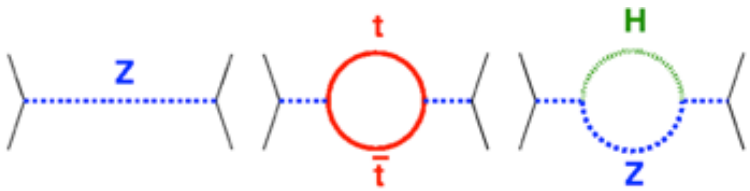
Top Physics

Alison Lister
(University of British Columbia)

For many years, mankind hunted for a new particle…

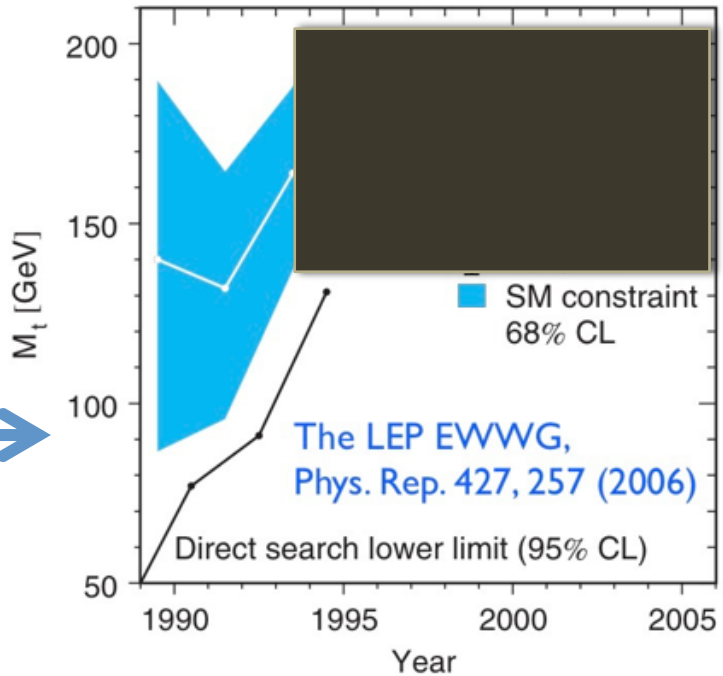
- 1976: Discovery of Upsilon (Fermilab)
  - Contains a 5th quark - the b-quark
  - From family structure of SM
    - Expect a 6th quark - race to find it
- Petra (e+e-) at DESY, Hamburg, $m_t > 23.3$ GeV (1984)
- Tristan (e+e-) in Japan: $m_t > 30.2$ GeV (late 1980s)
- UA1@SPS at CERN: $m_t > 44$ GeV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

Electroweak precision data:



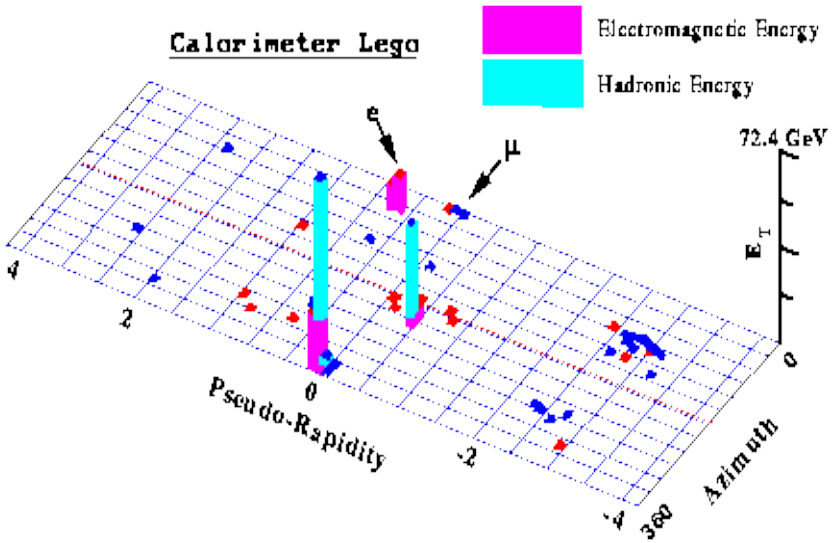
$$M_Z^2 = M_Z^{2\,0.\text{order}} / (1 - \Delta)$$

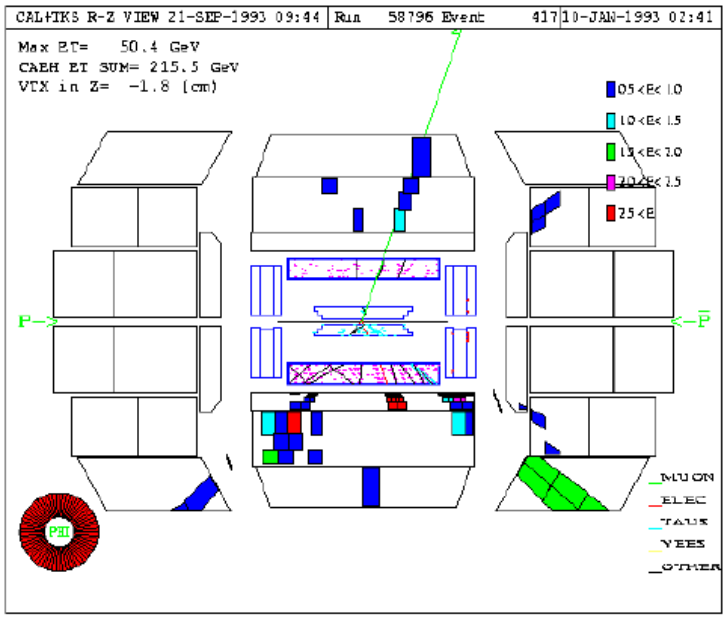
$$\Delta \approx \ldots m_t^2 \ldots + \ldots \ln m_h \ldots$$



Many years ago, in a land far far away

(22 years ago, at Fermilab)



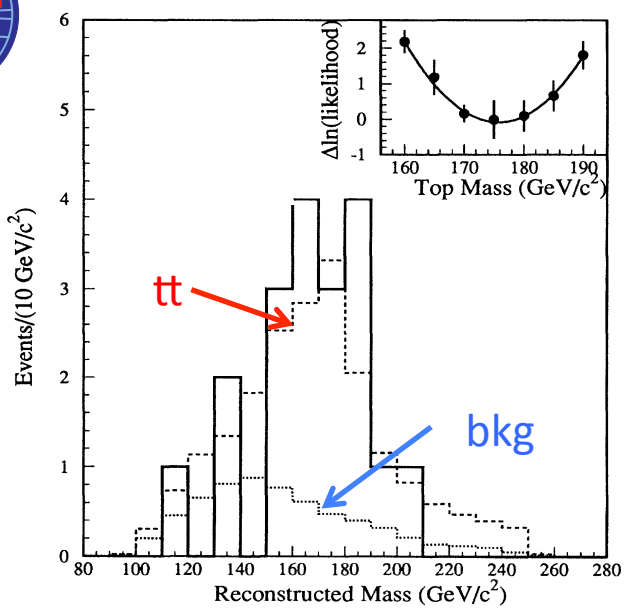


2 energetic jets (1 b-tagged @ CDF)
Isolated e and mu
Significant MET

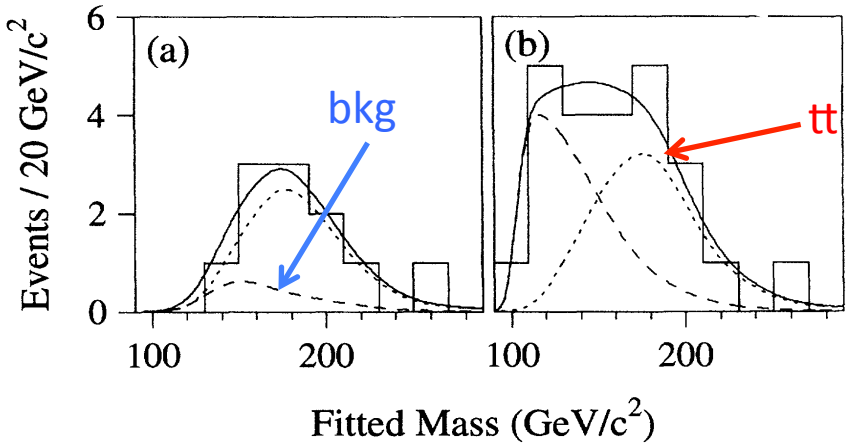
The quest for a new particle finally came to an end

(20 years ago)

4.8 sigma



4.6 sigma



m_{top}= 176 ±8 (stat) ±10 (syst) GeV/c^2

σ_{tt} = 6.8 $^{+3.6}_{-2.4}$ pb

Phys. Rev. Lett. 73, 225 (1994)
Phys. Rev. Lett. 74, 2626 (1995)

m_{top}= 199 $^{-19}_{-21}$ (stat) ±22 (syst) GeV/c^2

σ_{tt} = 6.4 ± 2.2 pb

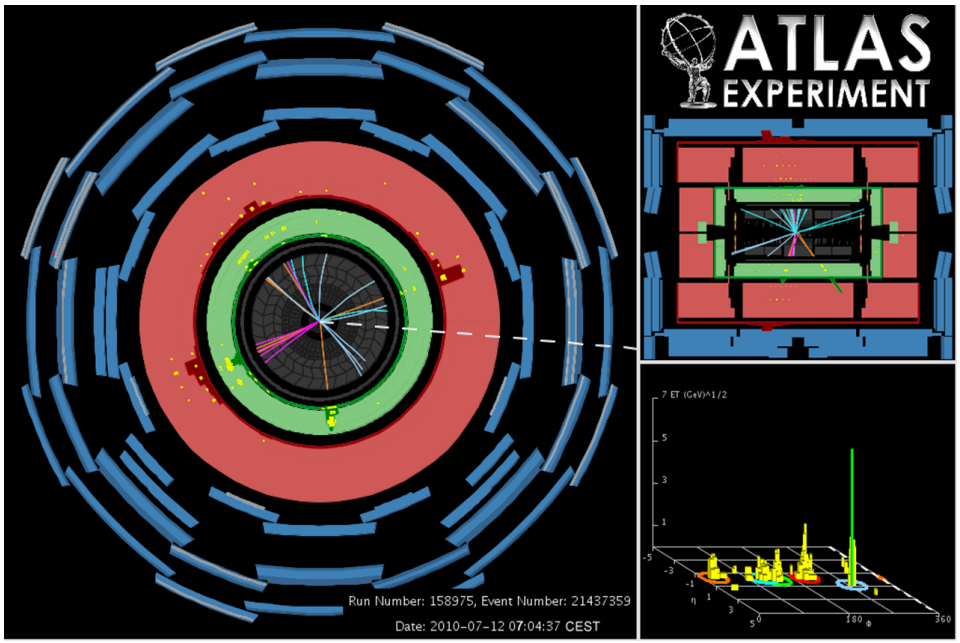
Phys. Rev. Lett. 74, 2632 (1995)

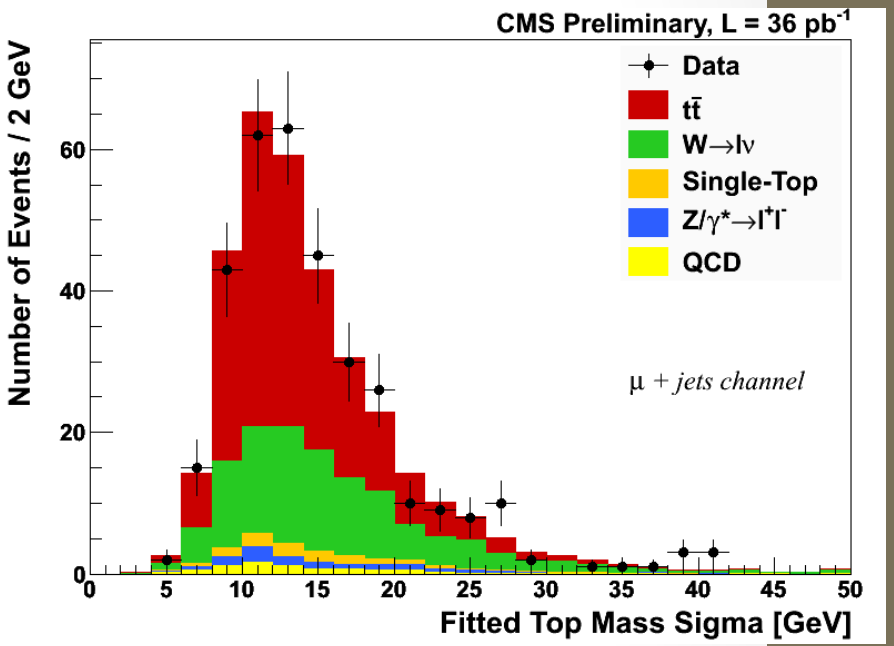
The world rejoiced!

(2nd March 1995)

Does it remind you of a recent picture from 2012?

Yet people kept looking near and far…





…Until one day the top found a new home and lived happily ever after

(4-5 years ago, CERN)

Or is it?

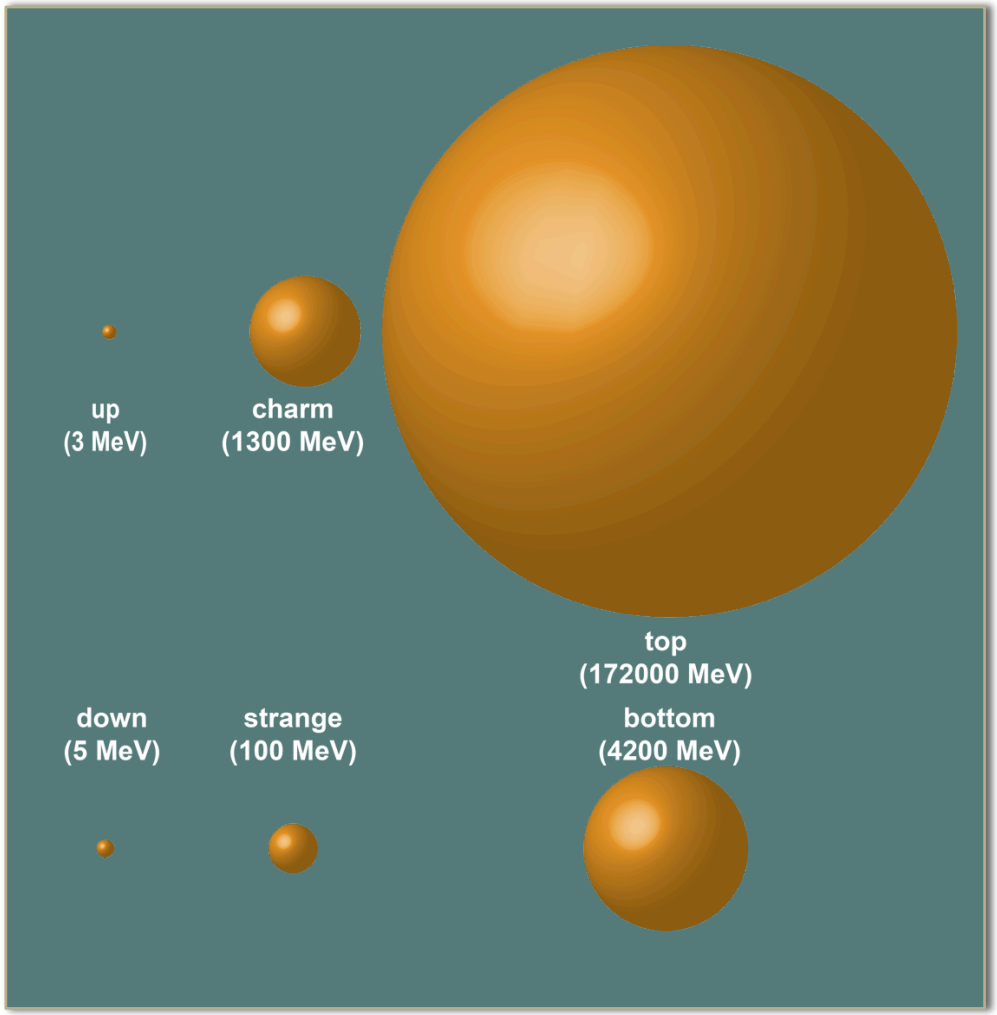
See special lecture next Friday by B. Klima

Content of these two lectures

- Why is the top still interesting?
- Top signatures
- Top cross section
  - Prediction
  - Inclusive
  - Differential
- Single top production any decay

- Top mass
- Other properties
- Searches for new physics with top quarks

What do we know about top

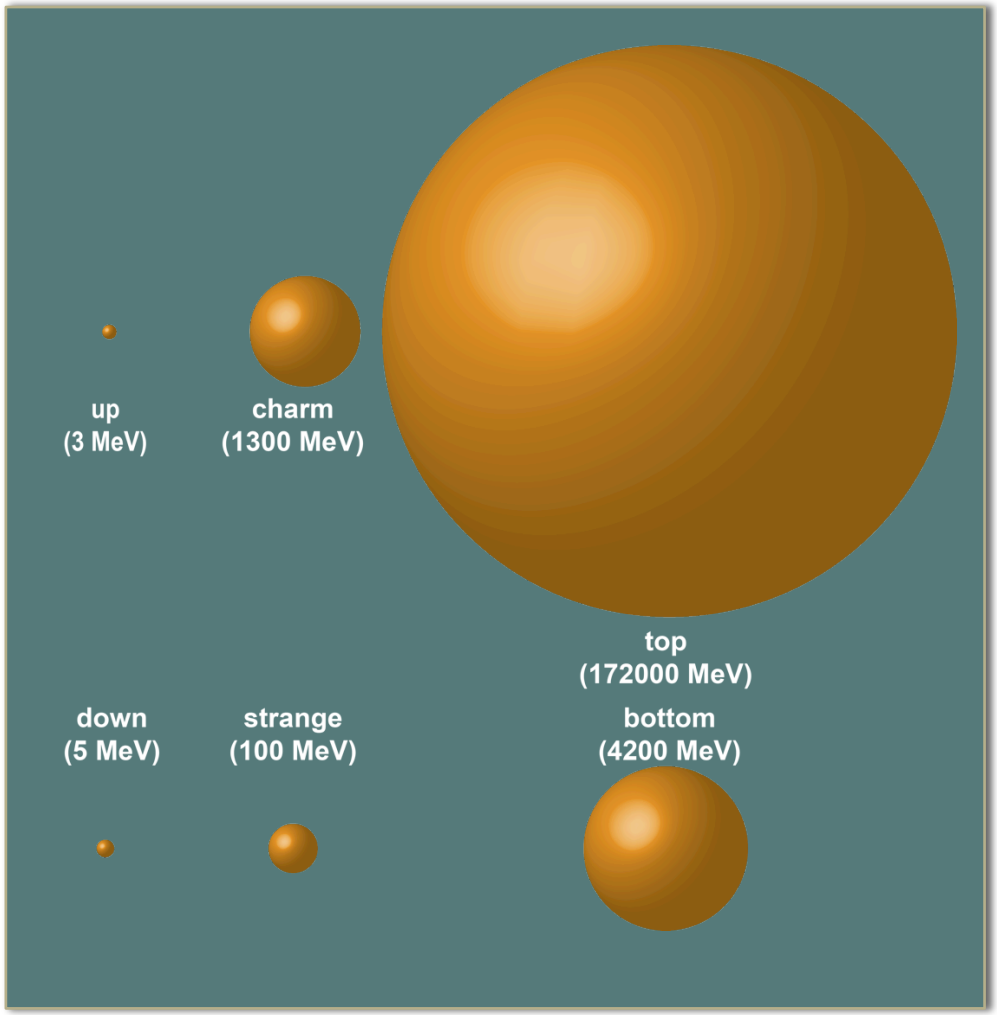


Experimentally confirmed facts:

- Top is the heaviest known fundamental particle
  - Mass ~ 173 GeV
- It is a quark (sees the strong force)
- Charge 2/3e
- Spin ½
- Decays almost exclusively to Wb
- Produced by strong and weak interactions

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

Why we still care about top



- Only place to study the properties of a bare quark
  - Lifetime < hadronisation
- Special role in EWSB?
- First place a new particle could be observed
  - Particularly if new particle couples to mass
- Top is a background to many other searches

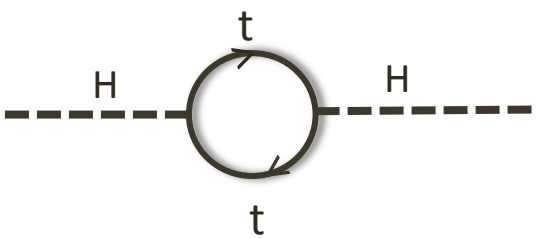
$$\tau_{had} \approx 2 \times 10^{-24} s$$

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

The Hierarchy Problem

Λ: scale of new physics

The Problem:



$$m_H^2 = m_{bare}^2 + \Delta m_H^2$$

$$\Delta m_H^2 \sim 3/(8\pi^2)\, y_t^2\, \Lambda^2$$

If $\Lambda \sim$ Plank scale:

$$m_H^2 \sim \Delta m_H^2 \times 10^{-32}$$

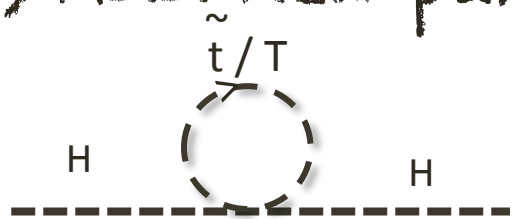
Possible Solutions:

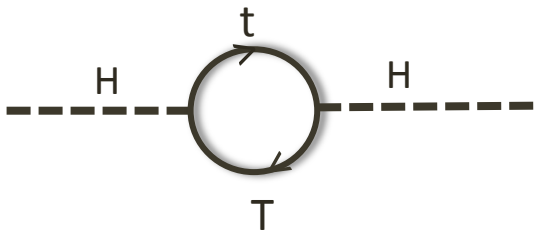
A) SM only low energy effective theory

i.e. $\Lambda \ll$ Plank

If $\Lambda \sim$ TeV: $\Delta m_H^2 \sim O(m_H^2)$

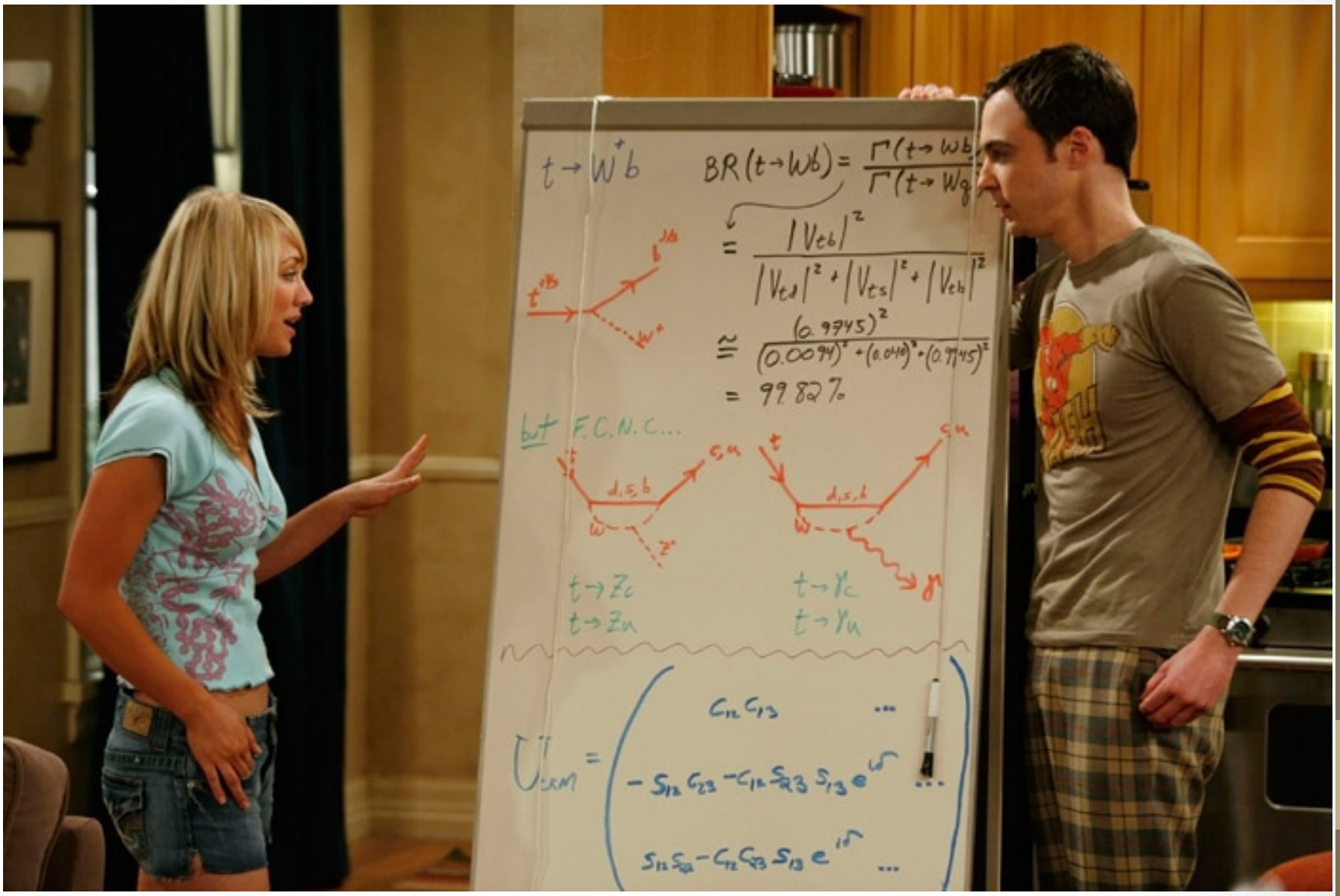
B) Add new particles (e.g. SUSY, top partners)





