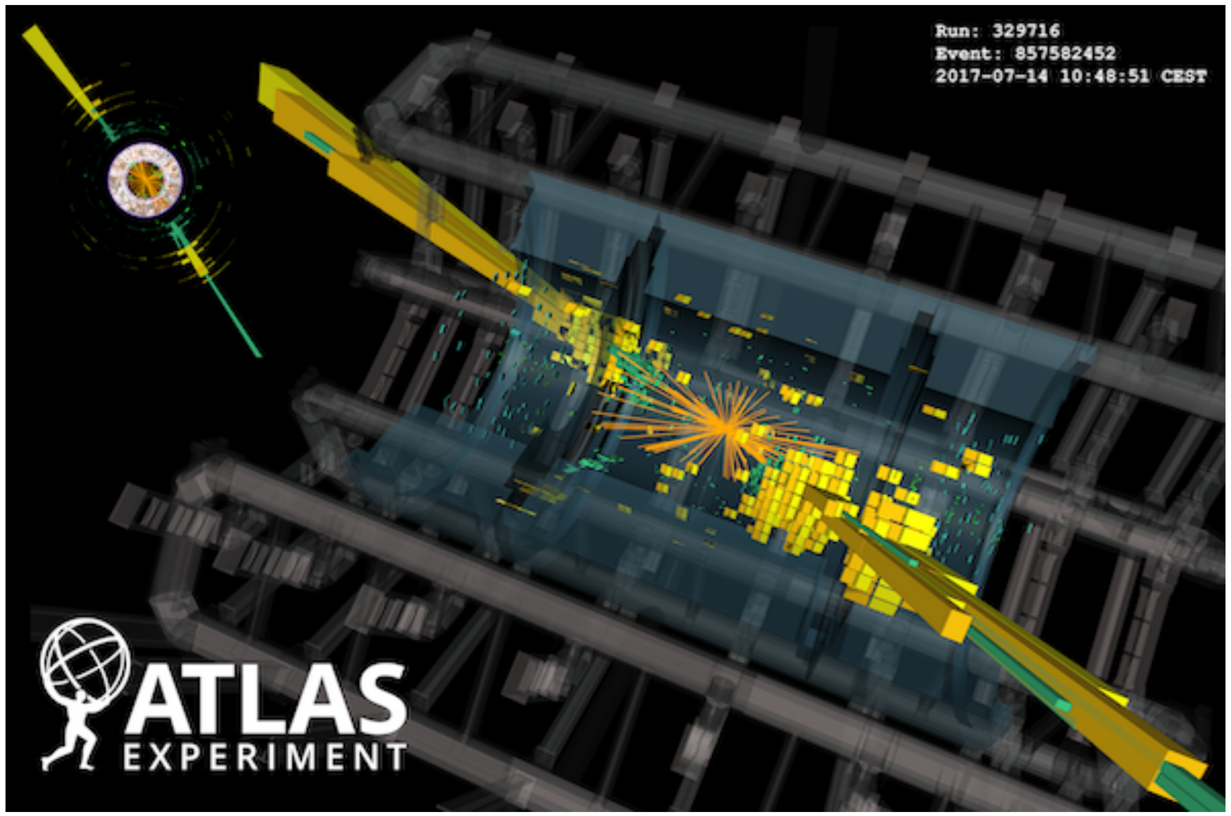
Standard Model Working Group Report



- EWK Group
  - $Z\gamma \to \ell\ell\gamma$
  - ZZ$\to$ 4ℓ
- W/Z Group
  - High mass Drell-Yan: Neutral & Charged Current
  - MET+jets
- Soft QCD
  - K^0_S and Λ strange spectra in the Underlying Event
- Photon+Jets
  - Lund Plane Measurements
  - Photon+2 jets
  - Event shapes in multijets
- ATLAS Global PDF and EFT Fits

See additional dedicated talks:
- Forward physics programme: Lydia Beresford (today)
- Precision electroweak programme: Fabrice Balli (today)
- Photon-photon fusion programme: Mateusz Dyndal (Friday)
- Triboson and VBS/VBF programmes: Karolos Potamianos (Friday)

Eram Rizvi

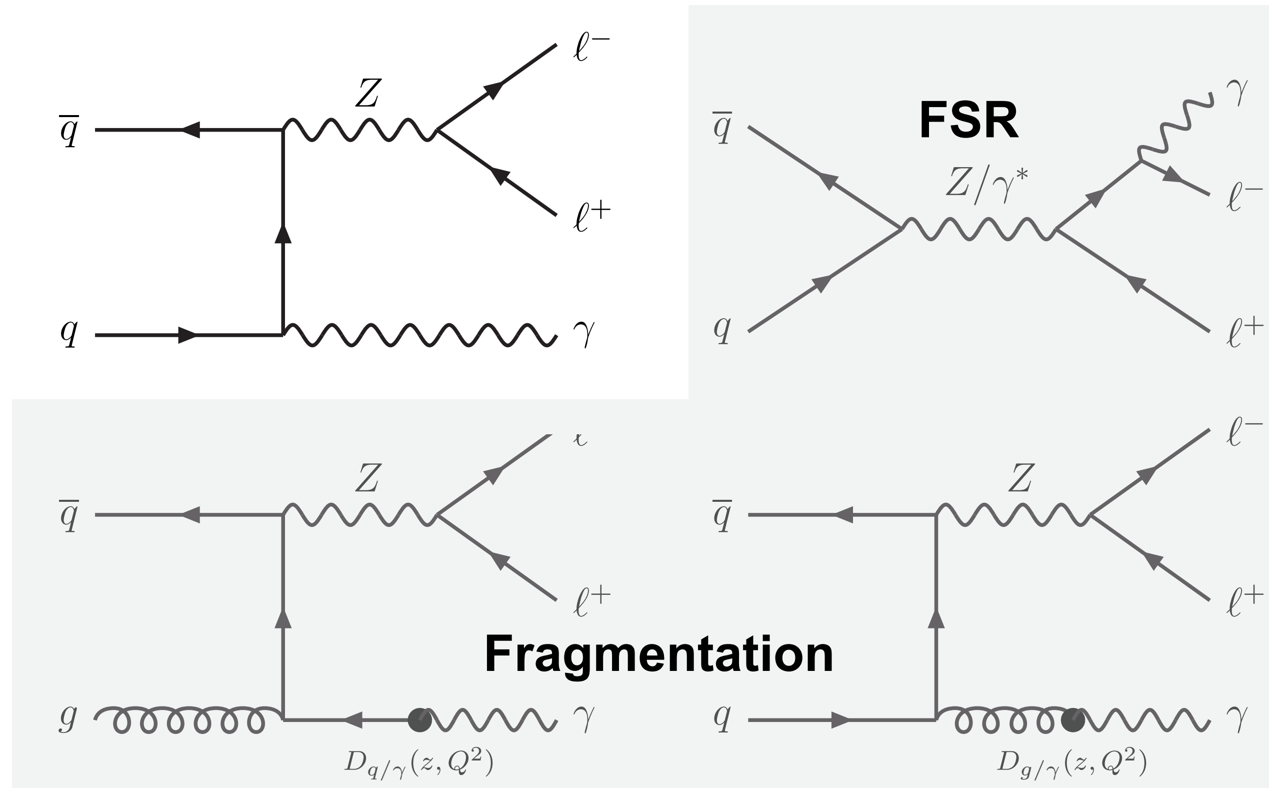
ATLAS EXPERIMENT

Queen Mary University of London

ATLAS Week
Berlin, Germany
7th — 11th October 2019

$Z\gamma \rightarrow \ell\ell\gamma$

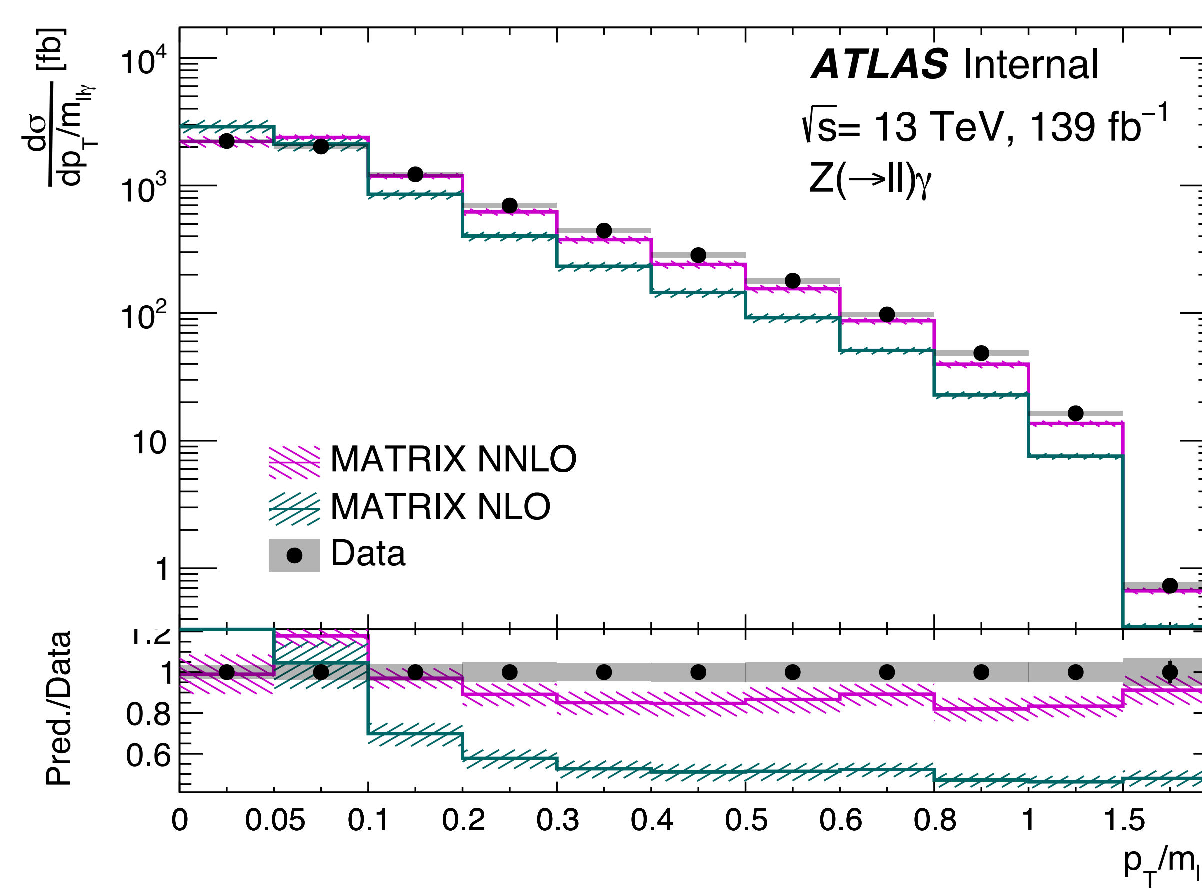
Full Run2 analysis
EPS CONF note with differential cross sections
E_T^γ, $m_{\ell\ell\gamma}$, $p_T^{\ell\ell\gamma}$



Selection:

p_T^ℓ> 30, 25 GeV
E_T^γ > 30 GeV
$m_{\ell\ell}$ > 40 GeV
$m_{\ell\ell} + m_{\ell\ell\gamma} > 2m_Z$ suppresses FSR contribution
Photon isolation suppresses fragmentation contribution

- Updated to include more observables
  $\Delta\phi(\ell\ell,\gamma)$, $\frac{p_T^{\ell\ell\gamma}}{m^{\ell\ell\gamma}}$
- Include NLO EW correction
- Improved pile-up background estimation
  - dominant at low $\Delta\phi(\ell\ell,\gamma)$



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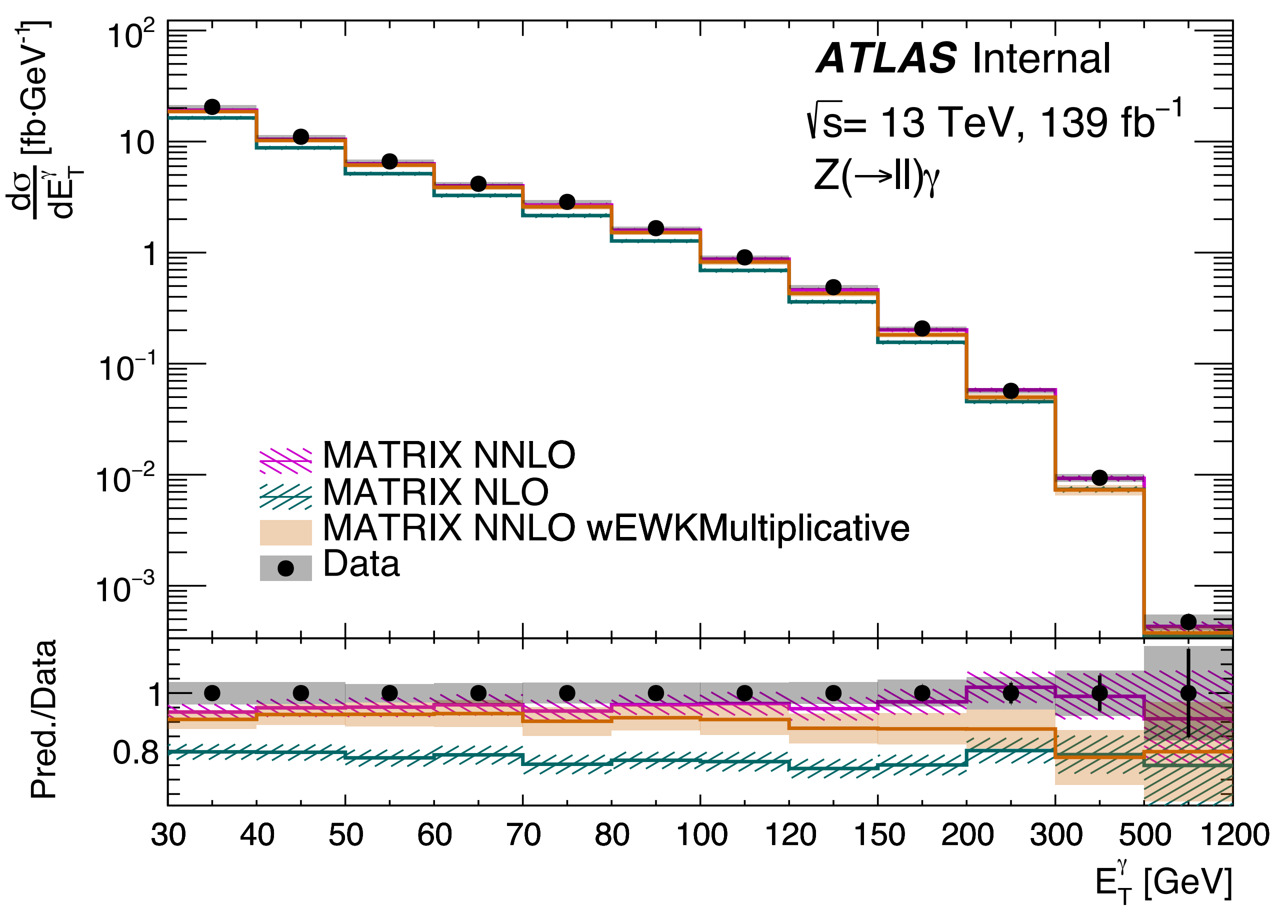
$Z\gamma \to \ell\ell\gamma$

Pile-up controlled using $\Delta z = z^{\gamma} - z_{\mathrm{vtx}}$ sidebands with $|\Delta z|$ > 50mm
Use conversion tracks in pixel with good z^{γ} resolution
Well modelled in MC
Photon pile-up fraction 2.1 ± 2.1% → 2.5 ± 0.5%

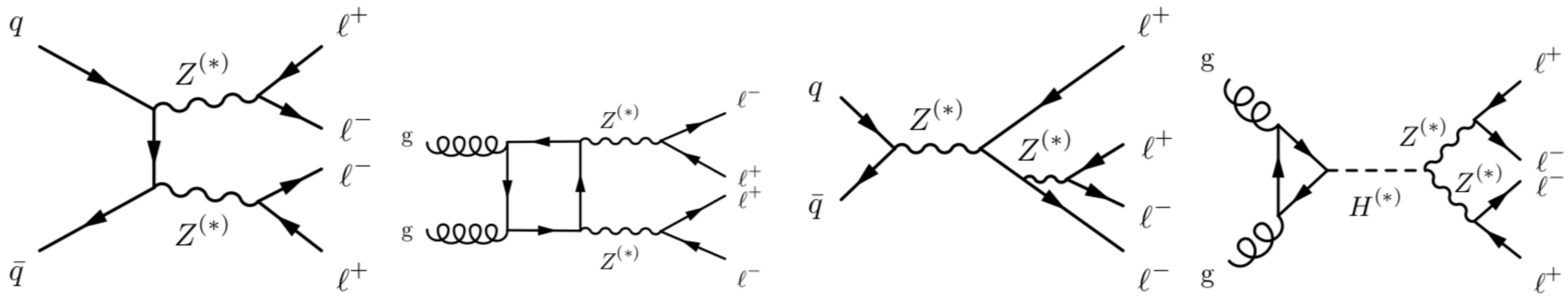
Investigating selection to reduce pile-up background
Consider additional VBS sensitive variables m_{jj} and Δy_{jj}

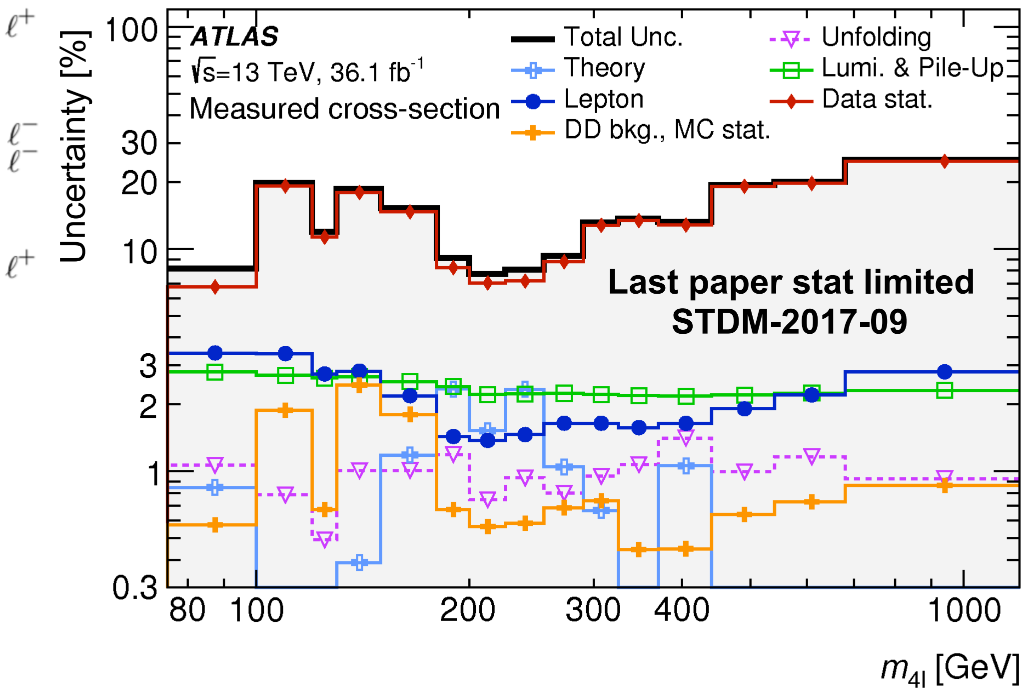


Largest errors:
Electron ID, Z+jets b/g and lumi

<table>
<tr><th>Source</th><th colspan="2">Uncertainty [%]</th></tr>
<tr><th></th><th>$e^+e^-\gamma$</th><th>$\mu^+\mu^-\gamma$</th></tr>
<tr><td>Trigger efficiency</td><td>–</td><td>0.2</td></tr>
<tr><td>Photon identification efficiency</td><td colspan="2">1.0</td></tr>
<tr><td>Photon isolation efficiency</td><td colspan="2">0.9</td></tr>
<tr><td>Electron identification efficiency</td><td>1.4</td><td>–</td></tr>
<tr><td>Electron reconstruction efficiency</td><td>0.3</td><td>–</td></tr>
<tr><td>Electron–photon energy scale</td><td>0.9</td><td>0.6</td></tr>
<tr><td>Muon isolation efficiency</td><td>–</td><td>0.4</td></tr>
<tr><td>Muon identification efficiency</td><td>–</td><td>0.7</td></tr>
<tr><td>Z + jets background</td><td colspan="2">1.3</td></tr>
<tr><td>Pile-up background</td><td colspan="2">0.6</td></tr>
<tr><td>Other backgrounds</td><td>0.8</td><td>0.7</td></tr>
<tr><td>Monte Carlo event statistics</td><td>0.4</td><td>0.4</td></tr>
<tr><td>Integrated luminosity</td><td colspan="2">1.7</td></tr>
<tr><td>Systematic uncertainty</td><td>3.2</td><td>2.9</td></tr>
<tr><td>Statistical uncertainty</td><td>0.6</td><td>0.5</td></tr>
<tr><td>Total uncertainty</td><td>3.2</td><td>3.0</td></tr>
</table>

$ZZ \rightarrow 4\ell$





Different mass regions dominated by
- single Z
- Higgs production
- ZZ production
- interference effects at high invariant masses.

Measure differential cross section vs m_{4l} [4e, 4μ, 2e2μ]

Full run2 analysis → higher granularity

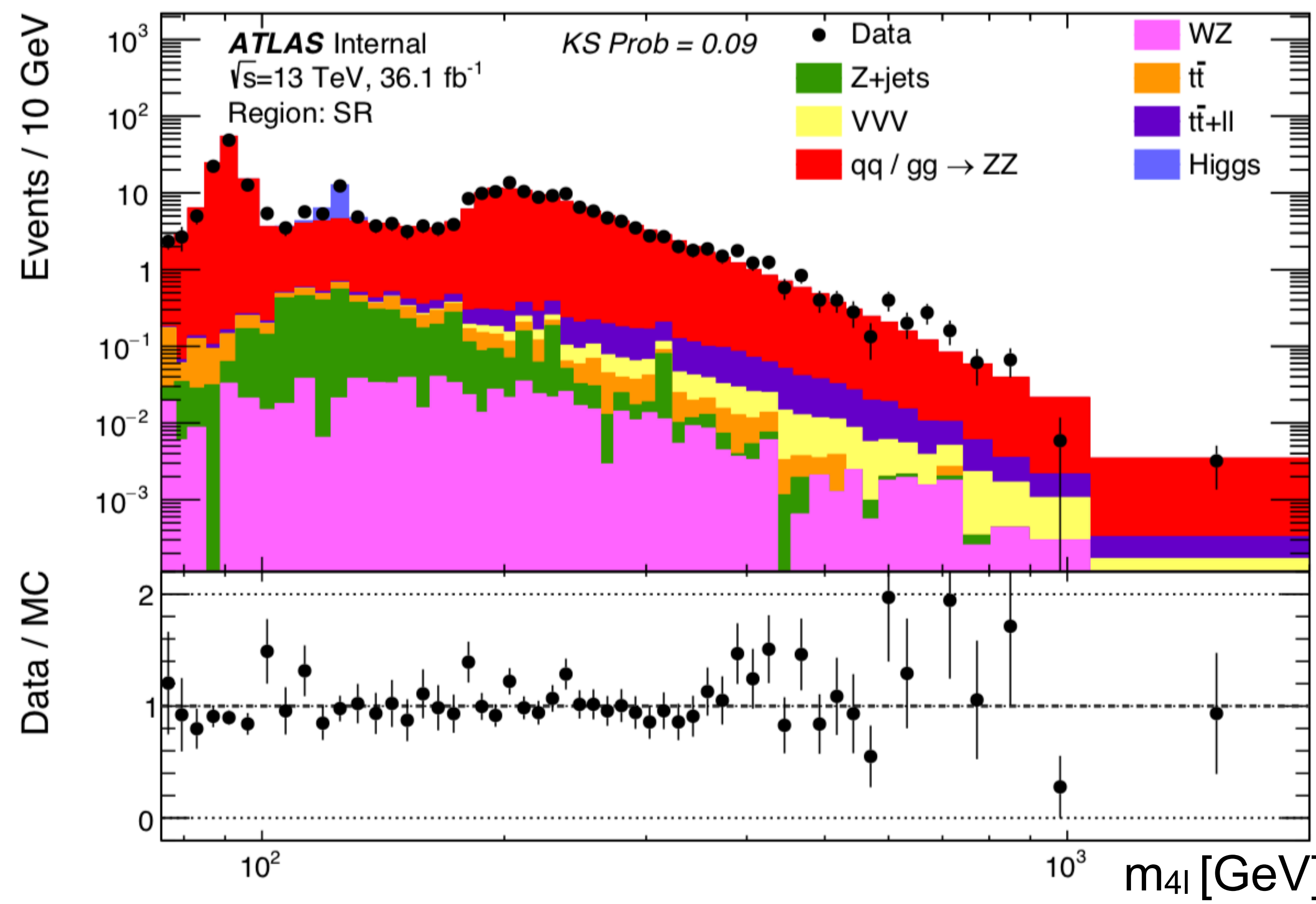
Double differential in p_{T4l}, y_{4l}, D_{ME} (ME discriminant).

Event selection - largely frozen
4l, $\Delta R(l,l) > 0.05$, $m_{ll} > 5$ GeV for OSSF pair, p_T>20, 10 GeV.
Leptons from two OSSF pair closest to Z mass.

Make the fiducial region as inclusive and re-interpretable as possible.

Larger phase-space than previous analysis, especially at low m4l

Leptonically decaying taus allowed in fiducial definition.



