High-mass Resonance Searches in ATLAS

Elham E Khoda
University of British Columbia

SLAC FPD Seminar
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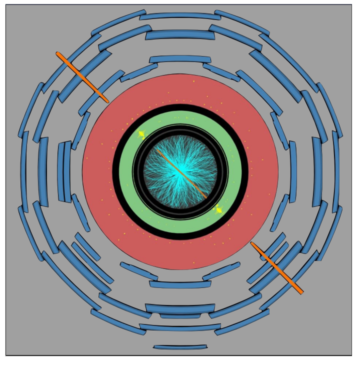
a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

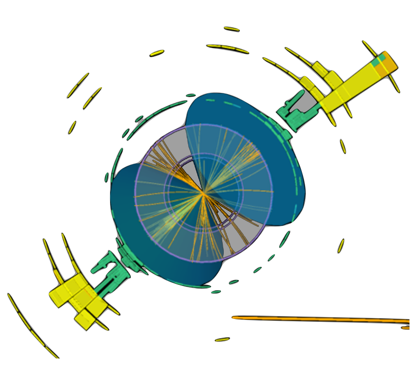
ATLAS EXPERIMENT

Outline

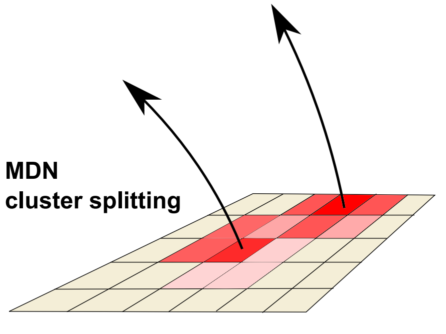
Intro to experimental setup: LHC and ATLAS



Dilepton Resonance Search



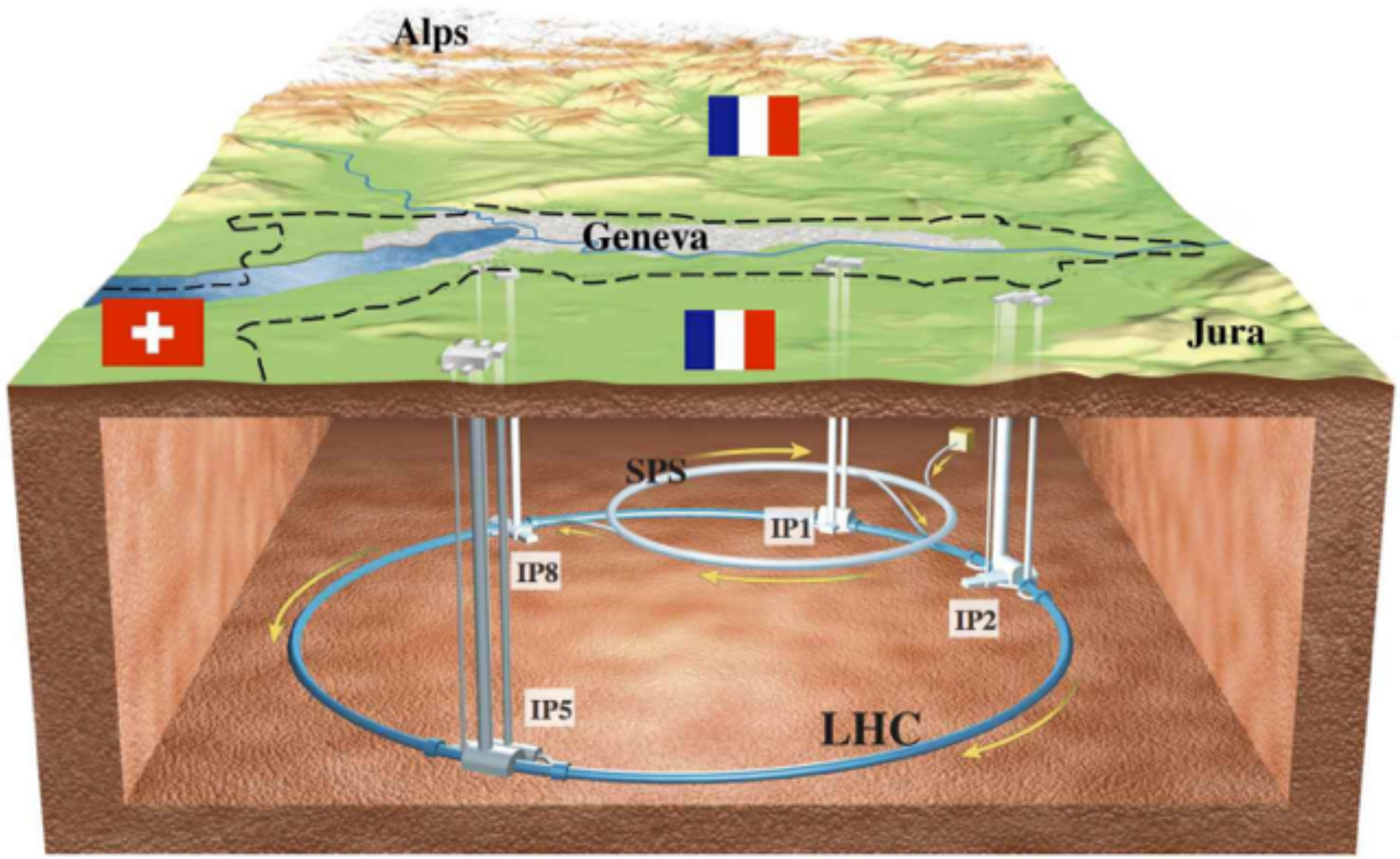
ttbar Resonance Searches



Pixel cluster splitting with Mixture Density Network

Large Hadron Collider at CERN

- World's largest and most powerful particle collider
- Collides protons (most of the time) bunches (~10^{11} protons in a bunch) spaced by 25 ns



centre of mass energy

2011: 7 TeV
2012: 8 TeV
2015-18: 13 TeV

In this talk

- Four major experiments on the LHC ring: ALICE, **ATLAS**, CMS, LHCb

The ATLAS Experiment

General purpose detector

Toroidal Magnet: 0.5 T

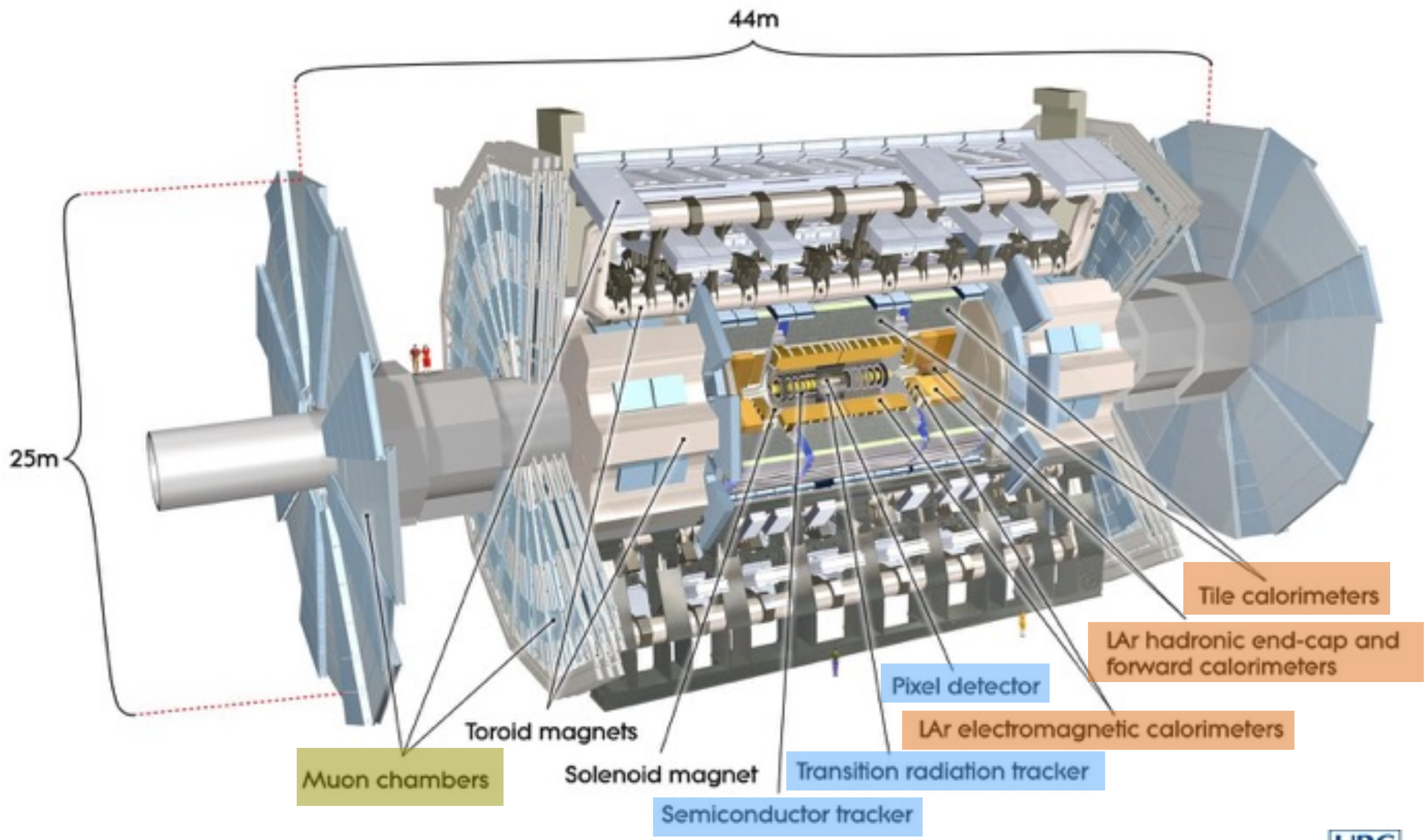
Muon Spectrometer: four different detector technology

Calorimeter: Electromagnetic (Liquid Argon), Hadronic (Liquid Argon (endcap) & Tile (barrel))

Solenoid Magnet: 2.0 T

Inner Detector:
three different detector technology

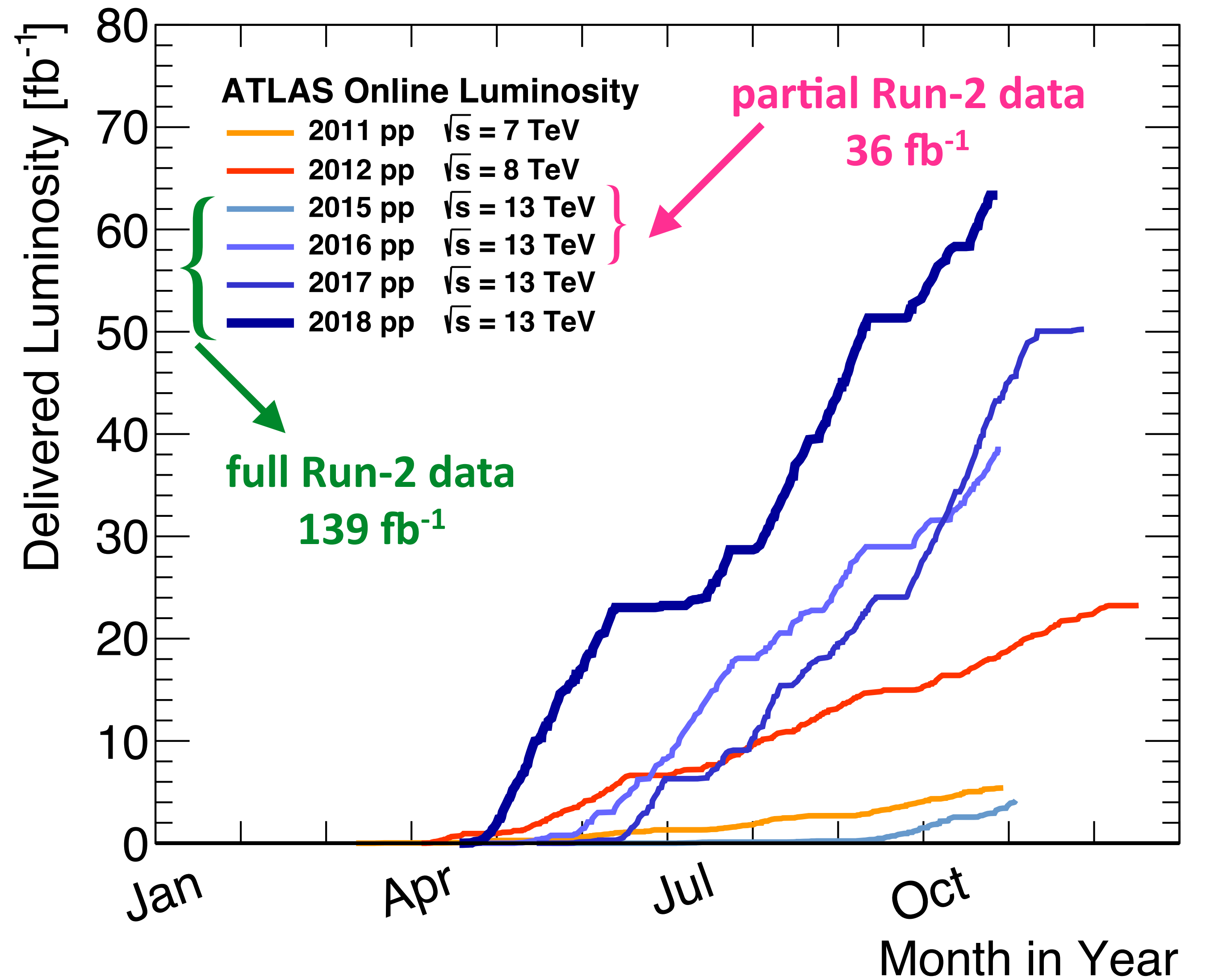
1. Silicon Pixel
2. Silicon Strip
3. Straw Tubes: Transition Radiation Tracker (TRT)



Full Run-2 data (2015-2018)

- LHC Run-II started in mid 2015

- ATLAS collected 147 fb^{-1} data during Run-2
- **139 fb^{-1}** data used for physics analysis
  - **95% data is usable for physics!**

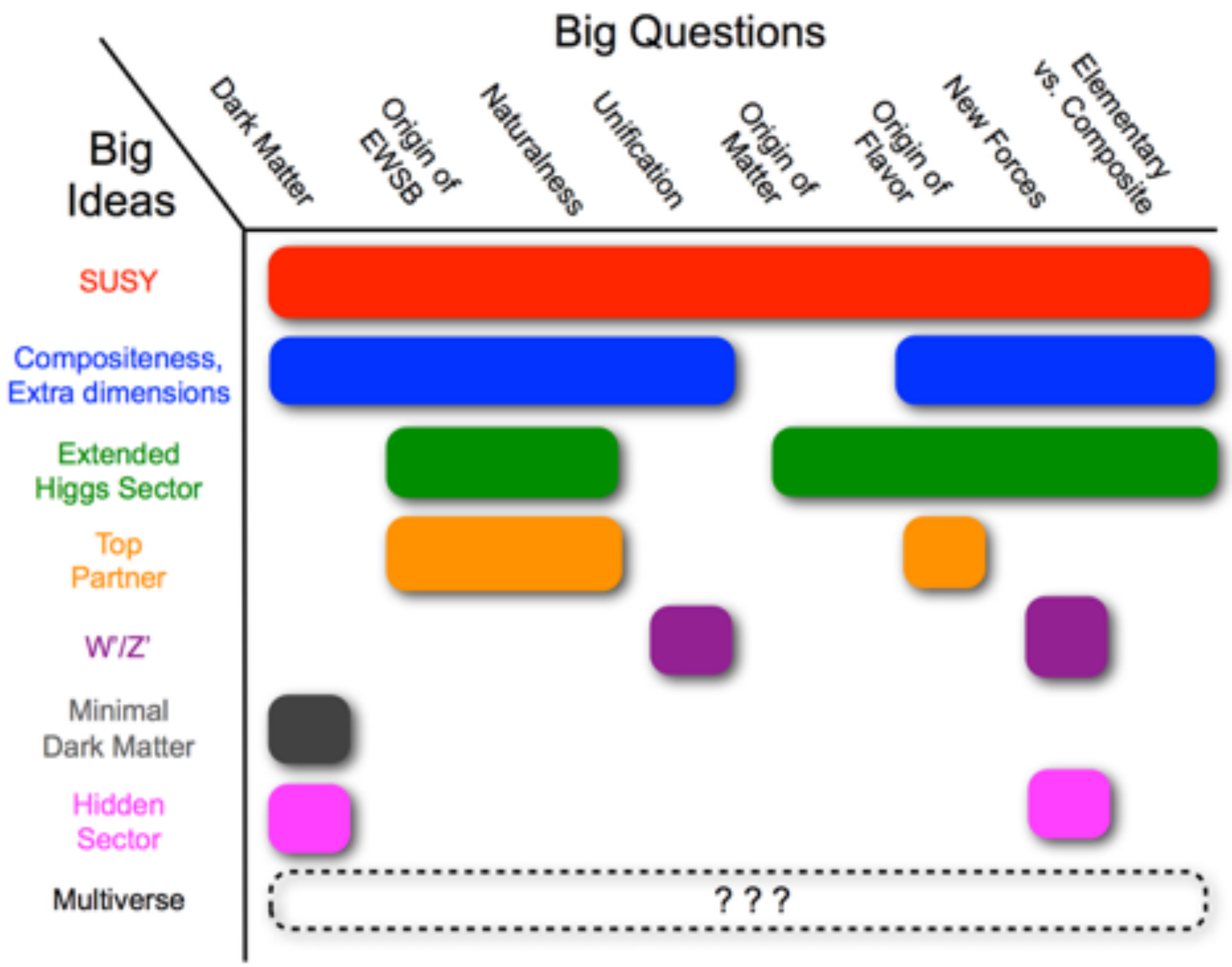


$$N_{pp\to A} = L \times \sigma_A$$
$$N_{pp\to A} = \text{No. of events of process } A$$
$$L = \text{Luminosity}$$
$$\sigma_A = \text{Cross-section of process} A$$

LuminosityPublicResultsRun2

Why High mass resonance search?

- The Standard Model (SM) of Particle Physics is a successful theory
- With Higgs discovery the SM became complete
- But there are several limitations to the SM

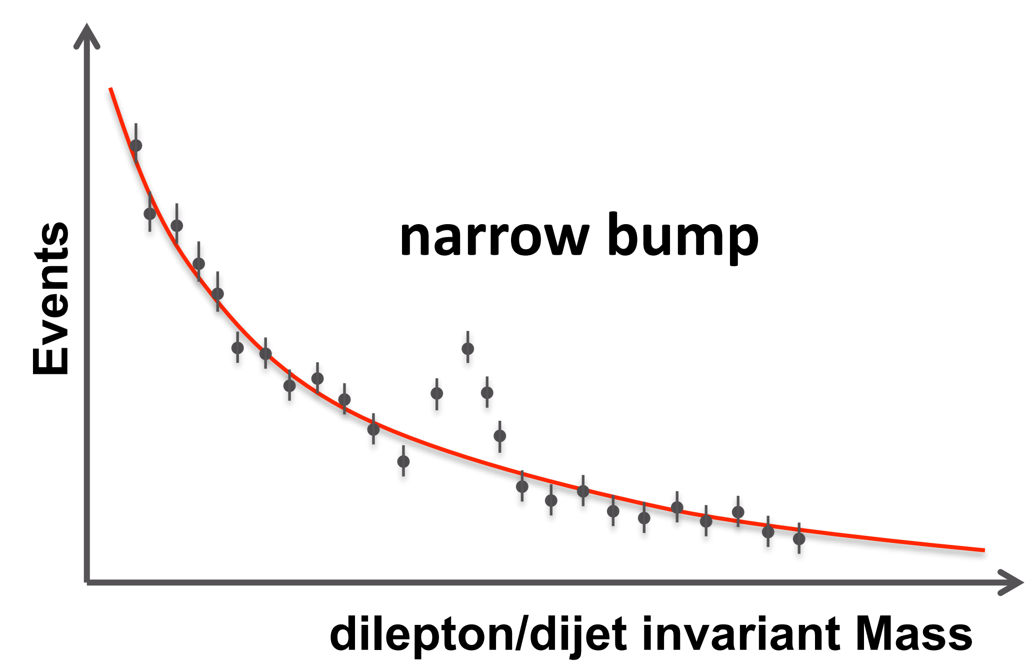


arXiv:1311.0299 [hep-ex]

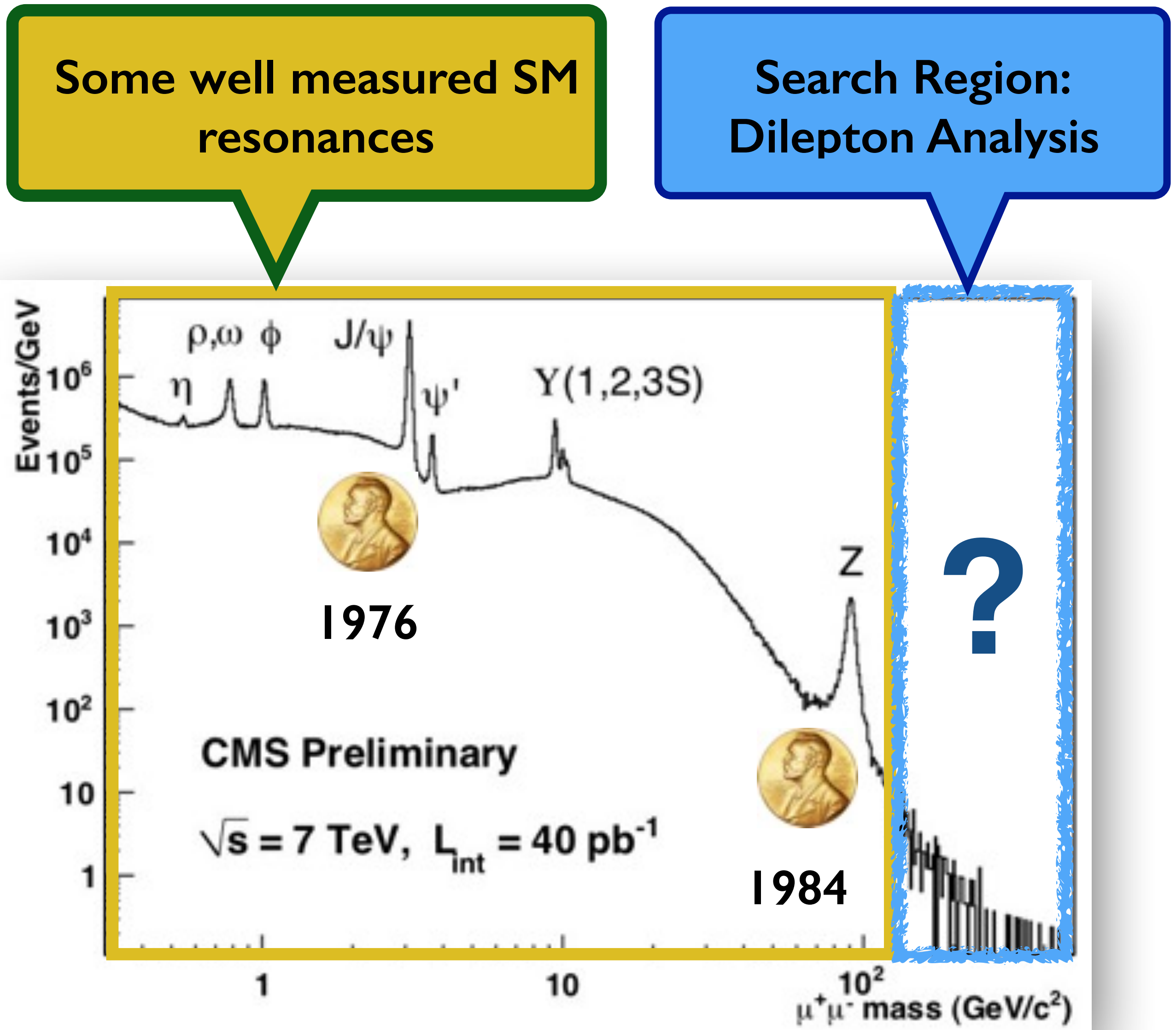
Many theories **Beyond the Standard Model (BSM)** predict new phenomena like:

➡ **narrow resonances** over the SM in the **dilepton or dijet mass spectrum**

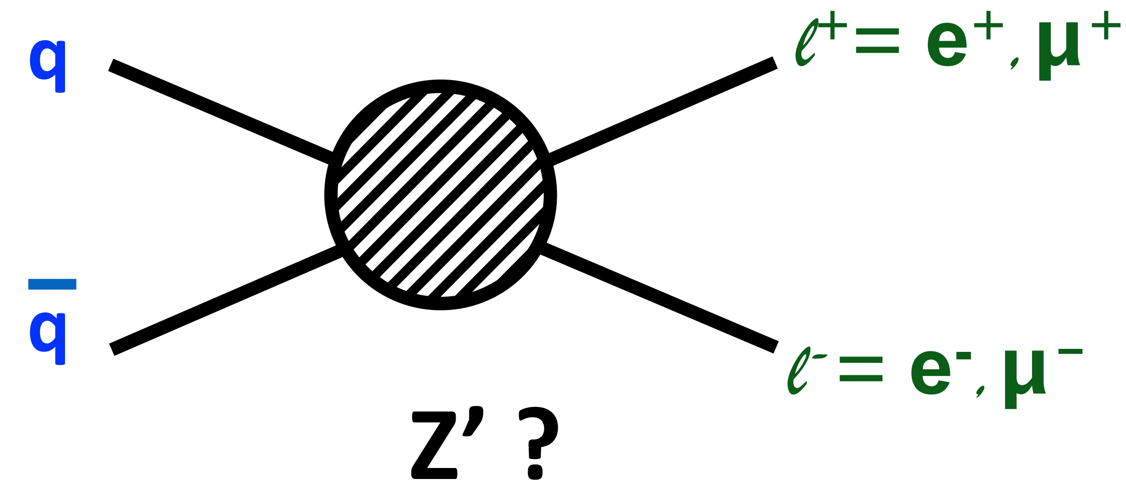
Some models: GUT models with extended symmetry, RS Graviton, KK gluon



Why Z′ →ll ?



arXiv:1206.4071 [hep-ex]



What is Z′ ?

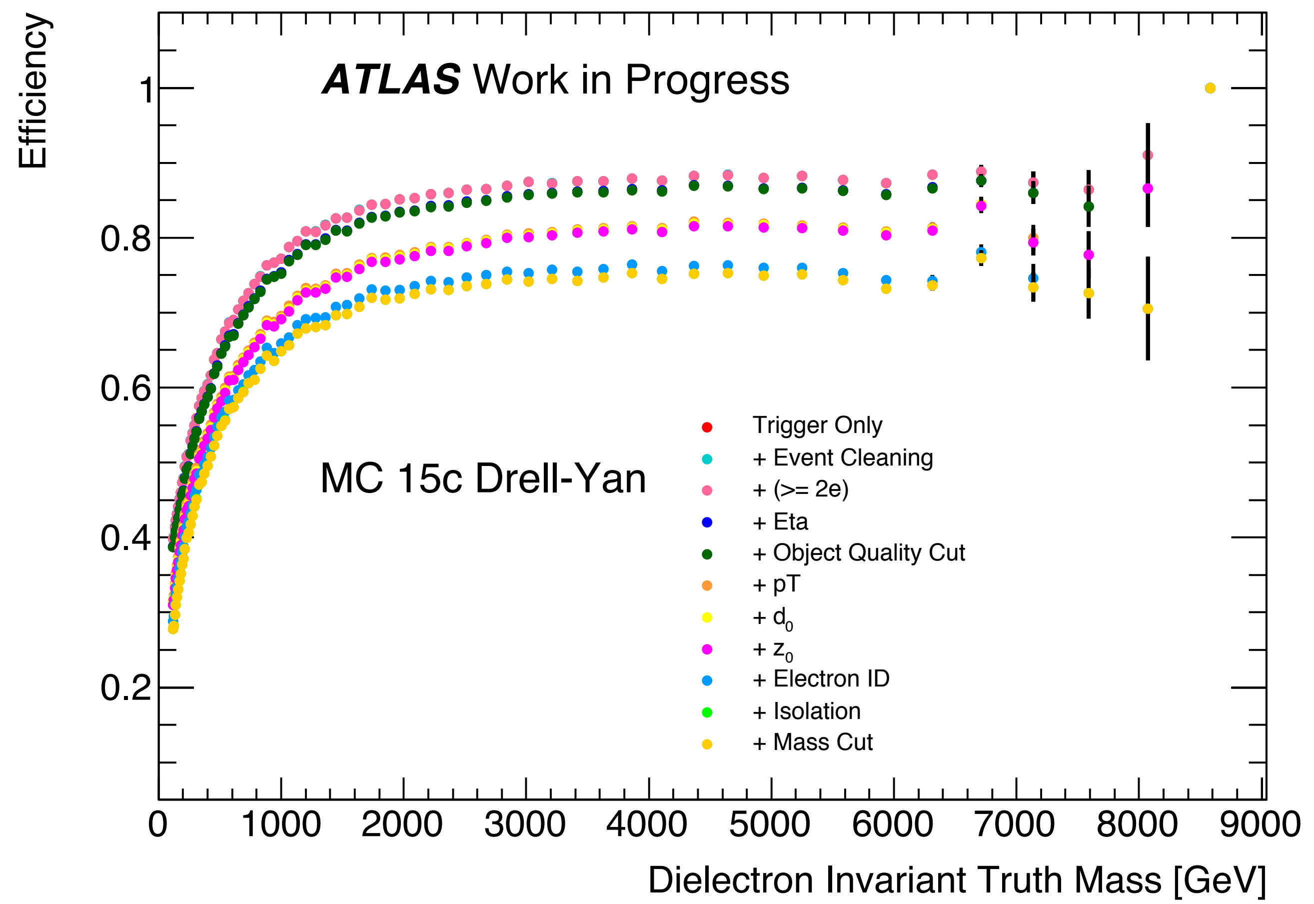
- Additional Spin-1 Gauge Boson
- **Sequential Model:** with same coupling to leptons (like SM Z)
- Also motivated by **Grand Unified Theories (GUT)**, such as **E_6 models**

- Very clean two lepton final state
- It was a very exiting search at the beginning of Run-2
  - Increase in COM energy to 13 TeV compared to Run-I
  - Data by the end of 2016 was ~10 times more than previous year (2015)

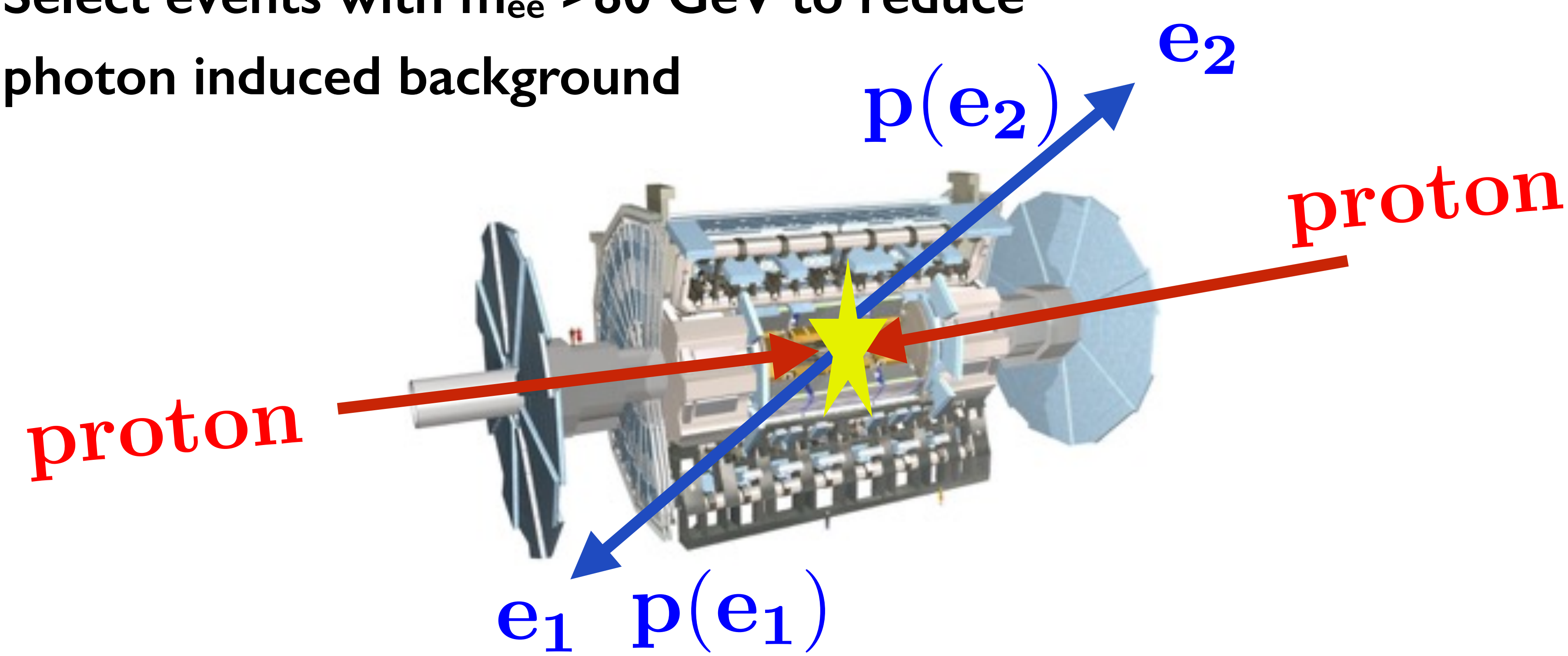
Event Selection (di-electron final state)

- **The event should have at least two electrons**
- Electron transverse momentum (p_T) > 30 GeV
- **Two isolated well reconstructed electrons are selected**
  - **Invariant mass =**

$$m_{ee}^2 = [p(e_1) + p(e_2)]^2$$

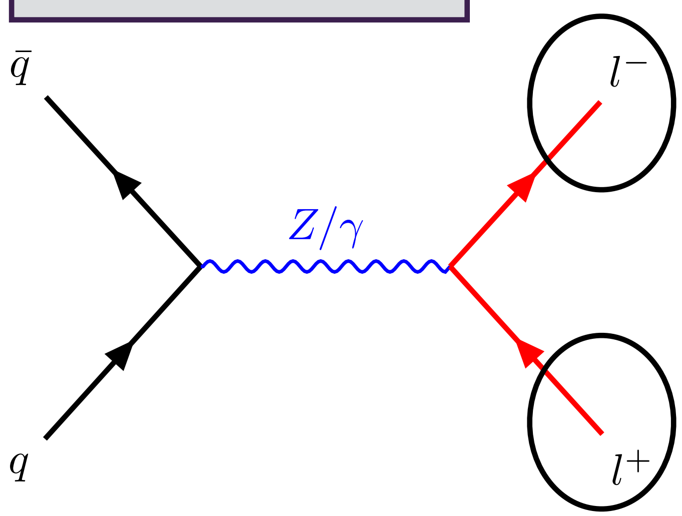


- **Select events with m_{ee} >80 GeV to reduce photon induced background**



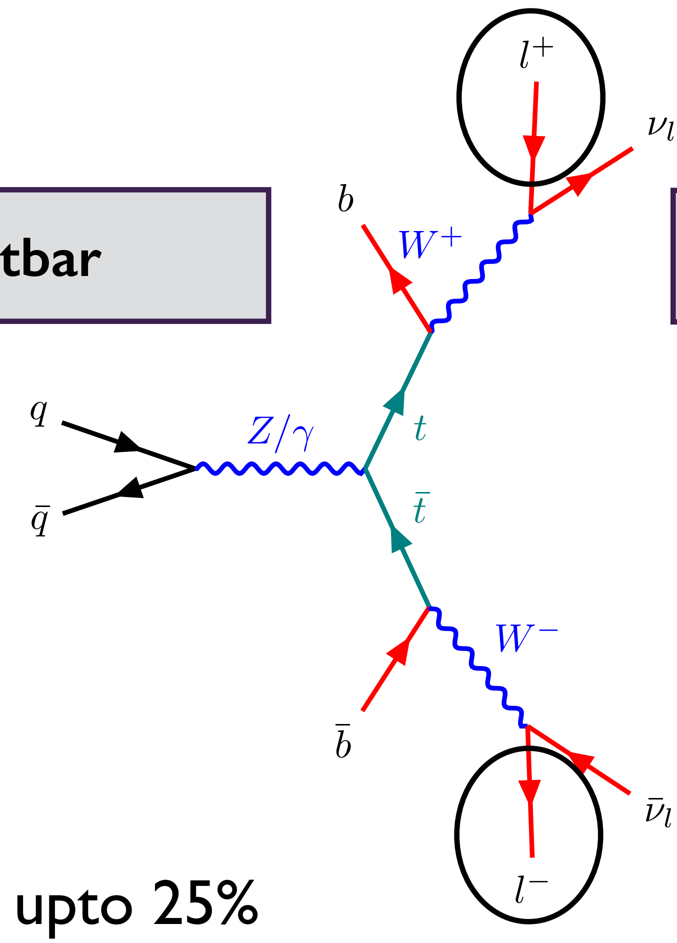
Background and Signal

Drell-Yan



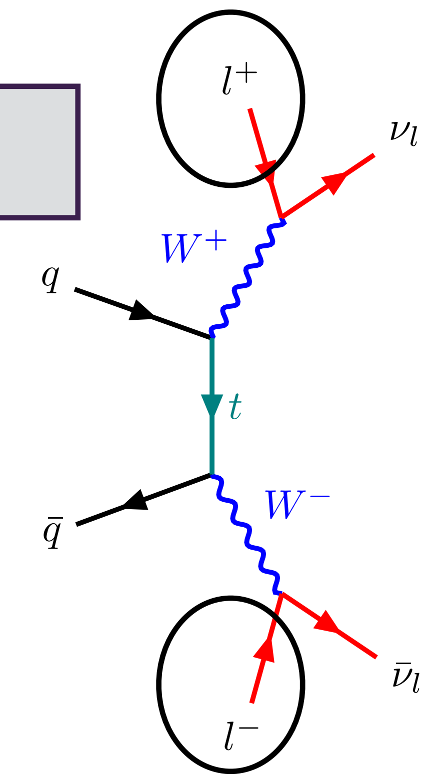
70-80%

ttbar



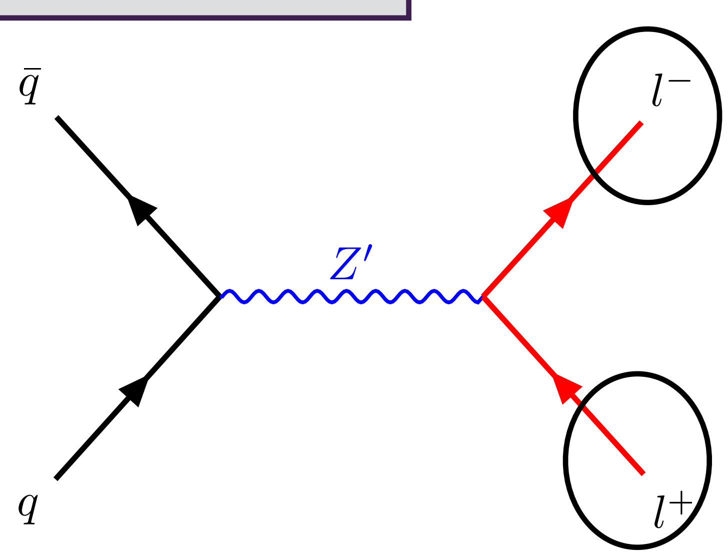
upto 25%

Diboson



6-7%

Z' signal

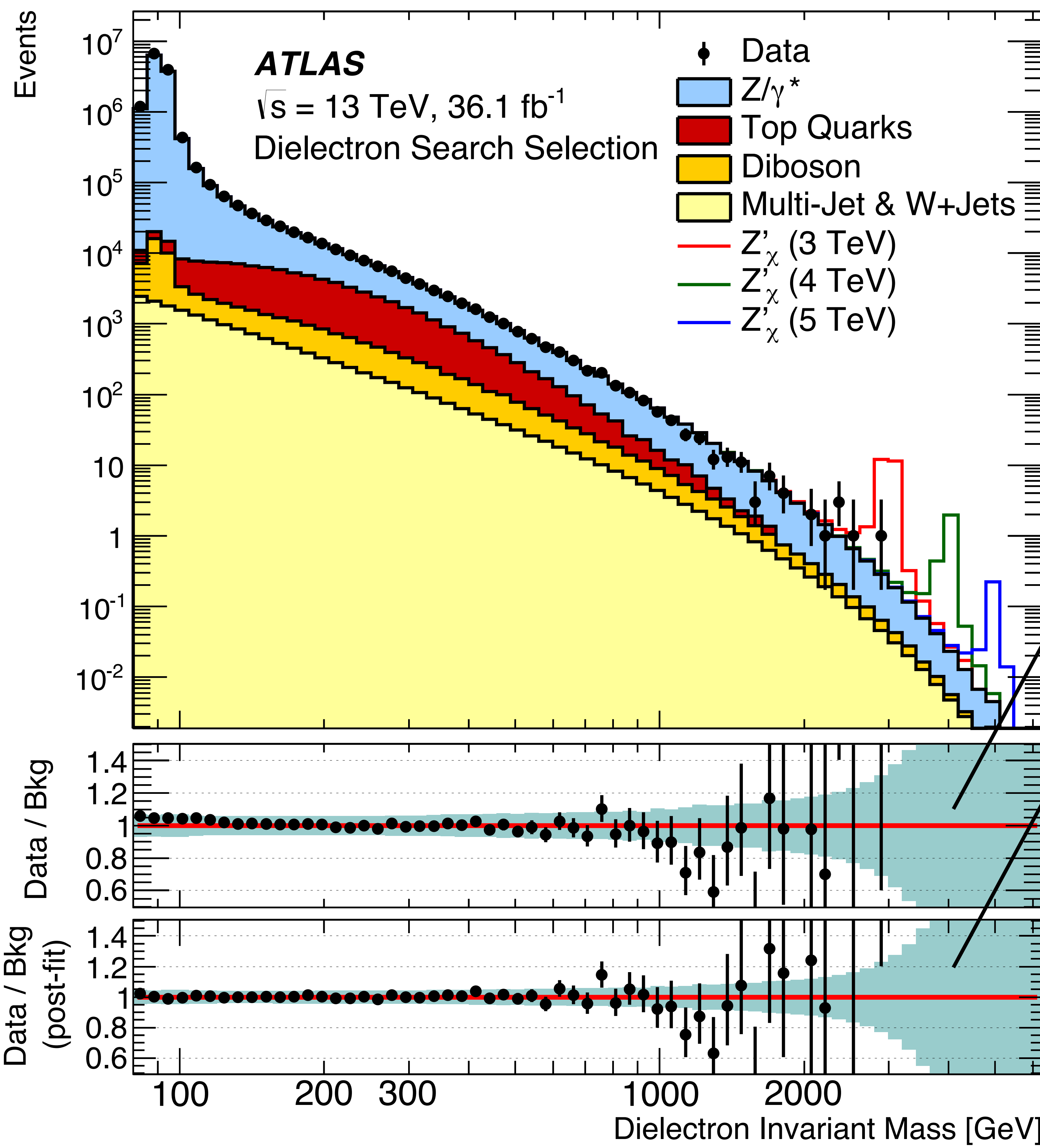


Larger backgrounds: Monte Carlo simulation
NLO ElectroWeak and NNLO QCD corrections

