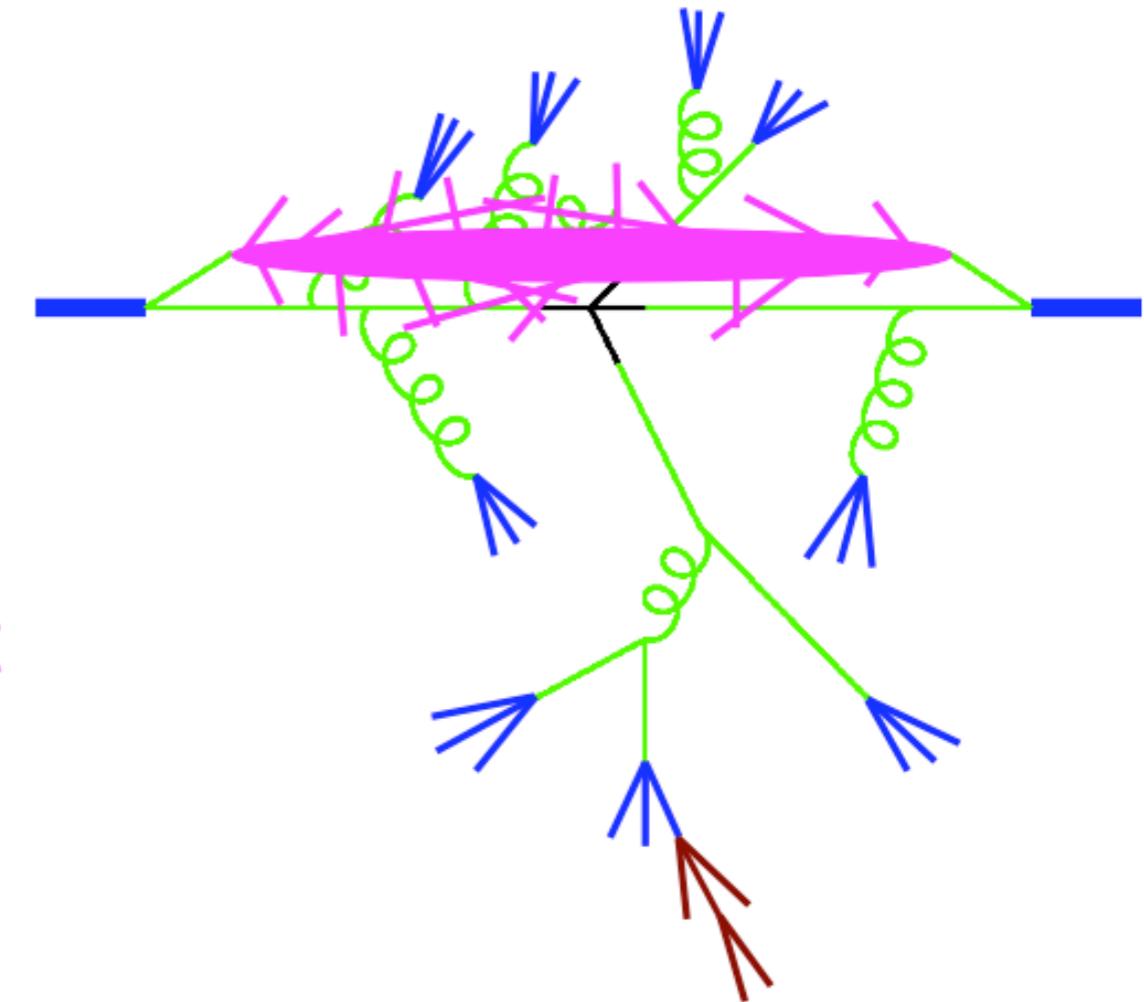
1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays



Monte Carlo

ttbar in
perturbative QCD

1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays

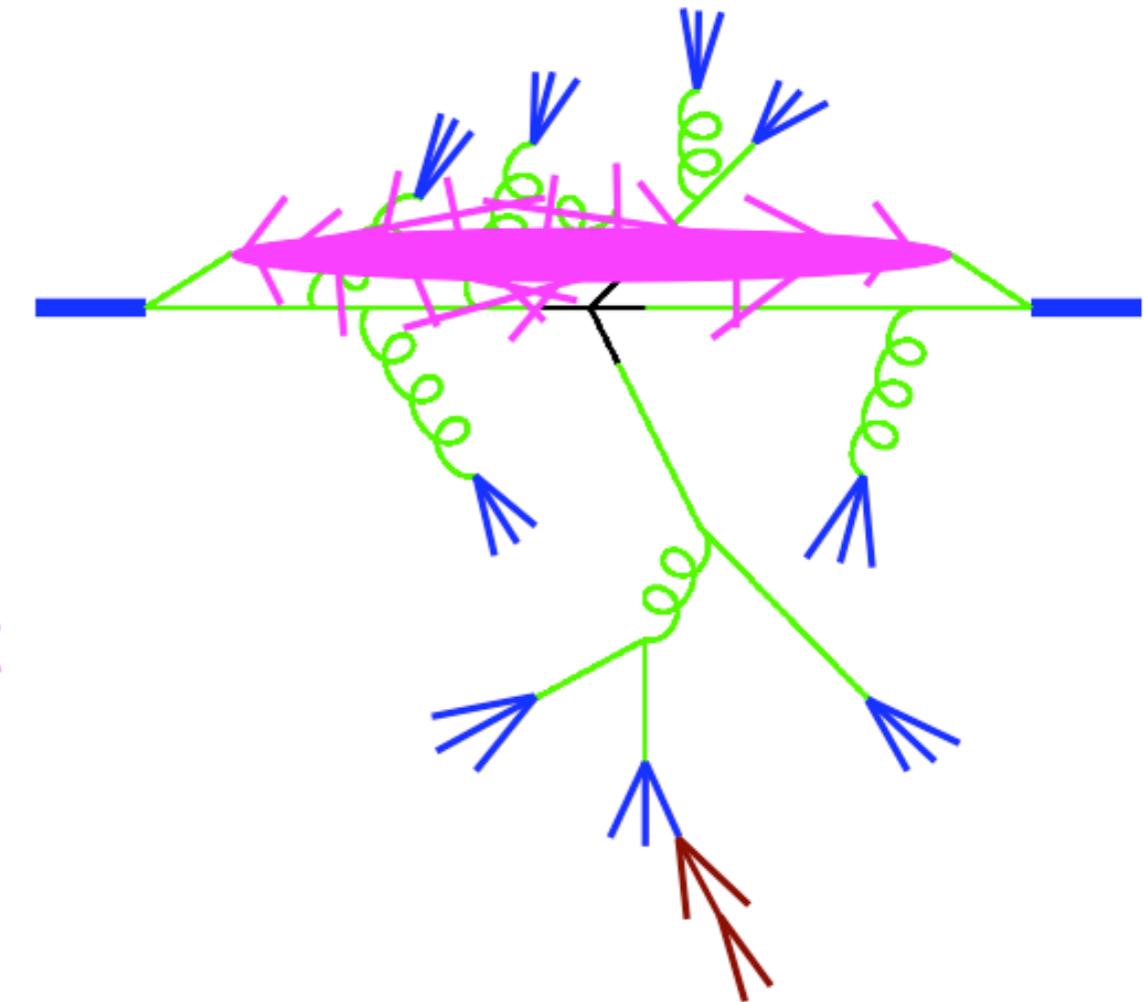


Monte Carlo

ttbar in
perturbative QCD

Soft / collinear
approximation for
QCD radiation

1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays



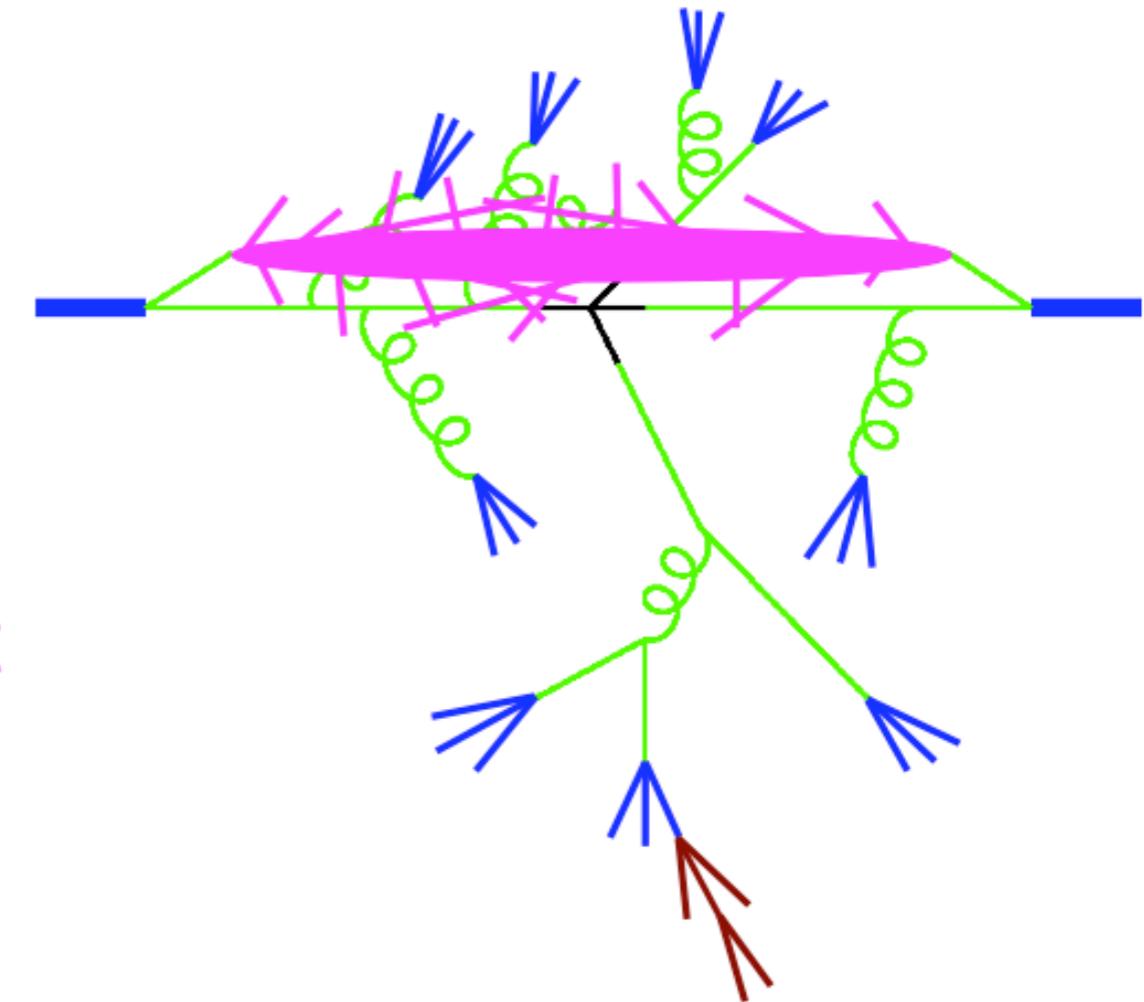
Monte Carlo

ttbar in
perturbative QCD

Soft / collinear
approximation for
QCD radiation

Non-perturbative
model

1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays



Monte Carlo

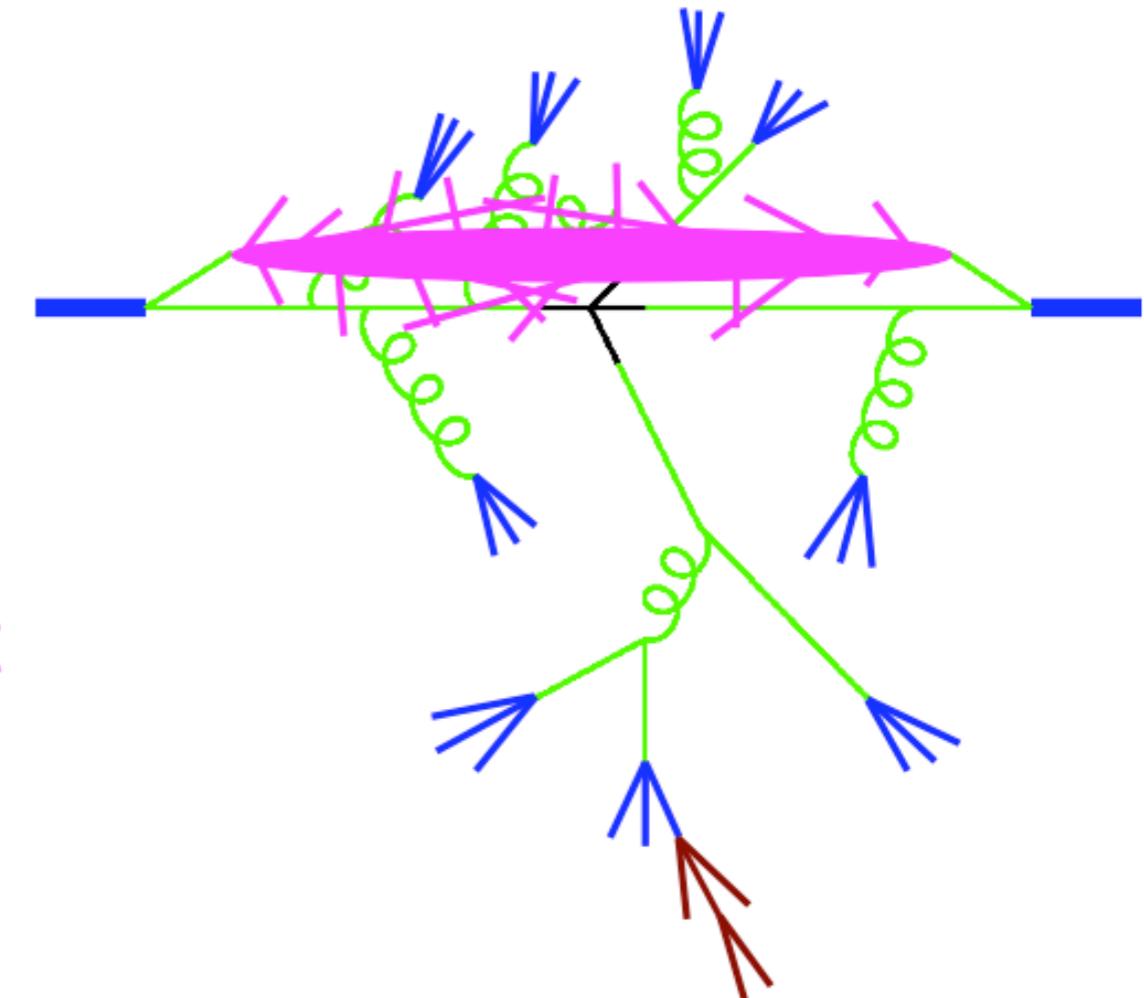
$t\bar{t}$ bar in
perturbative QCD

Soft / collinear
approximation for
QCD radiation

Non-perturbative
model

Important for e.g.
 b -decays

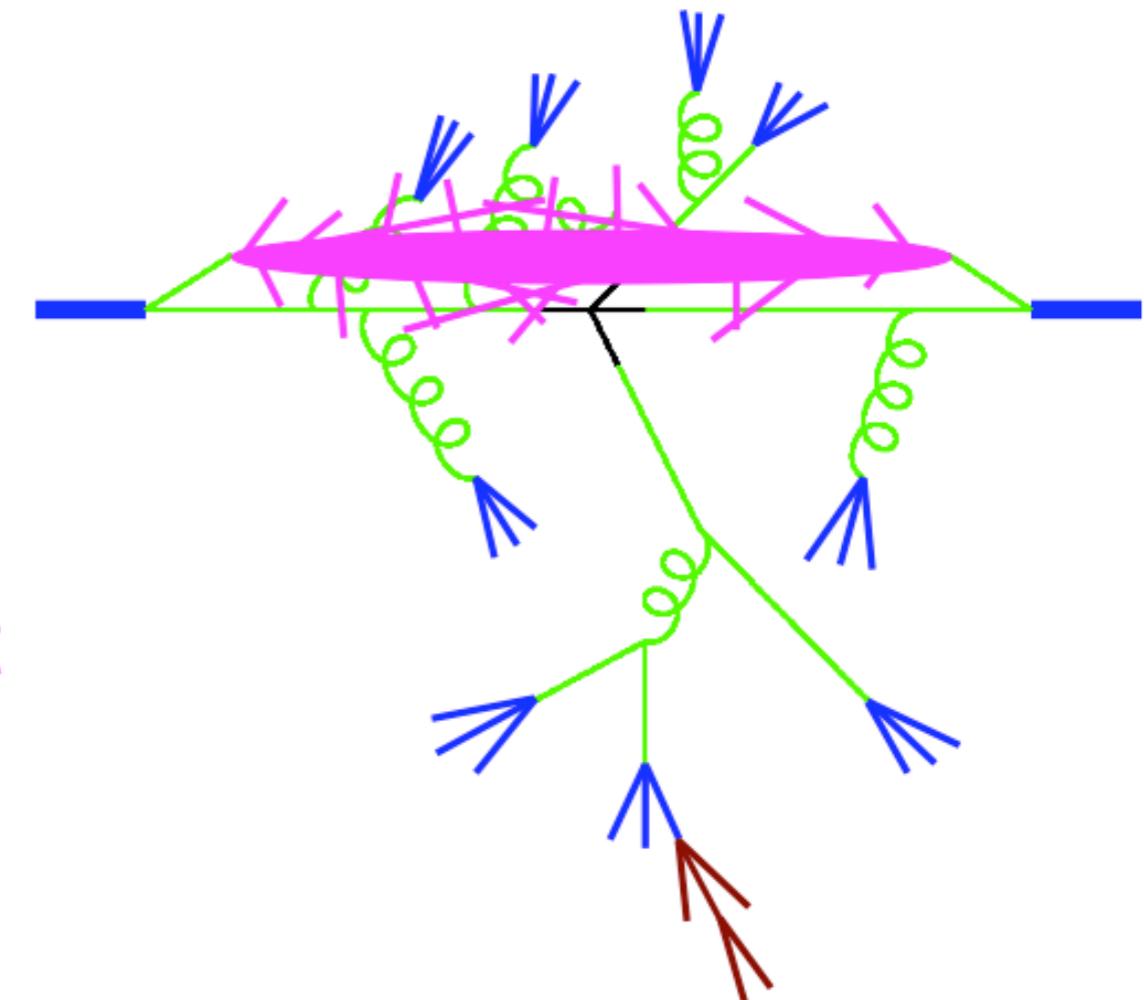
1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays



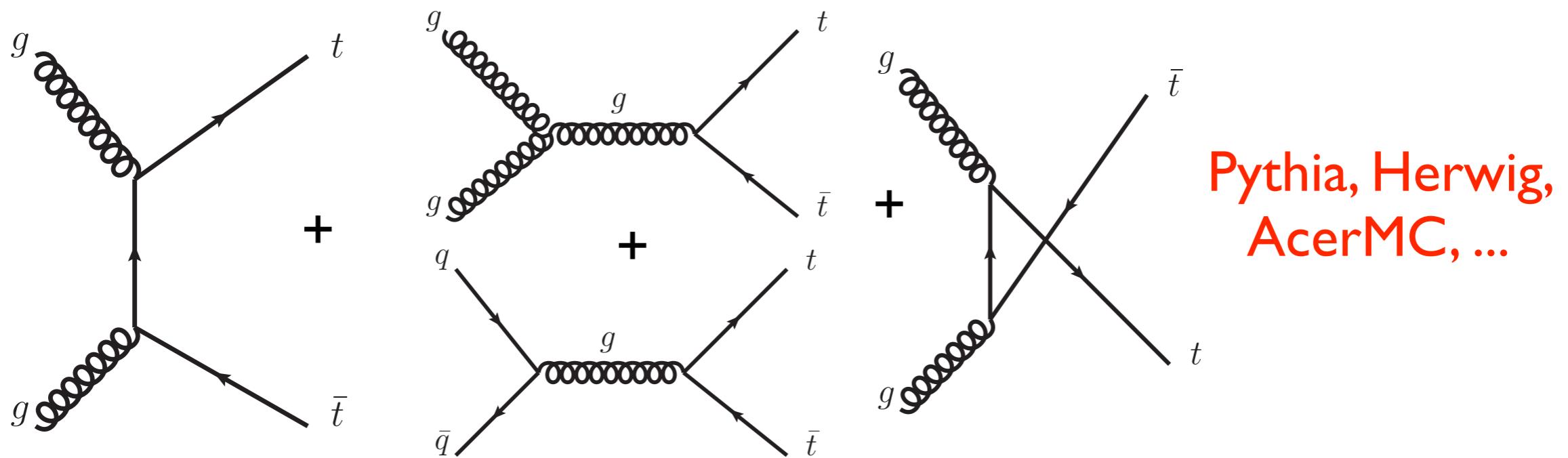
Monte Carlo

ttbar in perturbative QCD

- Soft / collinear approximation for QCD radiation
 - Non-perturbative model
 - Important for e.g. b-decays
- LO, Multi-leg LO, NLO

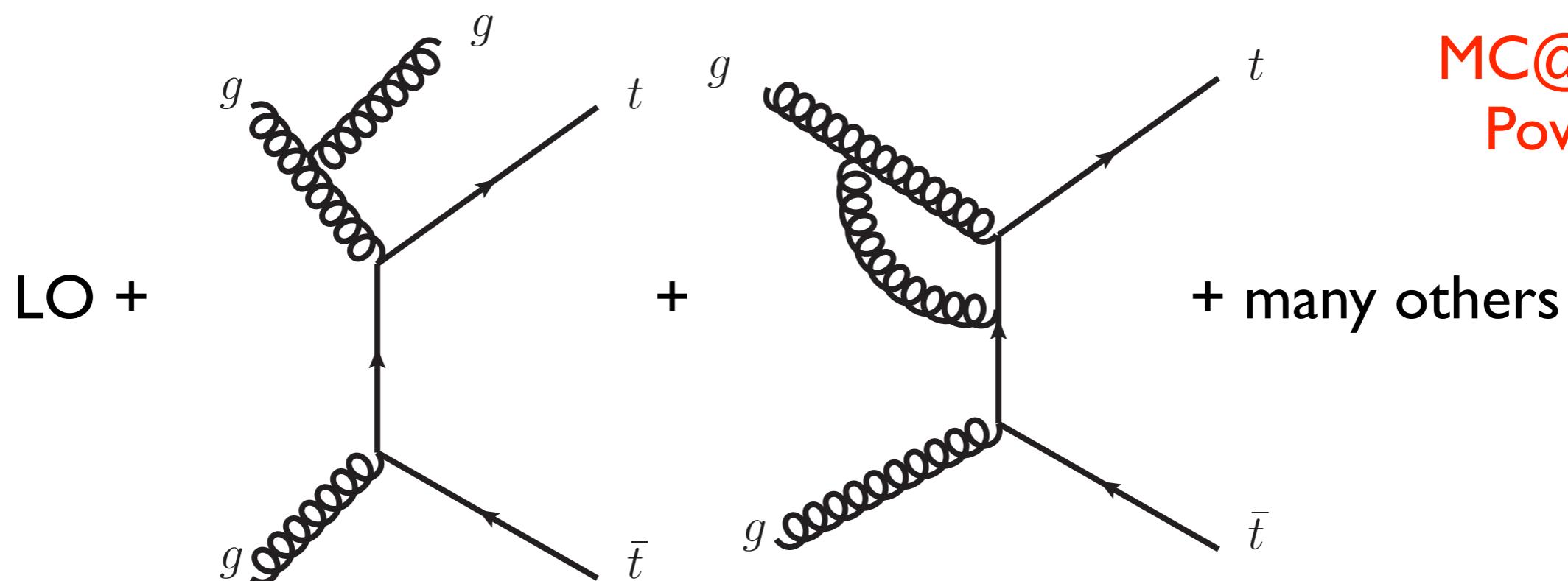


- ‘Simplest’ MC generators:
 - Hard process consists of lowest-order Feynman diagrams:



- No radiation in the hard process.
- Radiation only produced from parton shower - resummation valid for collinear / soft emissions.

