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The University of Manchester

Top Quark Physics

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HASCO Summer School 2013

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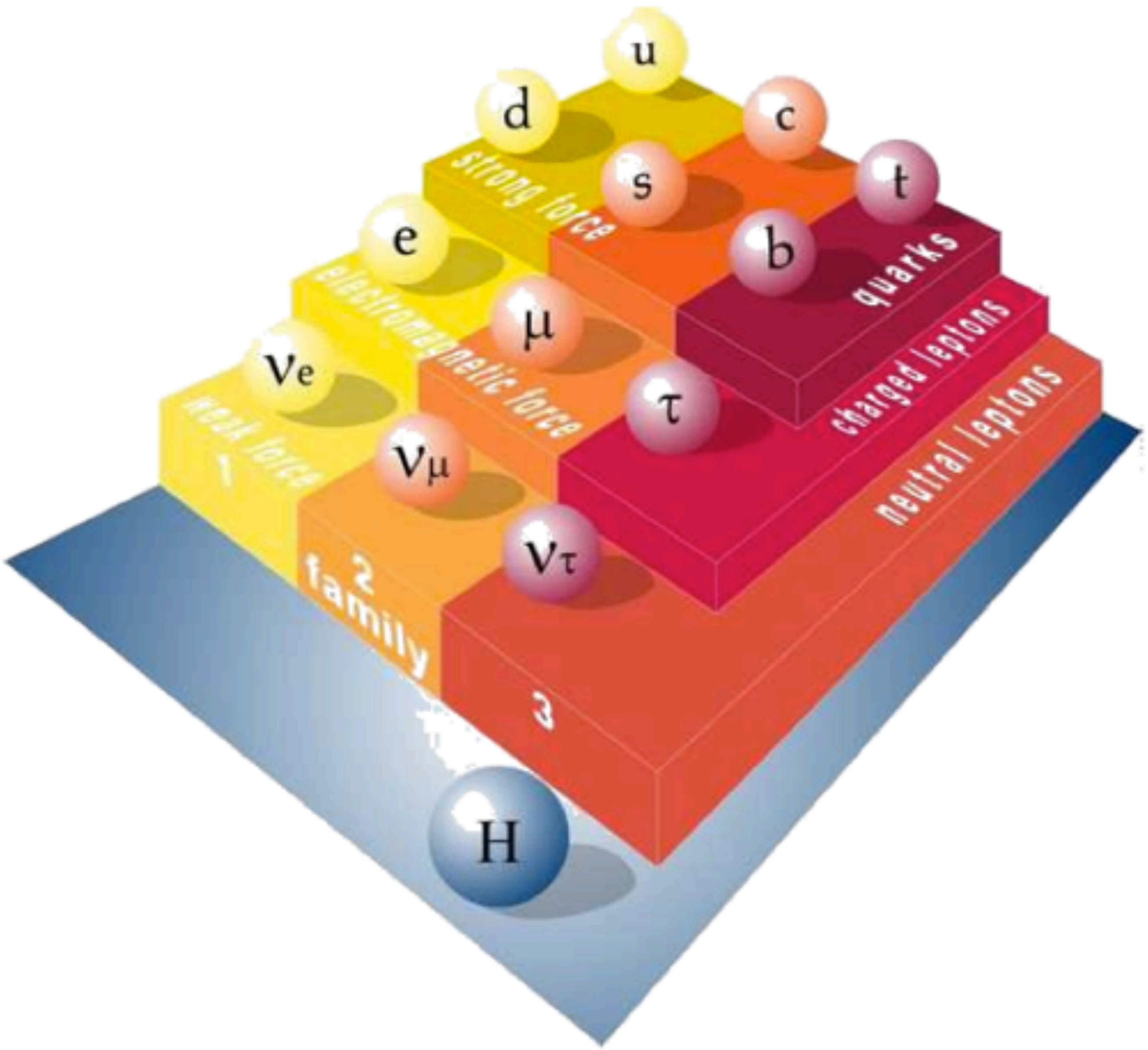
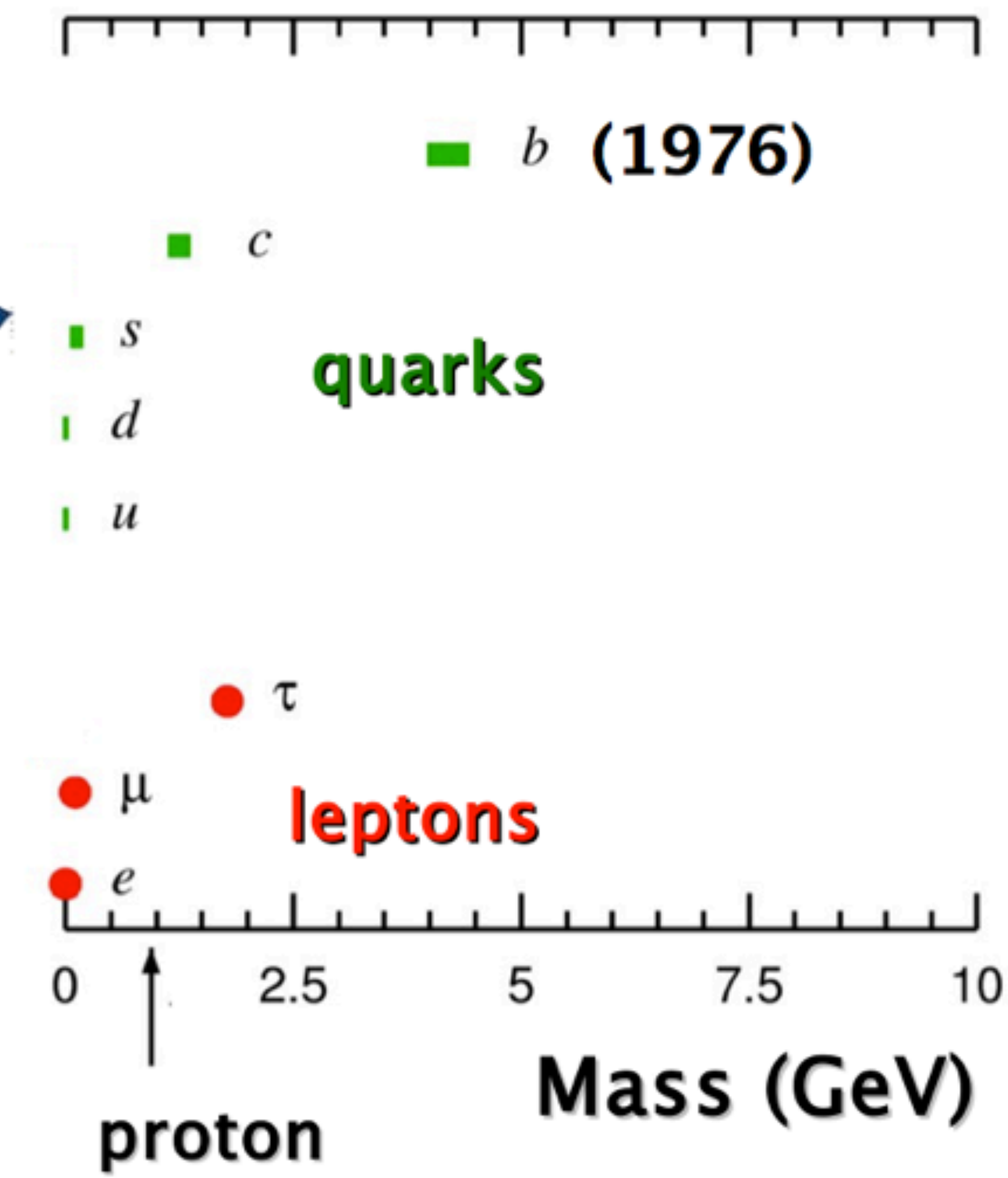
Outline

- 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

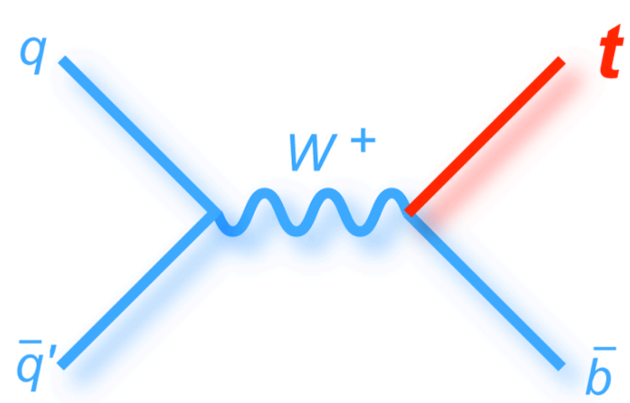




neutrino masses ≪ 1 eV

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→tb search channel



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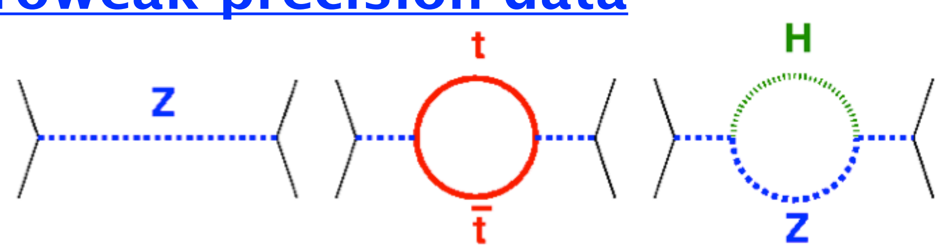
Electroweak precision data



$$M_Z^2 = M_Z^{2\ 0.\mathrm{order}} / (1 - \Delta)$$

$$\Delta \approx \ldots m_t^2 \ldots + \ldots \ln m_h \ldots$$

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

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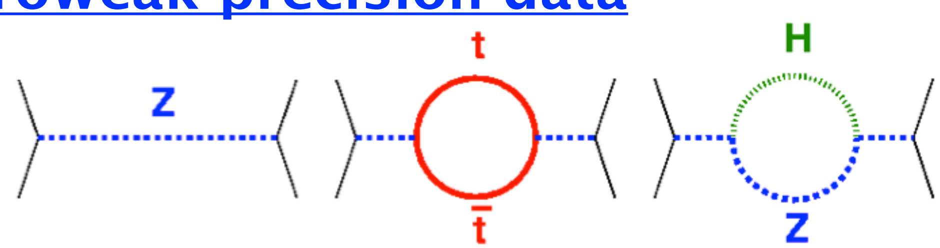

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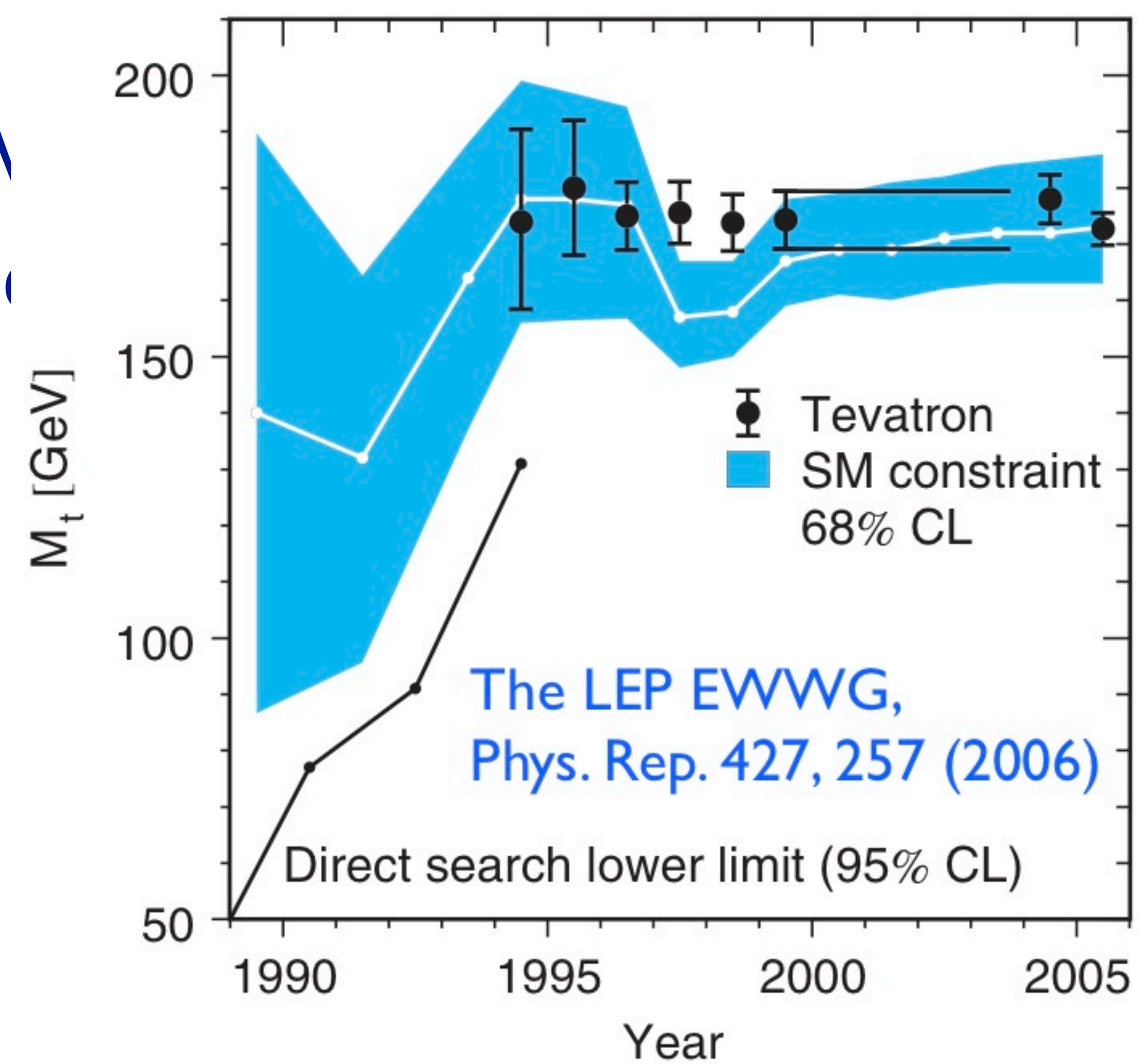


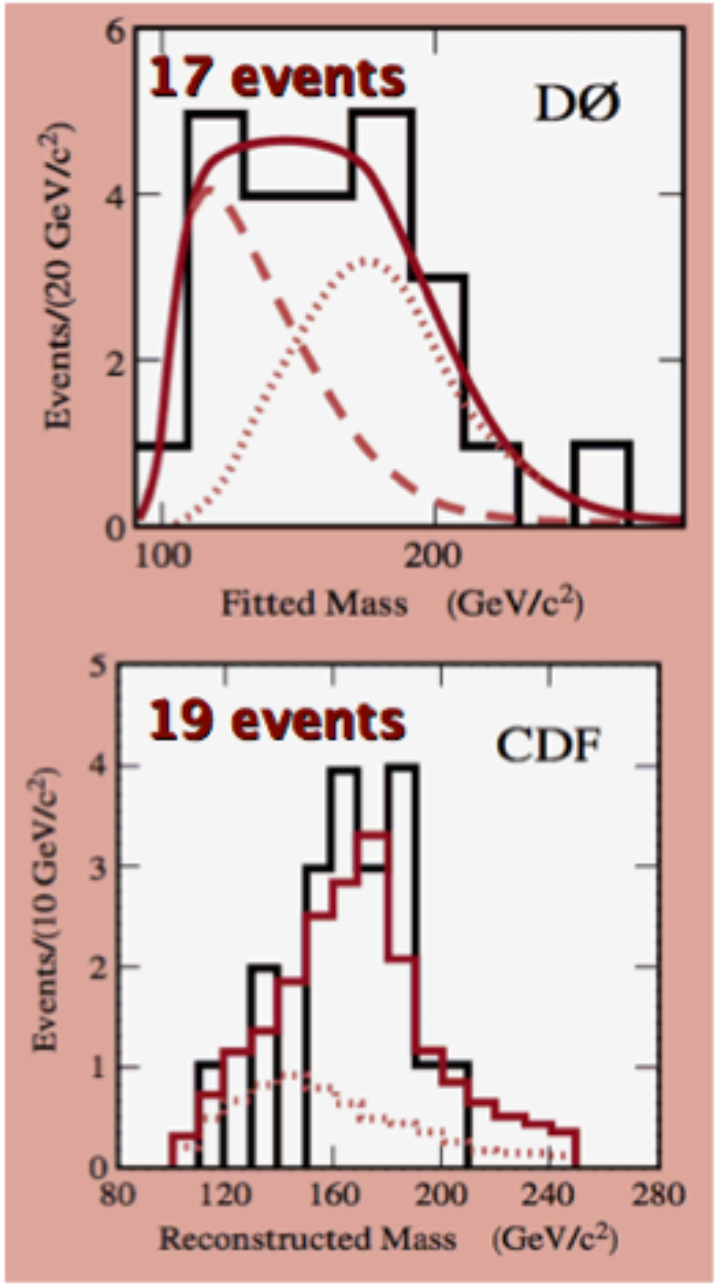
Top Quark Discovery

- 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

discovery

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



1995, CDF and DØ experiments, Fermilab

Top Quark Discovery

discovery

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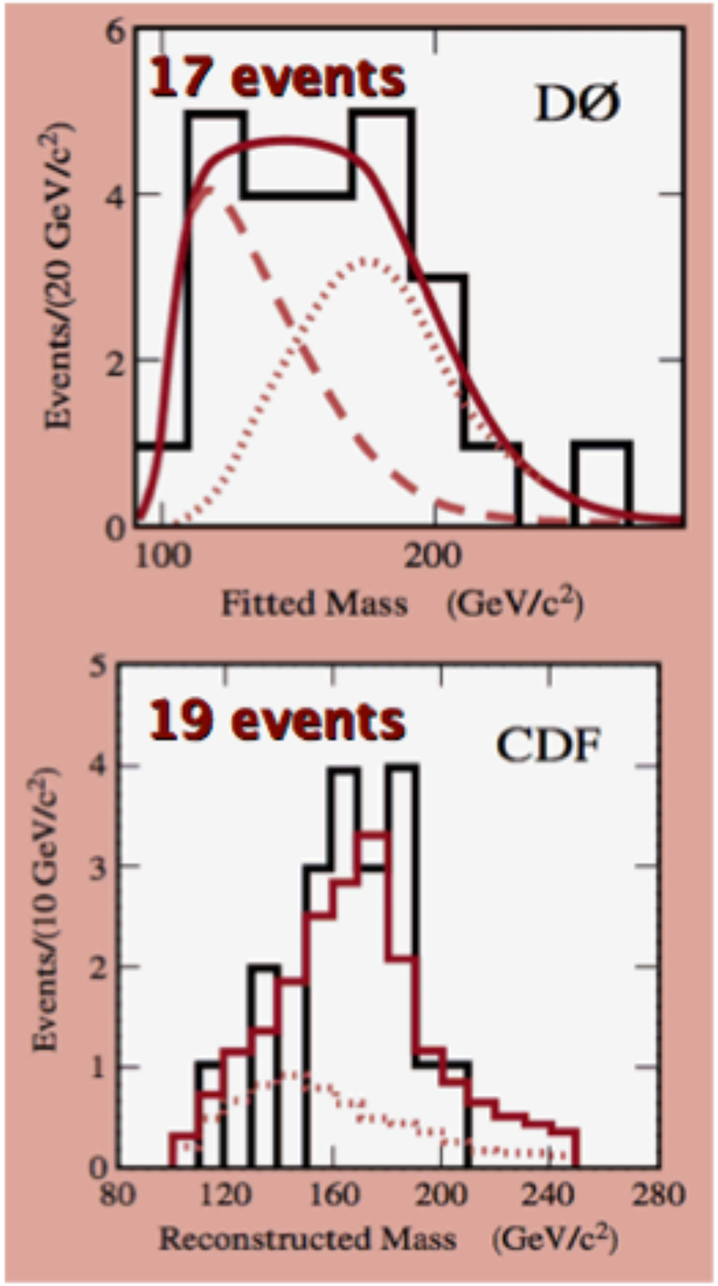


1995, CDF and DØ experiments, Fermilab

March 2nd, 1995:
First announcement of Top Discovery in public seminar at Fermilab

Top Quark Discovery

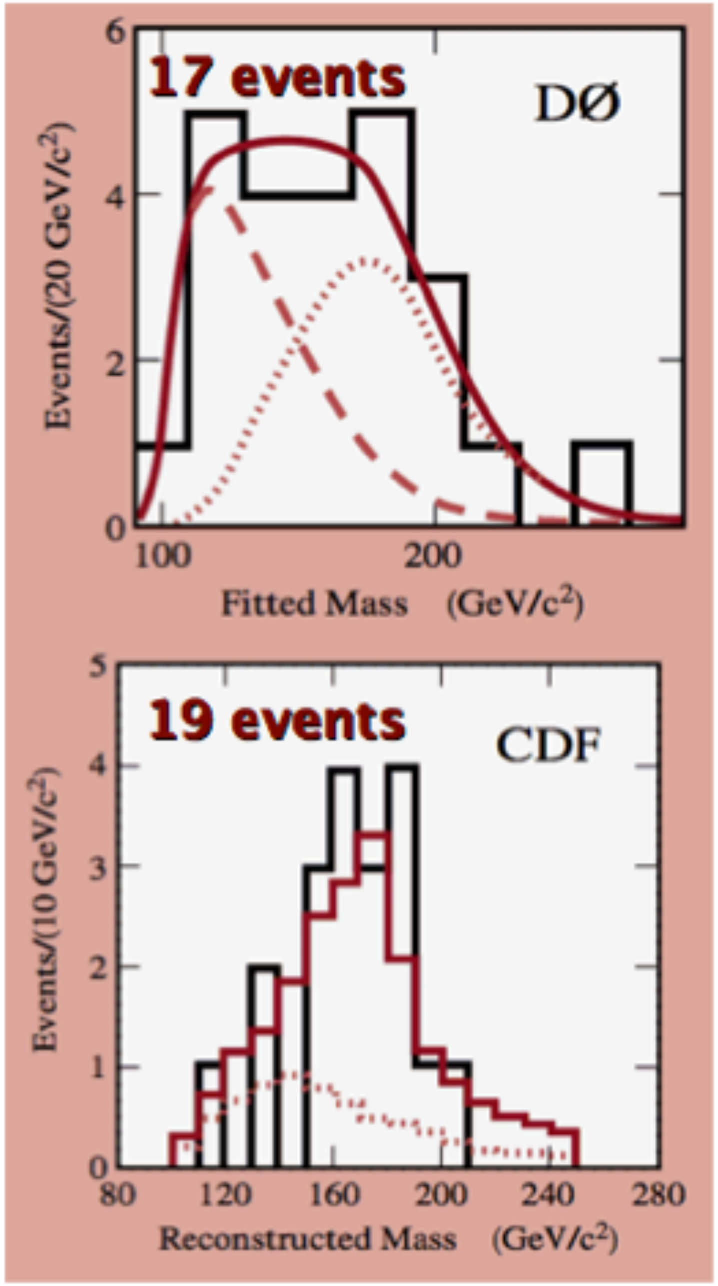
July 4th, 2012: **Higgs discovery**

March 2nd, 1995:
First announcement of Top Discovery
in public seminar at Fermilab

Top Quark Discovery

discovery

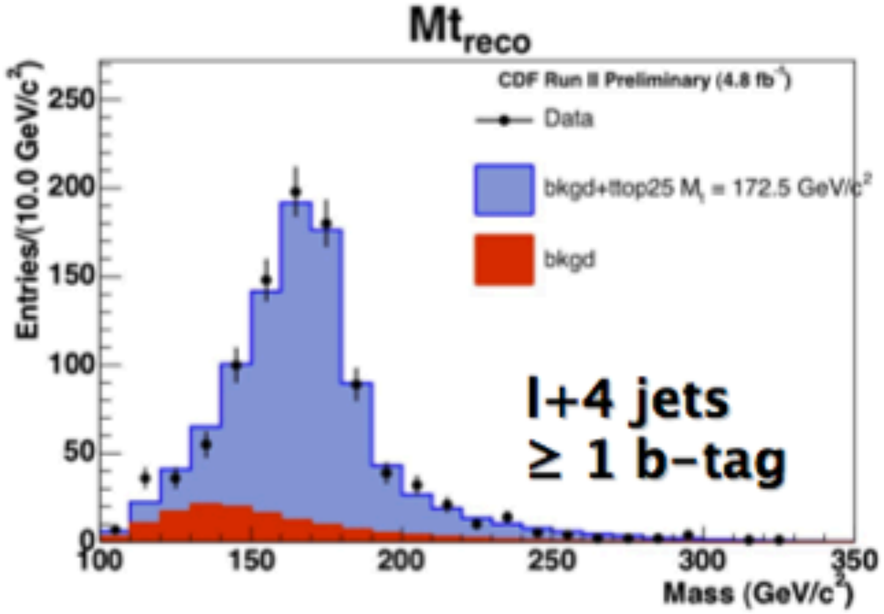
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

today

1000s of events



Top Quark Discovery

discovery

PRL 74, 2632 (1995)
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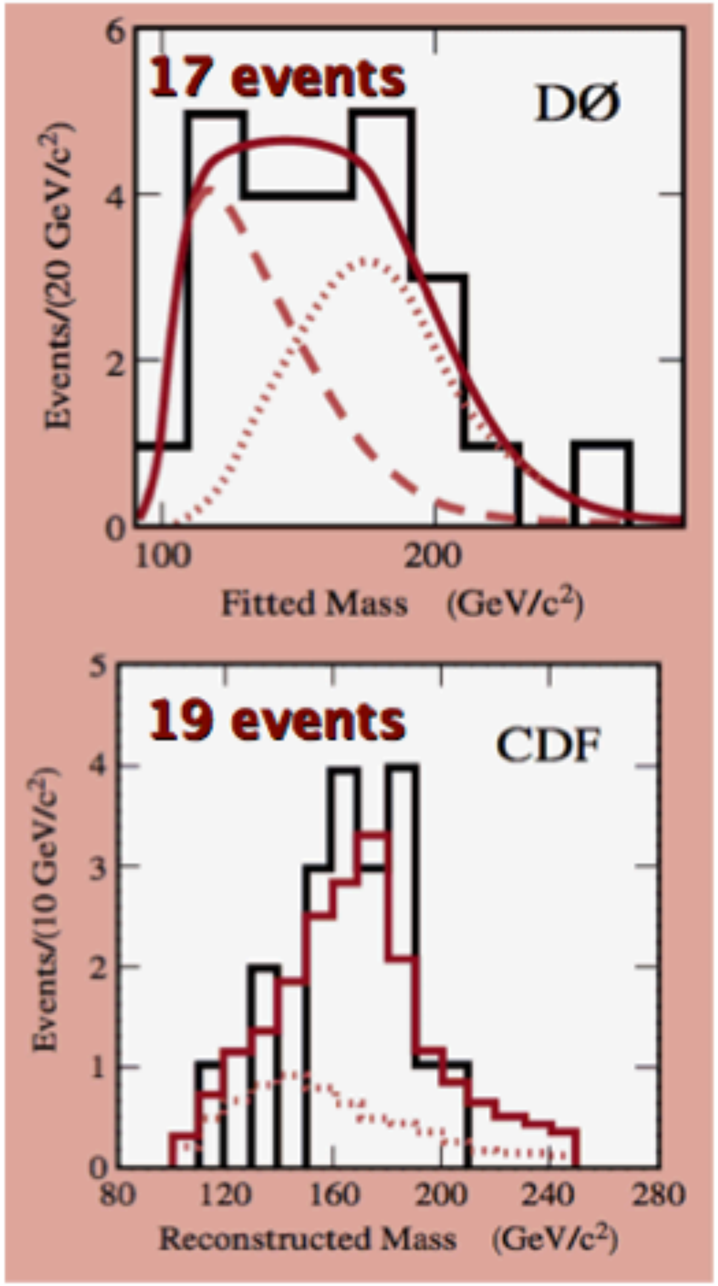

1995, CDF and DØ experiments, Fermilab

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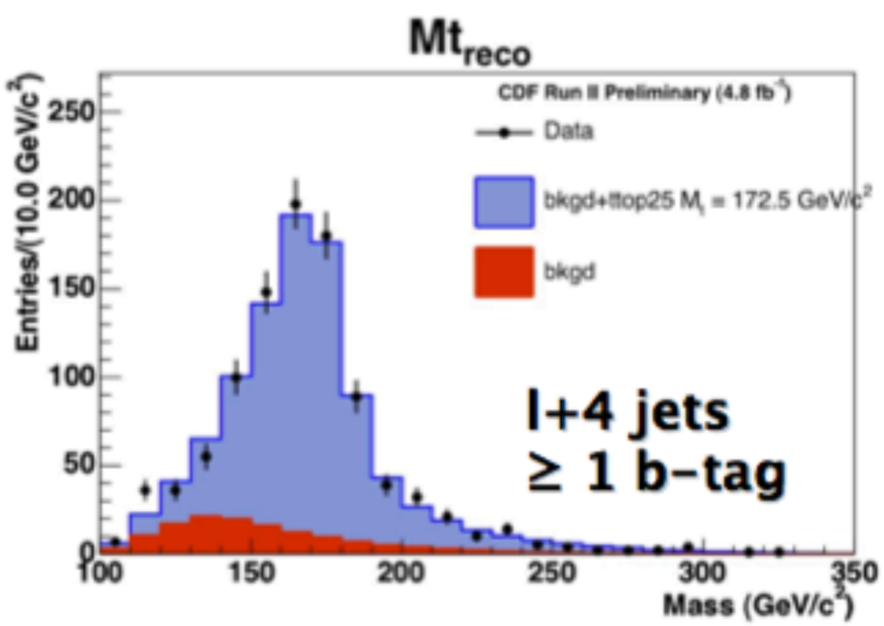
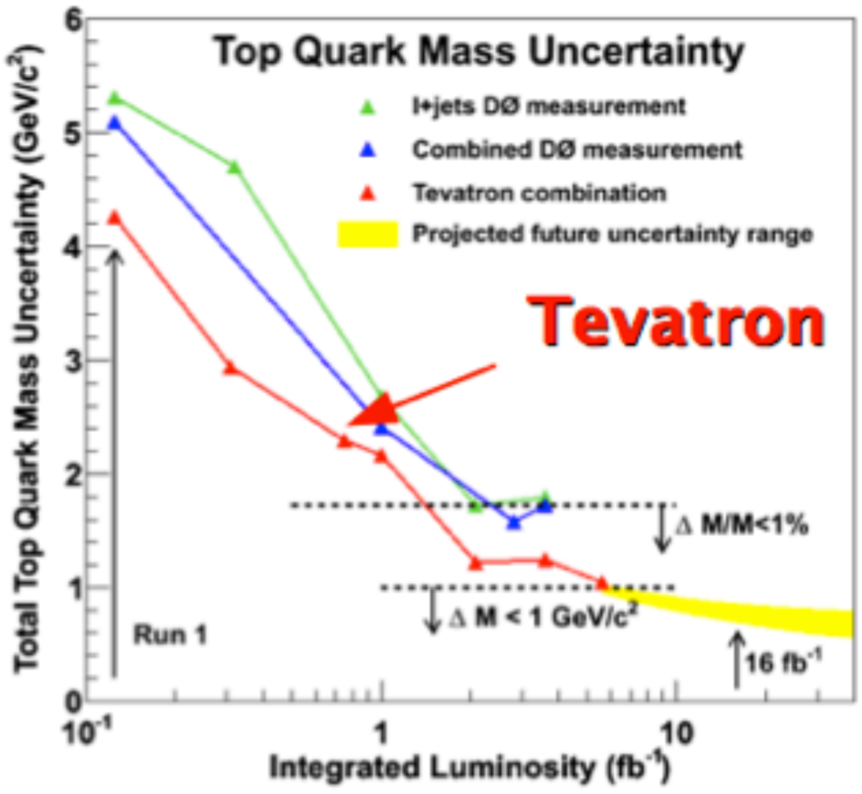


precision



Top Quark Discovery

discovery

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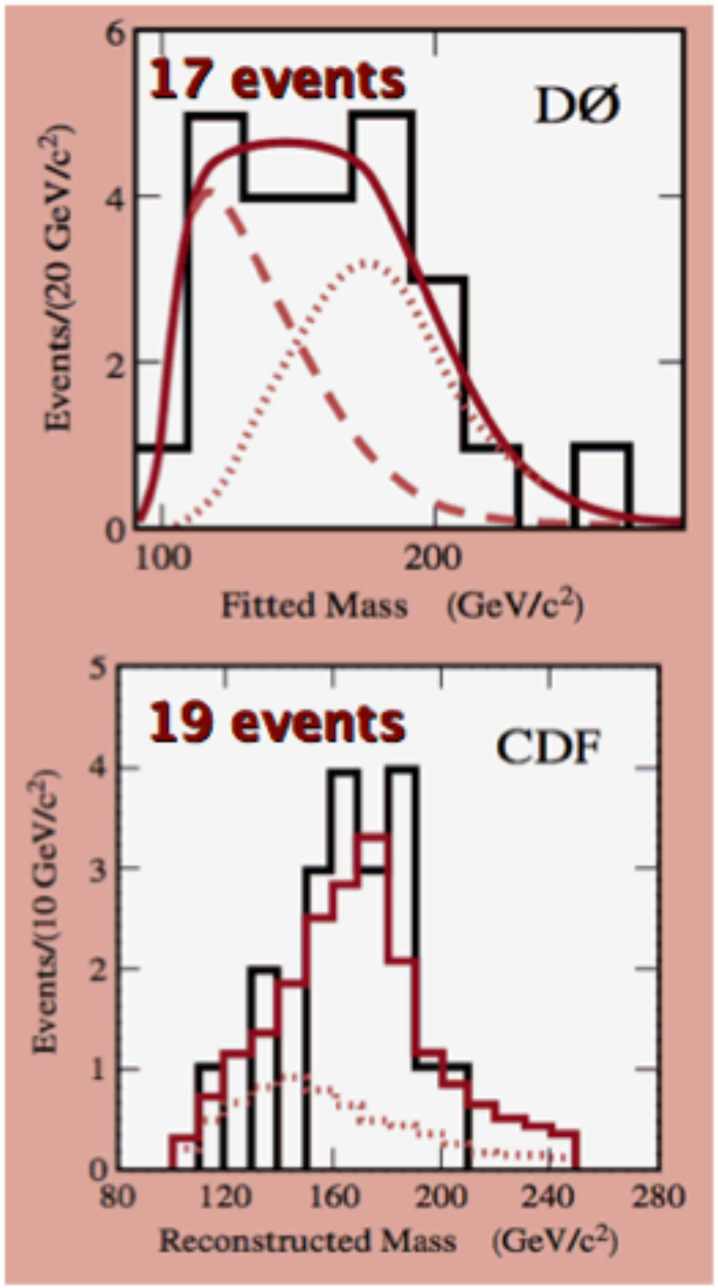

1995, CDF and DØ experiments, Fermilab

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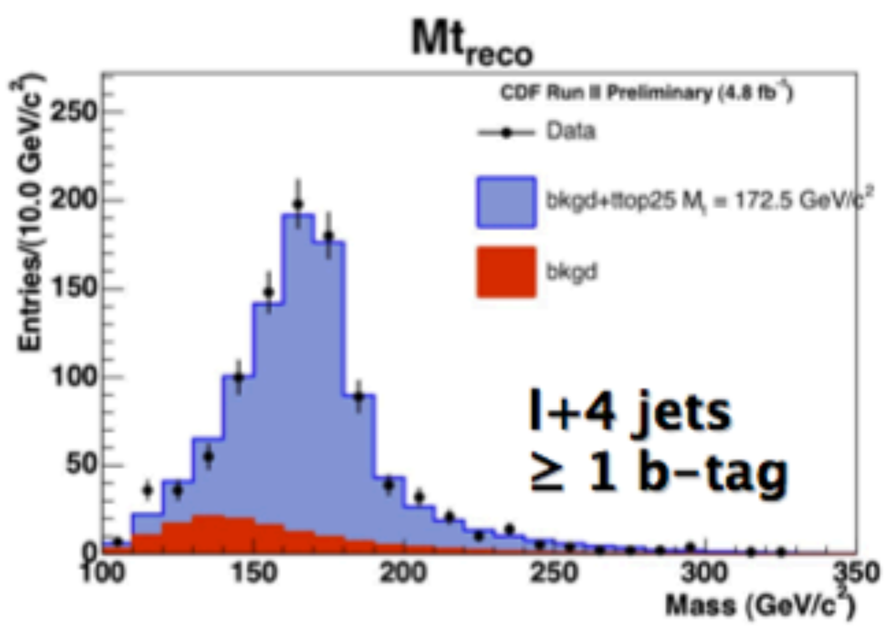
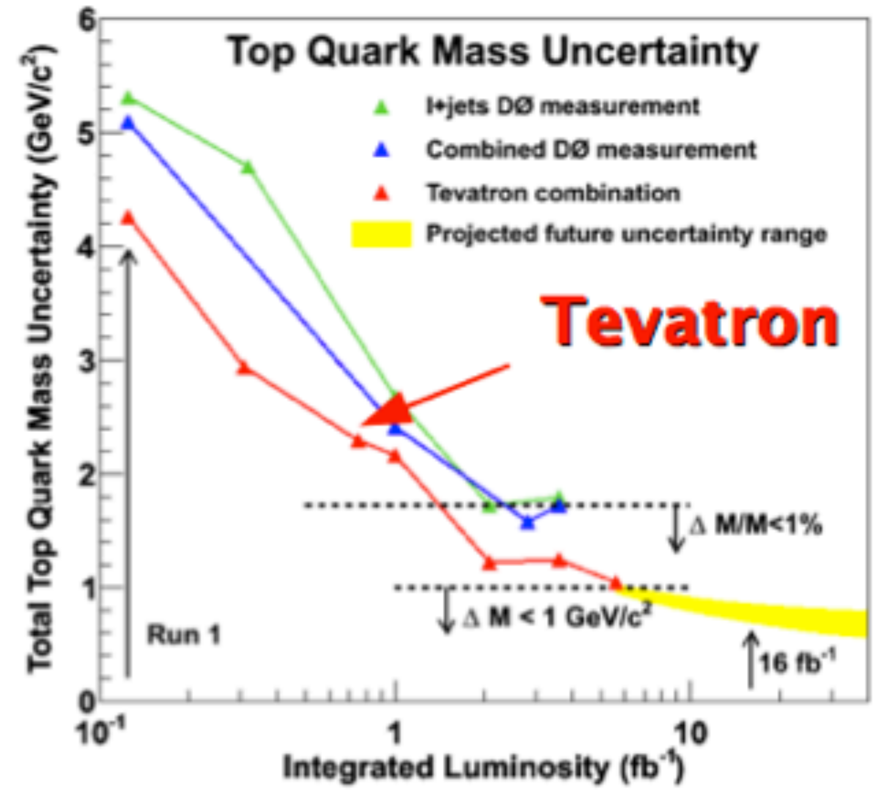
1000s of events



precision

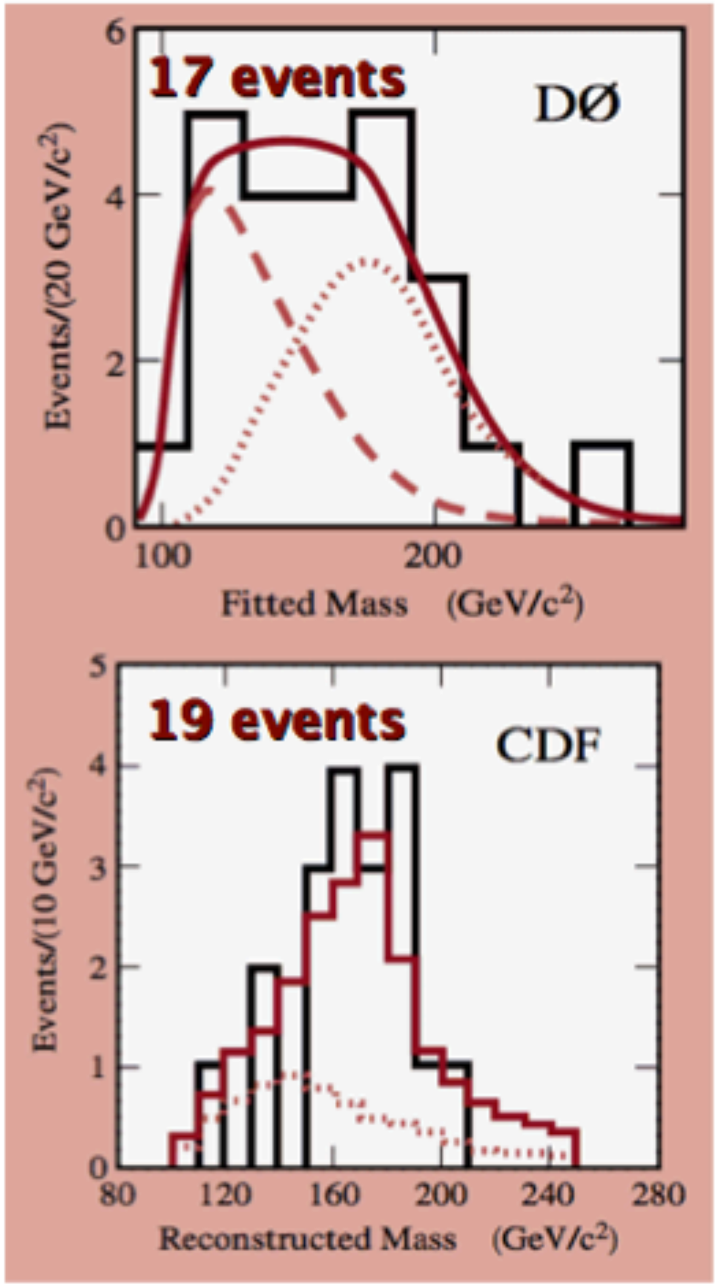


searches

Top Quark Discovery

discovery

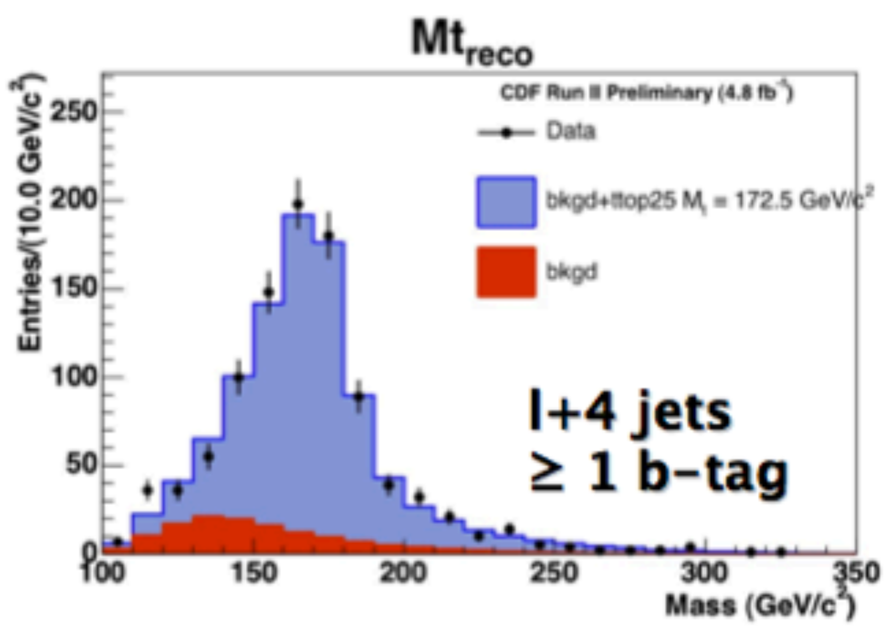
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