QCD & W+jets background: Estimated from data using data driven technique (5-15%)

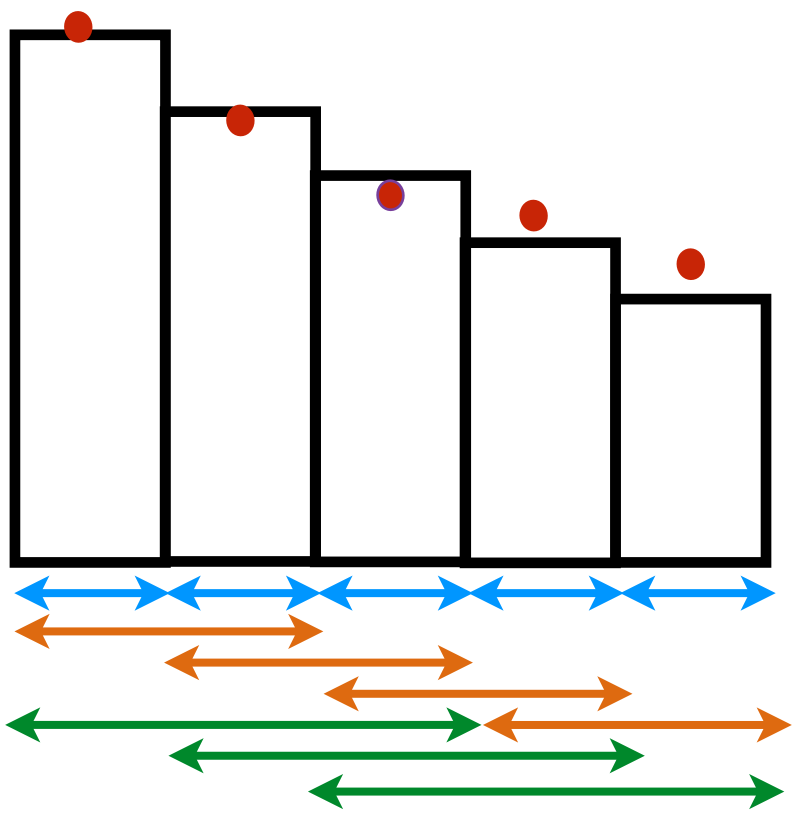
➡ contribution from jets misidentified as electrons

Invariant mass distribution



- The sky-blue band is the total contribution from systematic uncertainties
- Small contribution ~18% at 2 TeV
- **data over pre-fit background**
- **data over post-fit background**
  - ➡Background has been adjusted to the results from the fit to the data used in statistical analysis

Model Independent Search: BumpHunter



- **Searches in all contiguous bins:**
  - min interval: 1 bin
  - max interval: half of the distribution
  - Calculate local p-value for each search
- **BumpHunter statistic =** $-\ln(\min\{\text{local } p\text{-value}\})$

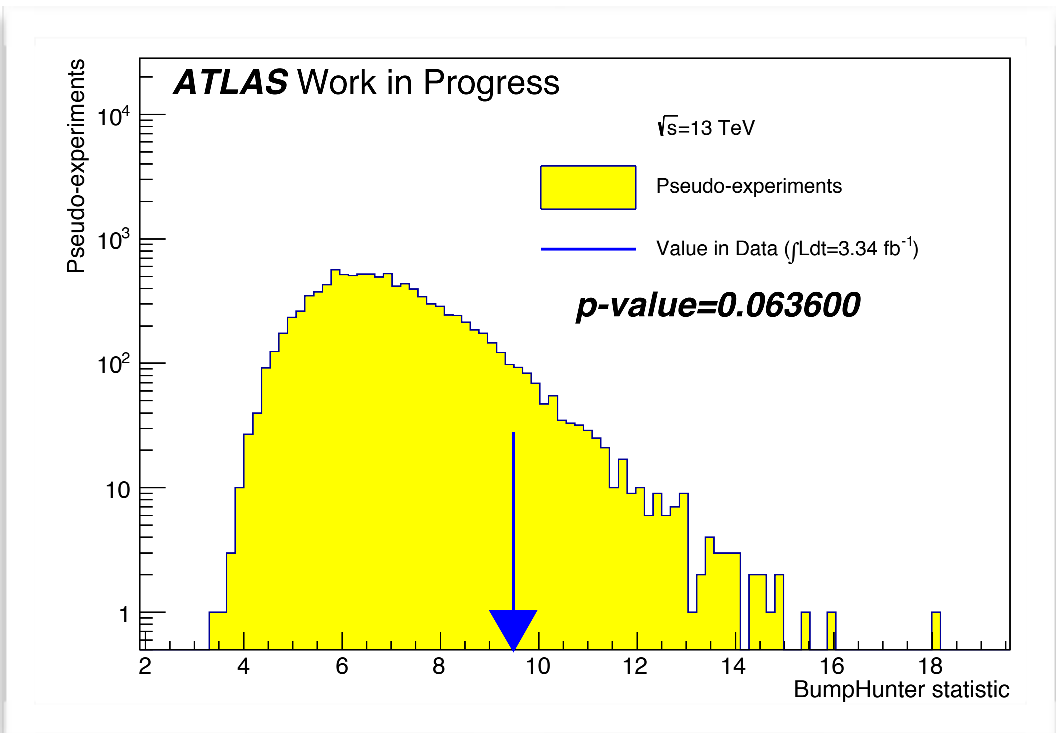
- **global p-value =**

$$\frac{\#\text{ of PEs where (bkg-only statistics } > \text{observed statistics)}}{\text{Total } \#\text{ of pseudo-experiments}}$$

➡ **Takes care of the trials factor**
- By the way the BH statistic and the global p-value is defined

➡ **Model independent test**
- No need of signal hypothesis

arXiv:1101.0390v2



Search in presence of systematics

- ● **Pseudo data or data**
- Nominal background
- Systematic uncertainties
- Best fit background

n_k : # of data events in k^{th} bin

b_k^0 : # of nominal background events in k^{th} bin

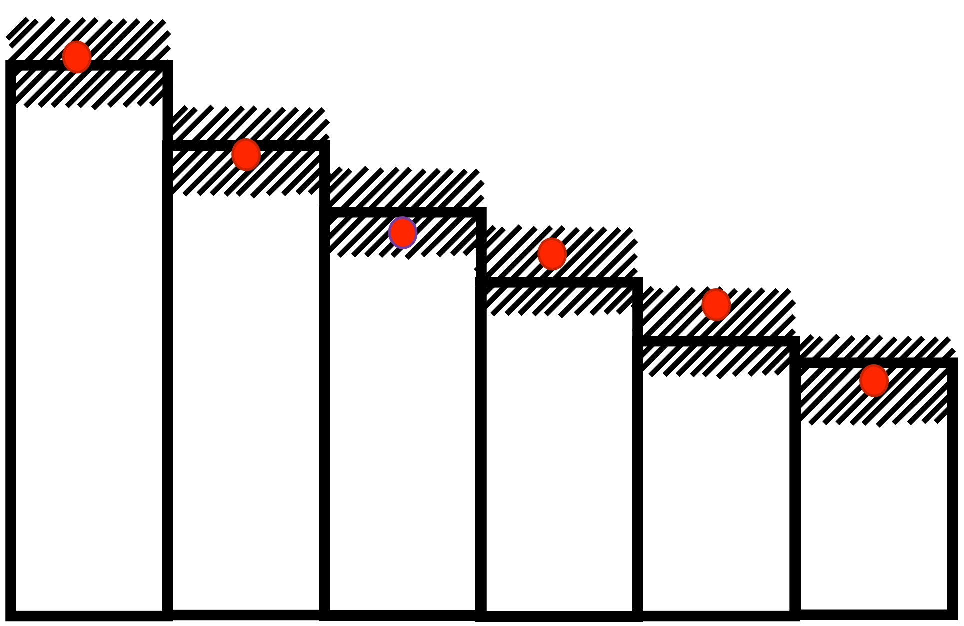
$$b_k = b_k^0 \left(1 + \sum_{i=1}^{N_{\text{sys}}} \theta_i \sigma_{ik}\right)$$

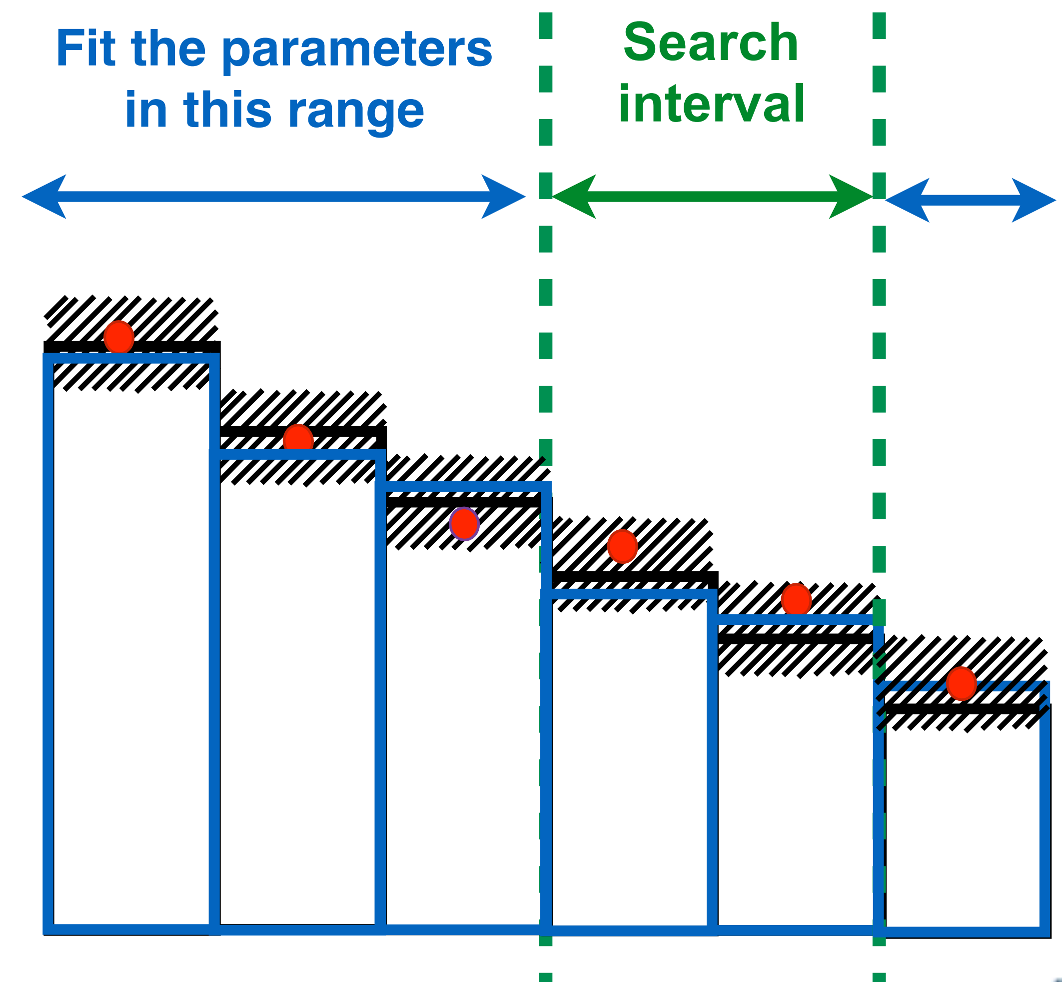
$$\mathcal{L}(\theta) = \prod_{k=1}^{N_{\text{bin}}} \frac{{b_k}^{n_k}}{n_k!} e^{b_k} \prod_{i=1}^{N_{\text{sys}}} G(\theta_i; 0, 1)$$

Gaussian constraint

θ_i : nuisance parameter

σ_{ik} : k^{th} bin content of i^{th} systematic



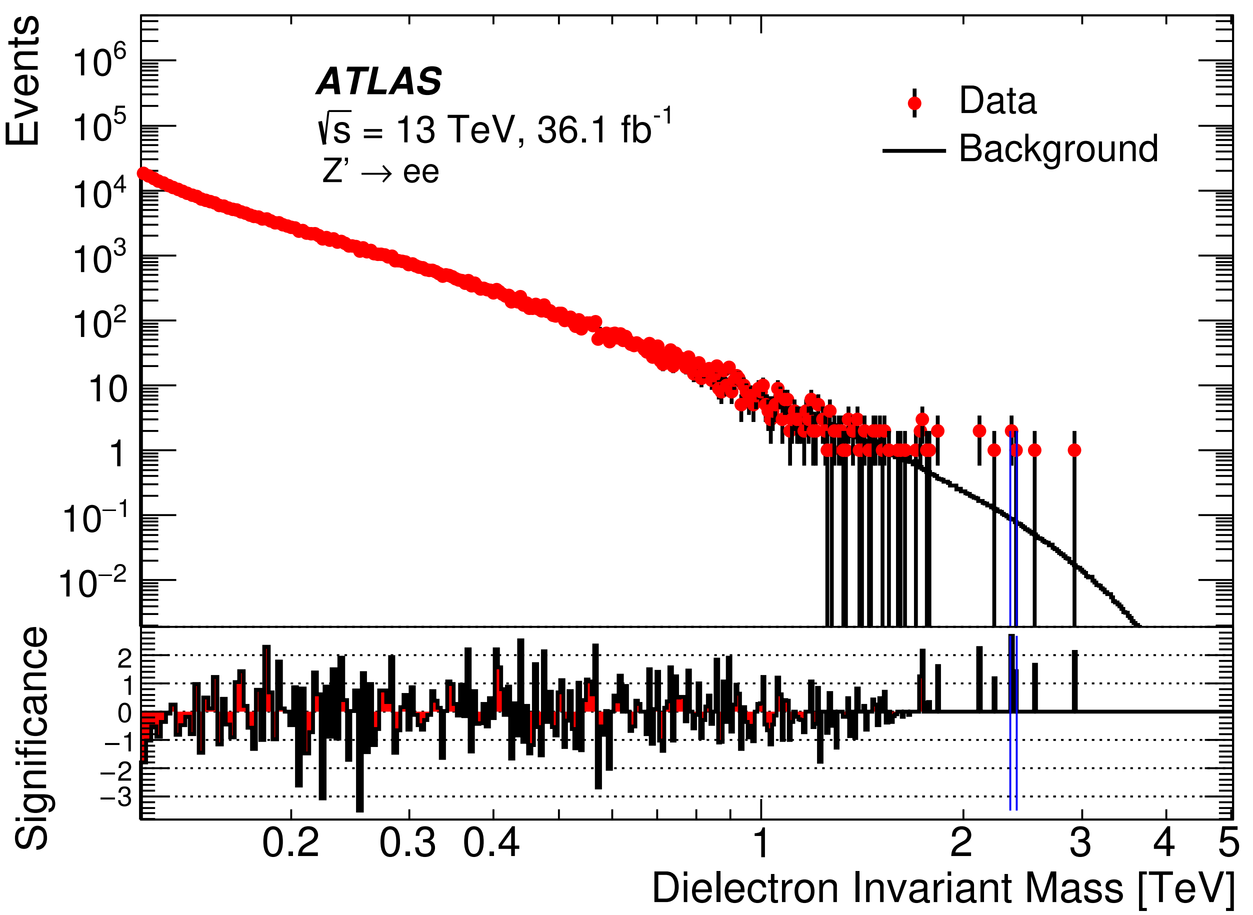


BumpHunter Results

- Searched for bumps only
- Most significant interval is marked by **blue** lines

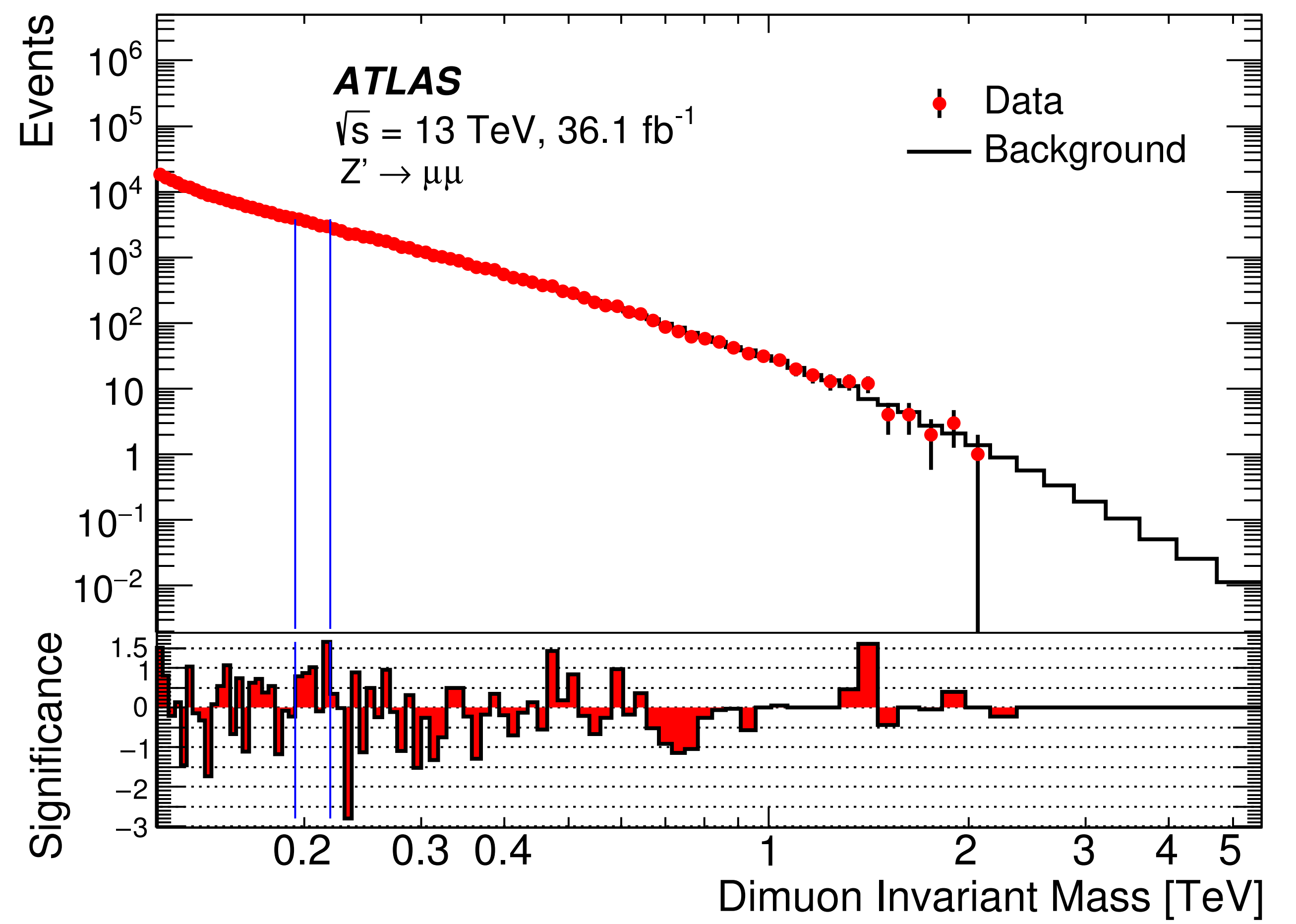
Electron Channel

Global p-value: 0.71 σ

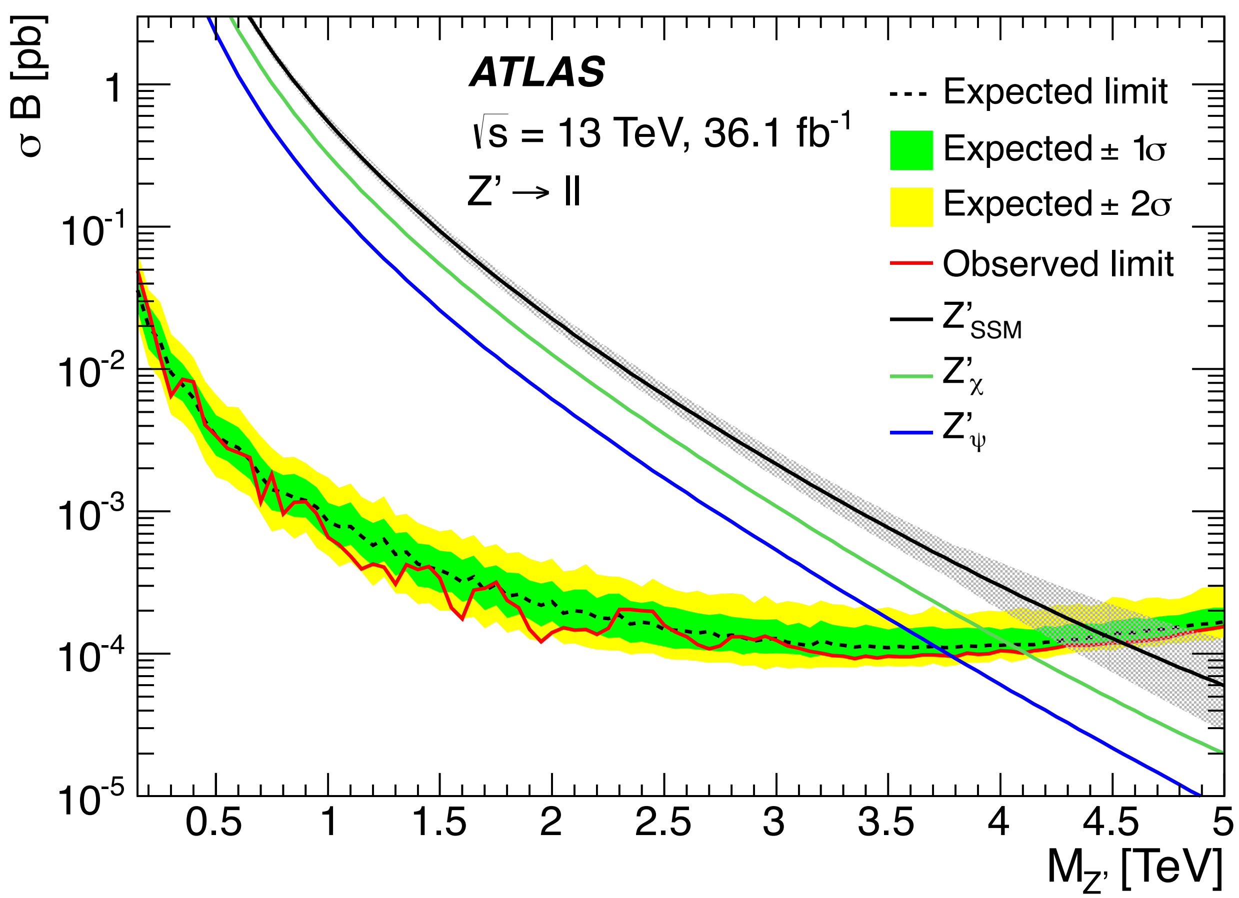


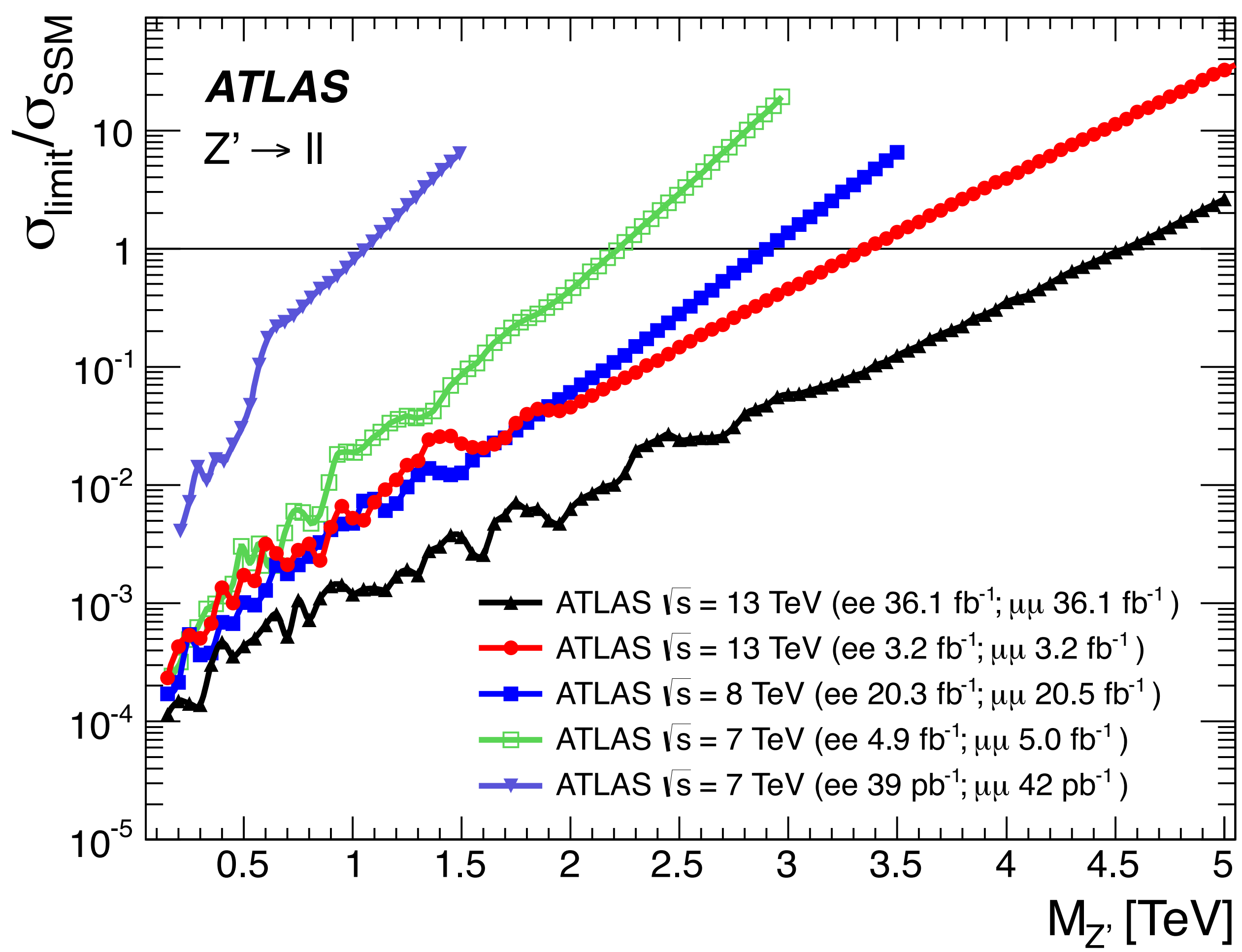
Muon Channel

Global p-value: 0.94 σ



Exclusion Limit

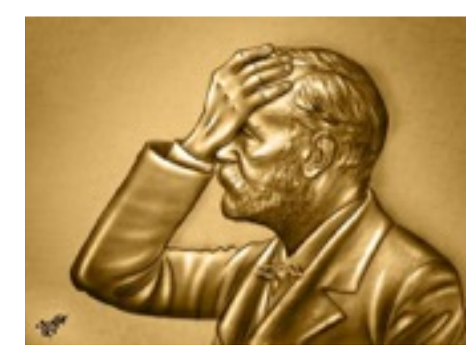




Journal of High Energy Physics, 10, 182 (2017)

Mass exclusion limit was increased all most by 1 TeV

- ➡ Mass limit of 4.5 TeV is set on the Z'_{SSM} with 3% width
- ➡ Mass limit of 4.1 TeV is set on the Z'_{E6} with 1.2% width



4 times more data at the end of Run-2 will not improve the result much

- ➡ Changing focus to other search

Moving ahead: focus on ttbar resonance

- **While we don't see new physics in the dilepton final state in Run-2, it could show up in the top-antitop final state**
  - The BSM boson could have different coupling to the top quark (mass, generation)
  - The new physics could be lepto-phobic

- **Like the previous search signal could come from several models:**
  - Spin-1 Z' Technicolor (TC2) model
  - Kaluza–Klein (KK) gluon
  - Spin-2 graviton (Bulk RS)

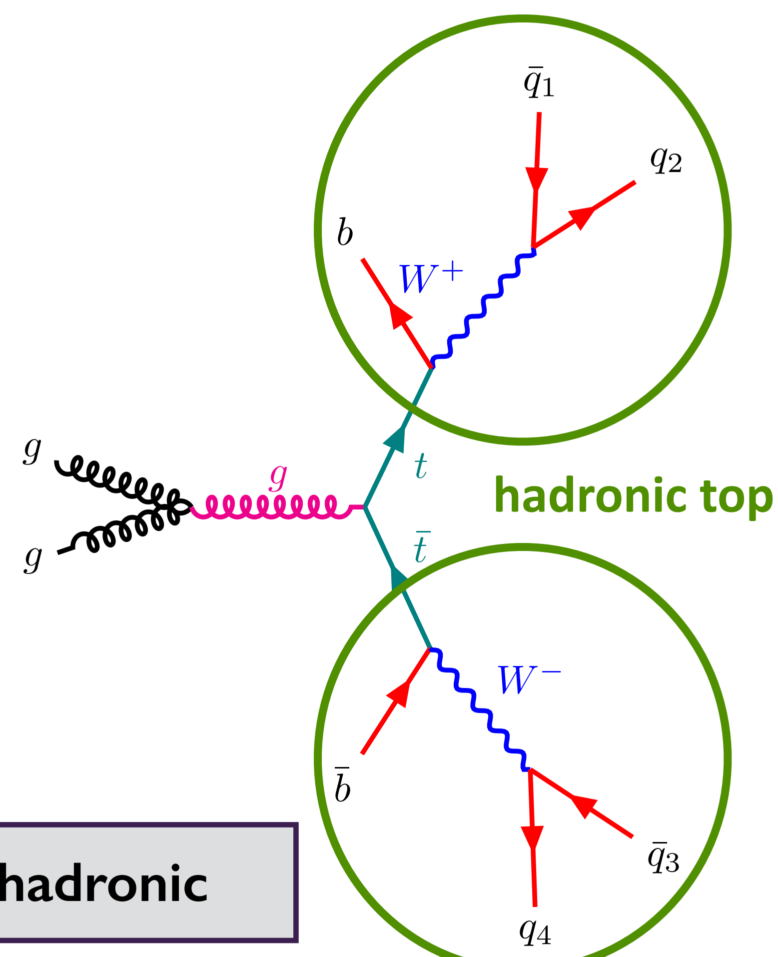
- **Lots of scope to improve the results compared to partial Run-2 (2015+2016)**

Major top-decay final states

- Two separate analysis for the two channels
  - ➡ All hadronic (~46%)
  - ➡ lepton+jets (only e & mu: ~30%)

All-hadronic Channel

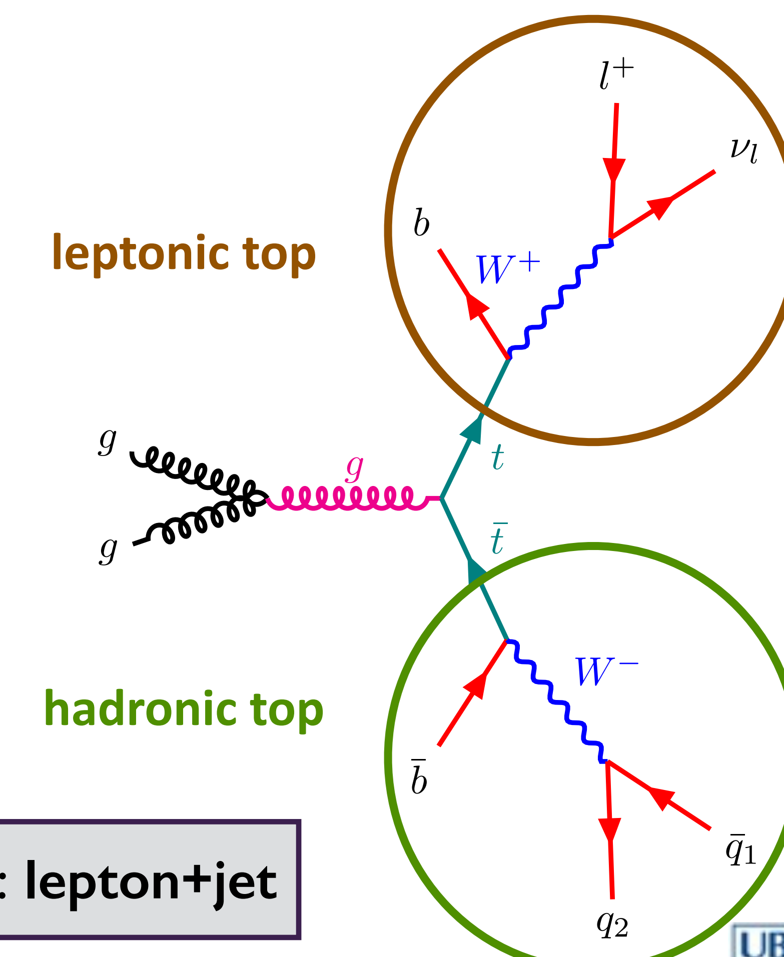
- Dominant background from SM $t\bar{t}$ process
- large contribution from QCD multi jet process



$t\bar{t}$ background: **all hadronic**

Lepton+Jet Channel

- Dominant background is SM $t\bar{t}$ process
- Contributions from W+jets, Z+jets, QCD