- Now have generators including the next order in the hard process:

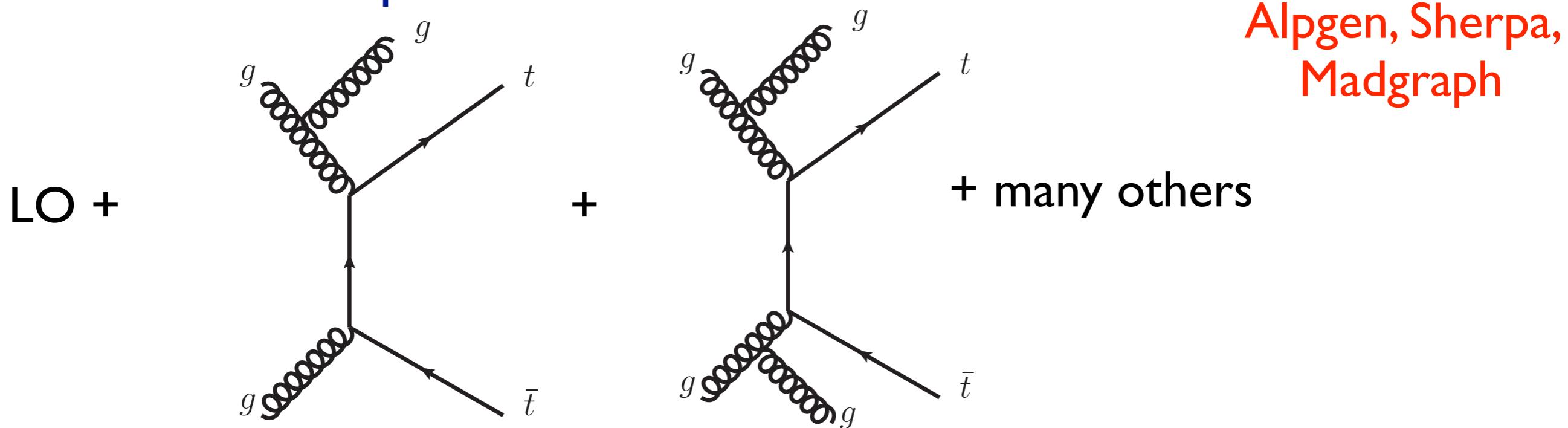


MC@NLO,
Powheg

- First emission now in the hard process - expect better modelling compared to LO.
- Additional emissions from parton shower - matching procedure needed to avoid double counting.

Multi-leg LO MC

- Generators that have up-to $N(\sim 3-5)$ additional emissions in the hard process:



- Note, no loop contributions.
- First N emissions now included in the hard process, additional emissions from the parton shower - matching algorithm needed to avoid double counting.

- LO MC generators:
 - No radiation in the hard process - all jet radiation comes from parton shower approximation.
- NLO MC generators:
 - First emission is in the hard process. Additional emissions from the parton shower approximation.
- Multi-leg LO generators:
 - First N ($\sim 3\text{-}5$) emissions in the hard process. Additional emissions from the parton shower approximation.
- Both NLO and ML-LO need to match to the parton shower.
- Which of NLO or ML-LO is better is analysis dependent.
- Uncertainties are important!

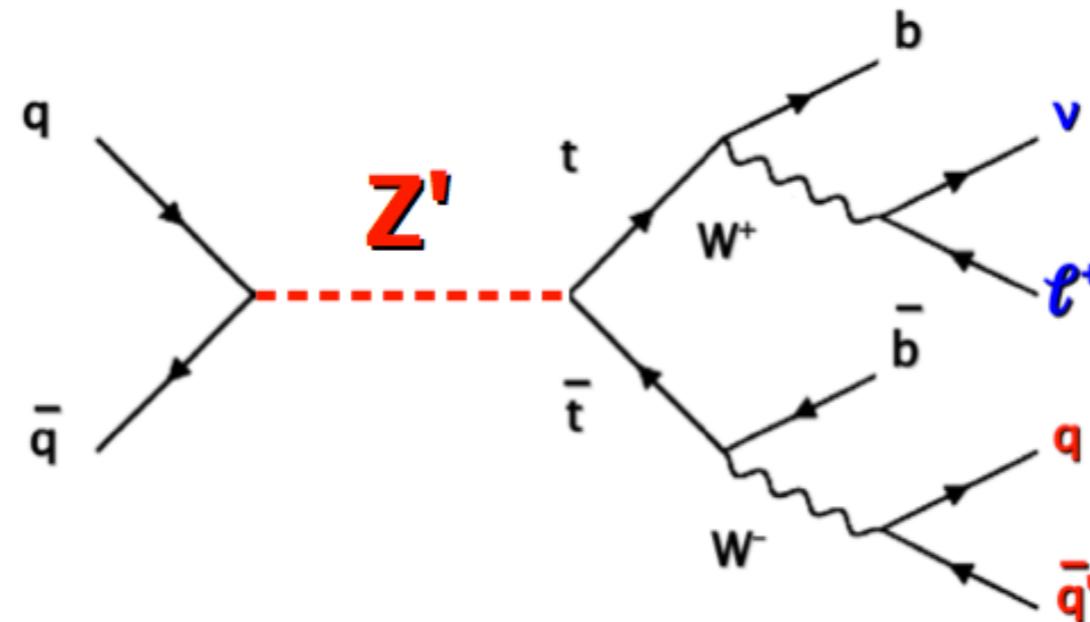
Top Quark Pair Production:

Inclusive cross section

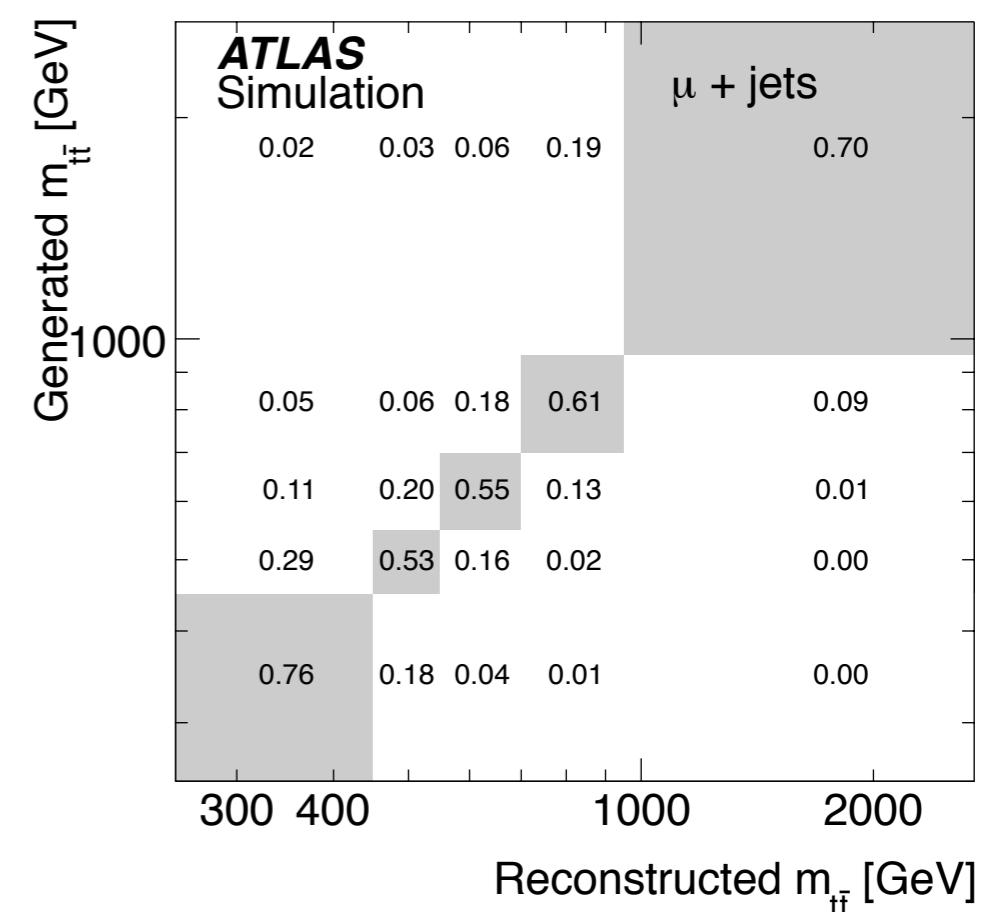
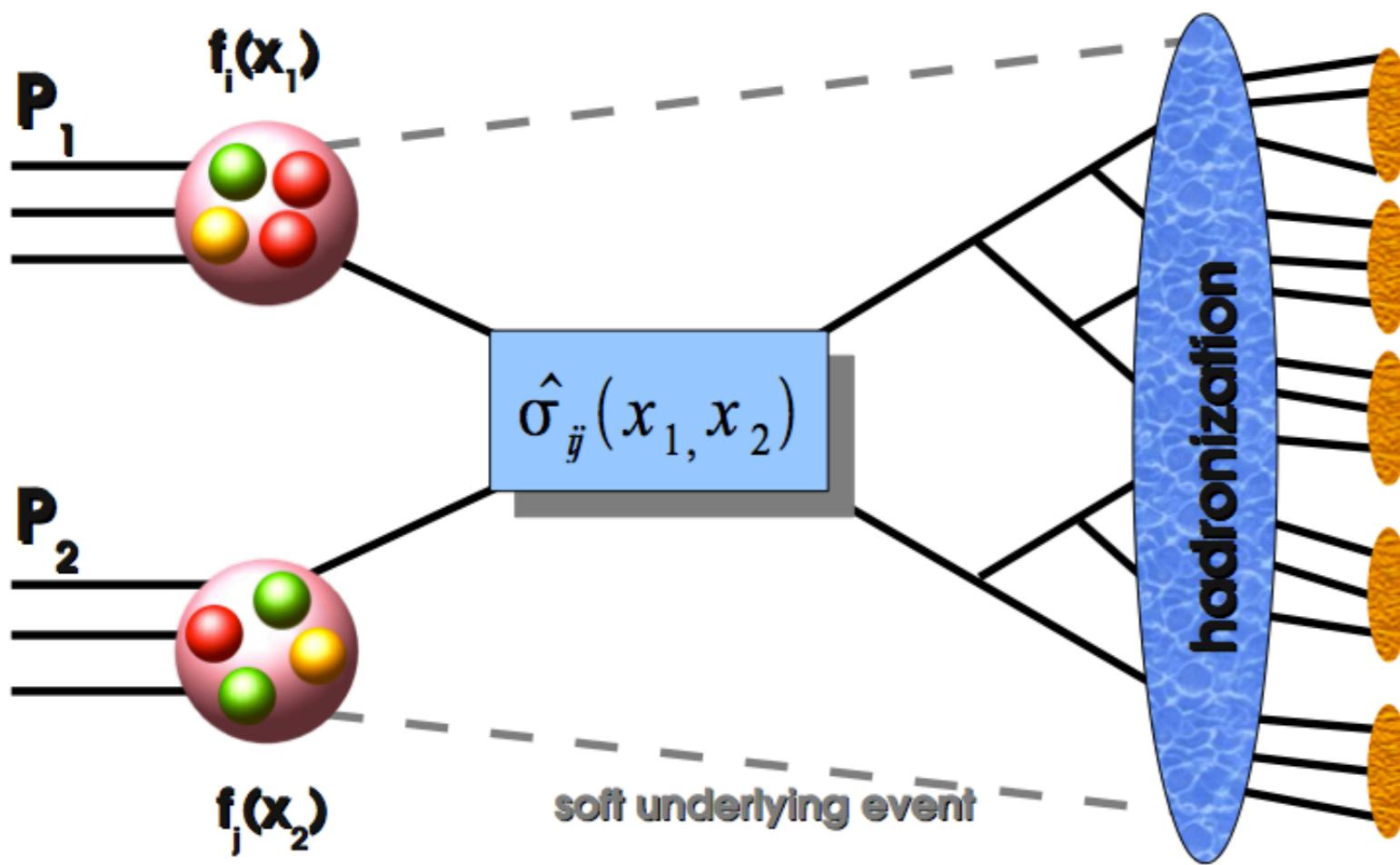
Modelling top quark production

Differential cross sections

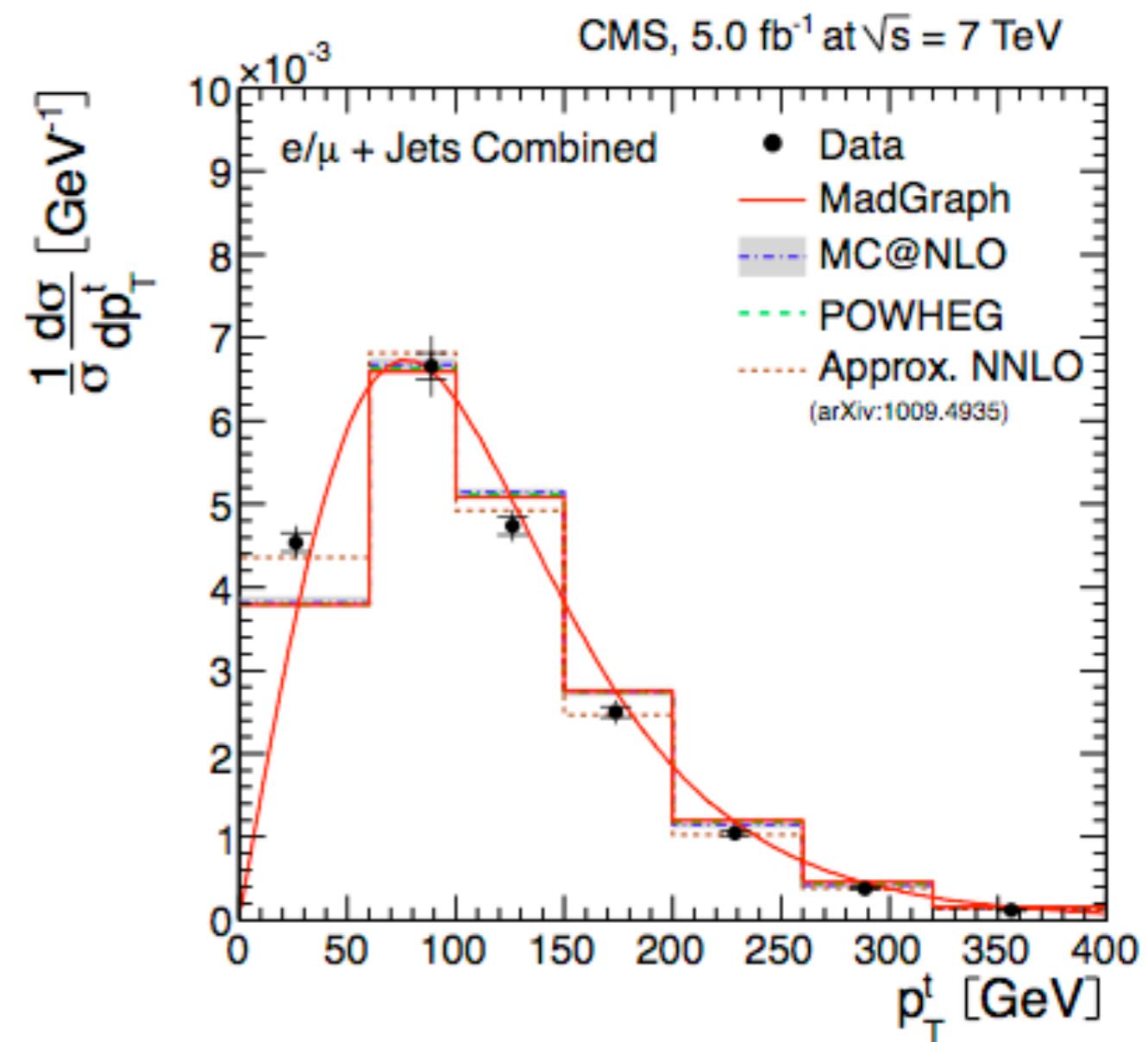
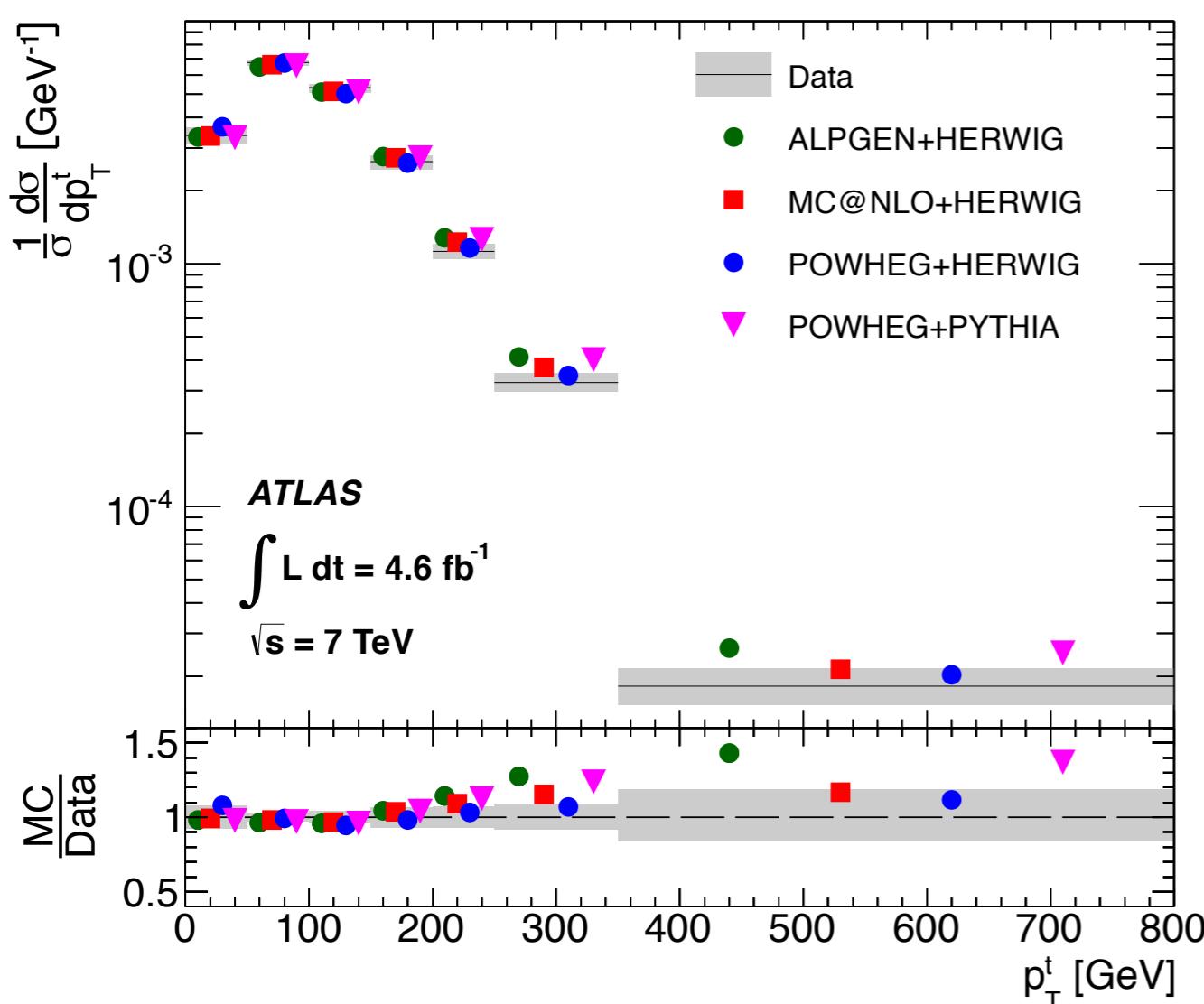
- Vital to test the theory beyond the inclusive cross section.
- Measure differential distributions of the top quarks themselves, but also measure top quarks produced with additional jets.
 - Test MC description of the data.
 - Test of new physics in tails, e.g. of invariant ttbar mass.