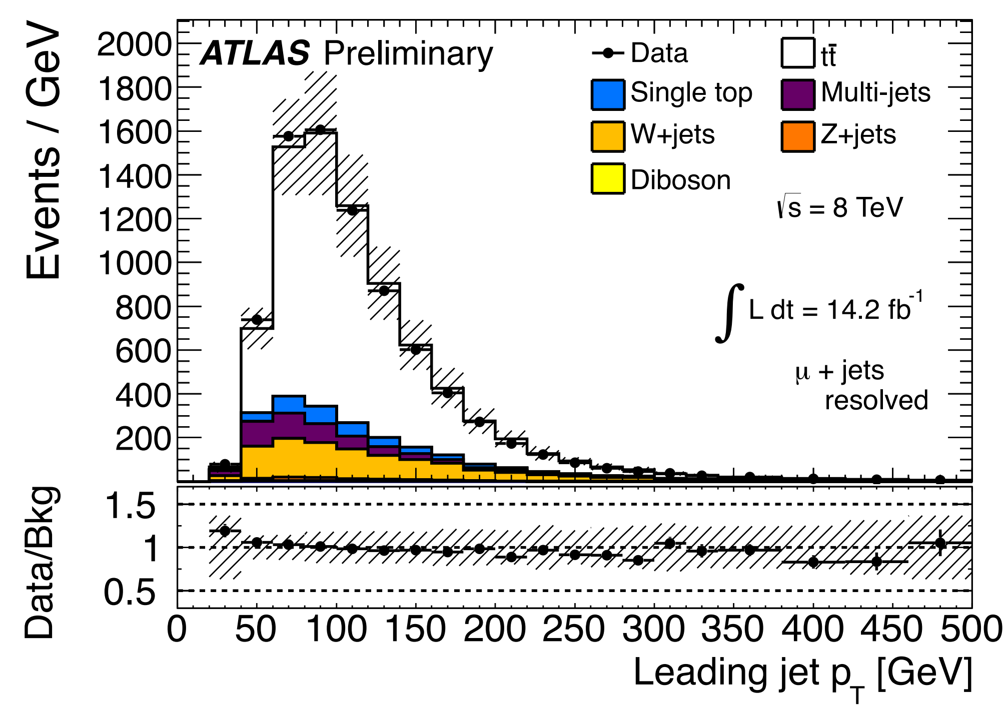
today

1000s of events

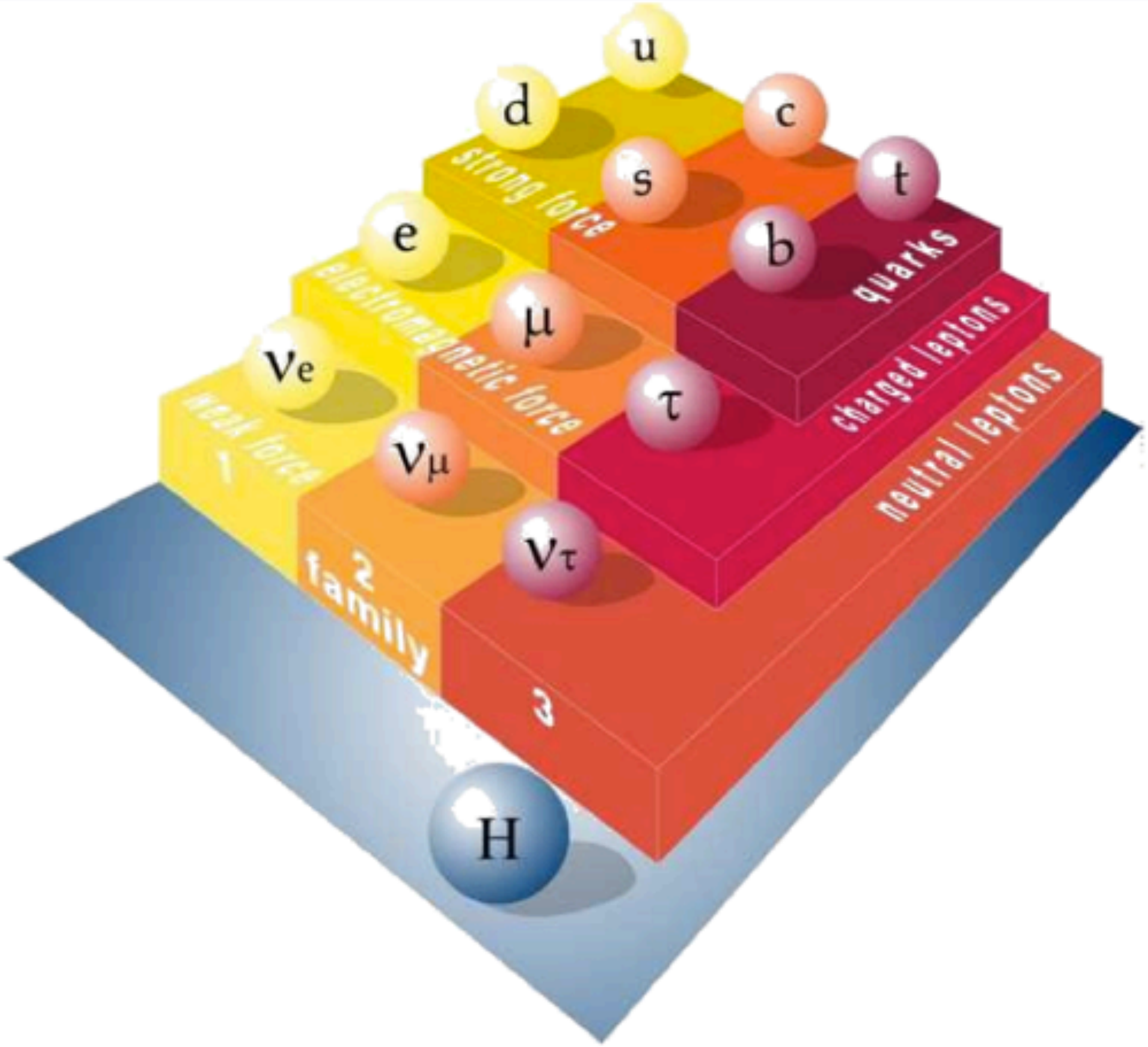


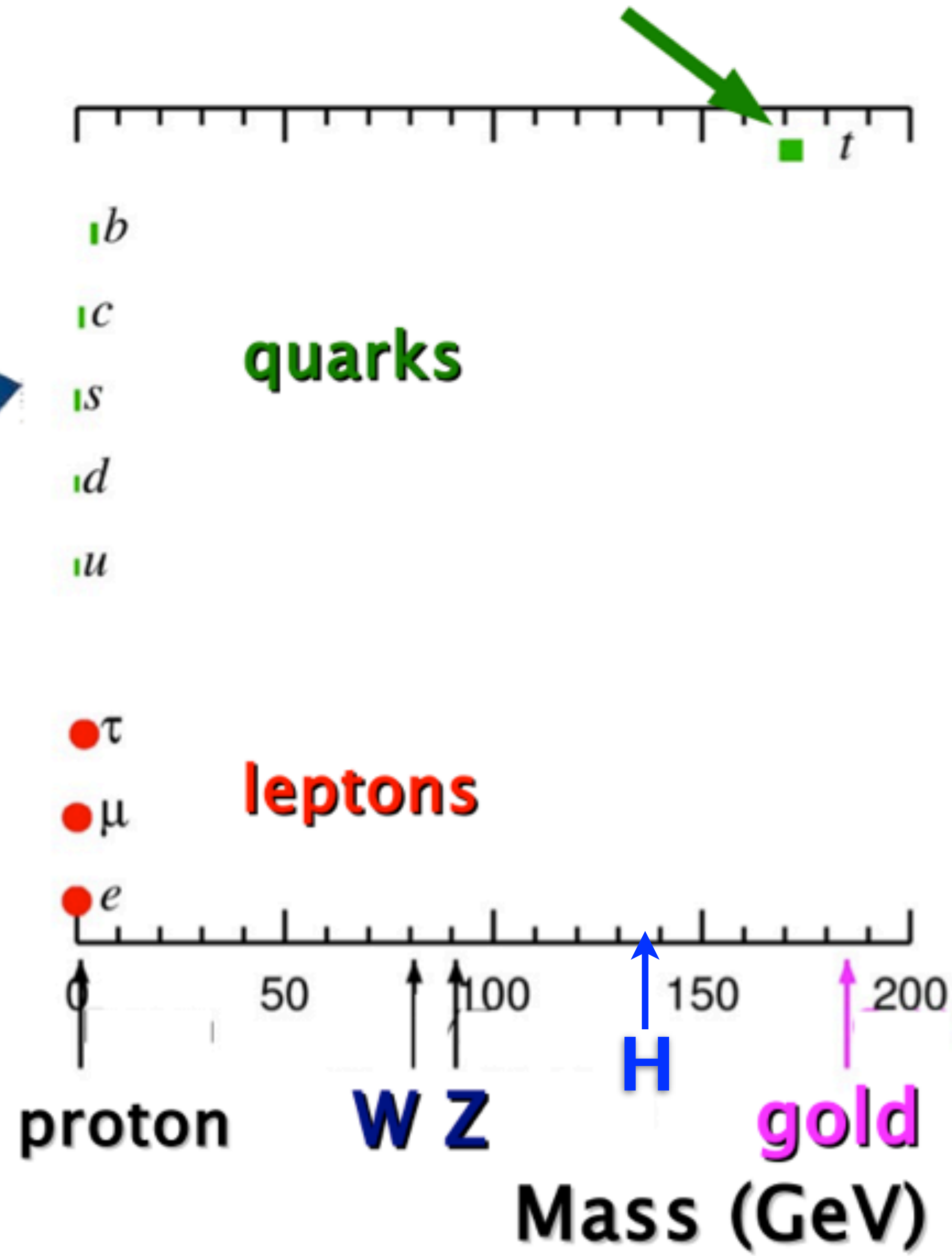
LHC: top quark factory

100000s of events

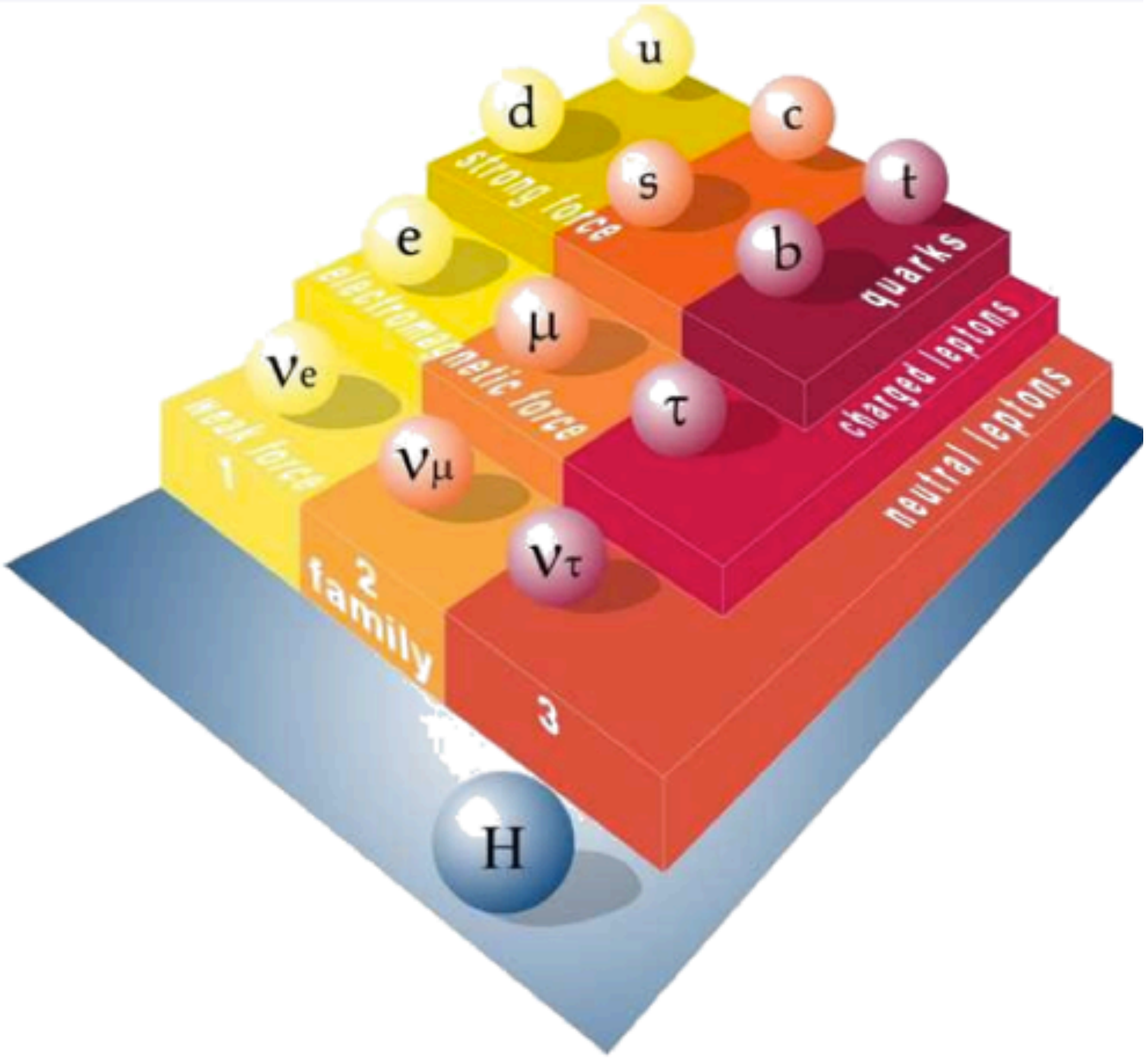


The Top Quark





Why The Top Quark



- In the SM it's the only quark:

1. With a natural mass:

$$m_{top} = y_t v/\sqrt{2} \approx 173 \text{ GeV} \Rightarrow y_t \approx 1$$

- Top quark interacts strongly with the Higgs sector - special role in EWSB?

2. That decays before hadronizing:

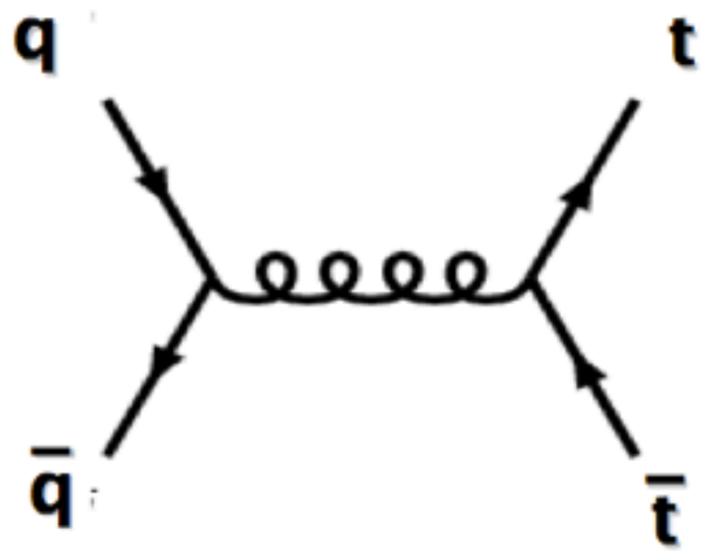
$$\tau_{had} \approx 2 \times 10^{-24} s$$

$$\tau_{top} \approx 5 \times 10^{-25} s$$

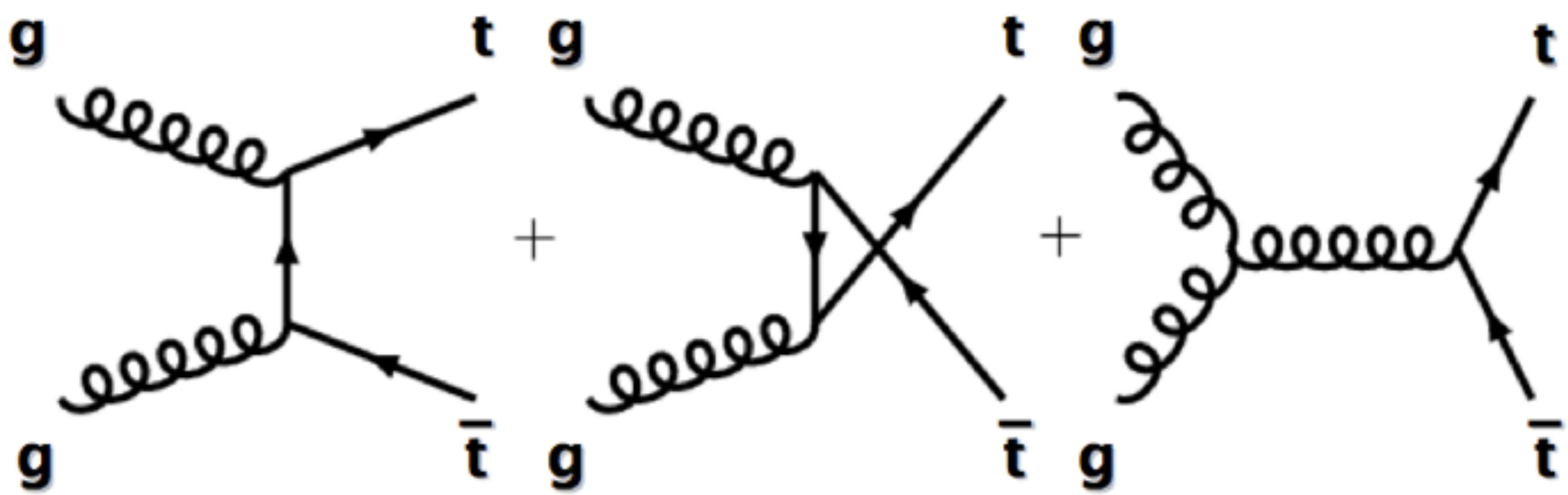
- Top is a unique window on QCD & EW physics.

Top Quark Production & Decay

Top Quark Pair Production



Tevatron (85%)

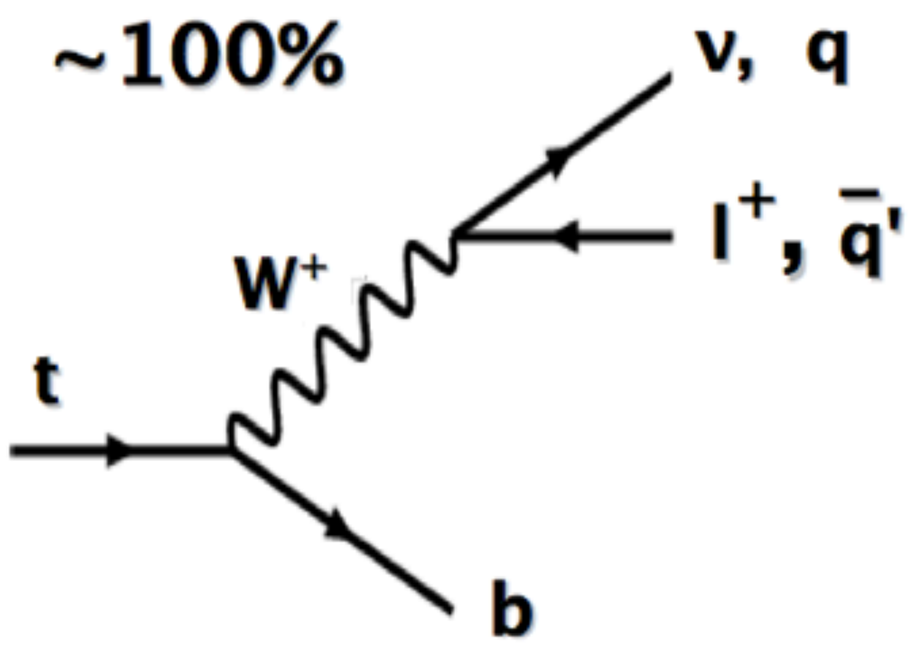


LHC (87%)

(14 TeV)

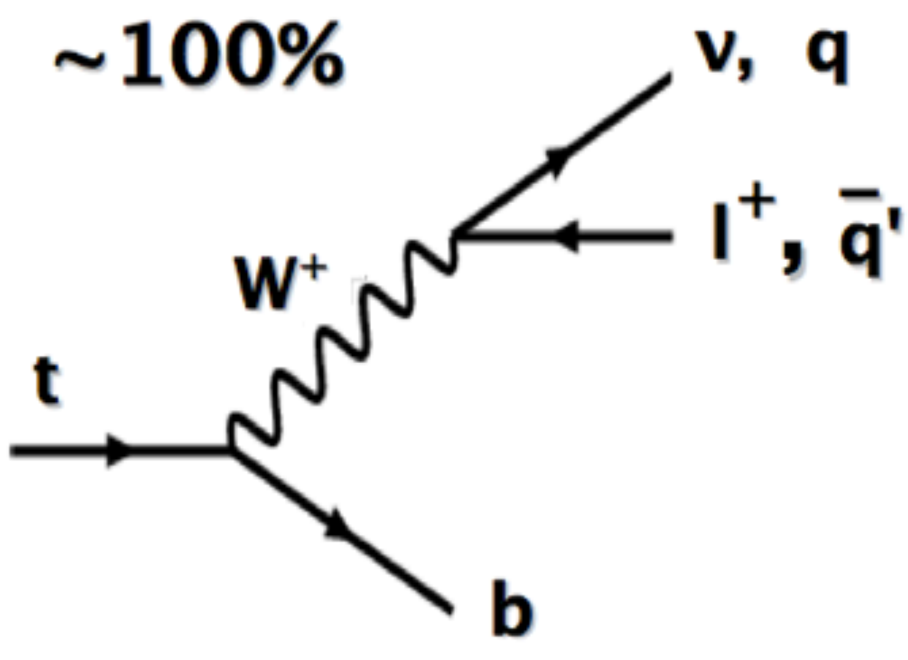
Top Quark Signatures

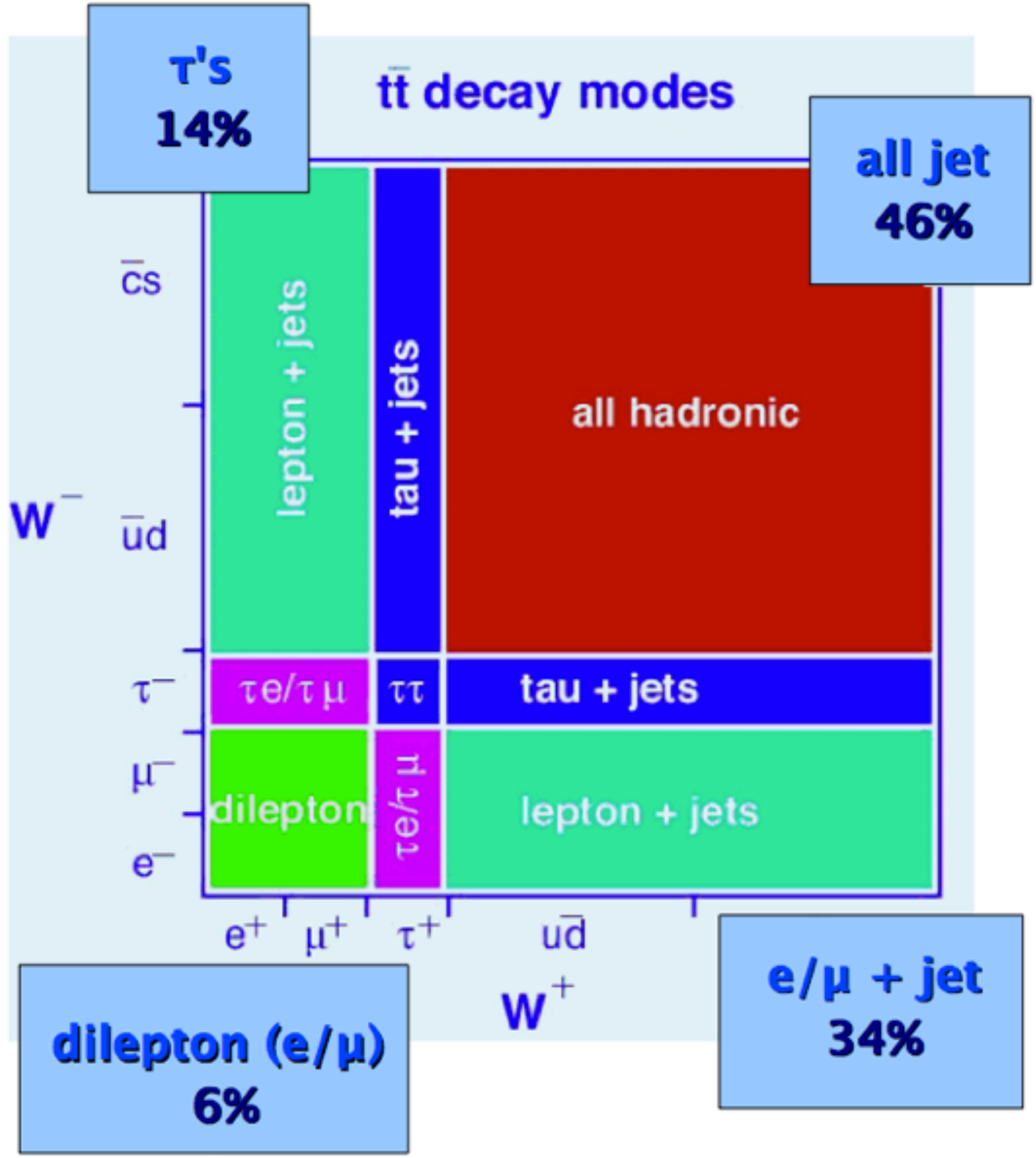
top decay:



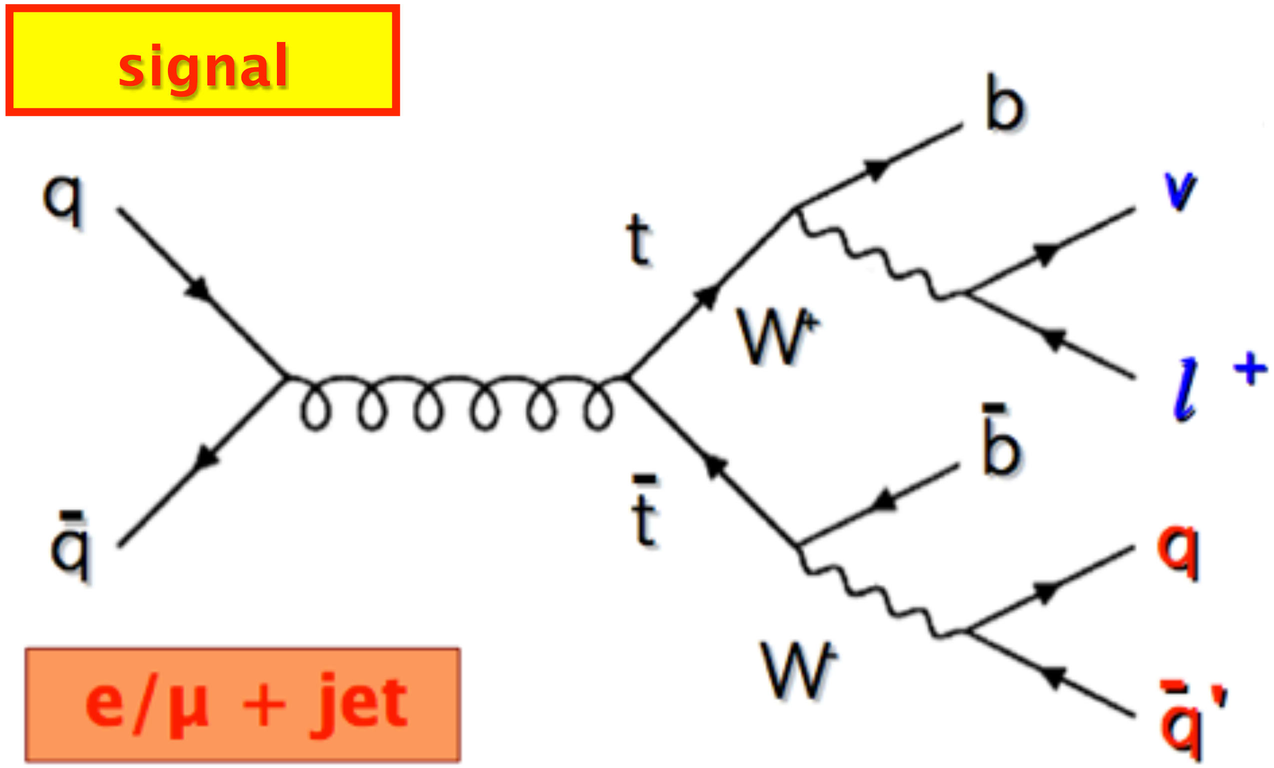
Top Quark Signatures

top decay:



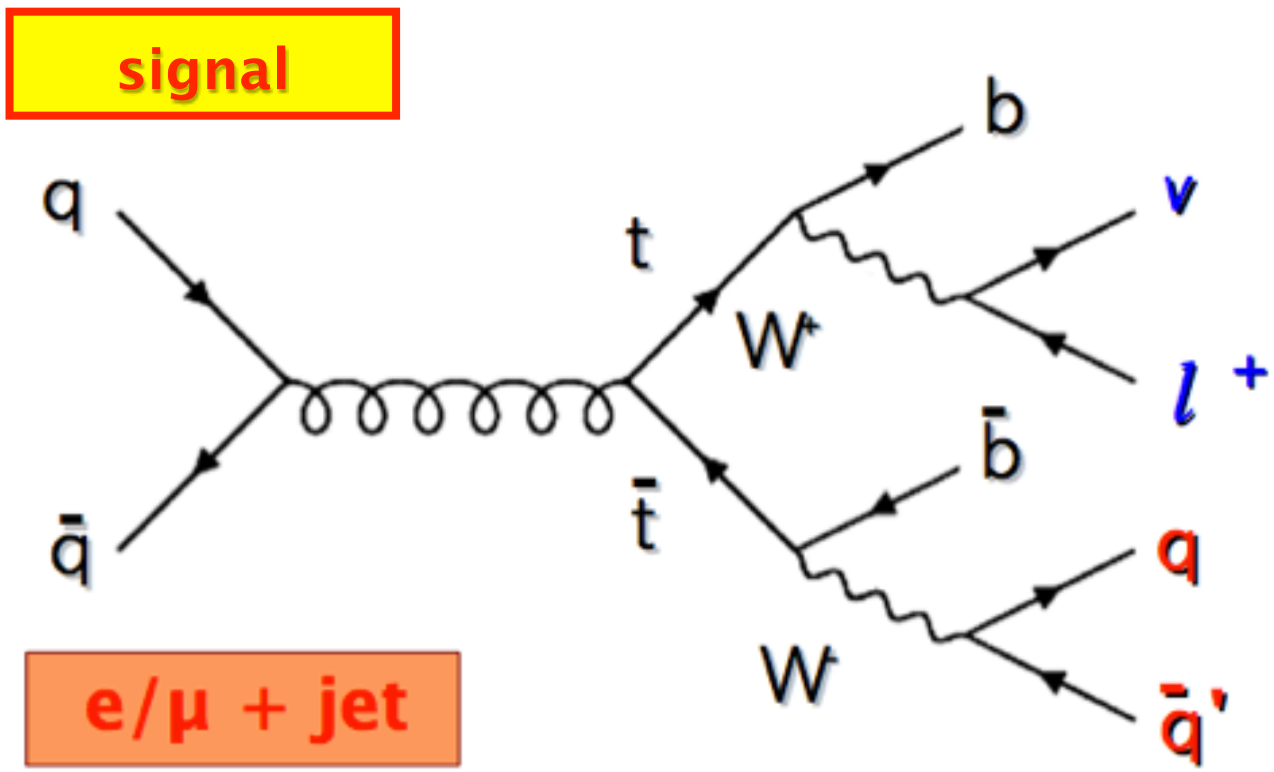


Lepton + Jets Signature



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

Lepton + Jets Signature



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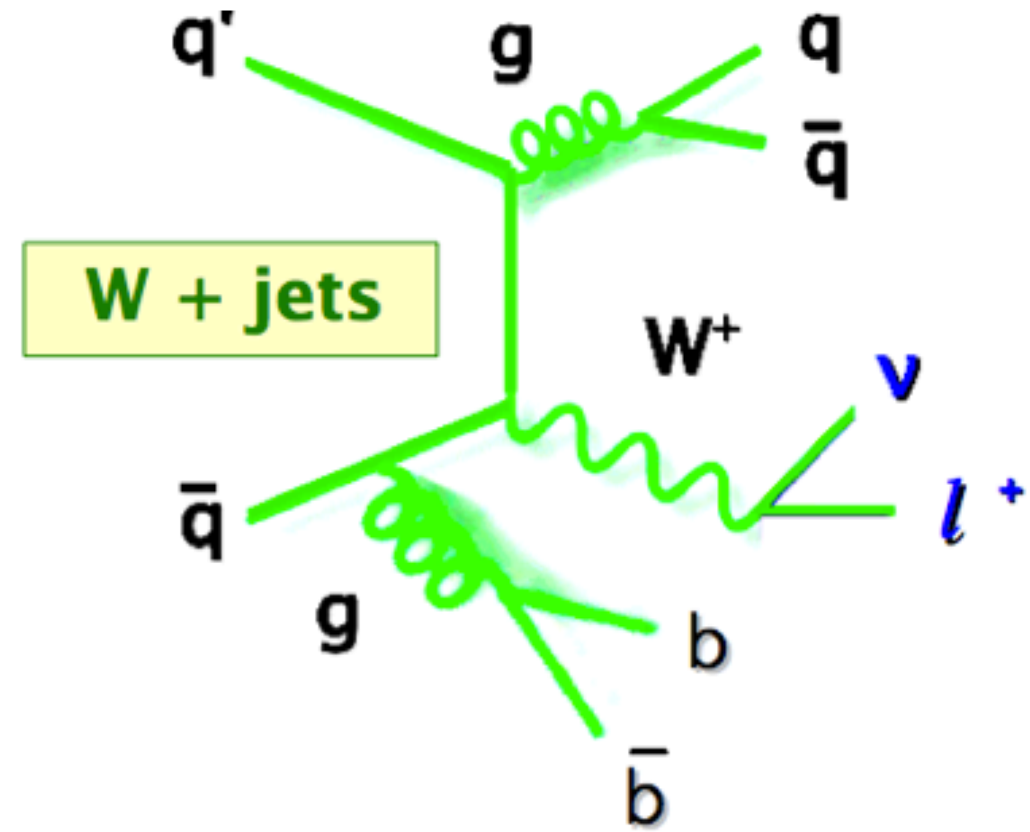
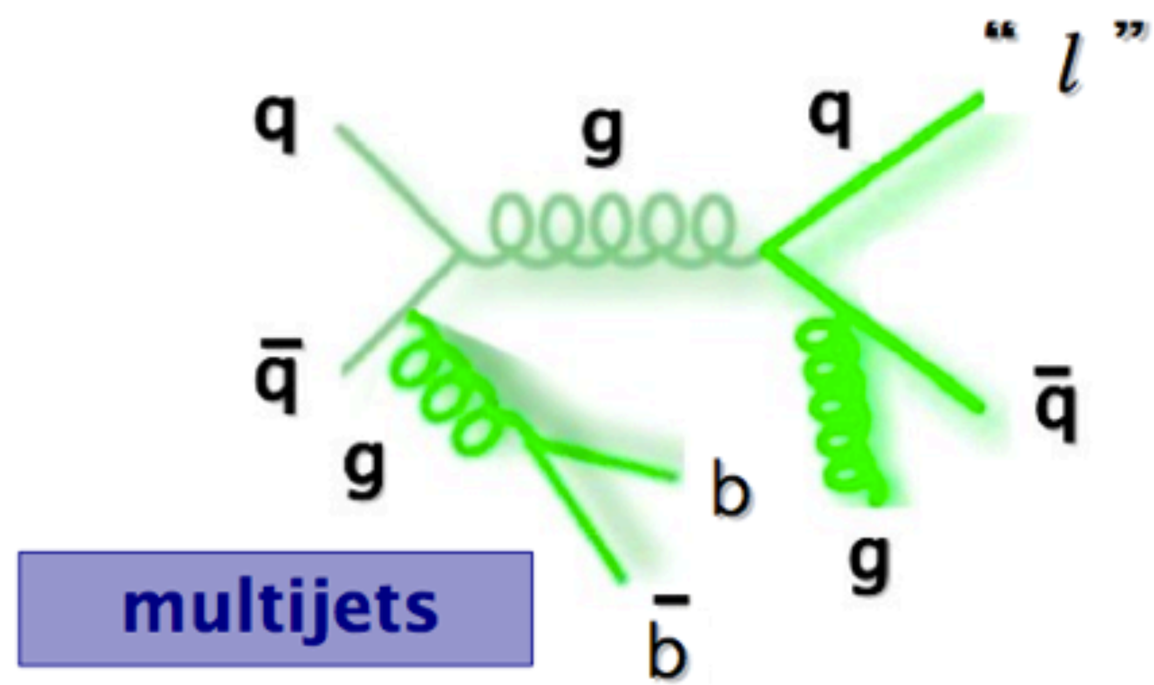
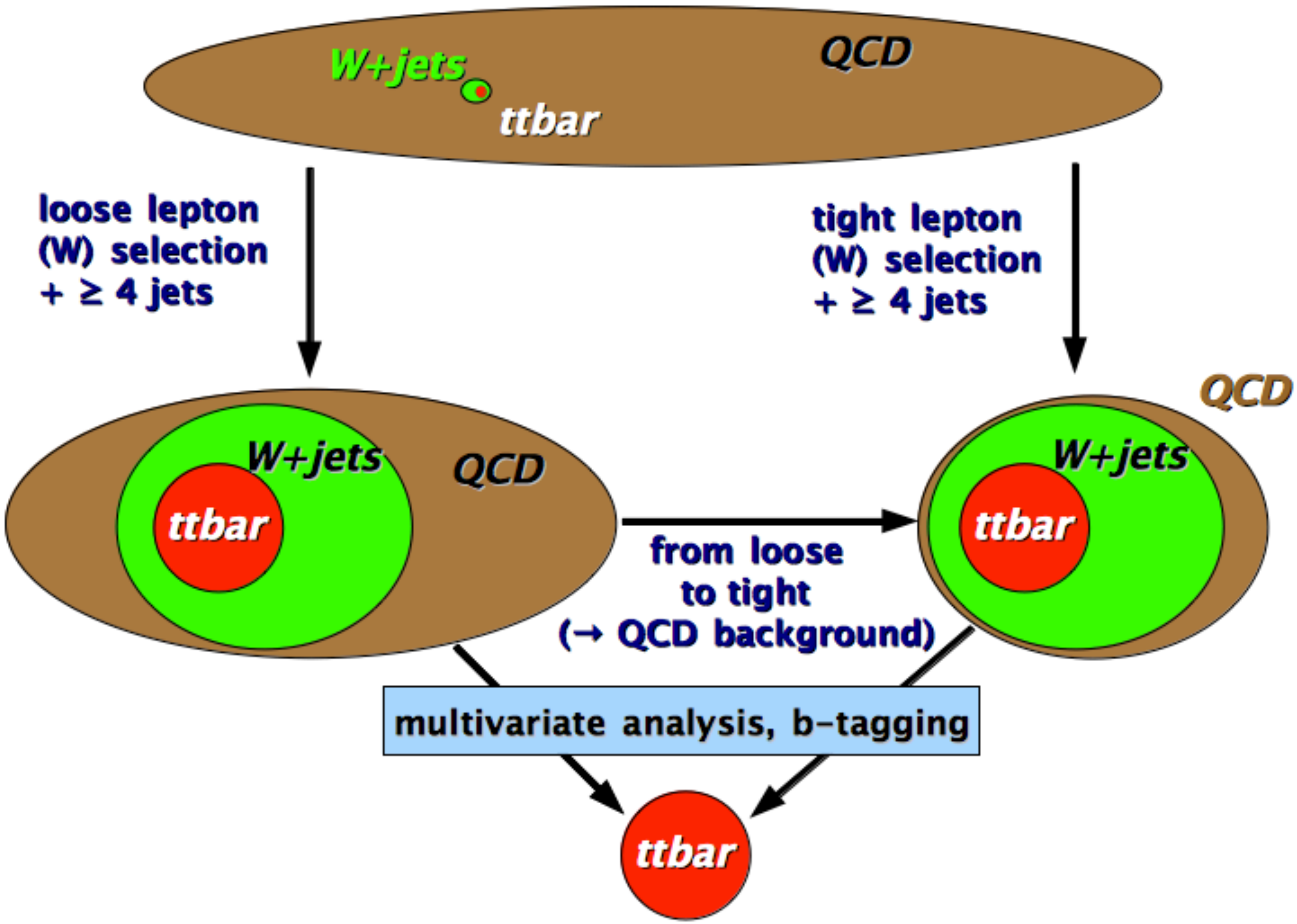
background





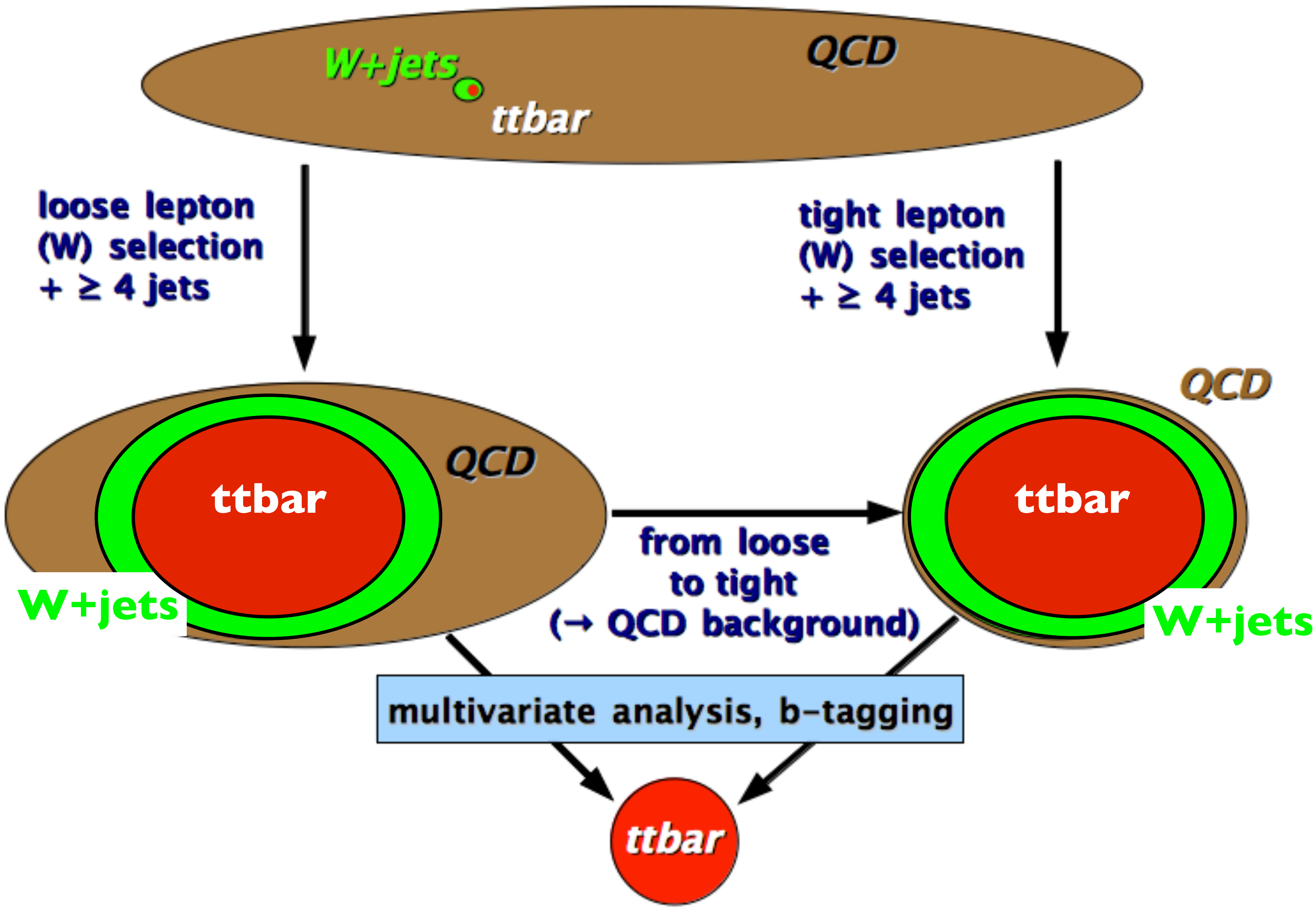
Lepton + Jets Signature

Tevatron



Lepton + Jets Signature

LHC



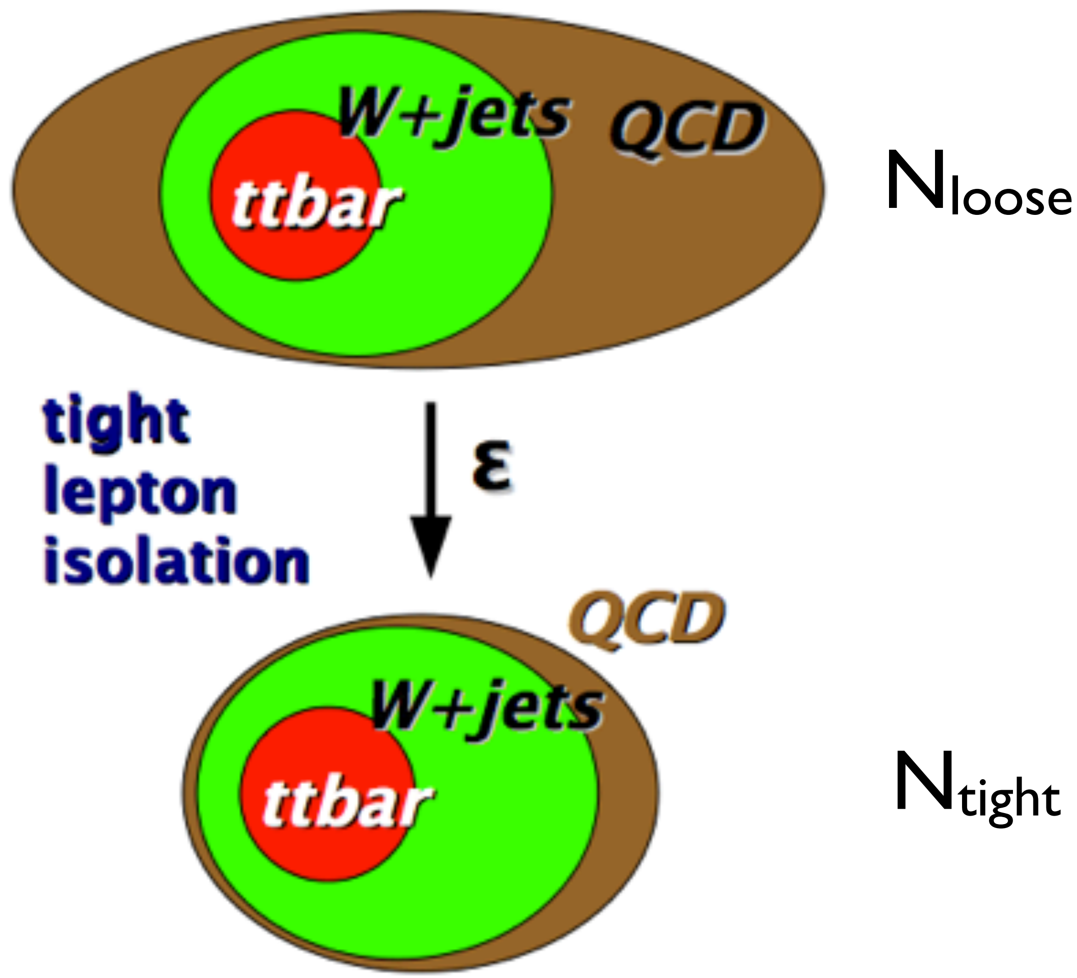
Multijet Background

lepton+jets

$$N_{loose} = N_{QCD} + N_{W+ttbar}$$

$$\downarrow \varepsilon \qquad \varepsilon_{QCD} \downarrow \qquad \varepsilon_{W+ttbar} \downarrow$$

$$N_{tight} = \varepsilon_{QCD} * N_{QCD} + \varepsilon_{W+ttbar} * N_{W+ttbar}$$