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$ZZ \to 4\ell$

EFT sensitivity probed with additional observables

$$m(Z),\ \Delta\phi(ZZ),\ \Delta Y(ZZ),\ p_T(Z),\ \cos\theta^*_{1,2}$$

$\cos\theta^*_{1,2}$ = angle of negatively charged lepton between lab and rest frame of Z_1 or Z_2

Ongoing work:
Data-driven background for reducible backgrounds

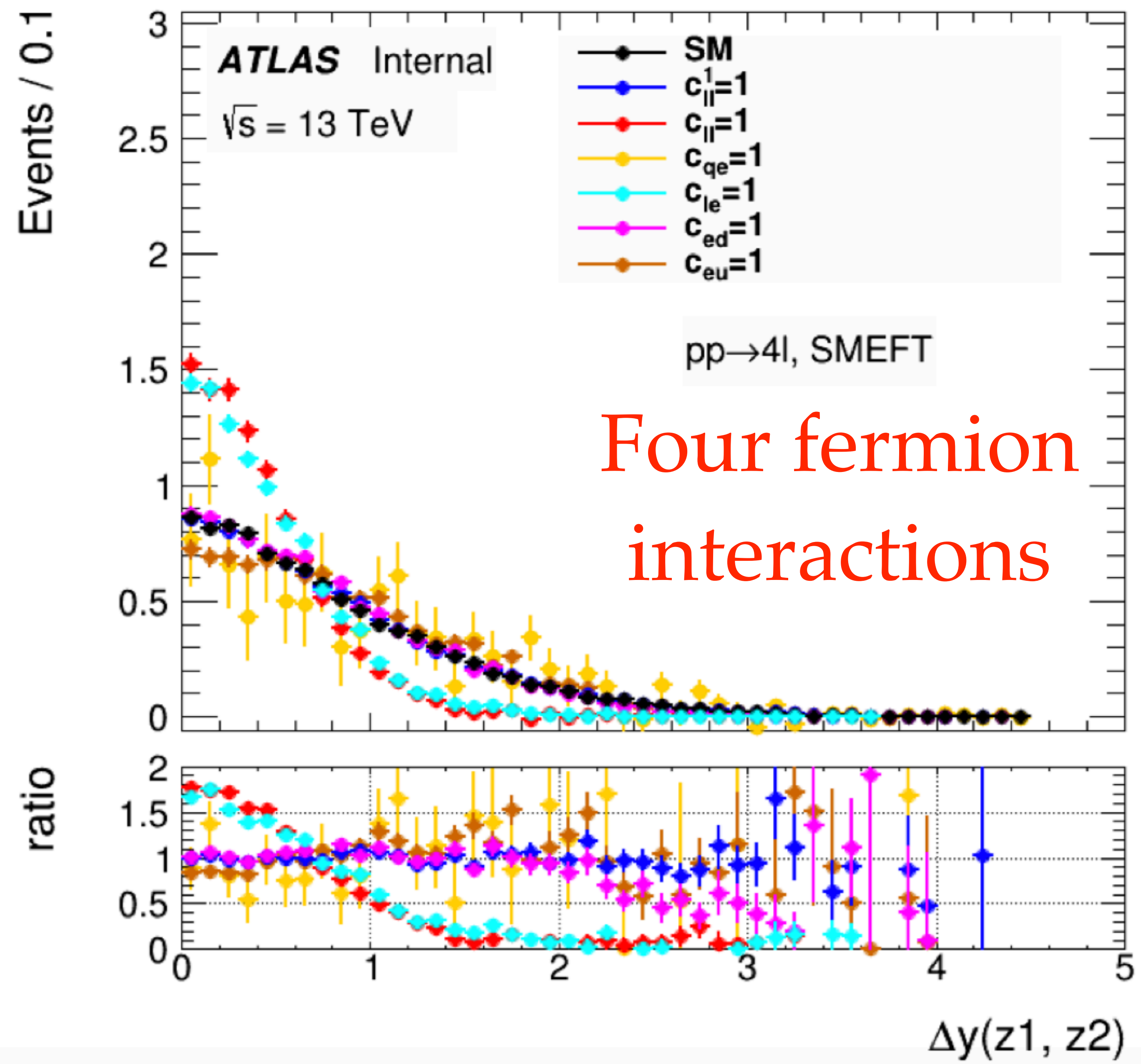
Binning - possibly loosen purity for high stats bins

Investigating applying "pre-unfolding" correction factors to the leptons, by applying the inverse measured efficiencies per-lepton in our events before correcting the data.

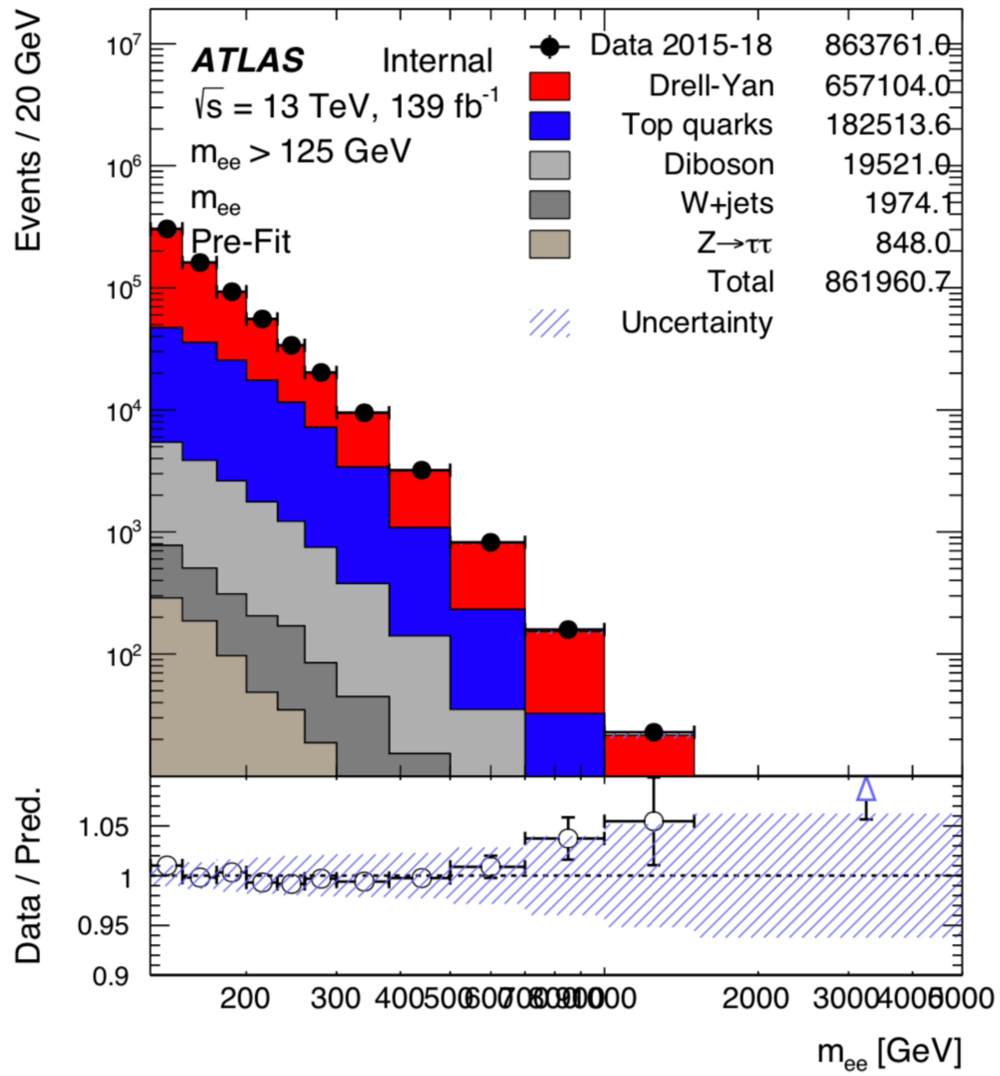
Include systematic uncertainties

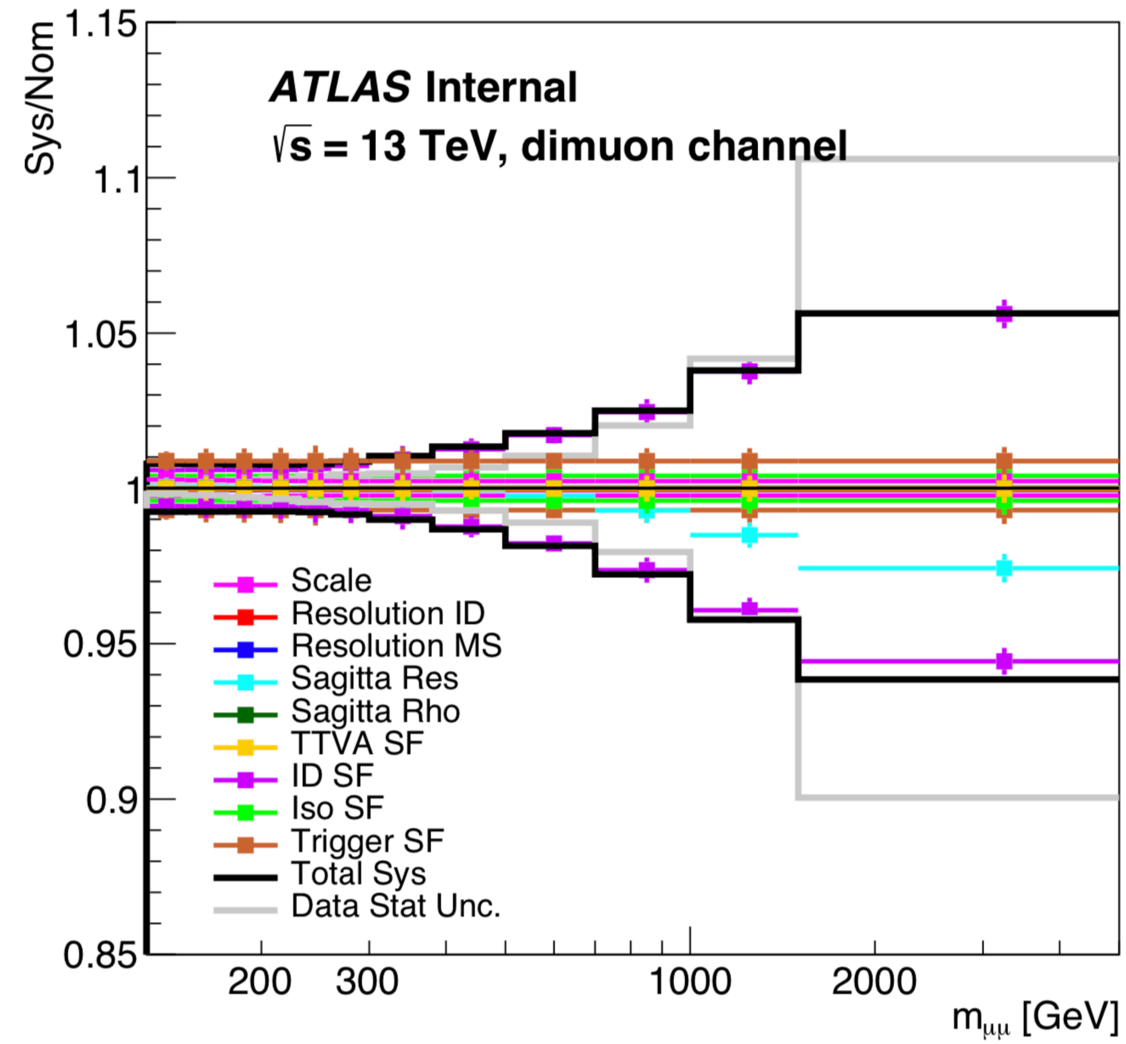
Interpretations of unfolded cross-sections
Z→4l BR extraction and possibly EFT interpretation

EB request planned in 1-2 months



High Mass DY — Neutral Current





Full Run2 precision measurement of high mass DY
→ important test of QCD and constraints on PDFs
→ High sensitivity to 4-fermion EFT operators (arXiv:1609.08157)
→ Can constrain running of EW couplings α_1 and α_2 (arXiv:1410.6810)

Measure double diff'ly $116<m_{ll}<3000$ GeV and $0<y_{ll}<2.4$
Include forward electrons $y_{ll}<4.9$
Syst limited up to 1 TeV; 2% precision up to m=500 GeV

Main challenge:
Large $t\bar{t}$ contribution ~ 30-35%
Estimate using data eμ control region
EFT interpretation starting now
EB request this autumn

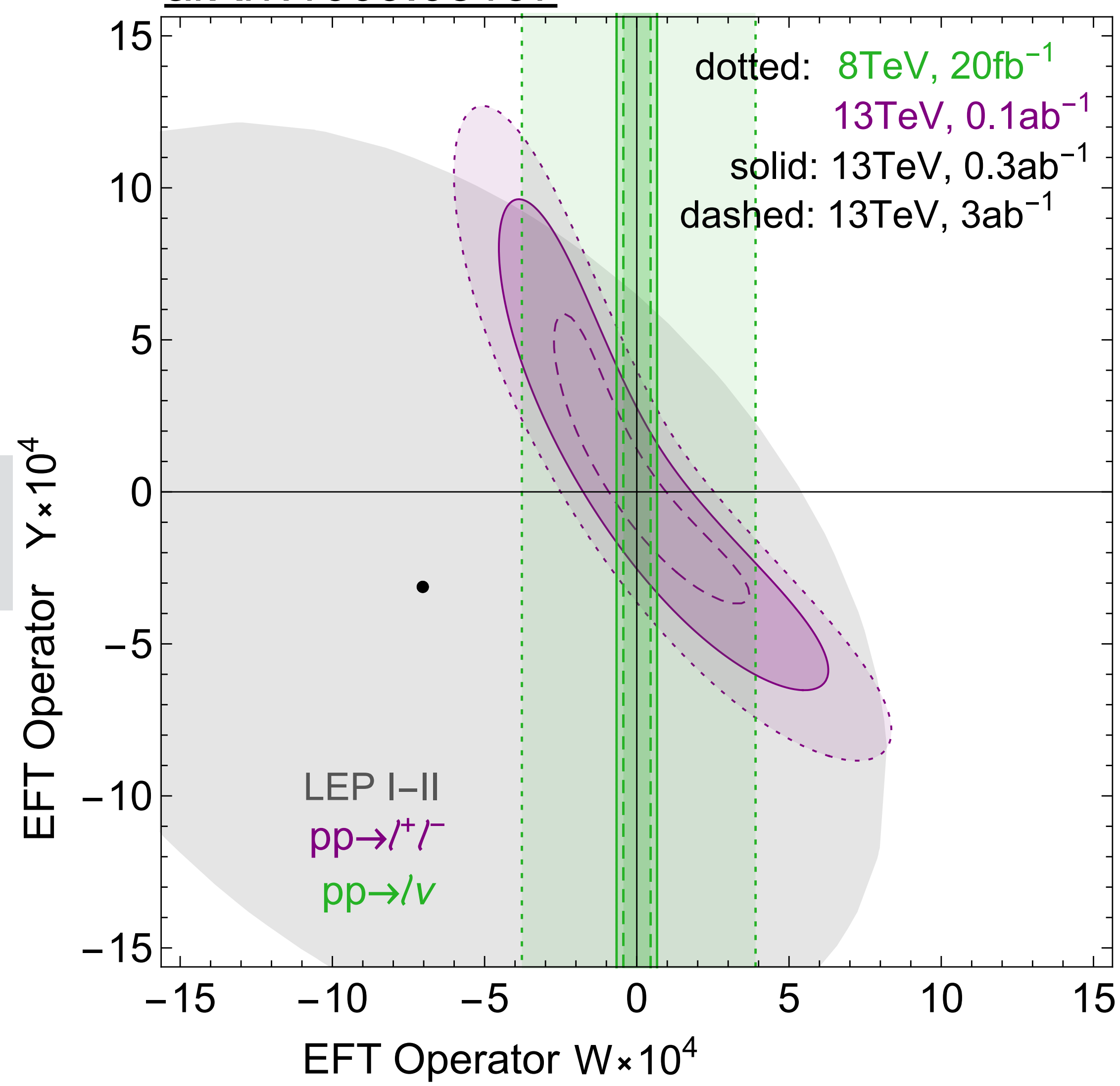
ANA-STDM-2018-42

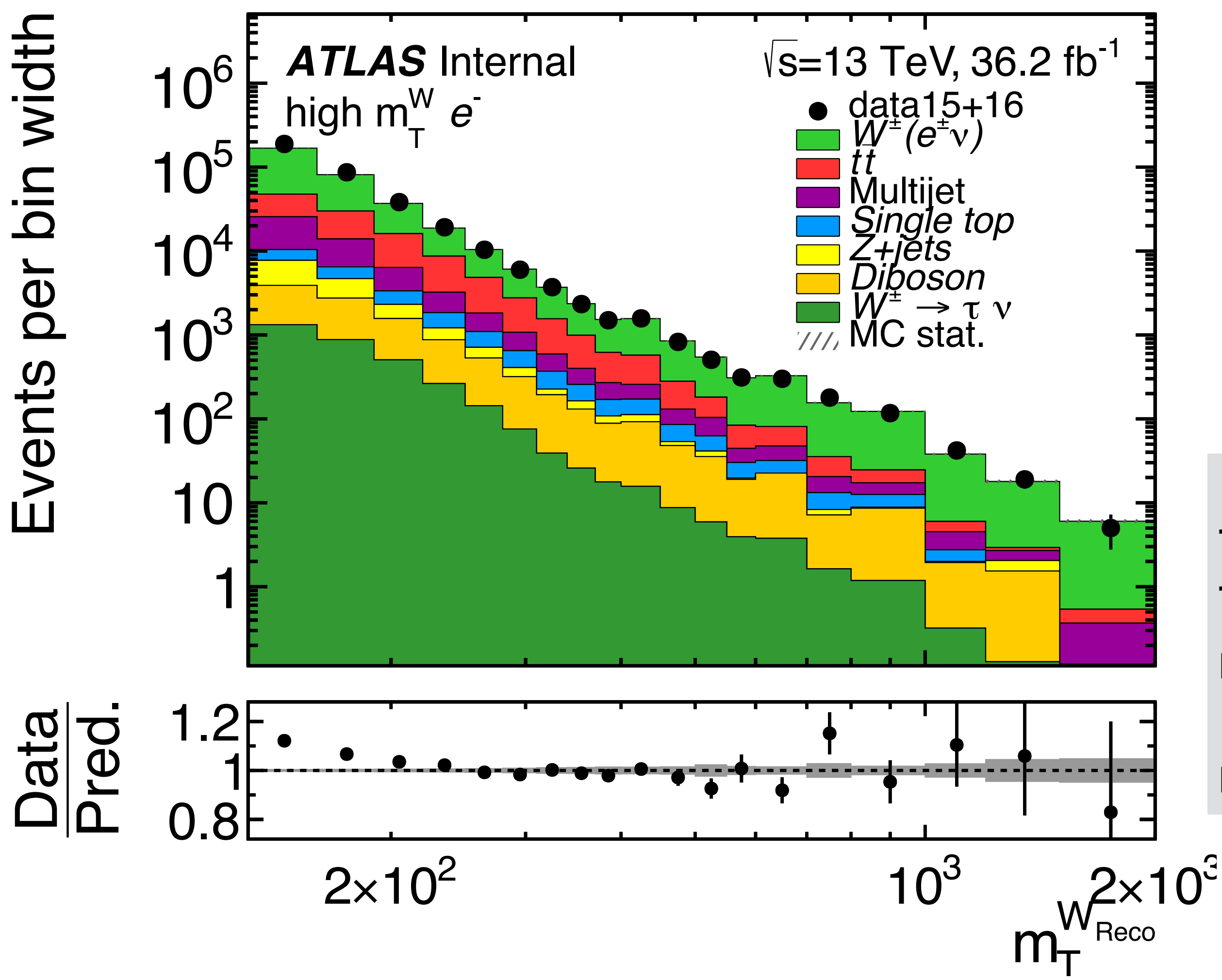
High Mass DY — Charged Current High m_T $W^\pm$

- Parallel charged current $W^\pm \to \ell\nu$ measurement
- Higher SM cross-section than neutral current DY
- Unfolded double differential cross section in m_T and lepton η
- Measure differential lepton charge asymmetry vs m_T
- Interpretations:
  - PDF constraints
  - EFT interpretation together with $Z/\gamma^* \to \ell\ell$ channel

100 fb^{-1} NC $Z/\gamma^* \to \ell\ell$ data reaches LEP precision
20 fb^{-1} CC $W^\pm \to \ell\nu$ data surpasses LEP by factor 4!

arXiv:1609.08157





Full Run2 analysis
Trigger, GRL
Tight electron p_T > 65 GeV
no loose leptons
$E_{T,miss}$ > 65 GeV
m_T > 130 GeV

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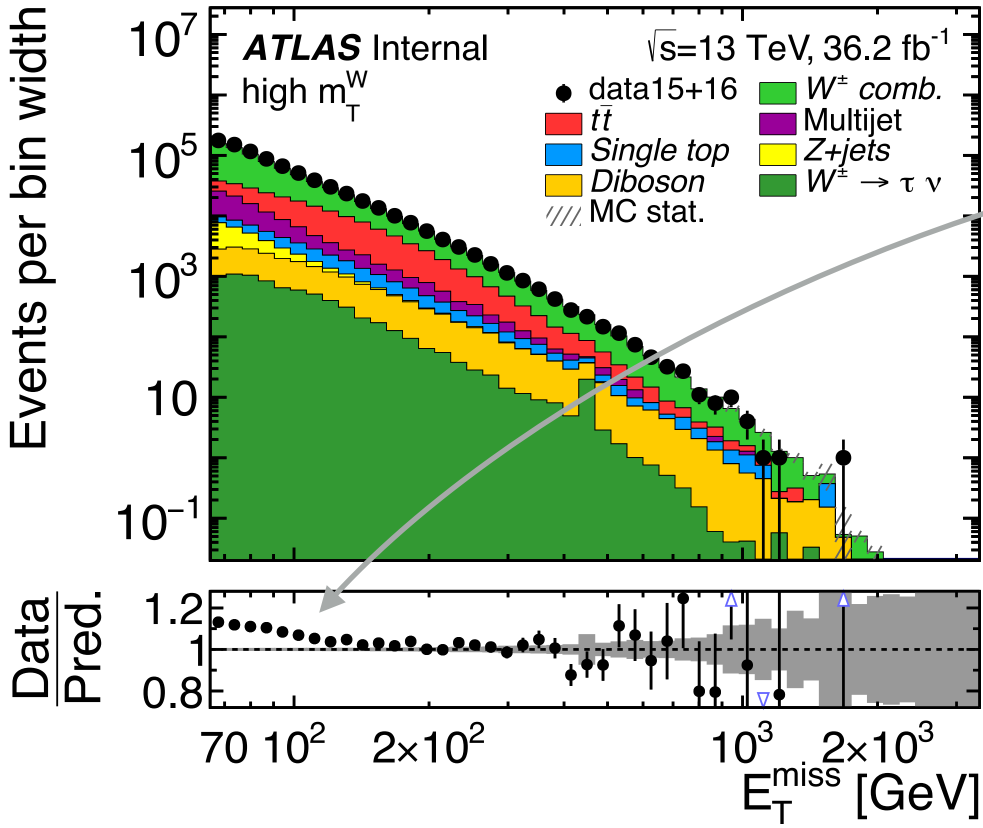
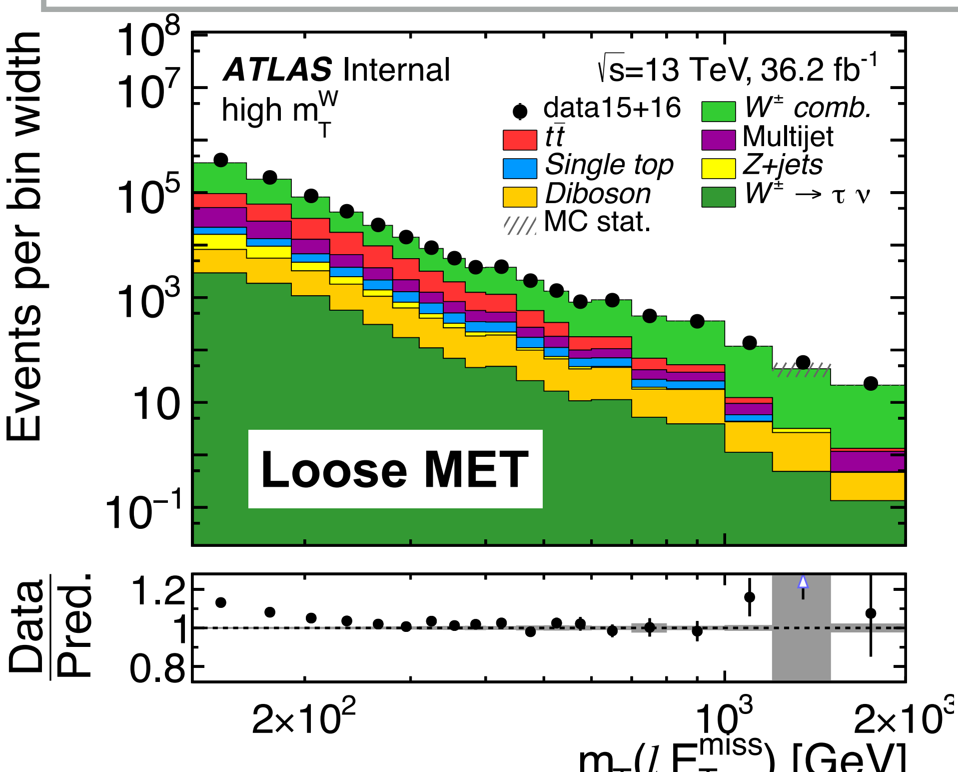
High Mass DY — Charged Current High m_T W±