- Challenging measurements to go from detector measurements to underlying physics - have to ‘unfold’ detector effects:



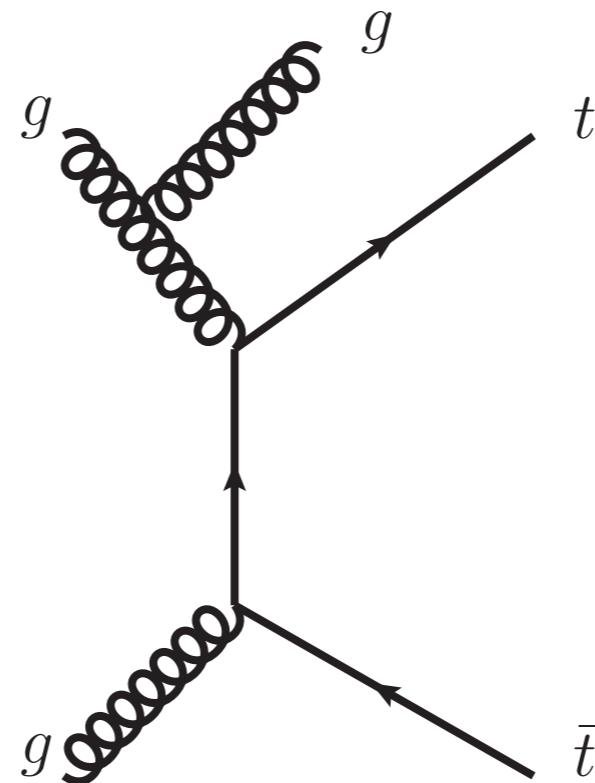
- Kinematic variables of top quarks:



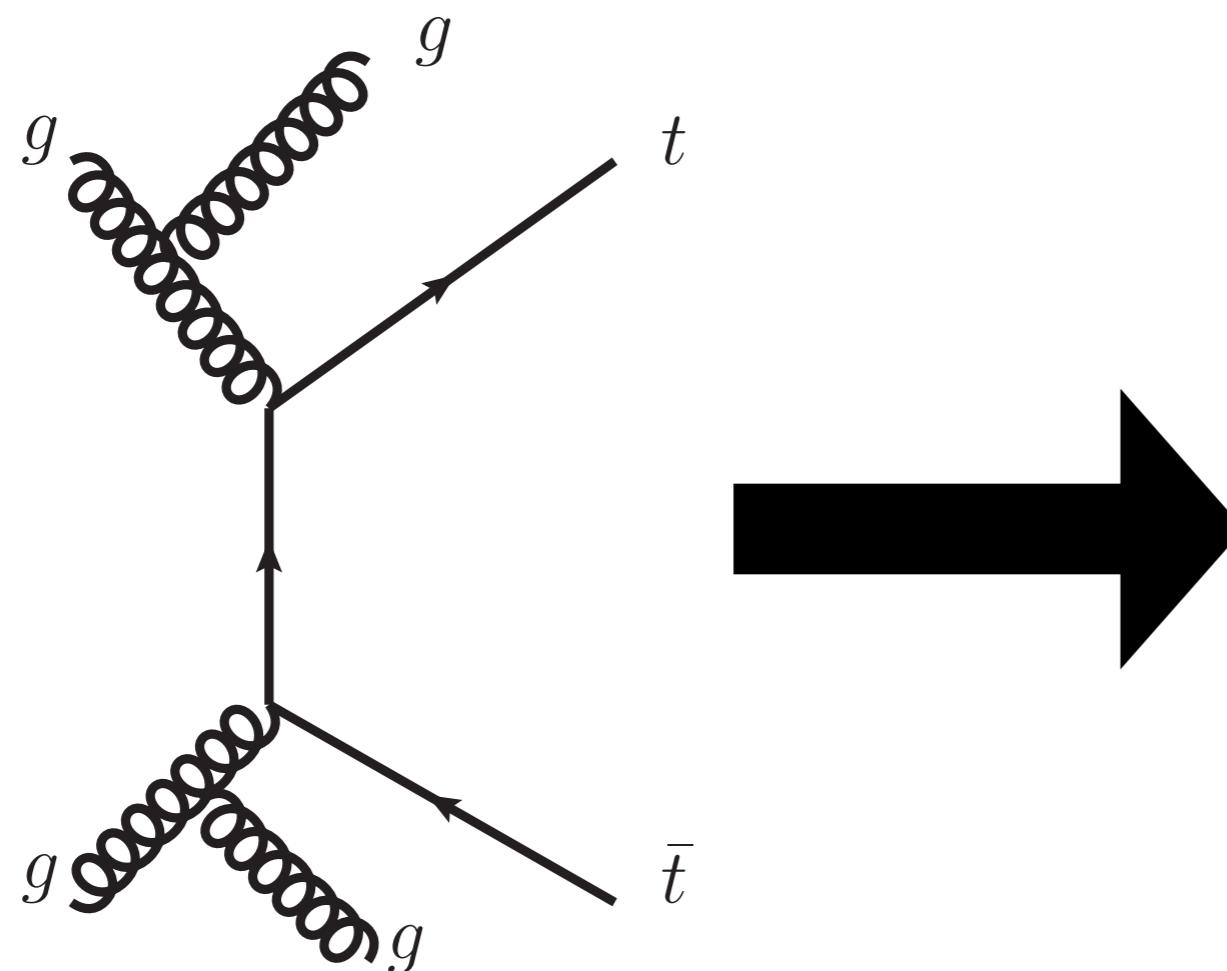
- Some tension, but generally good agreement with SM.

ttbar plus jets

- Production of ttbar with additional jets is interesting final state:
 - Directly test different MC model approaches discussed earlier.
 - Important background to other processes - ttbar+H & new physics with tops in the final state.
- LHC statistics offer the possibility for precise measurements & access to high jet multiplicities.

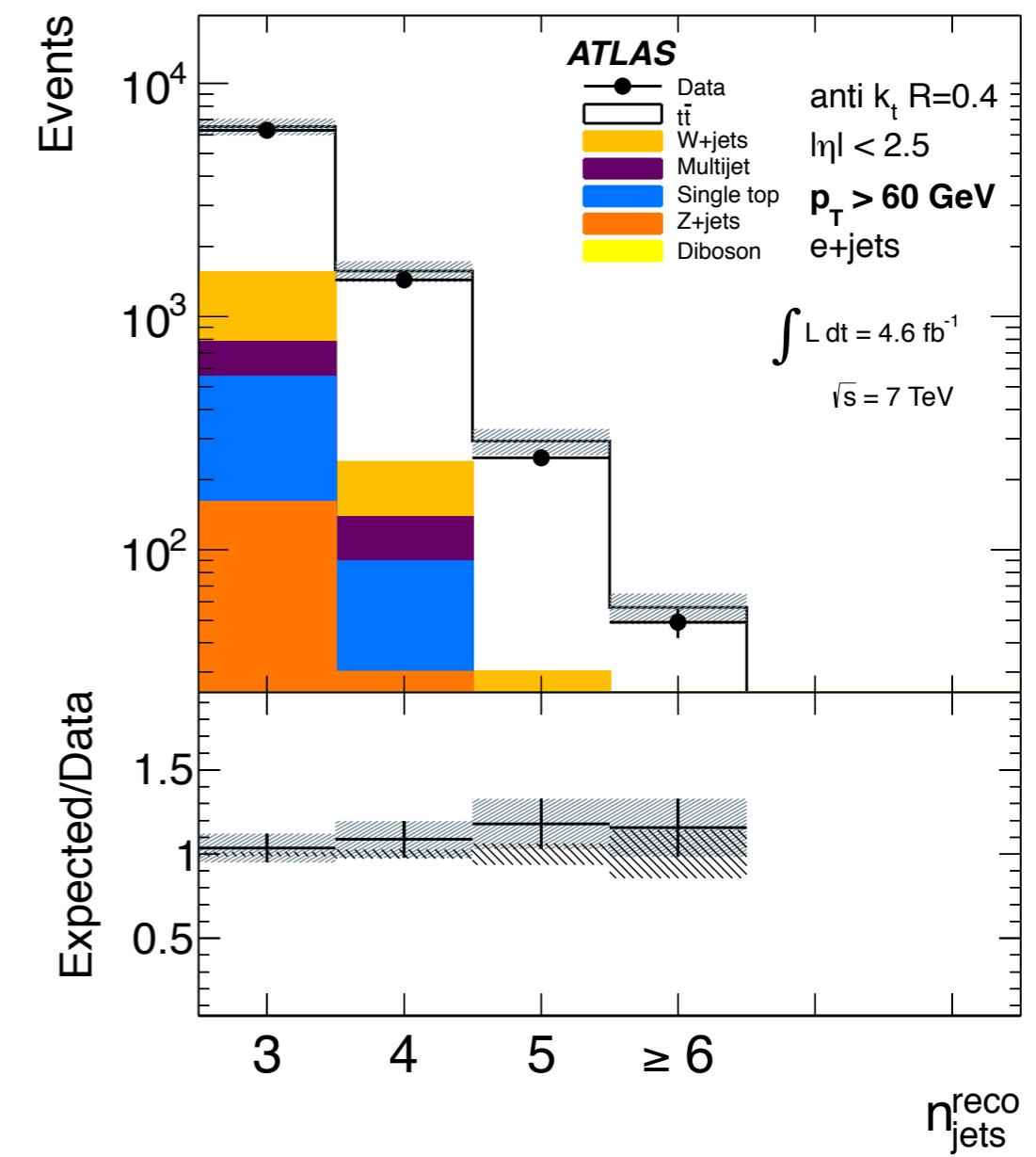
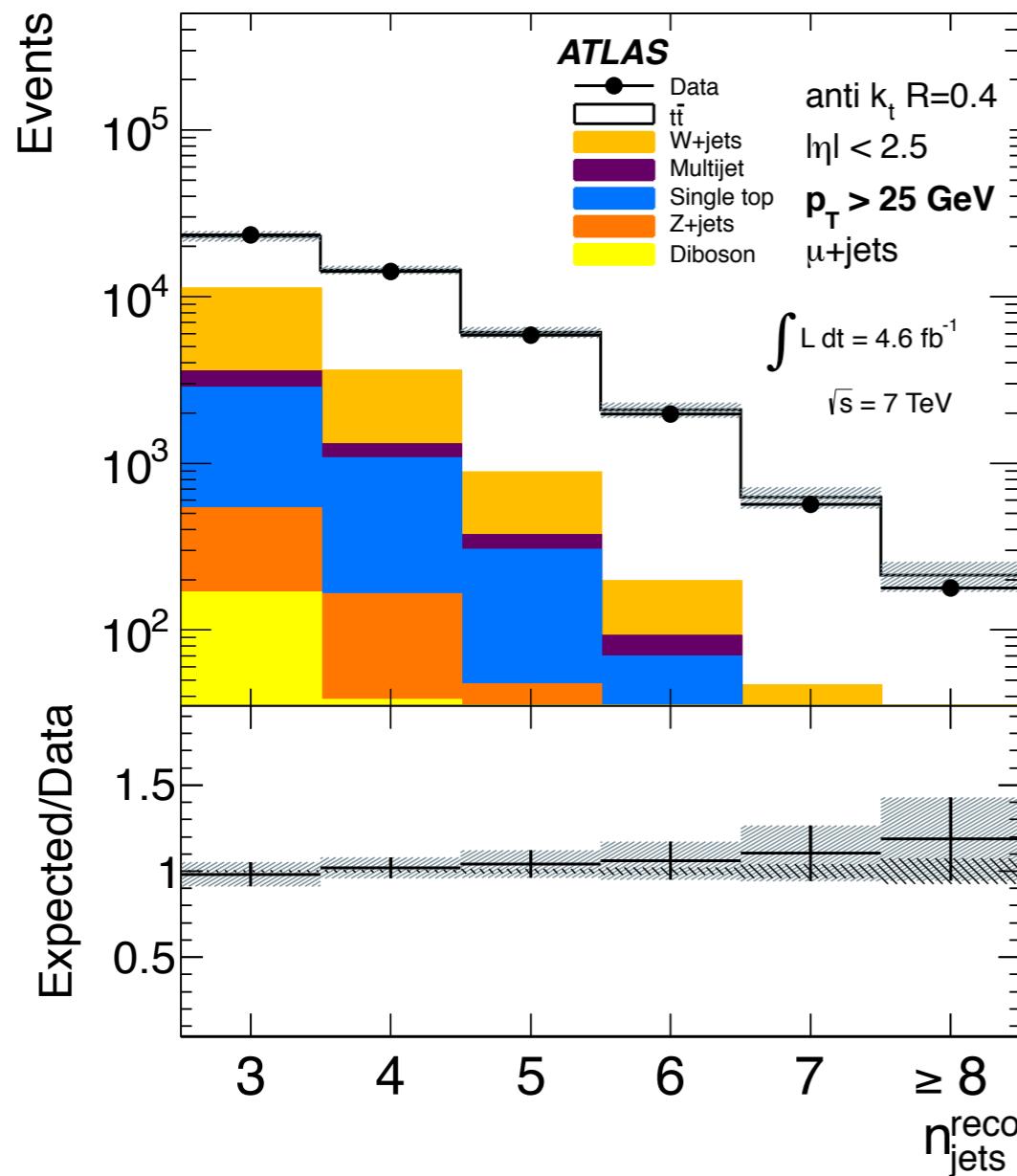


- Measurement of jet multiplicity in lepton+jets top events:



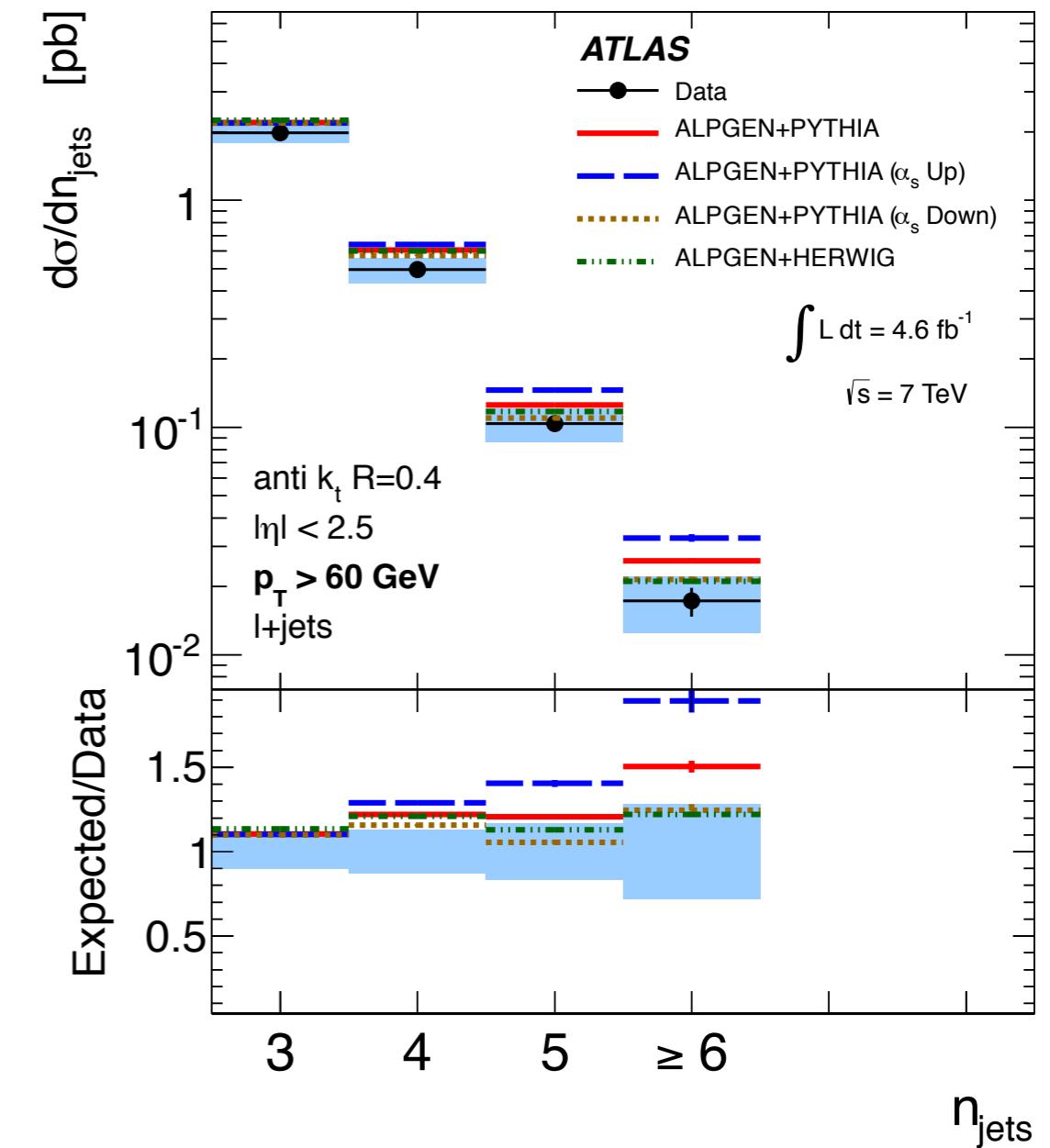
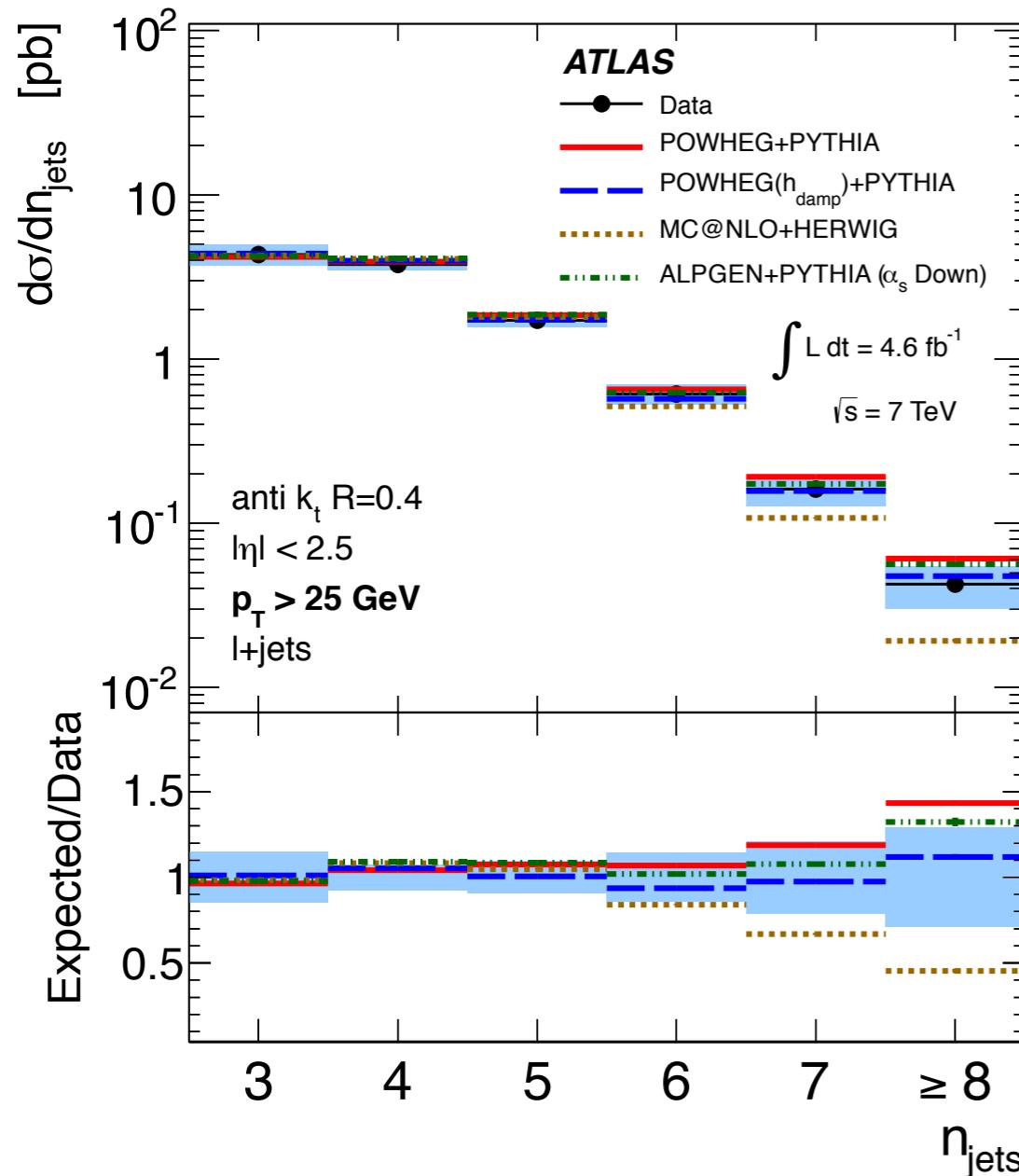
6 jets in the detector:
2 from W , 2 b-jets and
2 gluon jets

