Particle Flow reconstruction and searches for supersymmetry with large jet multiplicities at the ATLAS experiment

Stanford Linear Accelerator Laboratory (SLAC), 15 October 2019

Marco Valente
Département de Physique Nucléaire et Corpusculaire (DPNC)
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Outline

1. **The ATLAS detector and the LHC**
2. **Hadronic observables: jets and MET**
   1. Why we need hadronic observables?
   2. The ATLAS jet and MET reconstruction.
   3. The “issue” of pileup.
   4. Particle Flow reconstruction.
   5. Can be do better? Maybe…. neutral pileup mitigation!
3. **Searches for supersymmetry with large jet multiplicities**
   1. What is supersymmetry? How could that be observed?
   2. Searching for supersymmetry with with many jets
   3. Background estimation at 7-12 jets
   4. Do you want to see 12 jets results?
   5. Reinterpretation and current limits
4. **Conclusions and outlook**

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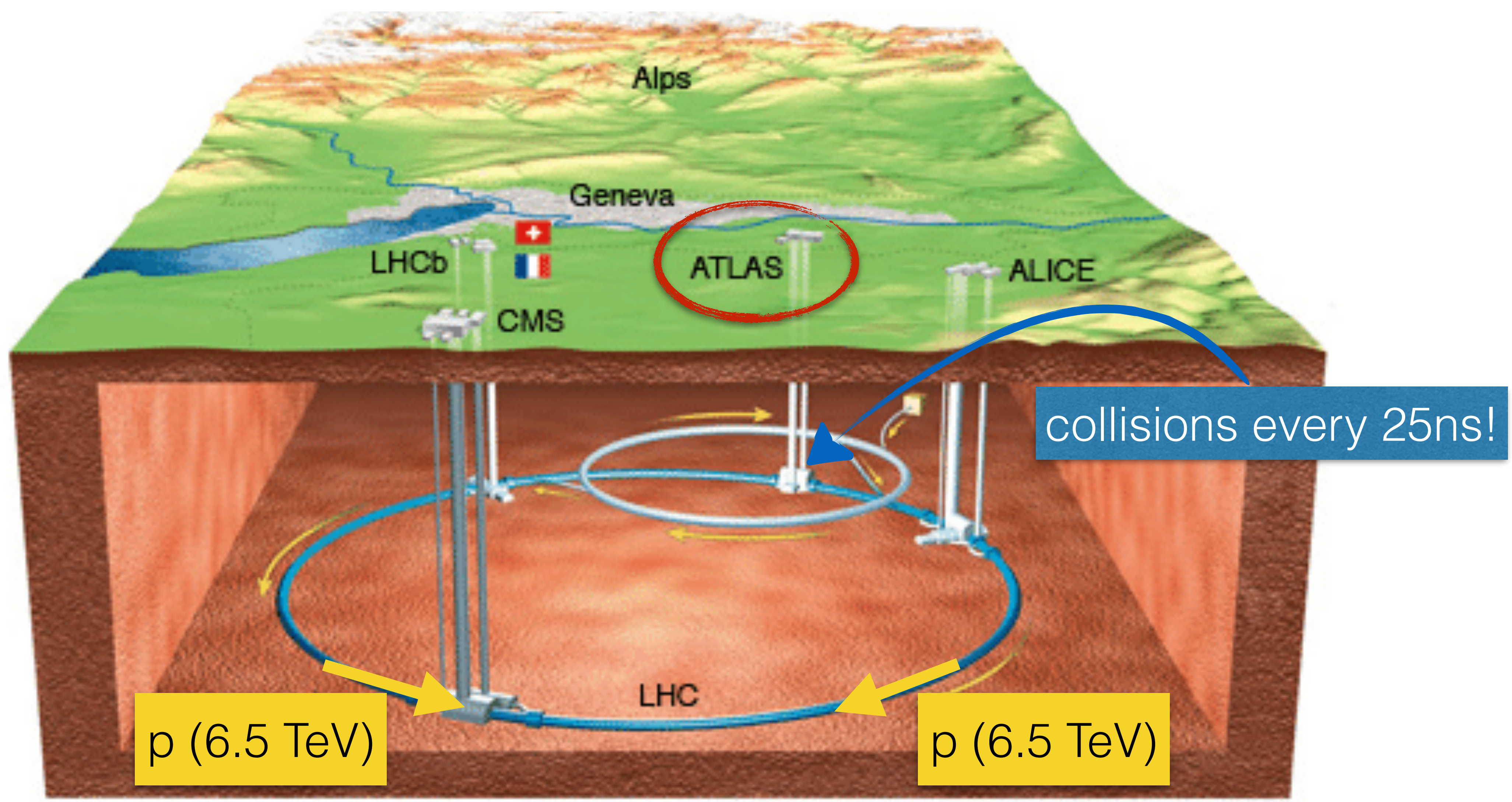
The Large Hadron Collider

Smashing protons at a new energy frontier



ATLAS is designed to study:

- Standard Model measurements (Higgs, top, etc.)
- Searches for new physics and bumps (Exotics, Supersymmetry, Dark Matter, etc.)

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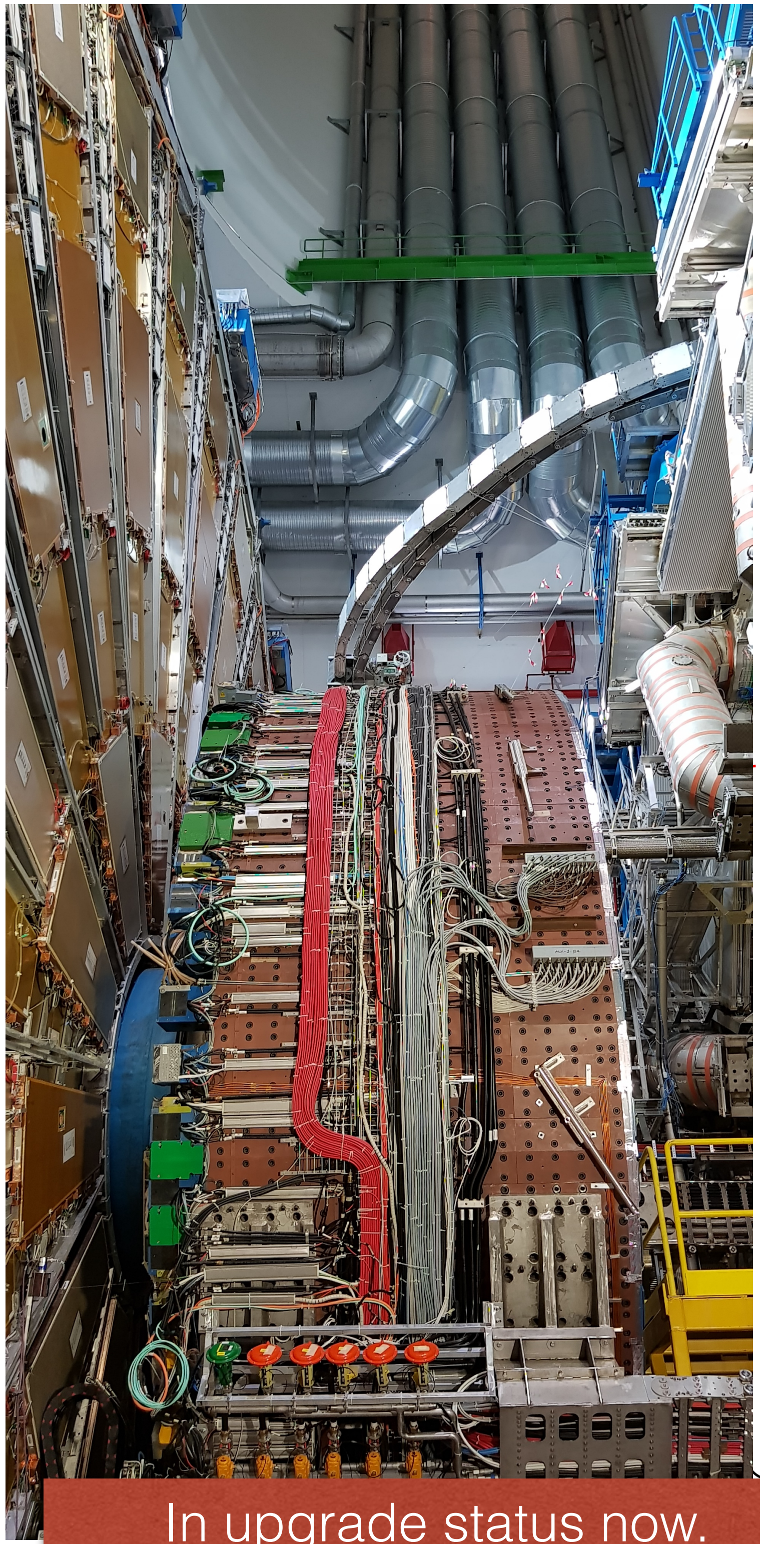
The ATLAS experiment

A detector of sub-detectors



In upgrade status now.
Operative again in 2021 (Run 3)

- Different (independent) sub-detectors:
  - **Inner Detector:** providing tracking for charged particles.
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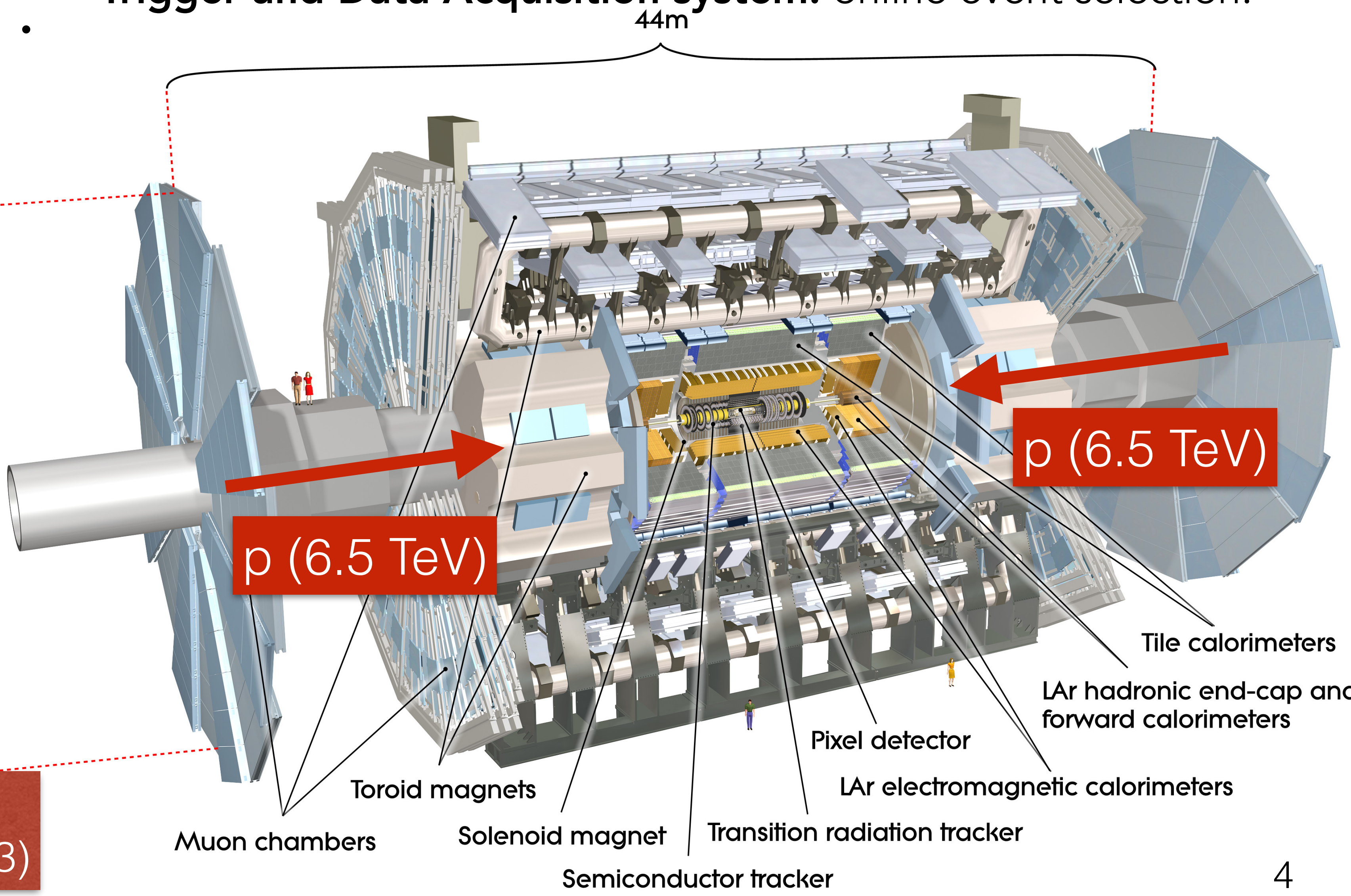

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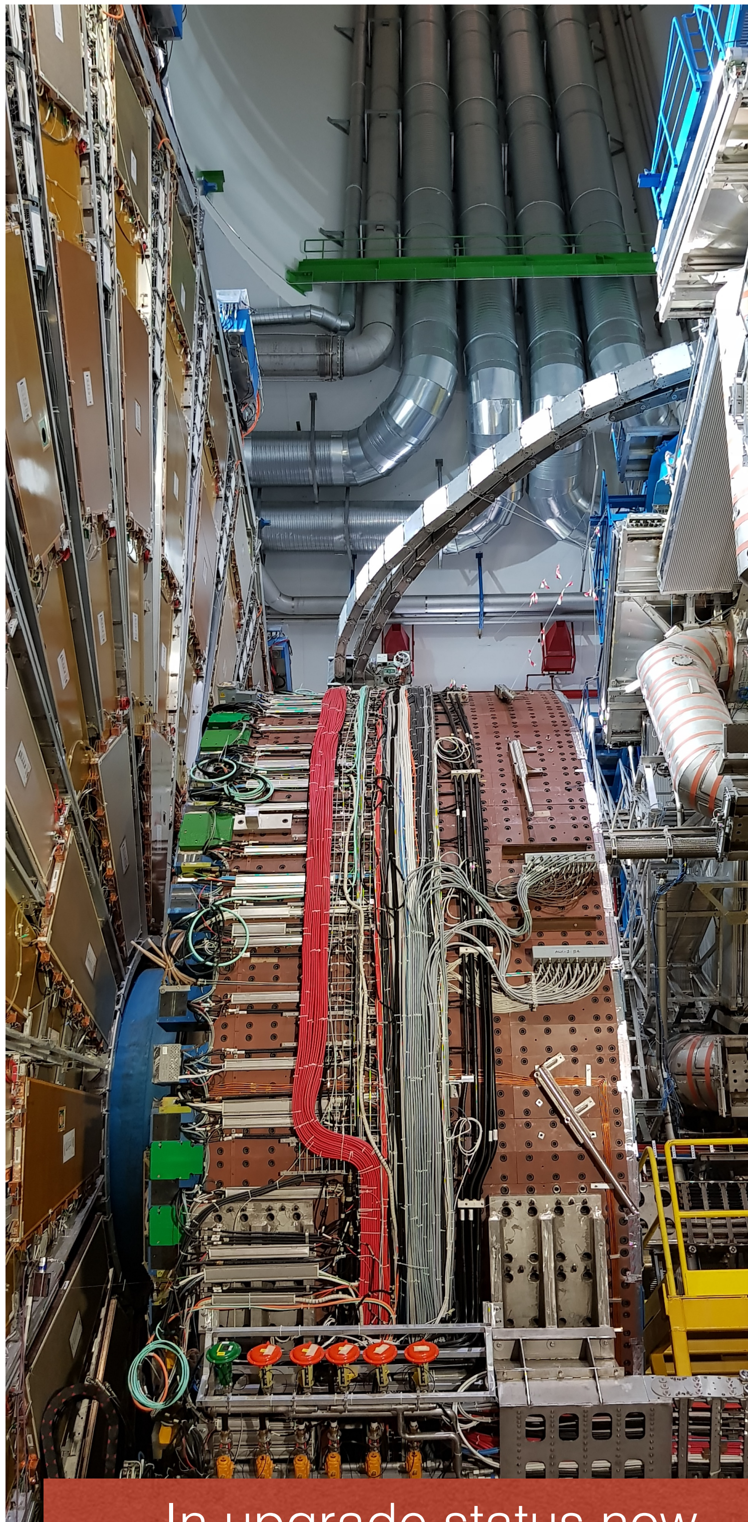

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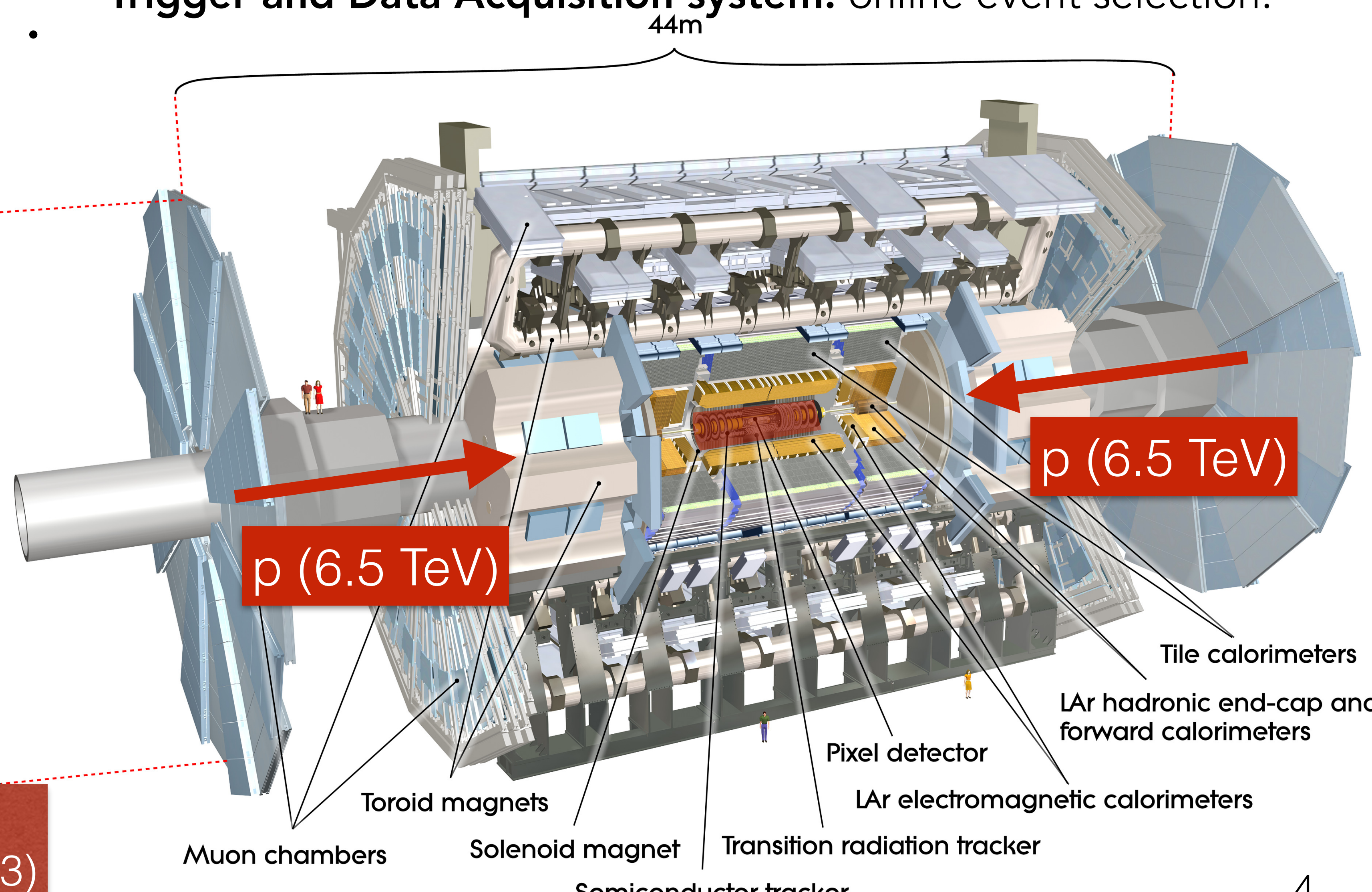

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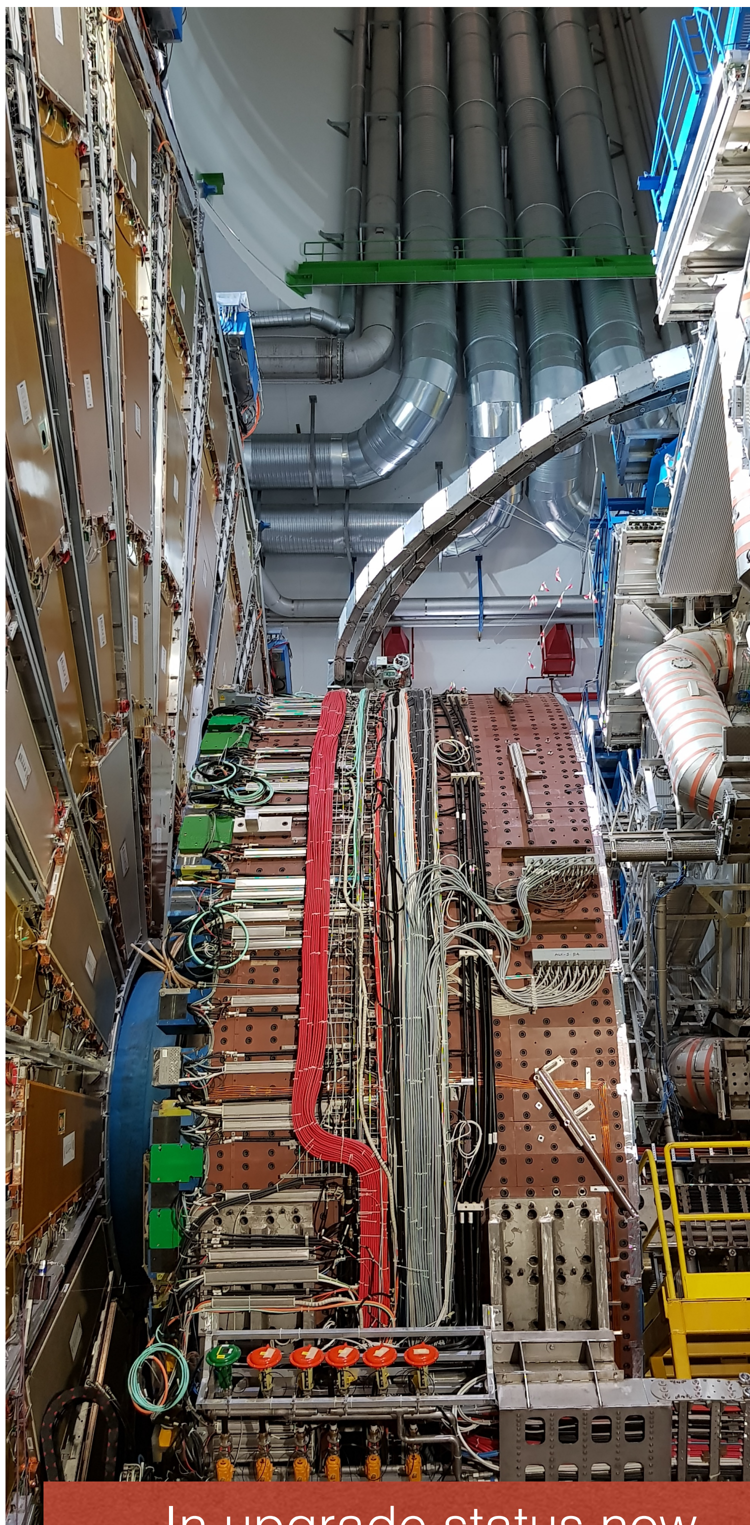

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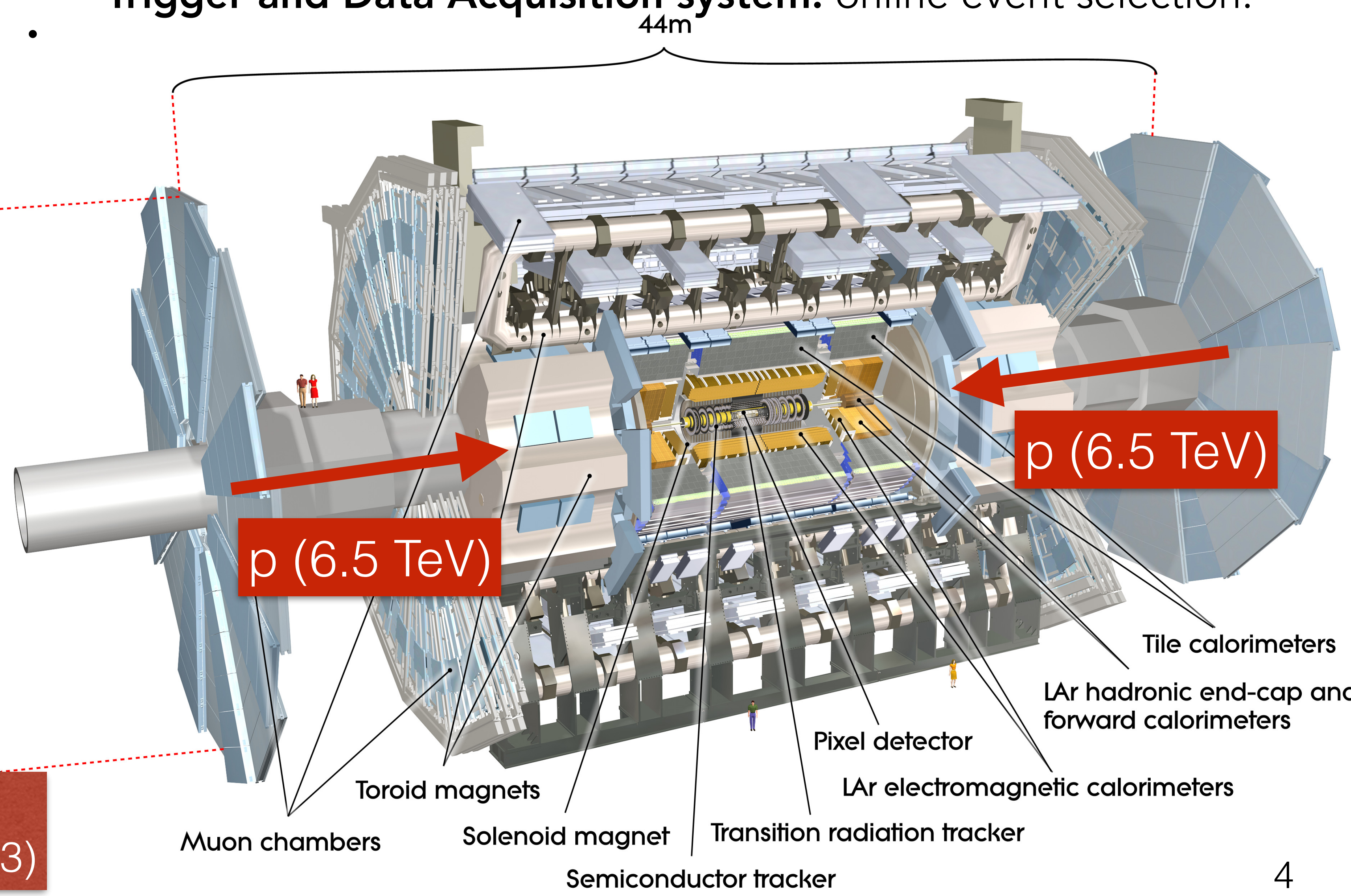

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The ATLAS experiment

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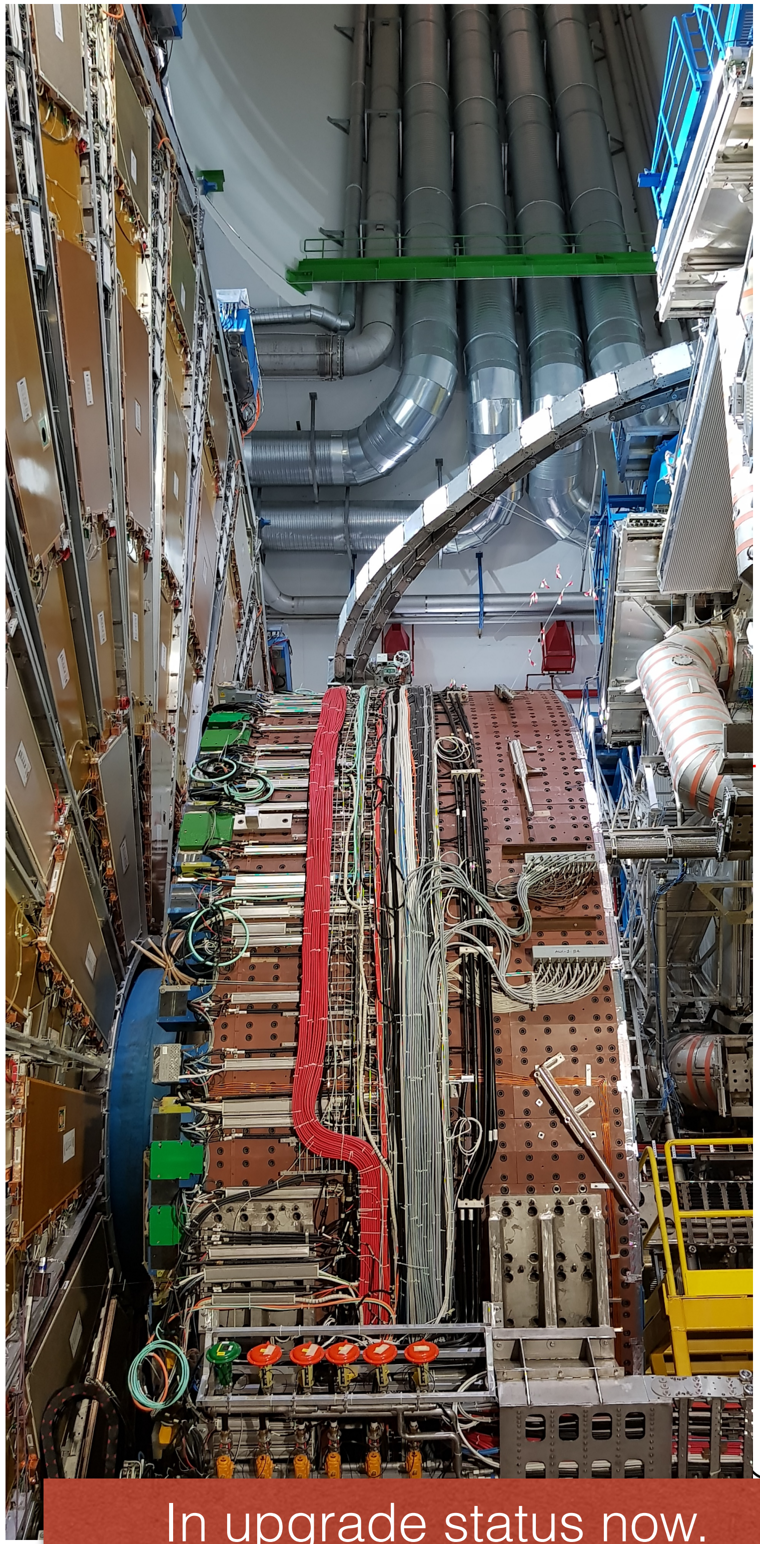

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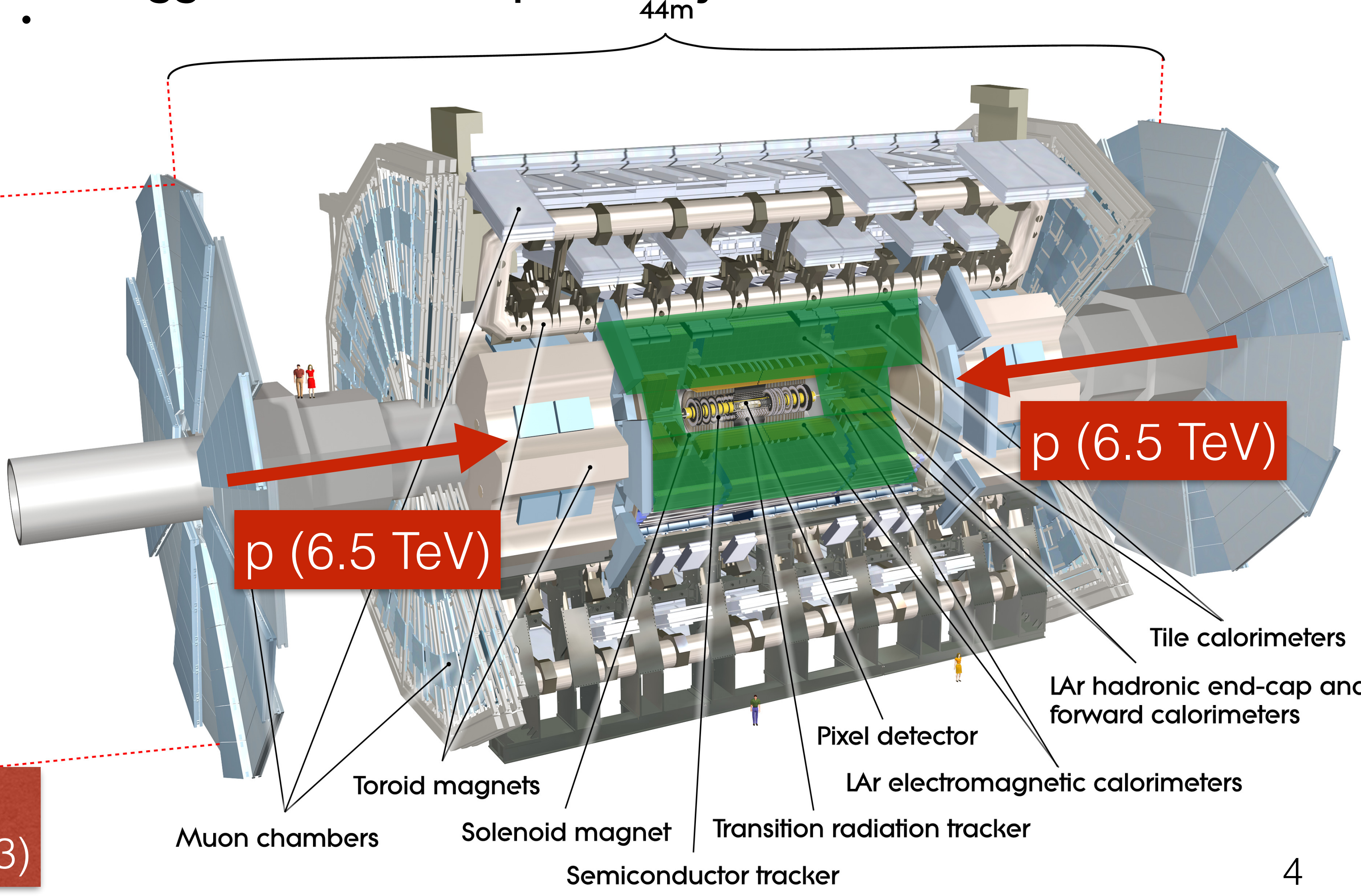

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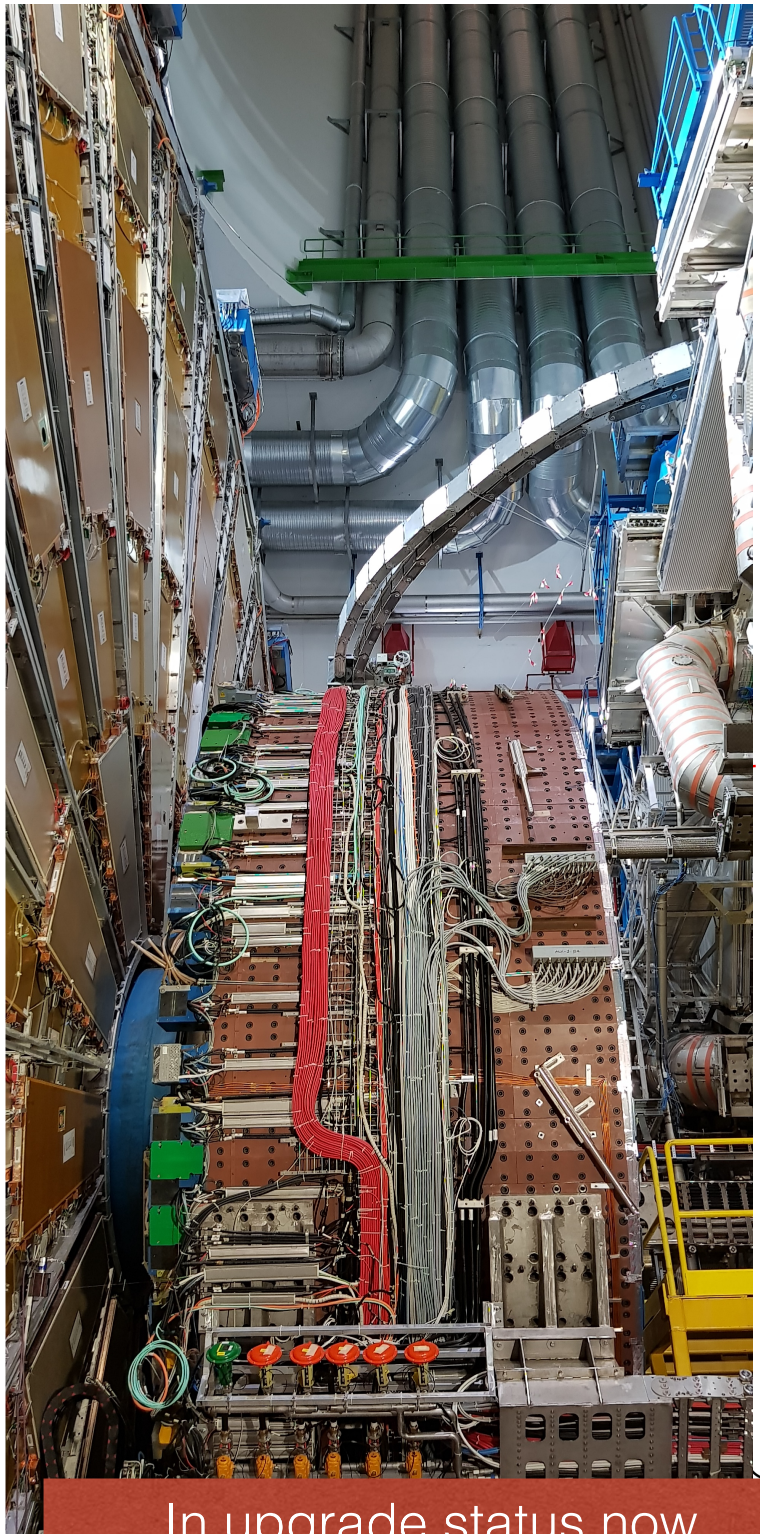