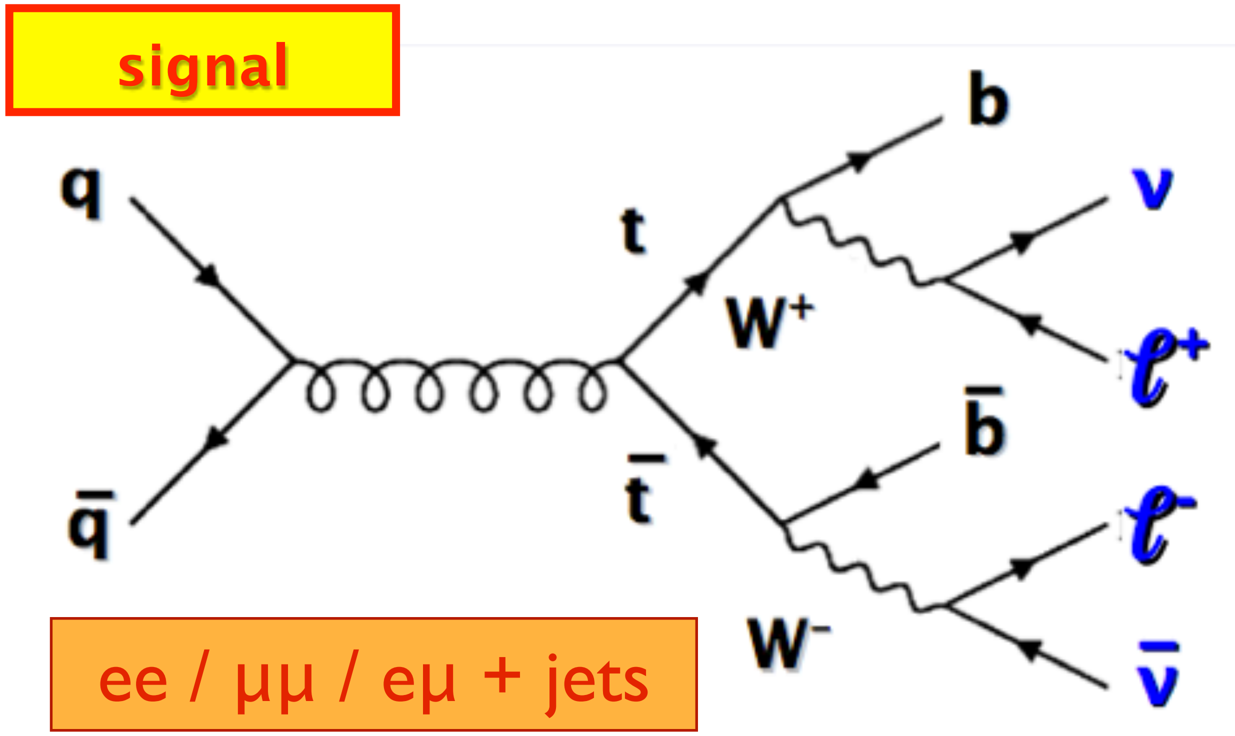


- ε_{QCD} : independent multijet (QCD) data set (e.g. small $\not{E}_T$)
- $\varepsilon_{W+ttbar}$: W+jets Monte Carlo simulation (normalization to data)

→ solve equations for N_{QCD} Try it!

→ determine multijet (QCD) background <u>entirely from data</u>

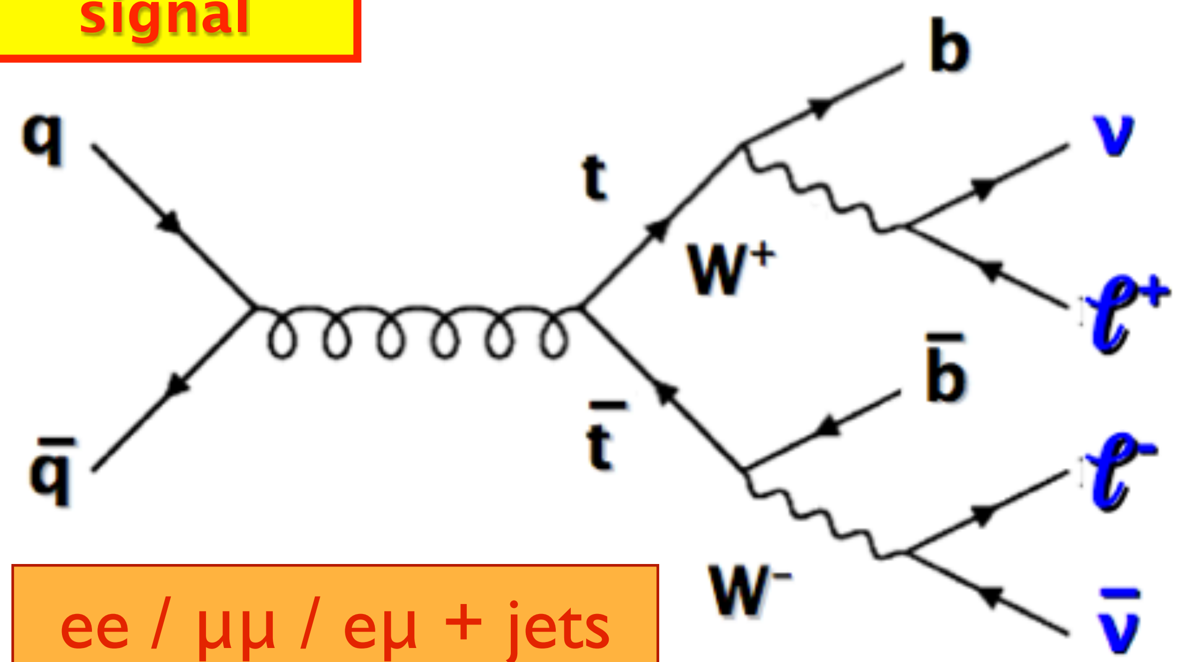
Dilepton Signature



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

Dilepton Signature

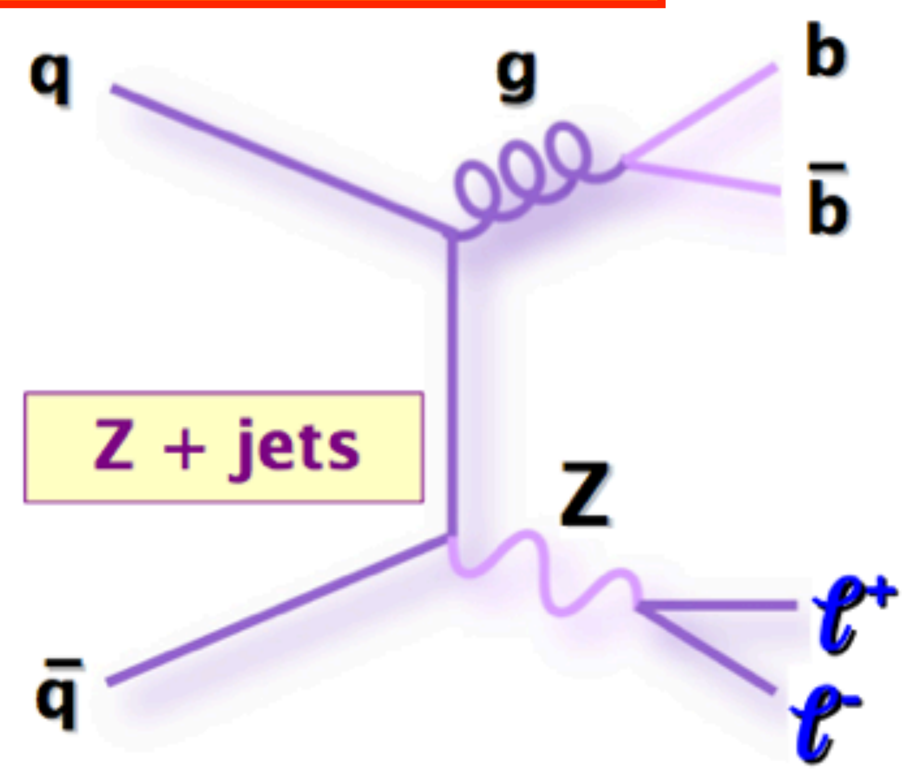
signal



ee / μμ / eμ + jets

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

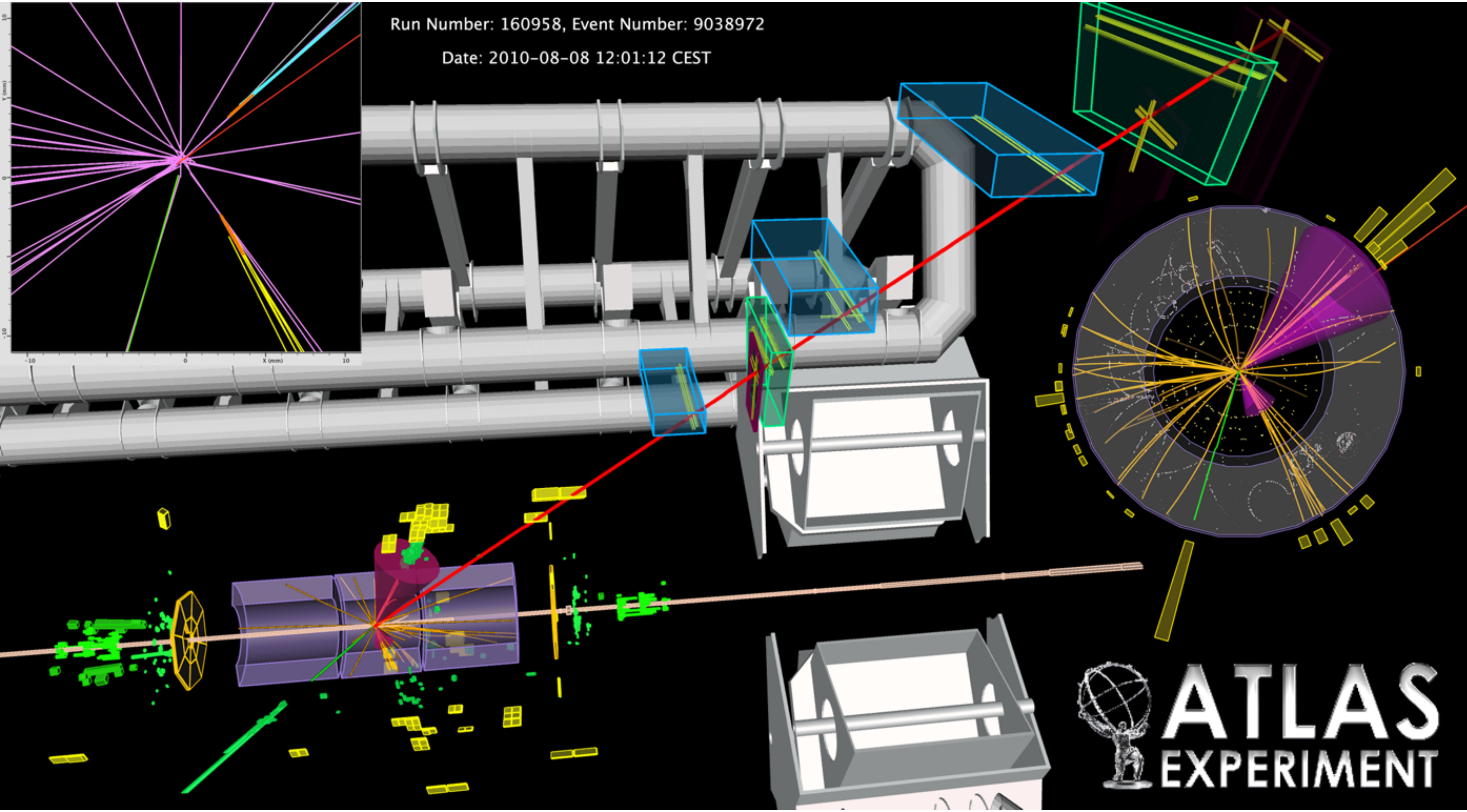
background



Z + jets

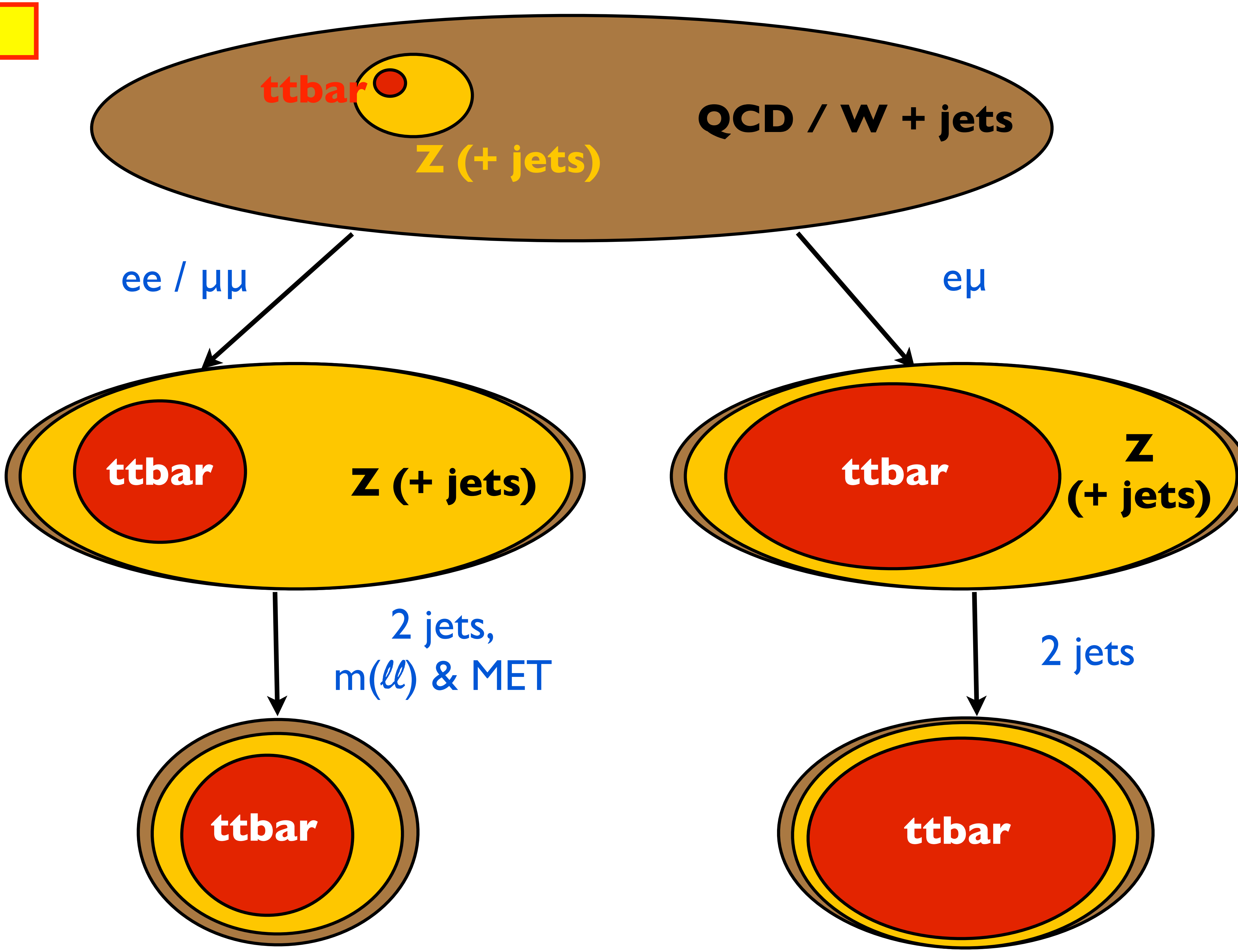
- less statistics
- less background

Dilepton Signature



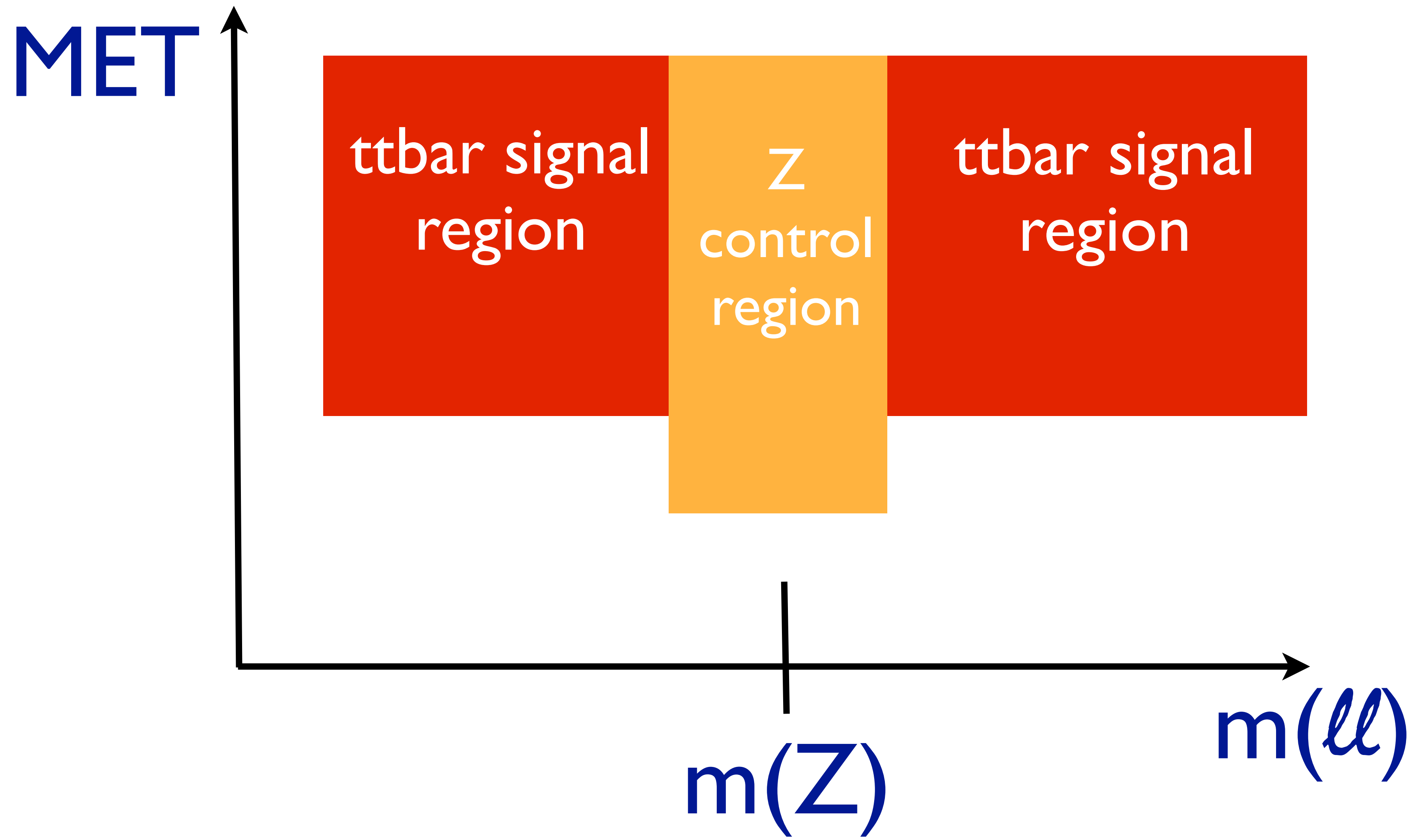
Dilepton Signature

LHC



Z+jets Background

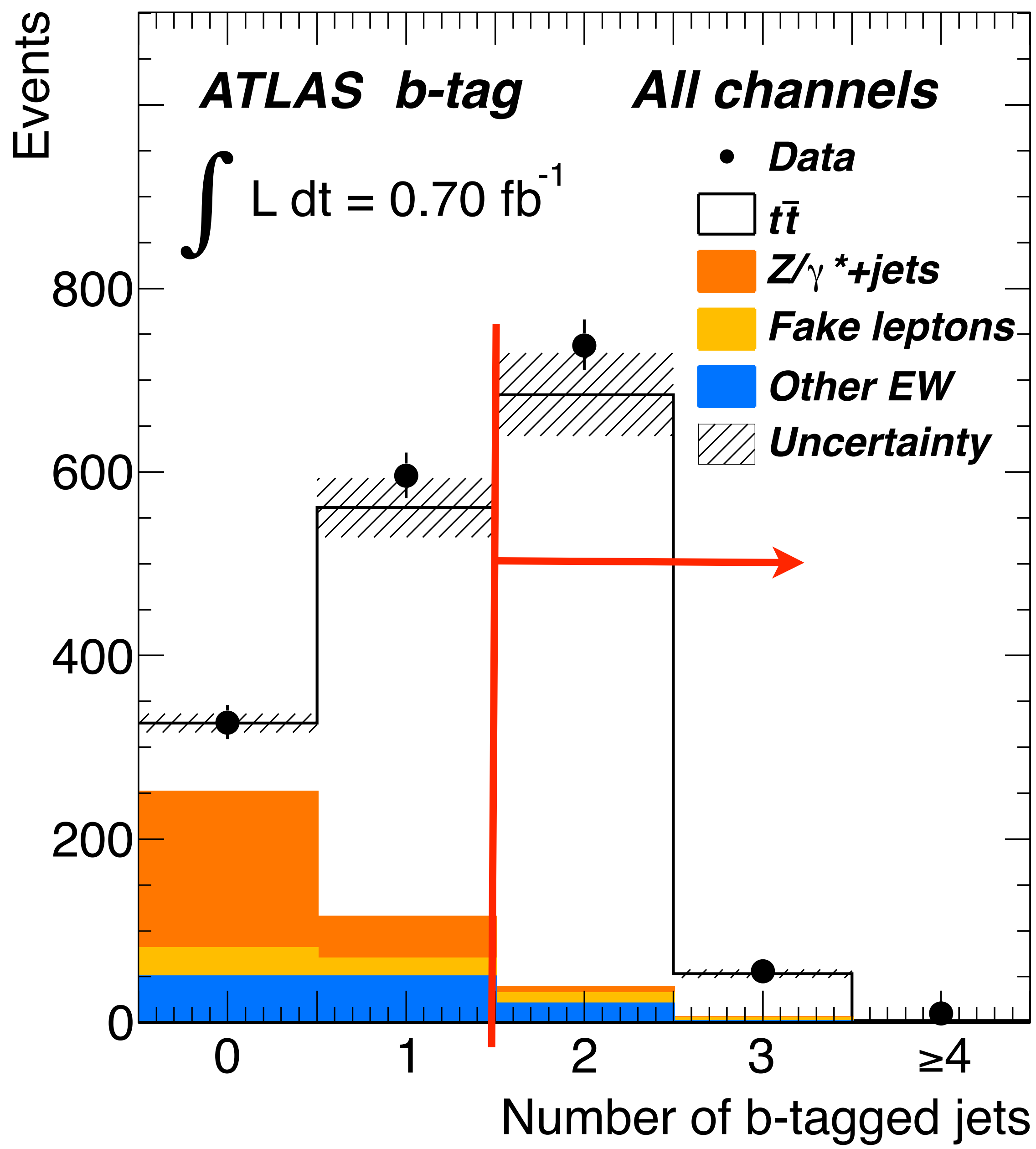
- Z events peak in m($\ell\ell$) at Z mass - use this to constrain the background in the signal region.

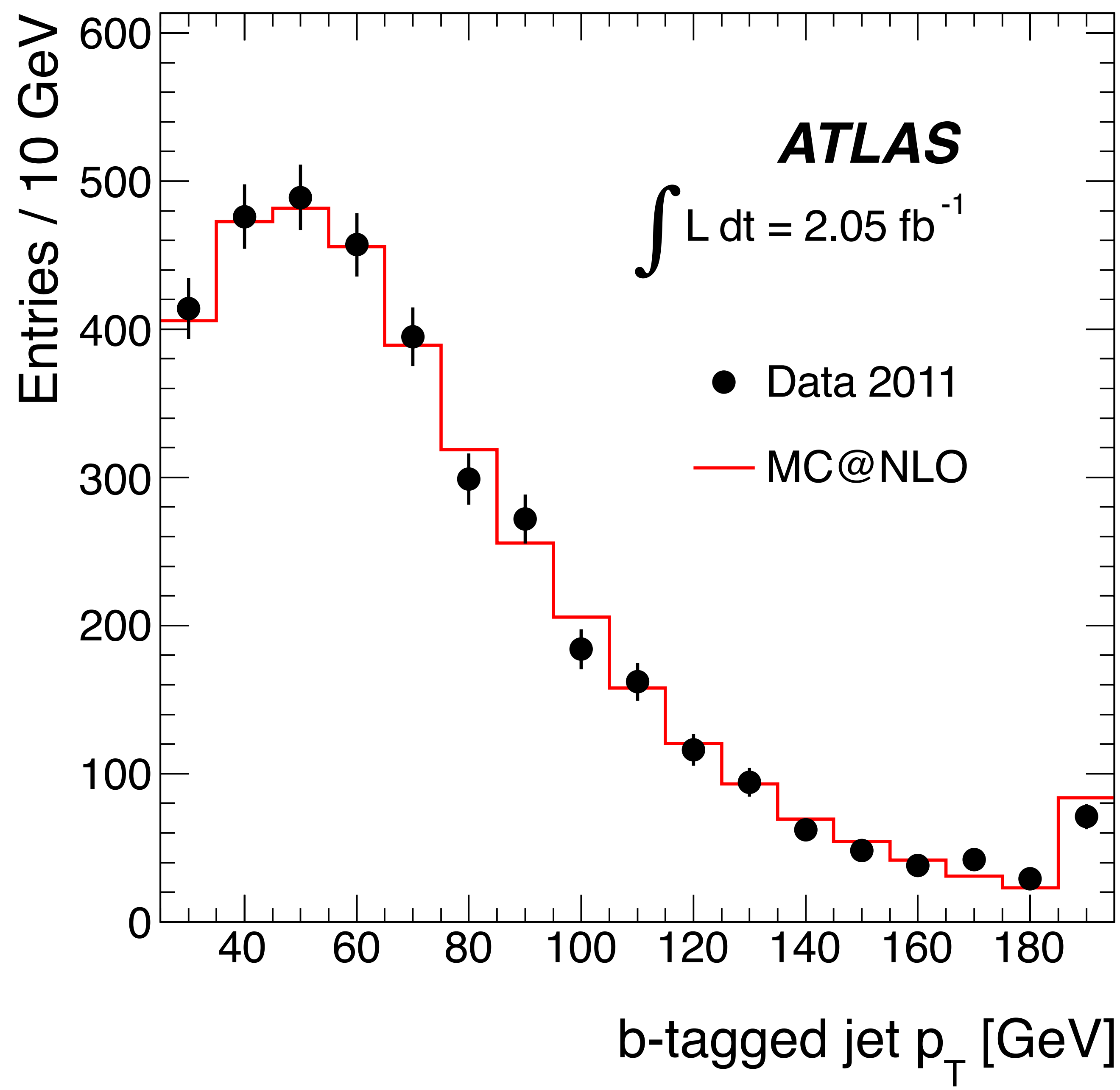


$$N^{Z}_{\rm sig} = \frac{N^{Z data}_{\rm control}}{N^{ZMC}_{\rm control}} N^{ZMC}_{\rm sig}$$

B-tagging in dilepton

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

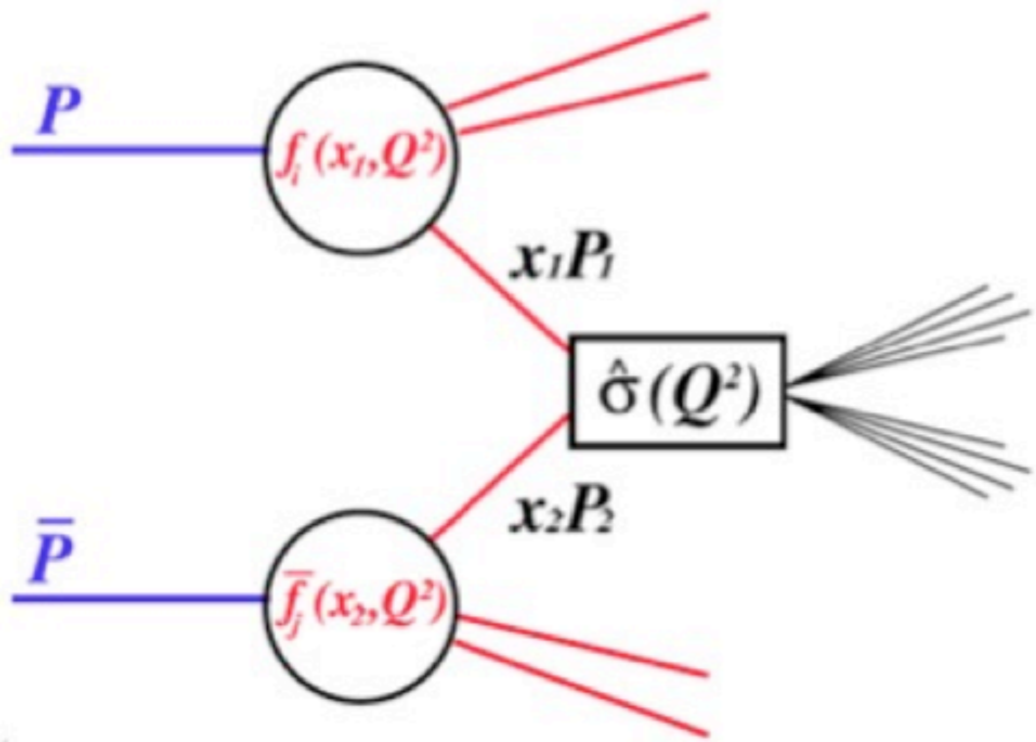




Top Quark Pair Production:

Inclusive cross section
Modelling top quark production
Differential cross section

Cross Sections at Hadron Colliders



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

Sum over incoming partons i, j

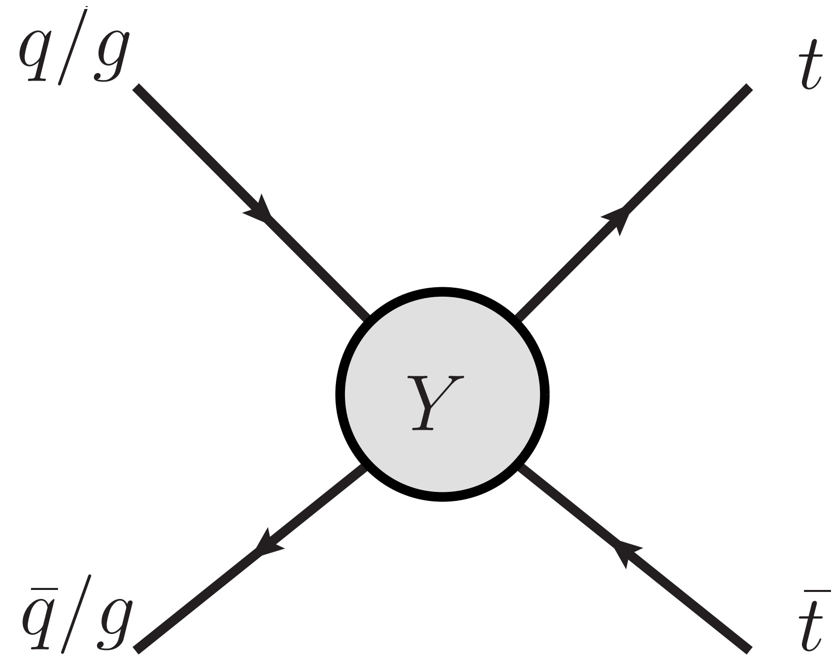
Momentum fraction for incoming parton

PDF for incoming parton i

"partonic" cross section

Partonic Cross Section

- 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.

Partonic Cross Section

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

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

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

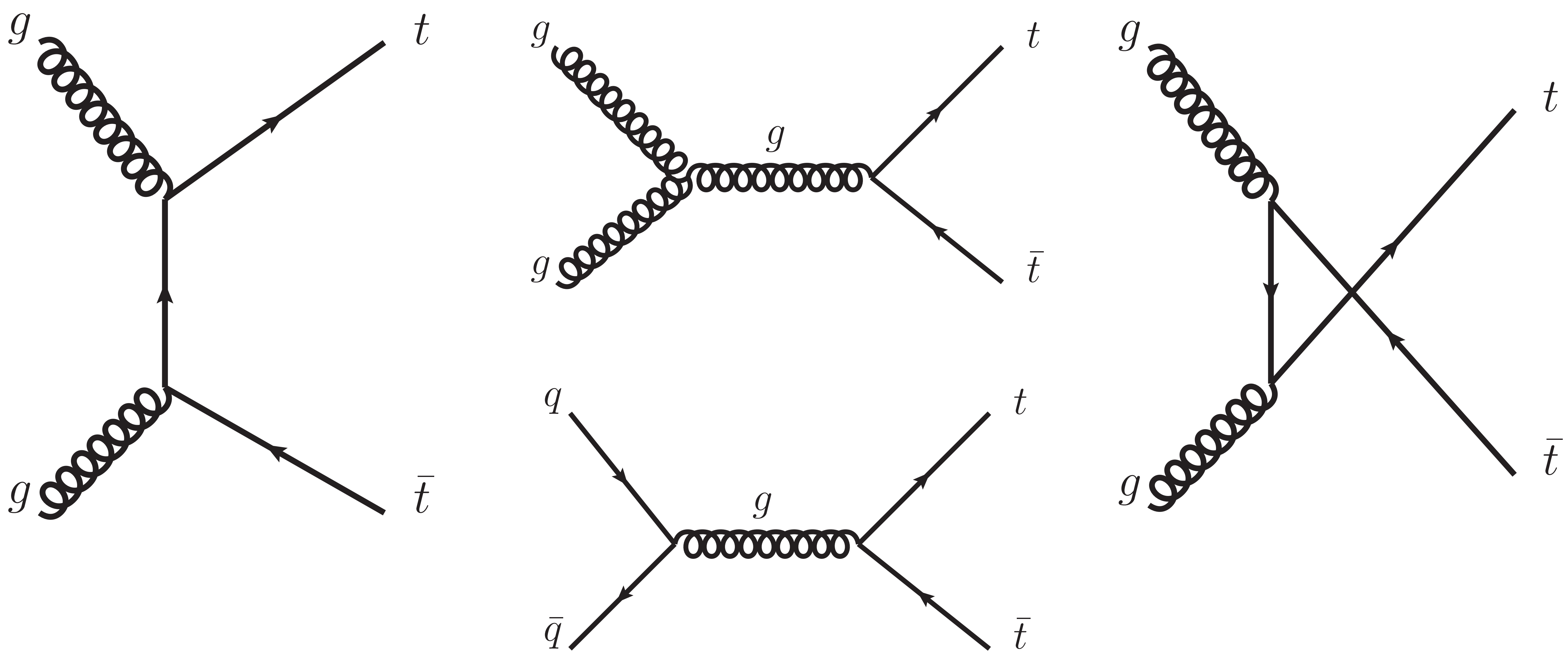
Next-to-leading order (NLO) term, proportional to α_s^3

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

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

Partonic Cross Section

- Simplest production of top pairs:



Partonic Cross Section

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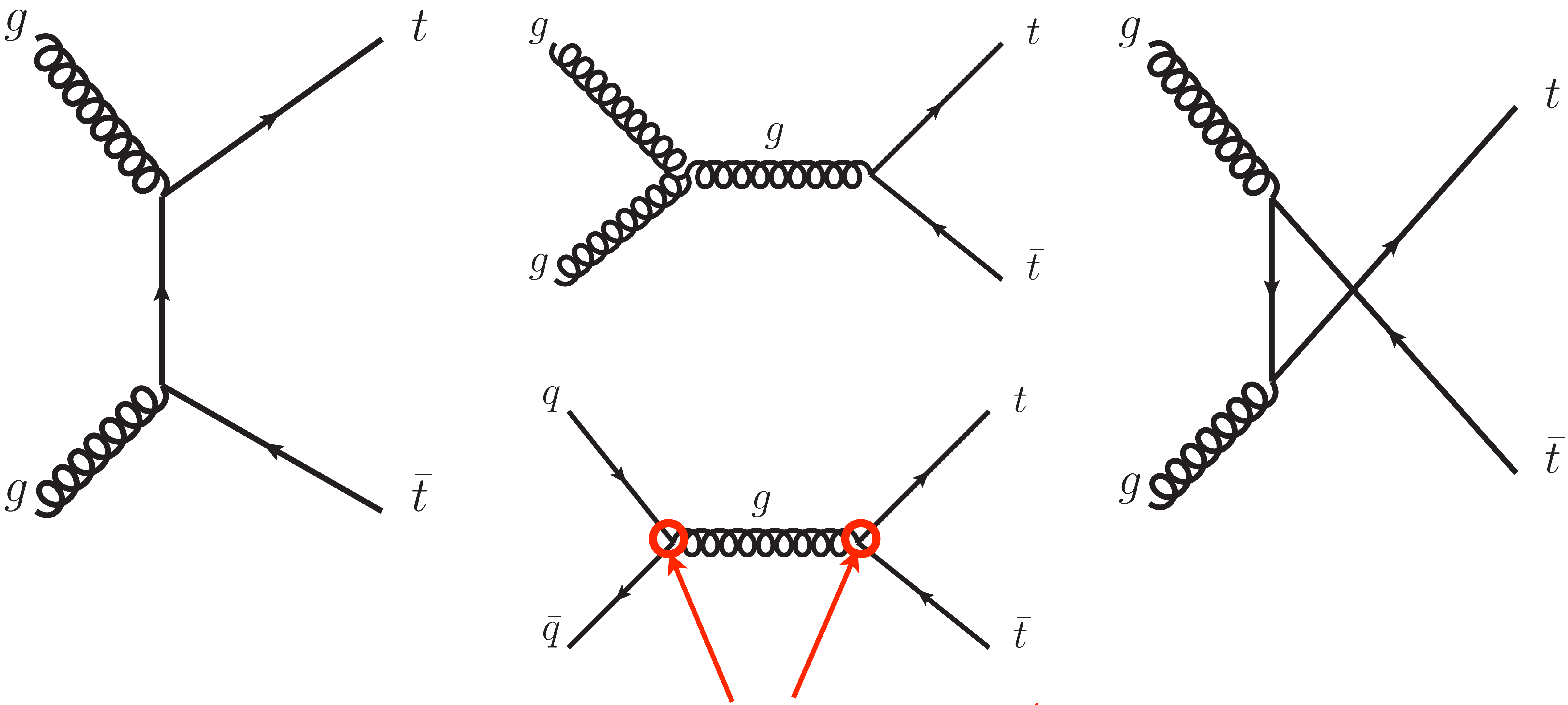
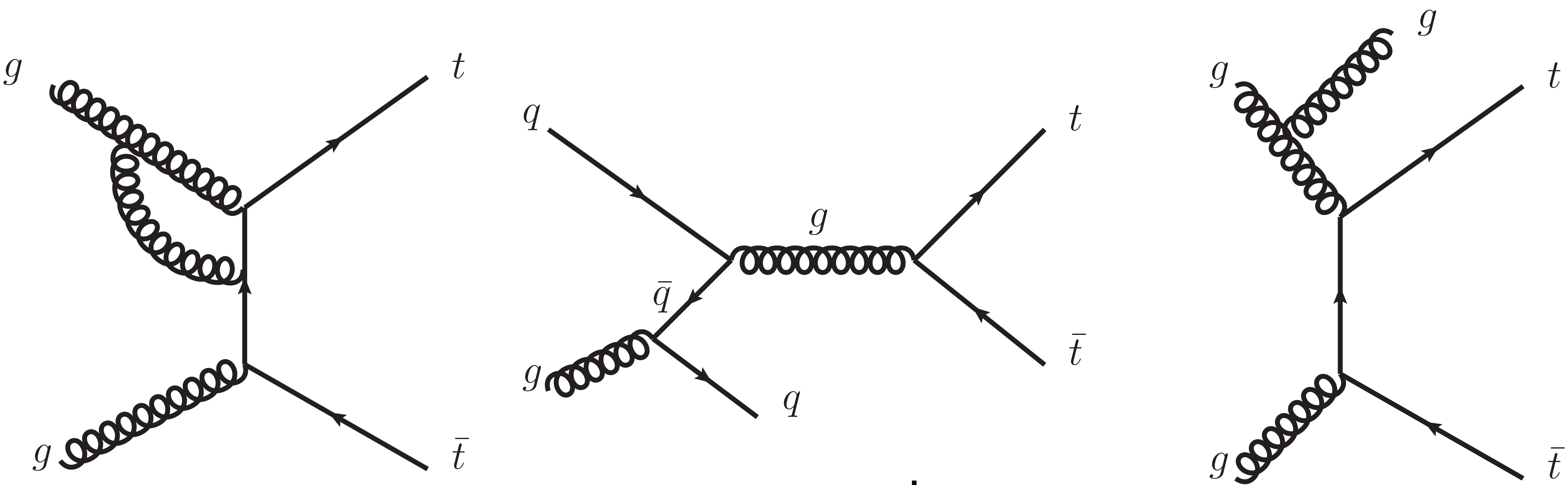