- Measurement of jet multiplicity in lepton+jets top events:



Differential Cross Sections

- Unfolded data compared to MC models:



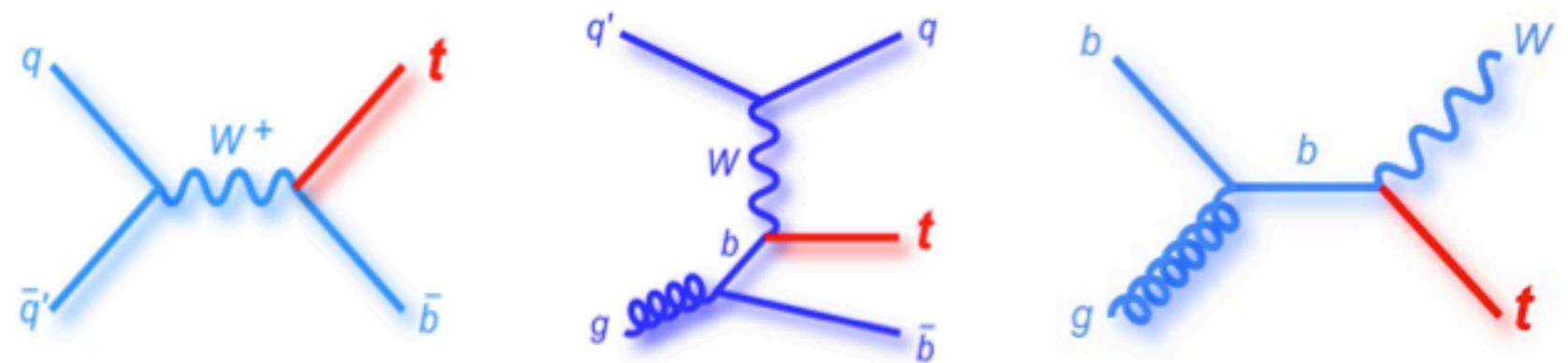
- Start to distinguish models at high $n(\text{jets})$.

Single Top Quark Production:

Tevatron discovery
LHC measurements

Single Top Production

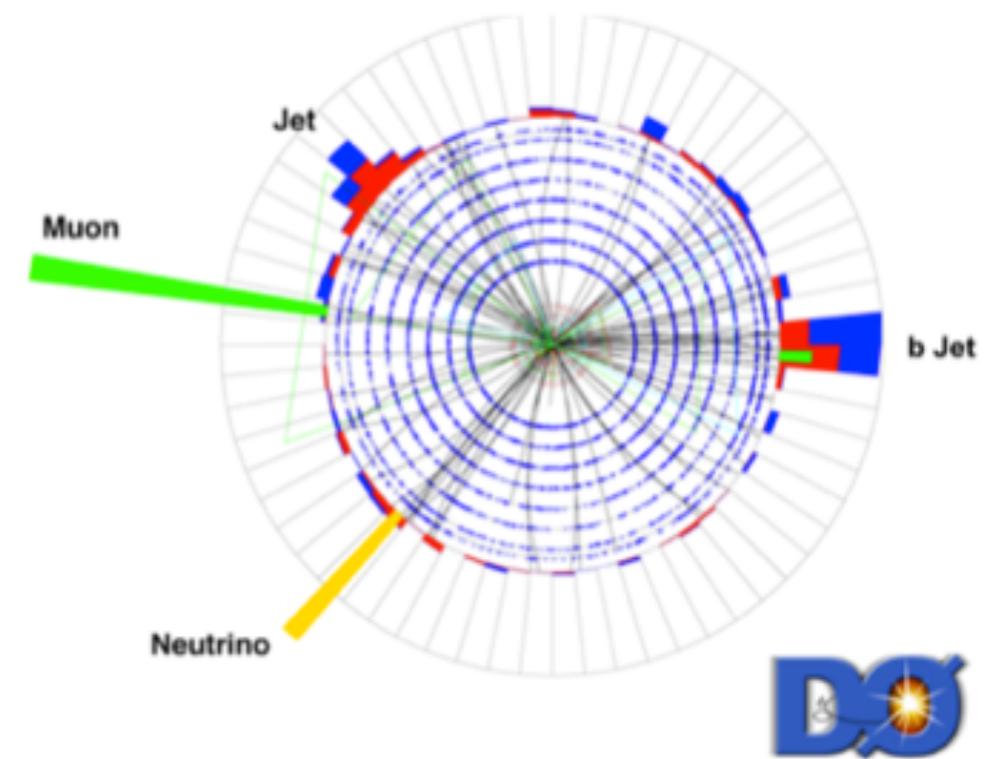
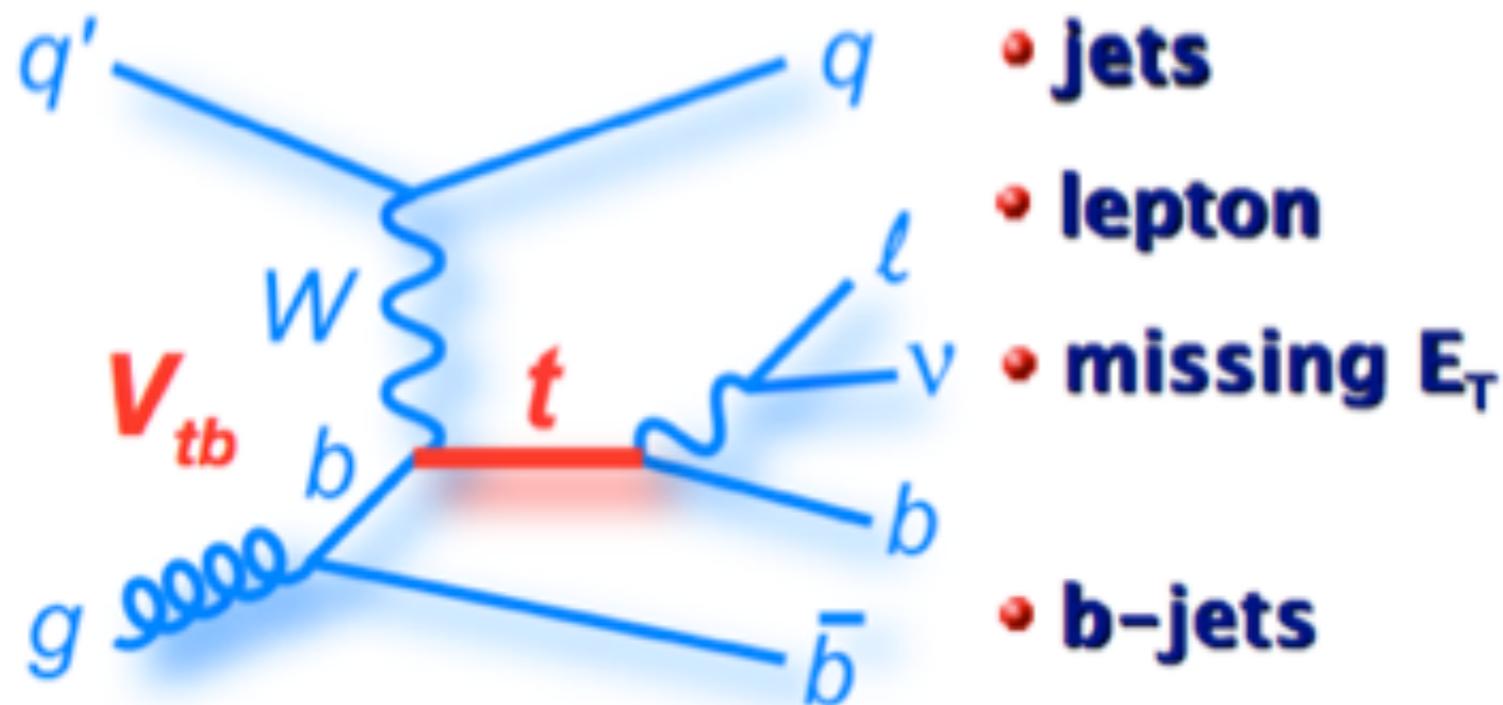
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \mathbf{V_{tb}} \end{pmatrix}$$



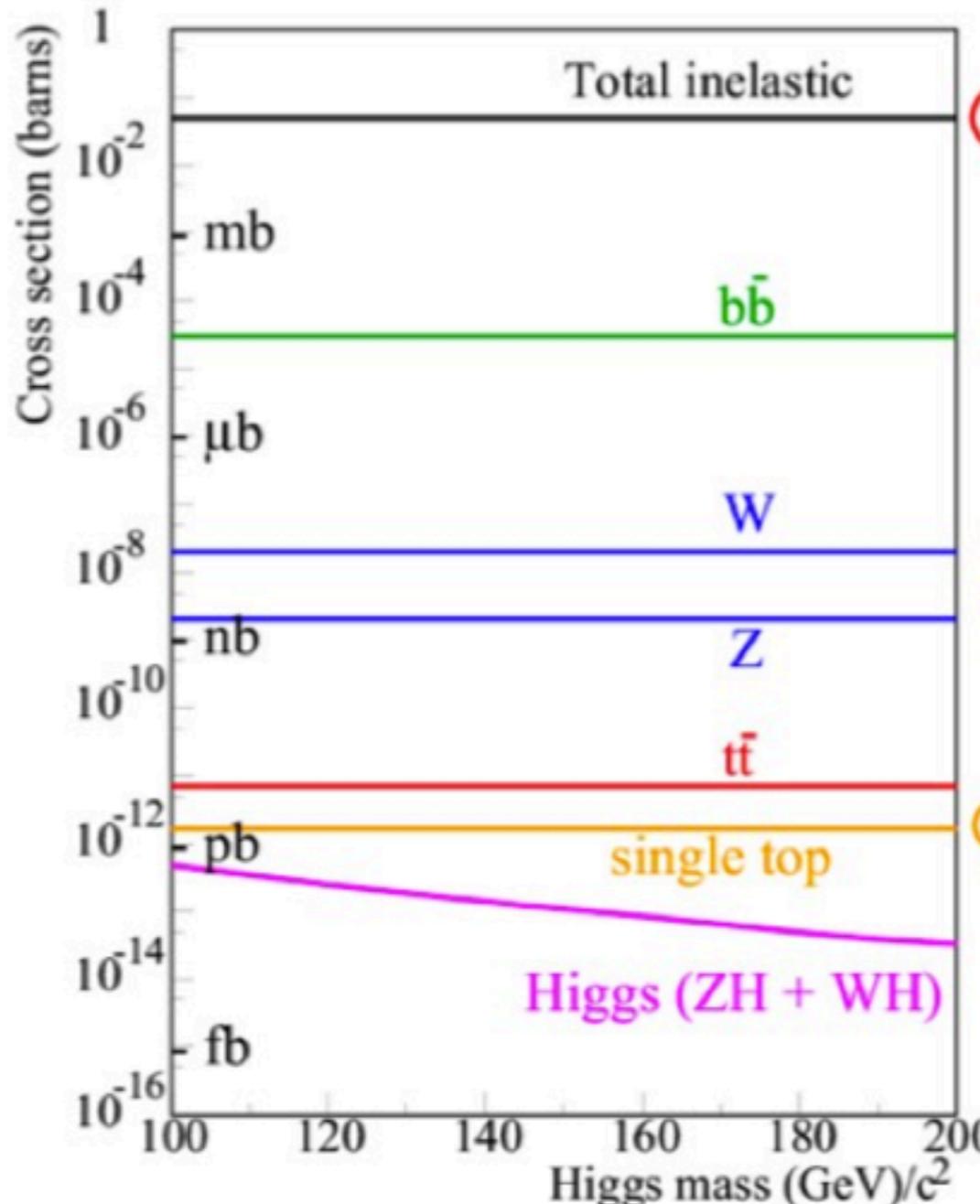
Collider	s-channel: σ_{tb}	t-channel: σ_{tqb}	Wt-channel: σ_{tw}
Tevatron: $p\bar{p}$ (1.96 TeV)	1.04 pb	2.26 pb	0.28 pb
LHC: pp (7 TeV)	4.6 pb	64.6 pb	15.7 pb