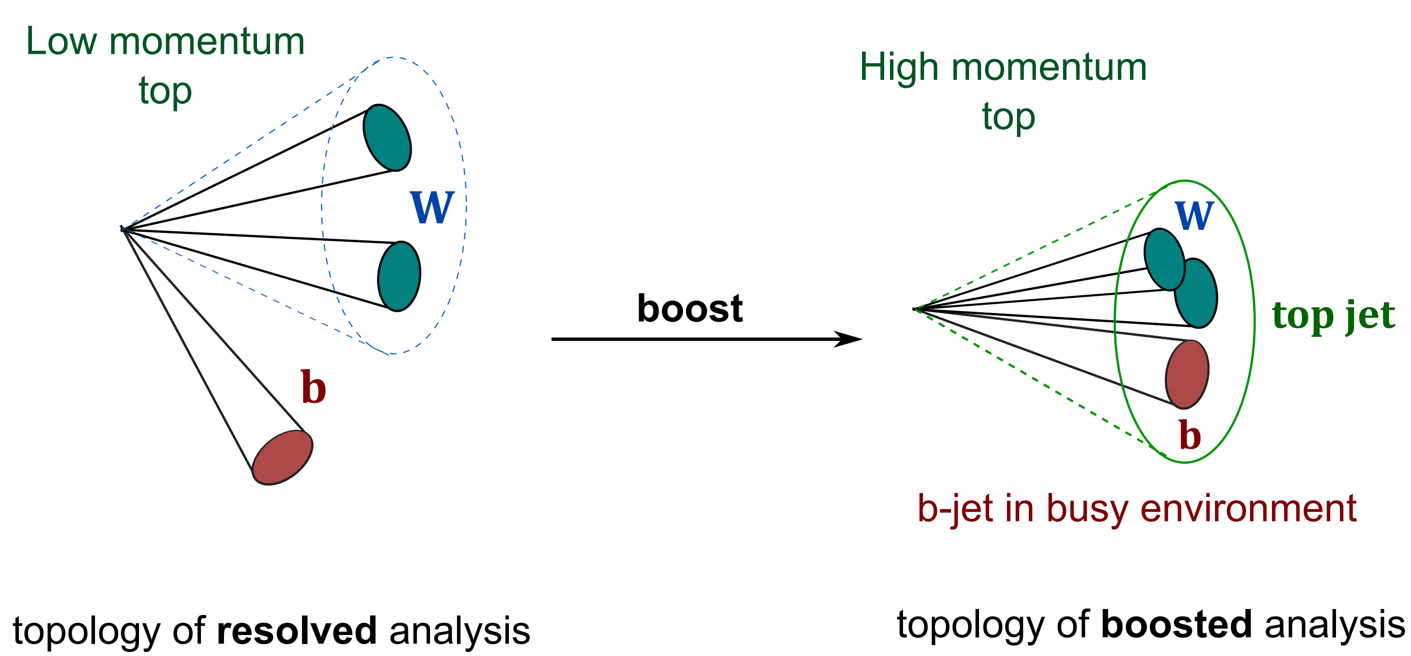
$t\bar{t}$ background: **lepton+jet**

High p_T top decay

Decay products of a high momentum top quark get collimated along the top quark momentum

Hadronic top:

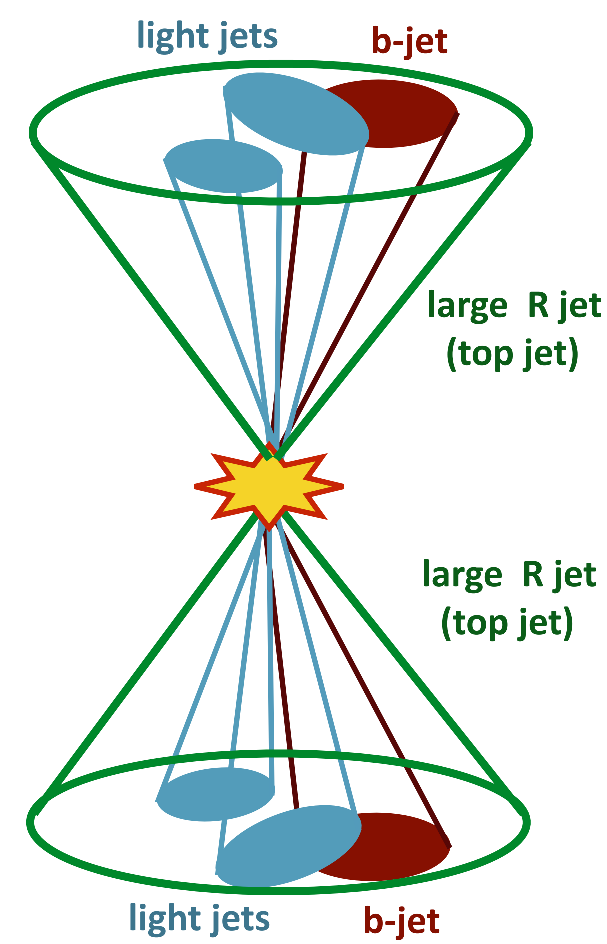
- All three jets come very close to each other
- Forms a **large radius jet** (R=1)



So, in the boosted regime the search is very dependent on the top-tagging techniques

Analysis Strategy: boosted all-hadronic ttbar

- Search for resonance in boosted all-hadronic ttbar final state
- **Observable:** m_{tt}
- **Background estimate:** functional form fit to data (in Signal regions)
- **Tool improvements:** top-tagging with DNN top tagger, VR track jet b-tagging with DL1 tagger
- **Signature:** bump on smoothly falling background



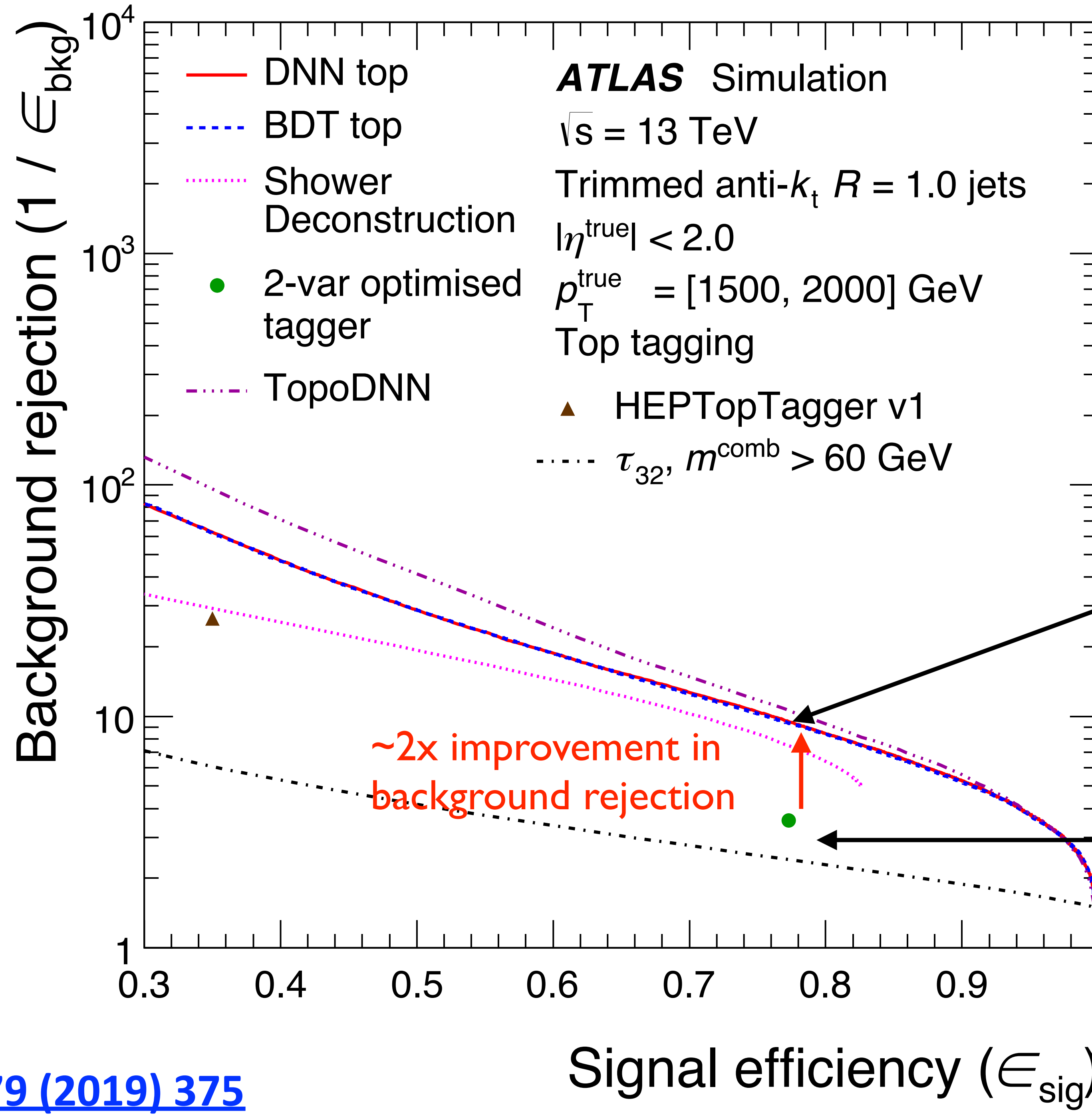
Things changed from partial Run-2 analysis:

- Bkg estimation with functional fit
- DNN top tagger, DL1 b-tagging

Full Run2 results: https://arxiv.org/abs/2005.05138

Improvements in top-tagging

- ~2x improvement in background rejection at very high p_T region



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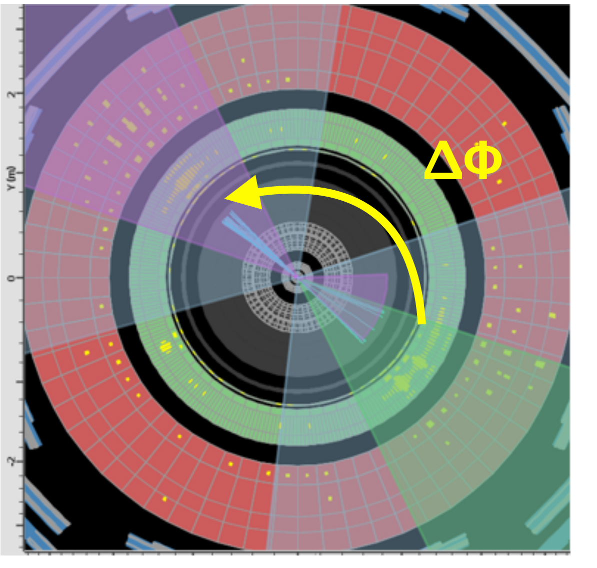
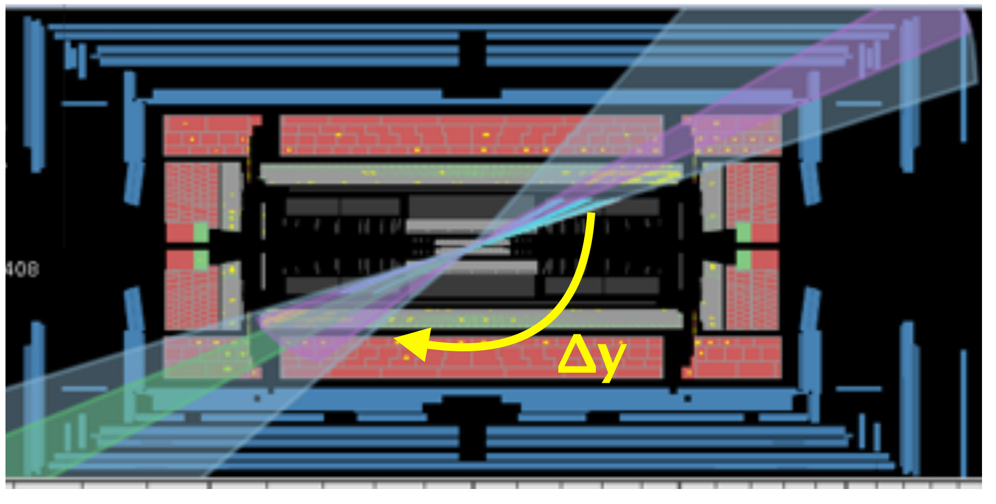
Event Selection

- **Large-R jet trigger** p_T > 360-460 GeV depending on data period
- **Event Cleaning:** GoodCalo, ≥ 1 primary vertex, Jet Cleaning (LooseBad)
- **Lepton veto:** Required exactly 0 lepton (el/mu) in the event

- >= 2 large radius jets with:
  - $p_{T,J1}$ > 500 GeV and $p_{T,J2}$ > 350 GeV
  - $\Delta\Phi$ (J_1,J_2) > 1.6 (back-to-back)
  - Δy(J_1,J_2) < 1.8 (remove t-channel SM ttbar production)





y = rapidity

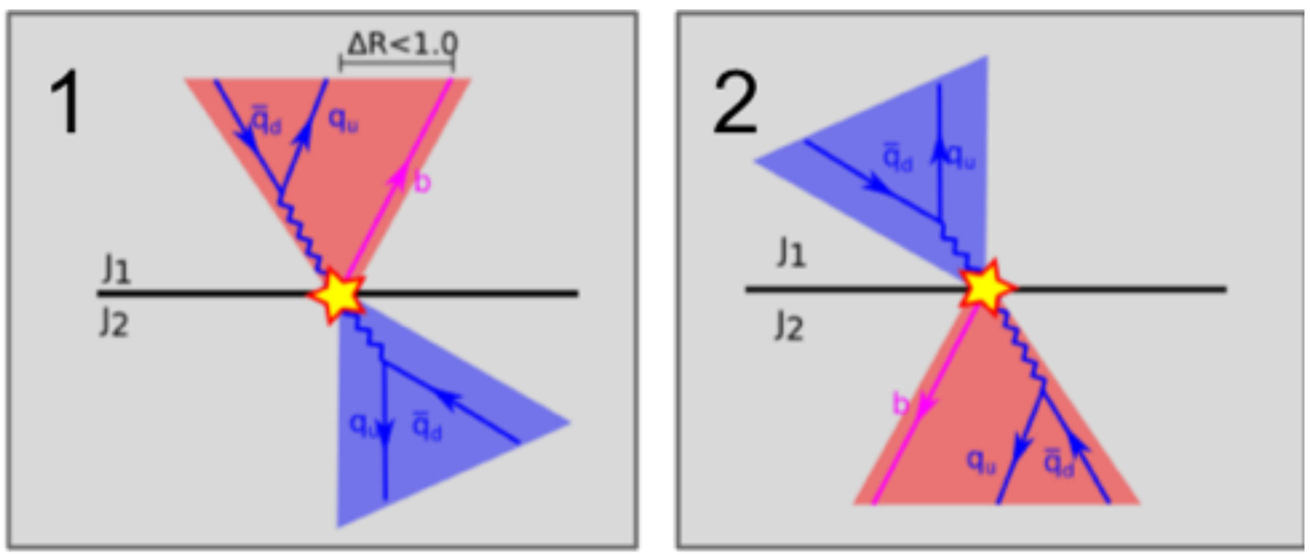
- Leading and sub-leading large-R jets are top-tagged (DNN top tagger 80% efficiency WP)
- m_{tt} > 1400 GeV

ATLAS-PHOTO-2018-002

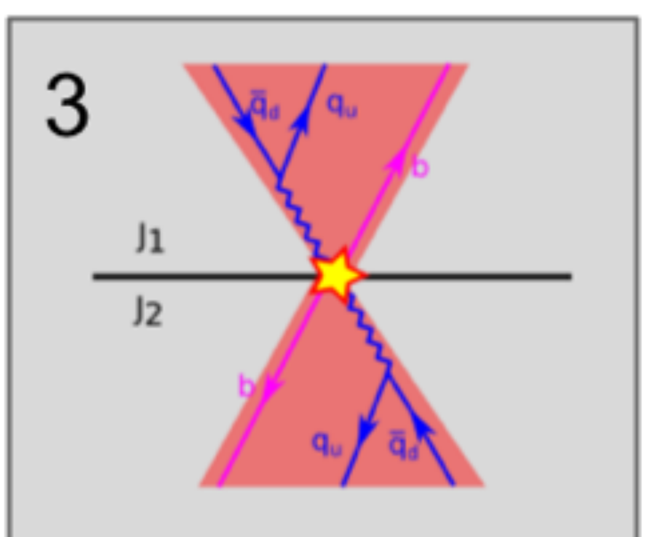
Control and Signal regions

- Top-jets are matched with b-tagged (variable radius) track jets (DL1 efficiency 77% WP) in the SR

0 b-tag Control Region: No b-jet close (dR < 1.0) to the top jets
1 b-tag Signal Region: One b-jet close to one of the top jets
2 b-tag Signal Region: Each top jet is associated with a b-jet



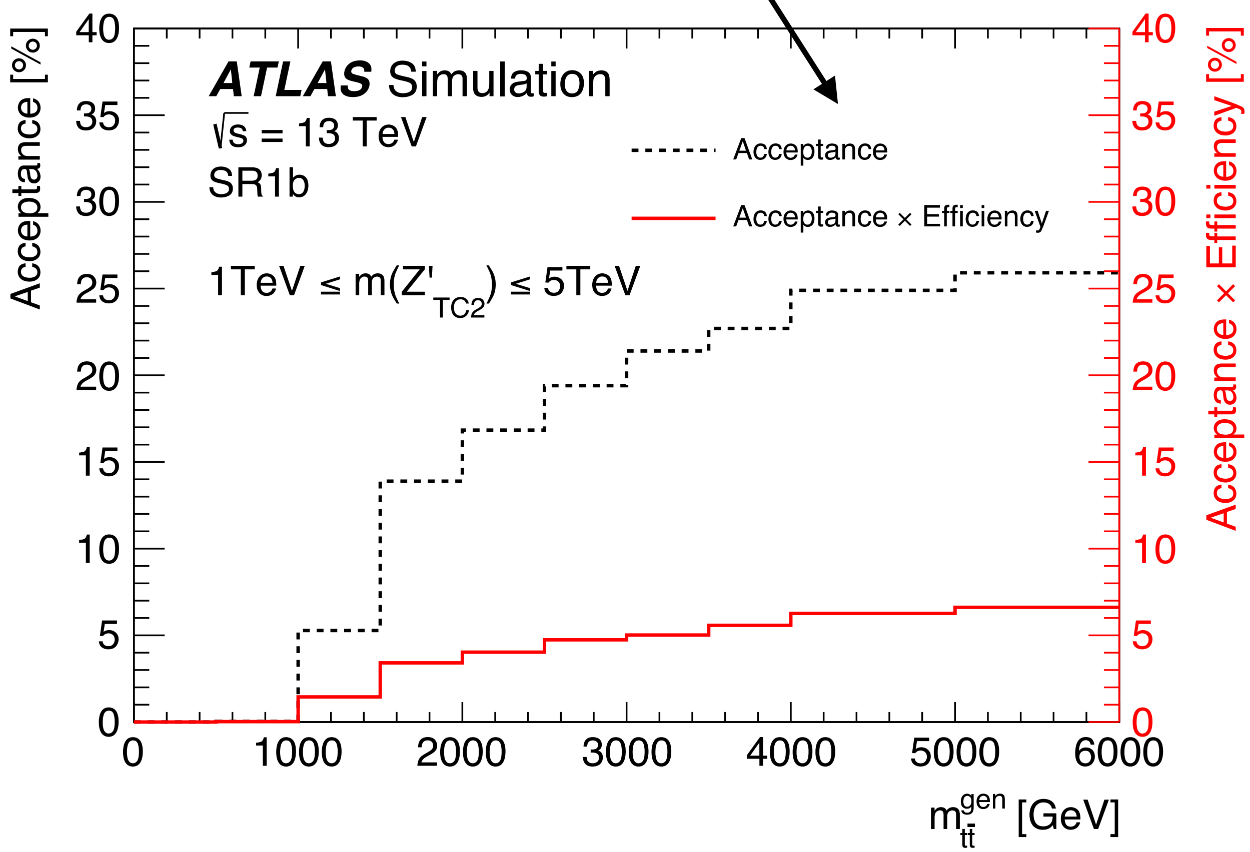
1 b-tag Signal Region

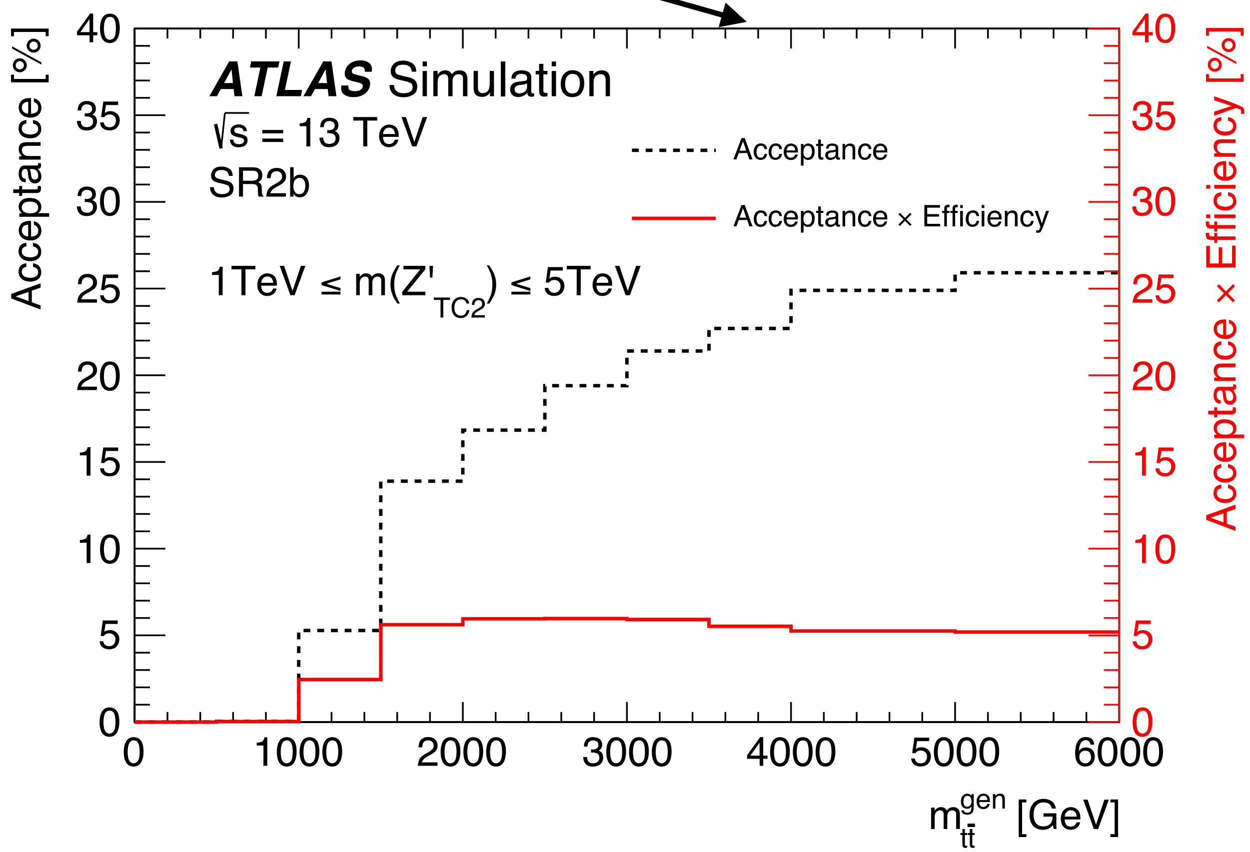


2 b-tag Signal Region

Selection Efficiency

- **Acceptance** times **efficiency** as a function of the invariant mass of a top-quark pair at the generator level
- Acc x eff is around 7% (1bSR) and 5 % (2bSR)



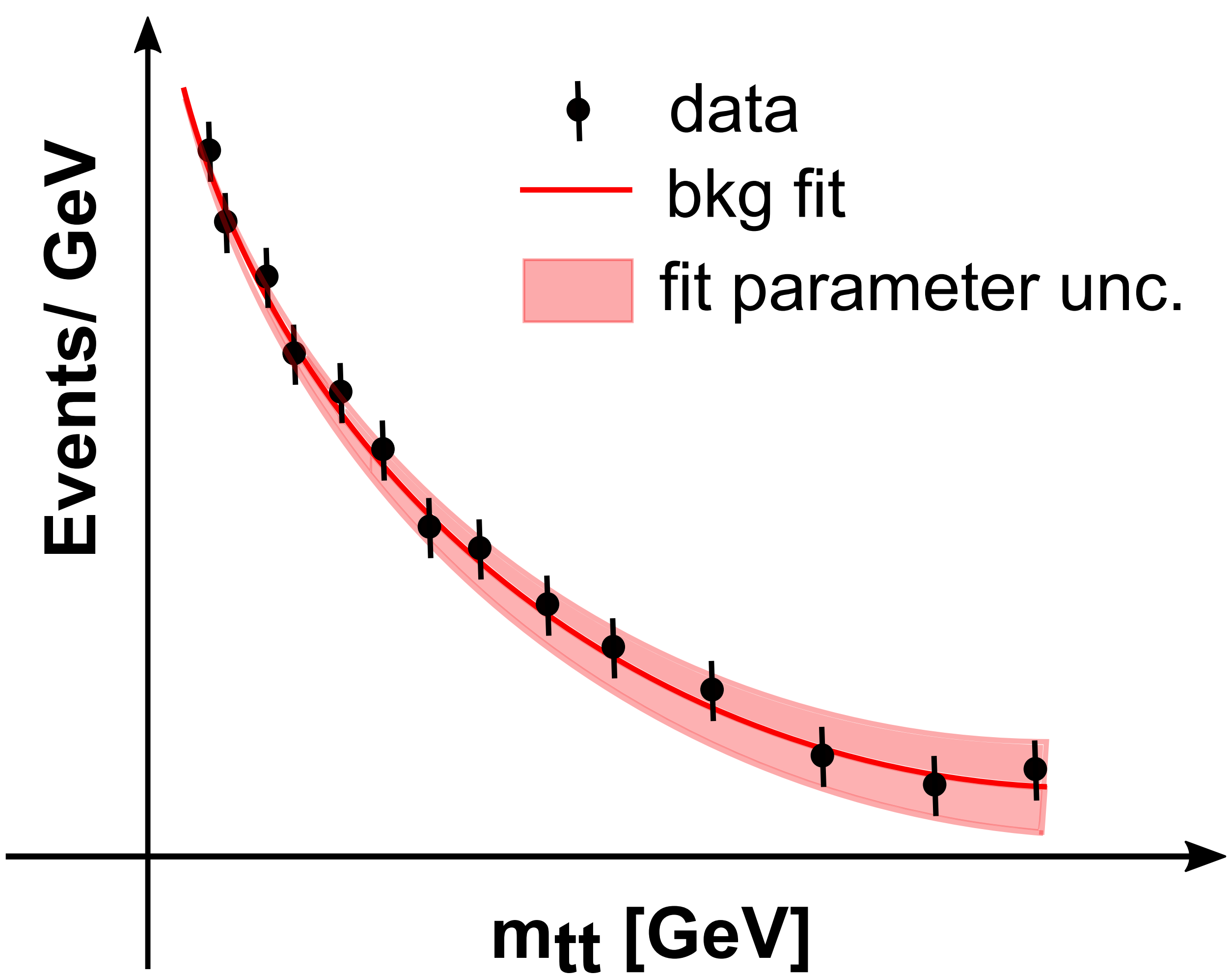


Background estimation

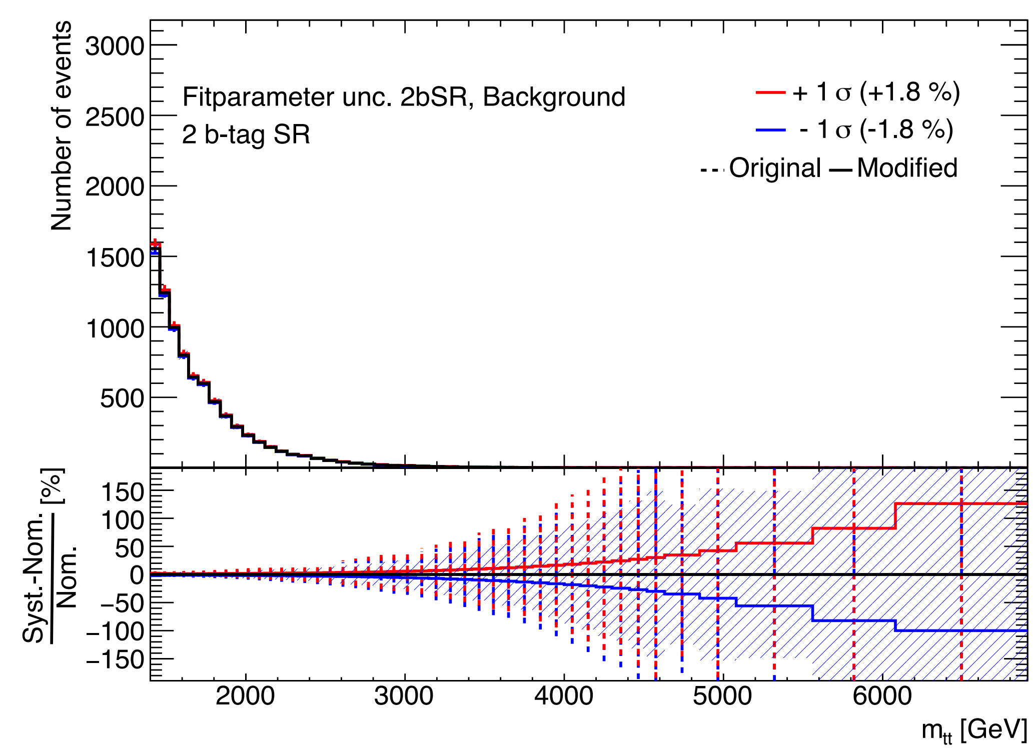
- Major background comes from **SM tt production** and **QCD multi jet process**
- Background is estimated from data by a functional fit to data
- **Smoothly falling function:**

$$f(x) = p_0(1-x)^{p_1} x^{p_2 + p_3 \log(x)}$$

- The function is validated in SRs using background-only sample
- tt MC + high-mass dijet MC + data-driven template of low-mass multijet sample

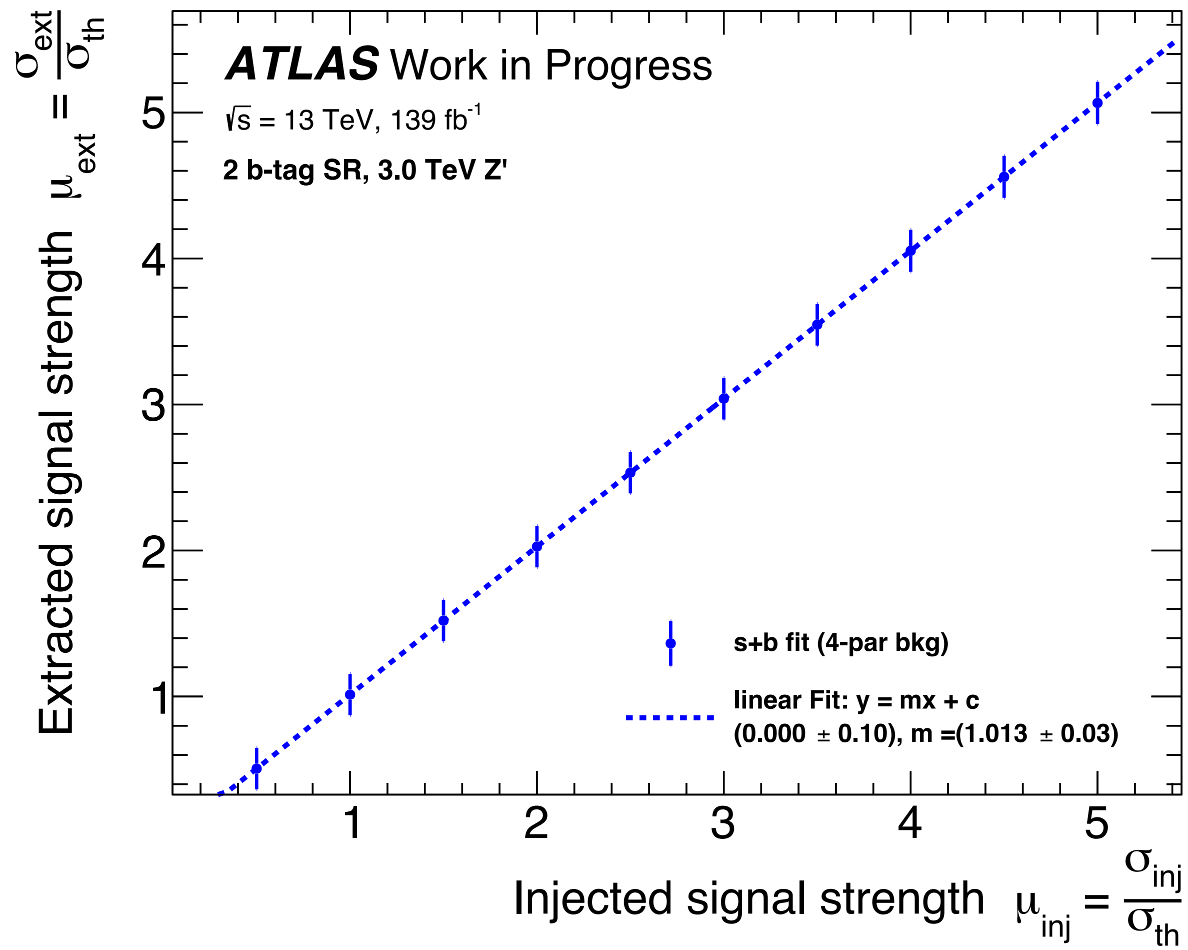


Uncertainties on fit parameters are considered as systematic uncertainty

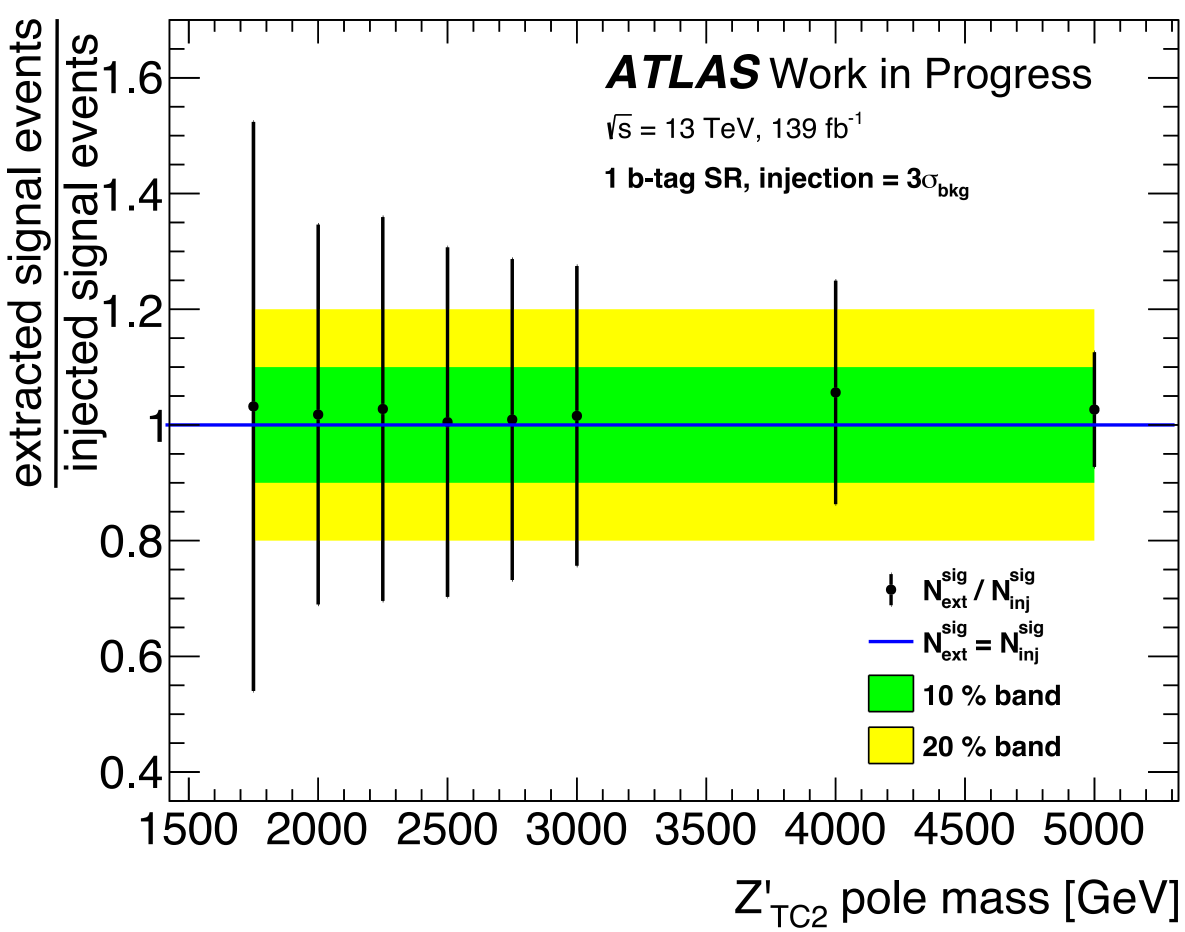


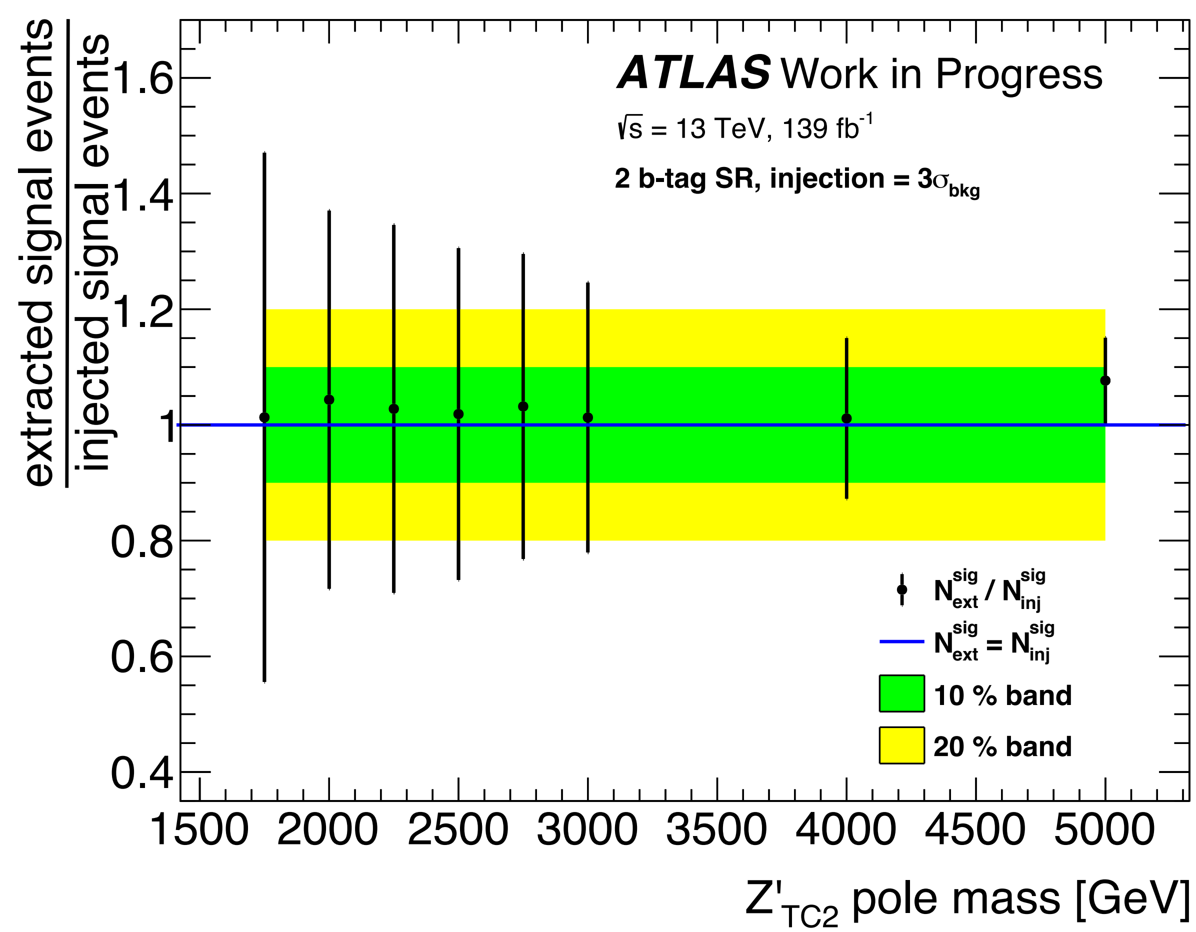
Signal Injection Test

- Ability of extracting signal was tested by injecting known signal
- Do a s+b fit
- Extracted vs injected strength: **linear trend**



