Measurement of the production cross-section of a single top quark in association with a Z boson at 13 TeV with ATLAS

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Outline

- Introduction
  - The top quark
  - Single top quark production at the LHC
  - Single top quark production in association with a Z boson
- The ATLAS Experiment
- Standard Model tZq production
  - Event selection
  - Background estimation
  - Multivariate analysis
  - Results
- ATLAS & CMS comparison
- Conclusions and outlook

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The top quark

- Discovered at Tevatron by the D0 and CDF experiments in 1995.
  - Since then, extensively studied both at Tevatron and at the LHC.
- Experimentally confirmed facts:
  - top is the **heaviest** known fundamental particle
    - m(t) ~ 173 GeV
  - it is a quark (sees the strong force)
  - charge 2/3e
  - spin1/2
  - decays almost exclusively to Wb
  - produced by strong and weak interactions.
- Why studying the top quark?
  - Only place to study the properties of a bare quark.
  - Special role in EWSB?
  - First place a new particle could be observed (e.g. if new particle couples to mass).
  - Top is a background to many other searches.

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How is the top quark produced at the LHC?

- Why studying the top quark?
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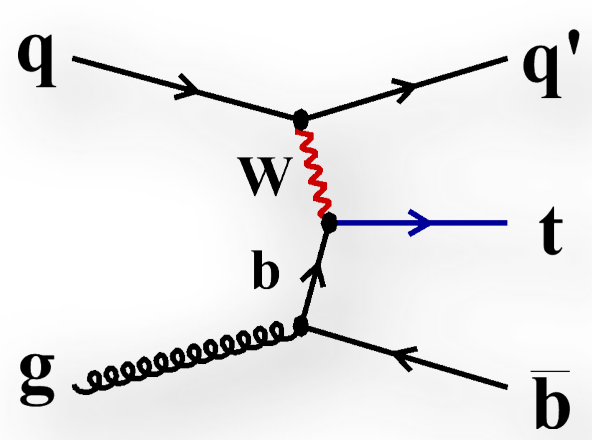
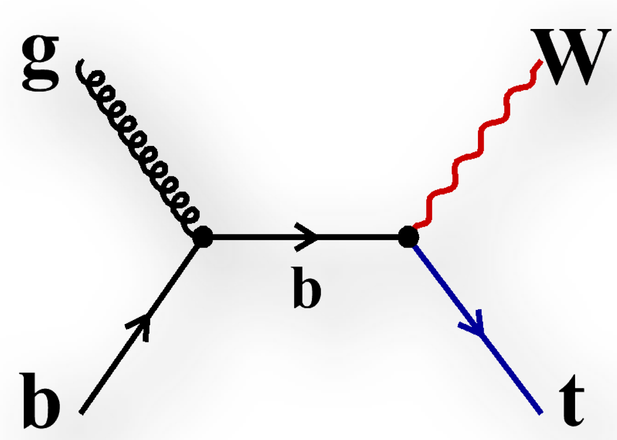
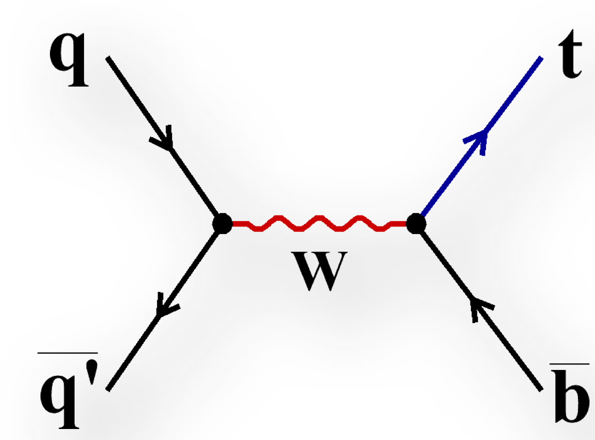
Single top quark production @LHC

t-channel	tW channel	s-channel

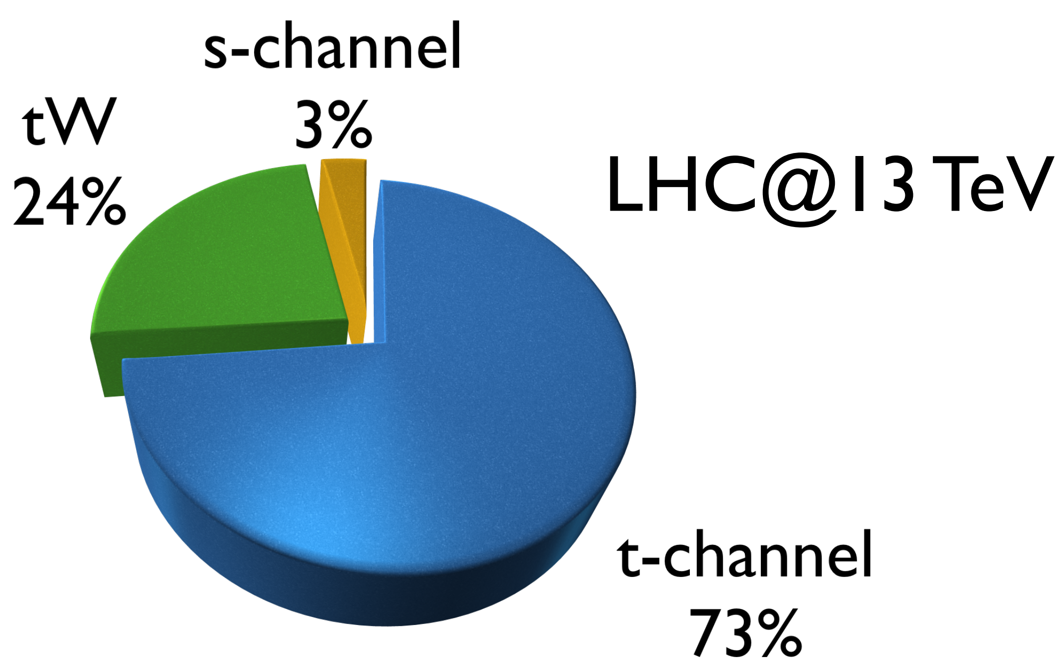






t-channel	tW channel	s-channel
$\sigma(7\ \text{TeV}) = 63.9^{+2.9}_{-2.5}\ pb$	$\sigma(7\ \text{TeV}) = 15.7 \pm 1.2\ pb$	$\sigma(7\ \text{TeV}) = 4.3 \pm 0.2\ pb$
$\sigma(8\ \text{TeV}) = 84.7^{+3.8}_{-3.2}\ pb$	$\sigma(8\ \text{TeV}) = 22.4 \pm 1.5\ pb$	$\sigma(8\ \text{TeV}) = 5.2 \pm 0.2\ pb$
$\sigma(13\ \text{TeV}) = 217.0^{+9.0}_{-7.7}\ pb$	$\sigma(13\ \text{TeV}) = 71.7 \pm 3.8\ pb$	$\sigma(13\ \text{TeV}) = 10.3 \pm 0.4\ pb$

NLO x-sec. from LHC Top WG



Single top quark production @LHC

- Important test of the **Standard Model**.
  - Measurement of V_{tb} of CKM matrix.
  - Indirect measurement of the top-quark mass.

- Improve knowledge of **PDFs**.
  - Cross-section ratio $R_t = \sigma(t)/\sigma(\bar{t})$: sensitive to u/d-quark ratio in PDF sets.
  - Test of b-quark PDF.

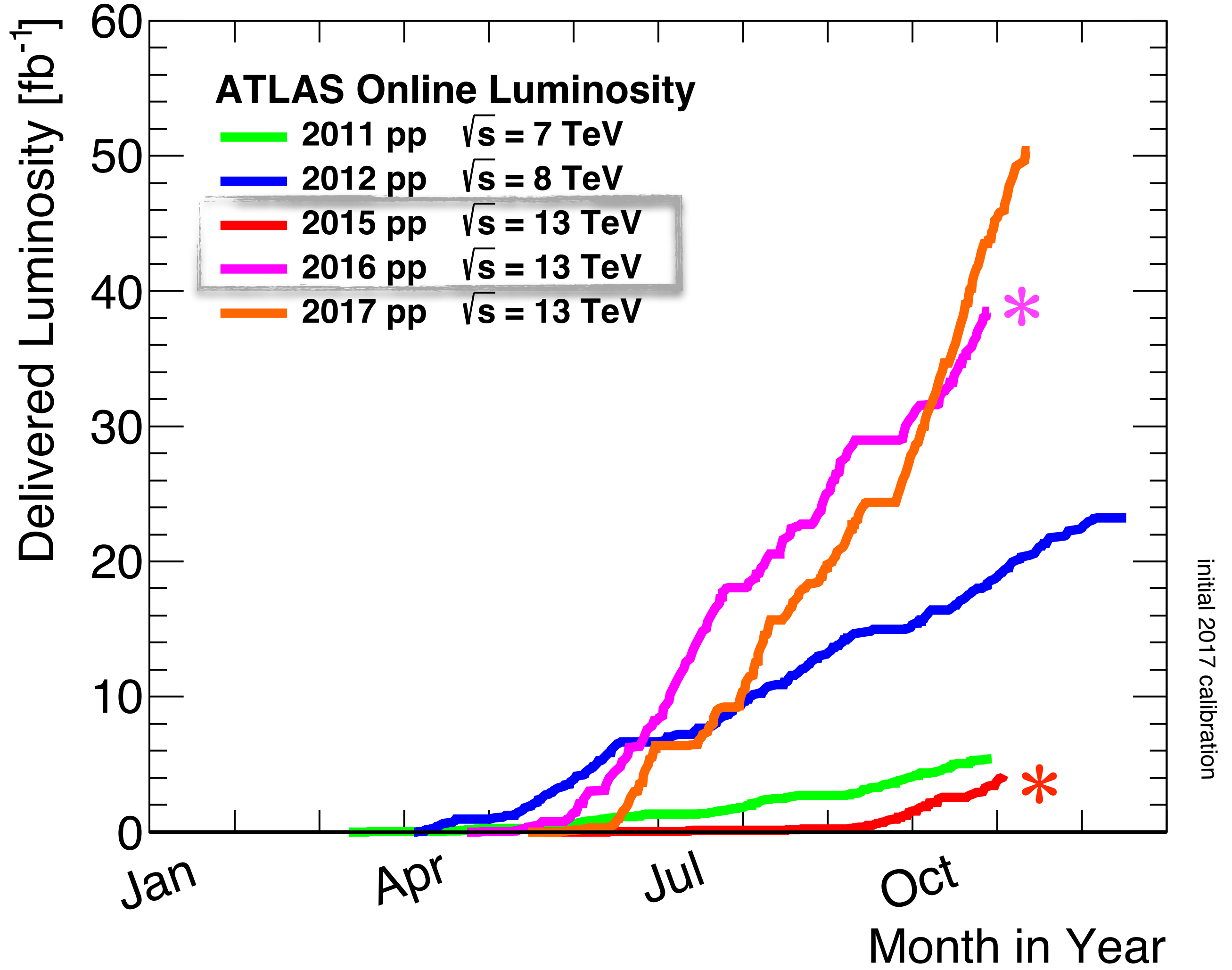
- Precise measurement input to **Monte Carlo tuning**, using unfolded distributions.

- Looking for **new physics**.
  - Modification of $\sigma(t)$ shape or in a variation of coupling w.r.t. SM expectations.

LHC Run2 data

- Fantastic LHC performance.
  - High integrated luminosity collected by the experiments.
- **LHC** is a **top factory**.
  - Allows for precision measurements in the top sector.
- Makes it possible to look for **rare processes**, e.g. **single top production in association with a Z boson** (**tZq**).
- Search performed on 2015+2016 data from LHC pp collisions at 13 TeV.

	13 TeV
2015	3.3 fb^{-1}
2016	32.8 fb^{-1}
	36.1 fb^{-1}



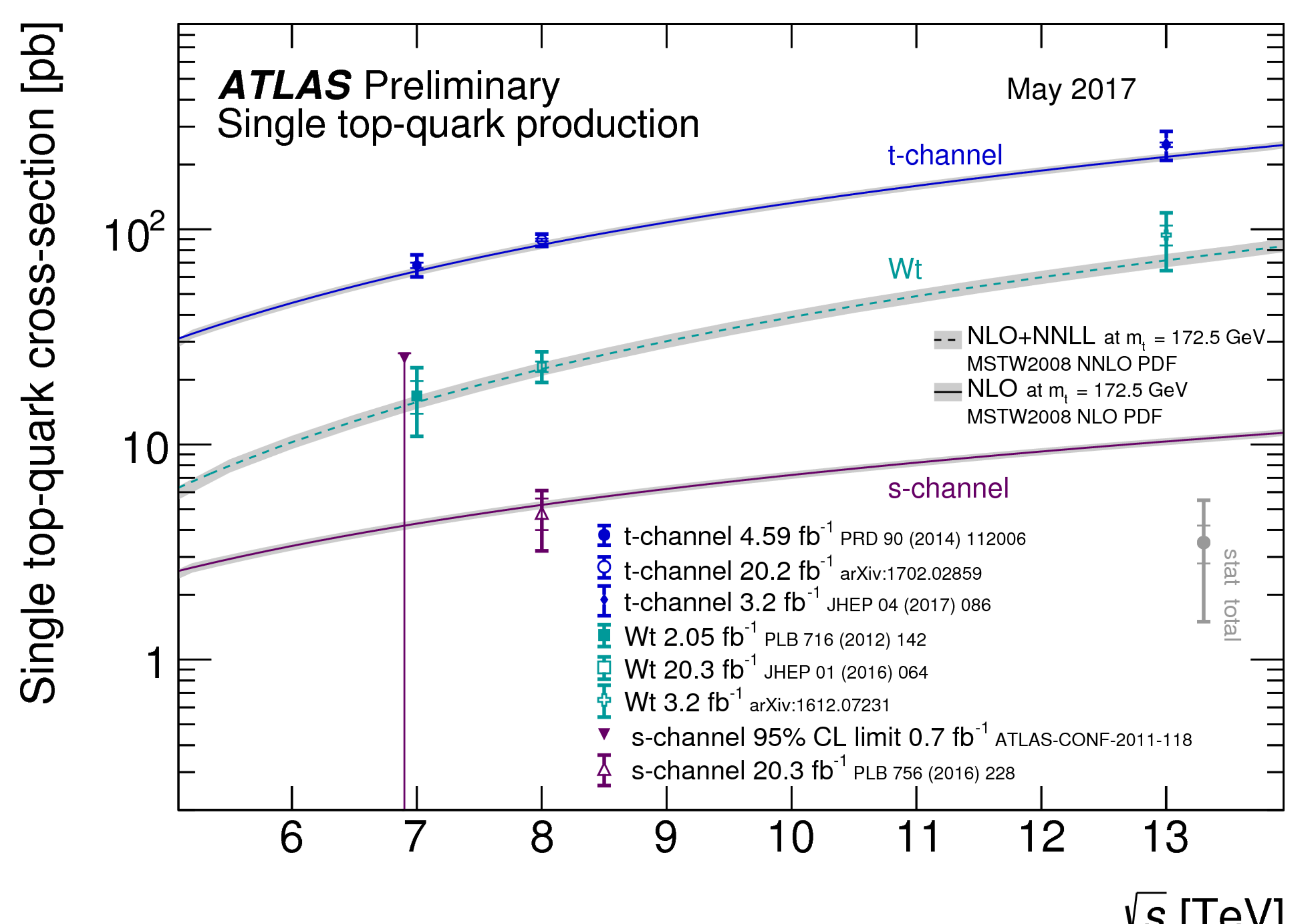
- How many single top events were produced in this dataset?

	x-sec (pb)	#events*
t-channel	217	8 M
tW	71.1	2.5 M
s-channel	10.3	300 K
tZq	0.8	30 K

*These do not include branching ratios.

Single top quark production @LHC

	7 TeV	8 TeV	13 TeV*
t-channel	PRD 90 (2014) 112006 cross sect. (with differential) + R_t + V_{tb}	EPJC 77 (2017) 531 cross sect. (with diff+fiducial) + R_t + V_{tb}	JHEP 04 (2017) 086 cross-section + R_t + V_{tb}
tW	PLB 716 (2012) 142 cross section + V_{tb}	JHEP 01 (2016) 064 cross sect. (with fiducial) + V_{tb}	arXiv:1612.07231 + paper in preparation cross sect. (with differential)
s-channel	ATLAS-CONF-2011-118 95% CL upper limit on cross section	PLB 756 (2016) 228 cross section 3.2σ observed	—



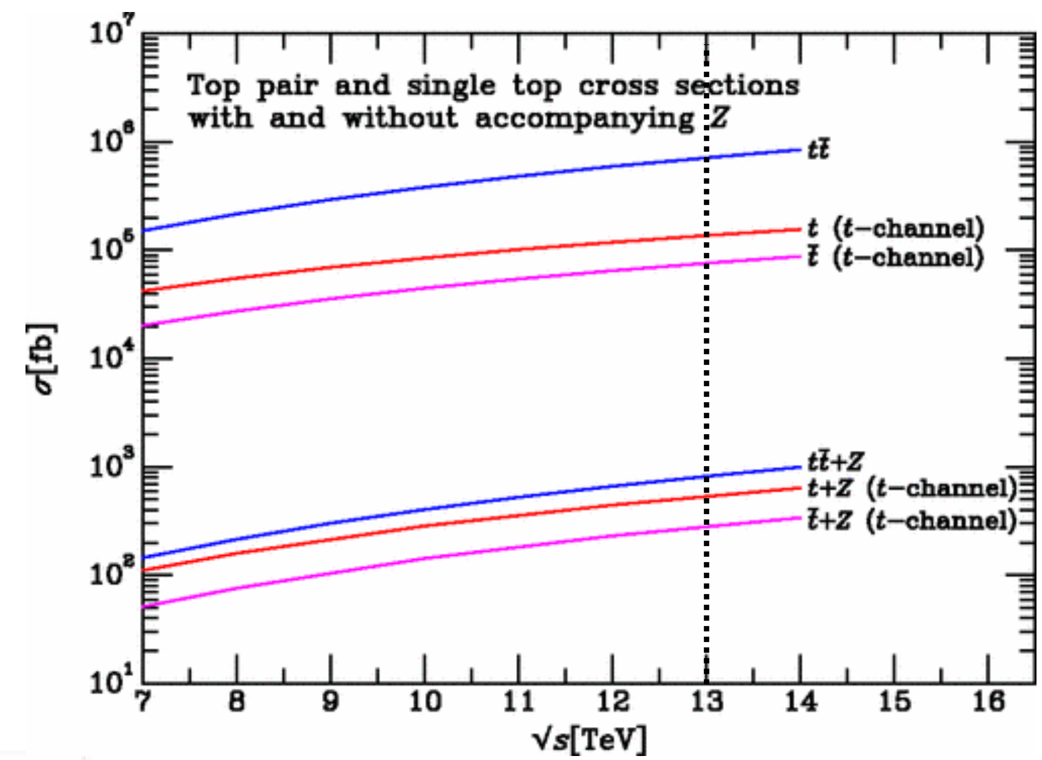
*With partial datasets.

Single top in association with a Z boson

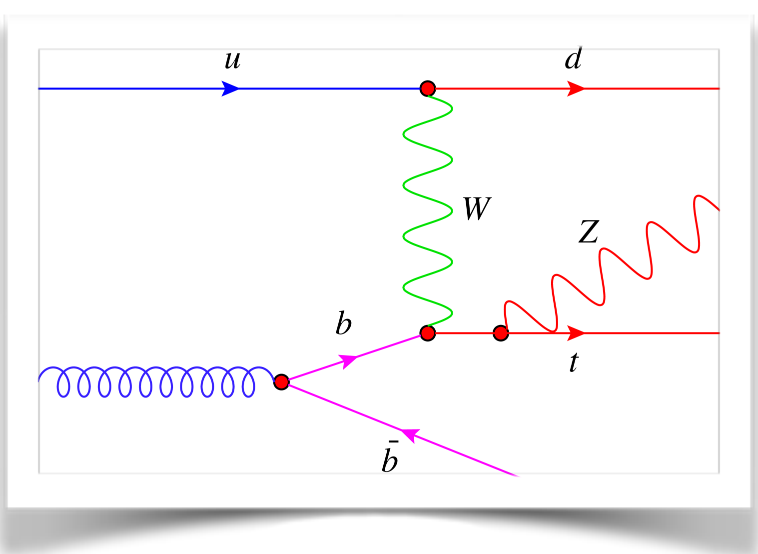
- Standard Model single-top production in association with a Z boson (t-channel) not measured before Run2.
  - CMS search on 8 TeV data [JHEP 07 (2017) 003].
    - Observed (expected) significance 2.4σ (1.8σ).

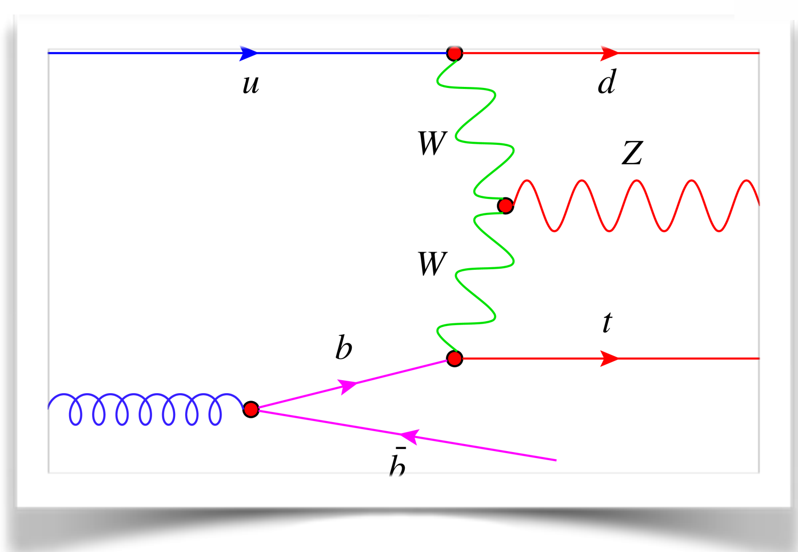
- SM tZq probes both tZ and WWZ couplings.
  - $t\bar{t}Z$ only probes tZ - previously measured by ATLAS and CMS.

- SM tZq background for:
  - FCNC tZ production,
  - tH final state.



from 10.1103/PhysRevD.87.114006

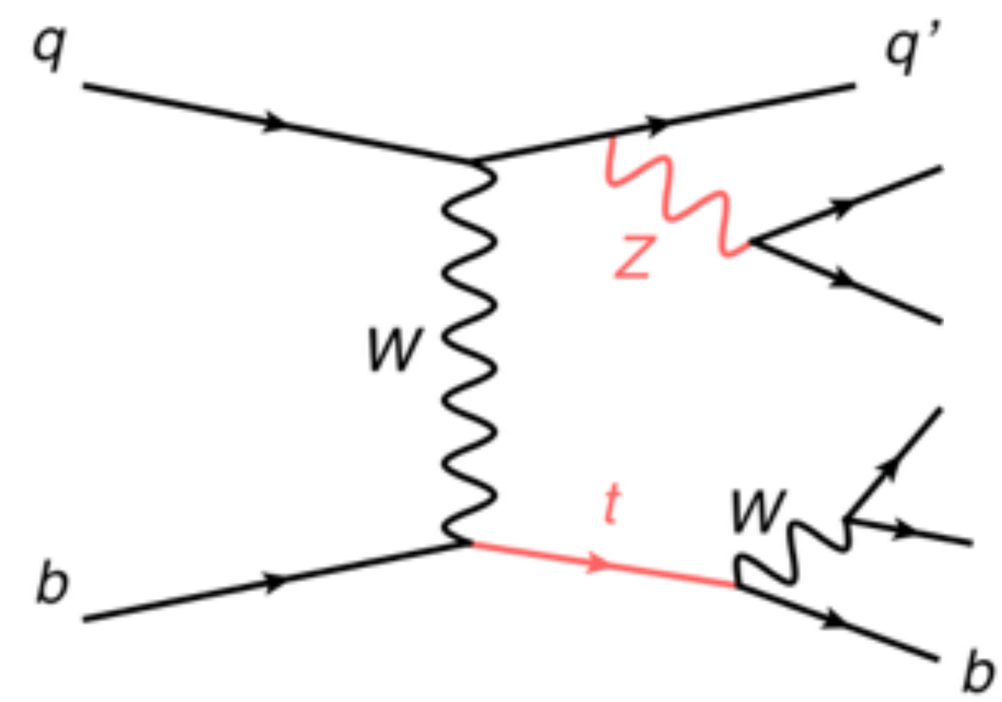




$\sigma_{NLO}(tZq)$ = 800 fb

What are we looking for?

- Four different final states available, depending on:
  - decay of the W boson from the top
  - decay of the Z boson.



- **Fully hadronic channel**
  - both W and Z decay hadronically
  - ≥ 6 jets

- **Single lepton channel**
  - W decays leptonically, Z decays hadronically
  - 1 lepton, ≥ 4 jets

- **Dilepton channel**
  - W decays hadronically, Z decays leptonically
  - 2 leptons, ≥ 4 jets
  - Z to charged leptons(~5.3%) promising but large Z+jets background
  - Z to neutrinos(~5.2%) interesting for mono top searches

- **Trilepton channel - BR ~2.2%**
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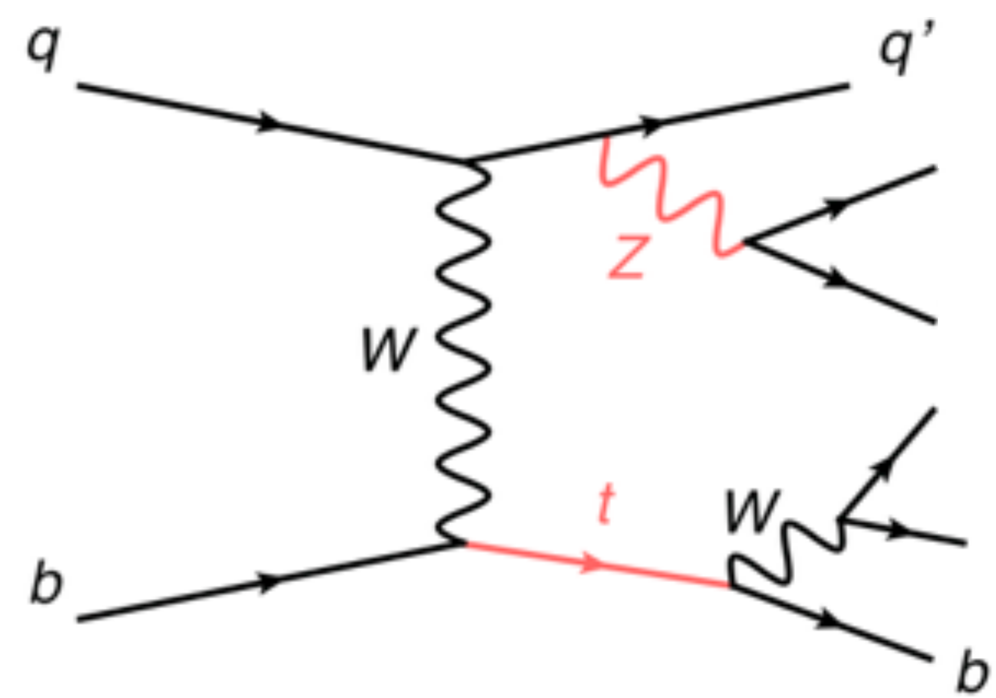

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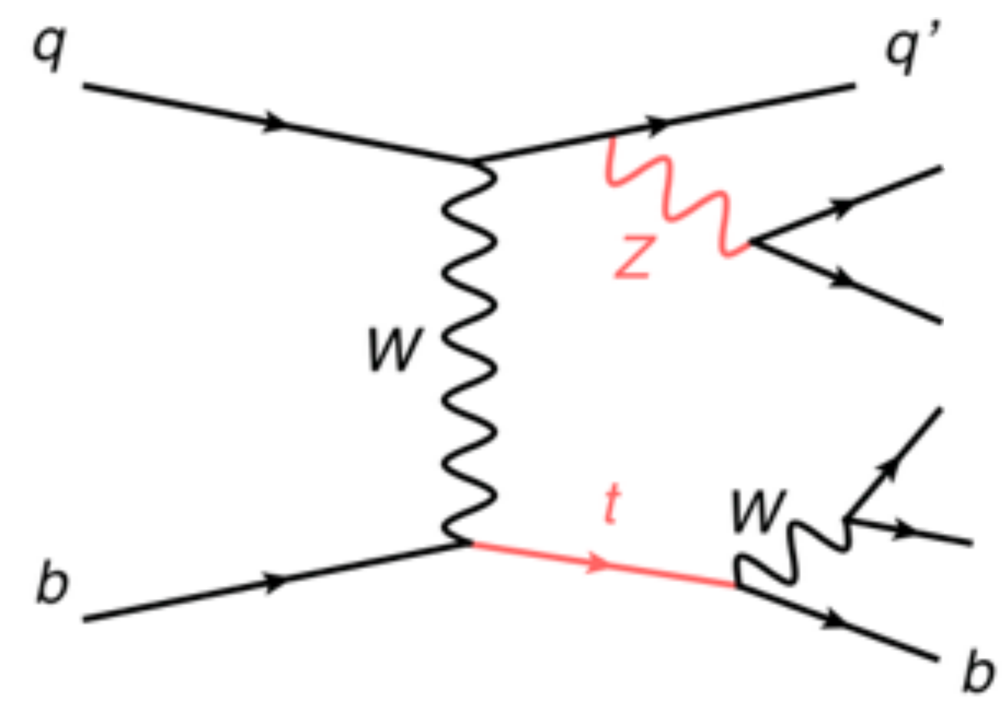

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How do we reconstruct these objects?