Direct sensitivity to $|V_{tb}|$

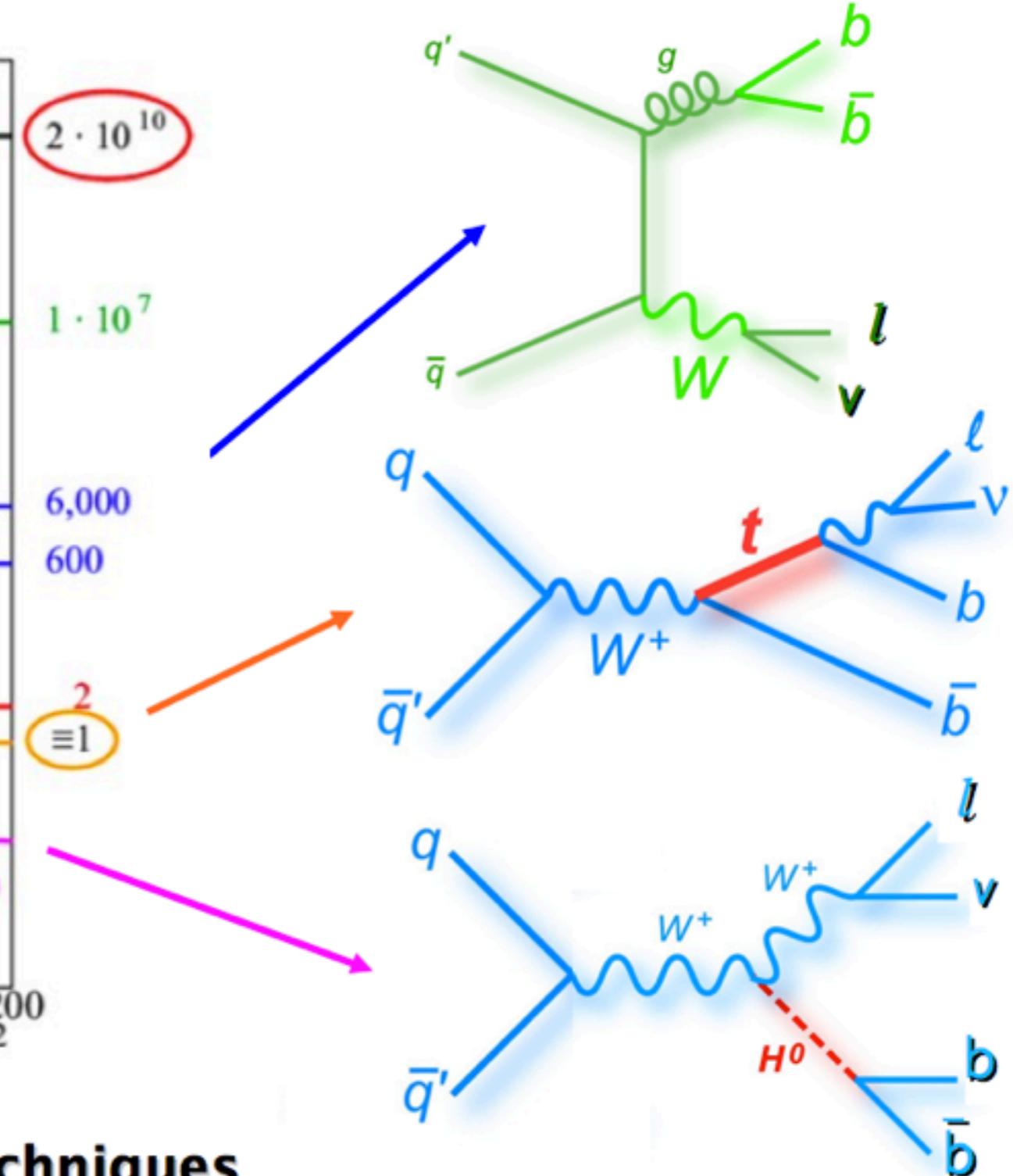
t-channel



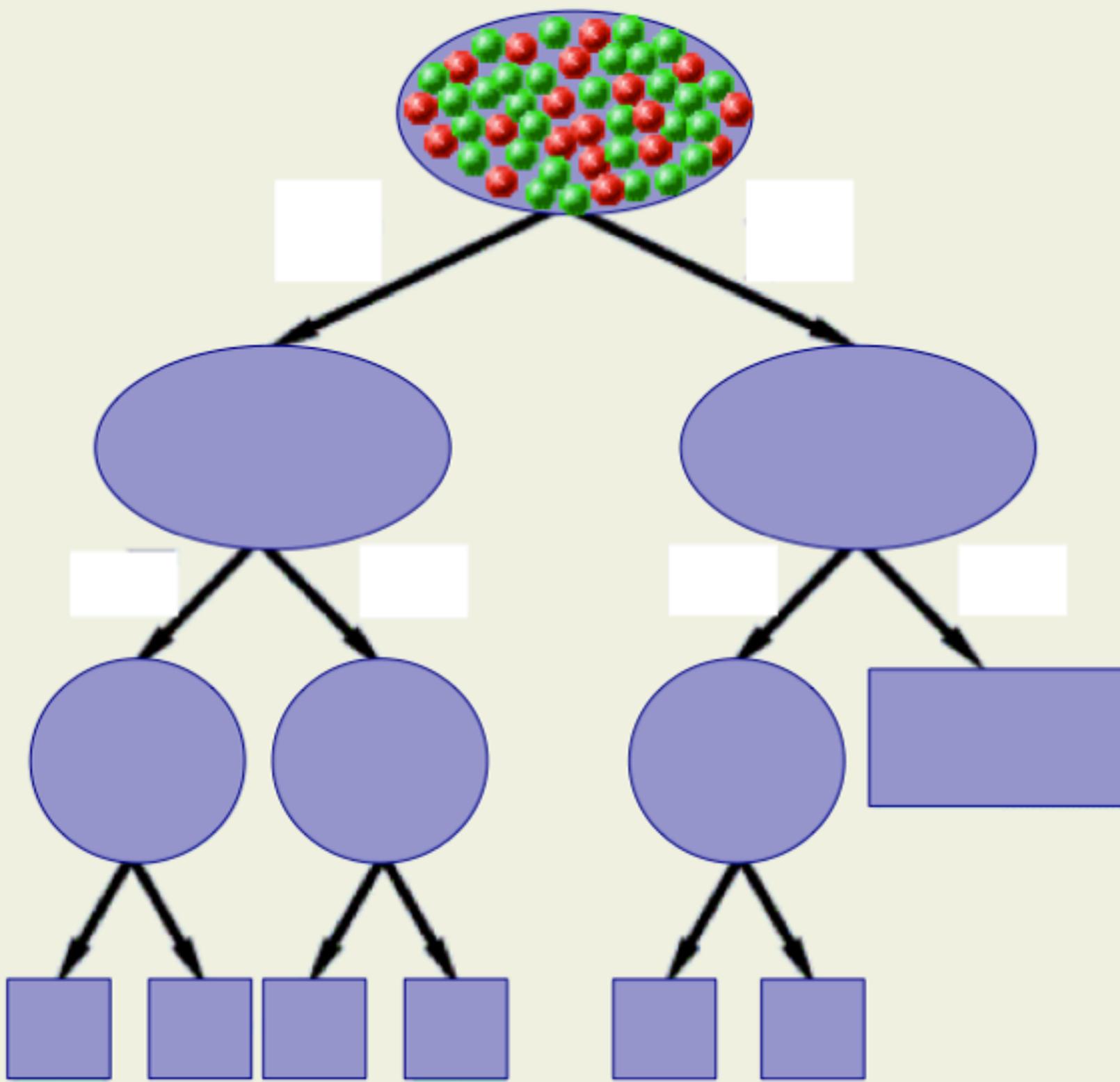
Backgrounds



⇒ multivariate analysis techniques

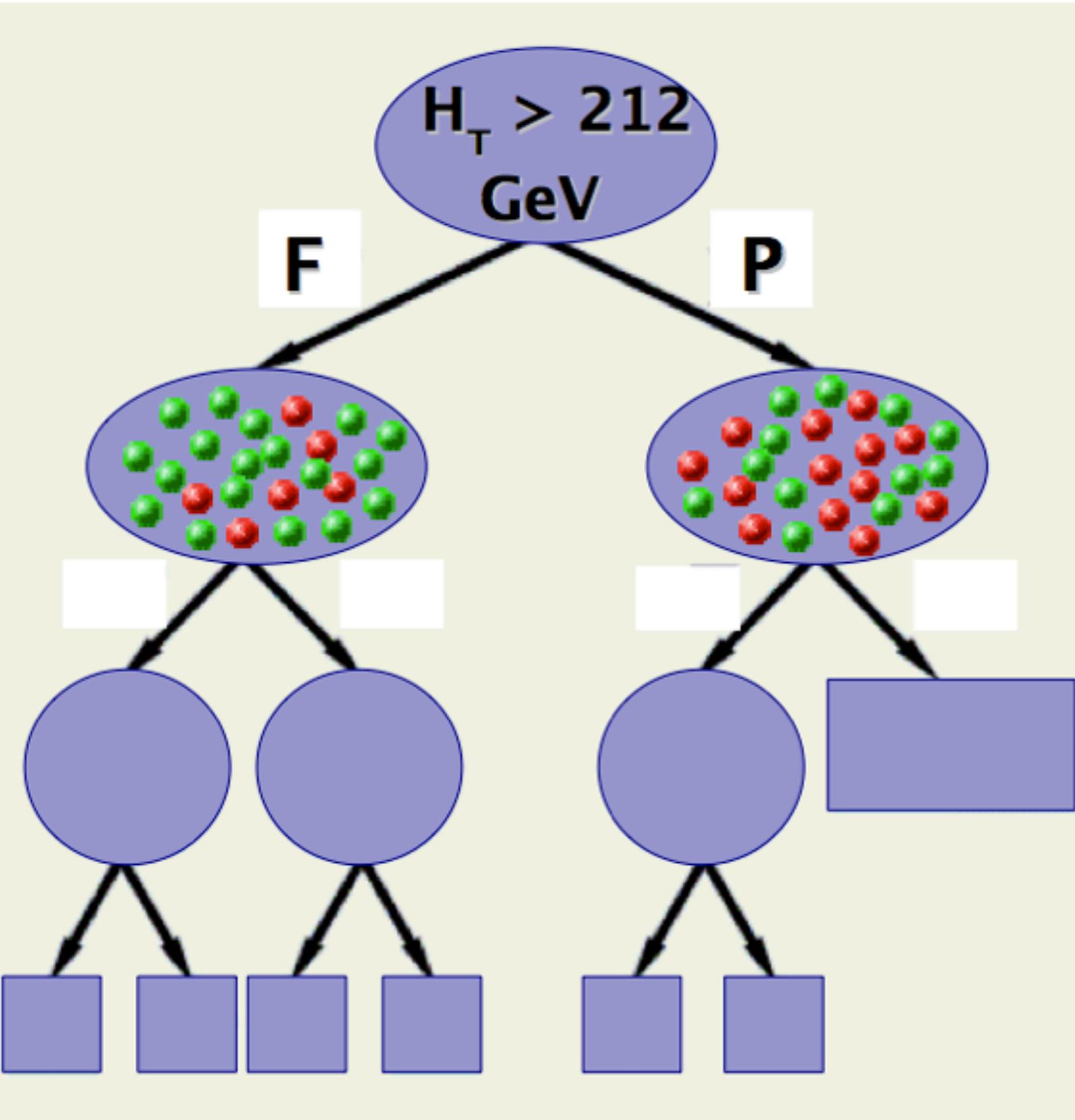


Boosted Decision Trees



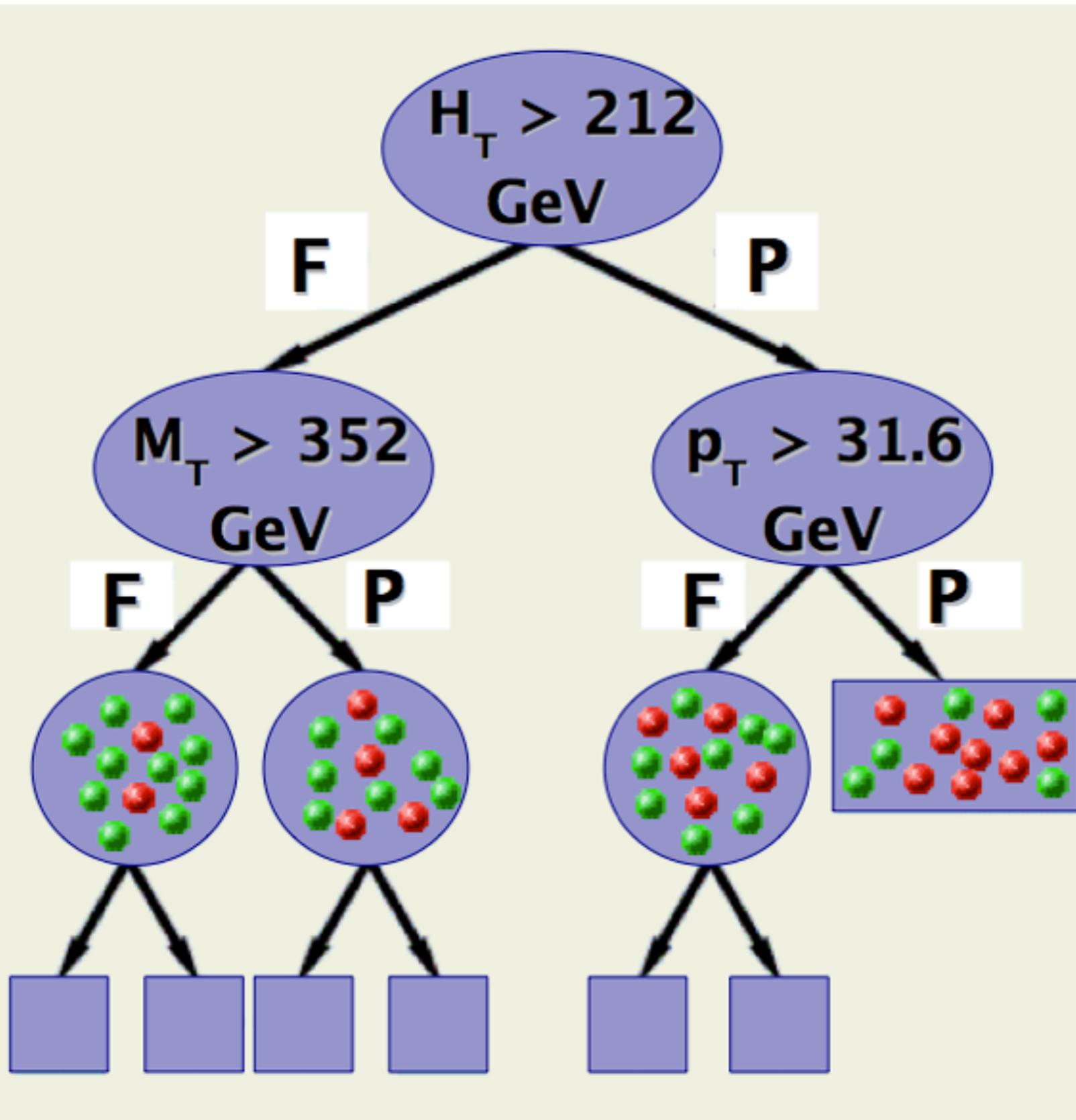
- **IDEA: recover events that fail criteria in cut-based analyses**

Boosted Decision Trees



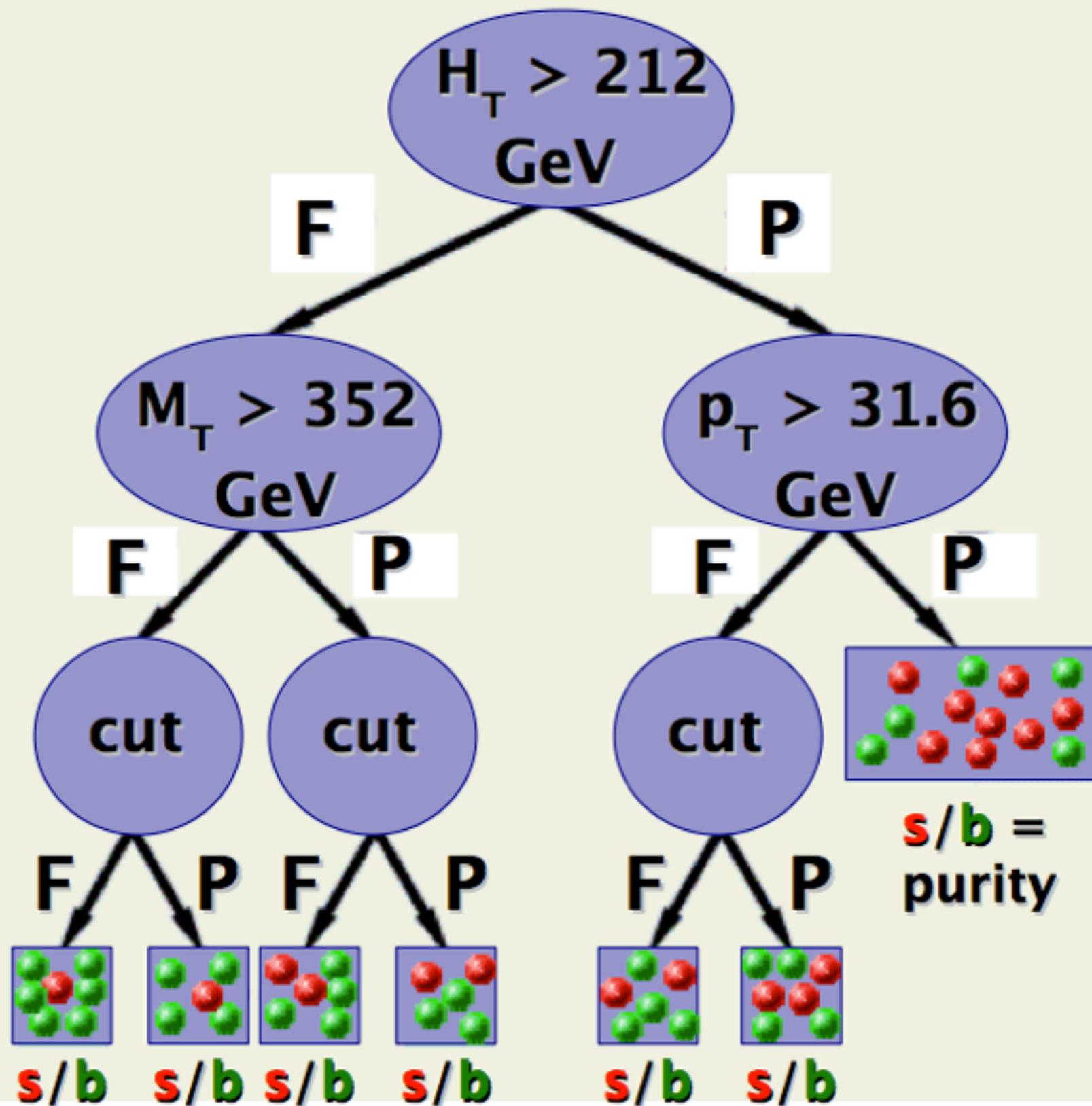
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Boosted Decision Trees



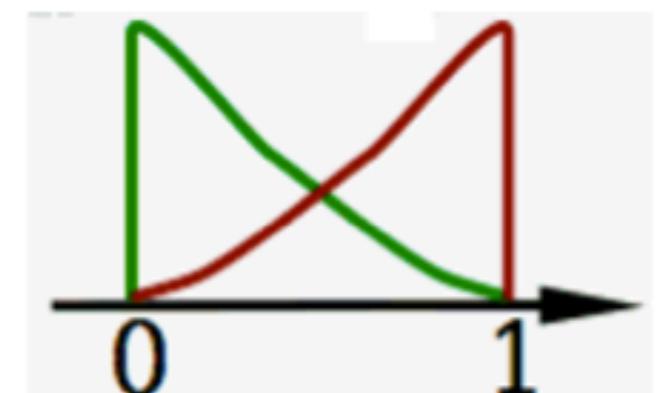
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Boosted Decision Trees

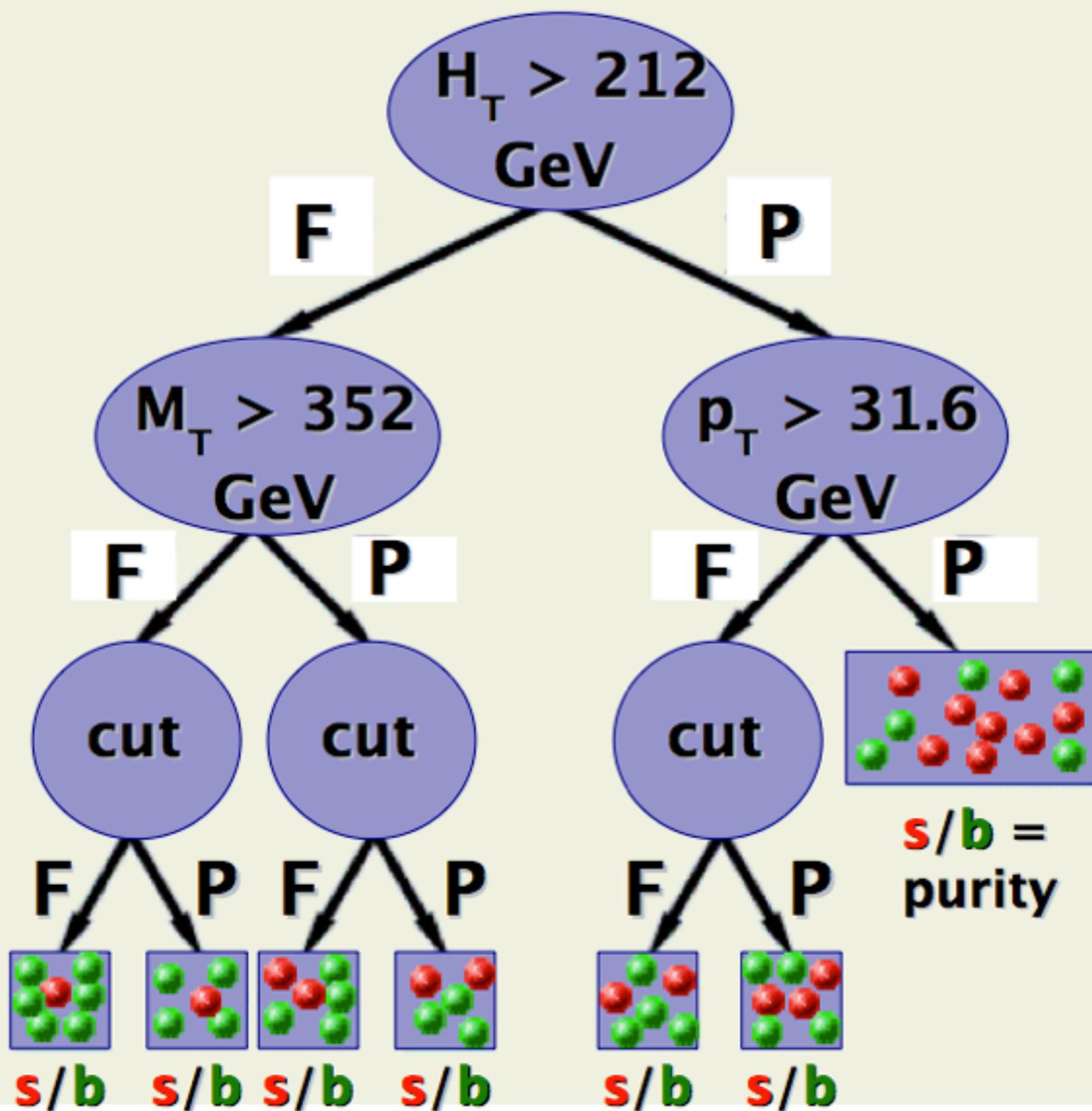


- **IDEA:** recover events that fail criteria in cut-based analyses

- result:
weight for every event
background **signal**



Boosted Decision Trees

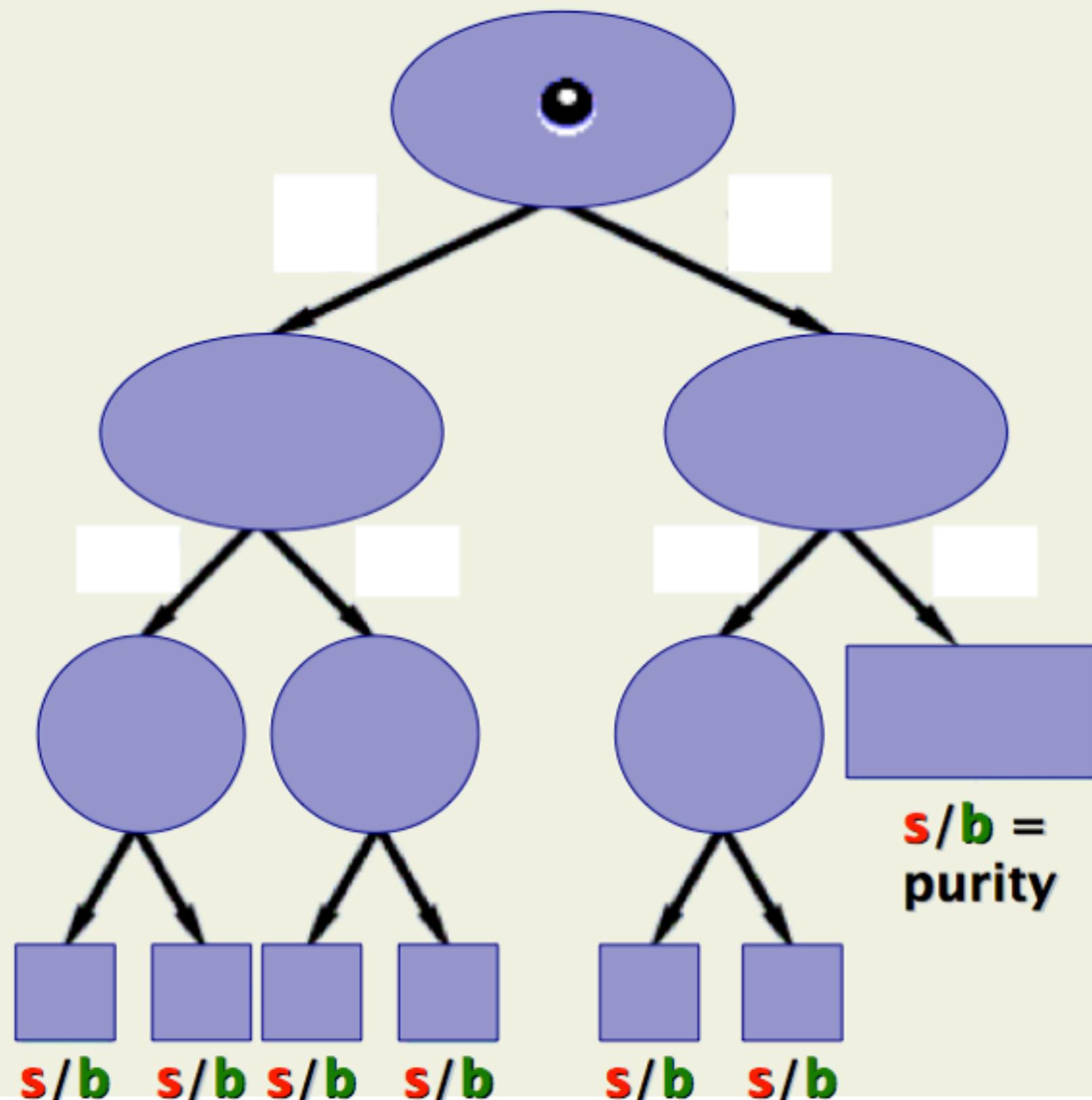


- **IDEA:** recover events that fail criteria in cut-based analyses

boosting:

- train tree: T_k
 - derive weight: α_k
 - retrain tree: T_{k+1}
- to minimize error**
- average: $T = \sum \alpha_i T_i$