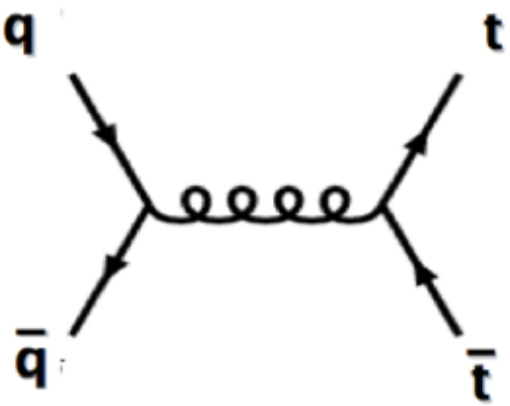
loops cancel

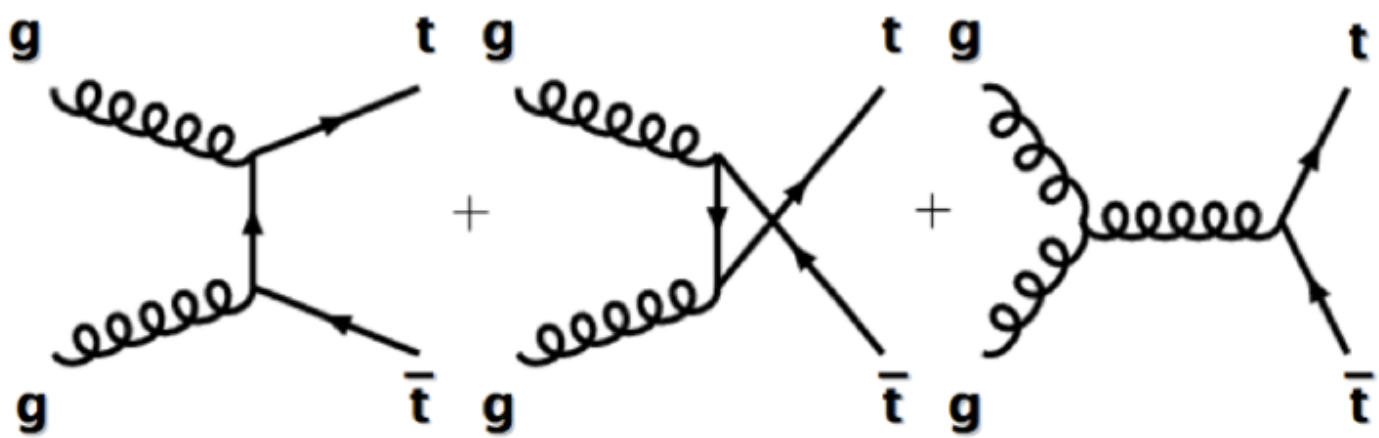
Why we really still care about Top



TOP PRODUCTION AND DECAY

Pair Production @ LO



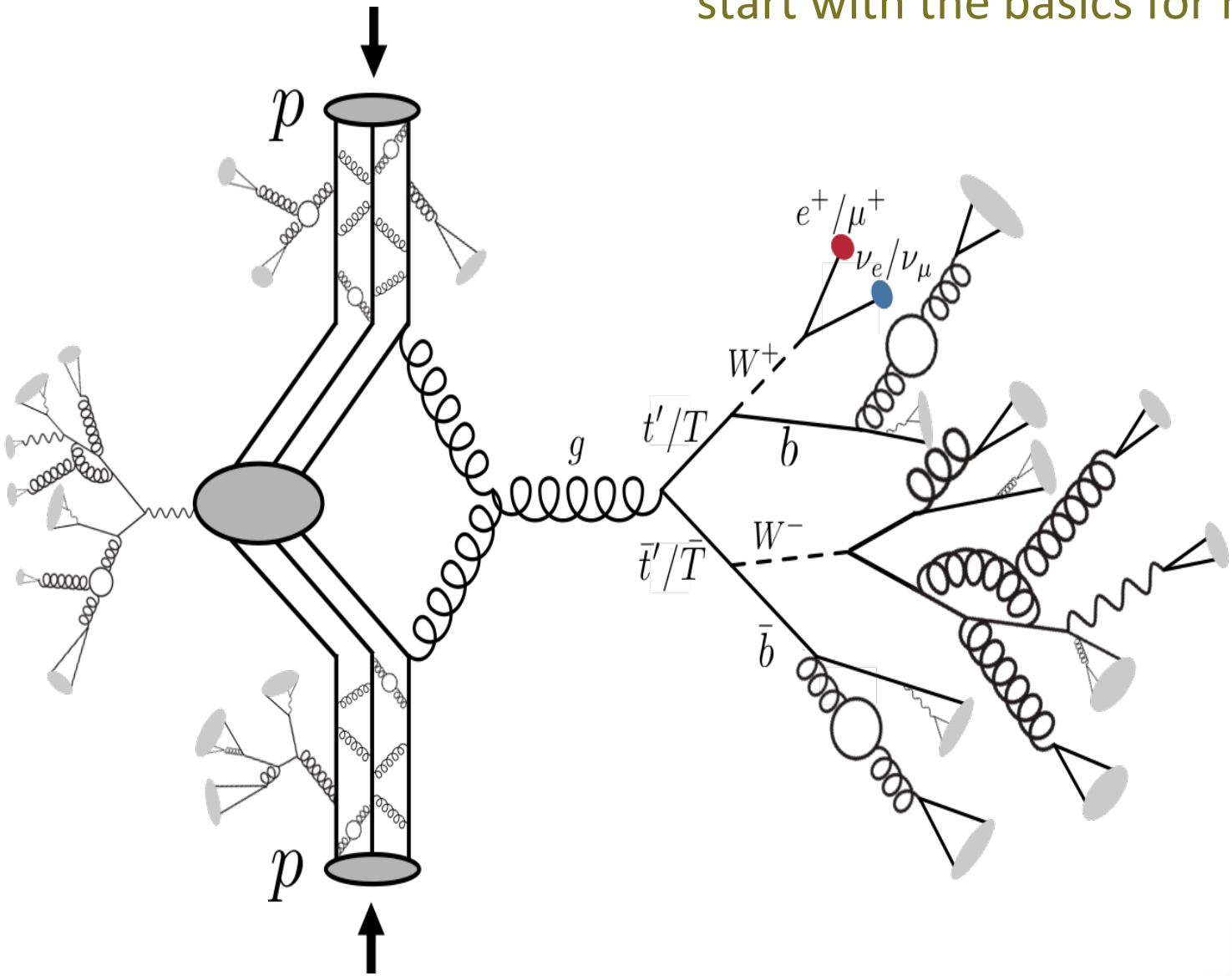


	TeVatron	LHC 7 TeV	LHC 8 TeV	LHC 14 TeV
gg	15.4%	84.8%	86.2%	90.2%
$qg + \bar{q}g$	-1.7%	-1.6%	-1.1%	0.5%
qq	86.3%	16.8%	14.9%	9.3%

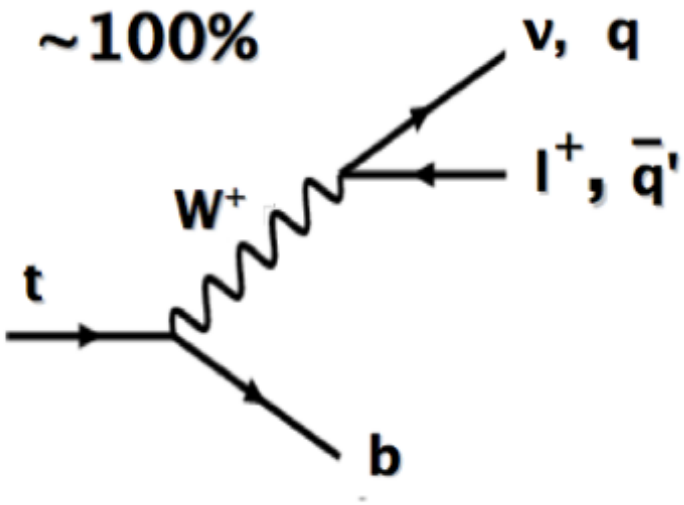
MSTW2008NNLO

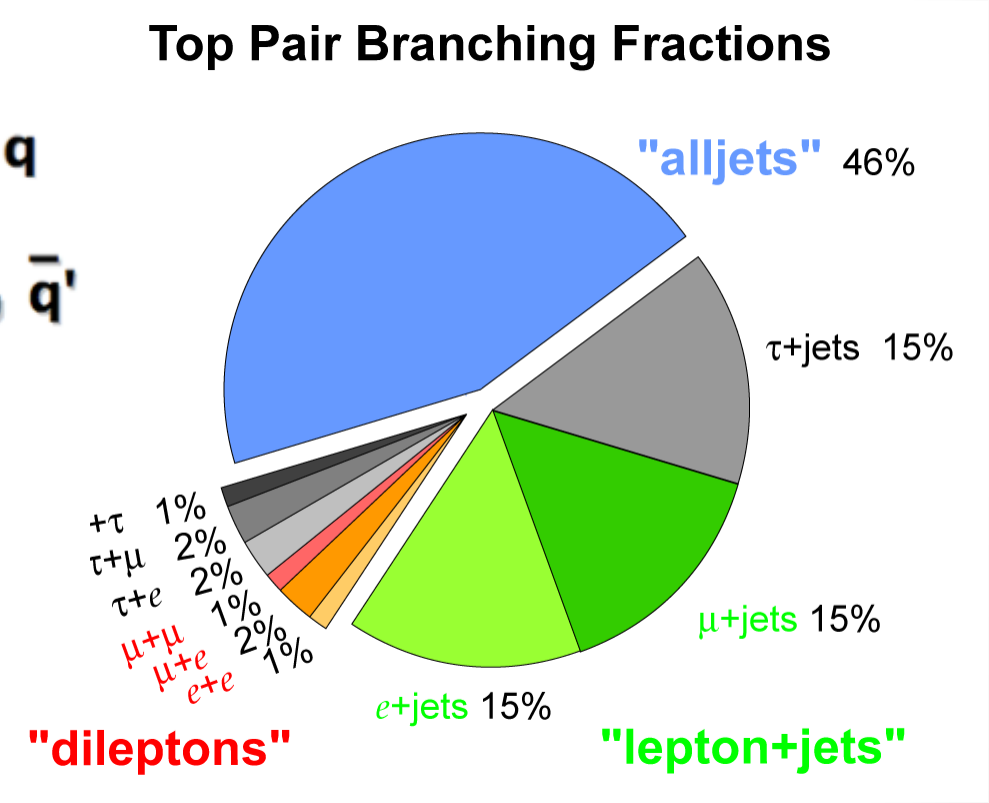
Pair Production

Things are a bit more complicated than that but lets start with the basics for now…

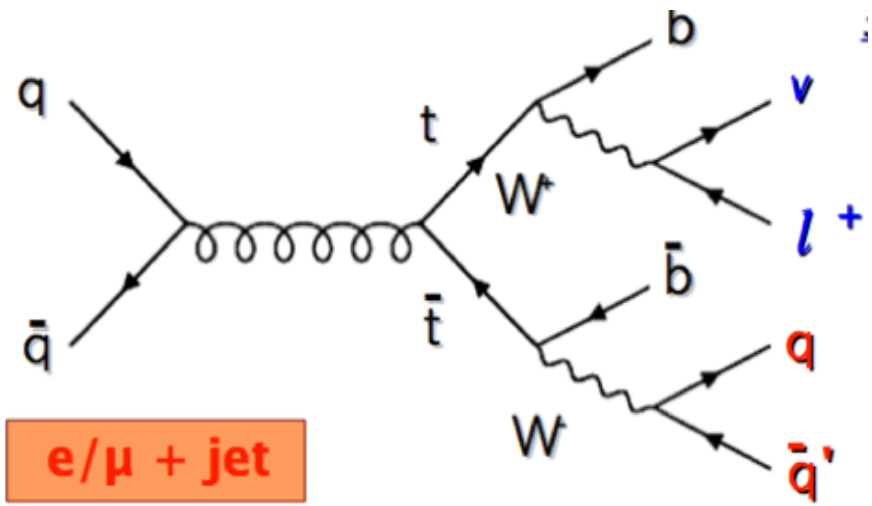


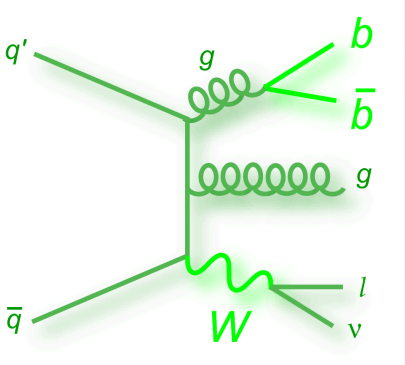
Top Decay

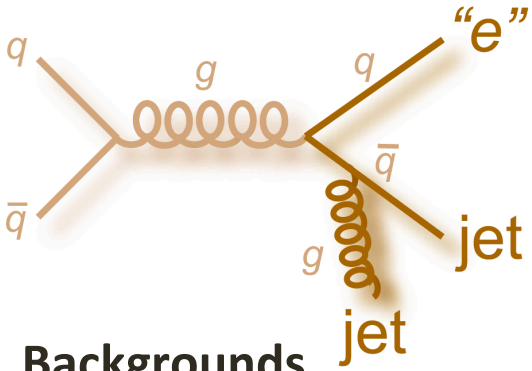

~100%
ν, q
l+, q̄'
W+
t
b


Top Pair Branching Fractions
"alljets" 46%
τ+jets 15%
μ+jets 15%
e+jets 15%
+τ 1%
τ+μ 2%
τ+e 2%
μ+μ 1%
μ+e 2%
e+e 1%
"dileptons"
"lepton+jets"

Lepton plus jets channel







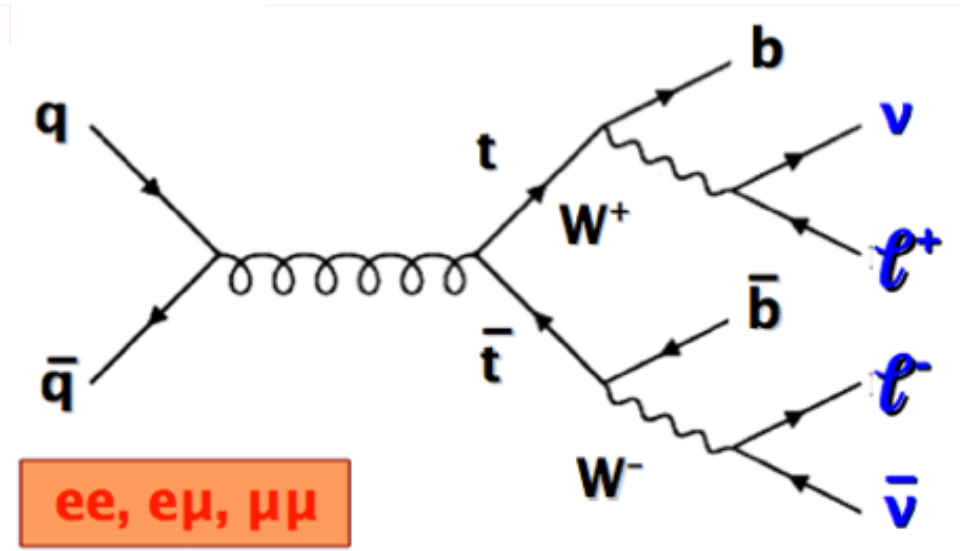
Shopping list

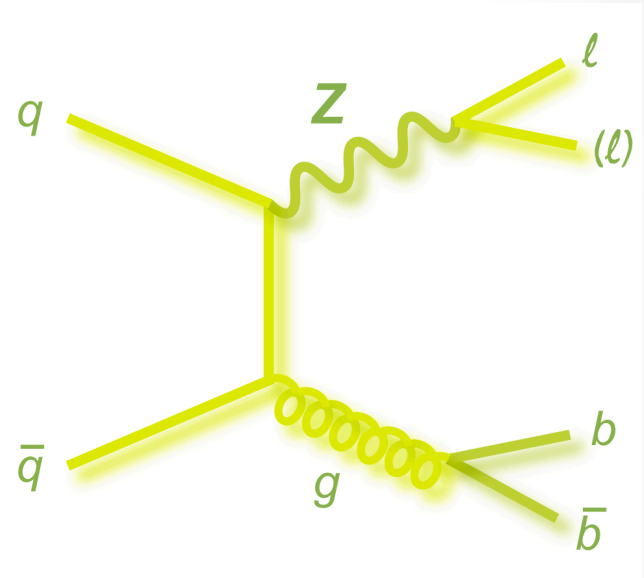
- 1 lepton
- Missing transverse momentum
- ≥ 4 jets
  - 2 from b-hadrons

Backgrounds

- W+jets
- Single top
- Dibosons
- Z+jets
- QCD multi-jet 'fakes'

Dilepton channel





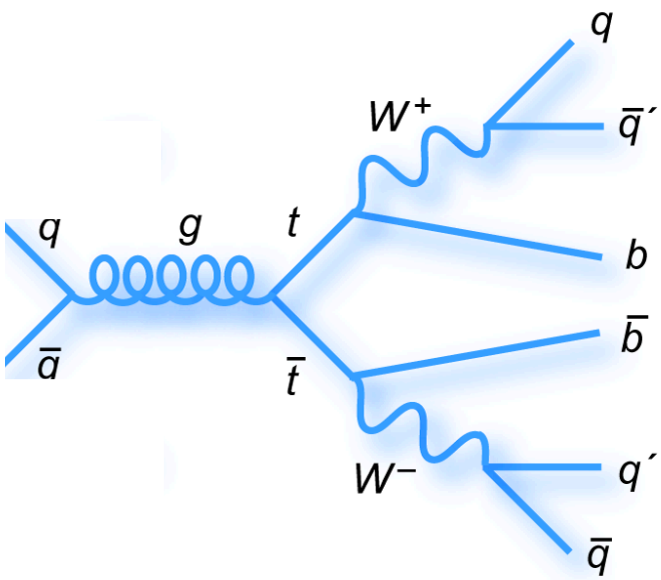
Shopping list

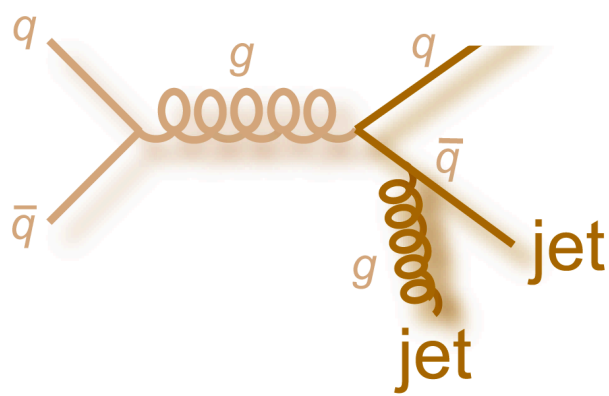
- 2 leptons
- Missing transverse momentum
- ≥ 2 jets
  - 2 from b-hadrons

Backgrounds

- Z+jets
- Single top
- Dibosons
- QCD multi-jet 'fakes'

All Hadronic channel





Shopping list

- 0 leptons
- No Missing transverse momentum
- ≥ 6 jets
  - 2 from b-hadrons

Backgrounds

- QCD multi-jet

We sadly won't be discussing this channel much in these lectures

Relative merits

L+jets:

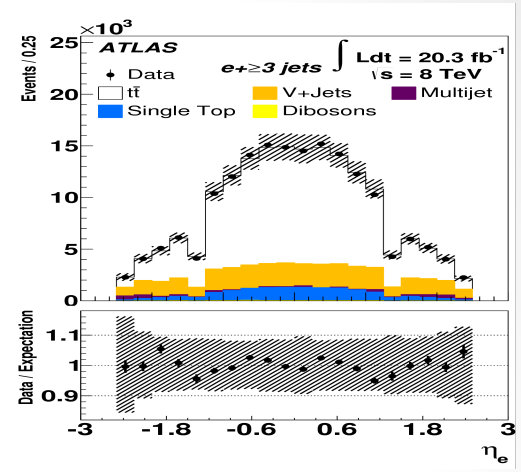
- Reasonable branching ratio
- Reasonable S/B
- Only 1 neutrino so can fully re-construct the ttbar system

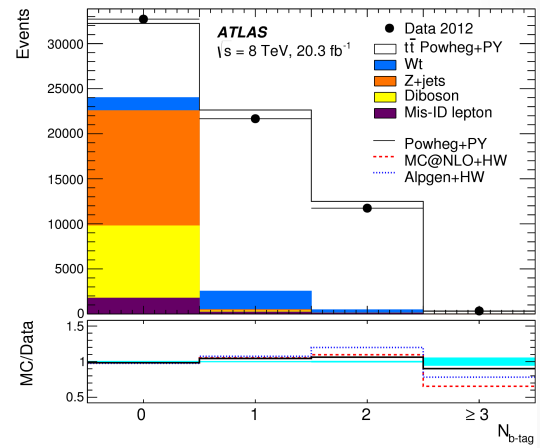
dilepton:

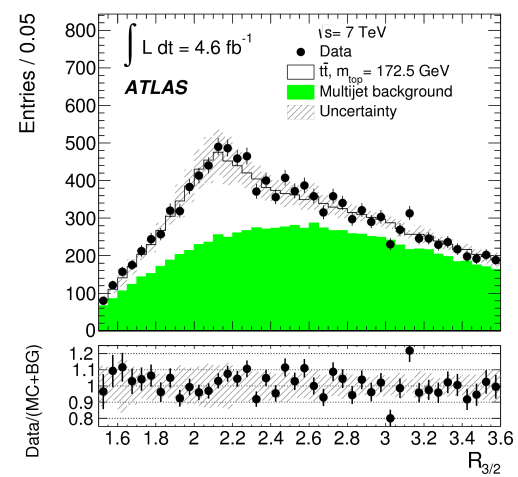
- Lowest branching ratio
- Highest S/B
- 2 neutrinos so harder to re-construct the ttbar system

All hadronic:

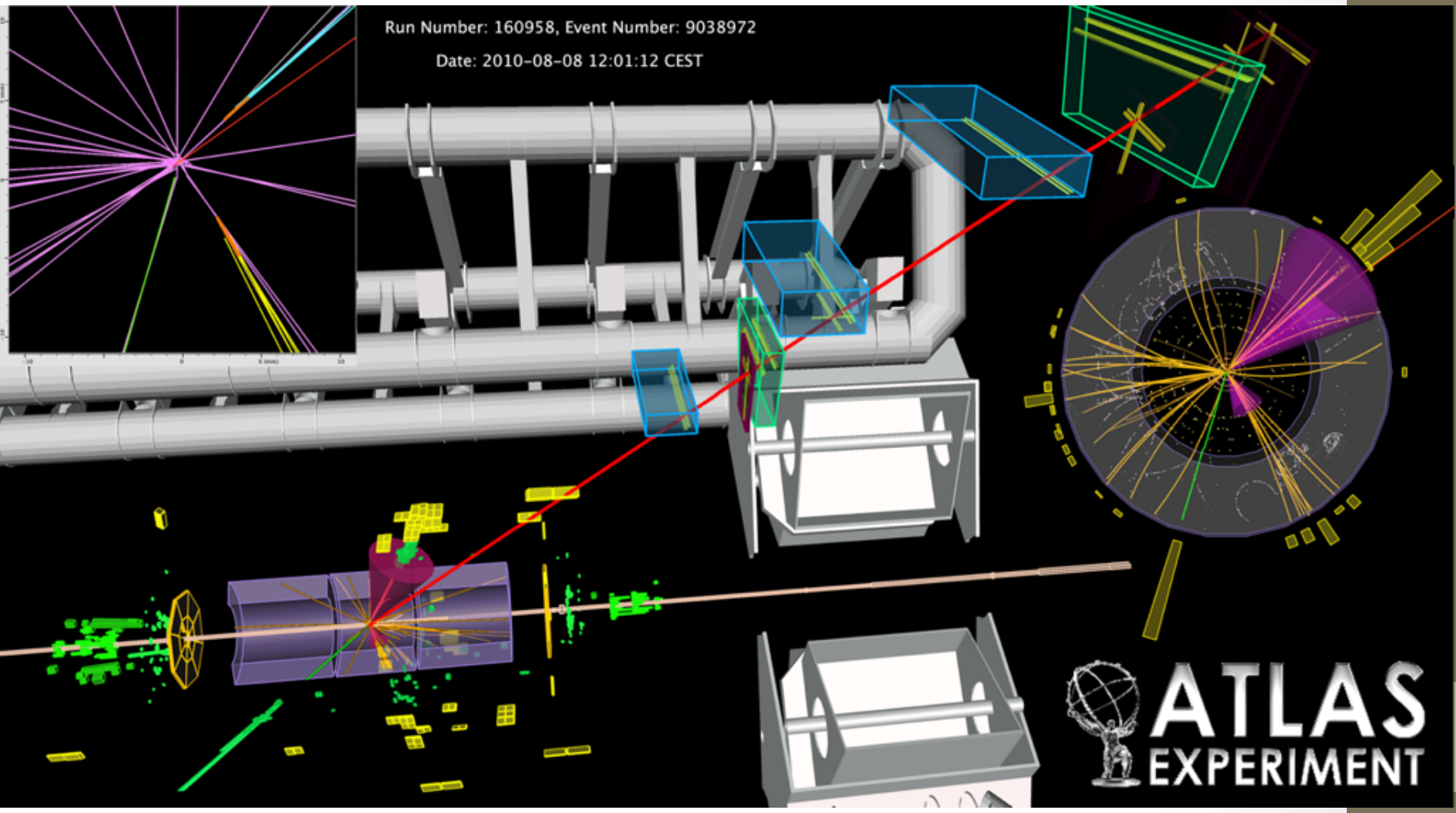
- Highest branching ratio
- Lowest S/B
- Hard to determine backgrounds from QCD
- Reconstructing ttbar system: combinatorial complexity



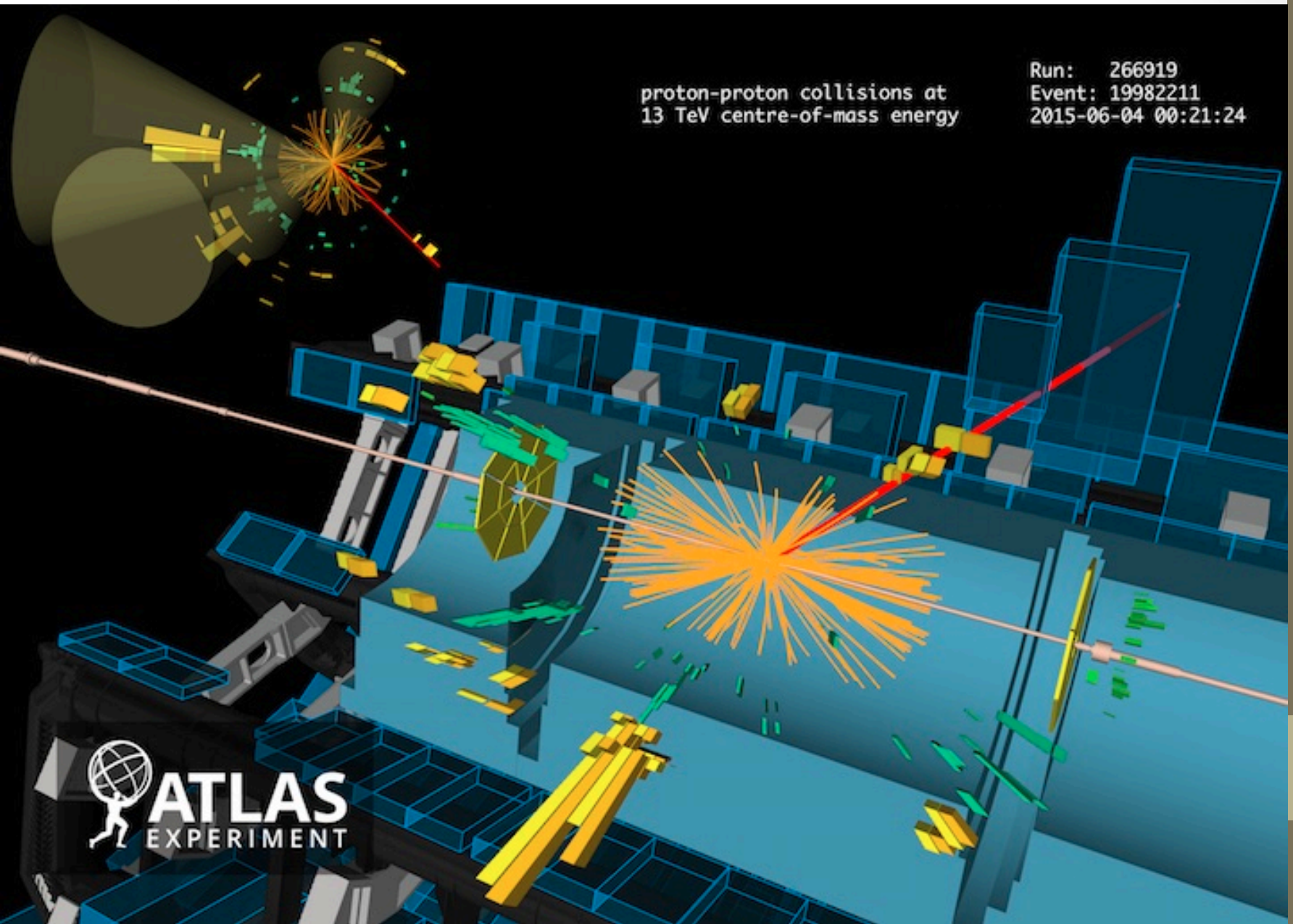




Dilepton (emu) event display

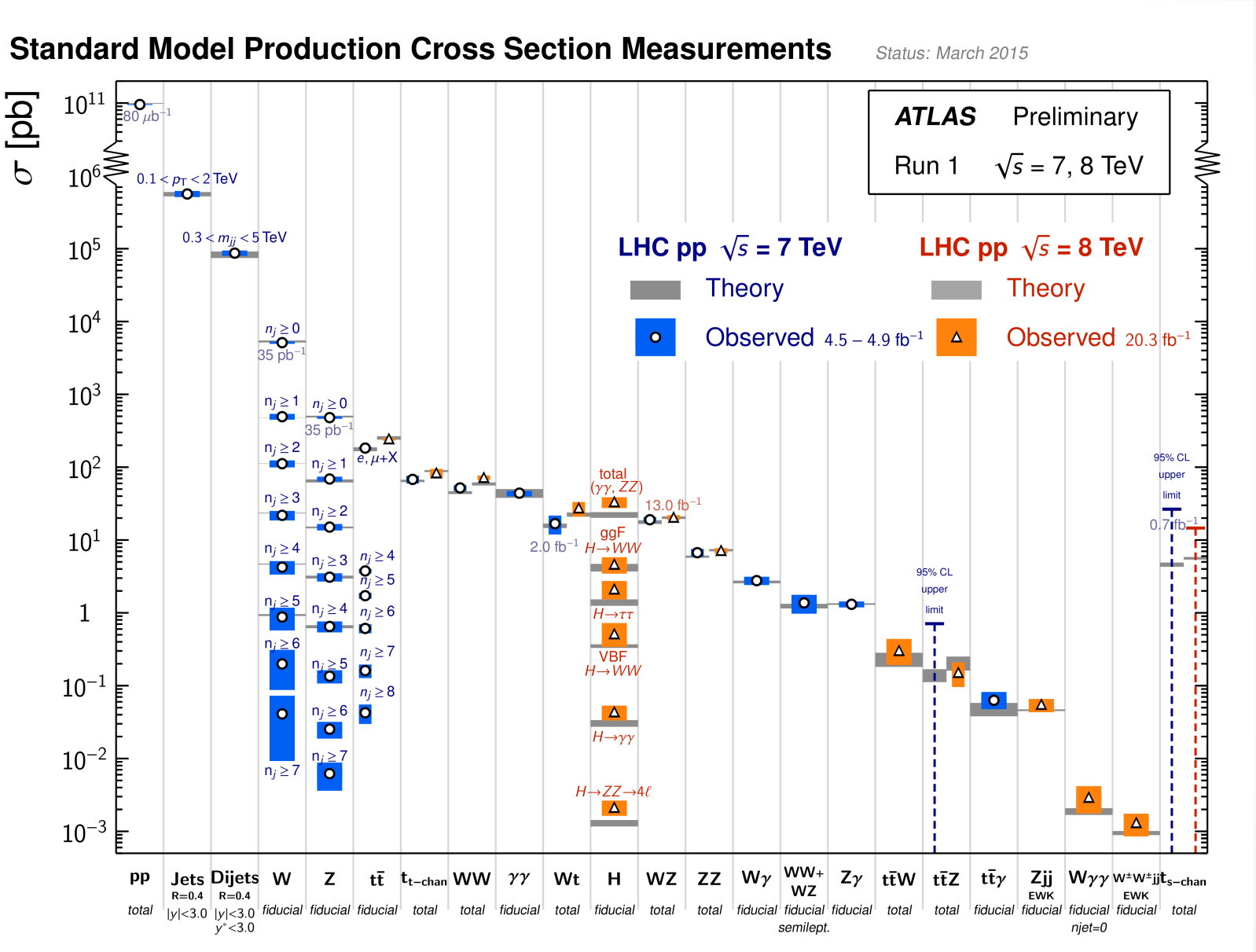


L+jets event display

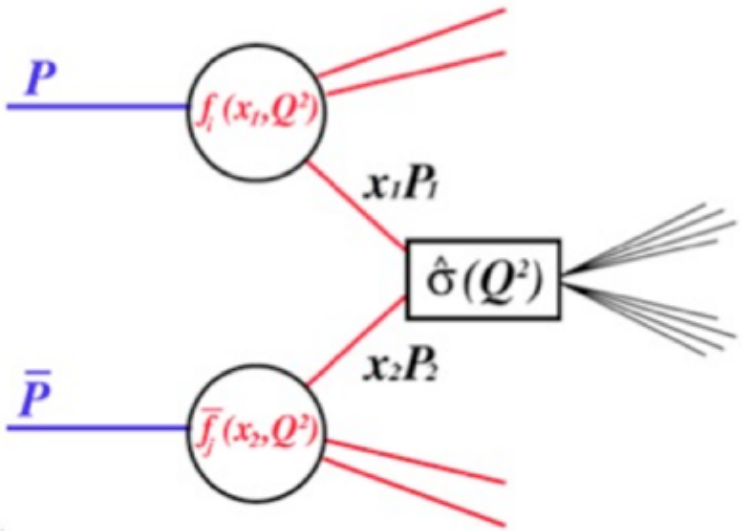


TOP PAIR PRODUCTION CROSS SECTION

How far we have come!



Calculations



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

Sum over incoming partons i, j

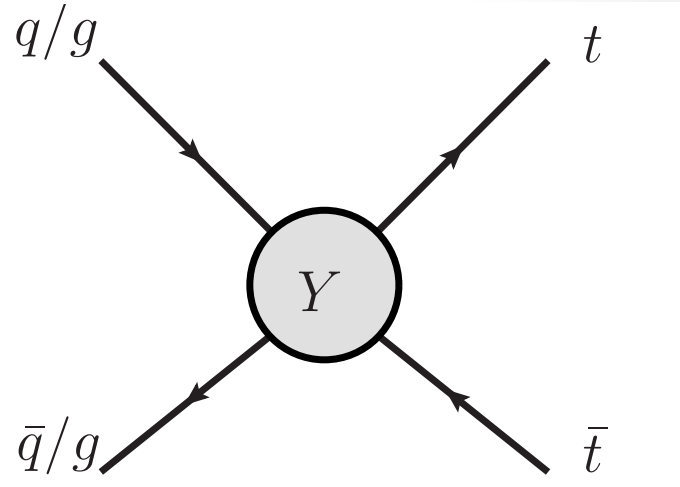
Momentum fraction for incoming parton

PDF for incoming parton i

"partonic" cross section

Partonic cross section

- Need to calculate everything that goes into Y
- Use perturbative expansion of Y in orders of strong coupling constant (α_s)
  - α_s~0.1 so series should converge



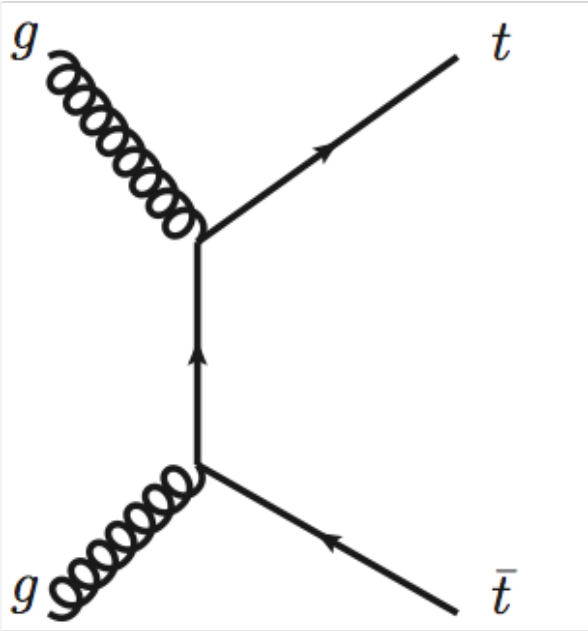
$$\sigma\left(q\bar{q}/gg \to t\bar{t} + X\right) = H^{(0)} + \alpha_s H^{(1)} + \alpha_s^2 H^{(2)} + \ldots$$

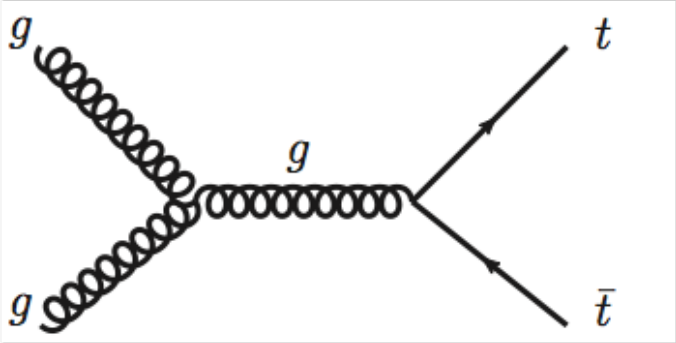
Leading order (LO) term, proportional to α_s^2

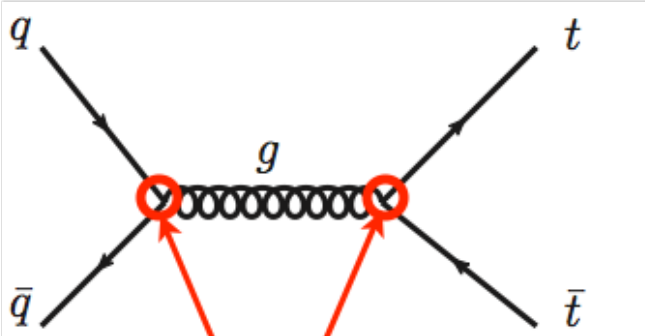
Next-to-leading order (NLO) term, proportional to α_s^3

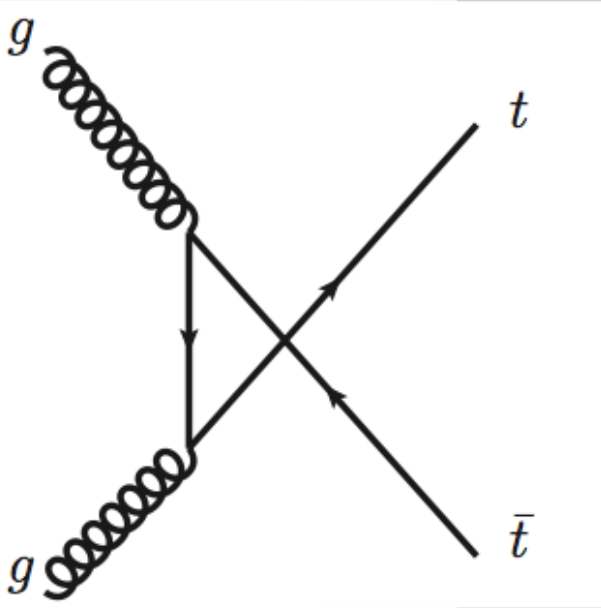
Next-to-next-to-leading order term, proportional to α_s^4

Leading Order





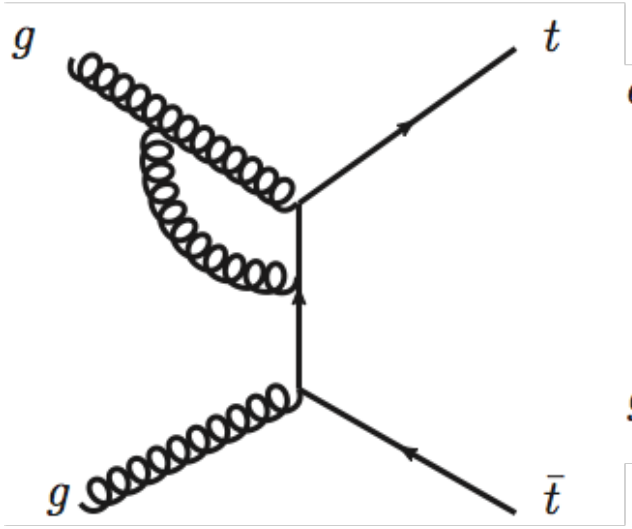


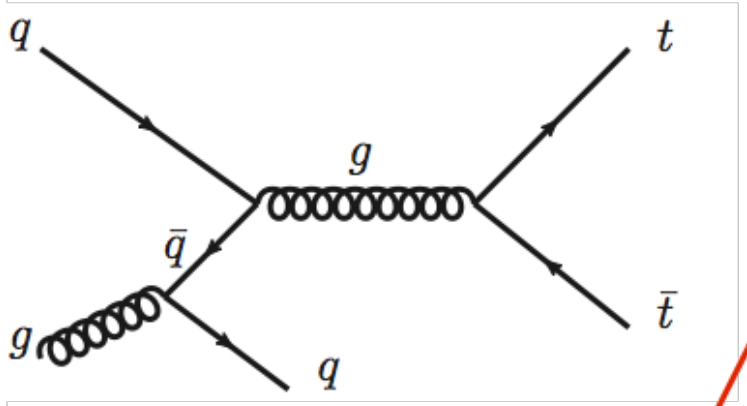


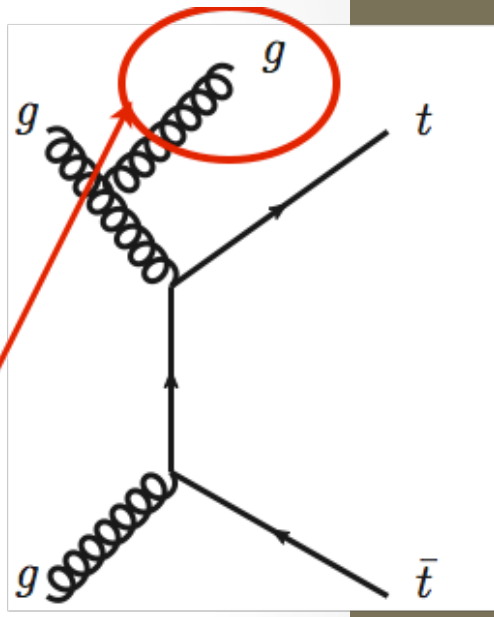
Each vertex contributes $\sqrt{\alpha_s}$

α_s = strong force (QCD) coupling constant

Next to Leading Order

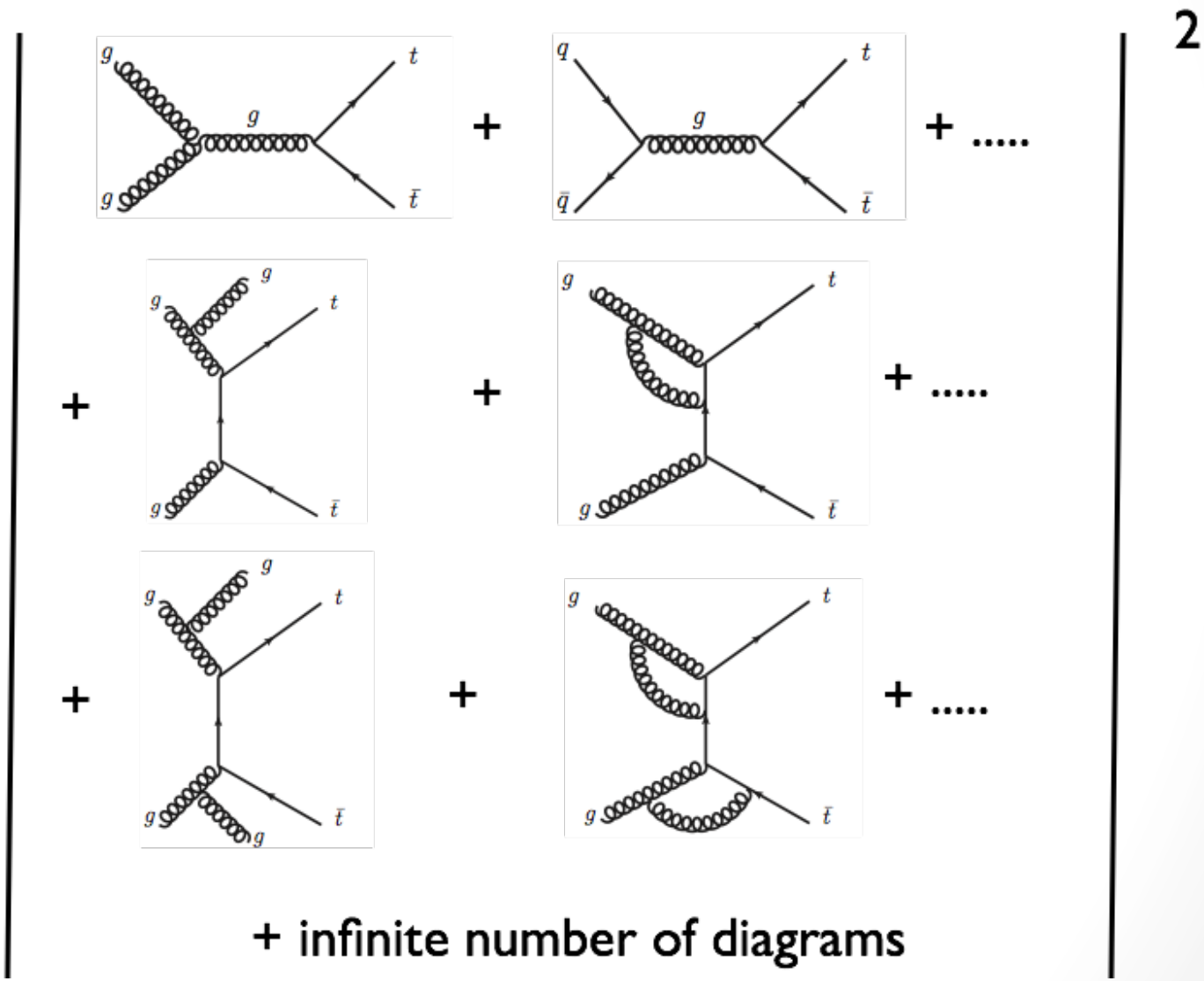






Extra gluon - results in extra jet of hadrons in detector (more later)