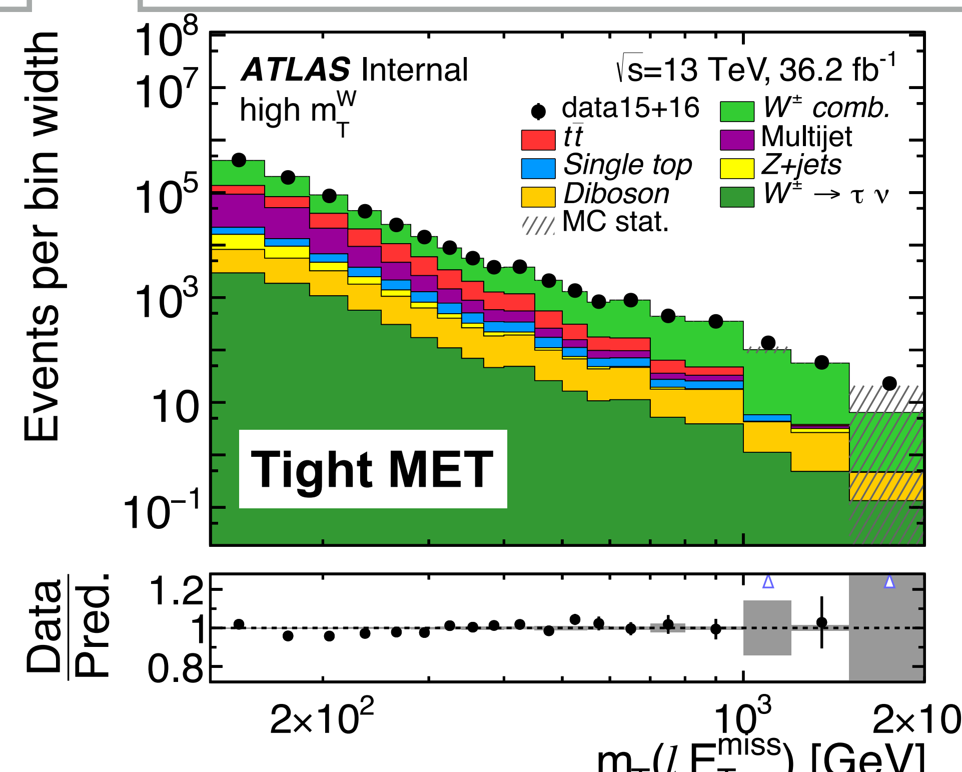
- Long-standing problem of ~15% MET mismodeling
- Also seen in W' searches
- Just within sys uncertainty

Discrepancy appears to due to (mis)calibration of loose objects in MET calculation in multijet matrix method

Loose objects enter MET with electron calib



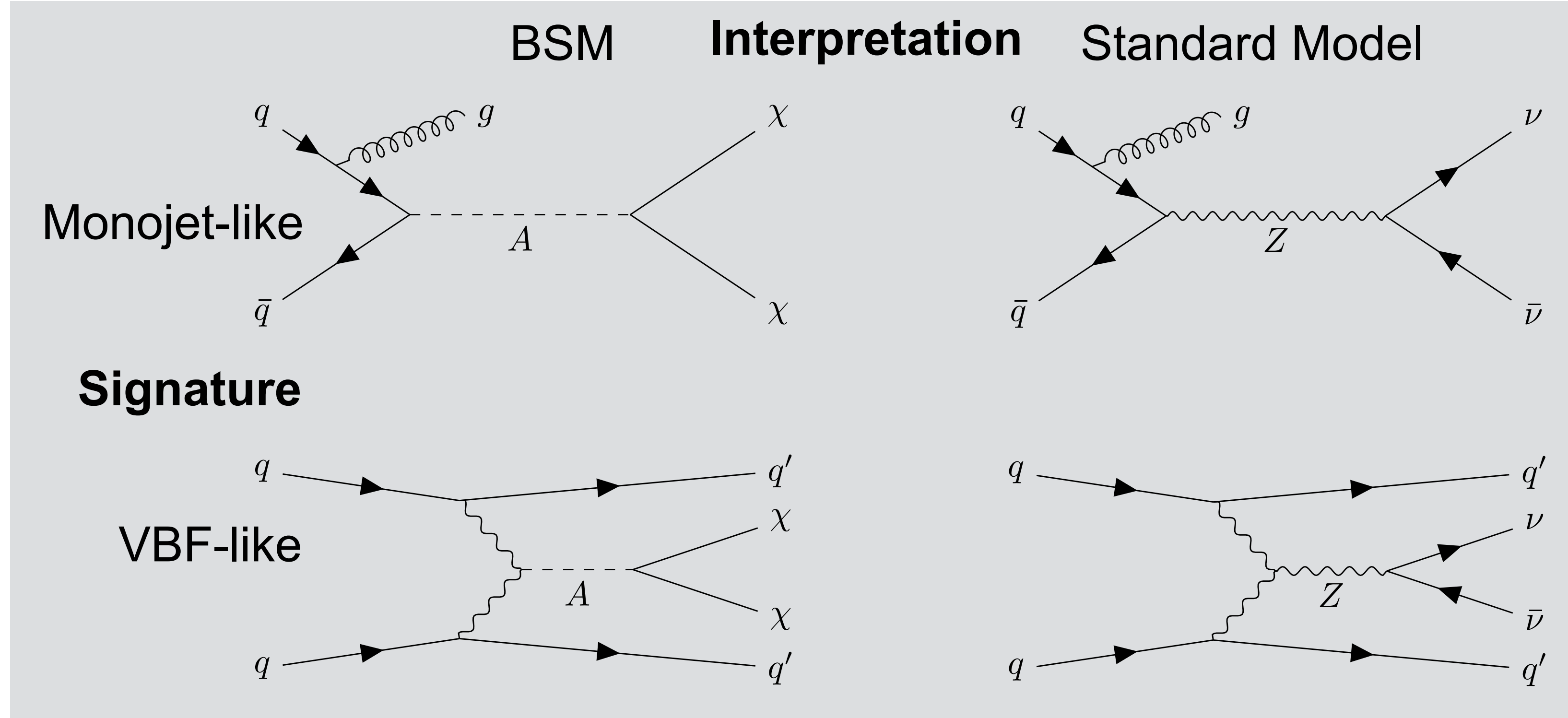
Tight objects enter MET with jet calib



Under discussion with Jet/MET group

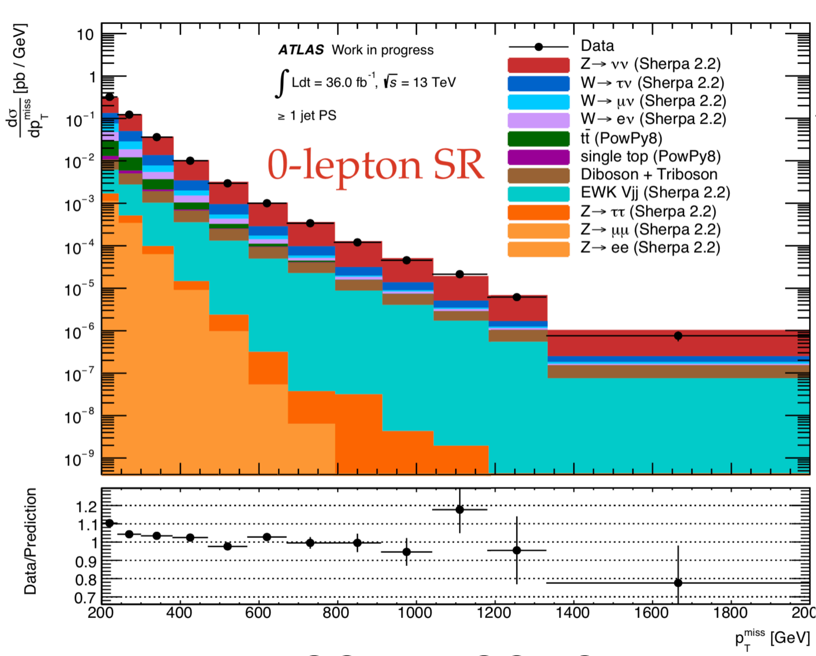
MET + X

Measure unfolded cross sections
Minimise model-dependence
→ allow BSM interpretation

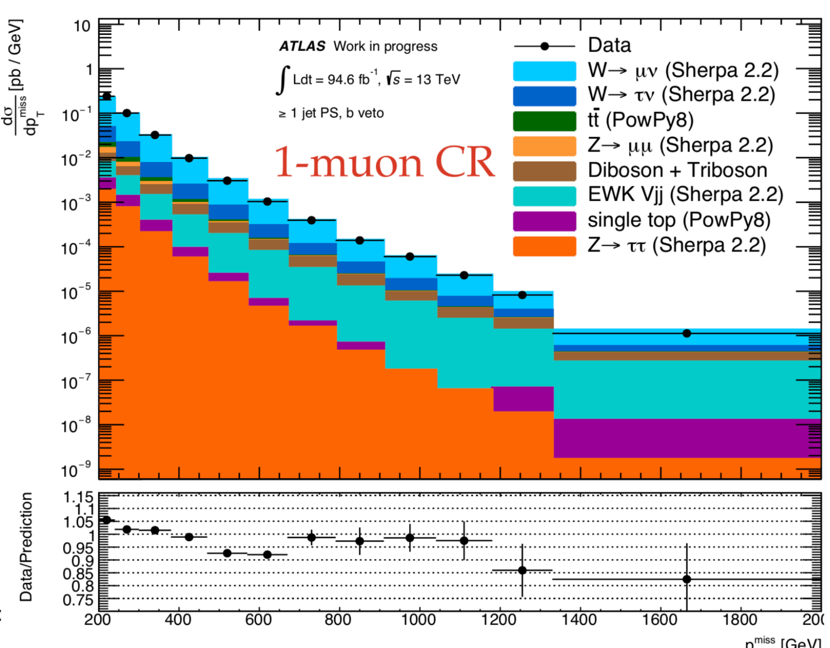


- Use full Run2 dataset
- Create pseudo-MET observable: treat charged leptons as invisible
- Measure in 0, 1, 2 lepton regions: $Z \rightarrow \nu\bar{\nu}$, $W \rightarrow \ell\nu$, $Z \rightarrow \ell\bar{\ell}$ for $p_{T,\mathrm{Miss}} > 200$ GeV
- Measure $Z \rightarrow \nu\bar{\nu}$+jets / $Z \rightarrow \ell\bar{\ell}$+jets ratio cancellation of uncertainties
- No background subtraction - constrain SM from control regions ($\ell^{\pm}$ and $\ell^{+}\ell^{-}$)

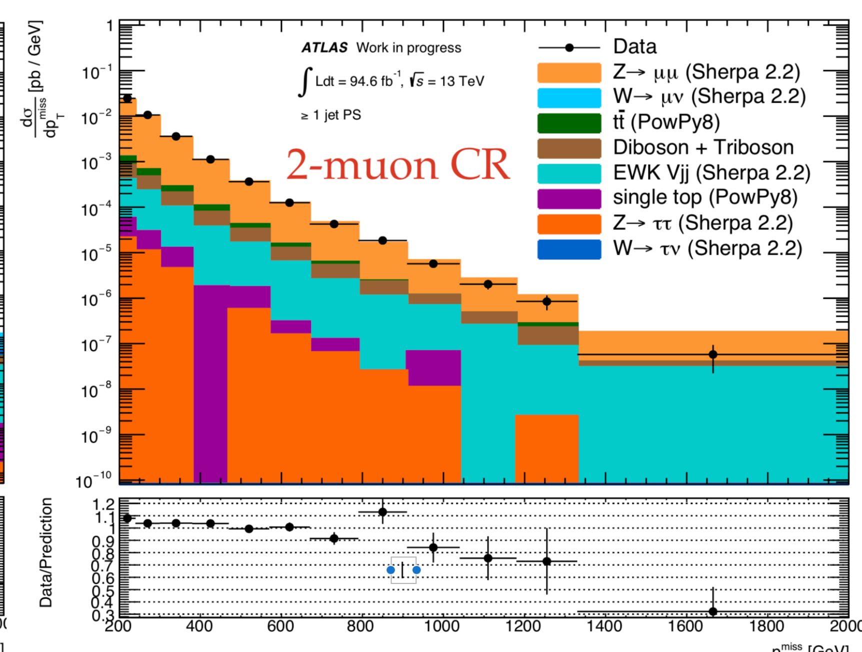
Finalising unfolding checks
EB Request this autumn



2015+2016



2018



2018

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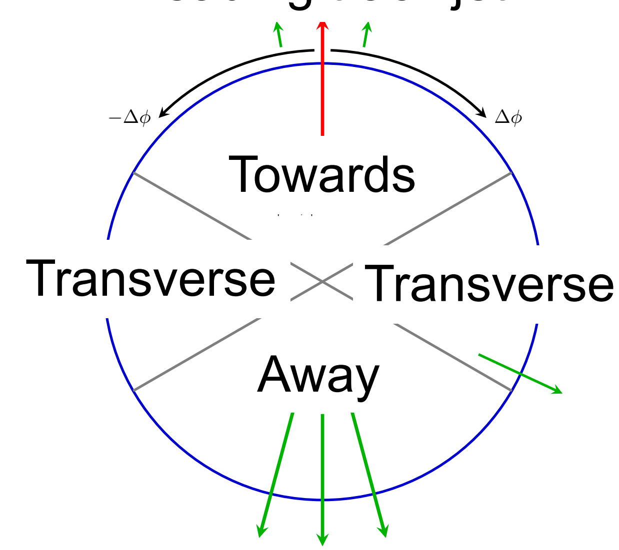
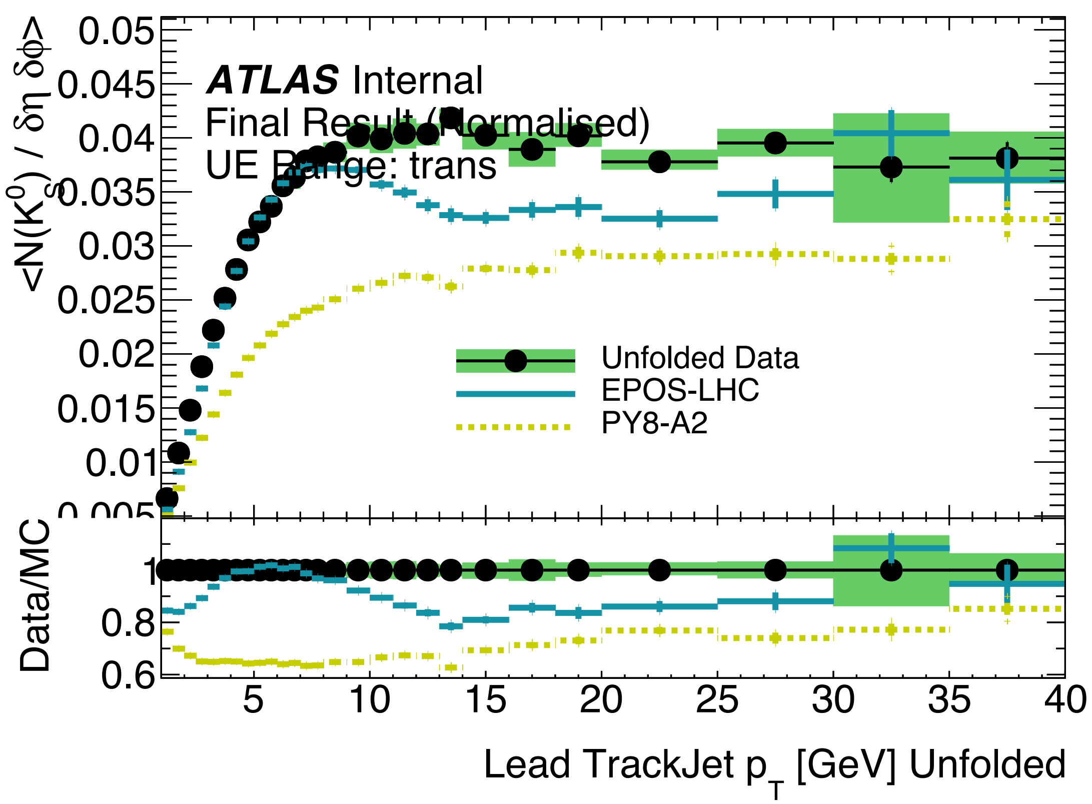
K^0_S and Λ Strange Particle Spectra of Underlying Event

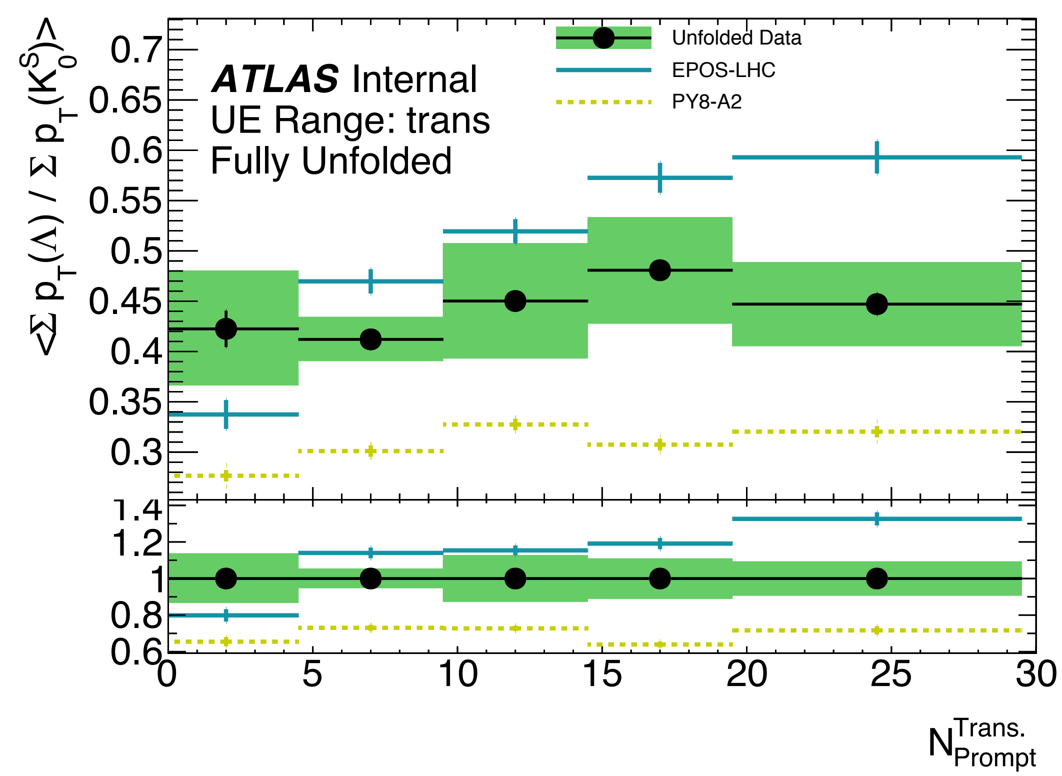
Measure strange particle spectra identified though displaced vertex weak decays:

$$K^0_S \rightarrow \pi^+\pi^-$$
$$\Lambda \rightarrow p + \pi^-$$
$$\bar{\Lambda} \rightarrow \bar{p} + \pi^+$$



Select events with track jet $10 \leq p_T \leq 35$ GeV
Upper cut ensures no leakage of energy into Transverse region
Measure $\langle N \rangle$ and $\langle \Sigma p_T \rangle$ as function of $N^{\text{Trans.}}_{\text{Prompt}} \propto$ Nr MPI





Trans Region: No dependence on track-jet p_T above 10 GeV
Other regions shape described better by Py8, but ~30% too low
EPOS tune describes low p_T region well, but not high p_T shape

Py8-A2 tune underestimates Λ yields and $\langle \Sigma p_T \rangle$
EPOS shape is wrong

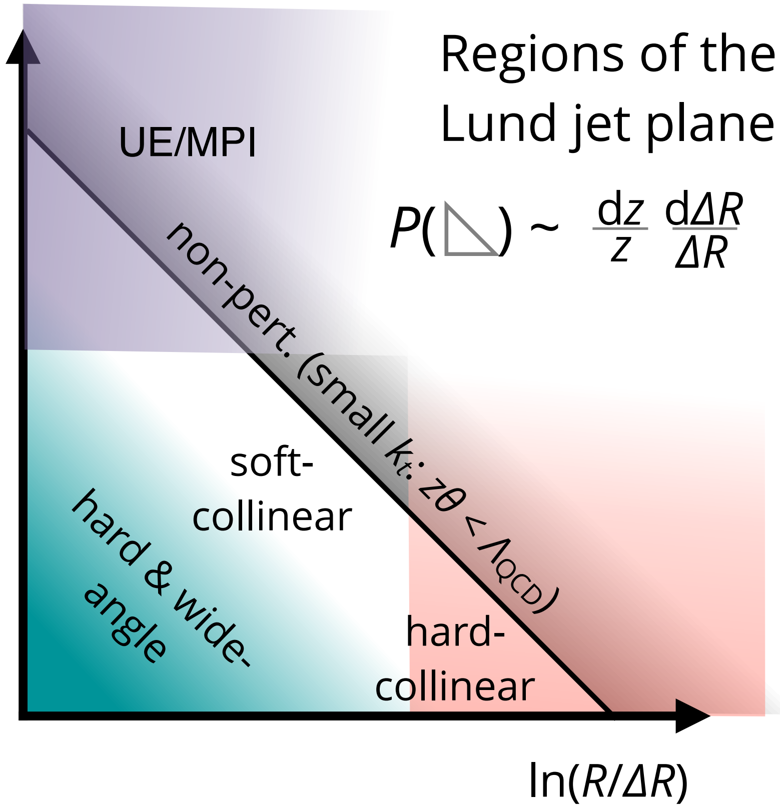
In EB Review

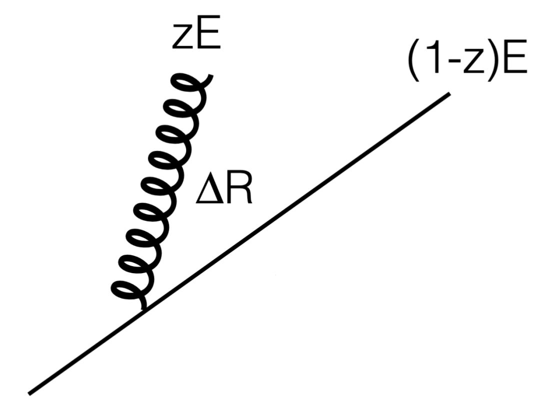
ANA-STDM-2018-60

Lund plane:
Phase-space map of soft gluon emission in:
- momentum fraction z
- opening angle / separation ΔR

Factorises physical effects:
perturbative vs non-perturbative region
underlying event
multiple parton interactions
collinear / wide angle emission

Powerful representation of jet radiation patterns

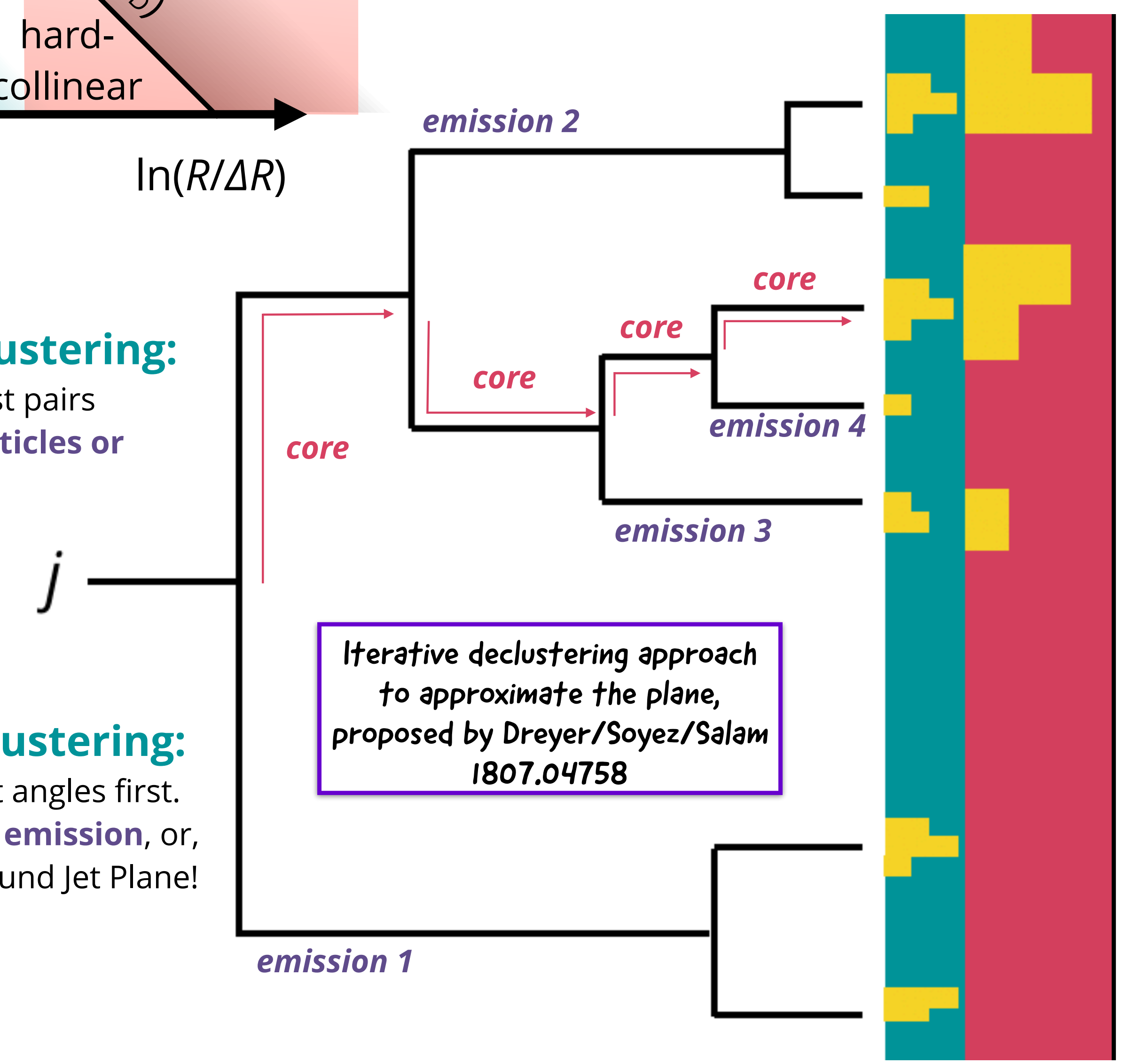




- Use jet clustering algorithm e.g. Cambridge/ Aachen
- Decluster jet stepwise following core of jet
- Each clustering step of proto-jet approximates point on Lund plane

1. C/A Reclustering:
Combine closest pairs of **charged particles or tracks!**

2. C/A Declustering:
Unwind, widest angles first. Each step is an **emission**, or, a point in the Lund Jet Plane!



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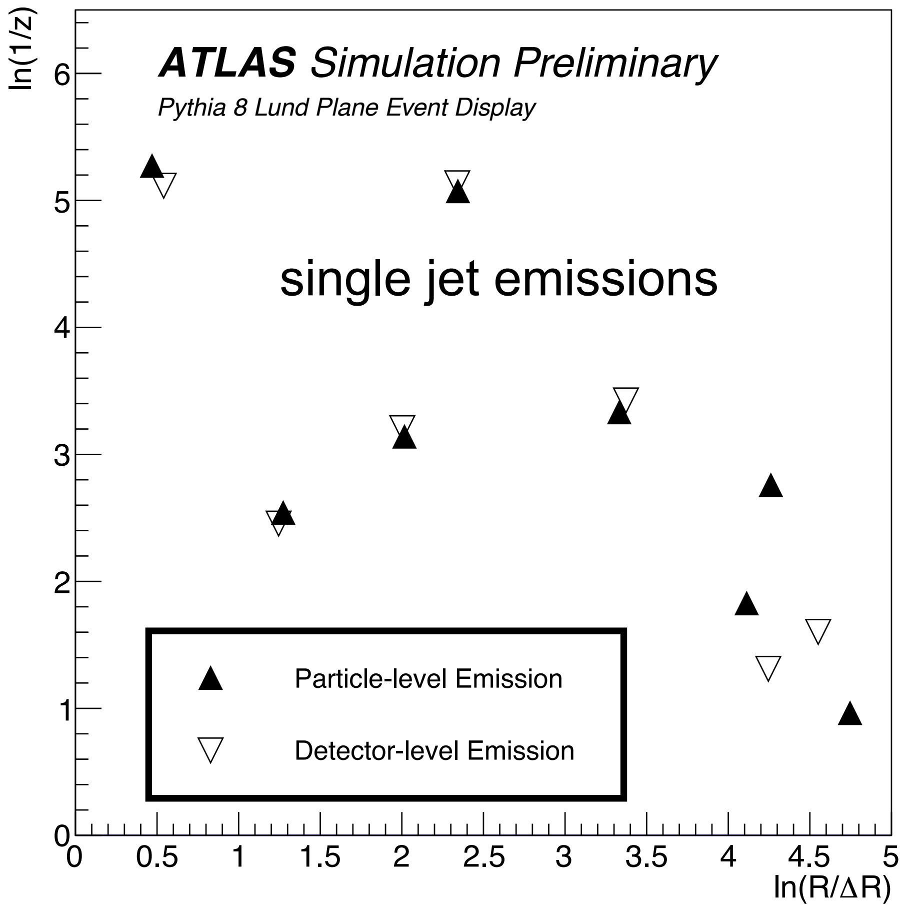
Lund Plane



Unfold data using geometric matching of emissions at truth / reco level

Use iterative Bayesian unfolding to correct for detector effects - 4 iterations

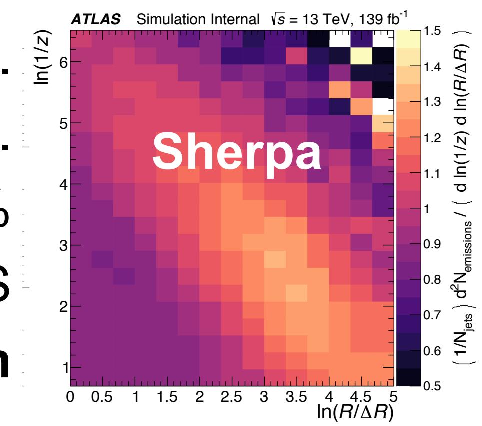
MC simulations compared to unfolded data.