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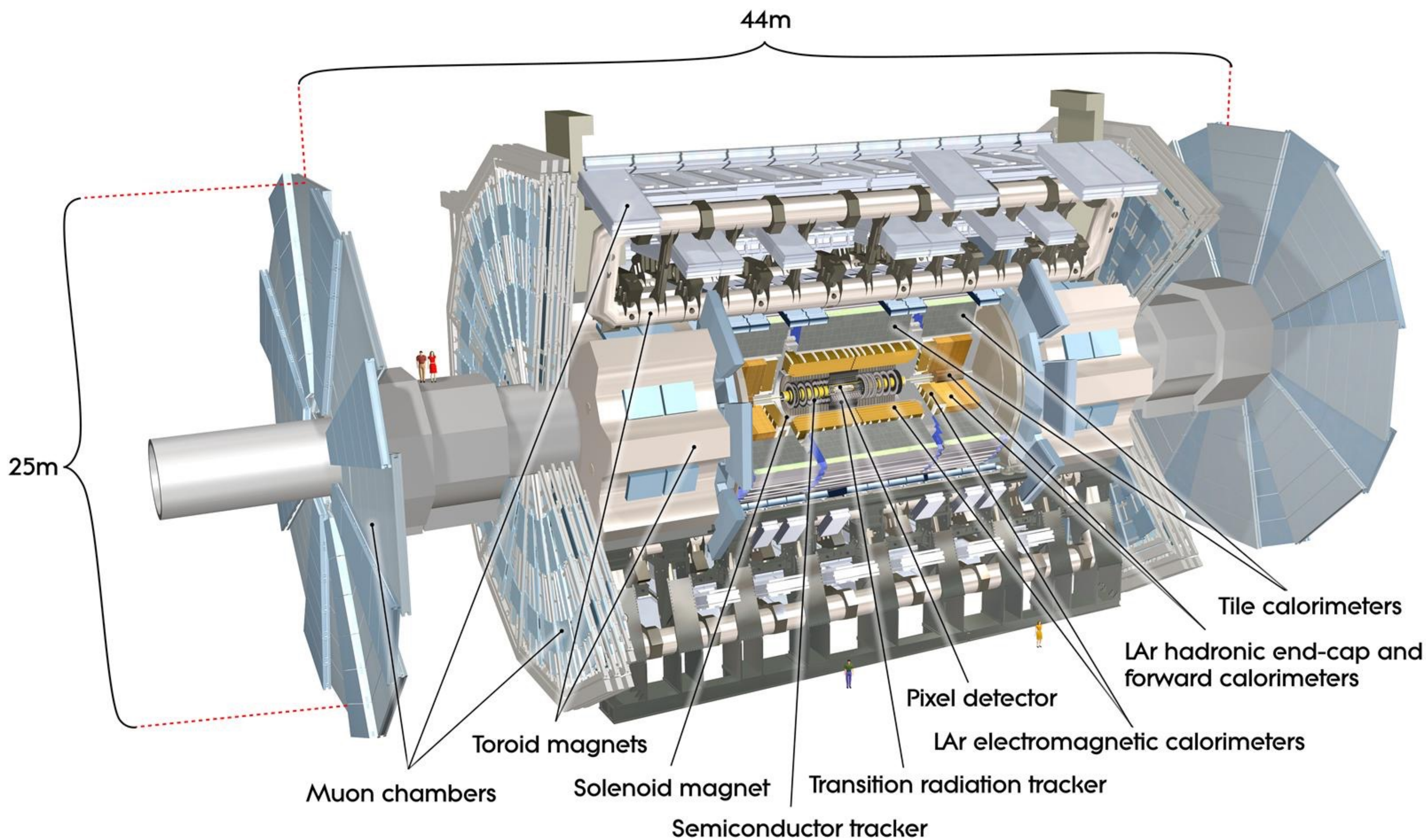
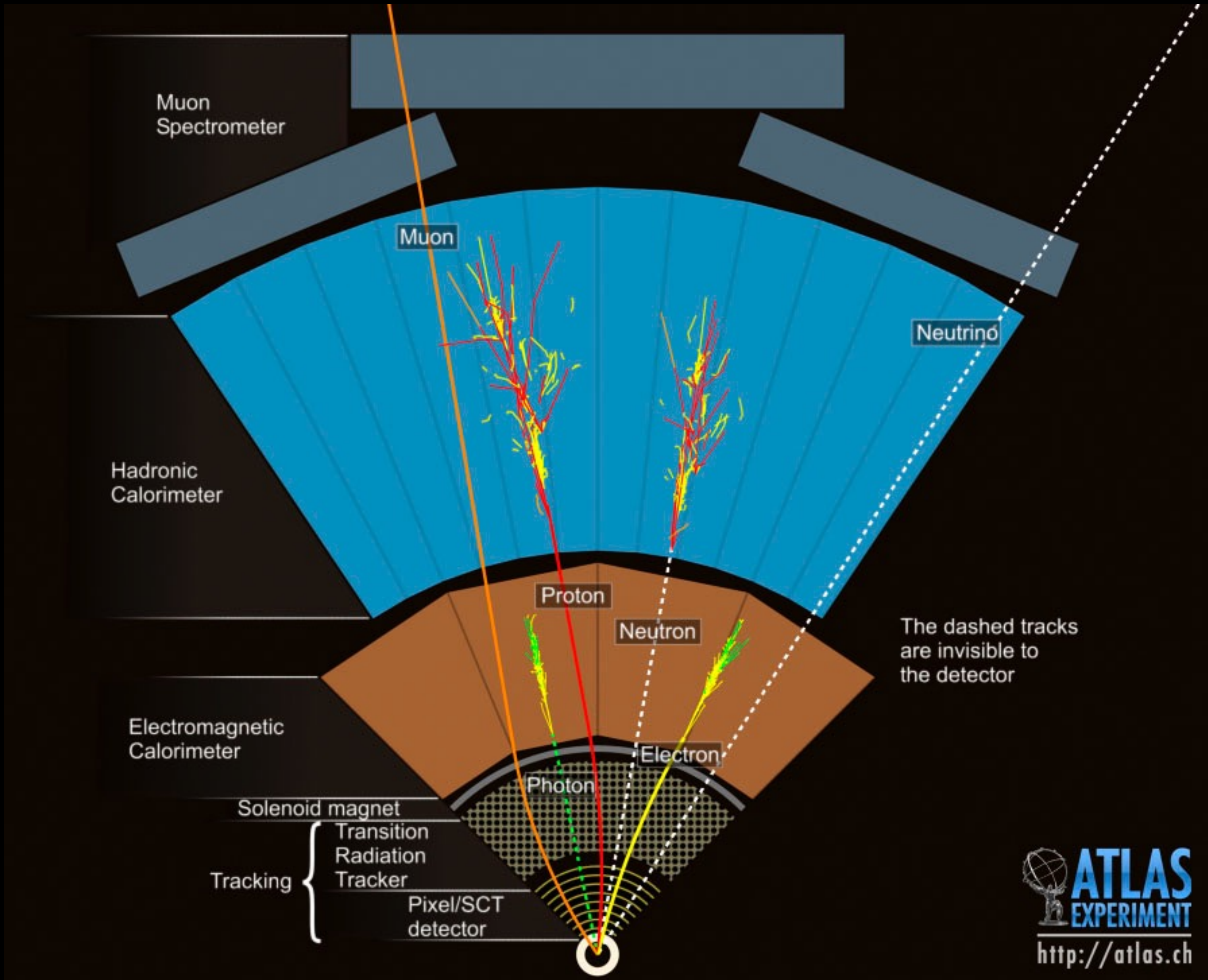
The ATLAS detector

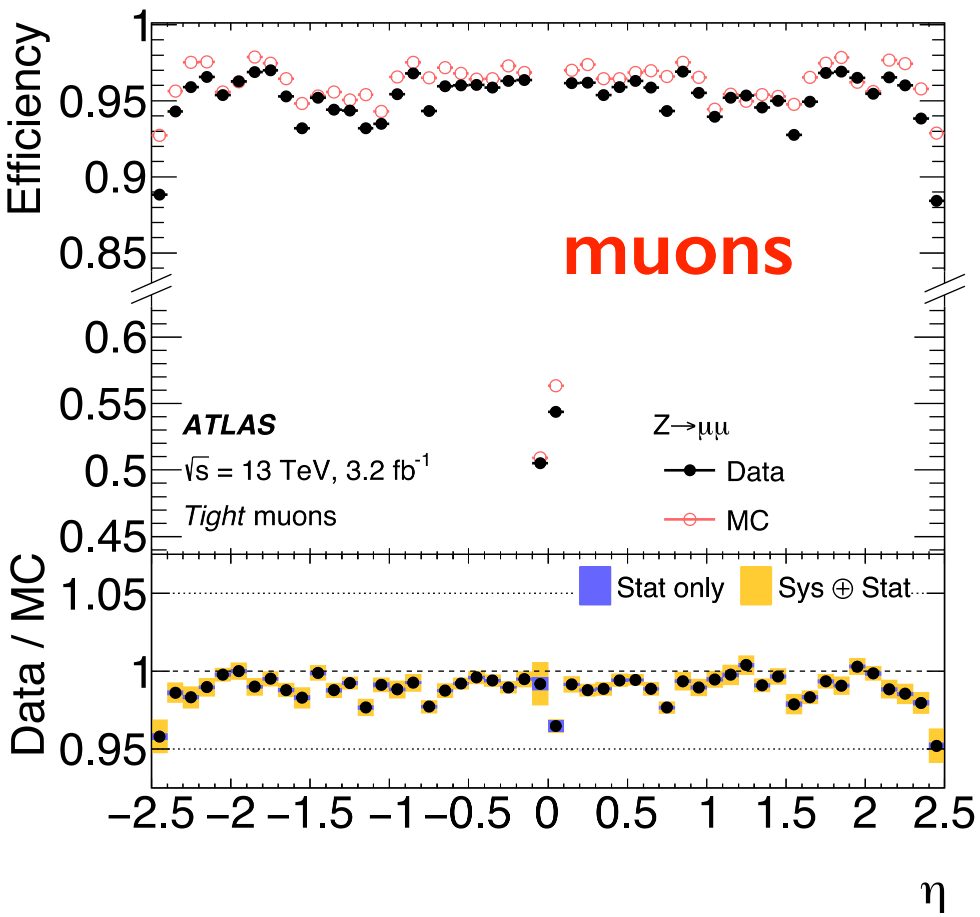


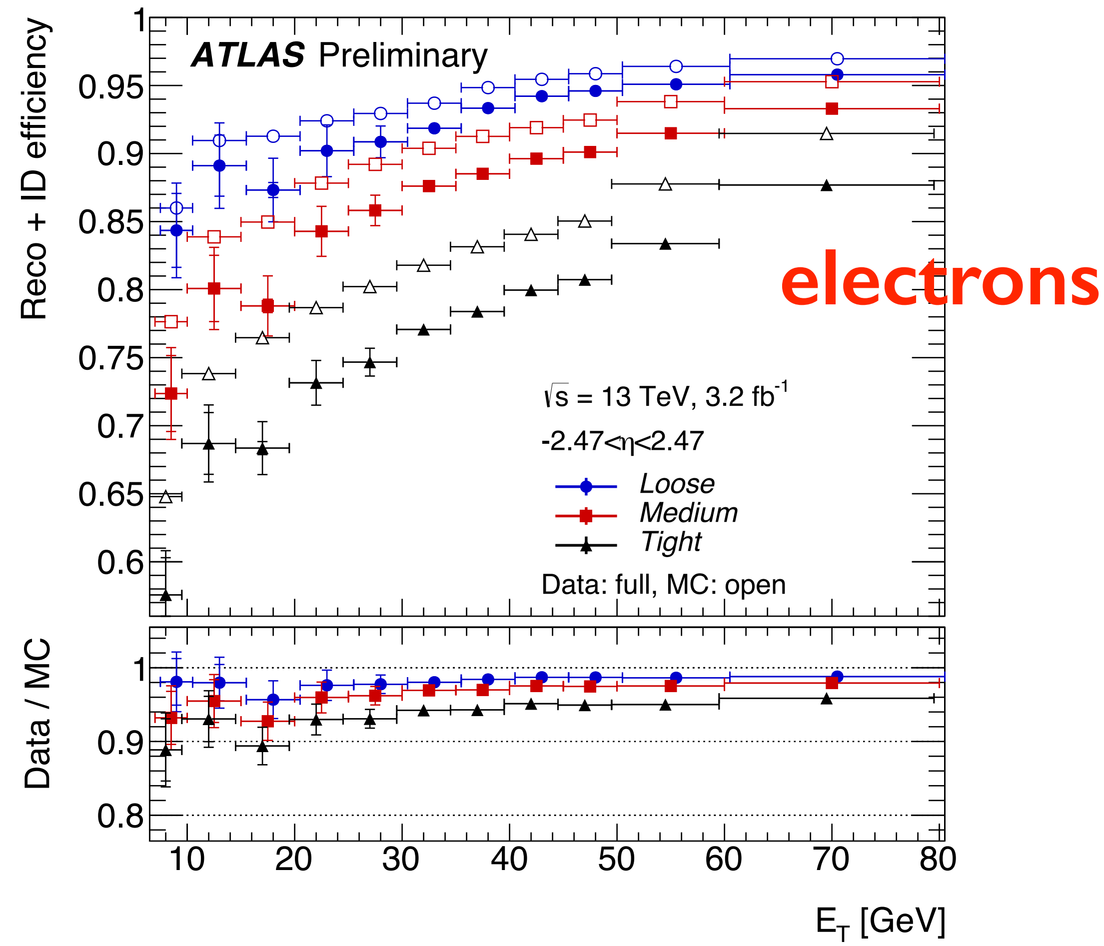
- Key detector upgrades for Run2:
  - trigger: L1 rates increased from 75 to 100 kHz, and High Level Trigger rates from 400 to 1000 Hz.
  - pixel detector: from a 3- to a 4-layer detector, with the addition of the Insertable B-Layer and a new beam pipe.

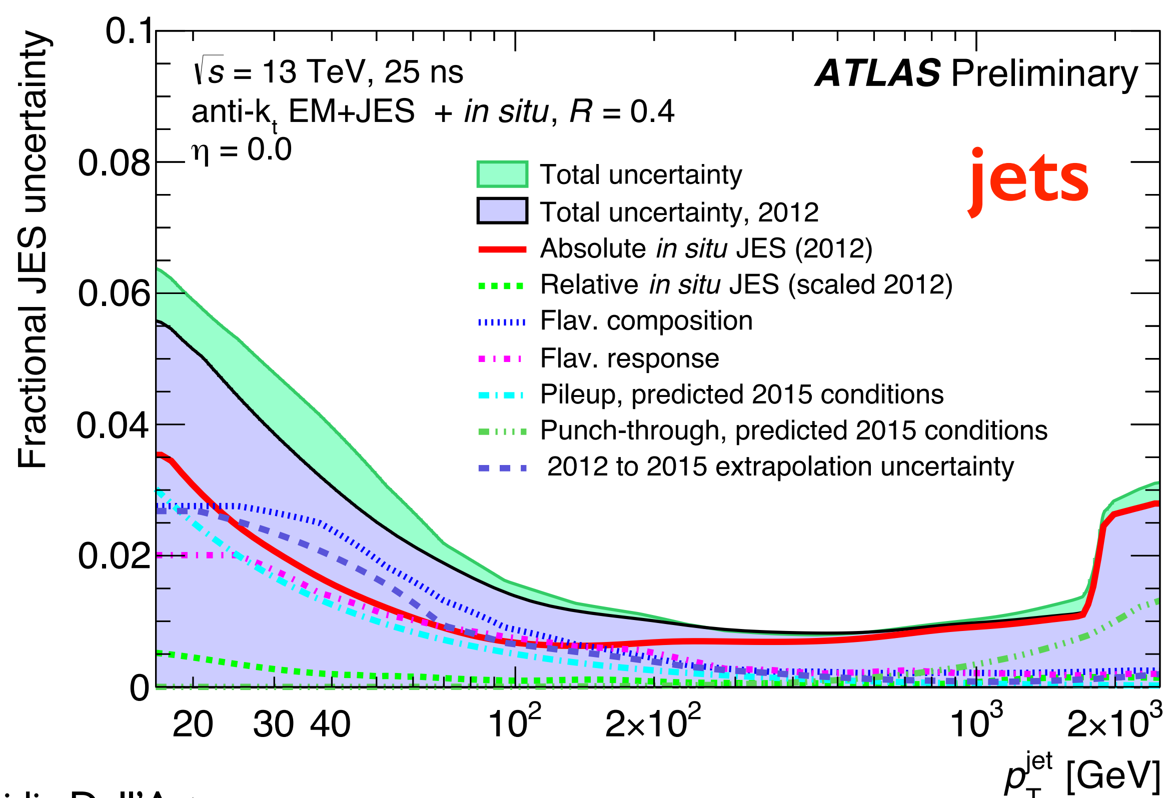
Particle identification

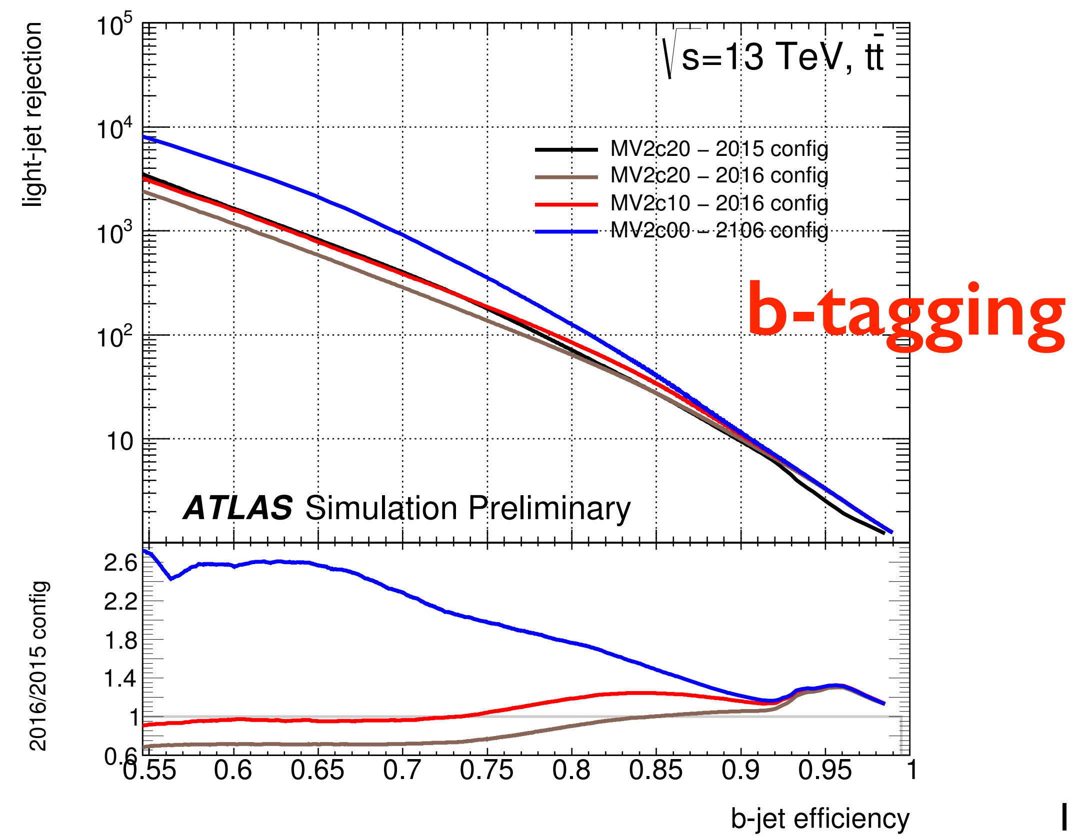


Performance









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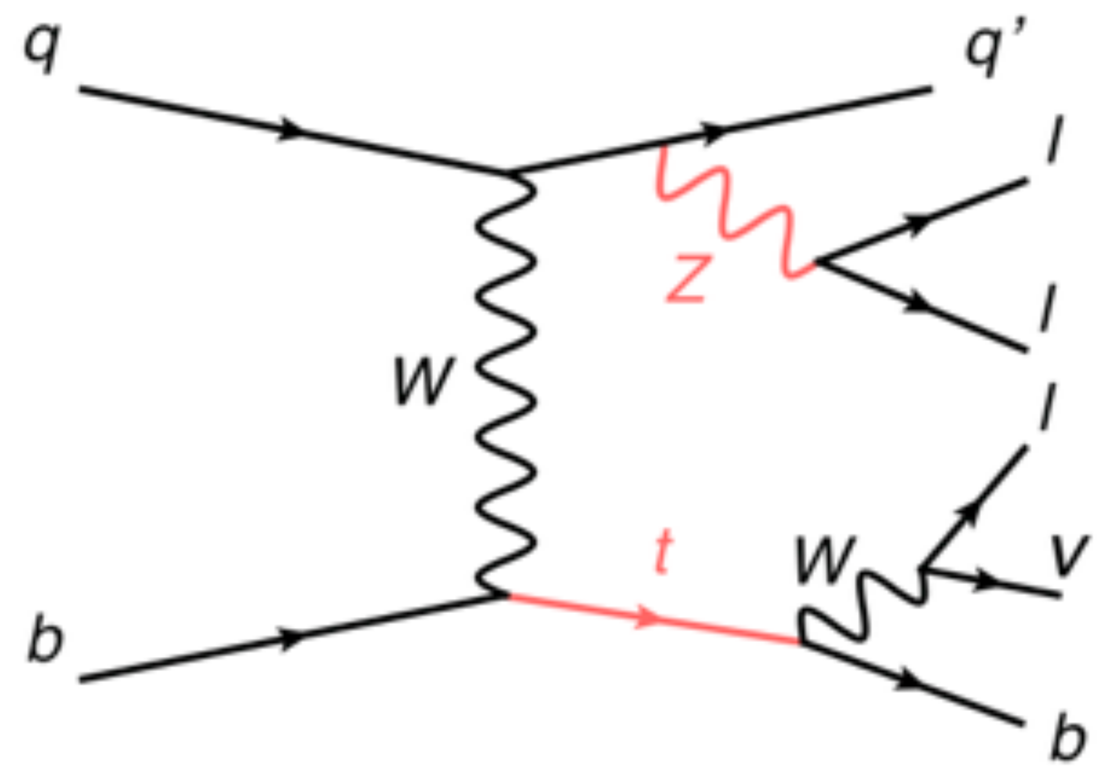
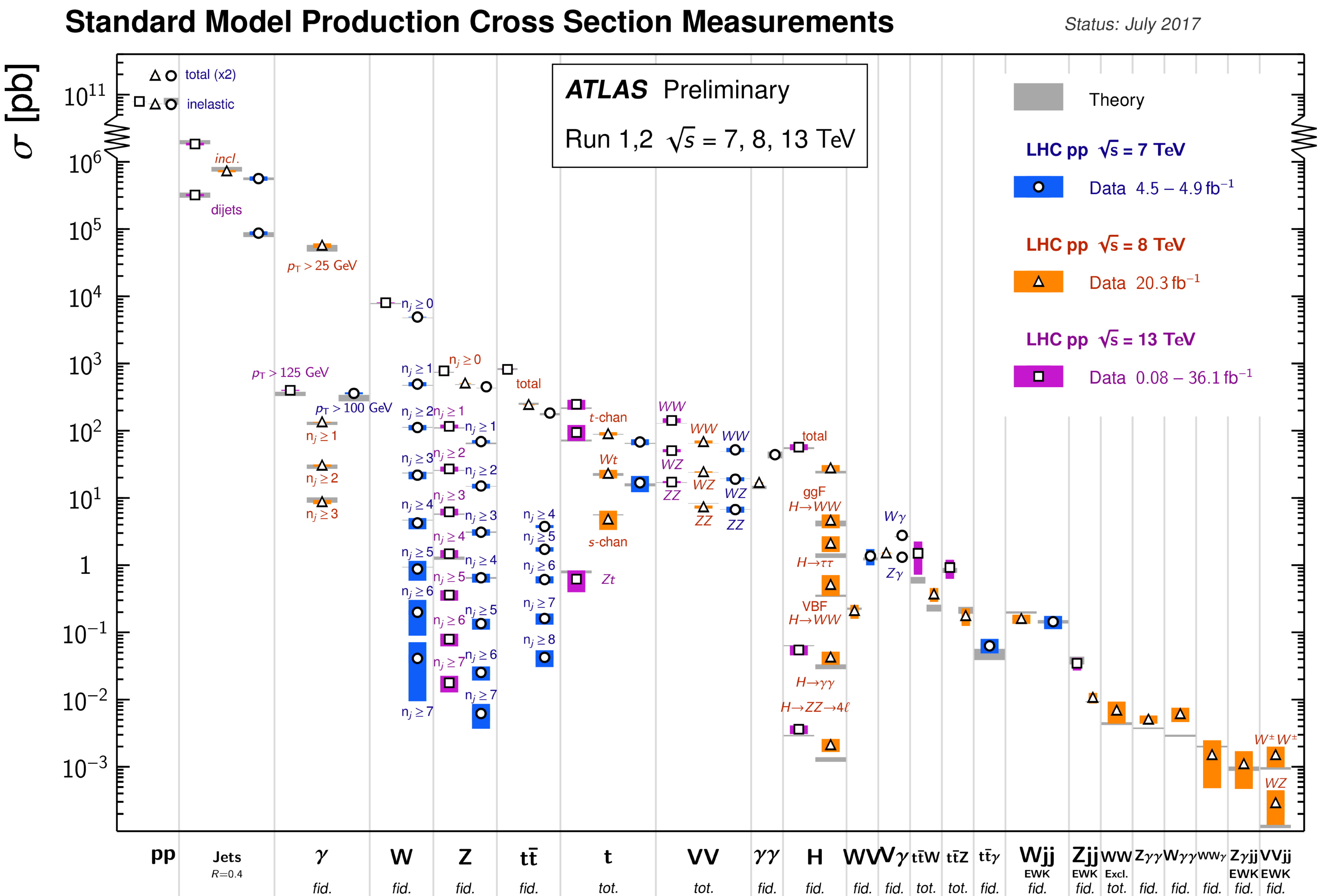
Event selection

- Leptons
  - exactly 3
  - $|\eta| < 2.5$
  - $p_T(l_1) > 28$ GeV
  - $p_T(l_2) > 25$ GeV
  - $p_T(l_2) > 15$ GeV
- Jets
  - exactly 2
  - $|\eta| < 4.5$
  - 1 b-tagged ($|\eta| < 2.5$)
  - p_T(jets) > 30 GeV



- In addition:
  - $\geq$1 opposite-sign same-flavour lepton pair with $|m_{ll} - m_Z| < 10$ GeV,
  - $m_T(l_W,\nu) > 20$ GeV.

Backgrounds



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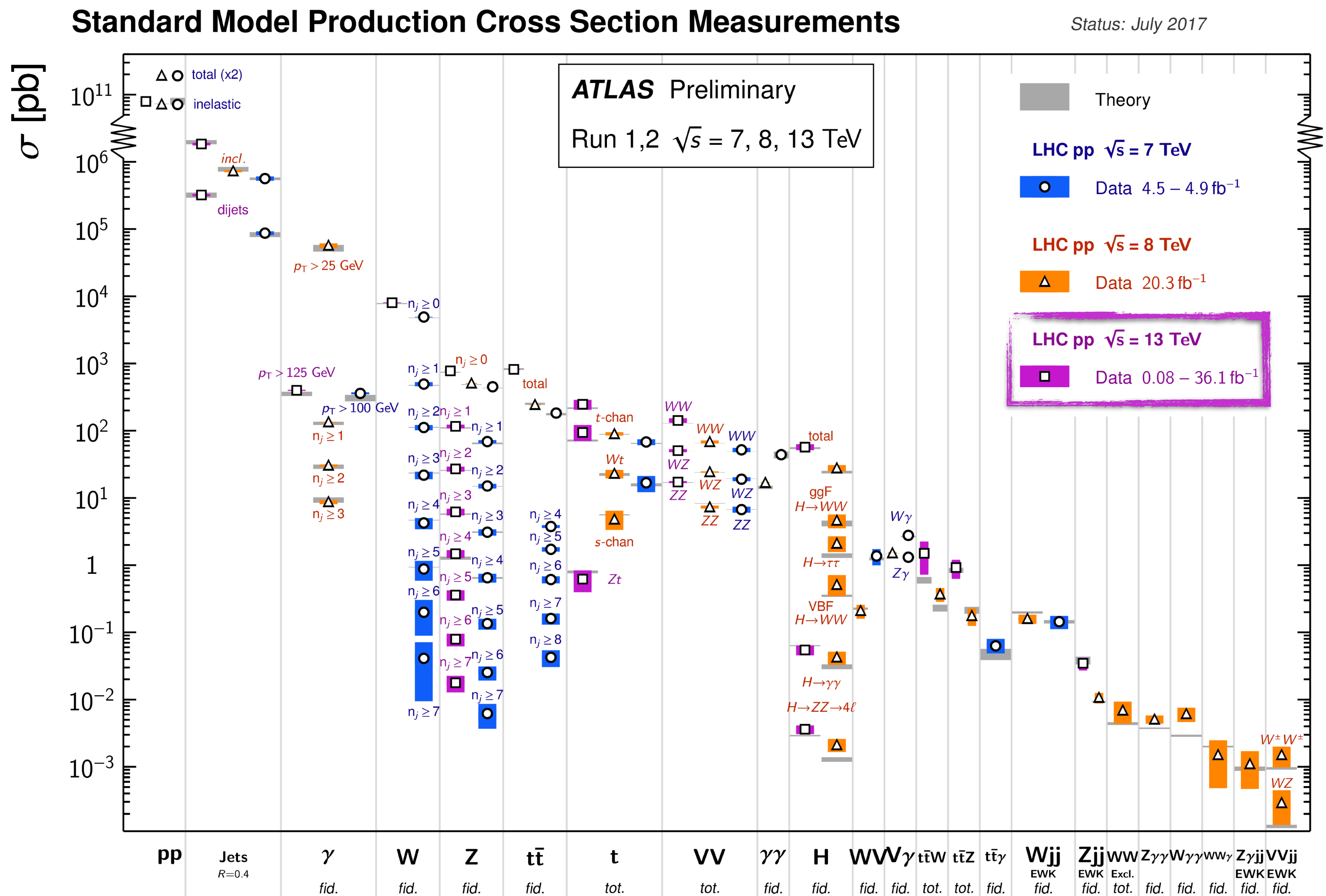

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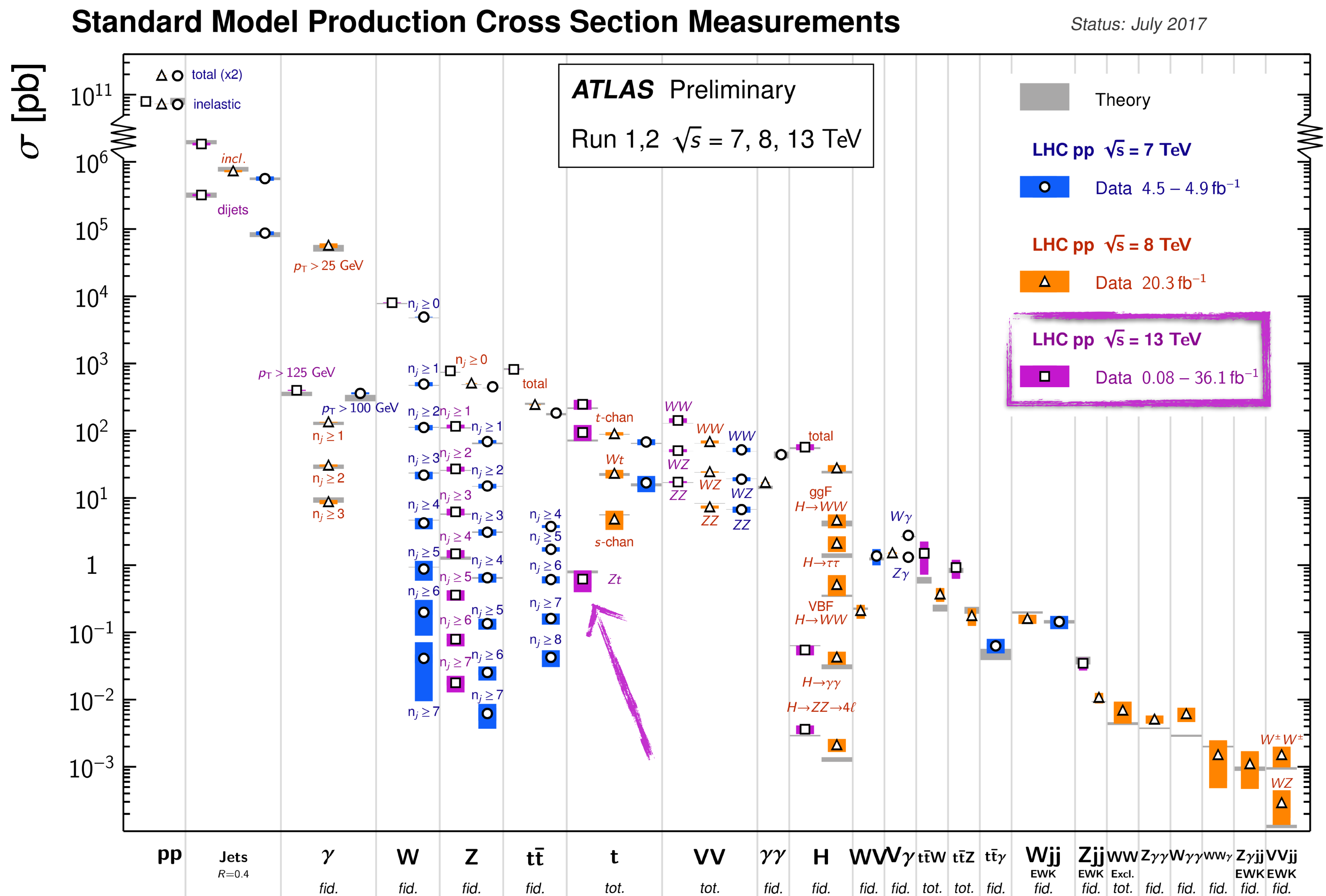