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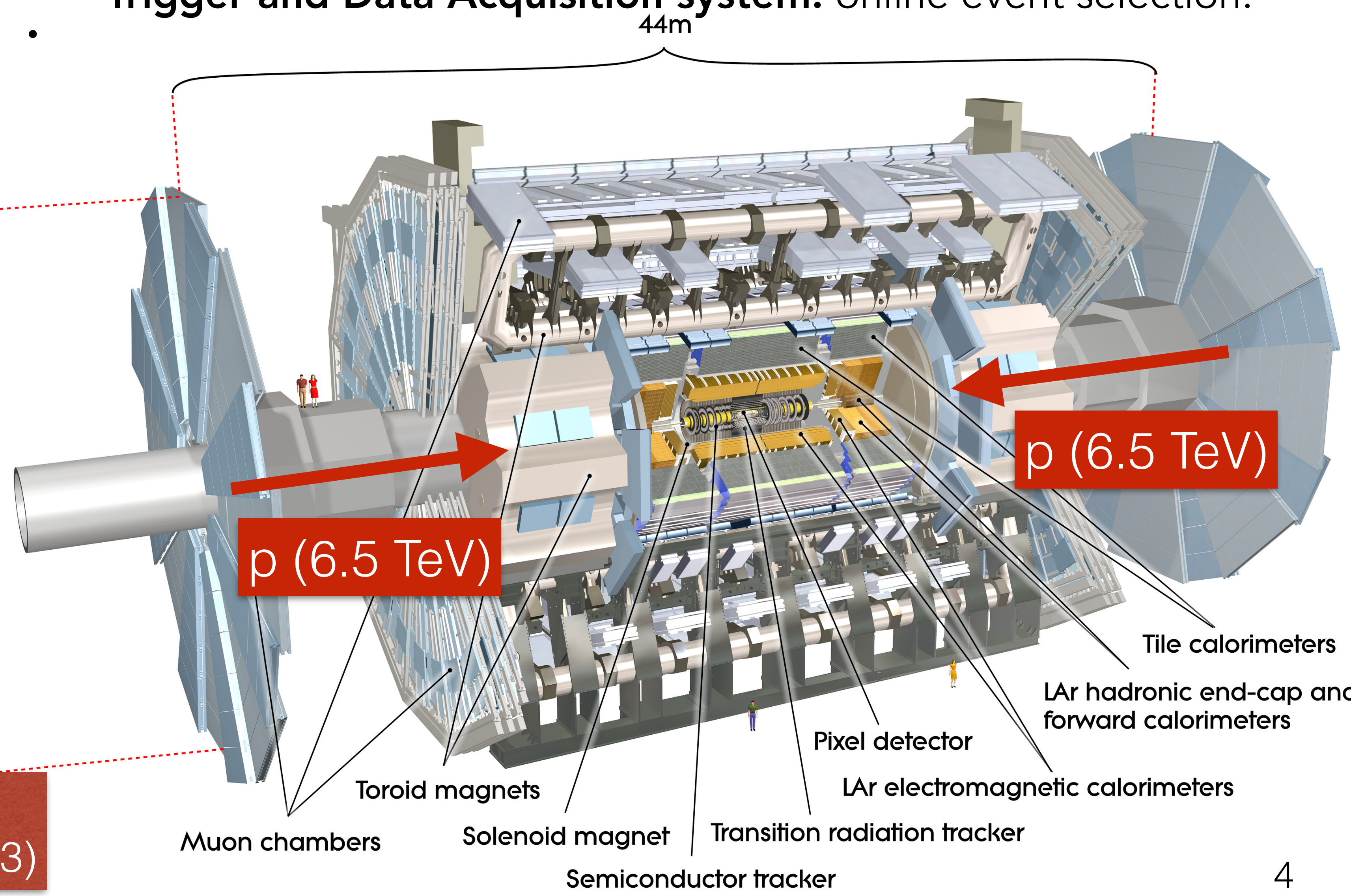

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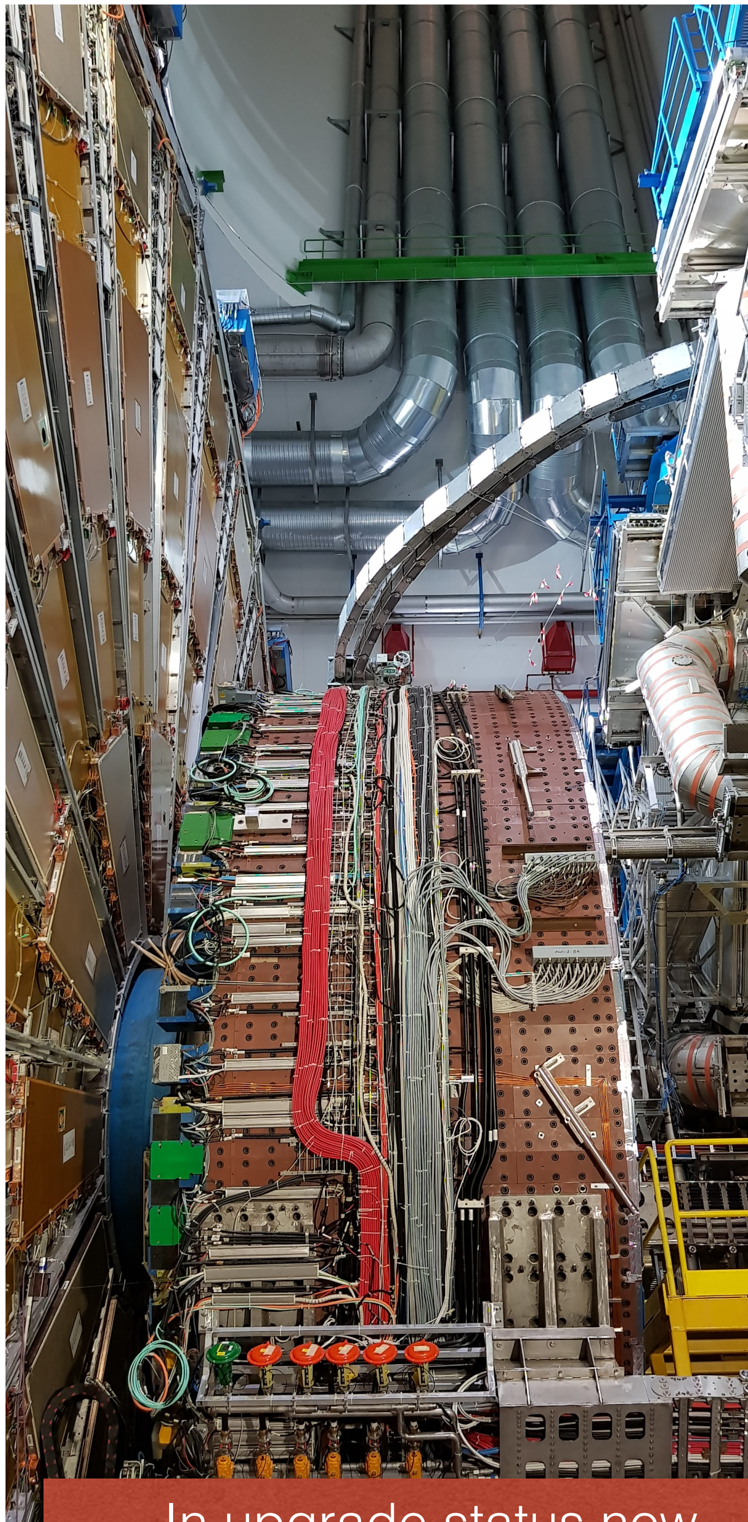

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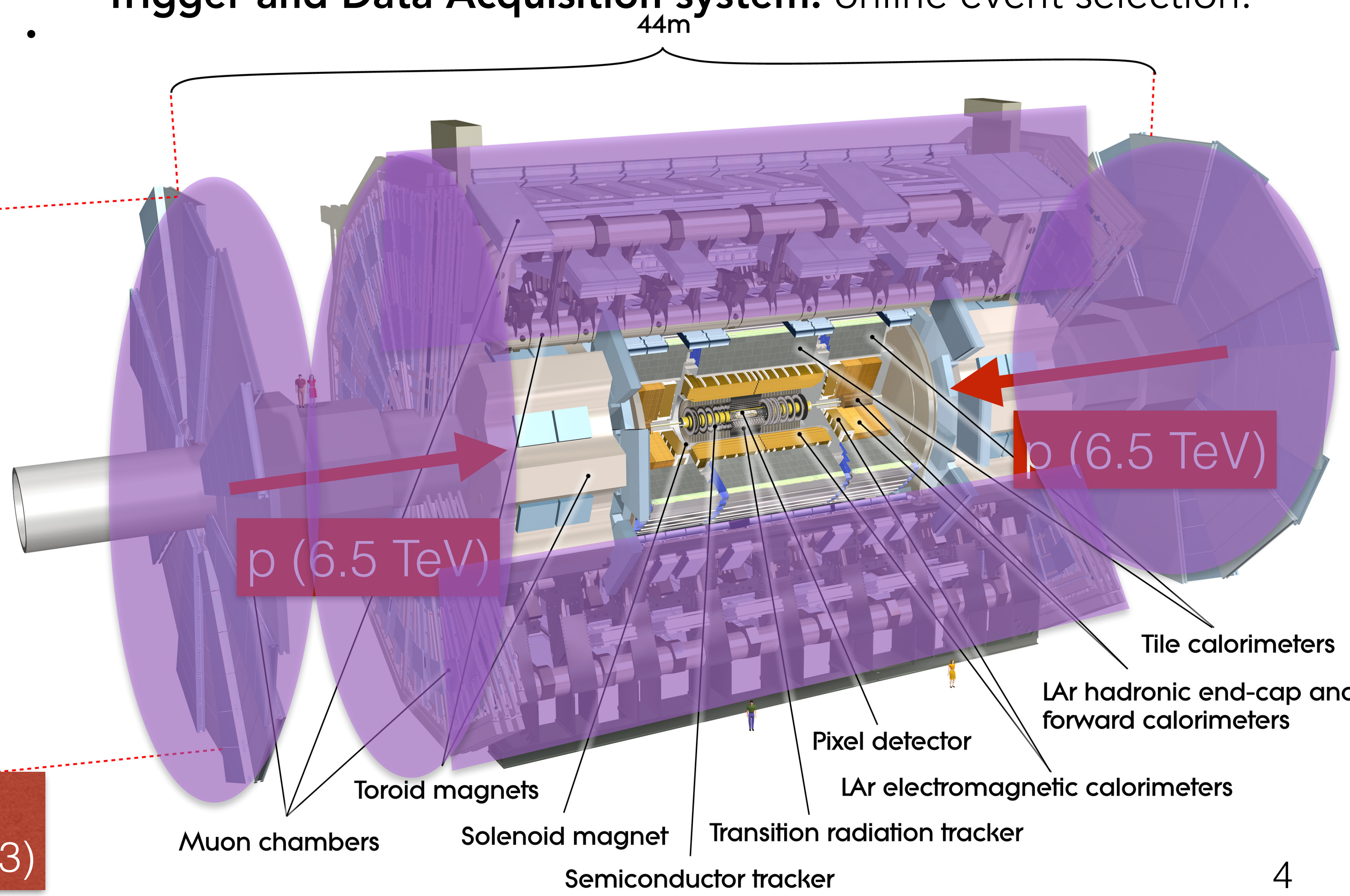

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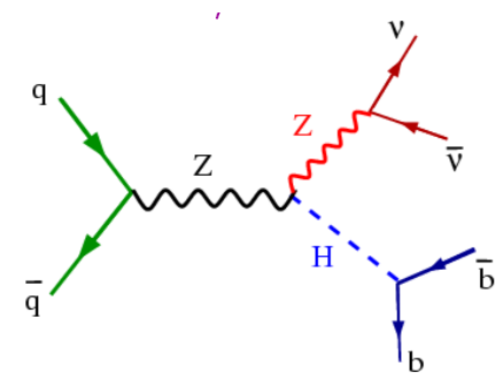
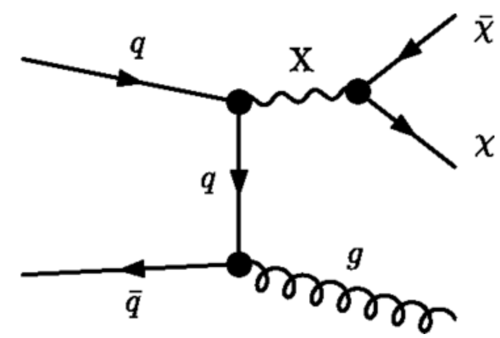
Why hadronic reconstruction?

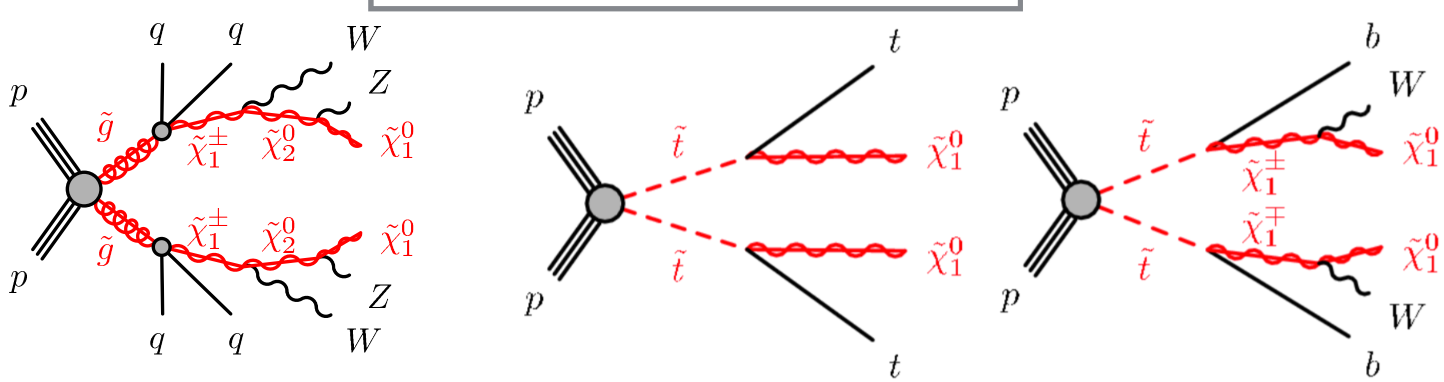
Higgs



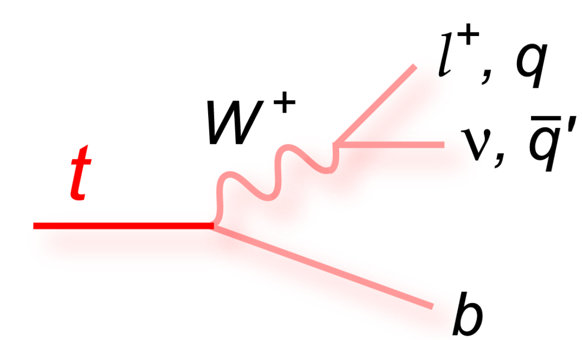
Dark Matter



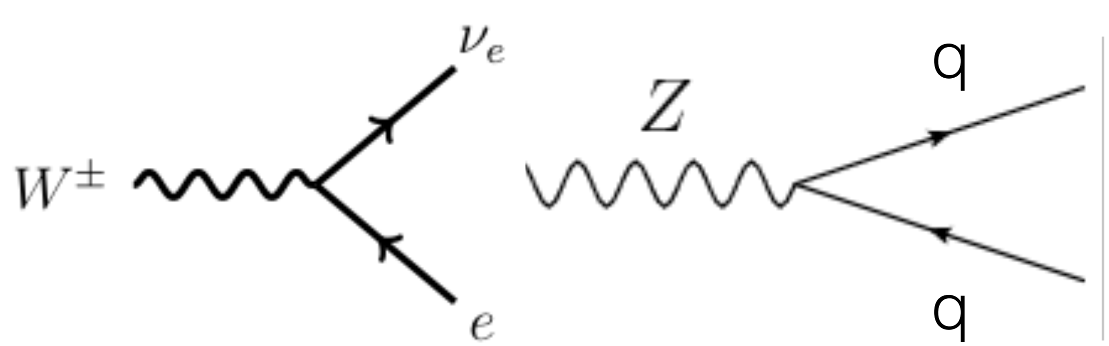
Supersymmetry



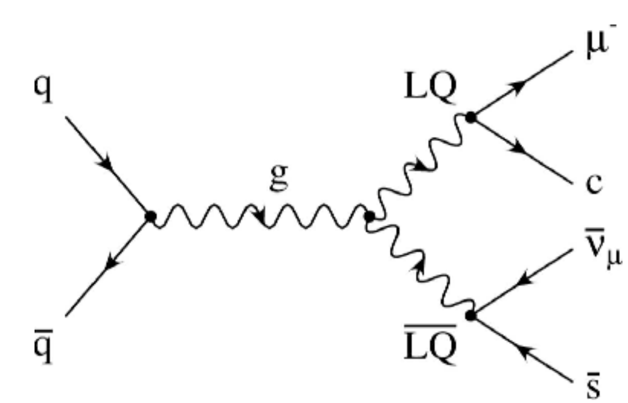
Top physics



Standard Model



Exotics



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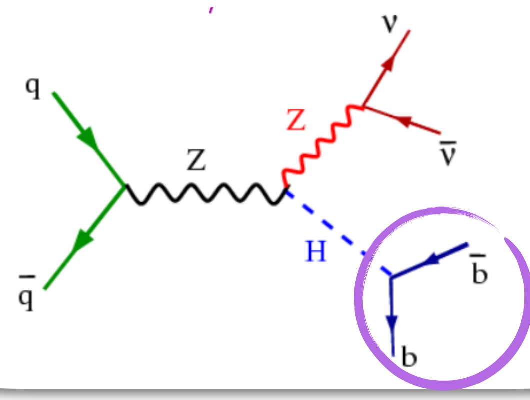
Why hadronic reconstruction?

Strongly interacting particles

Higgs



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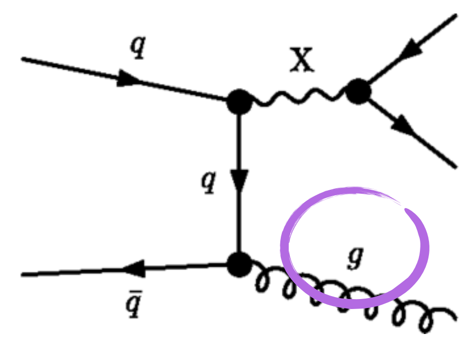
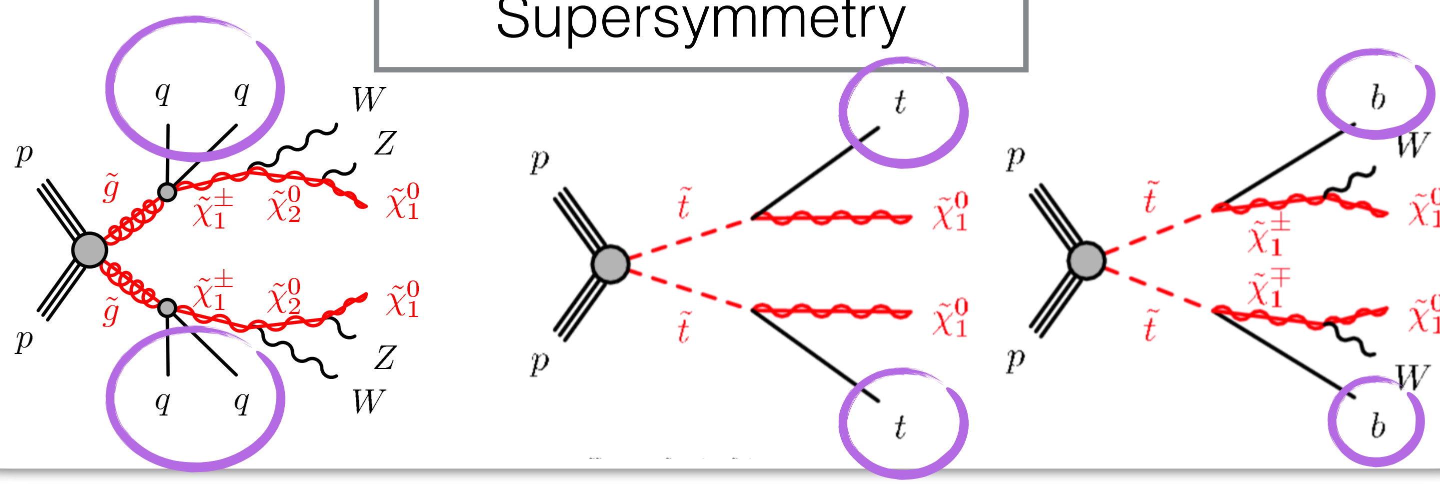


Supersymmetry



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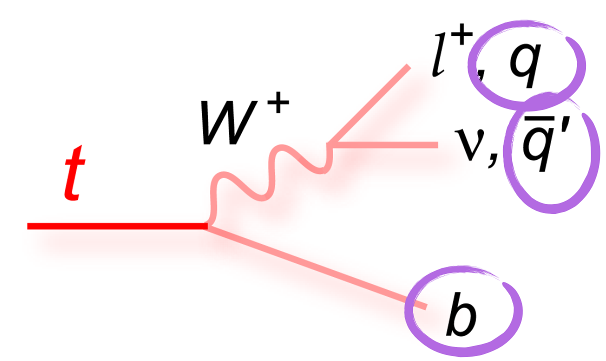

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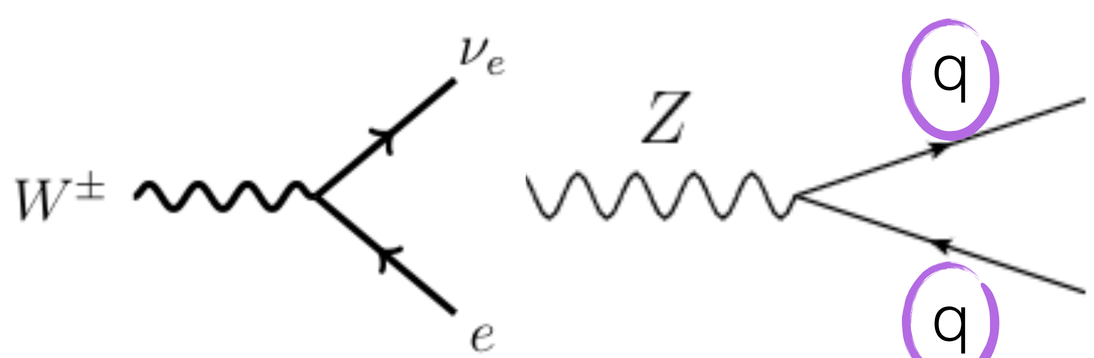

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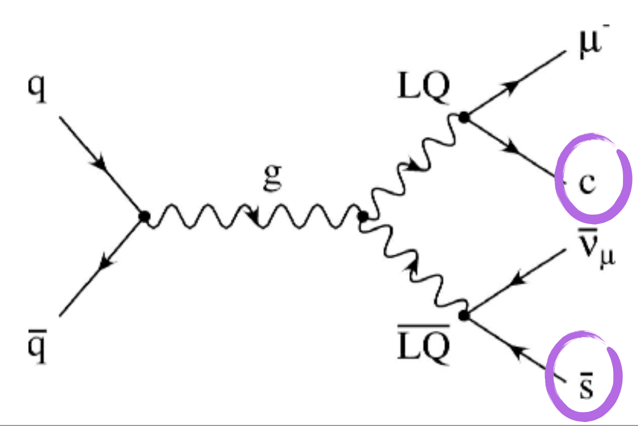
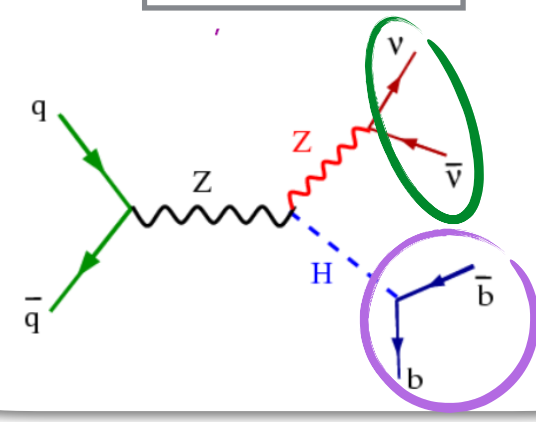


Why hadronic reconstruction?

Strongly interacting particles

Non-interacting particles

Higgs



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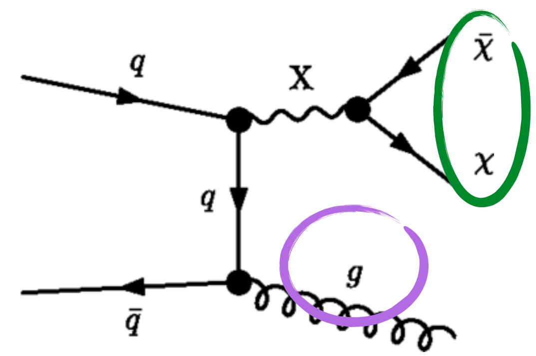
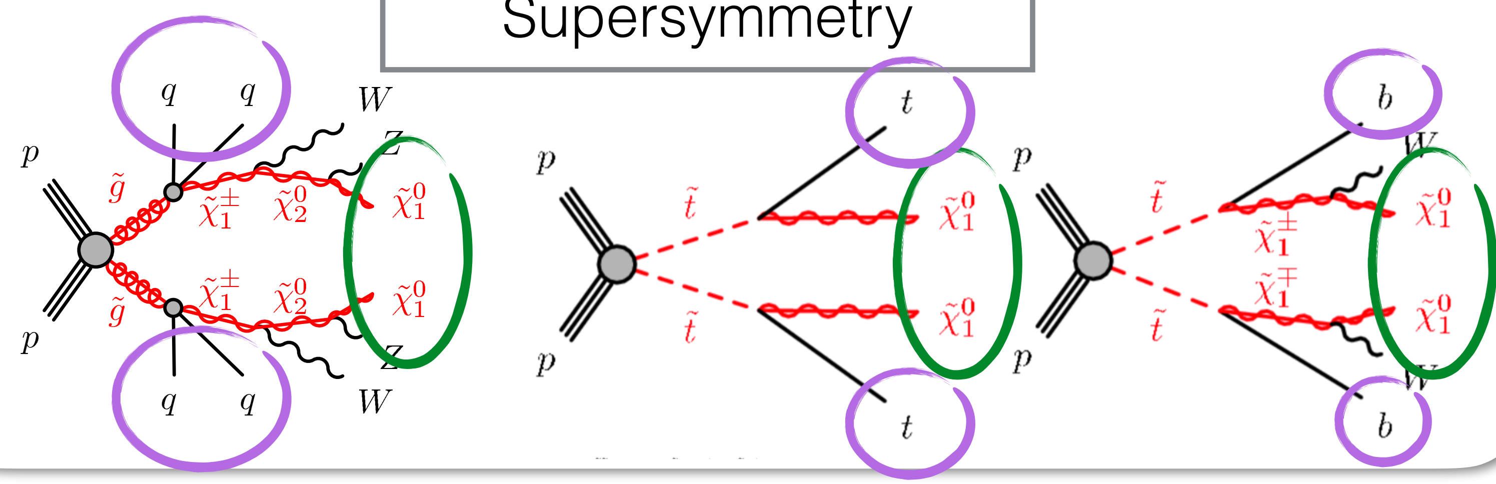


Supersymmetry



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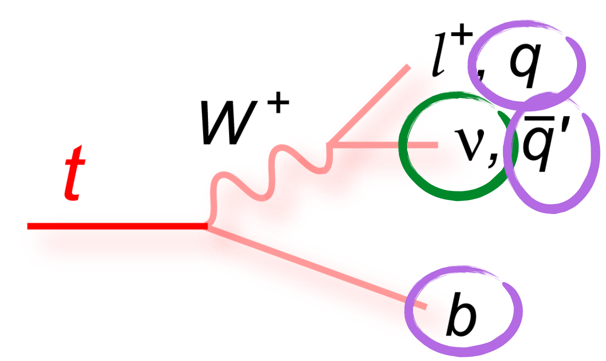

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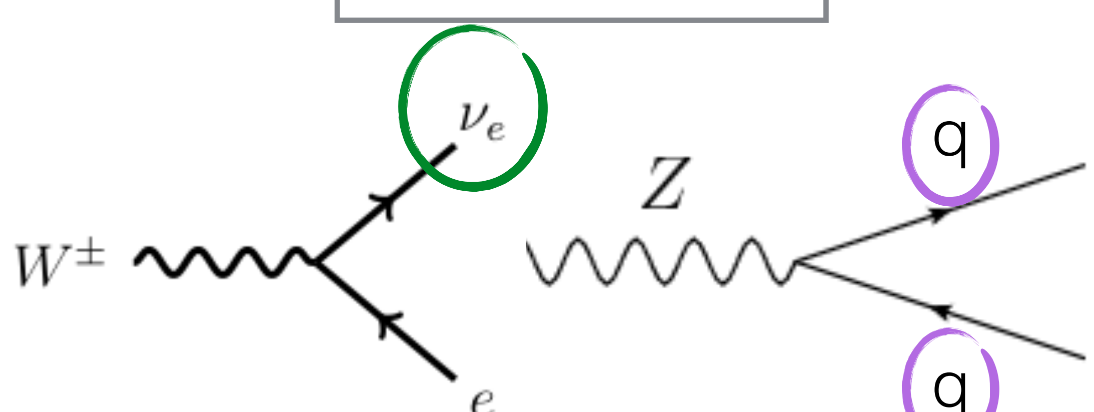

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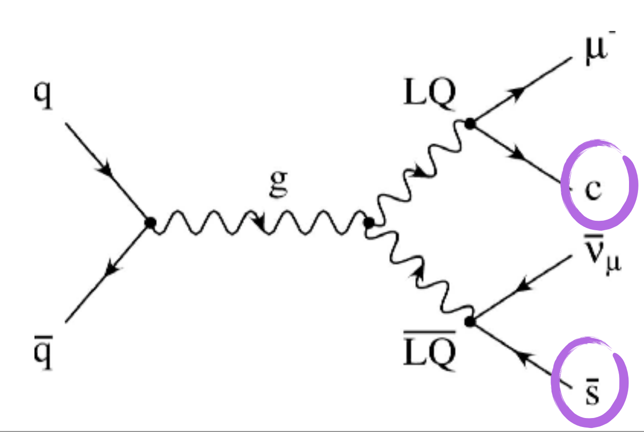

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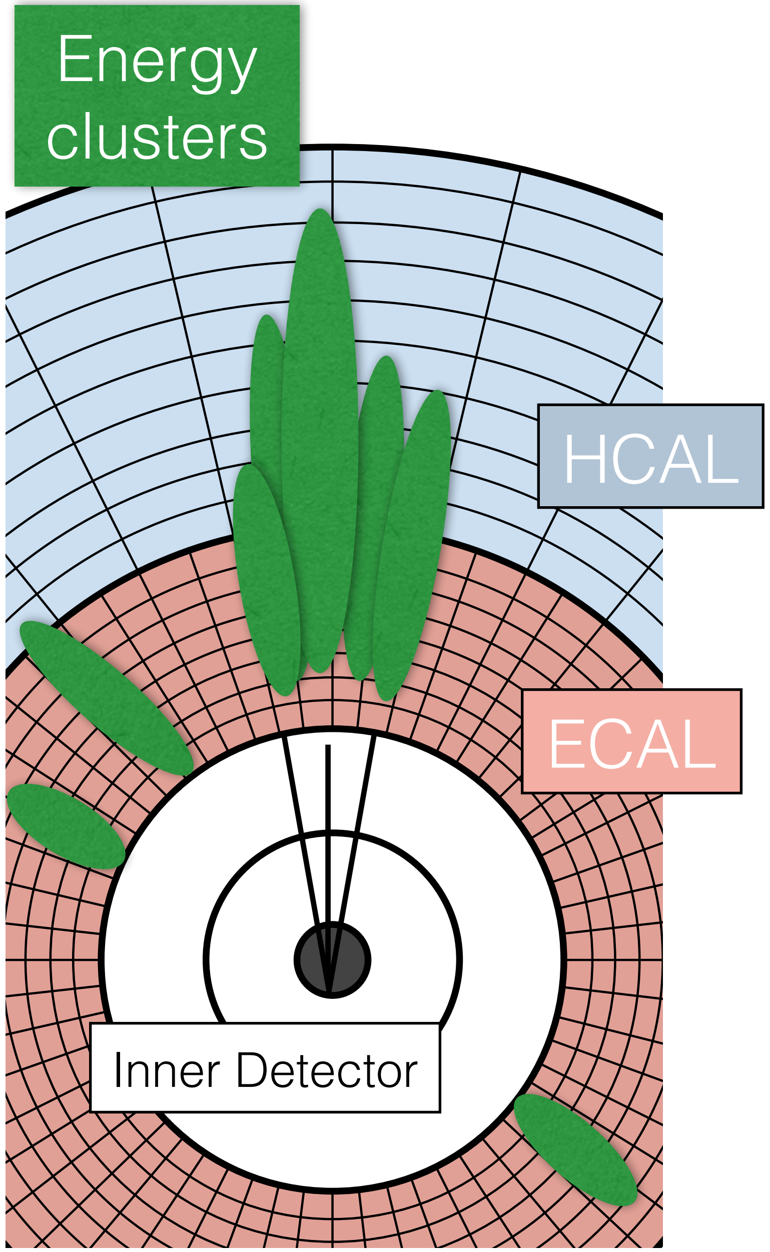
Jets and ATLAS jet reconstruction

- Jets: main observable for quarks and gluons.
- ATLAS jet finding algorithm:
  1. **Clustering** of local energy deposits in the calorimeter (a.k.a. topoclusters).
  2. Run **jet finding** on clusters with recombination algorithm (anti-kt).
  3. **Calibrations** to account for dead materials and calorimeter effects.
- **Pure calorimeter jet finding approach!**



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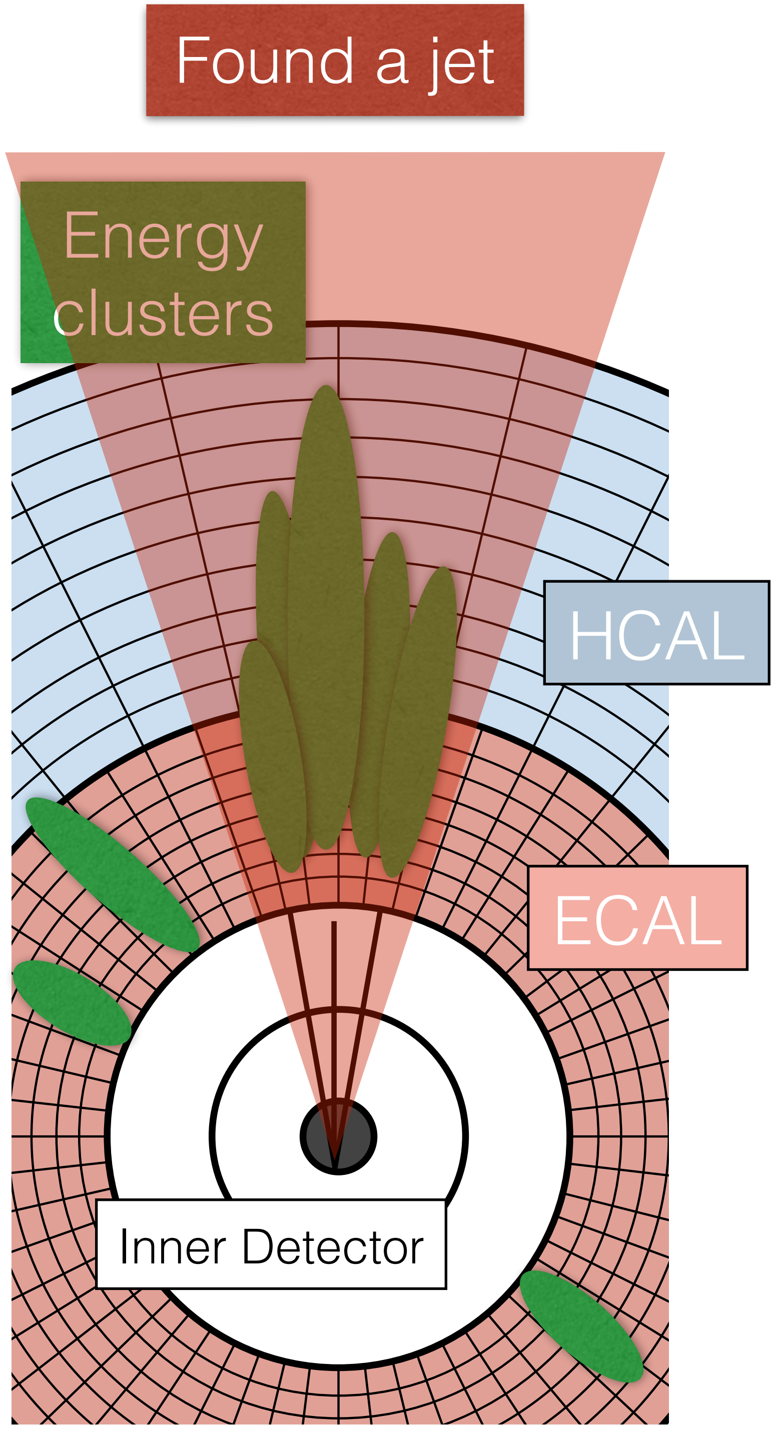
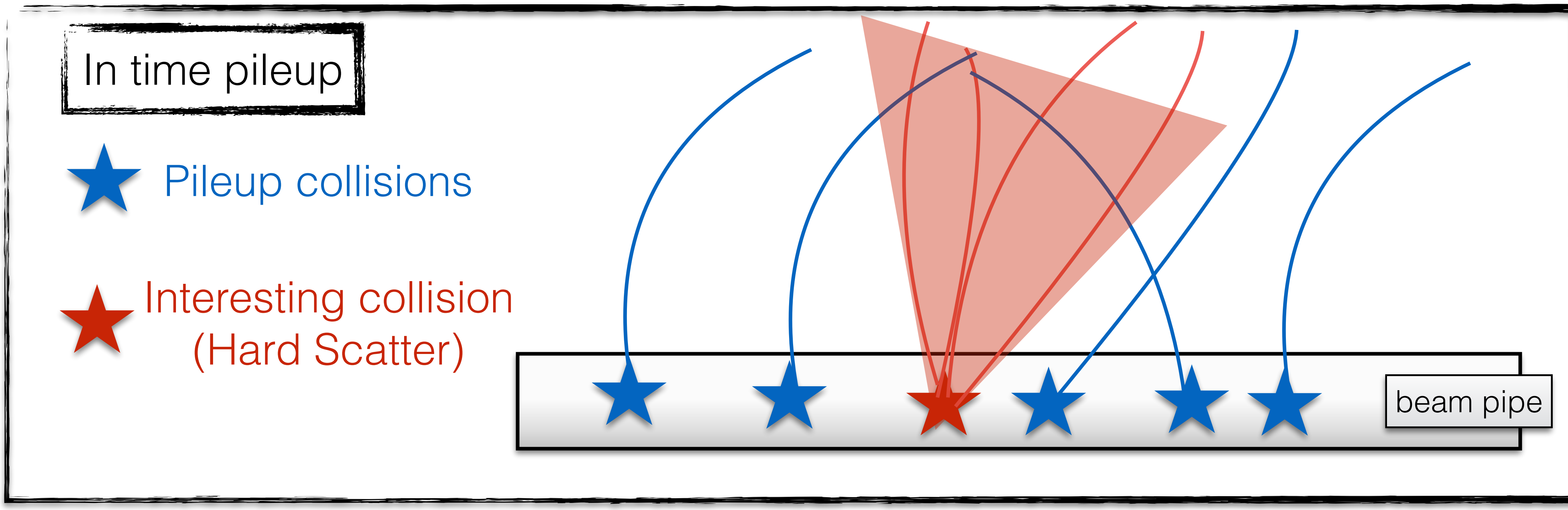
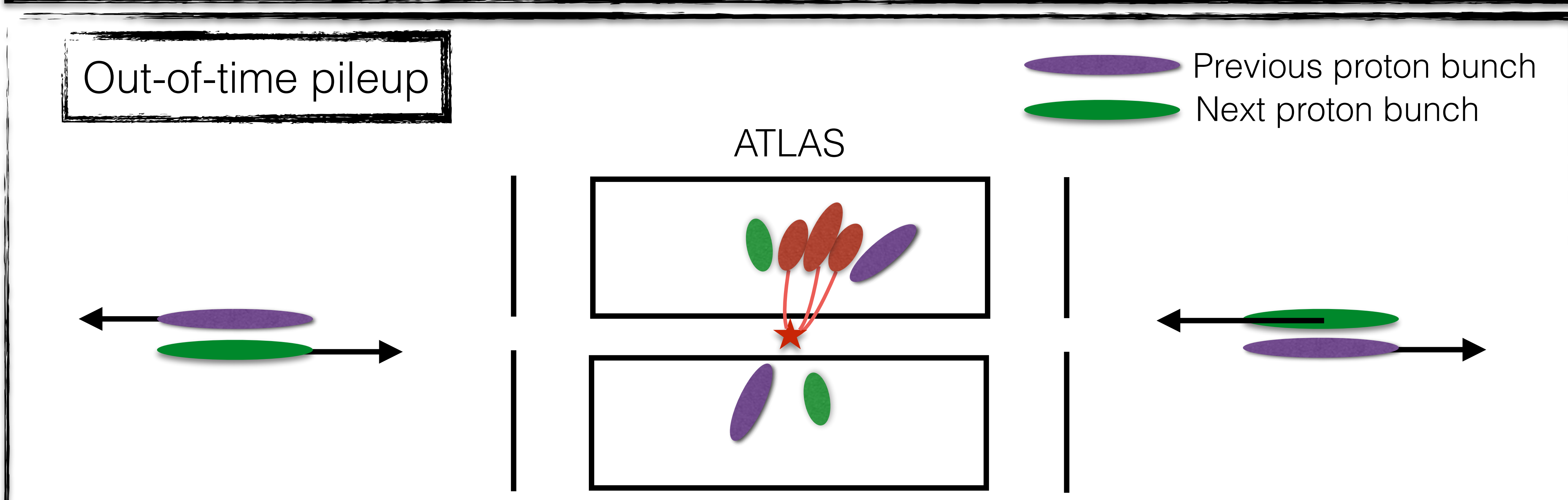


The “issue” of pileup (1)

Pileup jets and identification

Pileup is necessary for increasing data rates at ATLAS.
However, this comes with a cost…





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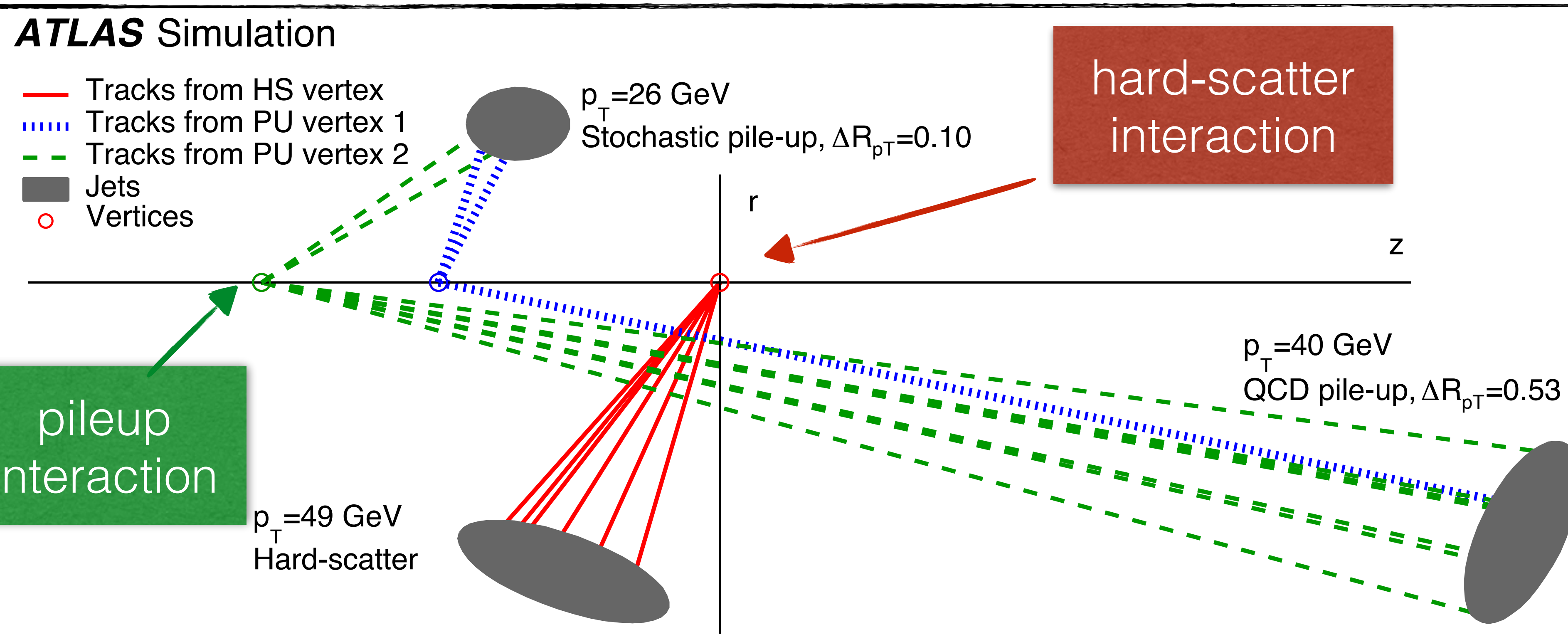
The "issue" of pileup (2)

Pileup jets and identification



Need to remove pileup jets for signal identification!