Injected signal = 3 x background uncertainty



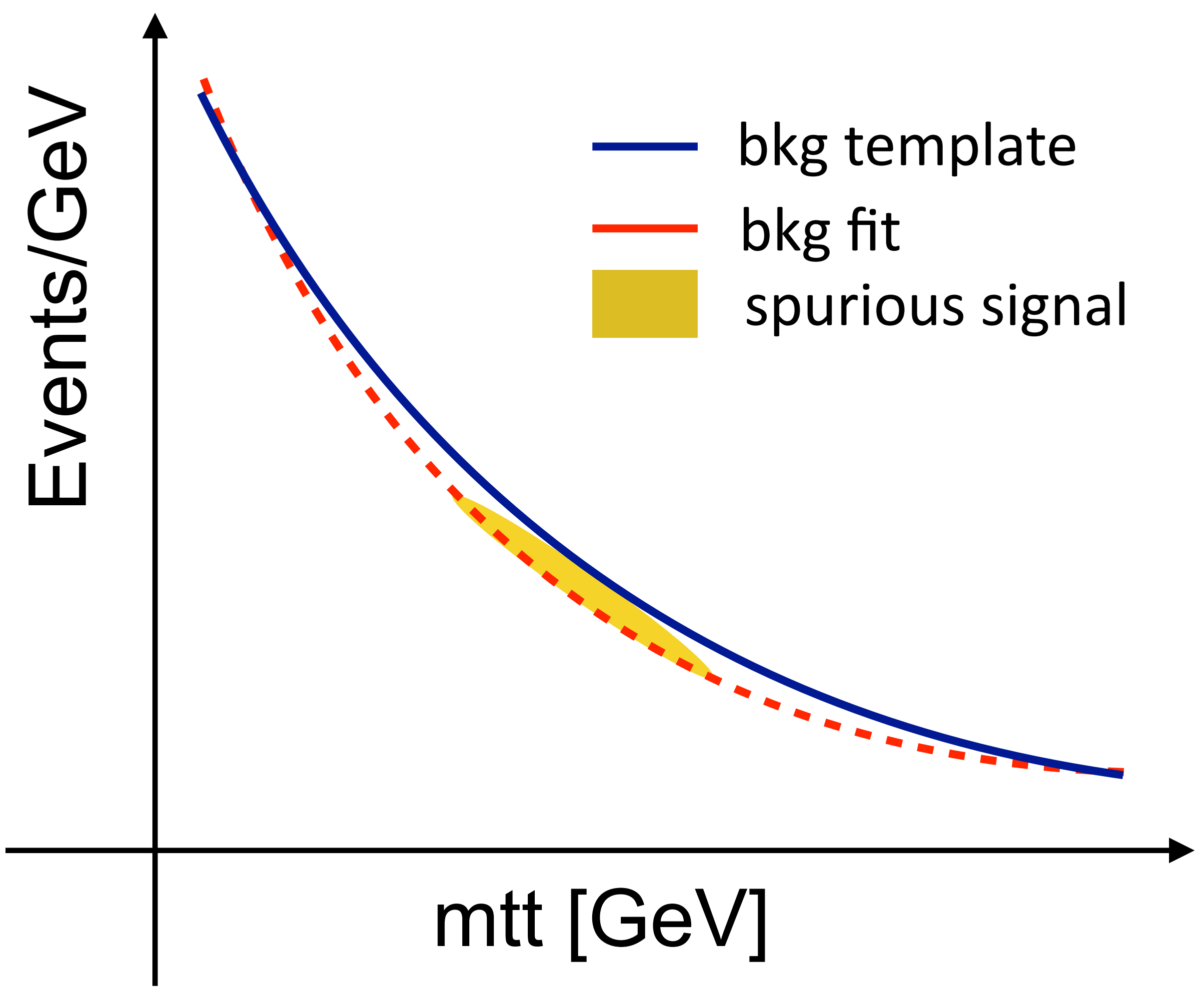


Spurious Signal Test

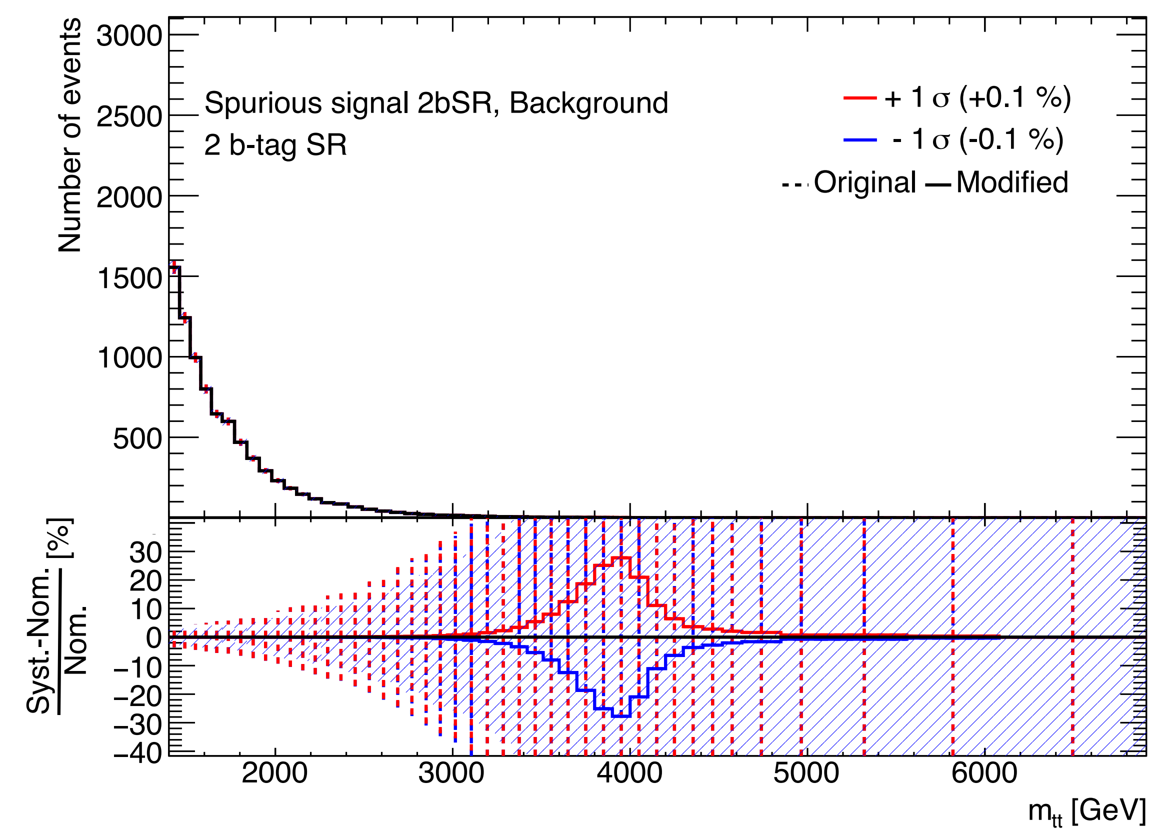
Number of fit parameters optimized based on the following:

1. lowest chiSq
2. Wilk's test
3. minimize the spurious signal yield obtained by s+b fit to this b-only template

- Signal shape dependent "localized" uncertainty is assigned as spurious signal unc.

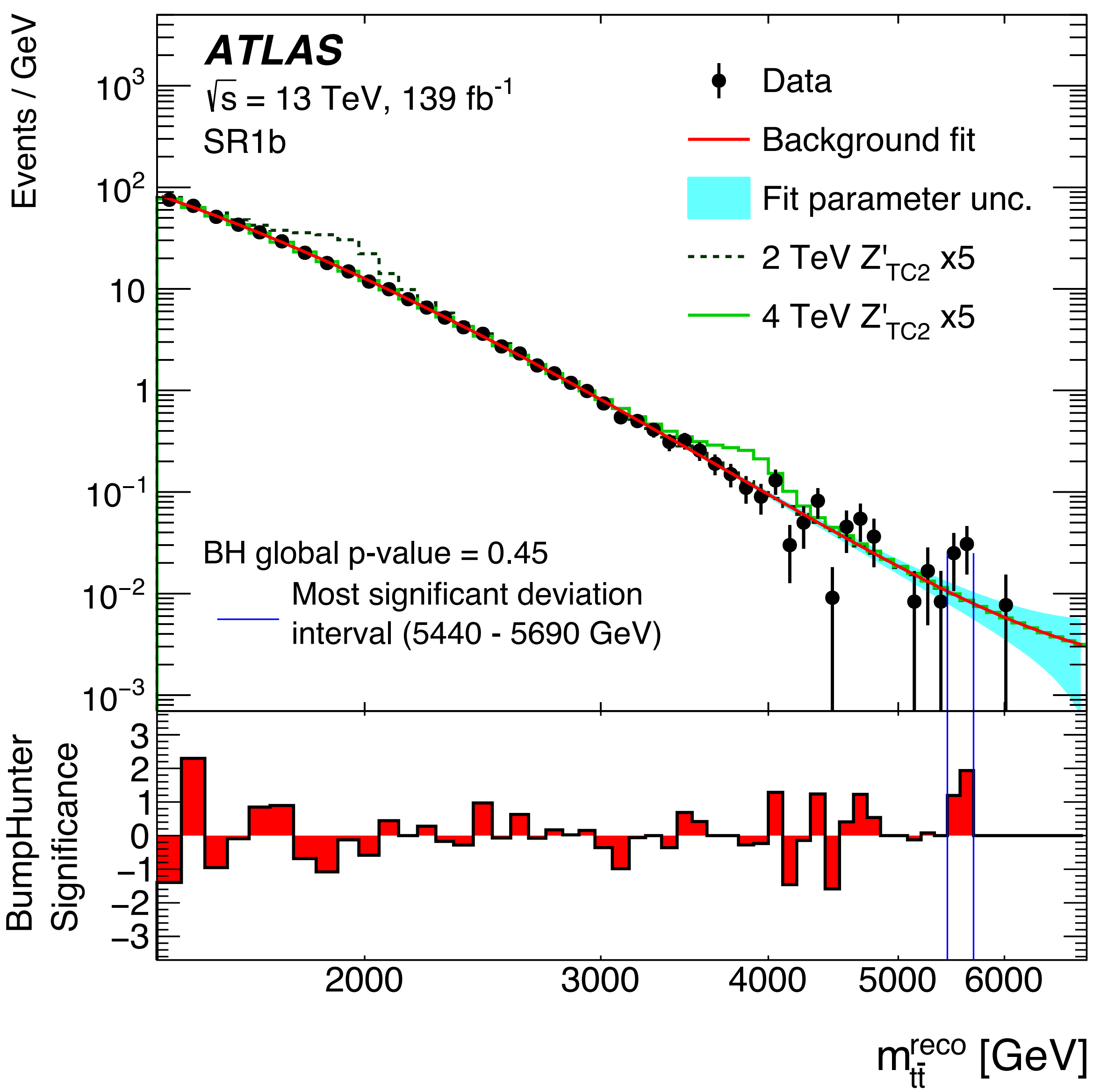


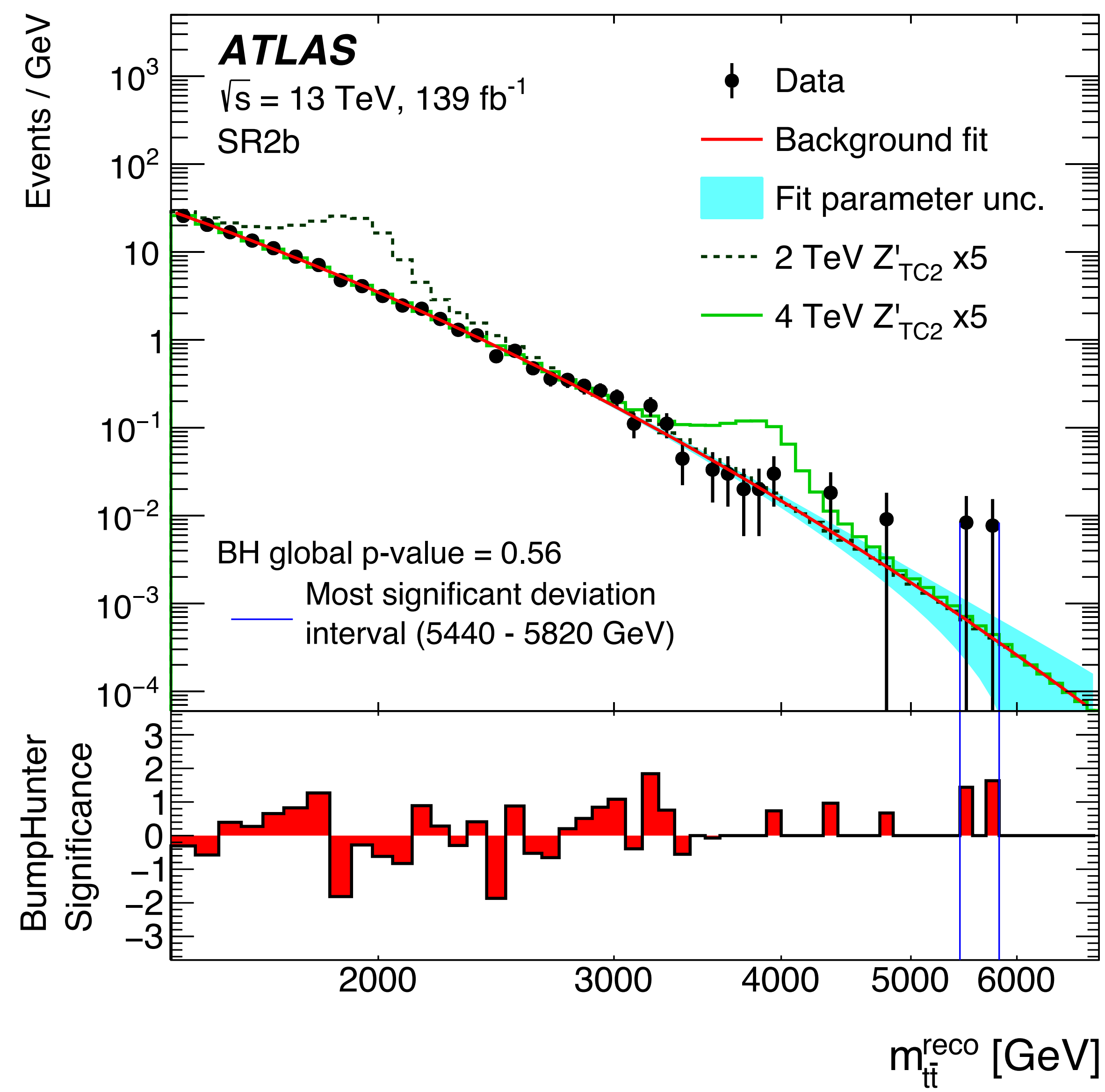
spurious signal unc. at 4 TeV



m_{tt} distributions and BumpHunter scan

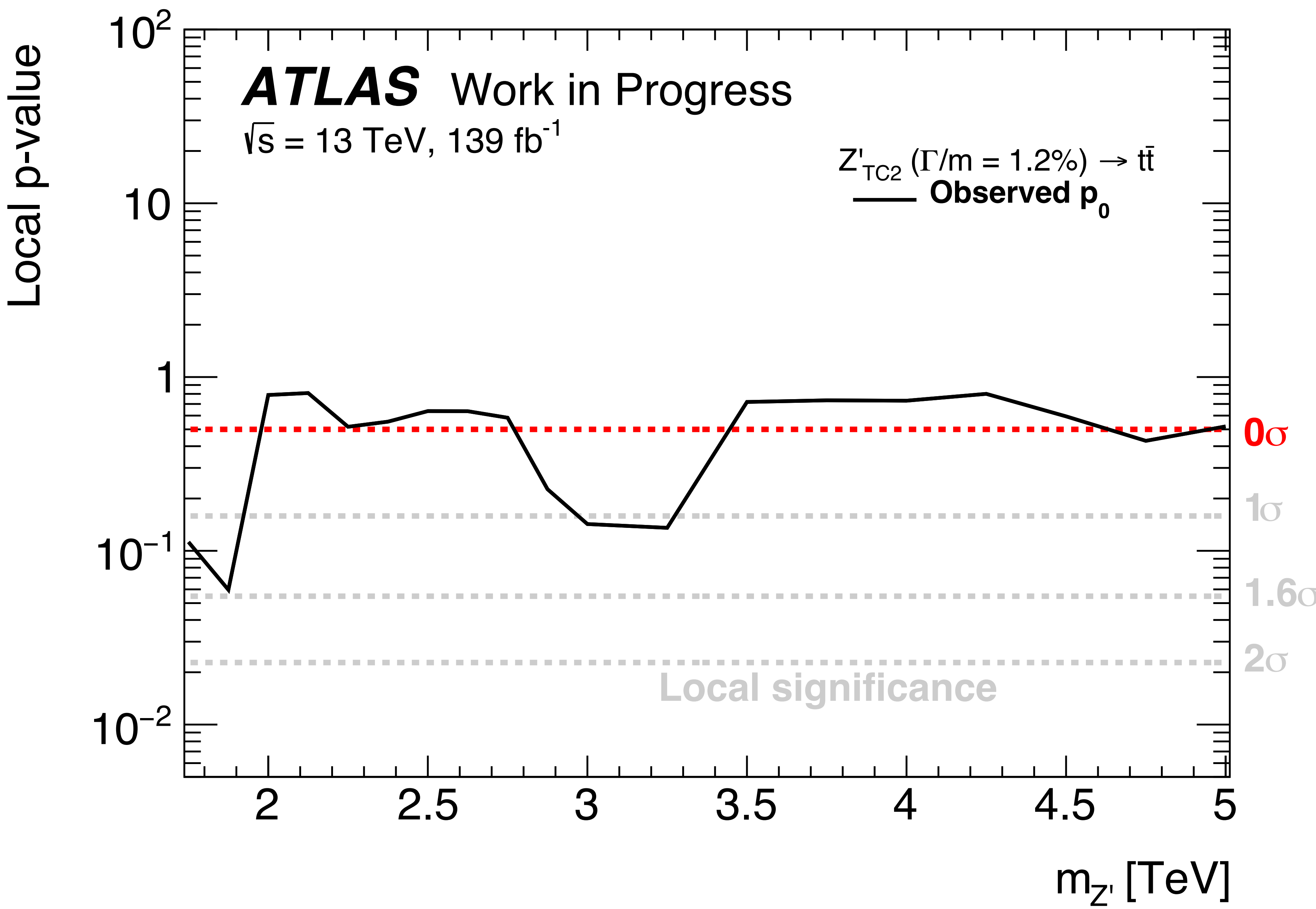
- No significant discrepancy observed in data
- **Global significance:** < 0.2 sigma





Significance scan with Z' model (1.2%)

Signal model specific search gives ~1σ local
=> No significant deviation!
Both SRs are combined

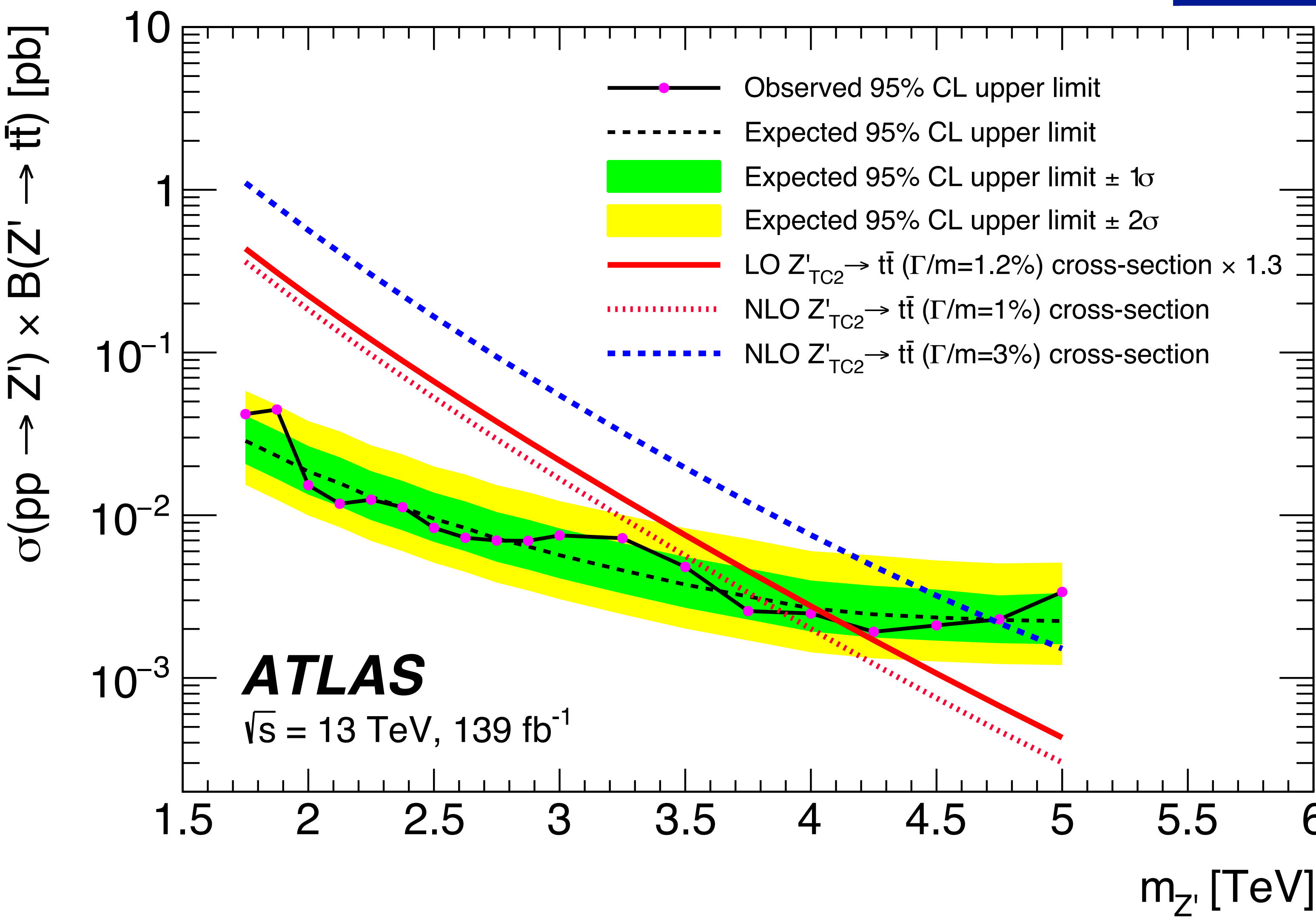


Exclusion Limit

Observed and expected upper limits on the cross section x BR of $Z'_{TC2} \rightarrow tt$

- Limit set on Z'_{TC2} with 1%, 1.2% and 3% width

Model	Expected [TeV]	Observed [TeV]
LO Z'_{TC2} (Γ = 1.2%)	4.0	4.1
NLO Z'_{TC2} (Γ = 1%)	3.8	3.9
NLO Z'_{TC2} (Γ = 3%)	4.7	4.7

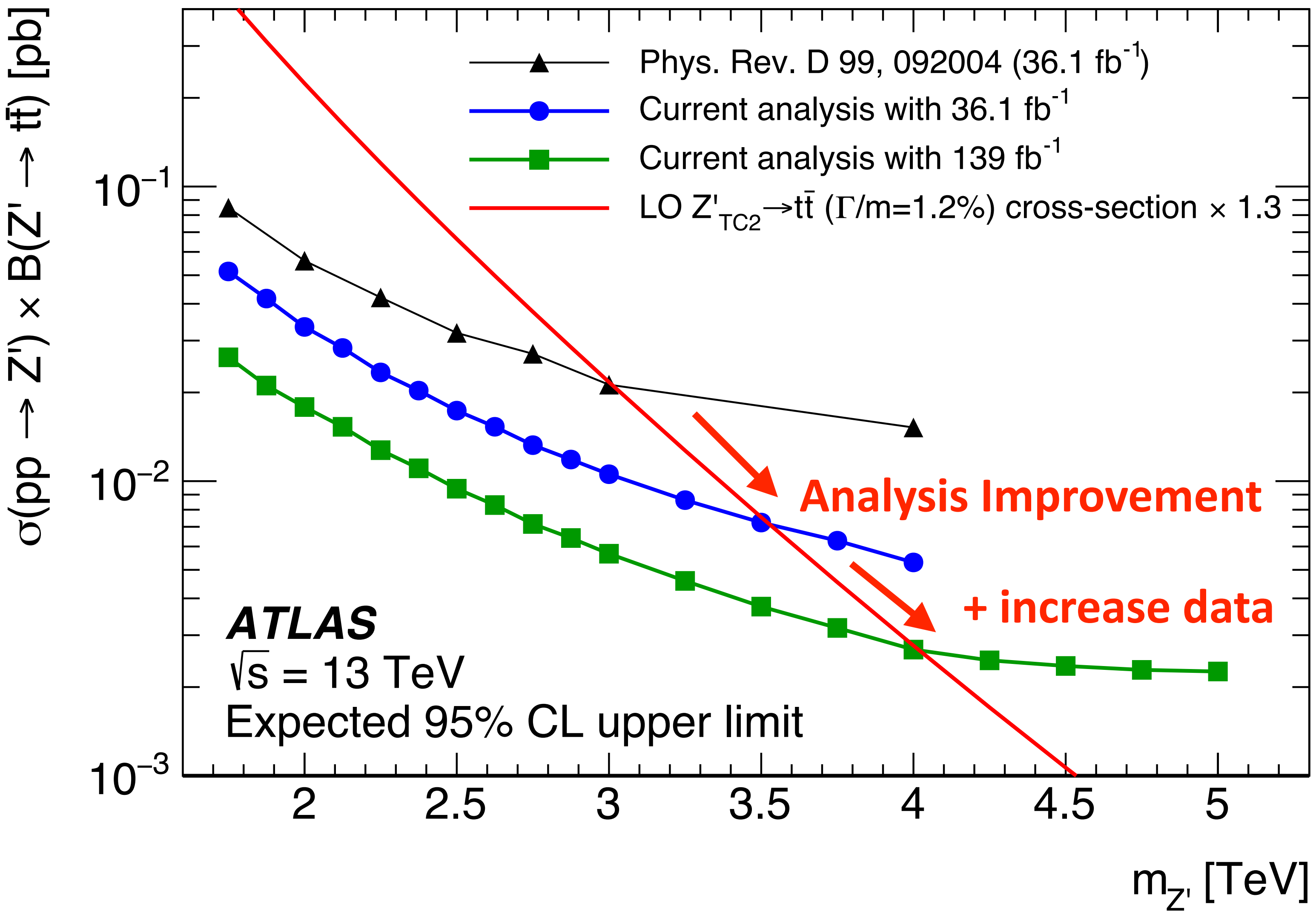


Solid red line: LO Z'_{TC2} (Γ = 1.2%) cross sections x 1.3 (k-factor)

Dotted pink line: NLO Z'_{TC2} (Γ = 1%) cross sections

Dotted blue line: NLO Z'_{TC2} (Γ = 3%) cross sections

Significant improvement in the limit



Great sensitivity gain exceeding increase of statistics!!

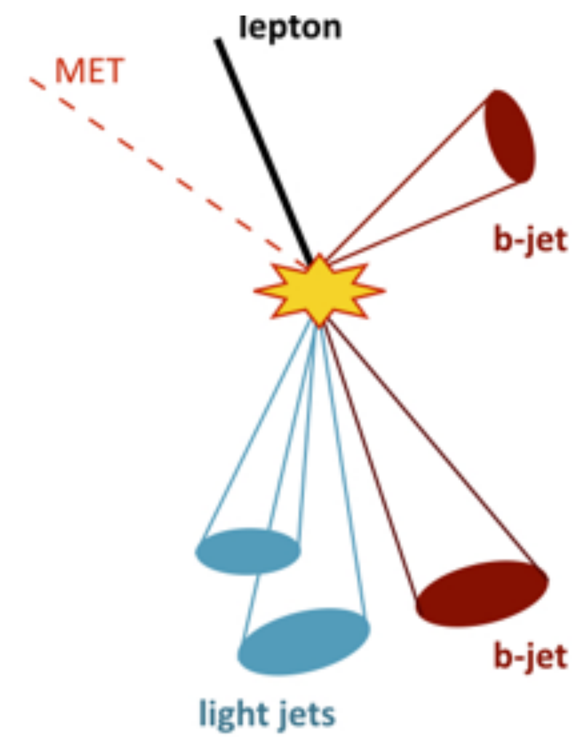
https://arxiv.org/abs/2005.05138

➡Submitted to JHEP

- New analysis techniques
  - ➡ *Improved the cross section limit by 2 times*
- Almost 4 times increase in data
  - ➡ *Improved cross section limit by another factor of 2*

	Expected [TeV]	Observed [GeV]
Old Analysis	3.0	3.2
New analysis at 36 fb^{-1}	3.5	
New analysis	4.1	4.0

Semi-leptonic tt resonance

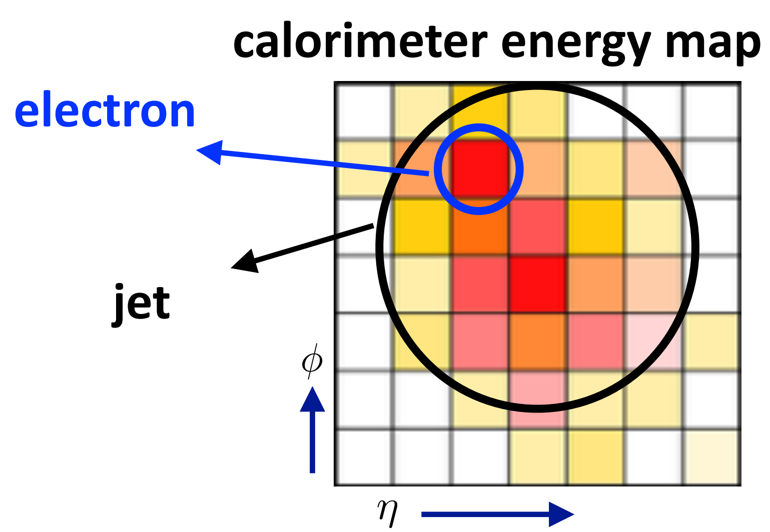


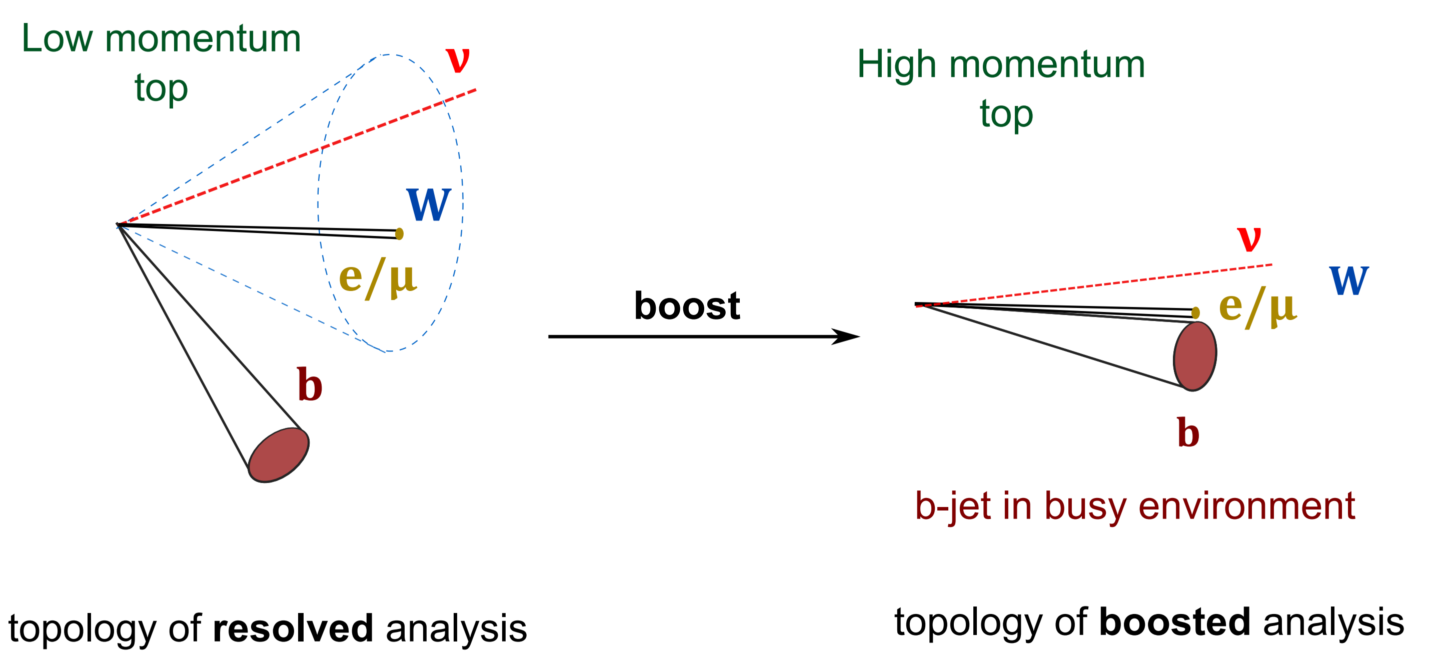
Challenges of the resolved topology

- Reducing the QCD background
- Reconstructing the hadronic top and the full ttbar system
- Studying ML-based algorithms to reconstruct the ttbar system more efficiently

Challenges of boosted topology

- Electron/muon comes very close to the the b-jet
- Sometimes they overlap



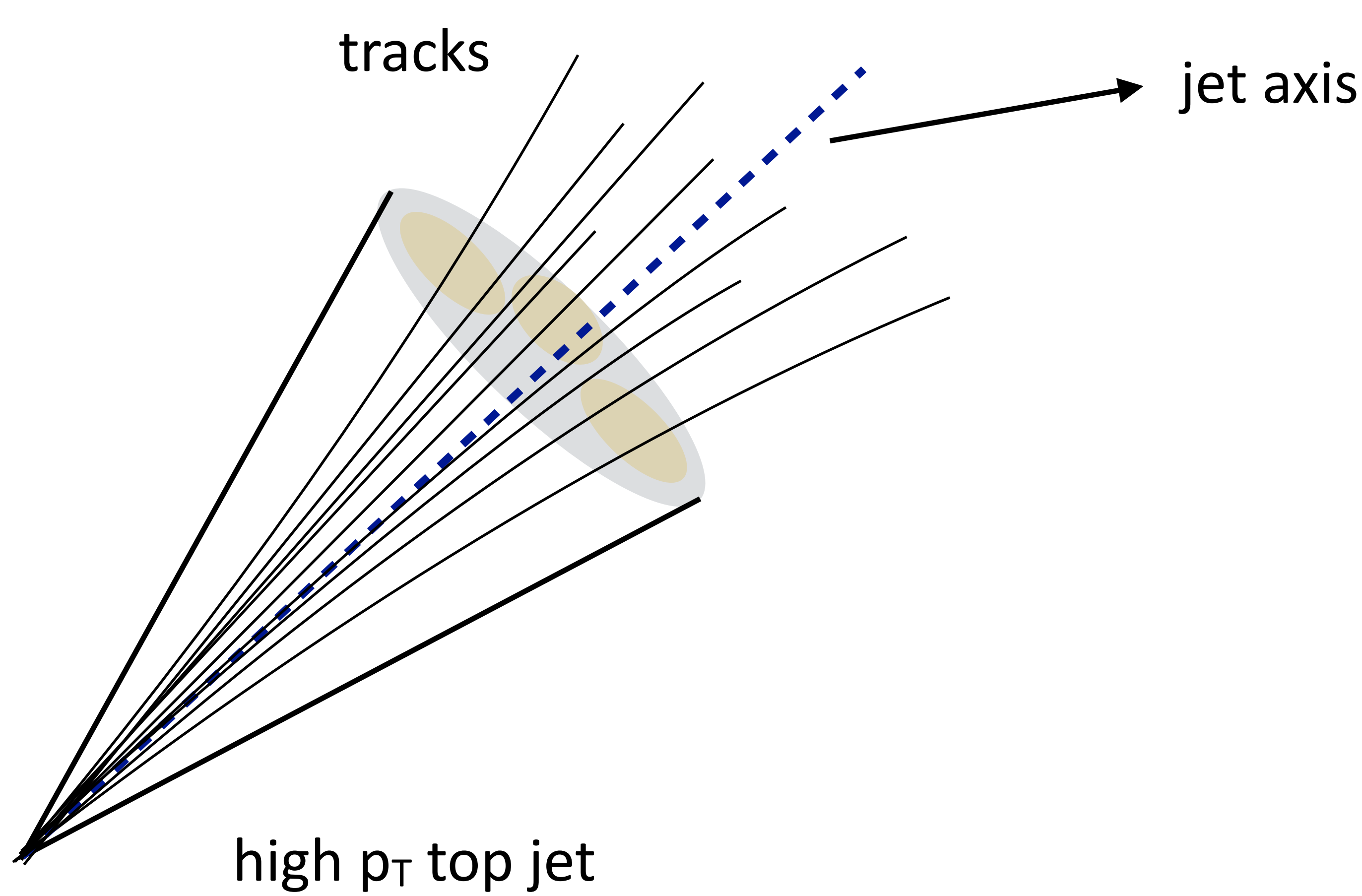


ATLAS could still be better

- ATLAS is a great detector and algorithms are optimized for years
- Still there is a lot of room for improvement

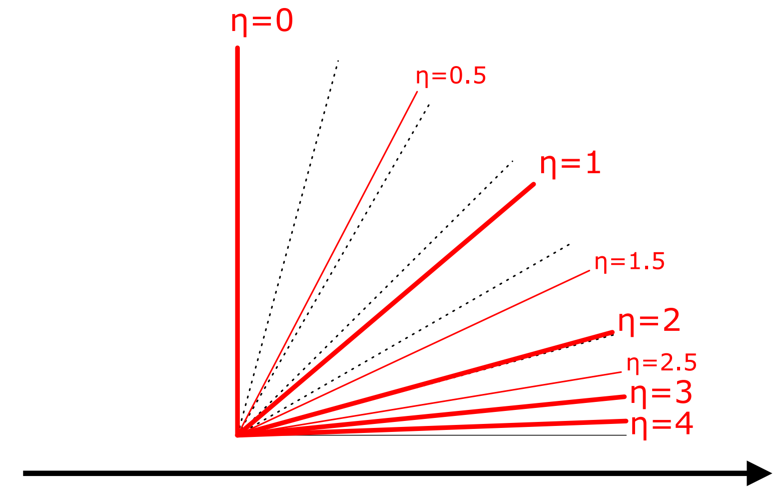
I will give one example:

- The core of the hadronic tops create many track in the inner detector
- Creates overlapping response on the tracking detector
- In this dense environment it becomes tricky to build the tracks efficiently

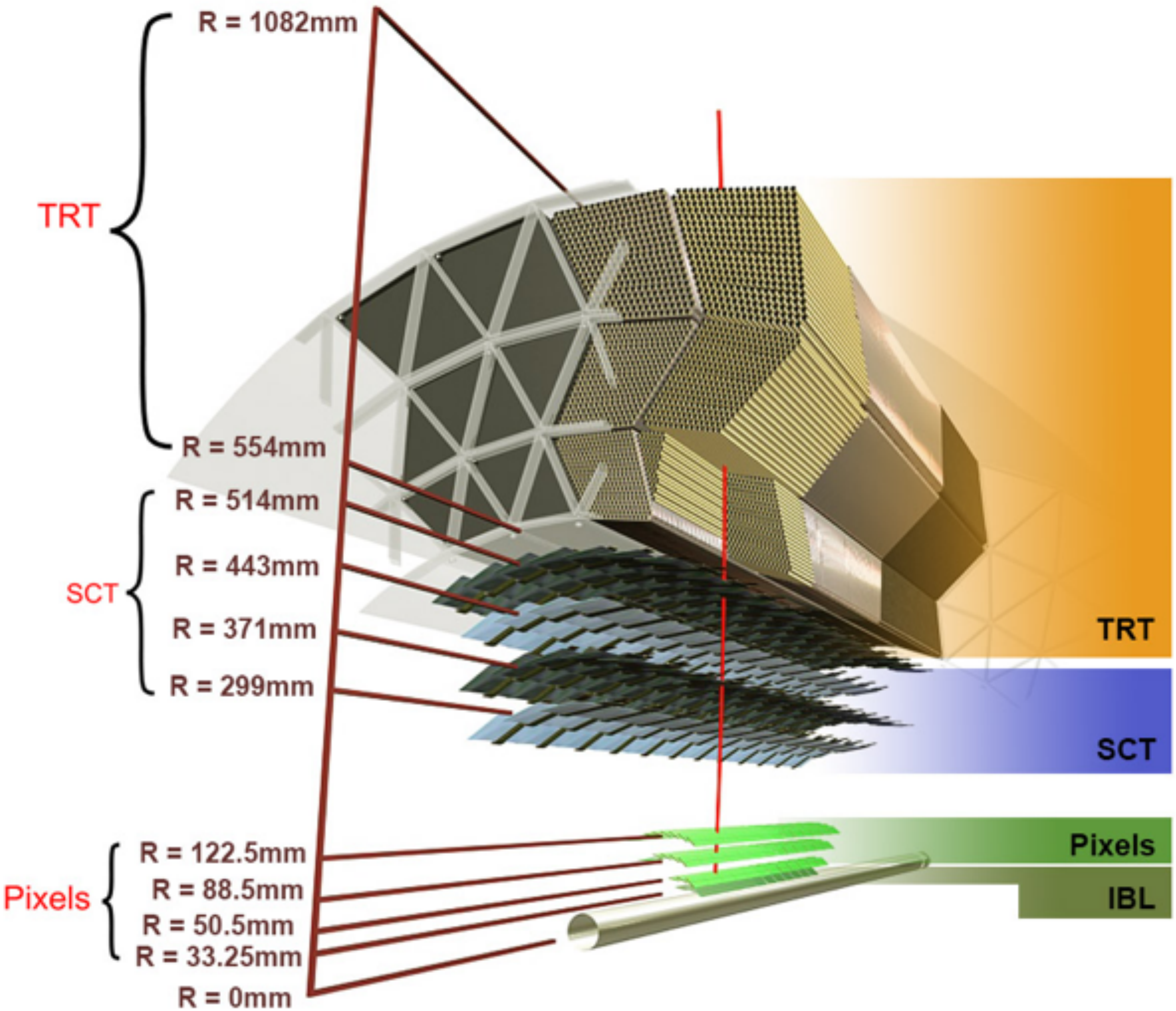


ATLAS Inner Detector (ID)

- The total ID coverage |η| < 2.5 with radius of 1.1m
- ID is inside 2T solenoid field



$$\eta = -\ln\tan(\frac{\theta}{2})$$



Subdetectors:

TRT:

Xe (Ar) filled straw tubes (= 4 mm), O(30) crossed straws per track.