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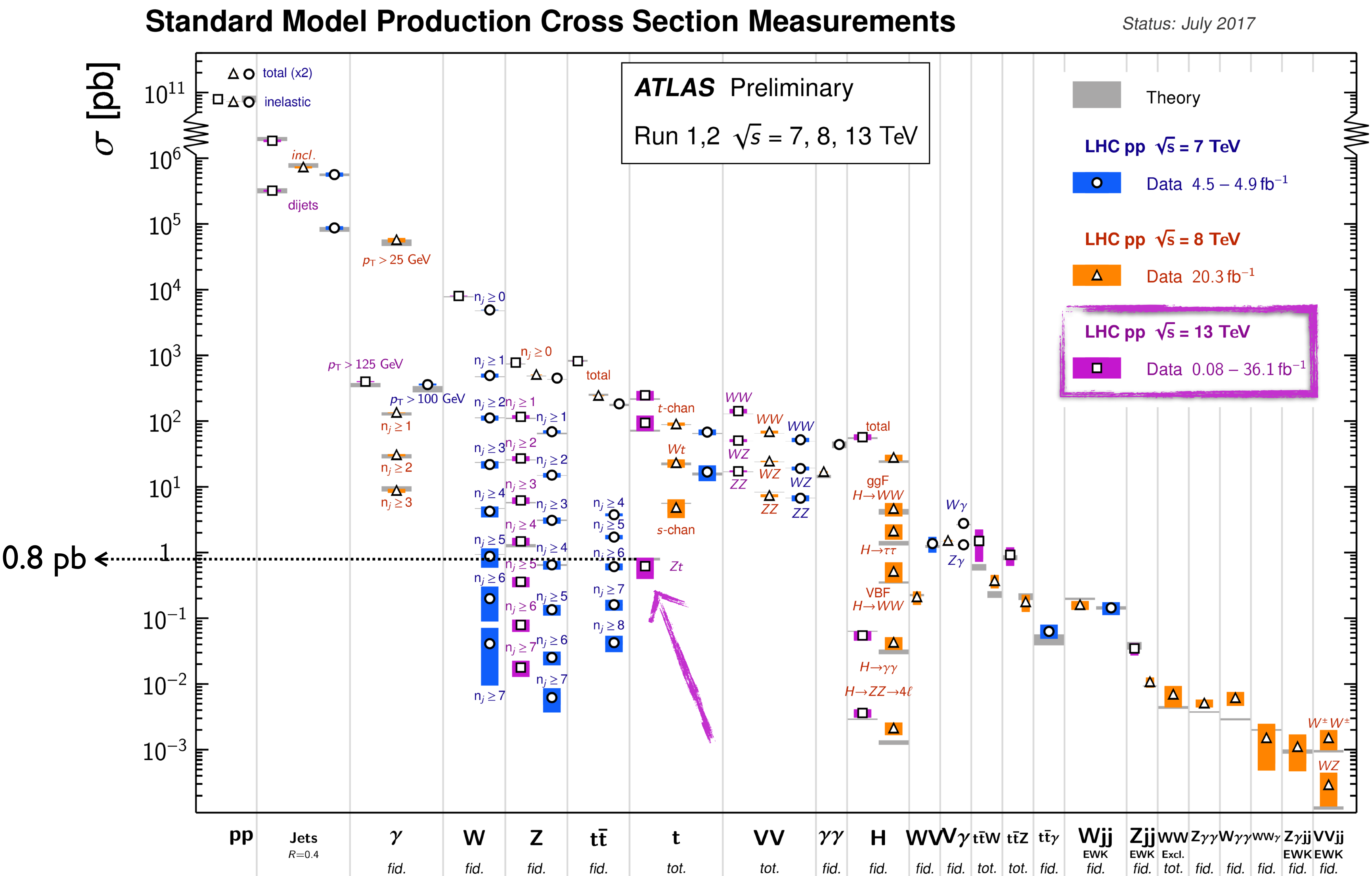

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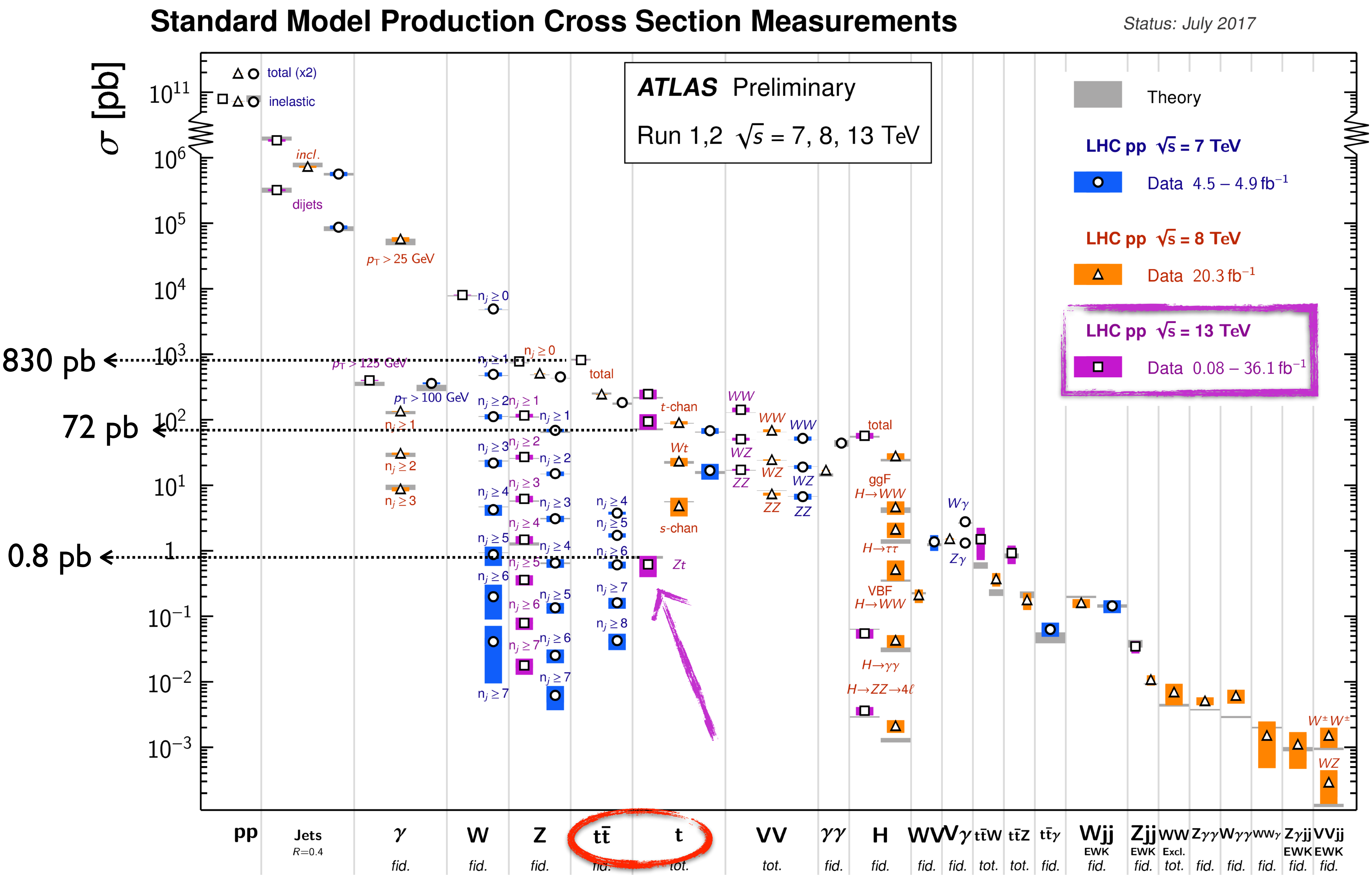

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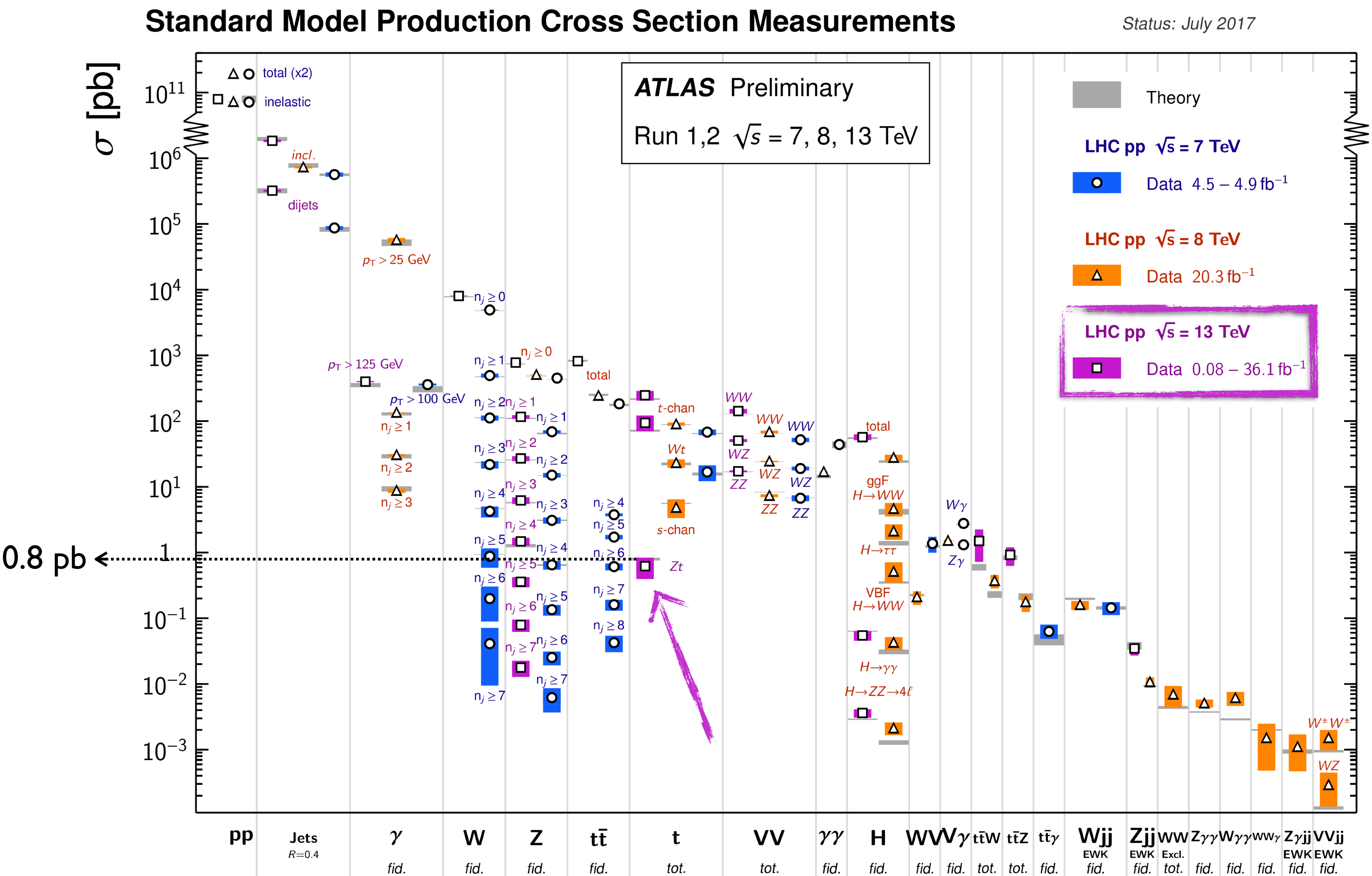

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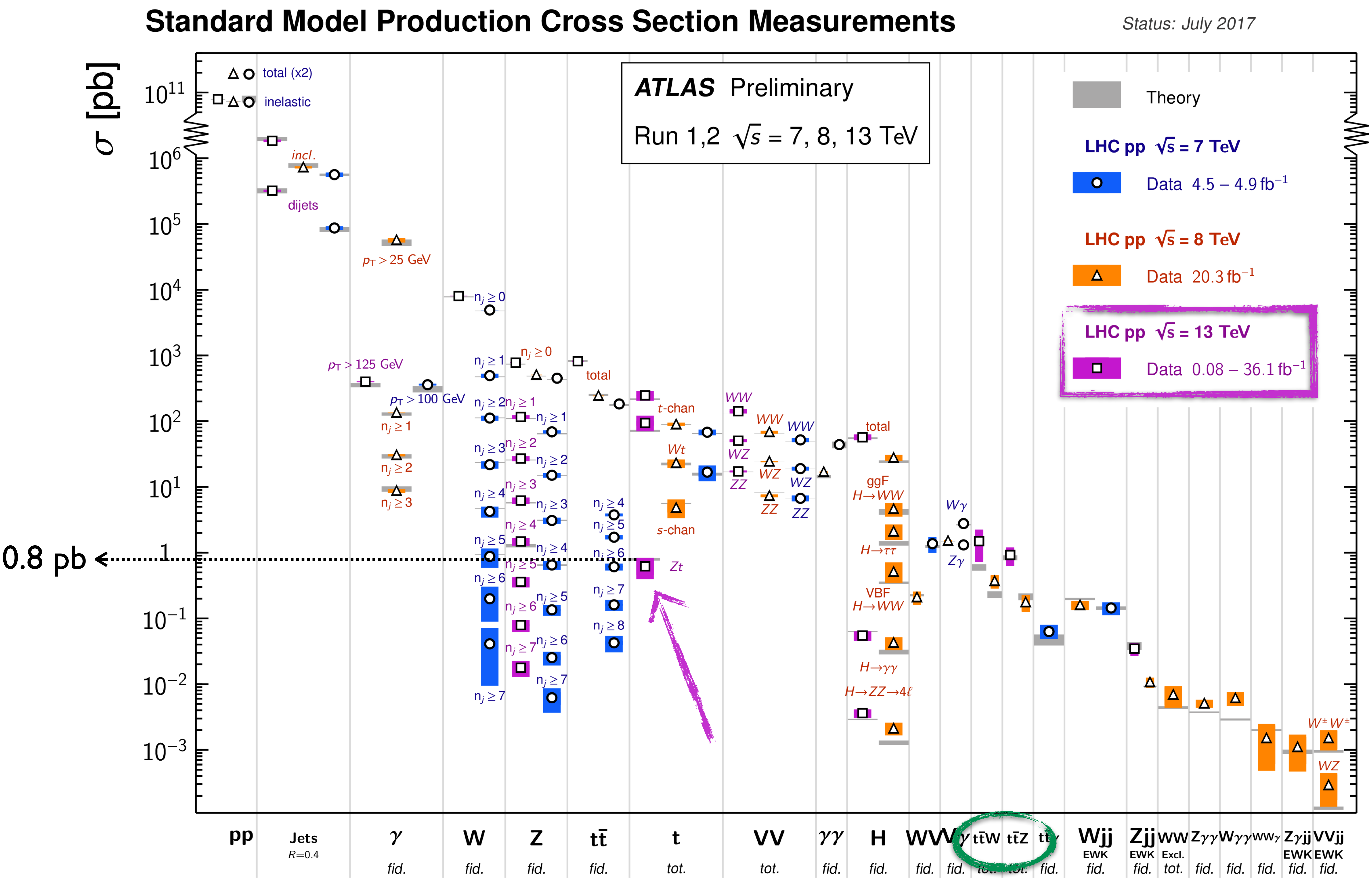

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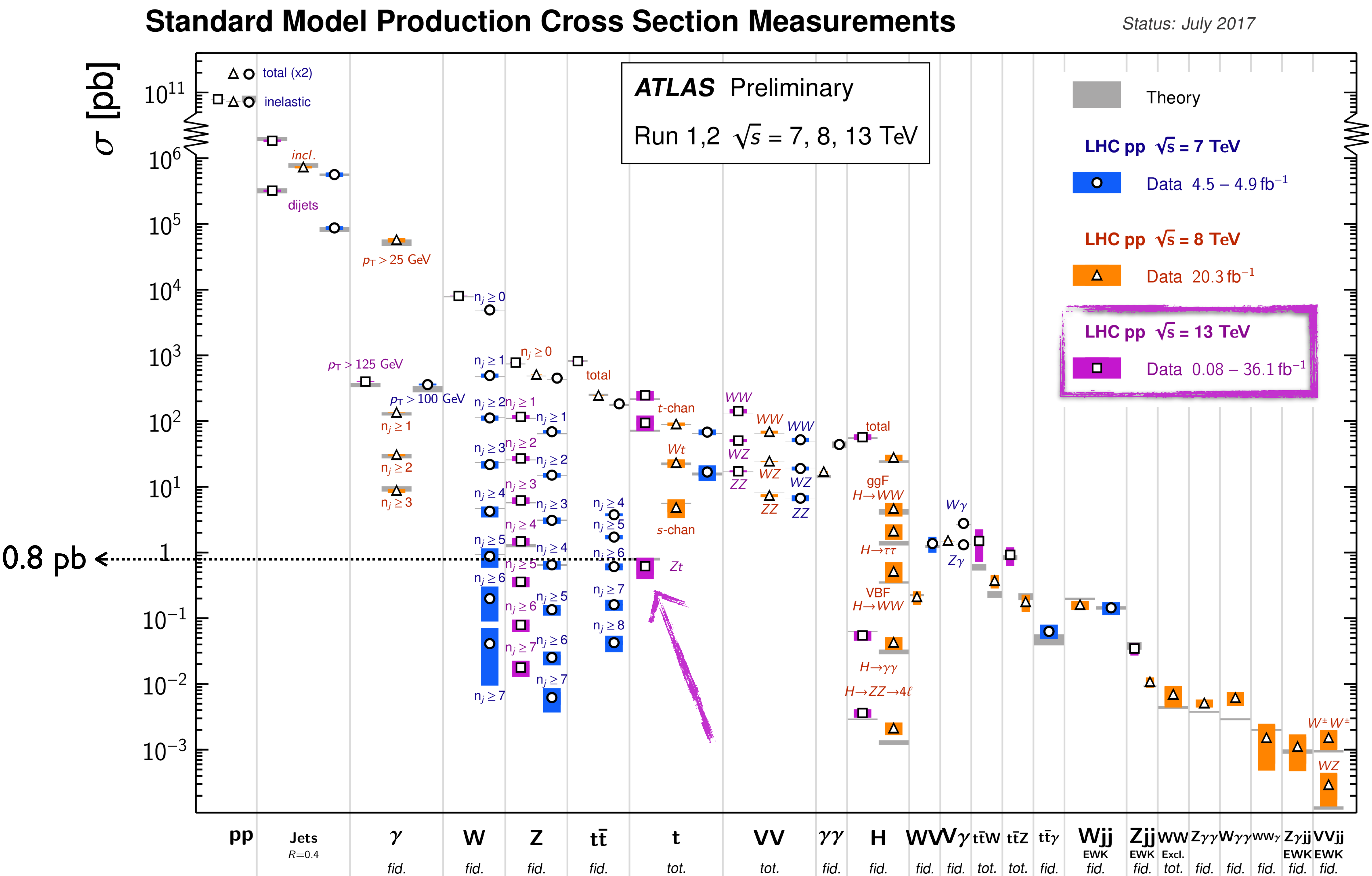

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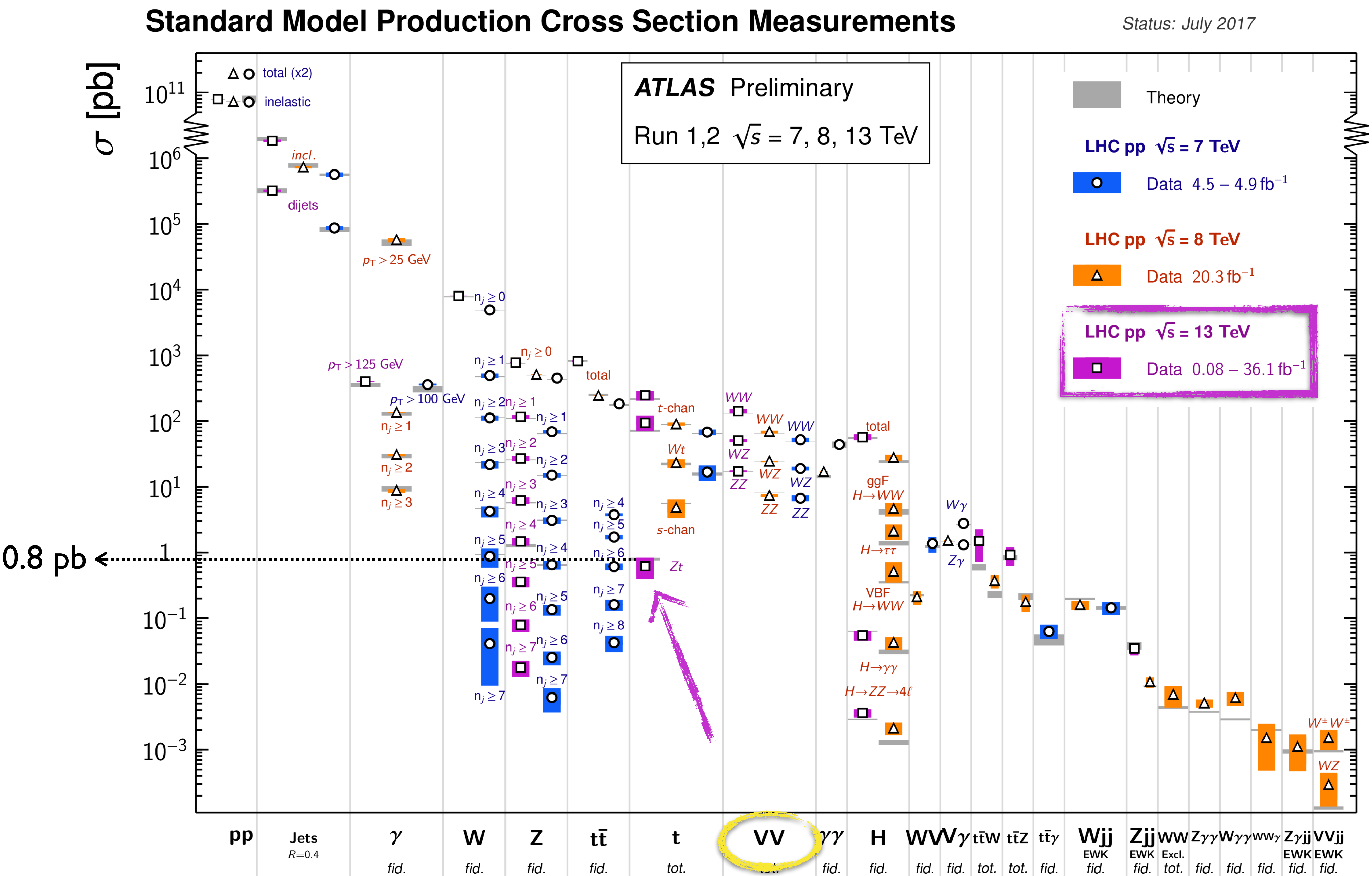

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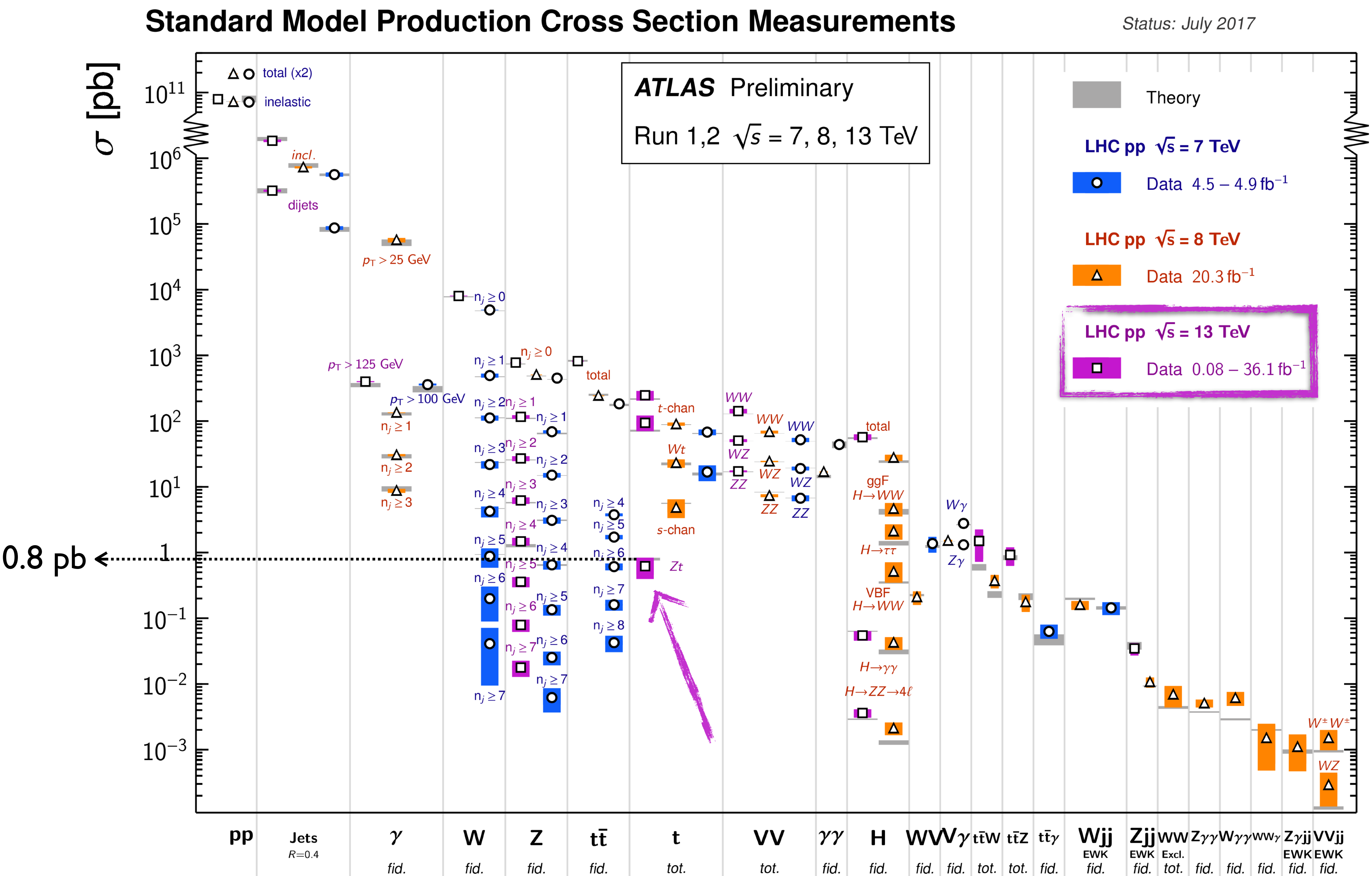

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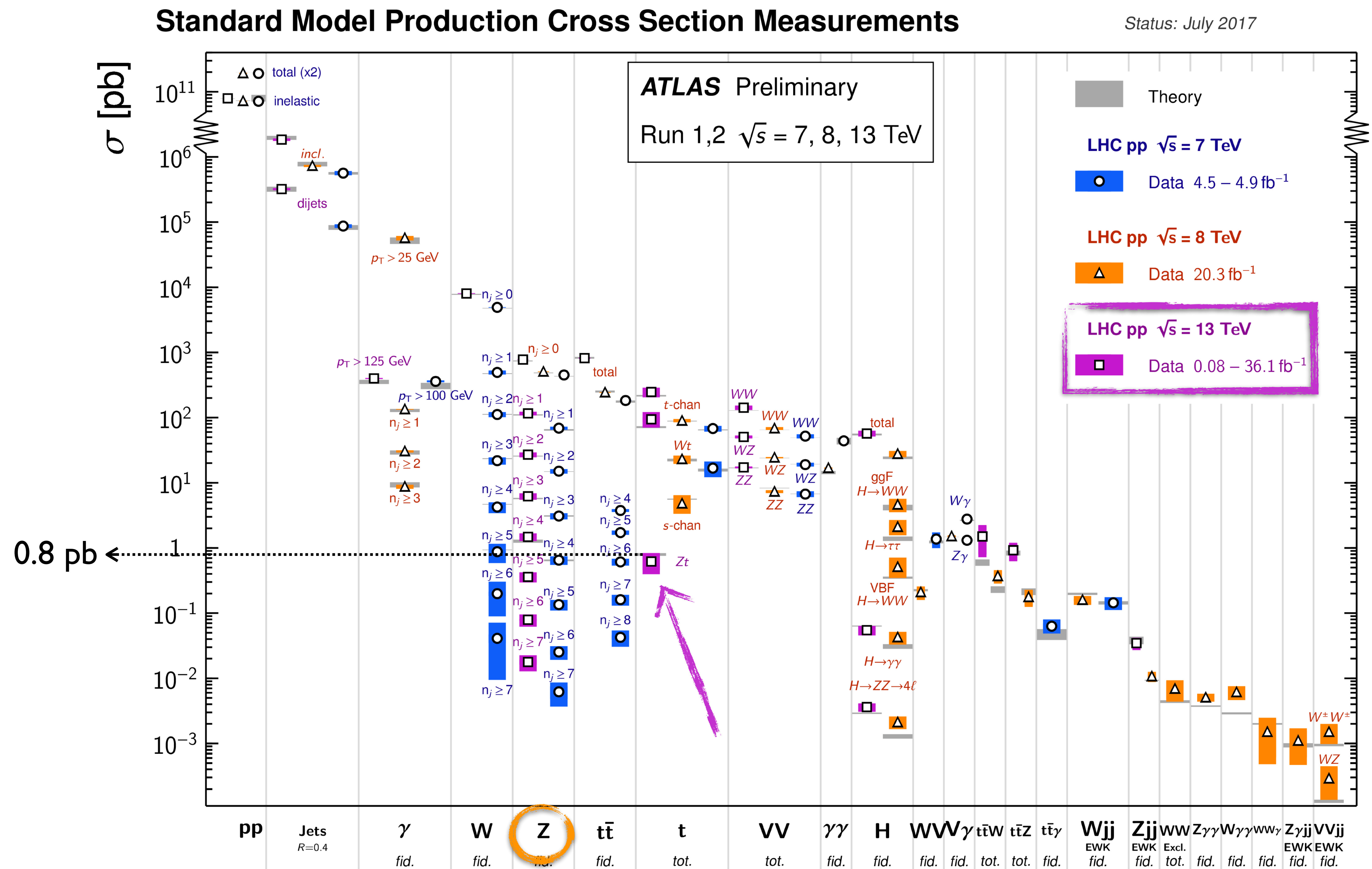

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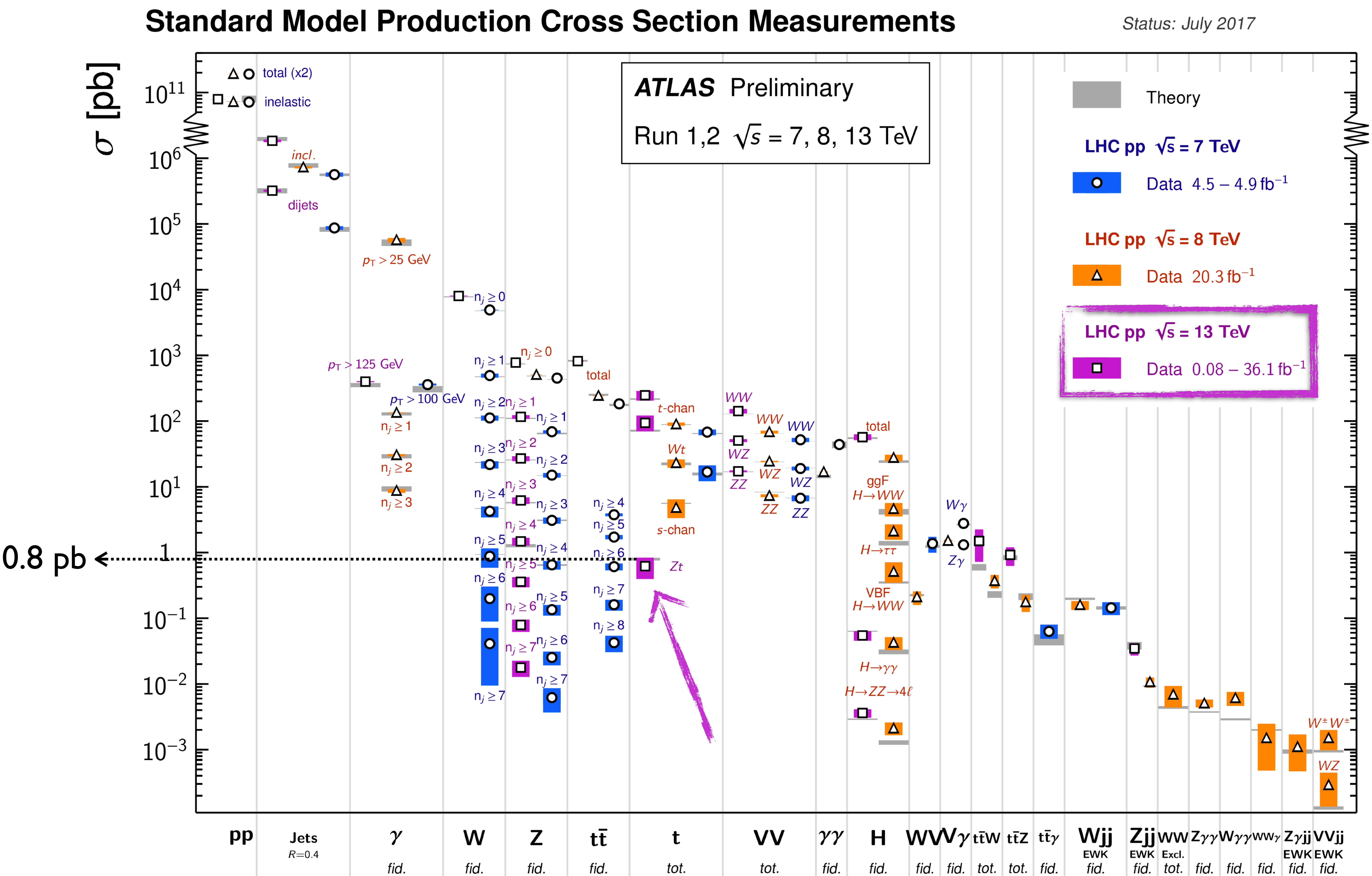


Signal, validation and control regions

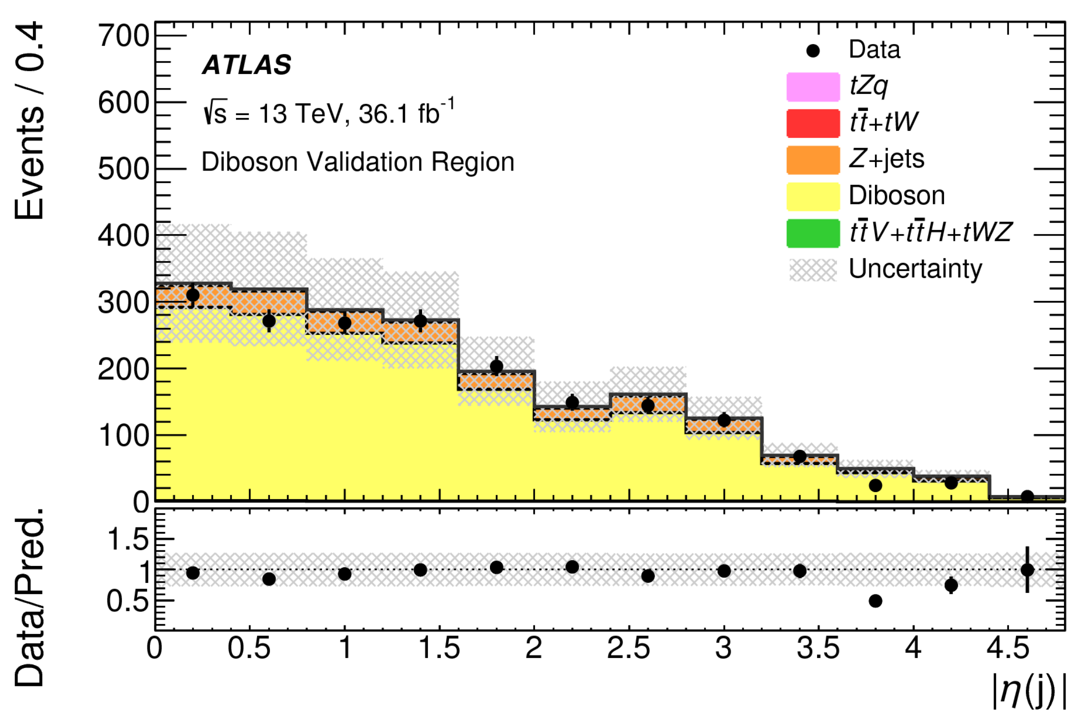
Common selections			
Exactly 3 leptons with $\|\eta\| < 2.5$ and $p_T > 15$ GeV $p_T(\ell_1) > 28$ GeV, $p_T(\ell_2) > 25$ GeV, $p_T(\ell_3) > 15$ GeV $p_T(\text{jet}) > 30$ GeV $m_T(\ell_W, \nu) > 20$ GeV			
SR	Diboson VR / CR	$t\bar{t}$ VR	$t\bar{t}$ CR
≥ 1 OSSF pair	≥ 1 OSSF pair	≥ 1 OSSF pair	≥ 1 OSDF pair
$\|m_{\ell\ell} - m_Z\| < 10$ GeV	$\|m_{\ell\ell} - m_Z\| < 10$ GeV	$\|m_{\ell\ell} - m_Z\| > 10$ GeV	No OSSF pair
2 jets, $\|\eta\| < 4.5$	1 jet, $\|\eta\| < 4.5$	2 jets, $\|\eta\| < 4.5$	2 jets, $\|\eta\| < 4.5$
1 b-jet, $\|\eta\| < 2.5$	—	1 b-jet, $\|\eta\| < 2.5$	1 b-jet, $\|\eta\| < 2.5$
—	VR/CR: $m_T(\ell_W, \nu) > 20/60$ GeV	—	—

- Control regions (CRs) to normalize background sources to data.
- Validation regions (VRs) to validate background modeling.