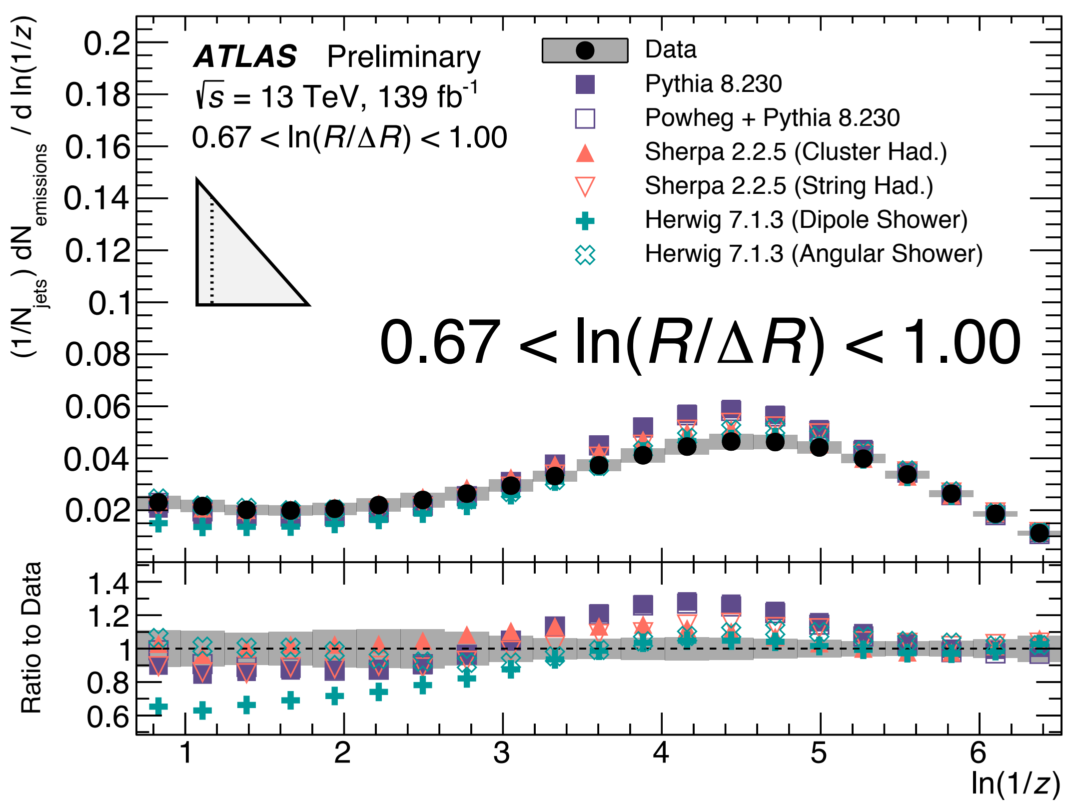
None compatible across entire 2D space.

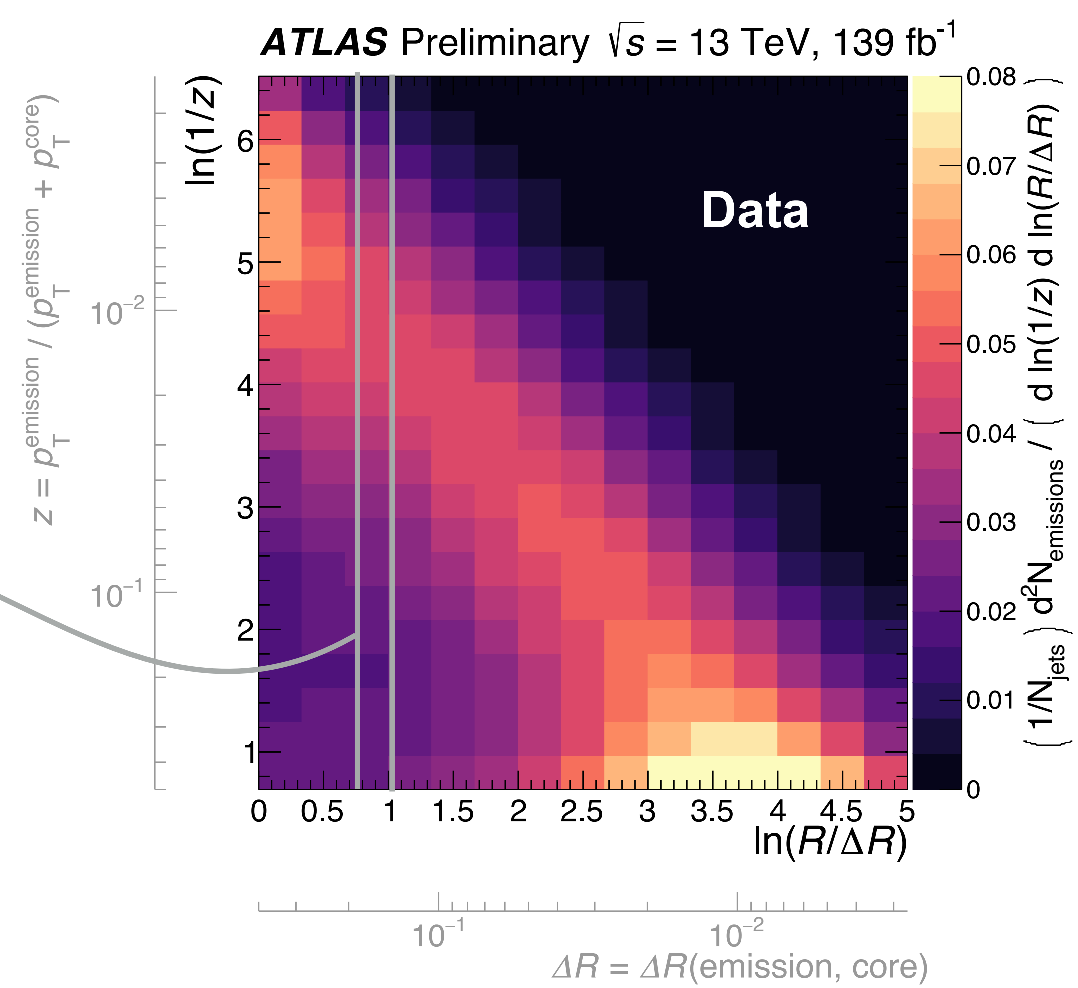
Precision better than 10%

Largest uncertainty due to MC modelling or JES

Paper draft in preparation





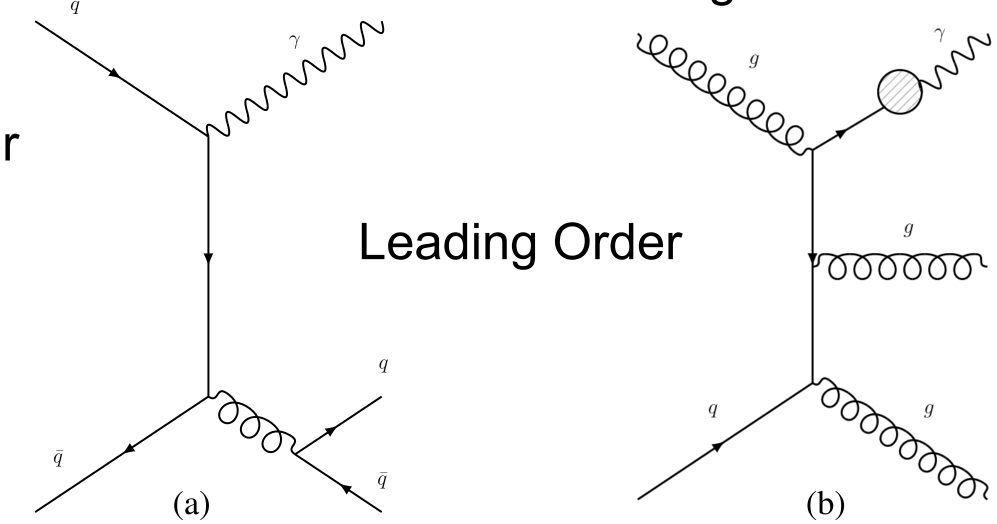


Photon + 2 jets

Prompt / direct isolated photon production offers test of pQCD
Kinematic correlations of photon & jets probes dynamics of hard scatter
Use to tune MC models

Direct Fragmentation

Leading Order



Fragmentation enriched region: $E_T^{\gamma} < p_{T,2}^{\text{jet}}$

Direct enriched region: $E_T^{\gamma} > p_{T,1}^{\text{jet}}$

Many observables under study:

$$E_T^{\gamma},\ p_T^{\text{jet}},\ |\Delta y^{\gamma-\text{jet}}|,\ \Delta\phi^{\gamma-\text{jet}},\ m^{\text{jet}-\text{jet}},\ \Delta\phi^{\text{jet}-\text{jet}},\ |\Delta y^{\text{jet}-\text{jet}}|,\ m^{\gamma-\text{jet}-\text{jet}}$$

Selection:
E_T^{γ} > 150 GeV
p_T^{jet} > 100 GeV and $\Delta R^{\gamma-\text{jet}}$ > 0.8 and $|y^{\text{jet}}|$ < 2.5

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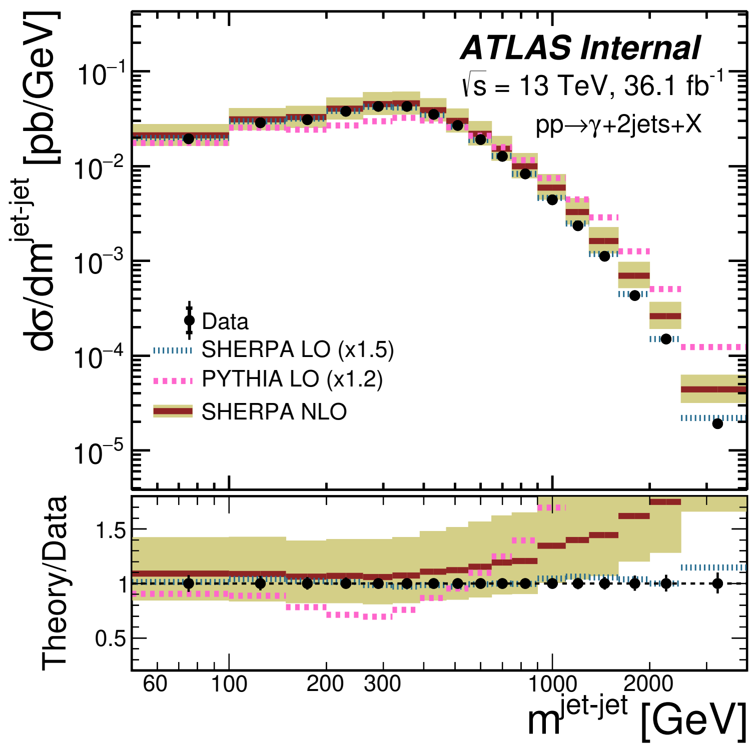
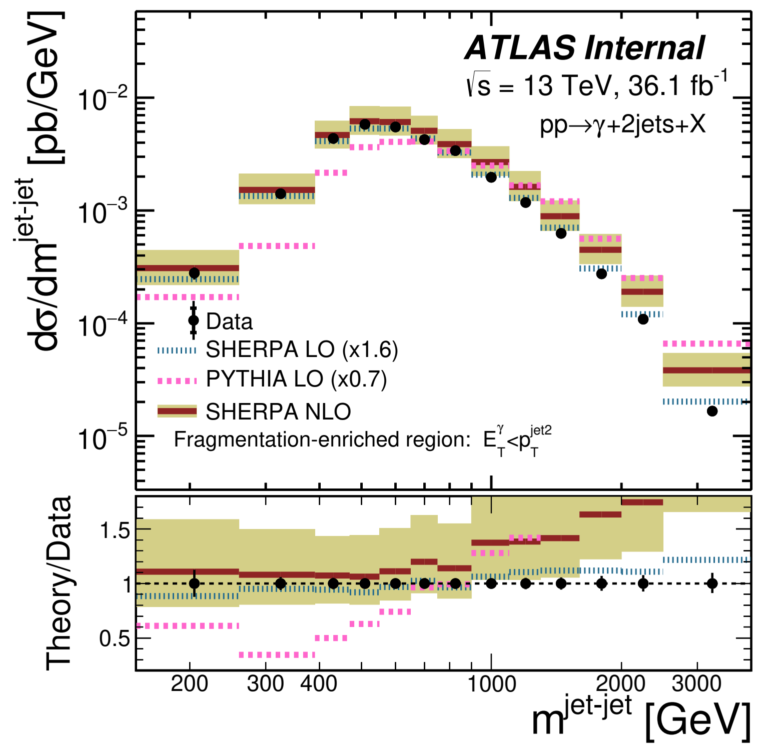
Photon + 2 jets

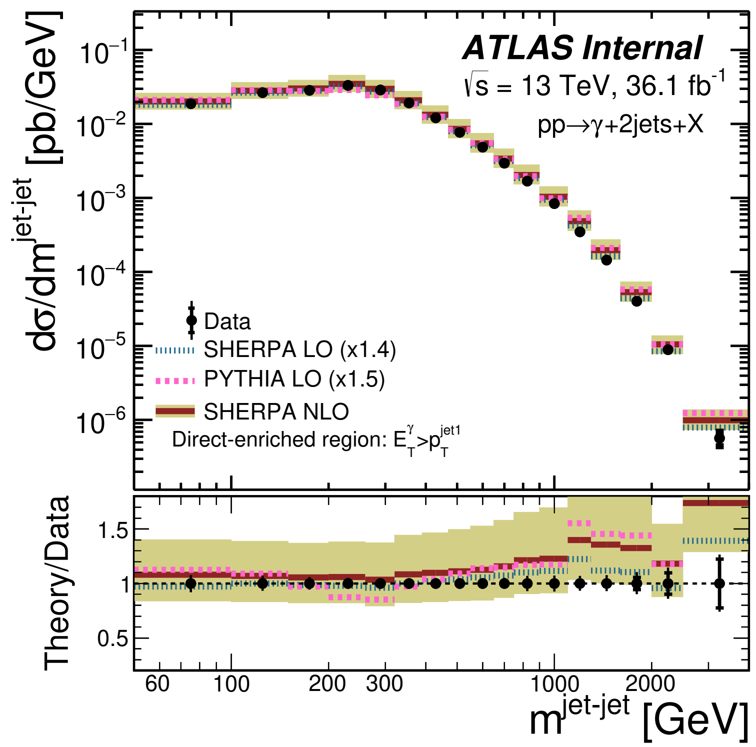
Inclusive

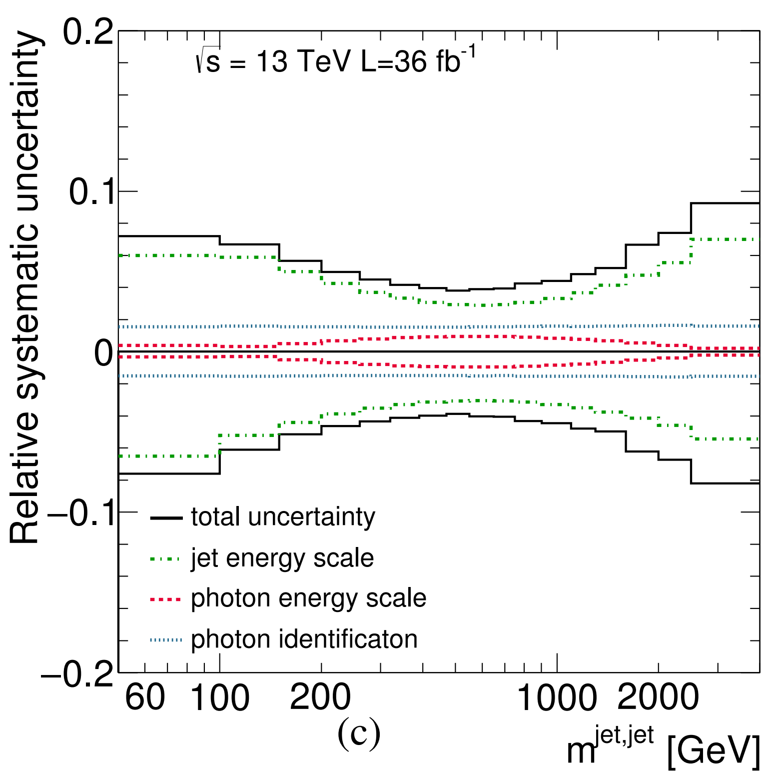


Fragmentation



Direct





Sherpa NLO describes data well except at high
$|\Delta y^{\gamma-\text{jet}}|$, $|\Delta y^{\text{jet}-\text{jet}}|$, $m^{\text{jet}-\text{jet}}$, $m^{\gamma-\text{jet}-\text{jet}}$

Sherpa LO provides good shape description except at
E_T^{γ}, $m^{\text{jet}-\text{jet}}$, $m^{\gamma-\text{jet}-\text{jet}}$

Experimental precision of 5-10% typically dominated by JES

Theoretical uncertainties larger than experimental

- μ_R, μ_F variation ~40%
- α_S ~ 4%
- PDFs ~ 1-5 %

Preparing draft for second circulation now

Event Shapes in Multijet Events

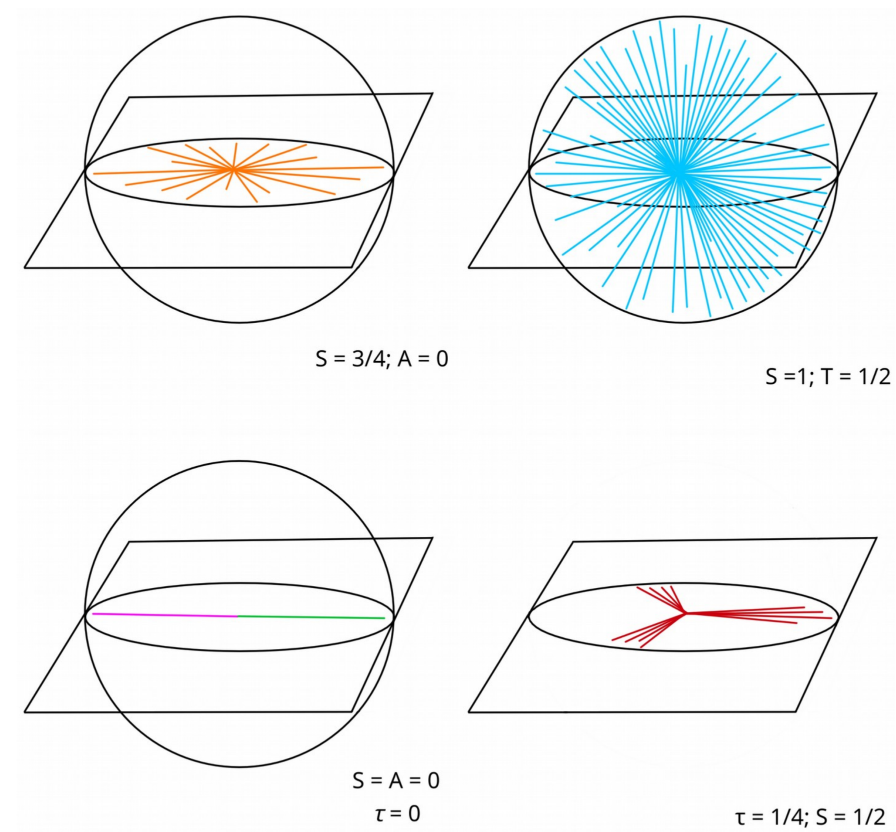
Describe geometric properties of hadronic jets
  homogeneity & isotropy of energy flow

Sensitive to
- hard / wide-angle emissions (at large values observables)
- resummation effects / soft logarithms (at small values of observable)

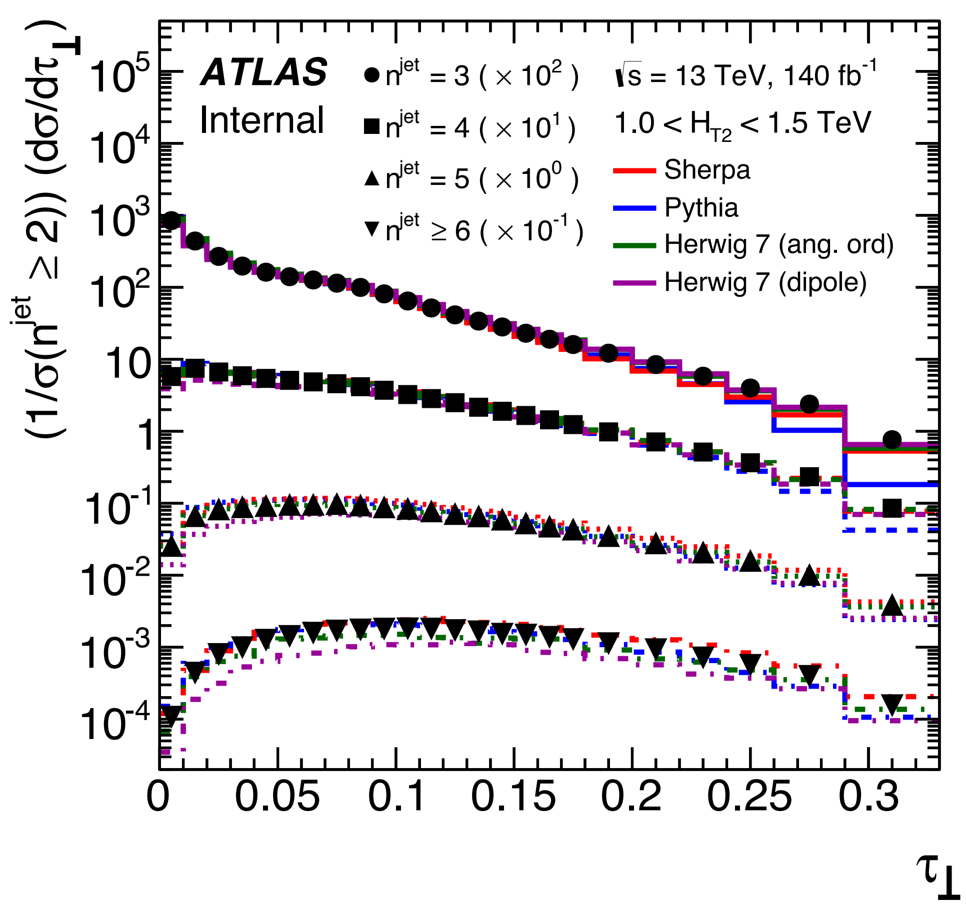
Several variables used: $\tau_\perp (= 1 - T_\perp)$, T_m , $S_\perp$, A , C , D