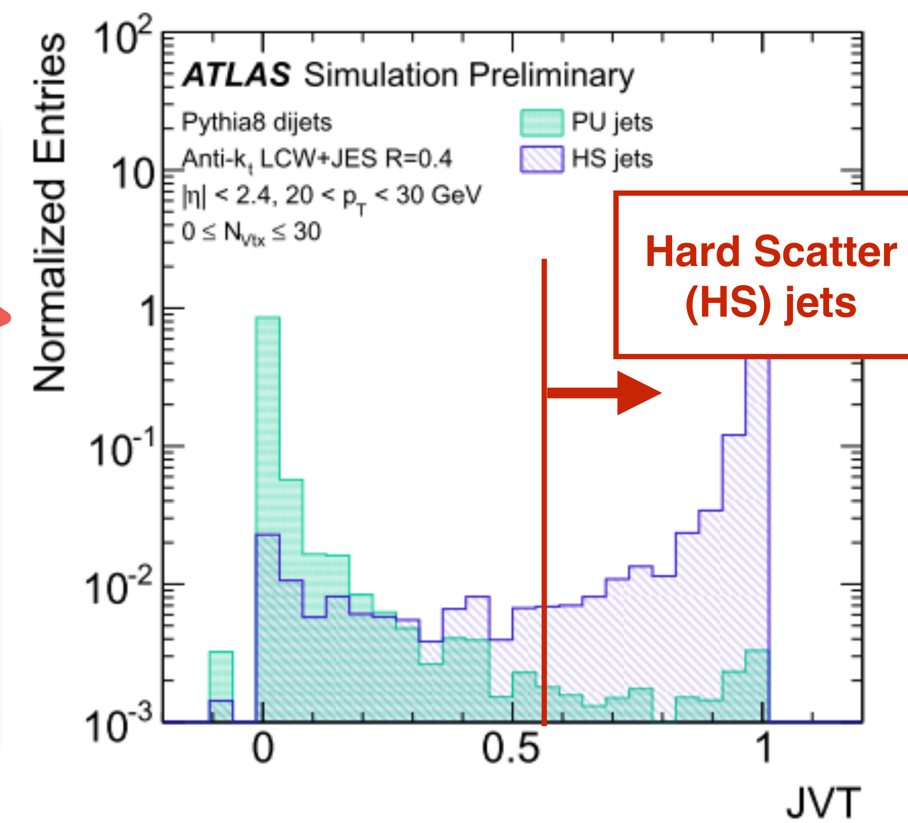
How can we suppress pileup jets?

With tracking information used after jet building! kNN

Two variables (based on tracking information):

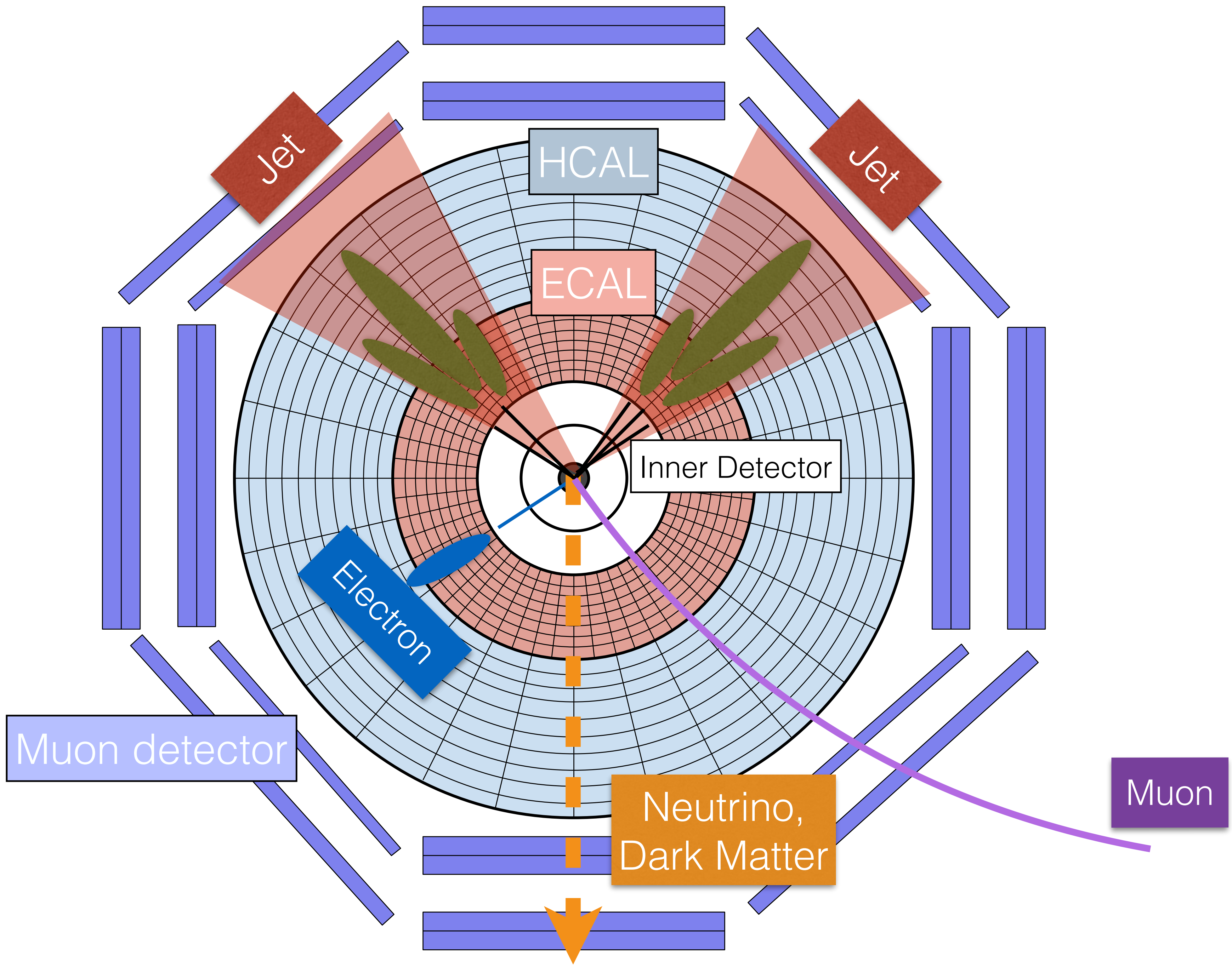
$$R_{pT} = \frac{\sum_k p_T^{trk_k}(PV_0)}{p_T^{jet}}$$

$$\mathrm{corrJVF} = \frac{\sum_k p_T^{trk_k}(PV_0)}{\sum_l p_T^{trk_l}(PV_0) + \frac{\sum_{n\geq 1}\sum_l p_T^{trk_l}(PV_n)}{(k \cdot n_{trk}^{PU})}}$$



And the invisible particles? How do we see them?

How to see invisible particles?



Conservation of transverse momentum!

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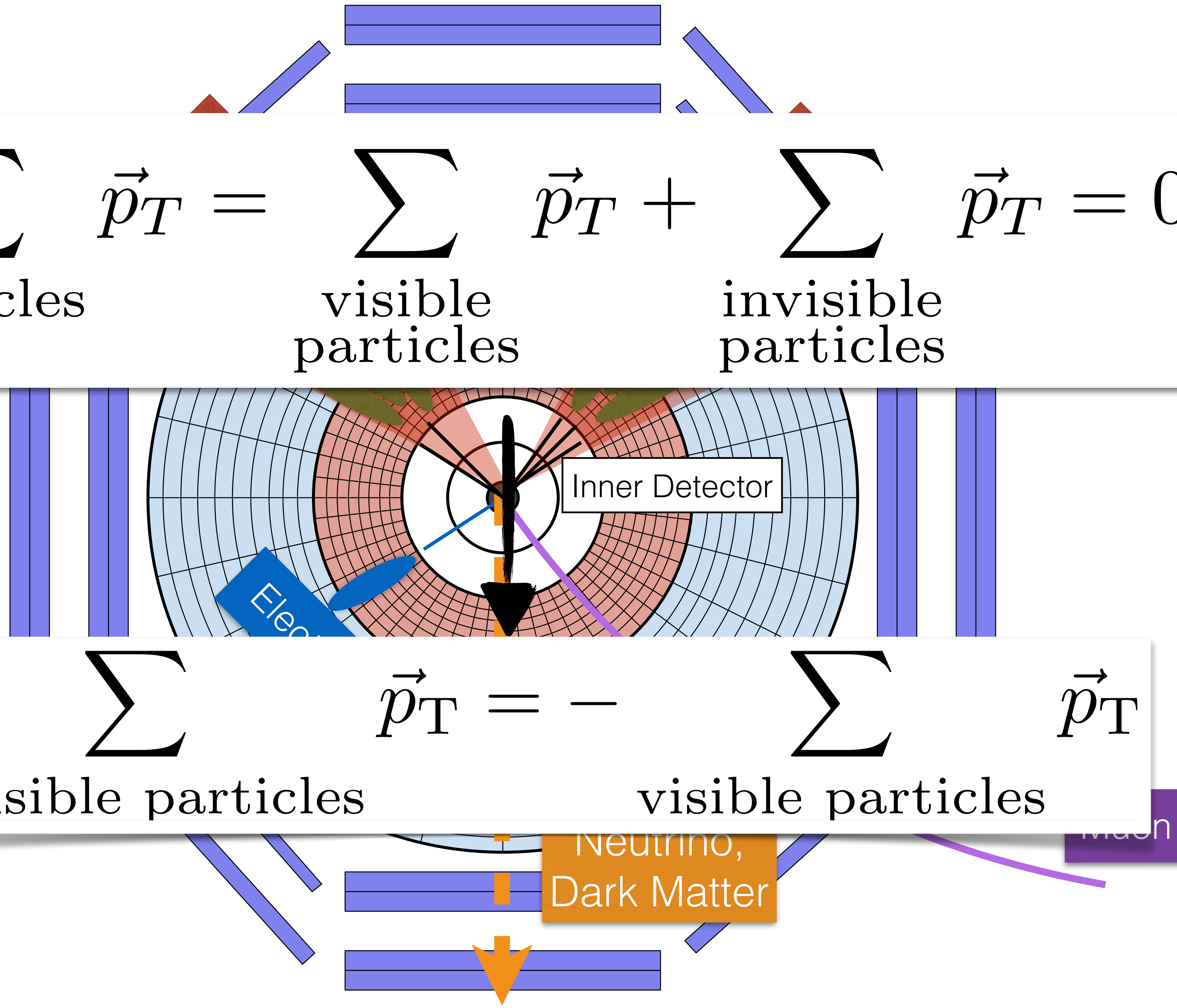
How to see invisible particles?



$$\sum_{\text{particles}} \vec{p}_T = \sum_{\substack{\text{visible}\\ \text{particles}}} \vec{p}_T + \sum_{\substack{\text{invisible}\\ \text{particles}}} \vec{p}_T = 0$$

$$\sum_{\text{invisible particles}} \vec{p}_{\mathrm{T}} = - \sum_{\text{visible particles}} \vec{p}_{\mathrm{T}}$$

Conservation of transverse momentum!

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Missing Transverse Momentum (MET)

Observing the invisible

$$E_{\mathrm{T}}^{\mathrm{miss}} = -\Bigg(\underbrace{\sum_{i\,\in \mathrm{muons}} \boldsymbol{p}_{\mathrm{T},i} + \sum_{i\,\in \mathrm{electrons}} \boldsymbol{p}_{\mathrm{T},i} + \sum_{i\,\in \mathrm{photons}} \boldsymbol{p}_{\mathrm{T},i} + \sum_{i\,\in \mathrm{hadronic}\ \tau} \boldsymbol{p}_{\mathrm{T},i} + \sum_{i\,\in \mathrm{jets}} \boldsymbol{p}_{\mathrm{T},i}}_{\text{hard term}} + \underbrace{\sum_{i\,\in \mathrm{Soft\ Term}} \boldsymbol{p}_{\mathrm{T},i}}_{\text{soft term}}\Bigg)$$

- **Hard term:** all well identified and calibrated physics objects.
- **Soft term:** all particles not associated to the hard term.

The soft term is important because it ideally balances the hard term.

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Soft term reconstruction

TST and CST

How to reconstruct the soft term?

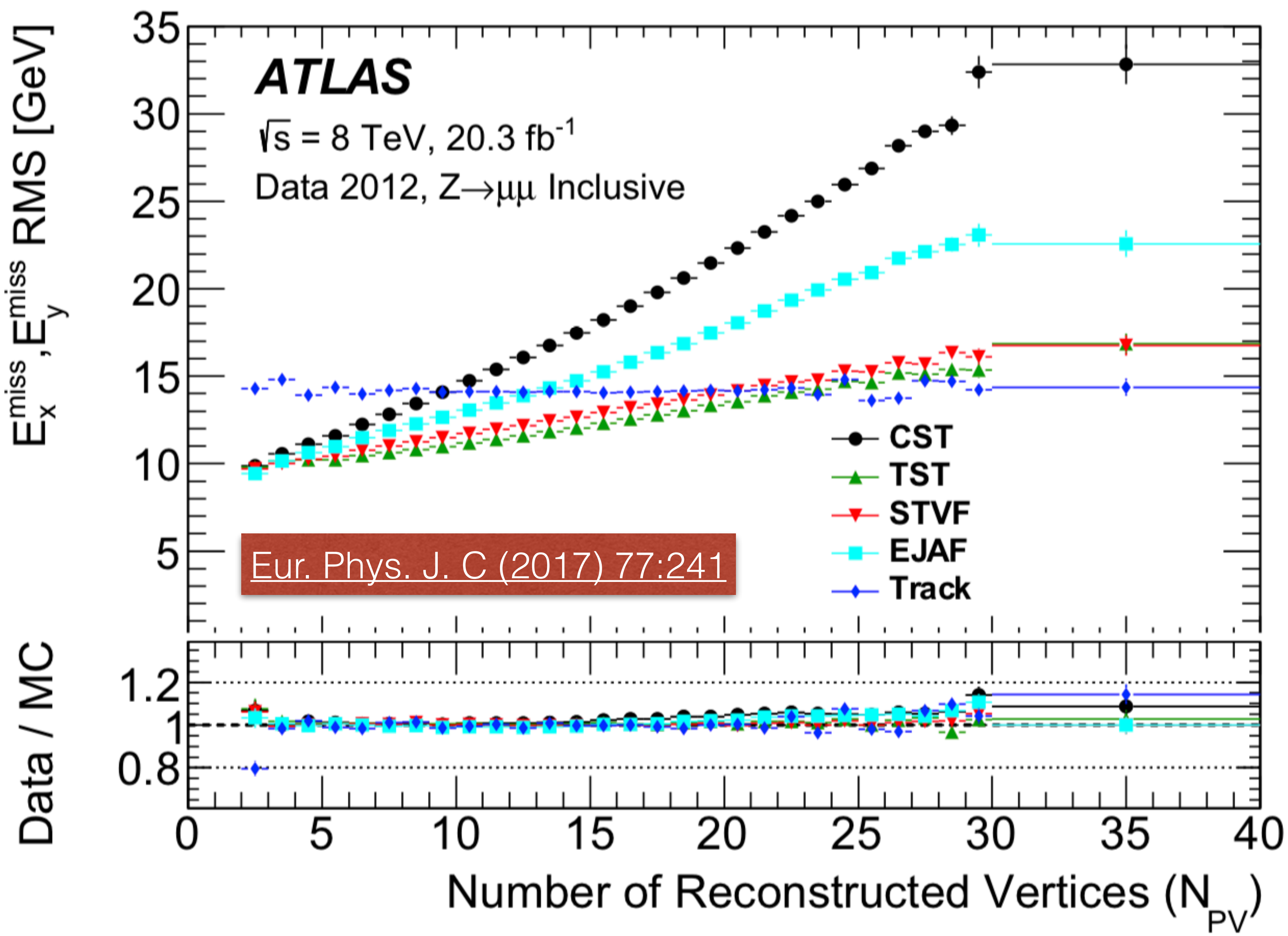
- Historically, two ways of reconstructing the MET soft term:
  - **Calorimeter-based Soft Term (CST):** all calorimeter clusters not associated to any hard object
  - **Track-based Soft Term (TST)**: all tracks not associated to any hard object

Calorimeter based Soft Term (CST)	Track based Soft Term (TST)
1. **Large** dependence by pile-up. 2. Natural inclusion of the neutral soft term component.	1. **Small** dependence by pile-up. 2. Missing neutral particles.

What is better? CST or TST?

How to reconstruct invisible particles?

Track-based Soft Term performs way better than CST!



Eur. Phys. J. C (2017) 77:241

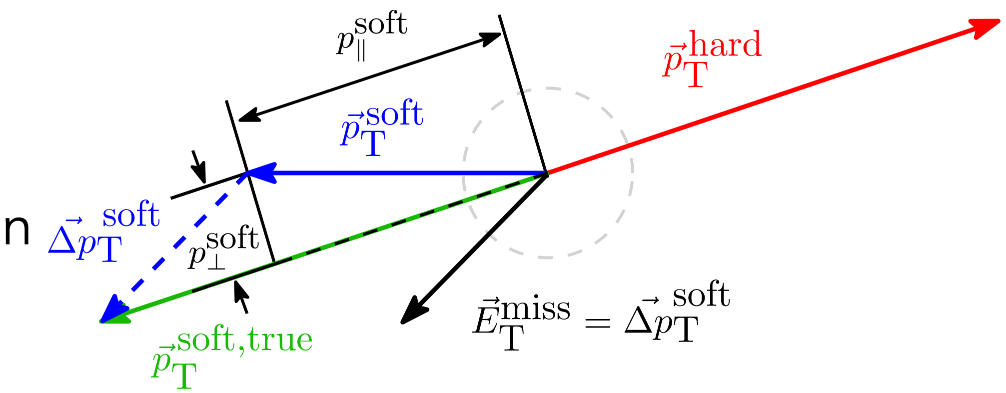
TST is what ATLAS analyses use today!

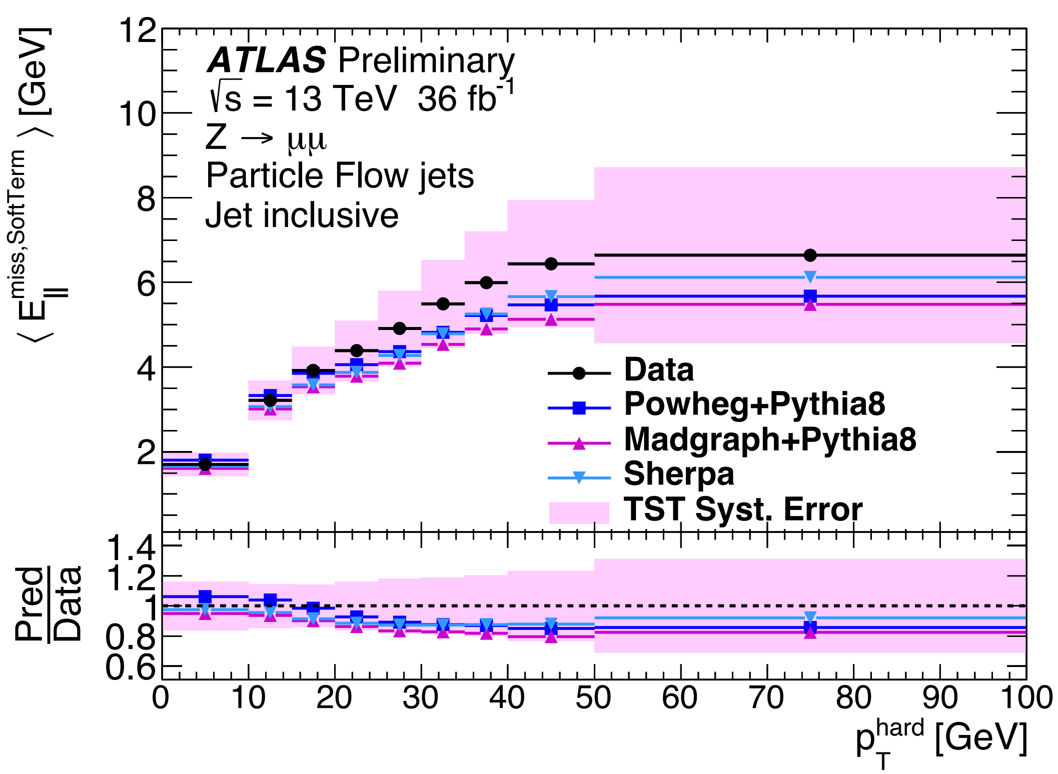
TST systematics uncertainties

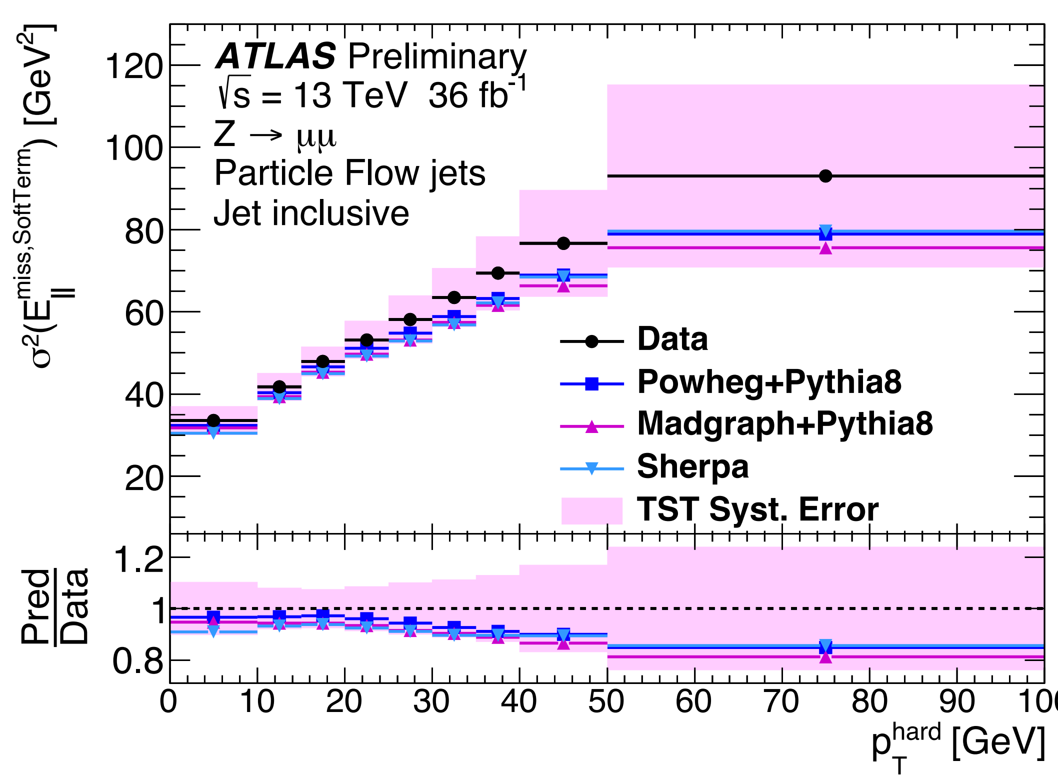
TST systematic uncertainties

The systematics uncertainties specifically derived for MET are the **TST systematics**. Computed on three projected quantities:

- Parallel scale: average value of p_T^{soft} projection parallel to p_T^{hard}.
- Parallel resolution: RMS value of p_T^{soft} projection parallel to p_T^{hard}.
- Perpendicular resolution: RMS value of p_T^{soft} projection perpendicular to p_T^{hard}.







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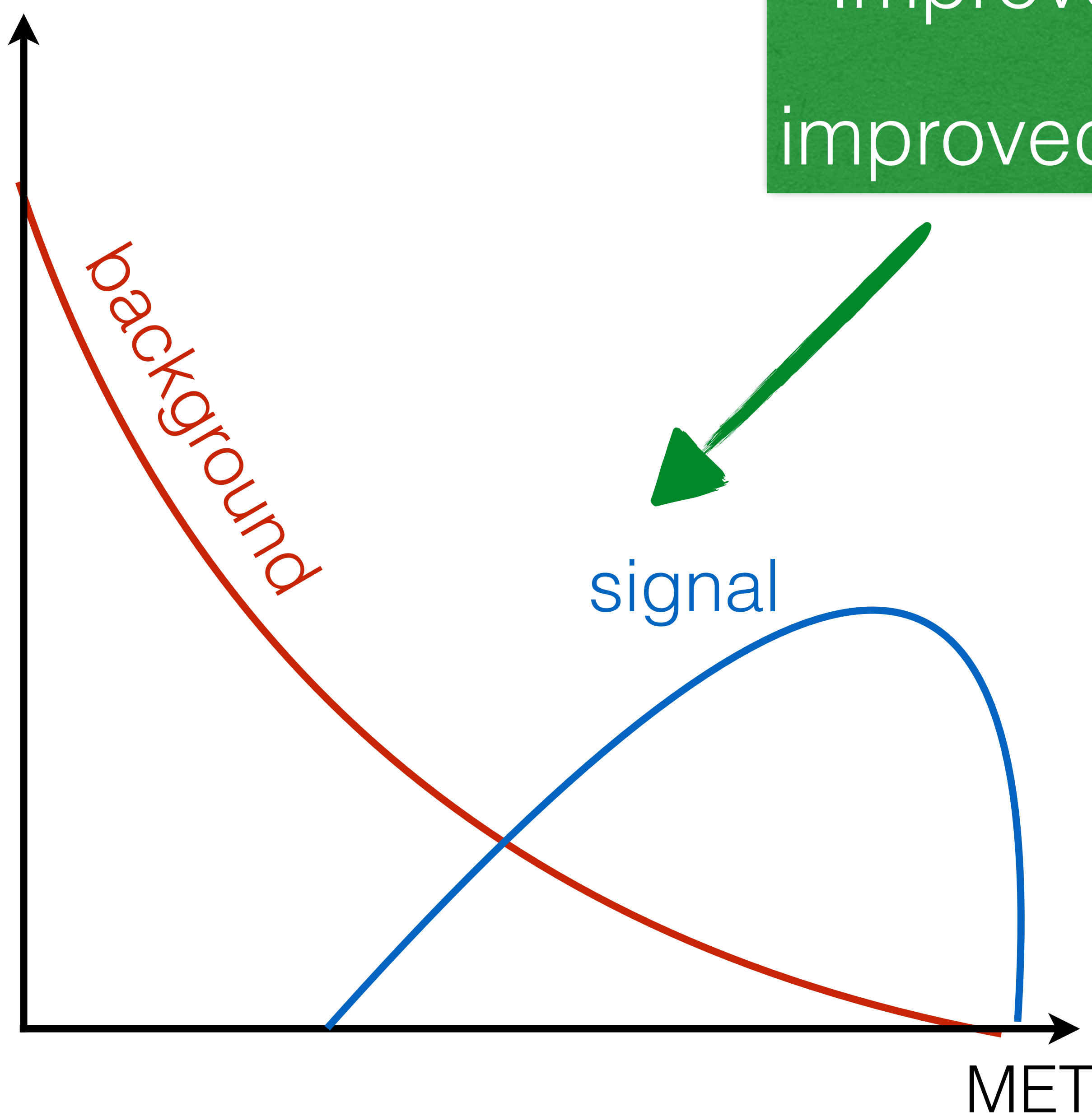
Can we do better?

Improved reconstruction
=
improved signal separation



How can we reconstruct hadronic objects better?

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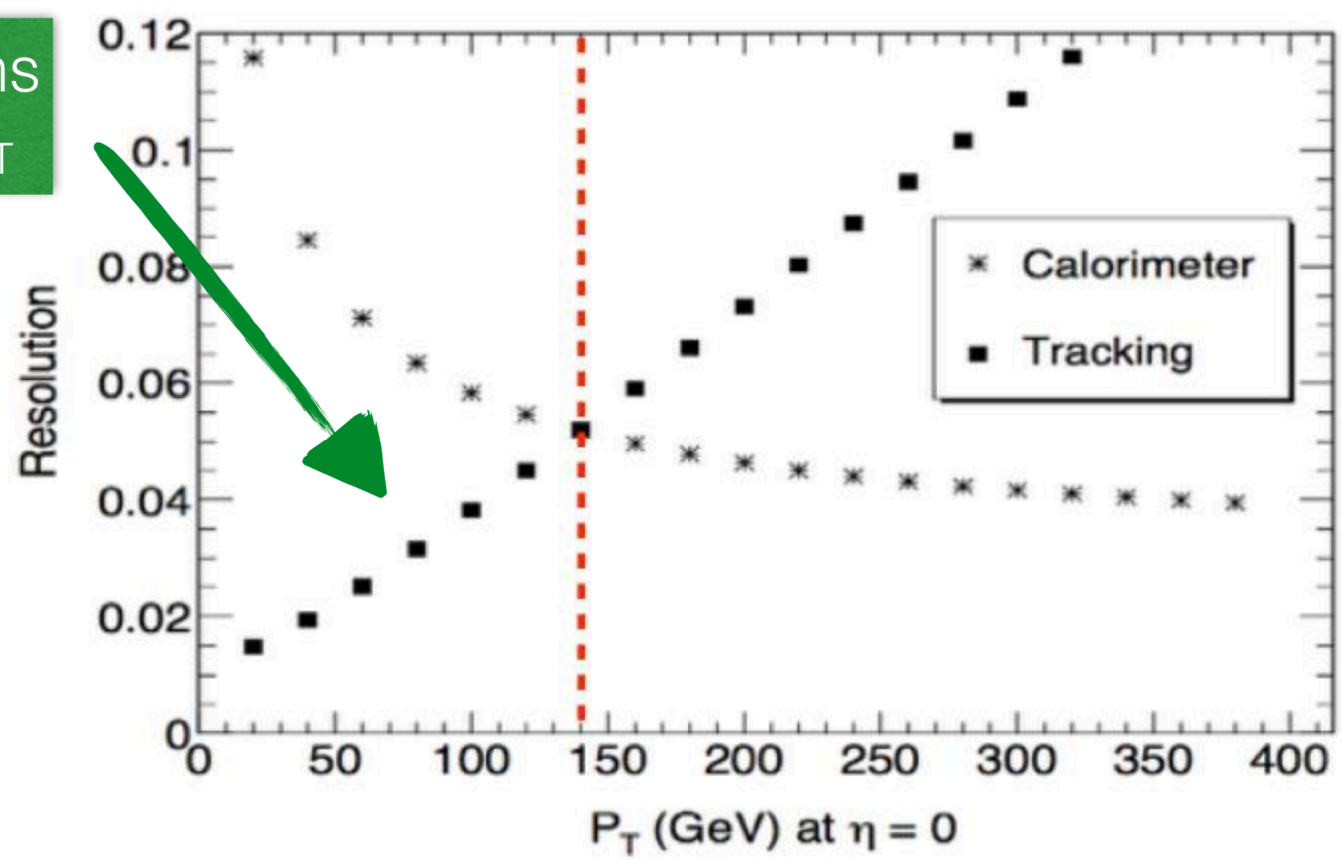
Particle Flow reconstruction (1)

The idea behind Particle Flow

- Idea: **combine the tracker and calorimeter information** before jet building!
- Already employed by different experiments (ALEPH, CMS, etc.)
- Expected improvements:
  1. **Optimal p_T resolution** from combined tracker-calorimeter information.
  2. **Removal of charged pileup before jet building.**

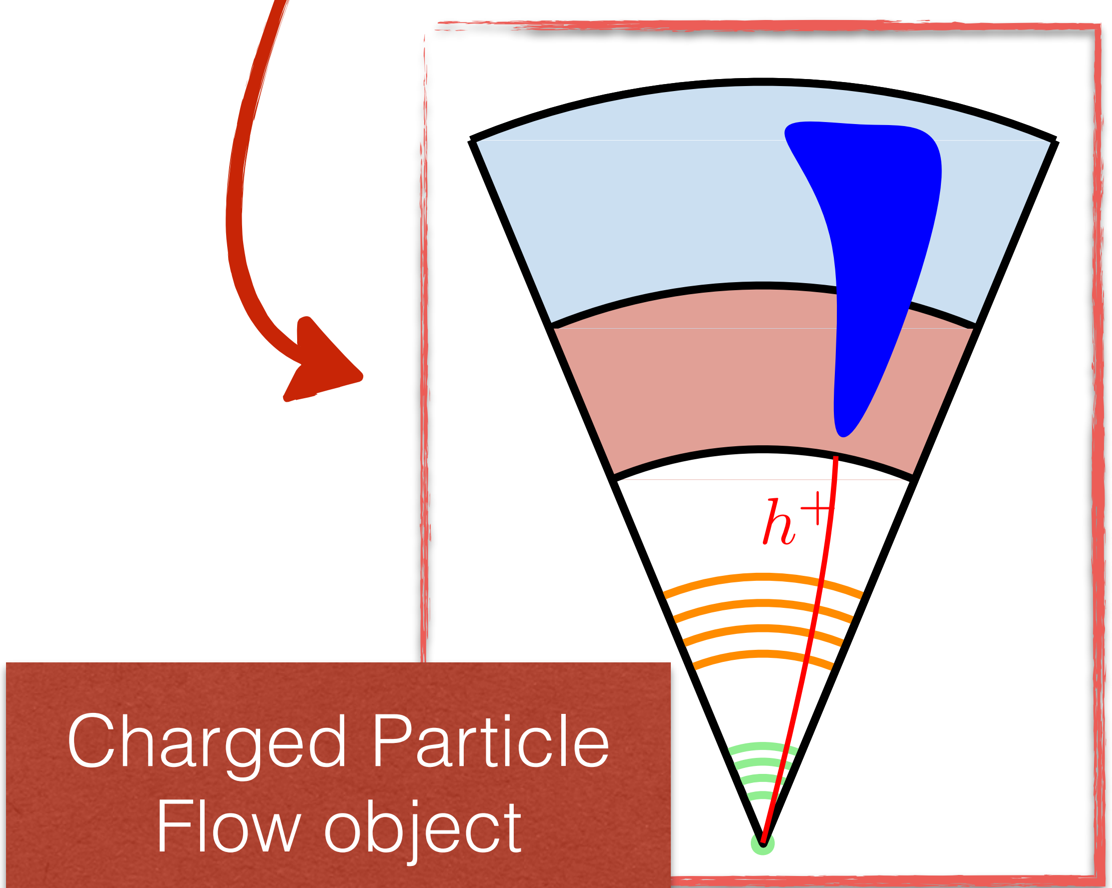
Tracker performs better at low p_T

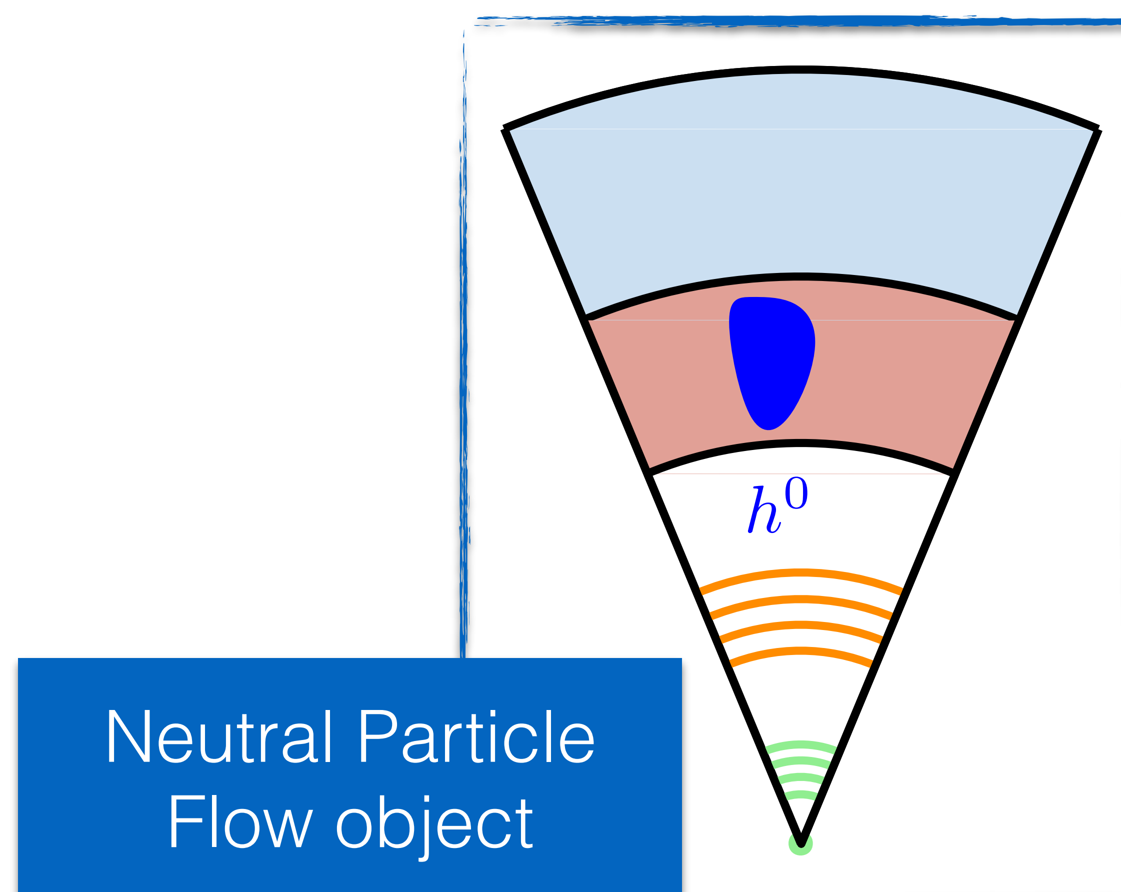


Particle Flow algorithm

- **Inputs:** all tracks and calorimeter clusters.
- **Algorithm:** associate tracks to calo clusters and combine informations (if charged)
- **Output:** set of charged and neutral Particle Flow objects.