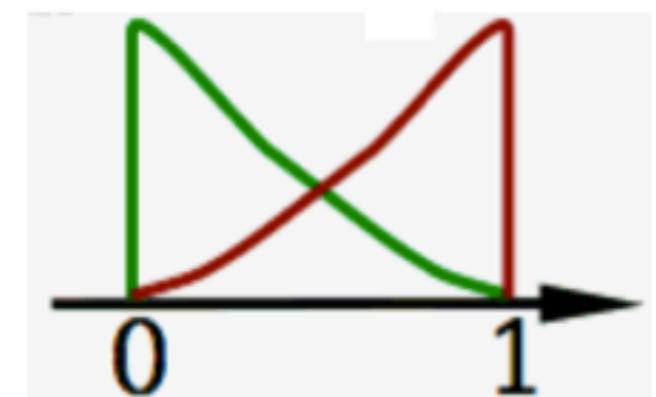
Boosted Decision Trees



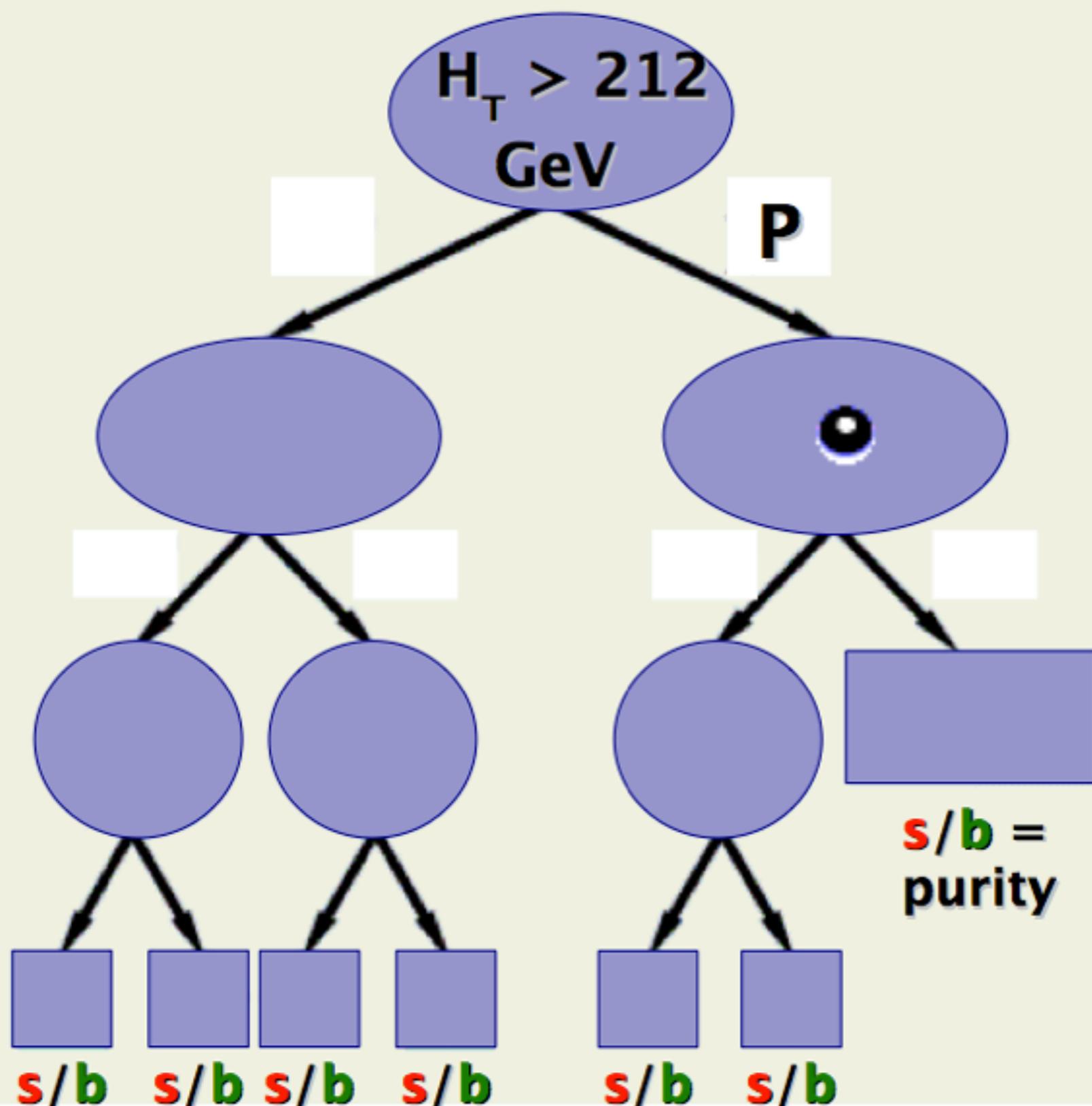
- **IDEA:** recover events that fail criteria in cut-based analyses