SCT:

4 layers of double sided strip 9 disks, 80 μm× ~ 6 cm,

Pixel:

3 layers, 3 disks, 50 × 400μm^2

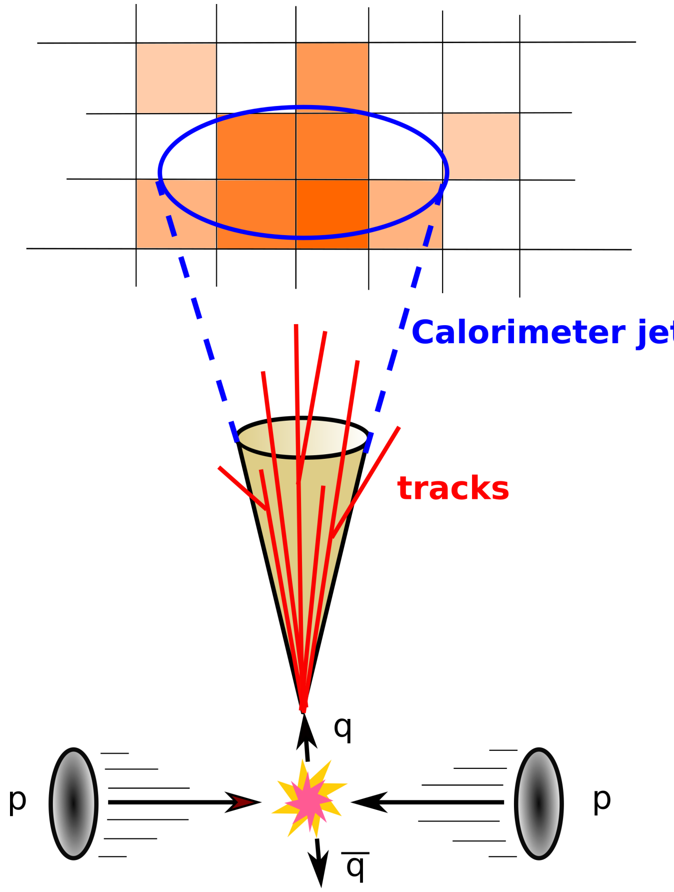
IBL:

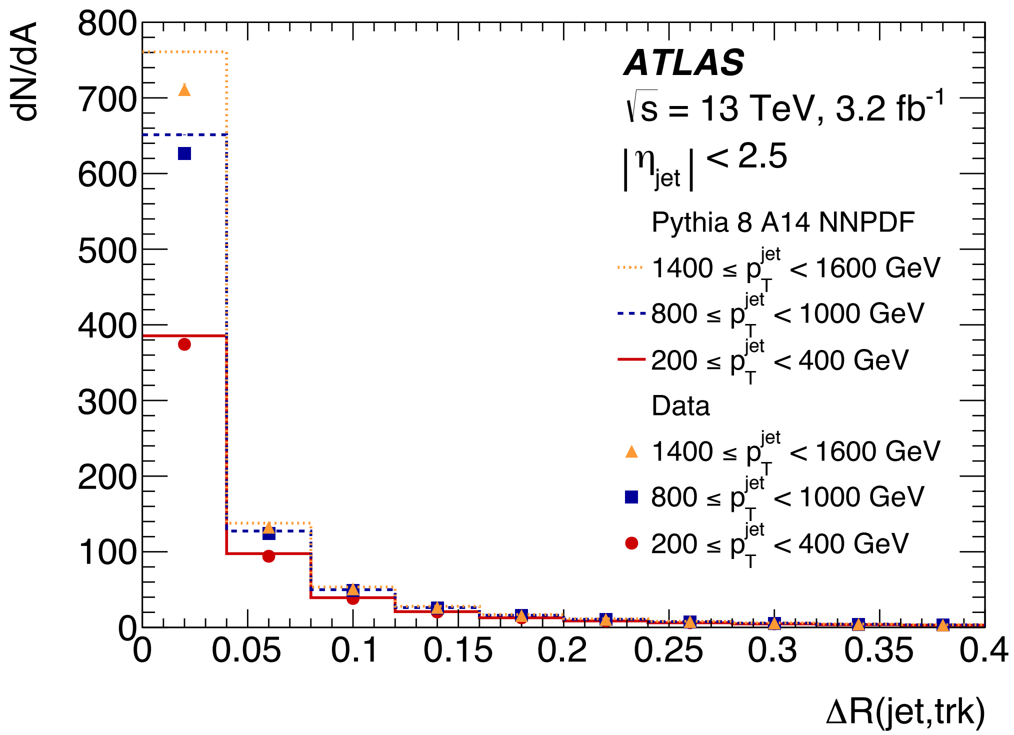
1 barrel layer, 50 × 250μm^2

Tracking in Dense Environment

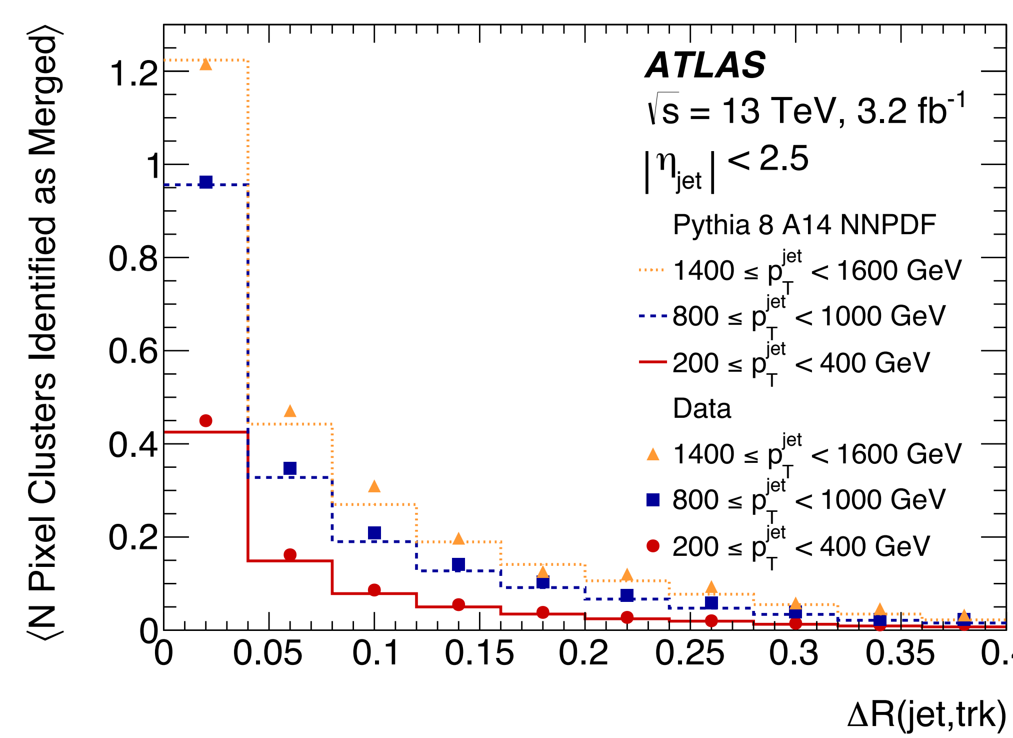
Dense Environment: average separation between highly collimated tracks is comparable to the granularity of individual sensors

Ex: **Cores of highly energetic hadronic top jets, or tau**





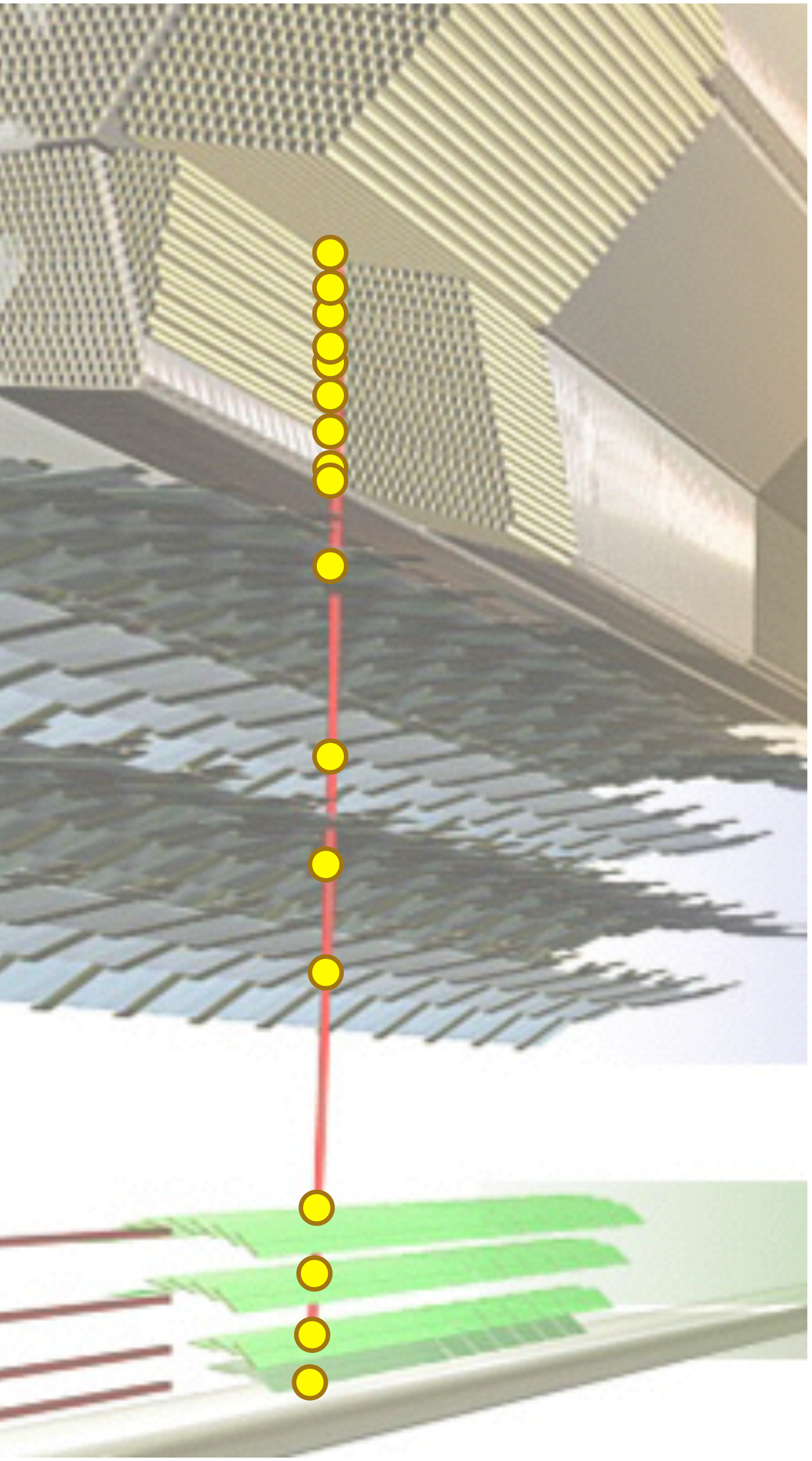
Number of pixel clusters identified as merged



Most tracks are located within an angular distance of 0.05 from the jet axis

Eur. Phys. J. C 77 (2017) 673

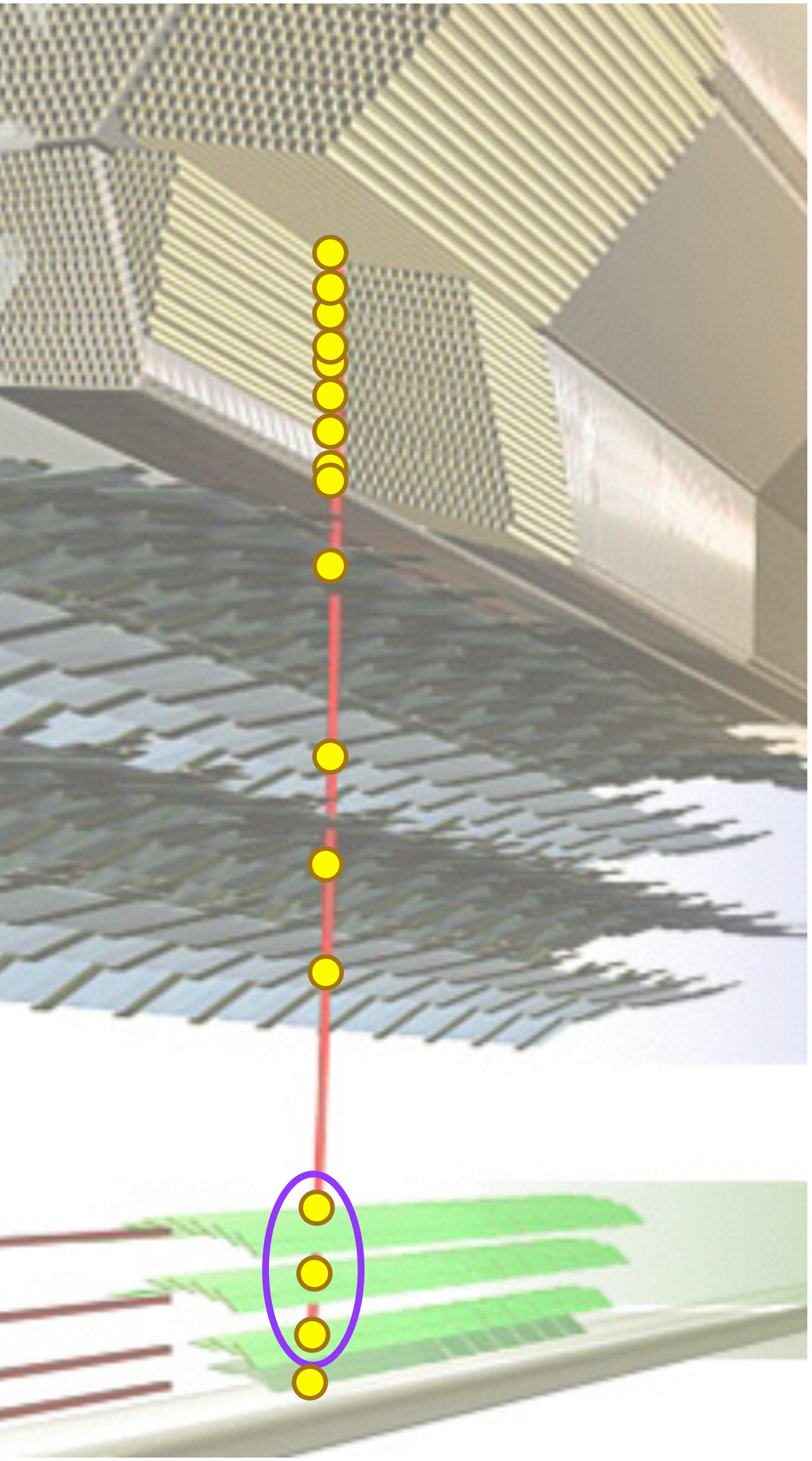
ID Track Reconstruction



Build Clusters

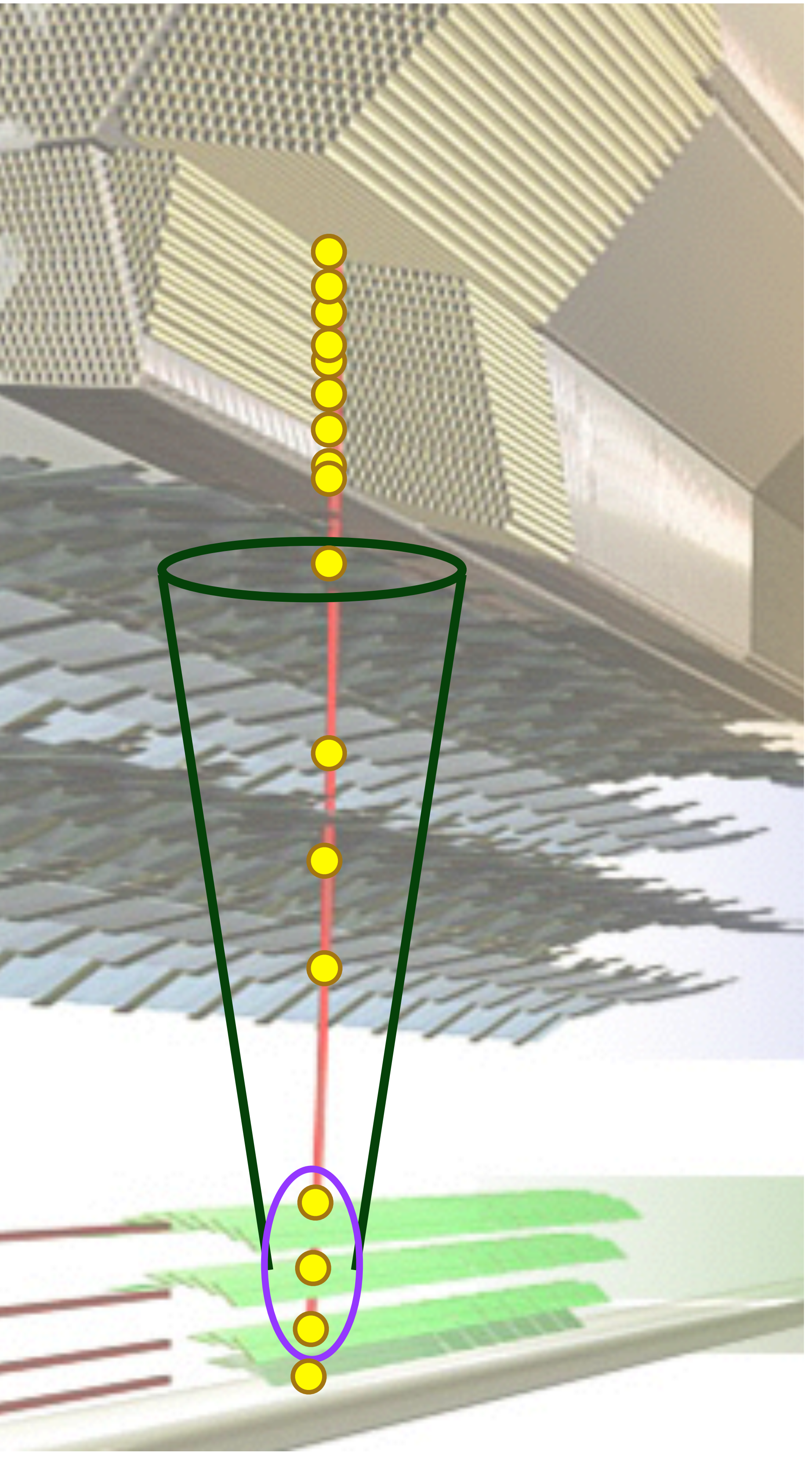
Design Credit: G. Gaycken

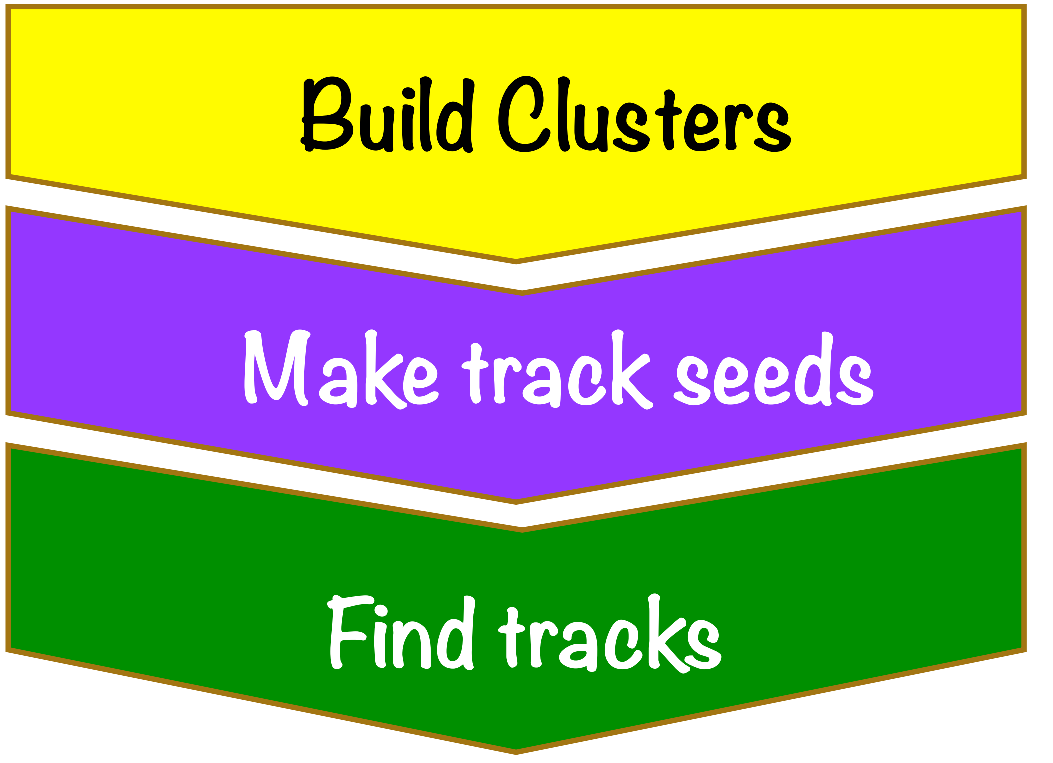
ID Track Reconstruction



Design Credit: G. Gaycken

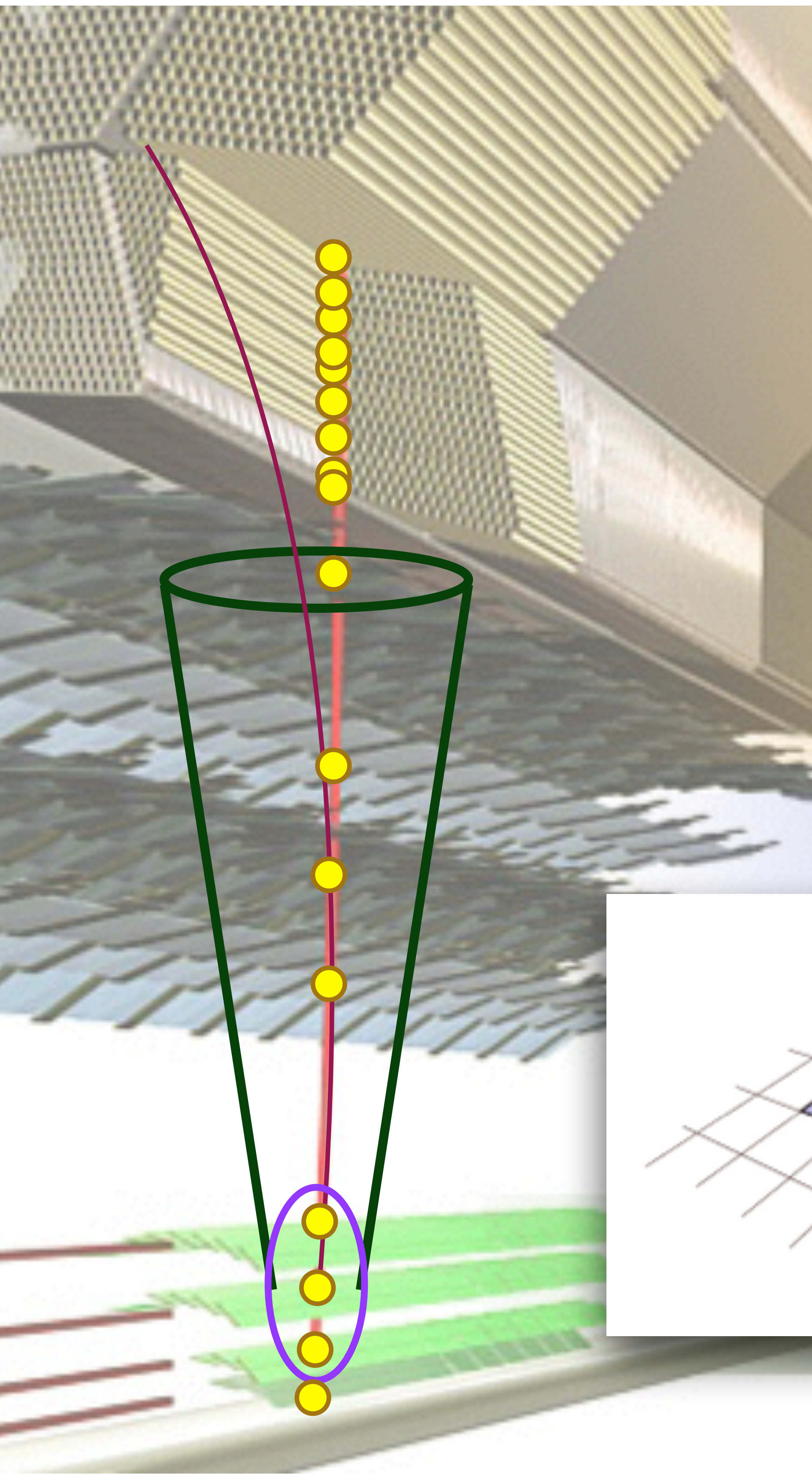
ID Track Reconstruction

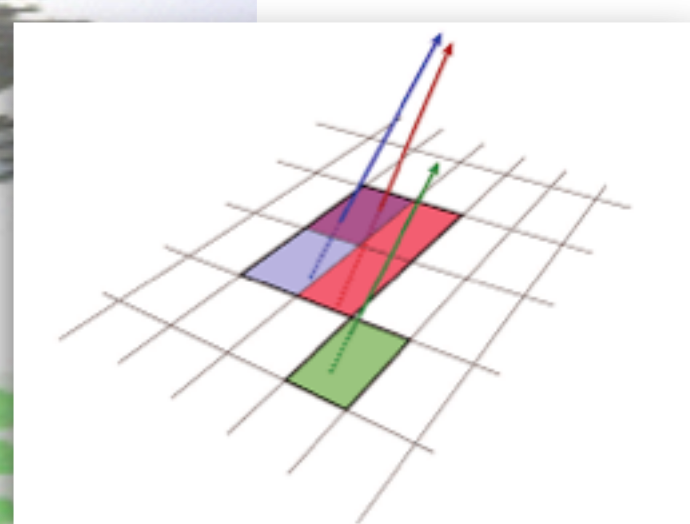




Design Credit: G. Gaycken

ID Track Reconstruction





Build Clusters

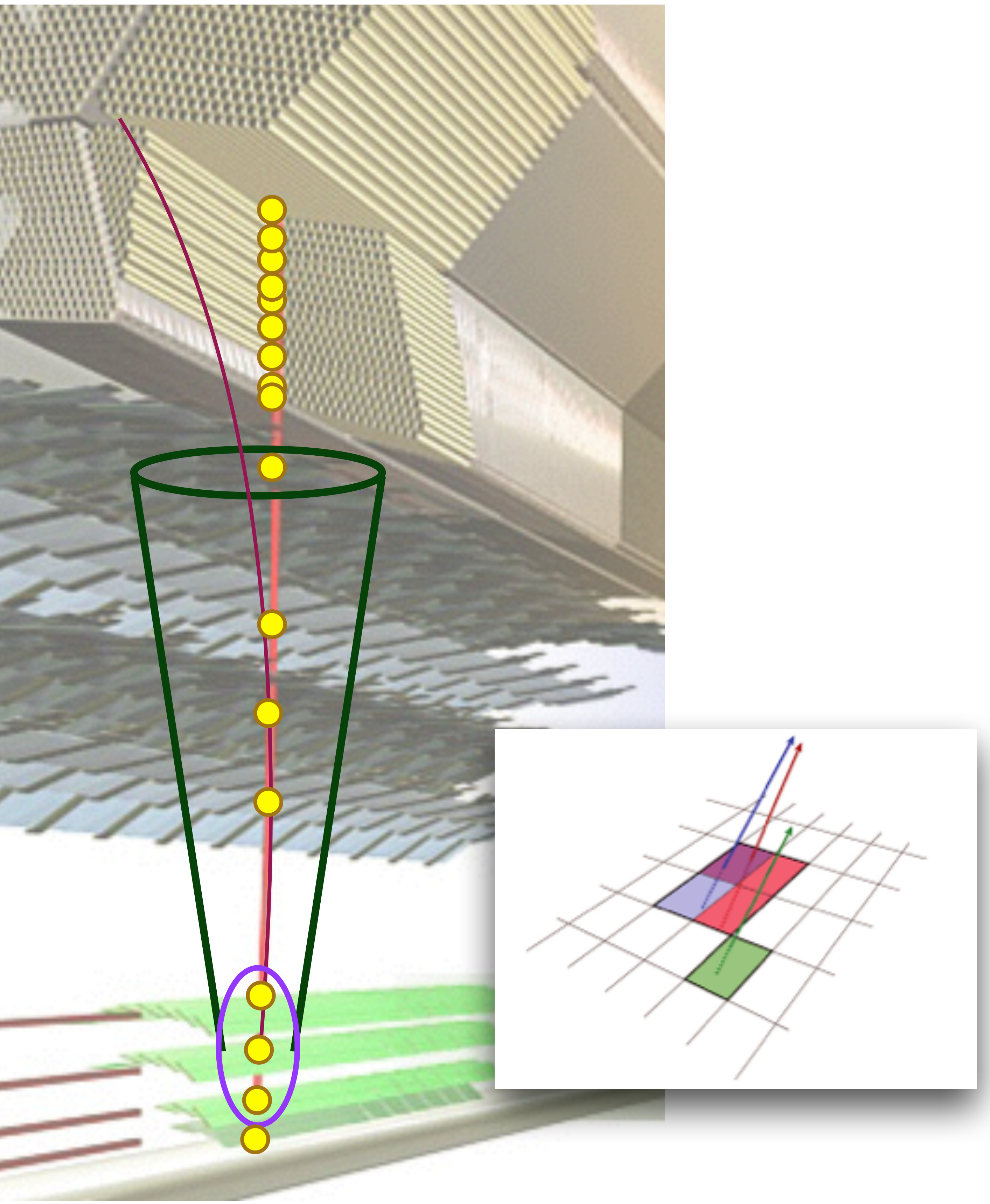
Make track seeds

Find tracks

Handle merged Pixel clusters (NN)

Design Credit: G. Gaycken

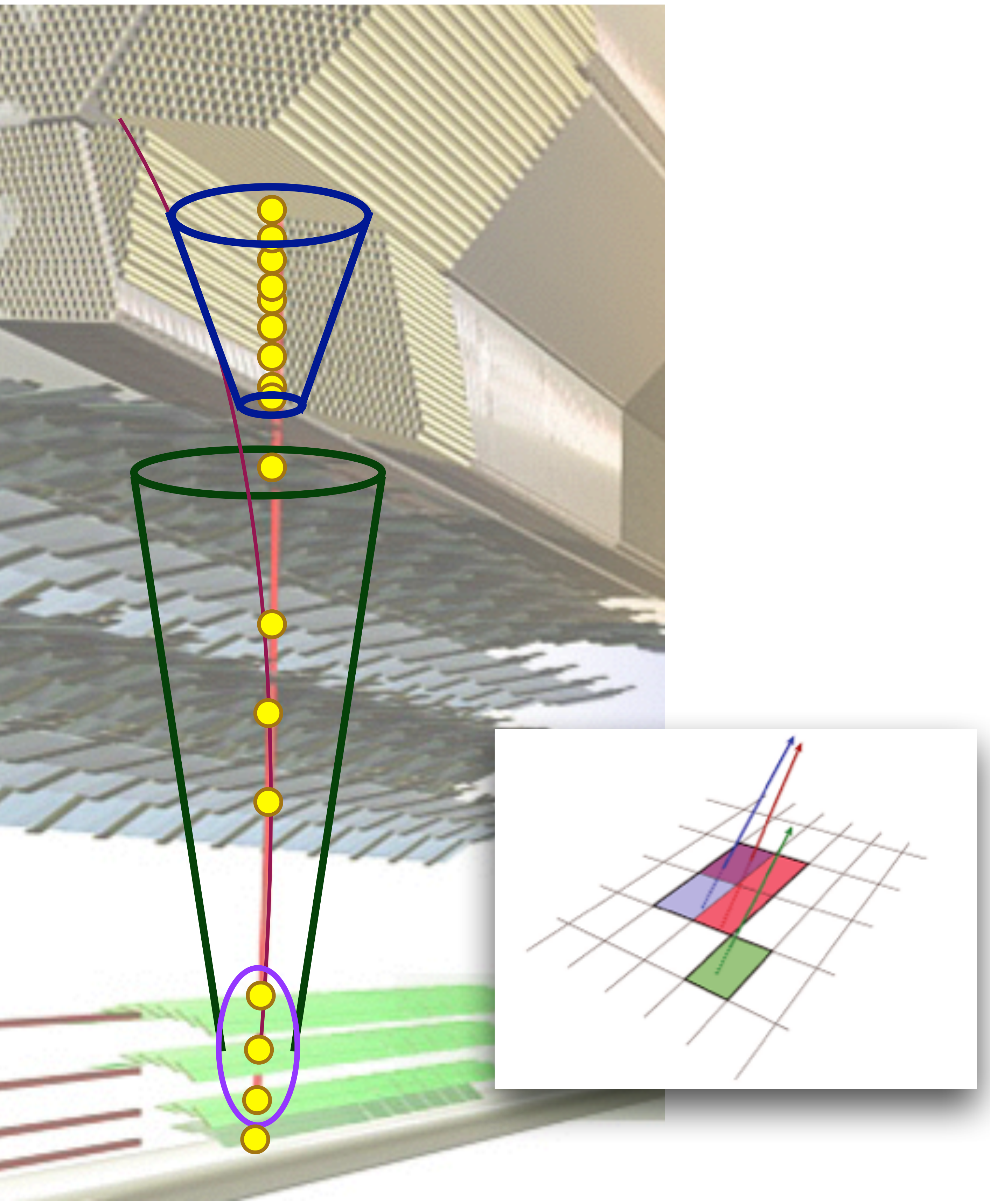
ID Track Reconstruction



- Build Clusters
- Make track seeds
- Find tracks
- Handle merged Pixel clusters (NN)
- Resolve ambiguities & fit track