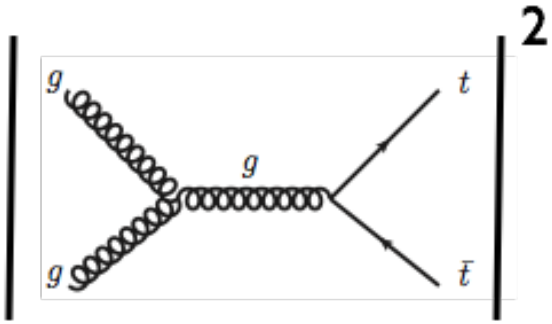
Calculate all allowed processes



Leading order

Contains all terms proportional to α_s^2

$\sigma_{LO} \propto$



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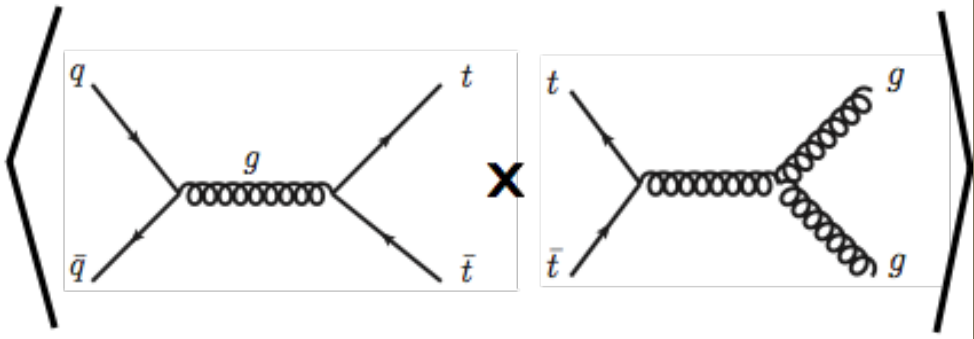

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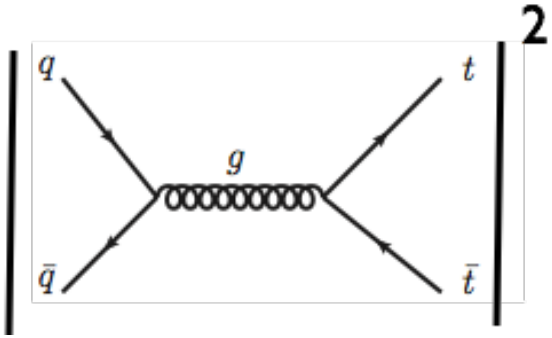

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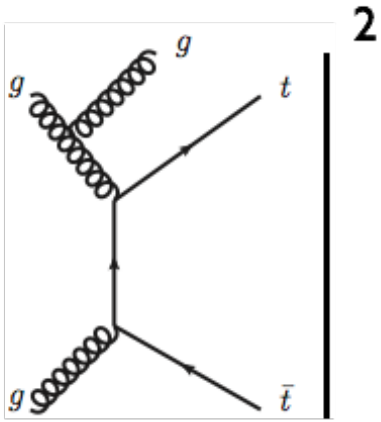
Next to Leading order

Contains all terms proportional to α_s^2 and α_s^3

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



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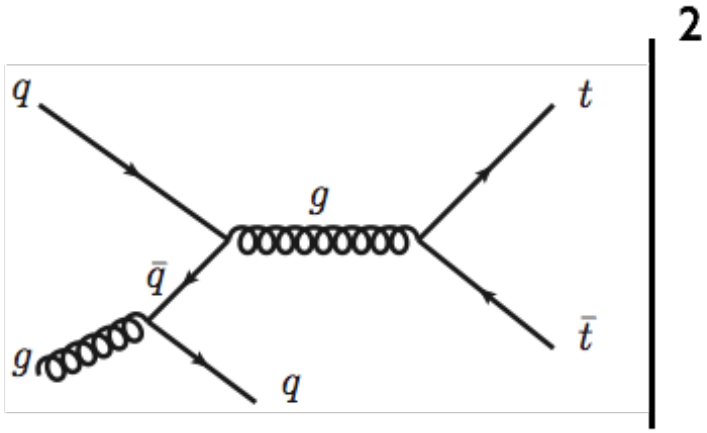

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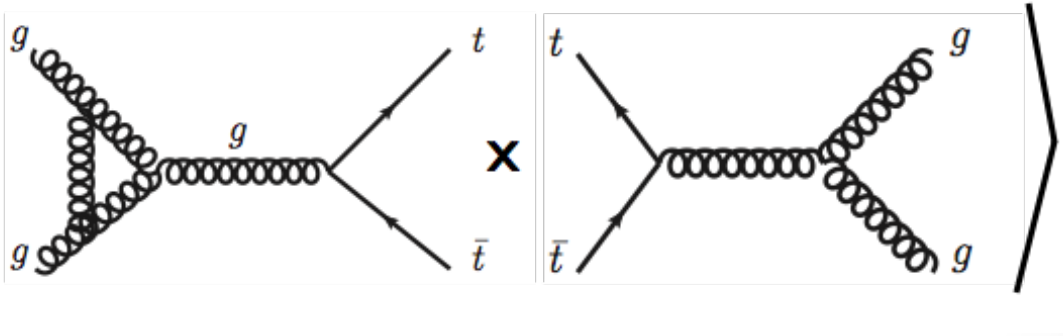
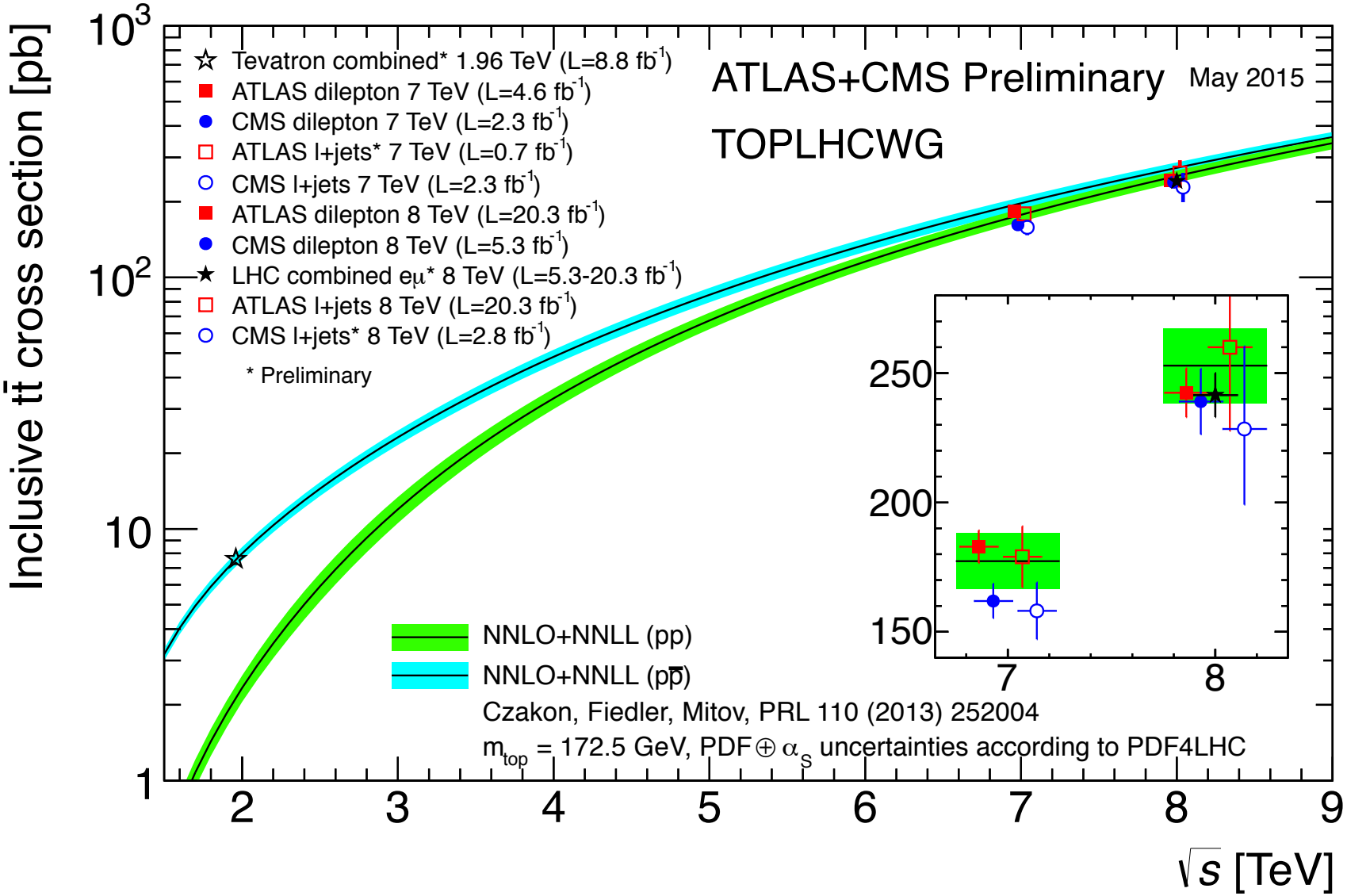


State of the art: NNLO

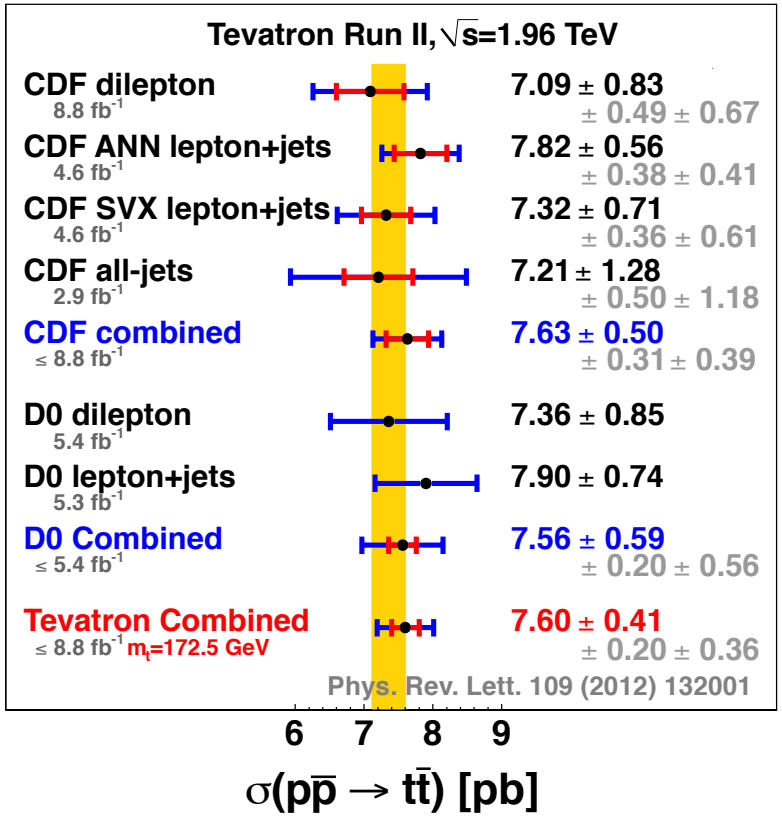
- Latest-greatest for the inclusive ttbar cross section: NNLO
- Latest-greatest for differential ttbar cross section: NLO
  - Expect NNLO differential distributions in a matter of months!

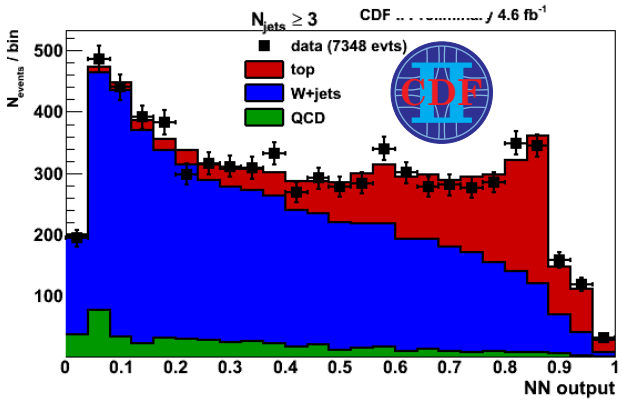
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$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

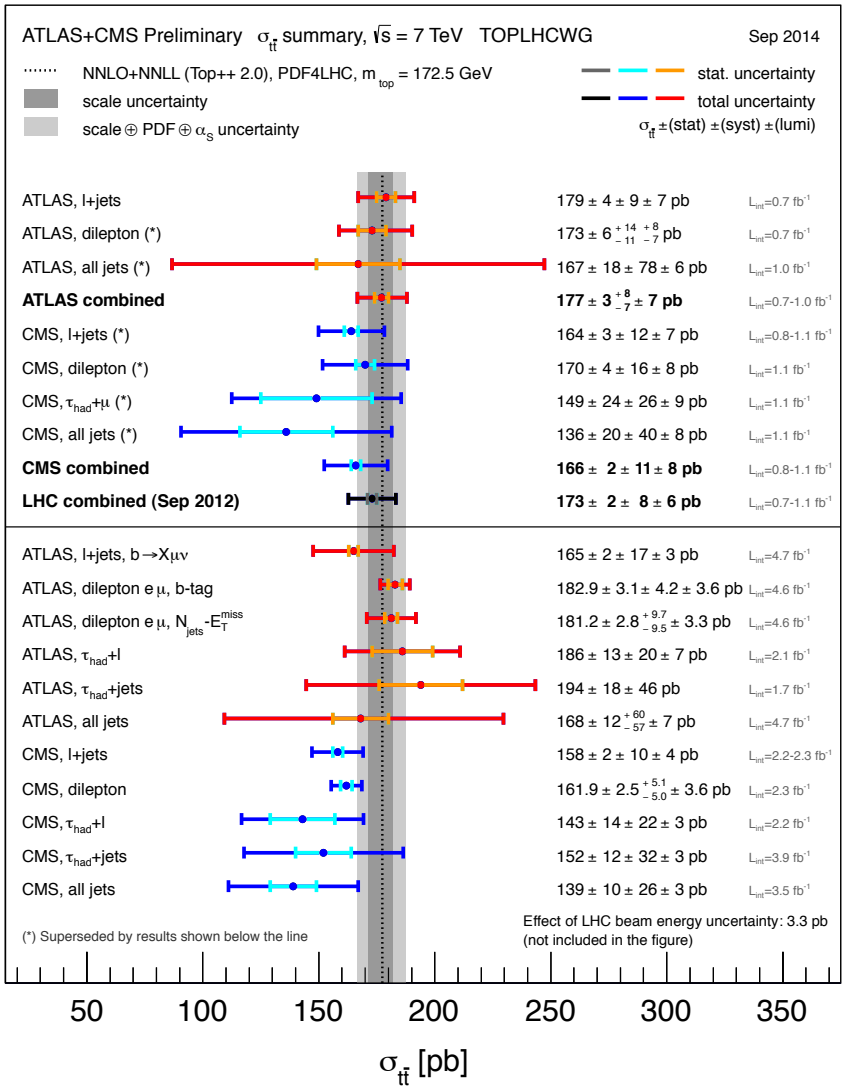
State of the art



ttbar cross section



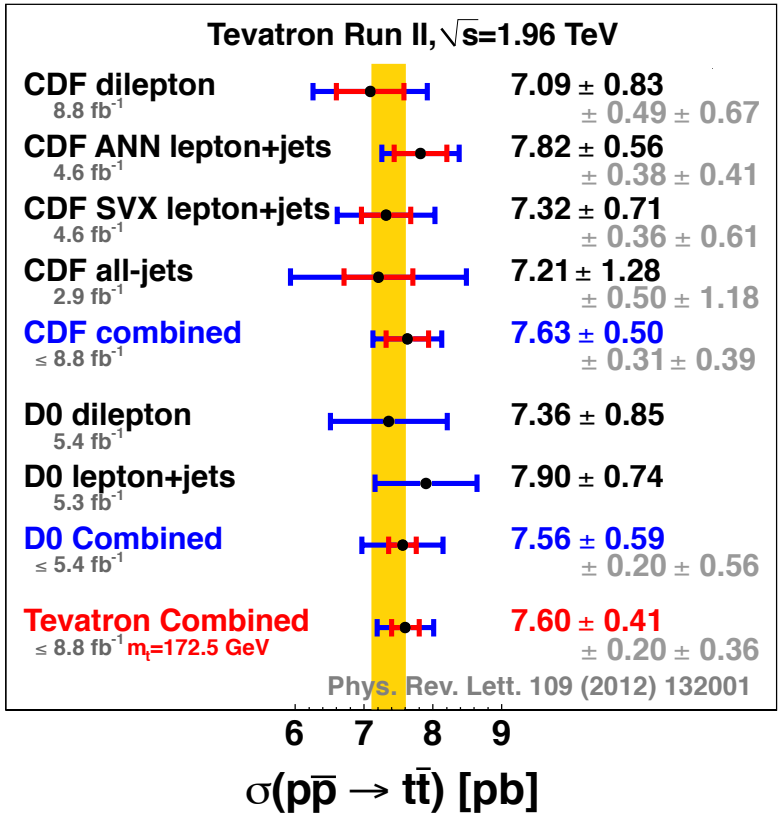


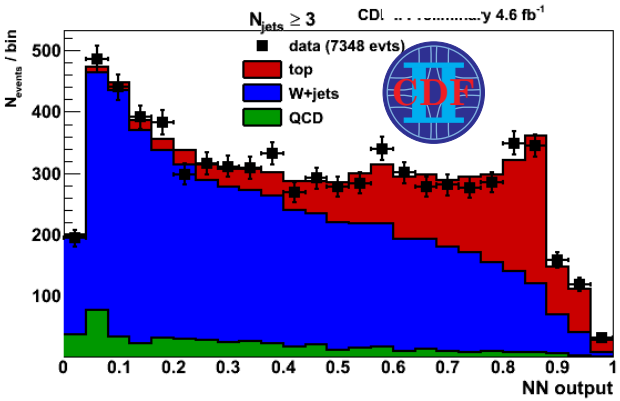


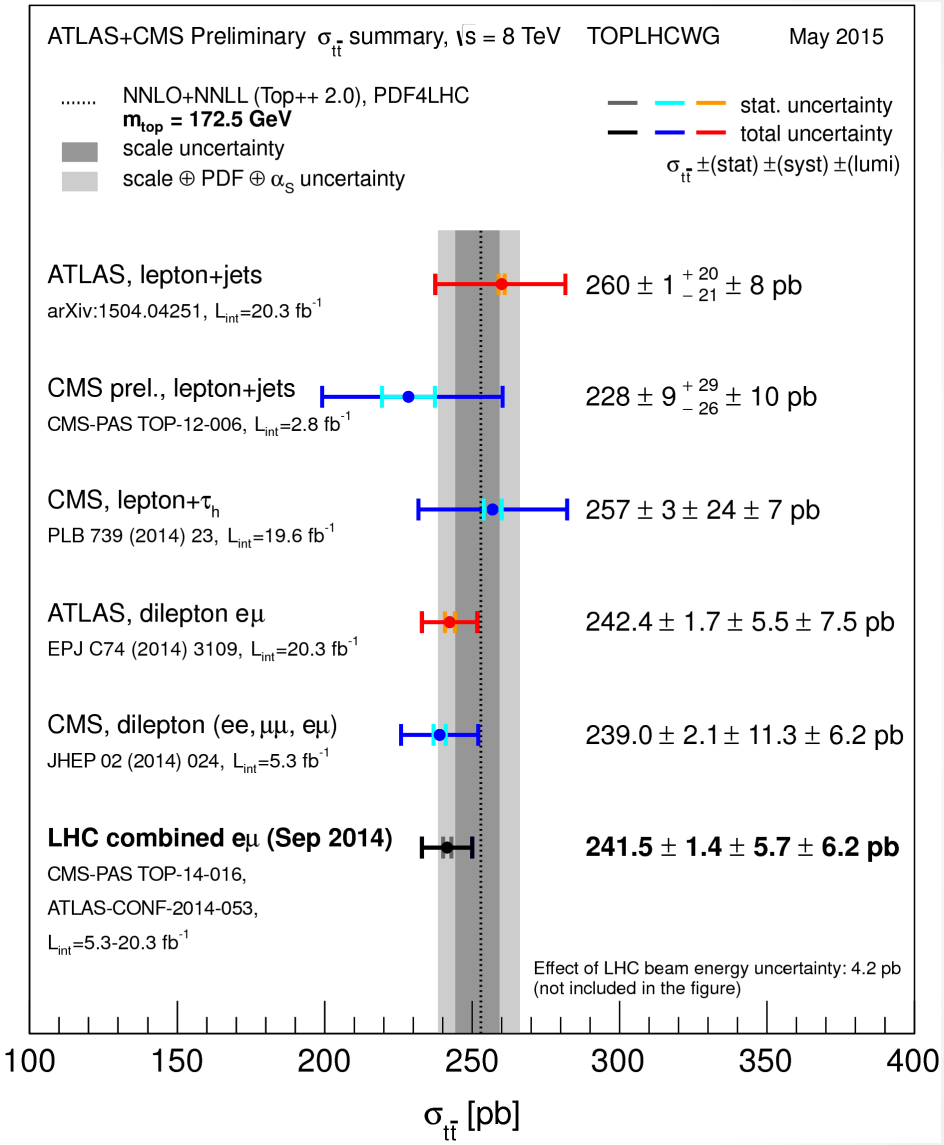
$\Delta\sigma_{the} \sim 5.4\%$

$\Delta\sigma_{exp} \sim 3.9\%$

ttbar cross section







$\Delta\sigma_{the} \sim 5.4\%$

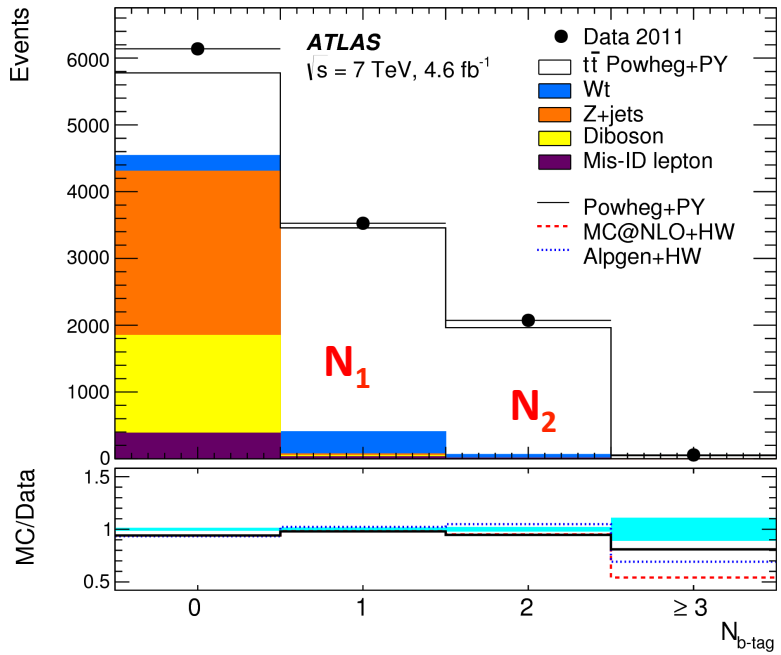
$\Delta\sigma_{exp} \sim 3.9\%$

ttbar cross section: dilepton

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

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

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



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

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

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

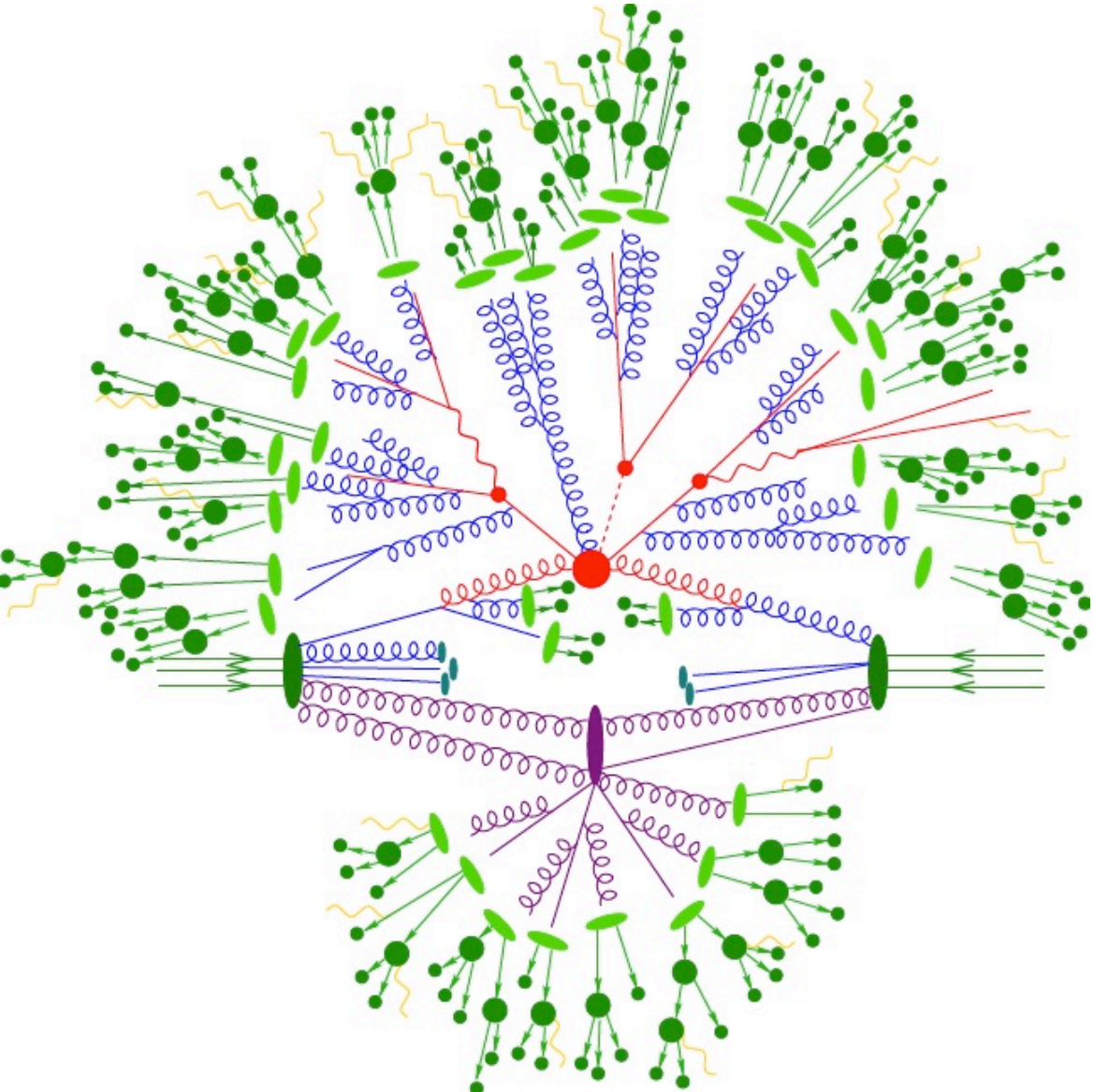
Measure N1 and N2 → extract ε_b and σ

- Analysis designed to be as insensitive as possible to large detector uncertainties
- Takes as much information as possible from the detector

ttbar cross section: dilepton

$\sqrt{s}$	7 TeV			8 TeV		
Uncertainty (inclusive $\sigma_{t\bar{t}}$)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
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