For jet building, we require these to come from the hard scatter vertex





Particle Flow algorithm

- **Inputs:** all tracks and calorimeter clusters.
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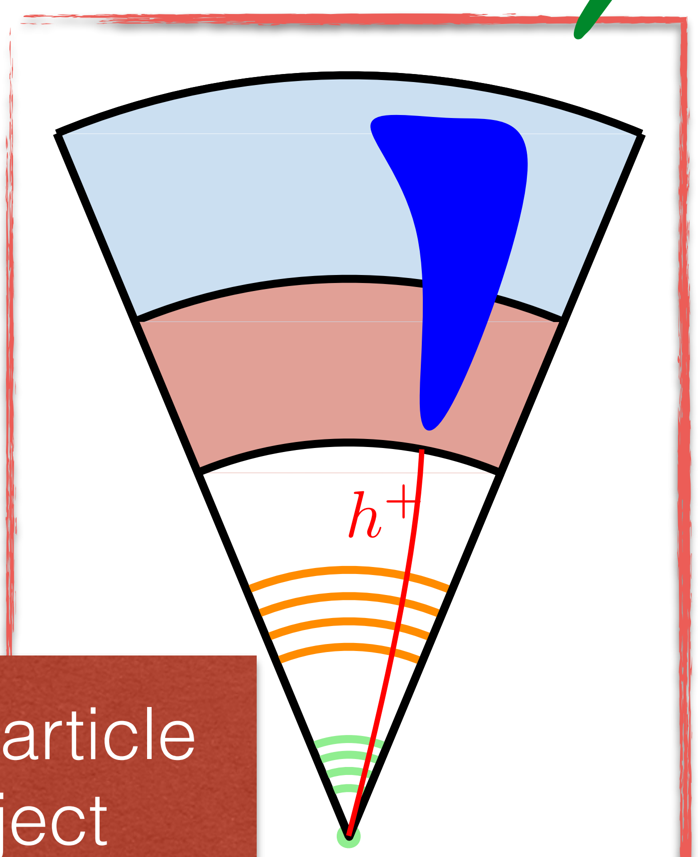
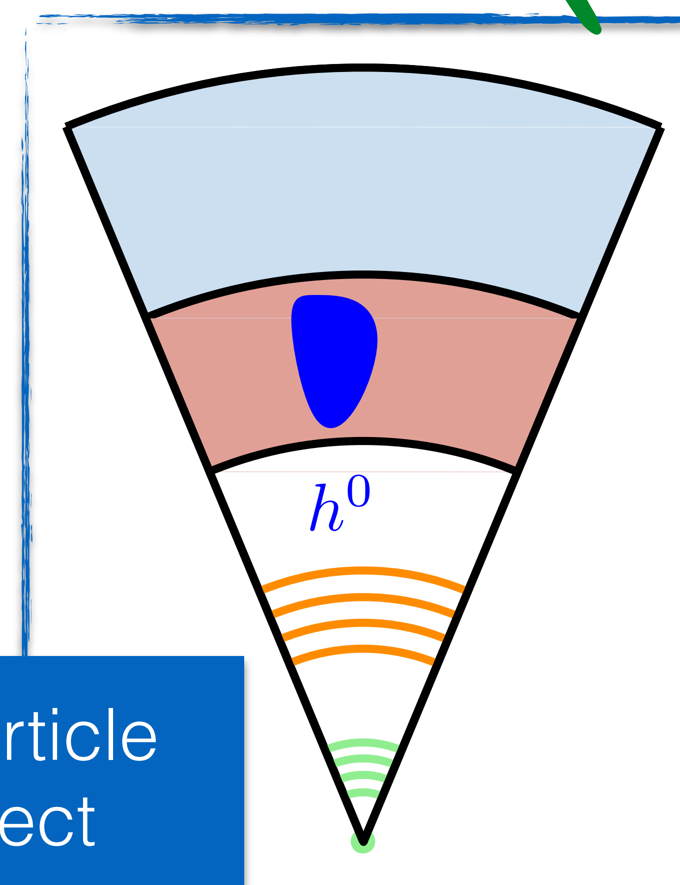
New inputs to jet algorithm

For jet building, we require these to come from the hard scatter vertex



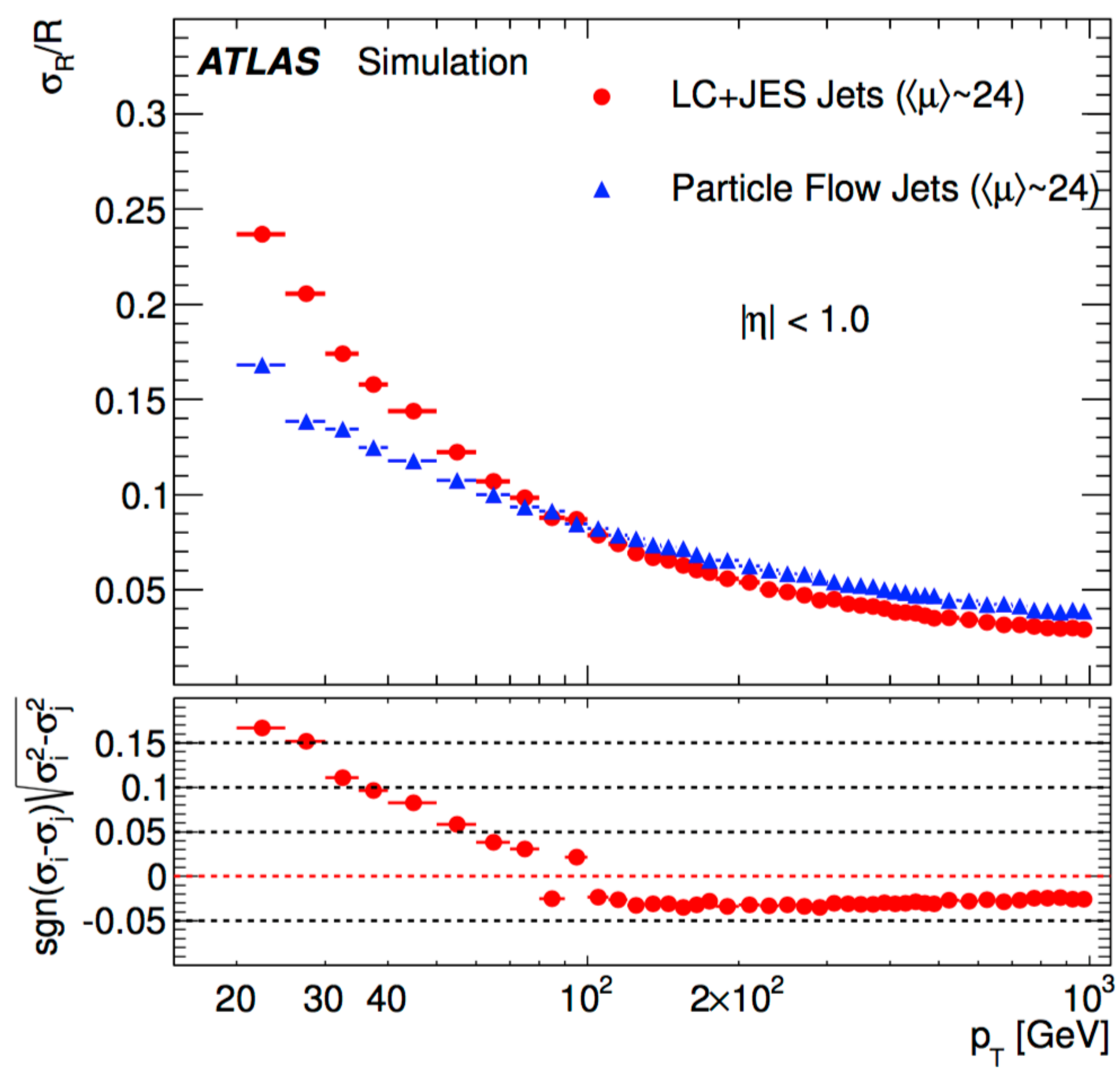
Charged Particle Flow object

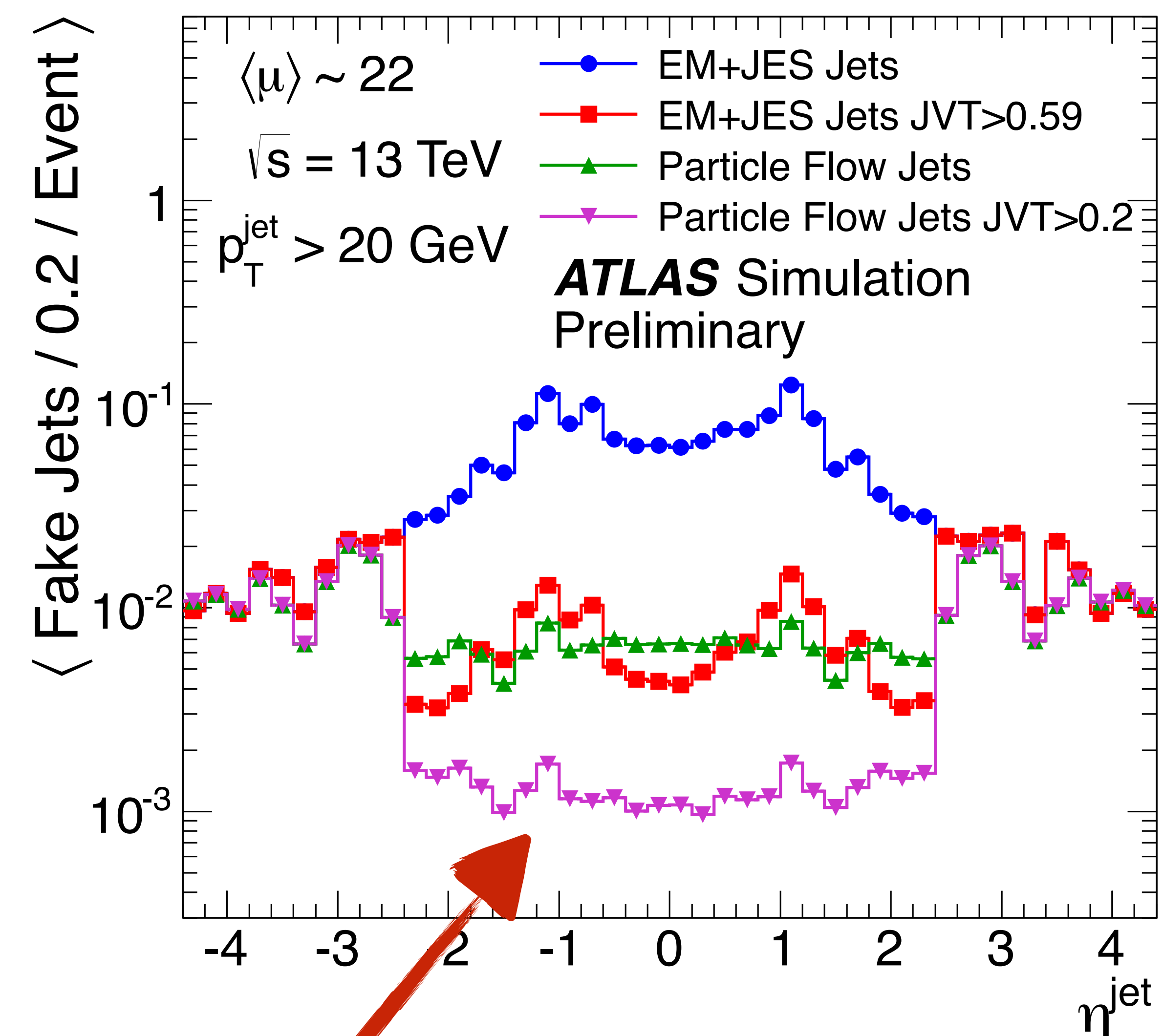


Neutral Particle Flow object

Impact on jets

Better resolution at low p_T thanks to the tracker information





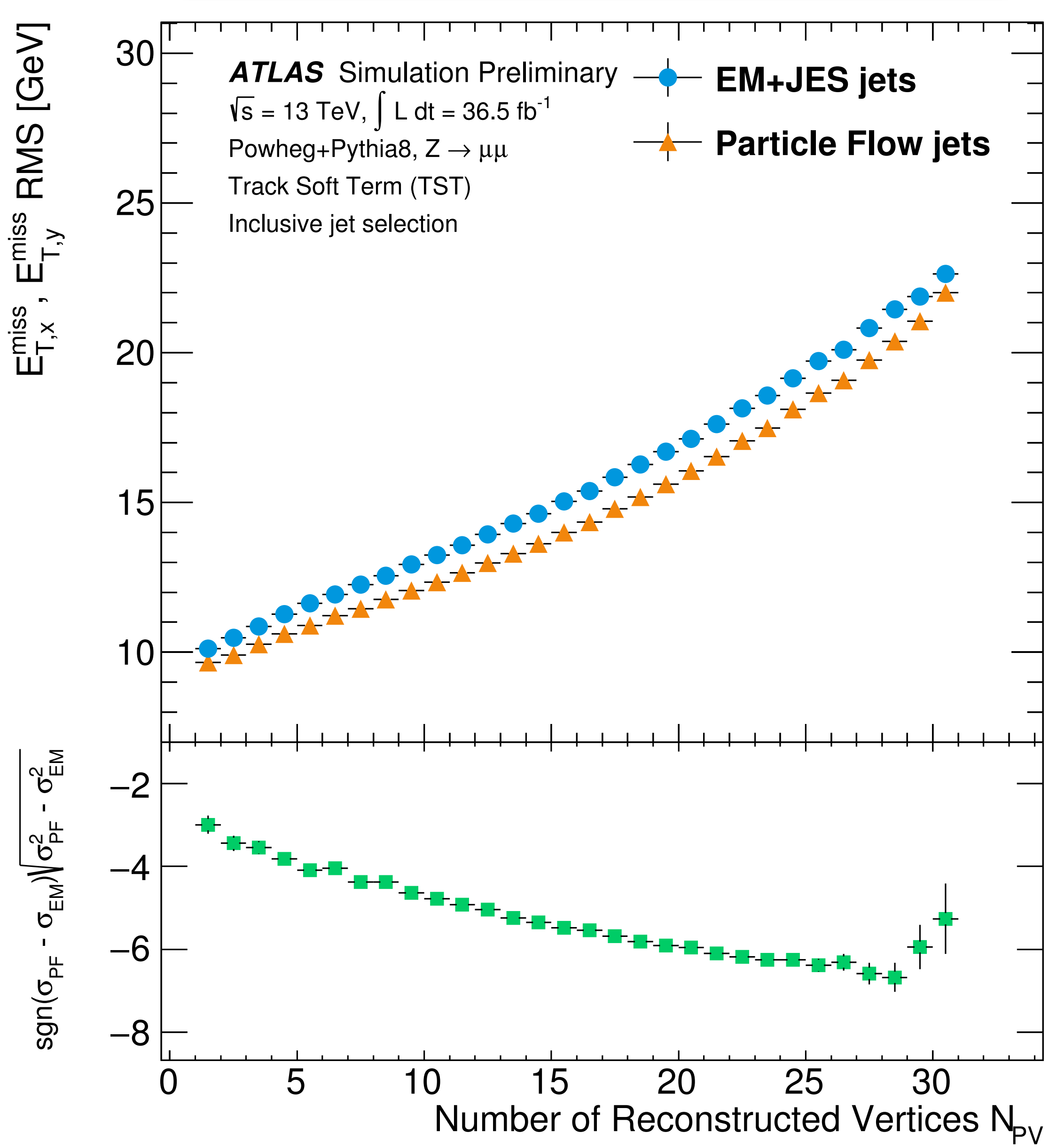
After application of tracker information, pileup jet rejection is better with Particle Flow!

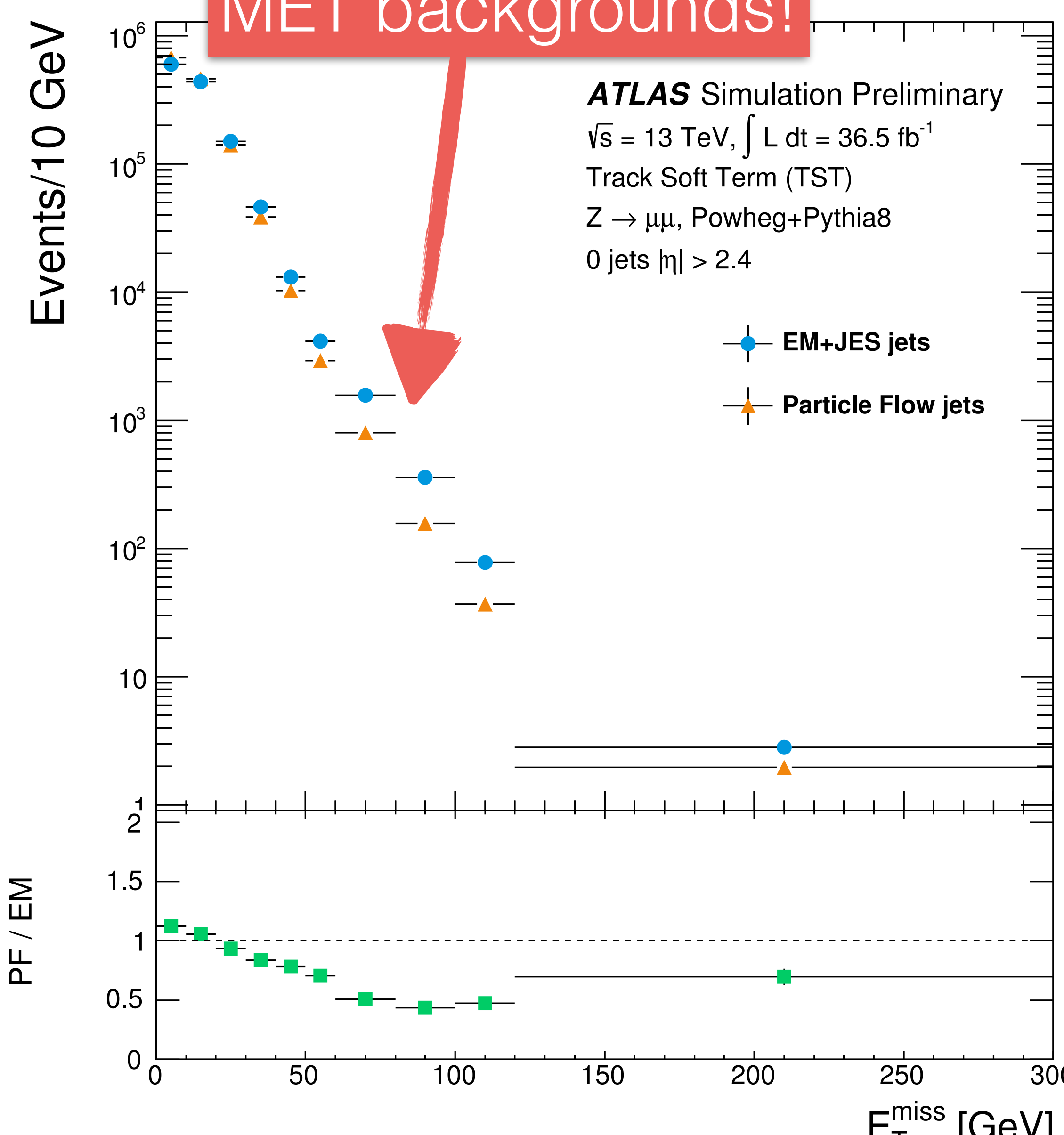
Impact on MET

$$E_T^{miss} = -\Big(\underbrace{\sum_{i\in\text{muons}} p_{T,i} + \sum_{i\in\text{electrons}} p_{T,i} + \sum_{i\in\text{photons}} p_{T,i} + \sum_{i\in\text{hadronic }\tau} p_{T,i} + \sum_{i\in\text{jets}} p_{T,i}}_{\text{hard term}} + \underbrace{\sum_{i\in\text{Soft Term}} p_{T,i}}_{\text{soft term}}\Big)$$

Improved MET resolution!

Lower tails for MET backgrounds!





Particle Flow reconstruction and searches for supersymmetry with large jet multiplicities at the ATLAS experiment

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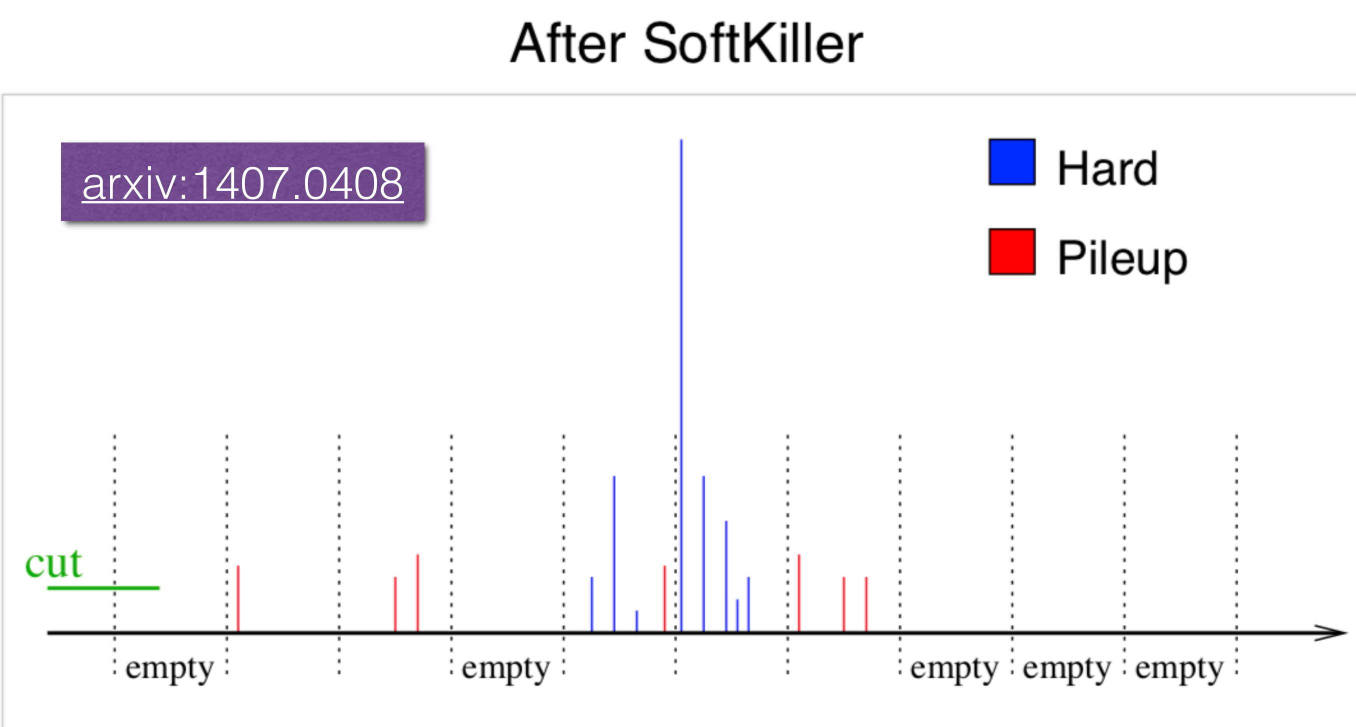
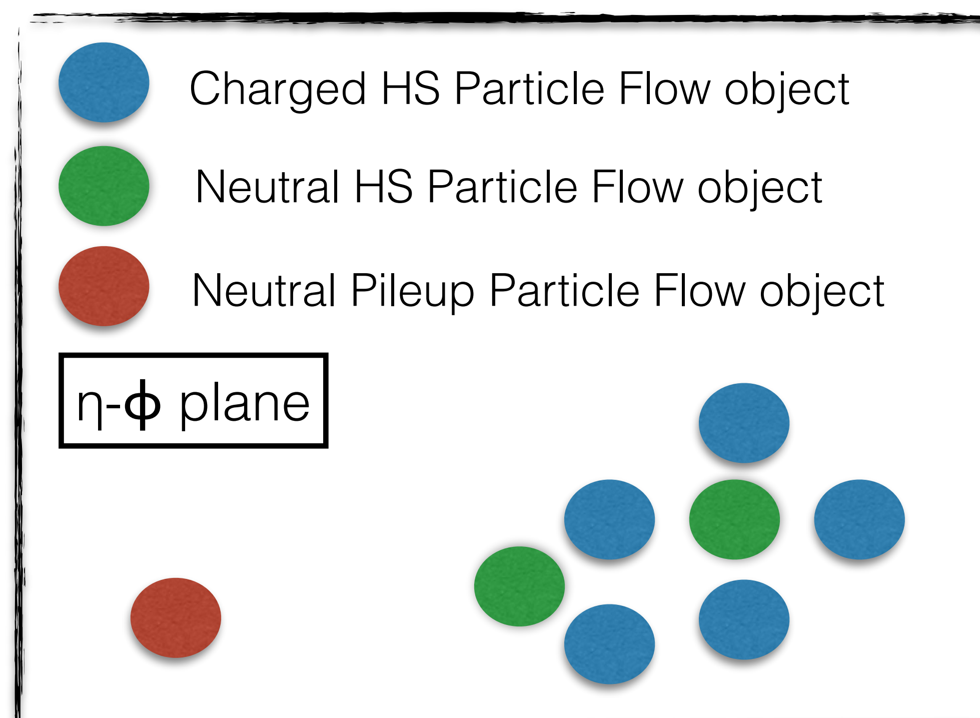
Can we do even better in future?

Particle Flow future prospects (1)

Neutral pileup suppression

- Why not applying pileup suppression also on neutrals?
- Different techniques already exist, but they are extremely simple.
- **Simple because they just look at:**
  1. Particles p_T.
  2. Proximity of neutrals to charged hard scatter particles.

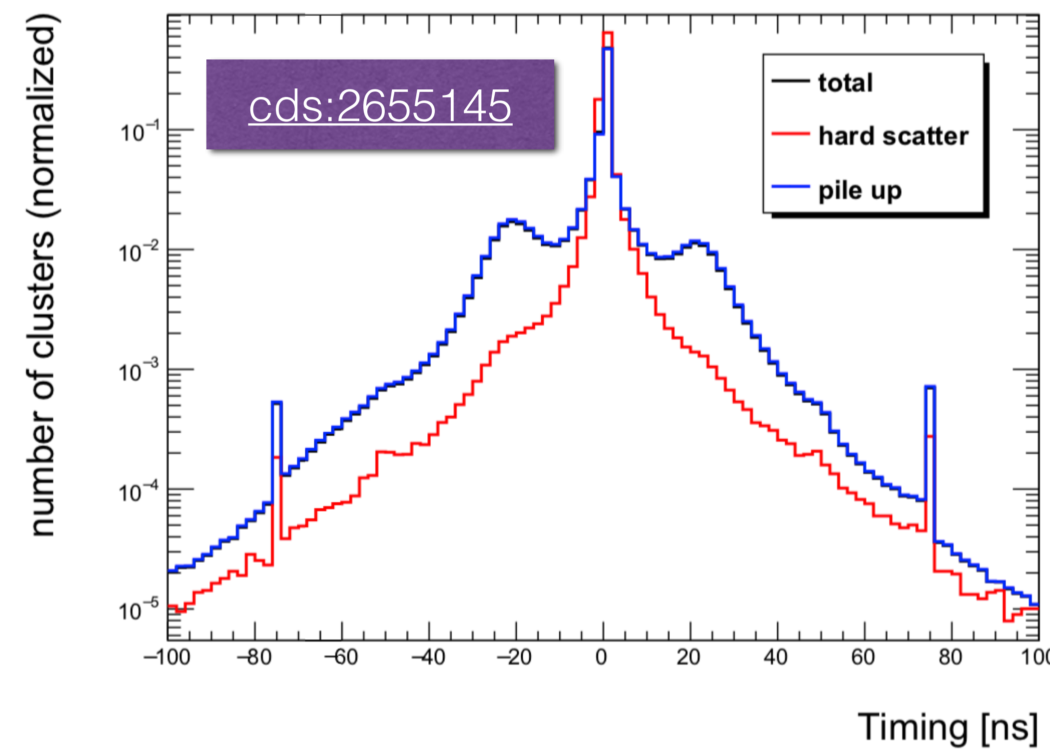


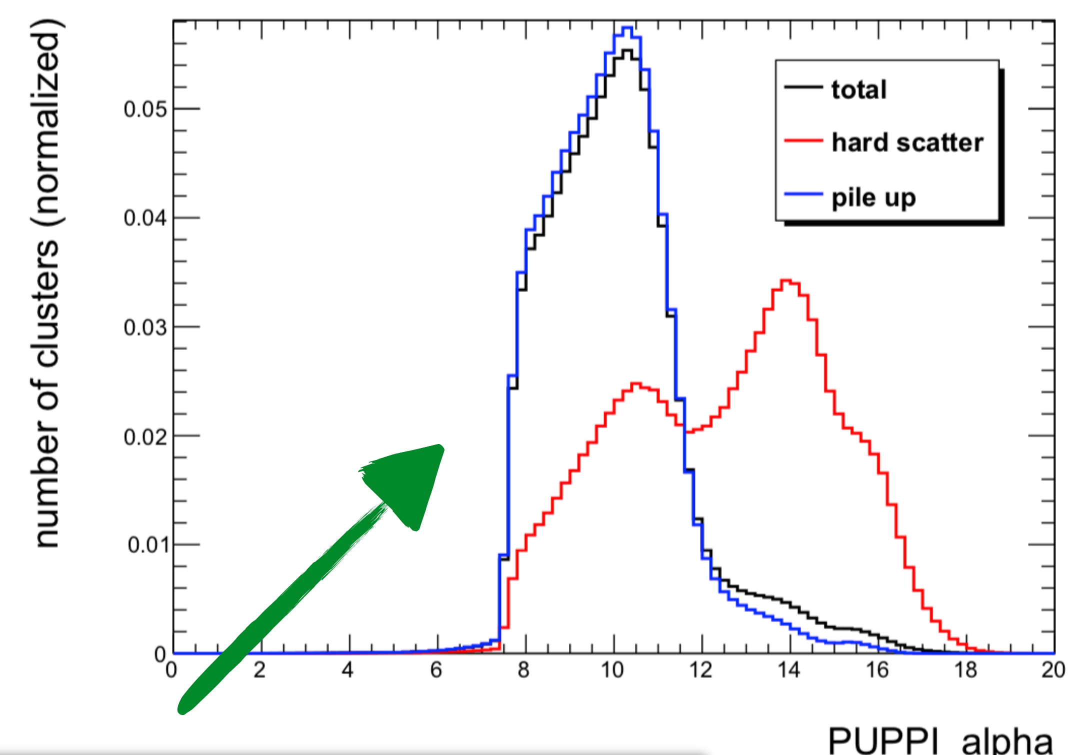


Particle Flow future prospects (2)

Neutral pileup suppression - Alternative approach with multivariate techniques

- **Question:** what if we use more information to remove neutral pileup?
- Decided to explore this with a summer student at CERN in 2018.
- A lot of possibly **useful variables**:
  - Kinematic quantities: pT, η, φ
  - Topocluster timing
  - And others…
- How to combine this information together? → **Machine Learning (ML)**





Quantity encoding proximity to charged HS particles

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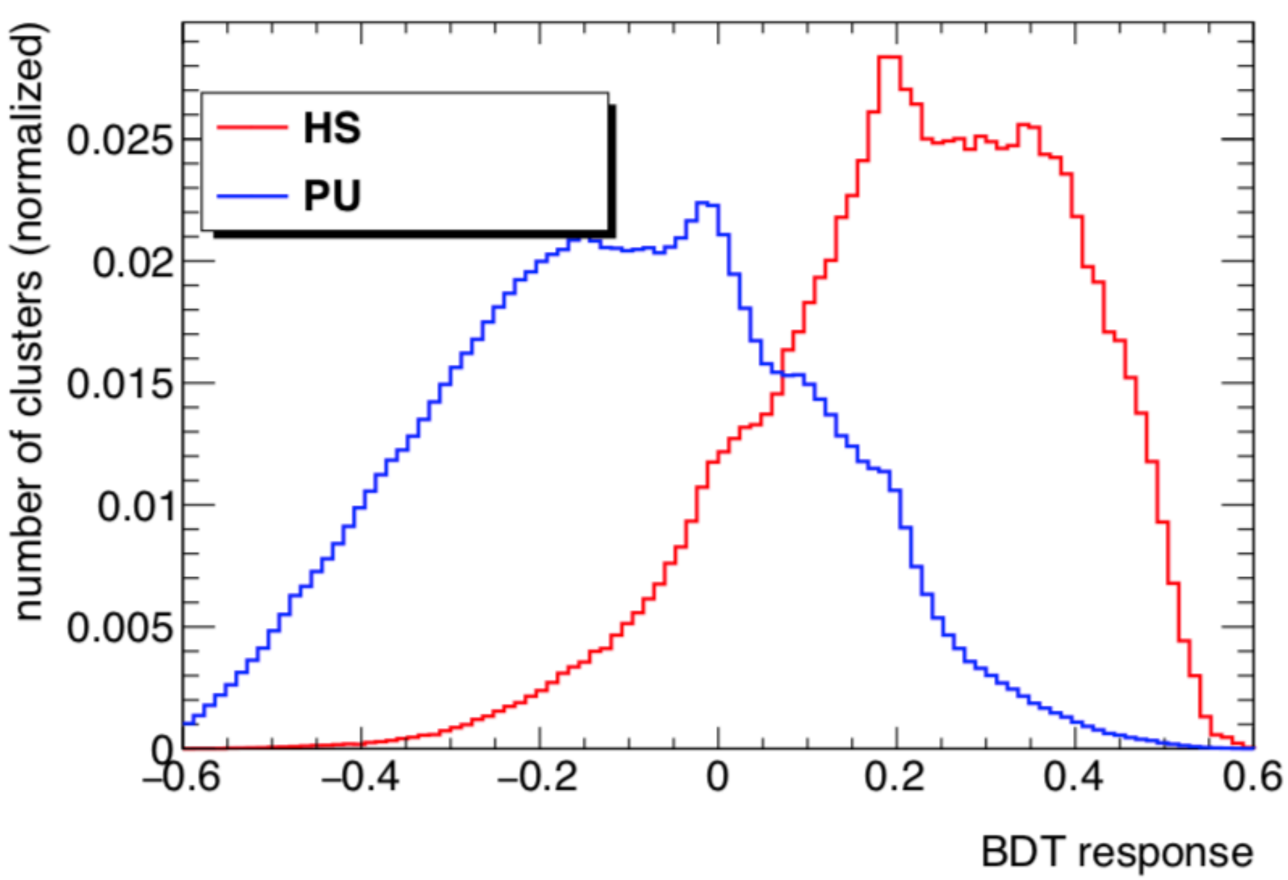
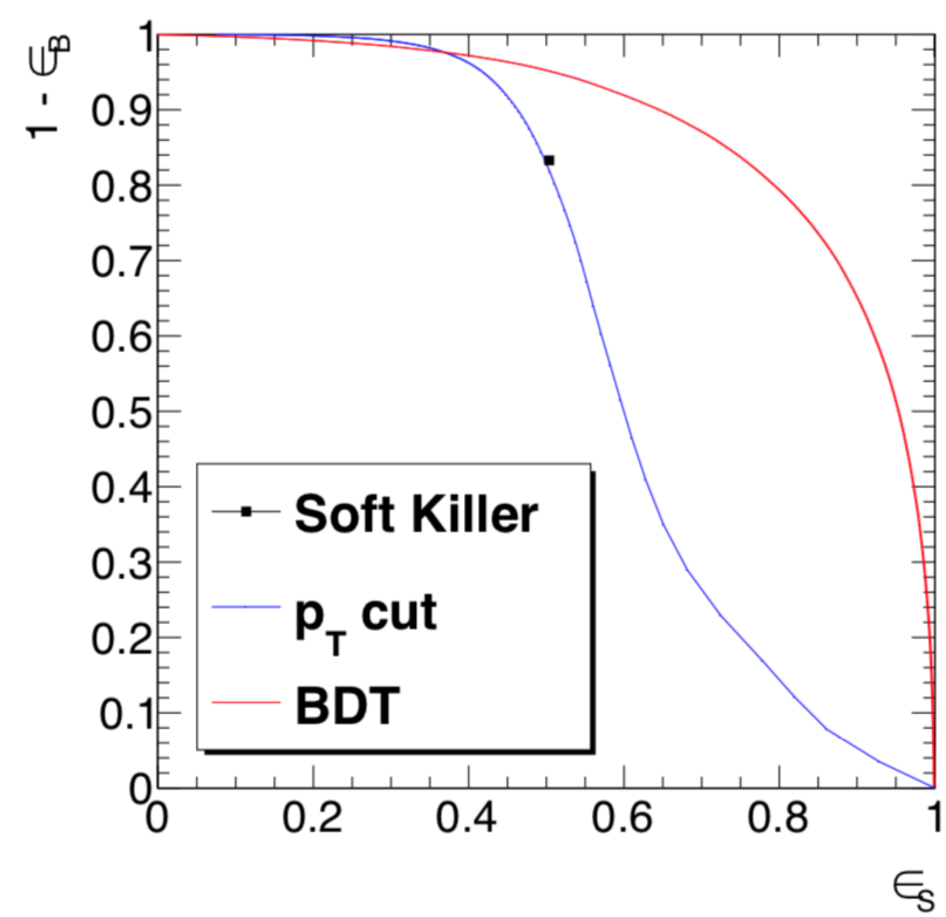
Particle Flow future prospects (3)

Neutral pileup suppression - Alternative approach with multivariate techniques

- Training performed using di-jet MC samples.
- BDT response offers good separation between Hard Scatter (HS) and Pileup (PU) neutral PFOs.
- BDT seems to offer better selection than p_T alone. Specially in the low p_T range.