Design Credit: G. Gaycken

ID Track Reconstruction



Build Clusters

Make track seeds

Find tracks

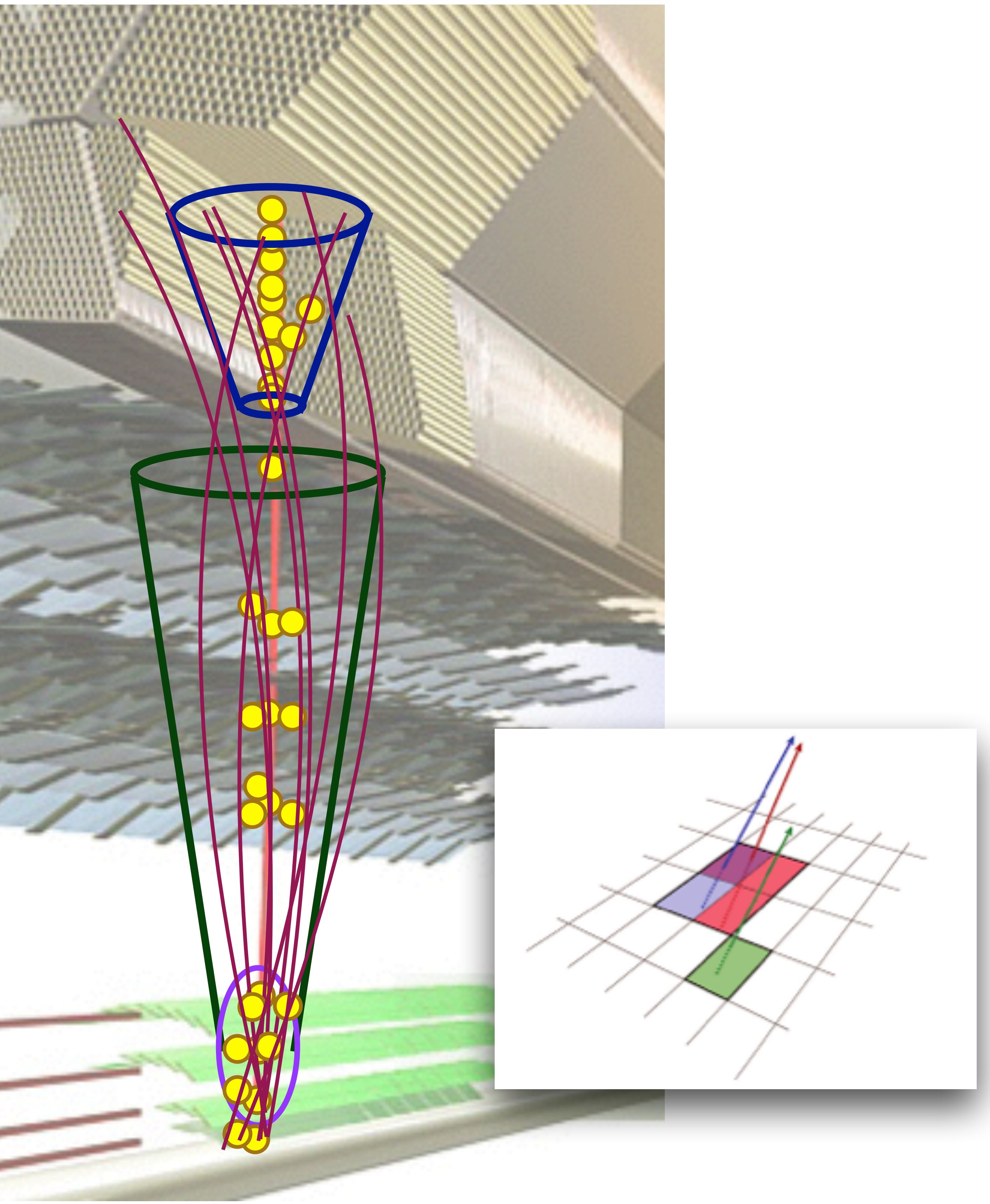
Handle merged Pixel clusters (NN)

Resolve ambiguities & fit track

Extend to TRT

Design Credit: G. Gaycken

ID Track Reconstruction



Build Clusters

Make track seeds

Find tracks

Handle merged Pixel clusters (NN)

Resolve ambiguities & fit track

Extend to TRT

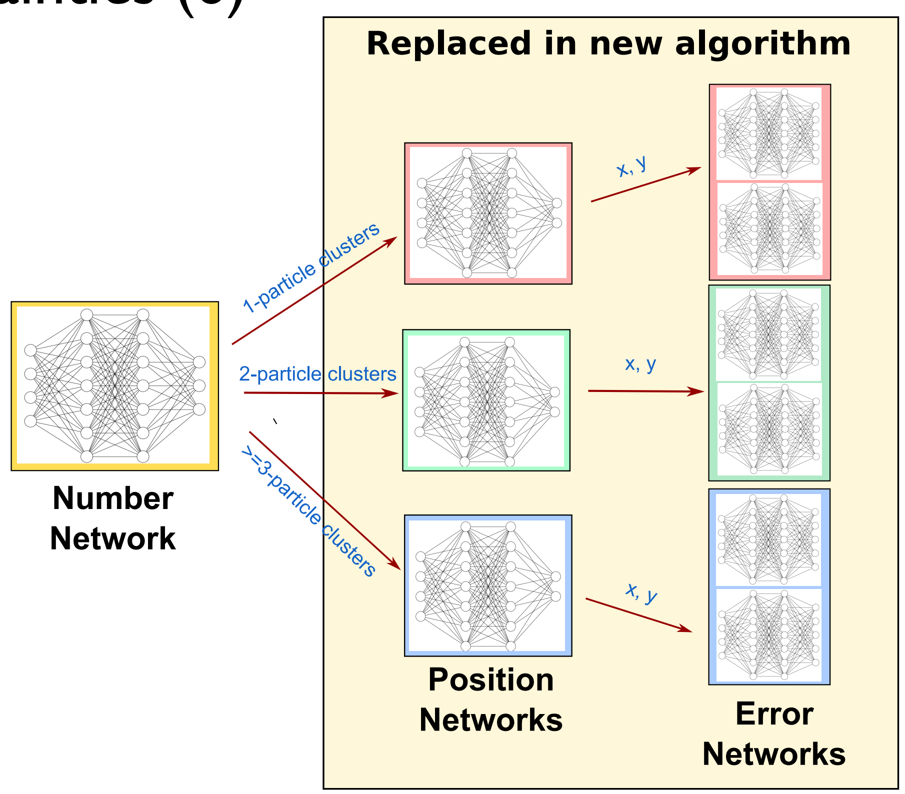
Design Credit: G. Gaycken

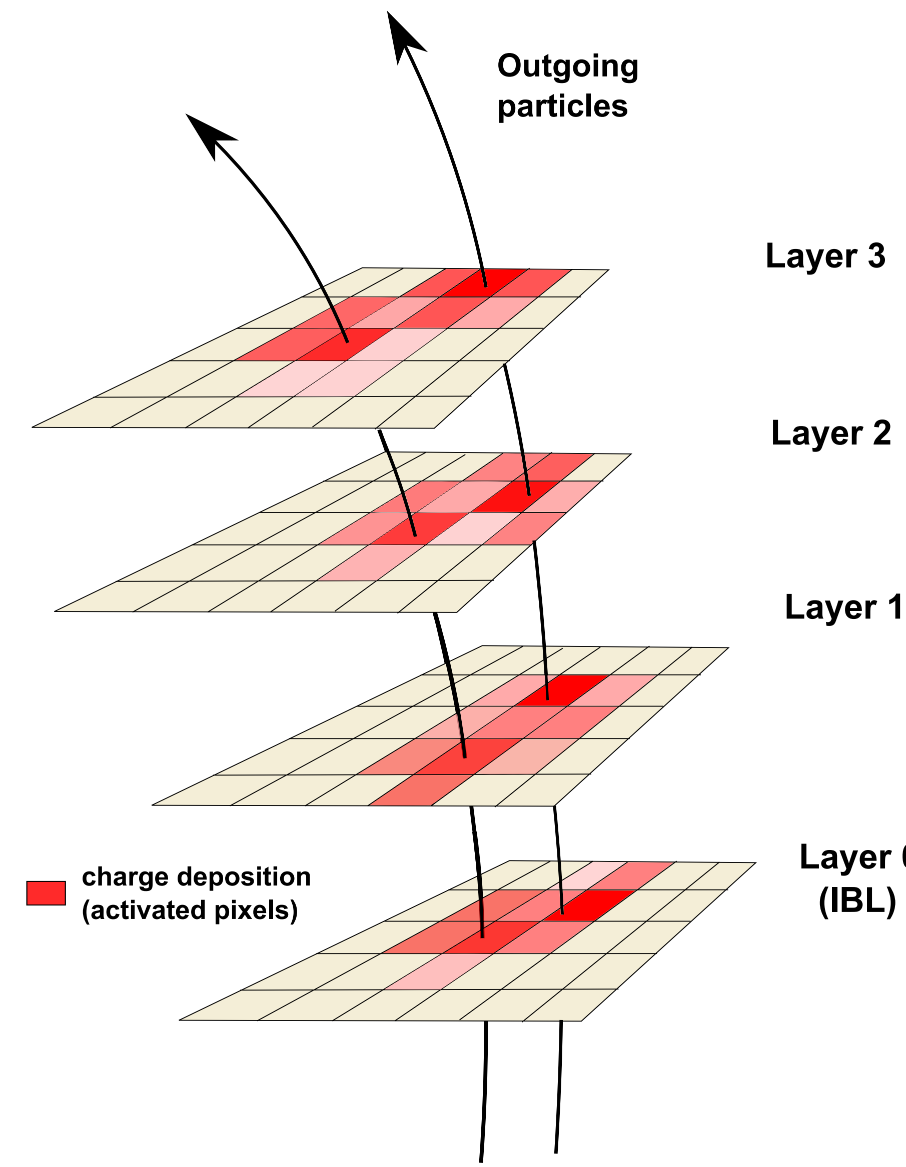
Merged Pixel Cluster splitting with MDN

- All tracks are scored in the ambiguity solving stage
- **Shared clusters** penalizes the track score
- Tracks with low score are not fitted and stored
  ➡ **loss of reconstruction efficiency**

In ATLAS, we use 3 sets of neural networks (total 10)

➡ particle multiplicity (1)
➡ measure the hit positions (3)
➡ associated uncertainties (6)





New Algorithm: Mixture Density Network (MDN)

JINST 9 (2014) P09009

Standard NN vs MDN

- Input feature vector $\mathbf{x} = \{x_1, \ldots x_d\}$
- Target vector $\mathbf{t} = \{t_1, \ldots t_c\}$

➡A training example: $\{\mathbf{x}^q, \mathbf{t}^q\}$
➡Learns the underlying data generator:

$$p(\mathbf{t}, \mathbf{x}) = p(\mathbf{t}|\mathbf{x})p(\mathbf{x})$$

Standard Network: Square Error

1. **Gaussian approx.**

$$p(\mathbf{t}|\mathbf{x}) = \prod_{k=1}^{c} p(t_k|\mathbf{x}) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{1}{2\sigma^2}\sum_{k=1}^{c}\{f_k(\mathbf{x};\mathbf{w}) - t_k\}^2\right]$$

network function

global variance

weights

MDN

$$p(\mathbf{t}|\mathbf{x}) = \sum_{i=1}^{m} \alpha_i(\mathbf{x})\phi_i(\mathbf{t}|\mathbf{x})$$

kernel functions

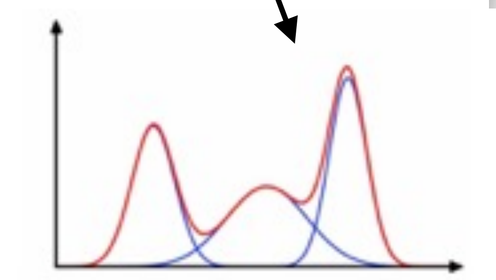
precision = 1/covariance

$$\phi_i(\mathbf{t}|\mathbf{x}) = \sqrt{\frac{\beta_i(\mathbf{x})}{2\pi}} \exp\left[-\frac{\beta_i(\mathbf{x})}{2}\|\mathbf{t} - \mu_i(\mathbf{x})\|^2\right]$$

Gaussian Mixture Model (GMM)

MDN: Gaussian approx. → Mixture Model

(liner combination of kernel functions)



2. **Build likelihood:**

$$\mathcal{L} = \prod_{q=1}^{n} p(\mathbf{t}^q, \mathbf{x}^q) = \prod_{q=1}^{n} p(\mathbf{t}^q|\mathbf{x}^q)p(\mathbf{x}^q)$$

3. **Minimize:**

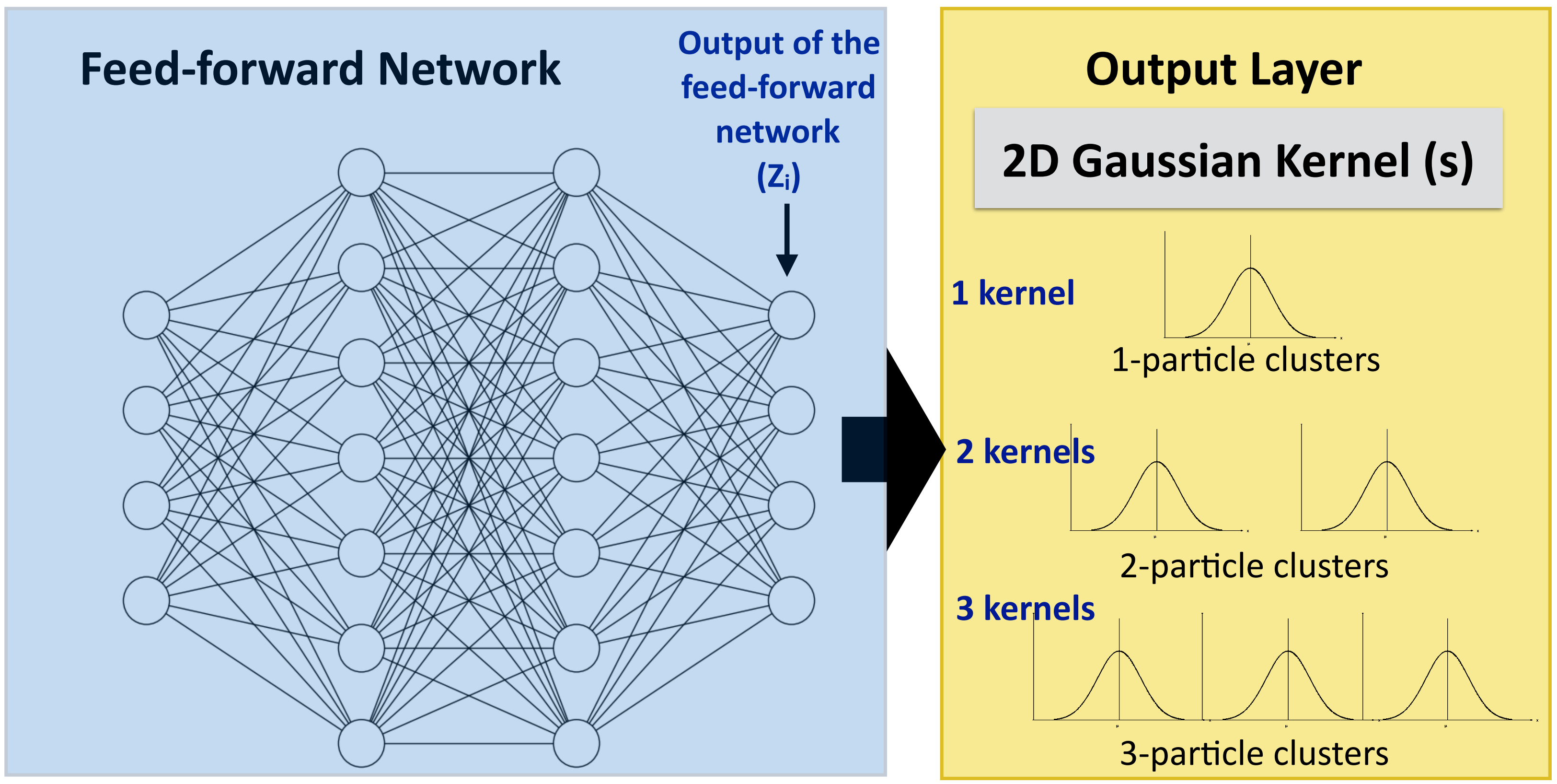
$$-\log \mathcal{L}$$

Same as Square Error Minimization | **MDN loss**

Bishop 1994

MDN: Architecture

Input
Same as the tracking NNs



$$p(\mathbf{t}|\mathbf{x}) = \sum_{i=1}^{m} \alpha_i \cdot \phi_i(\mu, \beta)$$

Software

Keras + theano

[PoS (LHCP2019) 009](#)

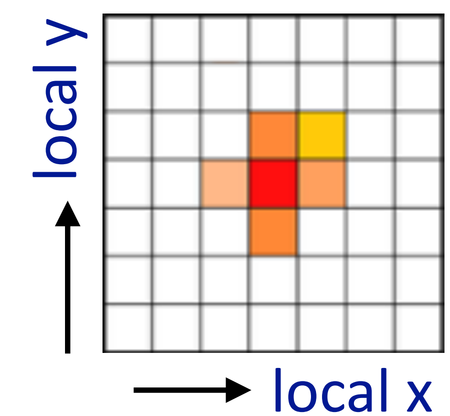
MDN: Performance (1-particle hit)

Position estimation metric: residual = difference between predicted and true position

Error estimation metric: pull = ratio of residual over predicted uncertainty

$$\text{residual} = x(y)_{\text{pred}} - x(y)_{\text{true}} \qquad \text{pull} = \frac{\text{residual}}{\sigma_{x(y),\text{pred}}}$$

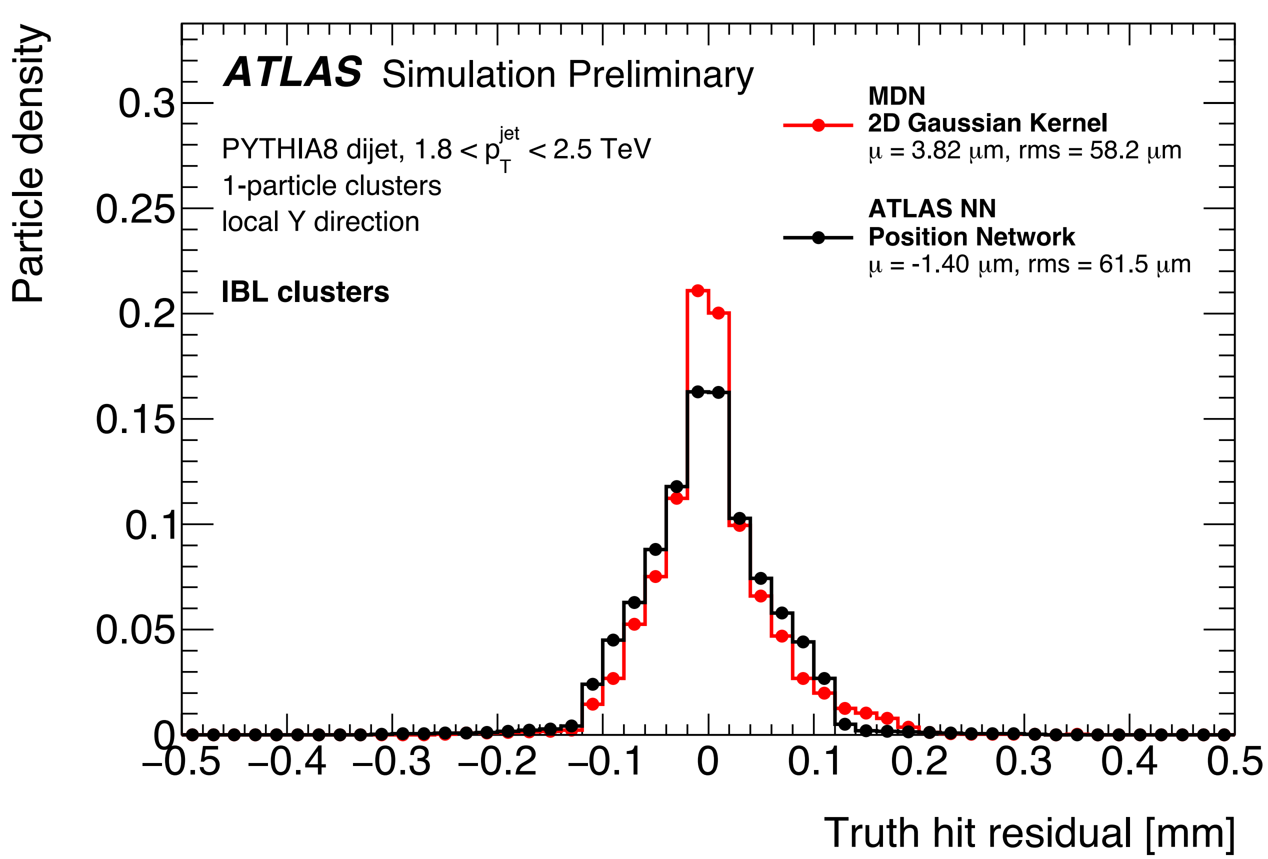
PoS (LHCP2019) 009

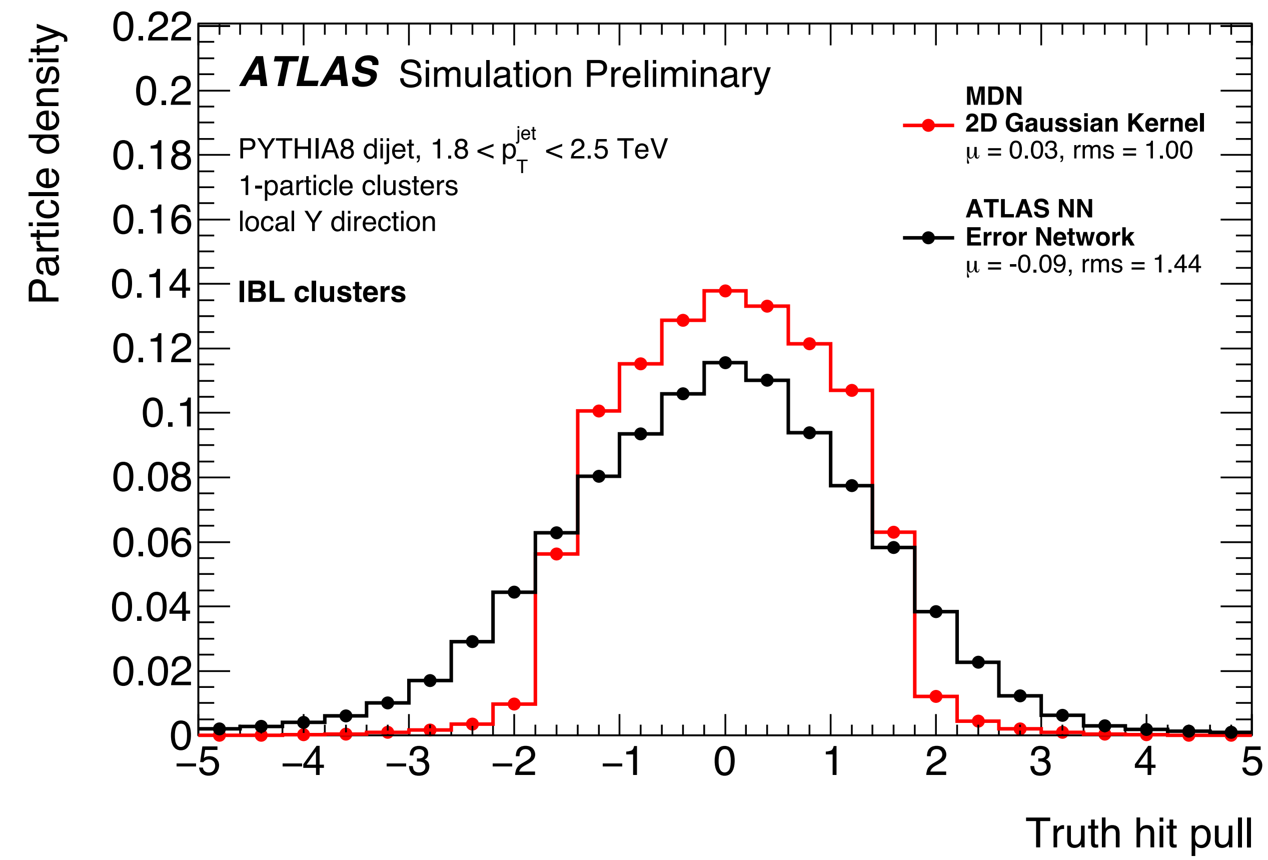


MDN residuals: large peak at zero -> more accurate

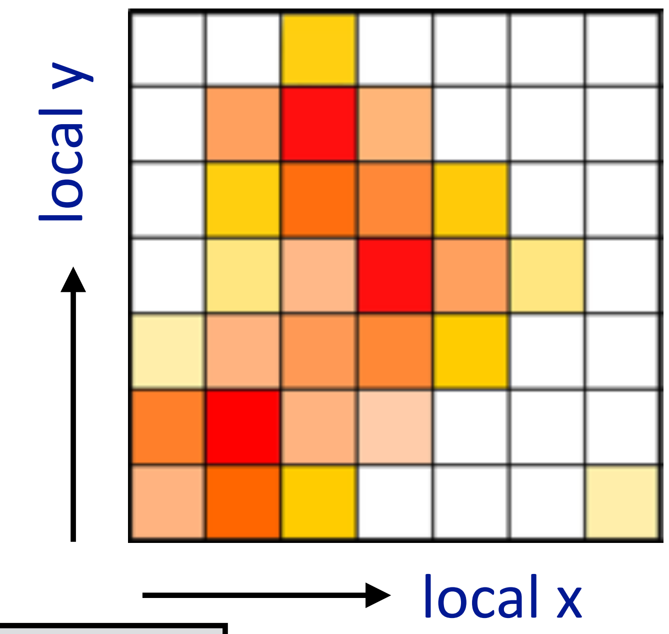
MDN Pulls: More consistent with standard normal distribution

IBL 1-particle clusters: y-direction





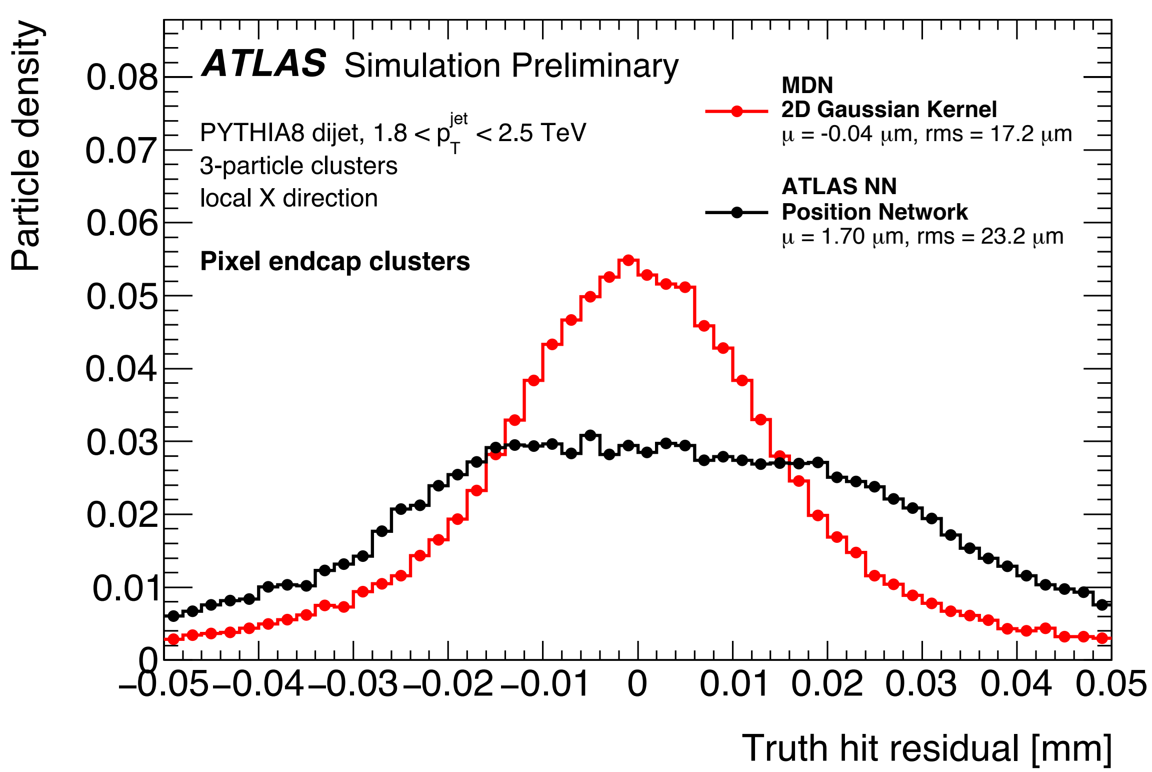
MDN: Performance (3-particle hit)



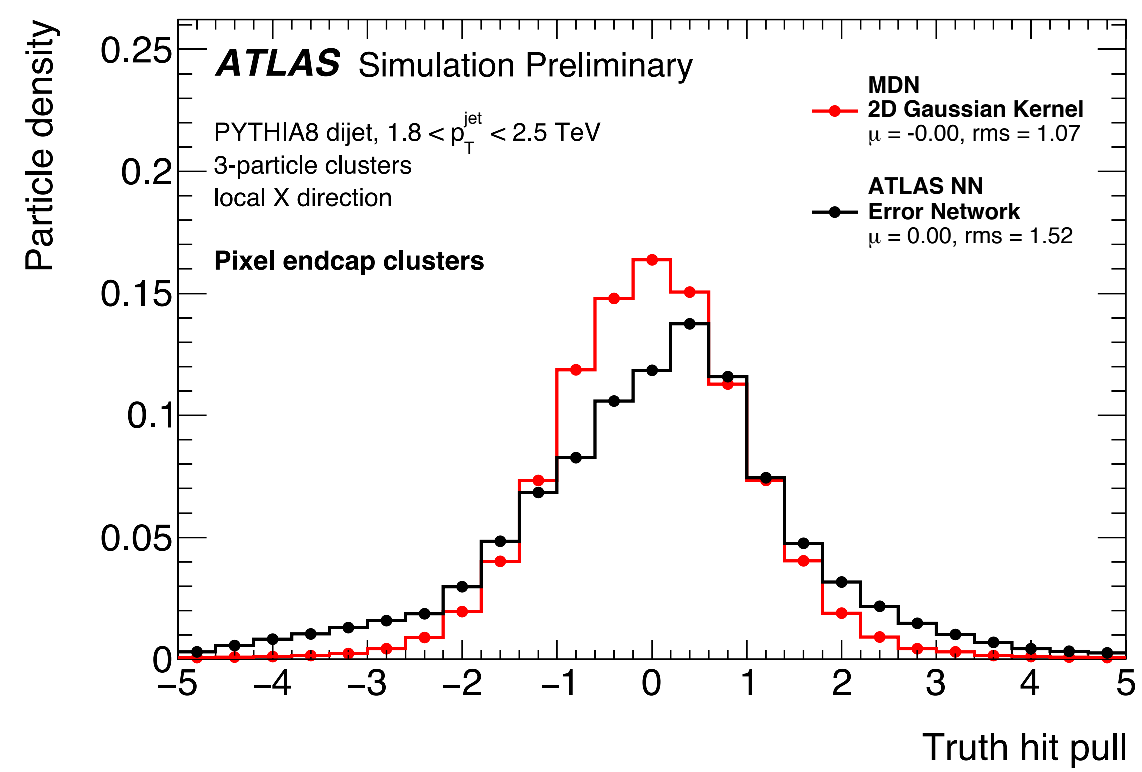
- Results for local-x direction

Endcap 3-particle clusters: local x-direction

Residual

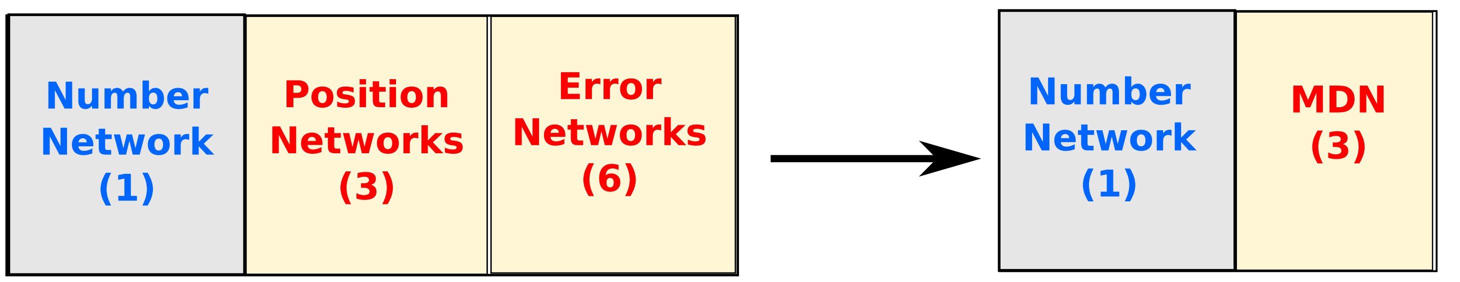


Pull



PoS (LHCP2019) 009

Next steps with MDN



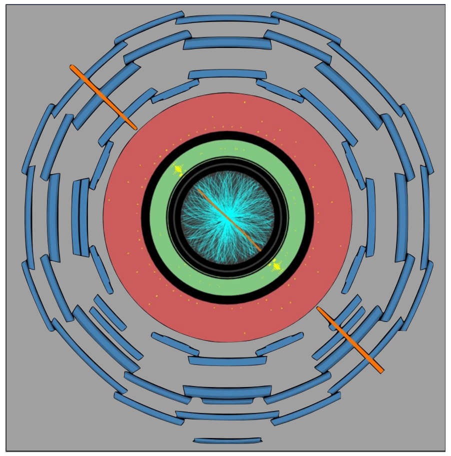
MDN shows promising performance

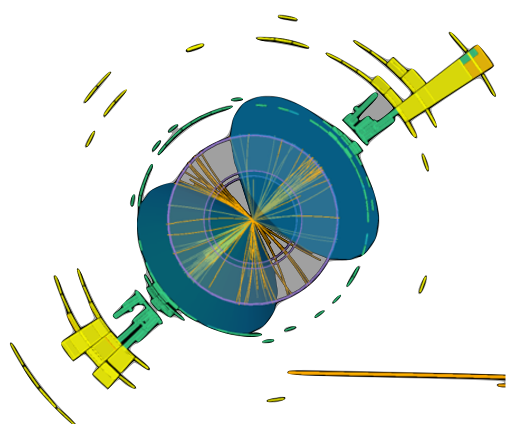
- Better hit resolution can get improve the impact parameter resolution, and it could show improvement in flavour tagging
- Currently being studied for Run-3

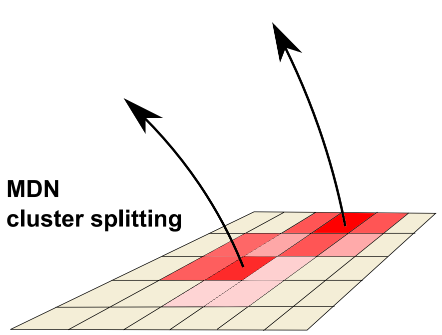
Cluster splitting in the context of future ATLAS tracking (ITk) is not studied yet properly

- MDN will be a very good option as a next generation algorithm

Summary







Dilepton Resonance Search

- Result shown with partial Run-2 data
- No significant deviation observed, **limit improved by 1 TeV** for 3% Z'_{SSM} model

ttbar Resonance Search

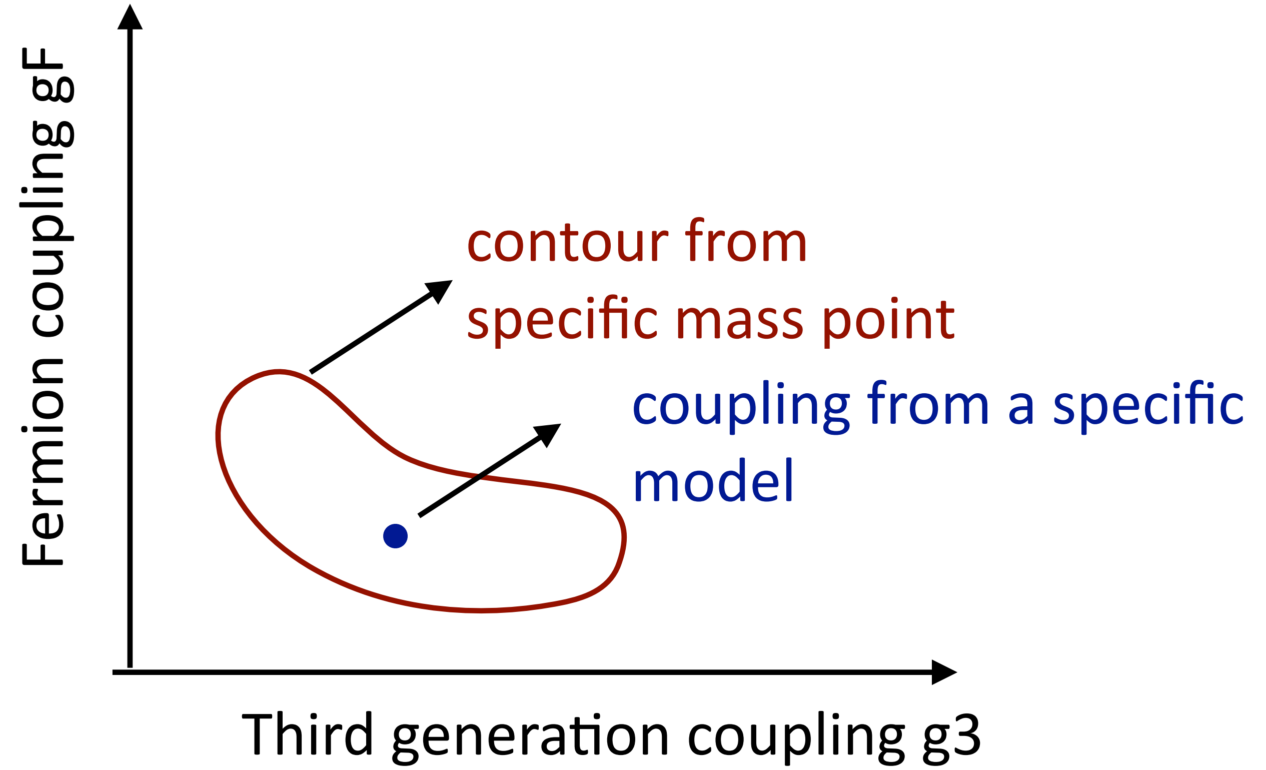
- Results with full Run-2 data in boosted all-hadronic channel
- **Limit improved by 1 TeV** for Z'_{TC2} models
- Semi-leptonic analysis is ongoing

Pixel cluster splitting with MDN

- Results are promising and currently being studied for Run-3
- Could improve impact parameter resolution since the hit resolutions are improved

Future of tt resonance

- **Combine different ttbar decay channels**
  - Combination is not done during Run-2
  - Will improved the limit
  - Several Benchmark models can be used

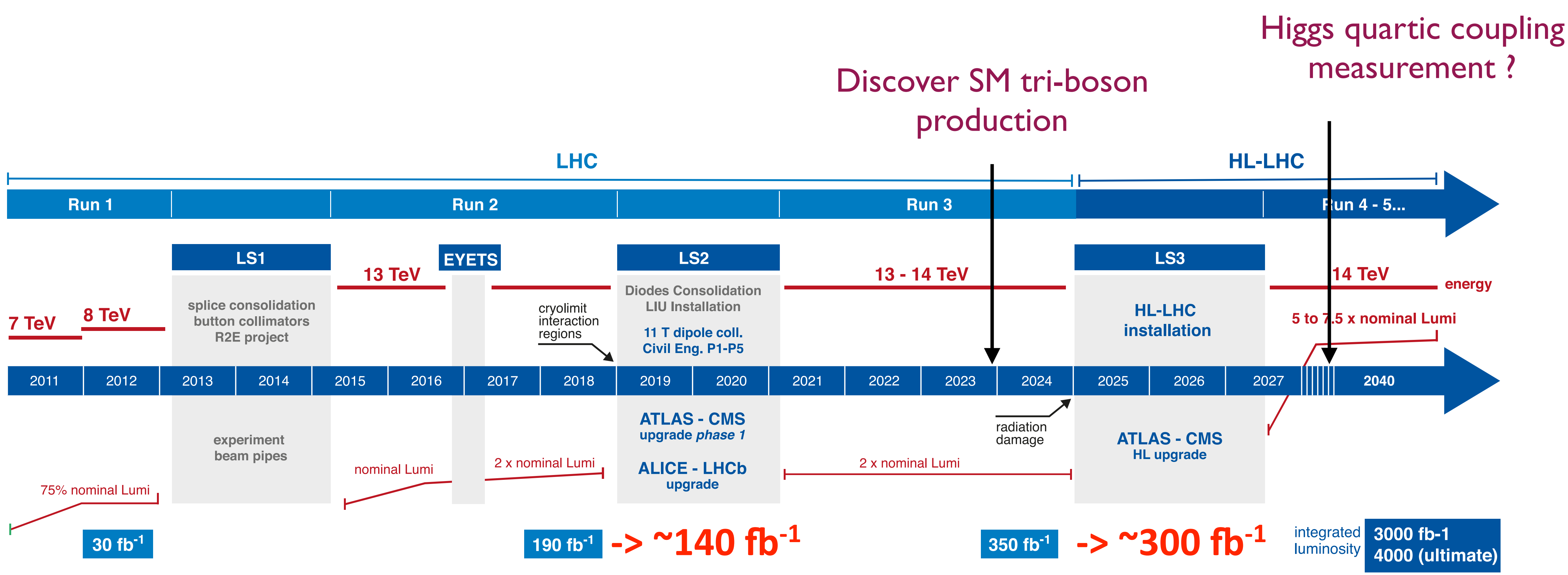


- **Take part in the bigger combination within Exotics group**
- **Benchmark:** *Heavy Vector Triplet (HVT)* model
- With the ttbar results, we will be sensitive to third generation coupling plane
- **Example:** quark-coupling (gQ) vs third generation coupling (g3)

- Not much gain by doubling the data at the end of Run-3, need better techniques
- New jet developments in ATLAS could improve the uncertainties
- Top-tagging on the new jet collections: could improve the background rejection by a factor of 1.5
- Novel techniques based on multivariate approach like *likelihood-free inference* could improve sensitivity

Whats Next?