Towards differential distributions…
It's even more complicated



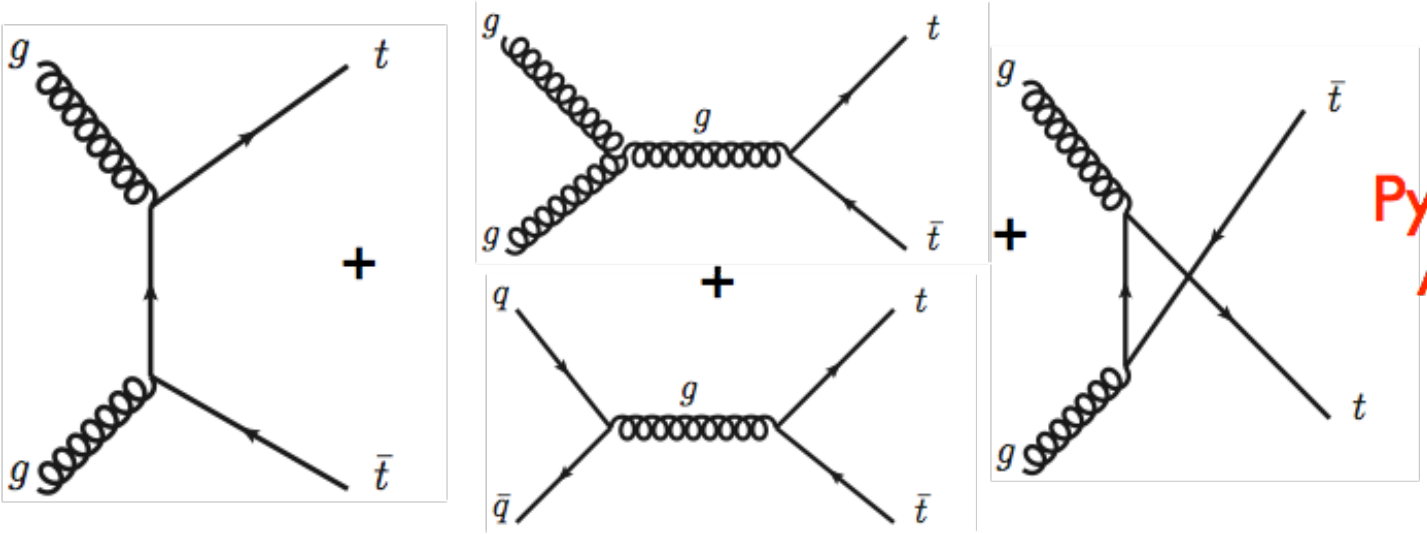
- Matrix element (hard)
- Parton Shower
- Multiple interactions
- Fragmentation and hadronisation
- QED radiation

Sherpa picture

MC IN TOP EVENTS

Simplest generators: LO

- Hard Process is only LO processes



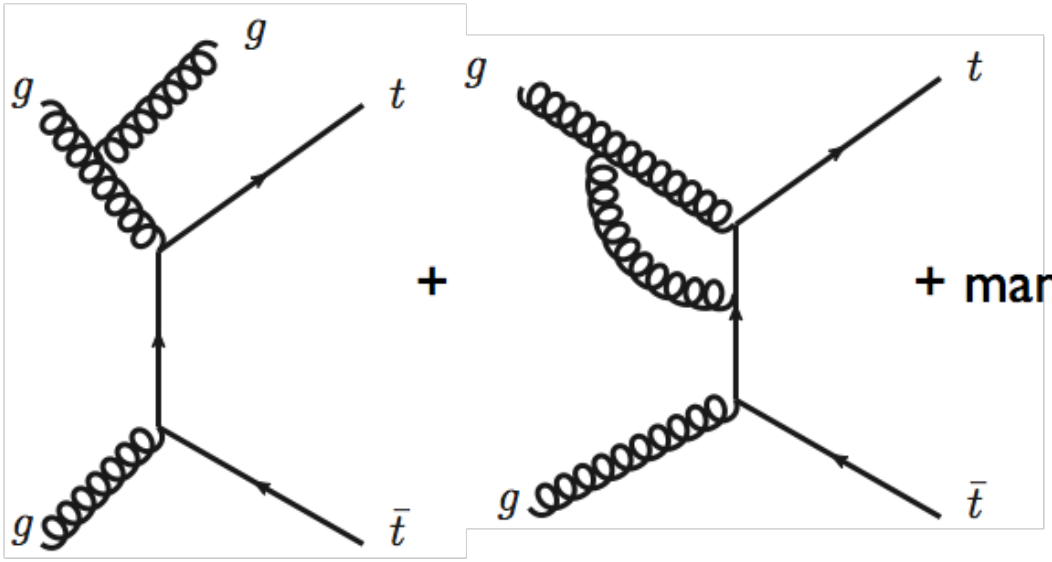
Pythia, Herwig, AcerMC, ...

- Radiation only from parton shower
  - Resummation valid for collinear and soft emissions

NLO generators

- Hard Process includes NLO processes

LO +



+ + many others

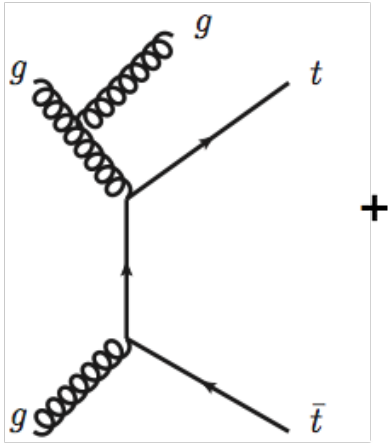
MC@NLO, Powheg

- First emission now in the hard process
  - Expect better modelling
- Additional radiation from parton shower
  - Need matching procedure to avoid double-counting

Multi-leg generators (LO and NLO)

- Hard Process includes up to N additional emissions

LO +



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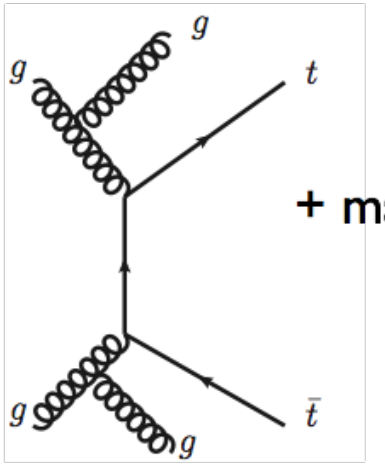


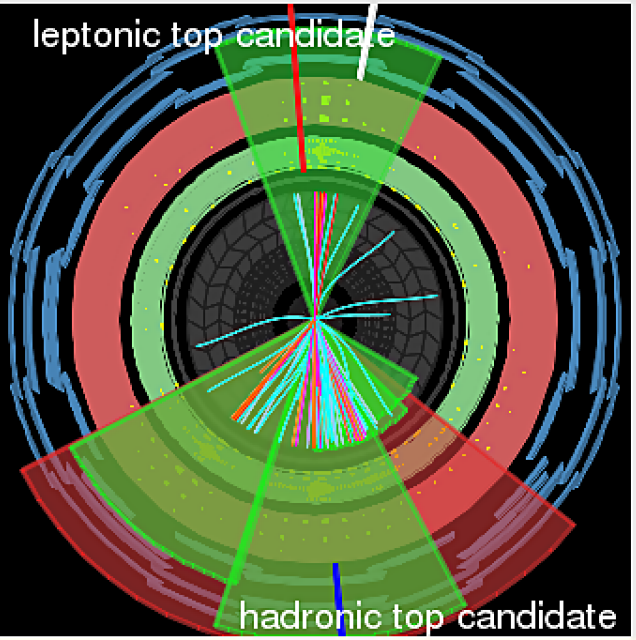
+ many others

Alpgen, Sherpa, Madgraph

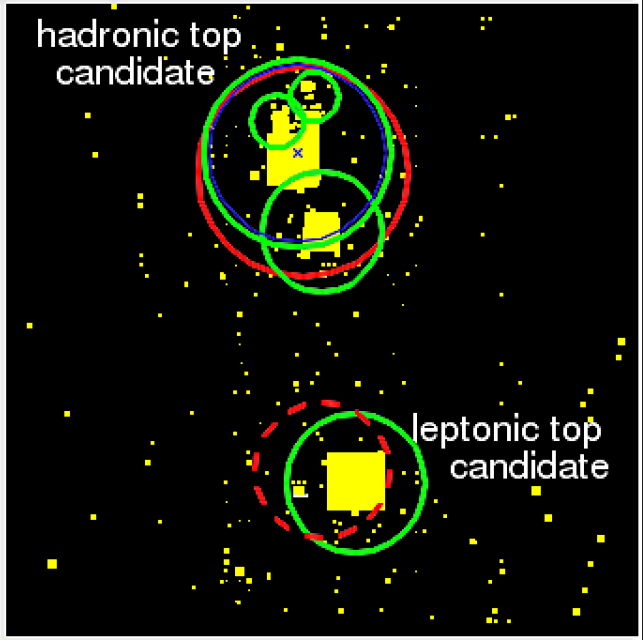
- No loop processes in LO!
- First N emission now in the hard process
  - Expect better modelling
- Additional radiation from parton shower
  - Need matching procedure to avoid double-counting
- NLO versions (e.g. aMC@NLO_MG5, Sherpa) available
  - Experiments starting to use them

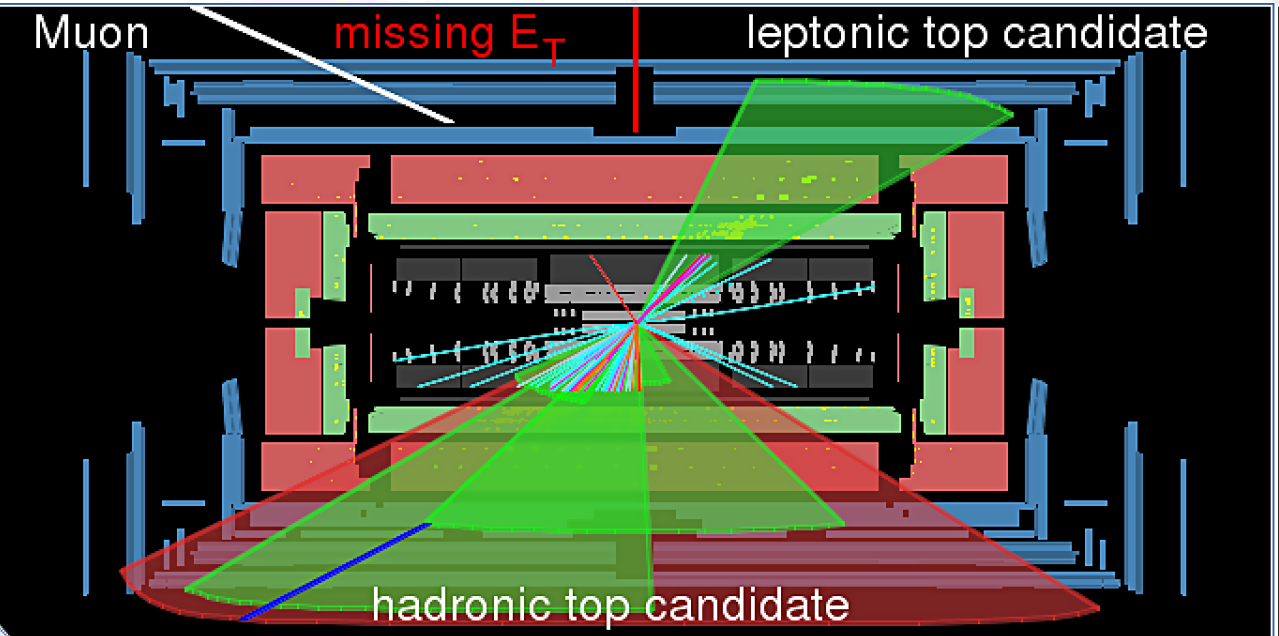
DIFFERENTIAL CROSS SECTIONS

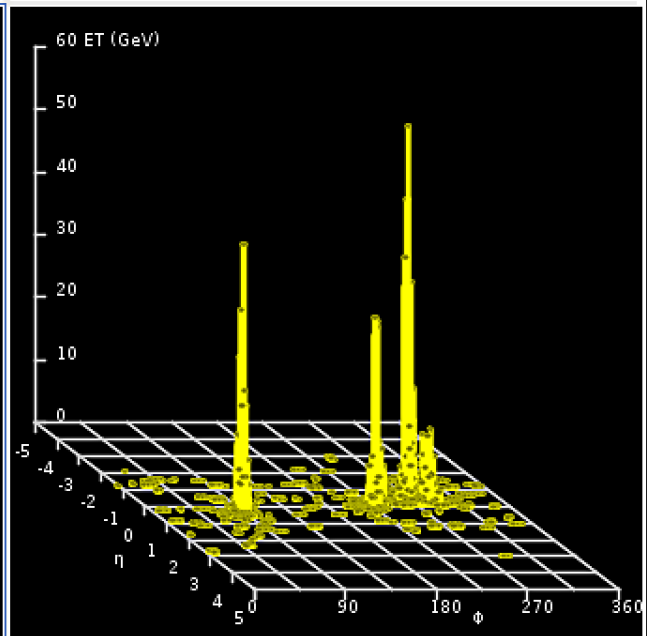
Short break…


leptonic top candidate
hadronic top candidate


ATLAS
EXPERIMENT
Run Number: 208781, Event Number: 34662984
Date: 2012-08-17 20:55:28 CEST

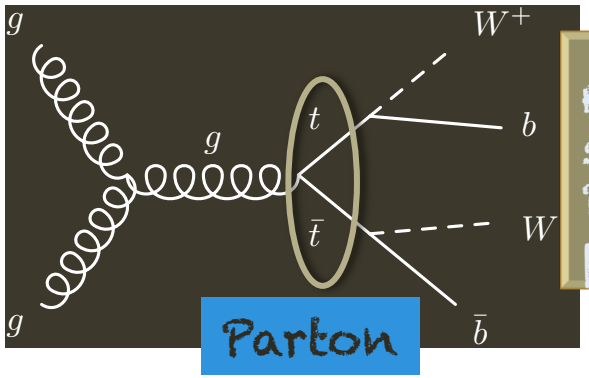

hadronic top candidate
leptonic top candidate


Muon
missing E_T
leptonic top candidate
hadronic top candidate

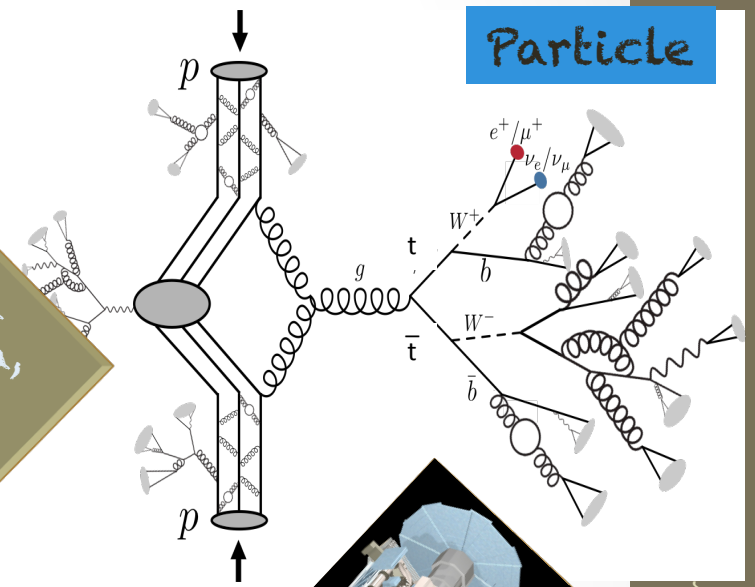

60 ET (GeV)
50
40
30
20
10
0
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
360
Φ

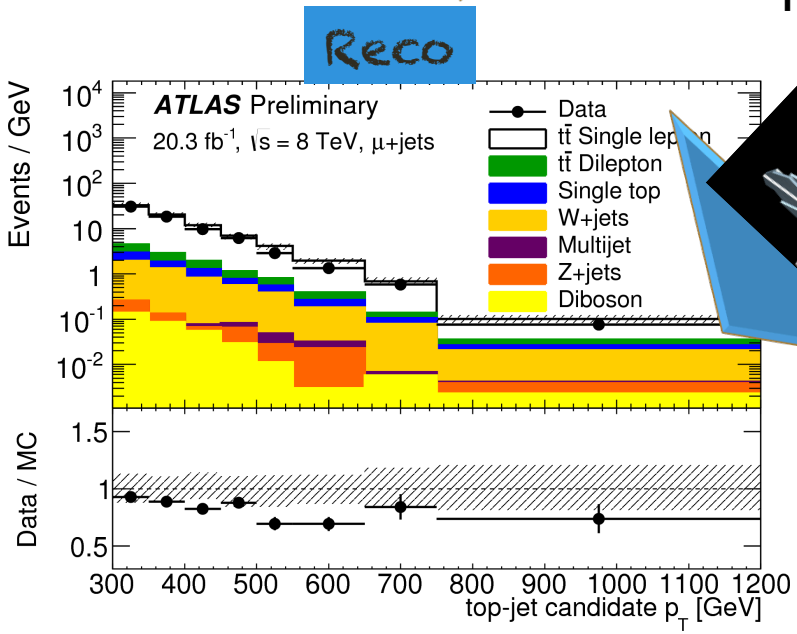
Unfolding: Parton vs Particle

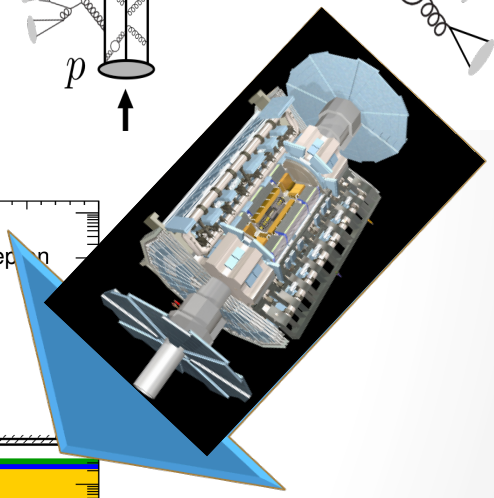
Matrix Element calculation (usually perturbative)



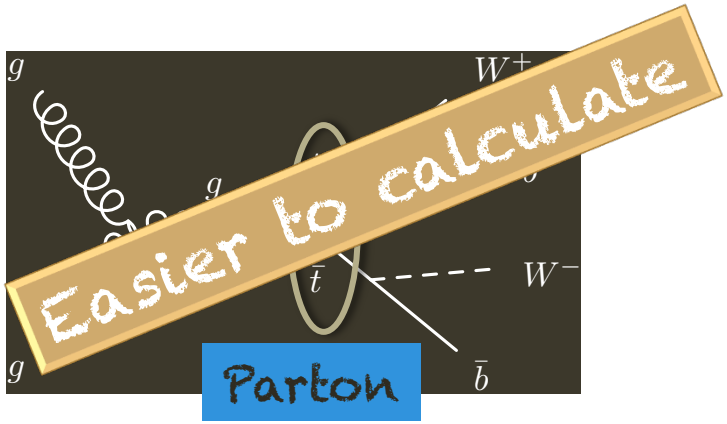
Fragmentation, parton shower, hadronisation, PDFs,... (often non-perturbative)