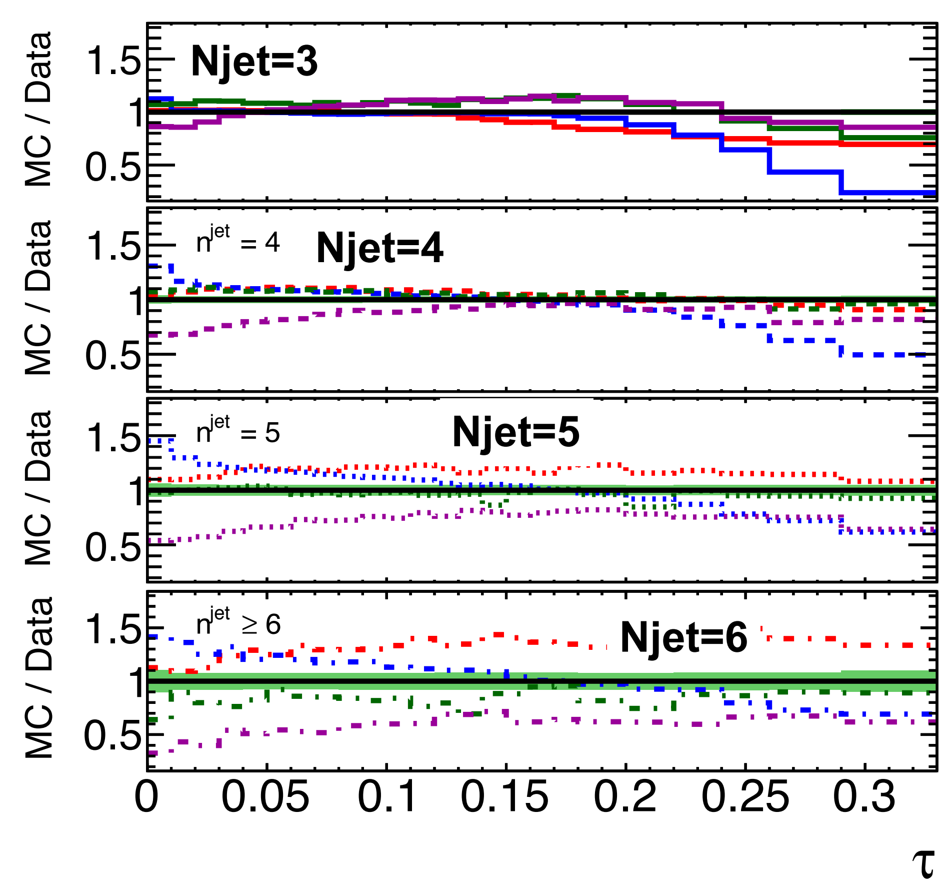
Transverse Thrust = $T_\perp = \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i |\vec{p}_{T,i}|}$ sum over jets

Thrust axis divides event in two hemispheres (dijets have low $\tau_\perp$)
Sphericity & Aplanarity describe homogeneity of event
Compare spectra as function of Njets



Full Run2 analysis 140 fb^{-1}
Use PFlow jets anti-kT(R=0.4)
p_T^{jet} > 100 GeV
$H_{T2} = p_{T,1}^{jet} + p_{T,2}^{jet}$ > 1 TeV





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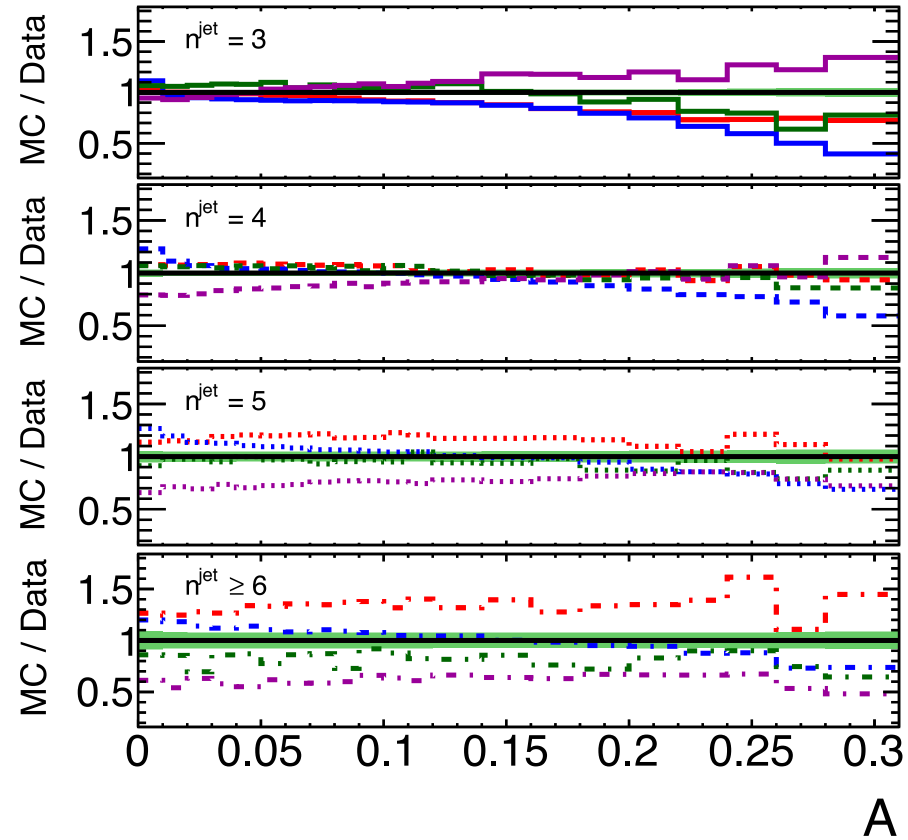
Event Shapes in Multijet Events

Compare to MC shower models / ME calculations:

- Pythia
- Herwig 7 (angular ordered shower)
- Herwig 7 (dipole shower)
- Sherpa

In 4 Njet bins x 3 H_{T2} bins x 6 observables
Spectra unfolded with Sherpa and Pythia

Uncertainties ~ 10%
Dominated by JES/JER or MC modelling

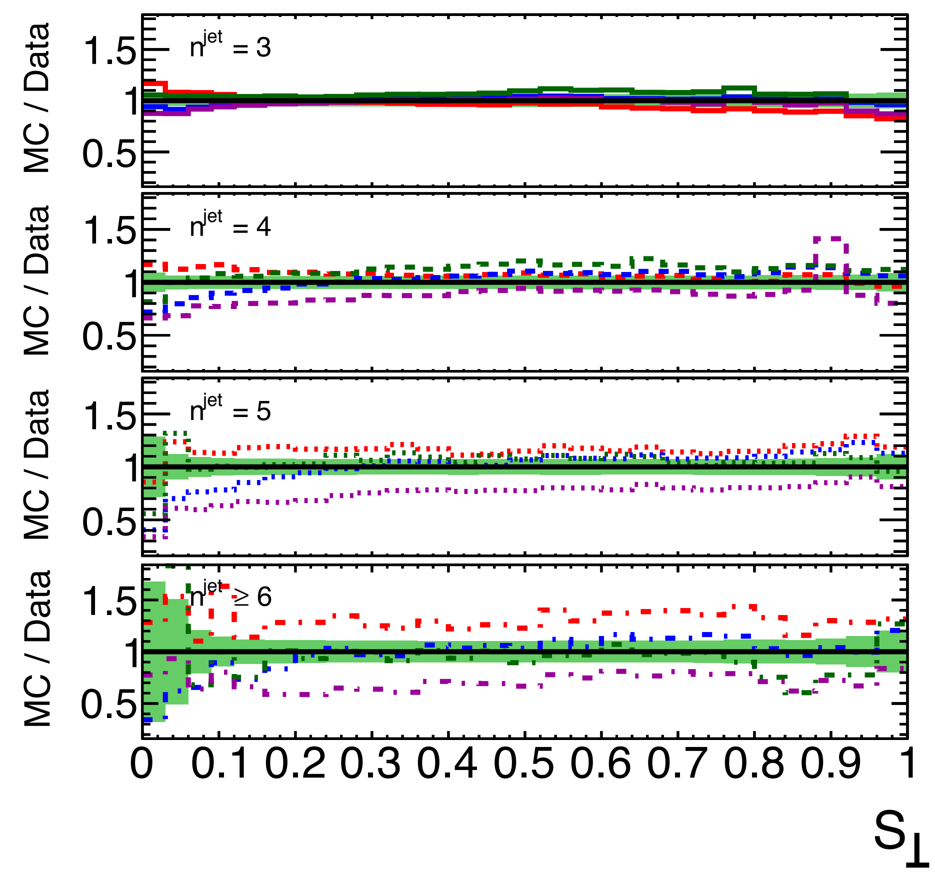


$1 < H_{T2} < 1.5$ TeV

Large Njet is generally worst described
only 2→2 and 2→3 processes included in ME

At low Njet Sherpa gives best description
Pythia & Herwig7 (ang.ord) are not bad

At large Njet Herwig7 (ang.ord) gives best description



$H_{T2} > 2$ TeV

Analysis in EB review

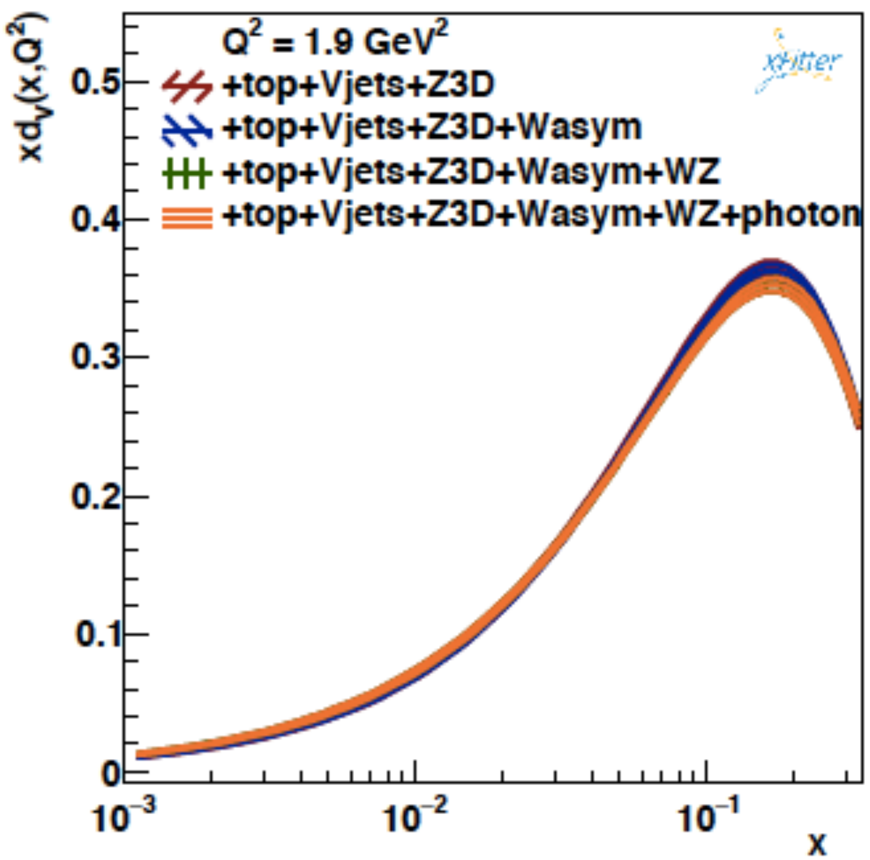
PDF Fits: W+jets, Z+jets, Z3D

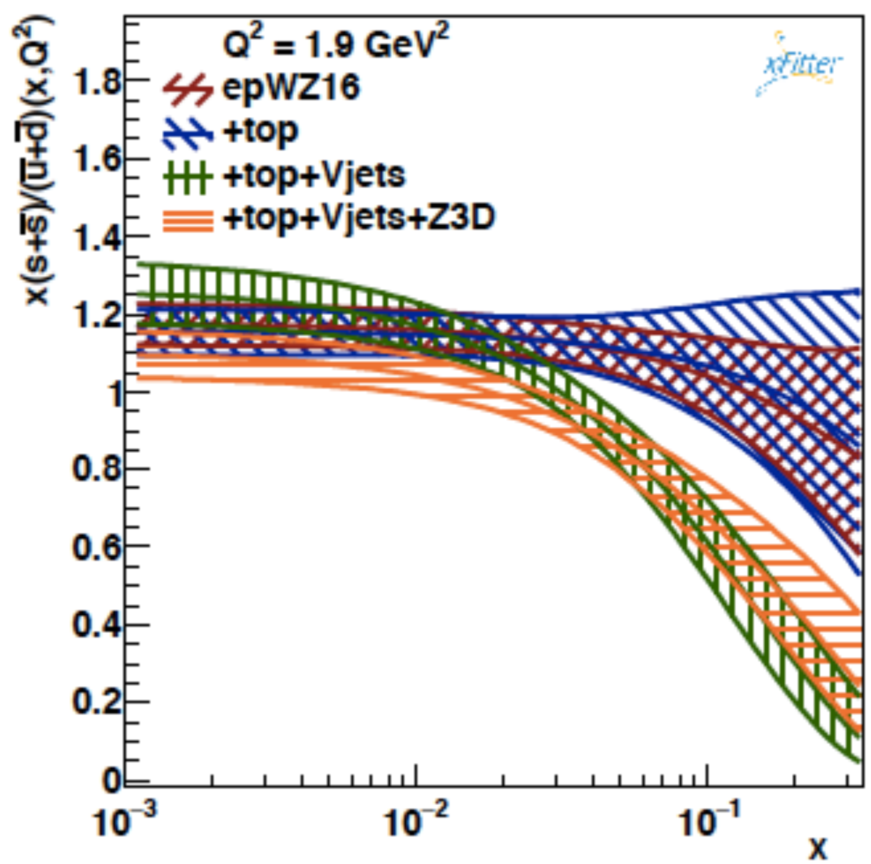
ATLASepWZ16 Fit
- combined HERA data
- precision W,Z cross sections √s=7 TeV

→

ATLASepWZ19 FitU
- combined HERA data
- precision W,Z cross sections √s=7 TeV
  (use e / μ data to correlate with W+jets)
- W+jets data √s=8 TeV
- mods to parameterisation , $Q^2_{min} = 10$ GeV²

ATL-PHYS-PUB-2018-017





Additional ATLAS data used in fits
- W+jets & Z+jets 8 TeV
- $t\bar{t}$ cross sections
- Z3D cross sections at 8 TeV
- direct photon production

Z3D: At large $|\cos\theta^*|$ and large |y| fiducial cuts suppress LO contributions → NNLO predictions to NLO accuracy

For this region use $A_{FB}(m,y)$ instead:

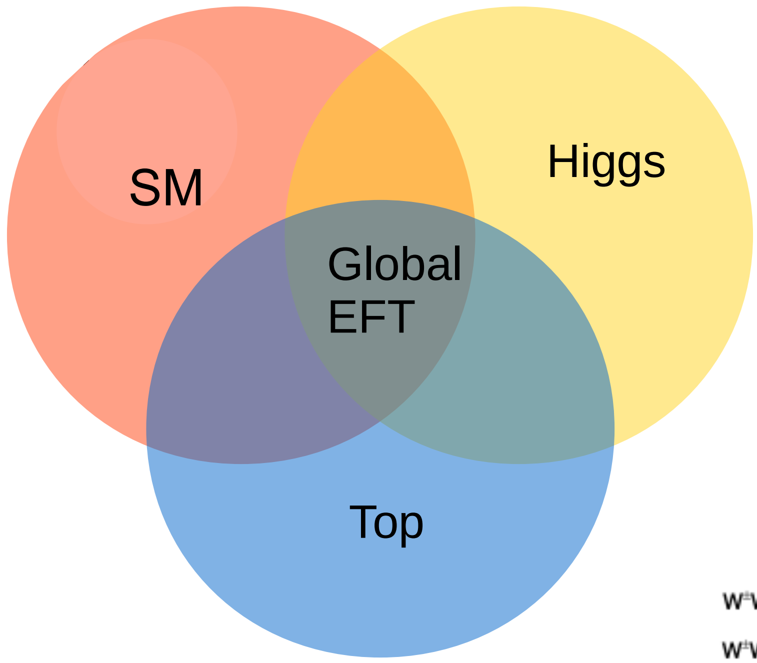
$$A_{FB}(m,y) = \frac{d^3\sigma_F - d^3\sigma_B}{d^3\sigma_F - d^3\sigma_B}$$

Some internal tensions arise adding Z3D to V+jets & $t\bar{t}$
7 TeV Z data partial χ^2/ndf 13.6/12 → 29.9/12 when adding Z3D

Ongoing discussion to include QCD scale uncertainties in fits
→ reduces tension (as expected)
→ doesn't affect impact of PDFs (mostly affects u_v , d_v , $\bar{s}$)

W+jets , Z+jets , Z3D
All variants confirm unsuppressed strange PDF at low x

Towards Global EFT Fit



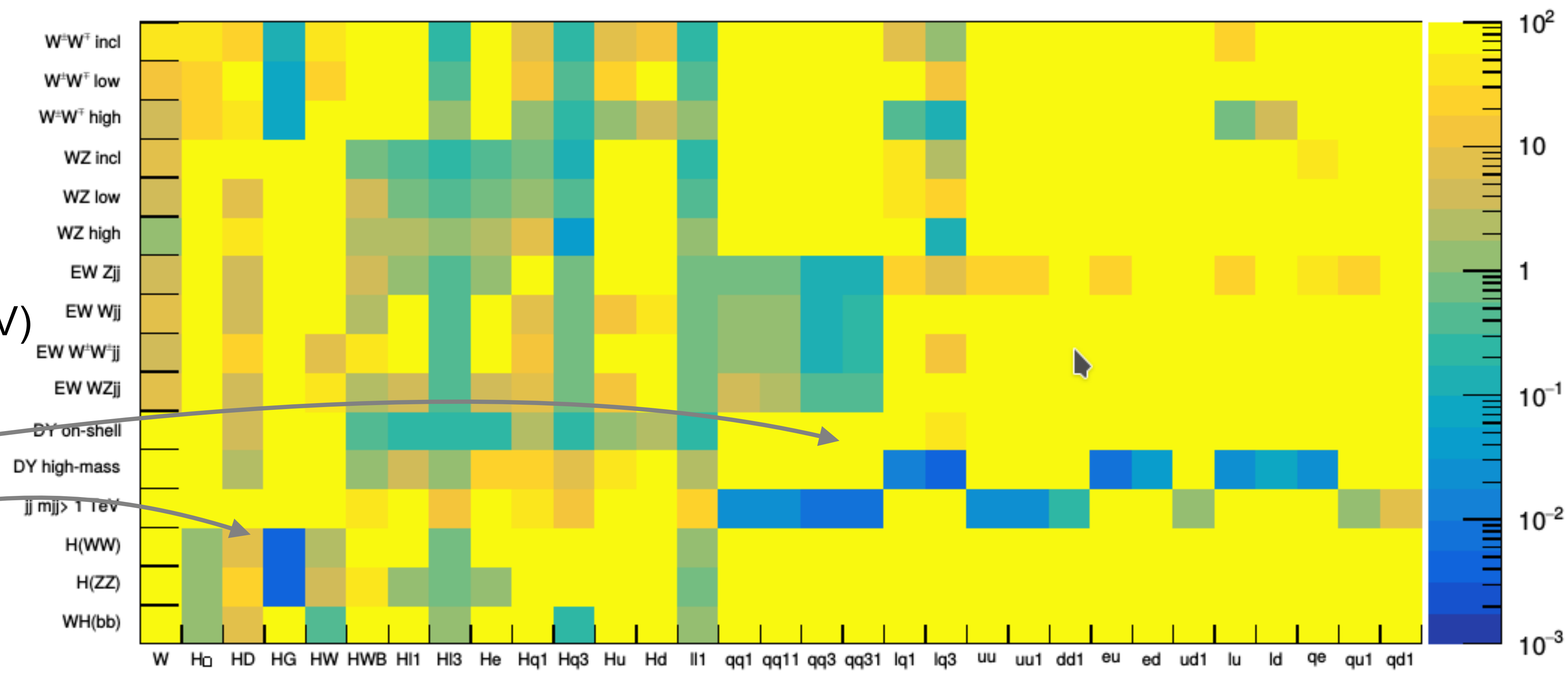
ATLAS Global EFT Efforts
1st workshop: https://indico.cern.ch/event/729117/
2nd workshop: https://indico.cern.ch/event/771170/
Working meeting: https://indico.cern.ch/event/809739/

First proof-of-principle combinations
WZ + same-sign WW Vector boson scattering (for quartic couplings)
SMWW + HiggsWW

Measurement sensitivity:

$$\frac{\sigma^{SM} - \sigma^{SM+EFT}}{\delta^{tot}}$$

Check EFT operators (Λ= 1 TeV)
High sensitivity in
- high mass Drell-Yan
- dijets production
- H→WW
- H→ZZ



> Need to have
Detailed information on analysis selection (cuts) → RIVET
Detailed information on unfolded results (+correlation) → HEPData
Good example: W/Z precision (→ PDFFits)

Try to agree with CMS (in view of later combination)
Some work ongoing with LHC EWWG group

SM Group concluded a very successful workshop in Belgrade (17-20th Sept.)
Lots of fruitful discussion with colleagues and theorists (Frank Krauss, Andrzej Siodmok, Matthieu Pellen)
Returned home enthused with many new ideas
About 30 ideas for new measurements! Almost all have no teams to work on them

Strong request from EFT theory community - publish DY separately for e, μ, τ cross sections

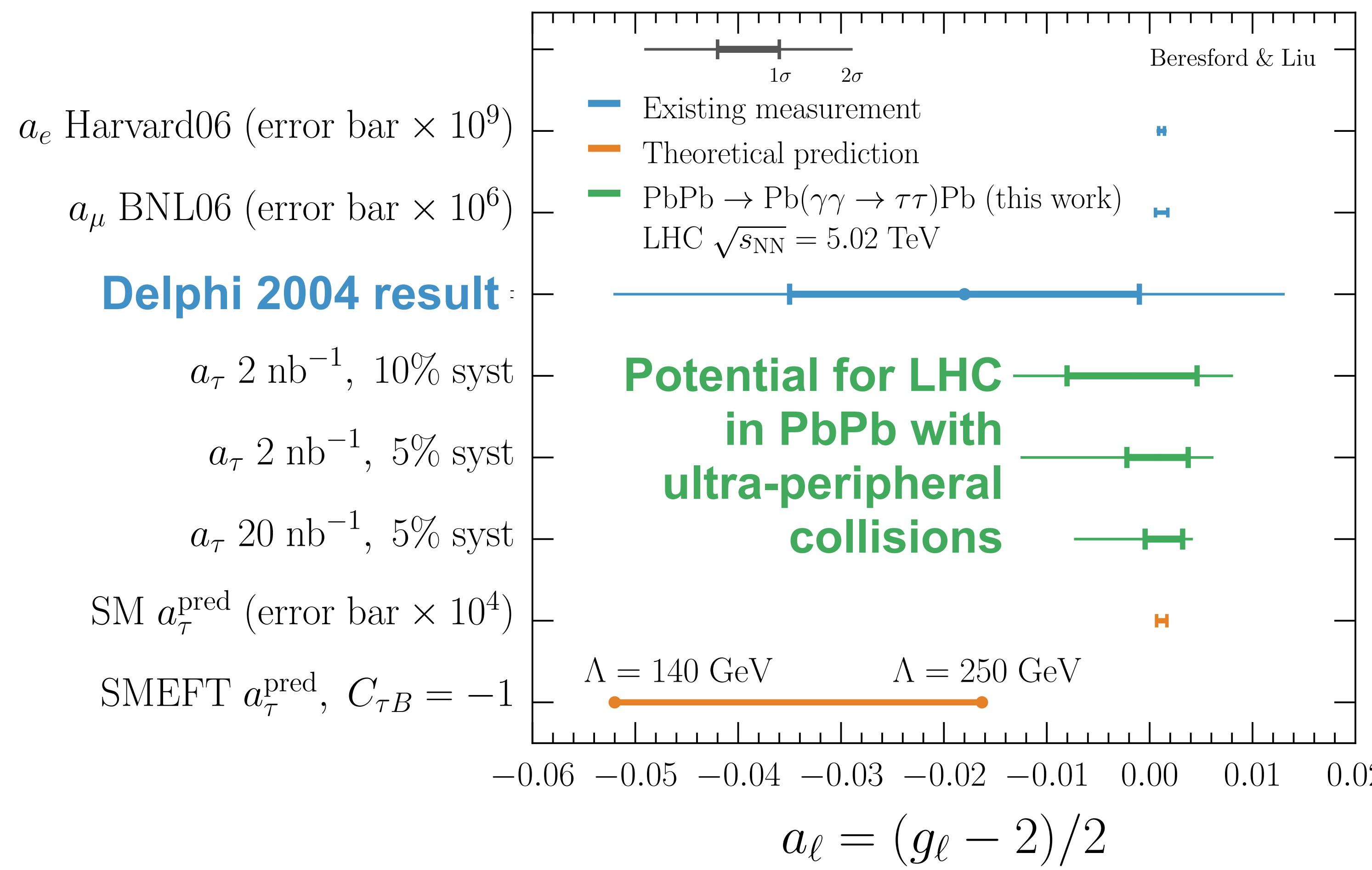
Axion search in low mass DY for m ~ 10 GeV - can we trigger low p_T muons / electrons in early 2021 data?