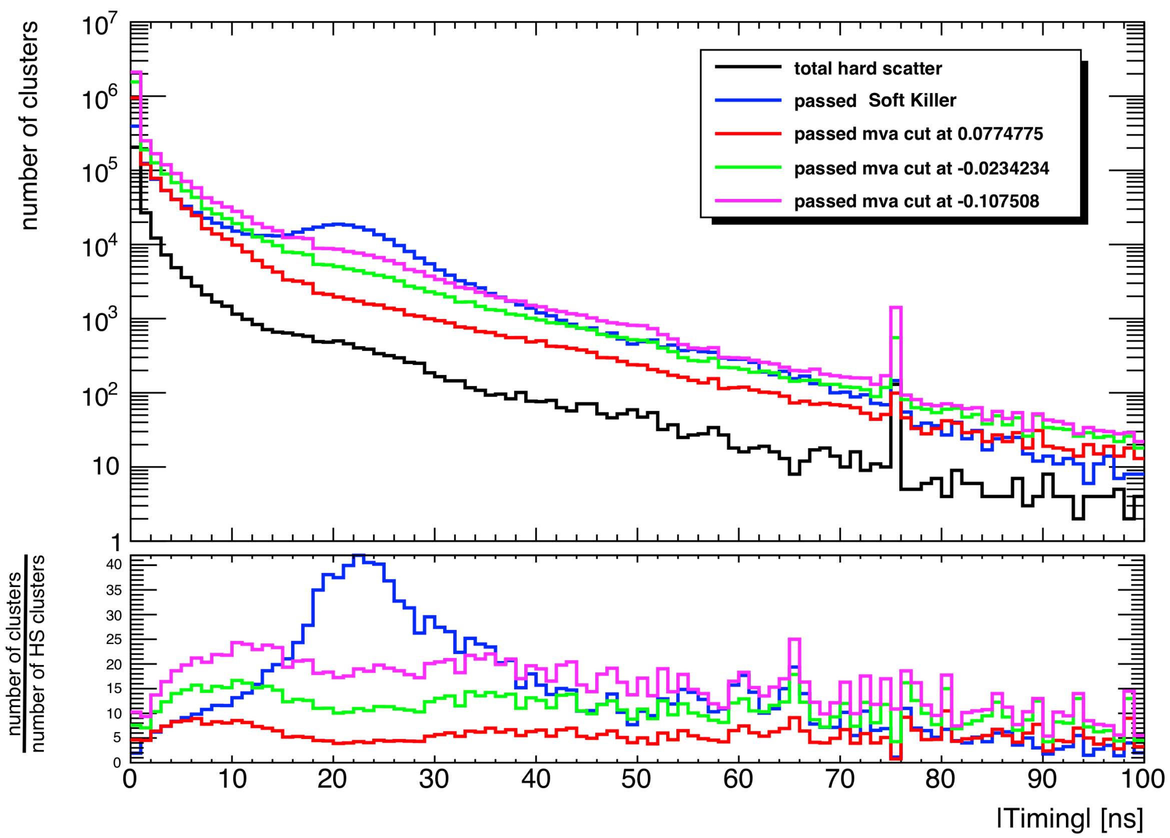


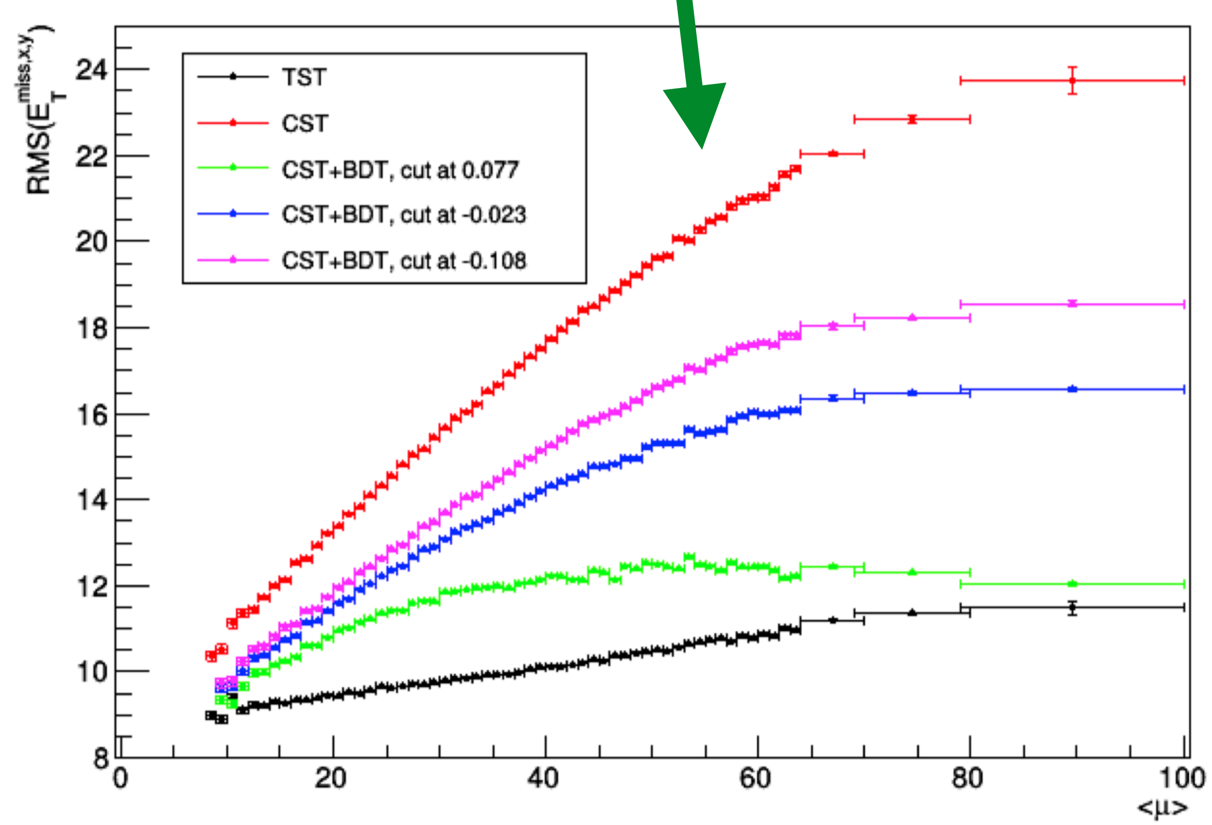


Impact on physics quantities

BDT learns also how to suppress timing peak!

CST resolution improves significantly with BDT

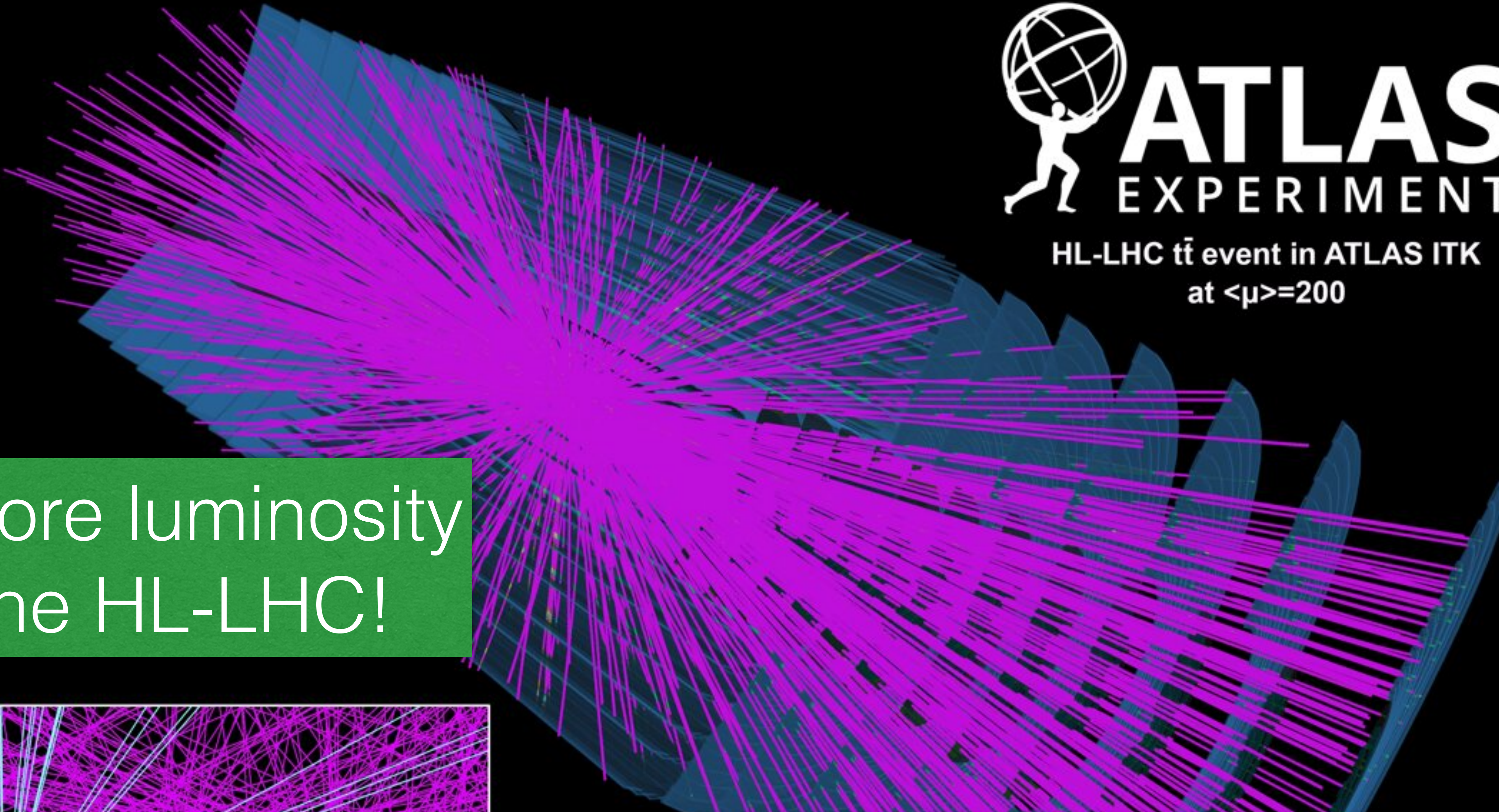




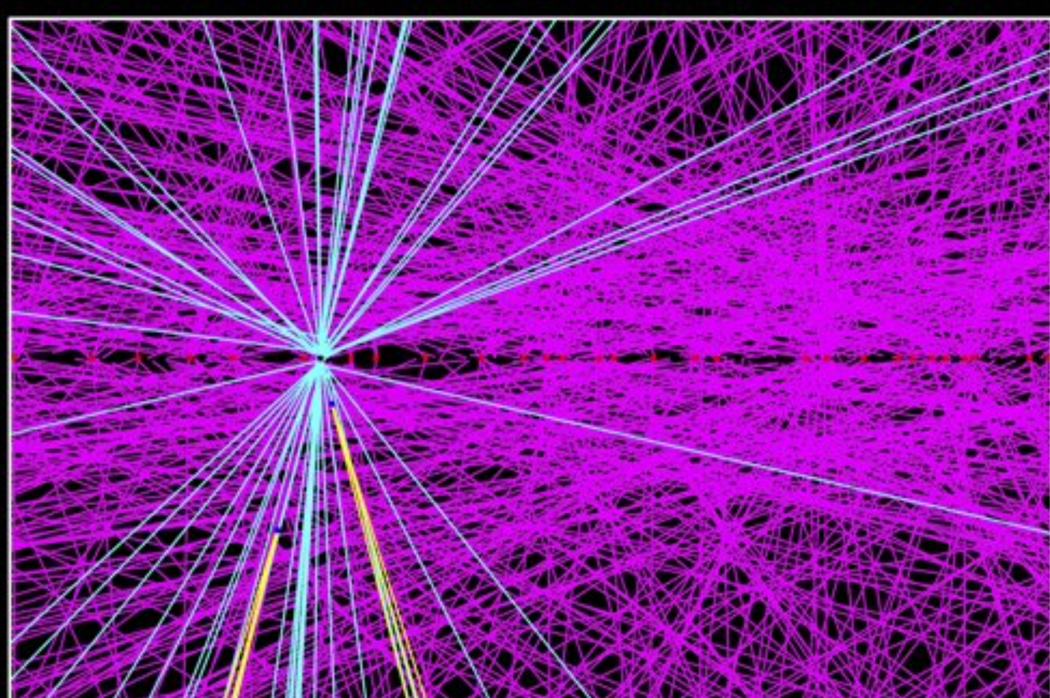
Intermediate summary

- **Hadronic objects are fundamental** for ATLAS physics.
- Until now, **tracking has been used only after jet reconstruction** for pileup suppression.
- **Particle Flow combines calorimeter and tracker information** before jet building providing different improvements.
- Could this be done better in future? Maybe with **neutral pileup mitigation! And also Machine Learning**!

Improvements for physics in future!



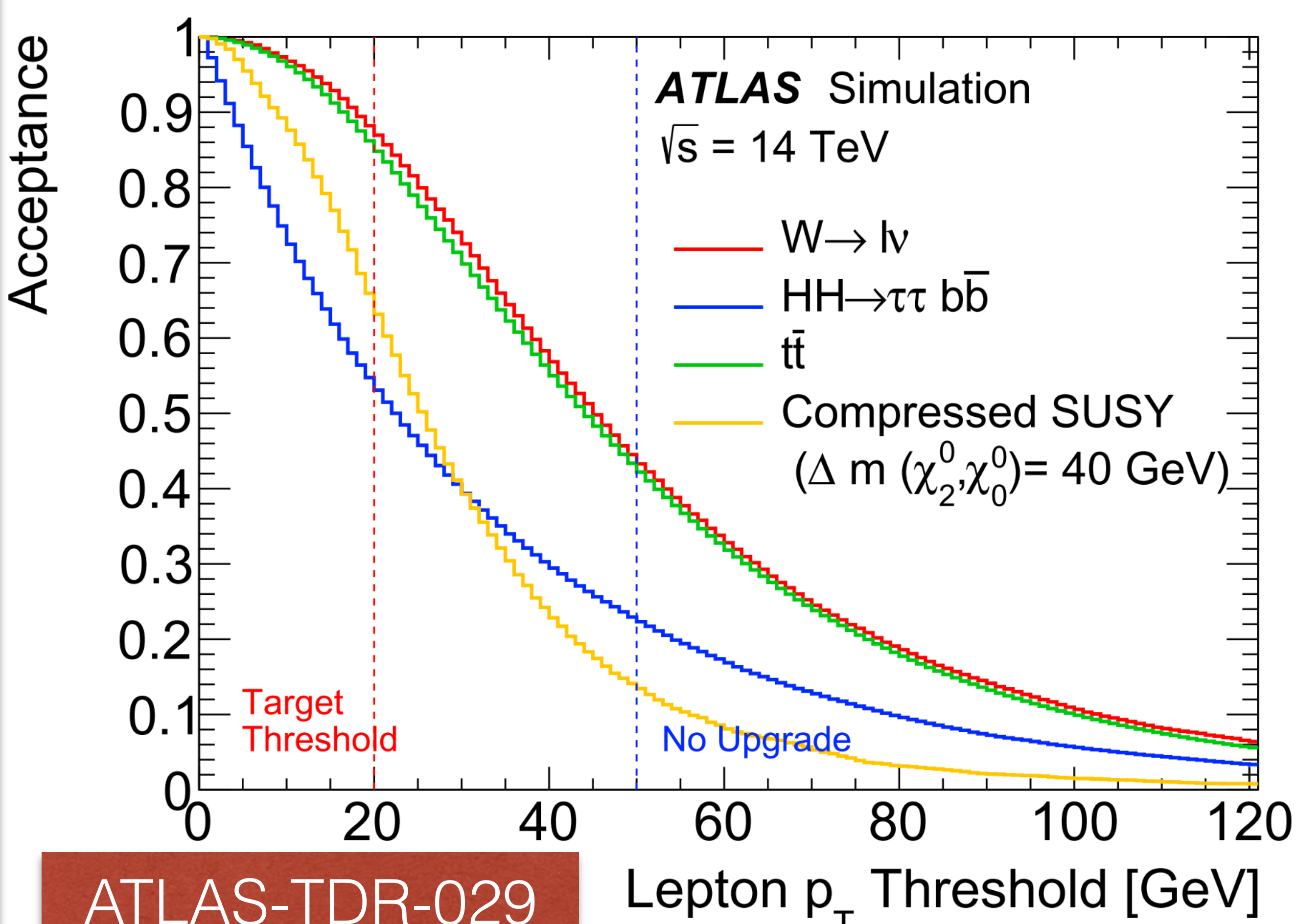
x 5 more luminosity
at the HL-LHC!

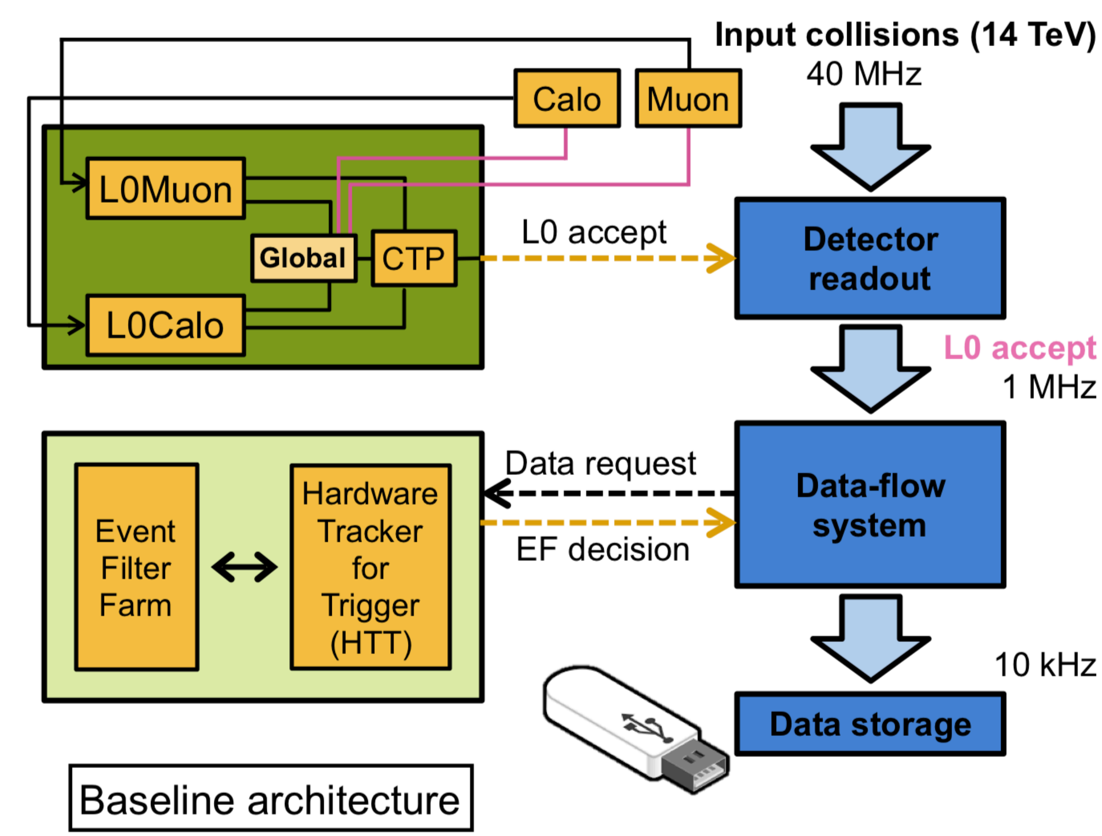


A lot of chances
to improve even
more at 200 simultaneous
pp collisions!

Online hadronic physics at HL-LHC (1)

- Tracking is very difficult at trigger level (CPU expensive).
- In order to exploit the full potential of the HL-LHC, it will be important to kill pileup also online!
- Hardware Track Trigger (HTT) aims at providing fast tracking for Event Filter (CPU farm) at 1MHz.





ATLAS-TDR-029

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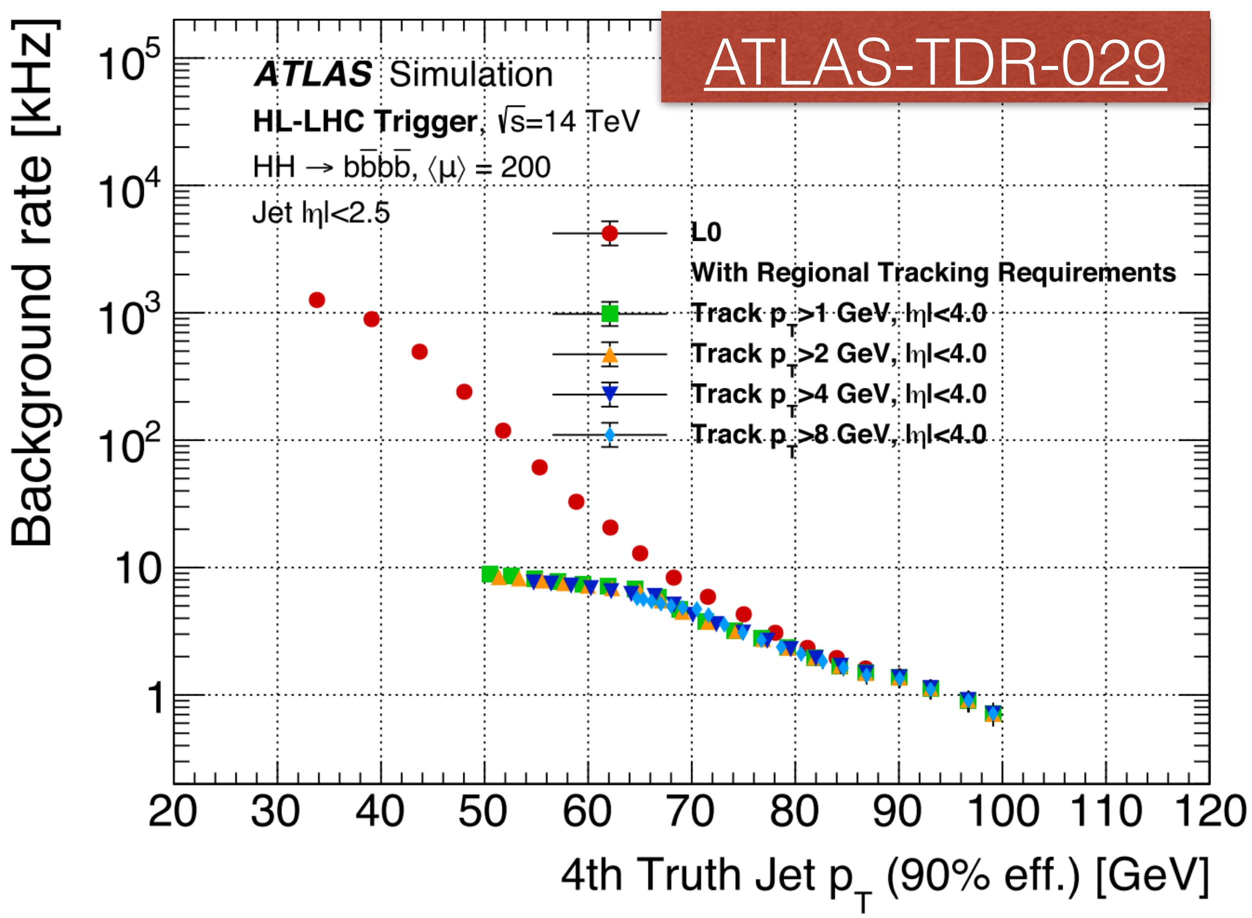
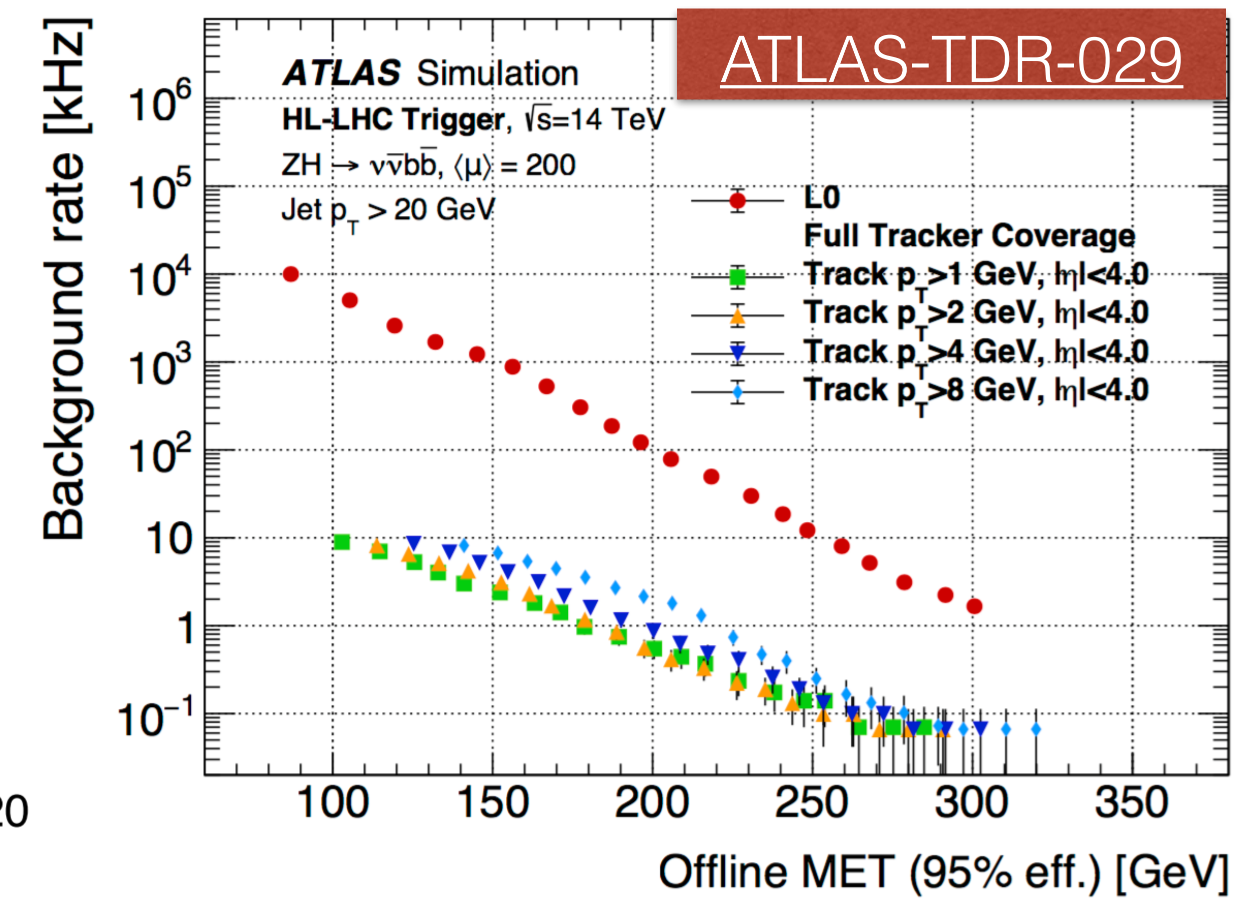
Online hadronic physics at HL-LHC (2)

Important to kill the pileup even in the trigger at HL-LHC!





The lower this cut, the more signal (ZH or HH) you get

Outline

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    1. Why we need hadronic observables?
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    4. Particle Flow reconstruction.
    5. Can be do better? Maybe…. neutral pileup mitigation!
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    2. Searching for supersymmetry with with many jets
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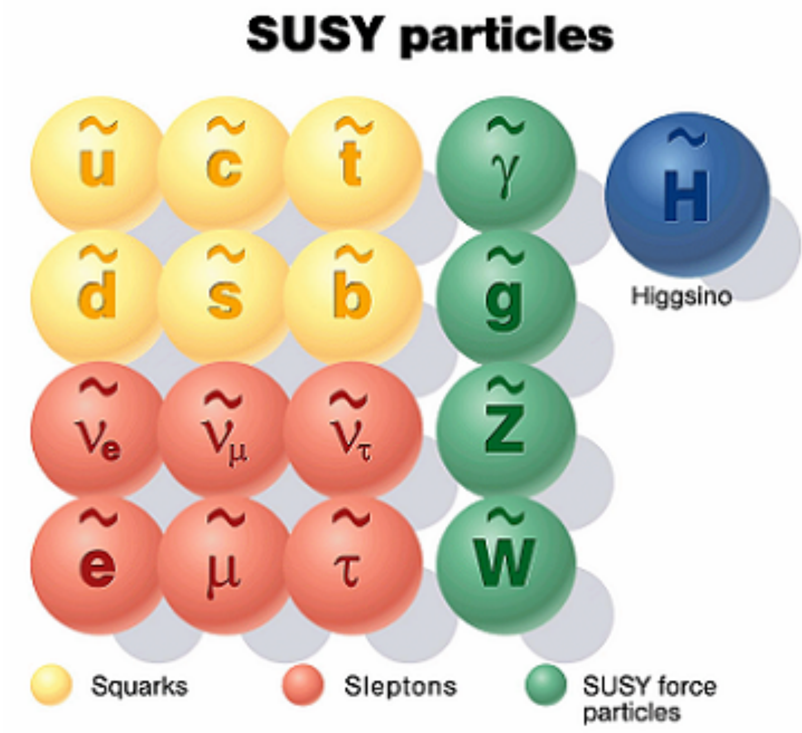
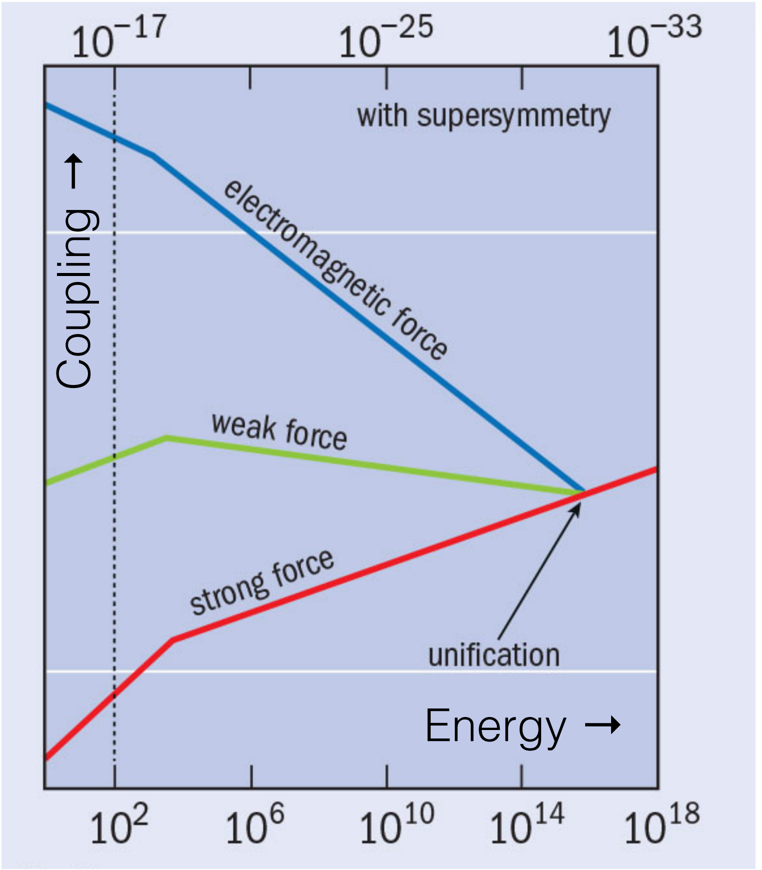
    4. Do you want to see 12 jets results?
    5. Reinterpretation and current limits
4. Conclusions and outlook

Why Supersymmetry?



- Supersymmetry (or SUSY) is one of the most **natural extensions of the Standard Model** (SM).

- Theoretical success due to:
  1. **Naturalness of the SM (**1-2 TeV stop and gluino).
  2. **Dark matter candidate** from Lightest Supersymmetric Particle (LSP).
  3. **Unification of SM with gravity** when locality is required.
  4. **Unification of elementary forces coupling** at high energy.



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Ingredients for a SUSY analysis

Simplified version

1. Define a clear signature
2. Physics objects and variables definition
3. Define a set of Signal Regions
4. Estimate the background in the Signal Regions
5. Validate the background
6. Unblind the results

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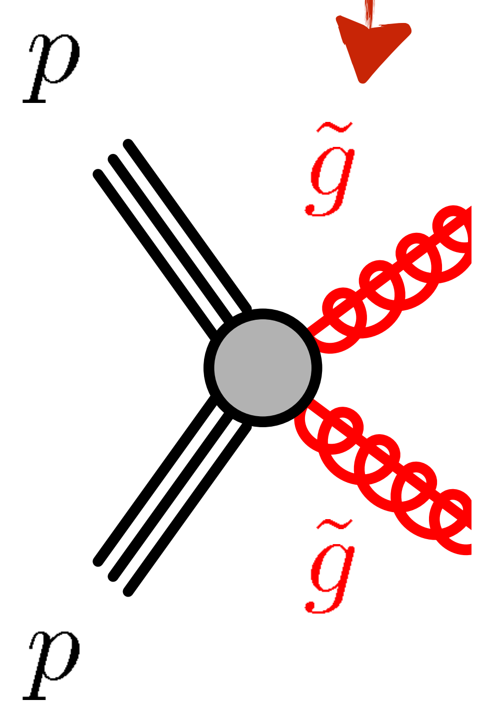
What is the signature of SUSY?

1-2 TeV gluinos produced in pairs at the LHC



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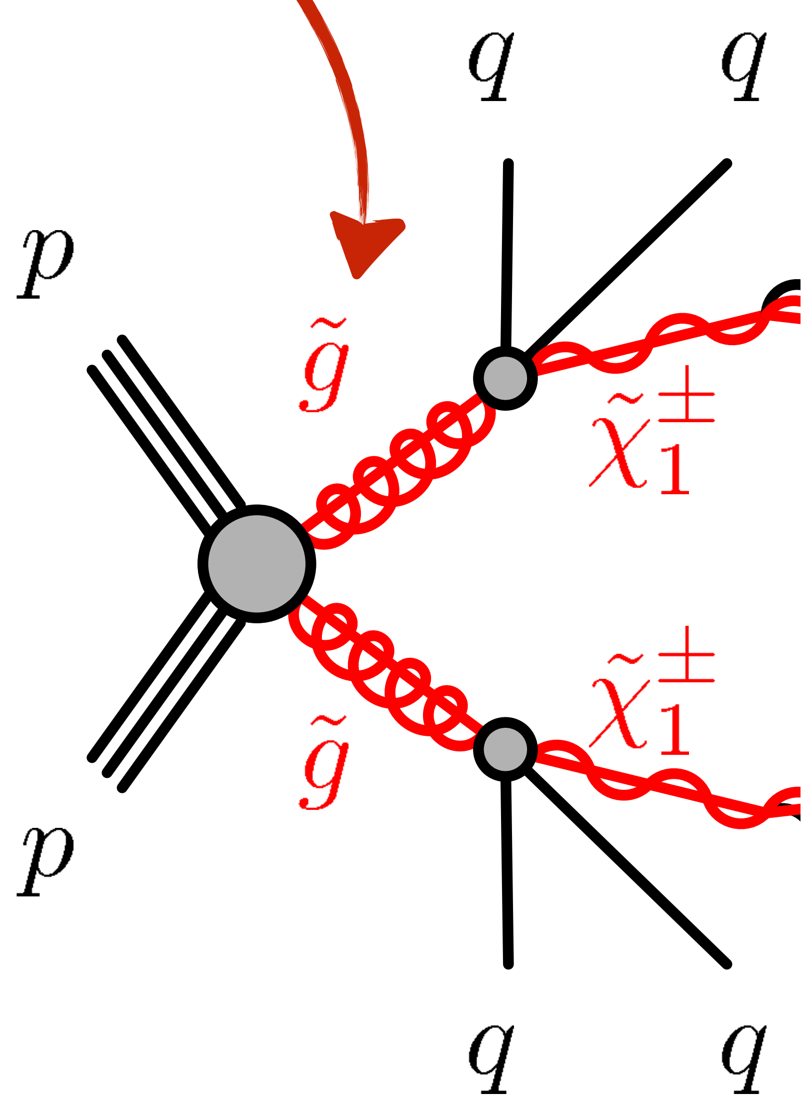

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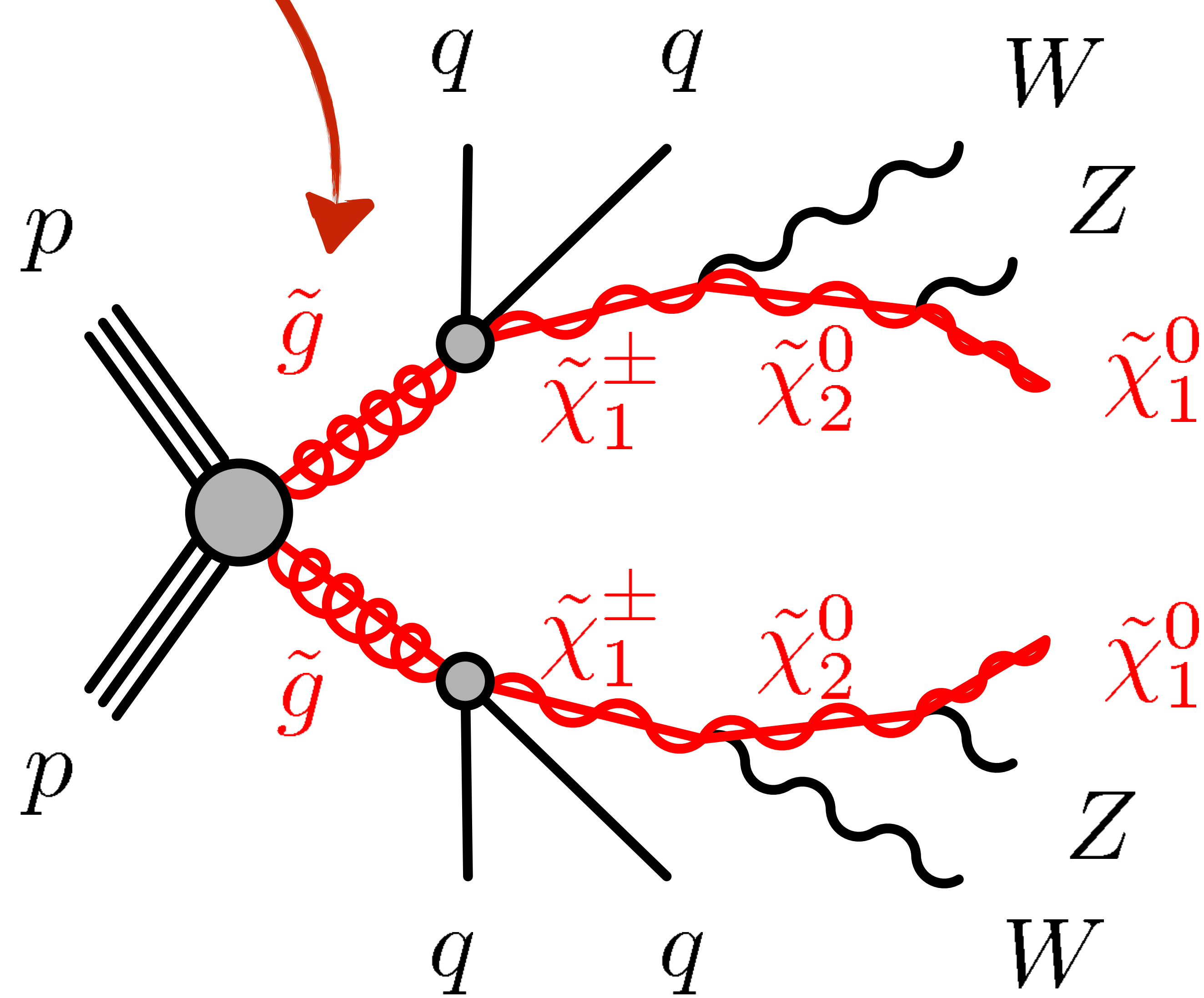

Particle Flow reconstruction and searches for supersymmetry with large jet multiplicities at the ATLAS experiment

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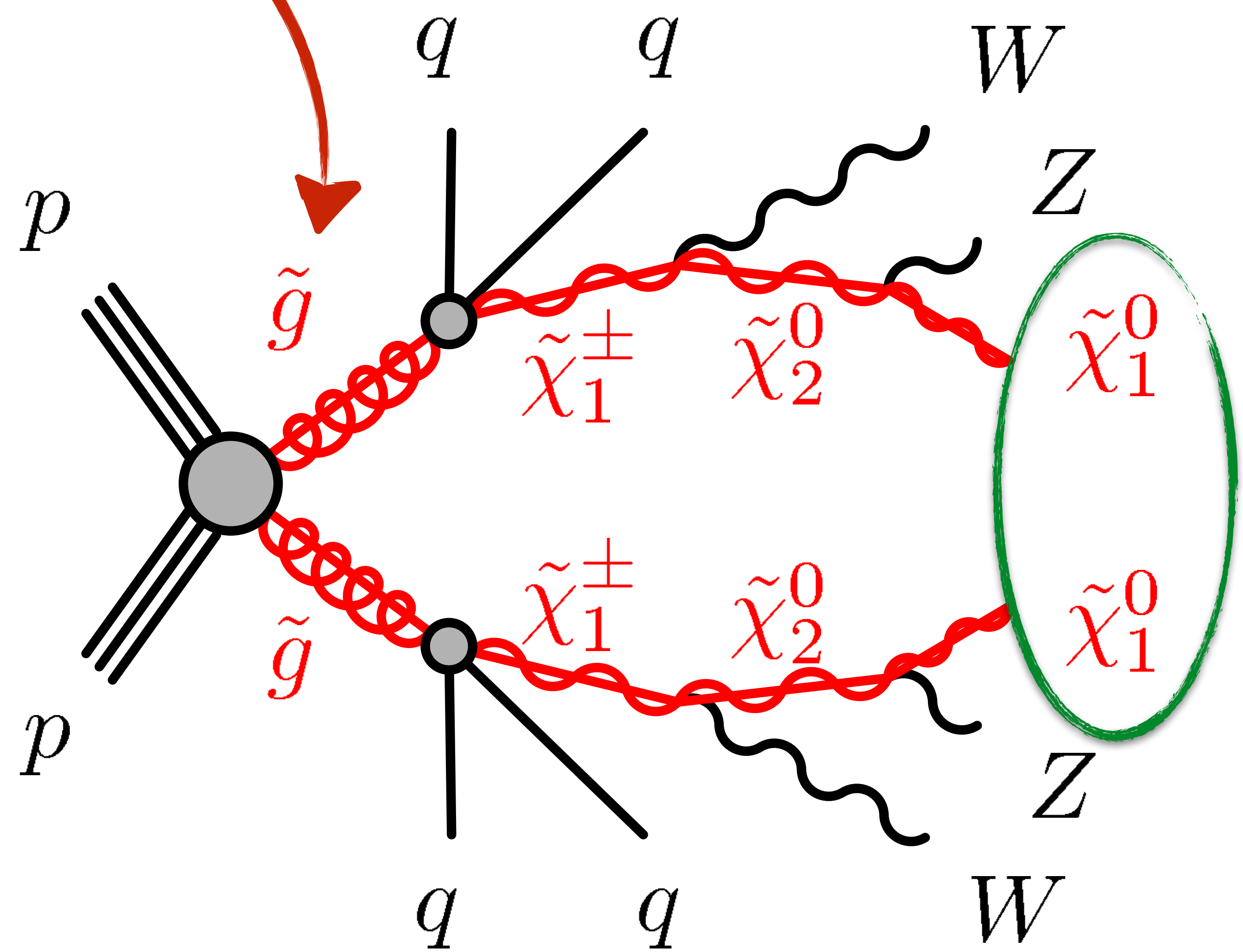
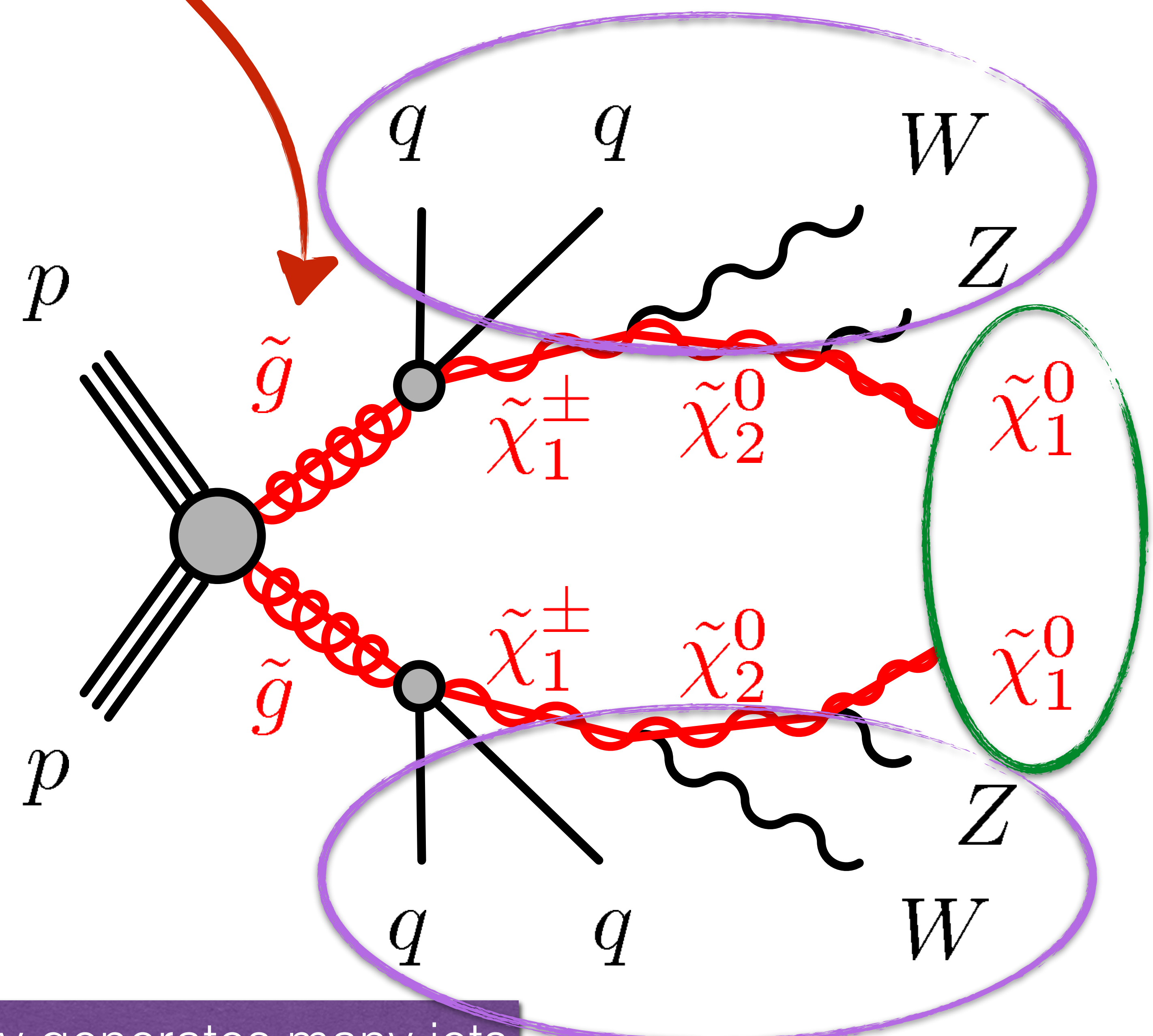


LSP escapes the detection producing MET

What is the signature of SUSY?