Background estimation - Dibosons

- Diboson (+ jets) events
  - mostly coming from WZ,
  - ZZ (where 4th lepton missed) contributing to 9% of total diboson.
- Estimated from MC
  - Sherpa (2.1.1).
- Normalisation corrected using scale factor derived in diboson VR ($m_T(W)$ > 60 GeV, to reduce Z+jets contamination).
  - Kinematic distribution shapes well described.
  - Uncertainty on scale factor from:
    - variation of the requirement on $m_T(W)$,
    - difference in SR between Sherpa and Powheg normalisations.

$SF_{diboson}$ = 1.47 ± 0.44



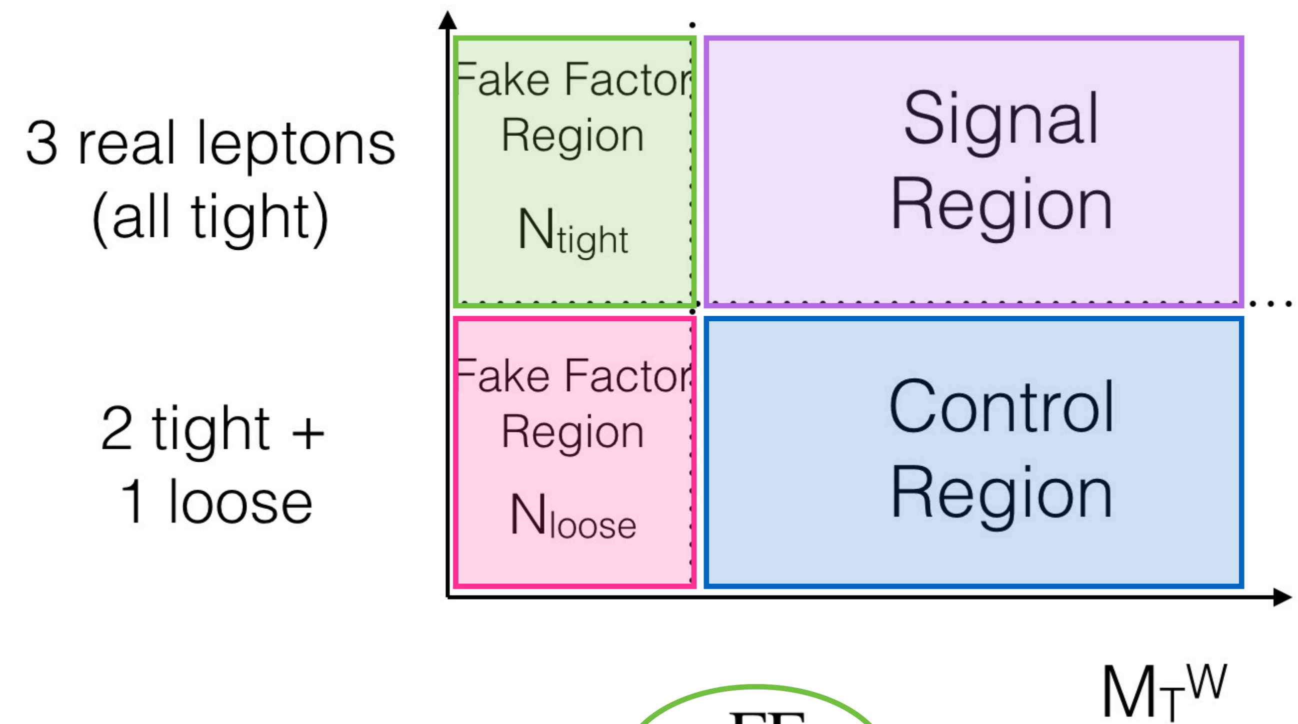
Background estimation - Z+jets fakes

- Using fake-factor method.
- Estimation done separately for electron and muon channels (as number of non-prompt or fake electrons and muons can be very different).

- Region defined by selecting events with $m_T(W) < 20$ GeV.
- Fake factors calculated as the ratio of data events that have three isolated leptons to events in which one of the leptons fails the isolation requirement.
  - Derived in bins of the $p_T(l_W)$ of the lepton not associated to the Z boson.
- Factors are then applied to events passing SR selection (including a $m_T(W) > 20$ GeV cut) that have one of the three leptons failing the isolation requirement.

- Contamination from other background sources taken into account and subtracted.

- Uncertainty: 40%.



$$F = \frac{N^{\mathrm{FF}}_{\mathrm{tight}}}{N^{\mathrm{FF}}_{\mathrm{loose}}}$$

$$F \times N^{\mathrm{CR}}_{\mathrm{loose}} = N^{\mathrm{SR}}$$

Background estimation - Others

- **$t\bar{t}V$ + $t\bar{t}H$**
  - Estimated from MC
    - MadGraph5_aMC@NLO (2.2.3) + Pythia8.
  - Normalised to NLO theoretical cross section.
  - 10% of total background.

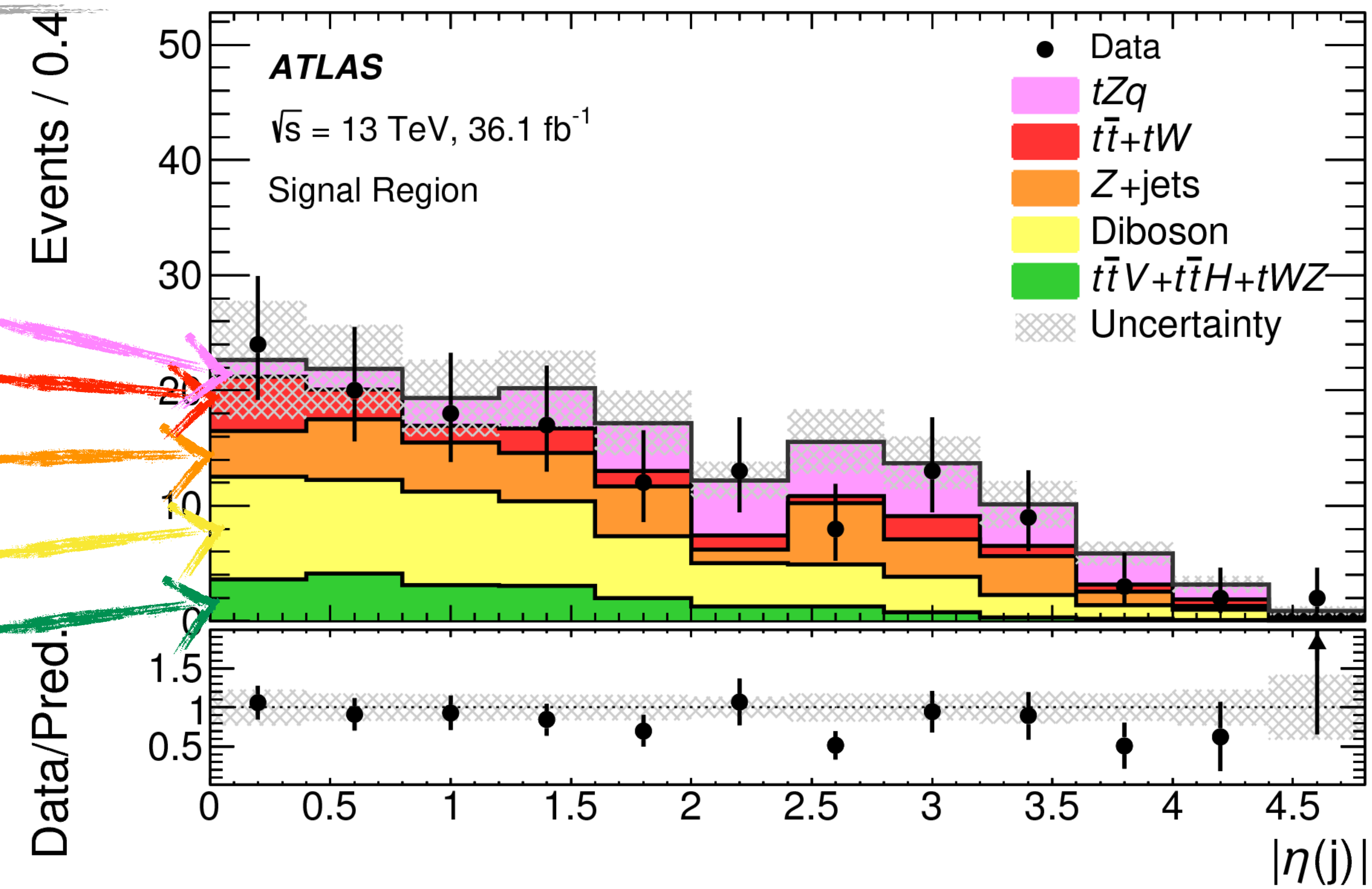
- **tWZ**
  - Estimated from MC
    - MadGraph5_aMC@NLO (2.2.3) + Pythia8.
  - Normalised to NLO theoretical cross section.
  - Contributes with 4 events.

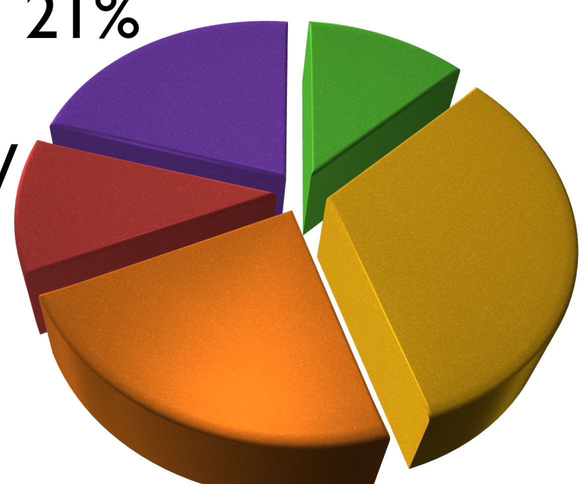
- **tW**
  - Estimated from MC
    - Powheg + Pythia6.
  - Normalisation corrected with data-driven scale factor (same as $t\bar{t}$).
  - Less than 1 event in SR.

Signal region

Channel	Number of events *
tZq	35 ± 9
$t\bar{t} + tW$	18 ± 7
$Z+$jets	37 ± 11
Diboson	53 ± 13
$t\bar{t}V + t\bar{t}H + tWZ$	20 ± 3
Total	163 ± 12

*from Asimov dataset





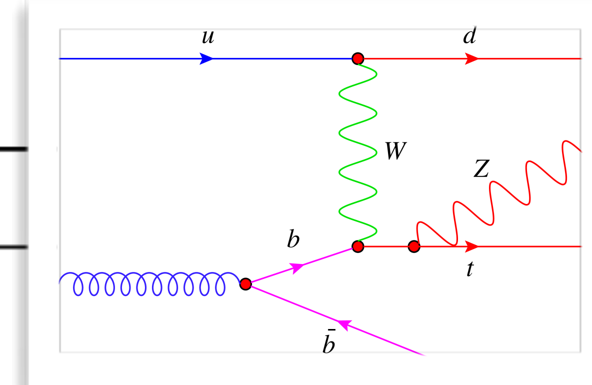
- tZq 3-lepton
  - BR = 2.2%
  - Selection eff = 5%

Multivariate analysis

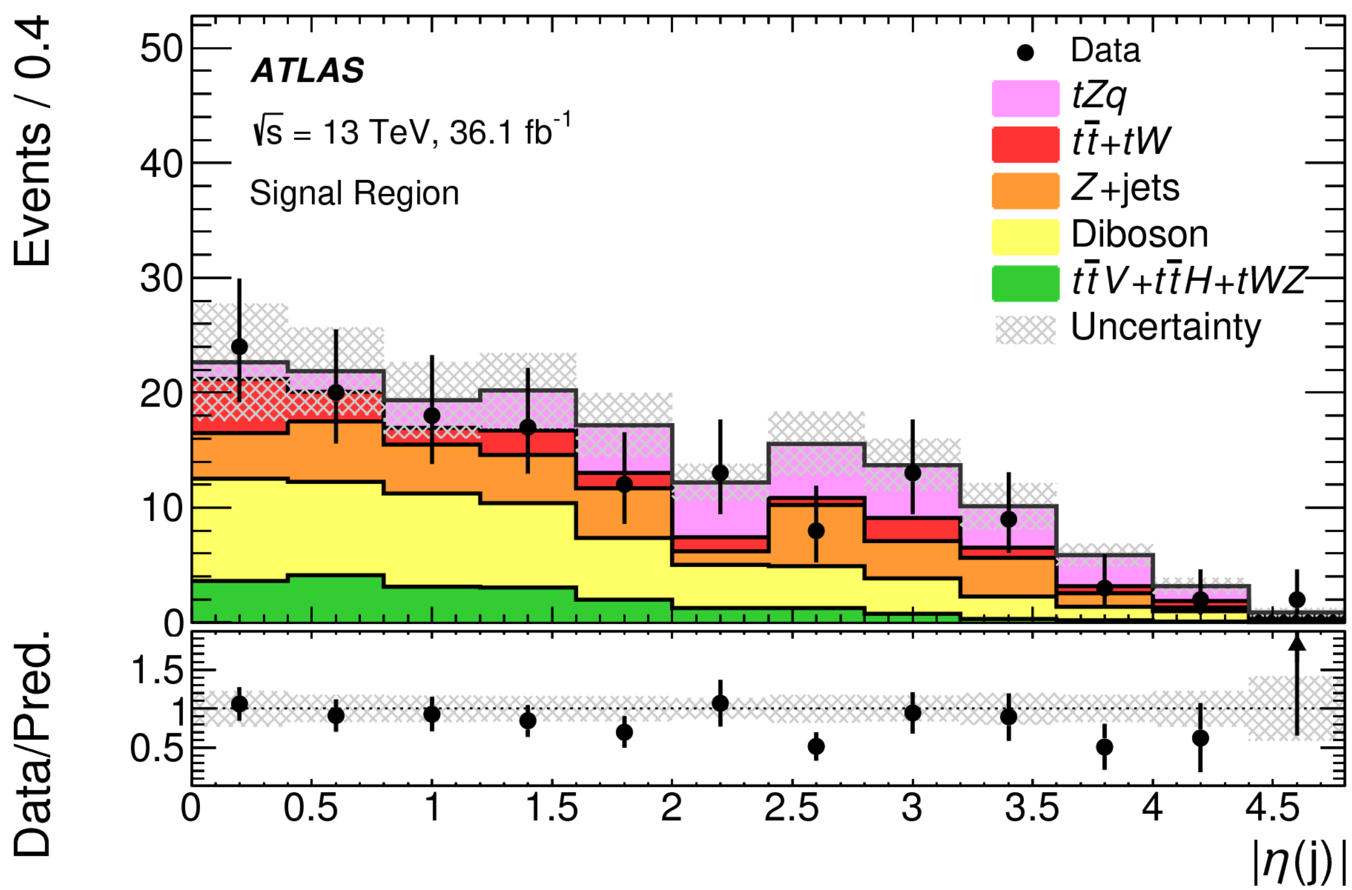
- Need better separation between signal and background.
  - Use multivariate analysis.
- NeuroBayes package used for training a neural network.
- Signal trained against all backgrounds (except $t\bar{t}$ because of low statistics).
- 10 variables kept for training.

- Several checks performed to make sure the procedure is sound.
- Checking:
  - NN stability
  - input variables and NN output in VRs
  - input variables and NN output in SR with $O_{NN} < 0.5$
  - (after unblinding) input variables and NN output in SR with $O_{NN} > 0.5$
  - (after unblinding) input variables and NN output in SR.

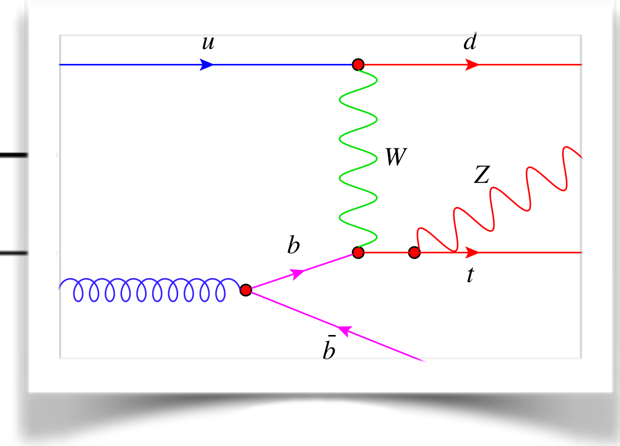
NN input variables



Variable	Definition
$\|\eta(\mathrm{j})\|$	Absolute value of untagged jet η
$p_{\mathrm{T}}(\mathrm{j})$	Untagged jet p_{T}
m_t	Reconstructed top-quark mass
$p_{\mathrm{T}}(\ell^W)$	p_{T} of the lepton from the W-boson decay
$\Delta R(\mathrm{j}, Z)$	ΔR between the untagged jet and the Z boson
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	Transverse mass of W boson
$p_{\mathrm{T}}(t)$	Reconstructed top-quark p_{T}
$p_{\mathrm{T}}(b)$	Tagged jet p_{T}
$p_{\mathrm{T}}(Z)$	p_{T} of the reconstructed Z boson
$\|\eta(\ell^W)\|$	Absolute value of η of the lepton coming from the W-boson decay



NN input variables



Variable	Definition
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$\Delta R(\mathrm{j}, Z)$	ΔR between the untagged jet and the Z boson
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	Transverse mass of W boson
$p_{\mathrm{T}}(t)$	Reconstructed top-quark p_{T}
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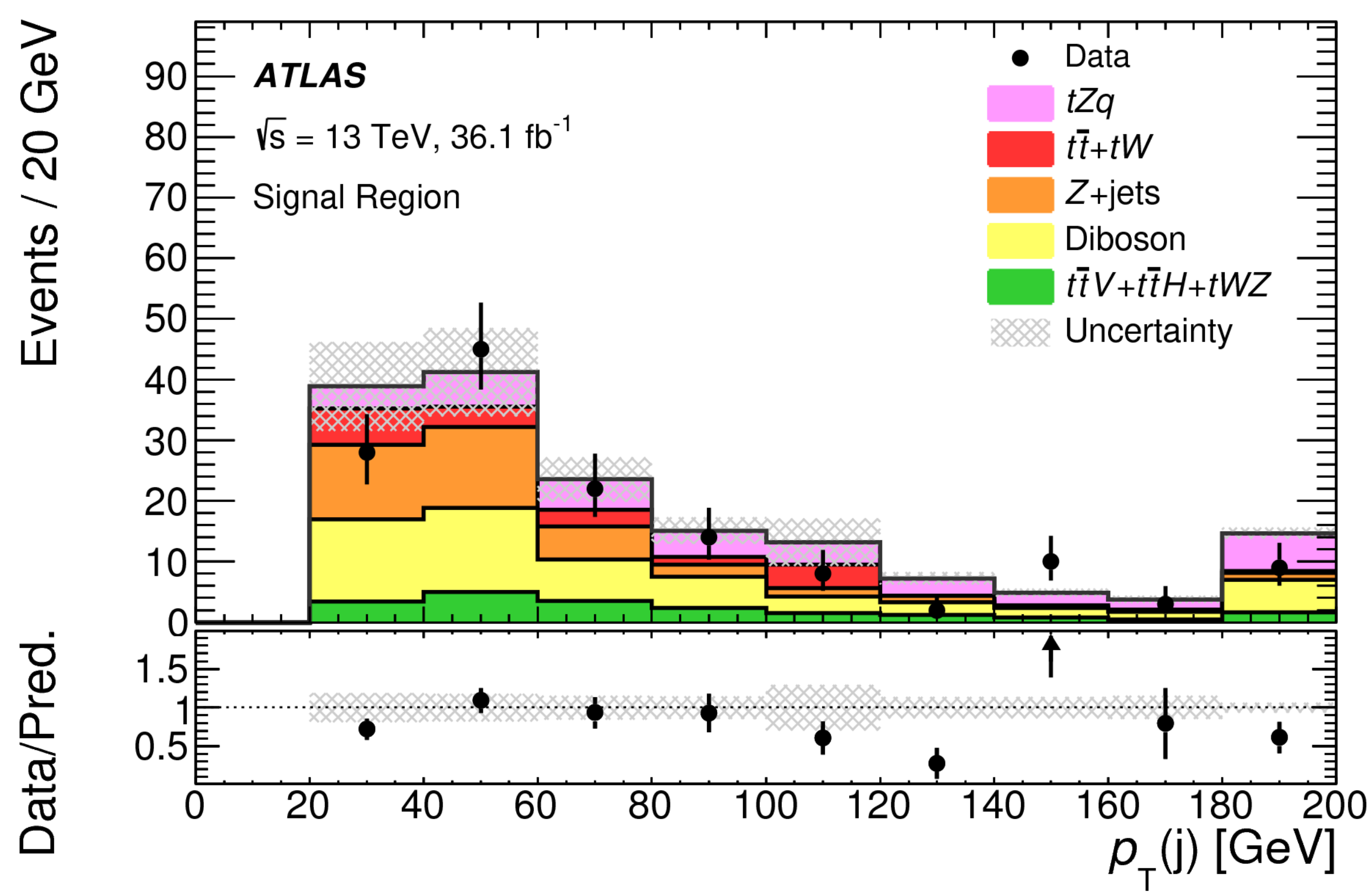
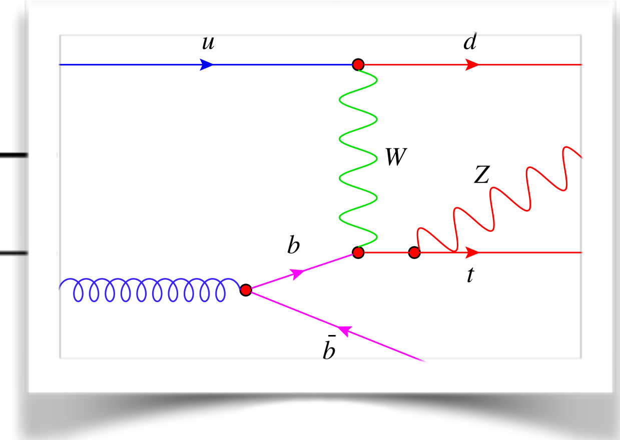


NN input variables



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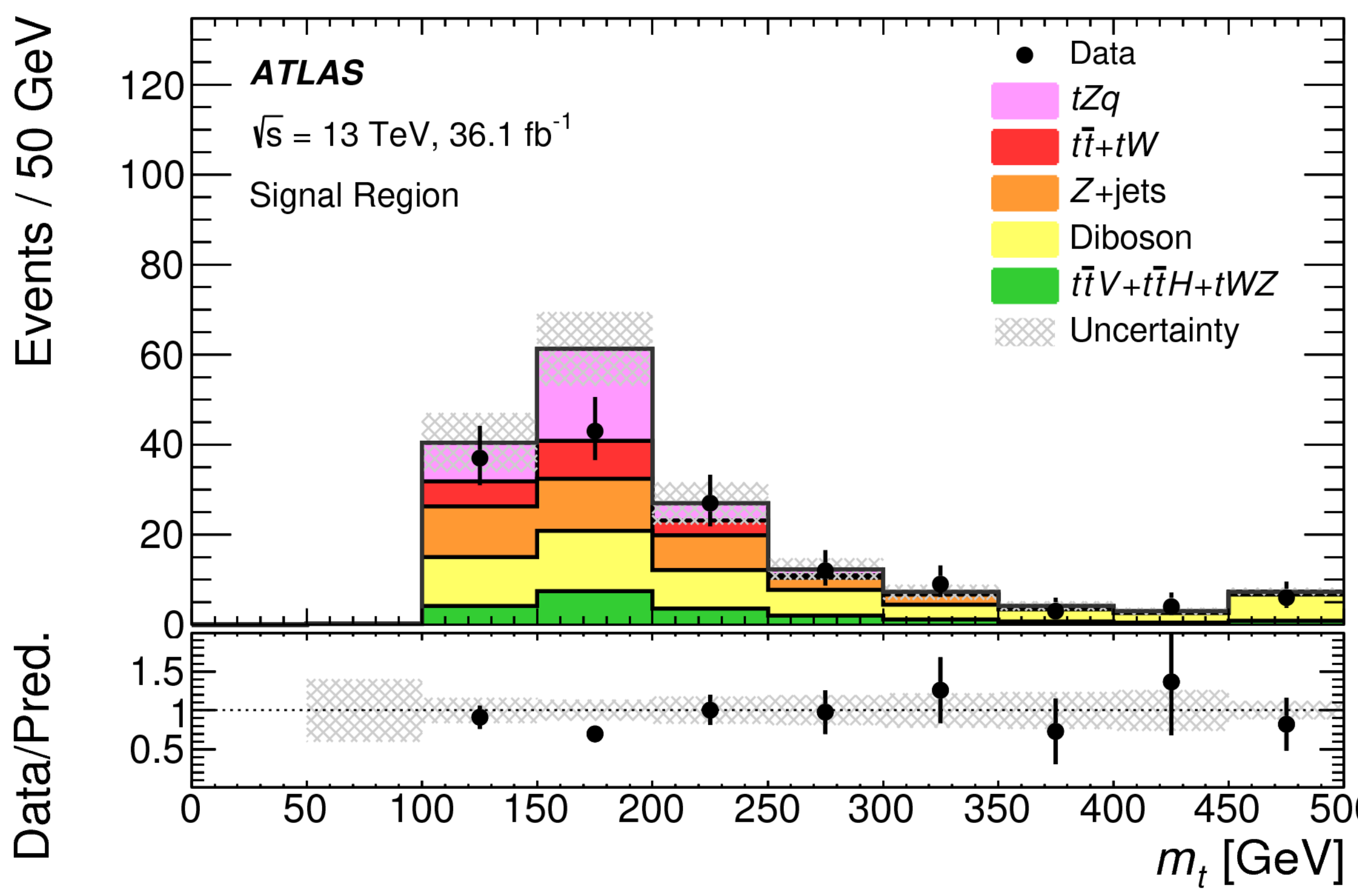

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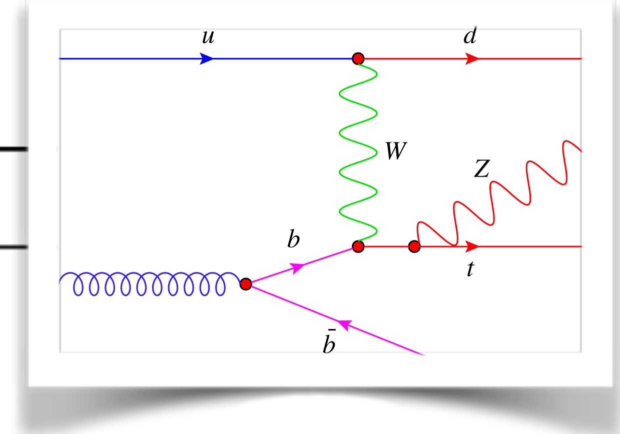