Measure fragmentation with Upsilons in jets - never done before

Perform feasibility study on $\sin^2\theta_W^b$ measured in Z+1b-jet system

Details of proposals / ideas see these talks:
New ideas: EWK sub-group
New ideas: W/Z sub-group
New ideas: Soft QCD sub-group
New ideas: Photons & Jets sub-group

Anomalous magnetic moment of τ lepton



New Ideas from SM Workshop - Belgrade

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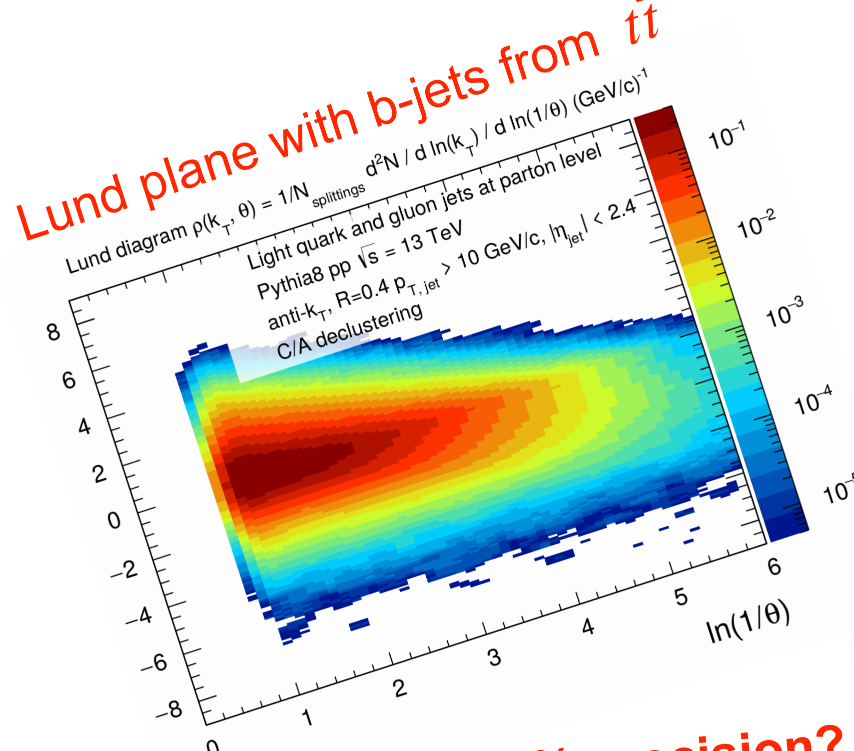
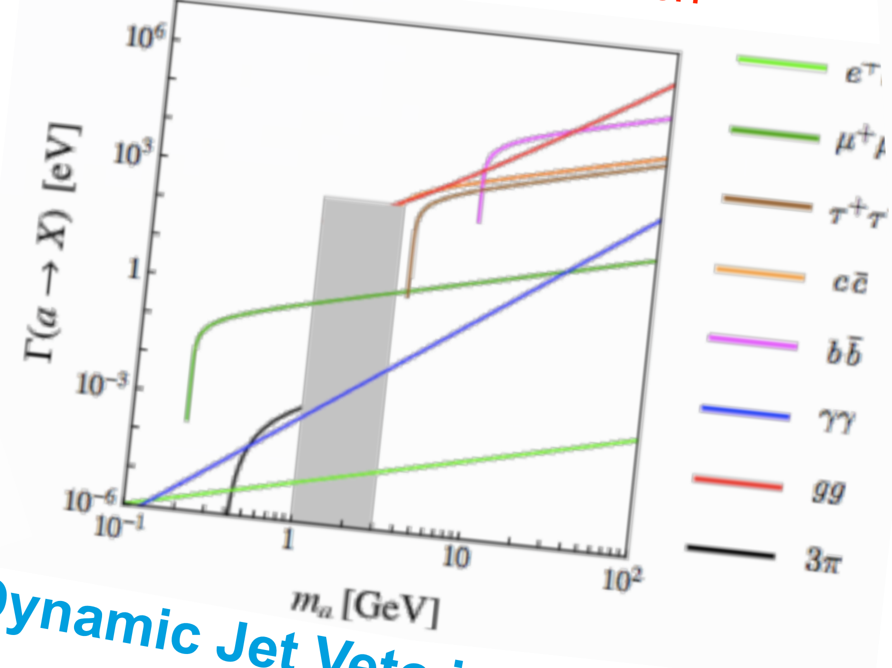
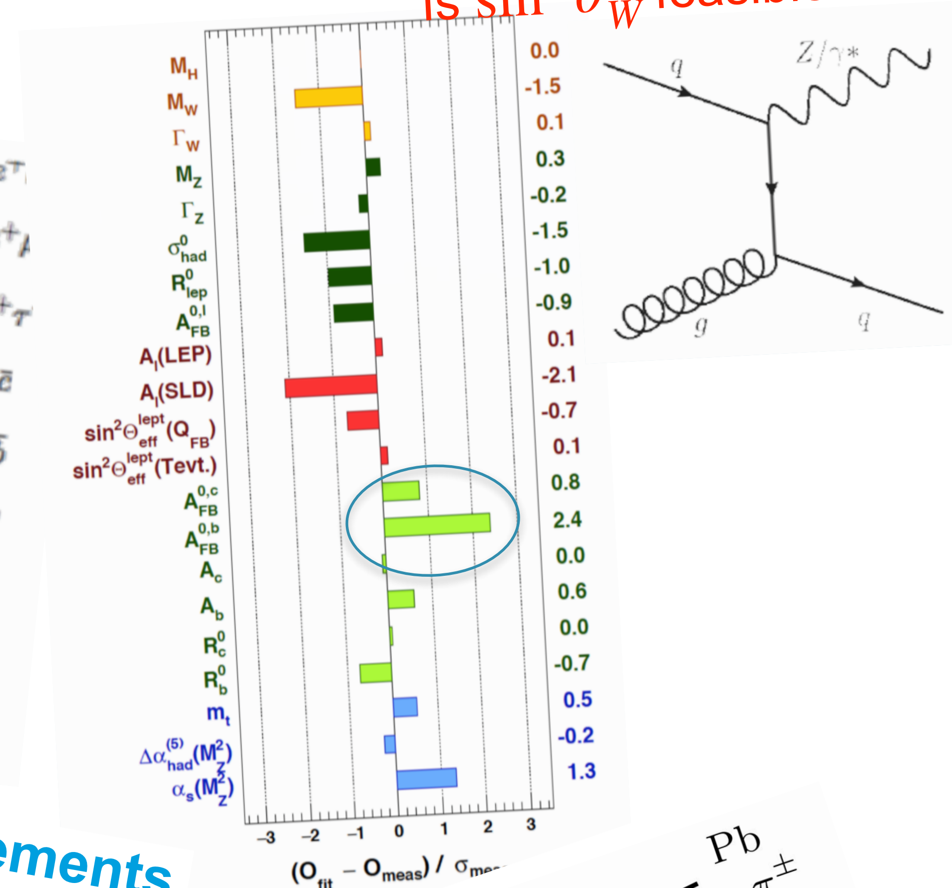
Lund plane with b-jets from $t\bar{t}$



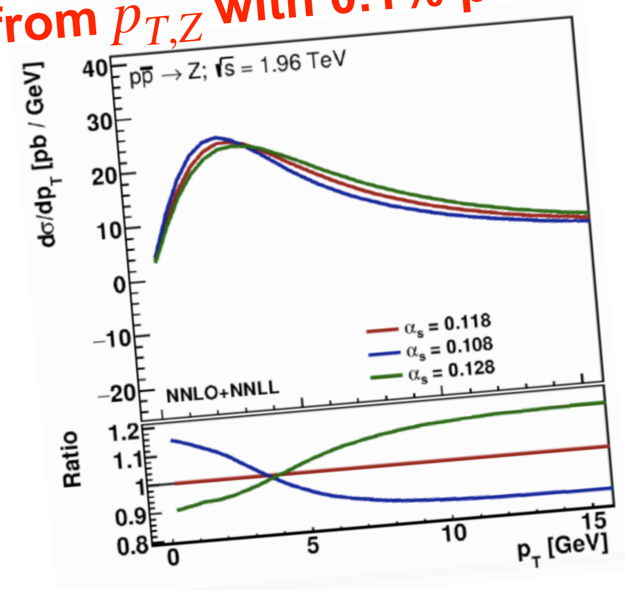
Low mass axion search



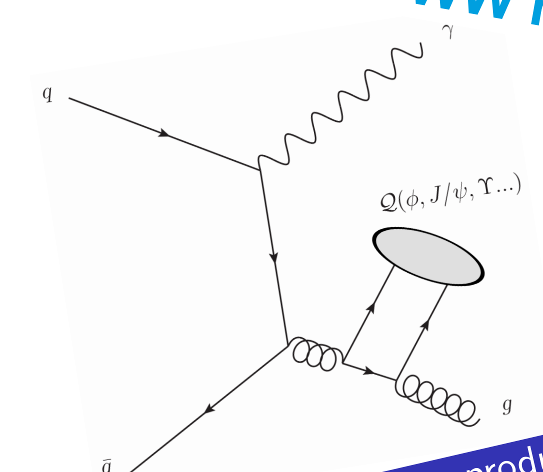
Is $\sin^2\theta_W^b$ feasible?



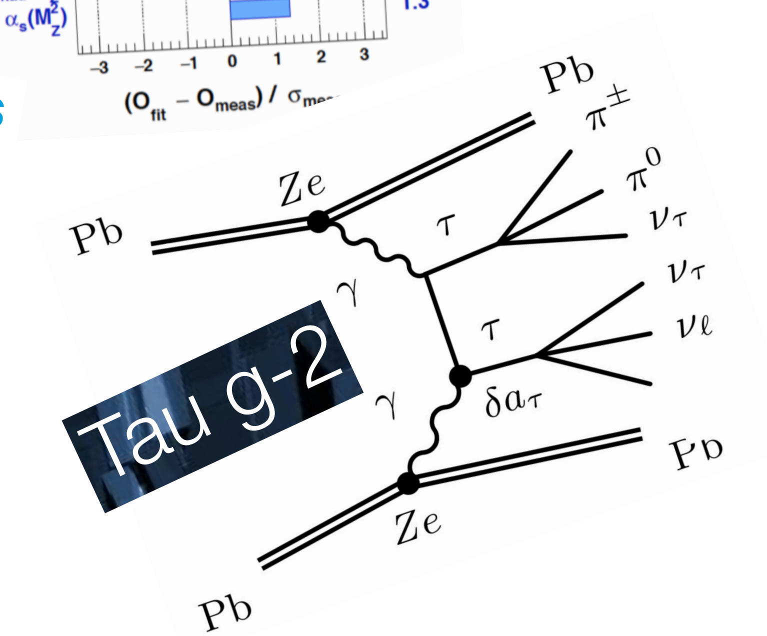
α_s from $p_{T,Z}$ with 0.1% precision?



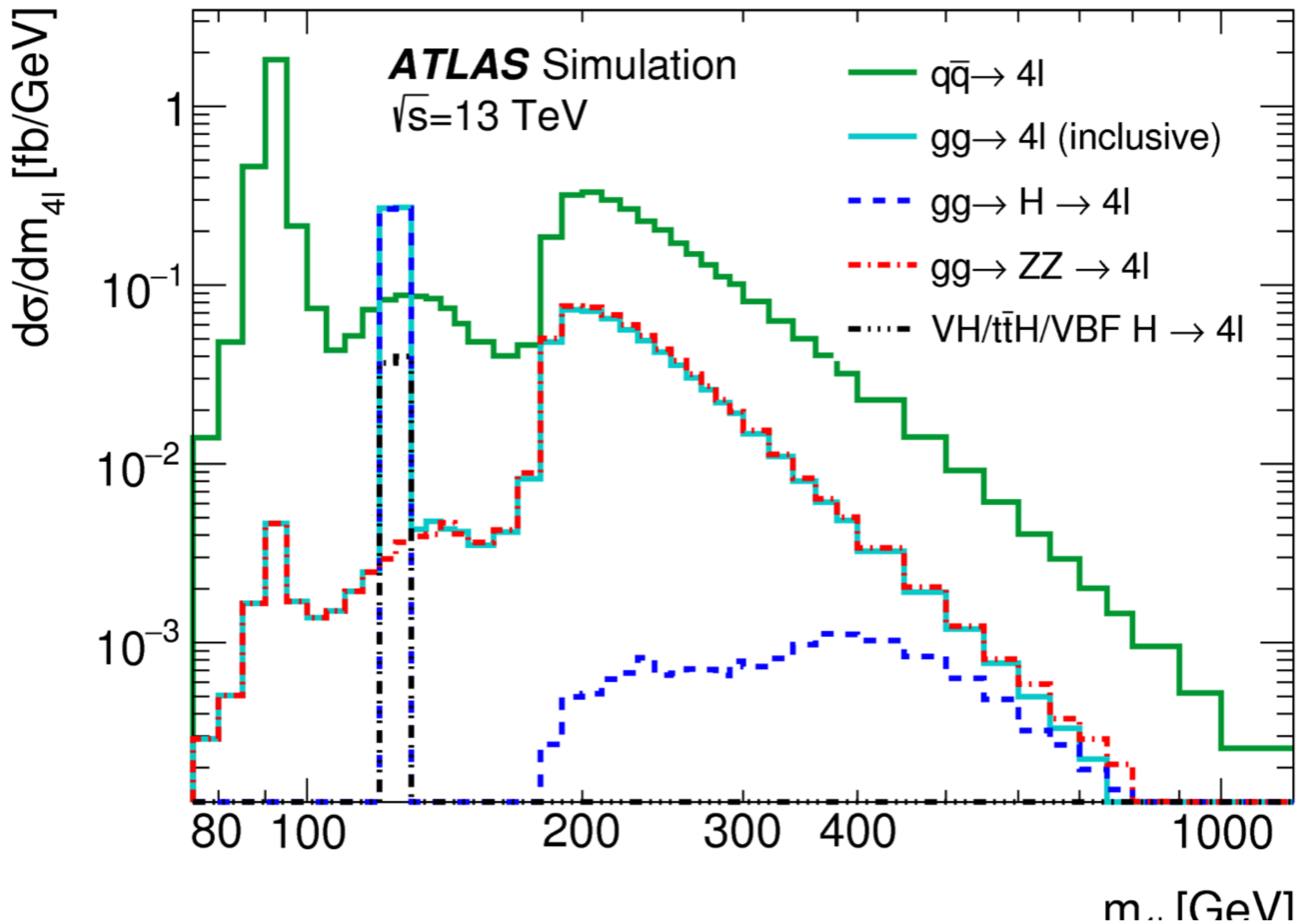
Dynamic Jet Veto in WW measurements

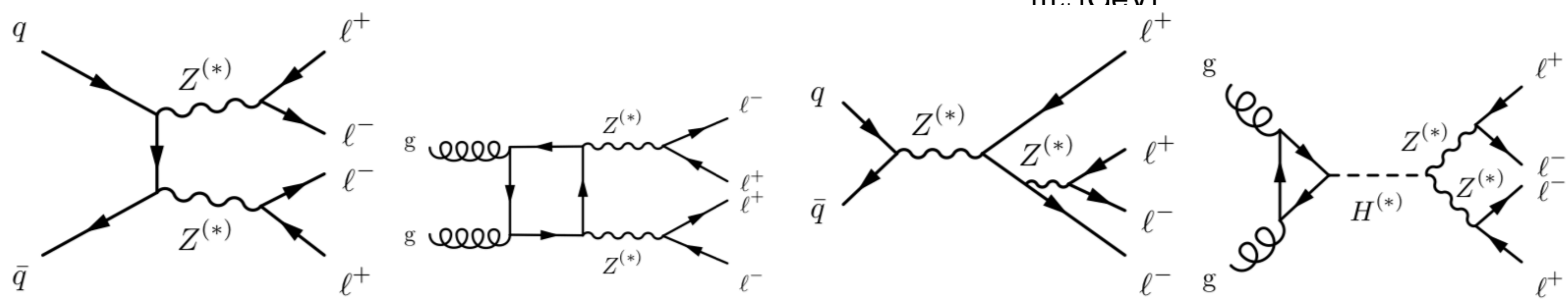


Photon plus heavy meson production

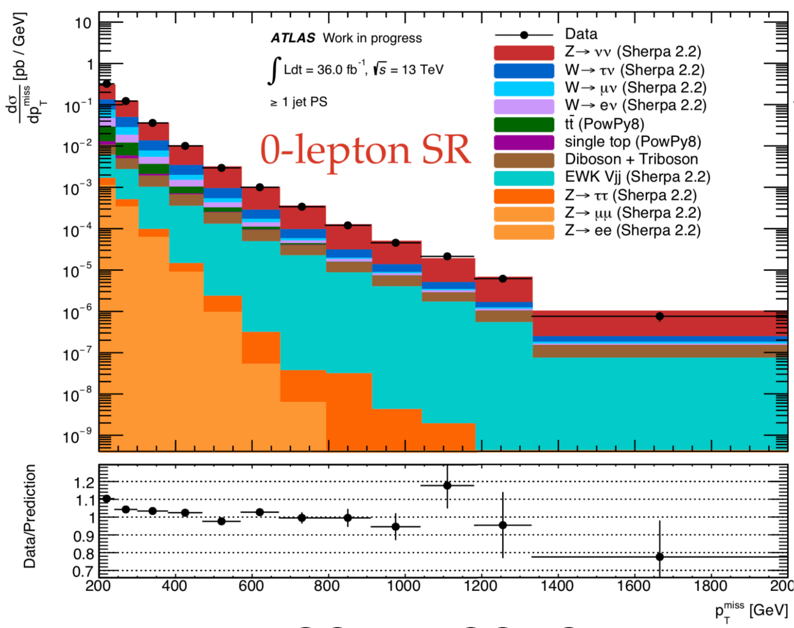


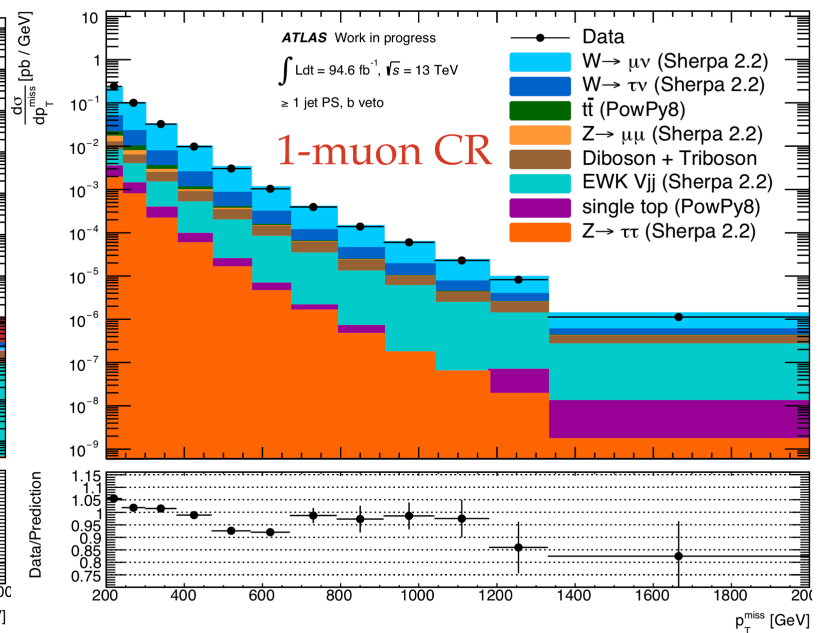
Backup

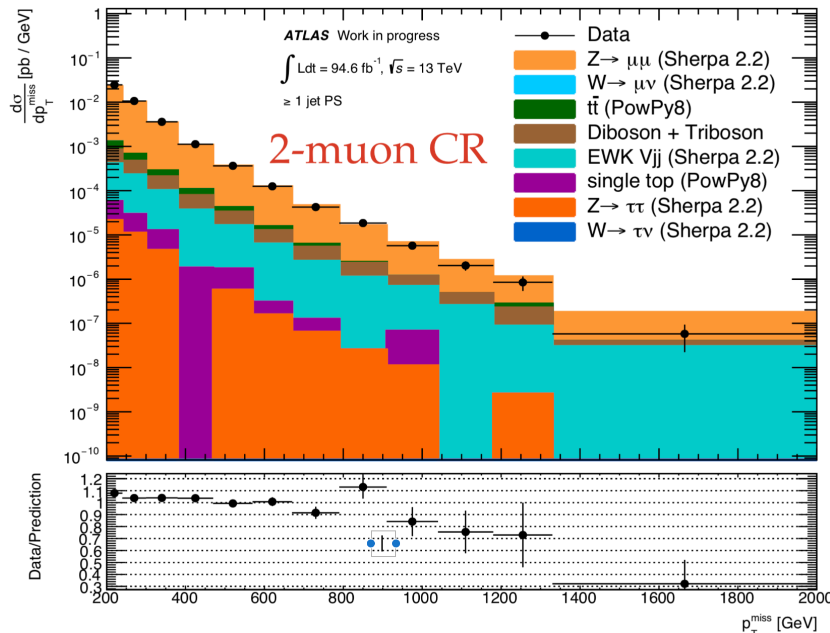

ATLAS Simulation
√s=13 TeV
qq̄→ 4l
gg→ 4l (inclusive)
gg→ H → 4l
gg→ ZZ → 4l
VH/tt̄H/VBF H → 4l
dσ/dm$_{4l}$ [fb/GeV]
m$_{4l}$ [GeV]


q
q̄
g
g
Z$^{(*)}$
H$^{(*)}$
ℓ$^+$
ℓ$^-$

MET + X

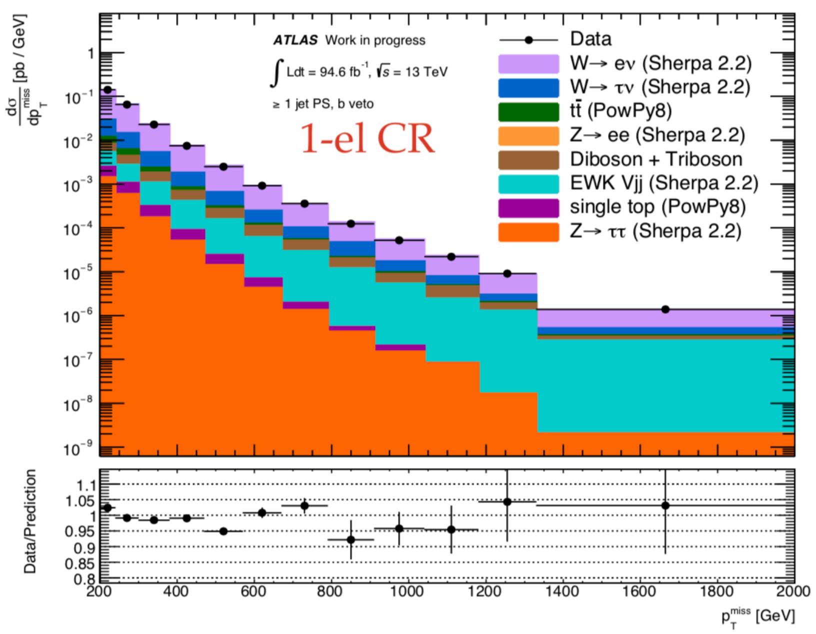


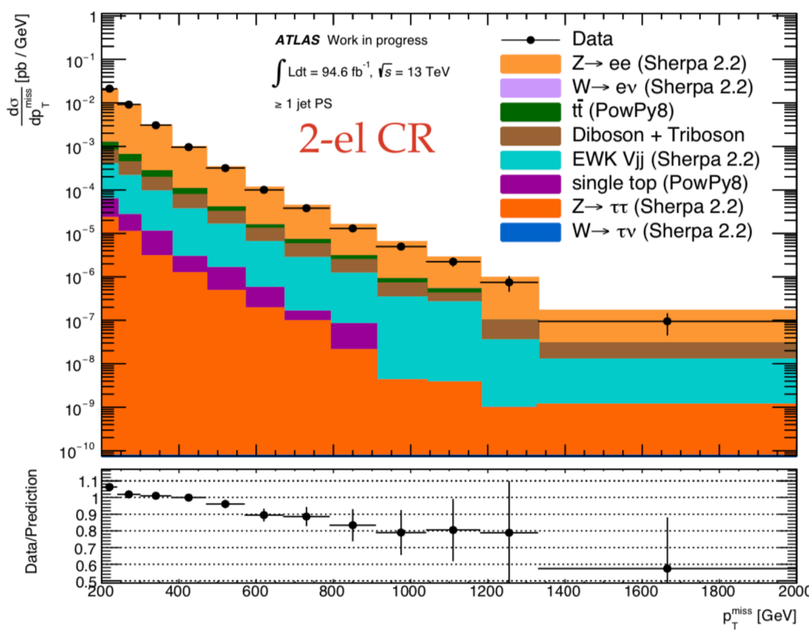




2015+2016 **2018** **2018**

No systematics included in the plots





Monojet-like: $p_T^{j1} > 120$ GeV,
VBF-like: $p_T^{j1} > 80$ GeV, $p_T^{j2} > 50$ GeV, $m_{jj} > 200$ GeV, 3rd jet veto

Plans: finalising unfolding cross-checks and plan to request an EB this autumn.