1-2 TeV gluinos produced in pairs at the LHC



LSP escapes the detection producing MET

Cascade decay generates many jets (up to 12!) and leptons

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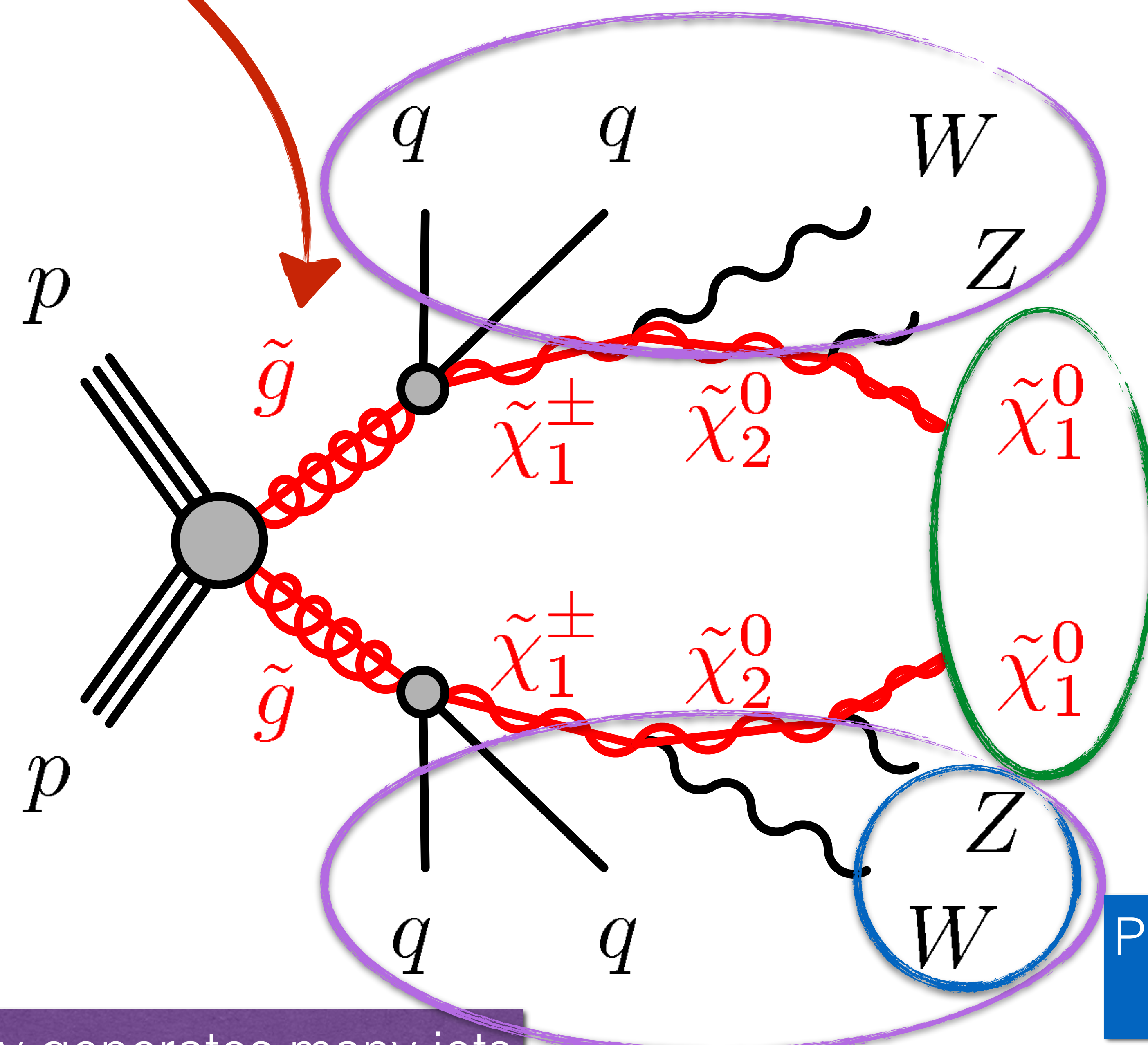
What is the signature of SUSY?

1-2 TeV gluinos produced in pairs at the LHC



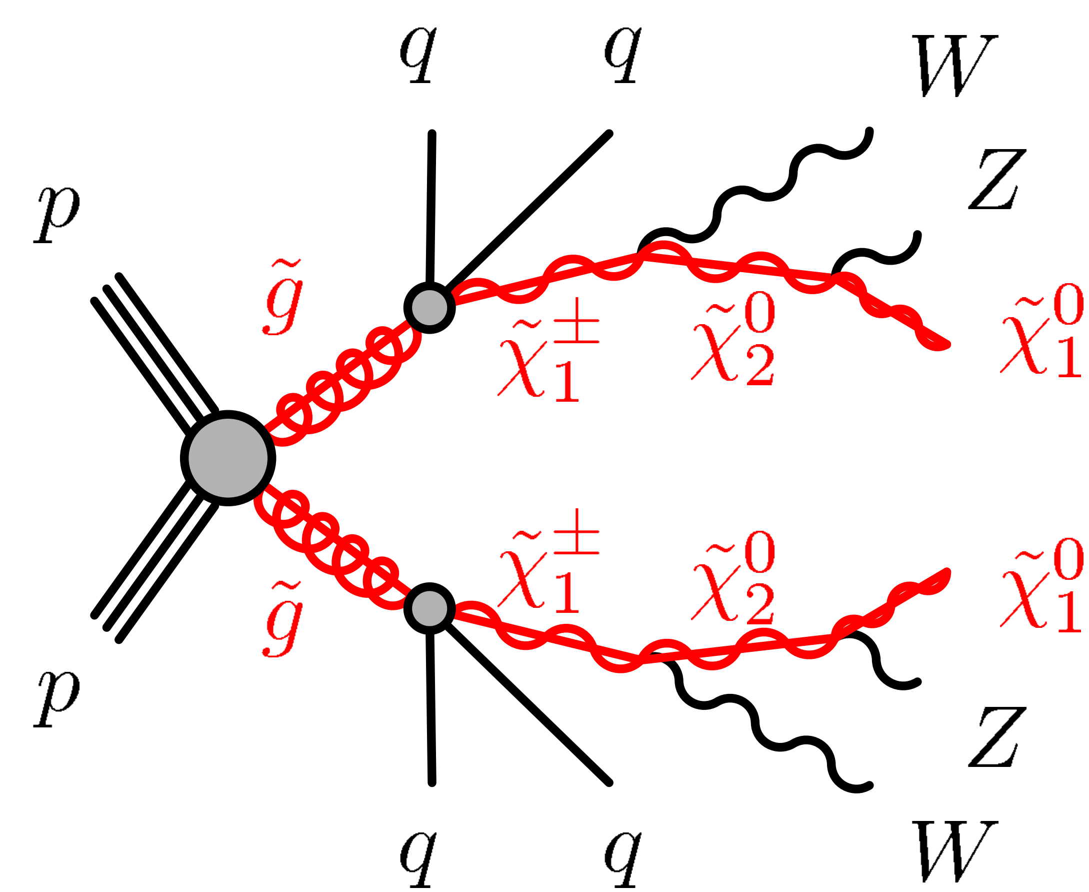
LSP escapes the detection producing MET

Possibly boosted objects

Cascade decay generates many jets (up to 12!) and leptons

The SUSY multijets 0l analysis

- What we are looking at:
  - Jet multiplicity from 8 to 12 (p_T > 50 GeV) and 7 to 9 (p_T > 80 GeV)
  - No leptons.
  - Moderate MET.
  - Additional requirements on b-tagged jets and boosted objects.



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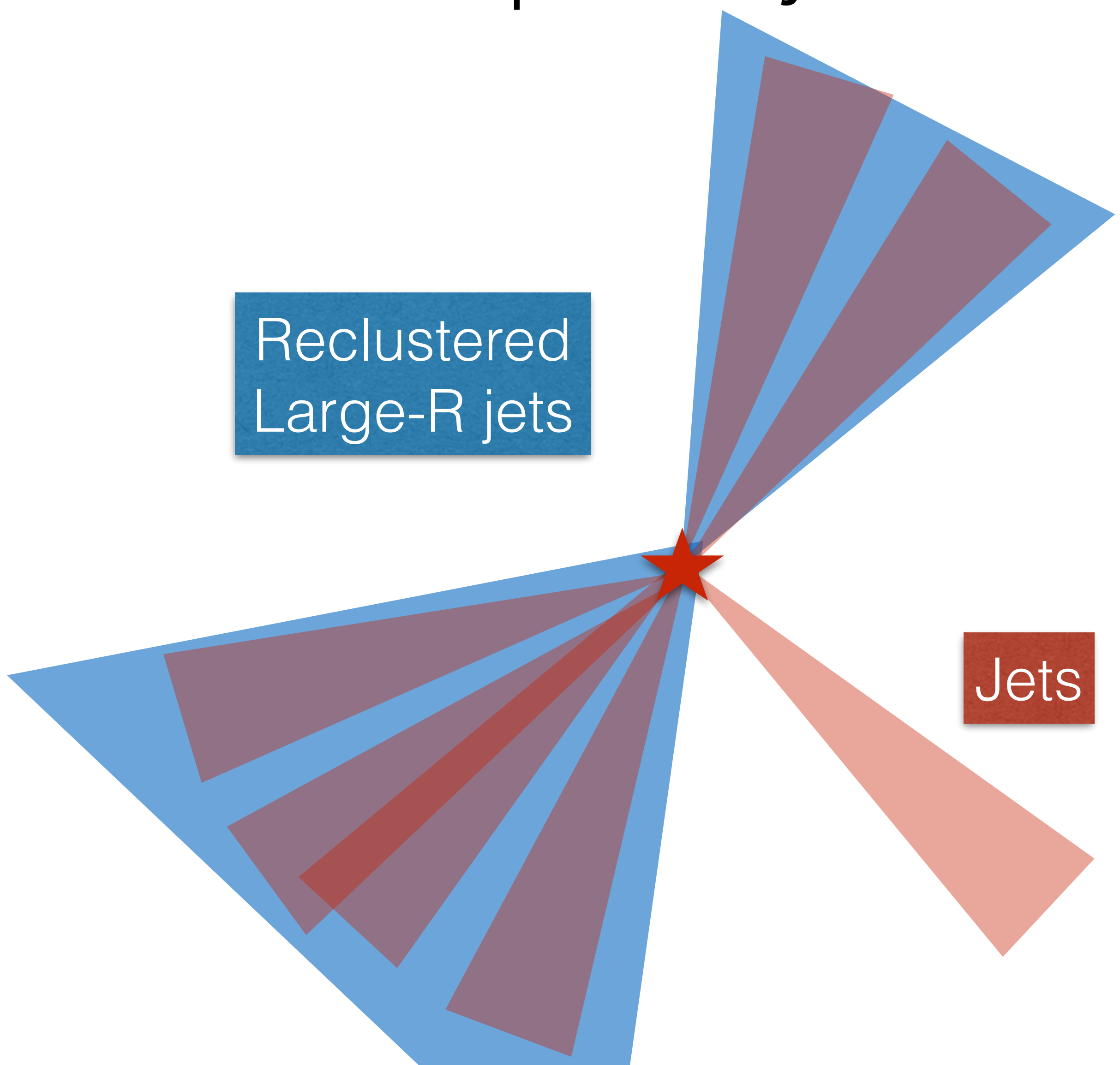
Physics objects and variables (1)

1. **Particle Flow jets**, fully calibrated and passing JVT selection.
2. Particle Flow reclustered Large-R jets, in order to access possibly boosted scenarios.



Event-level variable used for boosted event identification

$$M_{\mathrm{J}}^{\Sigma} = \sum m_j^{R=1.0}$$

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Physics objects and variables (2)

MET significance: is the measured MET compatible with the 0 MET hypothesis?

New

$$\mathcal{S} = \frac{E_T^{\text{miss}}}{\sigma(E_T^{\text{miss}})}$$

$$\approx$$

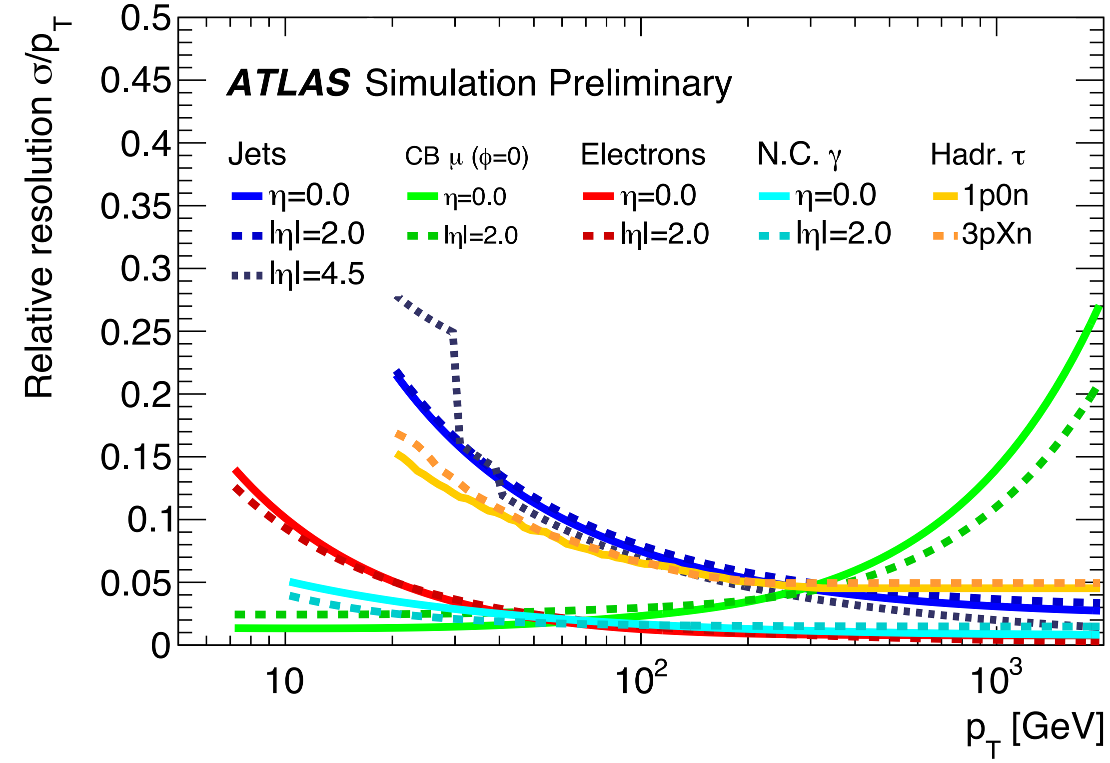
Old

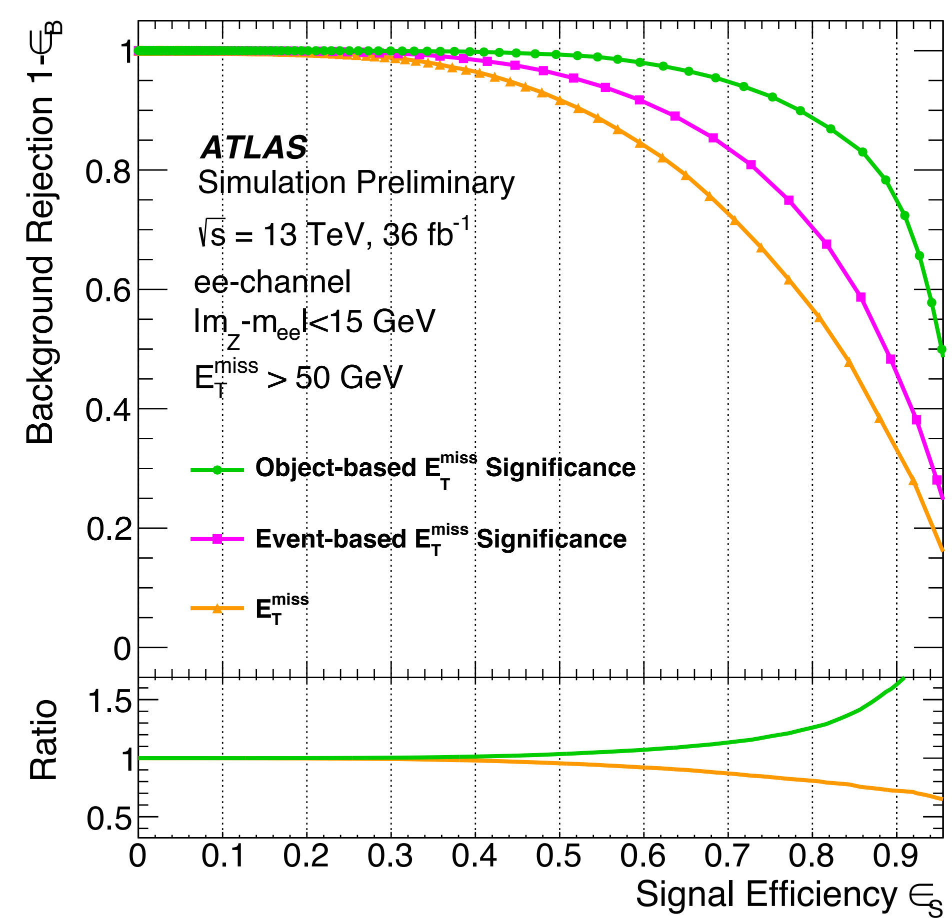
$$\frac{E_T^{\text{miss}}}{\sqrt{\sum p_{\mathrm{T}}}}$$

In the objet-based approach, $\sigma(E_T^{\text{miss}})$ is estimated from the resolution of each physics object.

Object-based MET significance does a very nice job!

We can use MET significance above 5 four our Signal Regions.





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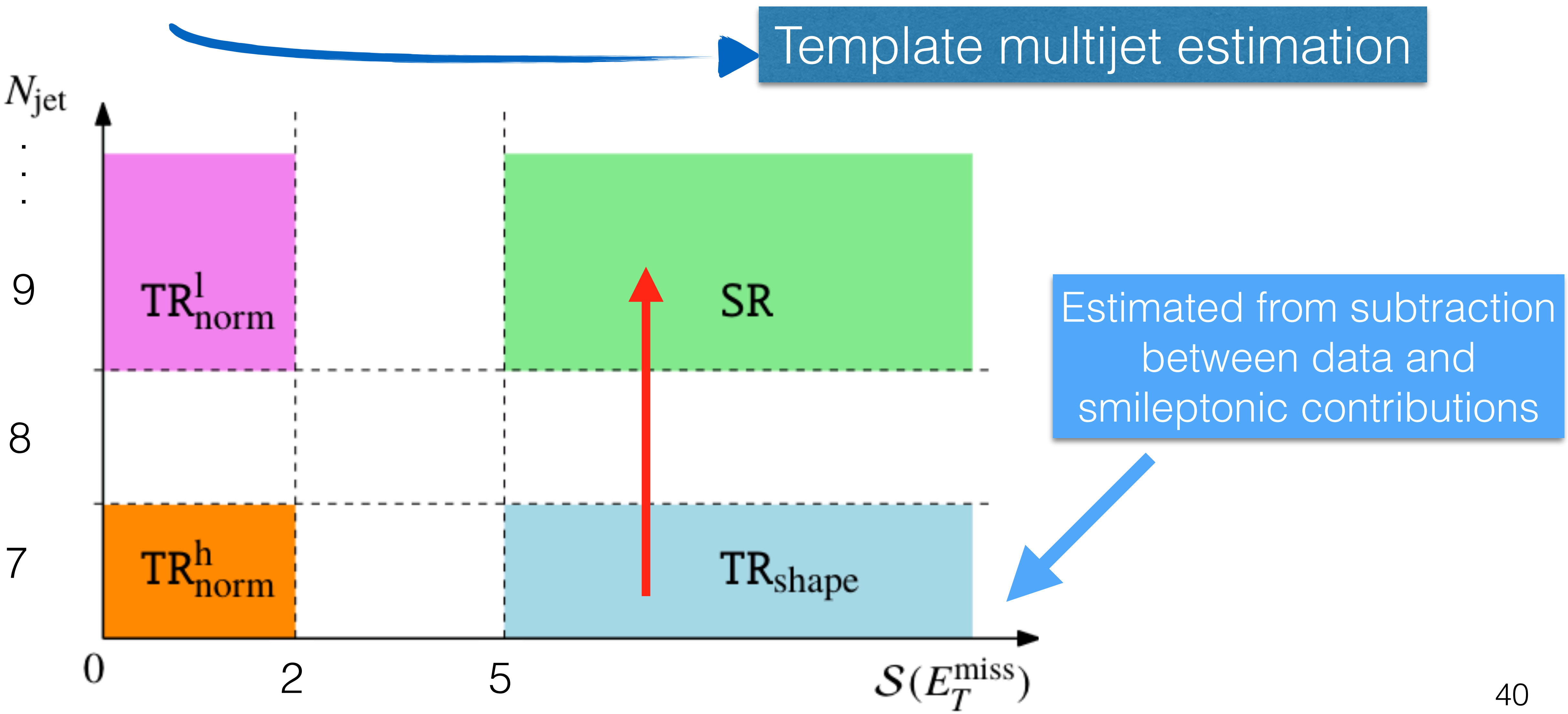
Multijets background estimation

The template method

- **Impossible to simulated multijet background (QCD) at 7-12 jets.**

Need a data-driven background estimation for multijet background.

- Idea: use invariance of MET significance shape to extrapolate multijet background from N_{jets}=7 for p_T > 50 GeV or (N_{jets}=5 for p_T > 80 GeV).



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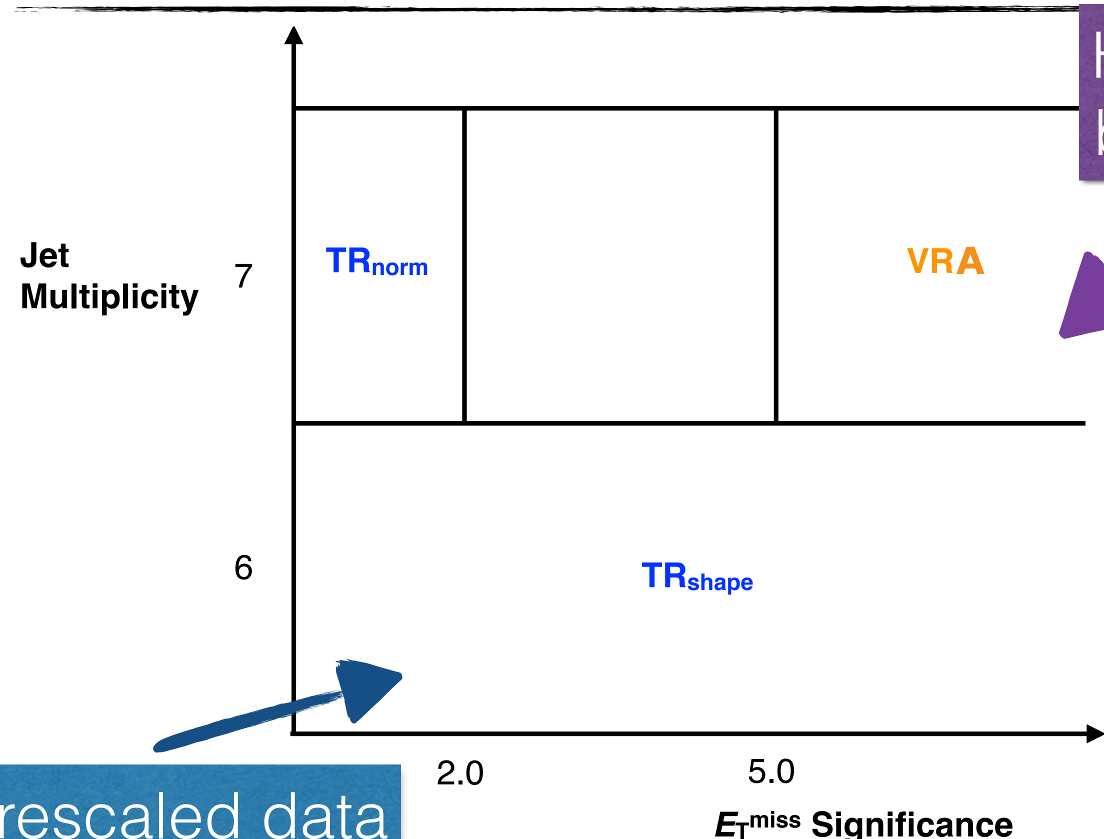
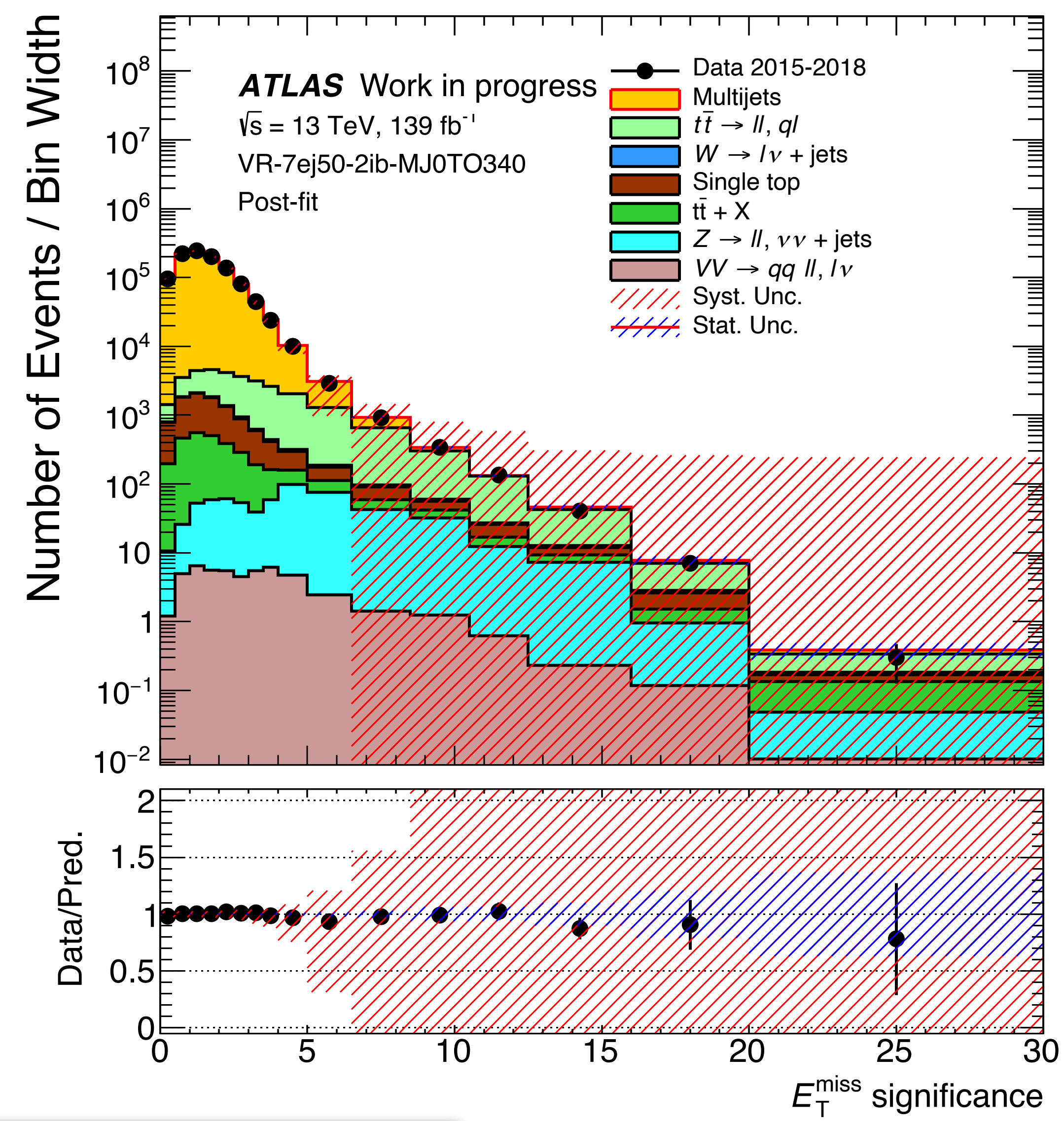
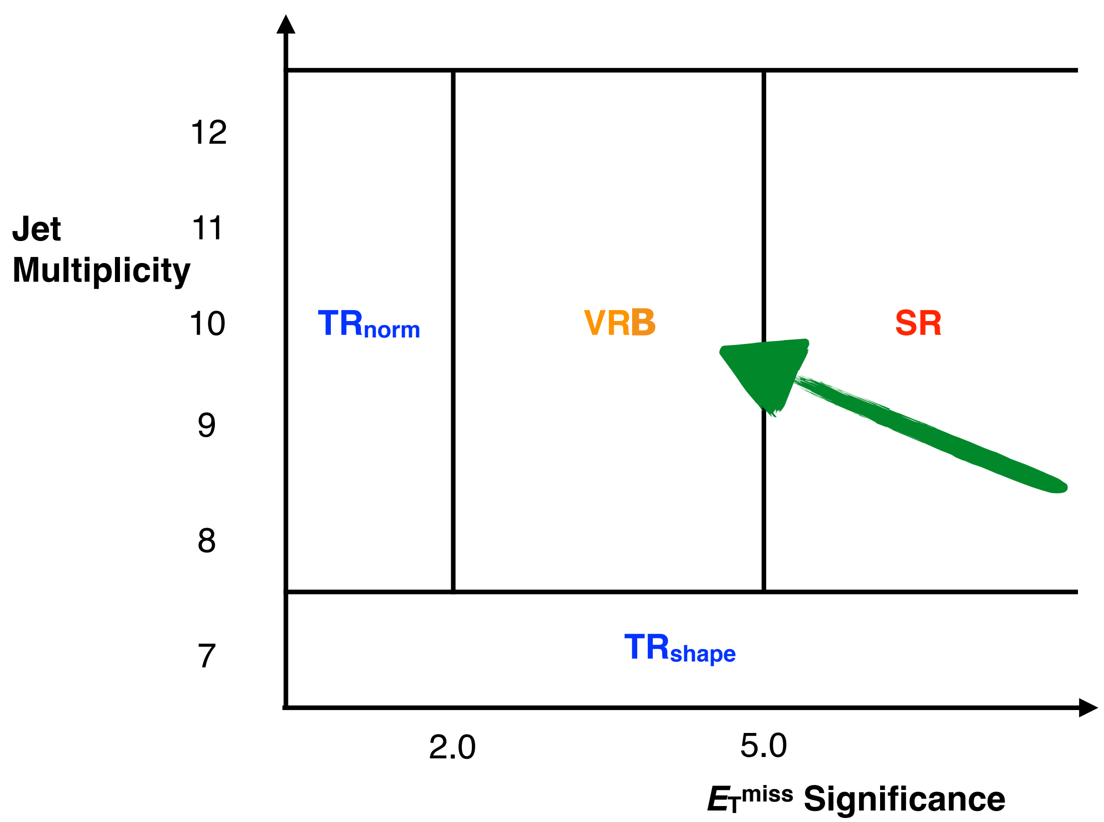
Background validation regions

High MET significance background validation



Prescaled data





Intermediate MET significance background validation

Ingredients for a SUSY analysis

Simplified version

1. Define a clear signature ✅
2. Physics objects and variables definition ✅
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4. Estimate the background in the Signal Regions ✅
5. Validate the background ✅
6. Unblind the results

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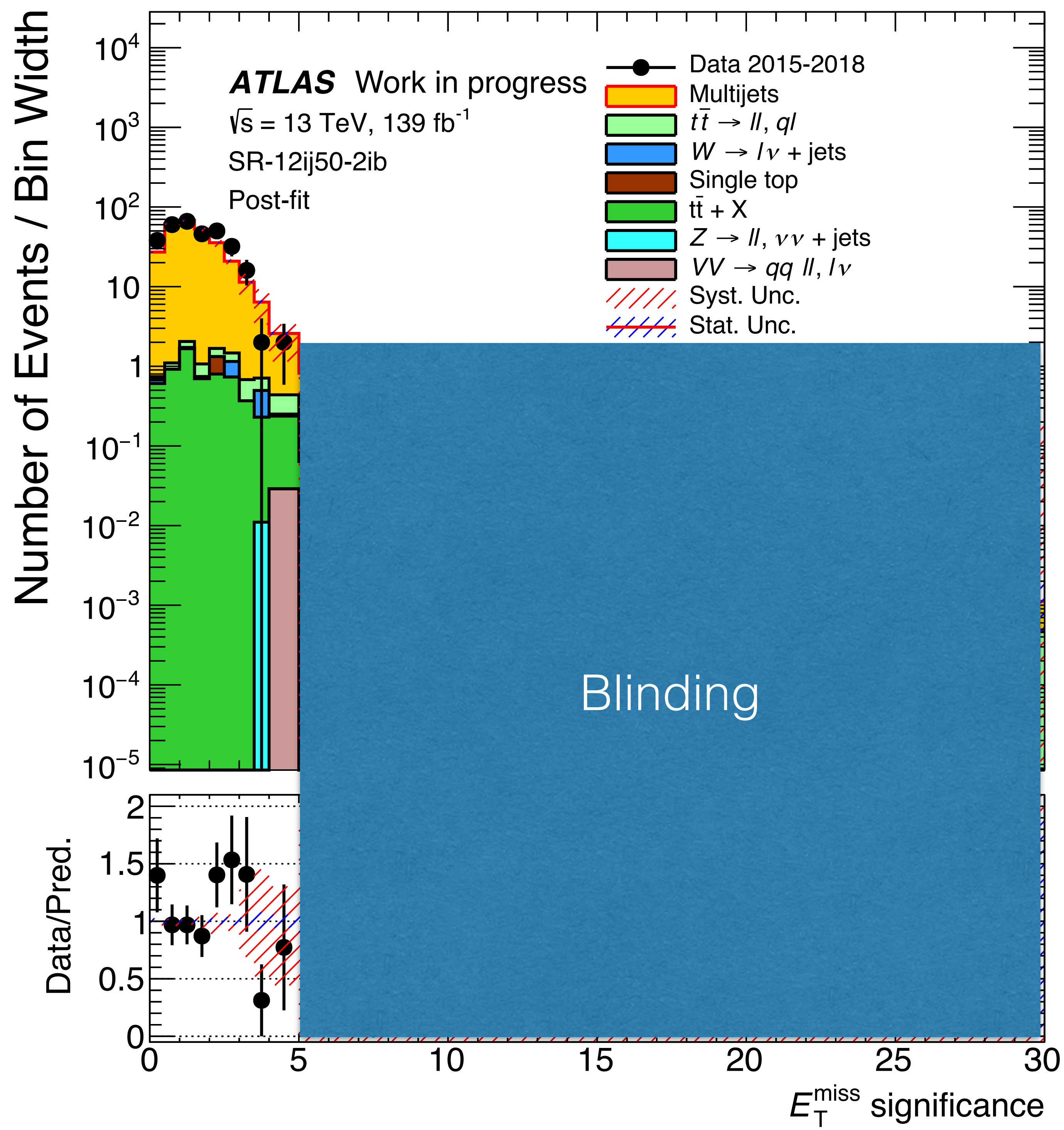
12 jets for the first time (1)

We can now unblind the analysis!