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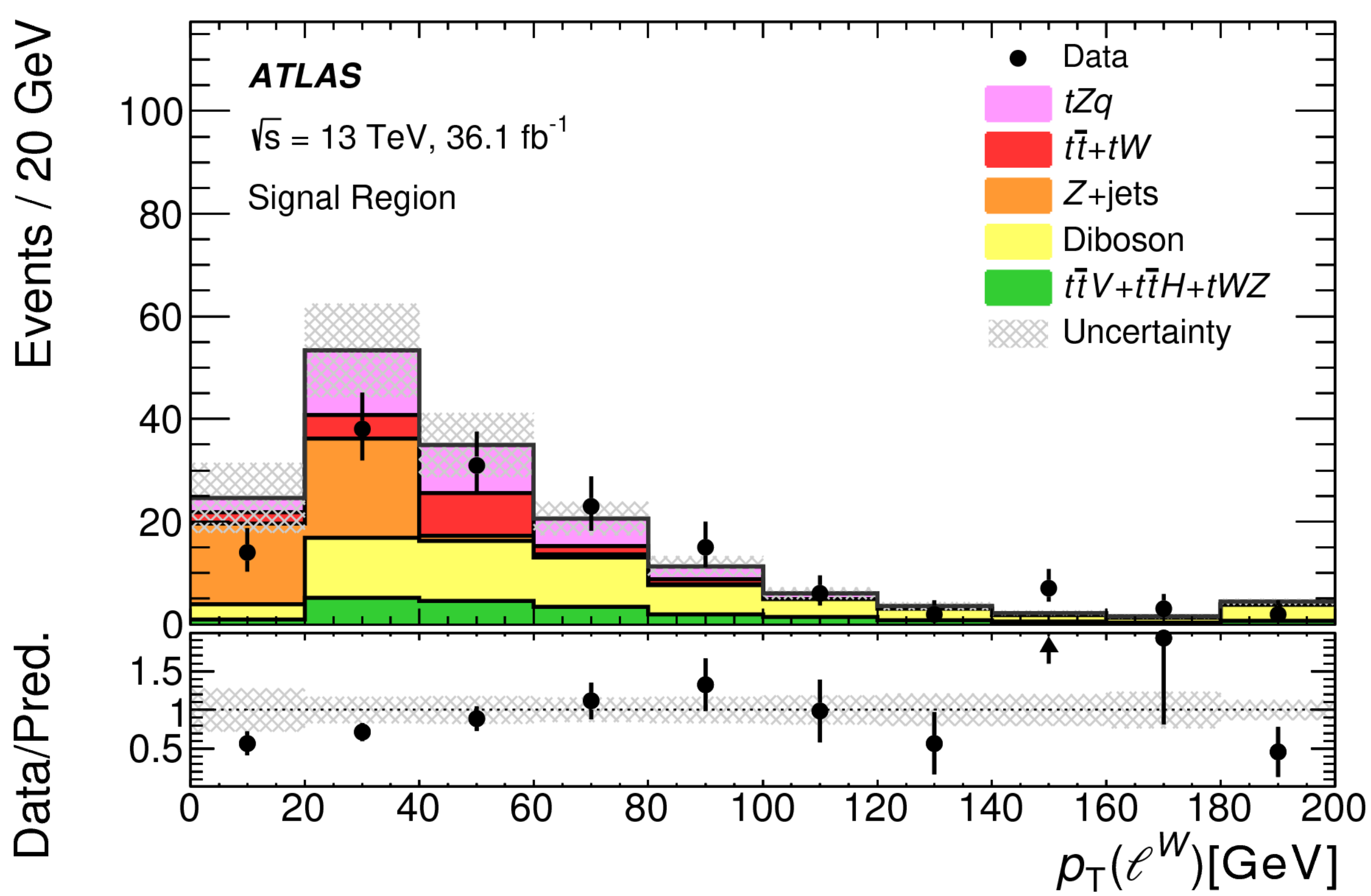
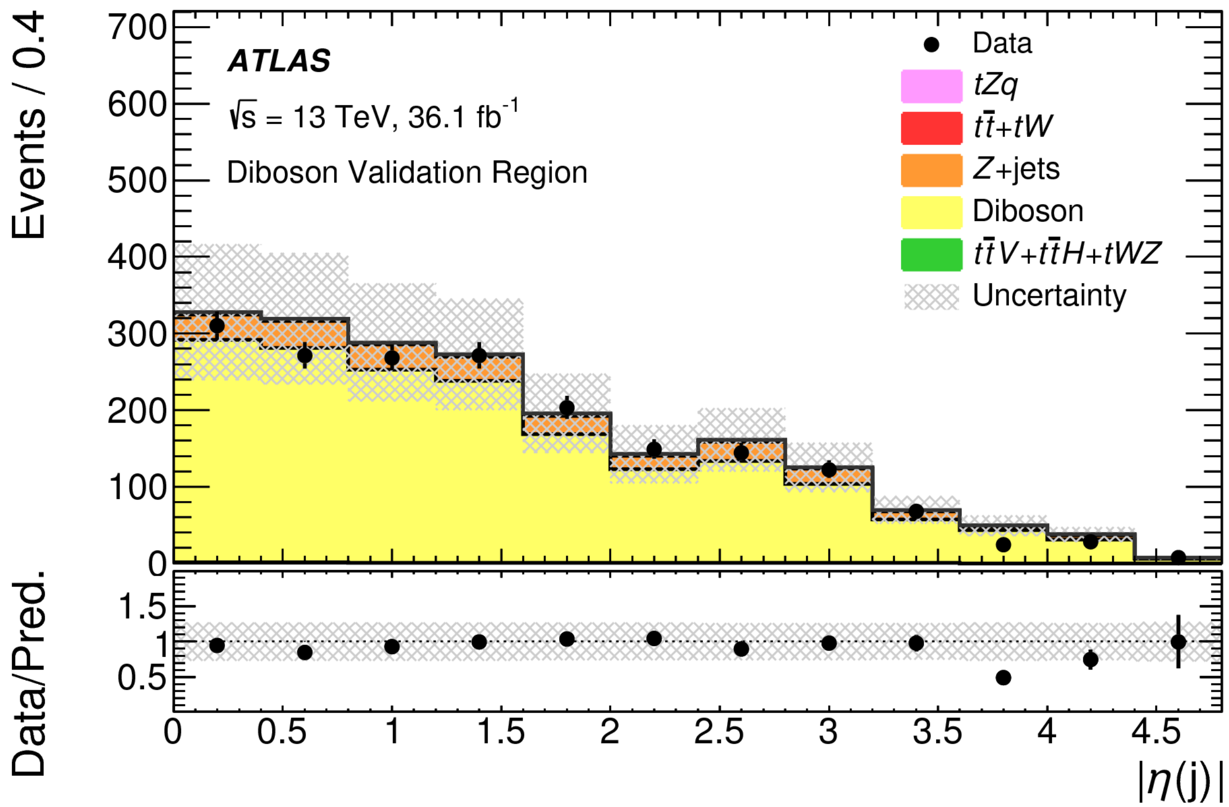
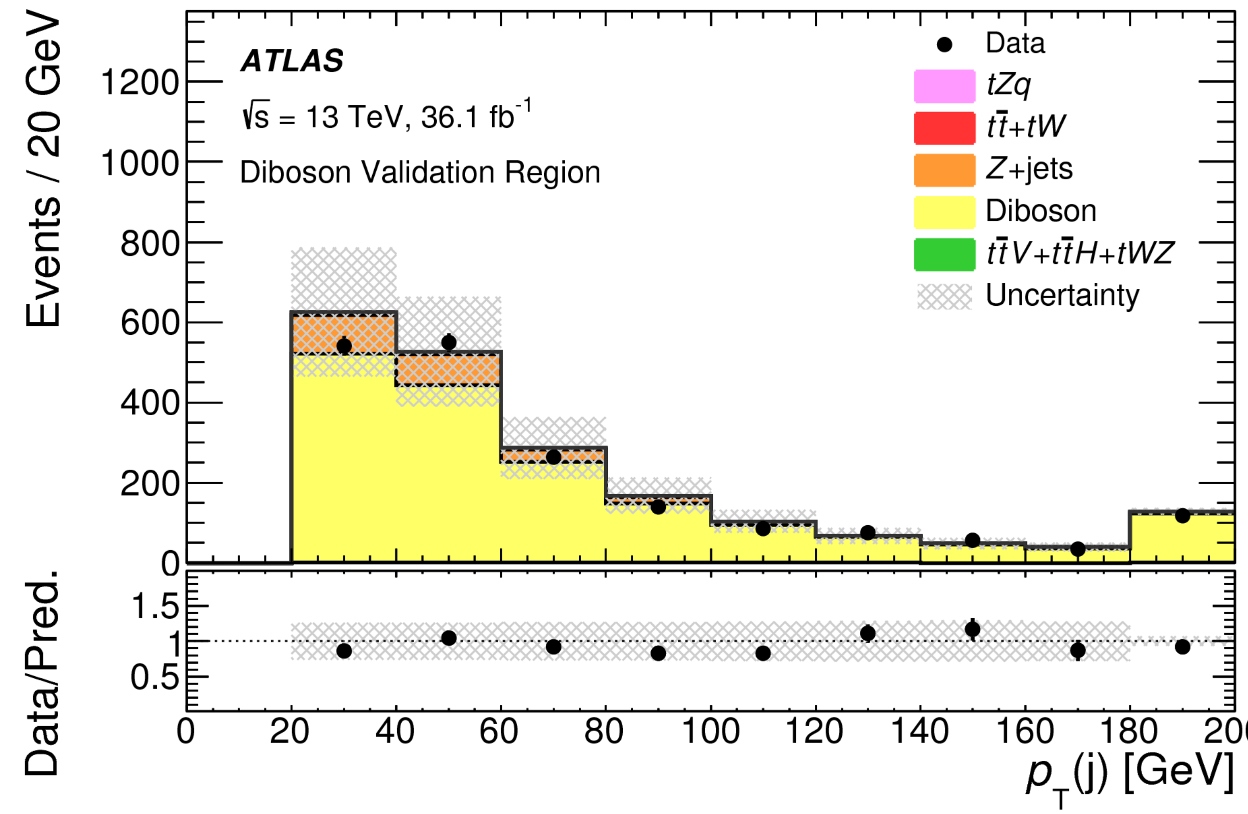
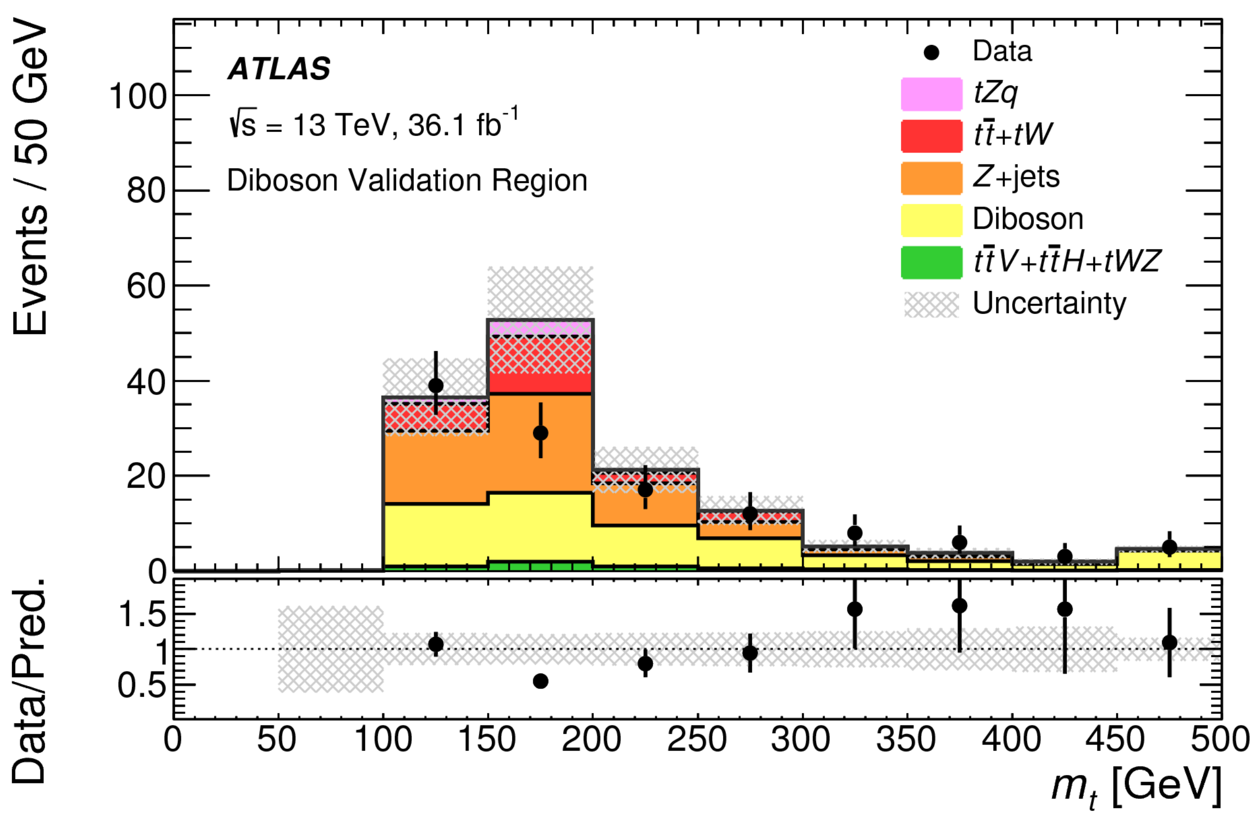
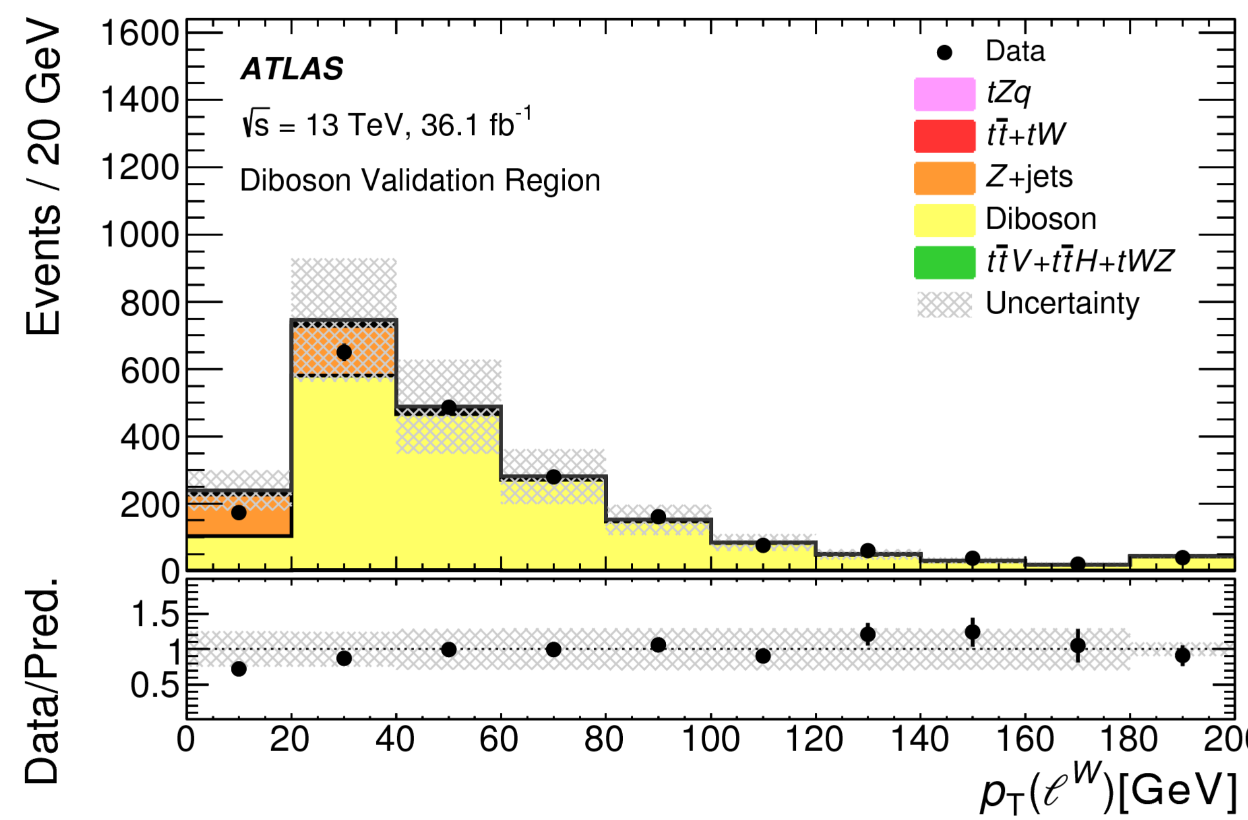