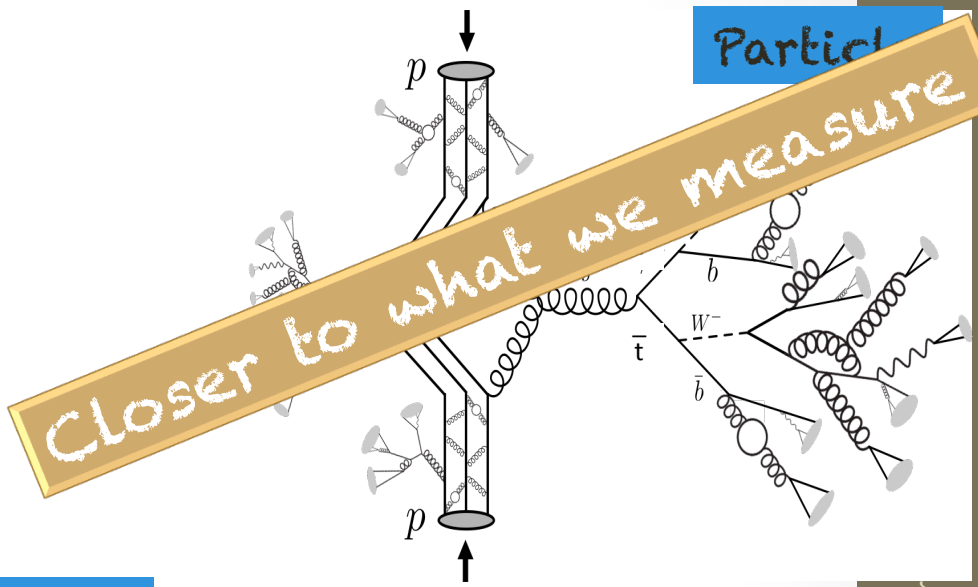


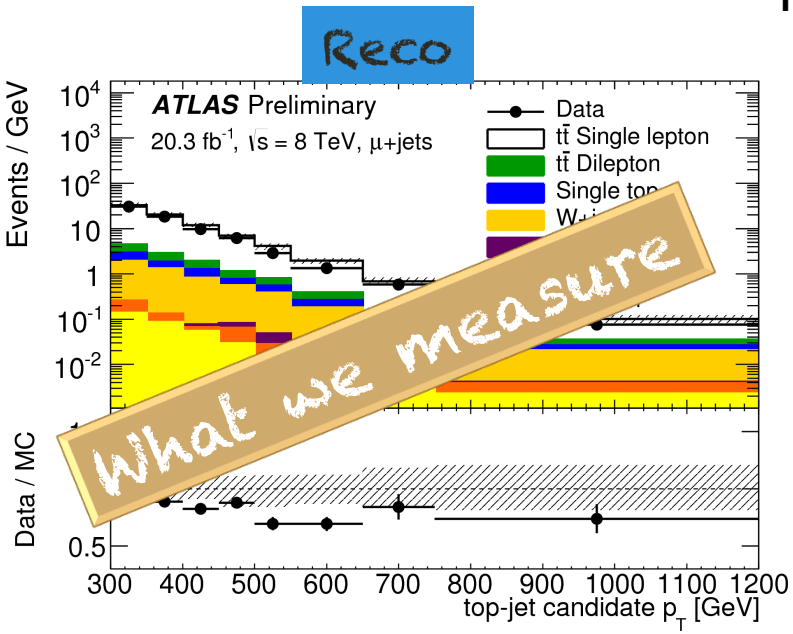




Unfolding: Parton vs Particle

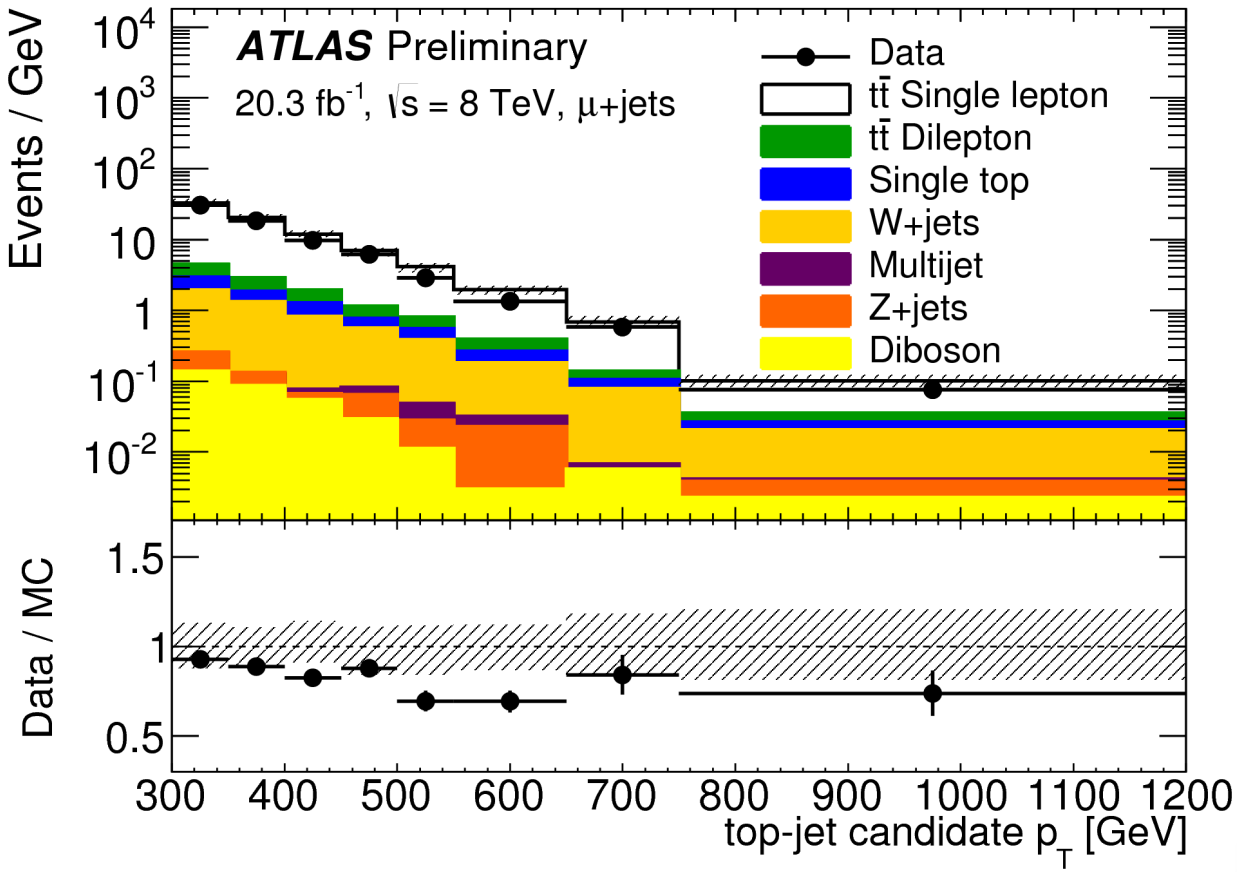






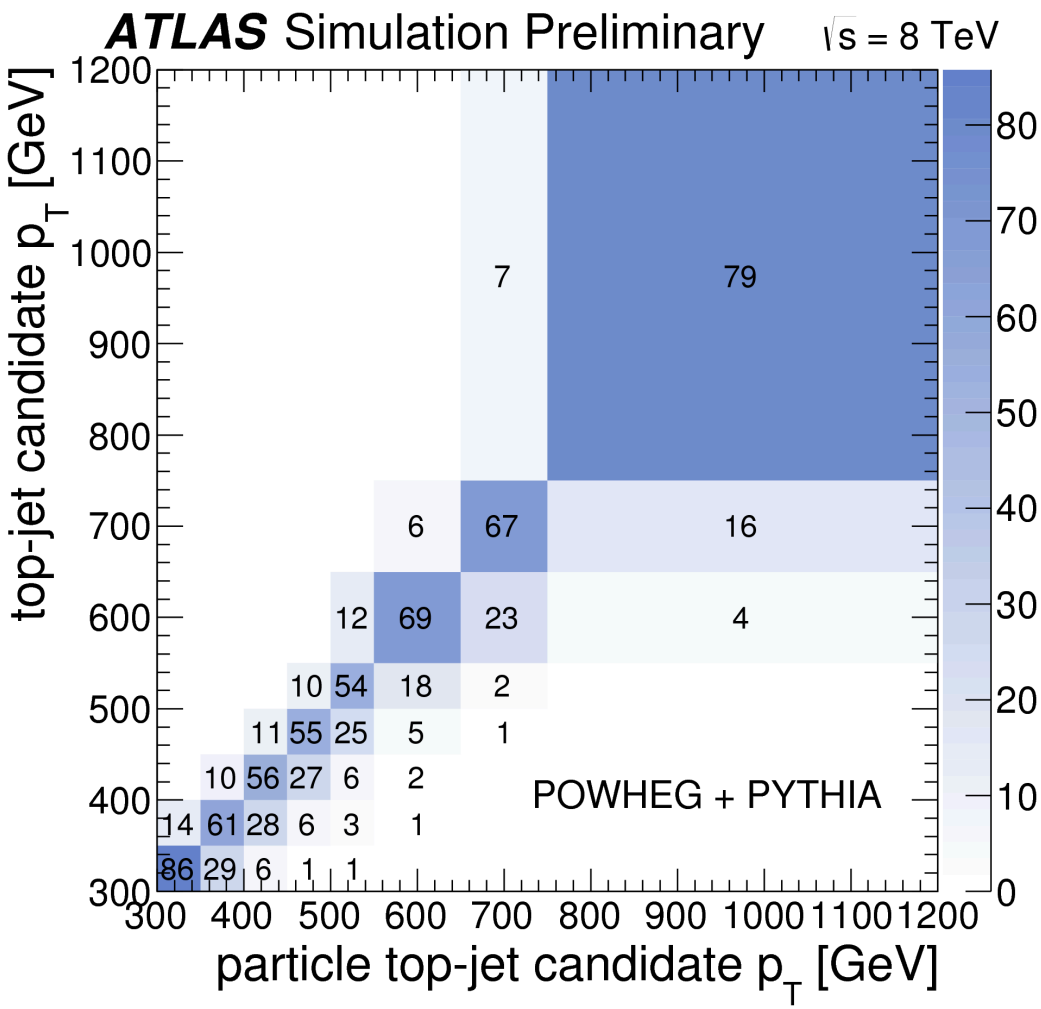
Unfolding: step-by-step guide

- Start with a relevant detector level distribution



Unfolding: step-by-step guide

- Start with a relevant detector level distribution (reco)
- Build matrix of reco level vs particle level variable
  - Are they the optimal variable definitions to use?



Sufficiently diagonal?

Tails not too large?

Think the MC can model it well?

Unfolding: step-by-step guide

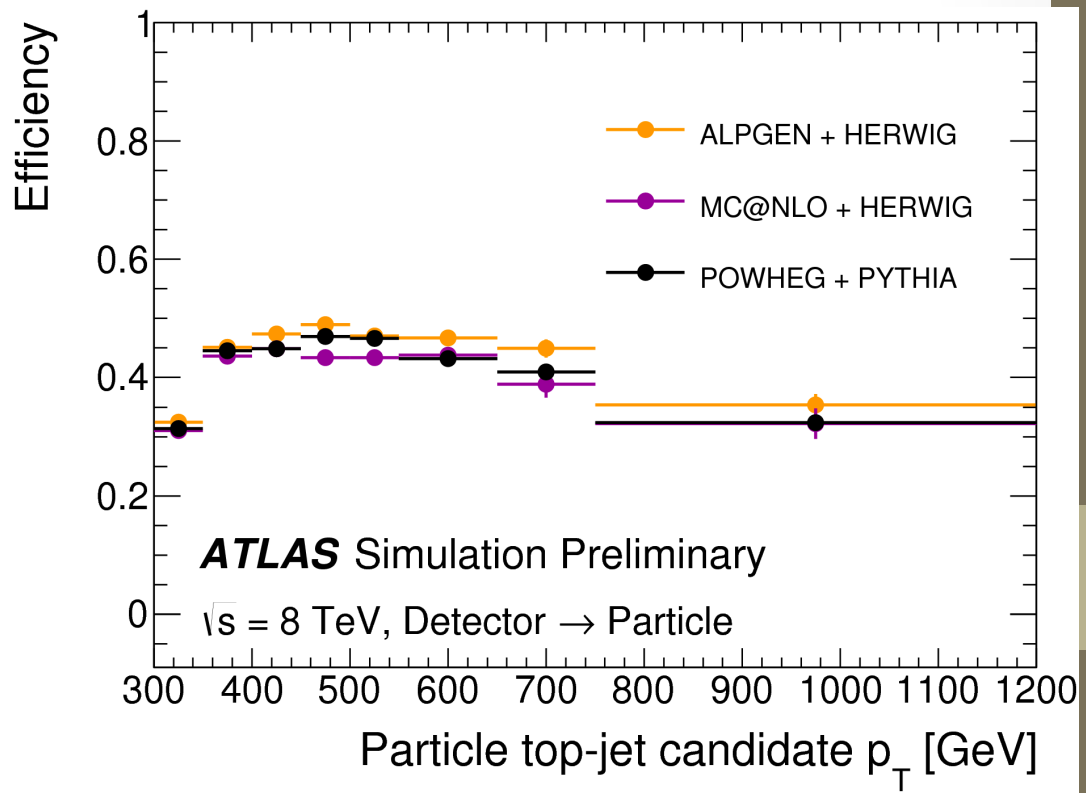
- Start with a relevant detector level distribution (reco)
- Build matrix of particle level vs reco level variable
- Choose unfolding method
  - If corrections are small: maybe bin-by-bin correction is enough?
  - Invert the matrix
    - Sadly not usually stable…
  - Pick one of the many unfolding procedures on the market (RooUnfold)
    - Single Value decomposition
      - Strength of the regularisation parameter?
    - Bayesian Unfolding (iterative unfolding)
      - Number of iterations?
    - … many many more…

Unfolding: step-by-step guide

- Start with a relevant detector level distribution (reco)
- Build matrix of particle level vs reco level variable
- Choose unfolding method
  - Check for biases in the method / stability
    - Closure
    - Stress-tests
      - e.g.change truth distribution, check can still infold

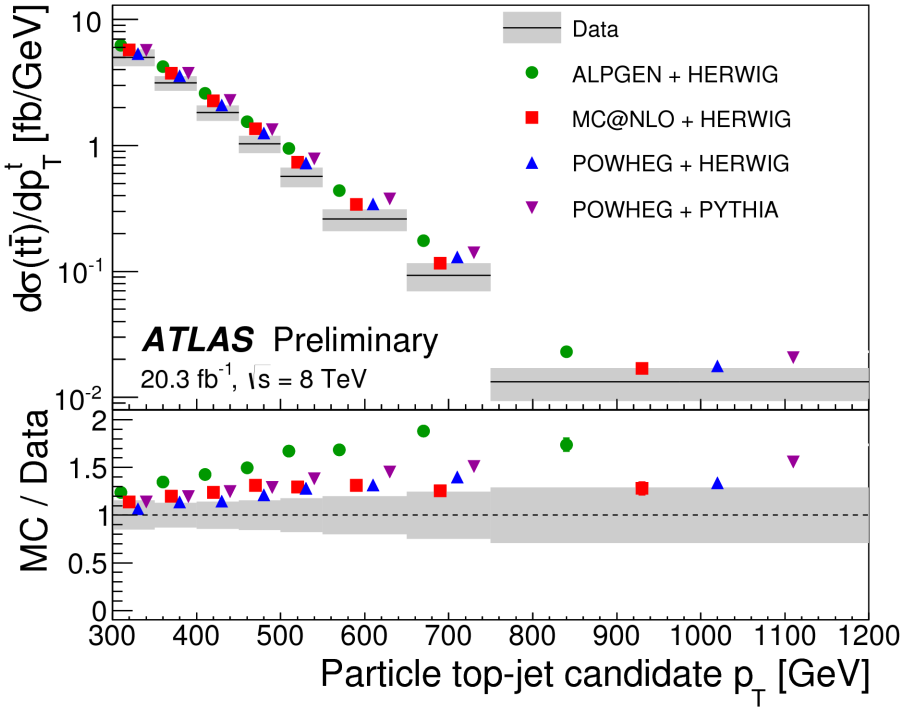
Unfolding: step-by-step guide

- Start with a relevant detector level distribution (reco)
- Build matrix of particle level vs reco level variable
- Choose unfolding method
- Correct for efficiency loss
  - Reconstructed objects not identical to particle level ones
    - Object reconstruction efficiency
    - Detector resolution



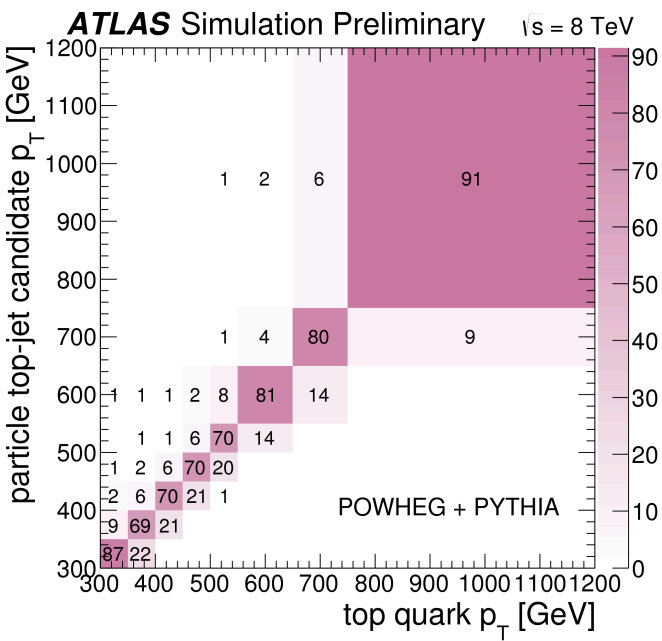
Unfolding: step-by-step guide

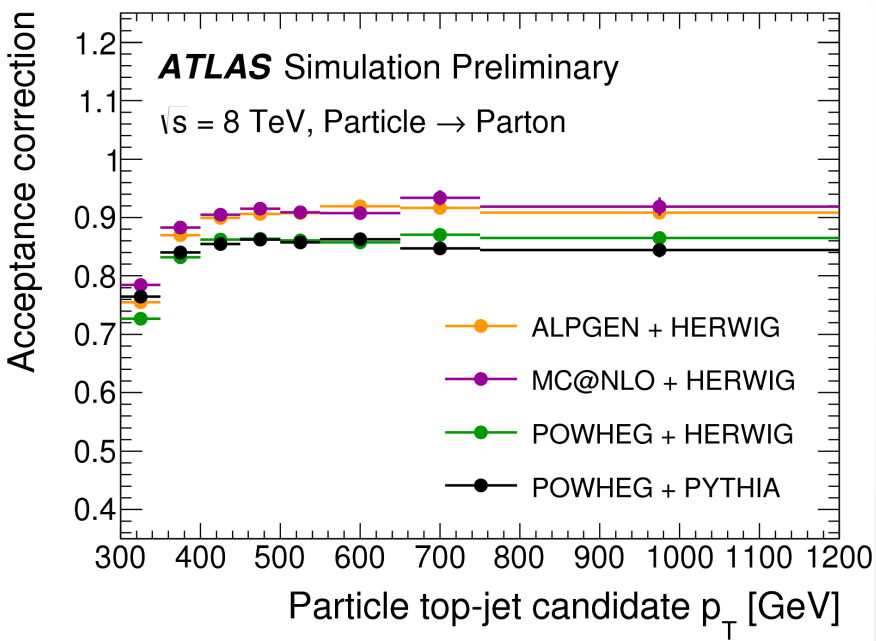
- Start with a relevant detector level distribution (reco)
- Build matrix of particle level vs reco level variable
- Choose unfolding method
- Correct for efficiency loss
- Get unfolded distribution!!!!
  - Compare to your favorite generators
  - Hope it teaches you something useful



Unfolding: step-by-step guide

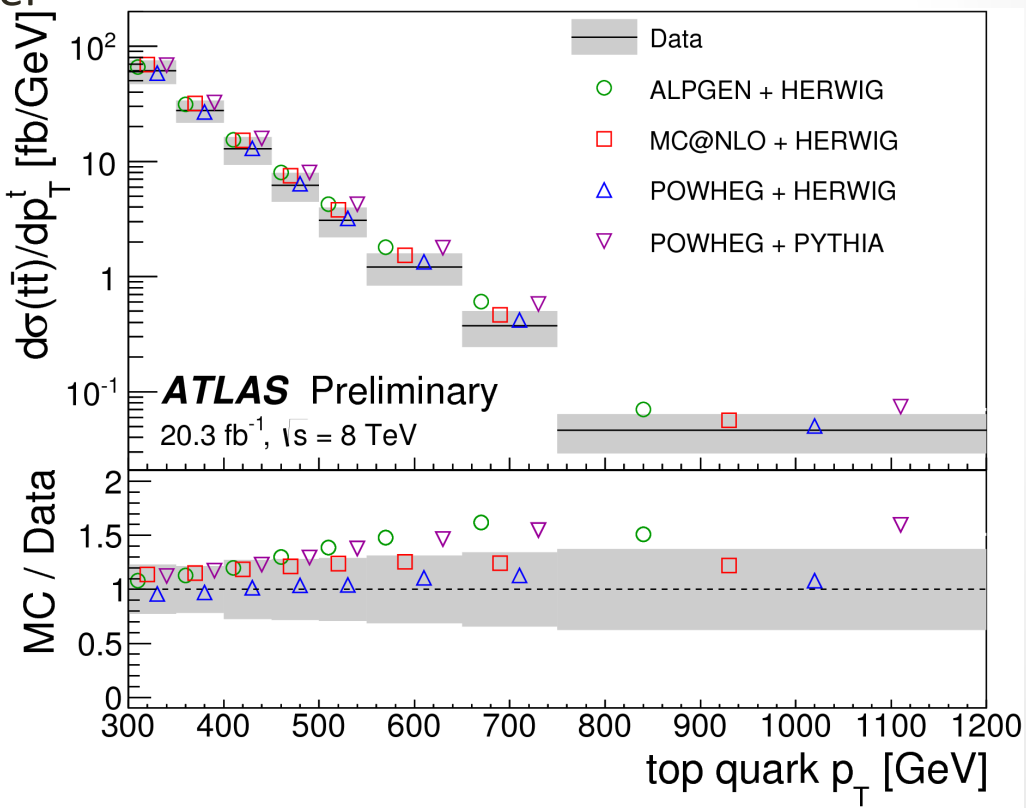
- Start with a relevant detector level distribution (reco)
- Build matrix of particle level vs reco level variable
- Choose unfolding method
- Correct for efficiency loss
- Get unfolded particle level distribution
- If also unfold to parton level
  - 2nd unfolding matrix
  - 2nd efficiency correction



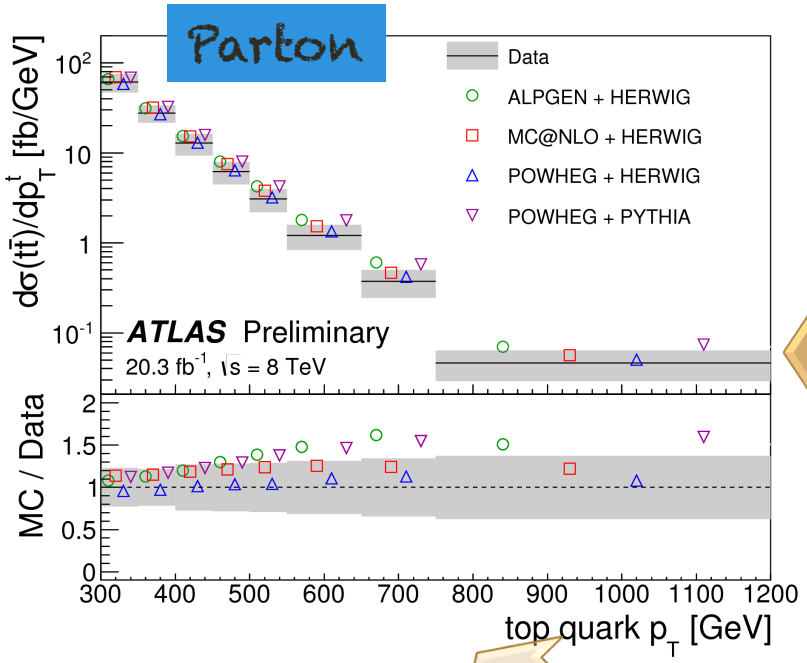


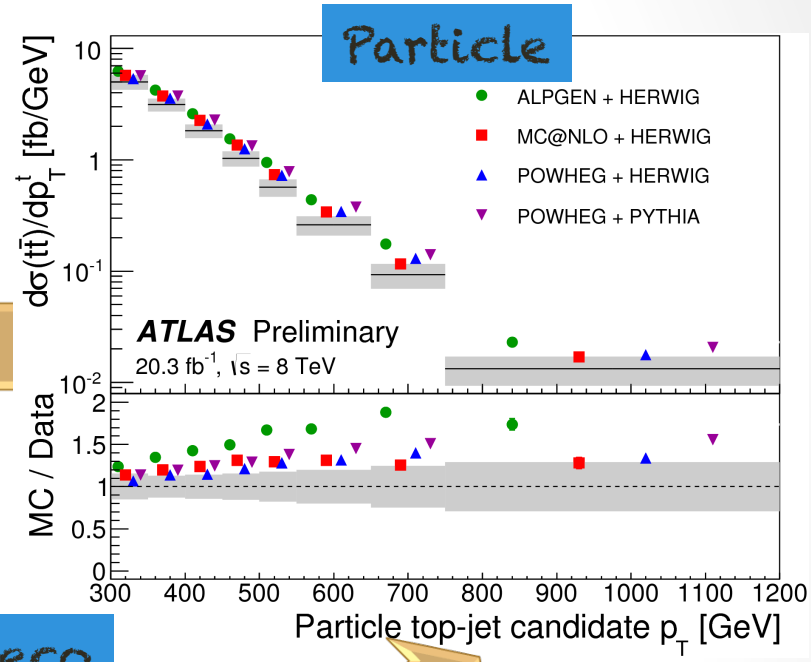
Unfolding: step-by-step guide

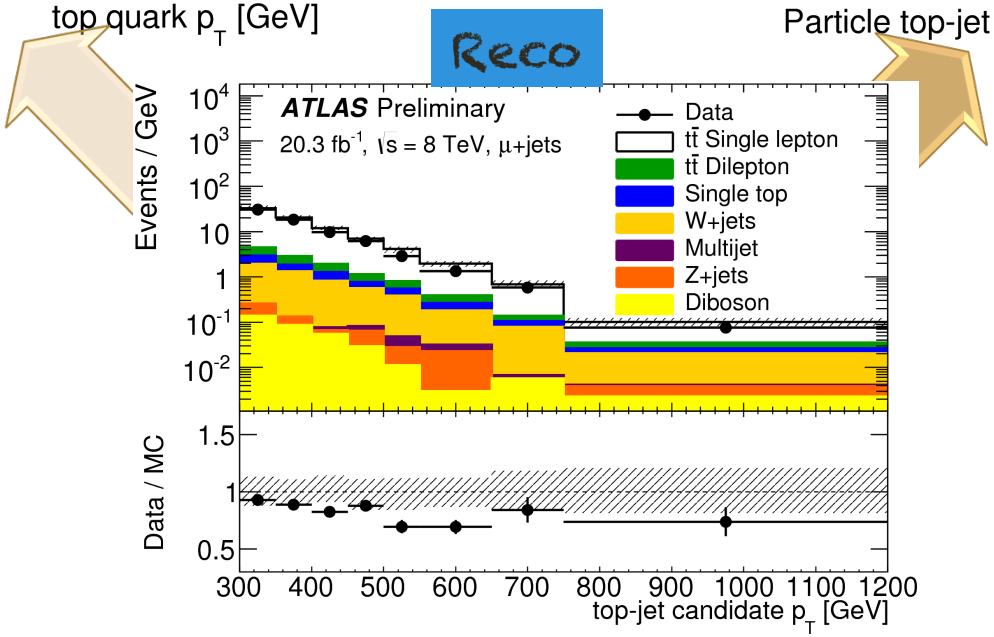
- Start with a relevant detector level distribution (reco)
- Build matrix of particle level vs reco level variable
- Choose unfolding method
- Correct for efficiency loss
- Get unfolded particle level distribution
- If also unfold to parton level
  - 2nd unfolding matrix
  - 2nd efficiency correction
  - Get unfolded distribution