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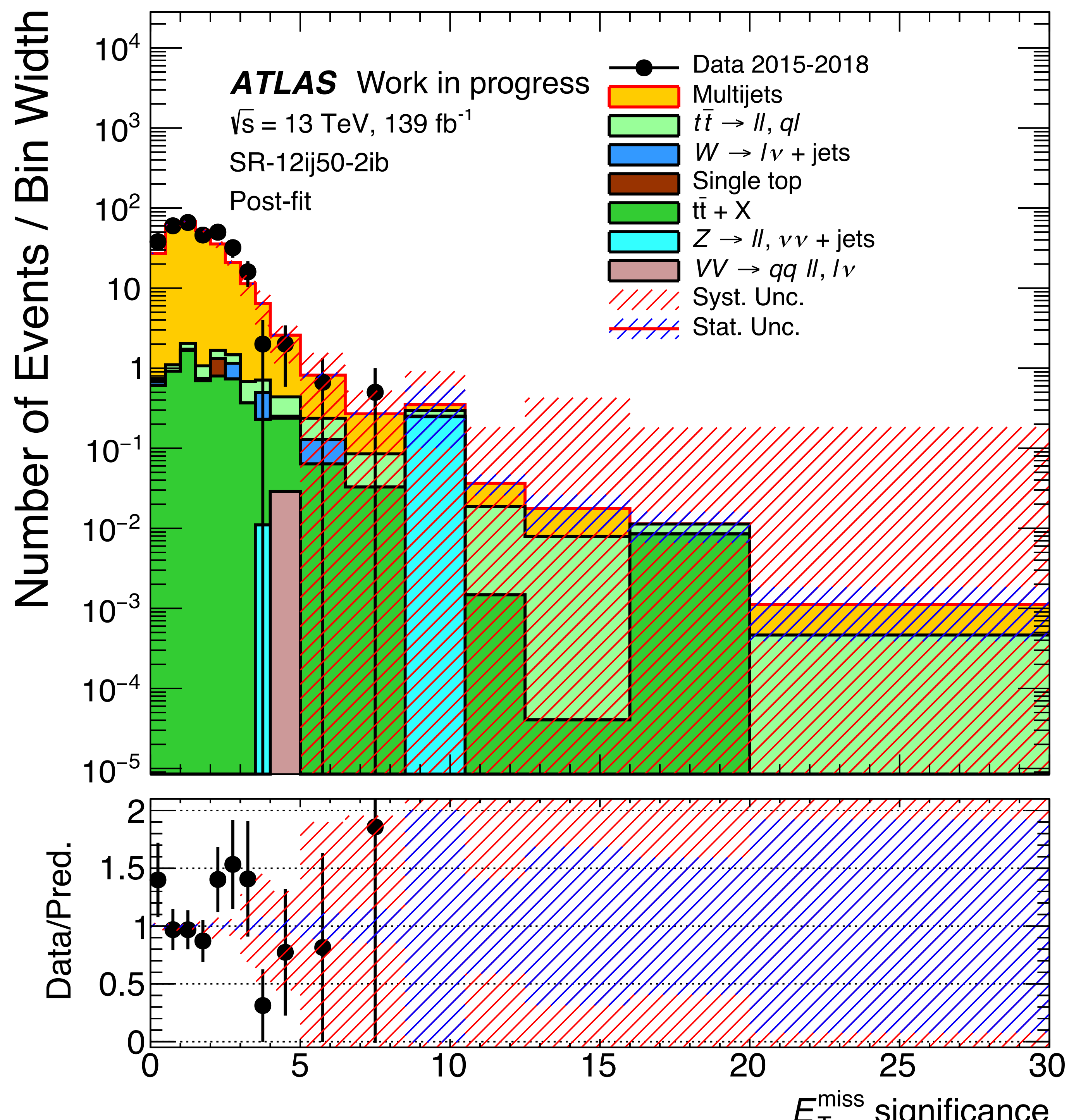
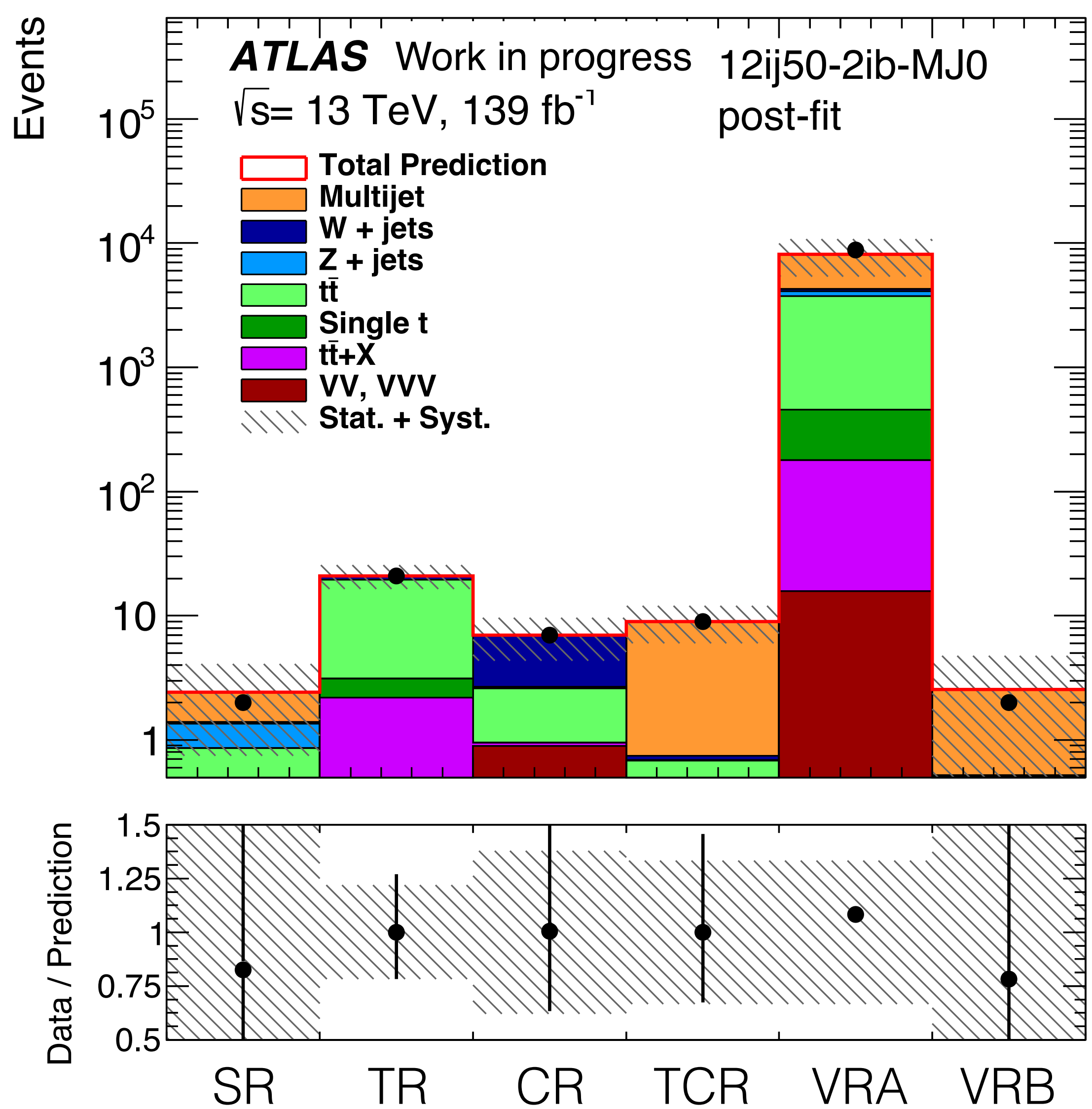
12 jets for the first time (1)

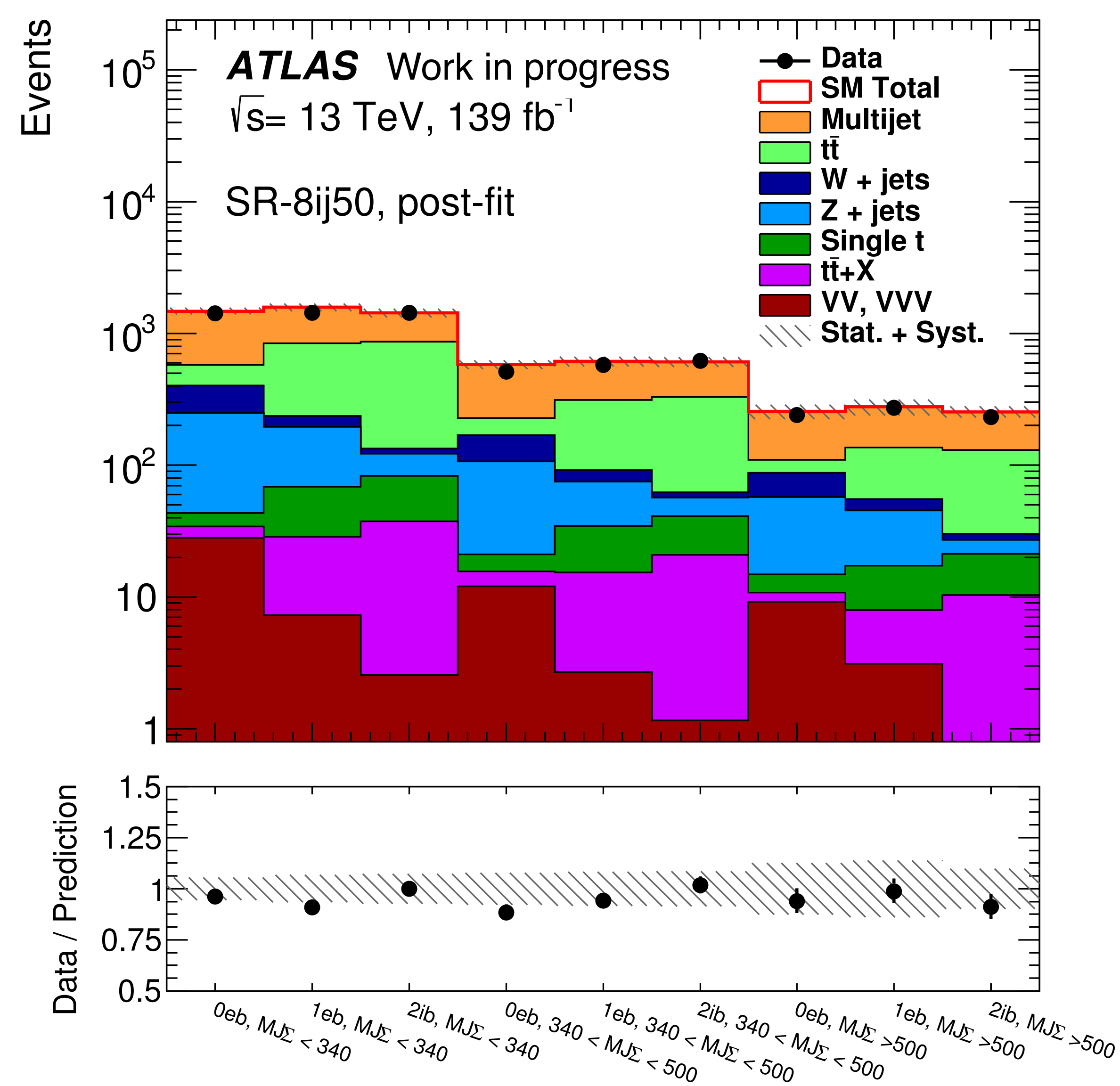
We can now unblind the analysis!



12 jets for the first time (2)

- No signal observed, but the modelling is great! Even with 12 jets!
- **No significant excess found in all other regions**, but amazing agreement between data and background prediction!





Nothing observed!
And now?

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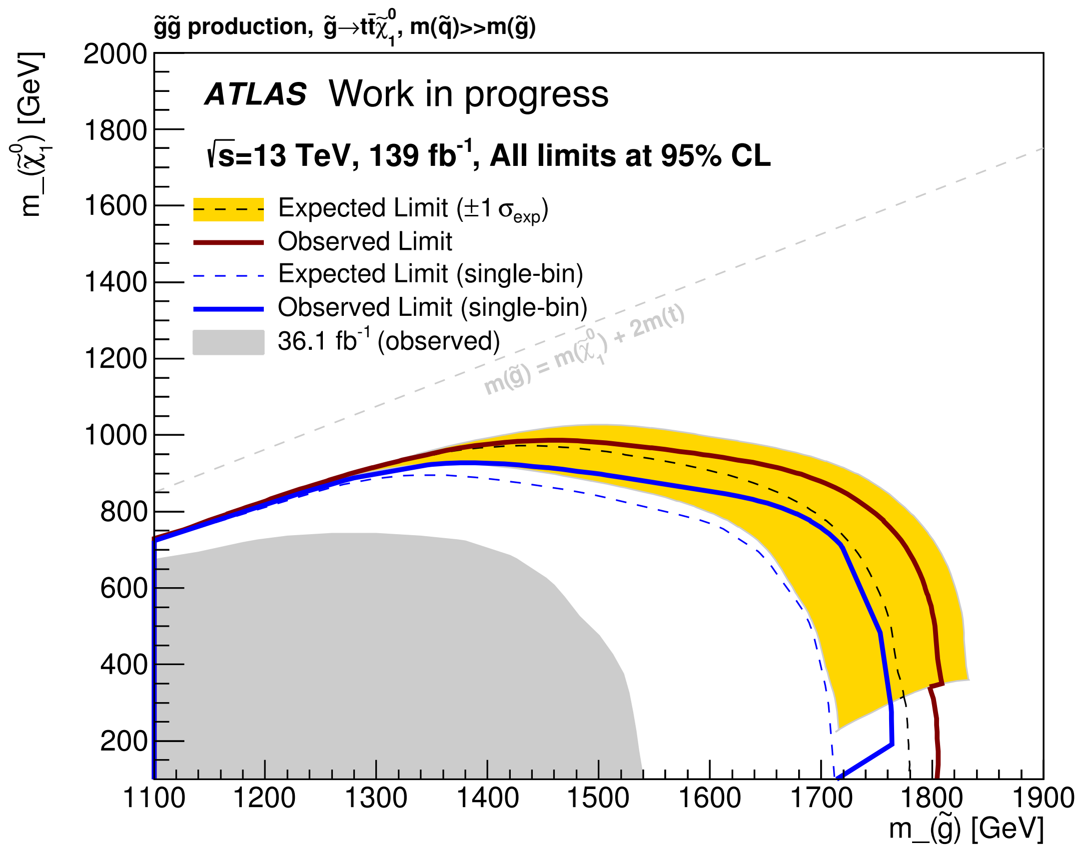
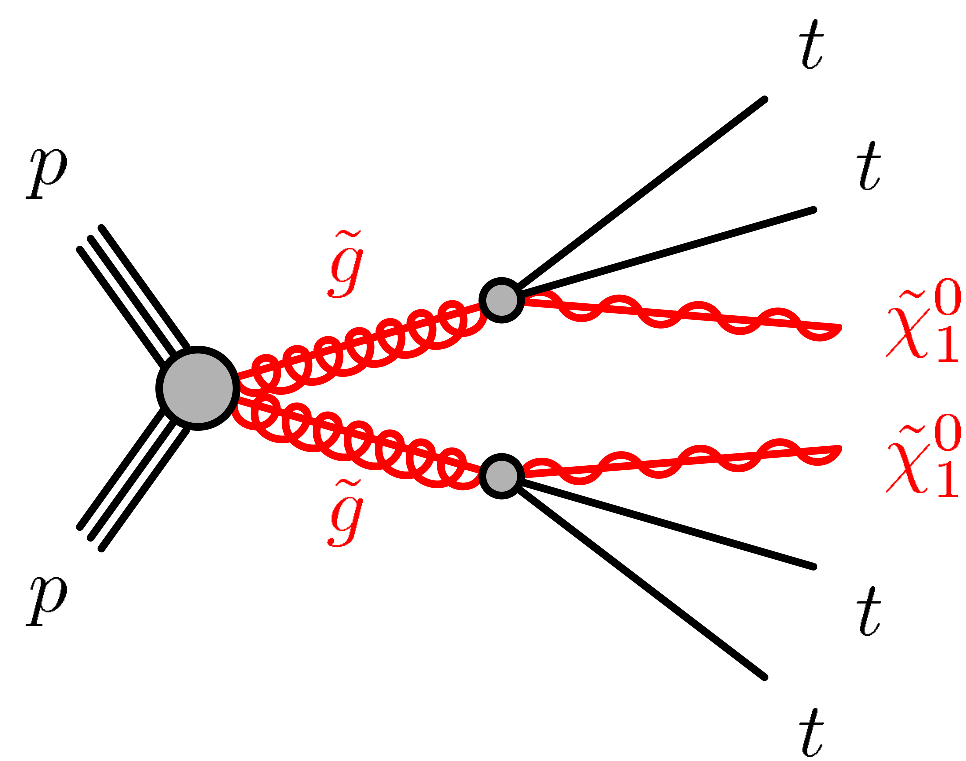
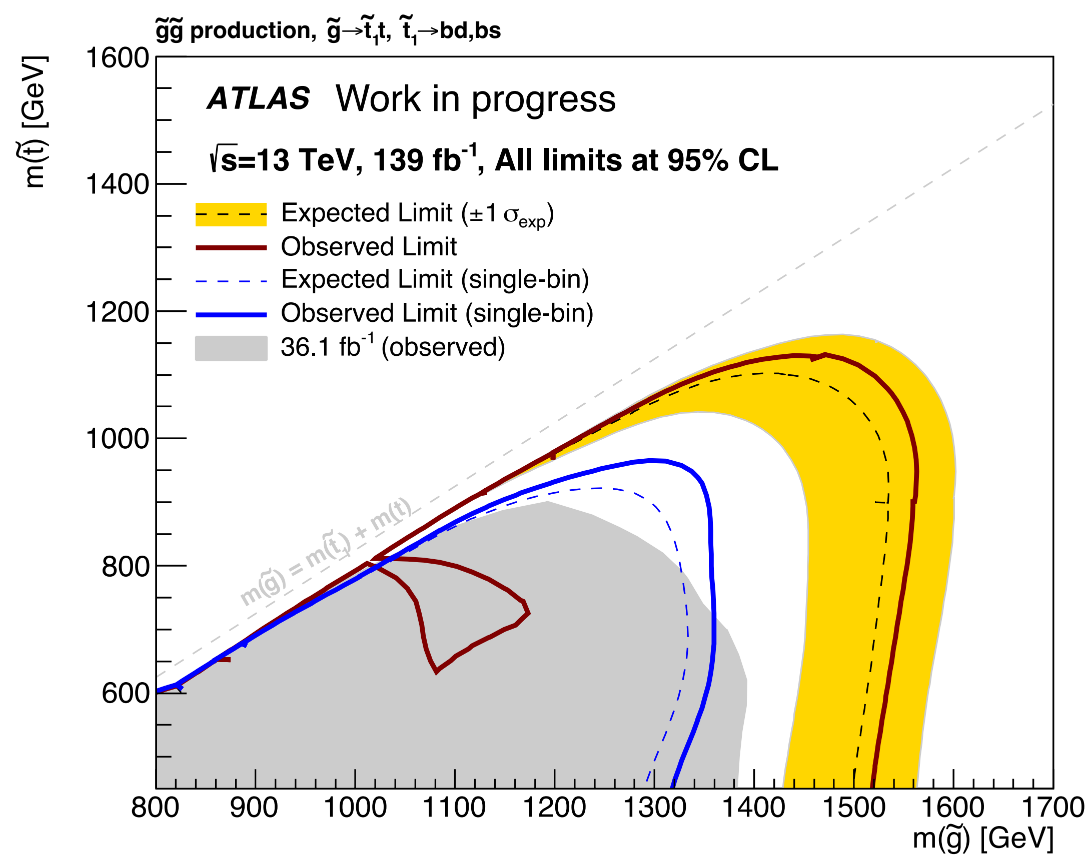
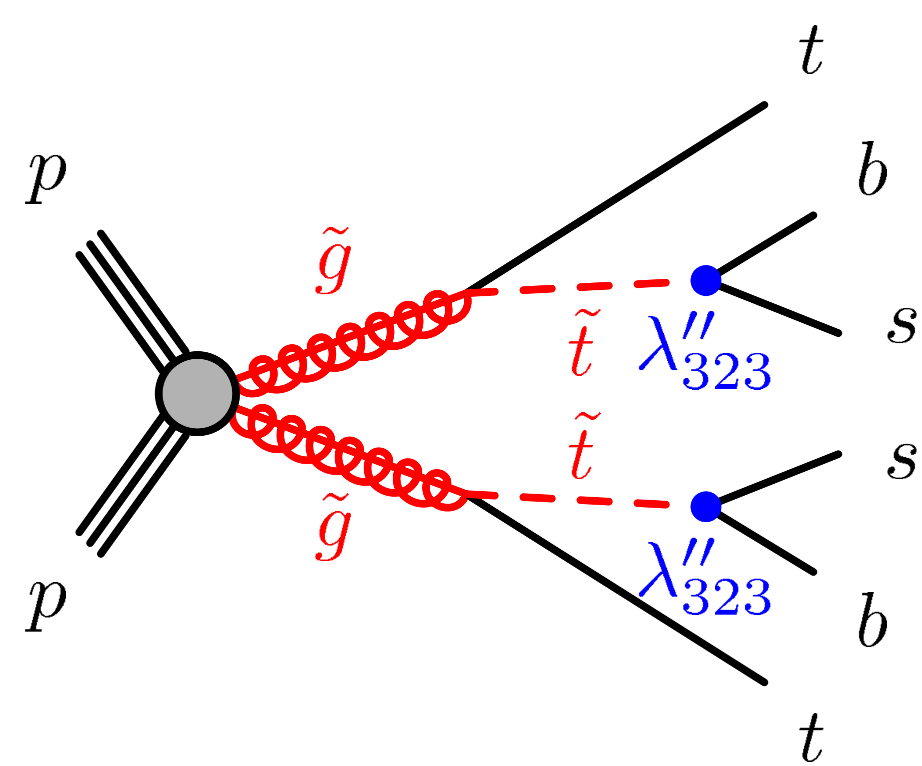
New limits with complete Run 2 dataset





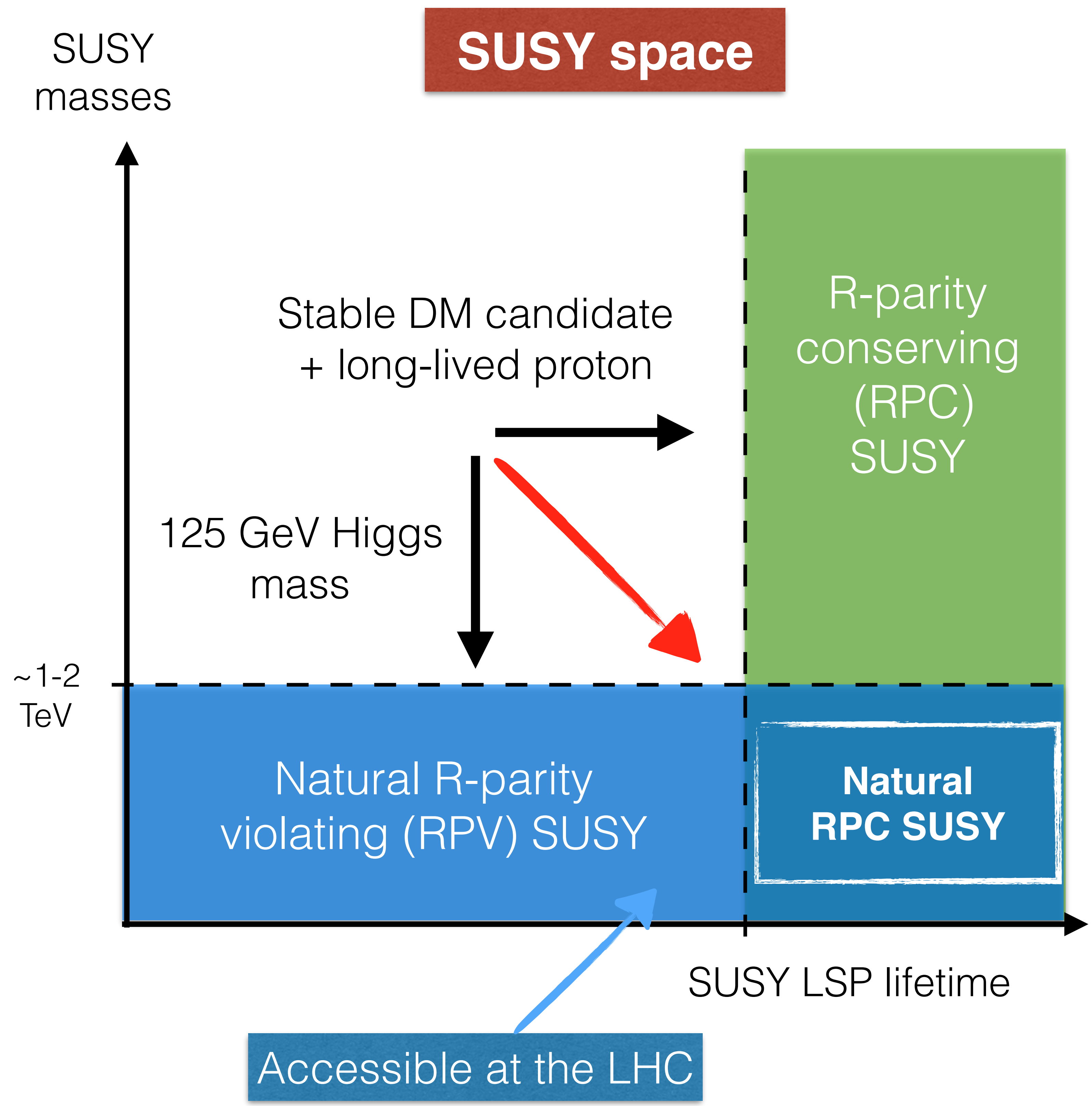




Can we extend our results to more complex SUSY scenarios?

Possible reinterpretations

R-parity violation



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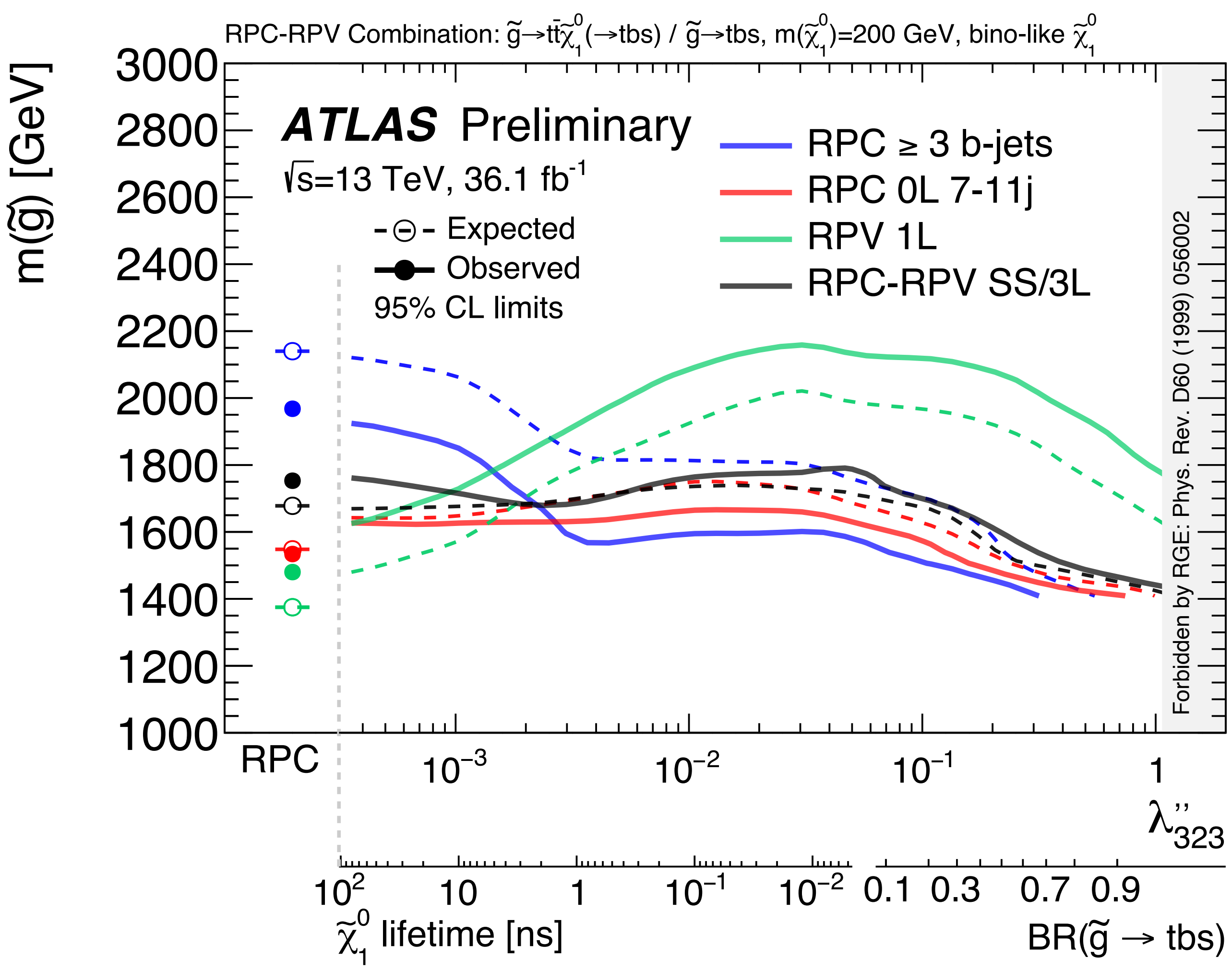
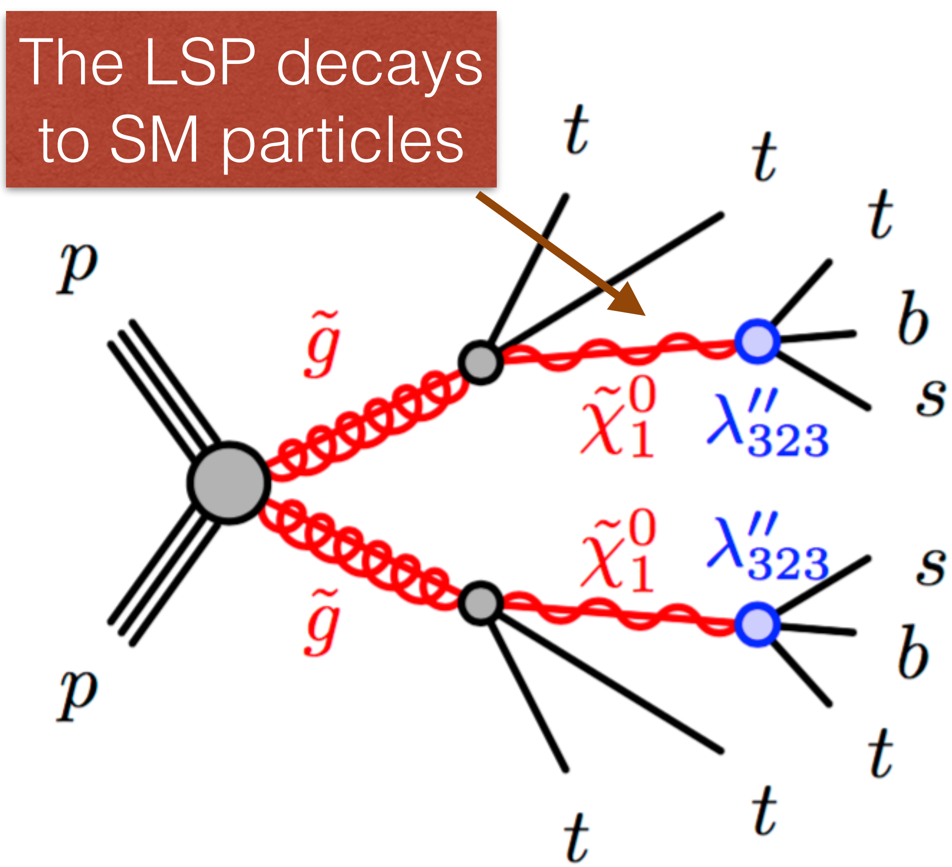
RPV reinterpretations

R-parity violation (RPV)

- This analysis cuts very low on MET significance —> good candidate for RPV reinterpretations!
- The analysis has been reinterpreted for R-parity violating (RPV) scenarios.
- 7-12 multijets analysis have stable sensitivity also to different RPV decays!





ATLAS-CONF-2018-003

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    4. Wanna see 12 jets results?
    5. Reinterpretation and current limits
4. **Conclusions and outlook**

Summary and outlook

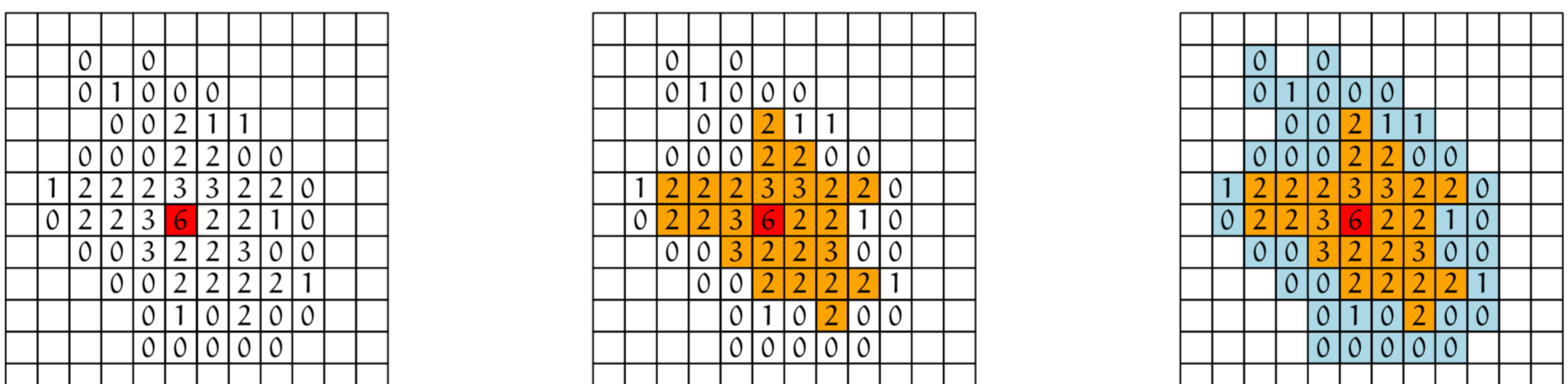
- The LHC Run 2 is finished and ATLAS is preparing now for Run 3 (2021).
- **Particle Flow jet/MET reconstruction is now well established** and will play a fundamental role in Run 3 and beyond.
- **Machine Learning** for neutral pileup mitigation seems to provide a possibly **useful tool for improving PFlow even more in future**.
- **Searches for SUSY are continuing at the LHC** and more complex scenarios are starting to get now more attention (RPV, EW SUSY, etc.).
- **0-lepton multijets analysis** has completed now the process of **complete Run 2 dataset** (paper published soon!).

Backup

Jet inputs - topoclustering

- Input constituents: ideal representation of final showering particles for jet building.
- Different possible constituent types.
- **ATLAS uses topoclustering constituents** today.
- Topoclustering (420 algorithm):
    1. Seeding from calorimeter cells having ϵ_{cell}>**4**.
    2. Seed growth using calorimeter cells satisfying ϵ_{cell}>**2**.
    3. Border creation using calorimeter cells passing ϵ_{cell}>**0**.
- **Pure calorimeter-based reconstruction** for these objects.

$$\epsilon_{\text{cell}}^{\text{EM}} = \frac{E_{\text{cell}}^{\text{EM}}}{\sigma_{\text{noise,cell}}^{\text{EM}}}$$



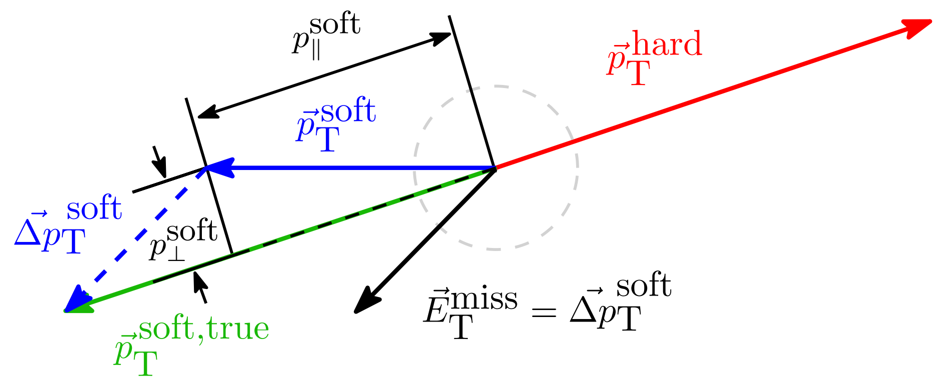
(a) Clustering of $|\epsilon_{\text{cell}}^{\text{EM}}| > 4$ cells. (b) Clustering of $|\epsilon_{\text{cell}}^{\text{EM}}| > 2$ cells. (c) Clustering of $|\epsilon_{\text{cell}}^{\text{EM}}| > 0$ cells.