Each vertex contributes $\sqrt{\alpha_s}$

α_s = strong force (QCD) coupling constant

Partonic Cross Section

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



+ many others

Partonic Cross Section

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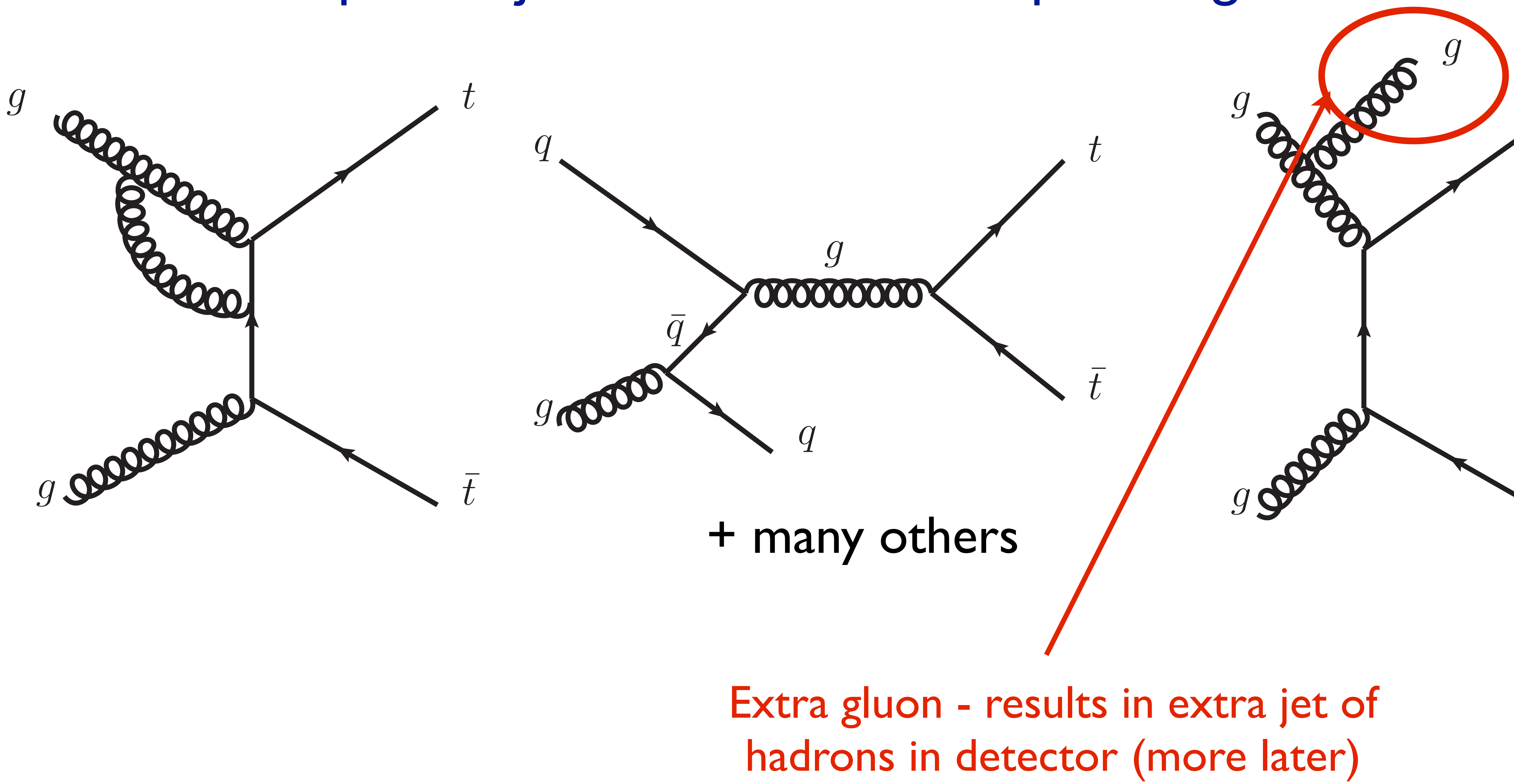
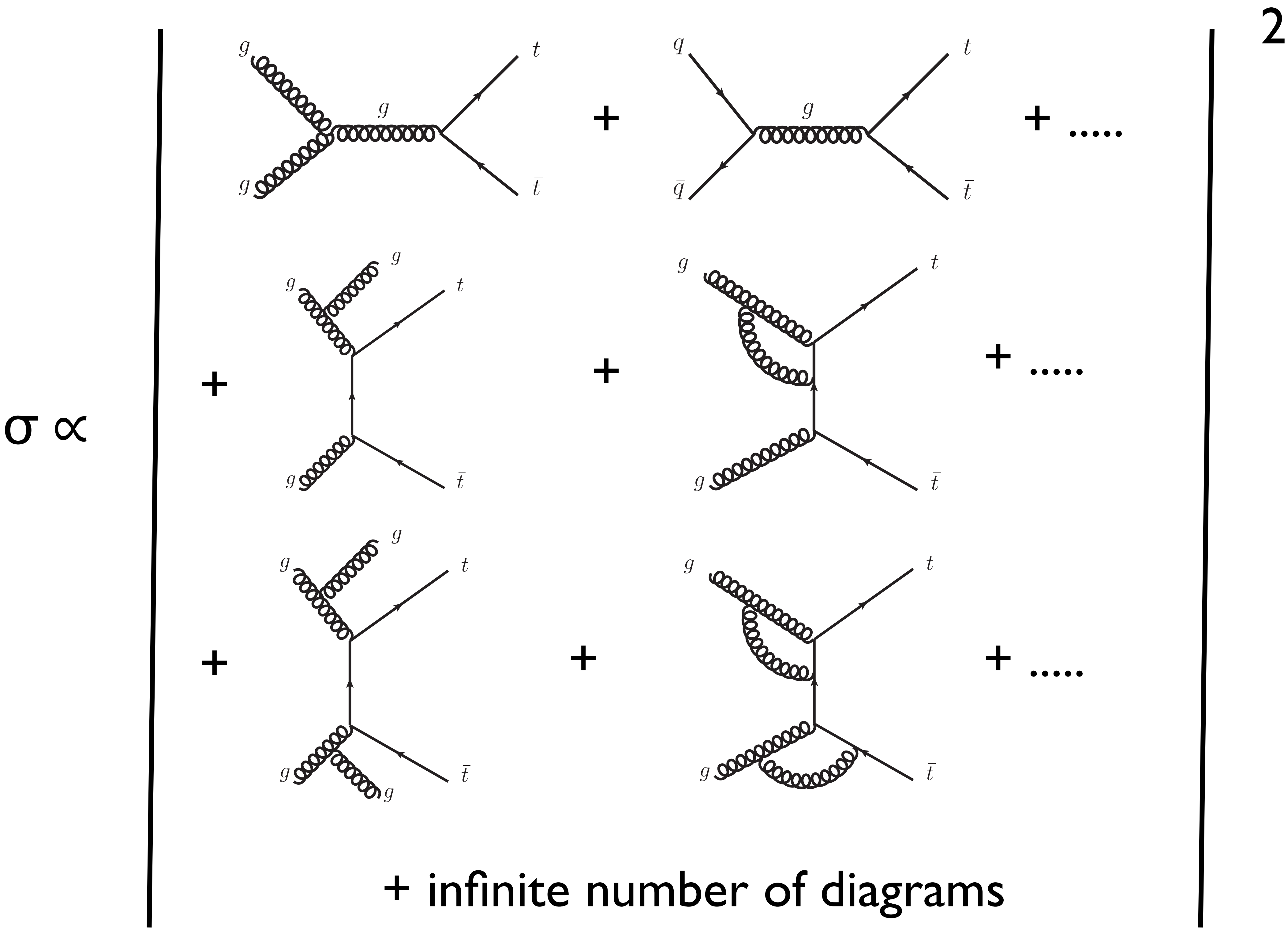


Partonic Cross Section

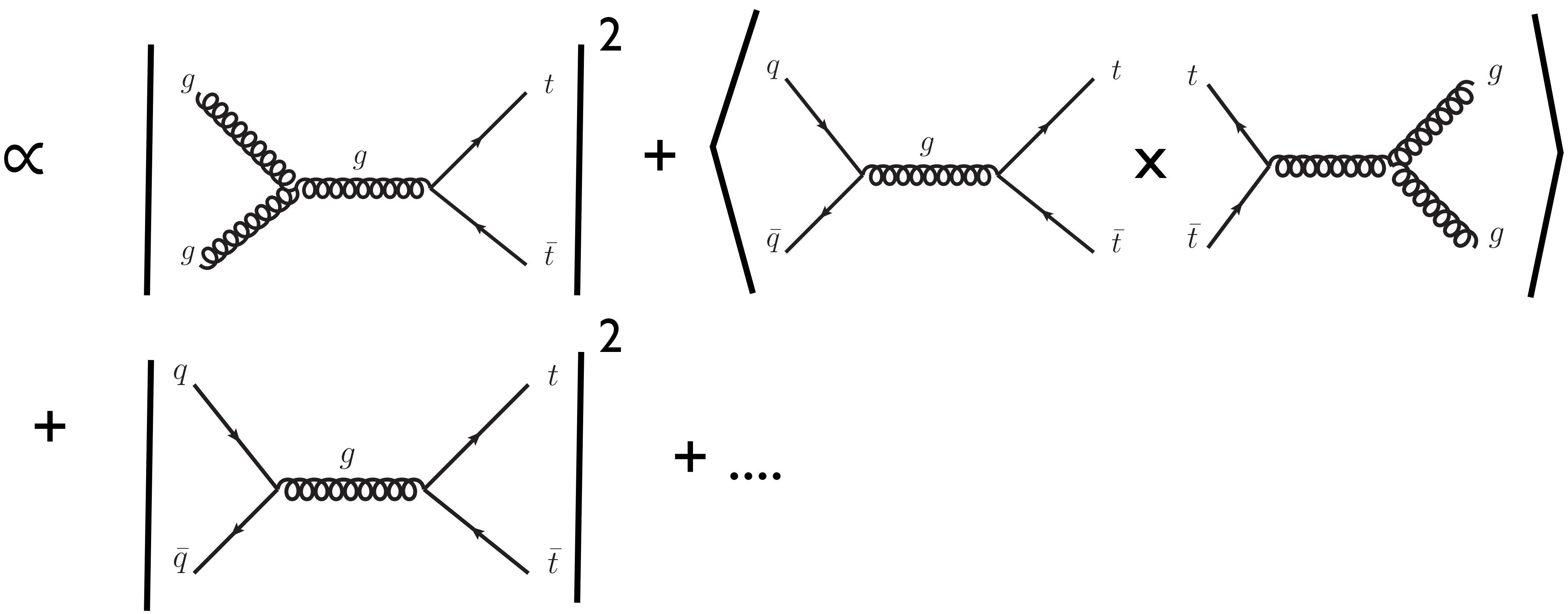
- Calculate all allowed processes:



Partonic Cross Section

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

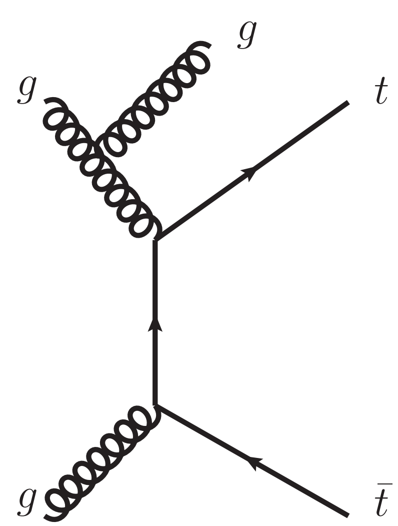
$\sigma_{LO} \propto$



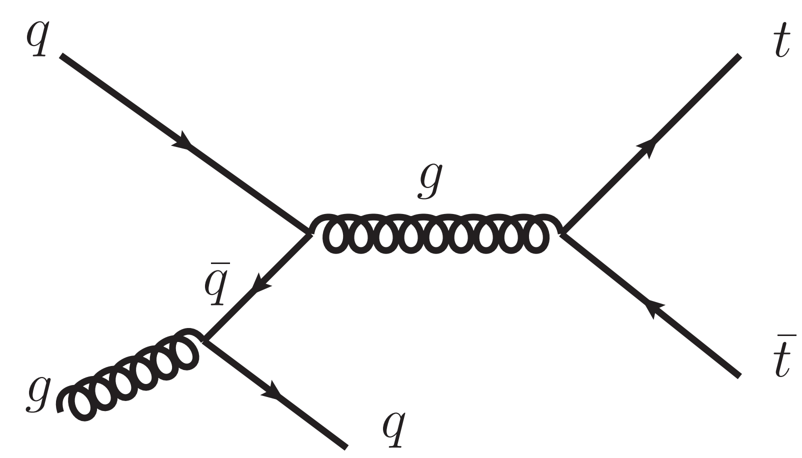
Partonic Cross Section

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

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

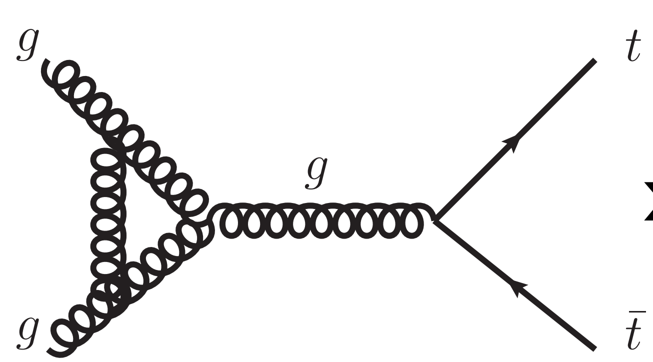


$|^2 +$ |

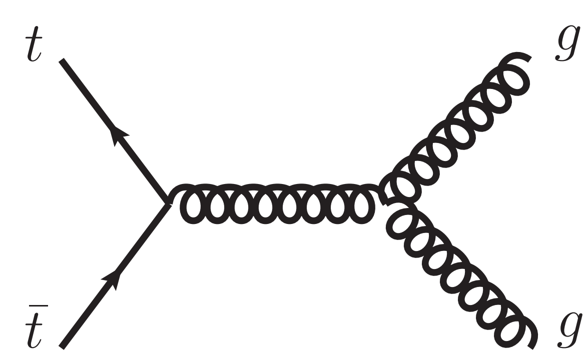


$|^2$

$+ \langle$



x



$\rangle$ + ...

NNLO Cross Section

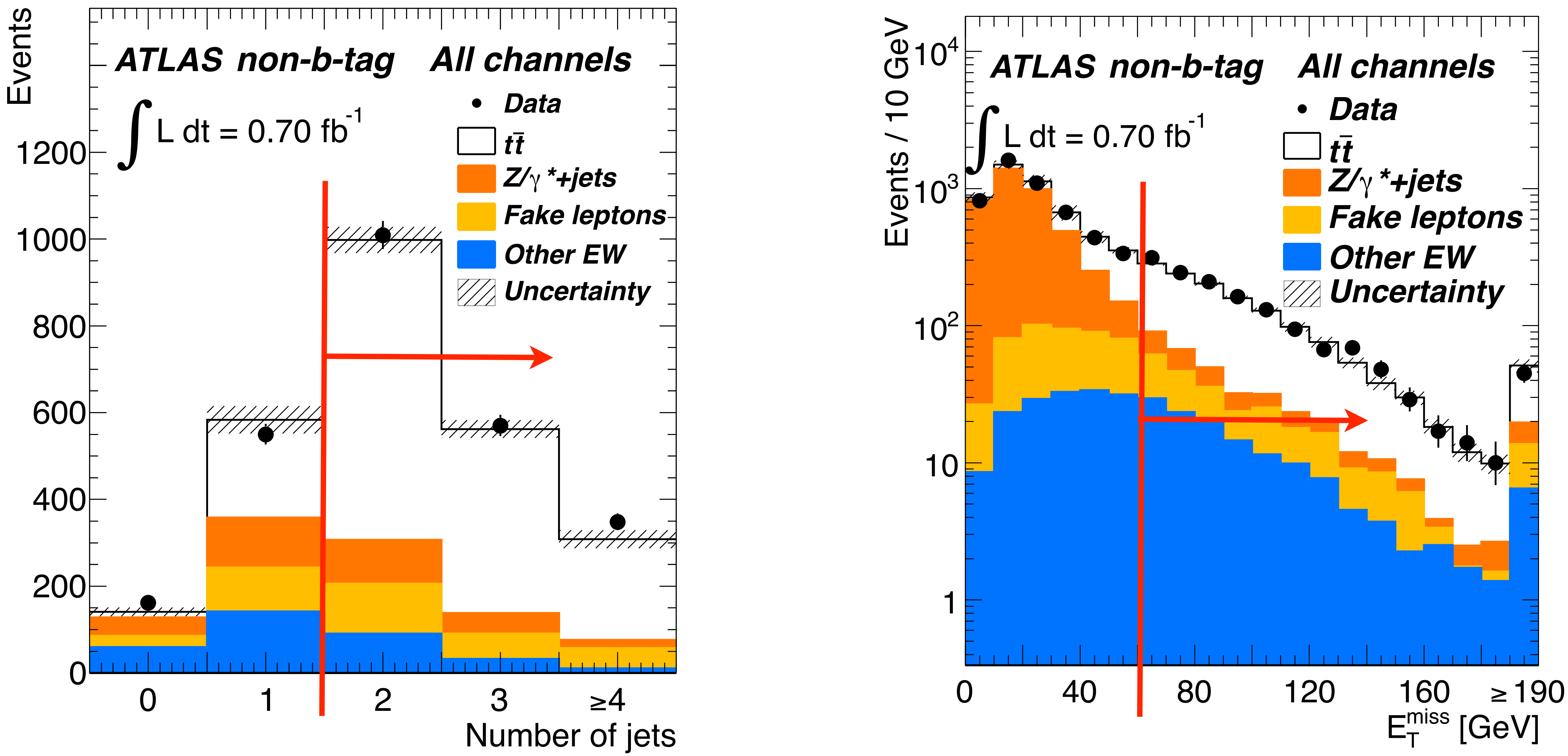
- State-of-the-art theoretical calculation calculates the inclusive ttbar cross section to NNLO.
  - Theoretical precision ~5%!

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(ℓℓ) & MET to remove Z events.



Dilepton Cross Section

- Extract cross-section by counting events:

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

Dilepton Cross Section

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Systematic uncertainties are key

Dilepton Cross Section

- Extract cross-section by counting events:

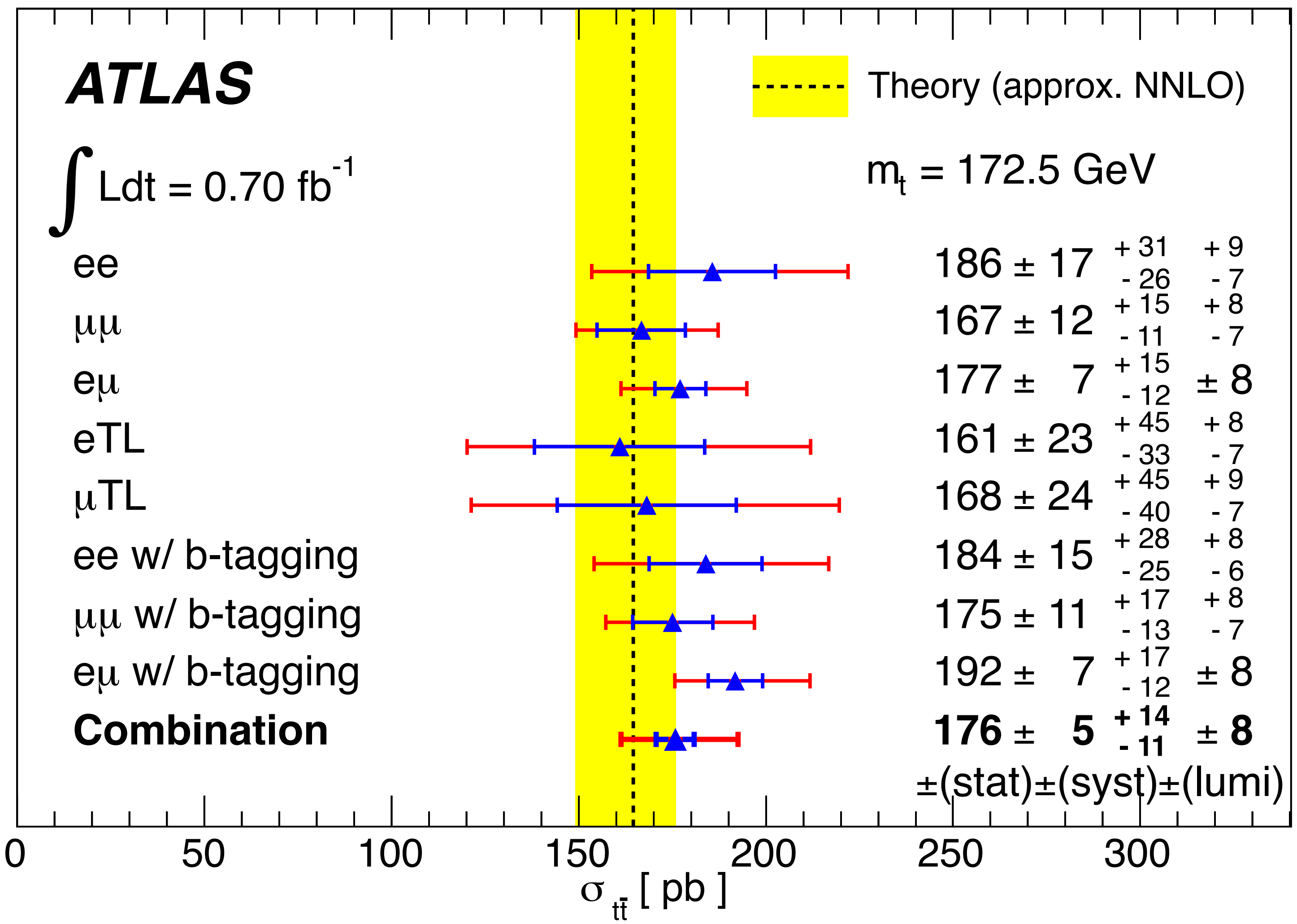
$$\sigma = \frac{N_{obs} - N_b}{\epsilon L}$$

Systematic uncertainties are key

Uncertainties $\Delta\sigma/\sigma$[%]	ee	$\mu\mu$	$e\mu$	eTL	μTL	Combined
Data statistics	$\pm$8.1	$\pm$6.1	$\pm$3.9	$\pm$14.1	$\pm$14.2	$\pm$2.9
Luminosity	+4.4/-3.8	+4.4/-3.9	$\pm$4.2	+5.1/-4.2	+5.4/-4.4	$\pm$4.3
MC statistics	$\pm$1.6	$\pm$1.2	$\pm$0.8	$\pm$5.5	$\pm$4.6	+0.7/-0.6
Lepton uncertainties	+6.2/-5.4	+2.9/-1.3	$\pm$3.1	$\pm$4.1	+1.8/-1.6	+2.6/-2.2
Track leptons	—	—	—	$\pm$4.4	$\pm$1.9	+0.3/-0.2
Jet/E_T^{miss} uncertainties	+5.7/-5.7	+6.4/-3.5	+4.7/-3.2	+14.8/-6.4	$\pm$13.1	+4.4/-3.4
b-tagging uncertainties	+1.2/-1.0	$\pm$0.7	—	—	—	+0.4/-0.0
Z/γ^*+ jets evaluation	$\pm$0.4	+0.5/-0.0	—	$\pm$6.2	+2.4/-2.7	+0.3/-0.2
Fake lepton evaluation	$\pm$3.3	1.5/-1.3	$\pm$3.0	$\pm$13.7	$\pm$15.1	$\pm$1.7
Generator	+12/-11	+4.5/-4.3	+4.8/-4.5	+14/-11	+14/-13	+5.1/-4.9
All syst.(except lumi.)	+16.4/-14.4	+8.8/-6.4	+8.2/-6.8	+27.9/-20.7	+26.5/-23.7	+8.0/-6.5
Stat. + syst.	+18.9/-16.9	+11.6/-9.5	+10.1/-8.8	+31.8/-25.2	+30.7/-27.8	+9.6/-8.2

Dilepton Cross Section

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



NNLO+NNLL prediction: 172 pb

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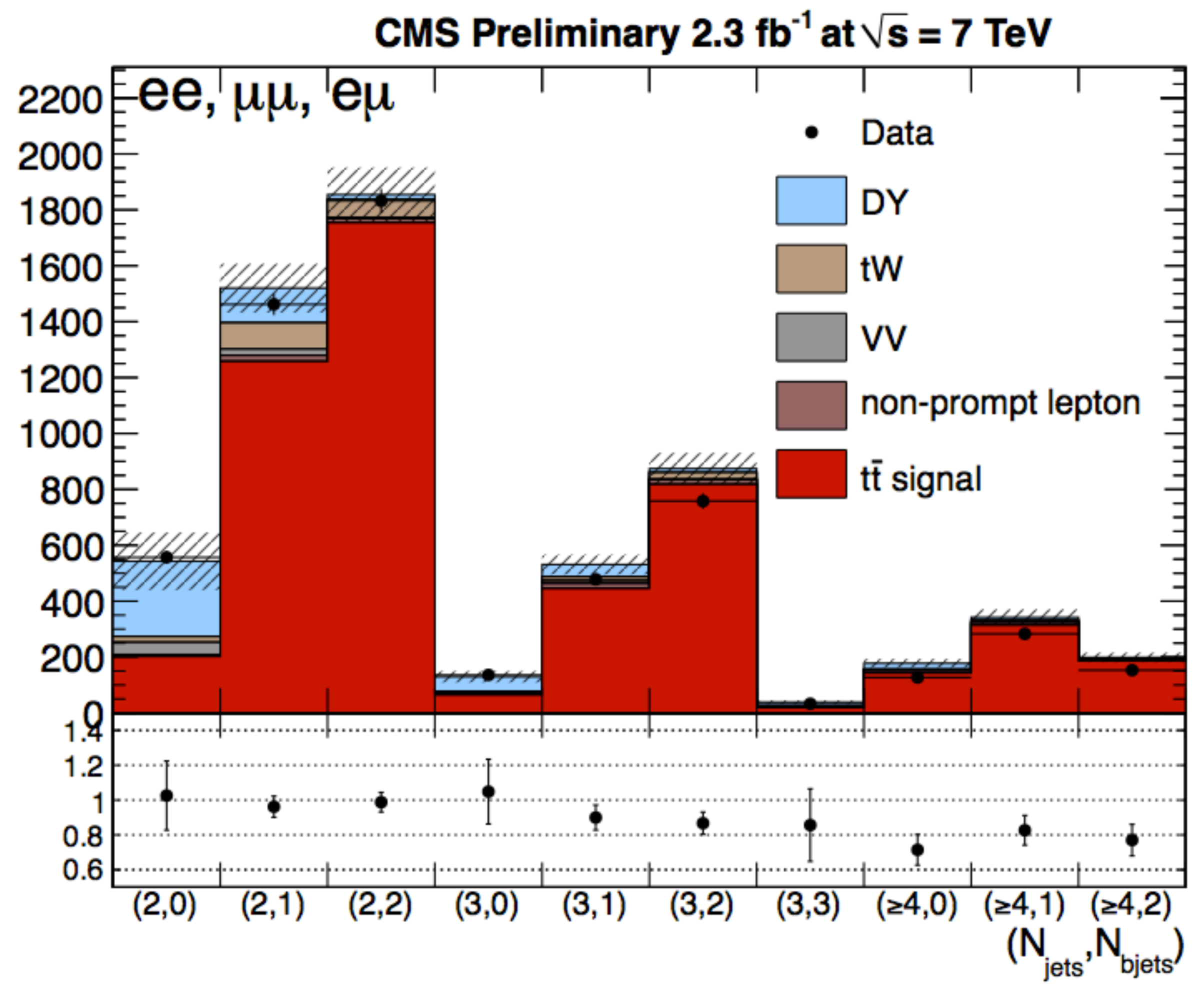
Dilepton Cross Section

- CMS analysis using 2011 data reaches <5% precision:



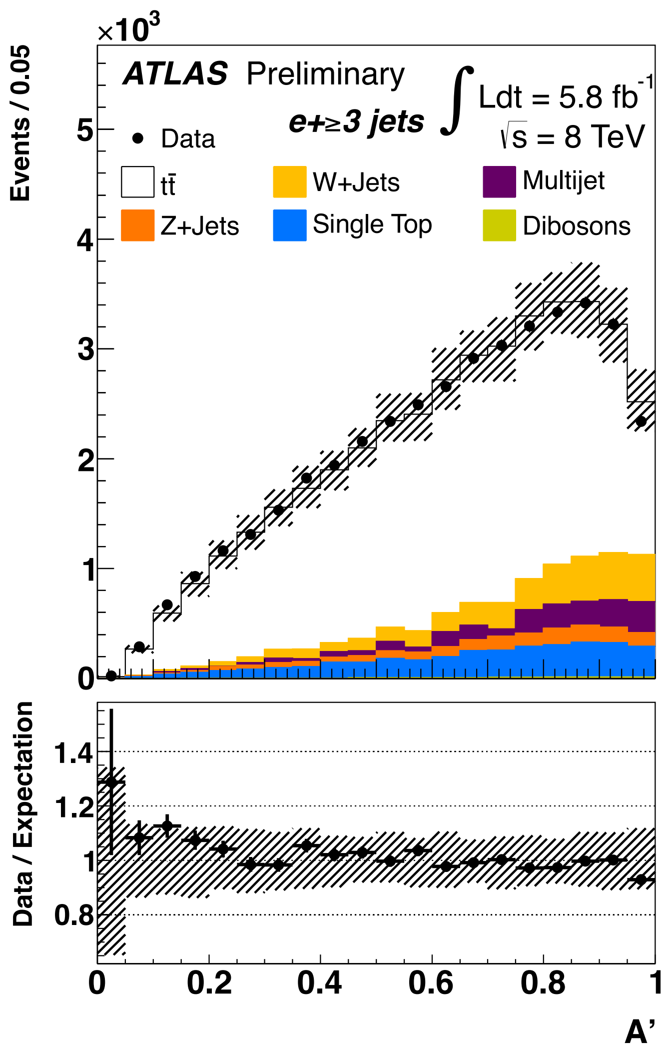
$$\sigma_{t\bar{t}} = 161.9 \pm 2.5(\mathrm{stat.})^{+5.1}_{-5.0}(\mathrm{syst.}) \pm 3.6(\mathrm{lumi})\ \mathbf{pb},\ \delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim 4.2\%$$

Main systematics: lepton efficiencies ~ 2%, jet energy scale ~ 2%

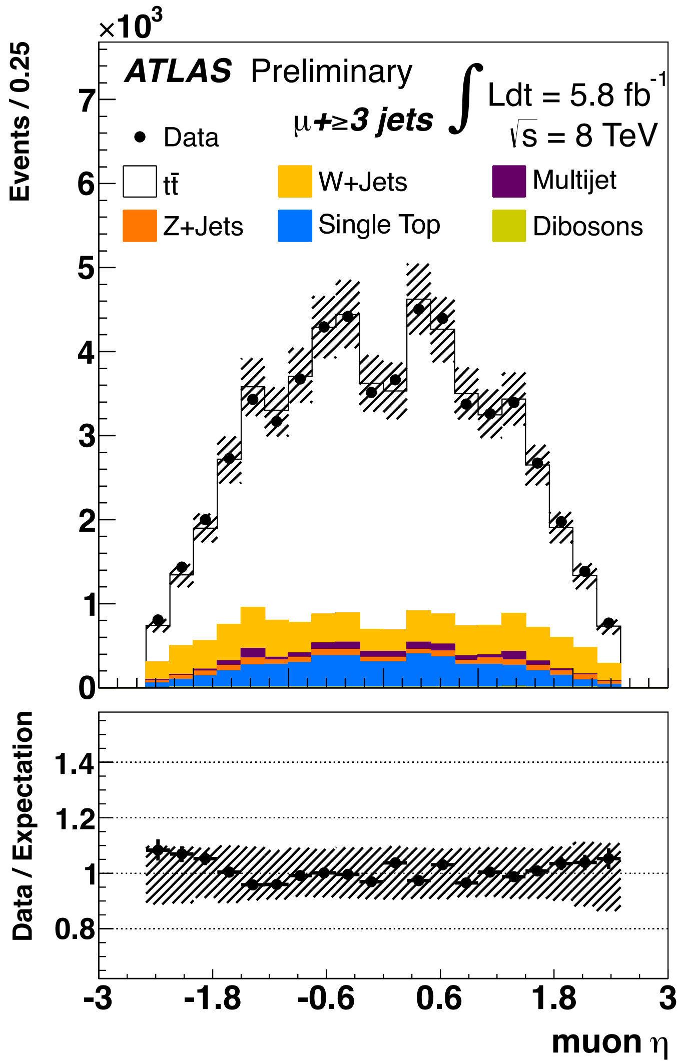
- NB: ttbar modelling uncertainties smaller than ATLAS.

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:



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



Lepton + Jets Cross Section

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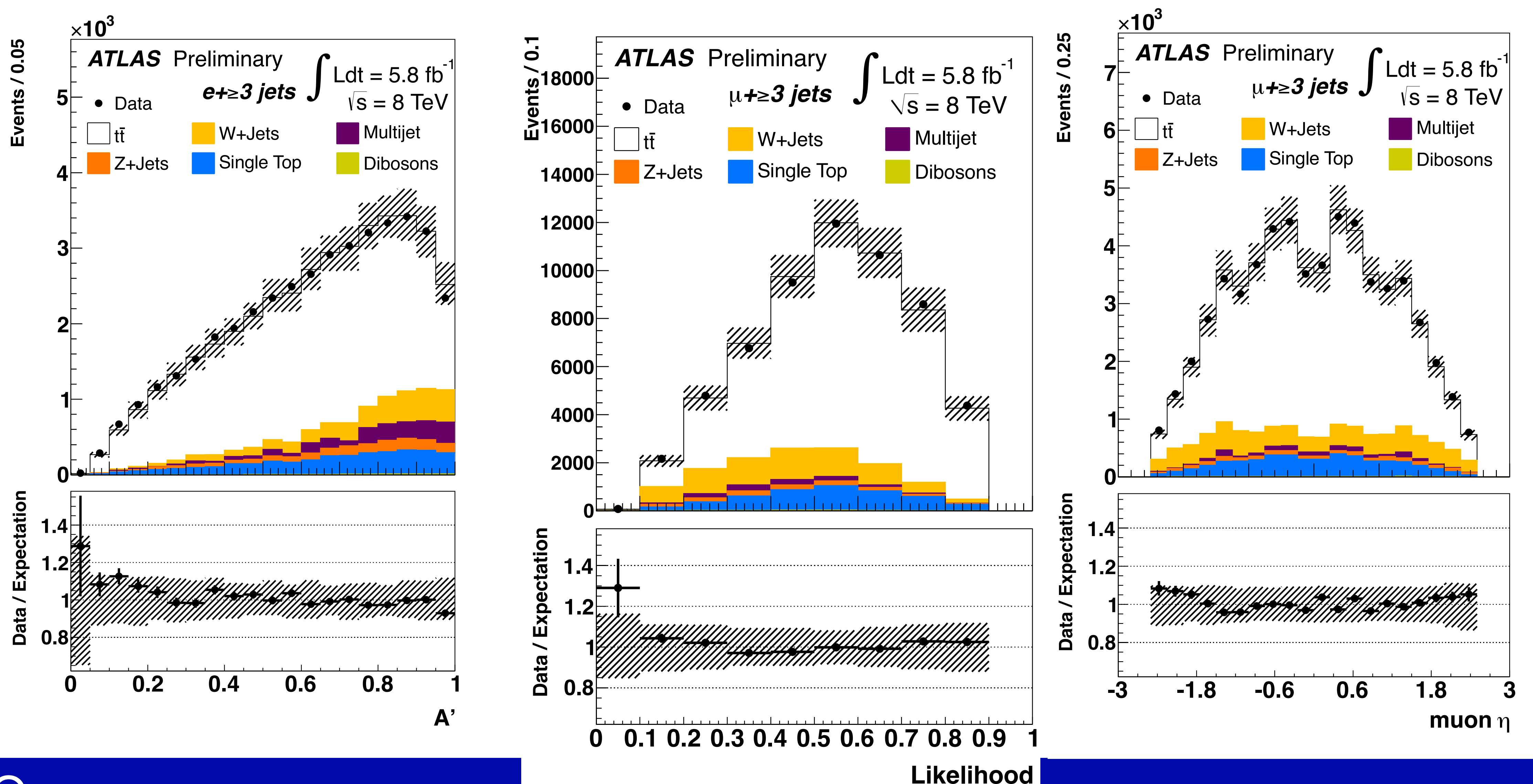


Lepton + Jets Cross Section

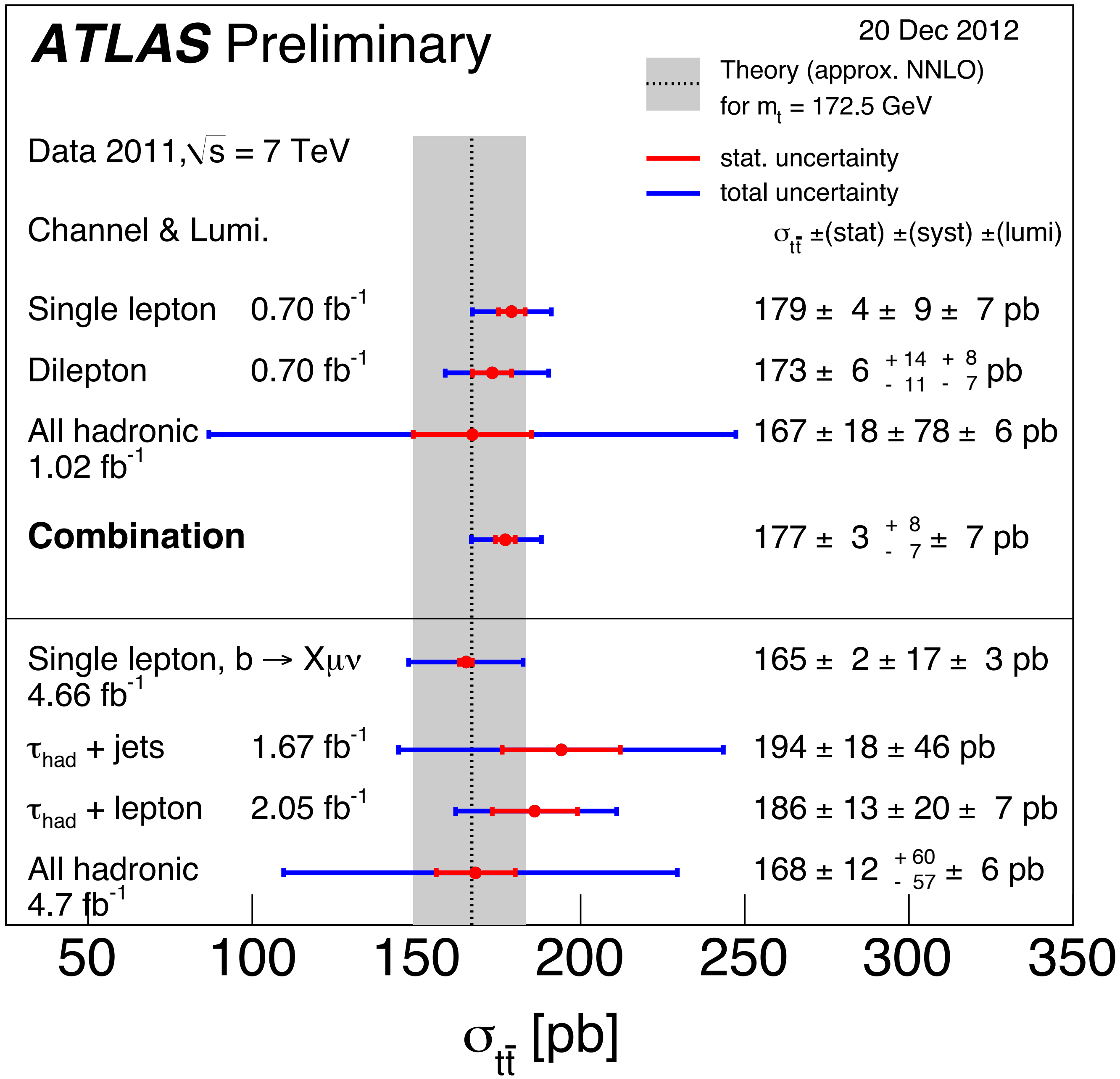
- Fit likelihood distribution for ttbar cross section and W + jets normalization:

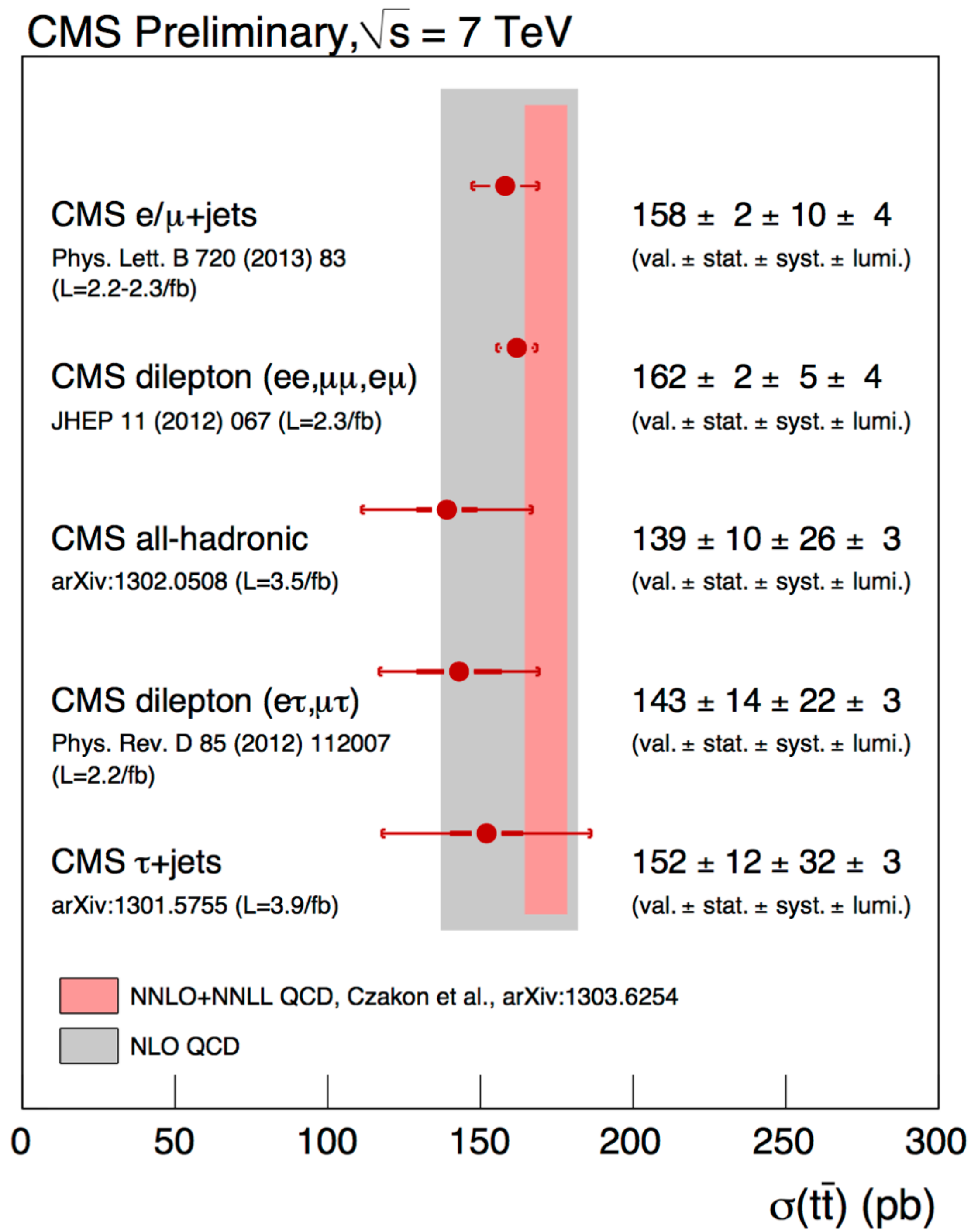
$$\sigma_{t\bar{t}} = 241 \pm 2\ (\text{stat.}) \pm 31\ (\text{syst.}) \pm 9\ (\text{lumi.})\ \text{pb.}$$

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.