- Shift the focus to SM measurements
- Open to different physics like electro-weak tri-boson production, Higgs self-coupling via di-Higgs production
- Goal is to explore new physics using the measurement data with the Effective Field Theory approach
- Explore ML techniques (using M-Learned likelihoods) to overcome several limitations of EFT
- Balance out my skills by gaining experience on hardware projects



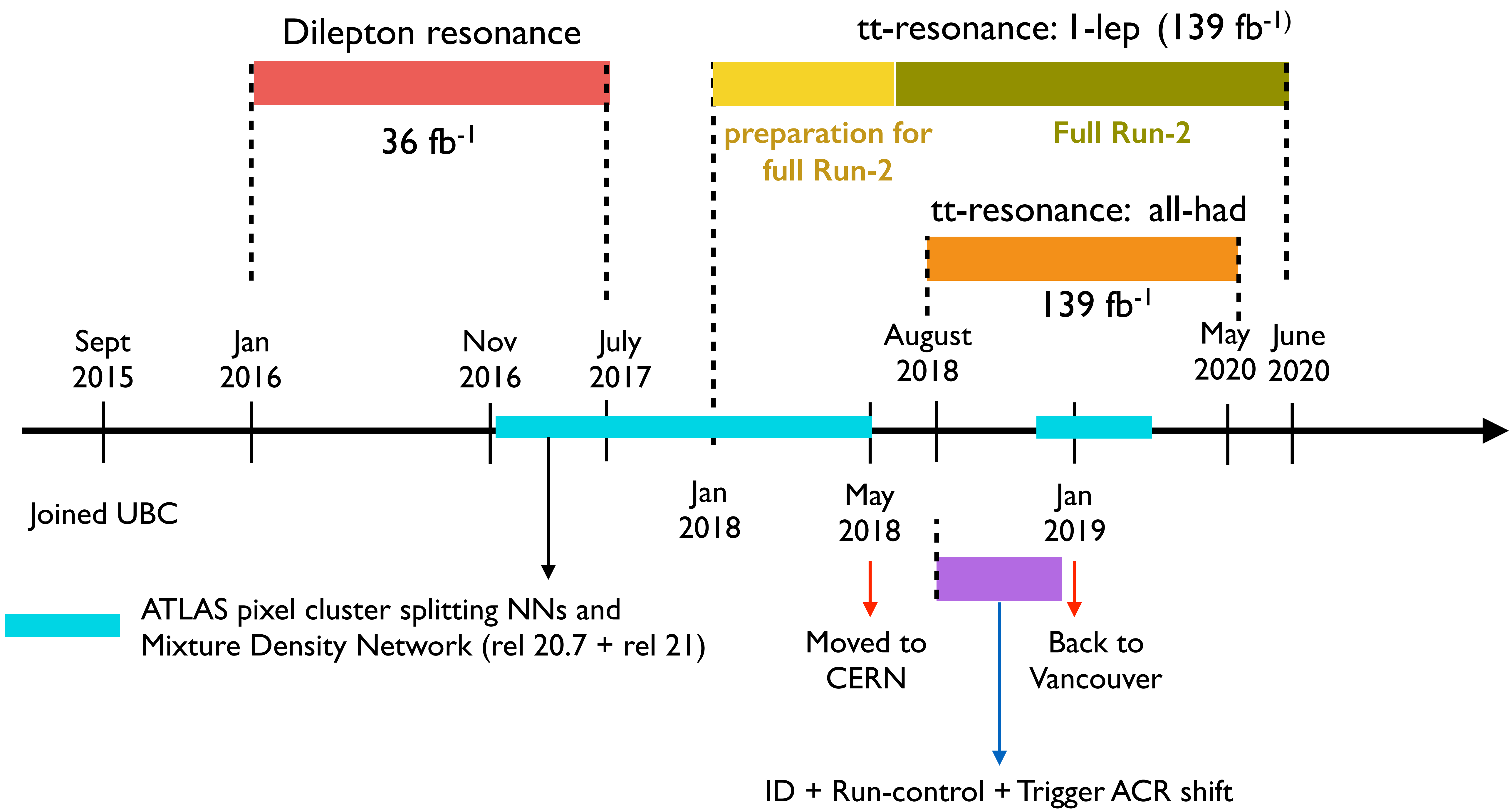
Thank you for your attention

Particular appreciation to the dilepton & tt-Res teams and the UBC ATLAS group

Wedgemount Lake, BC, Canada

Extra slides

My PhD timeline

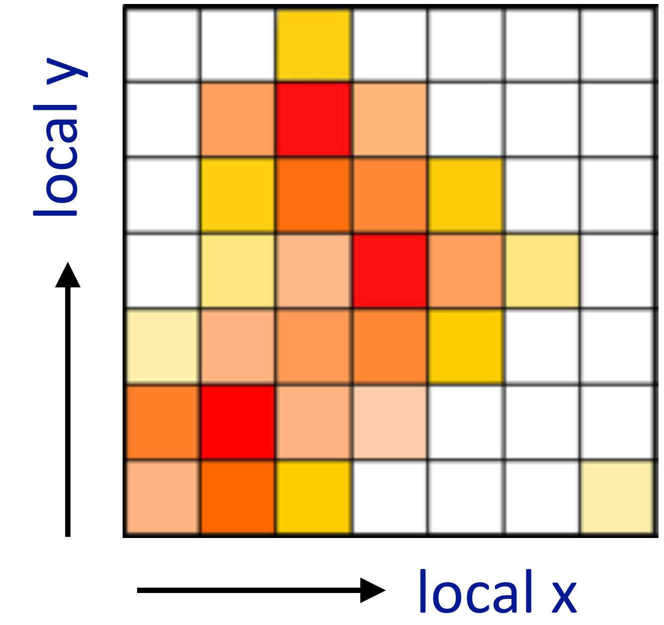


MDN hyperparameters

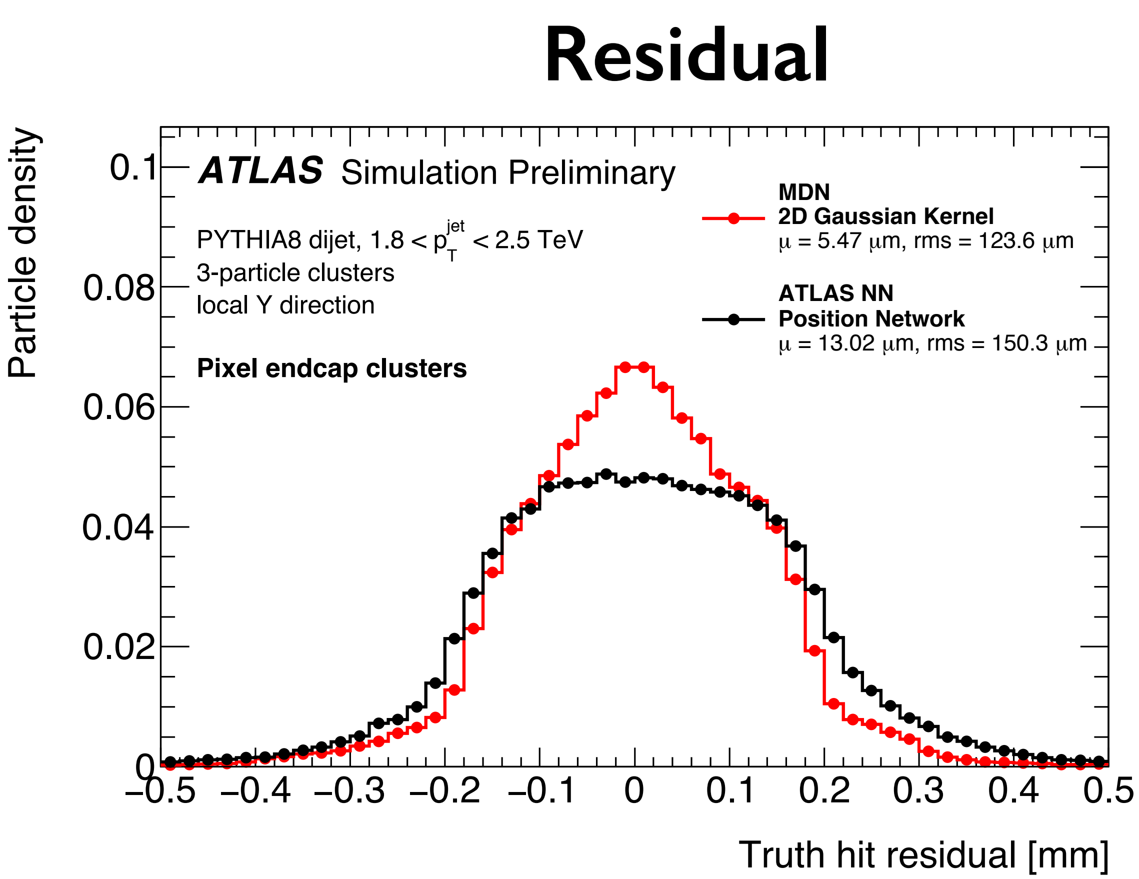
Hyperparamaters	MDN (1 particle)	MDN (2 particles)	MDN (3 particles)
Structure	(60)-100-50-50-(1-2-2)	(60)-100-80-50-(2-4-4)	(60)-100-80-50-(3-6-6)
Activation	ReLu	ReLu	ReLu
Output Layer	1 GMM	2 GMM	3 GMM
Output activation	(softmax-linear-absolute)	(softmax-linear-absolute)	(softmax-linear-absolute)
Learning rate	0.0001	0.0001	0.0001
L2 regularizer	0.0001	0.0001	0.0001
Batch Size	100	100	100
Gradient Clipping	clipnorm = 1	clipnorm = 1	clipnorm = 1
Loss Function	MDN loss	MDN loss	MDN loss

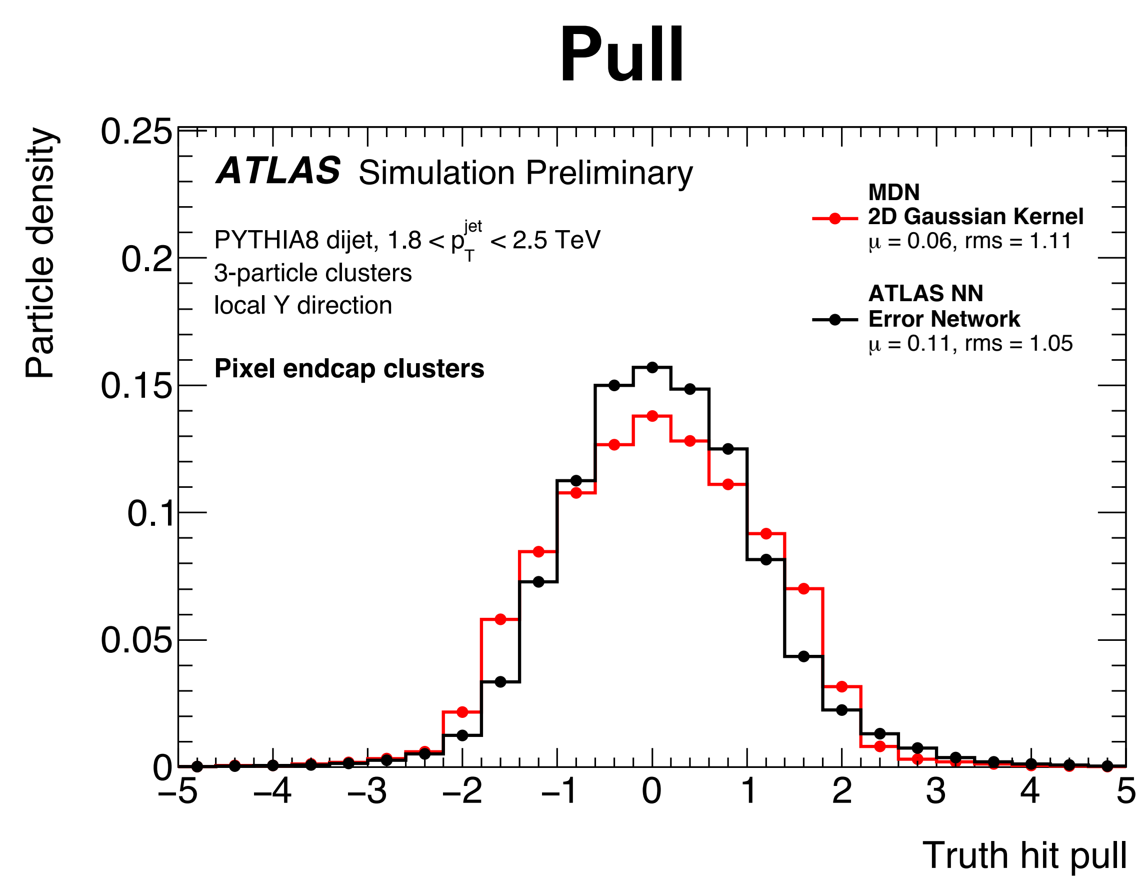
MDN: Performance (3-particle hit)

• Results for local-x direction



Endcap 3-particle clusters: x-direction





PoS (LHCP2019) 009

Event Reconstruction

Particles are reconstructed from different signatures on the sub-detectors

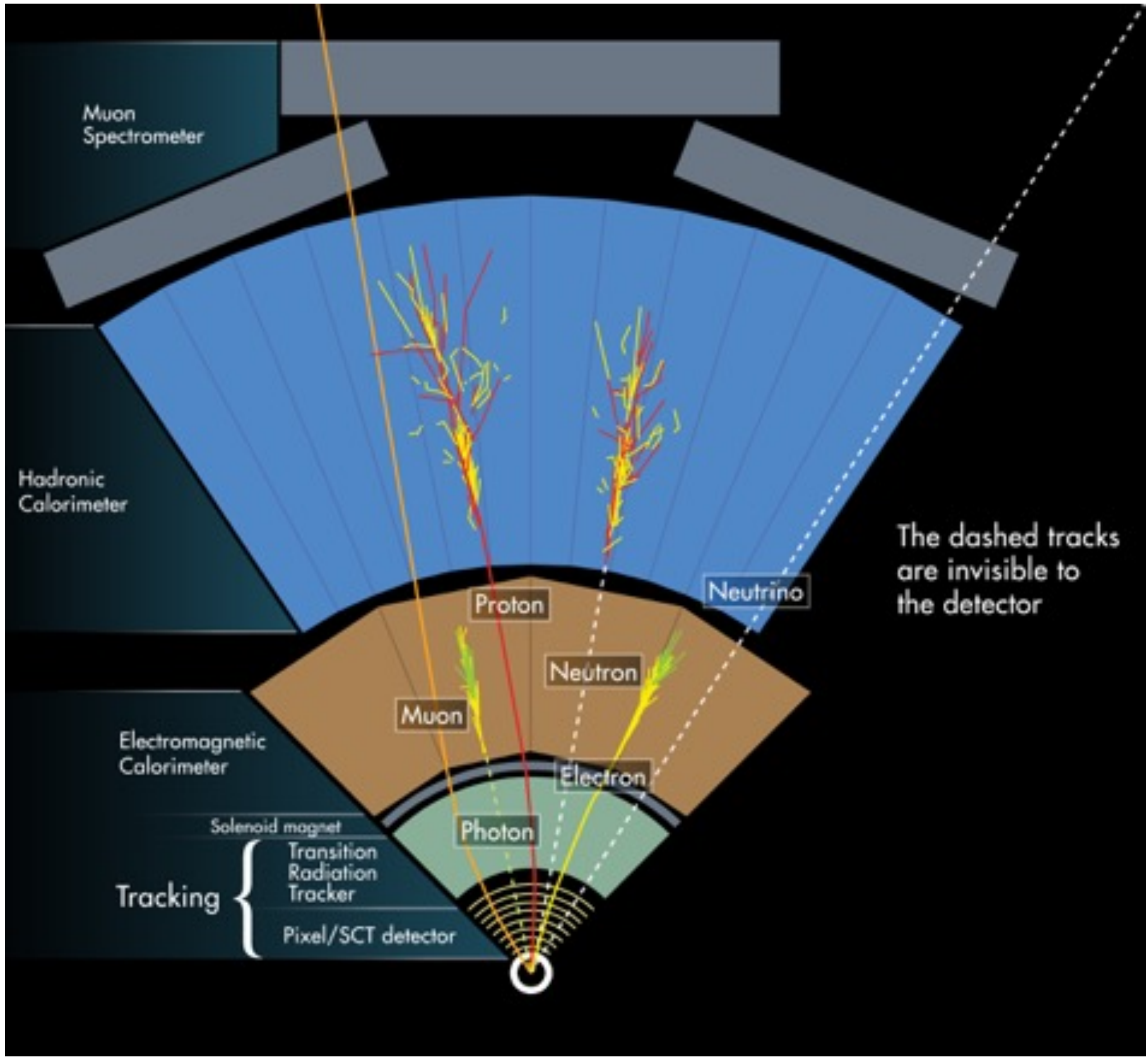
Electrons: Inner detector track + EM calorimeter deposit

Photons: EM calorimeter deposit, uses tracking & vertex reconstruction for conversion and isolation

Jets: Inner detector tracks (charged), EM Cal and HCal deposit

Muons: Inner detector and Muon spectrometer tracks

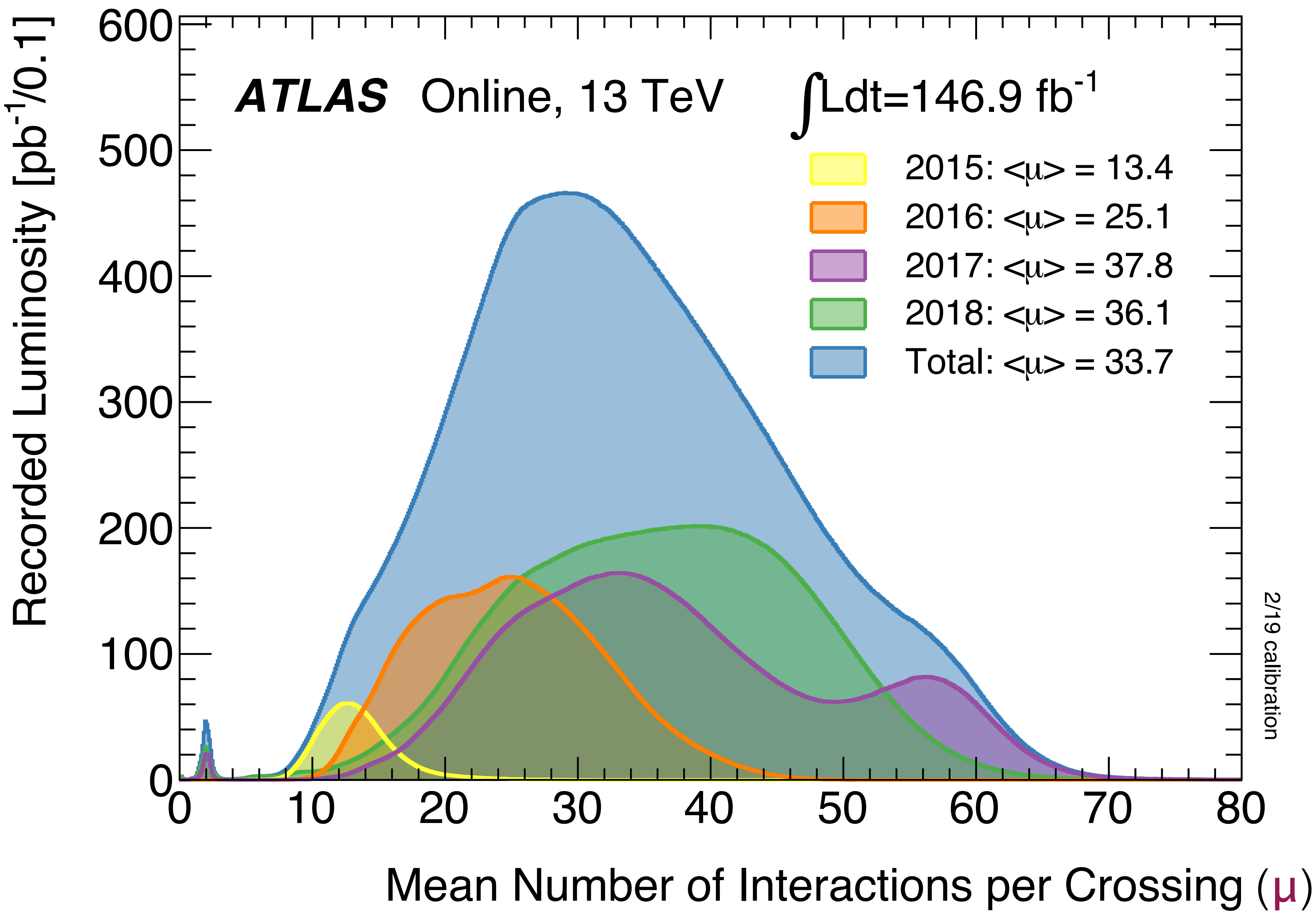
Neutrinos: Cannot detect, mostly resolved using missing transverse energy



- Tracking and vertexing is very important and used to reconstruct almost all the objects in ATLAS
- One of our project is on tracking in "Dense Environment"

Pileup profile: LHC Run-II

- μ increased by ~1.5 times in 2017-18



LuminosityPublicResultsRun2

Background composition: dilepton res

Drell-Yan process: ~70-80% and the relative contribution increases with mass
top process: ~25-1% and the and relative contribution decreases with mass
Diboson: ~6-7% and the relative contribution increases at high mass
multijet: ~5 - 15% and the relative contribution increases at high mass

m_{ee} [GeV]	80–120	120–250	250–400	400–500	500–700
Drell–Yan	11 800 000 ± 700 000	216 000 ± 11 000	17 230 ± 1000	2640 ± 180	1620 ± 120
Top quarks	28 600 ± 1800	44 600 ± 2900	8300 ± 600	1130 ± 80	560 ± 40
Dibosons	31 400 ± 3300	7000 ± 700	1300 ± 140	228 ± 25	146 ± 16
Multi-jet & W+jets	11 000 ± 9000	5600 ± 2000	780 ± 80	151 ± 21	113 ± 17
Total SM	11 900 000 ± 700 000	273 000 ± 12 000	27 600 ± 1100	4150 ± 200	2440 ± 130
Data	12 415 434	275 711	27 538	4140	2390
Z'_χ (4 TeV)	0.00635 ± 0.00021	0.0390 ± 0.0015	0.0564 ± 0.0025	0.0334 ± 0.0027	0.064 ± 0.004
Z'_χ (5 TeV)	0.00305 ± 0.00012	0.0165 ± 0.0006	0.0225 ± 0.0010	0.0139 ± 0.0007	0.0275 ± 0.0015

m_{ee} [GeV]	700–900	900–1200	1200–1800	1800–3000	3000–6000
Drell–Yan	421 ± 34	176 ± 17	62 ± 7	8.7 ± 1.3	0.34 ± 0.07
Top quarks	94 ± 8	27.9 ± 2.8	5.1 ± 0.7	< 0.001	< 0.001
Dibosons	39 ± 4	16.9 ± 2.1	5.8 ± 0.8	0.74 ± 0.11	0.028 ± 0.004
Multi-jet & W+jets	39 ± 6	16.1 ± 2.0	7.9 ± 2.3	1.6 ± 1.2	0.08 ± 0.27
Total SM	590 ± 40	237 ± 17	81 ± 7	11.0 ± 1.8	0.45 ± 0.28
Data	589	209	61	10	0
Z'_χ (4 TeV)	0.0585 ± 0.0035	0.074 ± 0.005	0.121 ± 0.011	0.172 ± 0.017	2.57 ± 0.27
Z'_χ (5 TeV)	0.0218 ± 0.0013	0.0295 ± 0.0021	0.040 ± 0.004	0.040 ± 0.004	0.280 ± 0.030

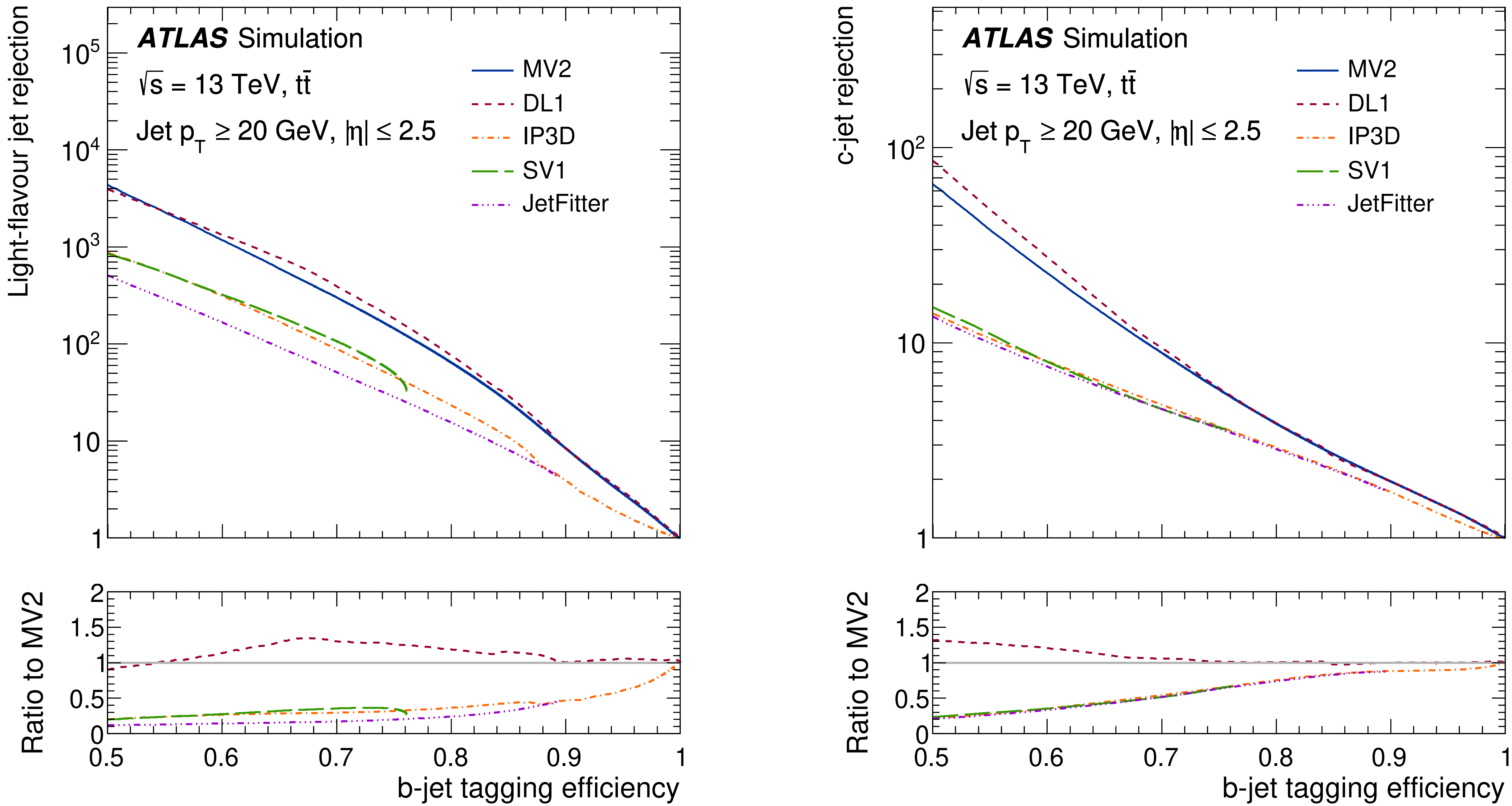
Systematic Uncertainties: dilepton res

- Overall the systematic uncertainty contribution is low in the analysis
- Major uncertainness come from PDF uncertainties (theory unc.) and lepton isolation and calibration (exp. uncertainty)

Source	Dielectron channel [%]		Dimuon channel [%]	
	Signal	Background	Signal	Background
Luminosity	3.2 (3.2)	3.2 (3.2)	3.2 (3.2)	3.2 (3.2)
MC statistical	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)
Beam energy	2.0 (4.1)	2.0 (4.1)	1.9 (3.1)	1.9 (3.1)
Pile-up effects	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)
DY PDF choice	N/A	<1.0 (8.4)	N/A	<1.0 (1.9)
DY PDF variation	N/A	8.7 (19)	N/A	7.7 (13)
DY PDF scales	N/A	1.0 (2.0)	N/A	<1.0 (1.5)
DY α_S	N/A	1.6 (2.7)	N/A	1.4 (2.2)
DY EW corrections	N/A	2.4 (5.5)	N/A	2.1 (3.9)
DY γ-induced corrections	N/A	3.4 (7.6)	N/A	3.0 (5.4)
Top quarks theoretical	N/A	<1.0 (<1.0)	N/A	<1.0 (<1.0)
Dibosons theoretical	N/A	<1.0 (<1.0)	N/A	<1.0 (<1.0)
Reconstruction efficiency	<1.0 (<1.0)	<1.0 (<1.0)	10 (17)	10 (17)
Isolation efficiency	9.1 (9.7)	9.1 (9.7)	1.8 (2.0)	1.8 (2.0)
Trigger efficiency	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)	<1.0 (<1.0)
Identification efficiency	2.6 (2.4)	2.6 (2.4)	N/A	N/A
Lepton energy scale	<1.0 (<1.0)	4.1 (6.1)	<1.0 (<1.0)	<1.0 (<1.0)
Lepton energy resolution	<1.0 (<1.0)	<1.0 (<1.0)	2.7 (2.7)	<1.0 (6.7)
Multi-jet & W+jets	N/A	10 (129)	N/A	N/A
Total	10 (11)	18 (132)	11 (18)	14 (24)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-05/

b-tagging performance



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/FTAG-2018-01/

Background composition: tt res all-had

Table 11: Event yields in the $|\Delta y(J, J)| < 1.8$ 0, 1 and 2 b-tag regions in 2015+2016+2017+2018 data.