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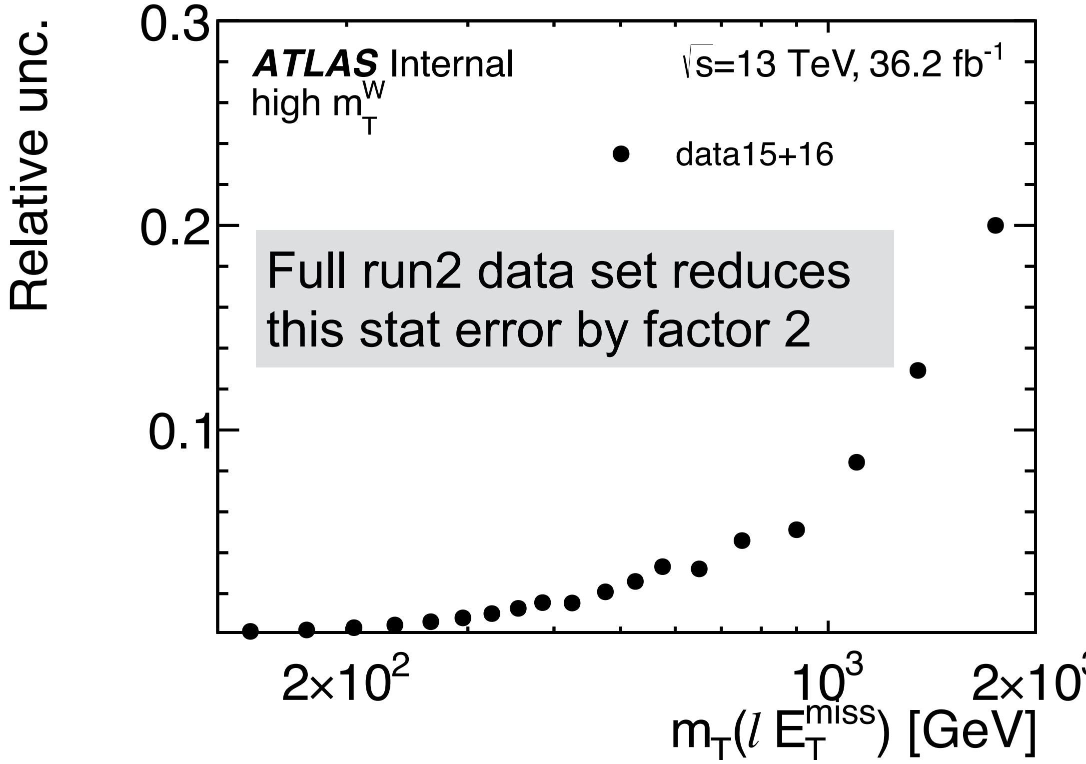
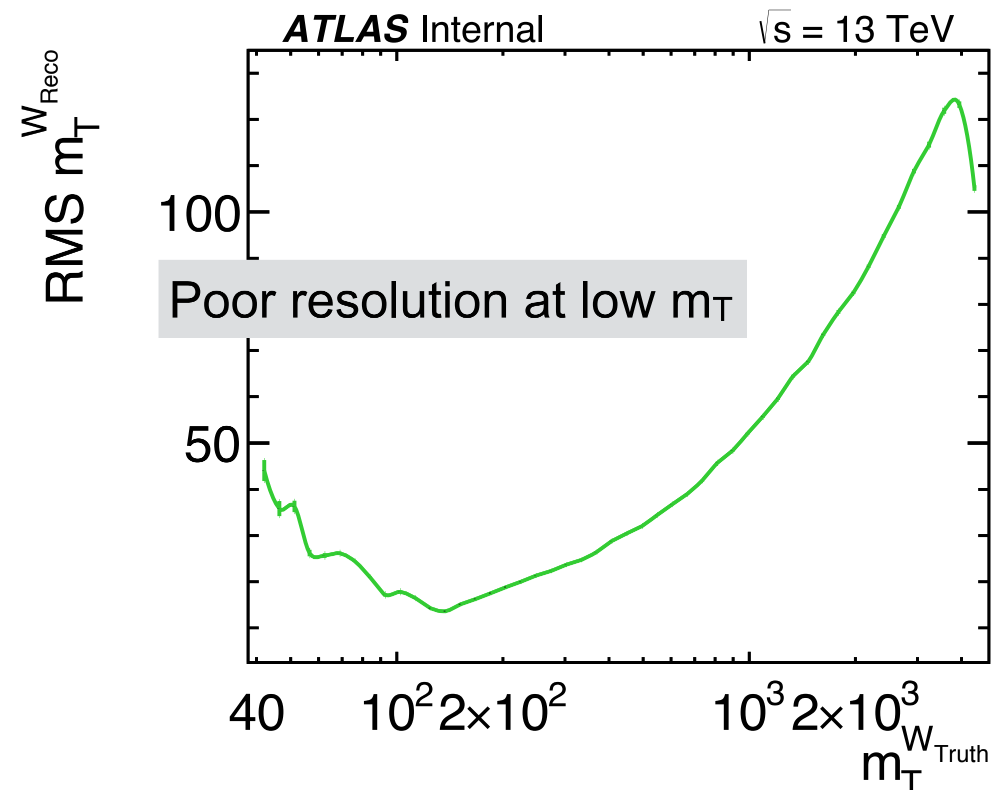
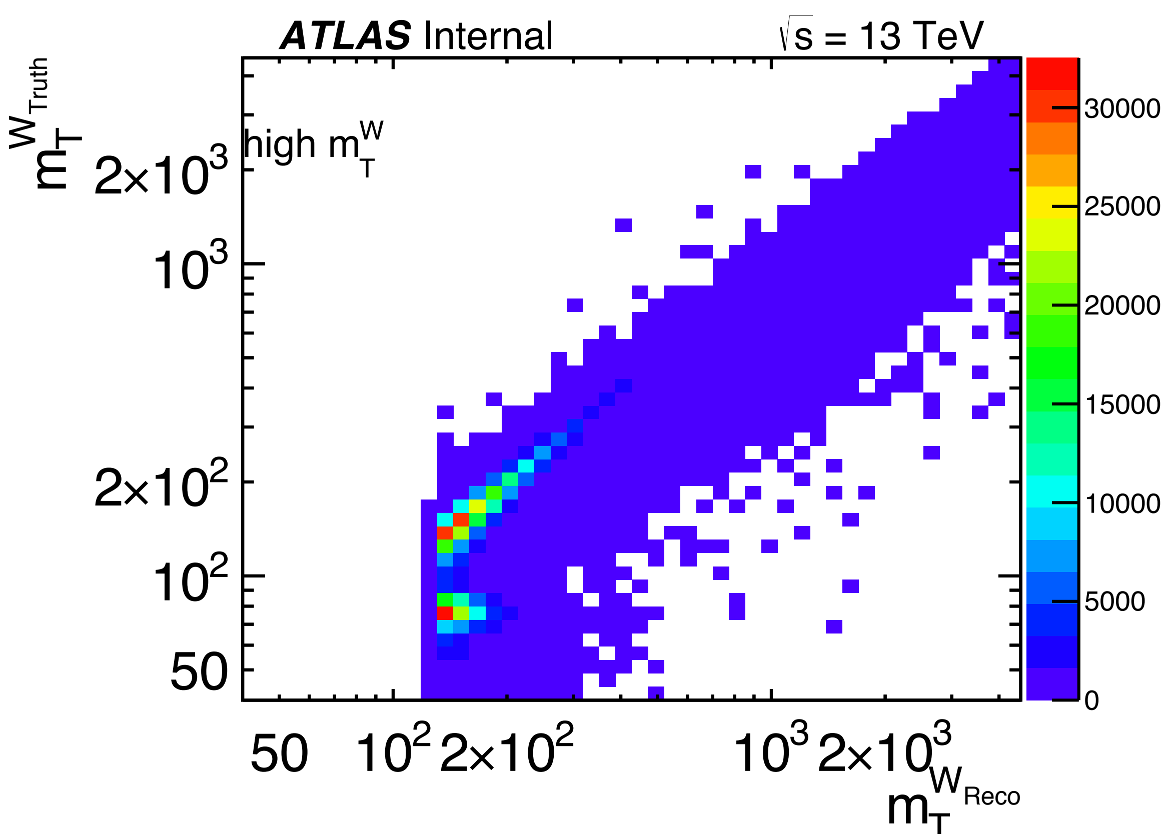
High Mass DY — Charged Current High m_T W±

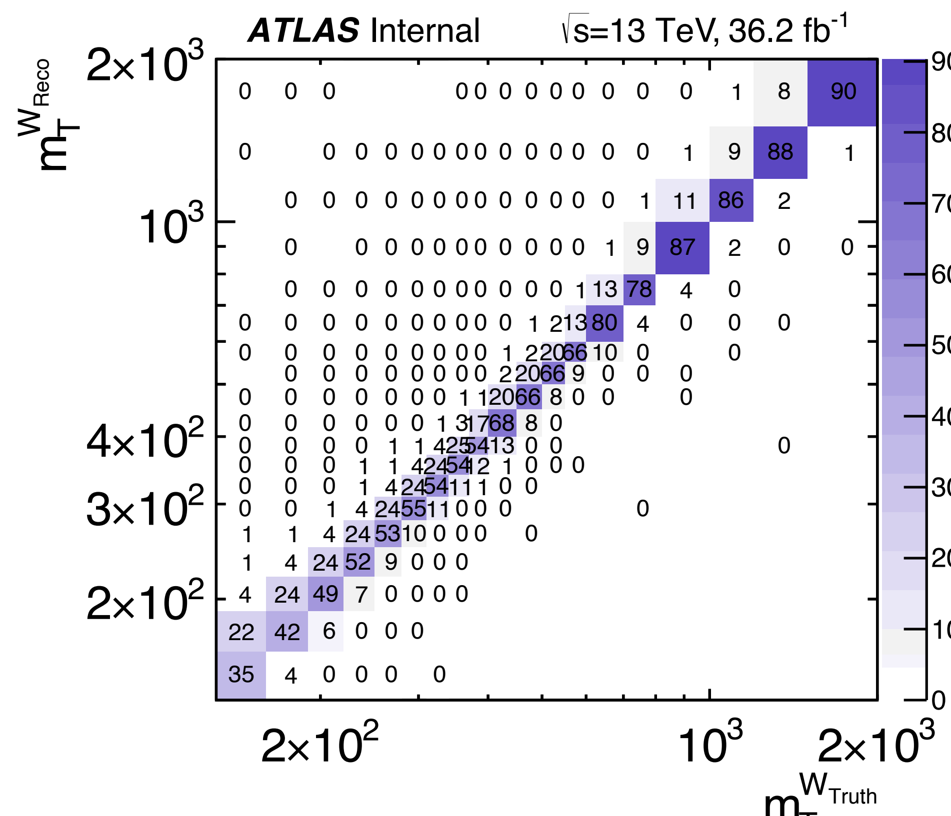


Full run2 data set reduces this stat error by factor 2



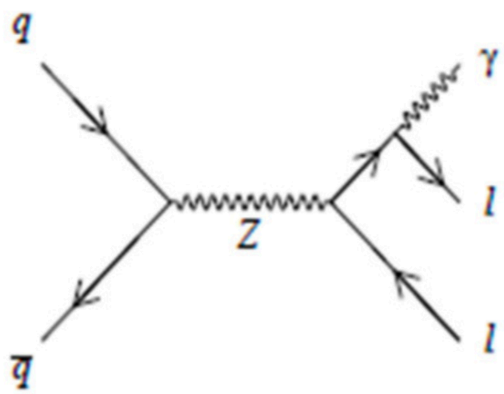
Poor resolution at low m_T





Bin purity >50% for m_T > 200 GeV. Purity ~35% below

$Z \to \ell\ell\gamma$ vertex Form Factor at 8 TeV



Test of $Z \to \ell\ell\gamma$

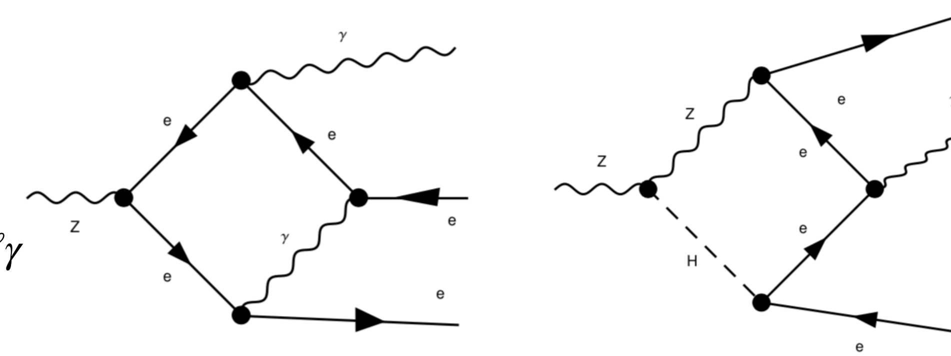
Sensitive to off-shell lepton radiation

Contributions from higher order loops

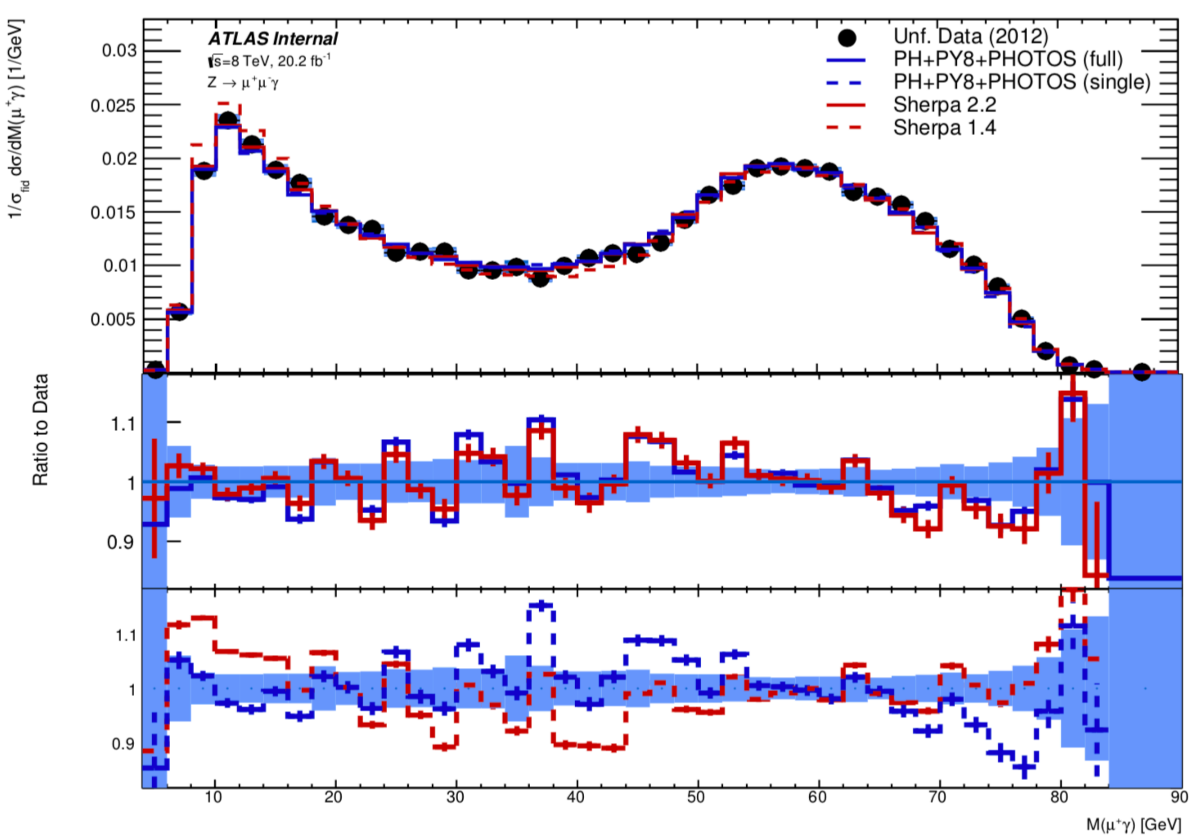
$Z \to \ell\ell$ sensitive to lepton virtuality Q and $m_{\ell\gamma}$

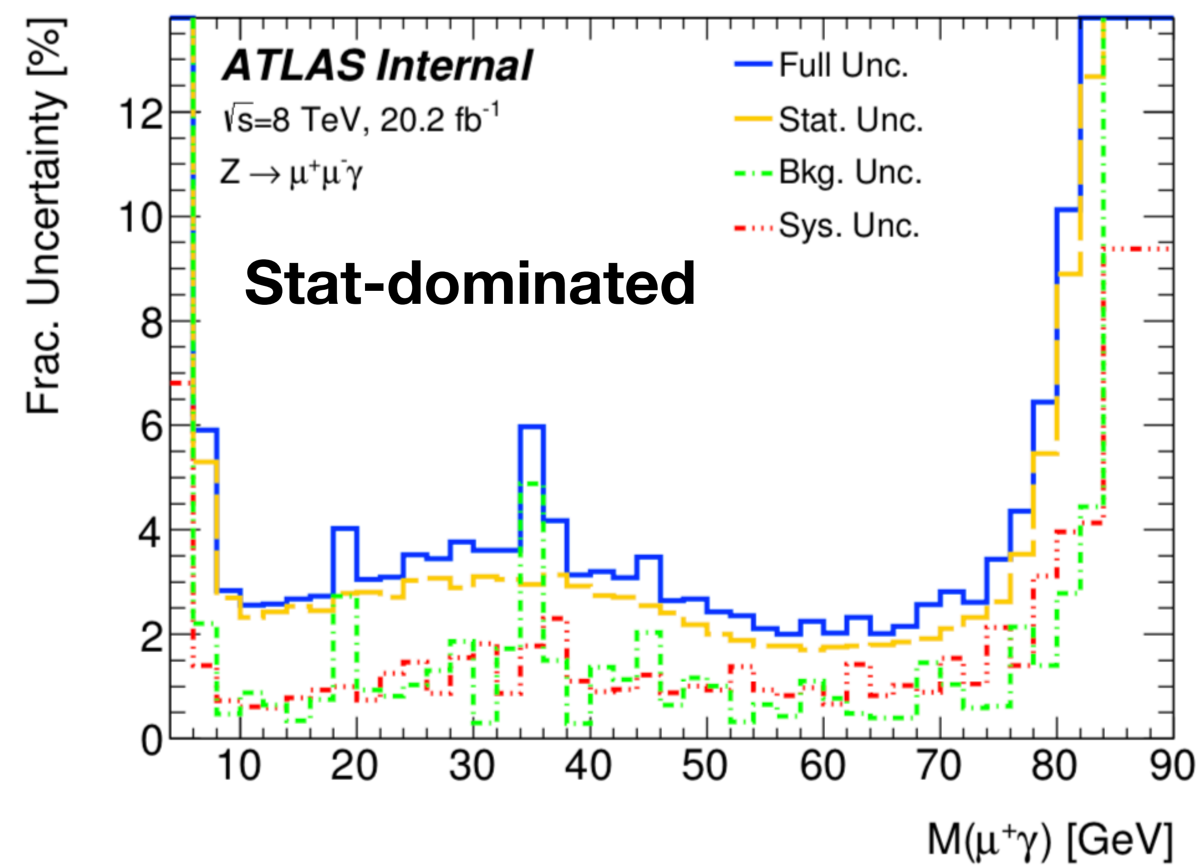
Measure Z vertex vs $m_{\ell\gamma}$

Direct measurement of Br($Z \to \ell\ell\gamma$)



Higher order 'anomalous' contributions





Significant deviation from LO Sherpa observed (>5σ)

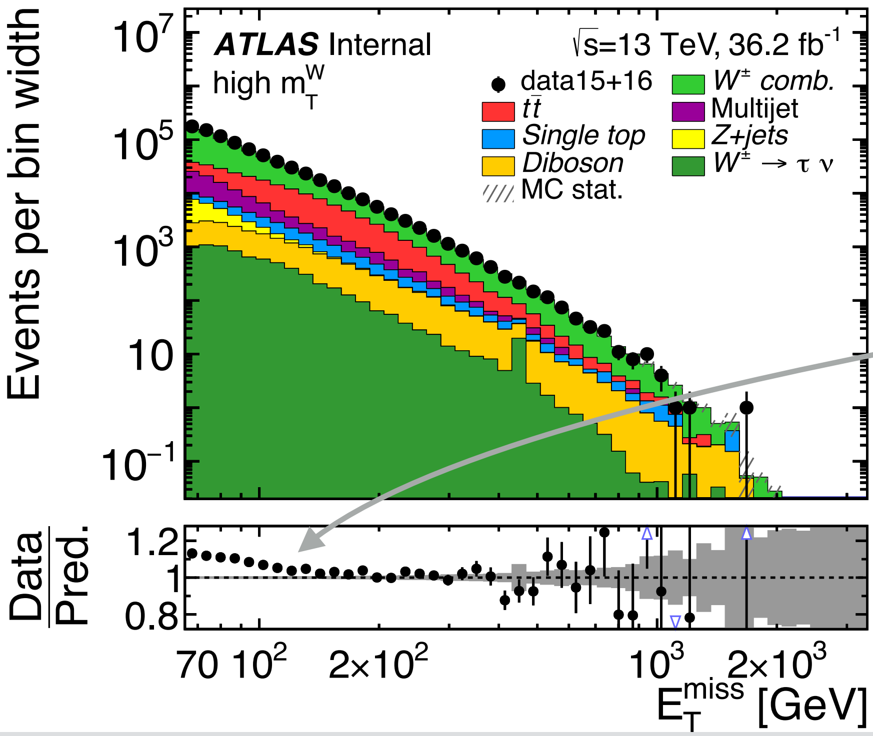
Powheg (NLO QCD and NLL QED FSR by PHOTOS) describes data better.

p_{TZ} in Powheg is reweighted to the data. All other MC were reweighted to corrected Powheg MC for comparison.

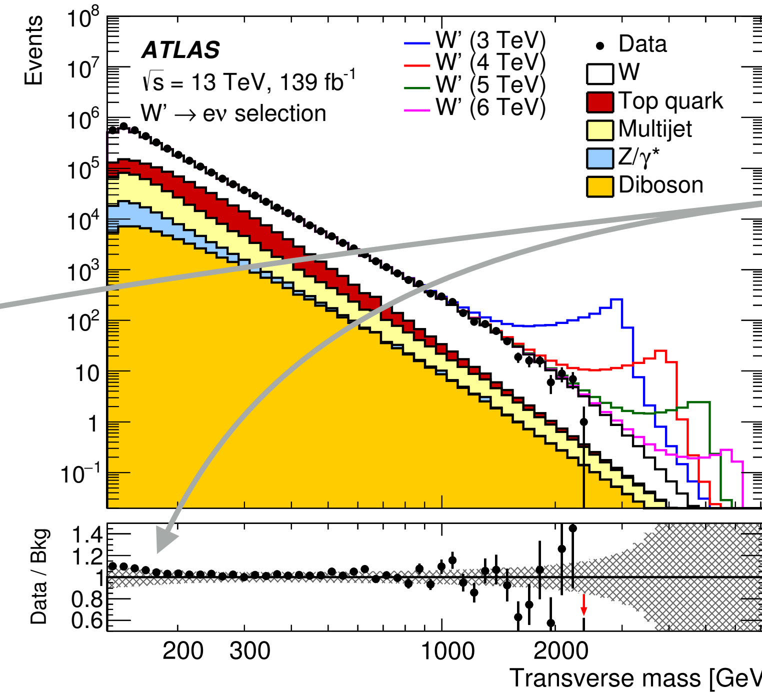
Difference of Sherpa 1.4 & Photos/Sherpa 2.2 is from missing single virtual photon (3-body decay of $Z \to \ell\ell\gamma$).

ANA-STDM-2017-05

High Mass DY — Charged Current High m_T $W^{\pm}$



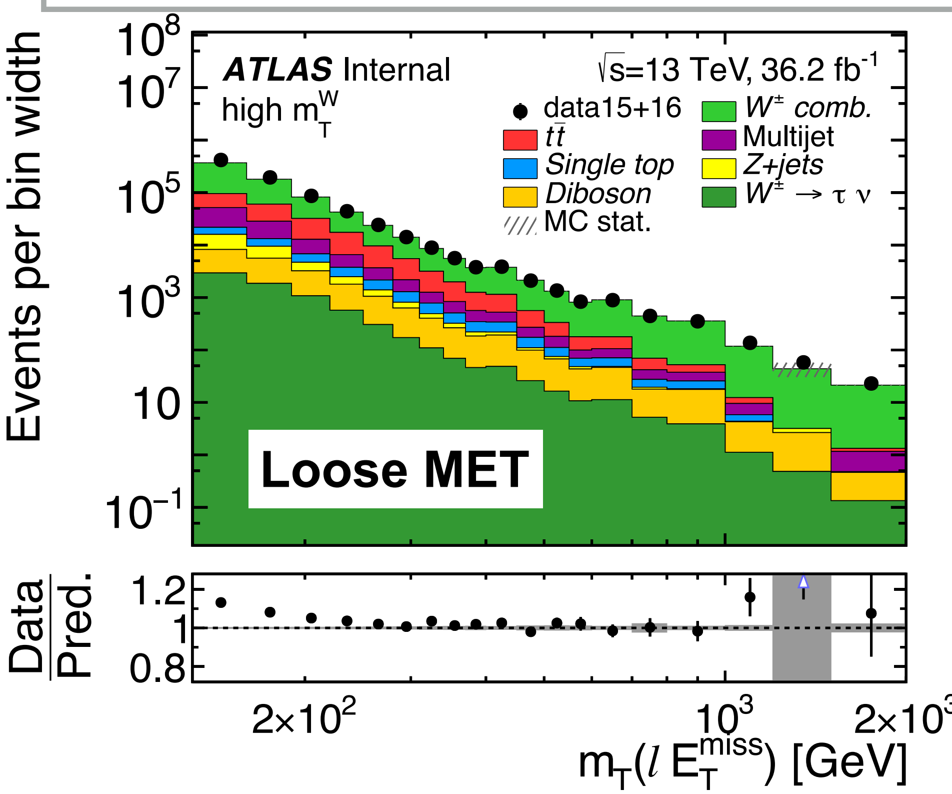
W' with full Run-2 data



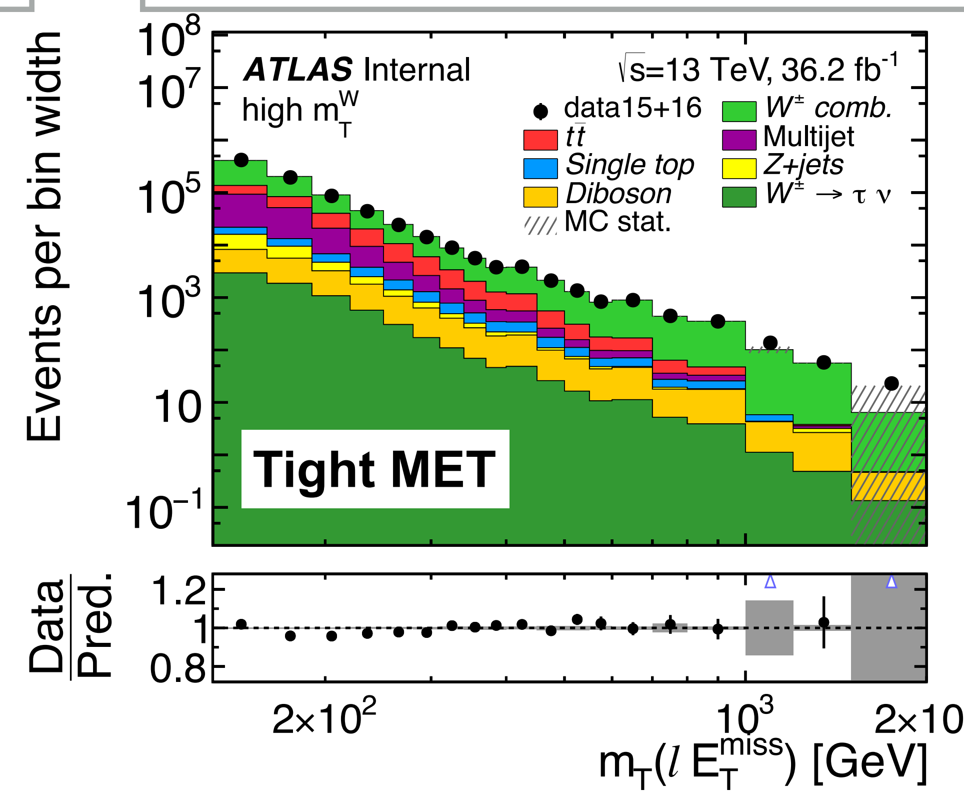
- Long-standing problem of ~15% MET mismodeling
- Also seen in W' searches
- Just within sys uncertainty