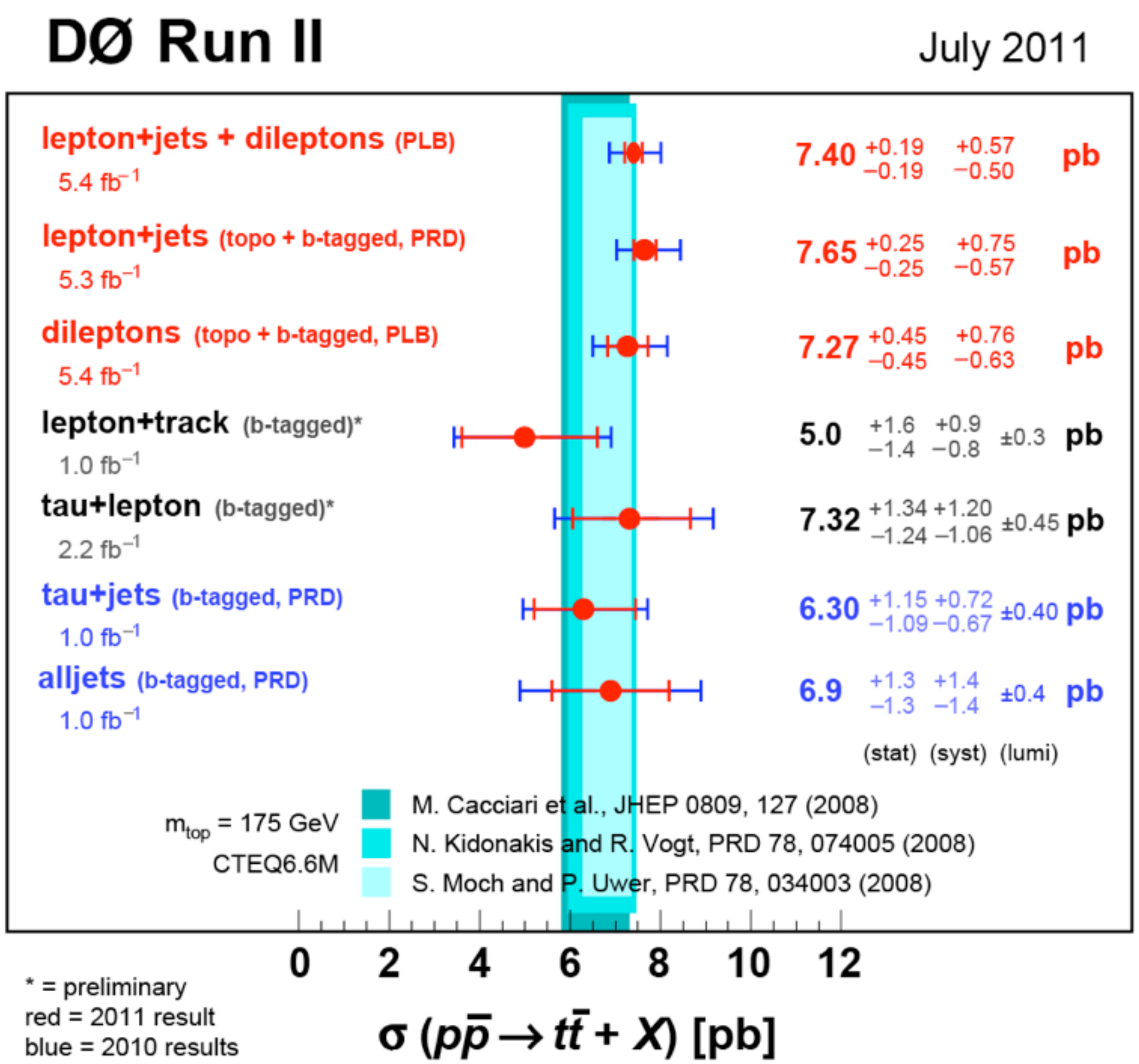
Top Pair Production LHC

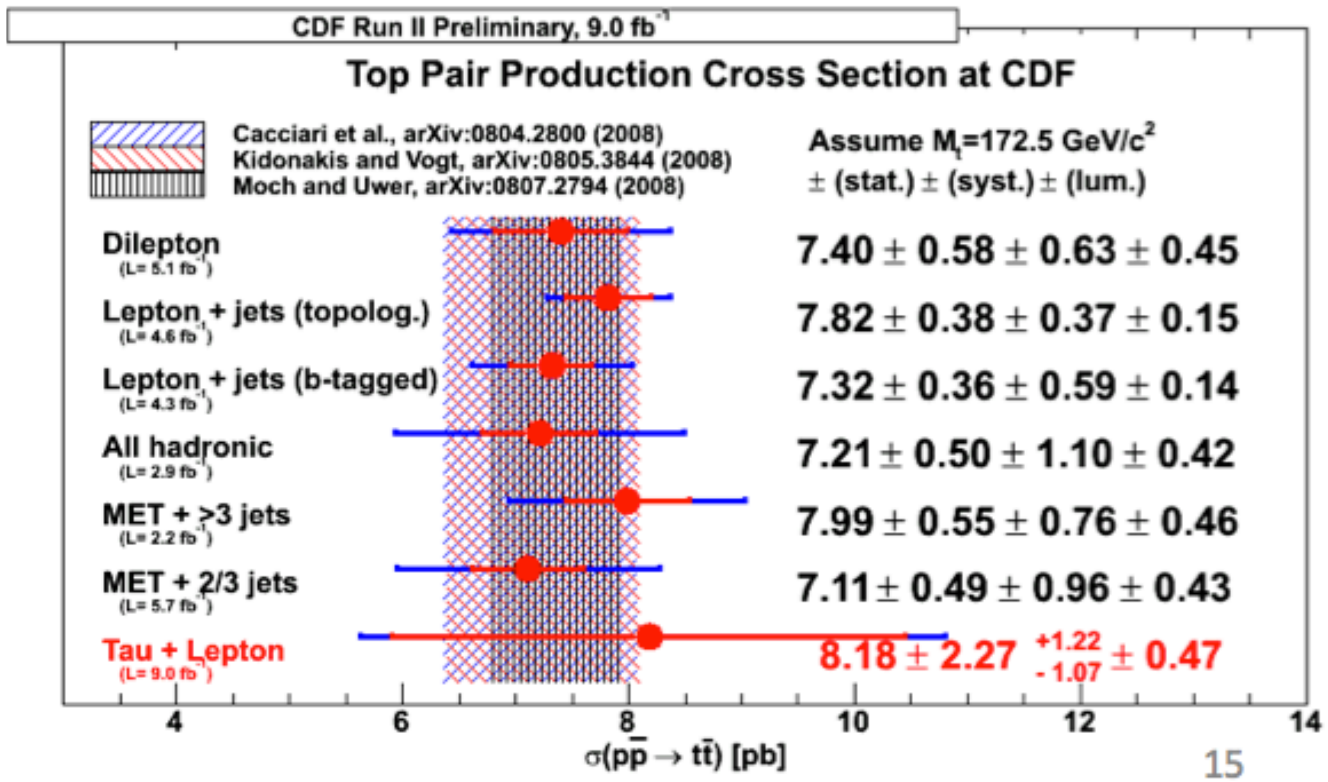




Good agreement with SM in all channels

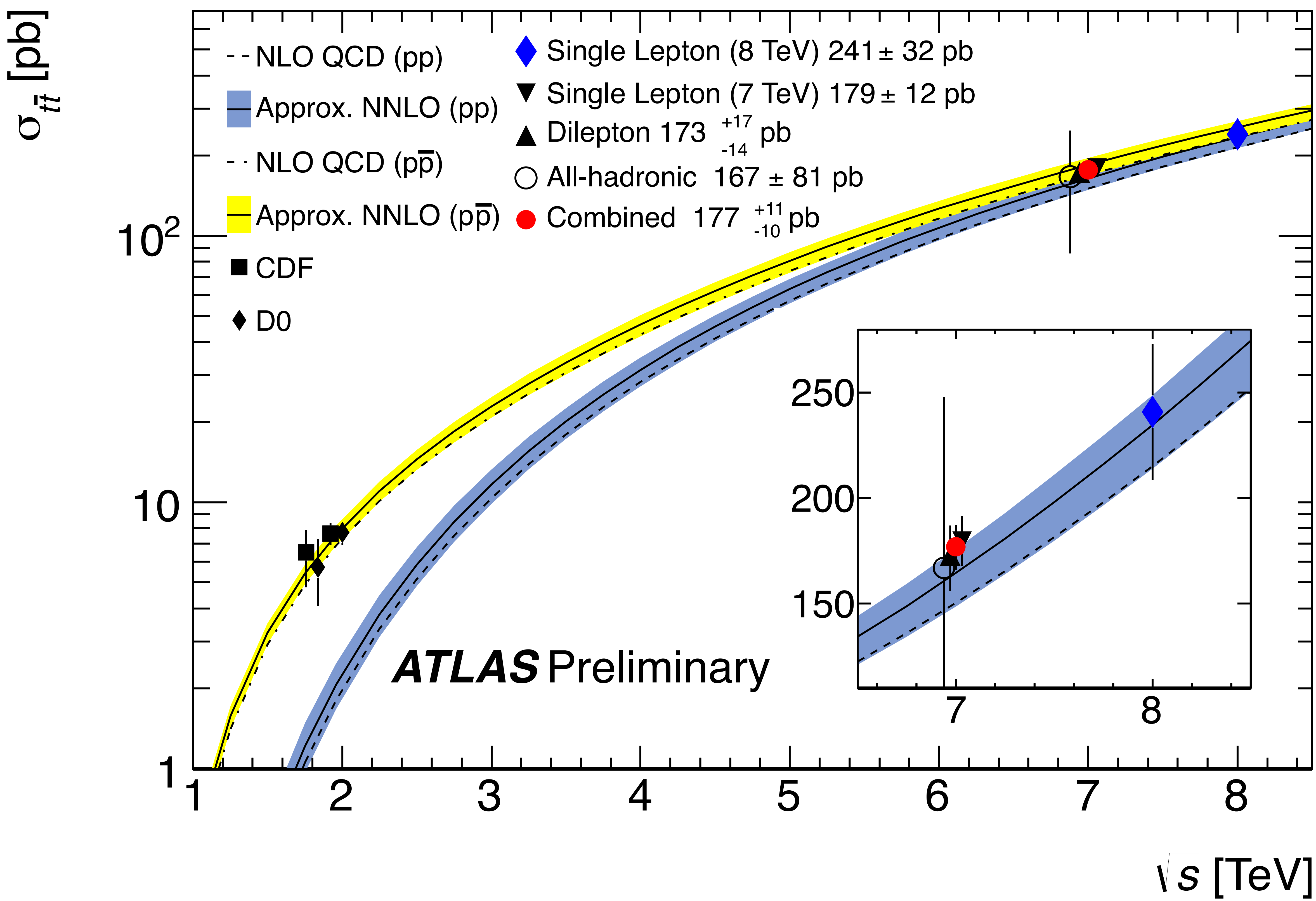
Top Pair Production Tevatron





Good agreement with SM in all channels

Top Pair Production



Top Quark Pair Production:

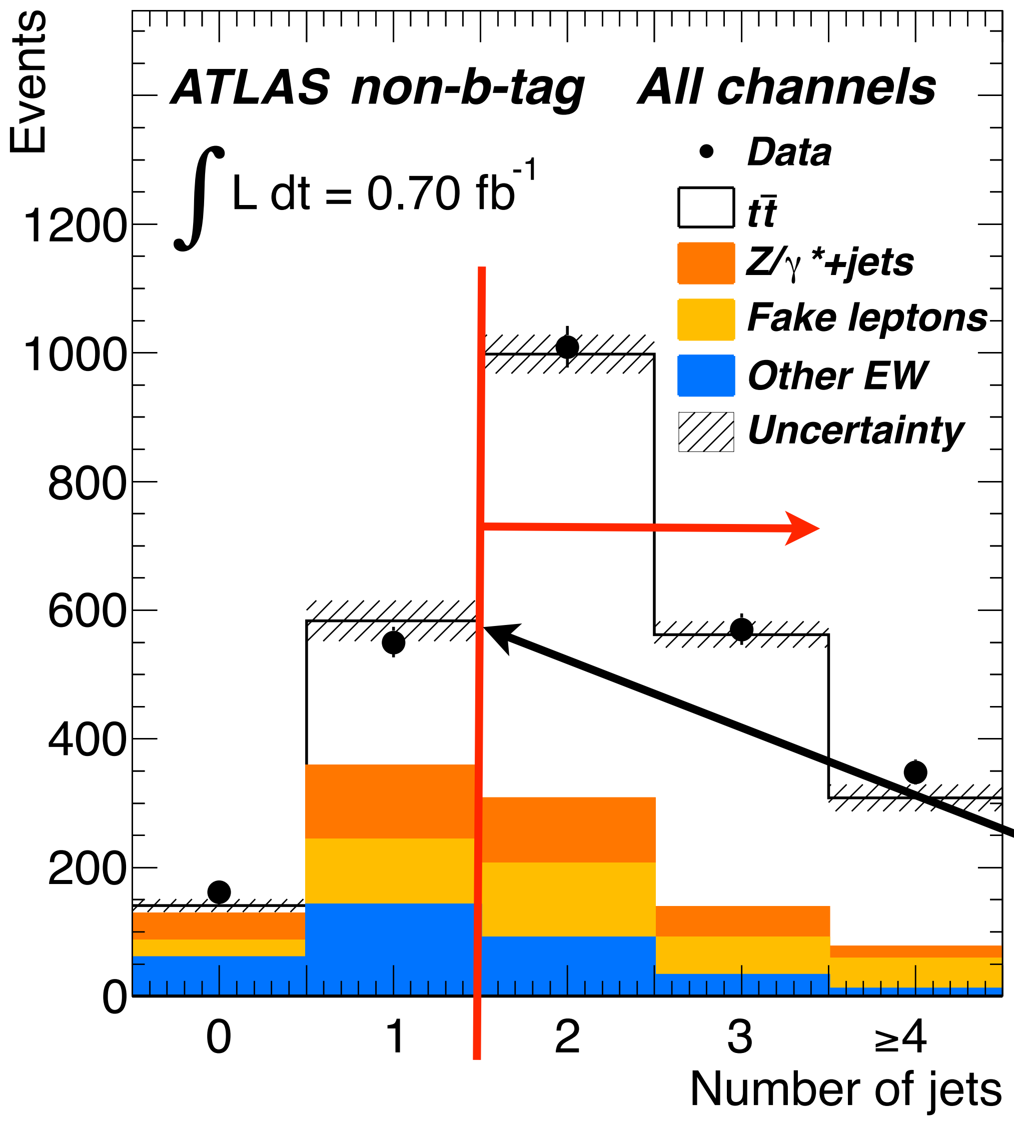
Inclusive cross section

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:



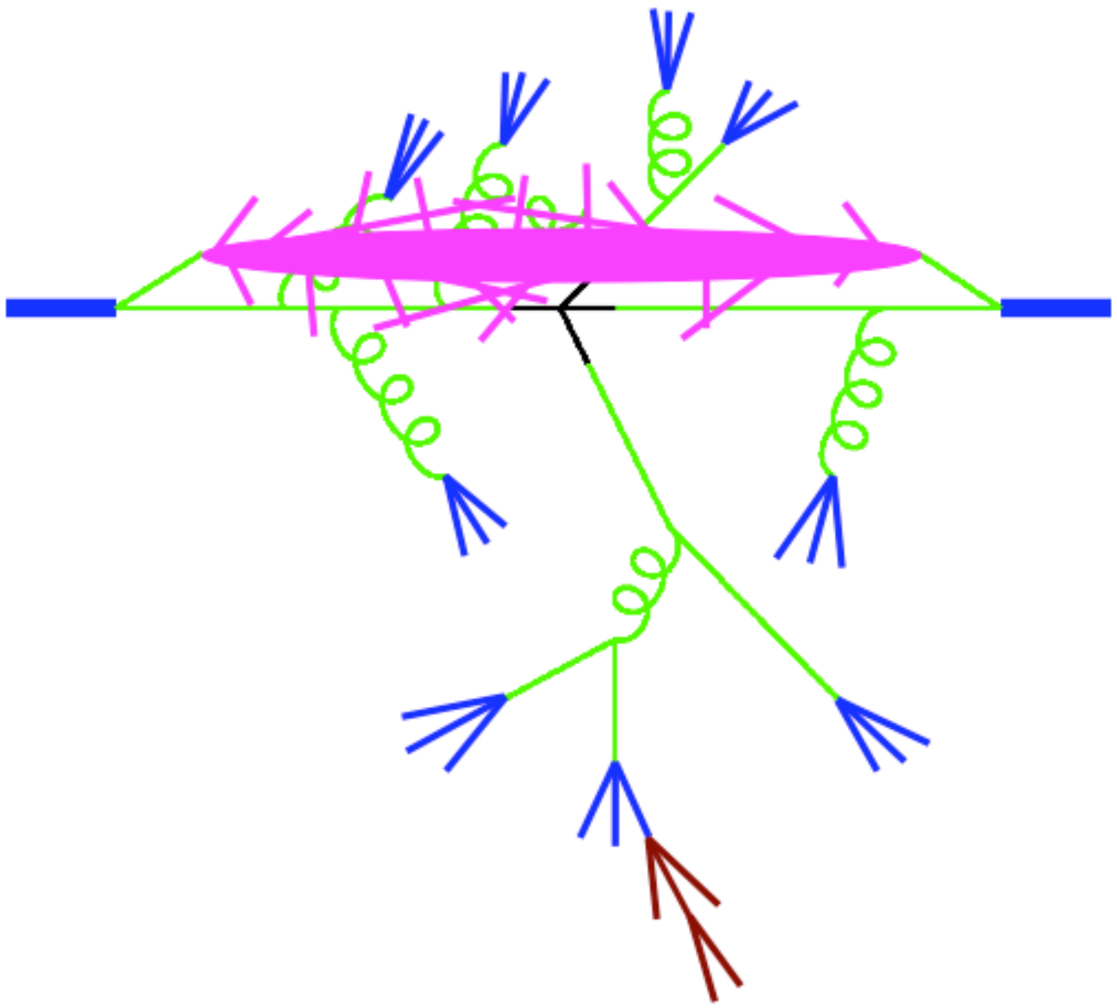
- Extract cross-section by counting events:

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

Selection efficiency evaluated using MC simulation.

Monte Carlo

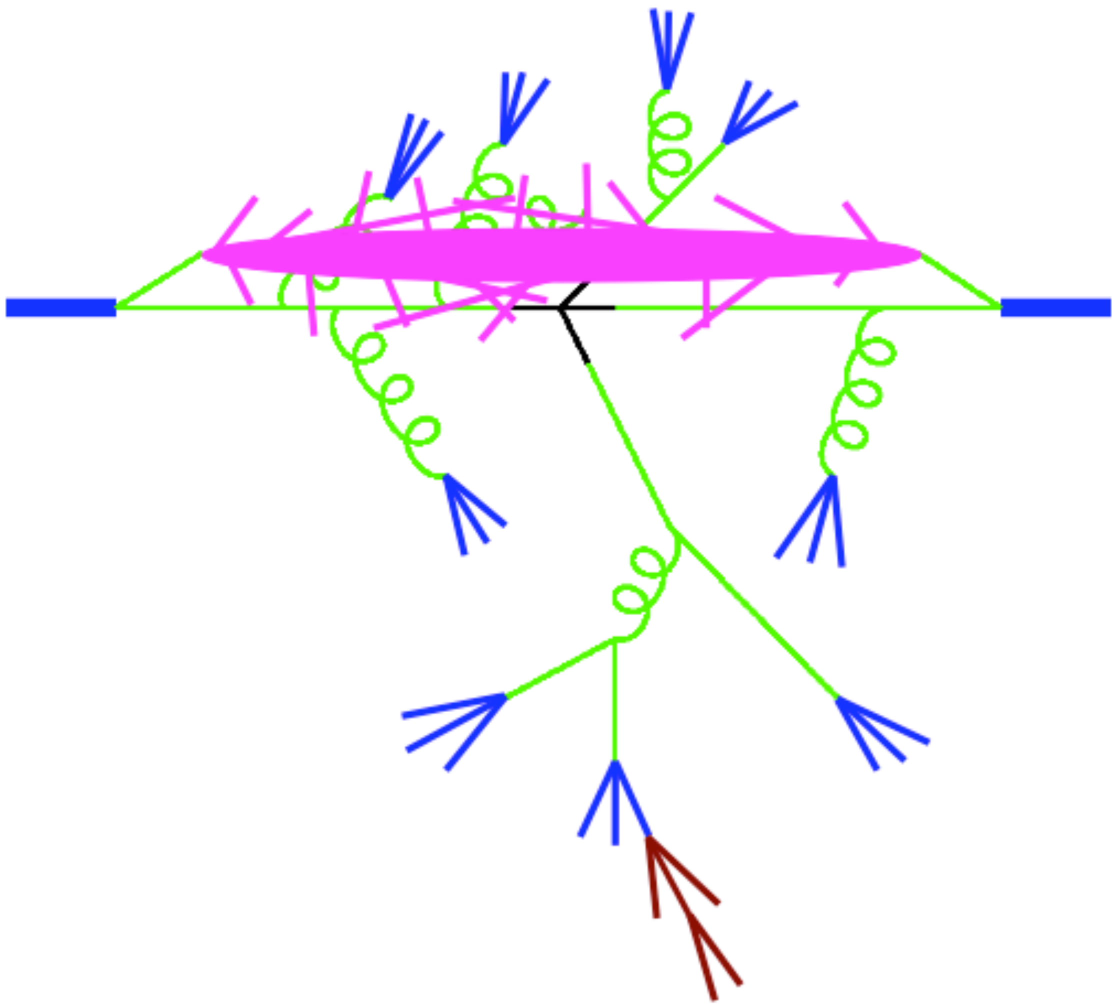
1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays



Monte Carlo

ttbar in perturbative QCD

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

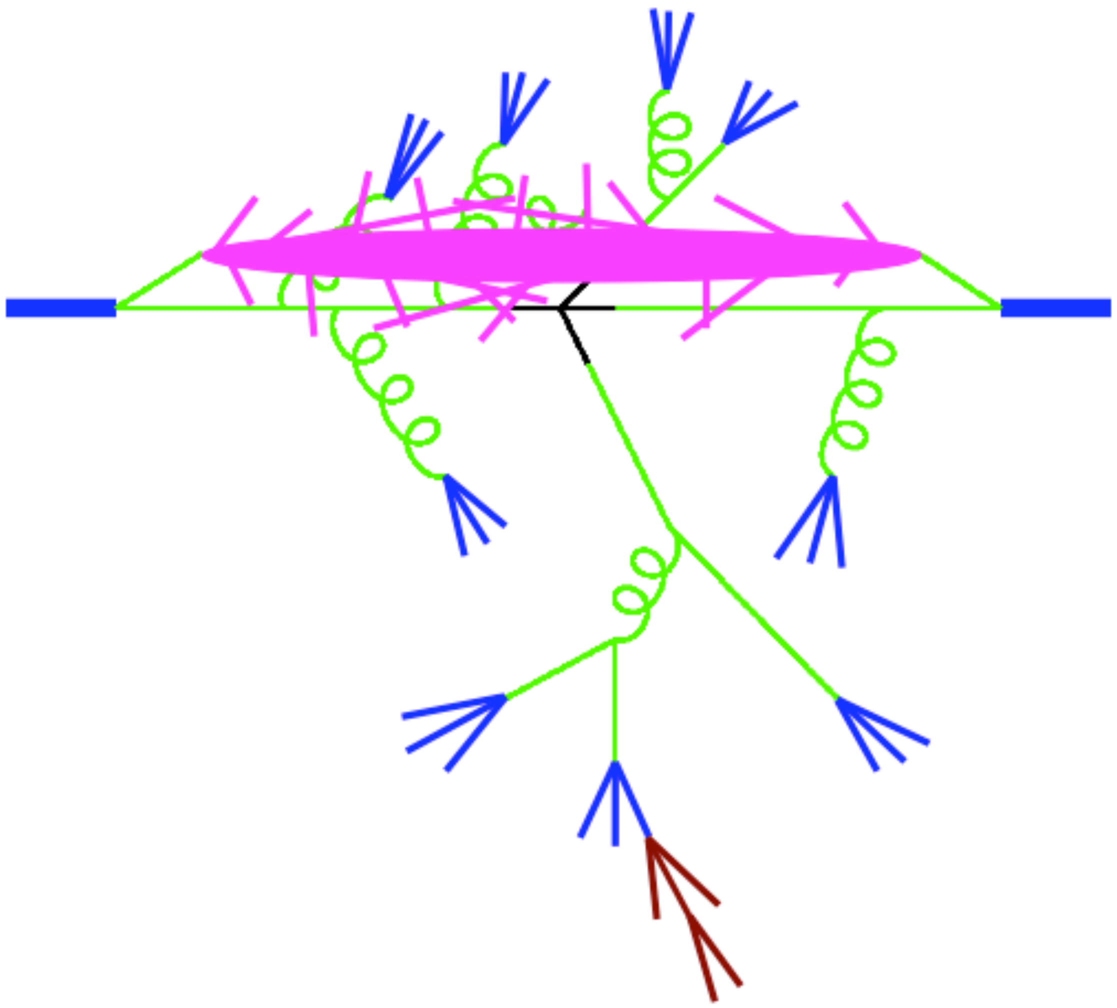


Monte Carlo

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
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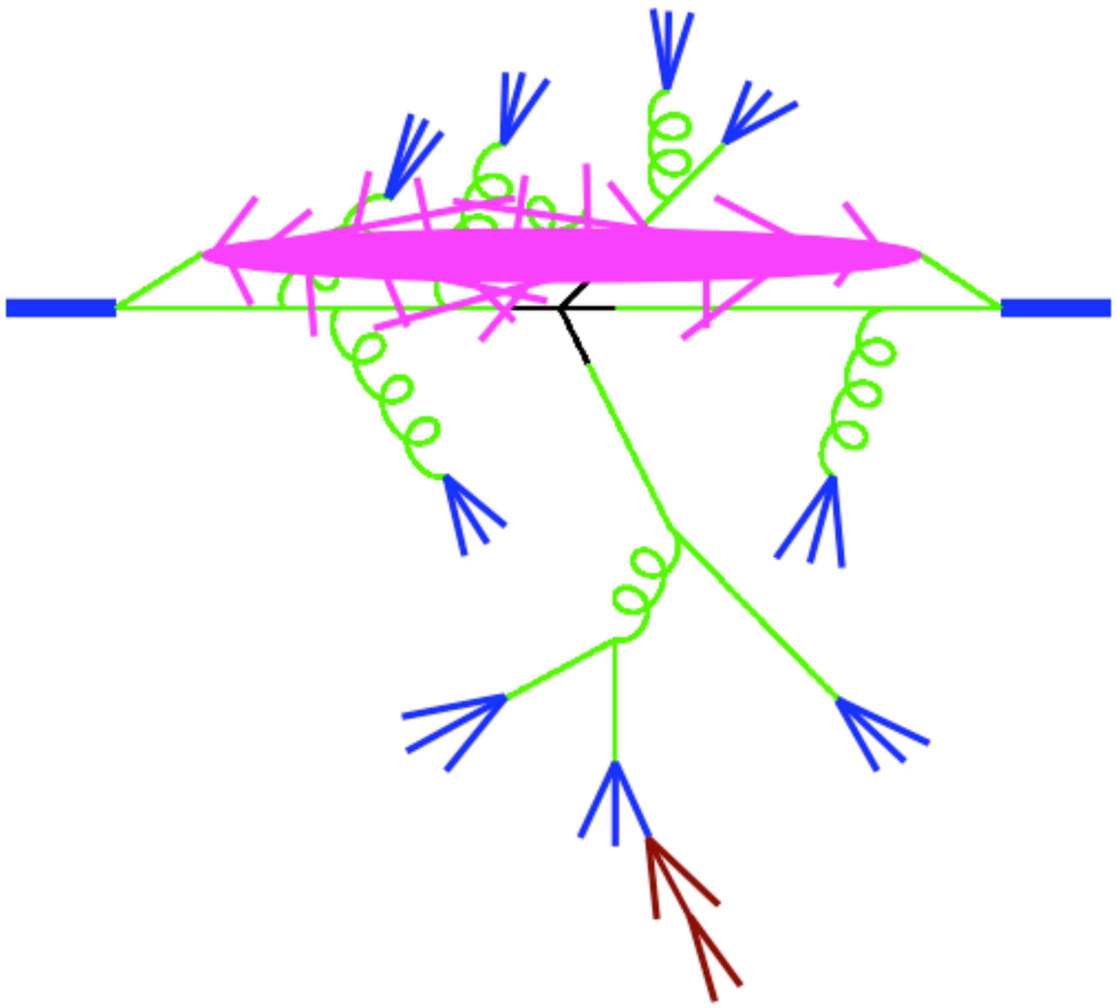
5. Unstable particle decays



Monte Carlo

ttbar in perturbative QCD

Soft / collinear approximation for QCD radiation

Non-perturbative model

Important for e.g. b-decays

1. Hard process
2. Parton shower
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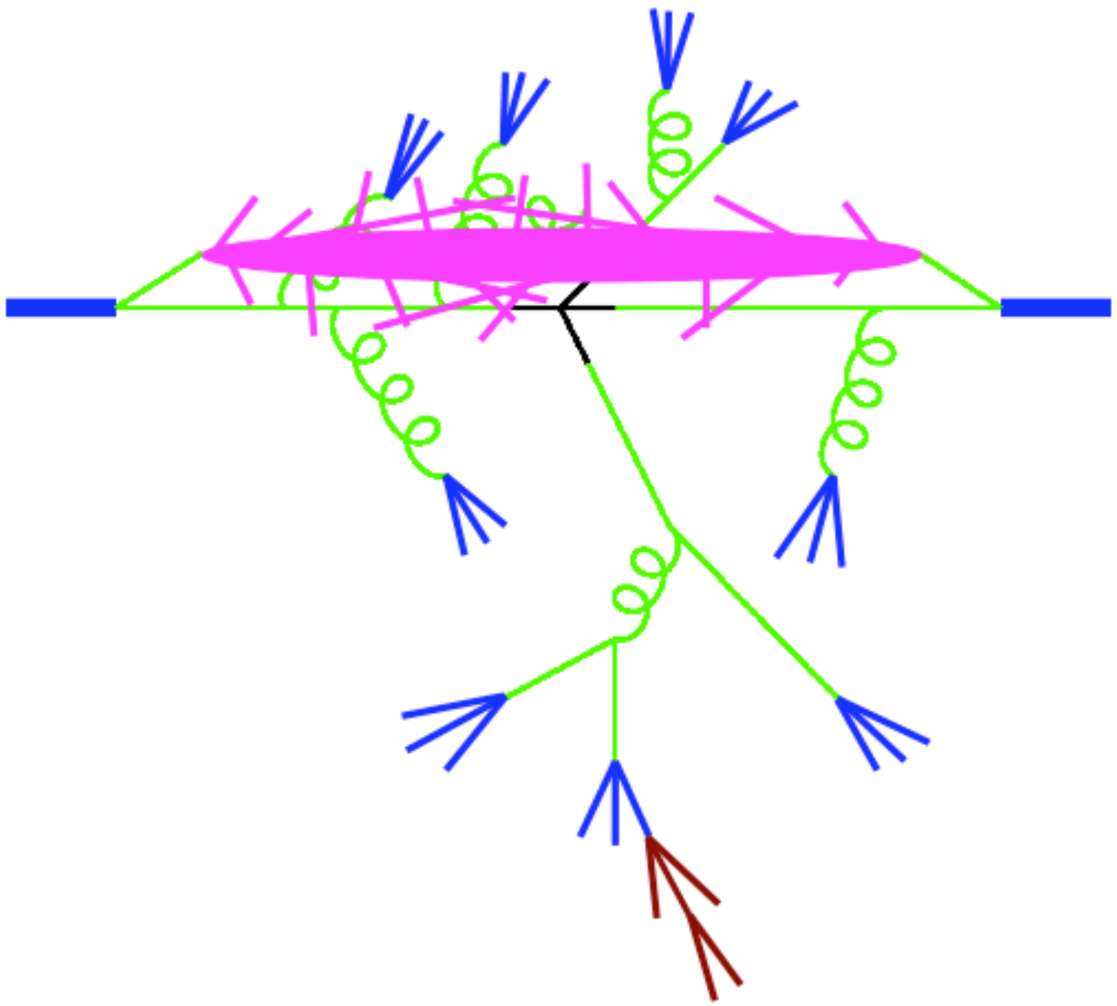

Monte Carlo

ttbar in perturbative QCD ← LO, Multi-leg LO, NLO

Soft / collinear approximation for QCD radiation

Non-perturbative model

Important for e.g. b-decays

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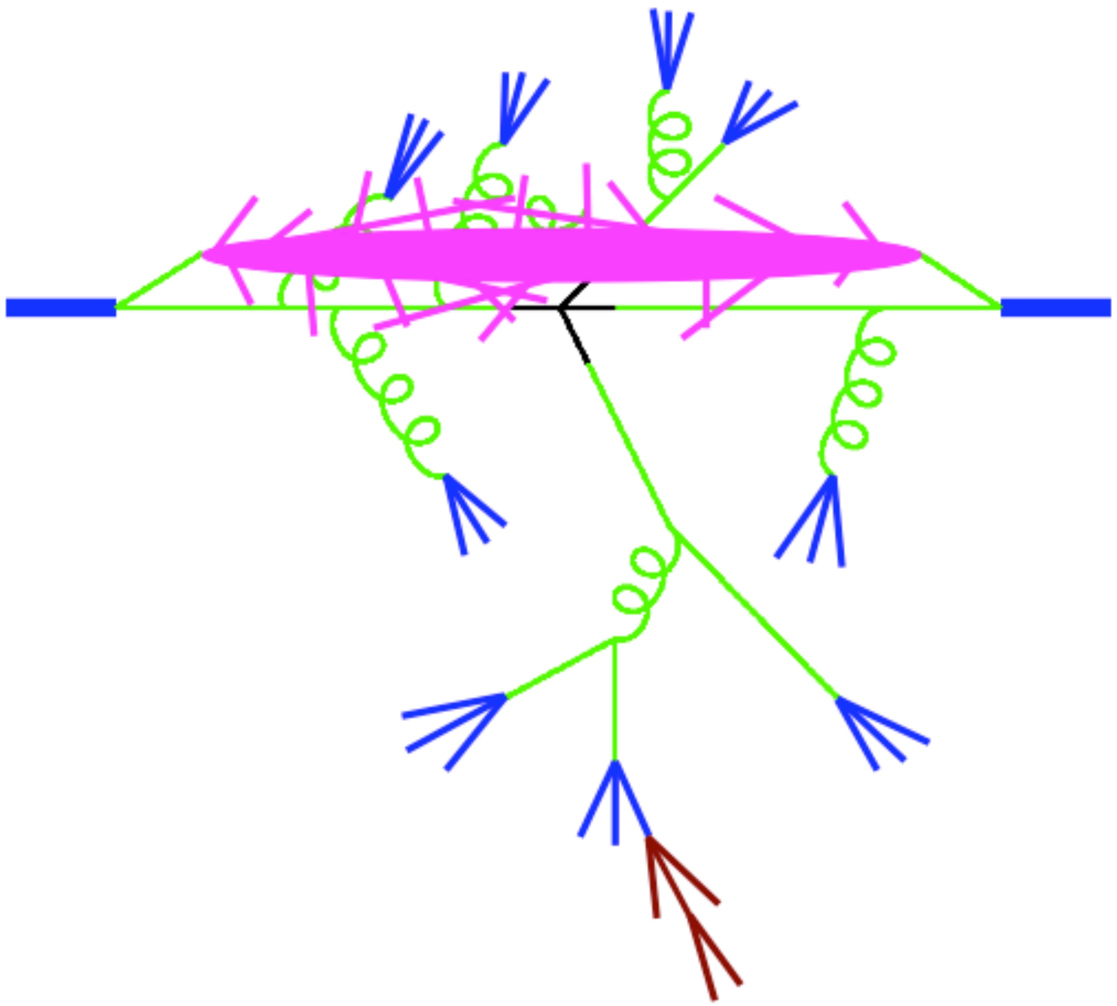
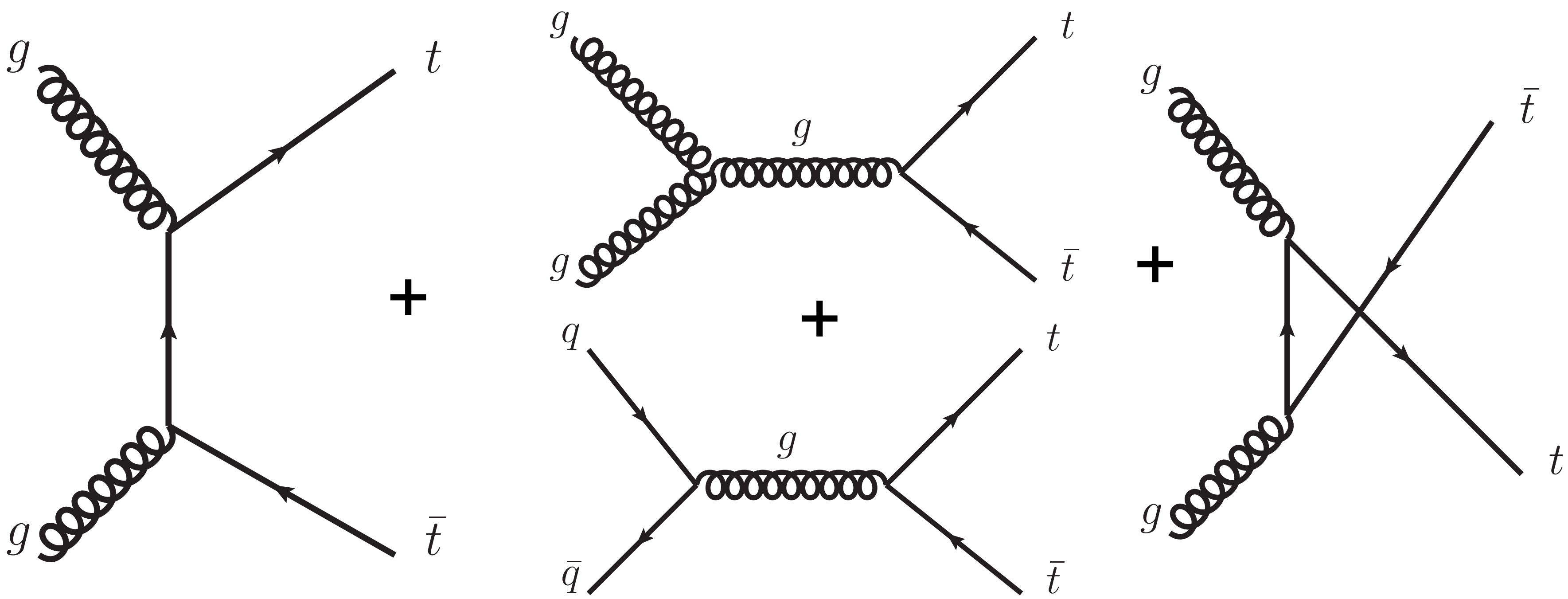
4. Underlying event
5. Unstable particle decays



Leading Order MC

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



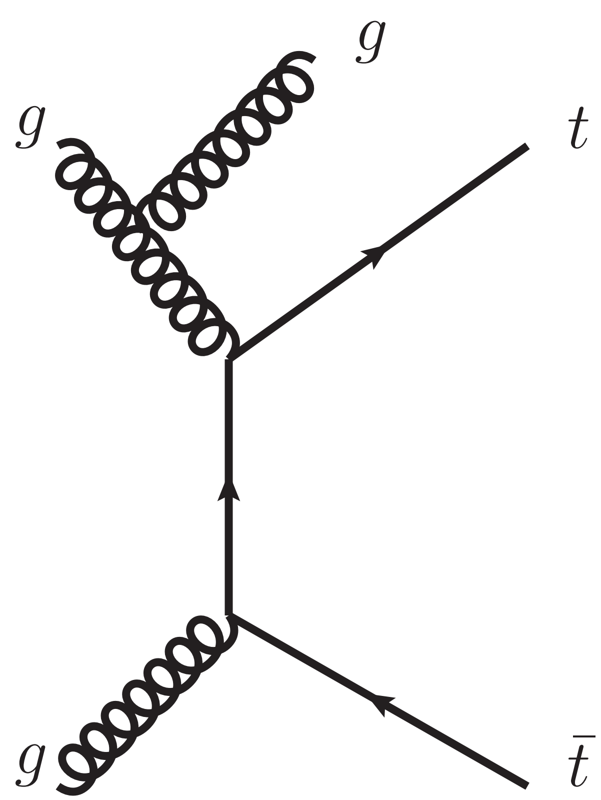
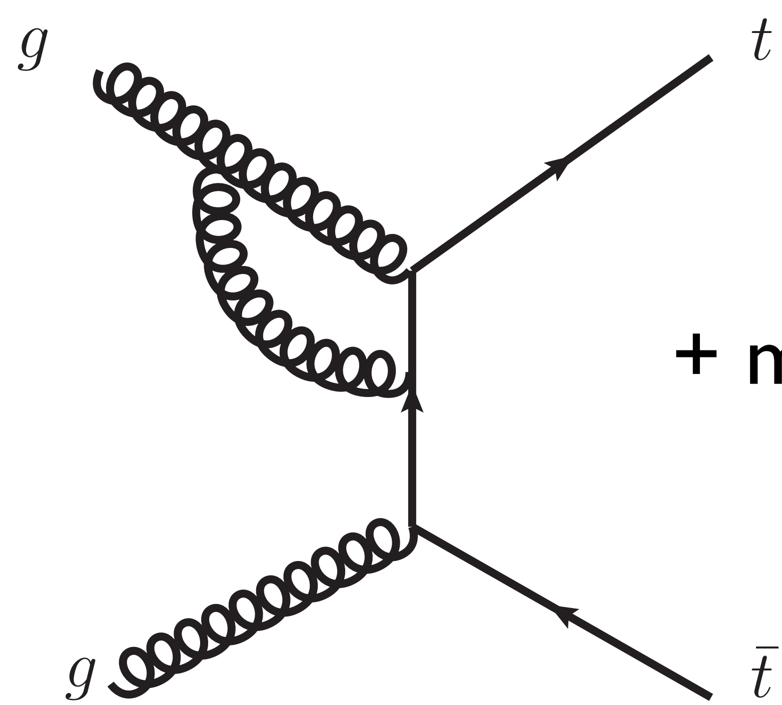
Pythia, Herwig, AcerMC, ...

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

Next-to-Leading Order MC

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

MC@NLO, Powheg

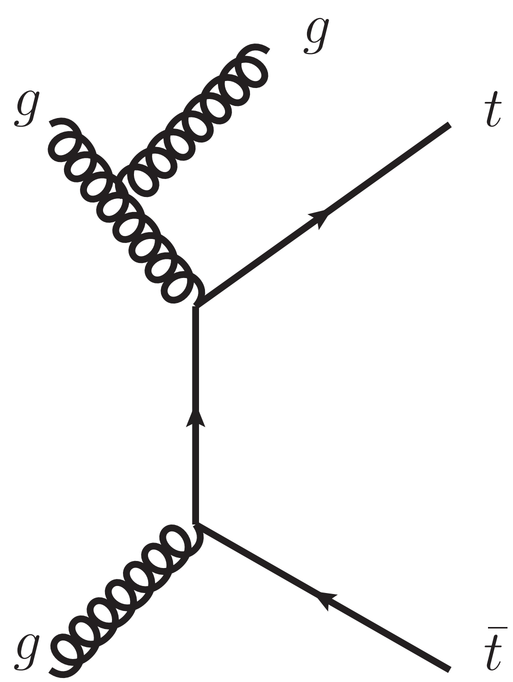
LO +  +  + many others

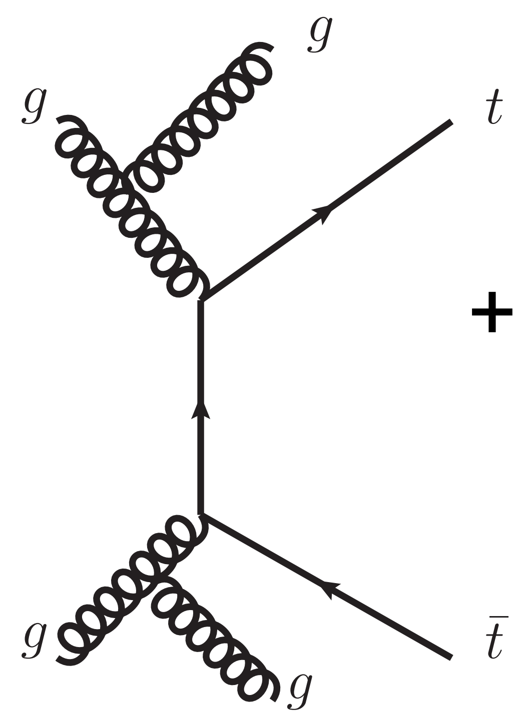
- First emission now in the hard process - expect better modelling compared to LO.
- Additional emissions from parton shower - matching procedure needed to avoid double counting.