- **result:** weight for every event

background **signal**

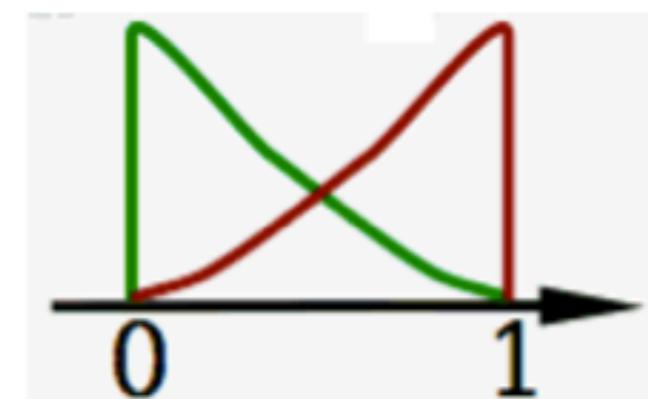


Boosted Decision Trees

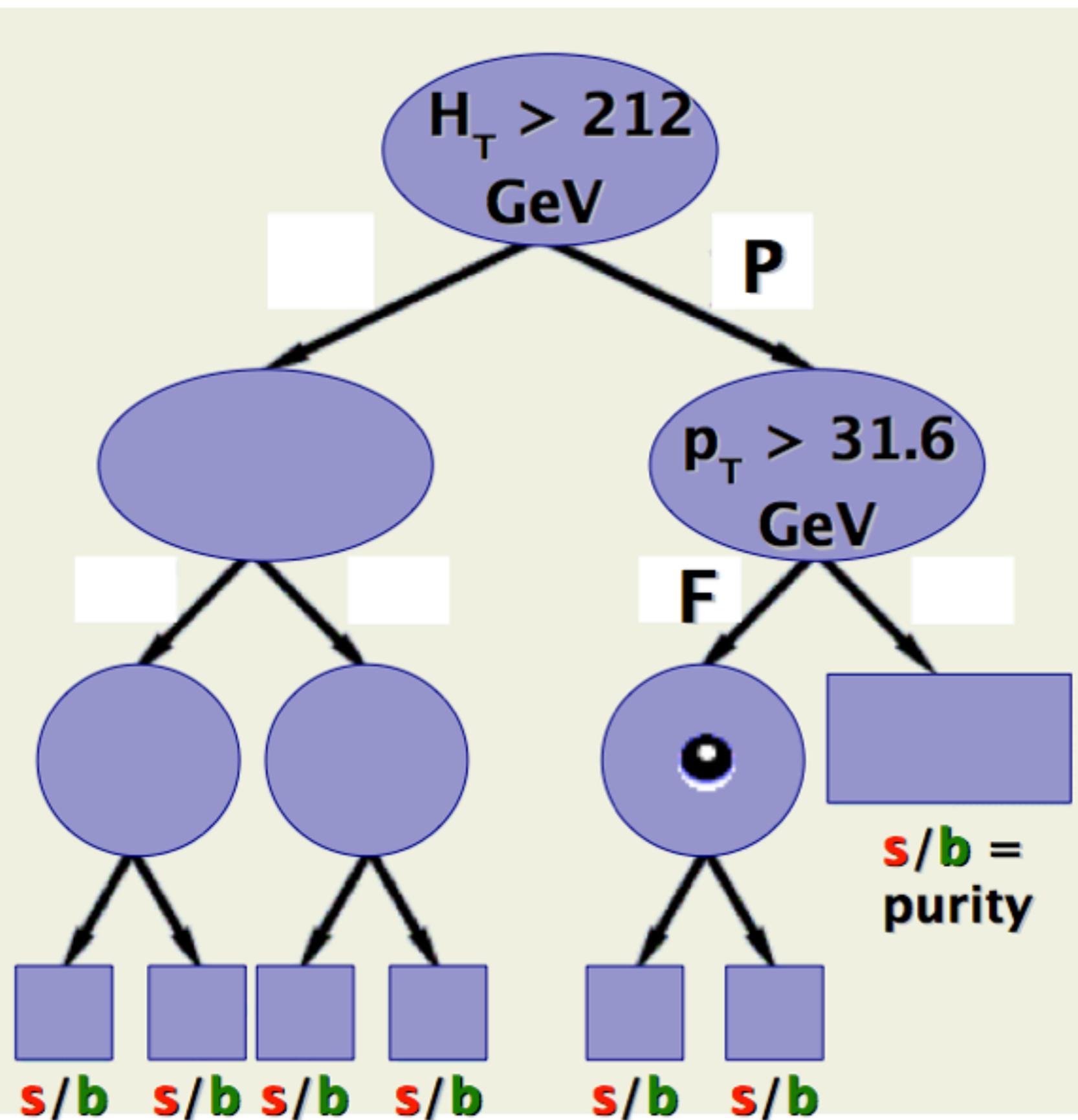


- **IDEA:** recover events that fail criteria in cut-based analyses

- result:
weight for every event
background **signal**



Boosted Decision Trees

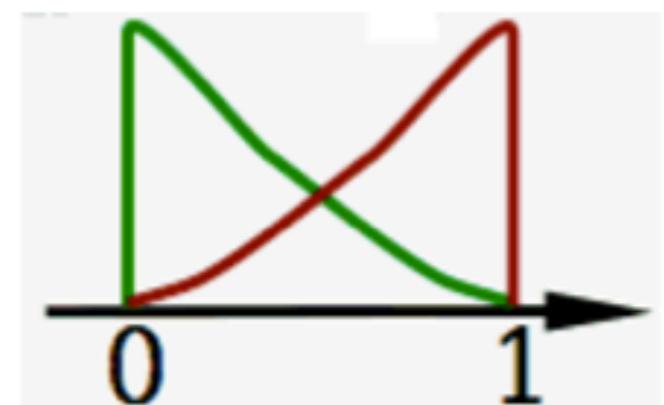


- **IDEA:** recover events that fail criteria in cut-based analyses

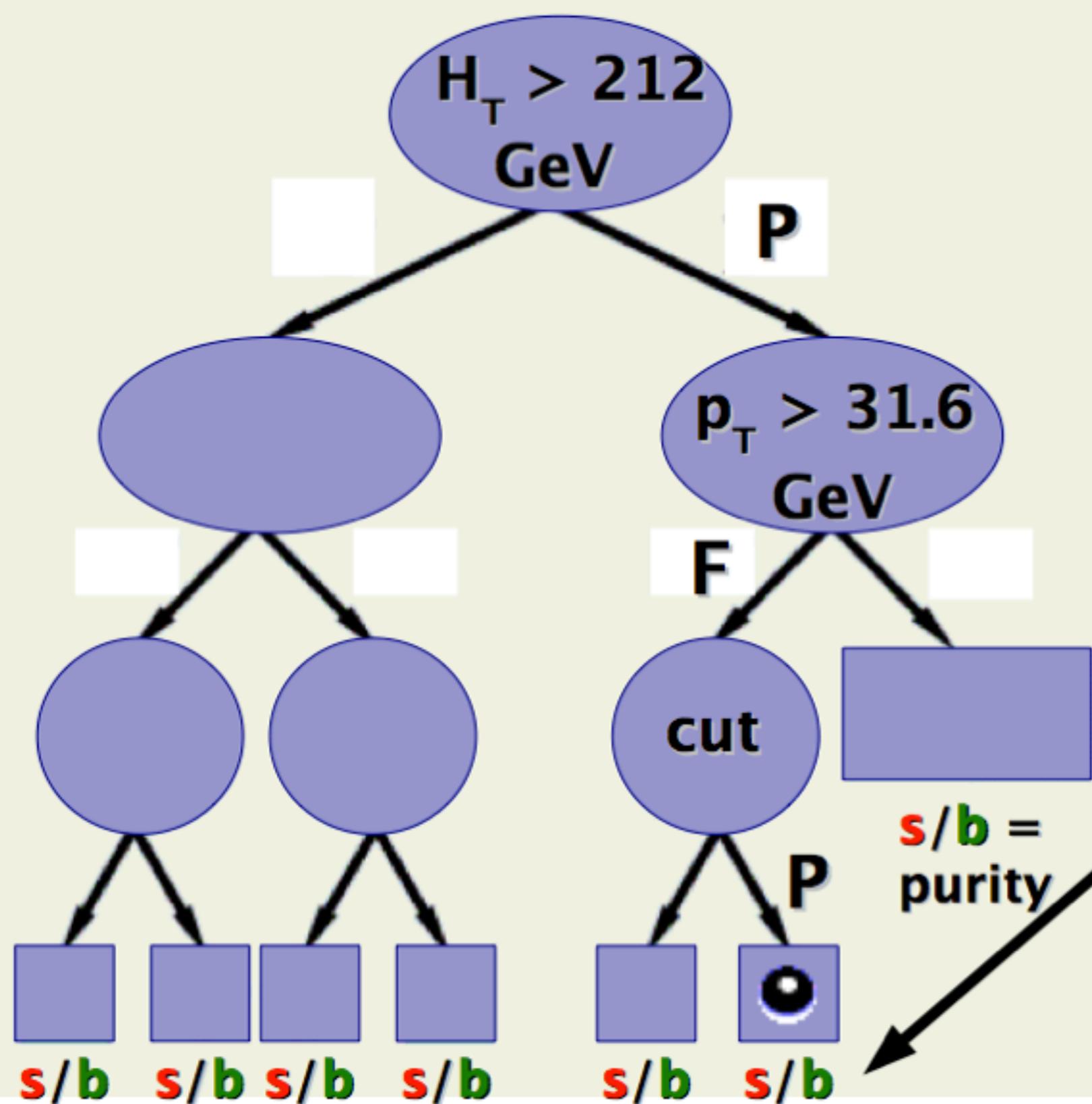
- **result:** weight for every event

background

signal



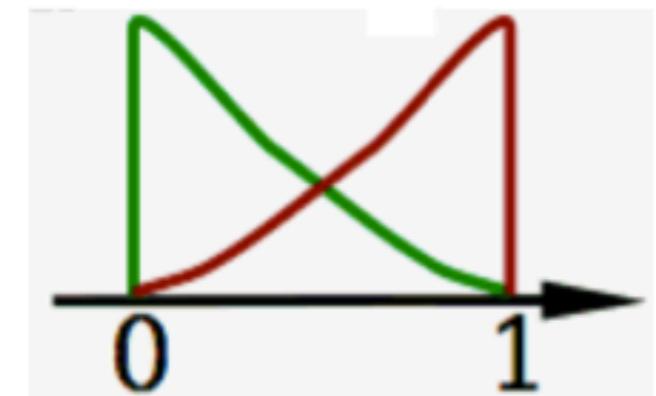
Boosted Decision Trees



- **IDEA:** recover events that fail criteria in cut-based analyses

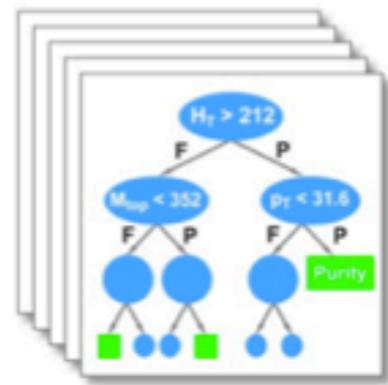
- **result:** weight for every event

background signal

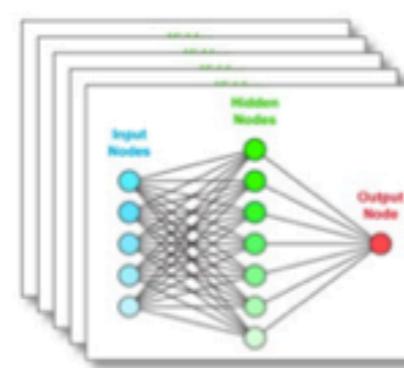


Single Top Discovery

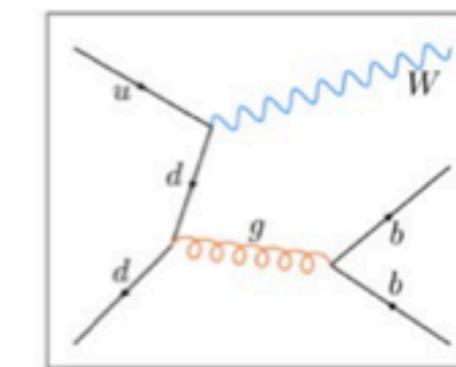
Boosted Decision Trees



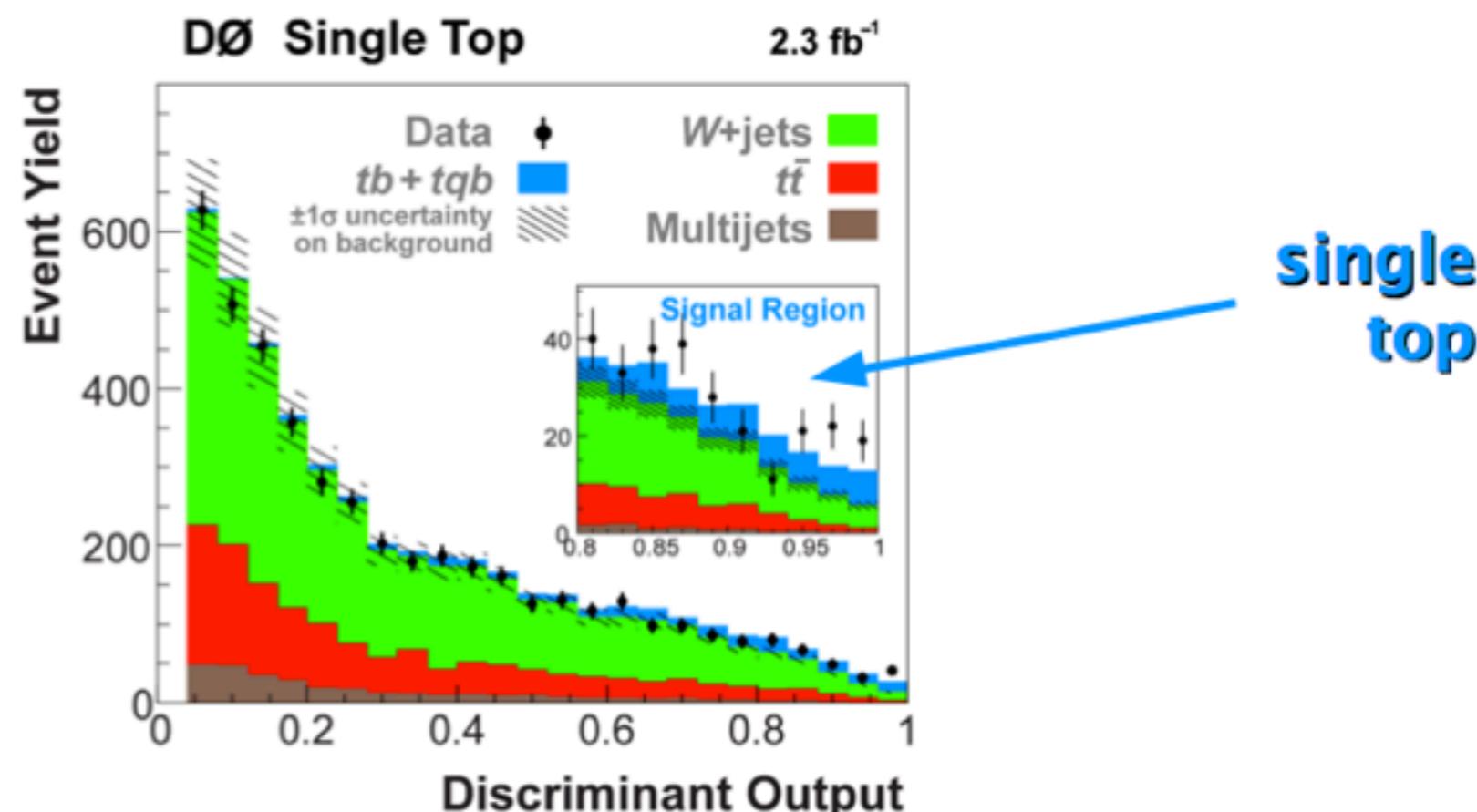
Boosted Neural Networks



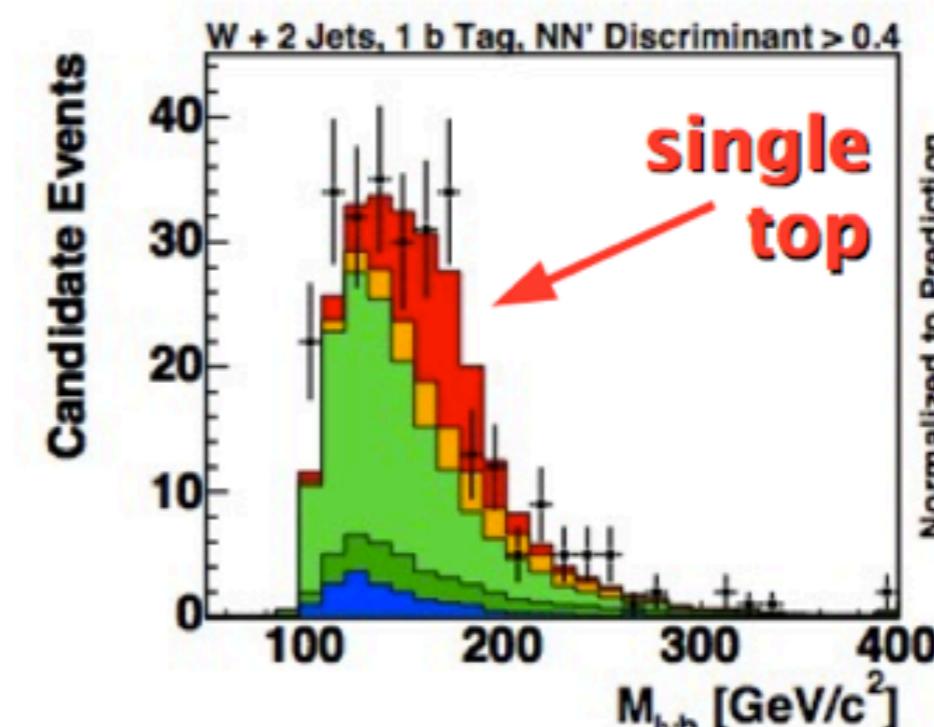
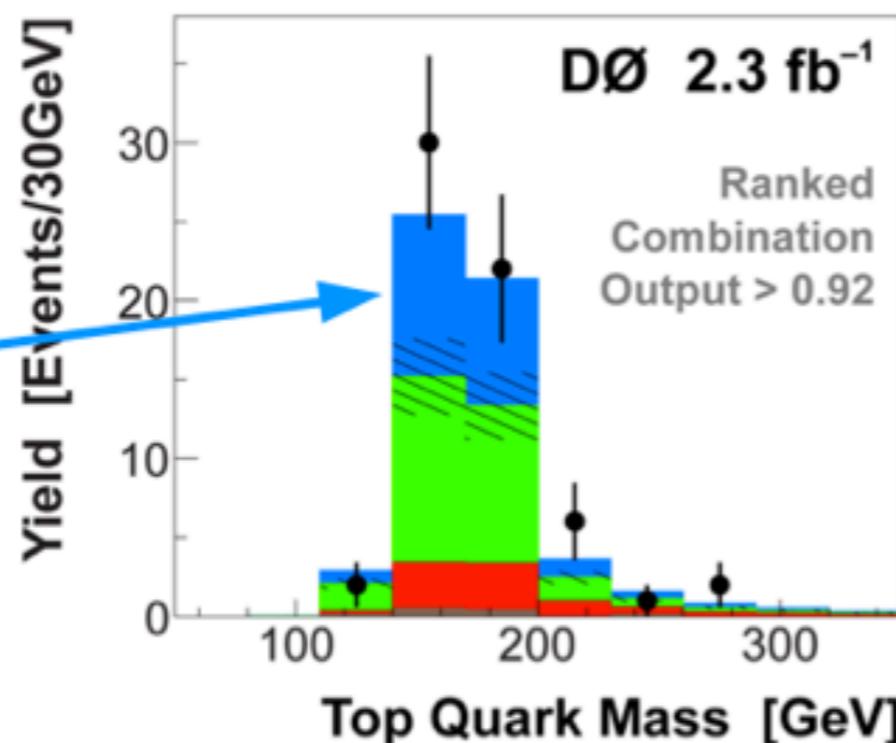
Matrix Elements



combine up to 12 different analysis channels:



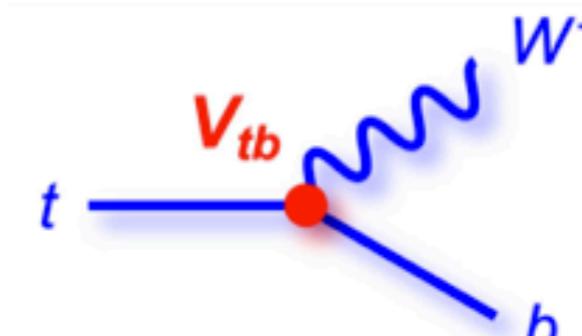
Single Top Discovery

single
top

Single Top Cross Section	Signal Significance	
	Expected	Observed
DØ 2.3 fb^{-1} arXiv:0903.0850 $m_{\text{top}} = 170 \text{ GeV}$		
$3.94 \pm 0.88 \text{ pb}$	4.5σ	5.0σ

Single Top Cross Section	Signal Significance	
	Expected	Observed
CDF 3.2 fb^{-1} arXiv:0903.0885 $m_{\text{top}} = 175 \text{ GeV}$		
$2.3^{+0.6}_{-0.5} \text{ pb}$	$>5.9 \sigma$	5.0σ

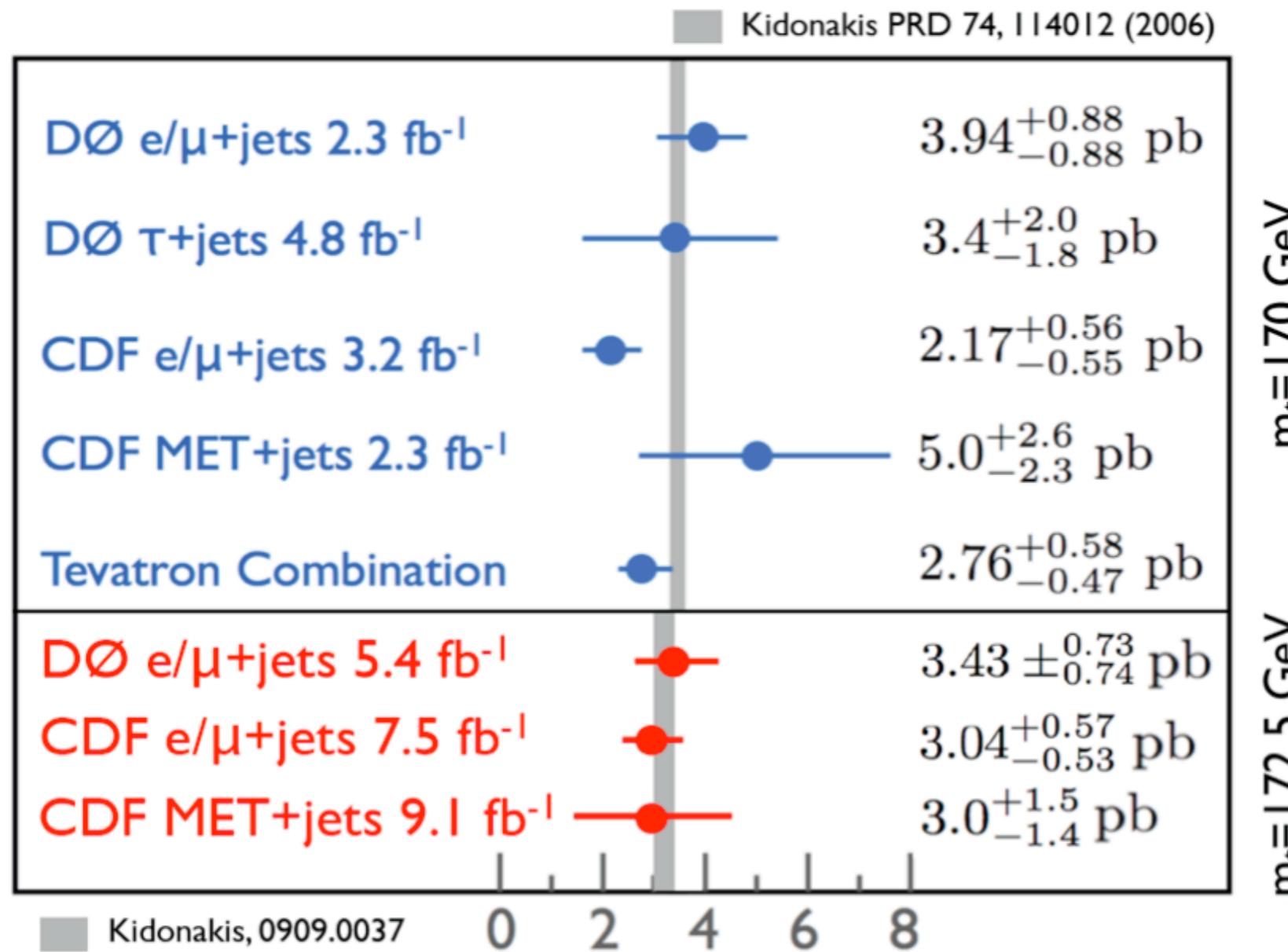
→ observation with 5.0σ !



$|V_{tb}| = 1.07 \pm 0.12$

$|V_{tb}| = 0.91 \pm 0.13$

Single Top Latest

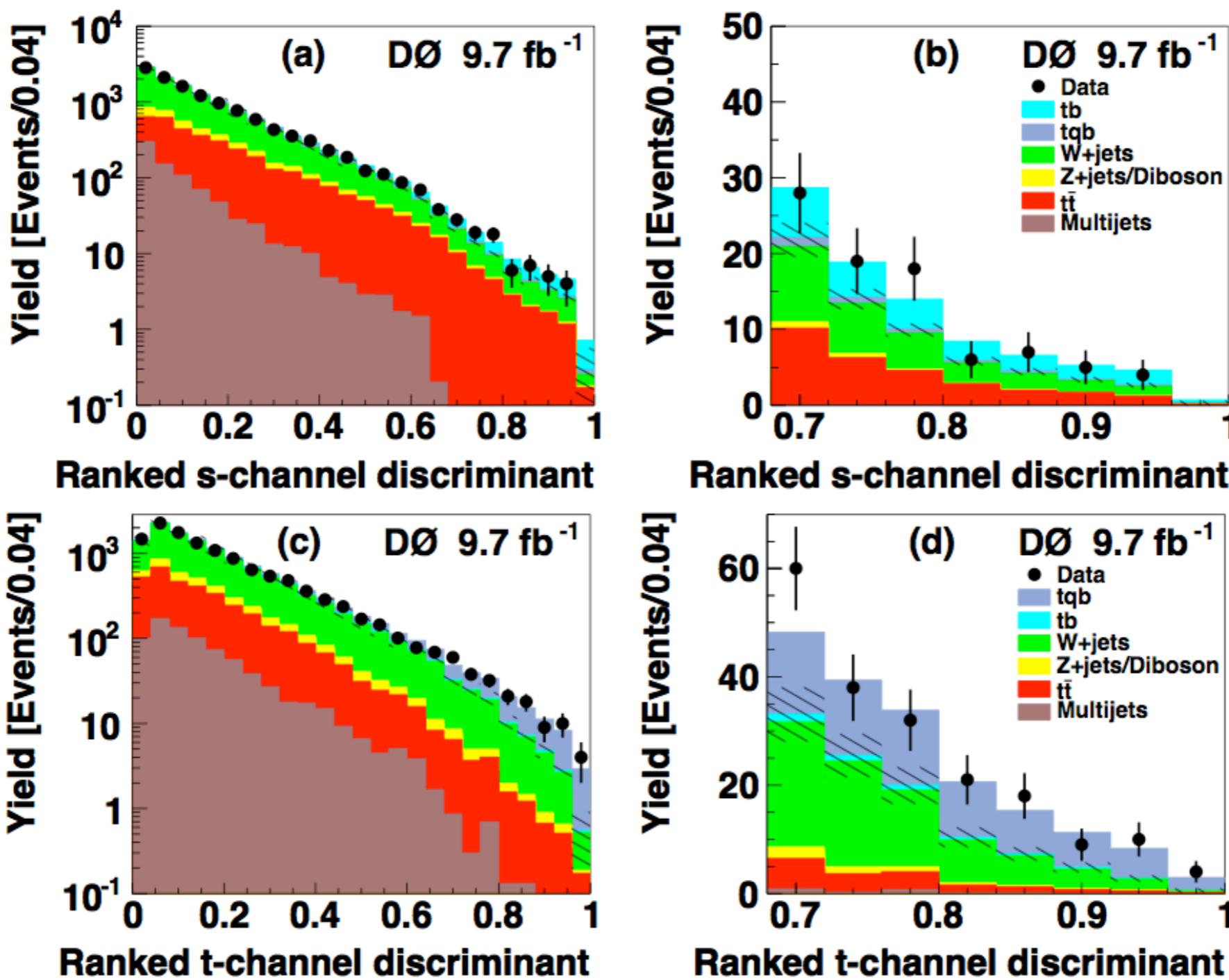


$|V_{tb}| = 0.88 \pm 0.07$,
 $|V_{tb}| > 0.77$ (@ 95% CL)
 $|V_{tb}| > 0.79$ (@ 95% CL)
 $|V_{tb}| = 0.96 \pm 0.10$
 $|V_{tb}| > 0.78$ (@ 95% CL)

Good agreement with SM

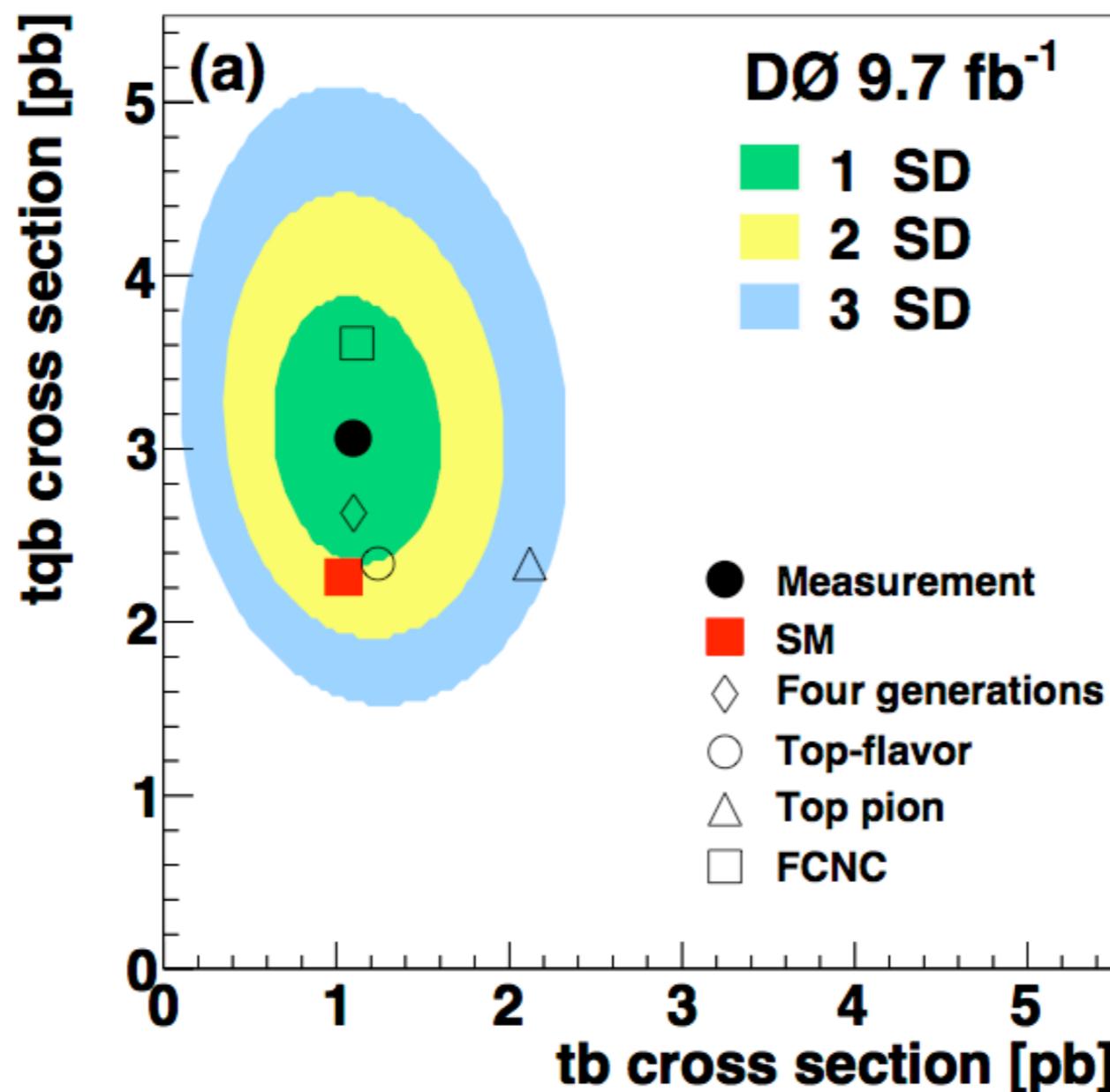
Separating s & t channel

- Use another multi-variate to discriminate between the s- and t-channel processes:



Separating s & t channel

- Simultaneous measurement of two channels:



First evidence for s-channel production

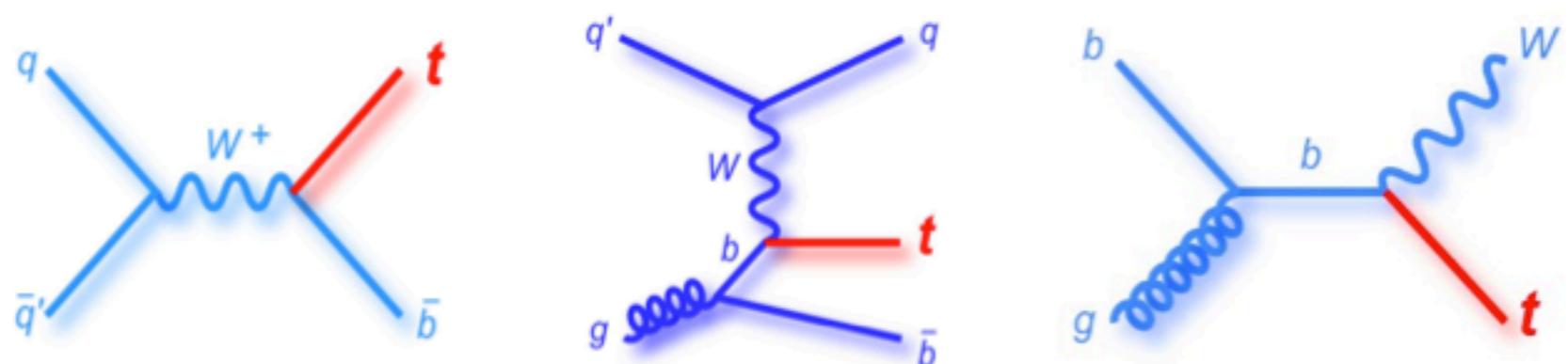
$$|V_{tb}| > 0.92 \text{ (@ 95% CL)}$$

Single Top Quark Production:

Tevatron discovery
LHC measurements

Single Top at LHC

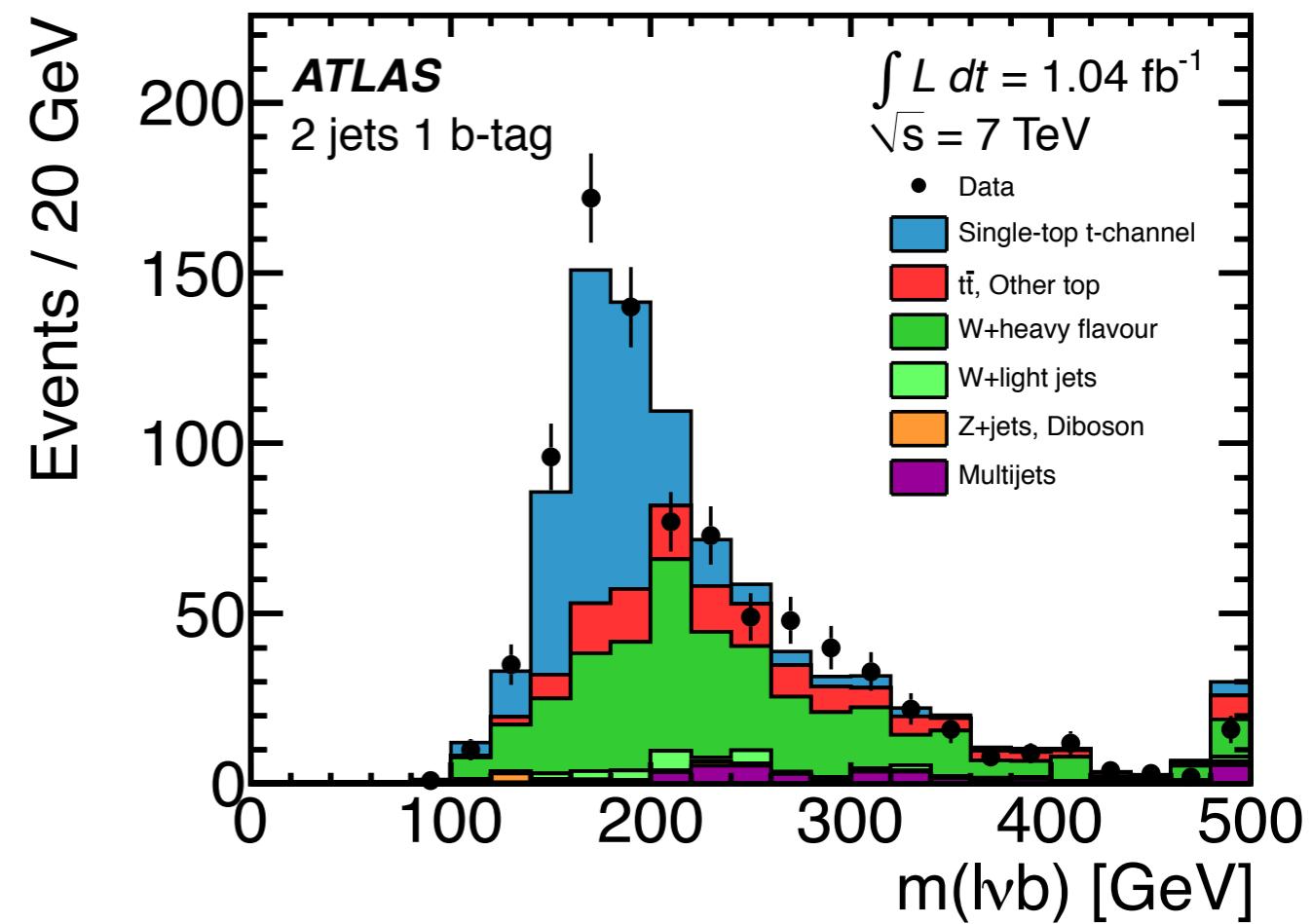
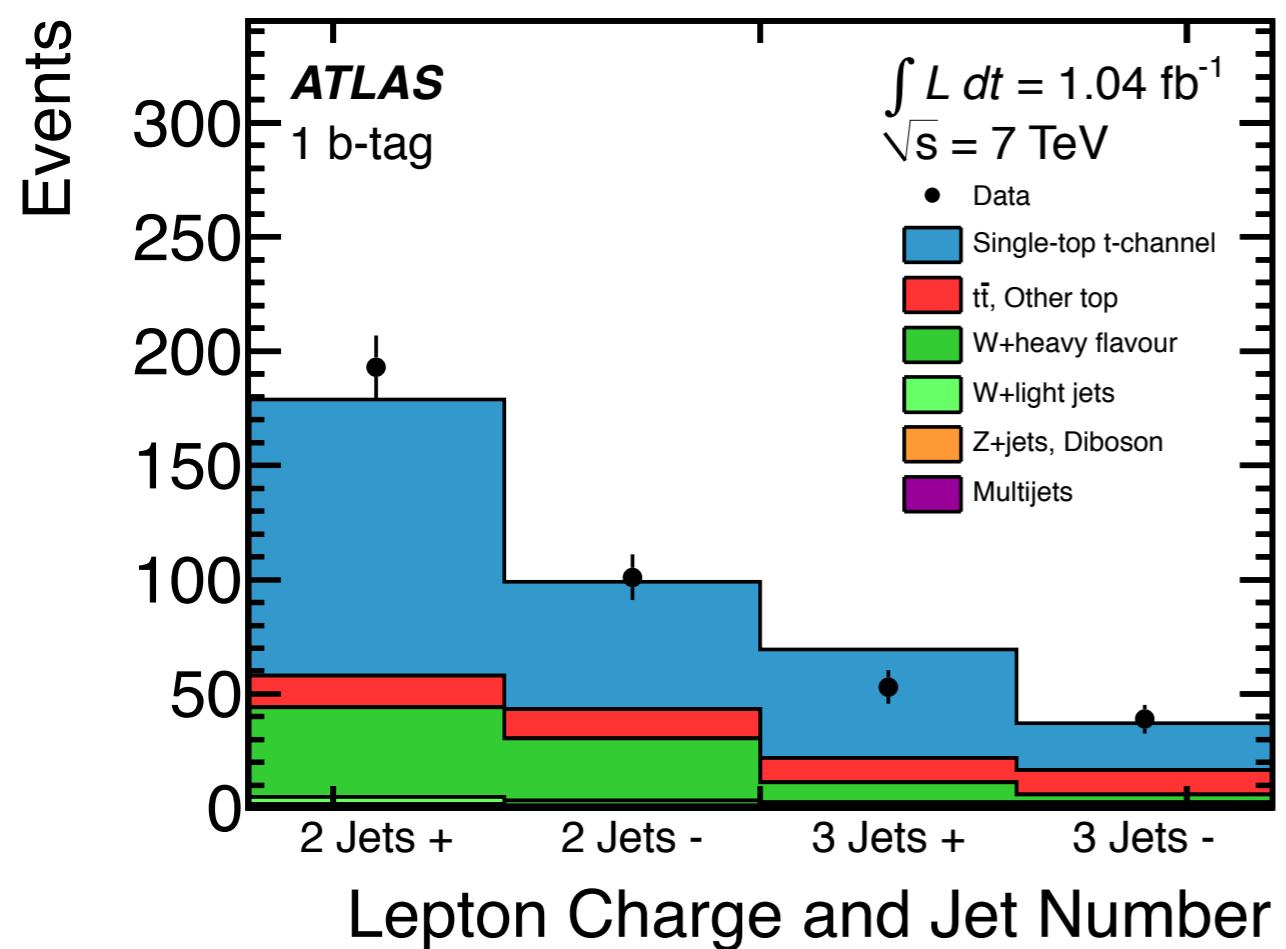
- Much higher cross section at LHC - better signal to background ratio for t-channel and Wt-channel:



Collider	s-channel: σ_{tb}	t-channel: σ_{tqb}	Wt-channel: σ_{tw}
Tevatron: $p\bar{p}$ (1.96 TeV)	1.04 pb	2.26 pb	0.28 pb
LHC: pp (7 TeV)	4.6 pb	64.6 pb	15.7 pb

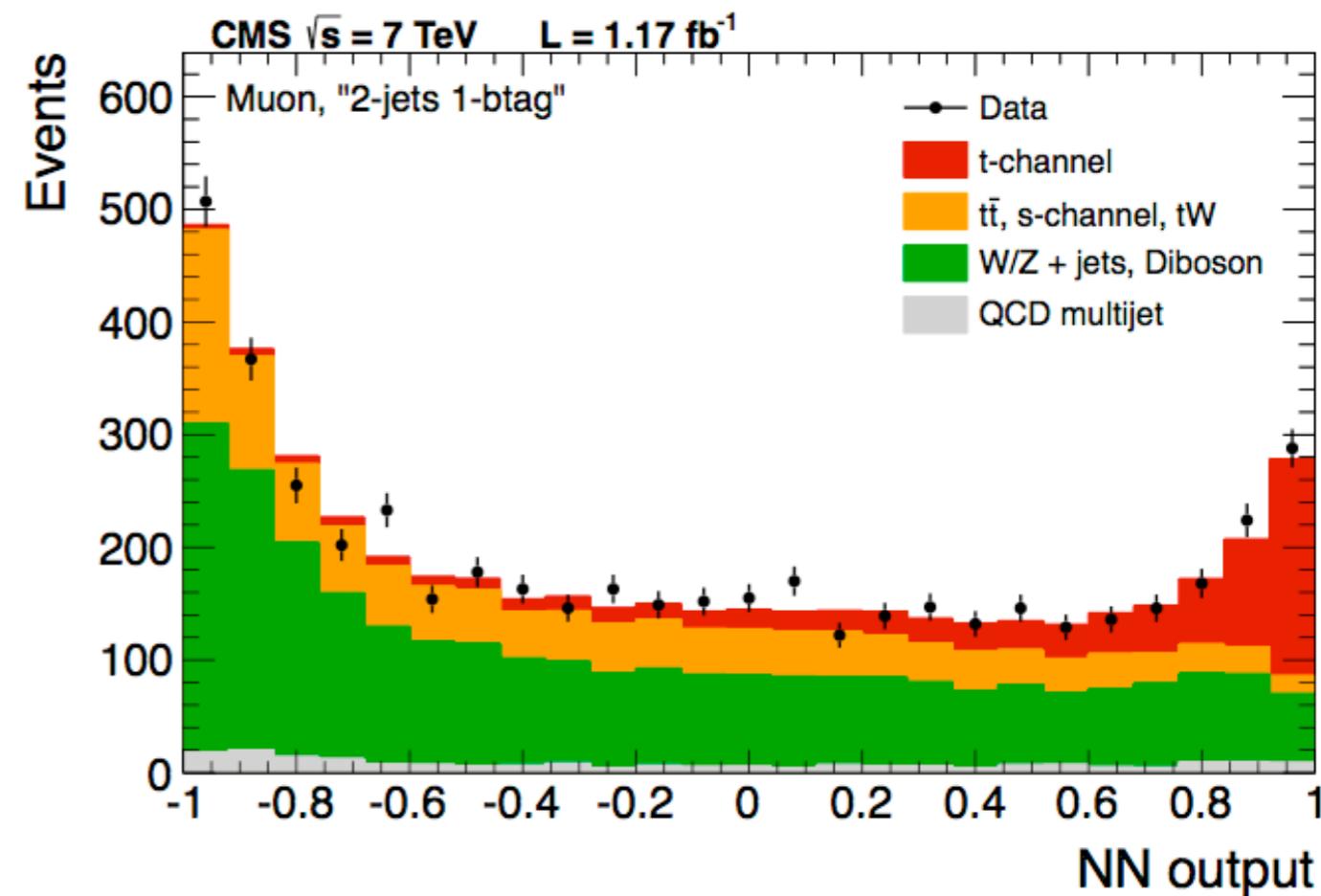
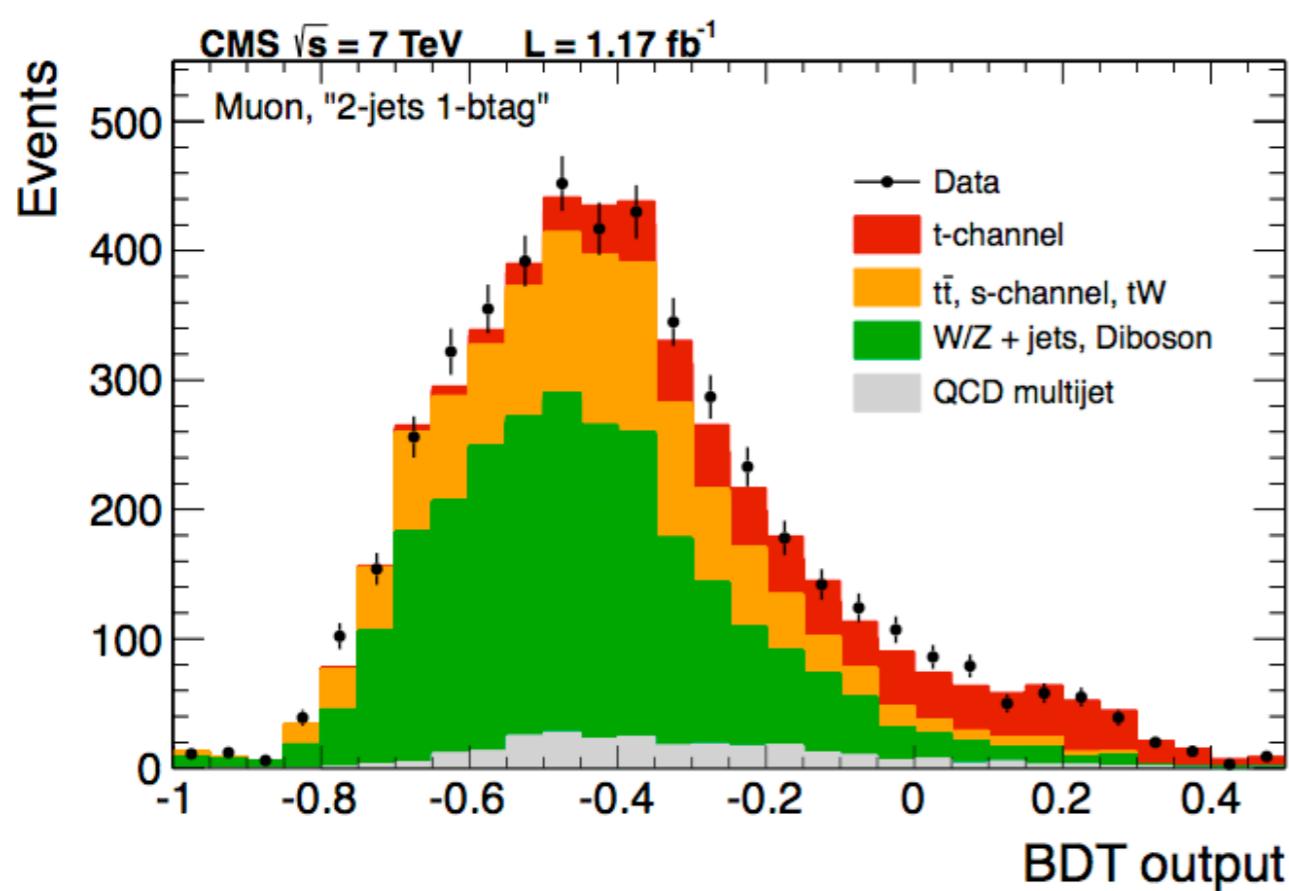
Single Top at LHC

- t-channel can be selected with cuts on events with one lepton and two or three jets:



Single Top at LHC

- Best sensitivity still comes from multi-variate analysis:



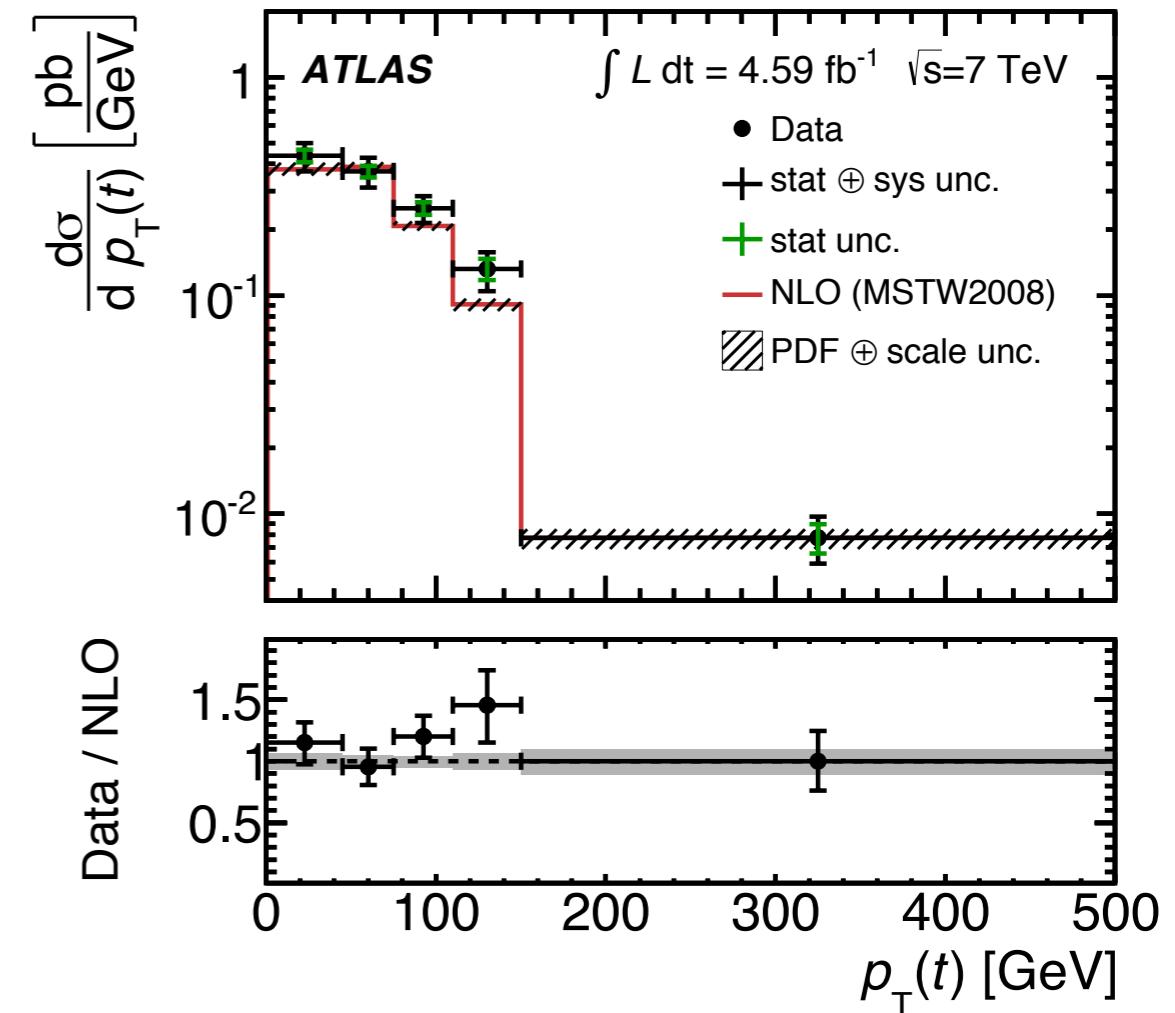
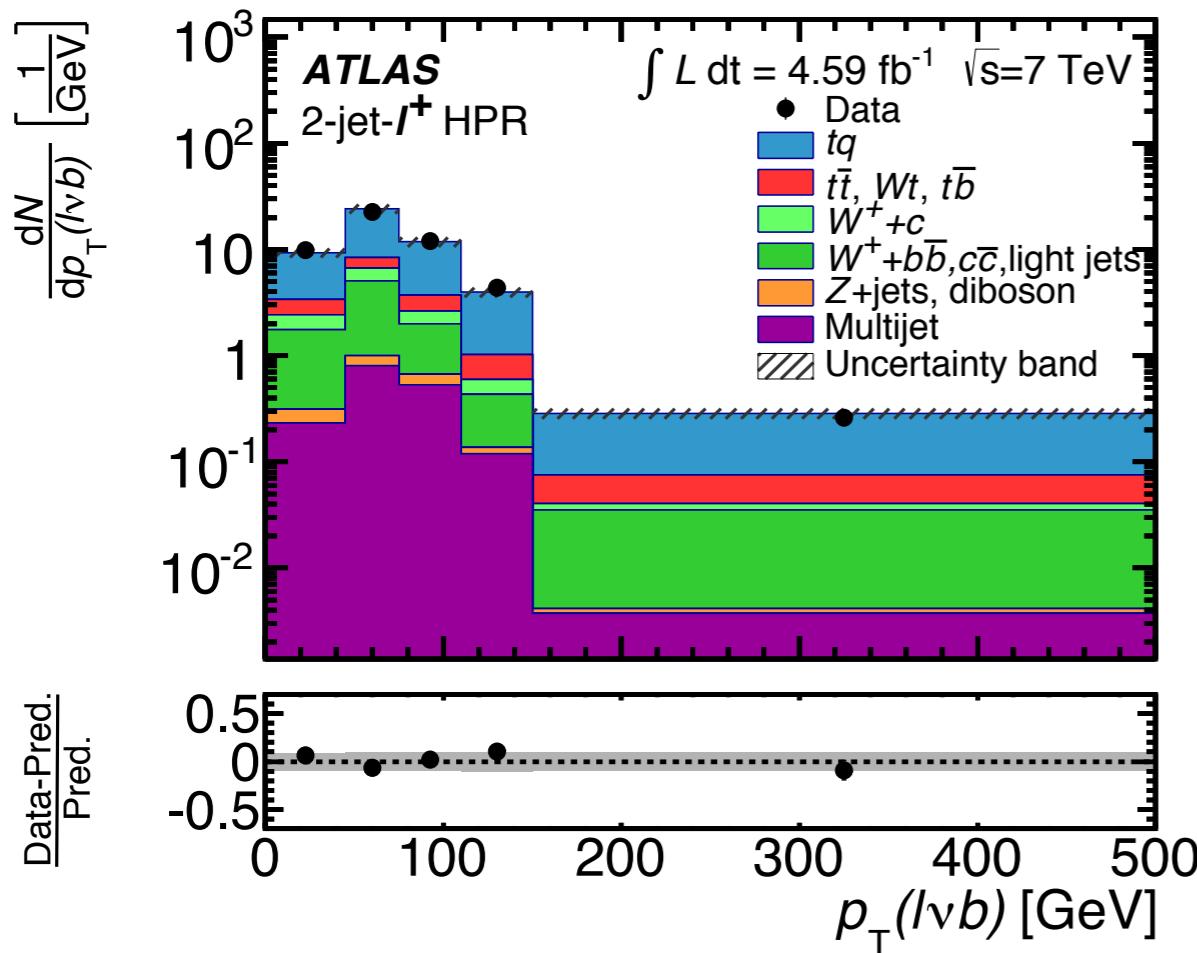
$$\sigma_{t\text{-ch.}} = 67.2 \pm 6.1 \text{ pb} = 67.2 \pm 3.7 \text{ (stat.)} \pm 3.0 \text{ (syst.)} \pm 3.5 \text{ (theor.)} \pm 1.5 \text{ (lum.) pb}$$

Good agreement with SM

$|V_{tb}| > 0.92$ (@ 95% CL)

Single Top at LHC

- Can now start to measure differential distributions of single top events:



Good agreement with SM

Summary

- Top quark pair production well established at both Tevatron and LHC.
- Measurements of inclusive cross section are in good agreement with SM NNLO prediction.
- Differential measurements start to probe interesting kinematic regions (high mass, high n(jets)).
- Single top moves from discovery to measurement phase.
- Experimental challenge is to continue to reduce systematic uncertainties.