NN input variables - Diboson VR

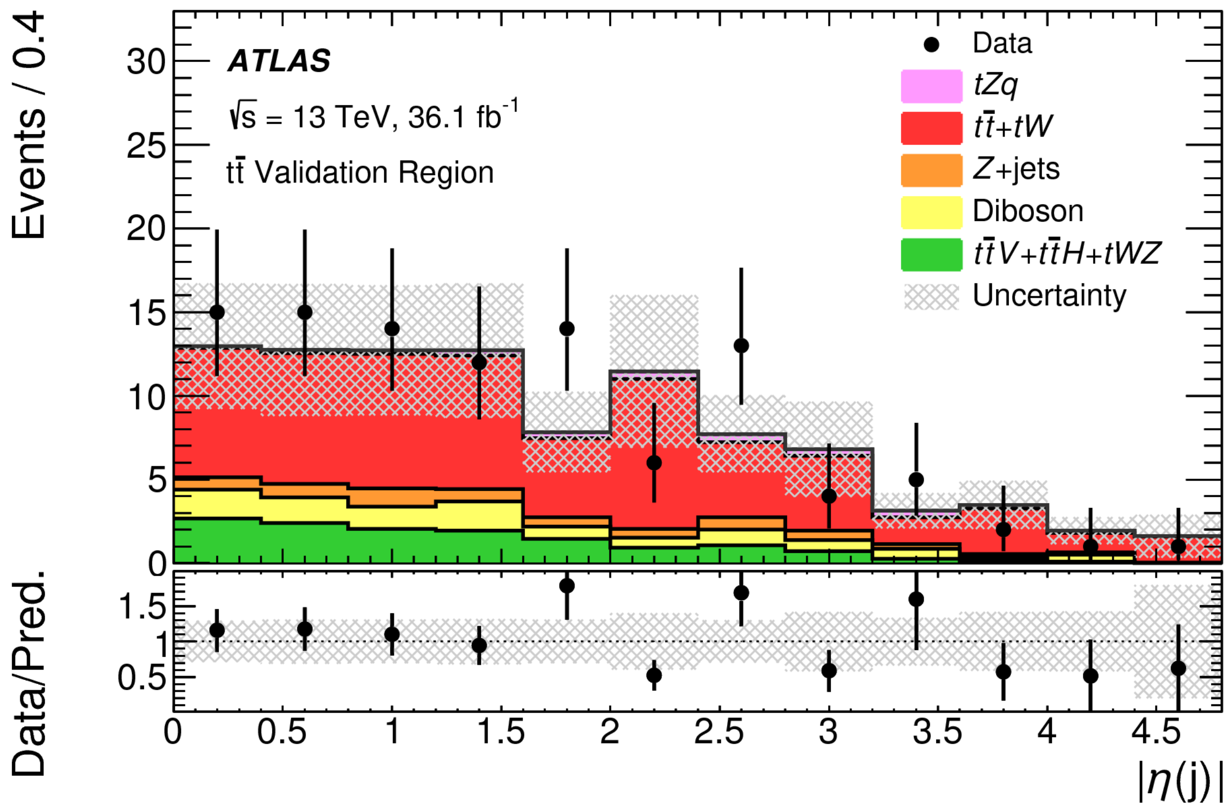


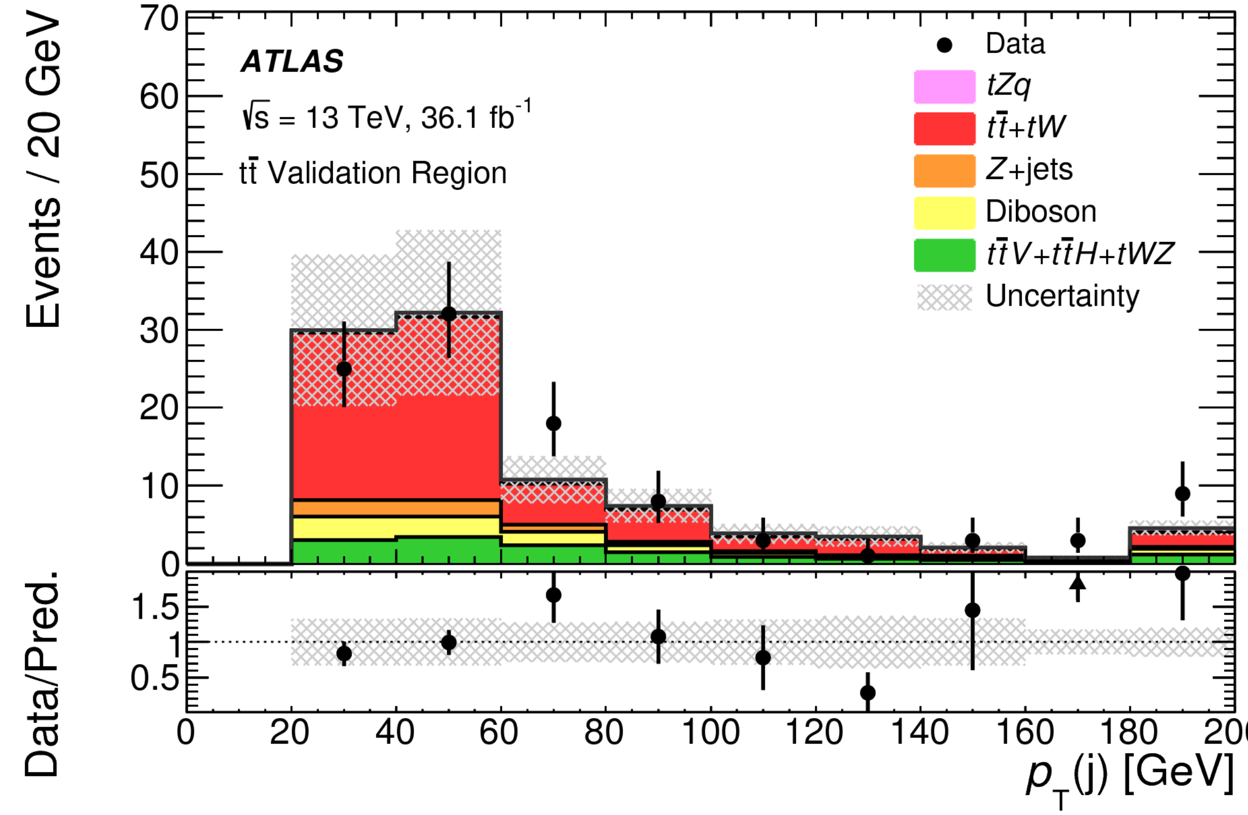


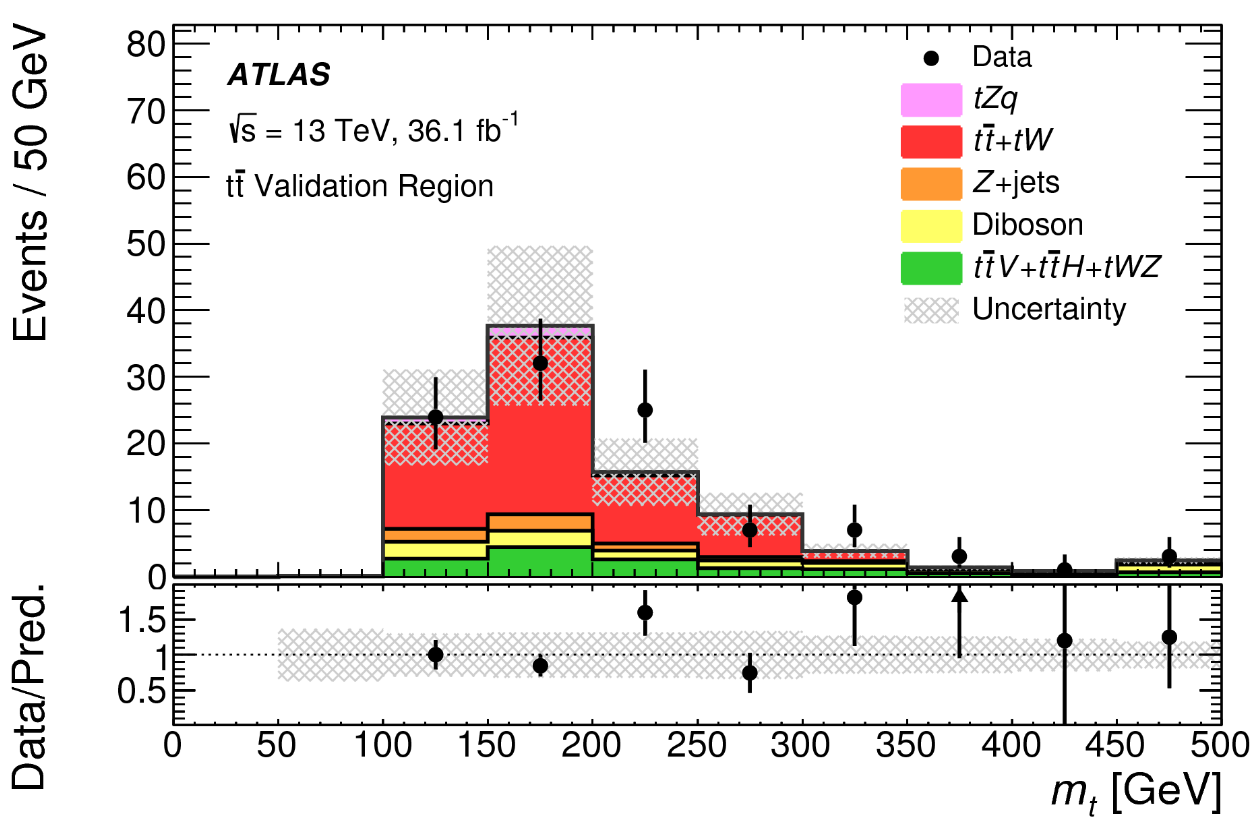


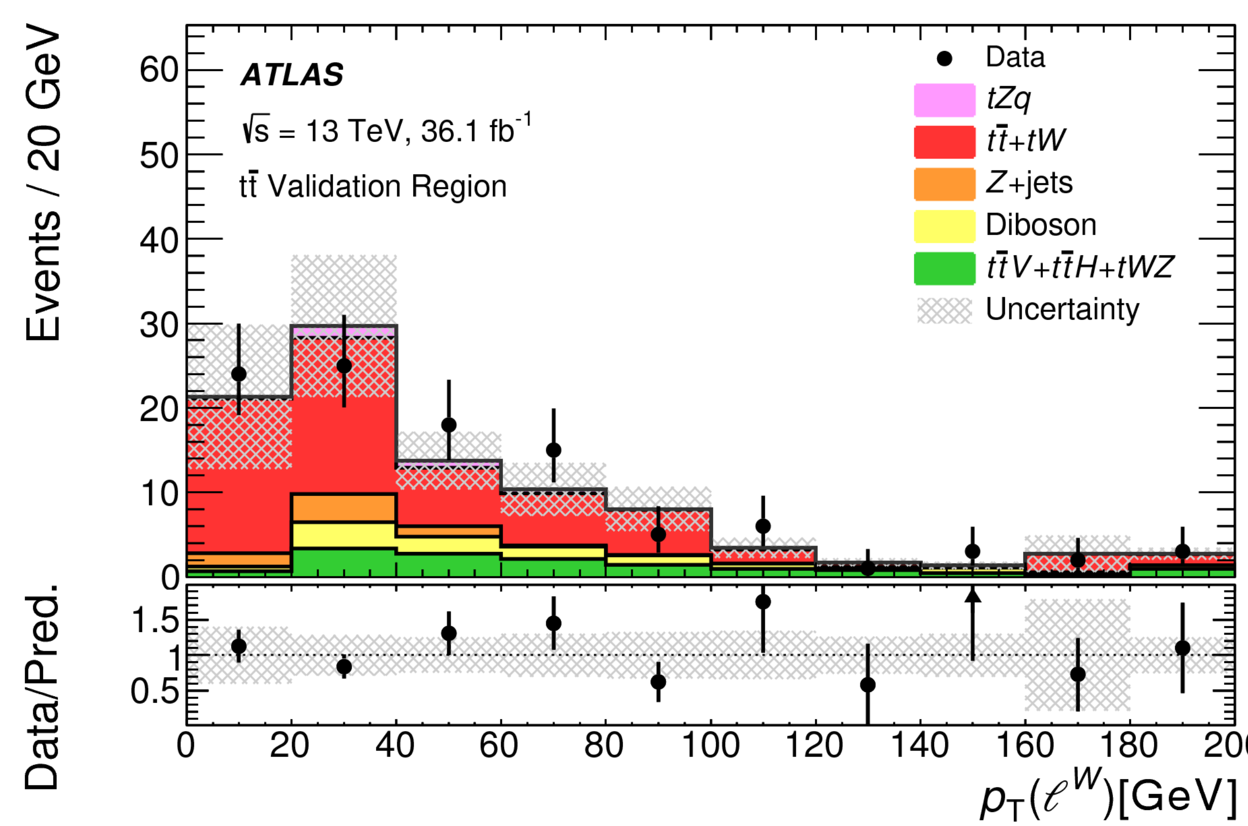


NN input variables - $t\bar{t}$VR

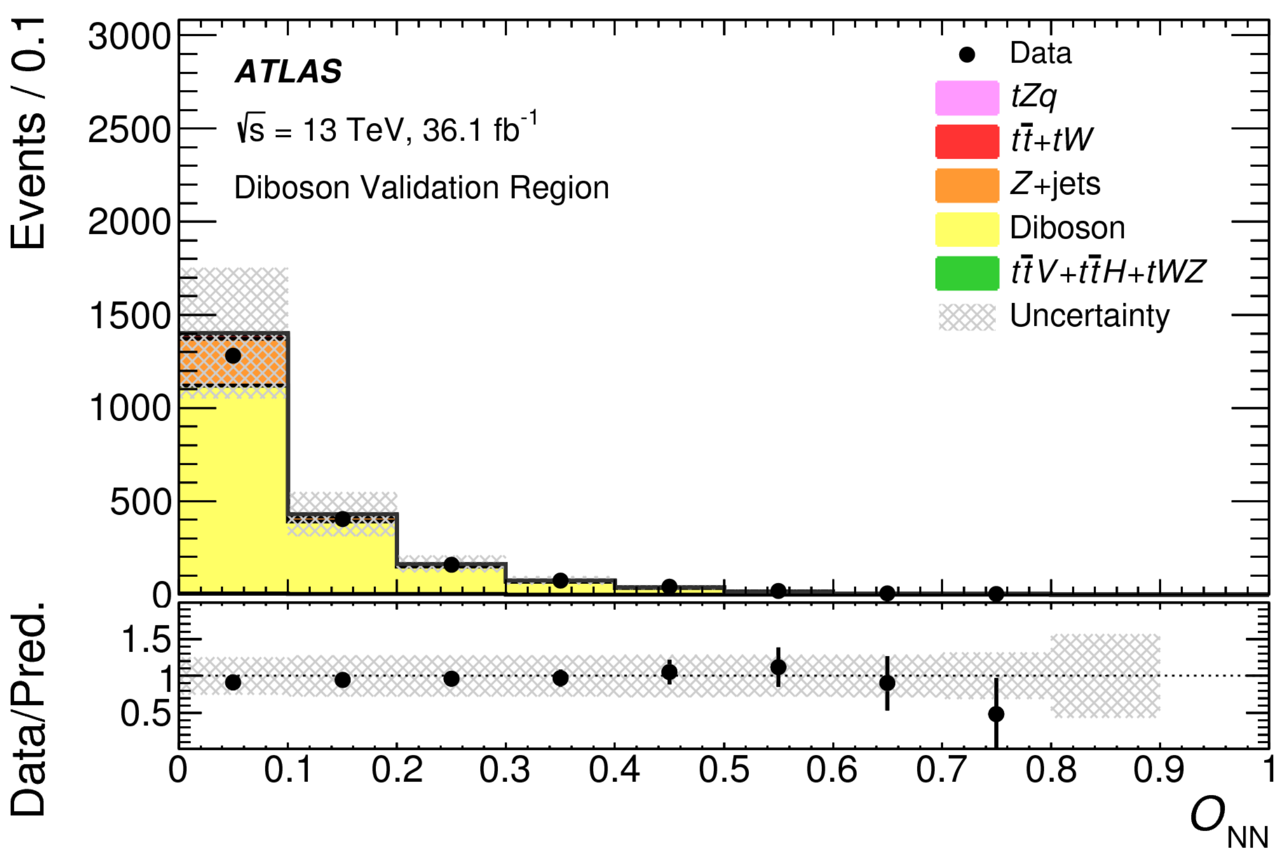


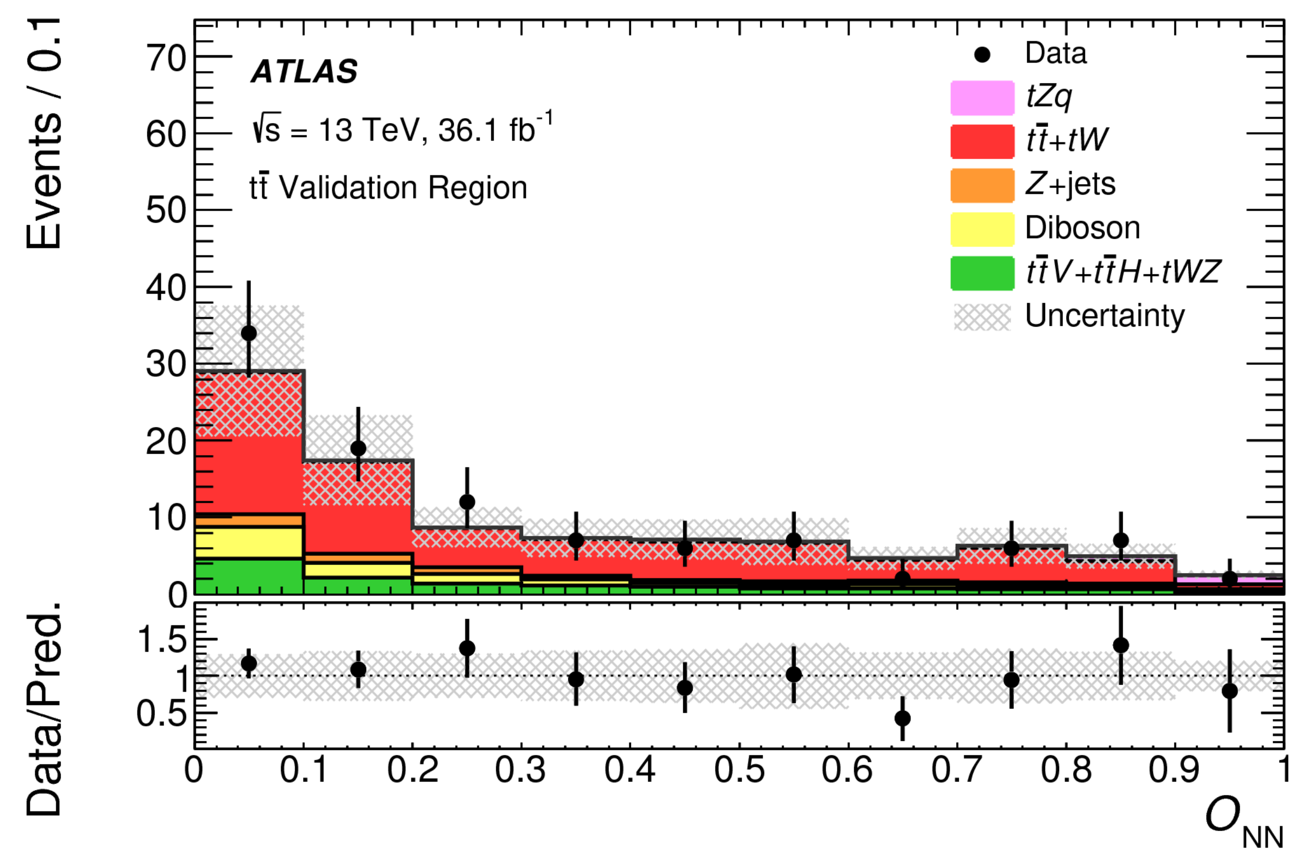






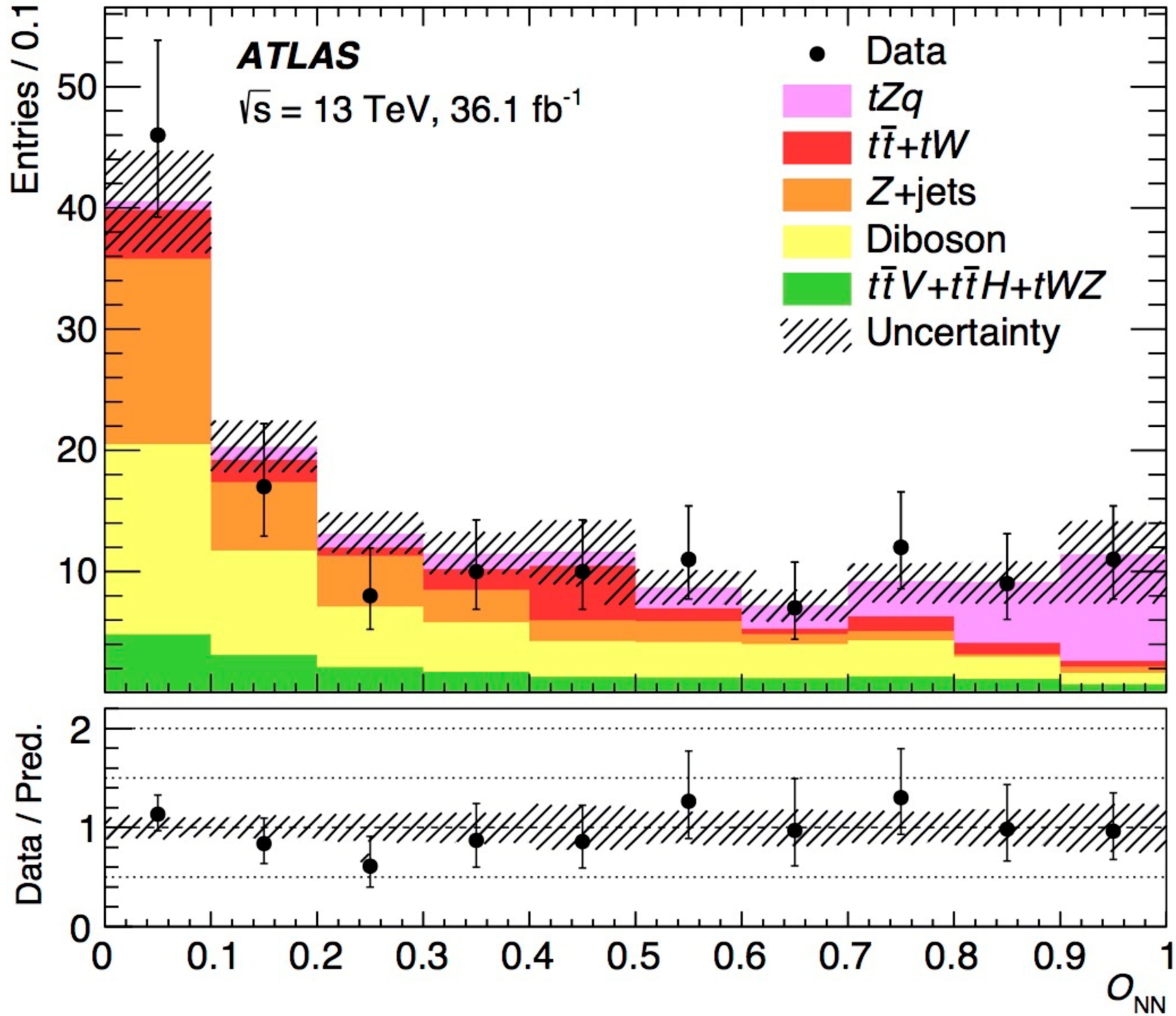
NN output in VRs



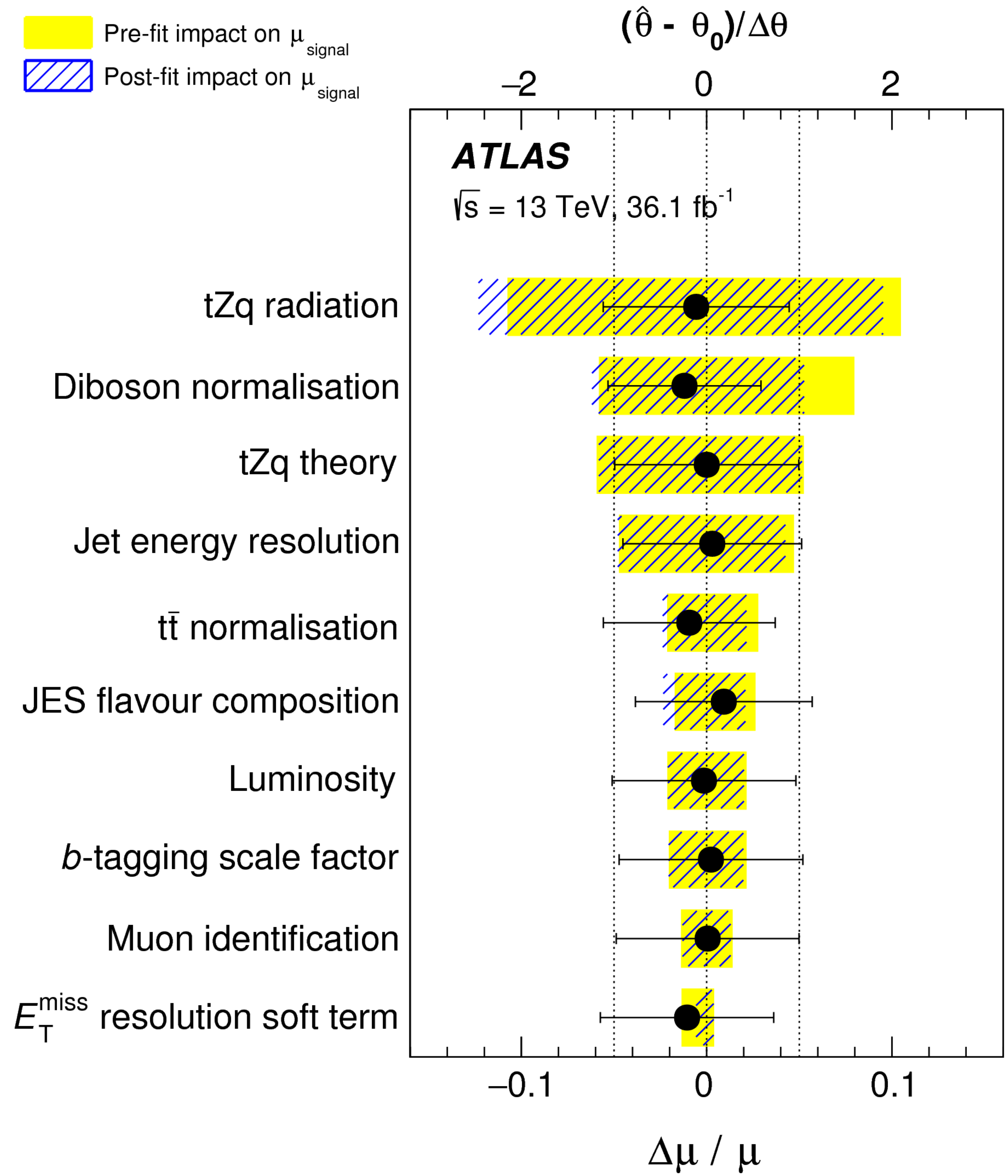


- Very nice confirmation of good modeling of backgrounds, including scale factors, NN input variables, NN output distribution.

NN output


ATLAS
√s = 13 TeV, 36.1 fb-1
Data
tZq
tt̄+tW
Z+jets
Diboson
tt̄V+tt̄H+tWZ
Uncertainty
Entries / 0.1
Data / Pred.
O_NN

Systematic uncertainties



- Object reconstruction and calibration uncertainties
- Signal PDF and radiation
- Background normalizations.
- Luminosity
- 3.2 % for 2015 and 2016 datasets.

Results

- Maximum-likelihood fit performed O_{NN}.
- Extract μ, ratio of the measured signal yield to the NLO SM expectation:

  0.75 ± 0.28 (stat. + syst.) ± 0.07 (th.)

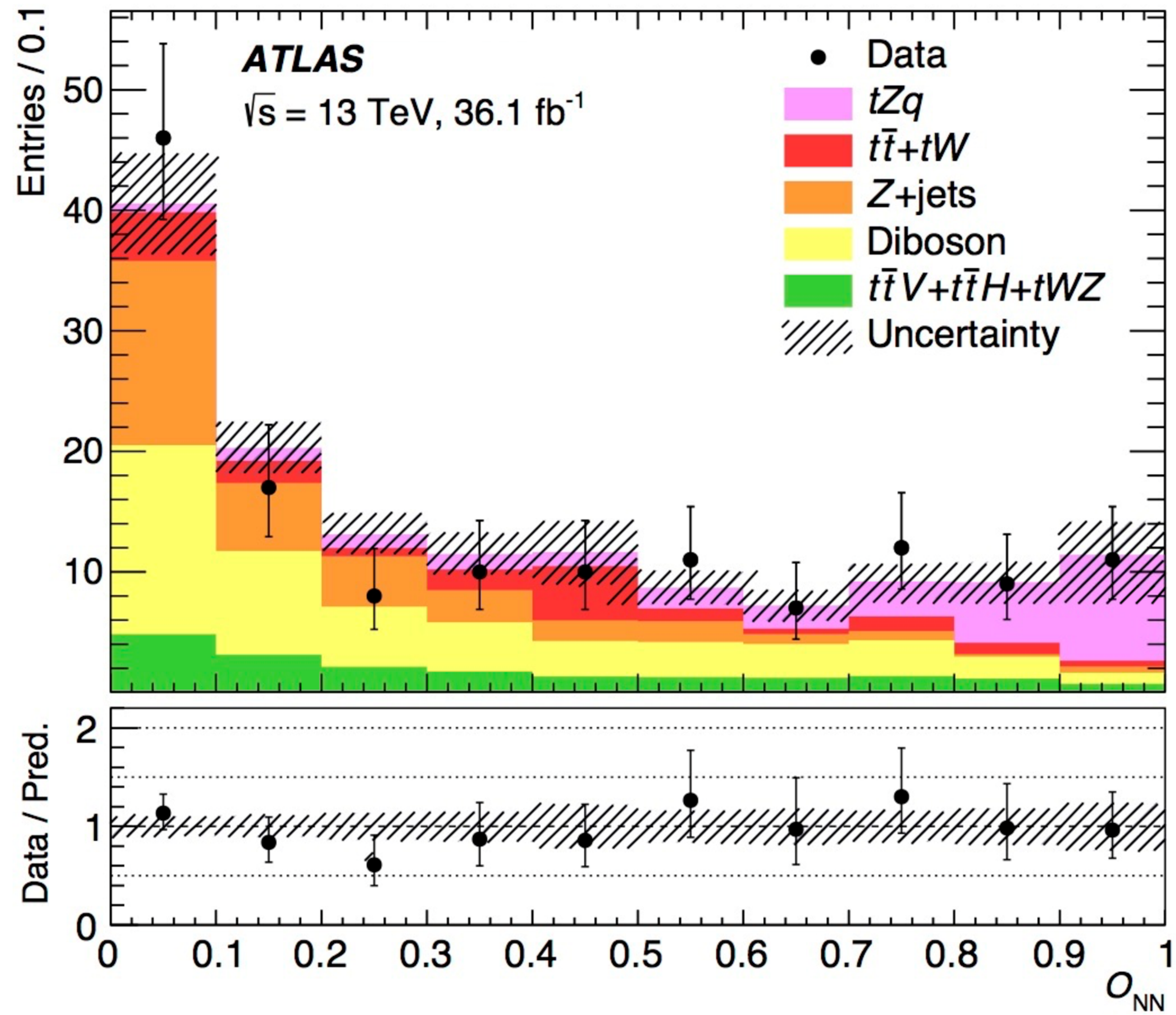
- Observed (expected) significance of extracted signal:

  4.2σ (5.4σ)

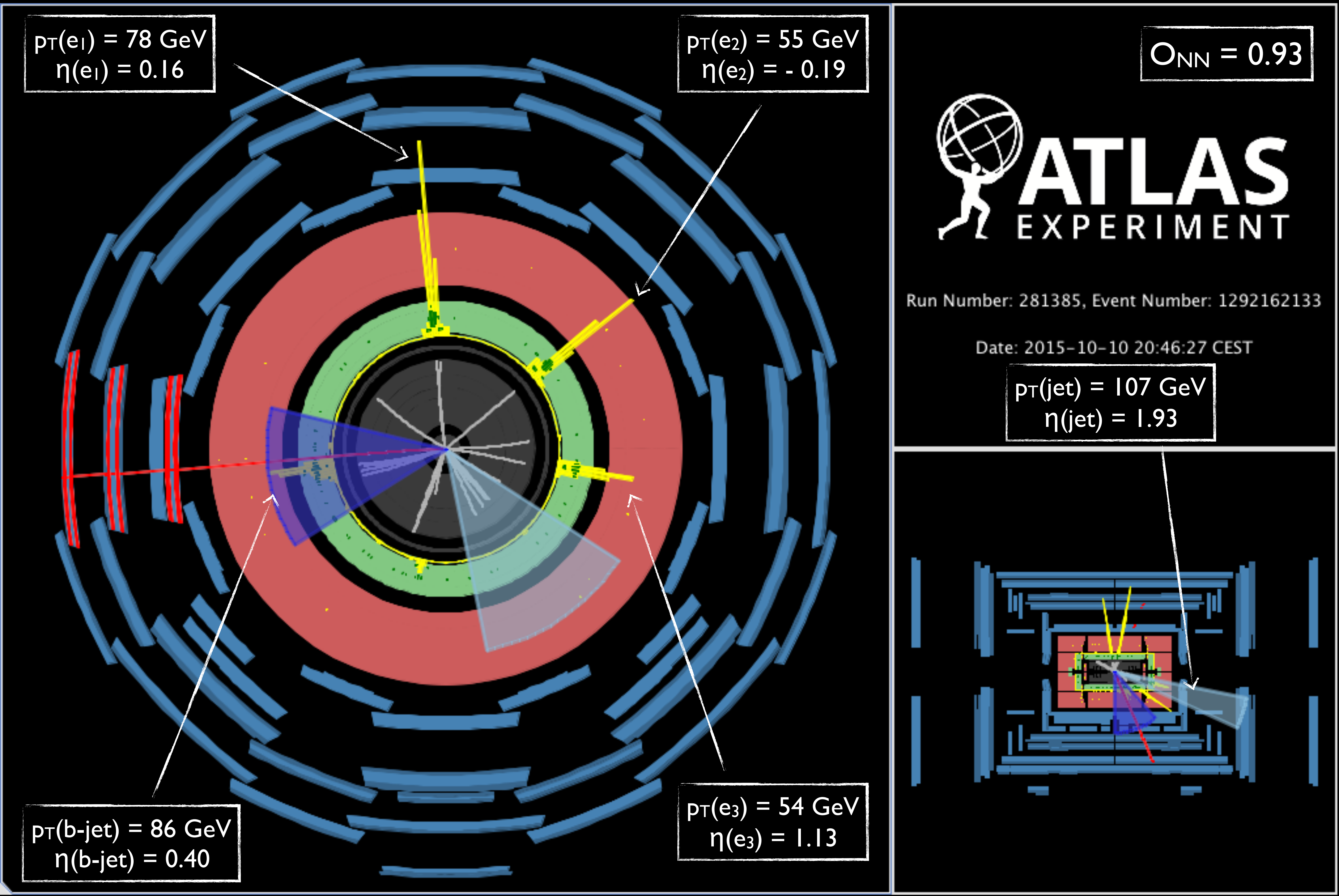
- From μ, obtain cross-section:

  600 ± 170 (stat.) ± 140 (syst.) fb

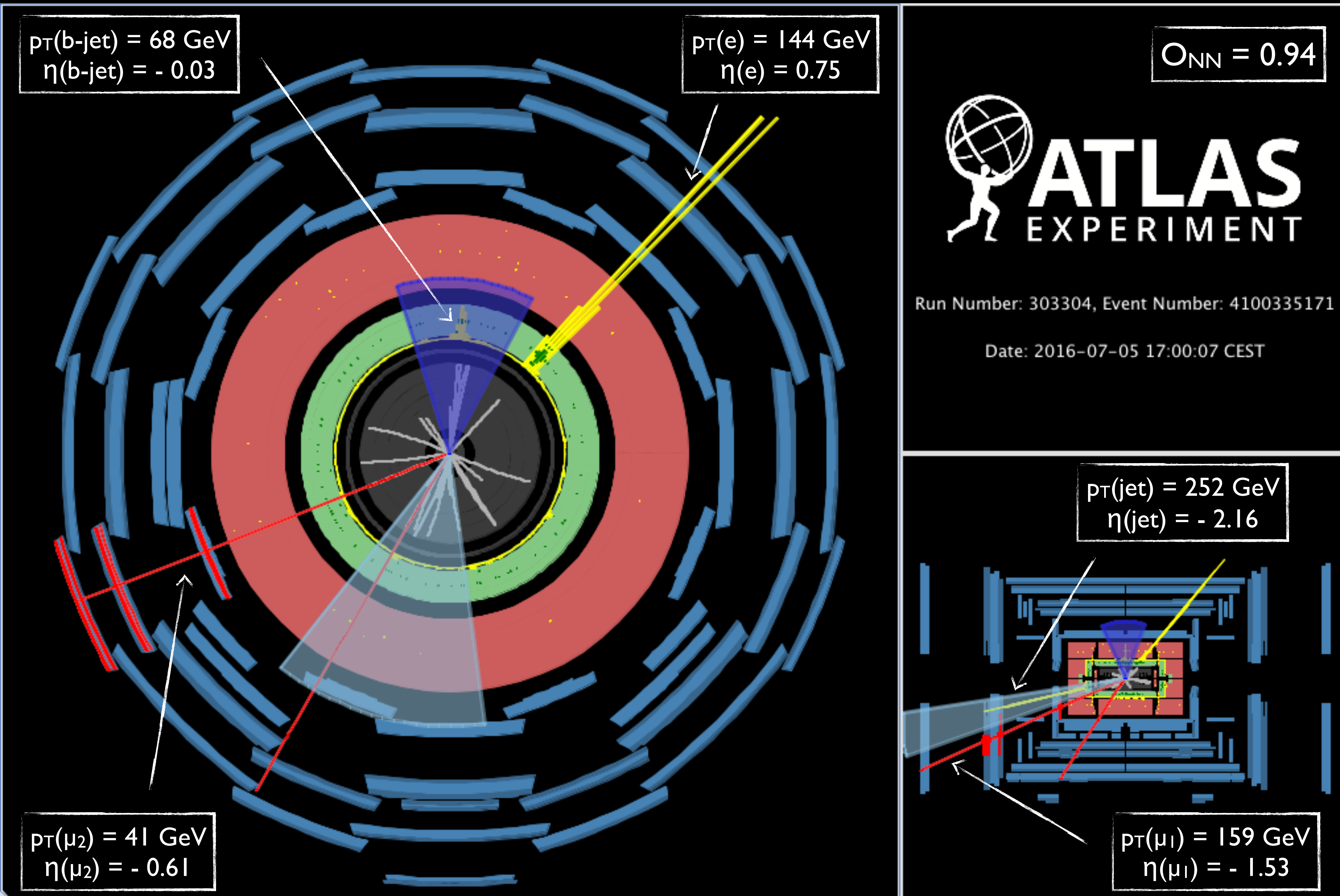
- to be compared to the NLO prediction of 800 fb.



Clear evidence of single top production in association with a Z boson in the t-channel.



pT(e1) = 78 GeV
η(e1) = 0.16
pT(e2) = 55 GeV
η(e2) = - 0.19
ONN = 0.93
ATLAS
EXPERIMENT
Run Number: 281385, Event Number: 1292162133
Date: 2015-10-10 20:46:27 CEST
pT(jet) = 107 GeV
η(jet) = 1.93
pT(b-jet) = 86 GeV
η(b-jet) = 0.40
pT(e3) = 54 GeV
η(e3) = 1.13



pT(b-jet) = 68 GeV
η(b-jet) = - 0.03
pT(e) = 144 GeV
η(e) = 0.75
ONN = 0.94
ATLAS
EXPERIMENT
Run Number: 303304, Event Number: 4100335171
Date: 2016-07-05 17:00:07 CEST
pT(jet) = 252 GeV
η(jet) = - 2.16
pT(μ2) = 41 GeV
η(μ2) = - 0.61
pT(μ1) = 159 GeV
η(μ1) = - 1.53

Outline

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  - The top quark
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  - Event selection
  - Background estimation
  - Multivariate analysis
  - Results
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CMS
LHCb
ALICE
ATLAS


CMS
LHCb
ALICE
ATLAS


CMS
LHCb
ALICE
ATLAS

ATLAS & CMS

ATLAS

- TOPQ-2016-14 (submitted to PLB)
- 36.1 fb^{-1}
- Significance obs(exp): 4.2 (5.4)σ
- $\mu = 0.75 \pm 0.21\ (\text{stat.}) \pm 0.17\ (\text{syst.}) \pm 0.05\ (\text{th.})$
- $\sigma(tZq) = 600 \pm 170\ (\text{stat.}) \pm 140\ (\text{syst.})$ fb

CMS

- CMS-PAS-TOP-16-020
- 35.9 fb^{-1}
- Significance obs(exp): 3.7 (3.1)σ
- $\mu = 1.31\ {}^{+0.35}_{-0.33}\ (\text{stat.})\ {}^{+0.31}_{-0.25}\ (\text{syst.})$
- $\sigma(tllq) = 123\ {}^{+33}_{-31}\ (\text{stat.})\ {}^{+29}_{-23}\ (\text{syst.})$

- Where does the difference between the cross sections come from?
- Is there any significant difference in the analysis strategy?

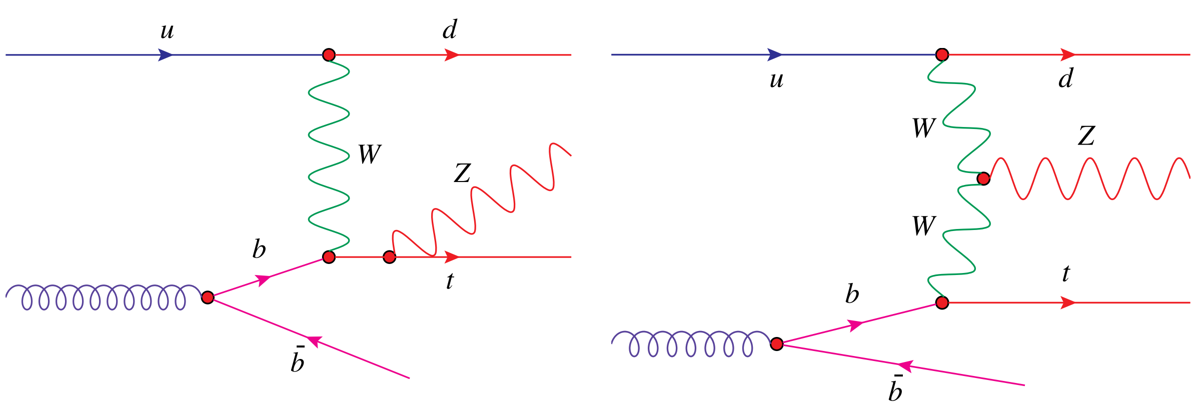
Signal samples & theory cross section

- Signal MC: LO rescaled to NLO.

- Theory cross section:
  - Z boson is forced to be on shell,
  - no cuts are applied,
  - 4-flavour scheme.

  - $\sigma_{NLO}(tZq)$ = 800 fb
    - ±6/7% scale

ATLAS

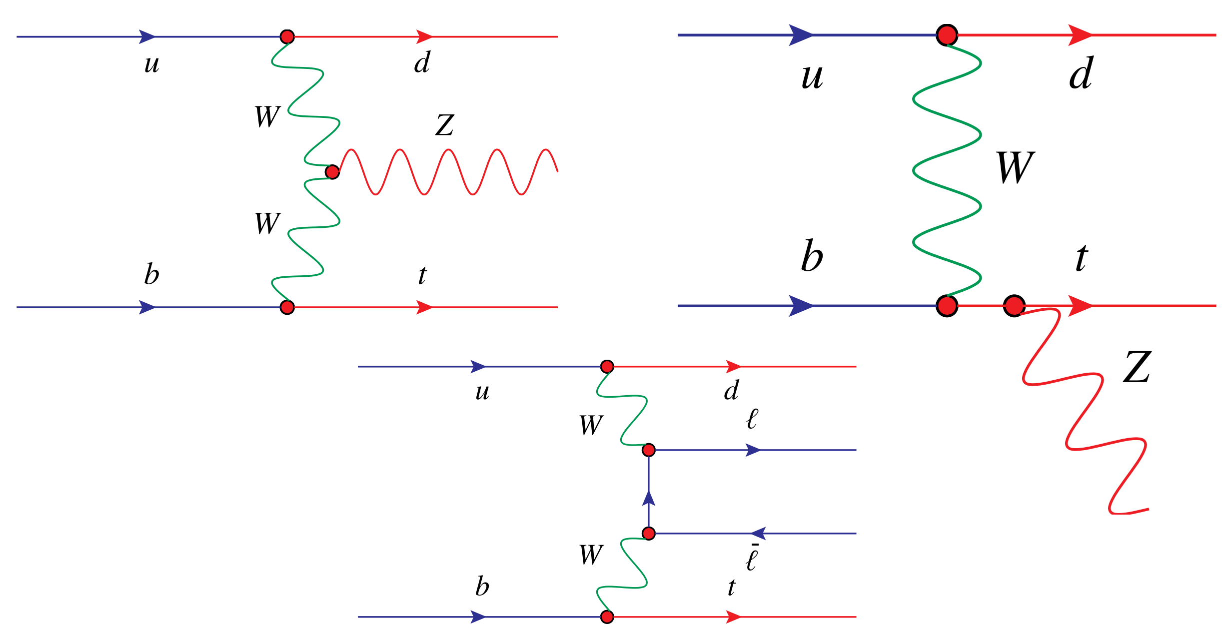


- Signal MC: NLO.

- Theory cross section:
  - Z boson can be off shell/γ* is also included,
  - m_{ll} > 30 GeV,
  - 5-flavour scheme (4FS for MC generation).

CMS

  - $\sigma_{NLO}(tllq)$ = 94 fb
    - ±2% scale
    - ±2.5% PDF



- Tau leptonic decays included.
- Different scale choice between ATLAS and CMS.

- Theory paper https://arxiv.org/abs/1302.3856
  - $\sigma_{NLO}(tZq)$ ~ 820 fb.

Event selection

ATLAS

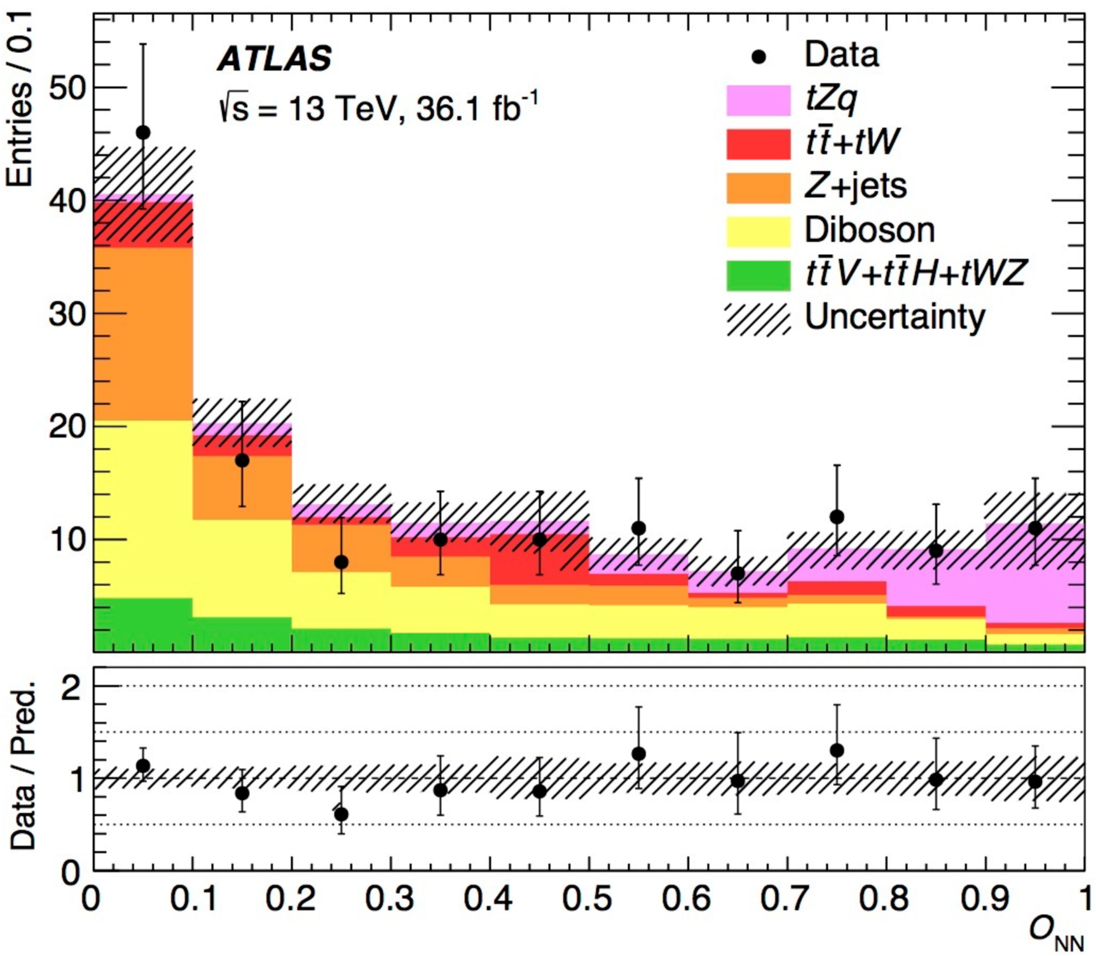
- Trigger
  - **single lepton triggers**
- Leptons
  - exactly three
  - **p_T(lep) > 28/25/15 GeV**
  - ≥ 1 OSSF pair
  - **$|m_{ll} - m_Z| < 10$ GeV**
- Jets
  - **exactly two**
  - p_T(jet) > 30 GeV
  - **1 b-tagged (77% WP, 1% mistag)**
- **$m_T(W) > 20$ GeV**

CMS

- Trigger
  - **OR of 1/2/3 lepton triggers**
- Leptons
  - exactly three
  - **p_T(lep) > 25 GeV**
  - ≥ 1 OSSF pair
  - **$|m_{ll} - m_Z| < 15$ GeV**
- Jets
  - **two or three**
  - p_T(jet) > 30 GeV
  - **1 b-tagged (83% WP, 10% mistag)**

- TRIGGER & LEPTON p_T
  - Keeping the 3rd lepton p_T lower increases the Z+jet contamination, giving a better handle on this bkg when training the NN.
- n_{jets}
  - Connected with LO vs NLO signal MC (LO does not take into account large fraction of signal in the 3 jets bin)
  - Having 3 jets might create ambiguity in defining the forward jet.
- b-tagging WP

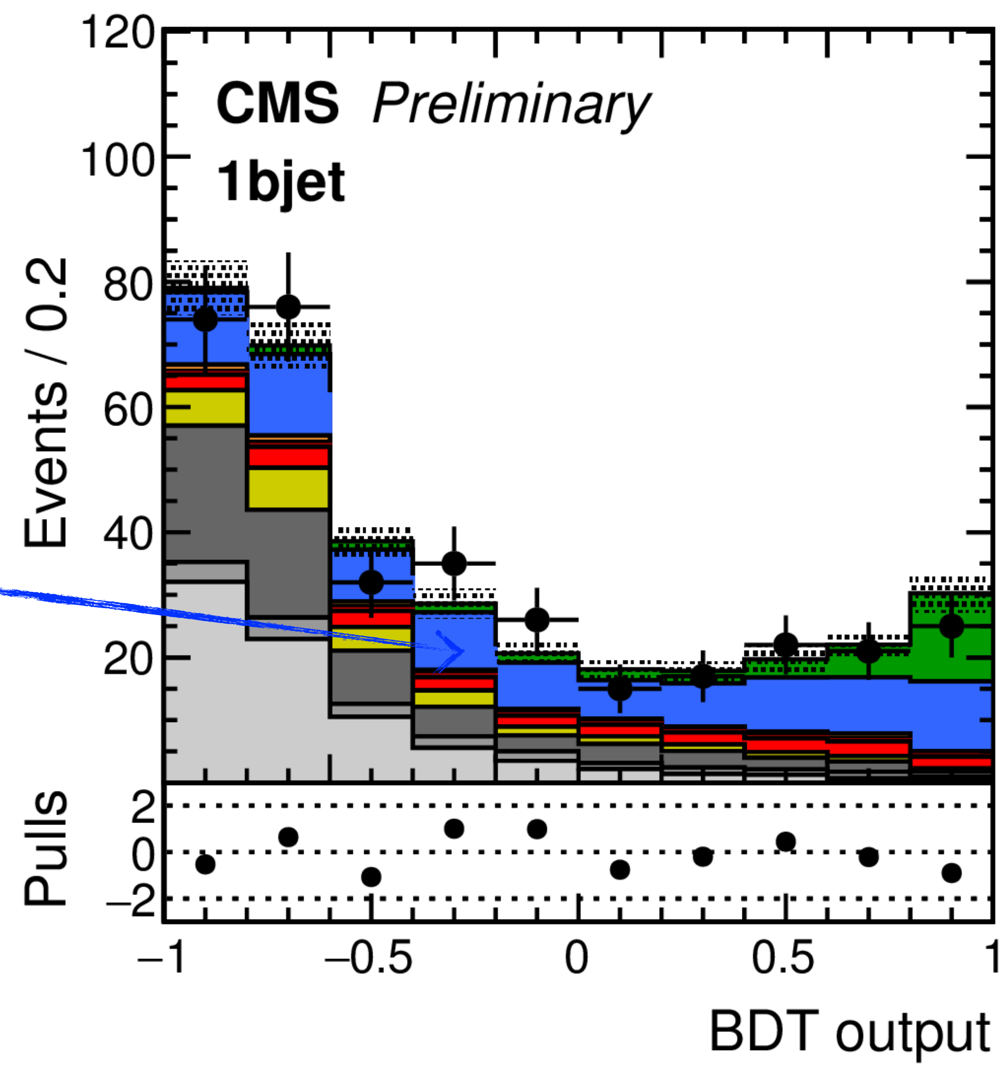
Background estimation



- Signal → tZq = tZq
- Fakes → $t\bar{t}$ + tW + Z+jets = NPL
- Diboson → Diboson = ZZ + WZ+c/b/light
- top → $t\bar{t}V$ + $t\bar{t}H$ + tWZ = tWZ + $t\bar{t}H$ + $t\bar{t}W$ + $t\bar{t}Z$

	ATLAS		CMS	
Signal	26	18%	32	9%
Fakes	51	35%	91	26%
Diboson	48	33%	186	54%
top	19	13%	35	10%

- Similar **multivariate** approach.
  - ATLAS uses **NN**,
  - CMS uses Boosted Decision Trees (**BDT**).
    - Training w/o fake estimation included.
- Different **fitting**.
  - ATLAS uses only 1 SR.
  - CMS uses one SR per channel (eee, eeμ, eμμ and μμμ) and control regions to constrain backgrounds.