Discrepancy appears to due to (mis)calibration of loose objects in MET calculation in multijet matrix method

Loose objects enter MET with electron calib



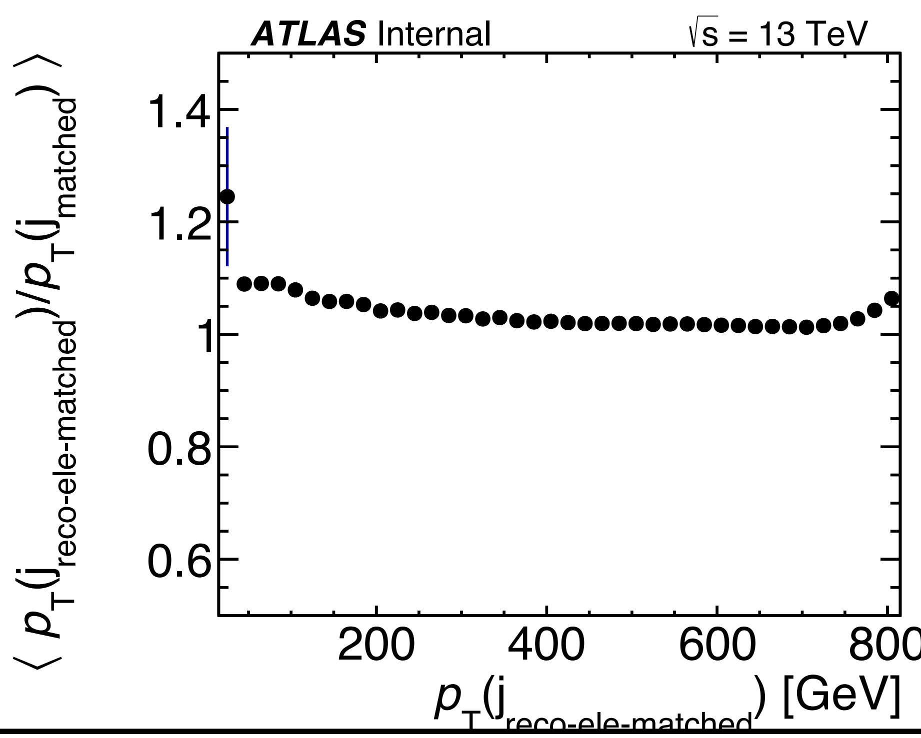
Tight objects enter MET with jet calib



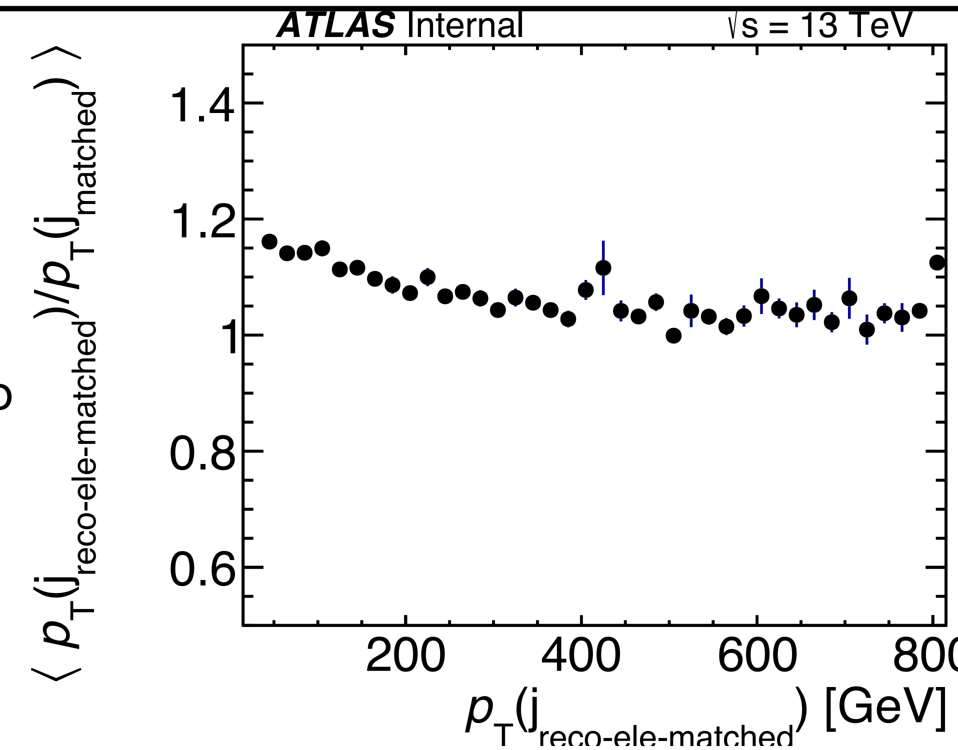
Under discussion with Jet/MET group

disable overlap removal

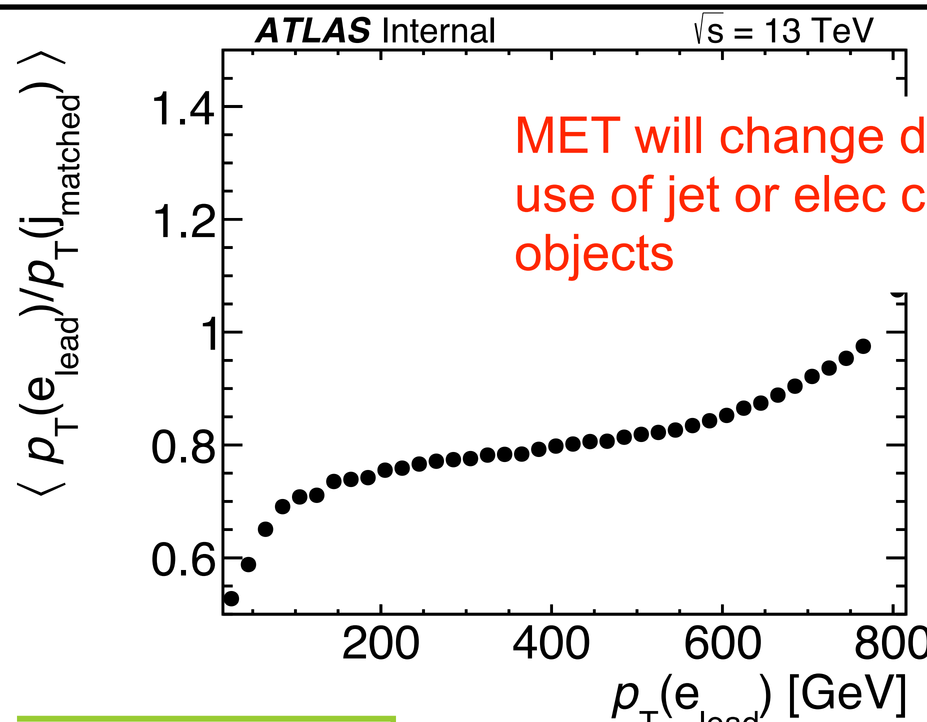
Response of truth jet matched as loose obj [jet] ~ 1



Response of truth jet matched as tight obj [jet] ~ 1

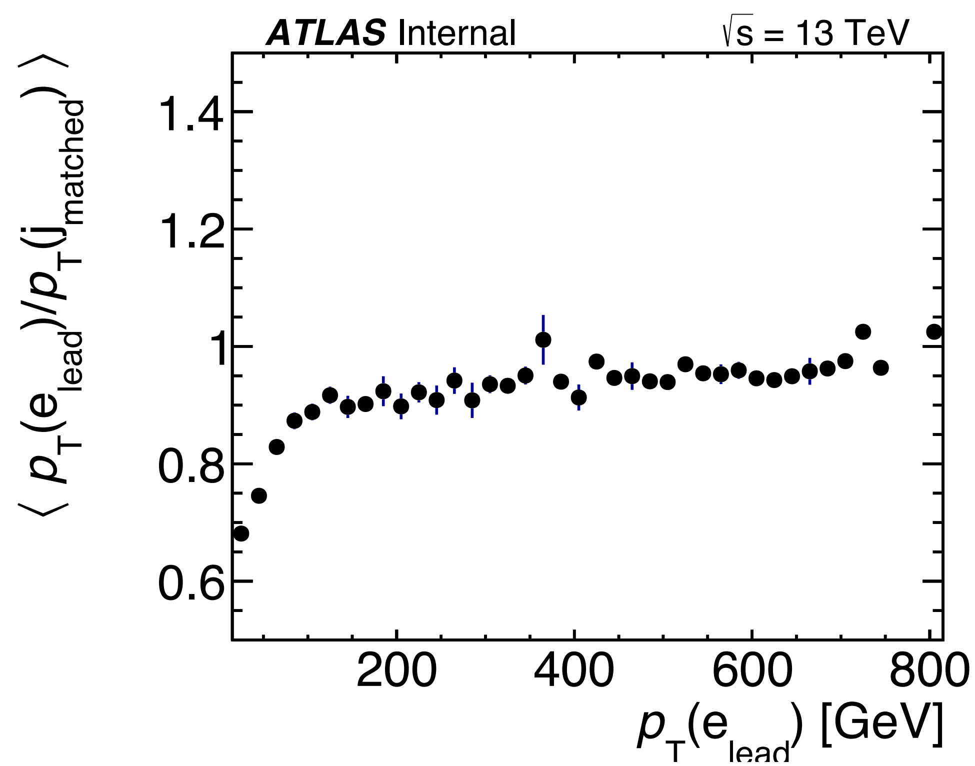


Response of truth jet matched as loose obj [elec] ~ 1



MET will change depending on use of jet or elec calib for loose objects

Response of truth jet matched as tight obj [elec] ~ 1



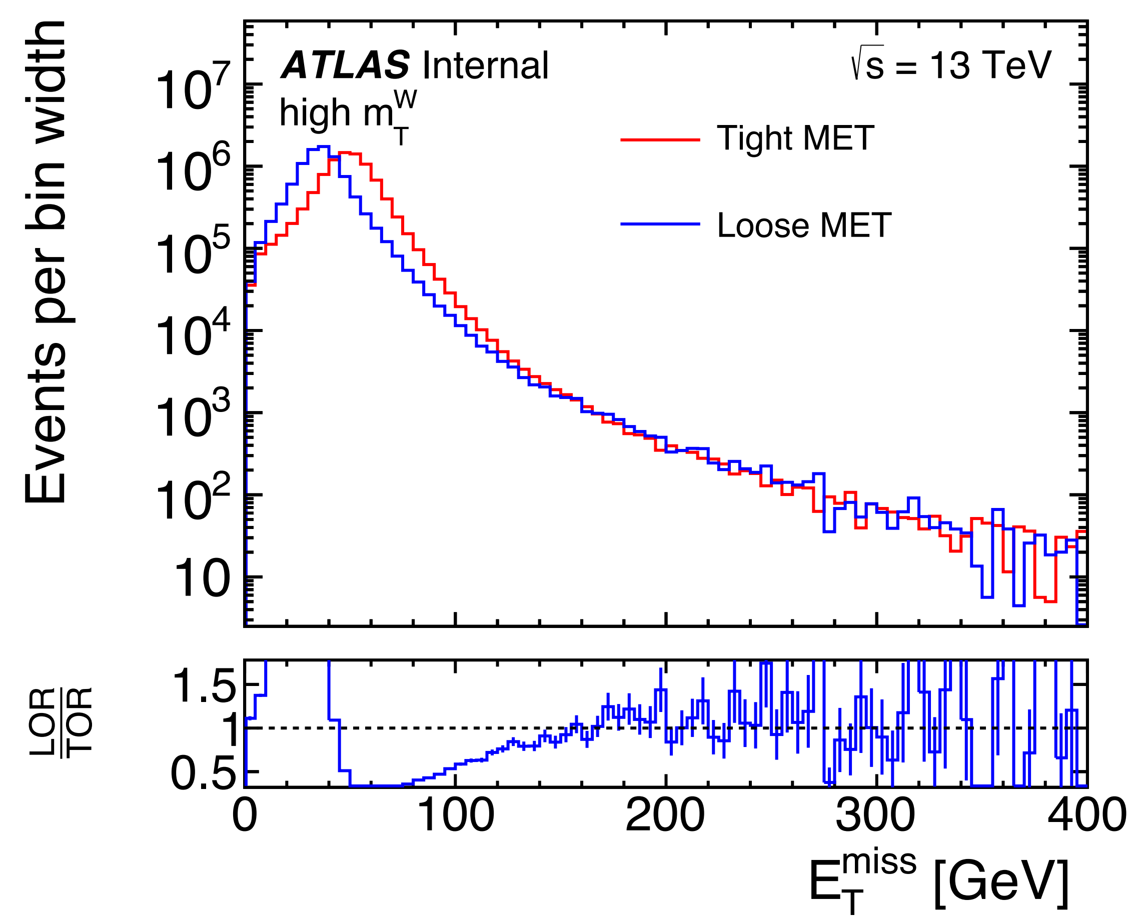
Consider two MET definitions:
Loose MET: loose electrons calibrated as electrons in MET calculation
Tight MET: loose electrons calibrated as jets in MET calculation

- selected exactly 1 electron with looseAndBLayer ID, $|\eta(e)| < 2.47$ and $p_T(e) > 30$ GeV from **W MC**

loose-not-tight electrons

➡ **tight MET shifts for loose-not-tight electrons to higher values**

➡ **expected due to jet calibration applied for loose objects which are (most likely) electrons**



Using tight MET increases multijet estimates

Use matrix method for multijet estimation
Rely on inverting lepton ID / iso conditions

$$\epsilon_{R/F} = \frac{N_{R/F}^{tight}}{N_{R/F}^{loose}}$$

$$\begin{pmatrix} N_T \\ N_L \end{pmatrix} = \begin{pmatrix} \epsilon_R & \epsilon_F \\ 1-\epsilon_R & 1-\epsilon_F \end{pmatrix} \begin{pmatrix} N_R \\ N_F \end{pmatrix}$$

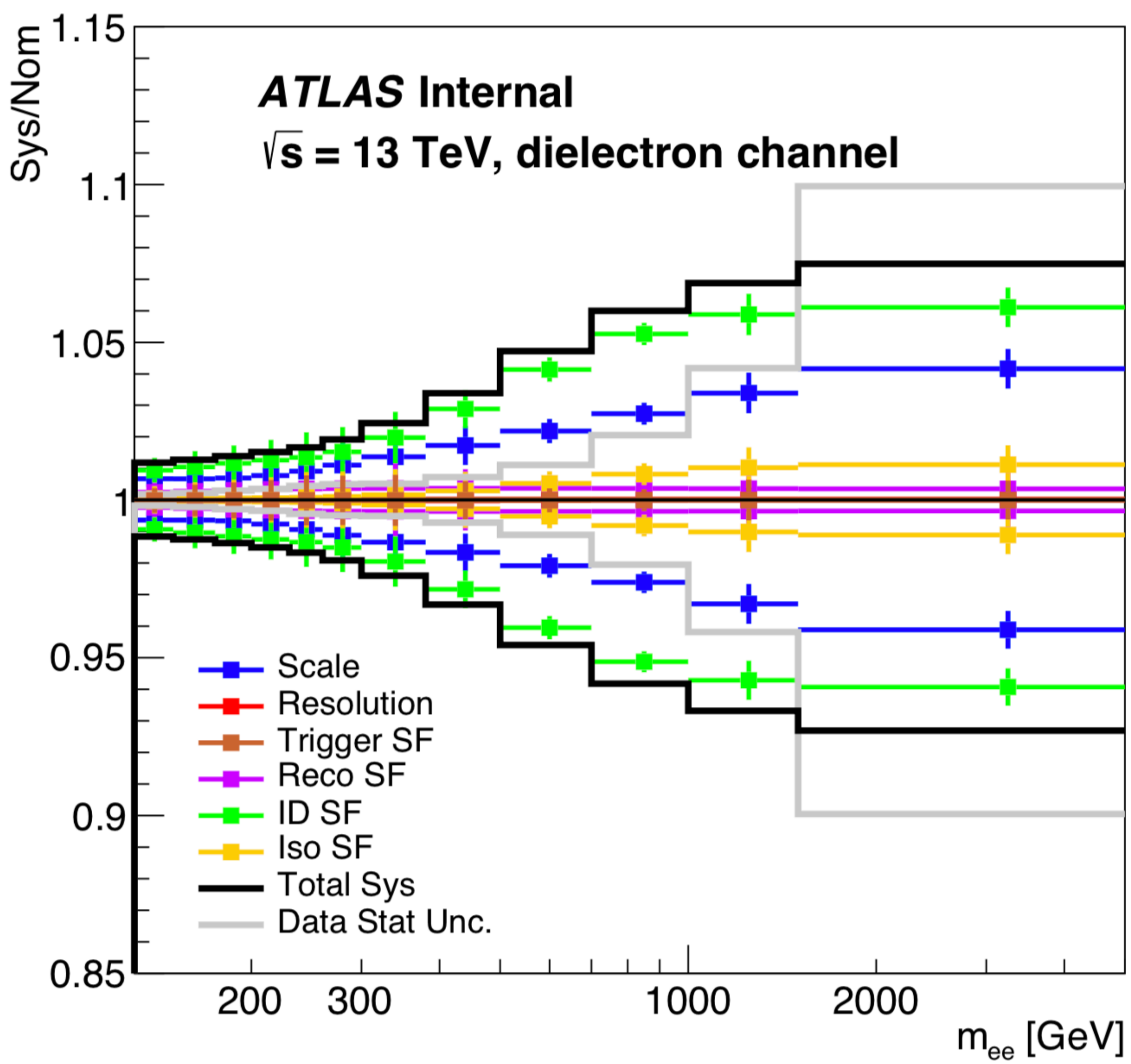
$$w_{MM} = \frac{\epsilon_F}{\epsilon_R - \epsilon_F}\left[\epsilon_R \cdot (N_L + N_T) - N_T\right]$$

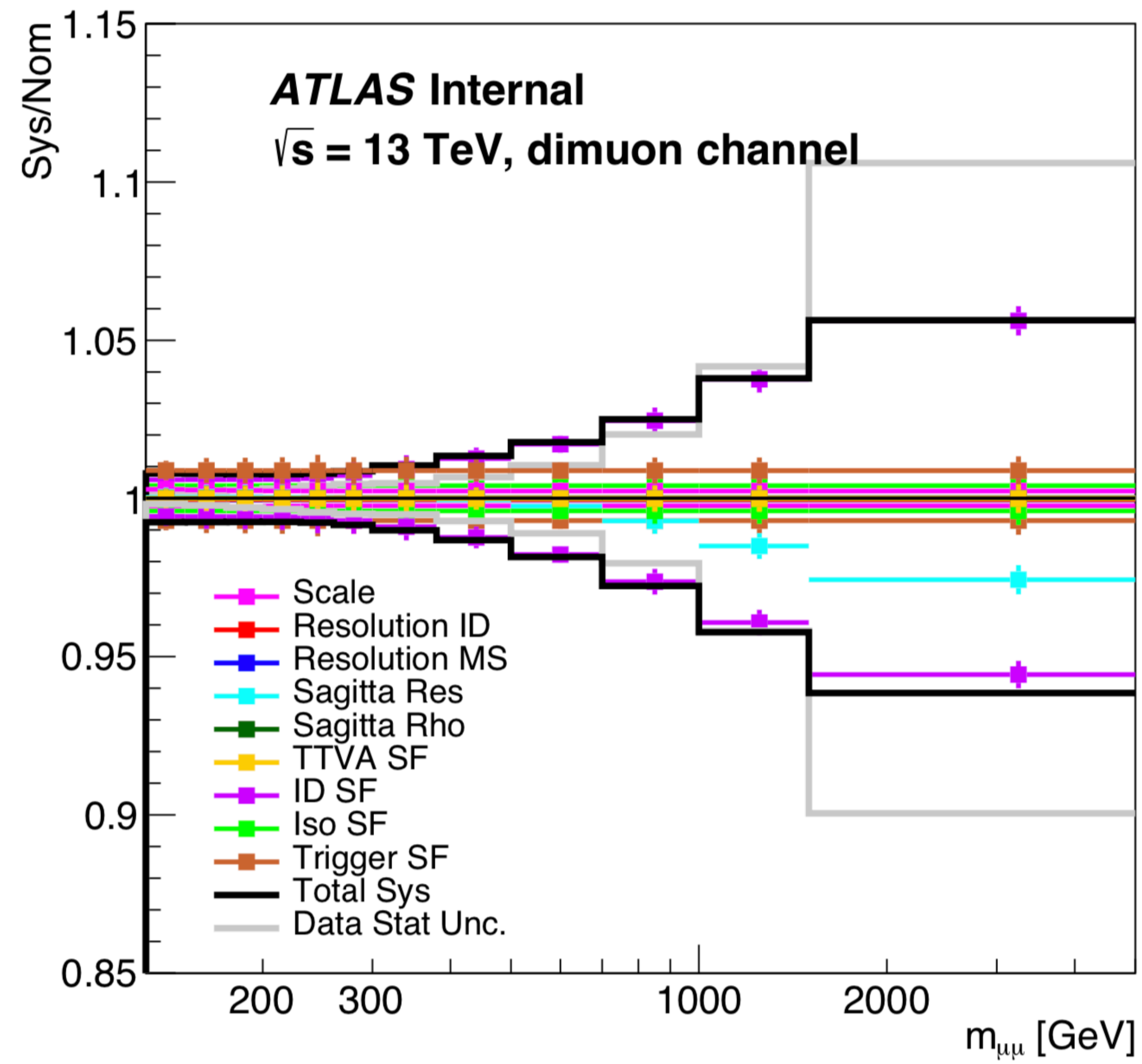
DD tight == electron tight level
DD loose == electron loose level

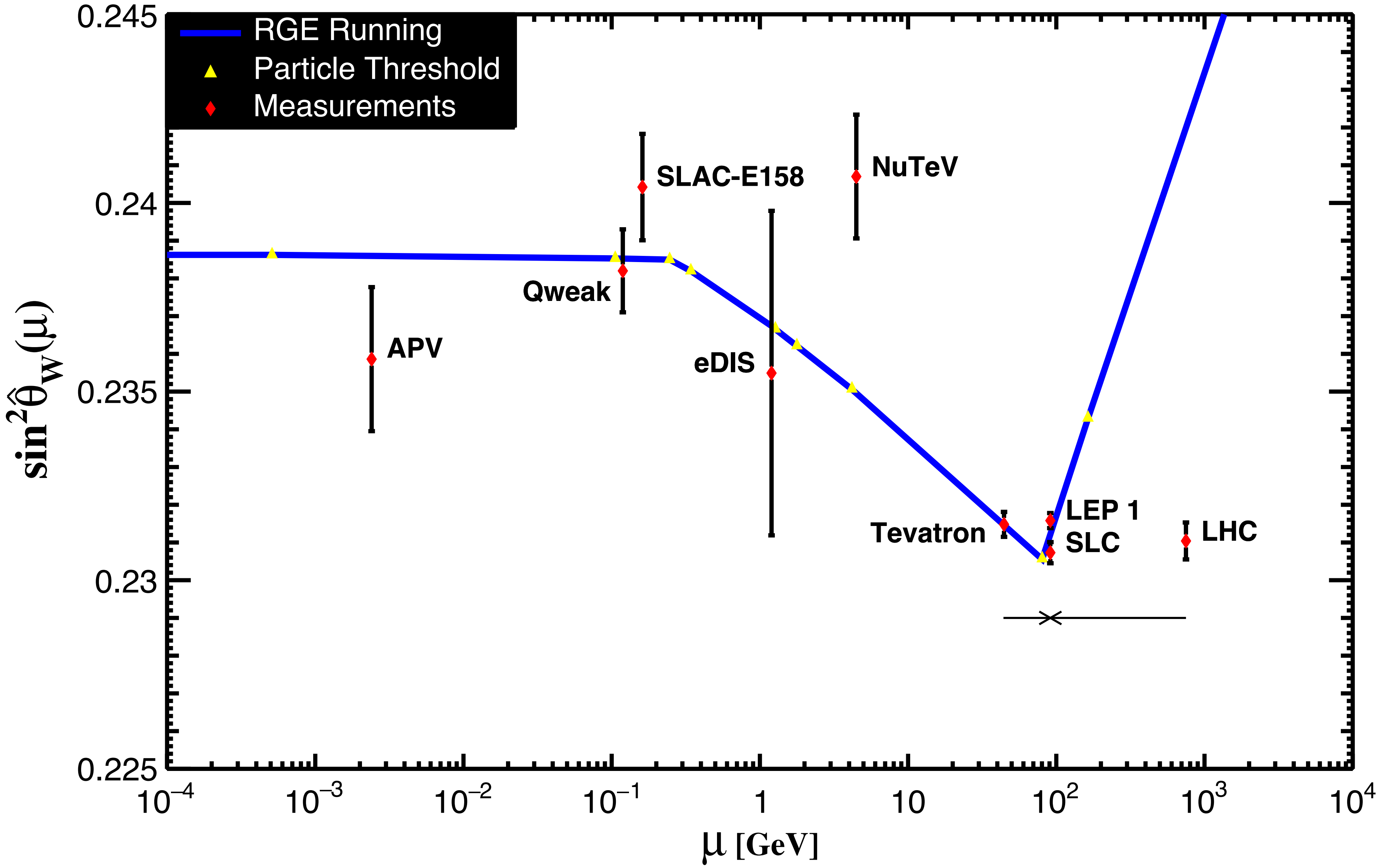
- MC backgrounds as usual
- data-driven method for MJ
- Strategy:

1. loosen some identification cuts to get two identification levels
2. measure the efficiency for loose to tight
3. use corresponding efficiency to define relation between N_L, N_T, N_R and N_F
4. invert the matrix to get an event weight

High Mass DY — Neutral Current







No electroweak coupling measurements above m_Z