Type	btag cat.0	btag cat.1	btag cat.2
$t\bar{t}$ **(all-had)**	2842.1 ± 1191.3 (2.5%)	5967.1 ± 43.2 (21.1%)	6195.7 ± 38.4 (75.9%)
$t\bar{t}$ **(non-all-had)**	261.8 ± 99.1 (0.2%)	500.7 ± 9.9 (1.8%)	229.2 ± 5.2 (2.8%)
Multijet	110 536.6 ± 1329.2 (97.3%)	21 794.8 ± 104.5 (77.1%)	1734.5 ± 11.8 (21.3%)
Total	113 640.5 ± 350.3	28 262.7 ± 113.4	8159.4 ± 40.4
Data	113 612 ± 337.1	26 964 ± 164.2	8160 ± 90.3

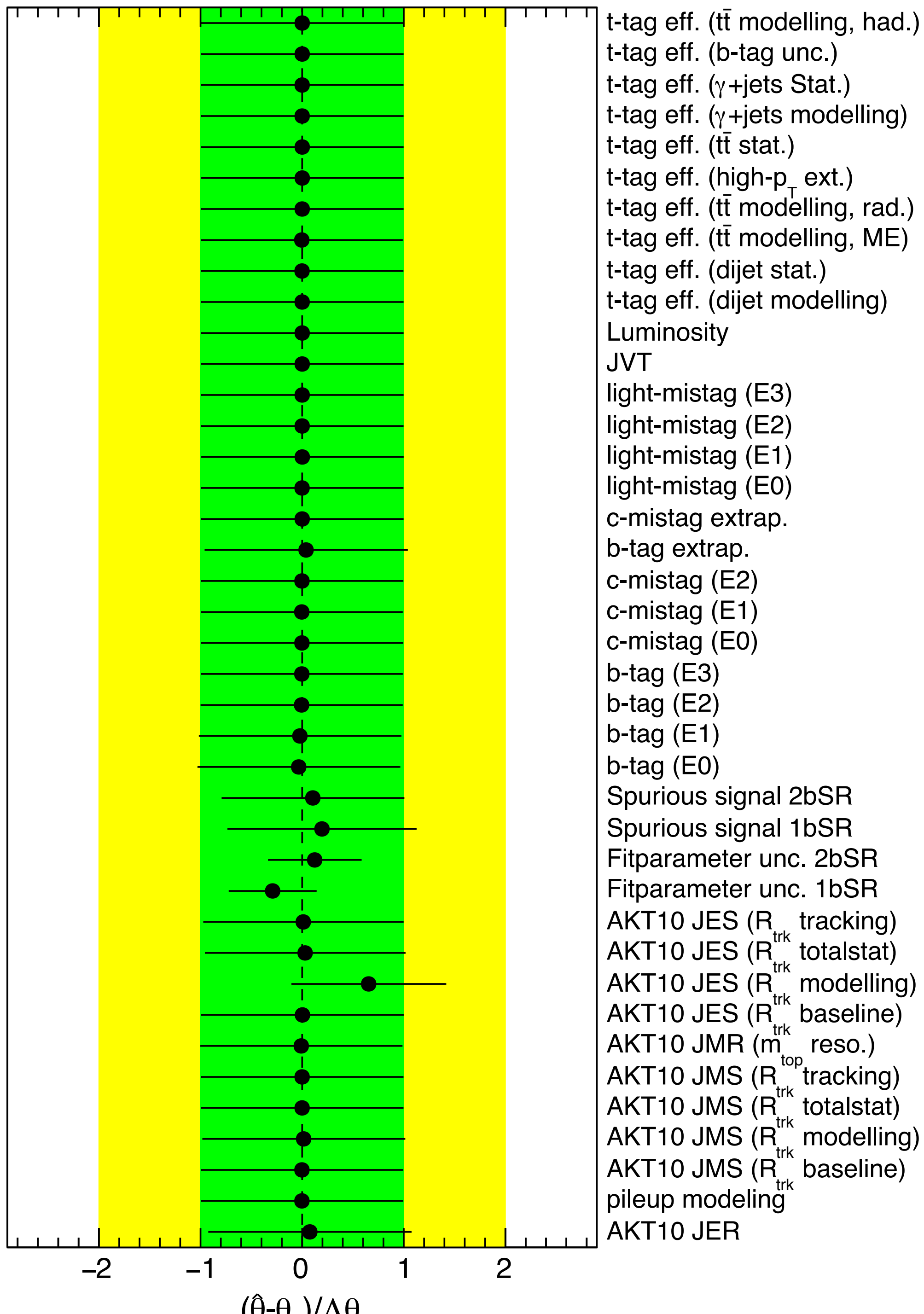
Systematic Uncertainties: tt res all-had

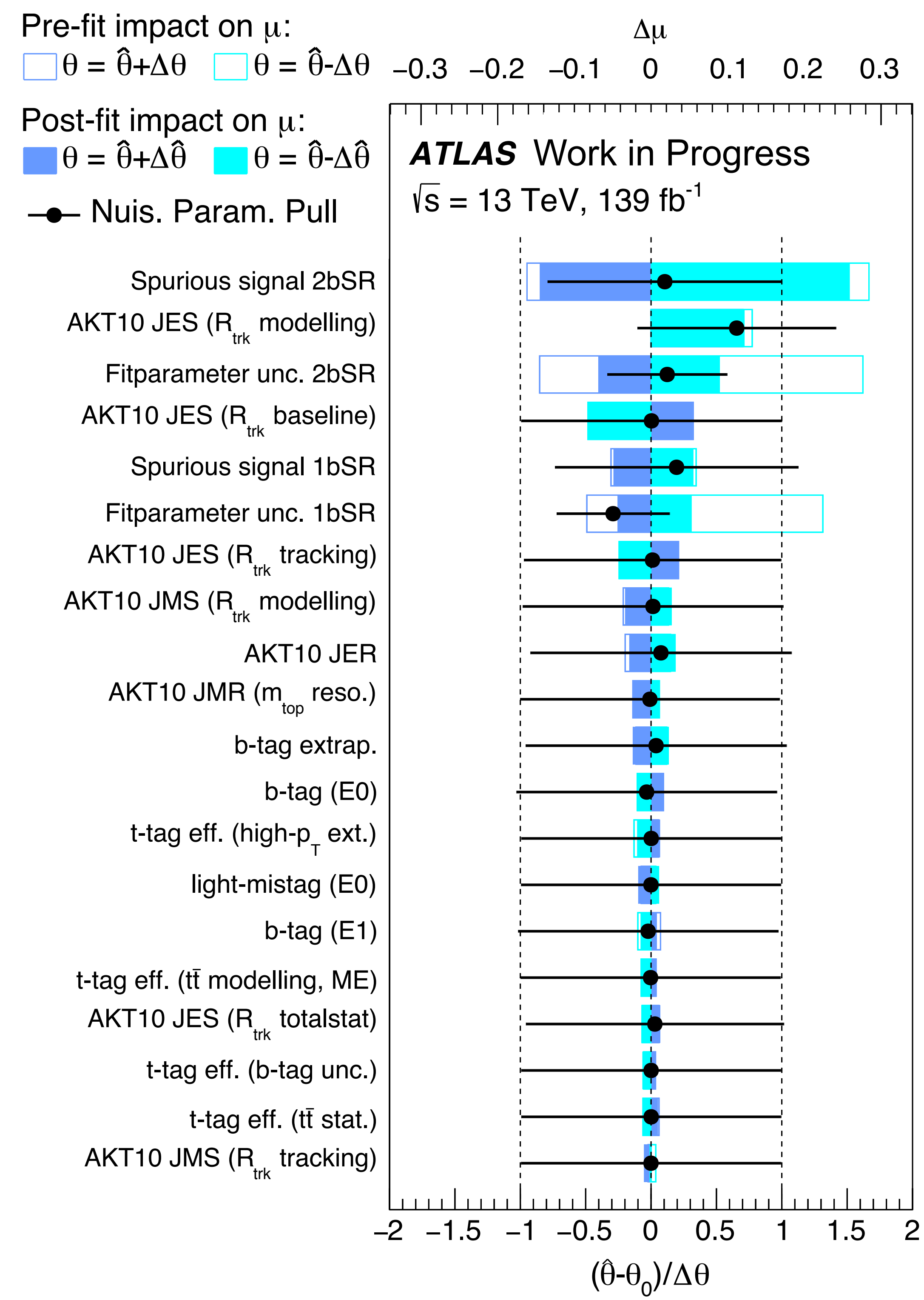
Major contribution comes from JES uncertainty (all combined shown here)

Source	**2 TeV Z' [%]**		**4 TeV Z' [%]**	
	SR1*b*	SR2*b*	SR1*b*	SR2*b*
JES	35	34	47	44
JMS	5.0	4.3	9.5	7.9
JER	0.1	0.1	0.1	< 0.1
JMR	3.9	4.0	8.0	8.0
b-tagging	14	5.0	23	5.3
Top-tagging	9.0	9.3	10	10

ttbar all-had: NP pull & NP ranking plot

Plots for **4 TeV** mass point is shown here





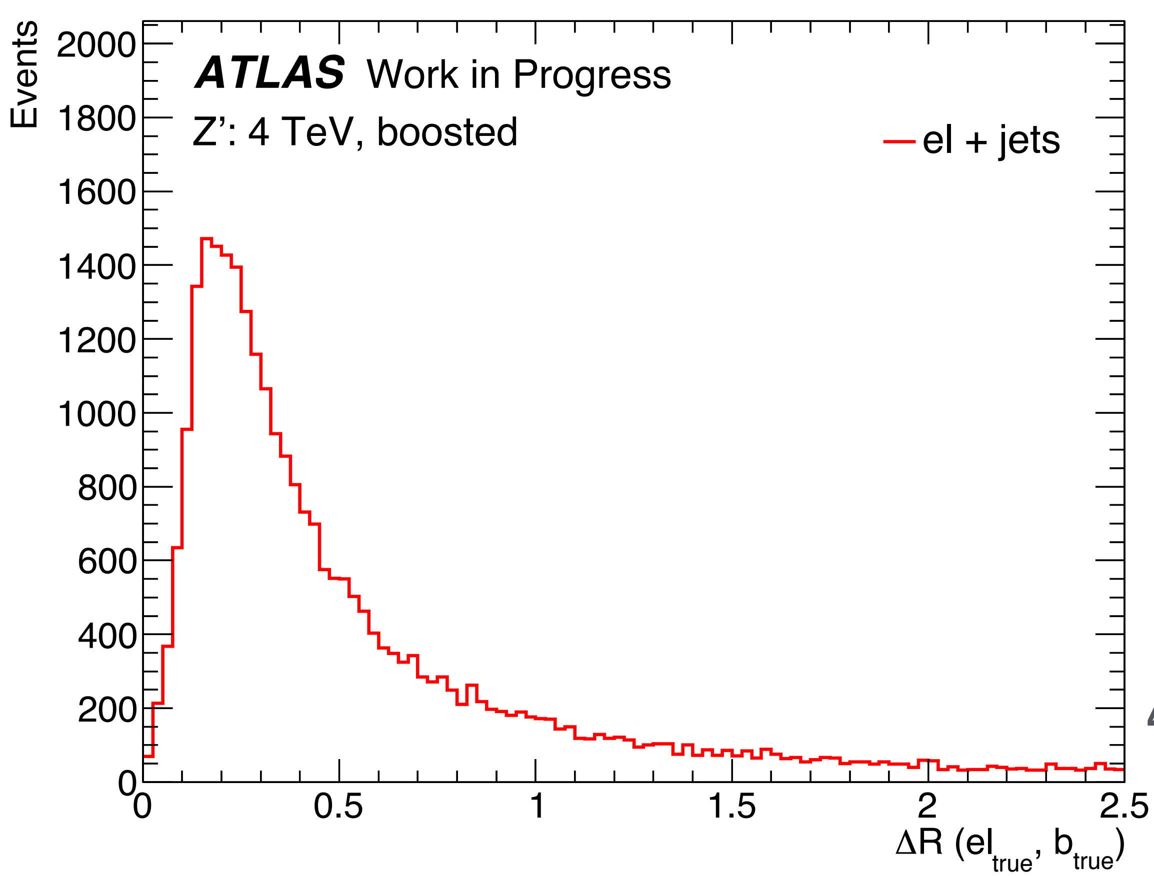
Angular distance between (el, b)

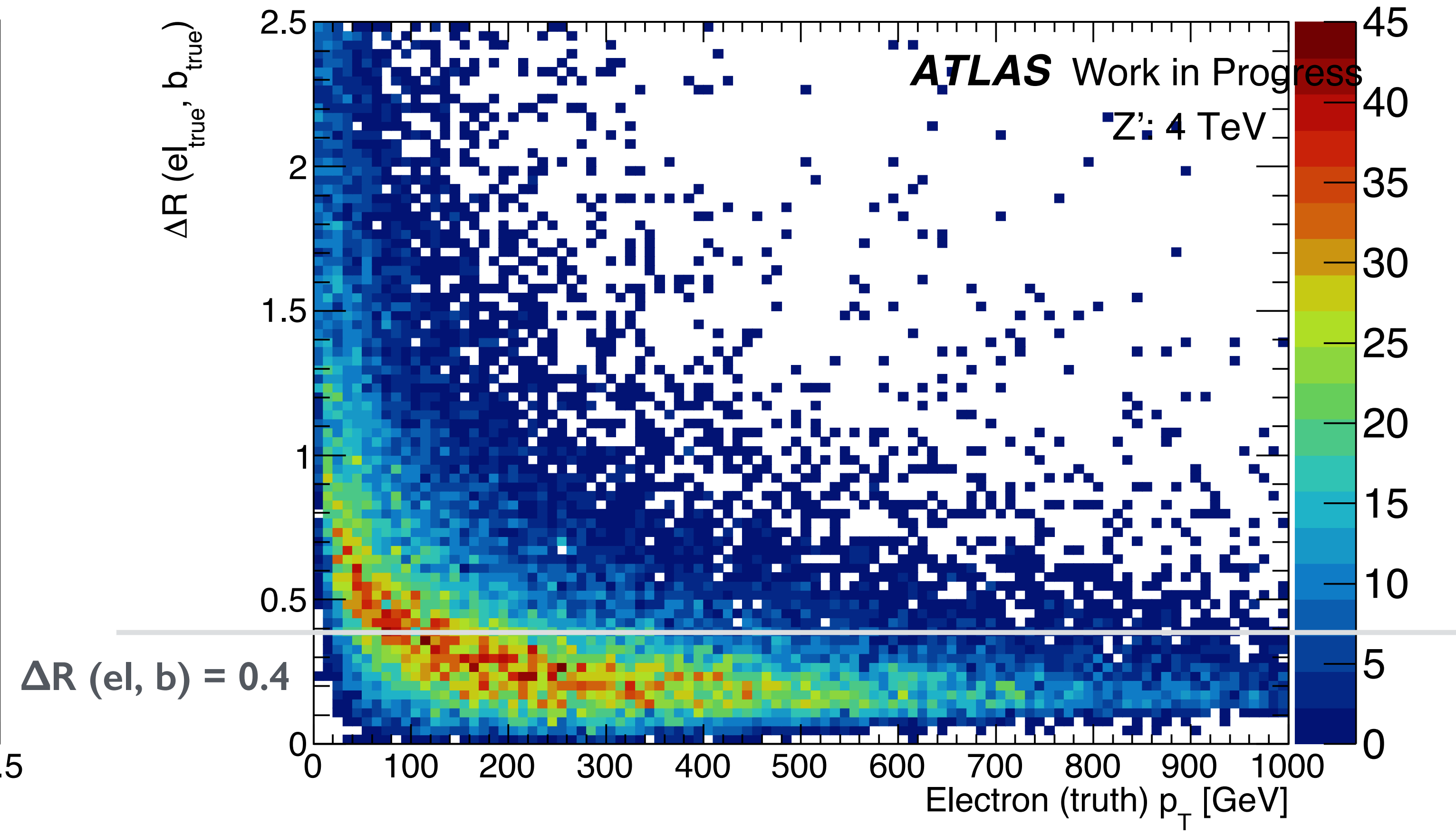
4 teV Z' signal

Truth level study

- ΔR (el, b): angular distance between the electron and the b-parton

Significant portion of events have electron and b parton close to each other





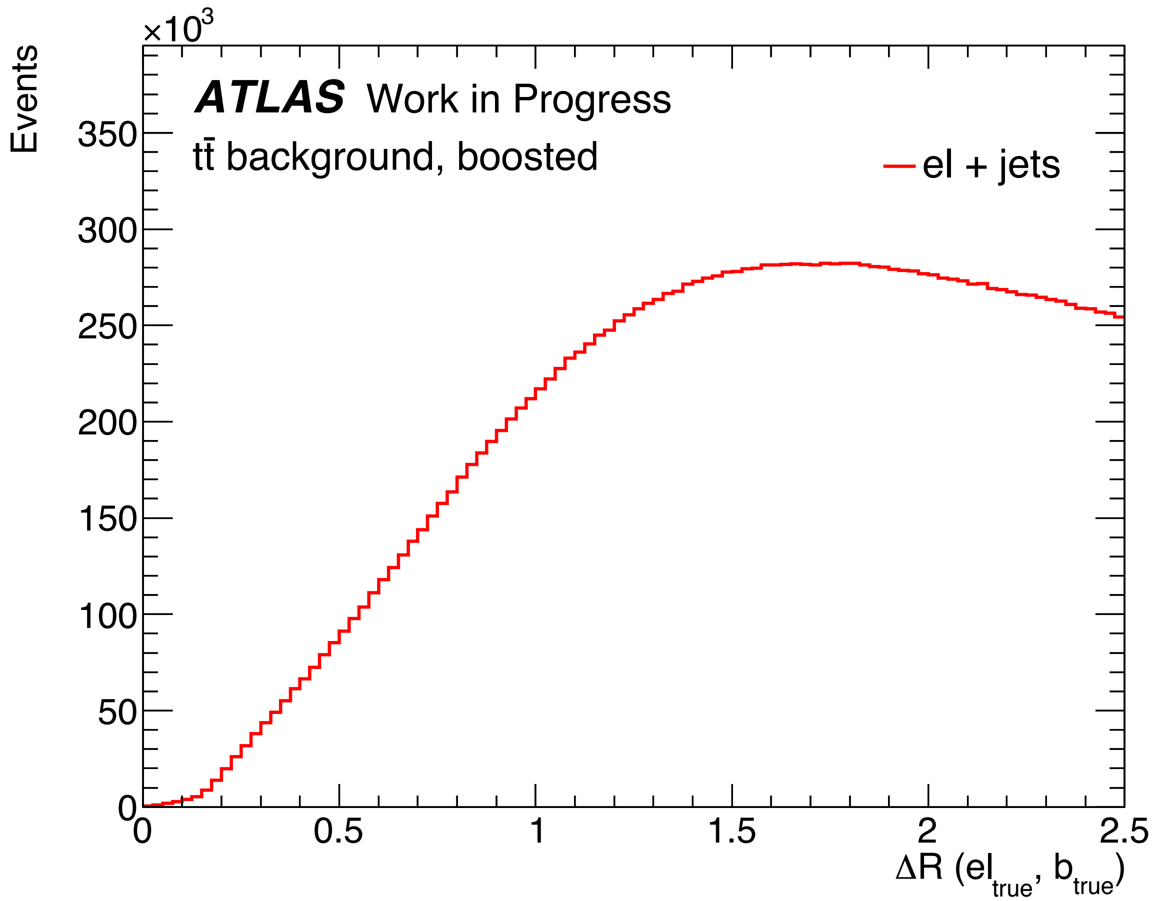
Angular distance between (el, b)

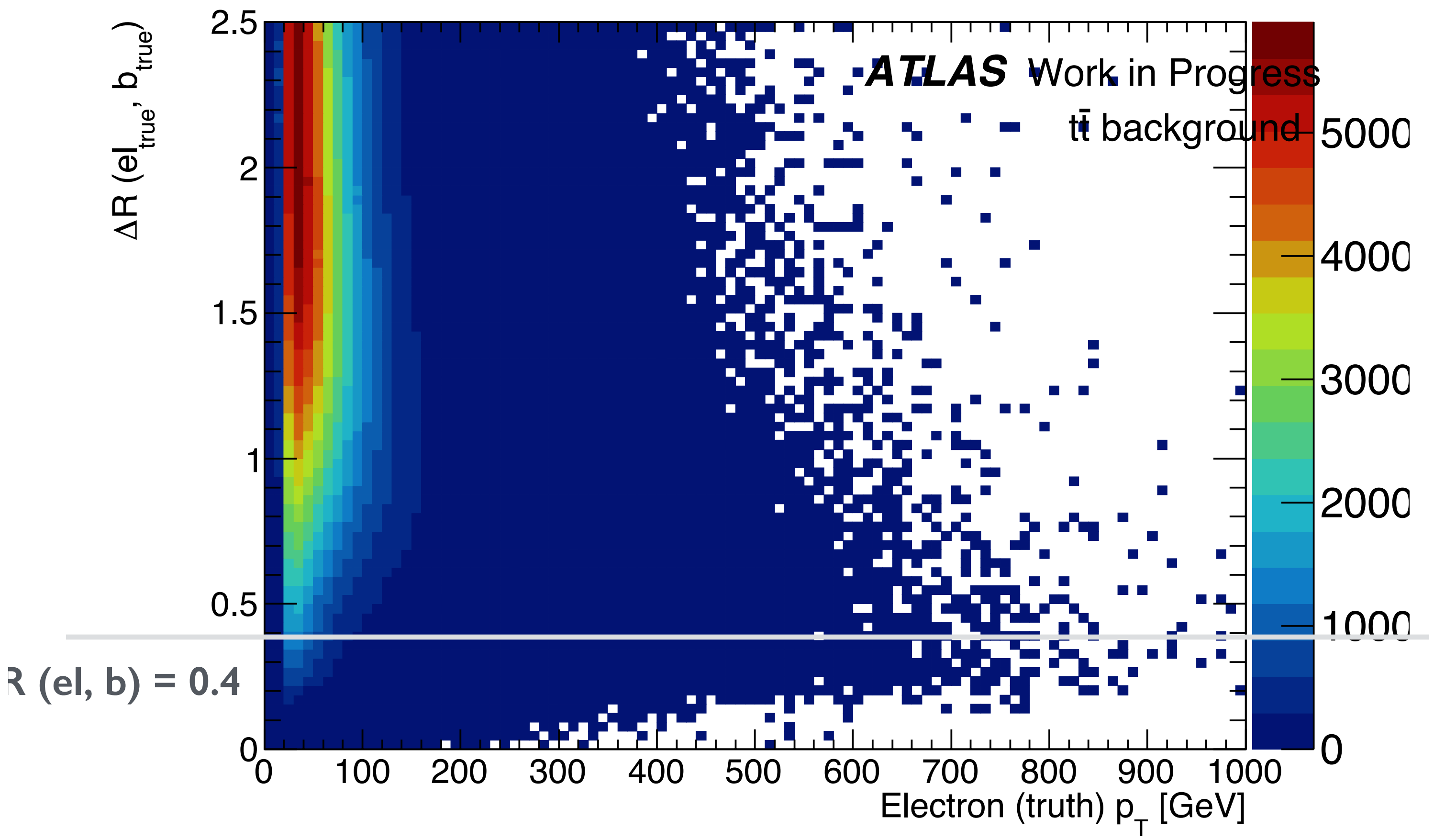
SM ttbar background

Truth level study

- ΔR (el, b): angular distance between the electron and the b-parton

Electron and b parton is usually far from each other: ΔR (el, b) > 0.4

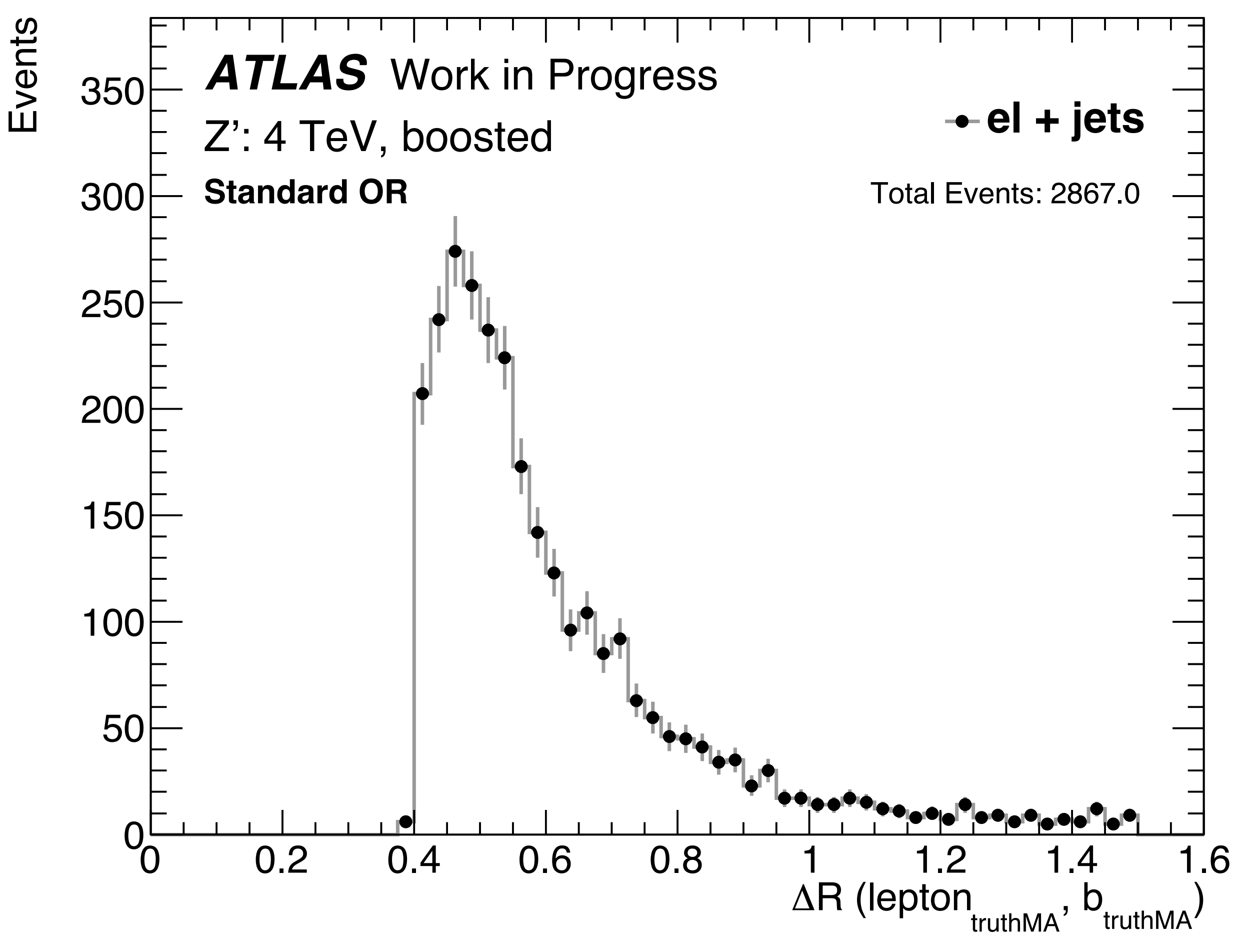


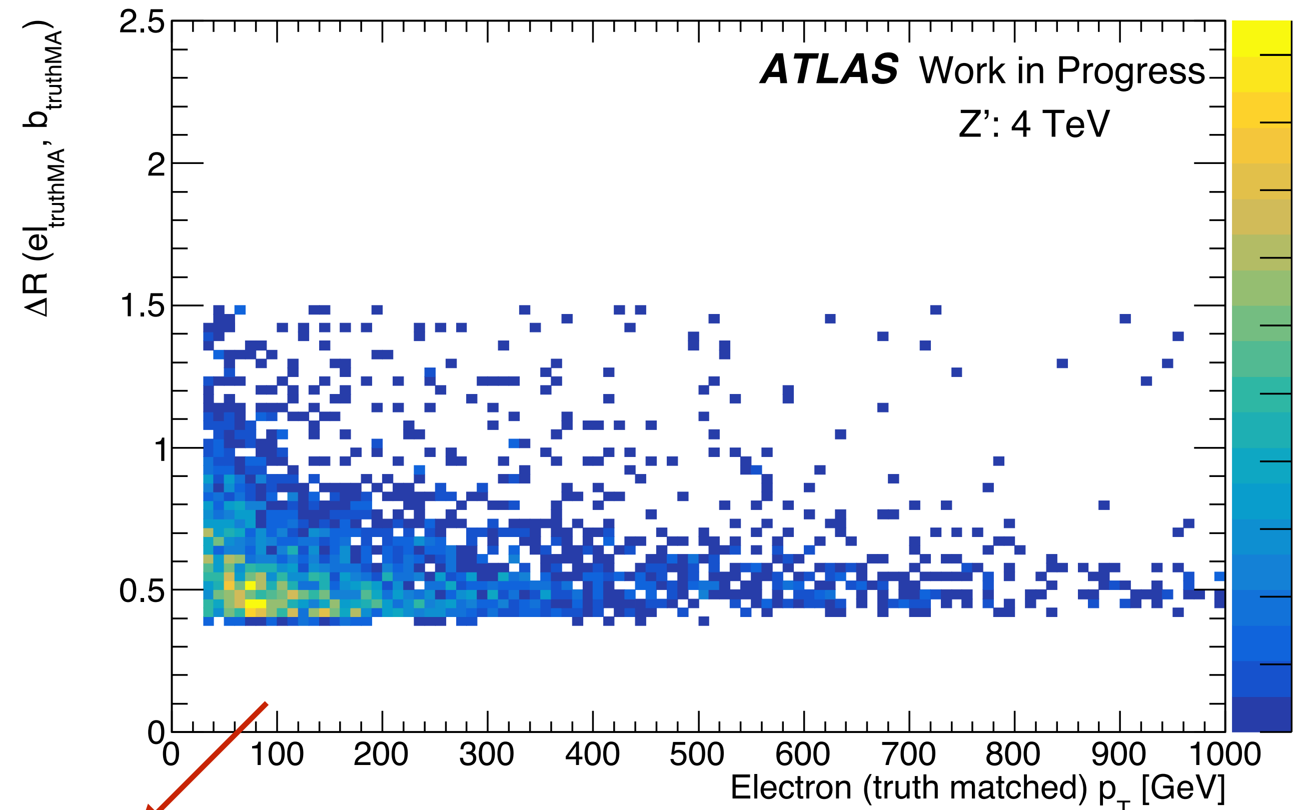


Standard Overlap Removal in ATLAS

- leptons and jets are build from the the same calorimeter clusters
- So, there is a chance of double counting
- To make sure we do not doubt count there is standard Overlap Removal (OR) requirement

- **Standard OR:** ΔR (el, jet) > 0.4
- Remember, jet radius = 0.4
- This is a general recommendation and most commonly used in ATLAS





Not good for this analysis. Removes quite bit of signal

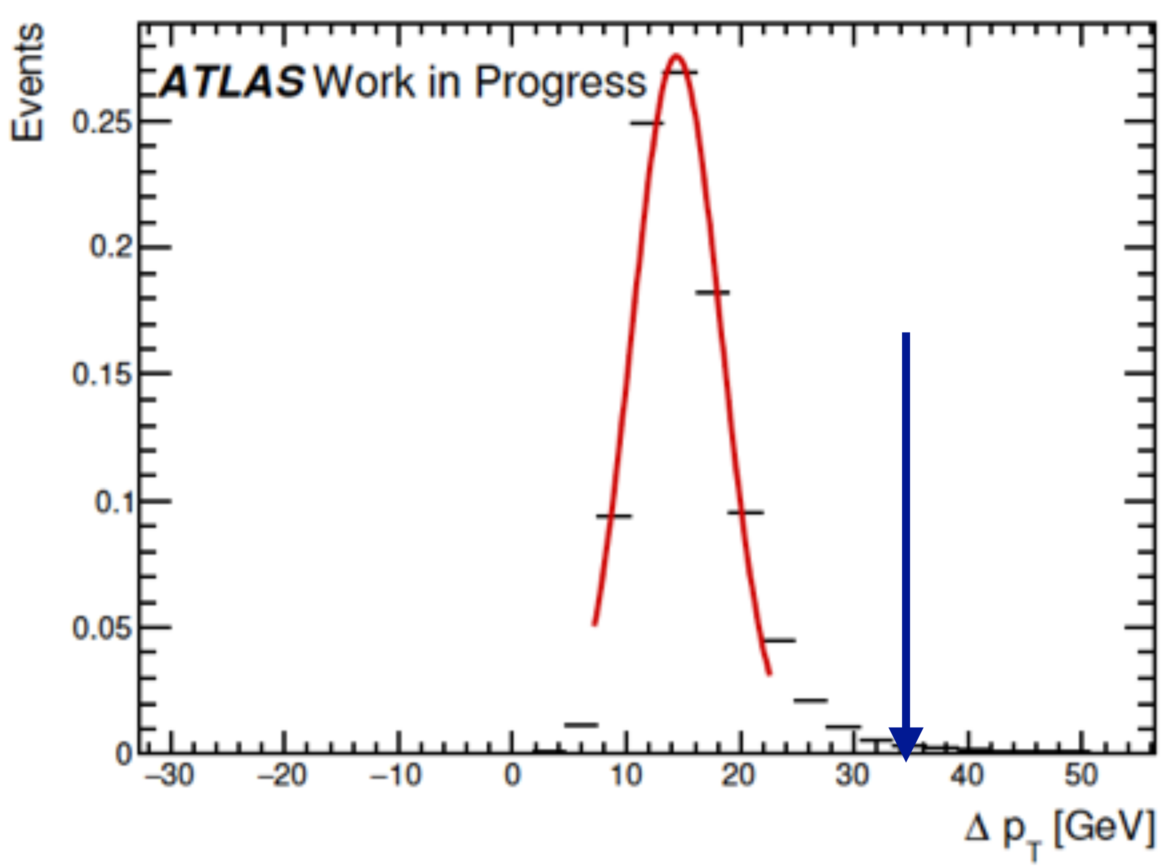
el-in-jets Overlap Removal

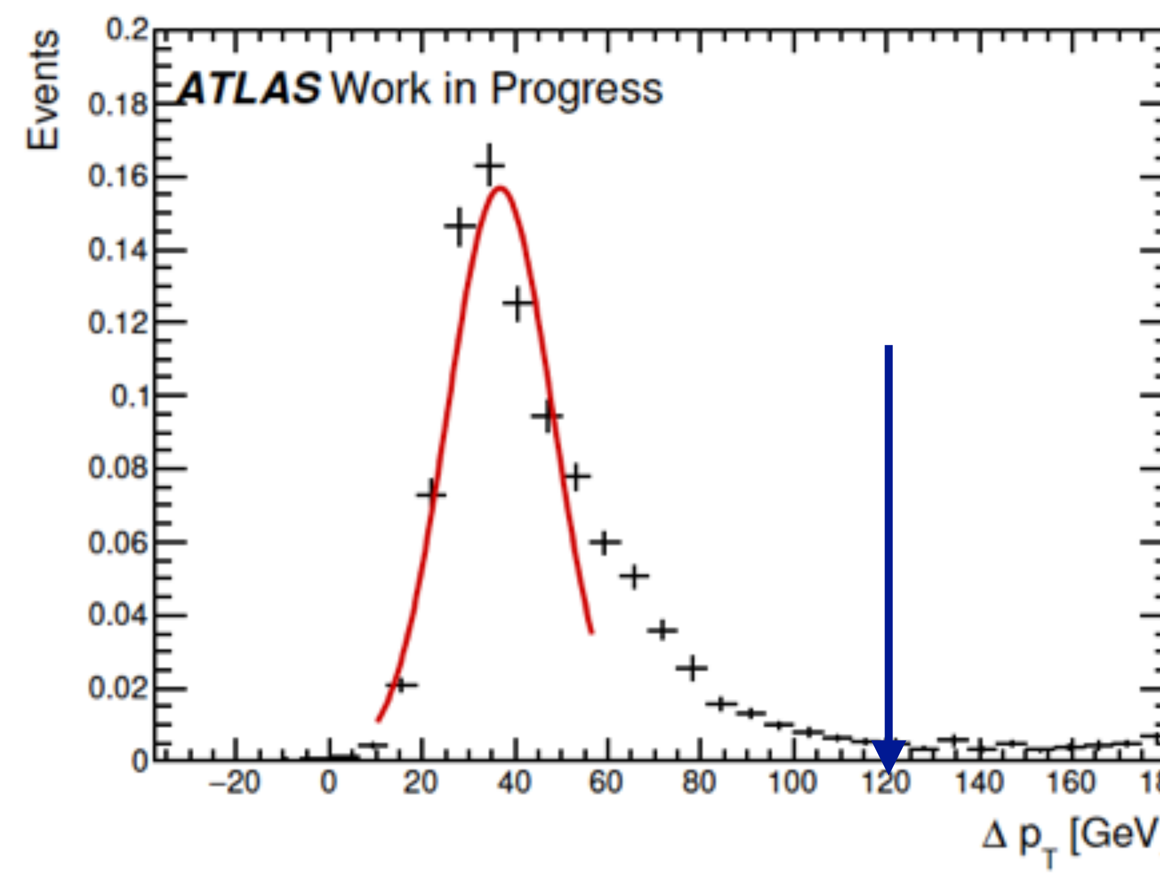
Electron pT is subtracted from each jet pT, if ΔR (el, jet) < 0.4

Is the electron and the jet coming from the same object?

- ΔpT (el, jet) was plotted for if ΔR (el, jet) < 0.4
- Large ΔpT (el, jet) => they are different object

Estimate a threshold (=pT CUT) by looking at the ΔpT





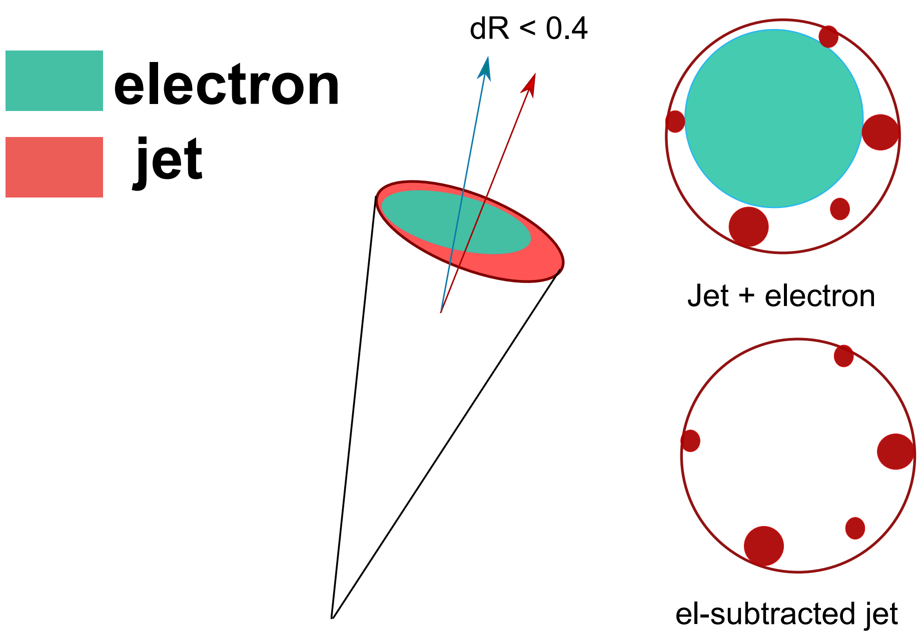
el-in-jets Overlap Removal

Steps:

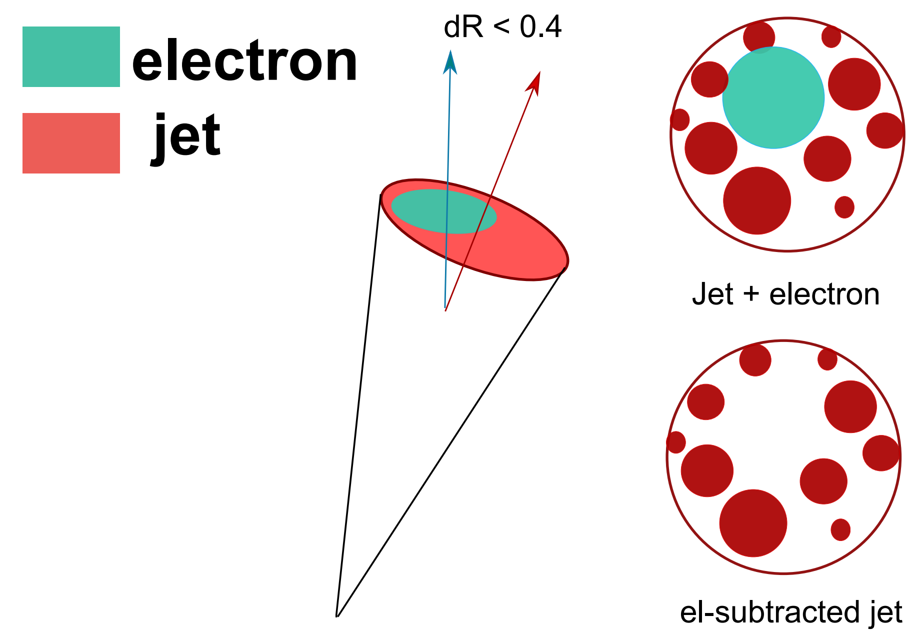
1. *If ΔR (el, jet) < 0.4* : subtract el 4-momentum from jet 4-momentum

2. Check the pT cut :
   - *If subtracted jet pT < pT CUT* : remove jet (the jet was constructed from the electron cluster)
   - otherwise re-calculate ΔR(el, el-subtracted jet)

Subtracted jet fails pT CUT



Subtracted jet passes pT CUT



el-in-jets Overlap Removal

Steps:

1. *If ΔR (el, jet) < 0.4* : subtract el 4-momentum from jet 4-momentum

2. Check the pT cut :
   - *If subtracted jet pT < pT CUT :* remove jet (the jet was constructed from the electron cluster)
   - otherwise re-calculate ΔR(el, el-subtracted jet)

3. Check ΔR(el, el-subtracted jet):
   - *If ΔR(el, el-subtracted jet) >= 0.2 :*
     ➡ keep both the **electron** and the **el-subtracted jet**
   - *If ΔR(el, el-subtracted jet) < 0.2 :*
     ➡ electron is coming from the b-jet
     ➡ electron 4-momentum is added back to the jet, and the electron is considered as **non-prompt**

Effect of systematic uncertainties

In the absence of systematics

$$p(n_k|b_k) = \frac{b_k^{n_k}}{n_k!}e^{-b_k}$$

n_k : # of data events in k^{th} bin

b_k : # of background events in k^{th} bin

In presence of systematics

$$p(n_k|\mu_k) = \frac{\mu_k^{n_k}}{n_k!}e^{-\mu_k}$$

$$\mu_k = b_k(1 + \sum_{i=1}^{N_{sys}} \theta_i \sigma_{ik})$$

θ_i : nuisance parameter

σ_{ik} : k^{th} bin content of i^{th} systematic