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Conclusions and outlook

- **Clear evidence** of single top production in association with a Z boson in the t-channel.

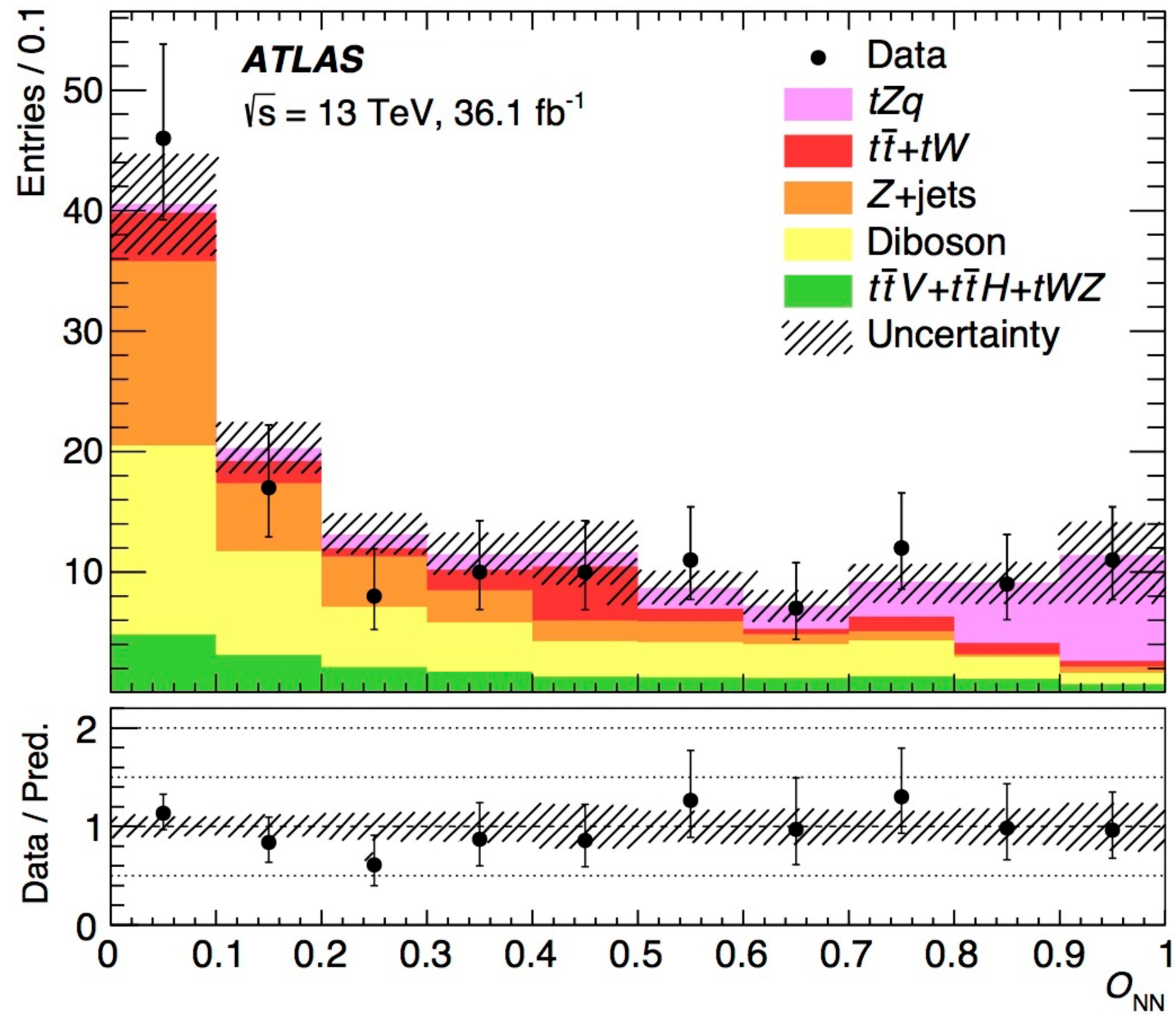
- Observed (expected) significance of extracted signal:

  4.2σ (5.4σ)

- Measured cross-section:

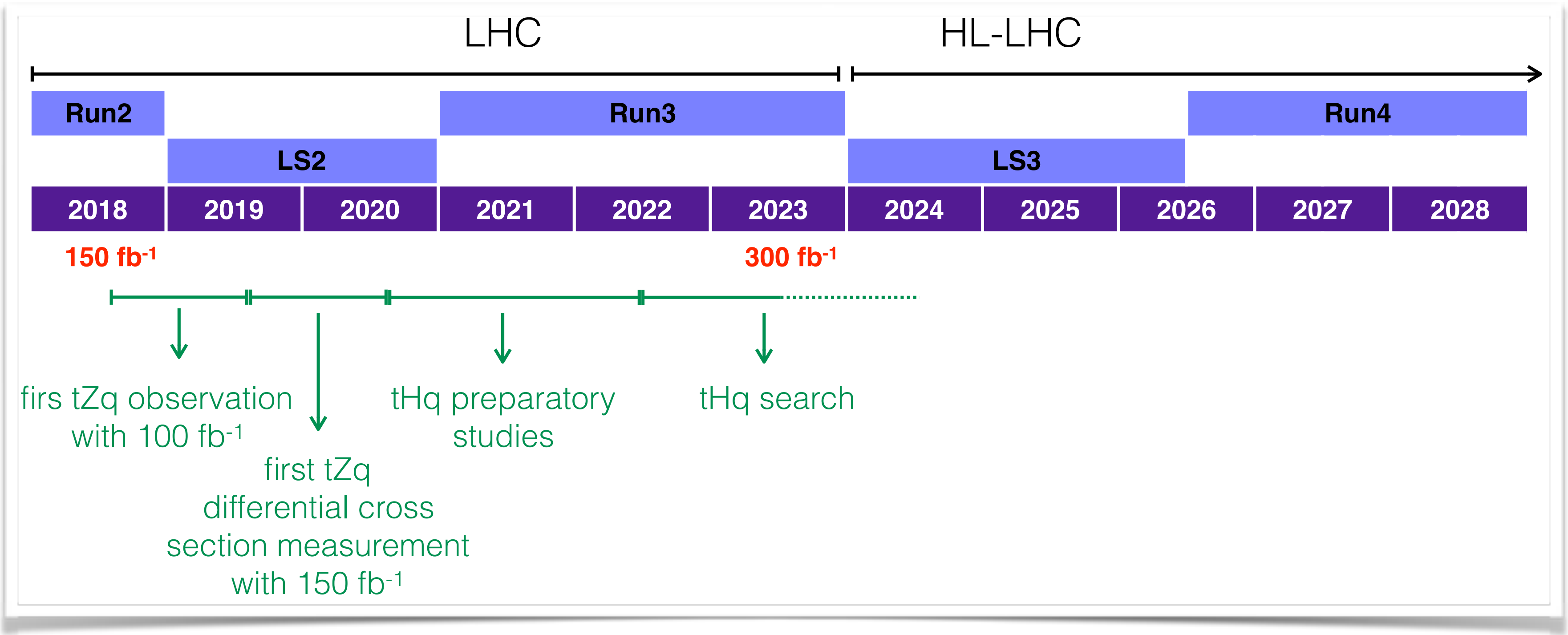
  600 ± 170 (stat.) ± 140 (syst.) fb

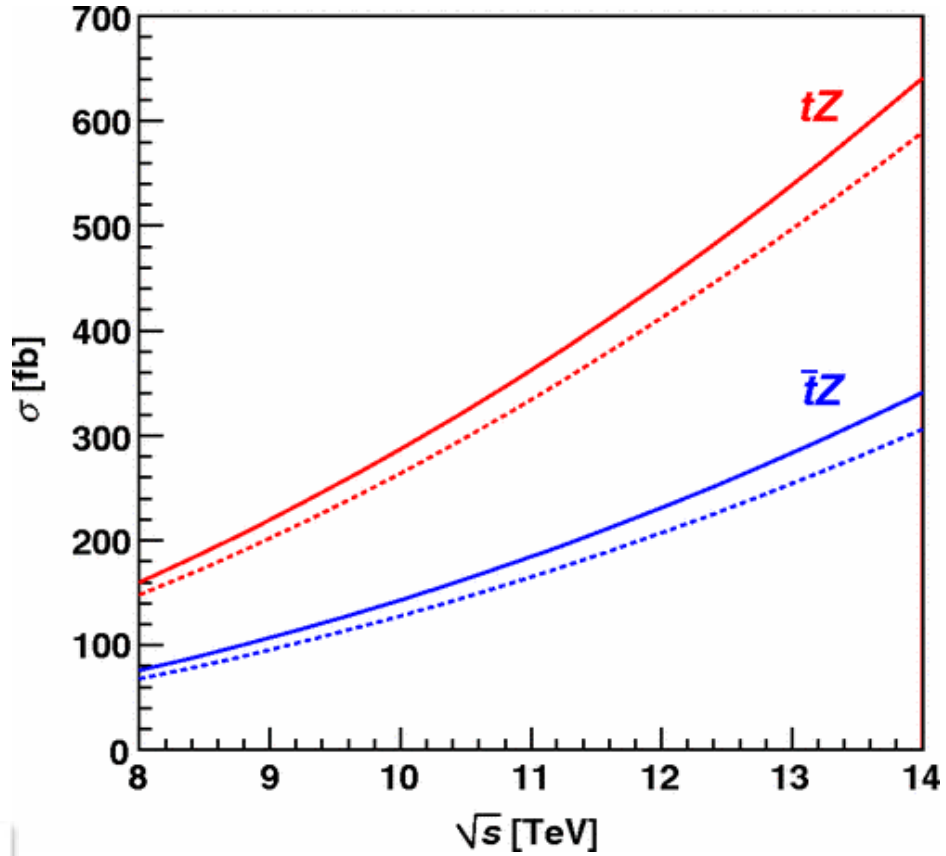
  to be compared to the NLO prediction of 800 fb.

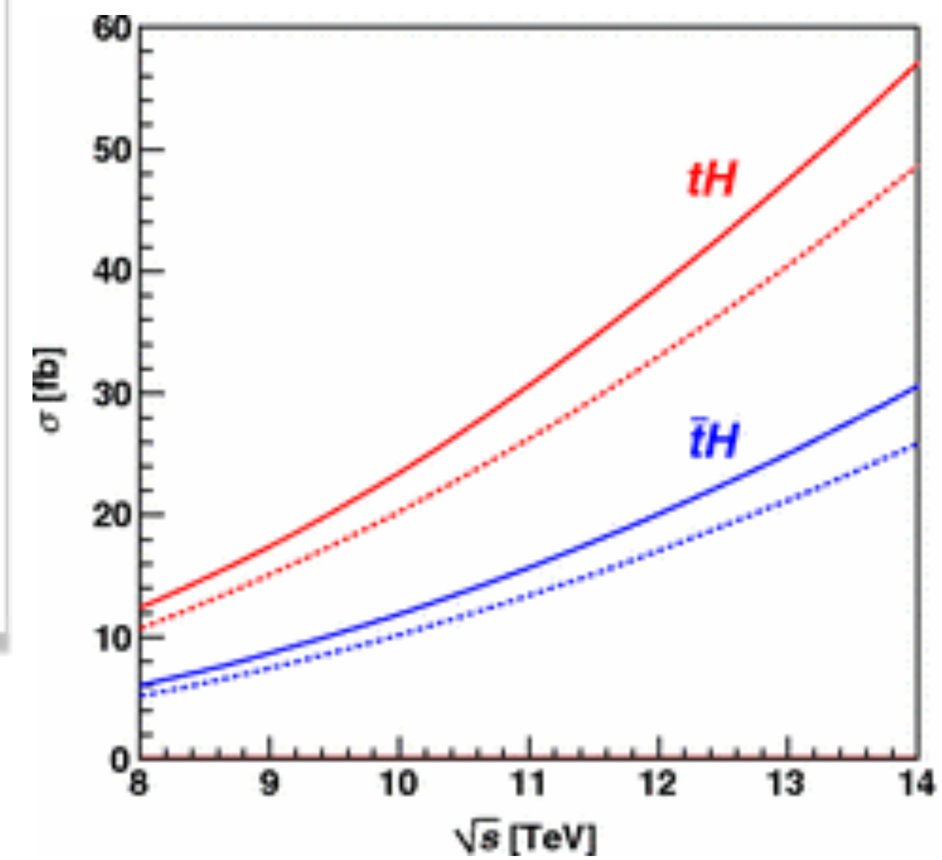


Conclusions and outlook

- Evidence is just the beginning of a long journey.
- The LHC Run2&3 and the HL-LHC will give the opportunity to study the top sector in more detail.
  - tZq observation with 100 fb^{-1}.
  - Possibility to look for the production of a single top in association with a Higgs boson with HL-LHC data.







Stay tuned for new interesting results!

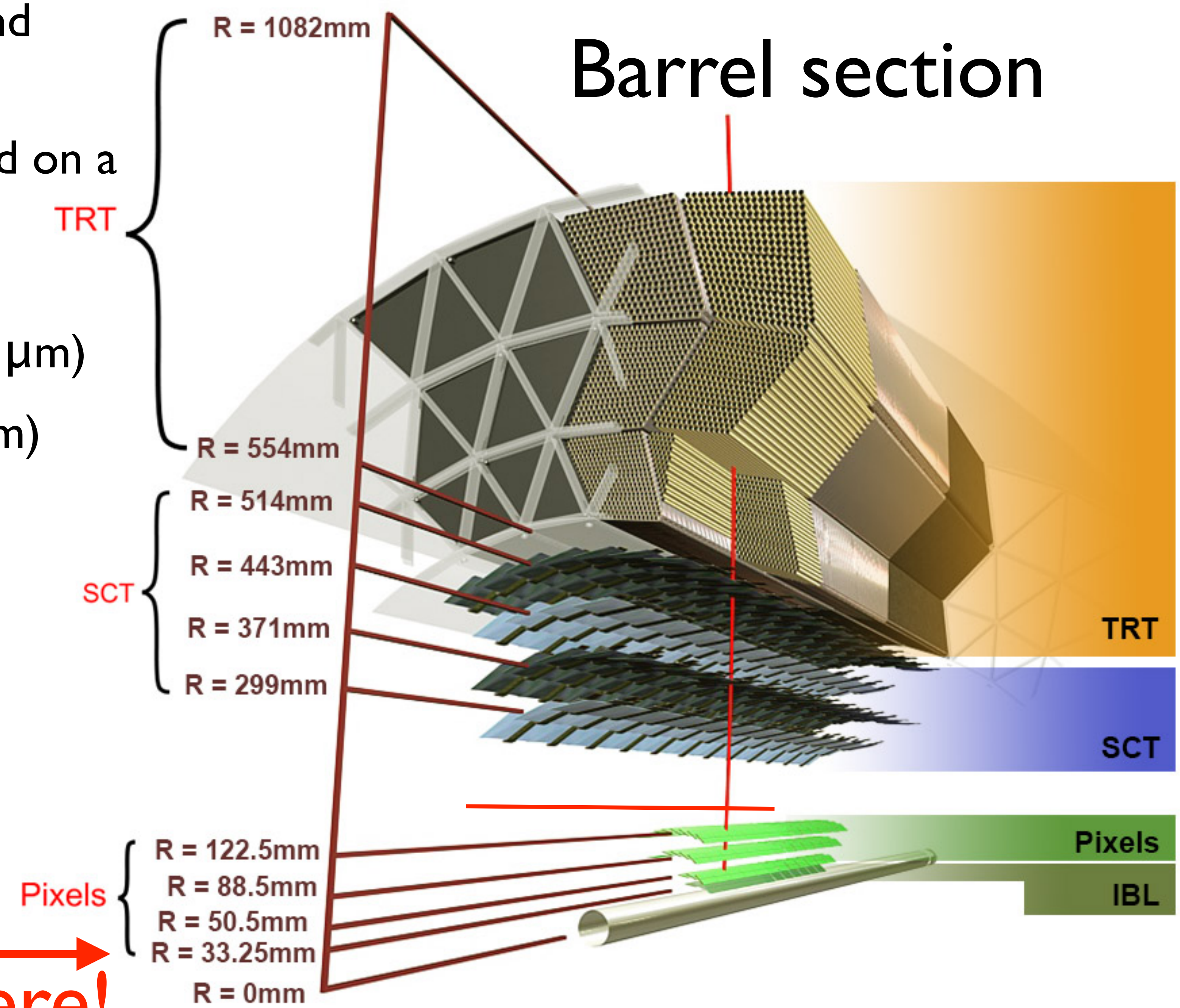
from 10.1103/PhysRevD.87.114006

BackUp

Pixel Detector Upgrade

- The ATLAS Inner Detector is made of three sub-detectors:
  - **Silicon Pixel**, **Silicon Strip** and **TRT** (Drift Tubes)
- A new innermost layer (IBL), mounted on a narrower beam pipe, was installed in ATLAS in May 2014
- Smaller pixel size (50x250 vs 50x400 μm)
- Closer to interaction region (R~3.3cm)
- Significantly more radiation hard
- H → bb primary physics motivation for the new detector!

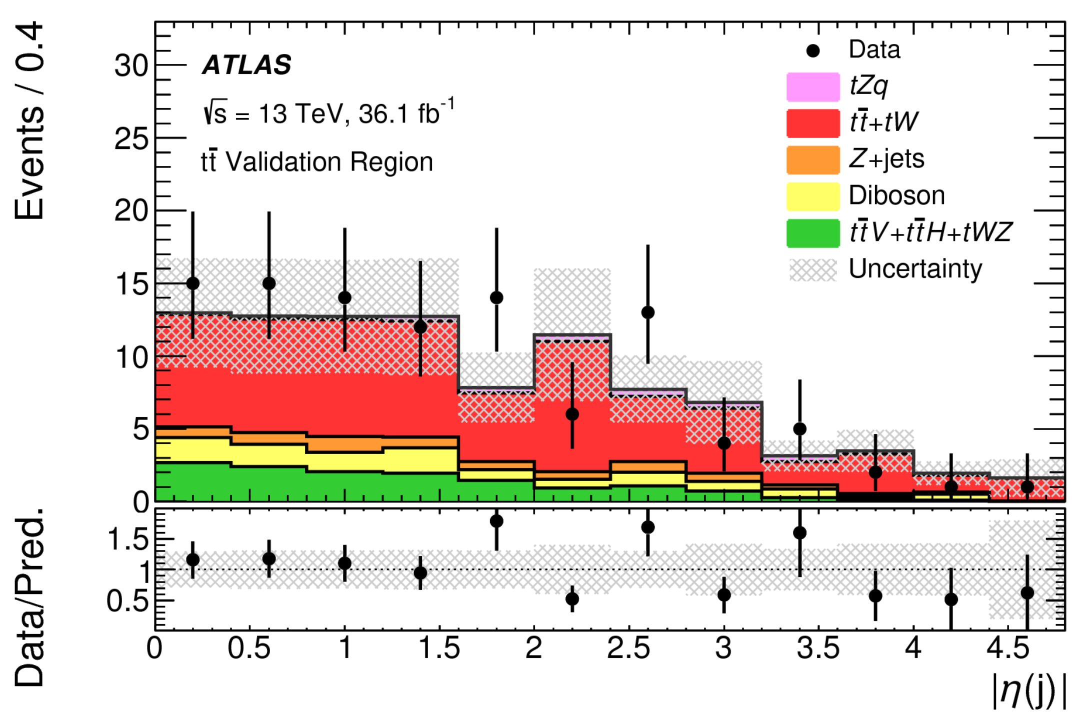
IBL inserted here!



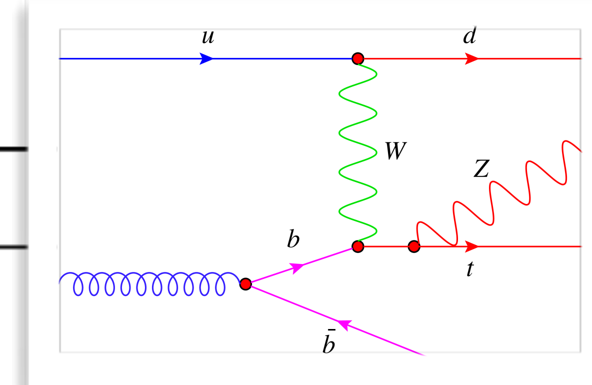
Background estimation - $t\bar{t}$

- Normalisation corrected using scale factor derived in $t\bar{t}$VR (OSOF, to reduce Z+jets contamination).
- Average of various scale factors obtained from different dilepton invariant mass cuts.
- Uncertainty on scale factor from:
  - variation of the mll requirement,
  - statistical uncertainty of the sample.

$SF_{t\bar{t}} = 1.21 \pm 0.51$



NN input variables



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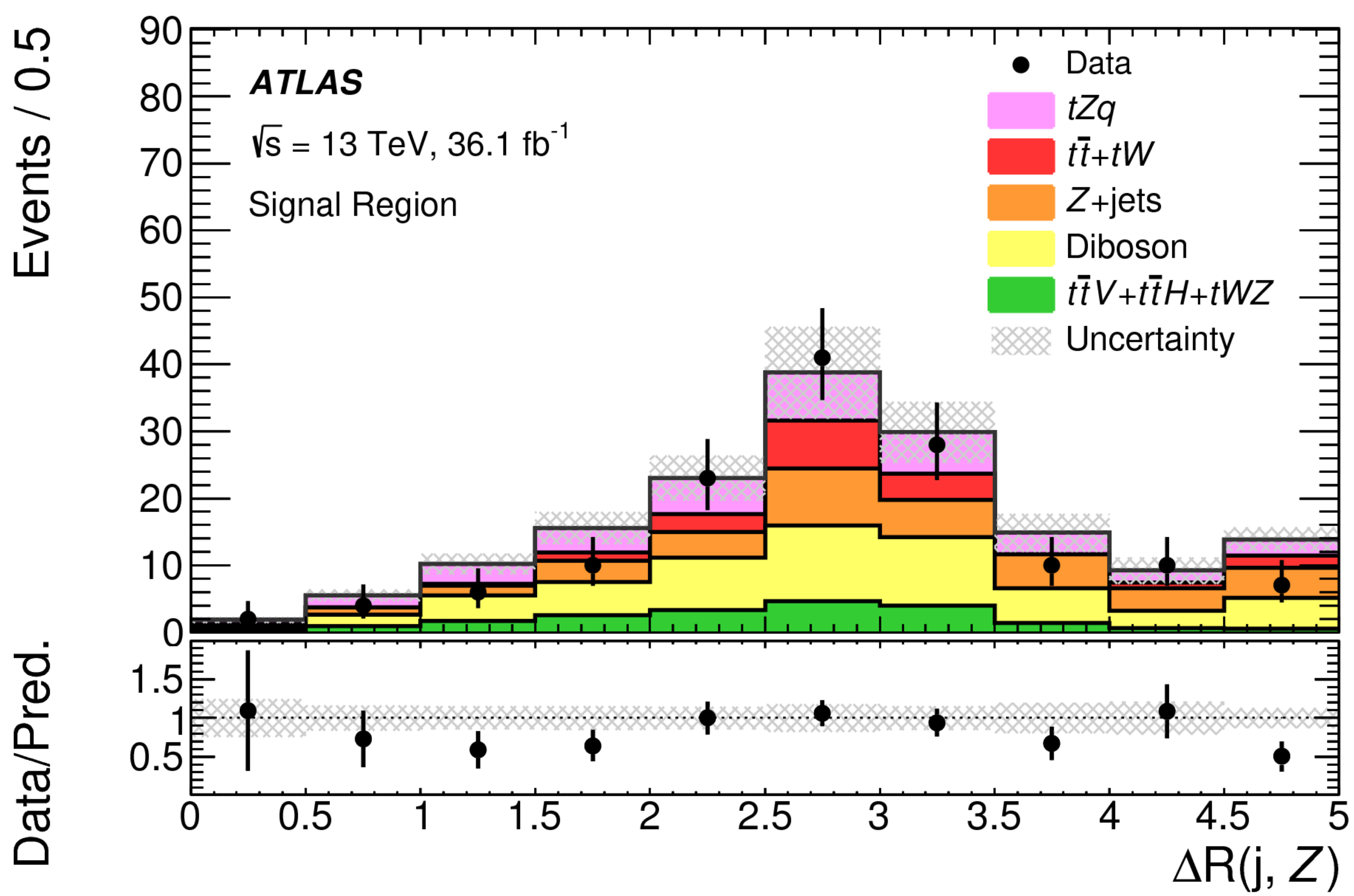

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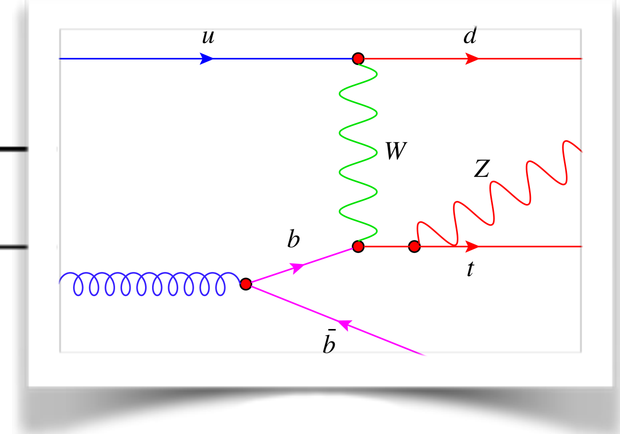

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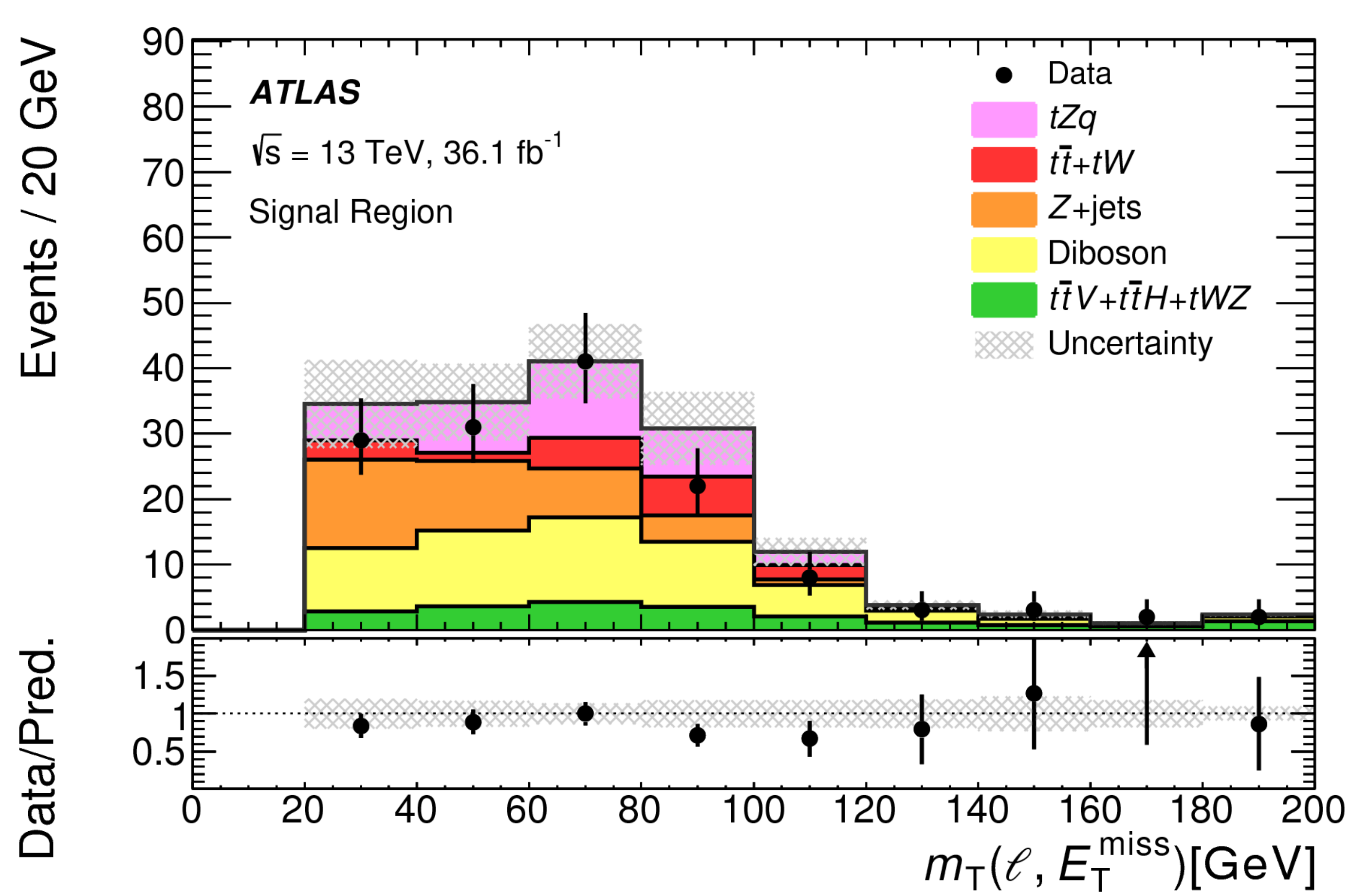