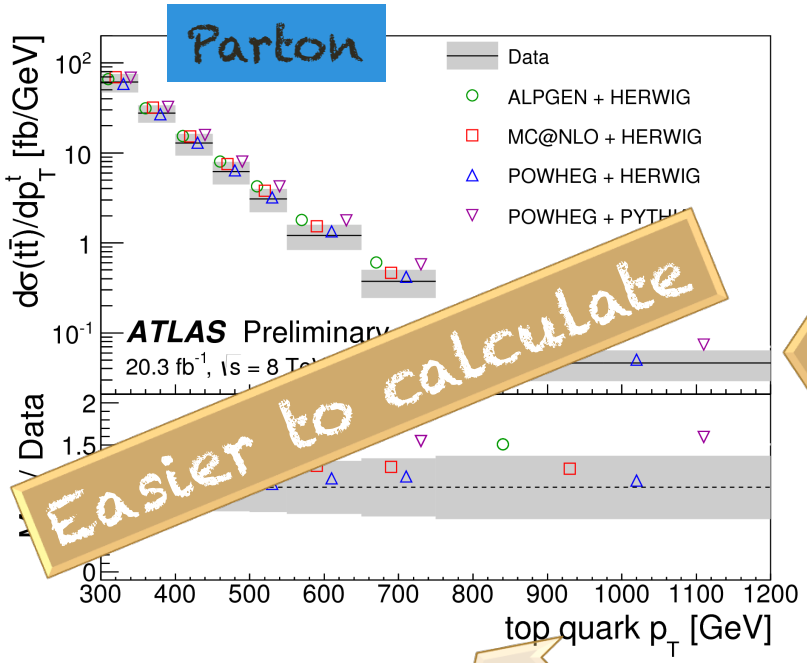
Unfolding: Parton vs Particle

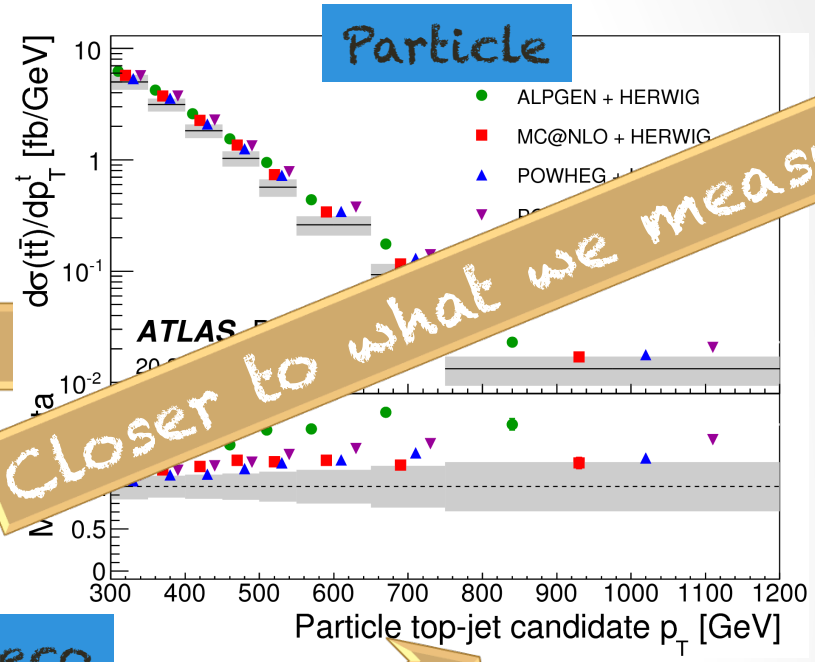


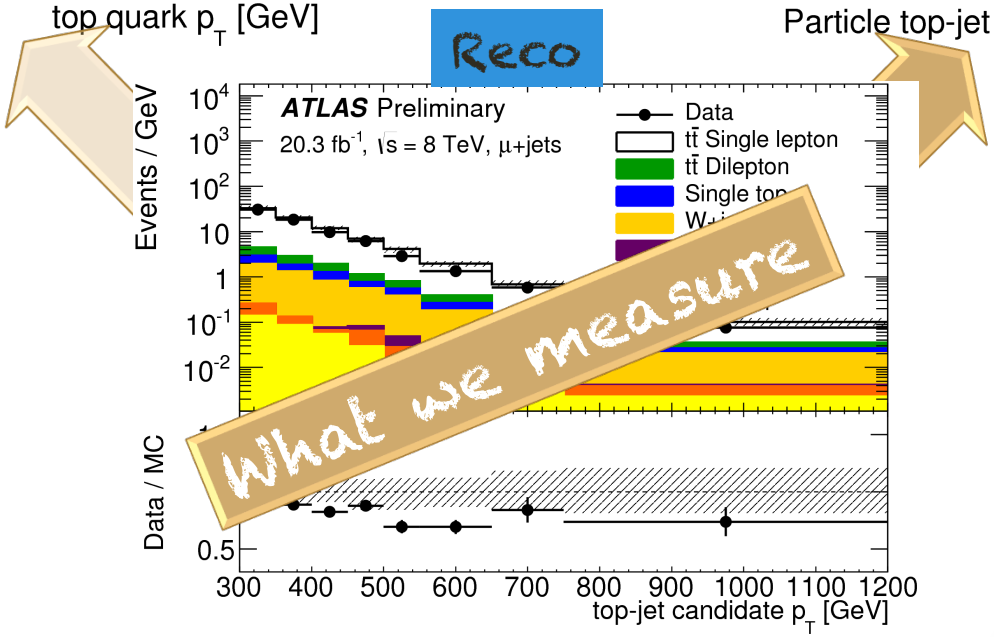




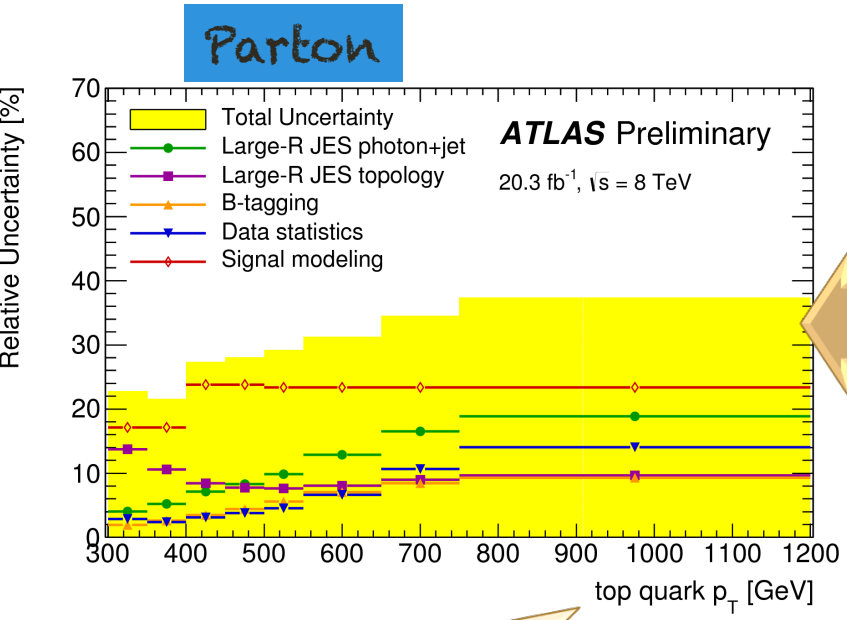
Unfolding: Parton vs Particle

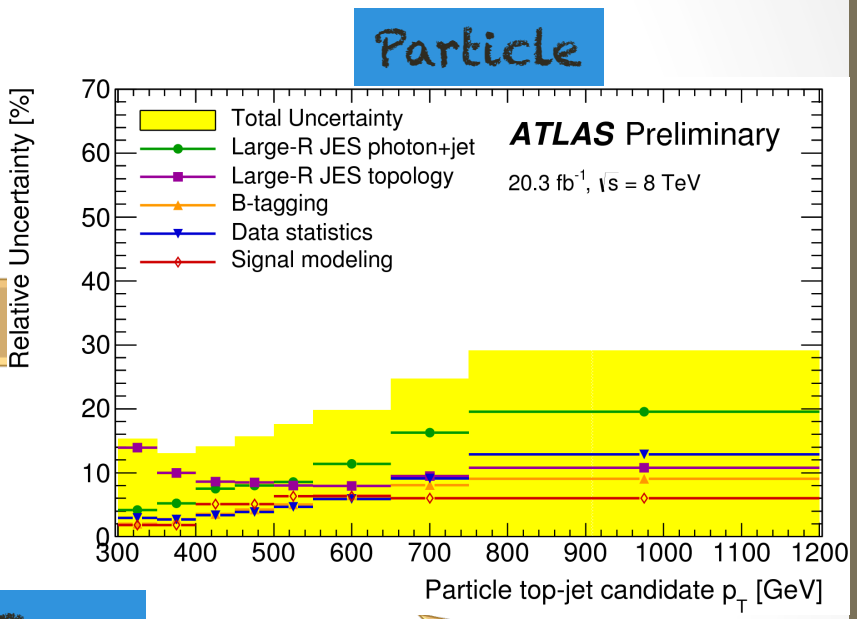


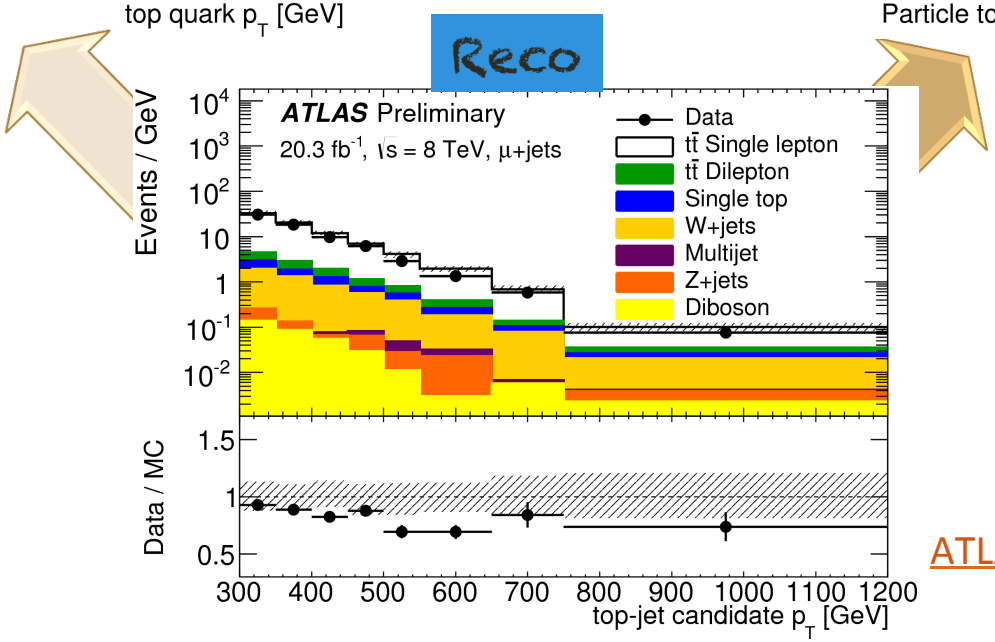




Unfolding: Parton vs Particle







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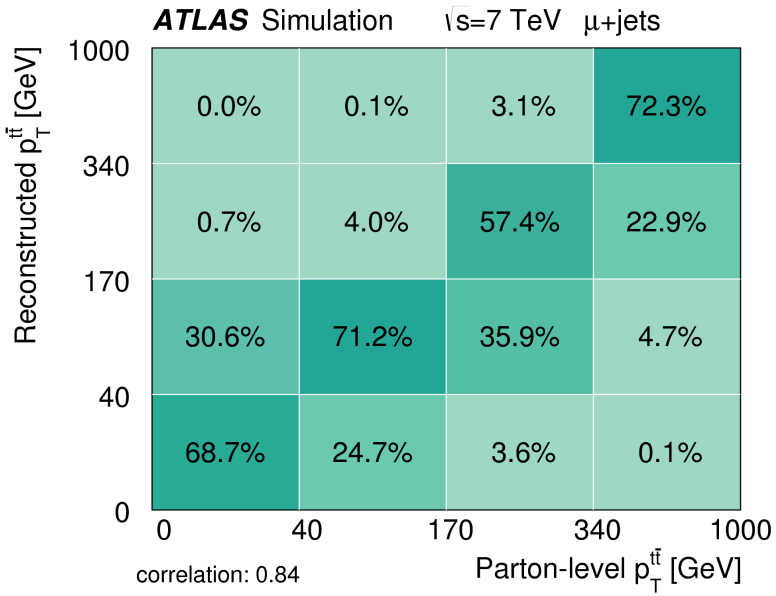
Unfolding: Parton vs Particle

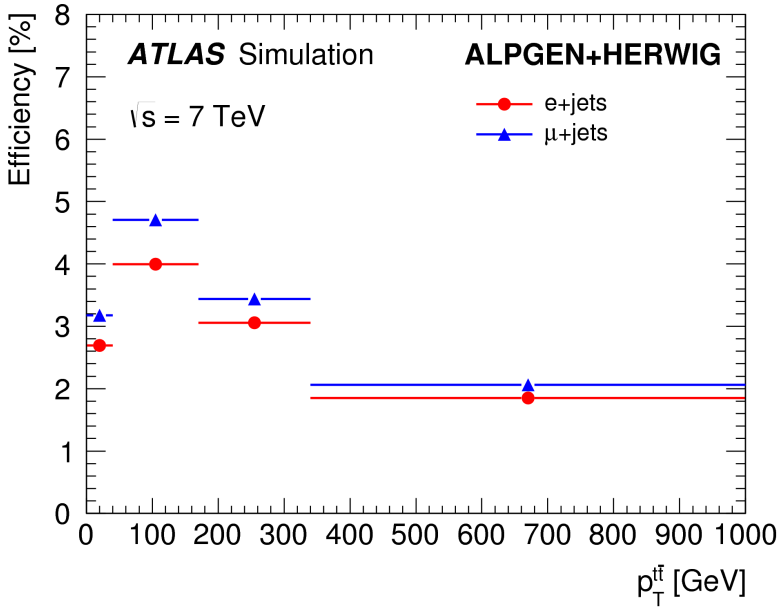
Which is better?

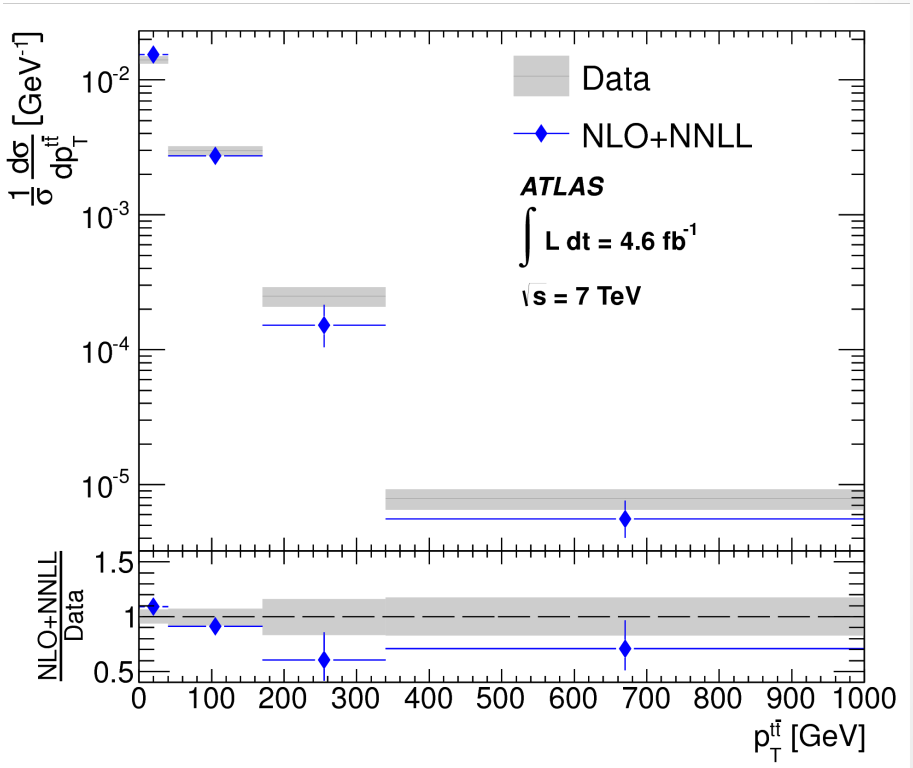
- Depends what you want to do with it...For example
- Comparison to fixed order predictions
  - Needs to be at parton level
- PDF fitting
  - Needs to be at parton level
- Constraining some of the parameters of the MC ('tuning')
  - Particle level if preferred
    - Lower uncertainties
    - Usually smaller MC dependent corrections
- My personal take: do both (when / where relevant) and make everyone happy!

Differential cross section



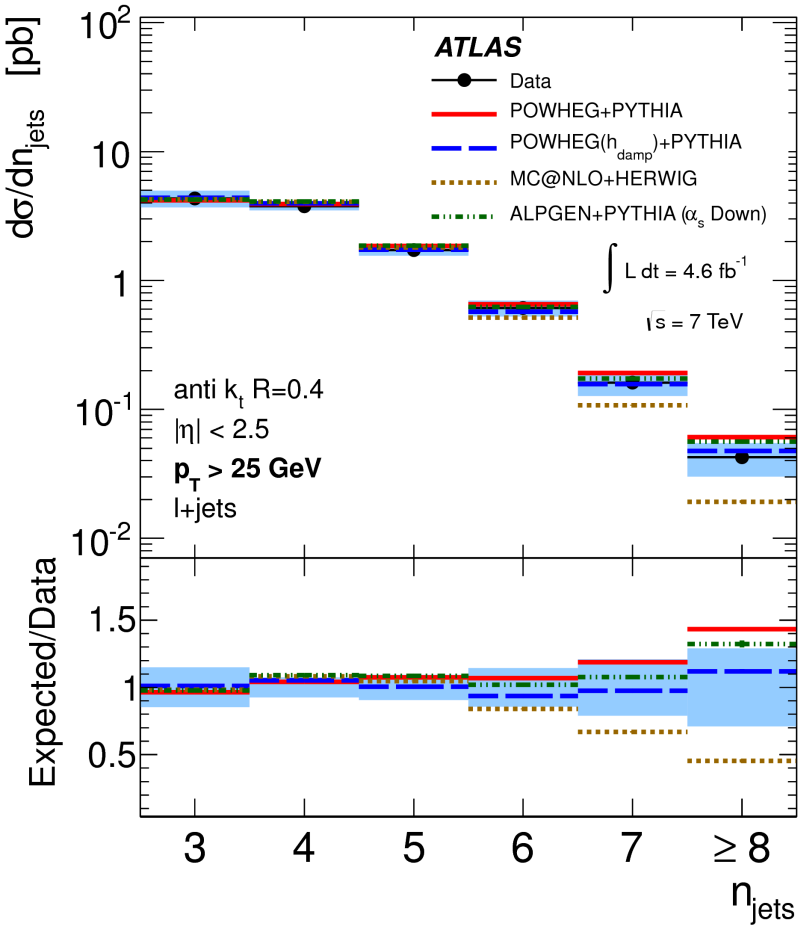
- Unfolding to parton level
  - Top is defined in MC as the top quark right before it decays
- Comparing to fixed order calculations

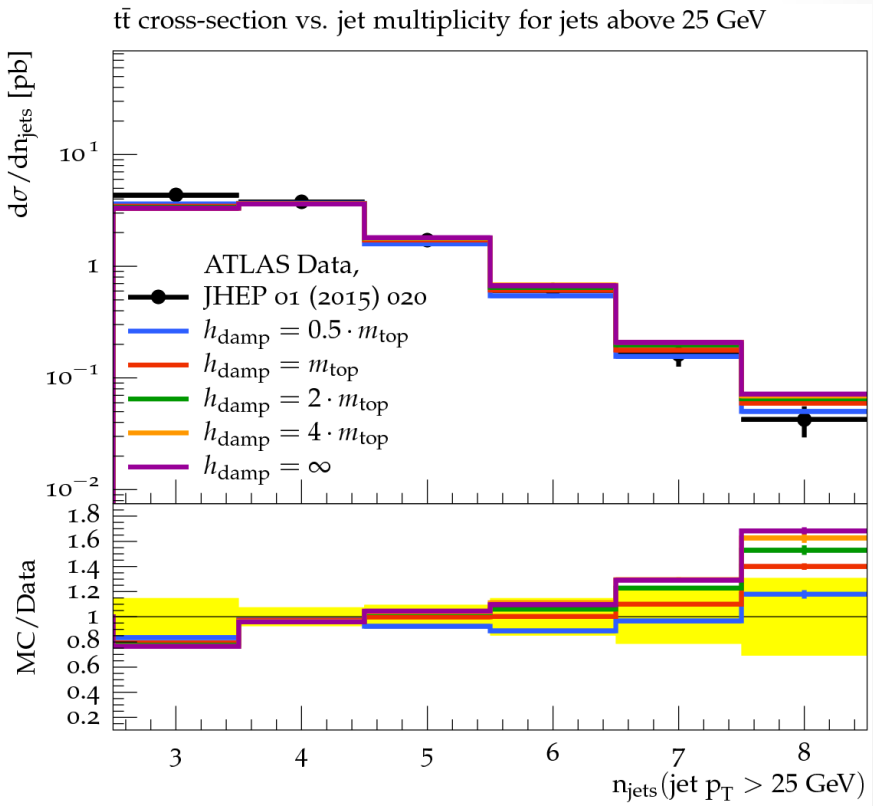




Differential cross section

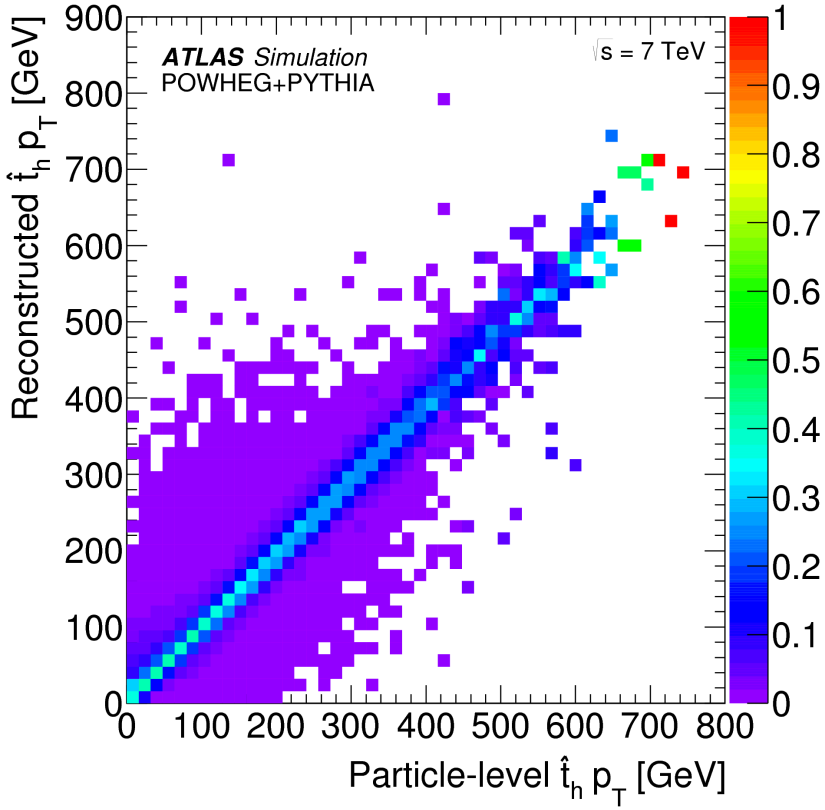
- Unfolding to particle level
- Select ttbar events with 1 lepton and >=3 jets
- Look at additional jets
  - Constrain amount of additional radiation