Multi-leg LO MC

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

Alpgen, Sherpa, Madgraph

LO + 

+ 

+ many others

- 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.

MC Generators

- 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 (~3-5) 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:

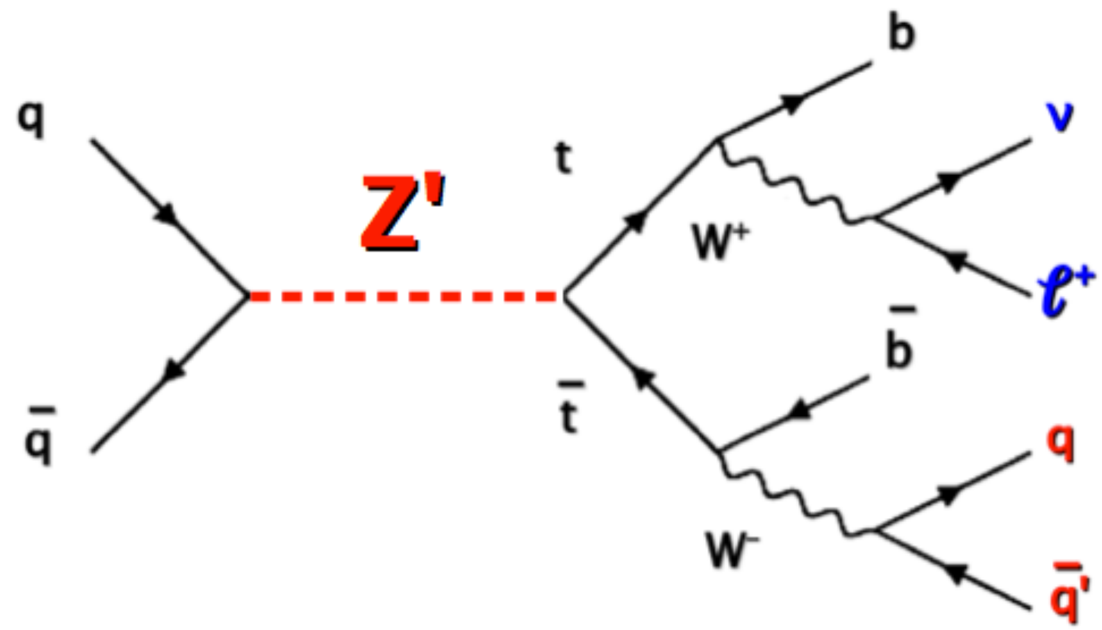
Inclusive cross section

Modelling top quark production

Differential cross sections

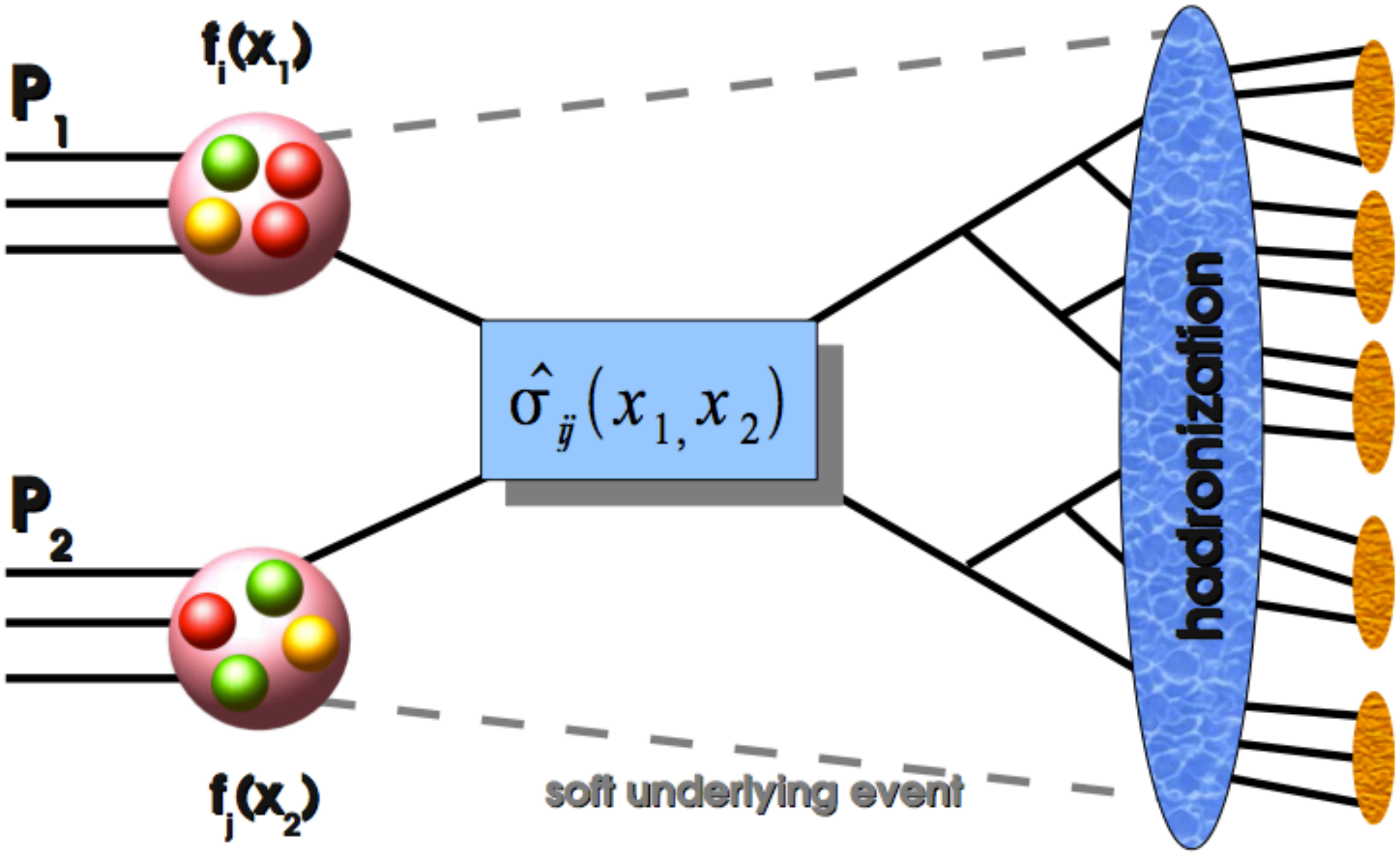
Differential Cross Sections

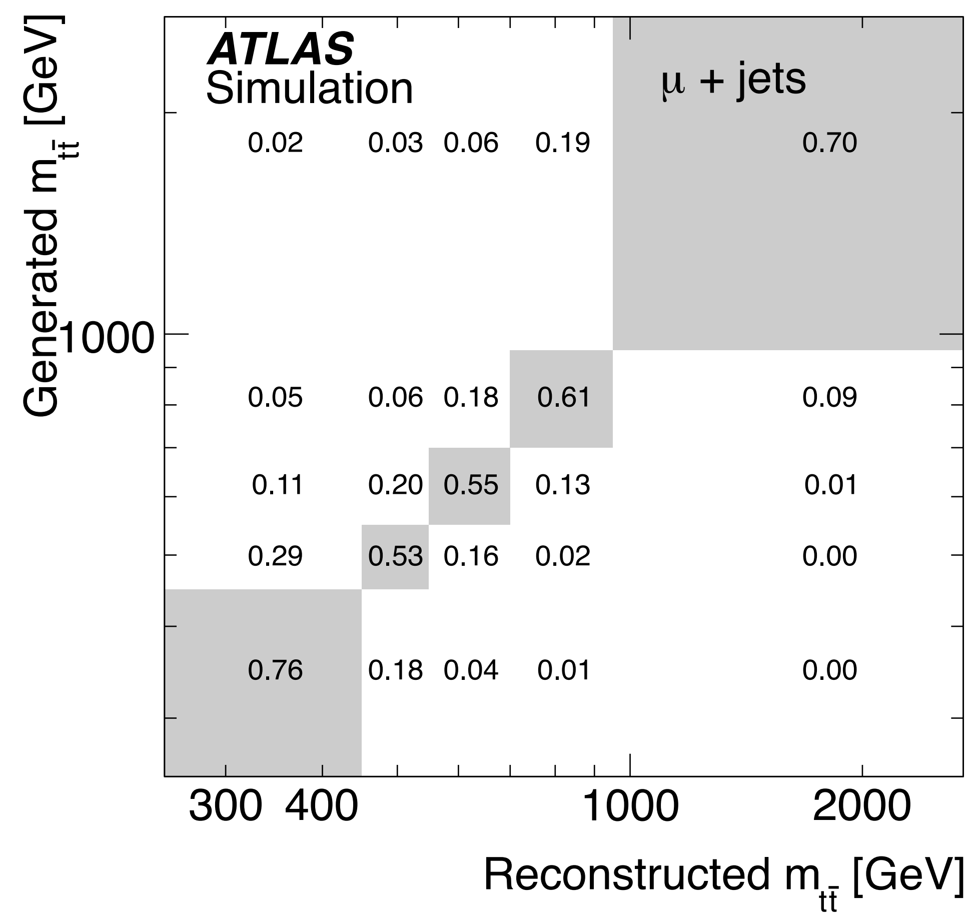
- Vital to test the theory beyond the inclusive cross section.
- Measure differential distributions of the top quarks themselves, but also measure top quarks produced with additional jets.
  - Test MC description of the data.
  - Test of new physics in tails, e.g. of invariant ttbar mass.



Differential Cross Sections

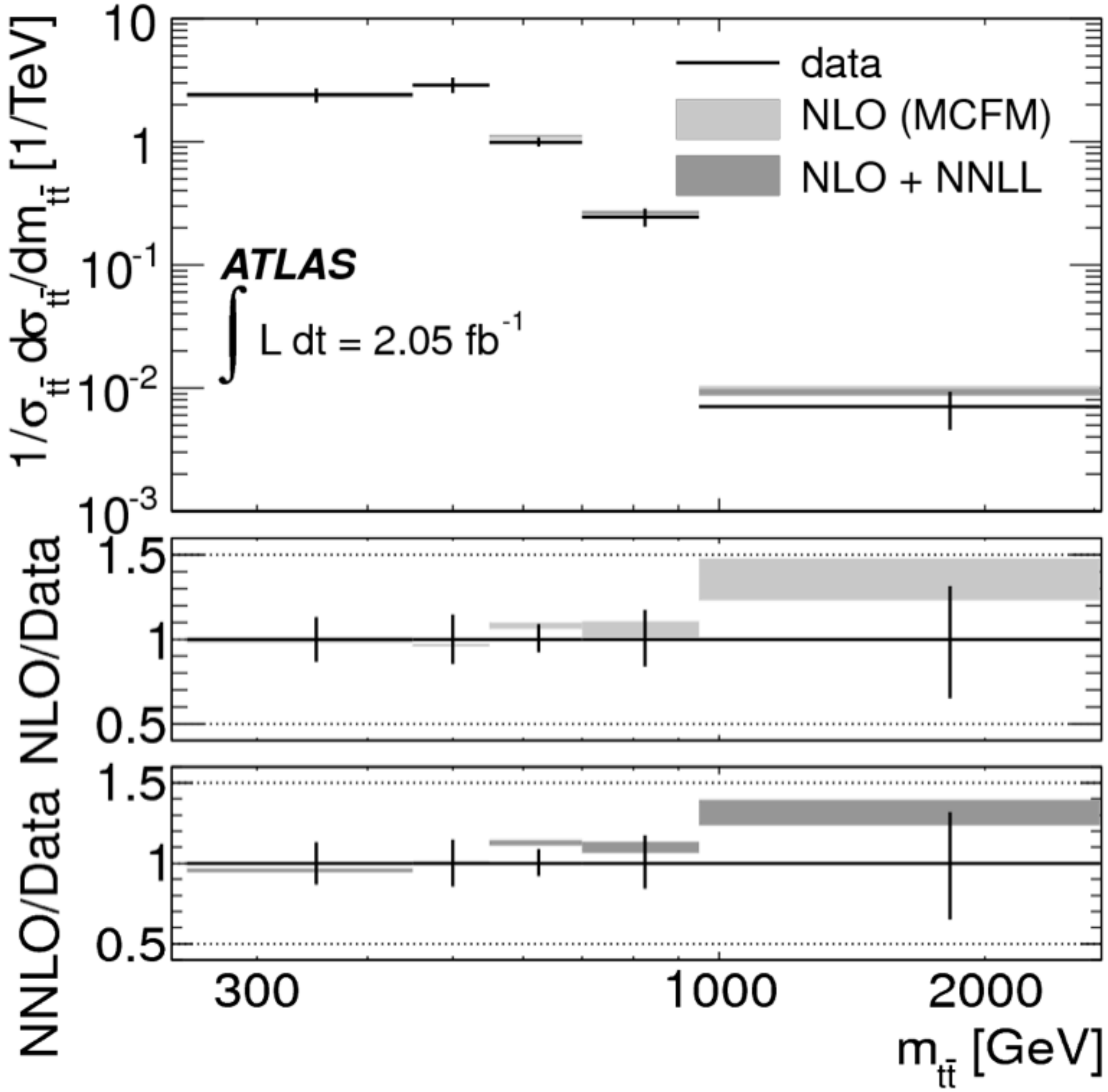
- Challenging measurements to go from detector measurements to underlying physics - have to ‘unfold’ detector effects:

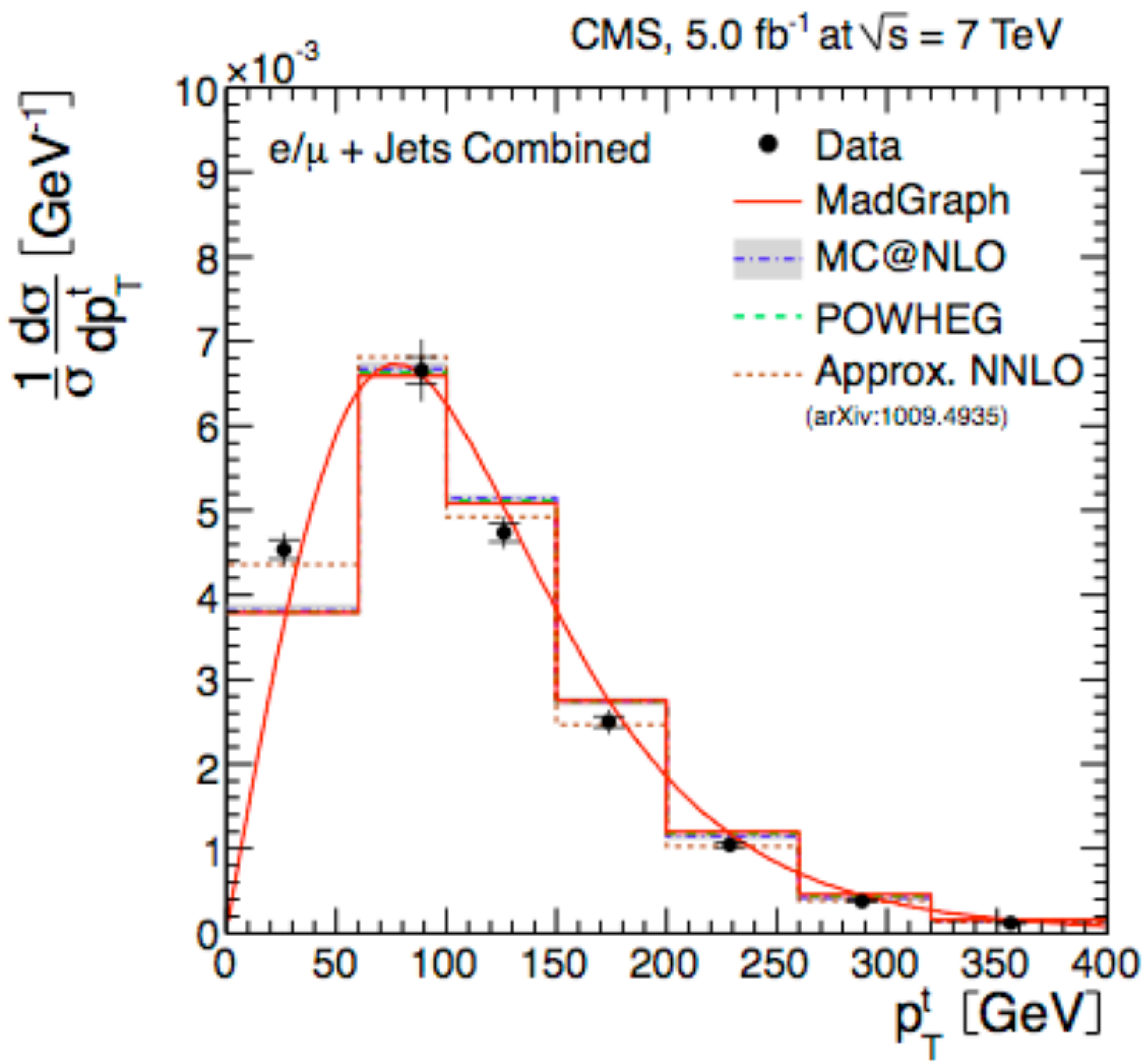




Differential Cross Sections

- Kinematic variables of top quarks:

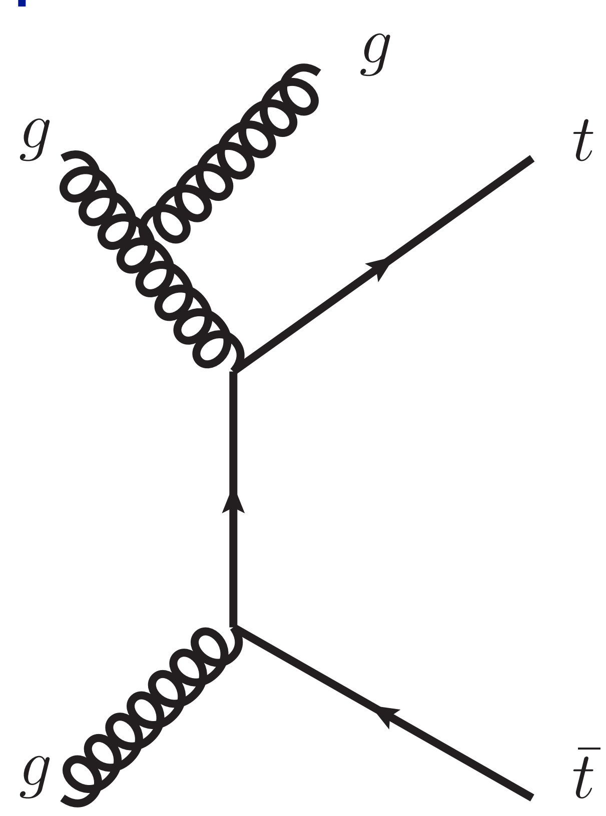




- Good agreement with SM.

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.



Jet veto measurement

- Select dilepton events with at least two b-tagged jets.
- Using the selected events, measure the fraction of events without an additional jet:

$$f(Q_0) = \frac{n(Q_0)}{N}$$

$$n(Q_0) = \text{Number of } t\bar{t} \text{ events with no jet with } p_T > Q_0$$

$$N = \text{Total number of } t\bar{t} \text{ events}$$

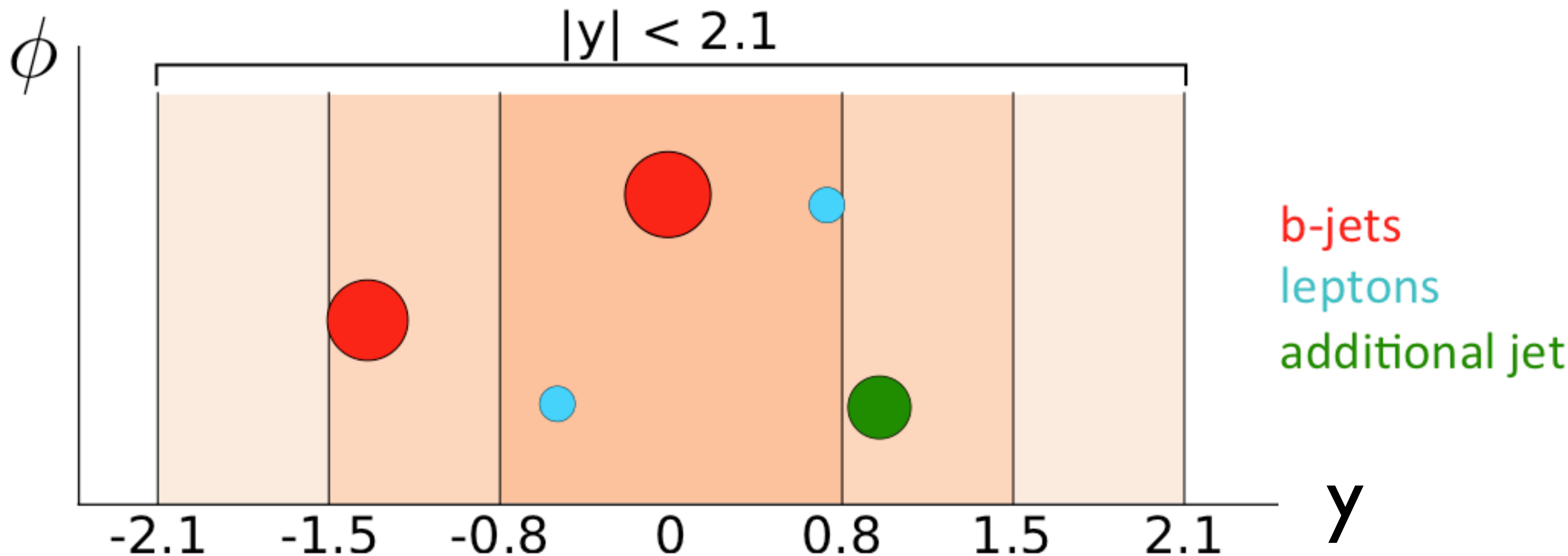
- Ratio measurement - many systematic uncertainties affect both n & N and largely cancel.
- Ratio directly sensitive to the amount of additional radiation.

Jet veto measurement

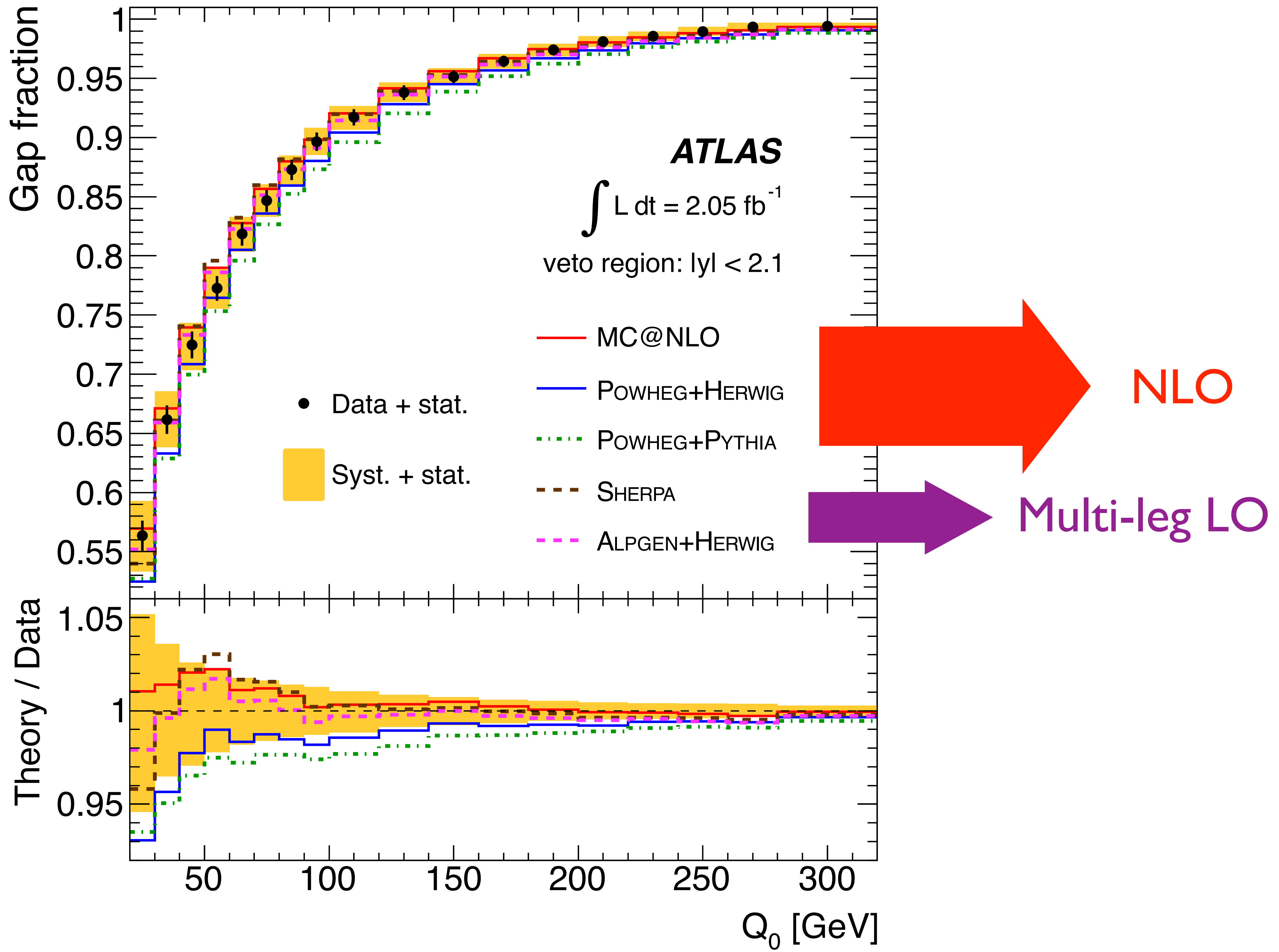
$$f(Q_0) = \frac{n(Q_0)}{N}$$

$N = \text{Total number of } t\bar{t} \text{ events}$

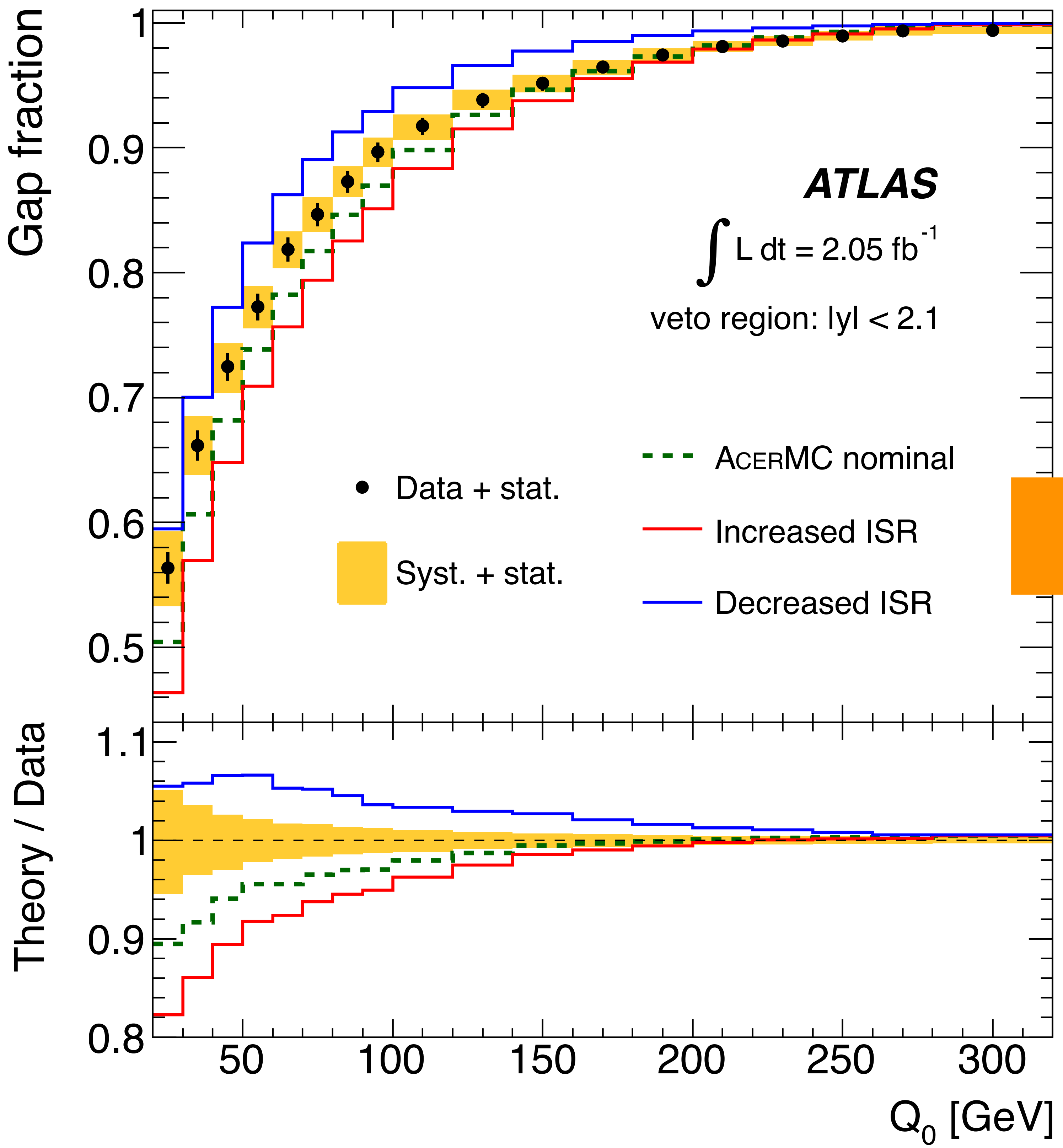
$n(Q_0) = \text{Number of } t\bar{t} \text{ events with no jet with } p_T > Q_0$



Jet veto measurement



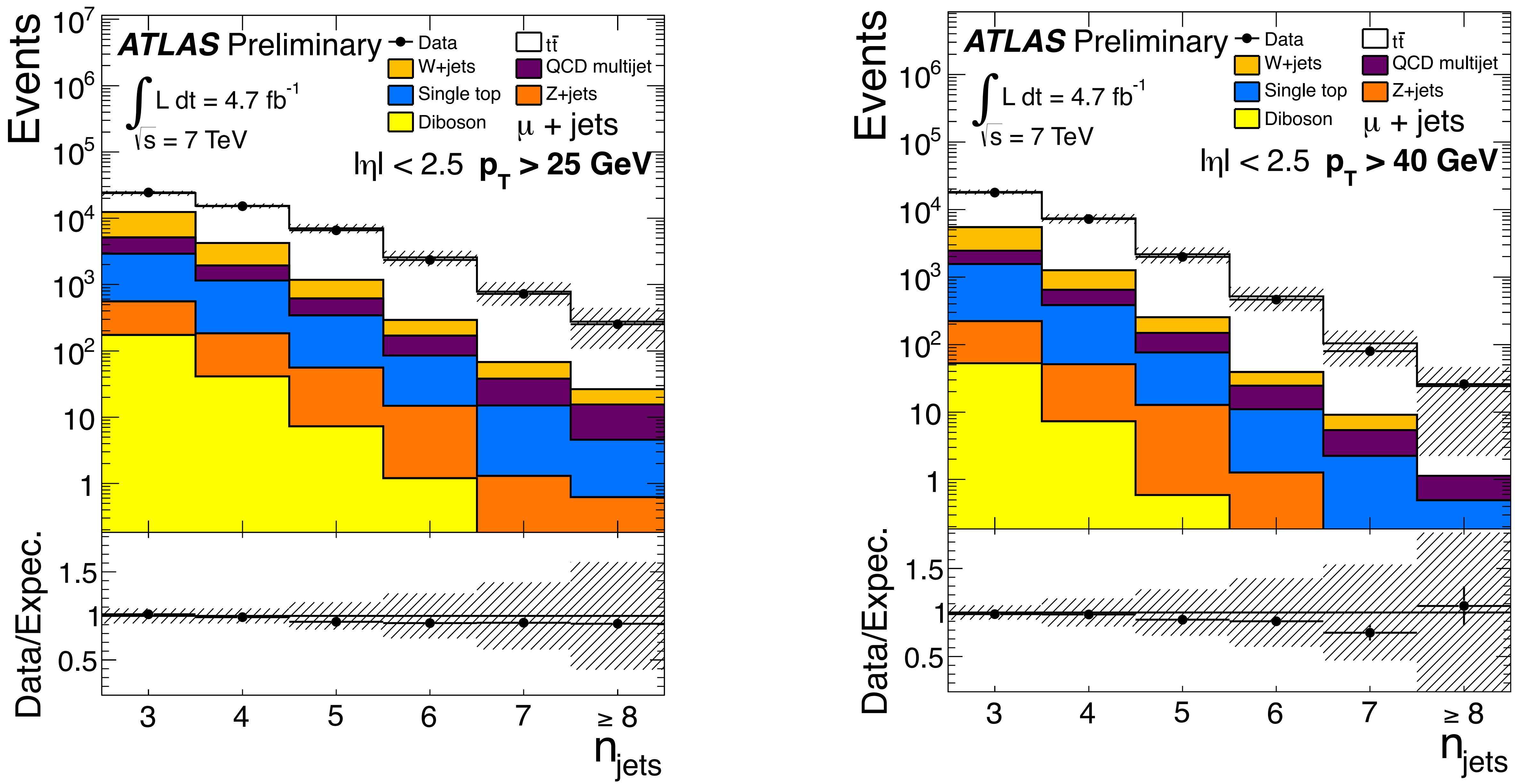
Jet veto measurement



LO

Differential Cross Sections

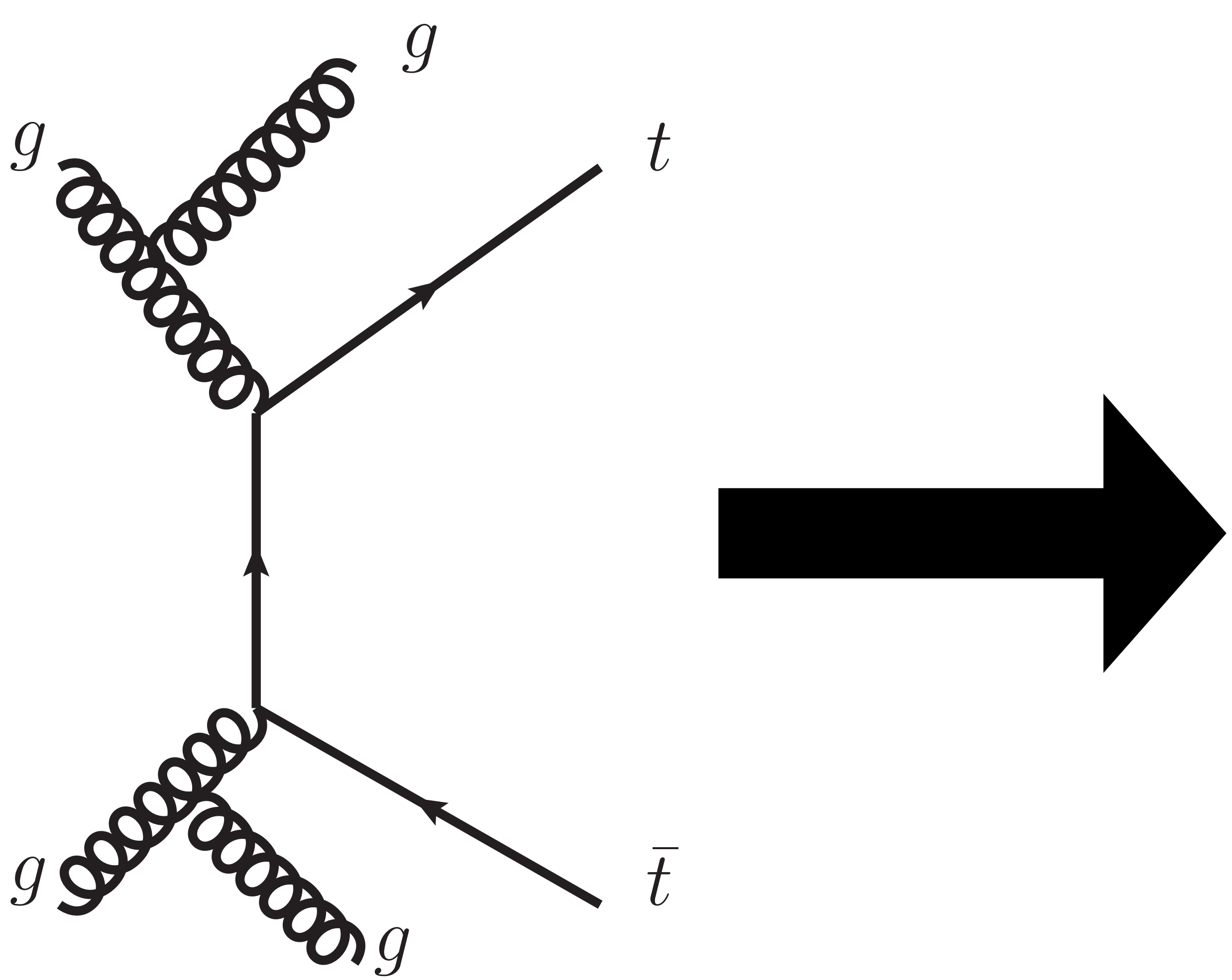
- Measurement of jet multiplicity in lepton+jets top events:



- Complimentary to veto analysis - sensitivity to high jet multiplicities.

Differential Cross Sections

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

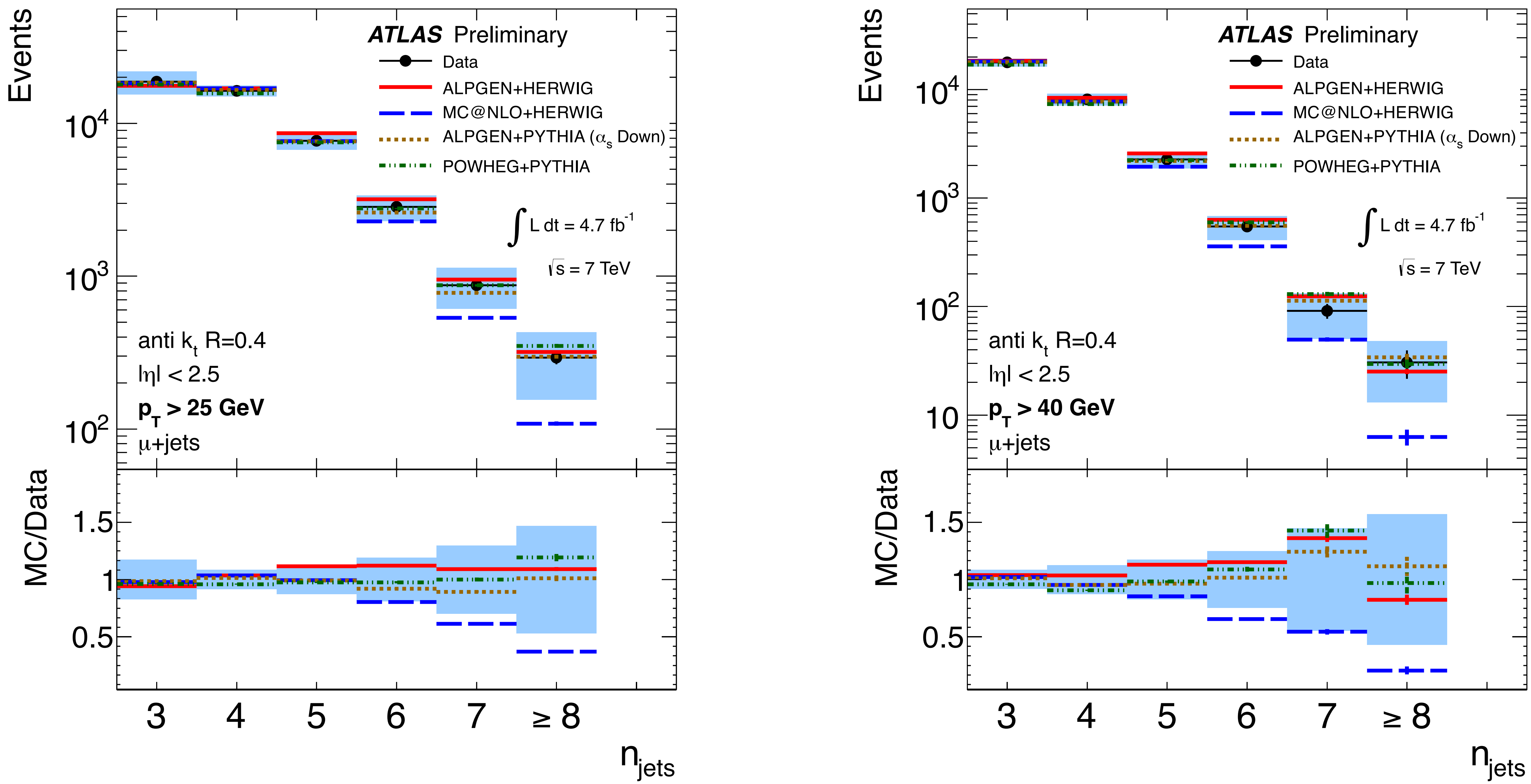


6 jets in the detector:
2 from W, 2 b-jets and
2 gluon jets

- Complimentary to veto analysis - sensitivity to high jet multiplicities.

Differential Cross Sections

- Unfolded data compared to MC models:



- Complimentary to veto analysis - start to distinguish models at high n(jets).