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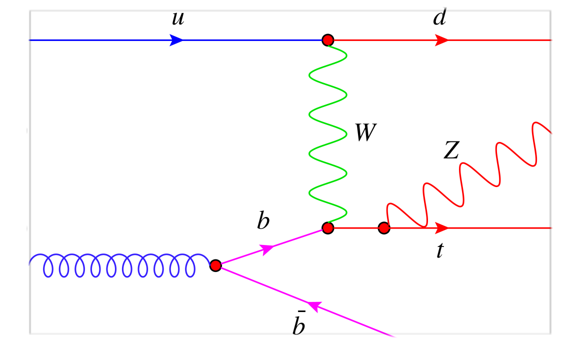

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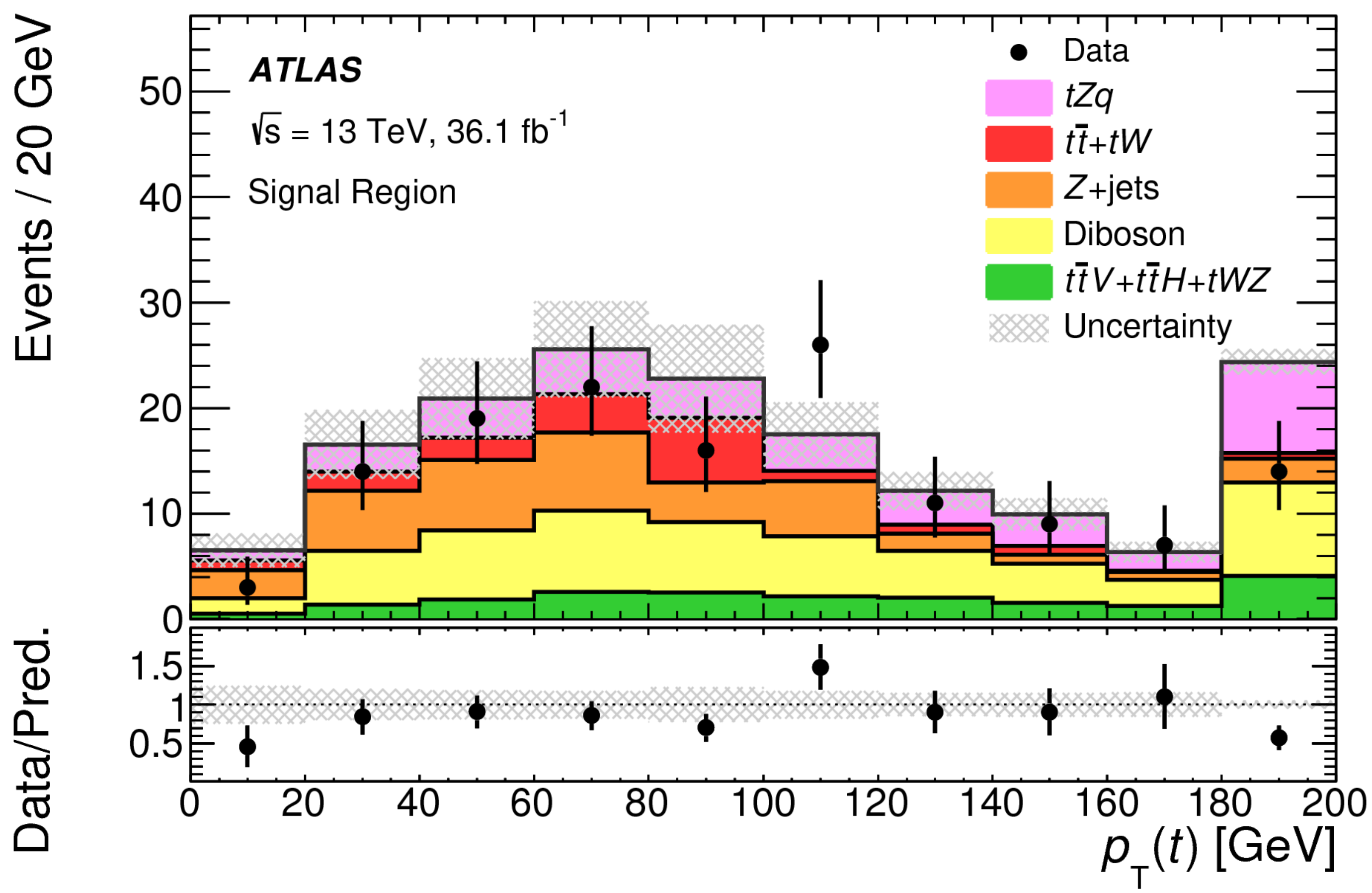

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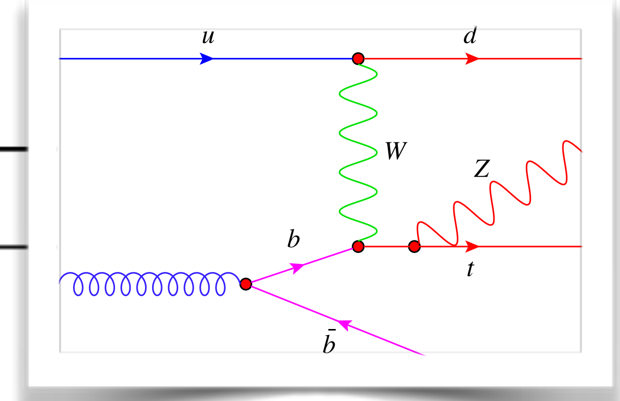

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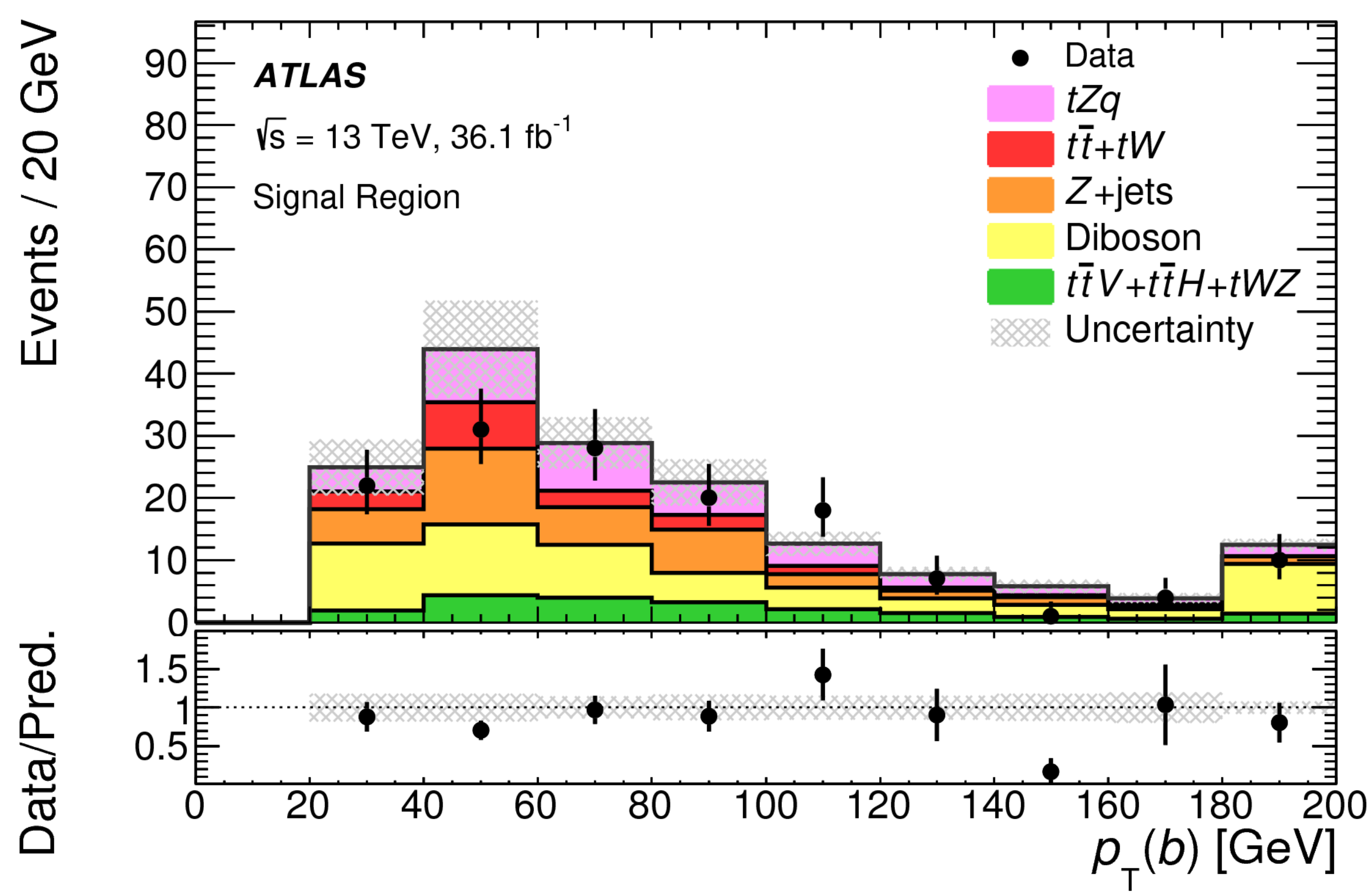
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	Transverse mass of W boson
$p_{\mathrm{T}}(t)$	Reconstructed top-quark p_{T}
$p_{\mathrm{T}}(b)$	Tagged jet p_{T}
$p_{\mathrm{T}}(Z)$	p_{T} of the reconstructed Z boson
$\|\eta(\ell^W)\|$	Absolute value of η of the lepton coming from the W-boson decay



NN input variables

Variable	Definition
$\|\eta(\mathrm{j})\|$	Absolute value of untagged jet η
$p_{\mathrm{T}}(\mathrm{j})$	Untagged jet p_{T}
m_t	Reconstructed top-quark mass
$p_{\mathrm{T}}(\ell^W)$	p_{T} of the lepton from the W-boson decay
$\Delta R(\mathrm{j}, Z)$	ΔR between the untagged jet and the Z boson
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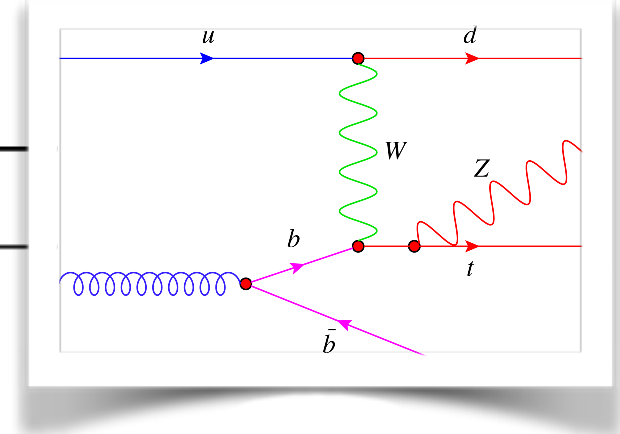
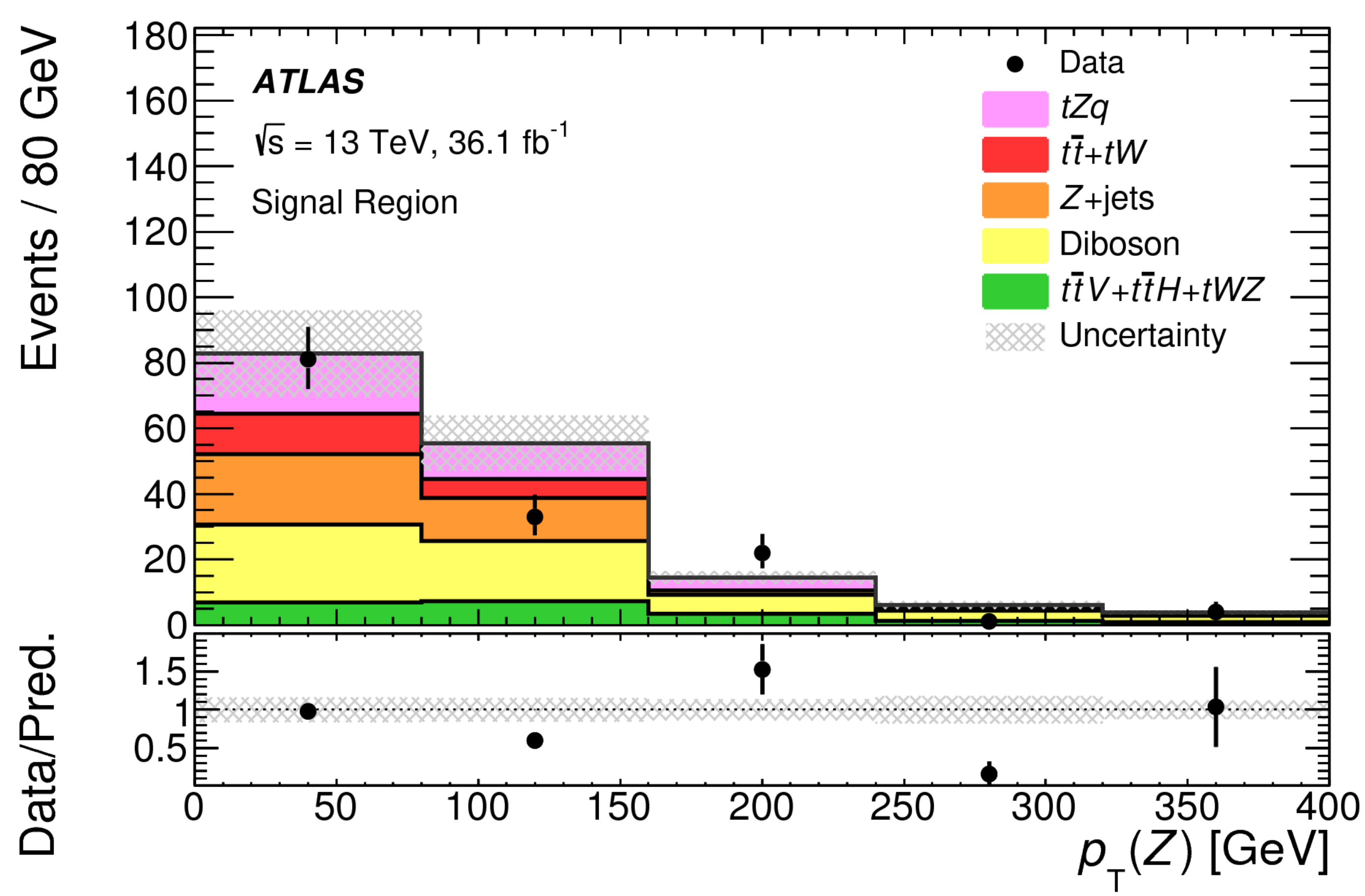
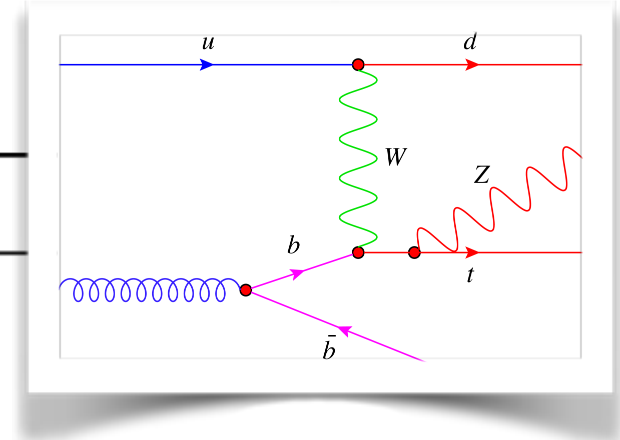




NN input variables



Variable	Definition
$\lvert\eta(\mathrm{j})\rvert$	Absolute value of untagged jet η
$p_{\mathrm{T}}(\mathrm{j})$	Untagged jet p_{T}
m_t	Reconstructed top-quark mass
$p_{\mathrm{T}}(\ell^W)$	p_{T} of the lepton from the W-boson decay
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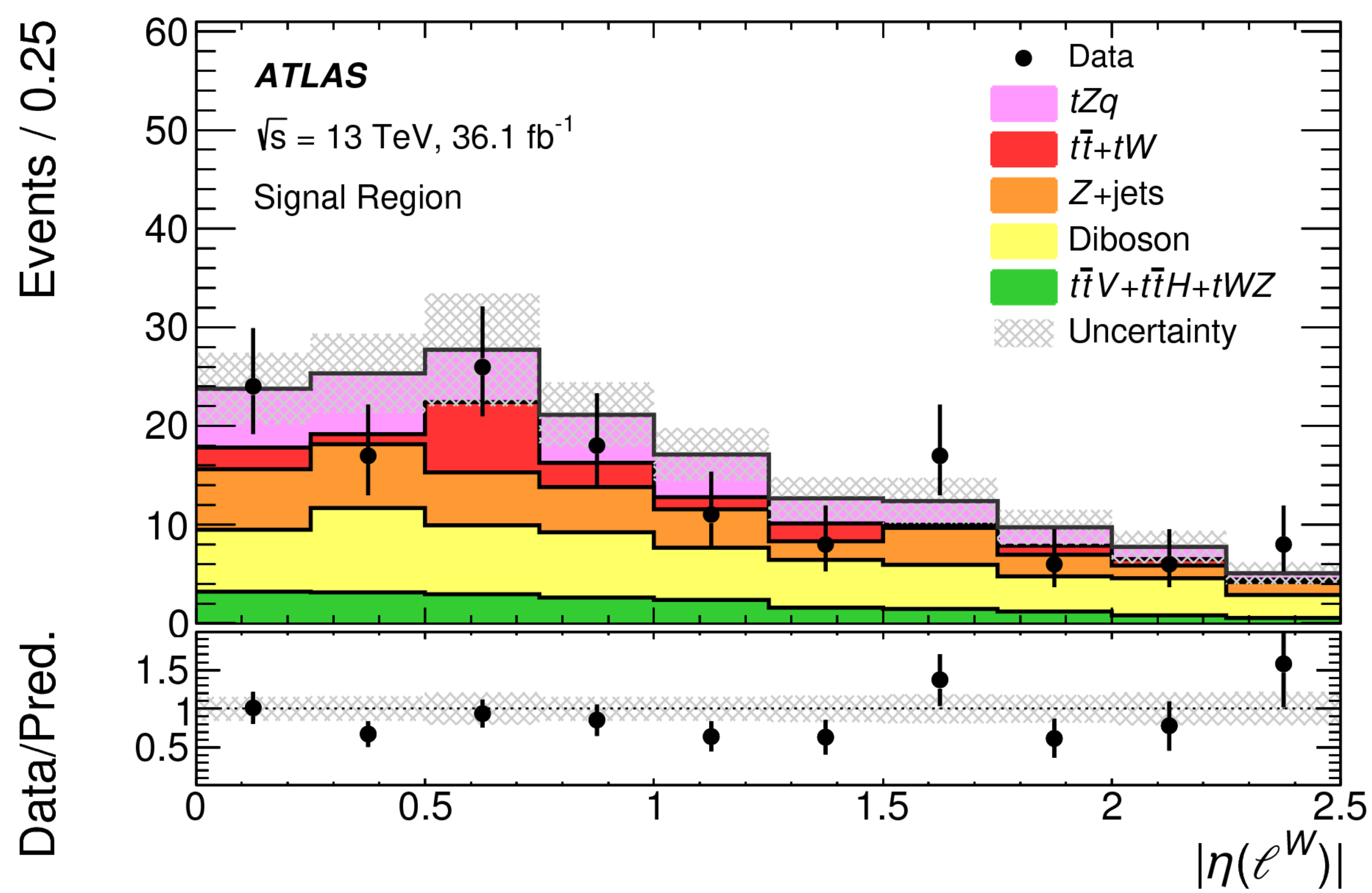


ATLAS & CMS

Signal samples & theory cross section

	FS	Scale	Cuts	x-sec (fb)	notes
tllq	5	$\mu = \frac{1}{2}\Sigma\sqrt{E^2 - p_z^2}$	-	94	CMS default
tllq	4	$\mu = \frac{1}{2}\Sigma\sqrt{E^2 - p_z^2}$	-	76	4 vs 5 FS 20% effect
tllq	5	$\mu = \frac{1}{2}\Sigma\sqrt{E^2 - p_z^2}$	m_{ll} > 80 GeV	89	
tZ(→ll)q	5	$\mu = \frac{1}{2}\Sigma\sqrt{E^2 - p_z^2}$	-	86	effect of missing contributions from off-shell/γ* and extra diagrams
tZq	4	$\mu = 4\sqrt{m_b^2 + p_{T,b}^2}$	-	800	ATLAS default
tZq	4	$\mu = \frac{1}{2}\Sigma\sqrt{E^2 - p_z^2}$	-	690	scale 15% effect
tZq	5	$\mu = \frac{1}{2}\Sigma\sqrt{E^2 - p_z^2}$	-	860	4 vs 5 FS 20% effect

- Need to converge on a common setup.
  - Include or not γ* contribution → current thinking is to include it
  - If including γ*, need to fix an m(ll) requirement → 30 GeV seems reasonable from the experimental side
  - Whether to use 4FS or 5FS → current thinking is 5FS (expected to be more precise for inclusive XS)
  - Which scale to use → theory guidance appreciated

Background estimation

- $t\bar{t}$ and Z+jets non-prompt lepton backgrounds estimated separately.

ATLAS

- $t\bar{t}$: data/MC SF from OSOF region
  - shape from MC.
- Z+jets: Fake Factor method
  - e/μ treated separately
  - binned in p_T of W lepton
  - FF: TTT/LTT in region with $m_T(W) < 20$ GeV
  - applied to LTT data.
  - Uncertainty:
    - 30/40% normalisation.

- All "NPL" (non-prompt leptons) sources estimated together.
- "templates" from data with LTT leptons.
- e/μ treated separately.
- "2 step normalisation"
  - fit $m_T(W)$ in the 0bjet CR and get first normalisation factors for all channels.
  - NPL e and μ yields: two free parameters independent of each other in the fit.
  - Uncertainty:
    - shape uncertainty based on changing isolation requirements.

CMS

Background estimation

- Signal → tZq = tZq
- Fakes → $t\bar{t}$+tW + Z+jets = NPL
- Diboson → Diboson = ZZ + WZ+c/b/light
- top → $t\bar{t}$V+$t\bar{t}$H+tWZ = tWZ + $t\bar{t}$H + $t\bar{t}$W + $t\bar{t}$Z

ATLAS

Channel	Number of events Real data	CMS
tZq	26 ± 8	32.3 ± 5.0
$t\bar{t} + tW$	17 ± 7	} 91.3 ± 12.1
$Z +$jets	34 ± 11	
Diboson	48 ± 12	186.4 ± 11.5
$t\bar{t}V + t\bar{t}H + tWZ$	19 ± 3	34.8 ± 2.5
Total	143 ± 11	

	ATLAS		CMS	
Signal	26	18%	32	9%
Fakes	51	35%	91	26%
Diboson	48	33%	186	54%
top	19	13%	35	10%

CMS

post-fit values

Process	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$	All channels	$\frac{N^{obs}}{N^{pred}}$
tZq	5.0±1.5	6.6±1.9	8.5±2.5	12.3±3.6	32.3±5.0	–
$t\bar{t}$Z	3.7±0.7	4.7±0.9	6.1±1.2	8.0±1.5	22.4±2.2	0.9±0.2
$t\bar{t}$W	0.3±0.1	0.3±0.1	0.7±0.2	0.6±0.2	1.9±0.3	1.0±0.2
Z Z	4.8±1.3	3.2±0.9	9.0±2.5	7.8±2.2	24.7±3.6	1.3±0.3
WZ+b	3.0±0.9	3.4±1.1	4.6±1.4	5.5±1.7	16.6±2.6	1.0±0.2
WZ+c	9.0±2.4	13.7±3.7	18.0±4.9	24.2±6.5	64.8±9.3	1.0±0.2
WZ+light	12.2±1.6	16.6±2.0	22.4±2.8	29.1±3.4	80.3±5.1	0.7±0.1
$t\bar{t}$H	0.6±0.2	0.9±0.3	1.0±0.3	1.5±0.4	4.0±0.6	1.0±0.2
tWZ	1.0±0.3	1.3±0.4	1.7±0.5	2.4±0.7	6.5±1.0	1.0±0.2
NPL: electrons	19.2±3.1	0.6±0.1	17.9±2.8	–	37.7±4.2	–
NPL: muons	–	7.2±2.3	31.1±9.9	15.3±4.9	53.6±11.3	–
Total	58.8±4.8	58.4±5.5	120.9±12.4	106.6±10.1	344.8±17.6	
Data	56	58	104	125	343	

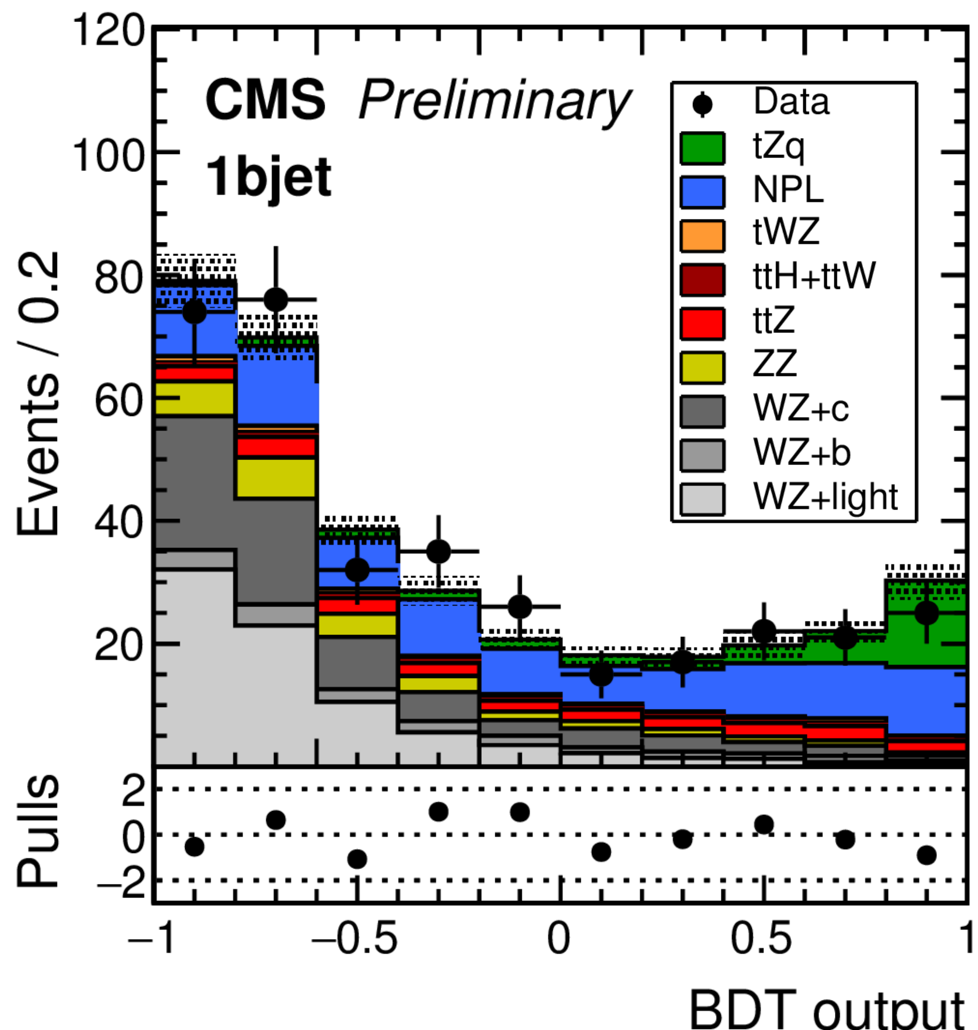
Multivariate analysis

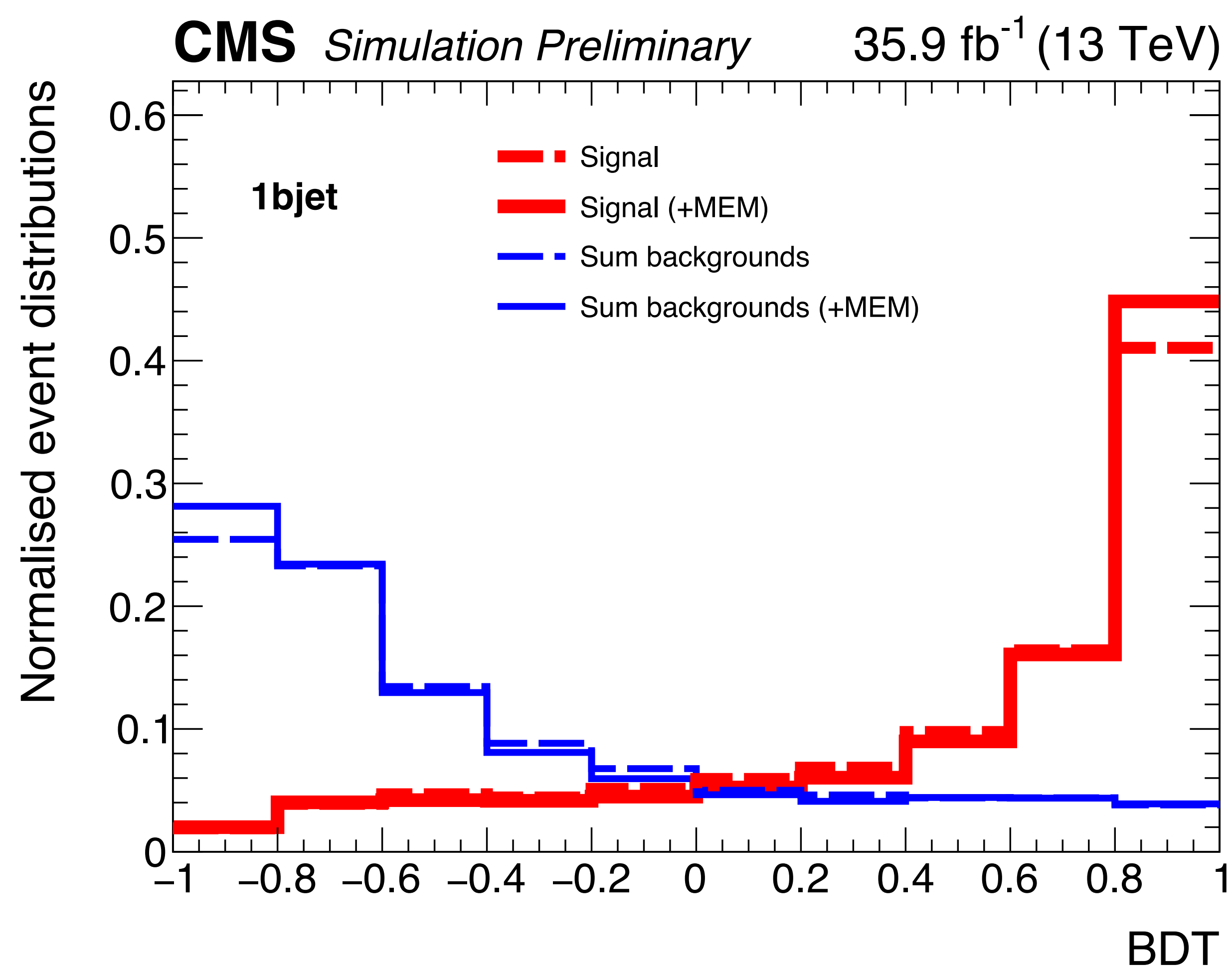
ATLAS

- **NN**
- Training with signal and all backgrounds ($t\bar{t}$ excluded, fakes included)
- 10 variables
  - List in the paper
  - Most discriminating: $\eta(\text{jet}_{\text{forward}})$ and $p_T(\text{jet}_{\text{forward}})$.

CMS

- **BDT**
- Training with signal and all backgrounds (**excluding** fakes because of lack of stat.)
- Two BDTs for the 1bj and 2bj SRs.
- Various variables used for training.
  - Including **MEM** (Matrix Element Method) as input variables.
    - 10% significance improvement.





Fitting

ATLAS

- Fitting O_{NN} in SR (all channels summed together).

CMS

- Fitting 12 regions simultaneously.
  - eee, eeμ, eμμ, μμμ.
  - BDT in 1bjet (signal region).
  - BDT in 2bjet (to control $t\bar{t}Z$).
  - $m_T(W)$ in 0bjet (to control WZ+jets).

ATLAS & CMS

- MC signal samples @LO for ATLAS and @NLO for CMS.
- Theory cross section calculations compatible but with several differences (tZq vs tllq, 4 vs 5 FS, scale choice).
  - Need to converge to a common approach.
- Some different approaches for the event selection (e.g. lepton p_T cuts, number of jets, b-tagging WP) and background estimation.
  - Visible effect on the background composition in the SR.
- Multivariate analysis (NN for ATLAS and BDT for CMS).
  - Main difference coming from the use of fakes in training.
- Different way of fitting NN/BDT output distributions.