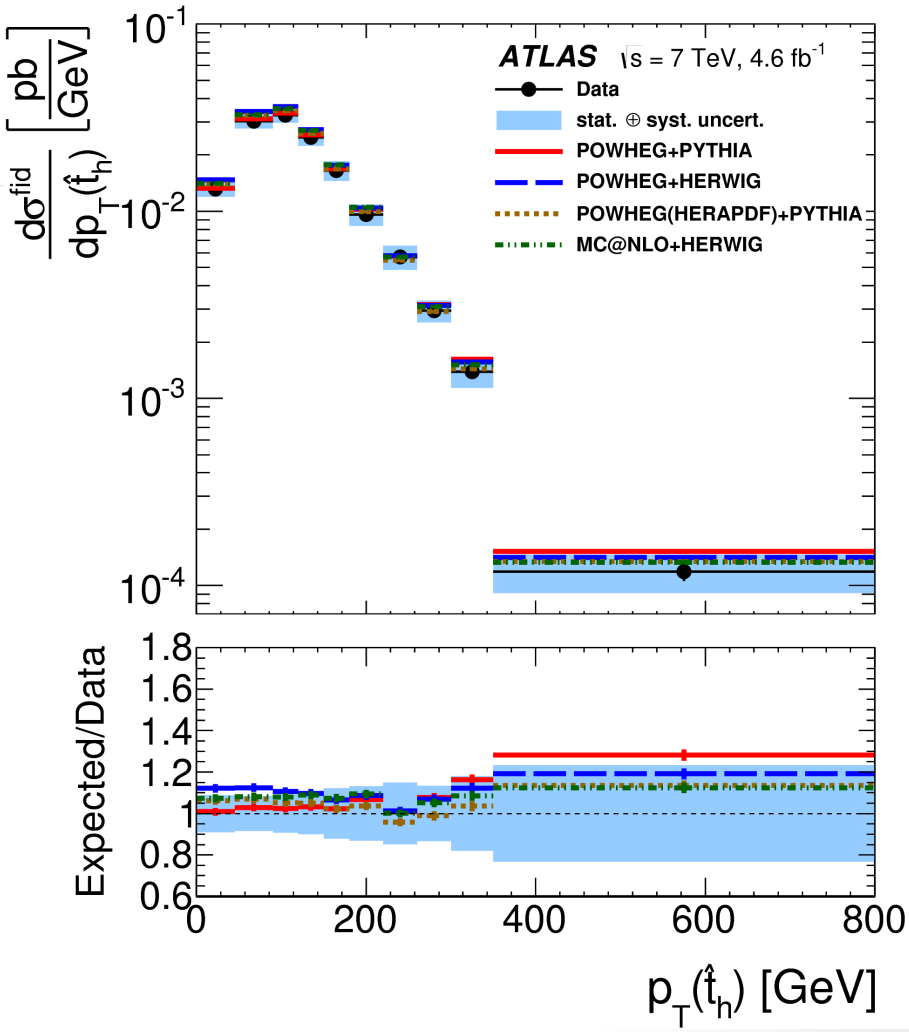




Differential cross section

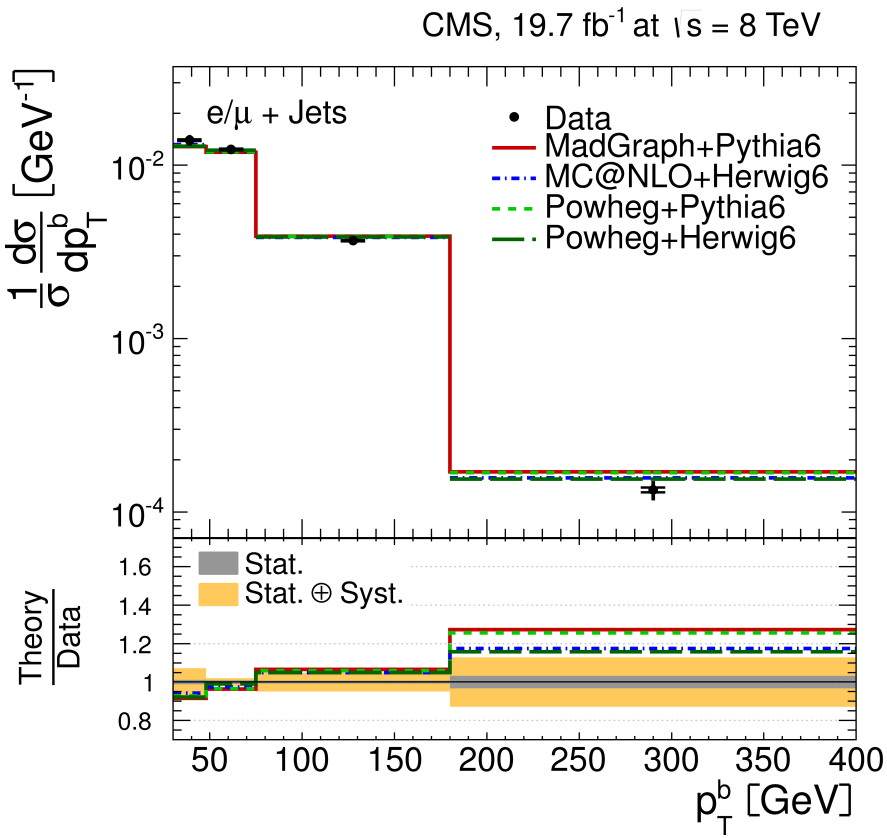
- Unfolding to particle level
- Reconstruct top at particle level
  - 'pseudo-top'
- Use same algorithm at reco level
- Constrain MC parameters

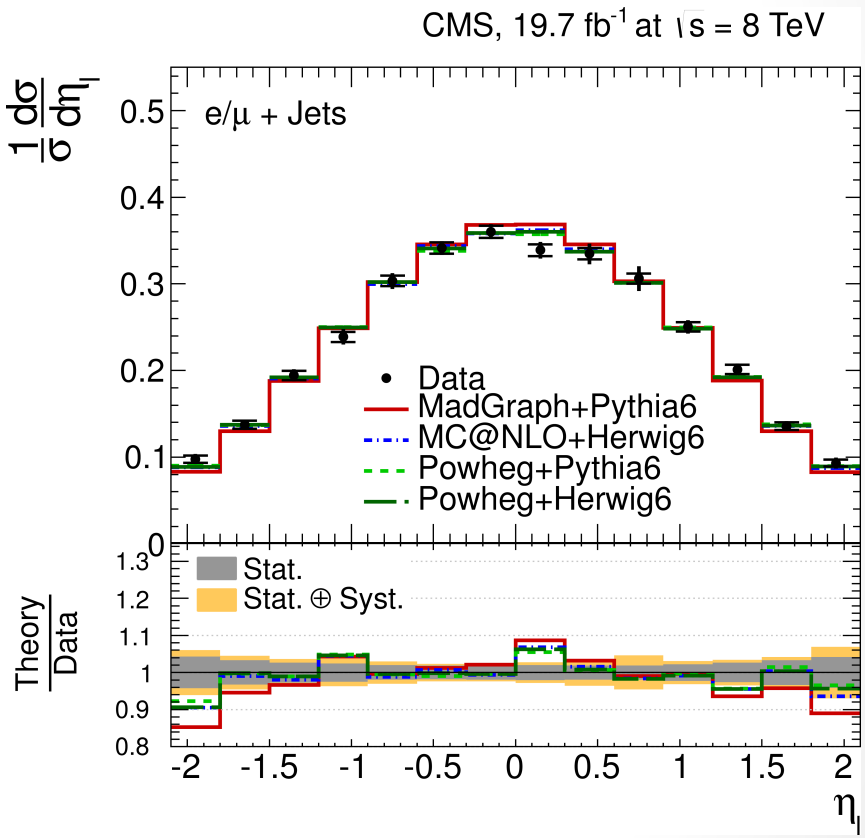




Differential cross section

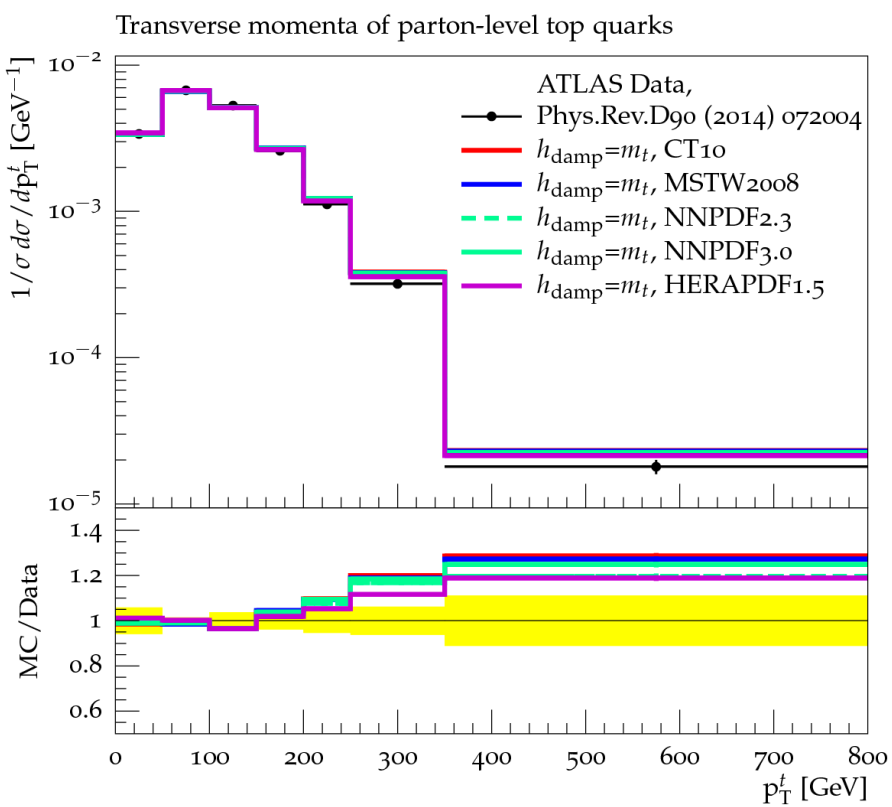
- Unfolding to particle level
- Don't always need to reconstruct the tops

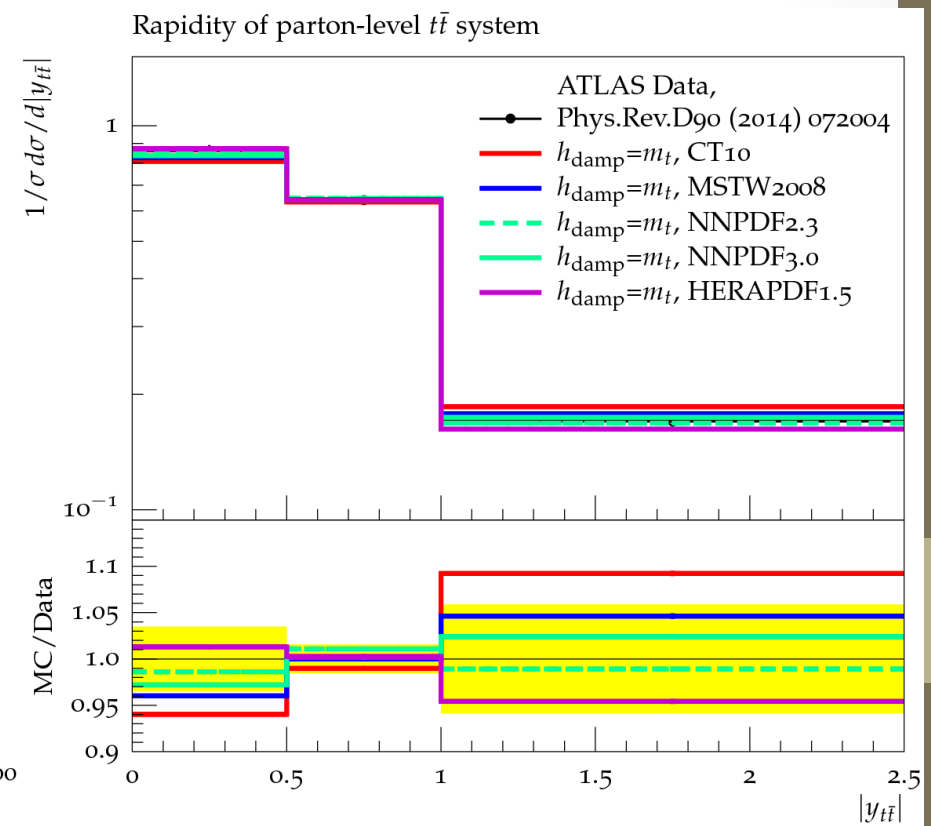




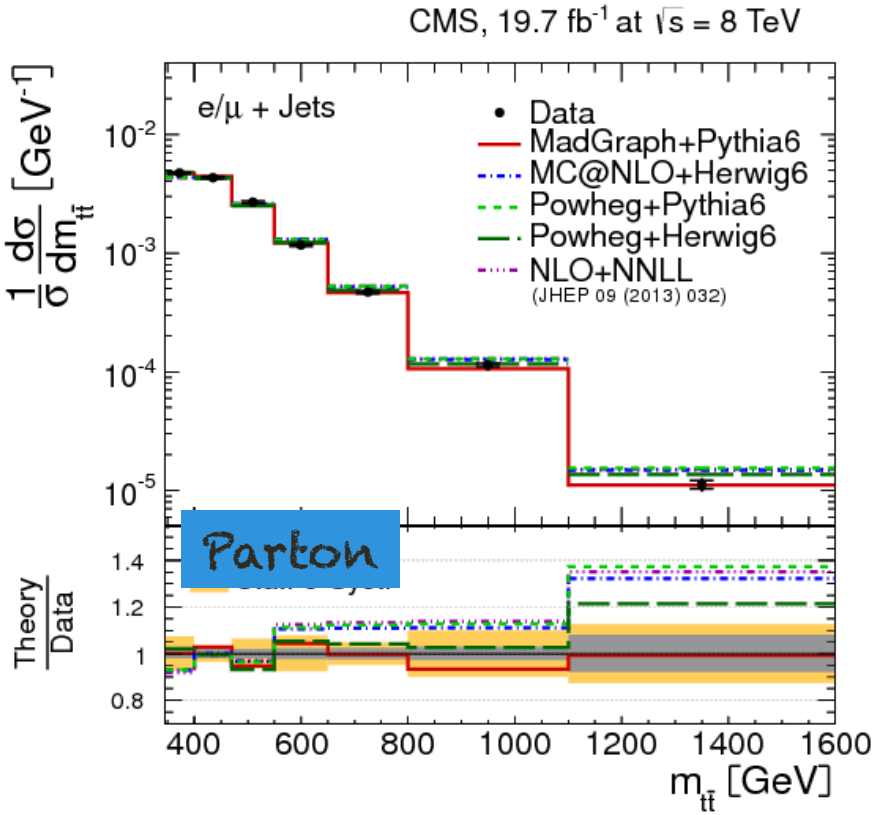
Differential cross section

- Comparing to PDFs
  - Parton or particle level
- Need to be parton level to be used in PDF fit
  - Work ongoing…

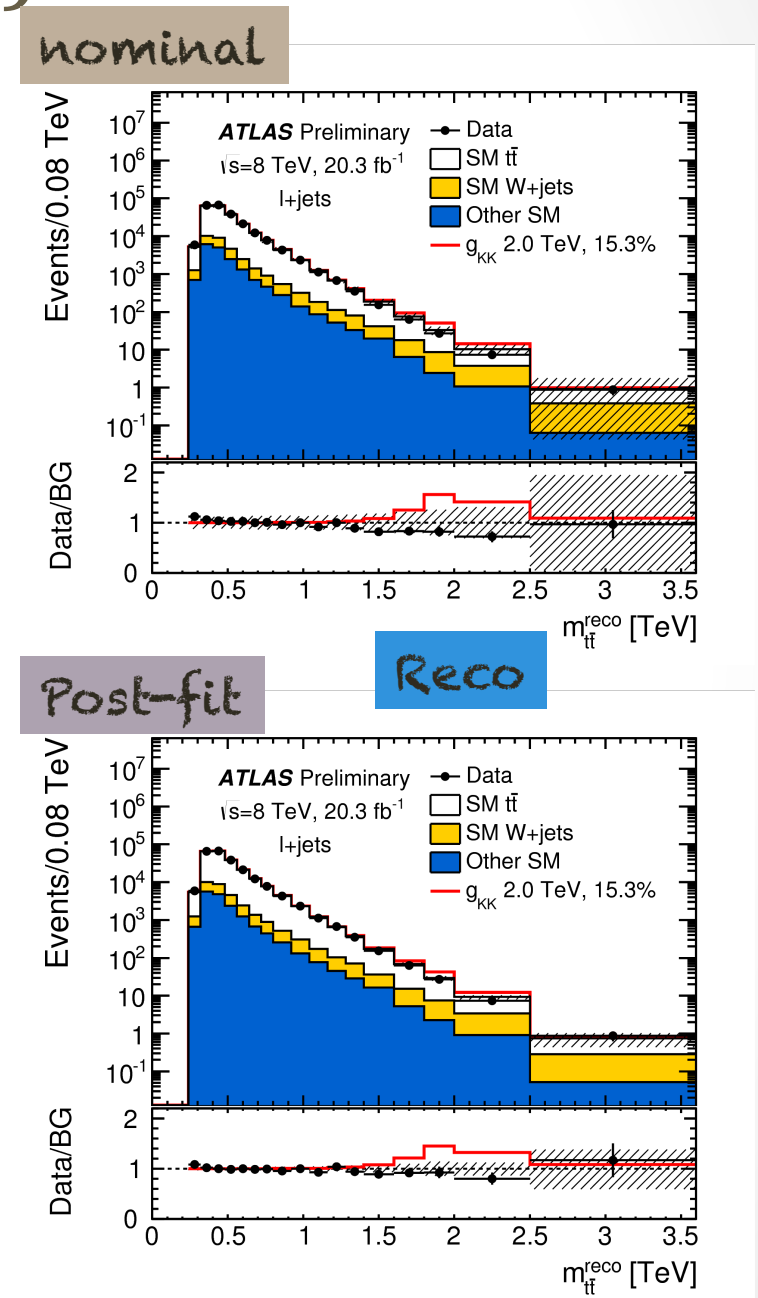




Tails (New Physics?)



- Improving the modelling uncertainties in ttbar production can help to see new physics!

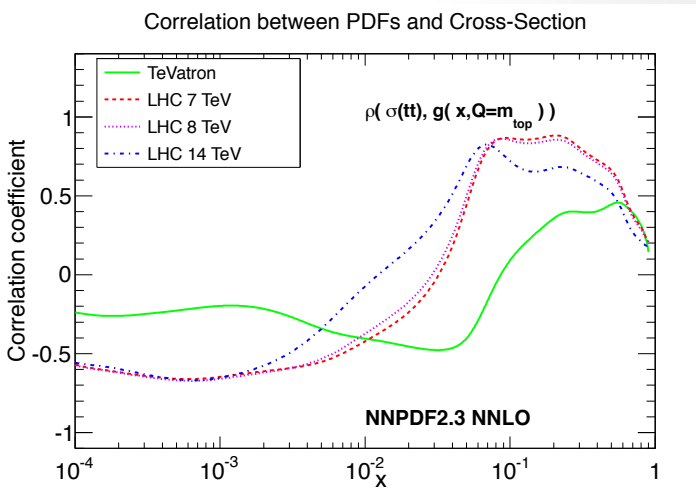


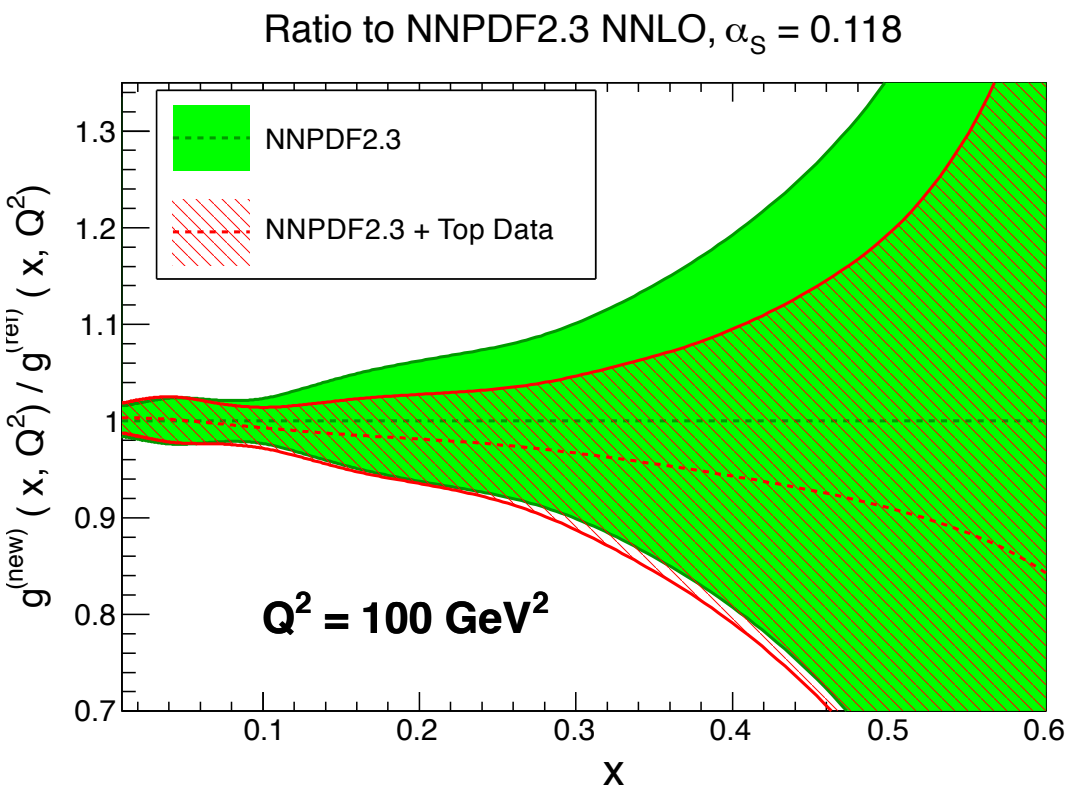
arXiv:1505.04480

arXiv:1505.07018

Constraining PDF

- ttbar events already used in some PDF fits
  - So far only inclusive cross section
- Probes gluon PDF in region x=0.1-0.5
  - Where PDF uncertainty is large





arXiv:1303.7215