MANCHESTER 1824

The University of Manchester

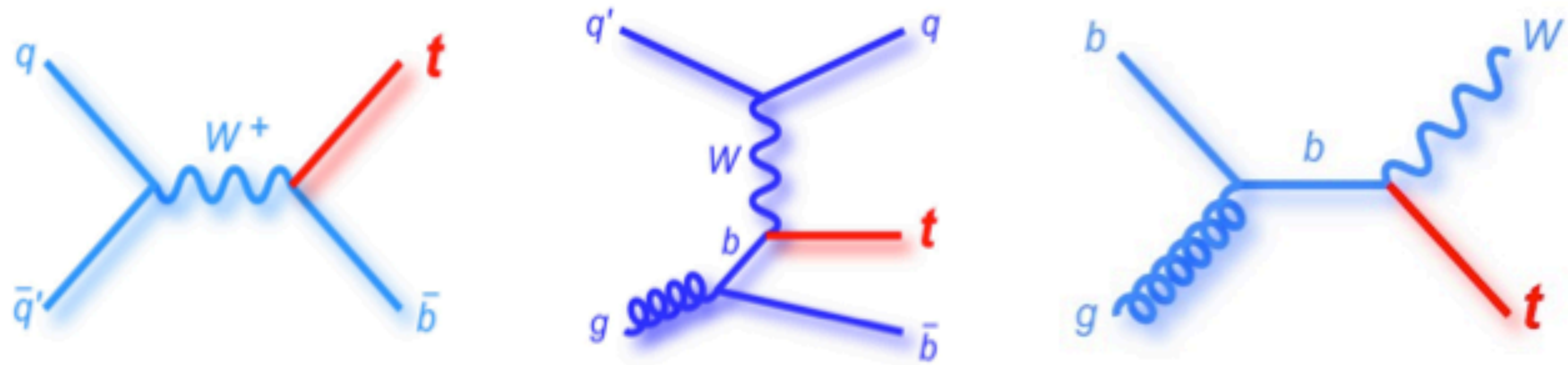
Single Top Quark Production:

Tevatron discovery

LHC measurements

Single Top Production

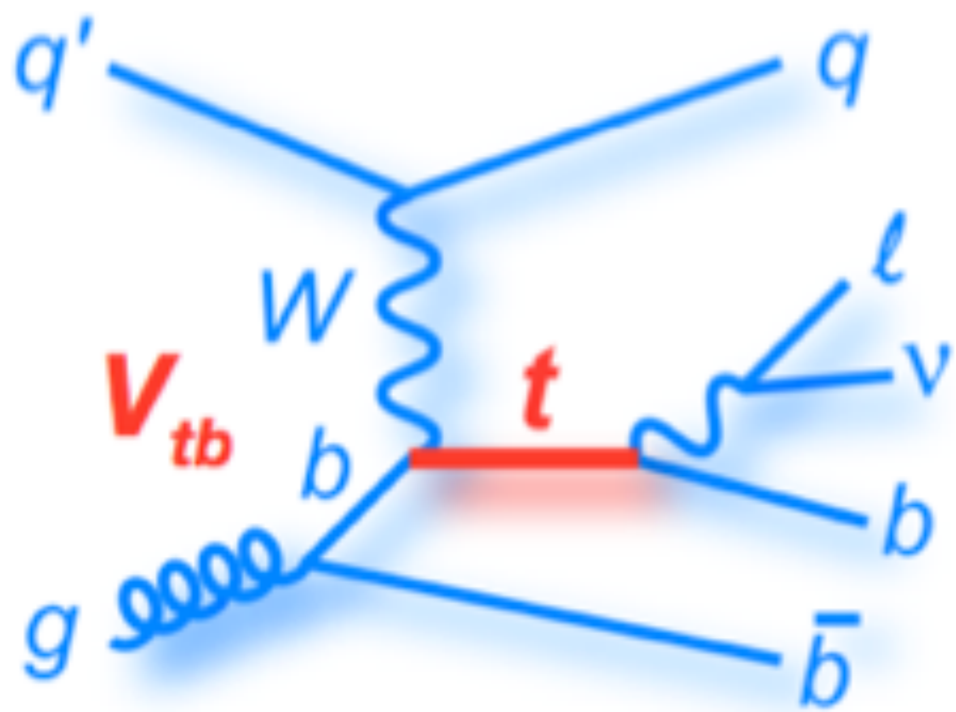
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



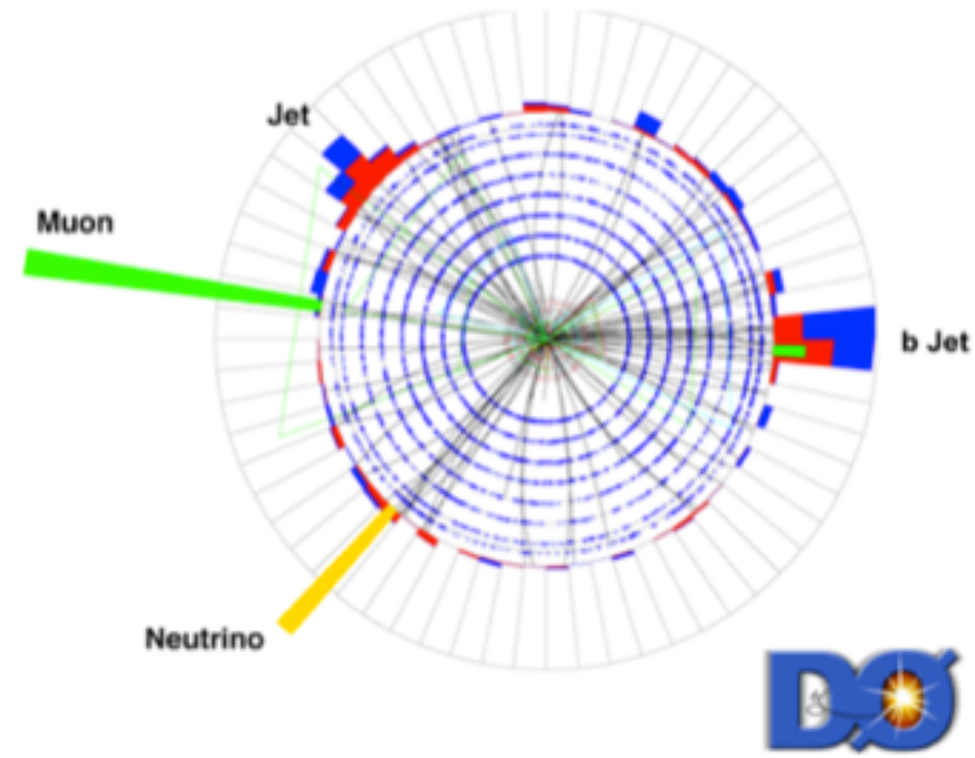
Collider	s-channel: σ_{tb}	t-channel: σ_{tqb}	Wt-channel: σ_{tW}
Tevatron: $p\bar{p}$ (1.96 TeV)	1.04 pb	2.26 pb	0.28 pb
LHC: pp (7 TeV)	4.6 pb	64.6 pb	15.7 pb

Direct sensitivity to $|V_{tb}|$

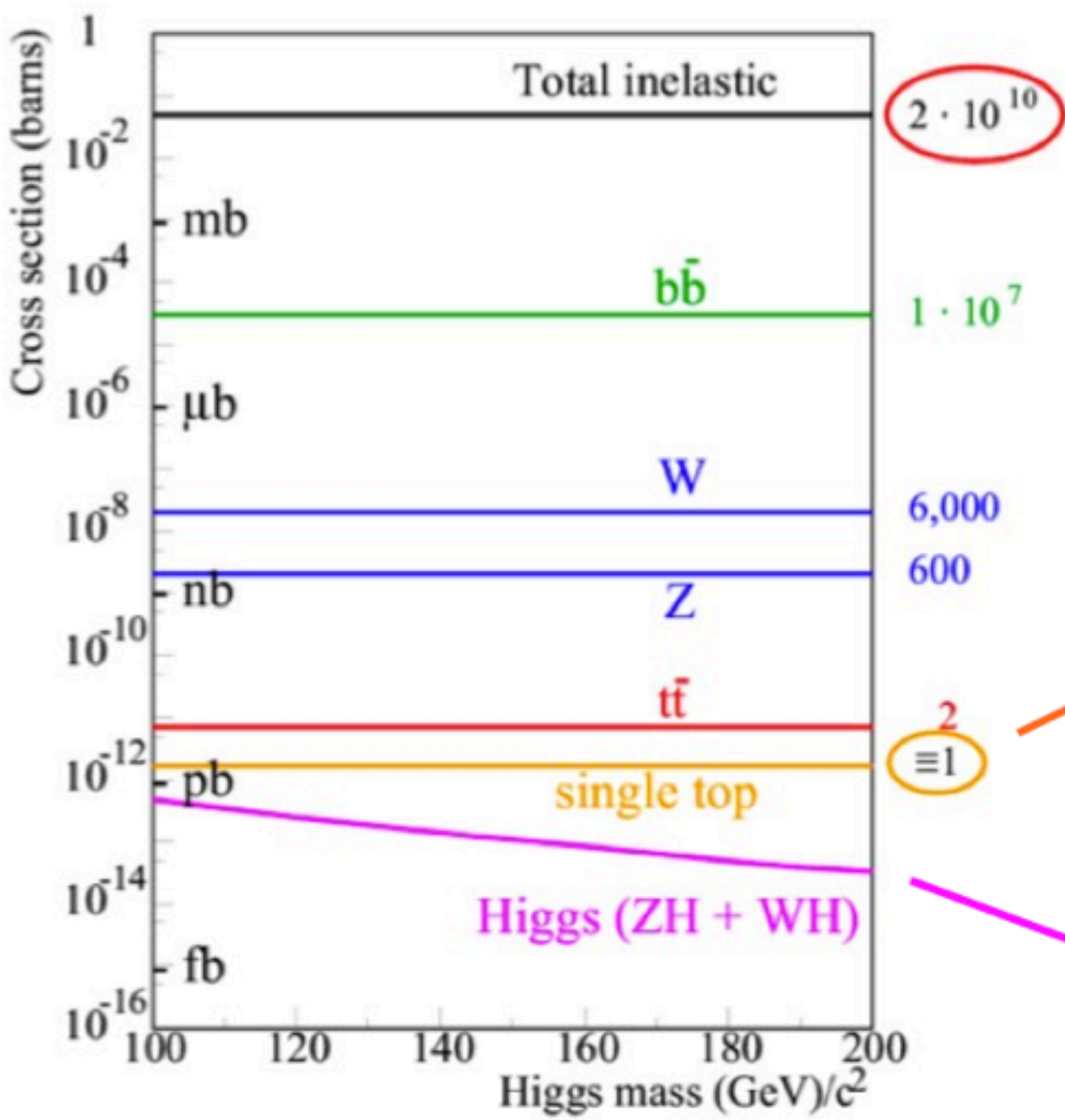
t-channel

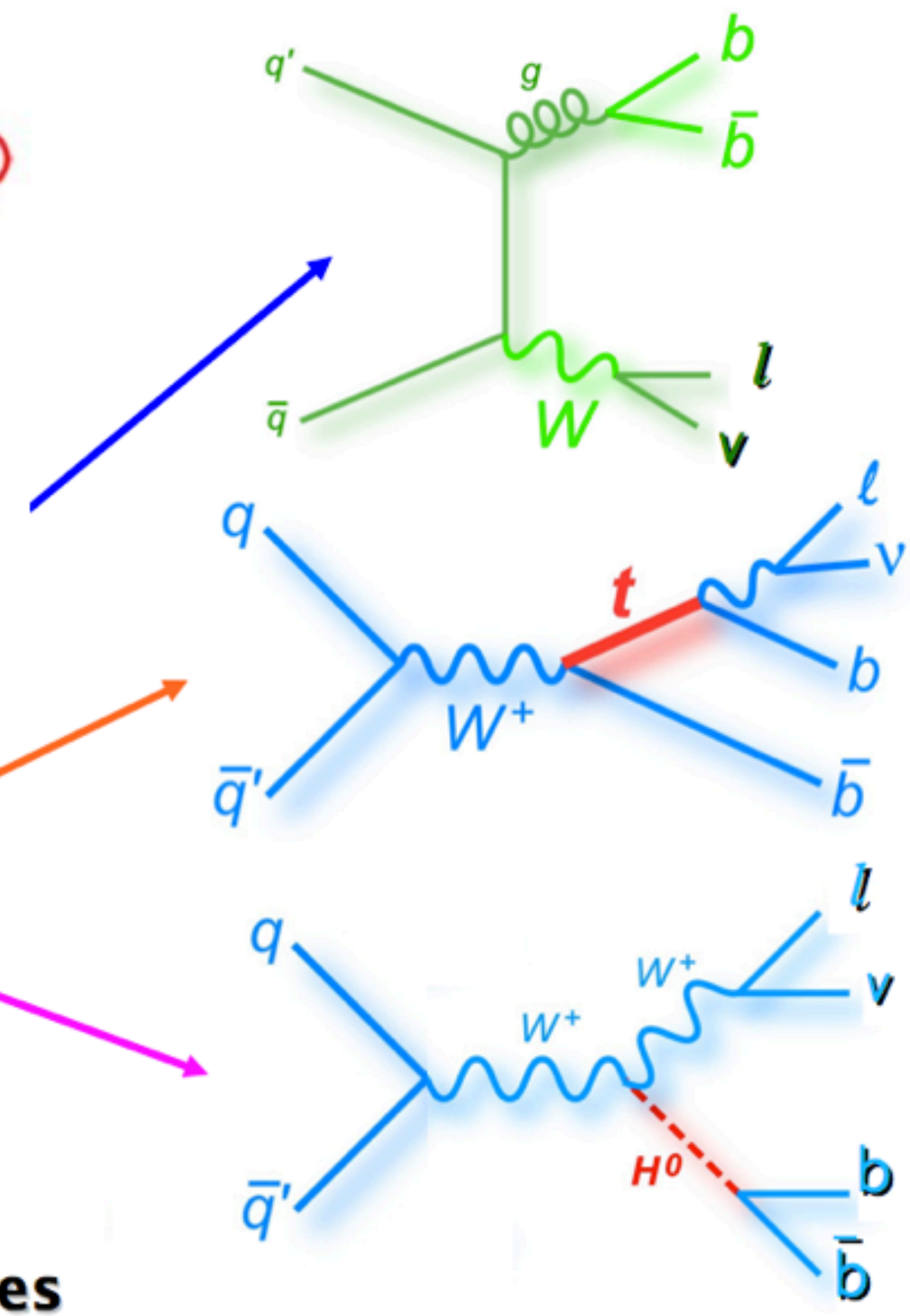


- jets
- lepton
- missing E_T
- b-jets



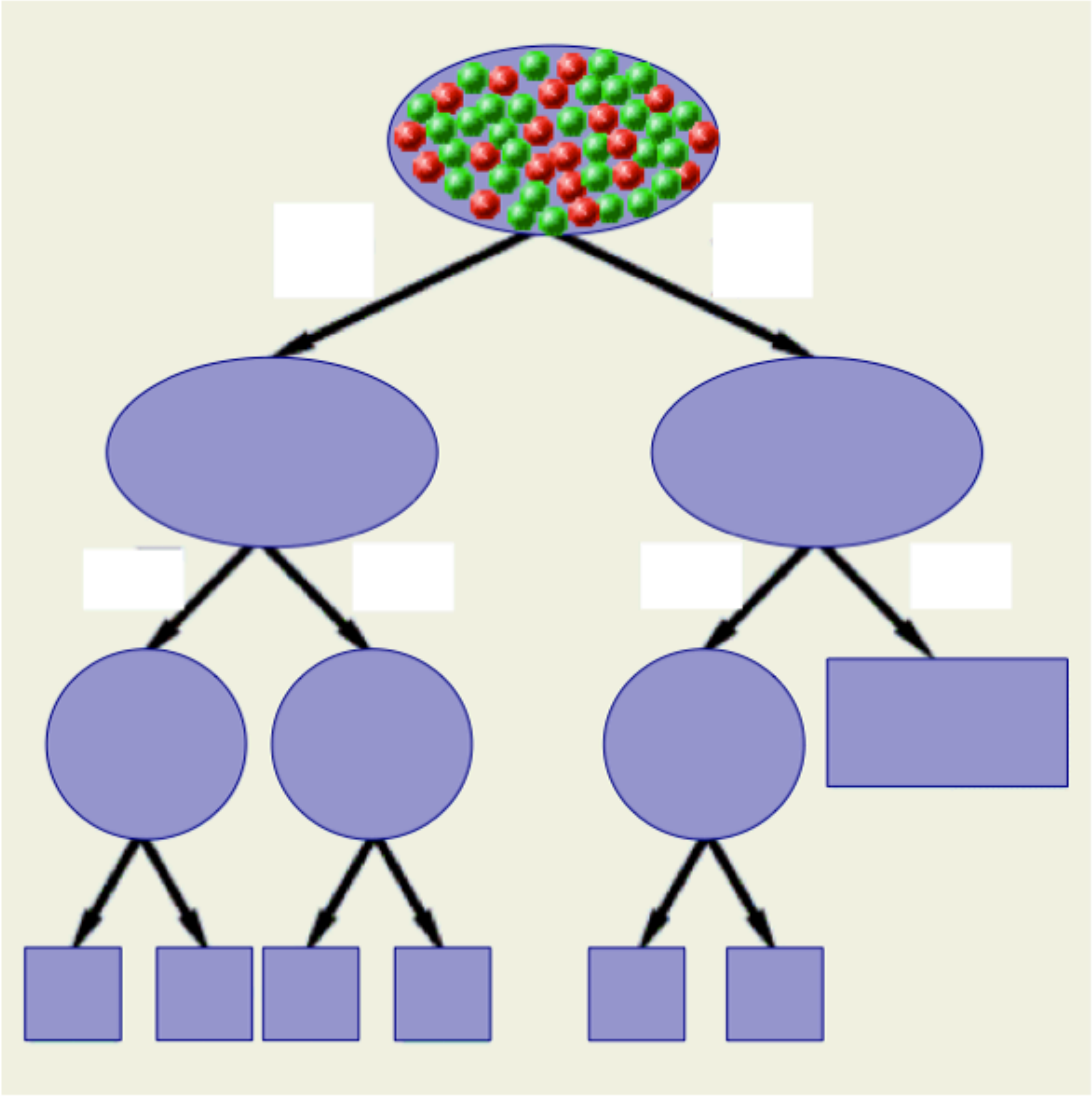
Backgrounds





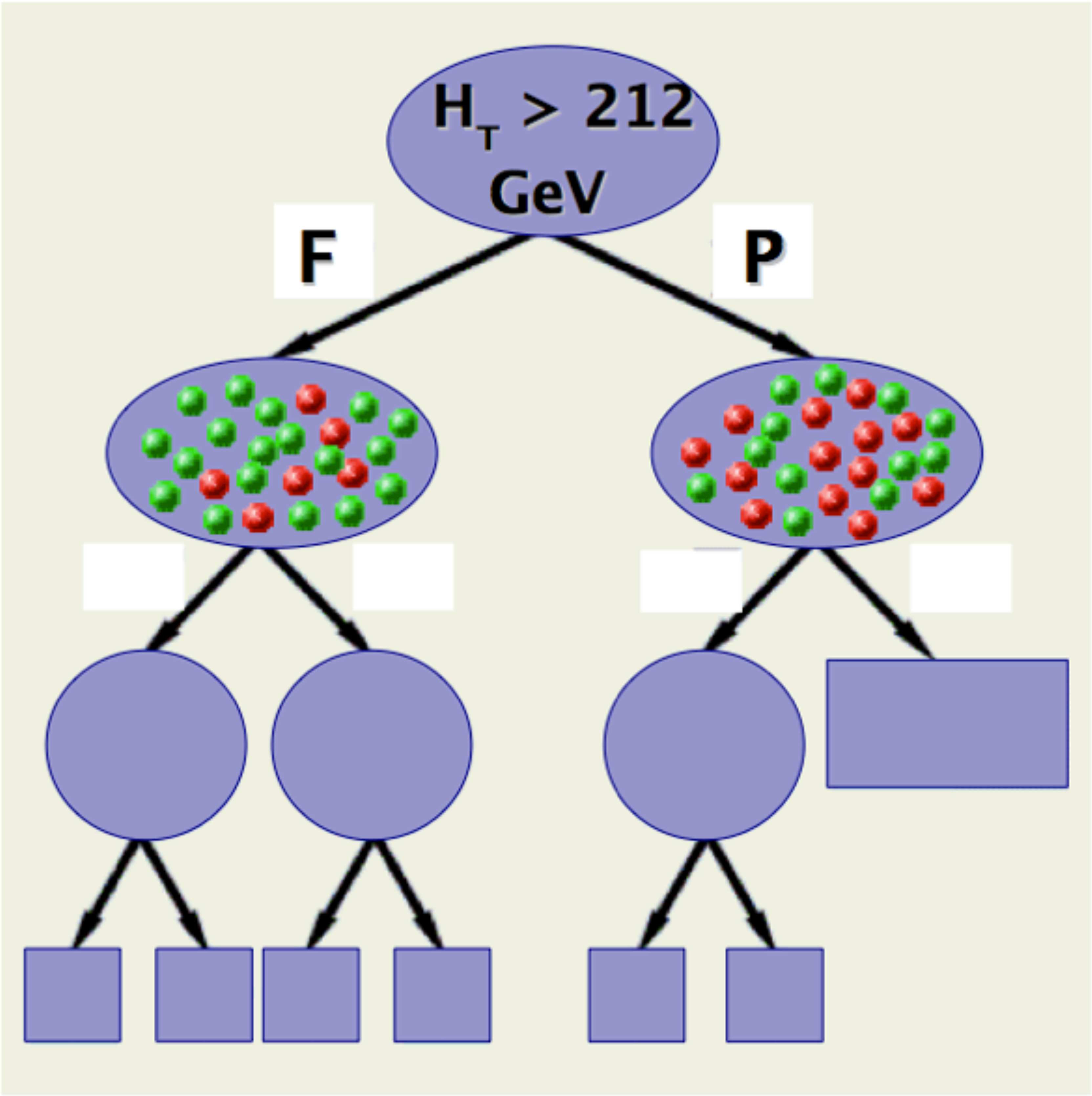
⇒ **multivariate analysis techniques**

Boosted Decision Trees



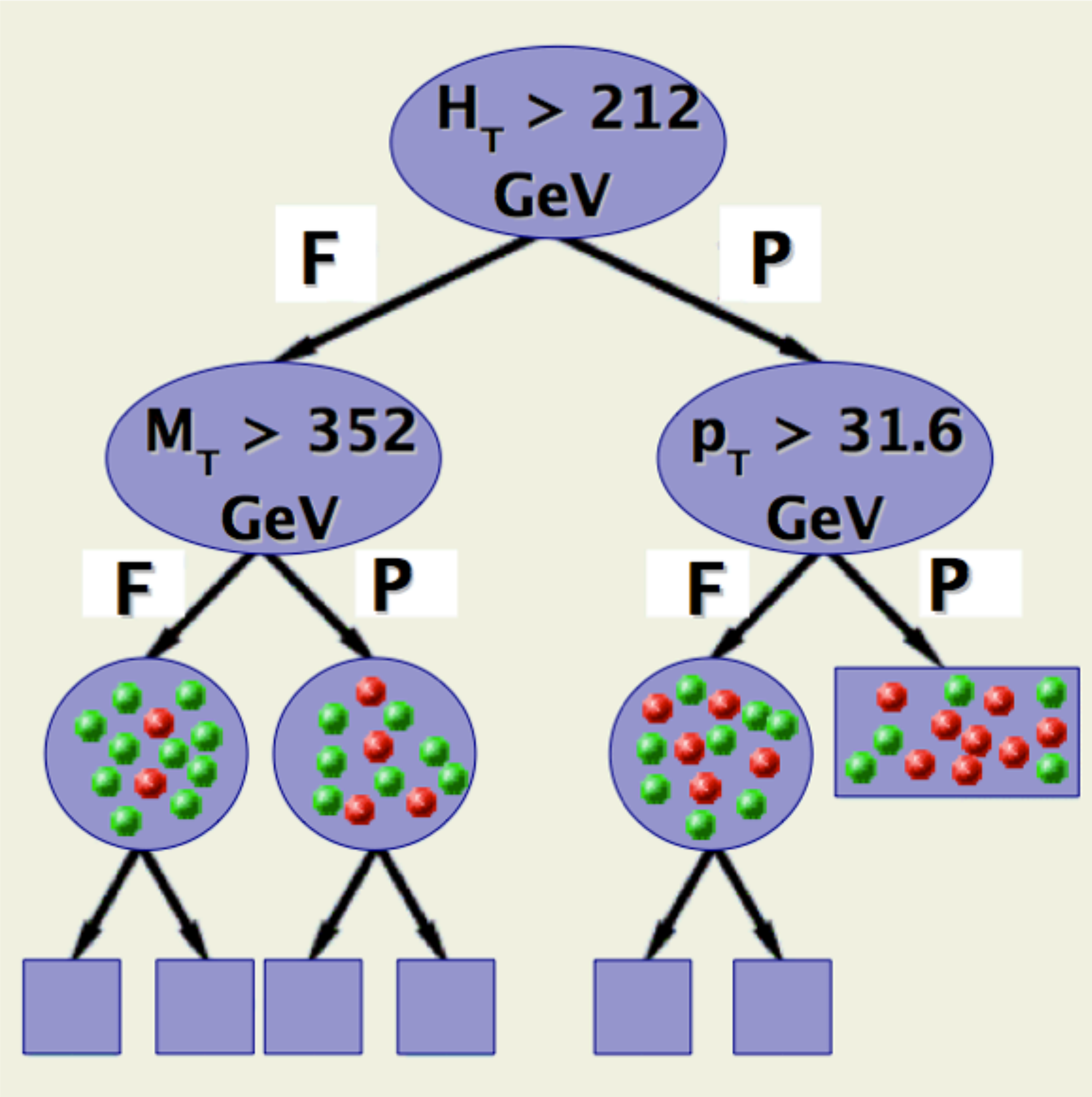
- **IDEA: recover events that fail criteria in cut-based analyses**

Boosted Decision Trees



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

Boosted Decision Trees



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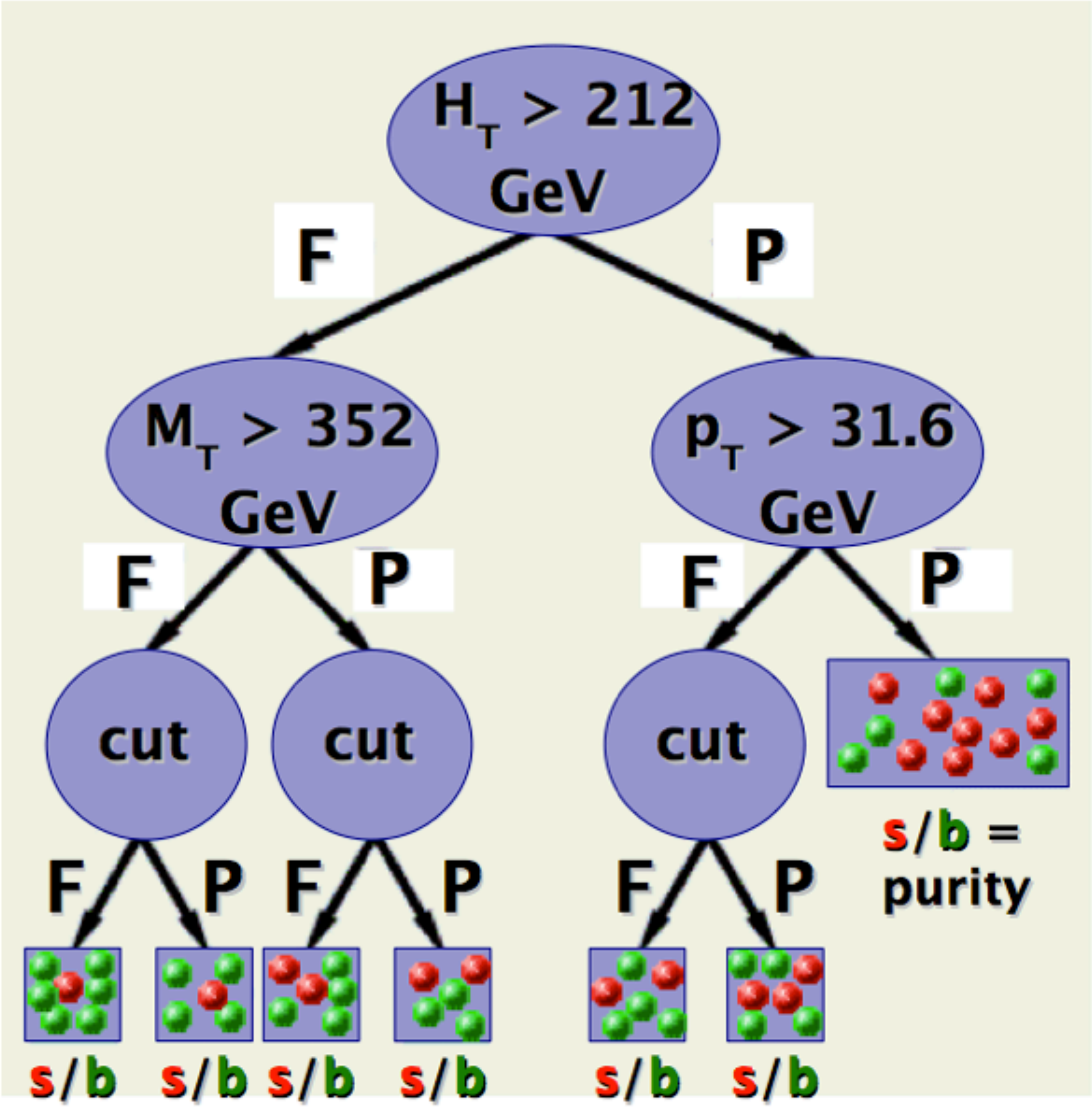
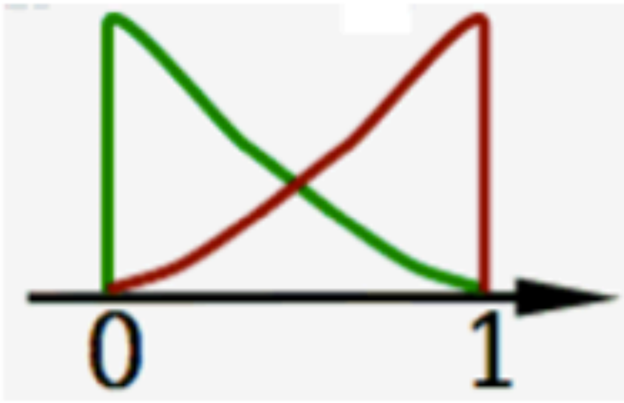


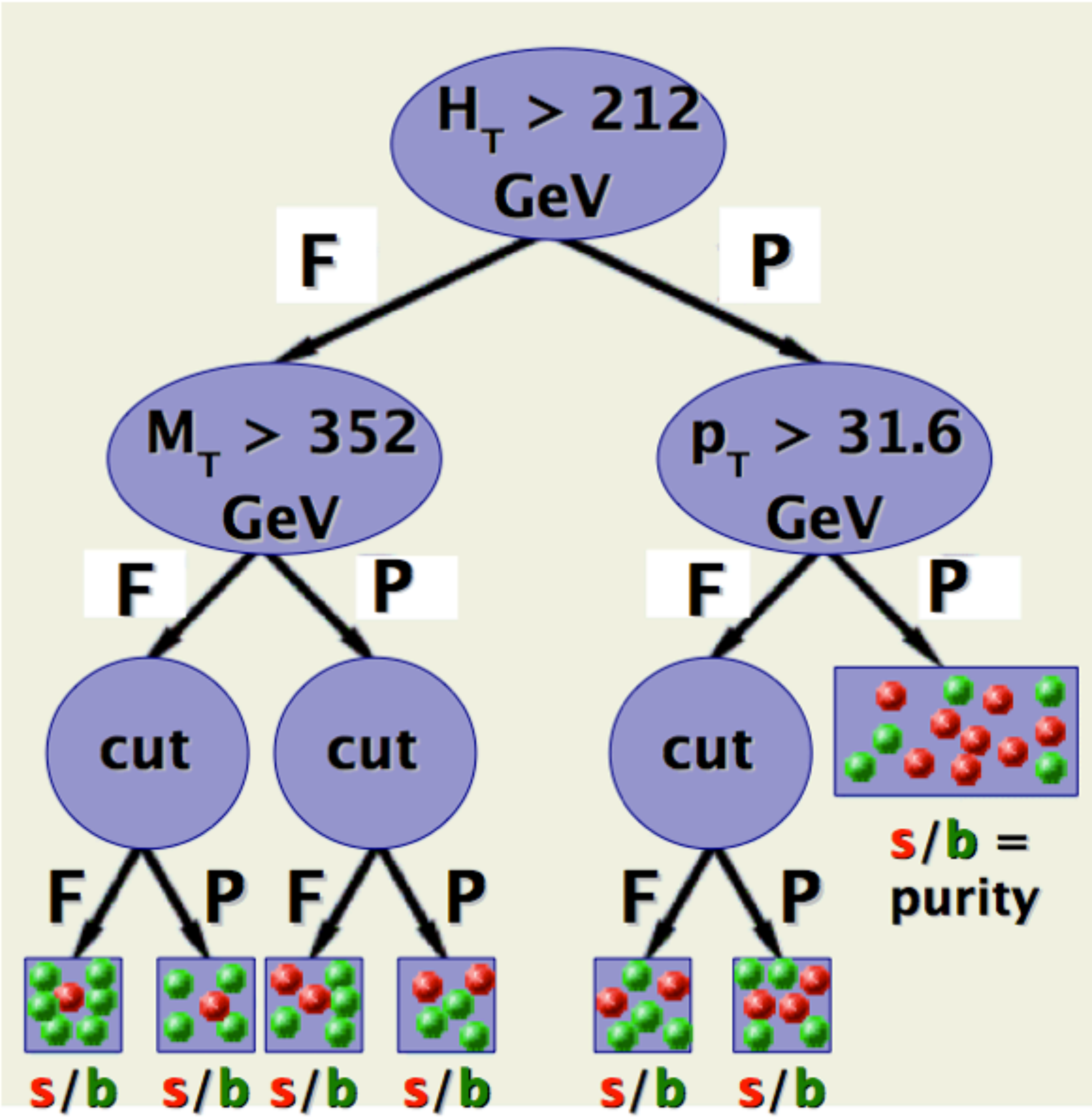
- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

background **signal**



Boosted Decision Trees

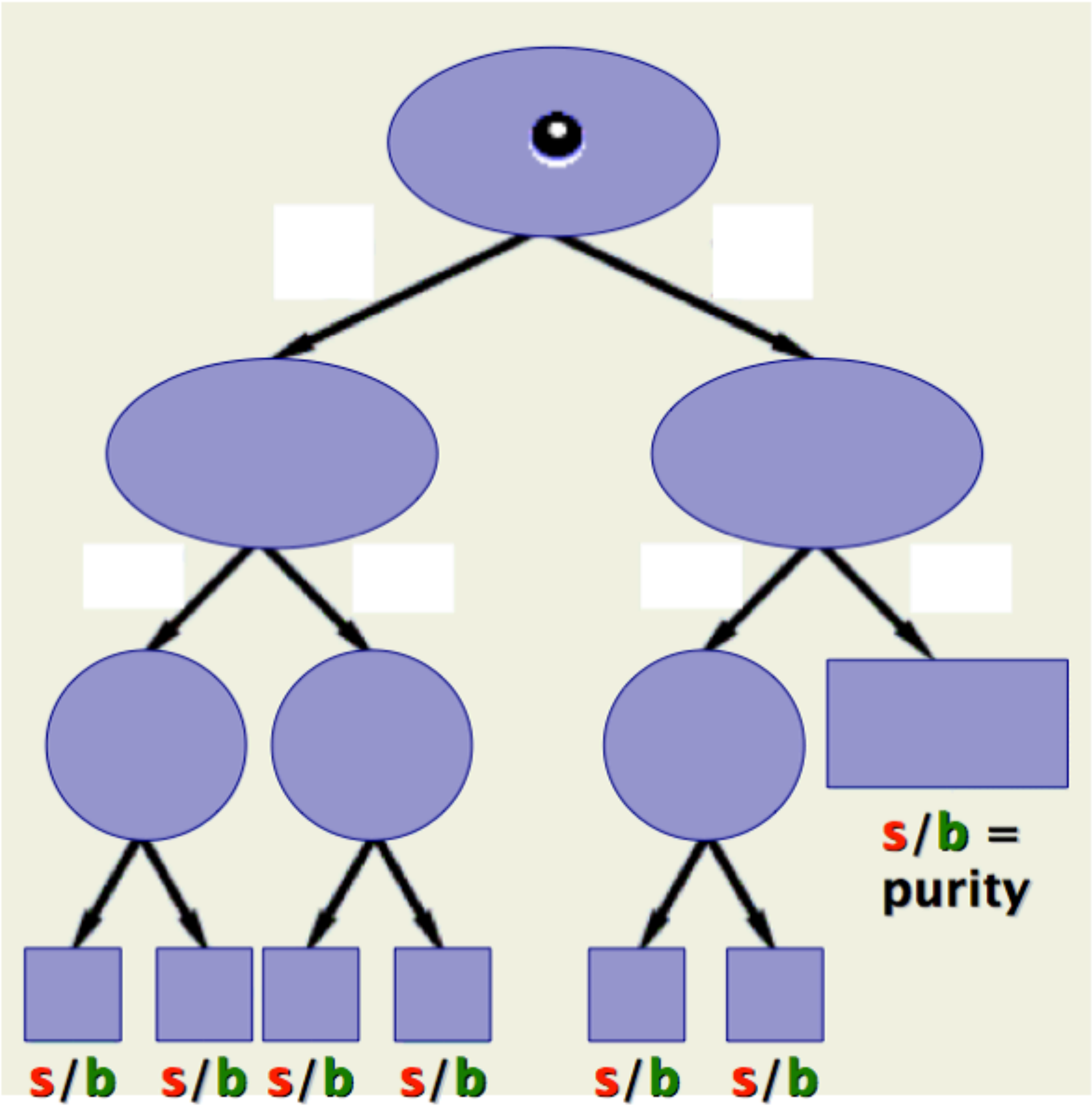


- **IDEA: recover events that fail criteria in cut-based analyses**

boosting:

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

Boosted Decision Trees



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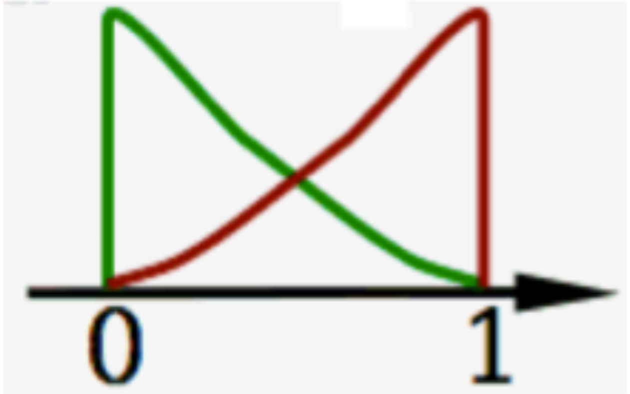
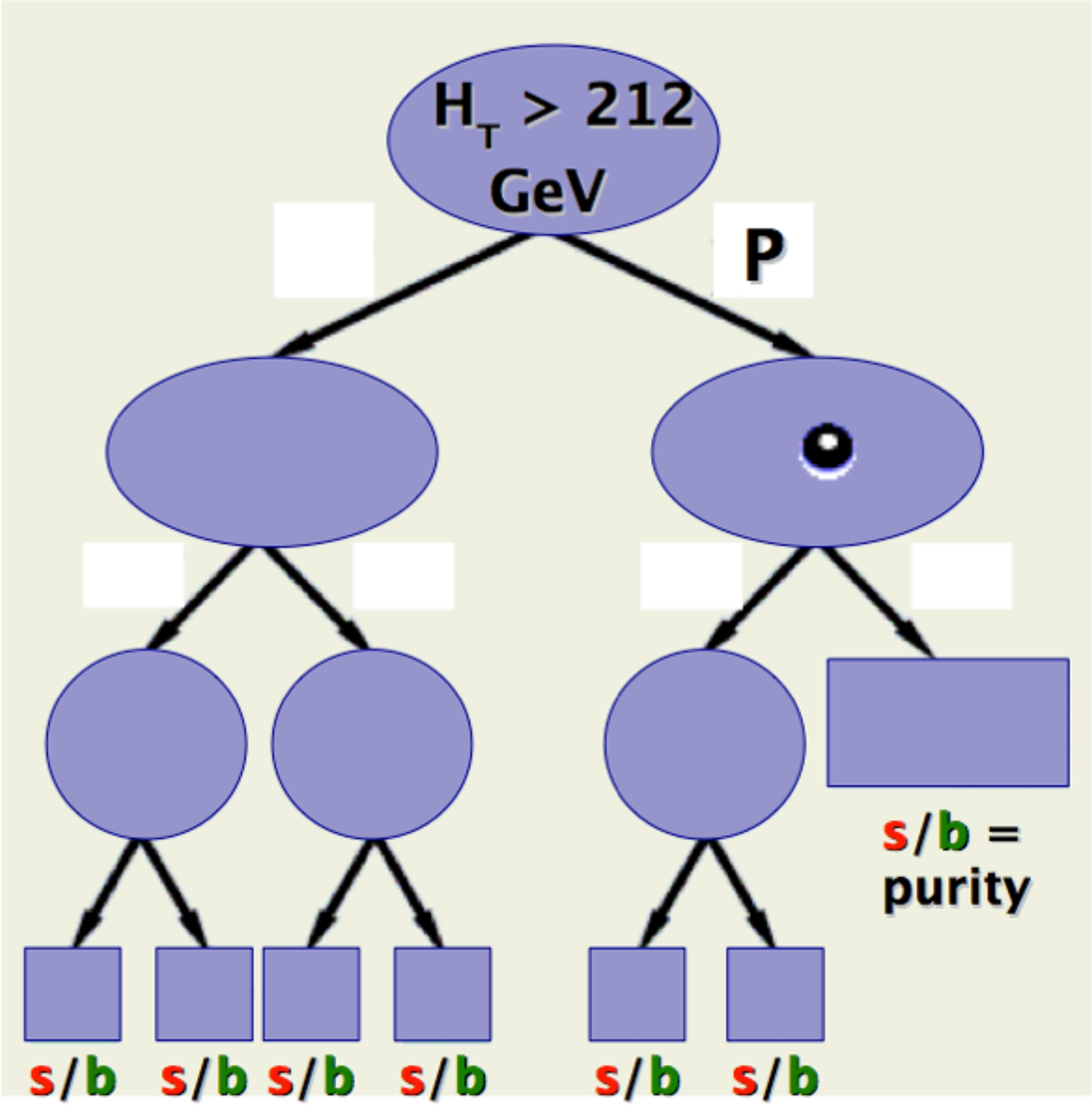


Boosted Decision Trees



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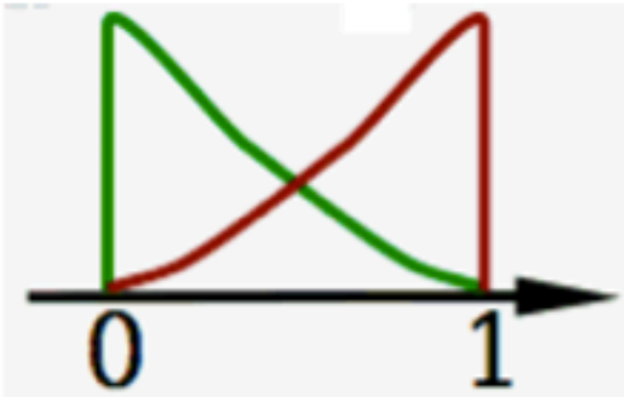
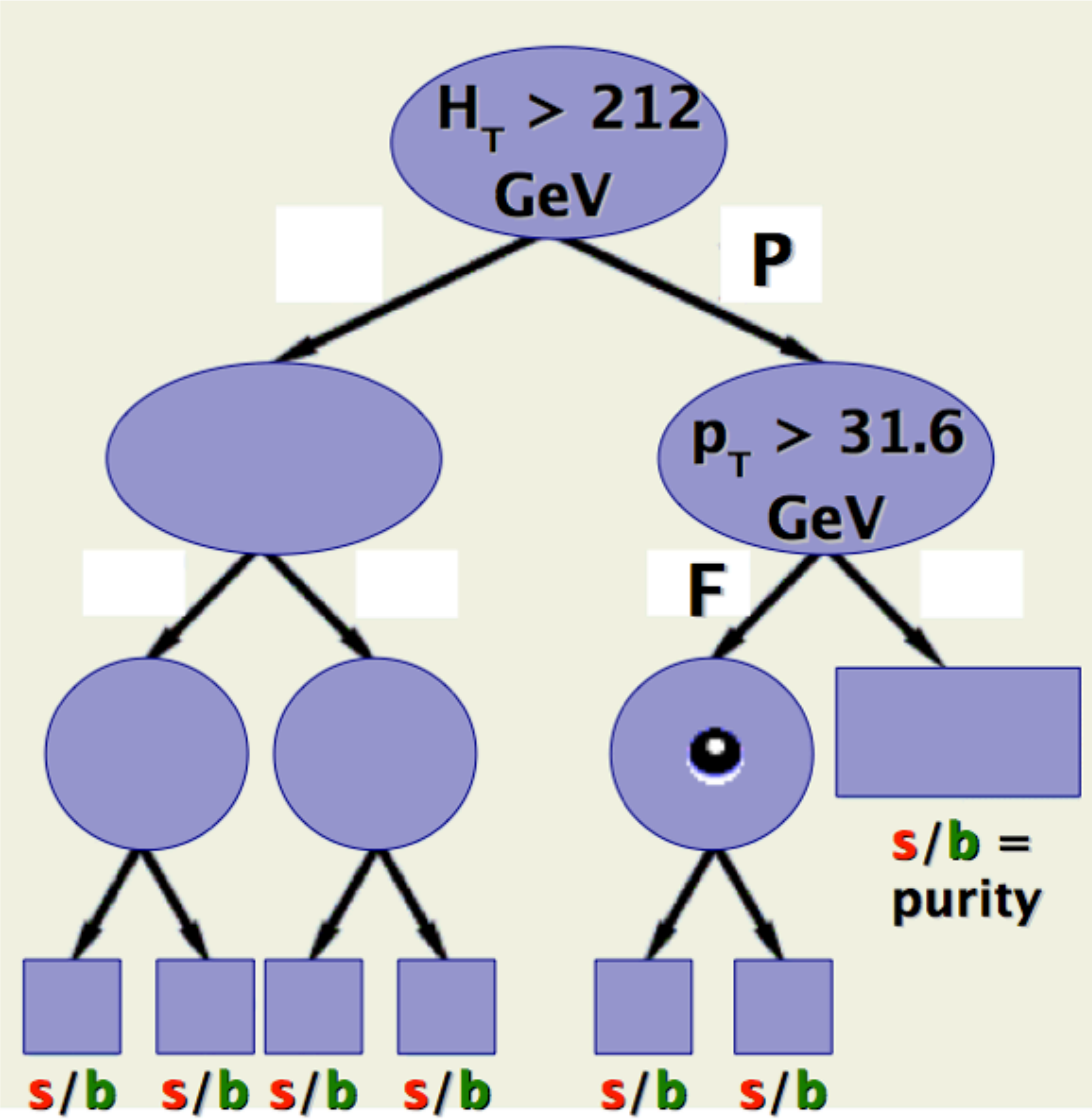
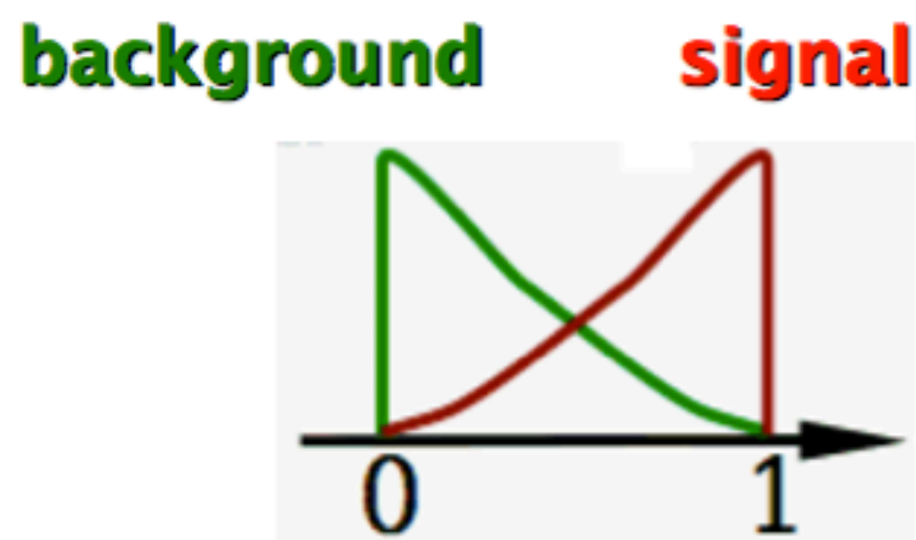
background **signal**



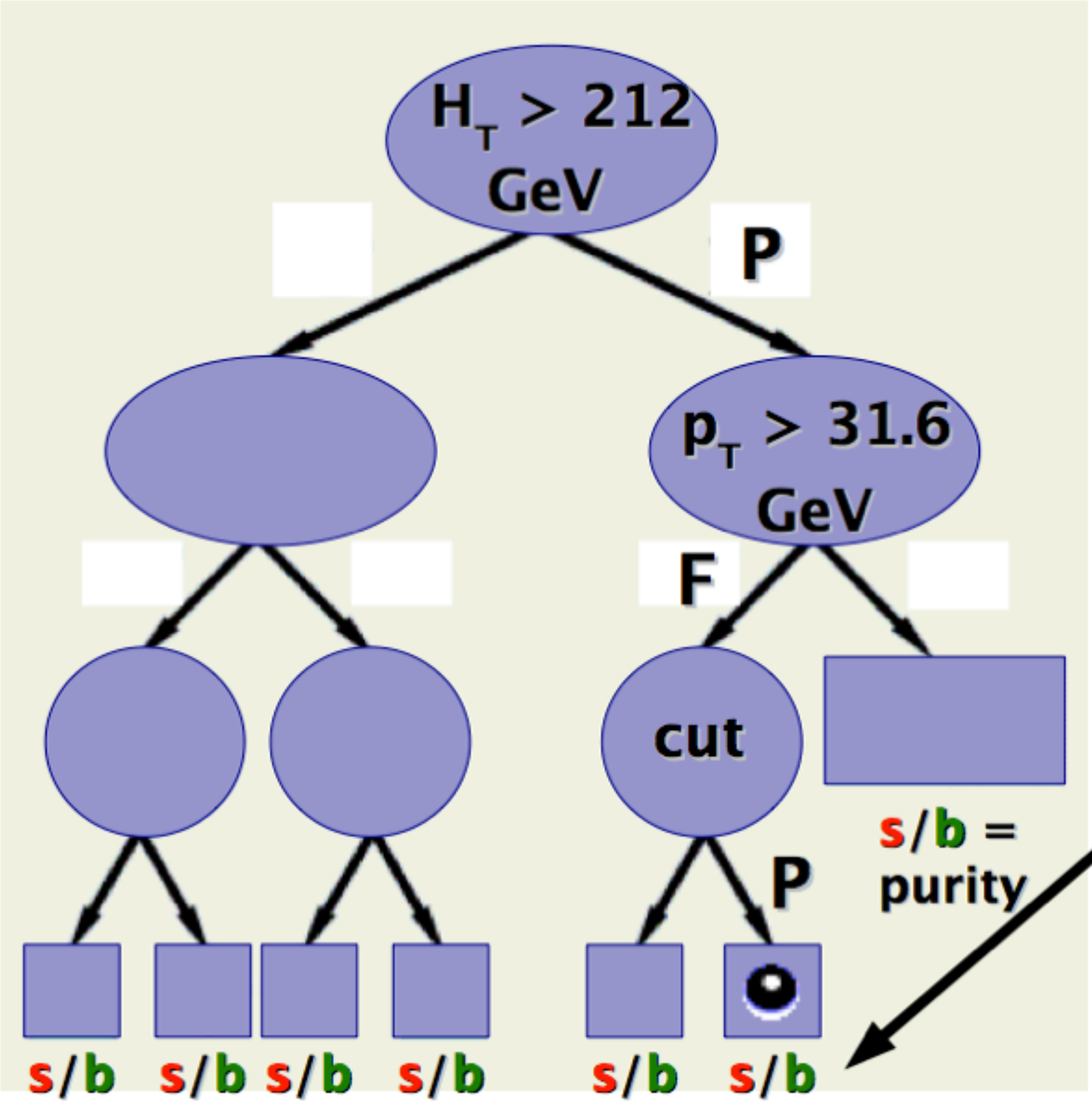
Boosted Decision Trees



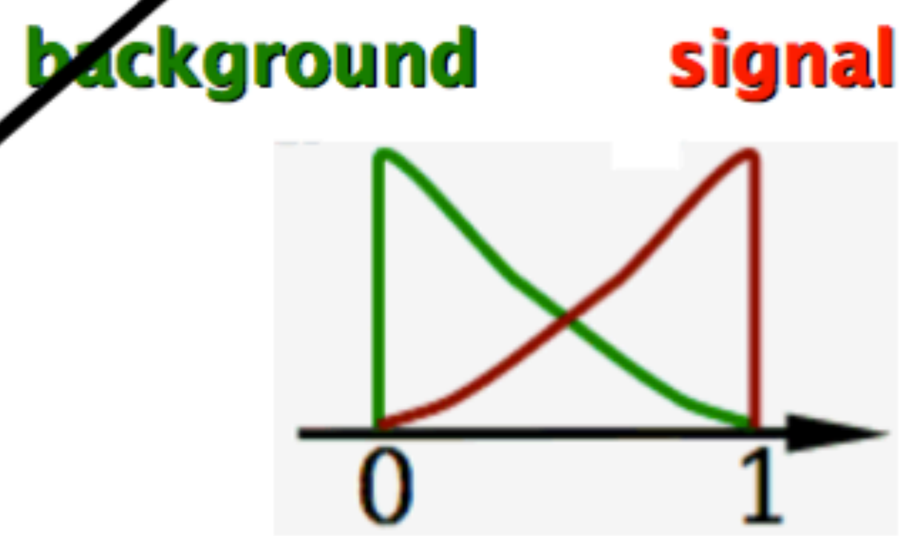
- **IDEA: recover events that fail criteria in cut-based analyses**
- **result:**
  weight for every event



Boosted Decision Trees

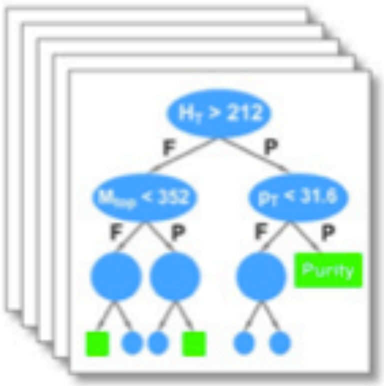


- **IDEA: recover events that fail criteria in cut–based analyses**
- **result: weight for every event**

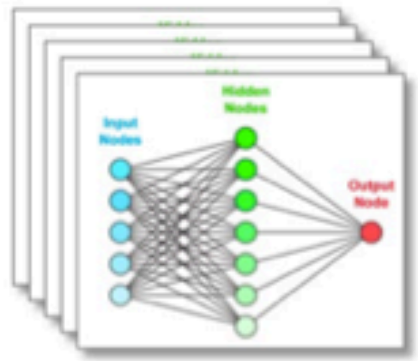


Single Top Discovery

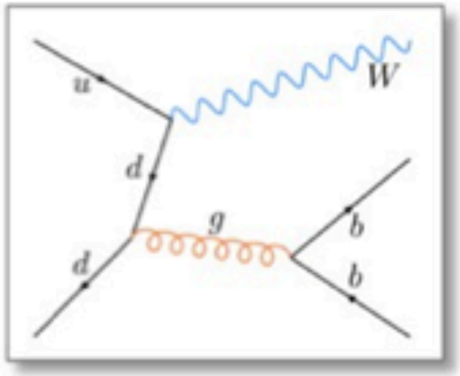
Boosted Decision Trees



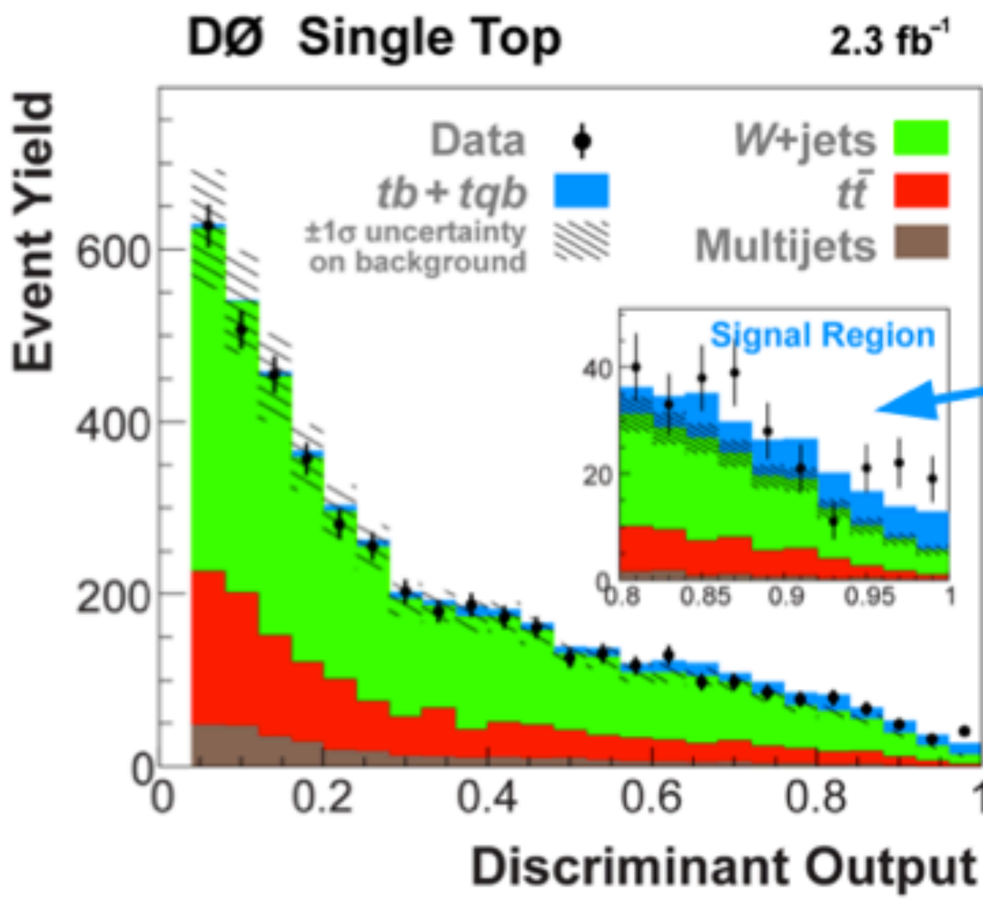
Boosted Neural Networks



Matrix Elements

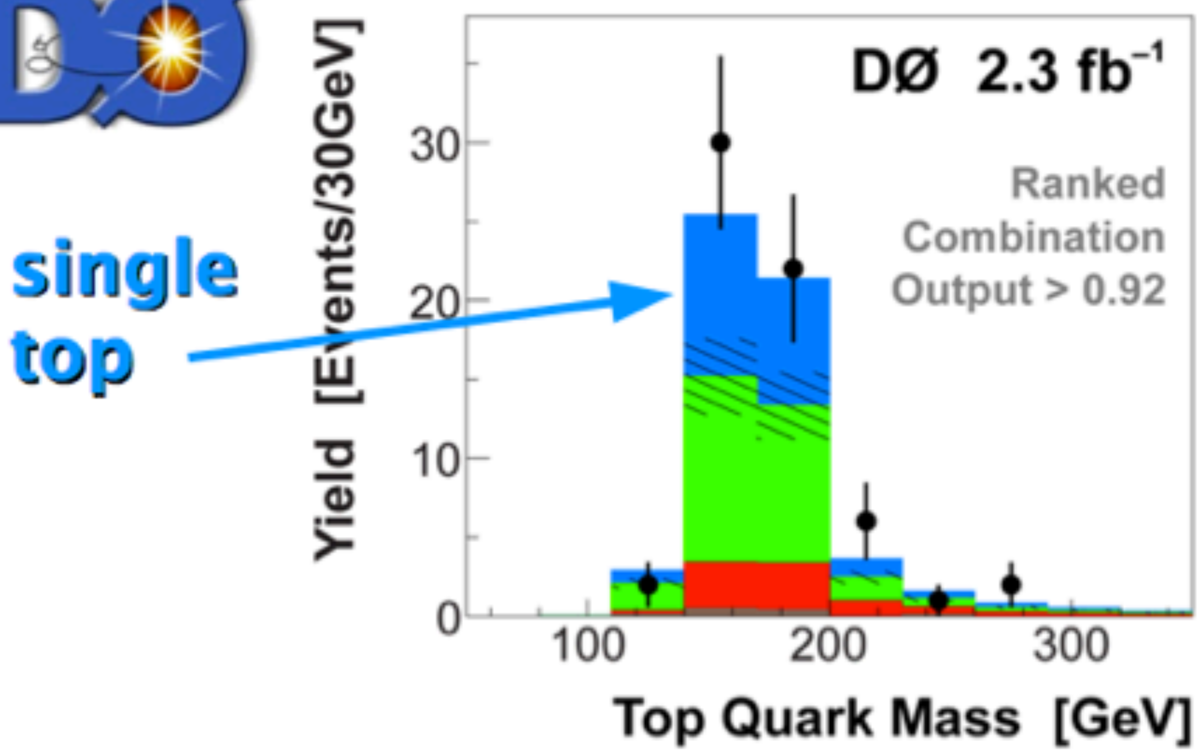


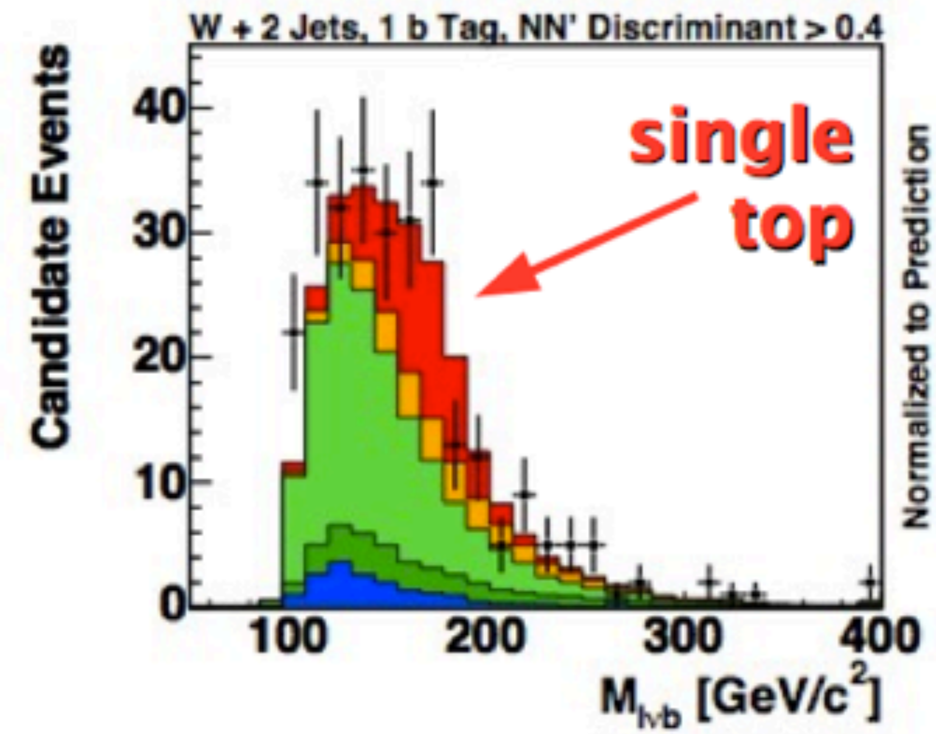
combine up to 12 different analysis channels:



single top

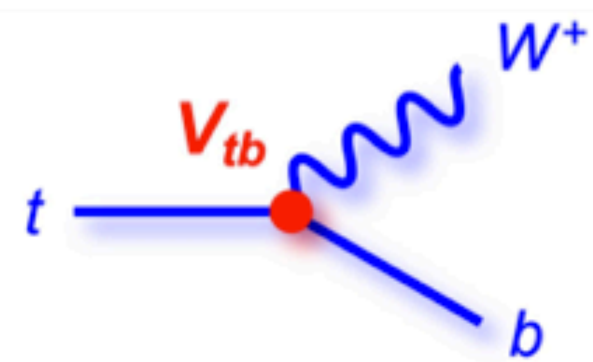
Single Top Discovery





Single Top Cross Section	Signal Significance Expected	Signal Significance Observed
DØ 2.3 fb^{-1} arXiv:0903.0850 m_{top} = 170 GeV		
3.94 ± 0.88 pb	4.5 σ	5.0 σ
CDF 3.2 fb^{-1} arXiv:0903.0885 m_{top} = 175 GeV		
$2.3\ ^{+0.6}_{-0.5}$ pb	>5.9 σ	5.0 σ

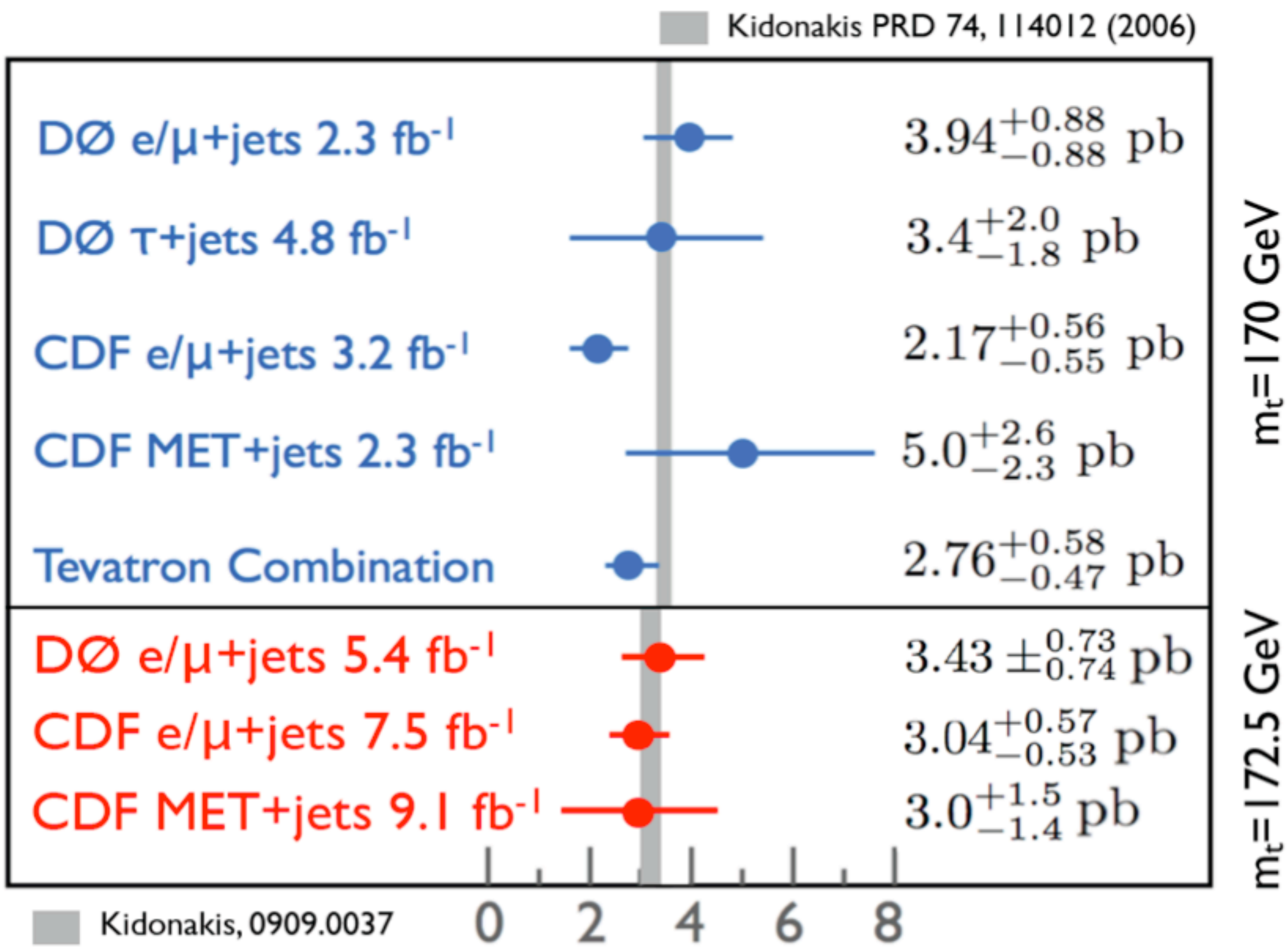
$\Rightarrow$ **observation with 5.0σ!**



DØ: $|V_{tb}| = 1.07 \pm 0.12$

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

Single Top Latest



$|V_{tb}|=0.88\pm0.07$,
$|Vtb| > 0.77$ (@ 95% CL)

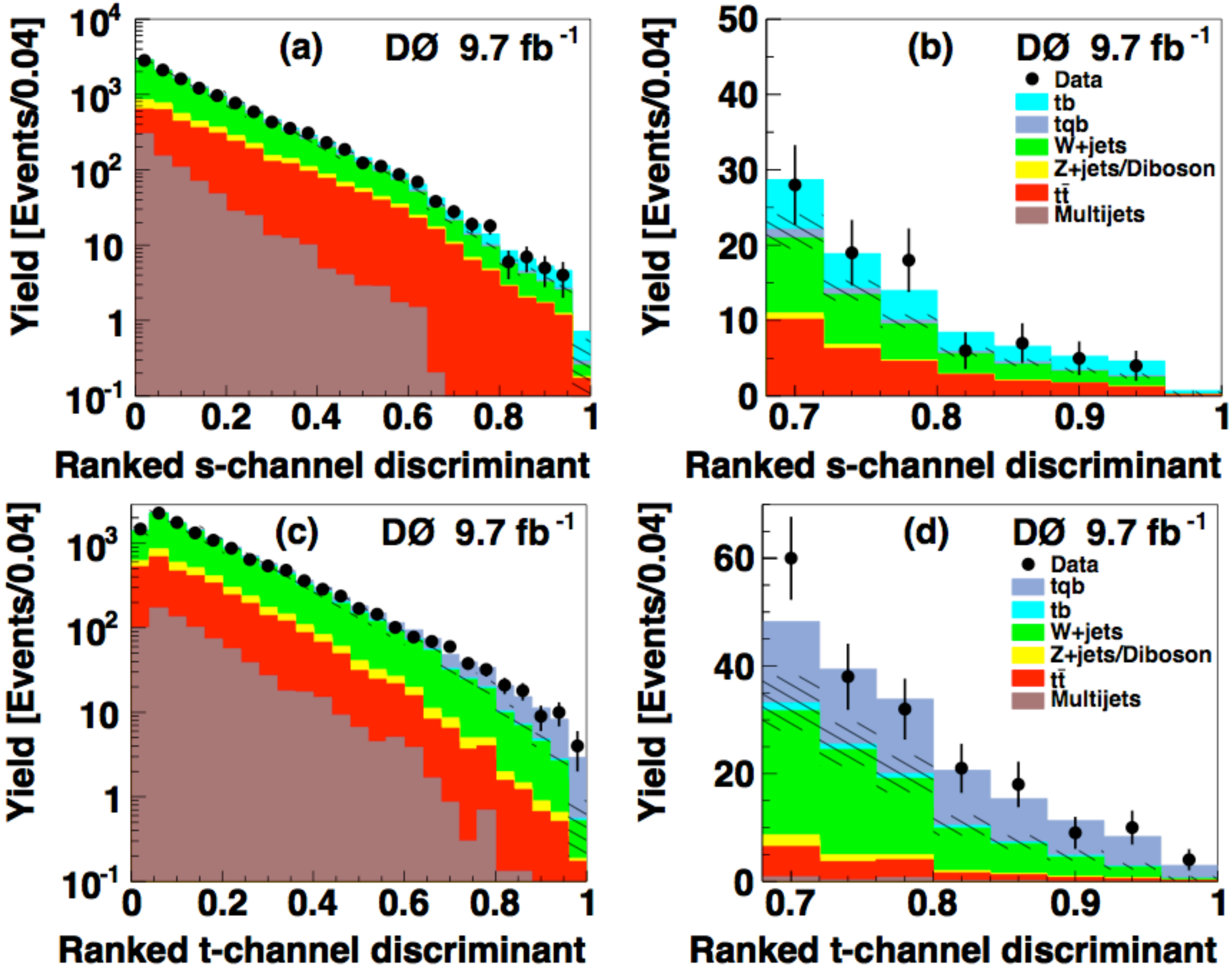
$|V_{tb}| > 0.79$ (@ 95% CL)

$|V_{tb}|=0.96\pm0.10$
$|V_{tb}| > 0.78$ (@ 95% CL)

Good agreement with SM

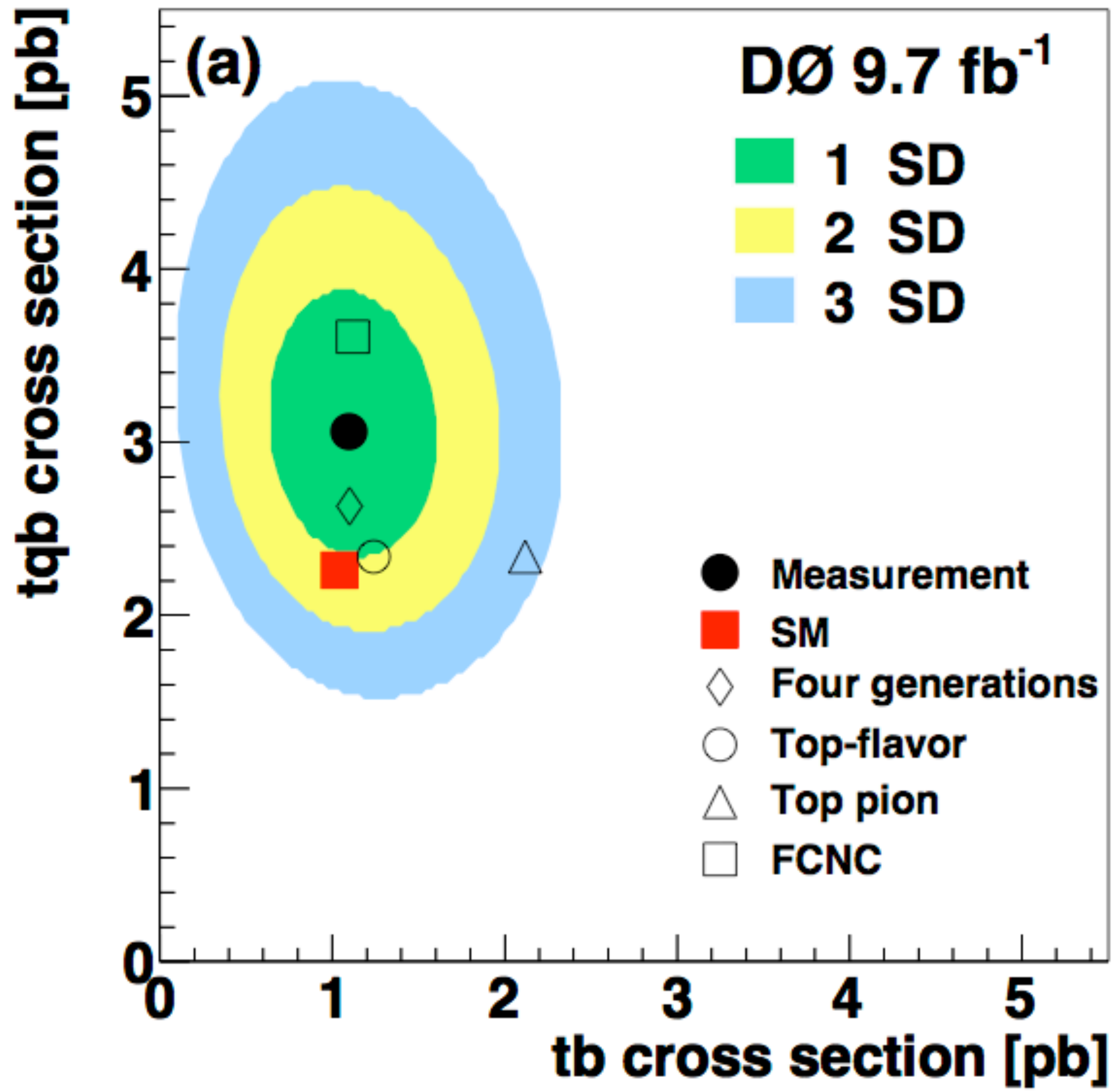
Separating s & t channel

- 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

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

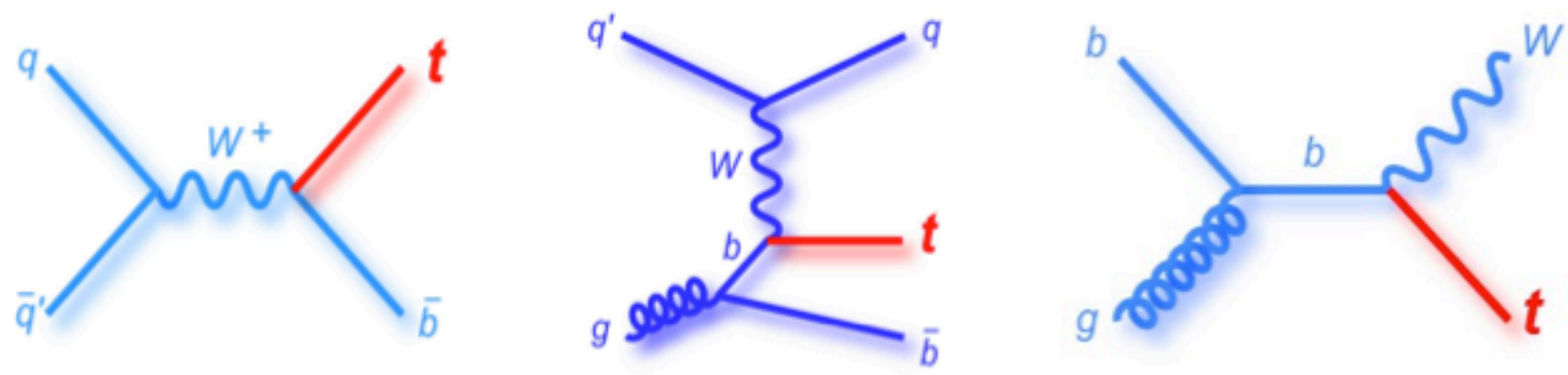
Single Top Quark Production:

Tevatron discovery

LHC measurements

Single Top at LHC

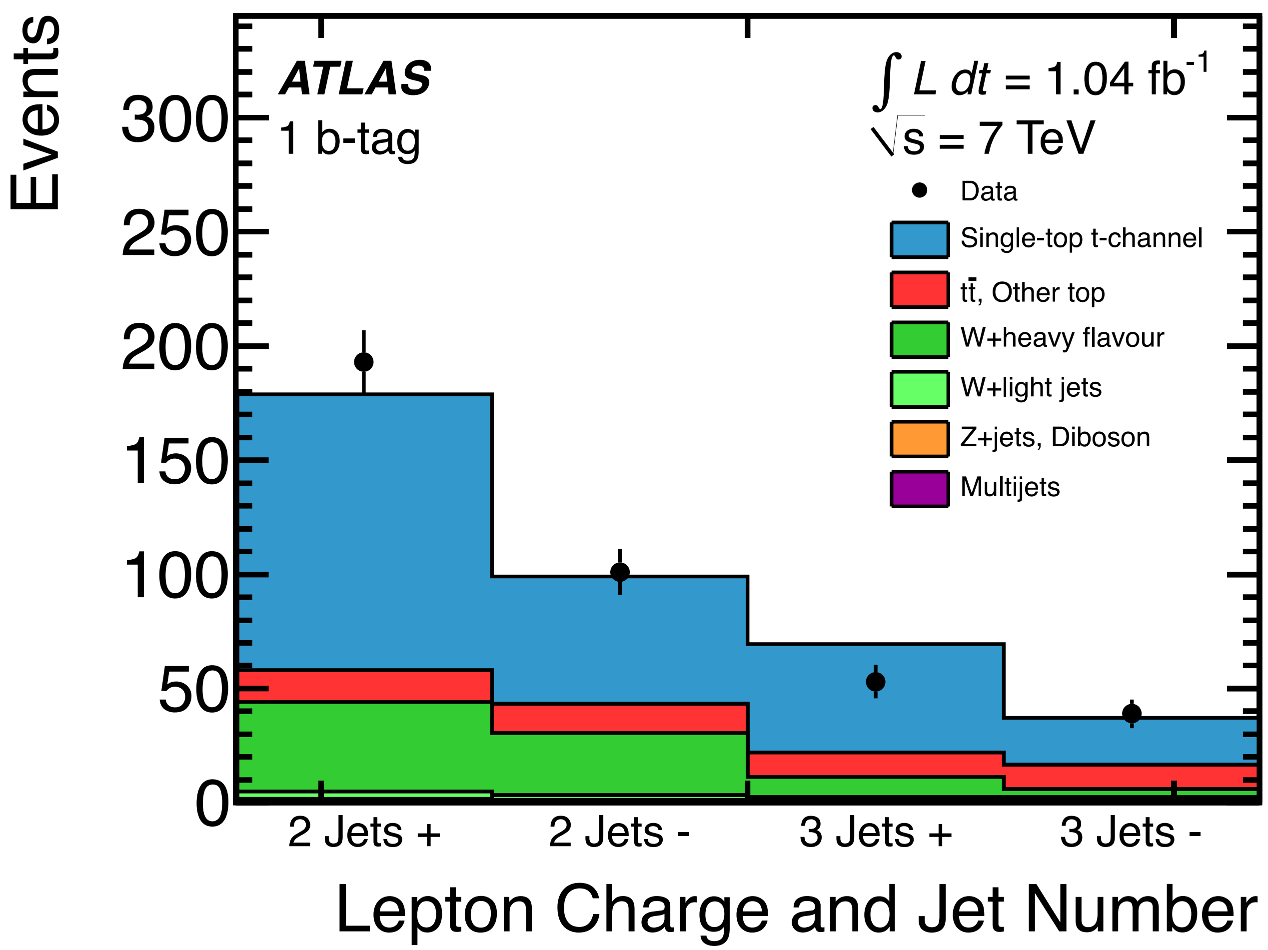
- Much higher cross section at LHC - better signal to background ratio for t-channel and Wt-channel:

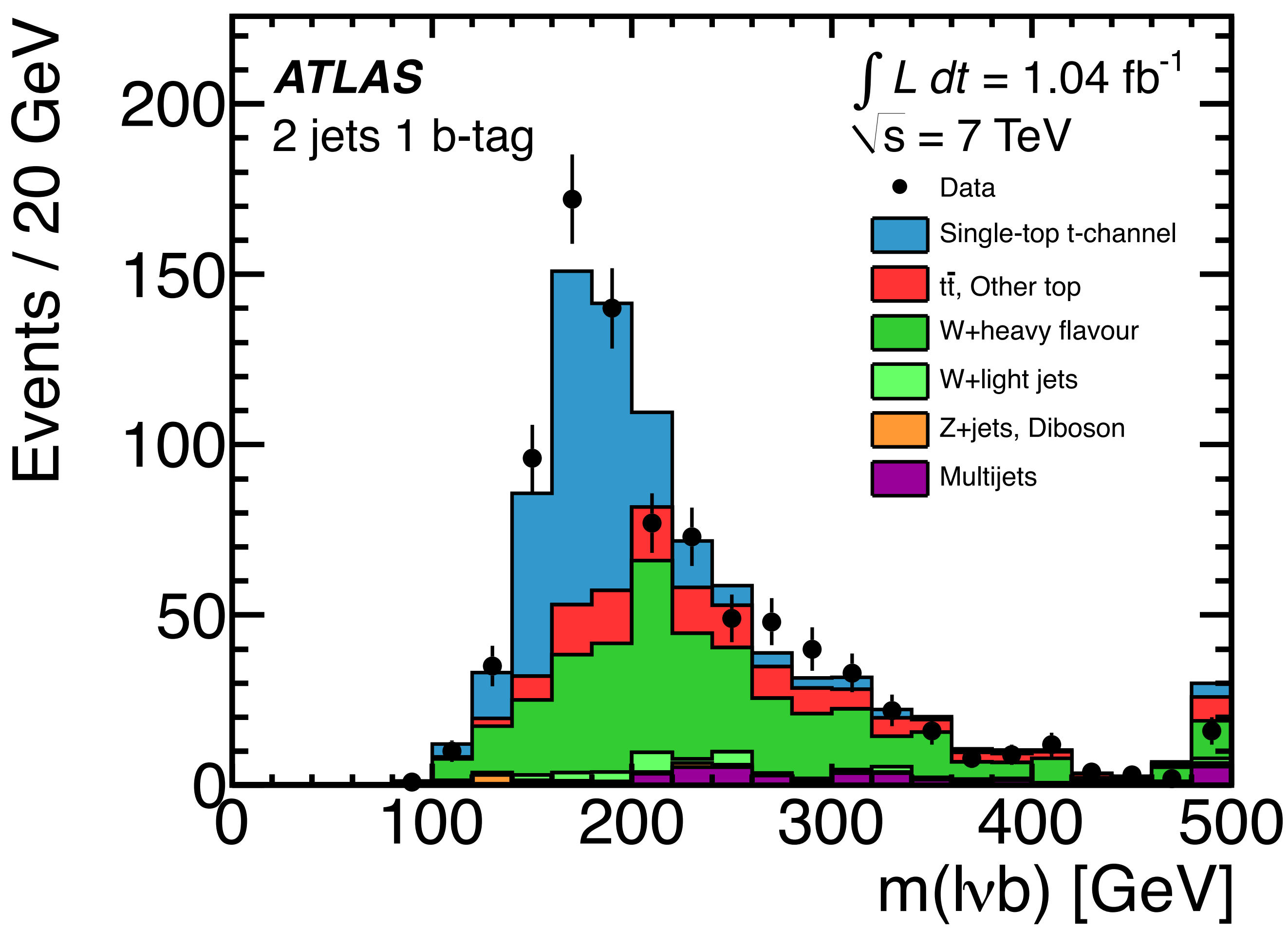


Collider	s-channel: σ_{tb}	t-channel: σ_{tqb}	Wt-channel: σ_{tW}
Tevatron: $p\bar{p}$ (1.96 TeV)	1.04 pb	2.26 pb	0.28 pb
LHC: pp (7 TeV)	4.6 pb	64.6 pb	15.7 pb

Single Top at LHC

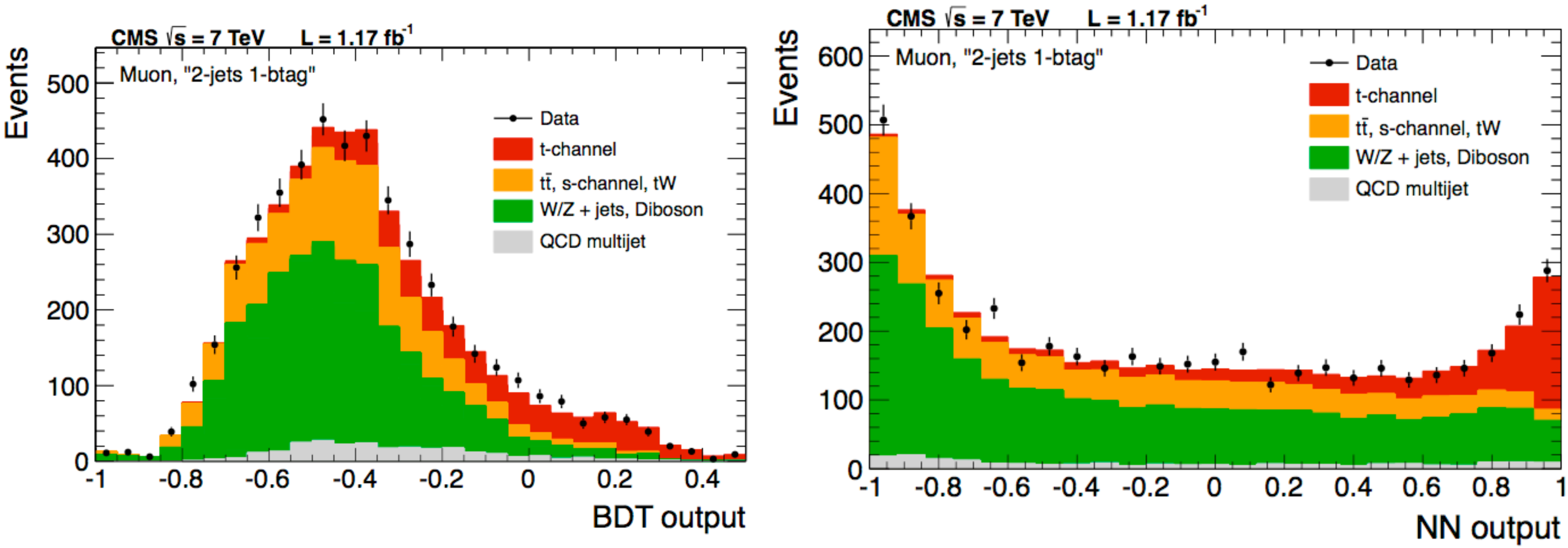
- t-channel can be selected with cuts on events with one lepton and two or three jets:





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)

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.