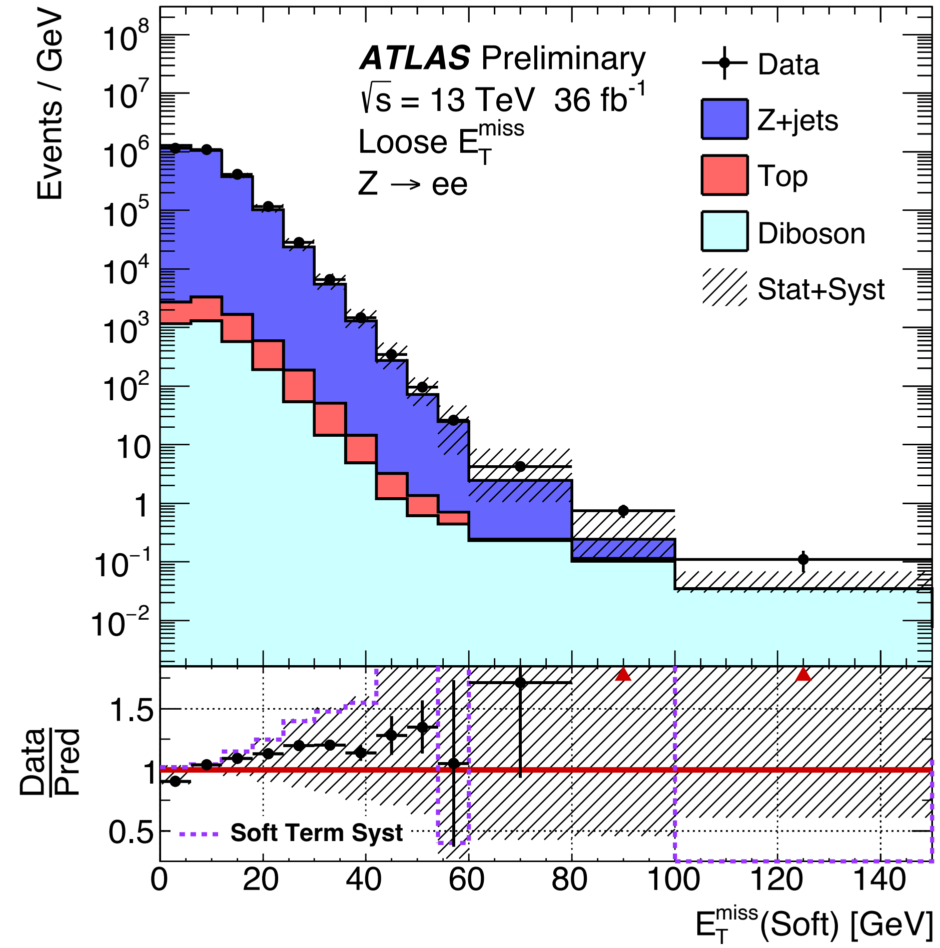
TST systematic uncertainties

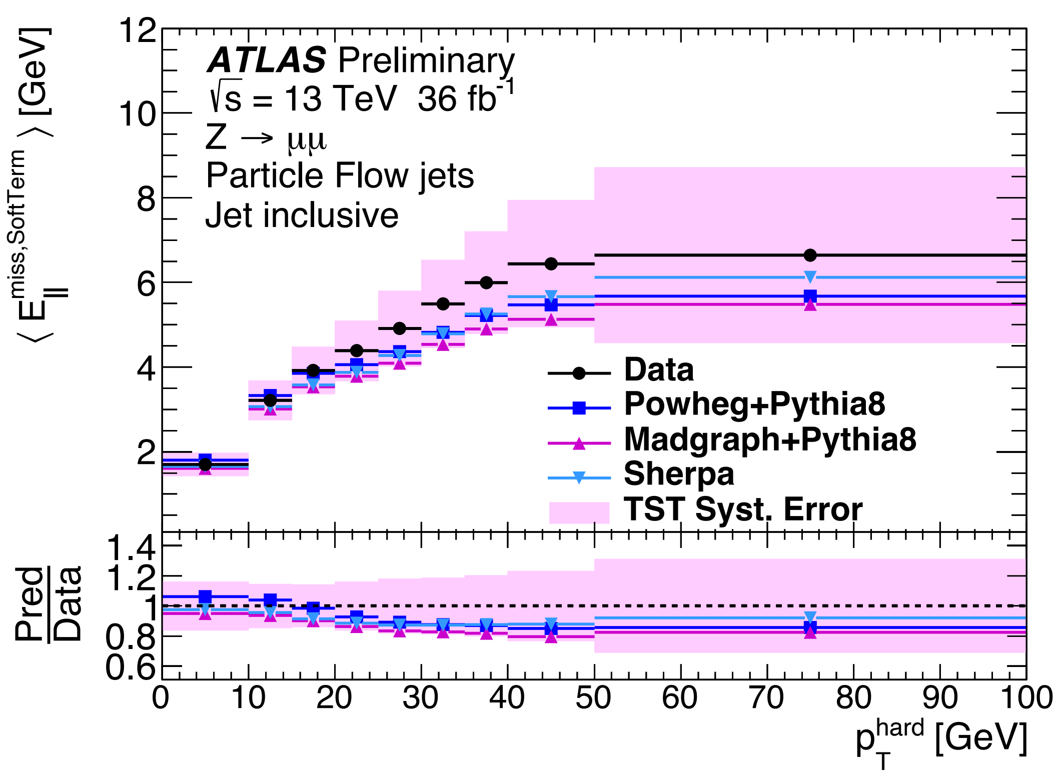
TST systematic uncertainties

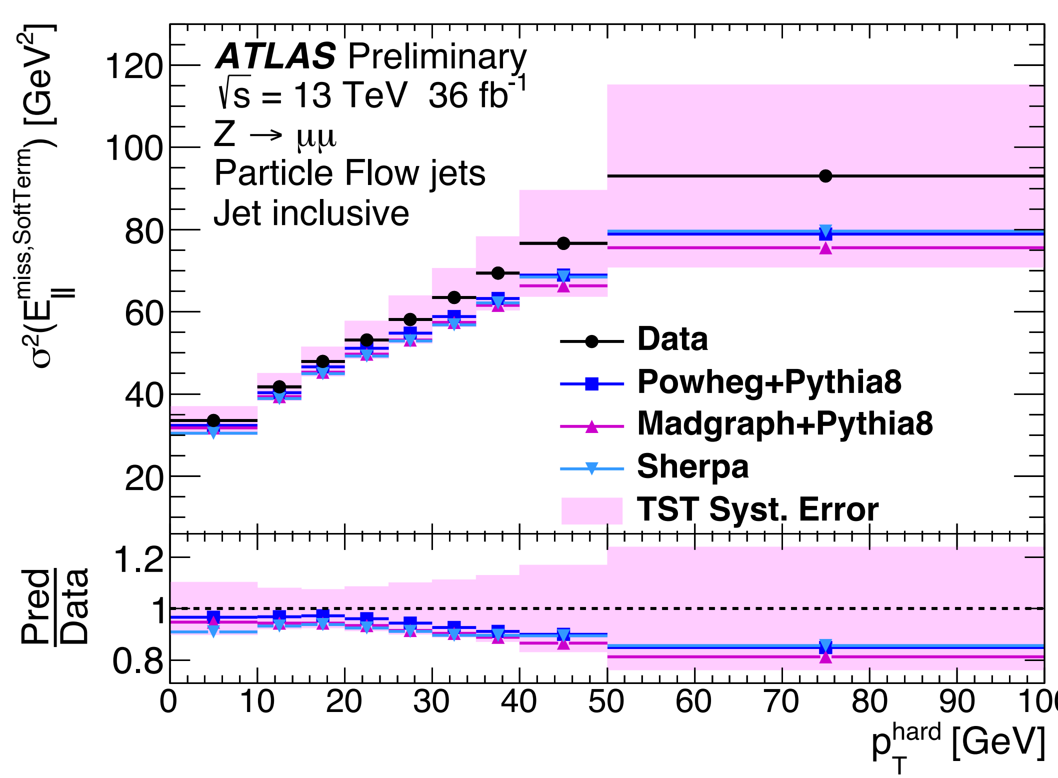
The systematics uncertainties specifically derived for MET are the **TST systematics**. These are evaluated by computing the maximal data/MC discrepancies of three projected quantities:

- Parallel scale: average value of p_T^{soft} projection parallel to p_T^{hard}.
- Parallel resolution: RMS value of p_T^{soft} projection parallel to p_T^{hard}.
- Perpendicular resolution: RMS value of p_T^{soft} projection perpendicular to p_T^{hard}.









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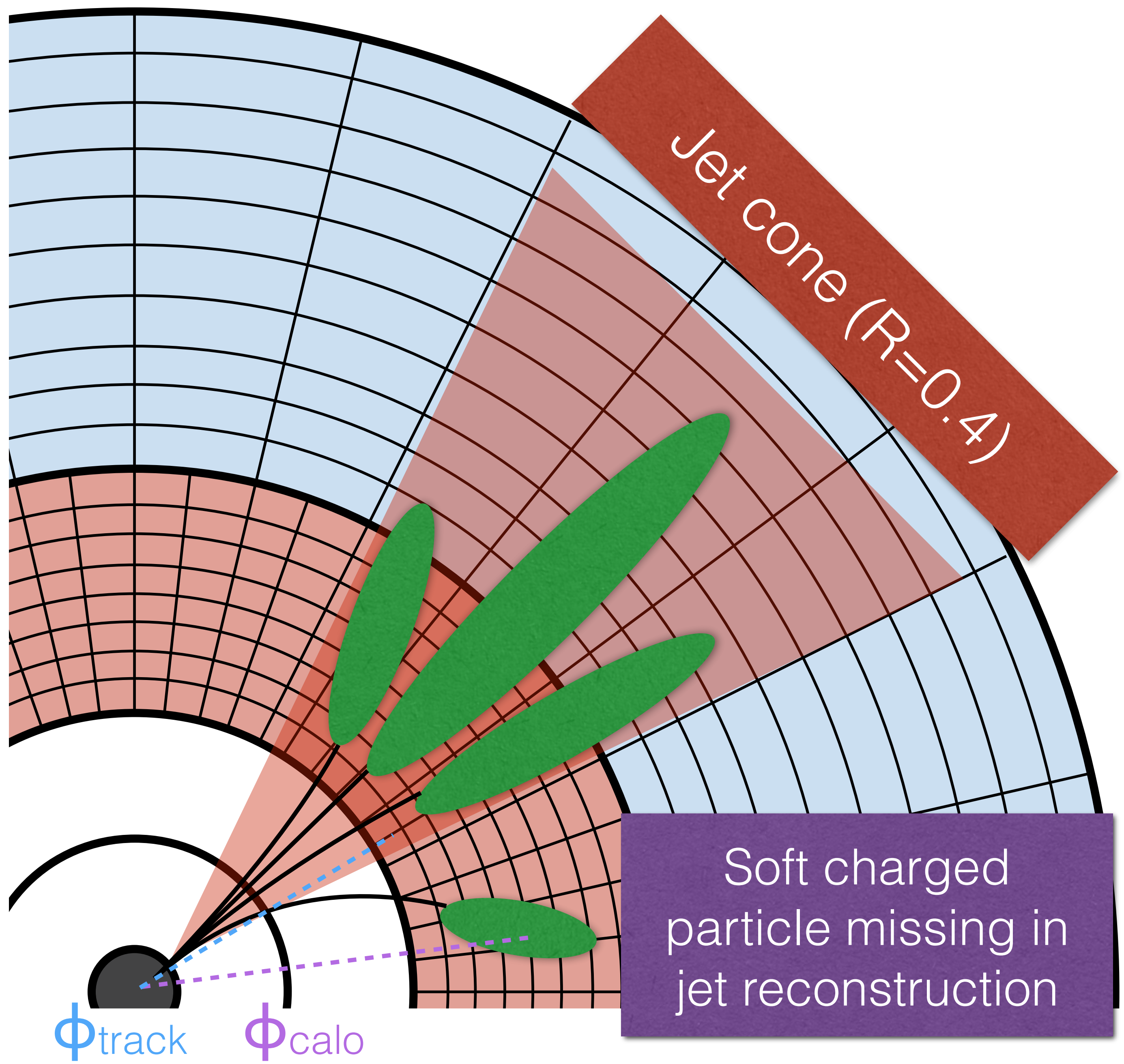
Particle Flow reconstruction (2)

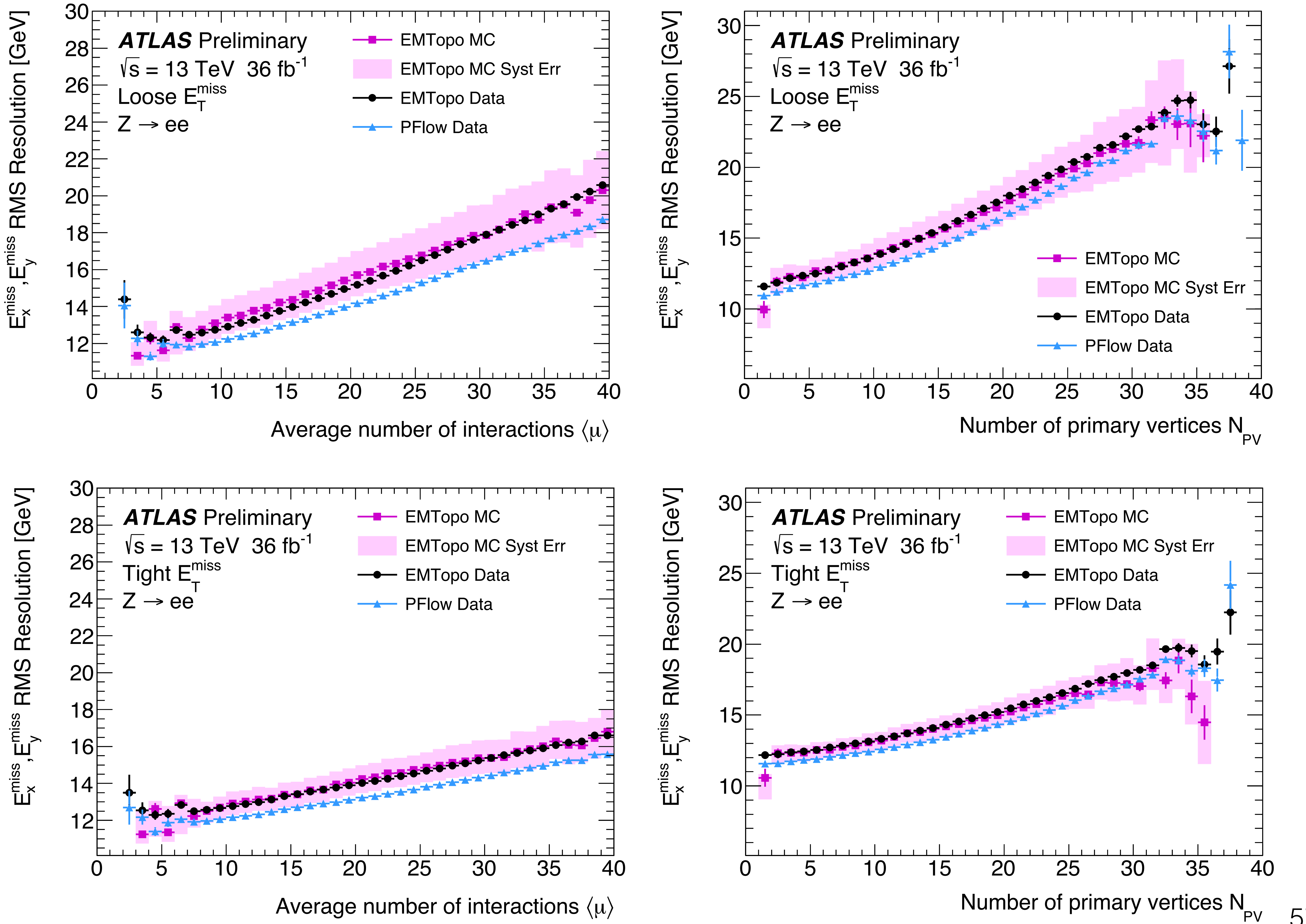
Another improvement

Inclusion of missing soft charged particles in jets
due to magnetic bending (very important for CMS!)



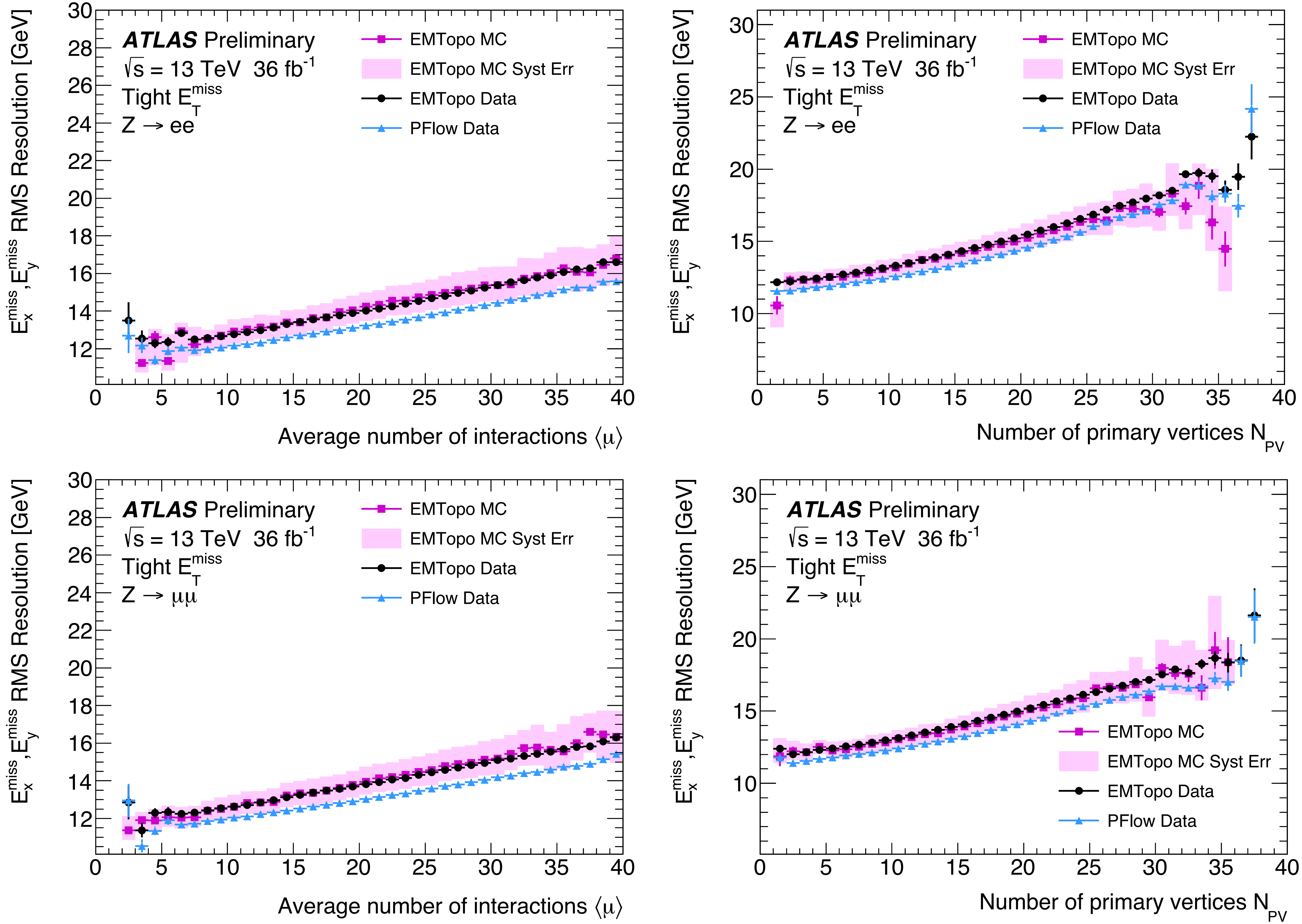
Particle Flow MET

Resolutions for Tight and Loose Working Points



Particle Flow MET

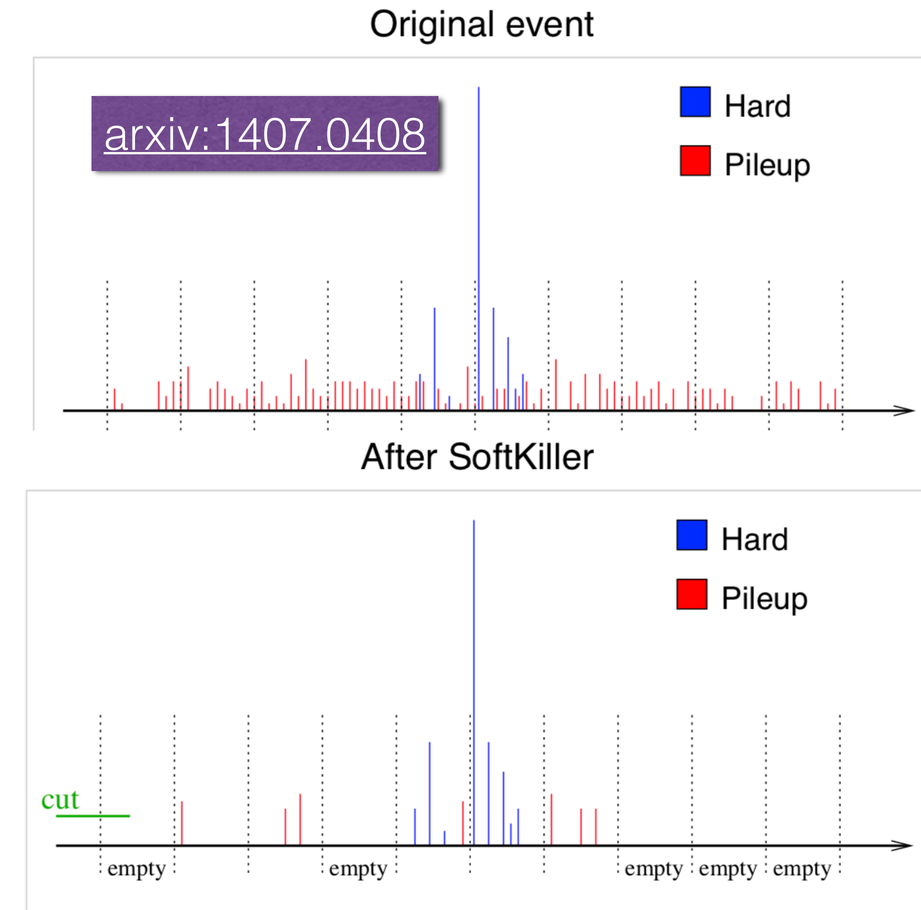
Resolutions for Z→ee and Z→μμ

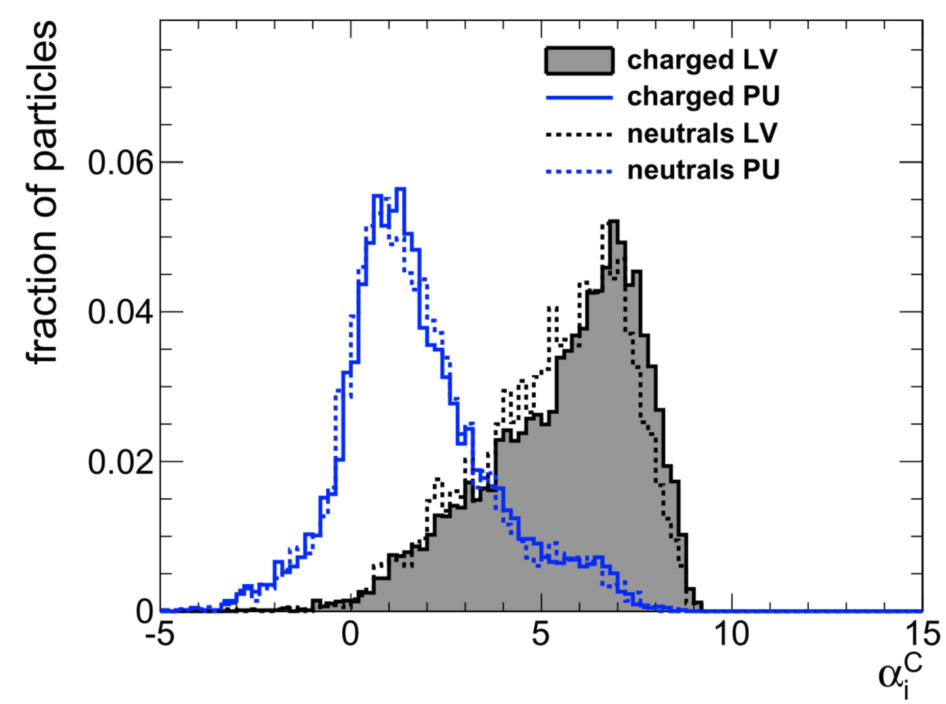


More on ML for neutral PU mitigation (1)

- On neutral PFOs, this is more difficult as no tracking information is available.
- Soft Killer (SK): divide η-ϕ plane into patches and choose the p_T cut implying 1/2 of filled patches by consituents.
- PUPPI: reject neutral pileup clusters using proximity with other high pT Charged hard-scatter clusters.

$$\alpha_i^C = \log \sum_{j\in \mathrm{Ch},} \frac{p_{Tj}}{\Delta R_{ij}^{\beta}} \Theta(R_{\min} \le \Delta R_{ij} \le R_0),$$





More on ML for neutral PU mitigation (2)

- Possible to identify pileup neutral PFOs using:

$$\left|\frac{E - E_{\mathrm{DigiHSTruth}}}{E_{\mathrm{DigiHSTruth}}}\right| < 0.5$$

- Possibly **useful variables**:
  - Kinematic quantities: pT, η, ϕ
  - Topocluster timing (t)
  - PUPPI α
  - LAr and Tile signal quality
  - Topocluster shape information
  - And others…

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MET triggers at HL-LHC

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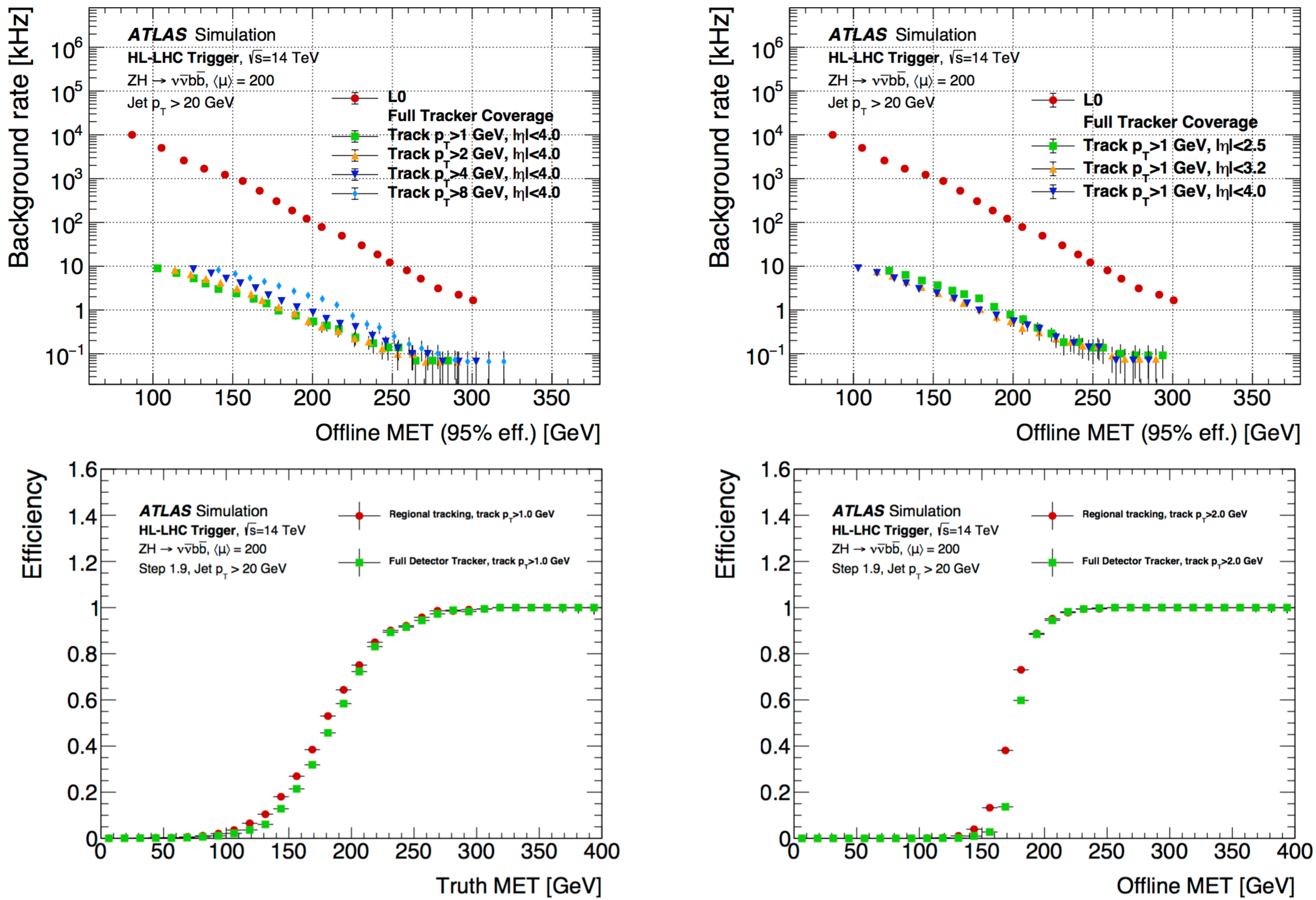
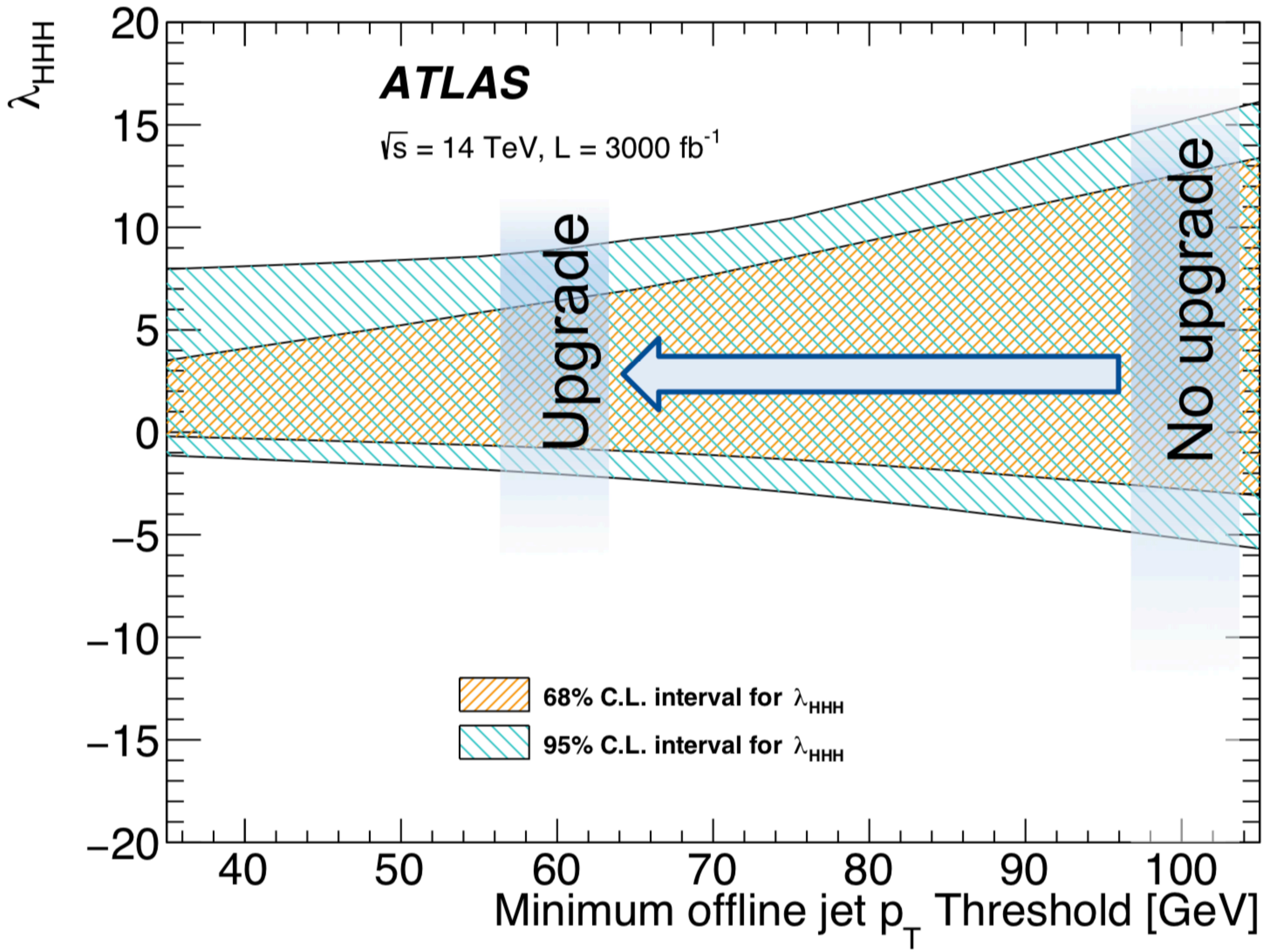


Impact on HHH coupling of TDAQ Phase-2 upgrade

ATLAS-TDR-029



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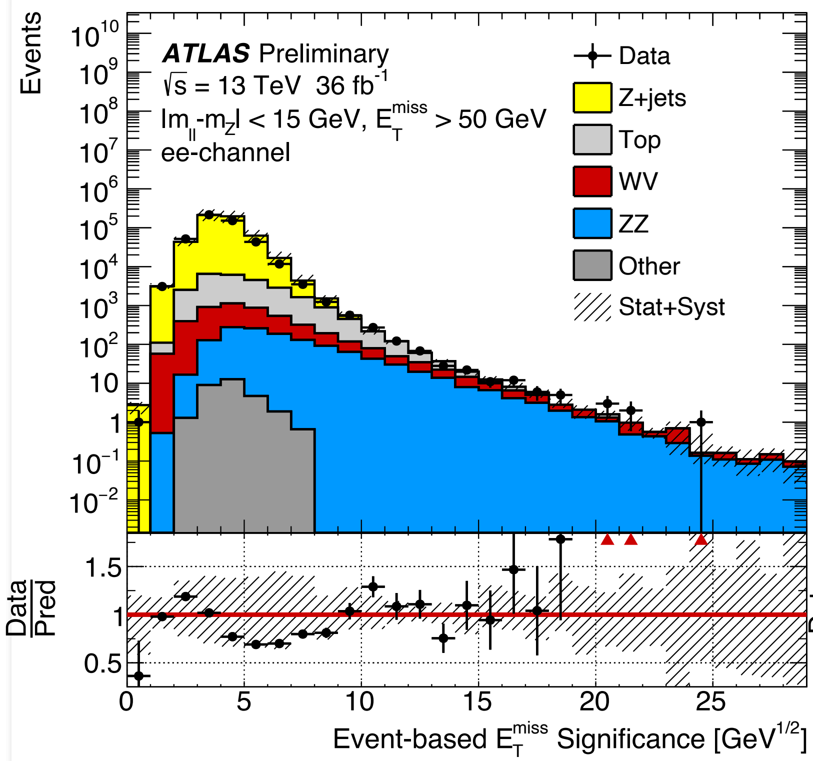
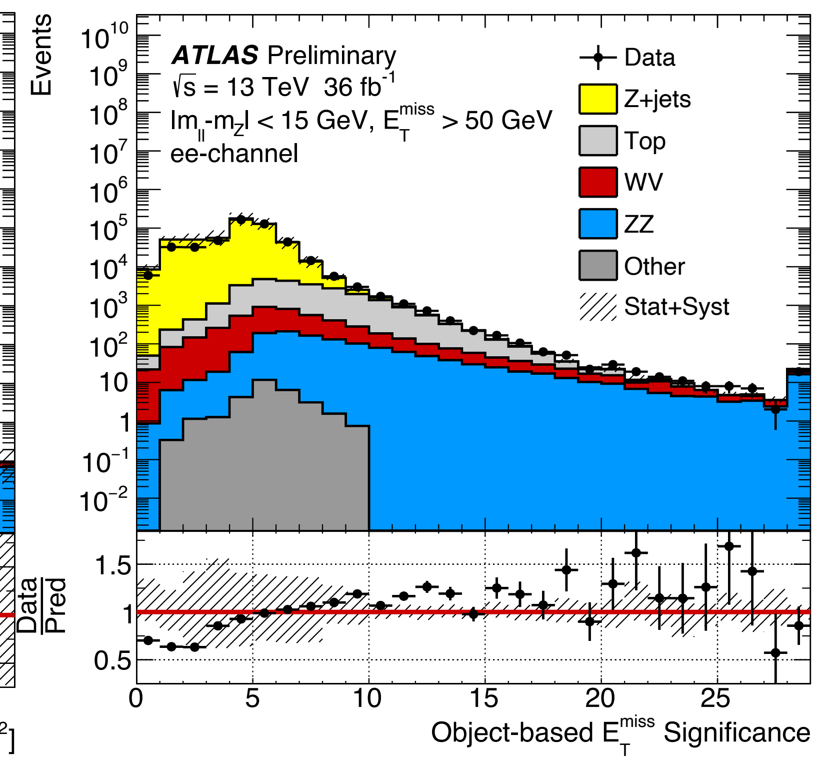
Object-based MET significance

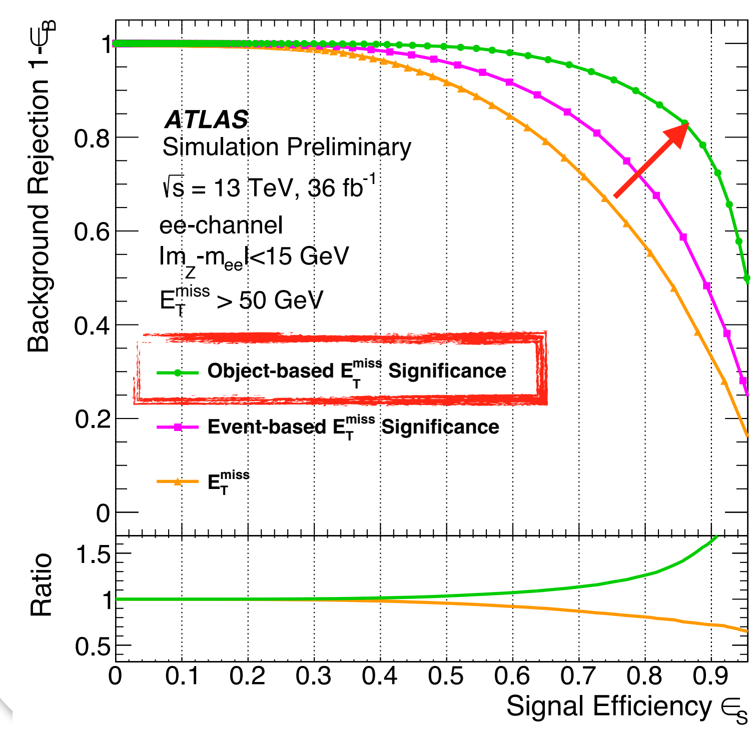
Object-based MET significance

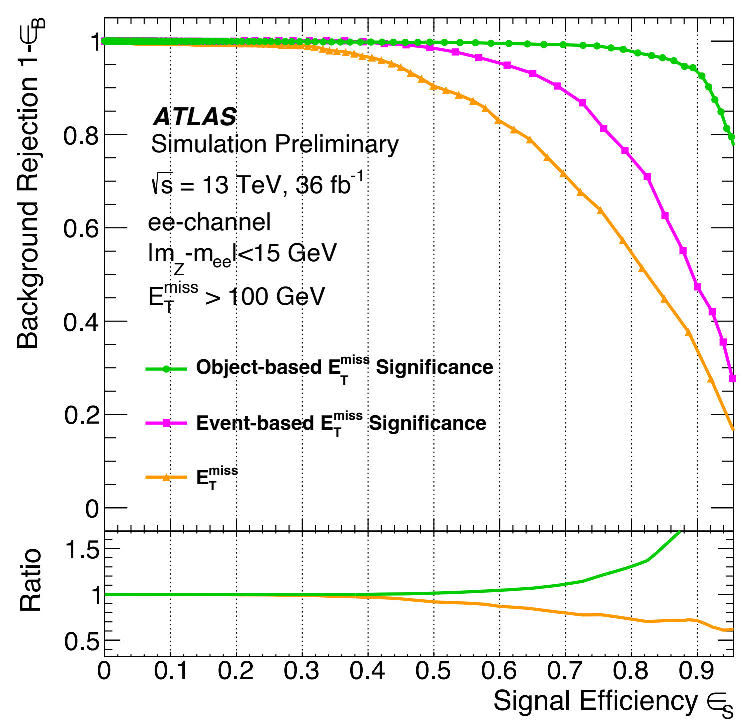
ATLAS object-based MET significance





Fake MET events ($Z\rightarrow ee$) has better separation from the ones with True MET.





ROC curves made using $Z\rightarrow ee$ and $Z\rightarrow ee\nu\nu$ as background and signal samples show clearly that **the object based MET significance provides better separation for events with true and fake MET**.

Multijets systematic uncertainties

- Background prediction needs an uncertainty before being compared to data.
- Considered systematics:
  - **Detector systematics:** accounting for the detector misconstruction effects (jet calibration uncertanties, b-tagging mismeasurement, etc.)
  - **Theory systematics:** accounting for wrong MC background modelling (ISR, FSR, etc.).
  - **Template systematics:** accounting for non closure, flavour and kinematic binning dependency.
- **Dominant systematics are generally the theoretical** (bad modelling of such an high jet multiplicity) **and template ones**.
- Jet systematics dominate the detector systematics due to the large number of jets O(10%).

Systematic	Relative difference (%)
JET_Flavor_Composition__1down	−5.2
JET_Flavor_Composition__1up	5.9
JET_Flavor_Response__1down	4.0
JET_Flavor_Response__1up	−3.8
JET_JER_DataVsMC_MC16__1down	0.2
JET_JER_DataVsMC_MC16__1up	0.2
JET_JER_EffectiveNP_1__1down	0.8
JET_JER_EffectiveNP_1__1up	0.8
JET_JER_EffectiveNP_2__1down	1.4
JET_JER_EffectiveNP_2__1up	1.4
JET_Pileup_OffsetMu__1down	−0.3
JET_Pileup_OffsetMu__1up	−1.8
JET_Pileup_OffsetNPV__1down	0.9
JET_Pileup_OffsetNPV__1up	−0.7
JET_Pileup_PtTerm__1down	−0.6
JET_Pileup_PtTerm__1up	0.5
JET_Pileup_RhoTopology__1down	−3.0
JET_Pileup_RhoTopology__1up	2.9
JET_PunchThrough_MC16__1down	−0.0
JET_PunchThrough_MC16__1up	0.0
JET_SingleParticle_HighPt__1down	−0.2
JET_SingleParticle_HighPt__1up	−0.2
MET_SoftTrk_ResoPara	−0.3
MET_SoftTrk_ResoPerp	−0.2
MET_SoftTrk_ScaleDown	0.3
MET_SoftTrk_ScaleUp	−0.3

The SUSY 0-lepton Multijets analysis (4)

Analysis strategy (Signal regions)

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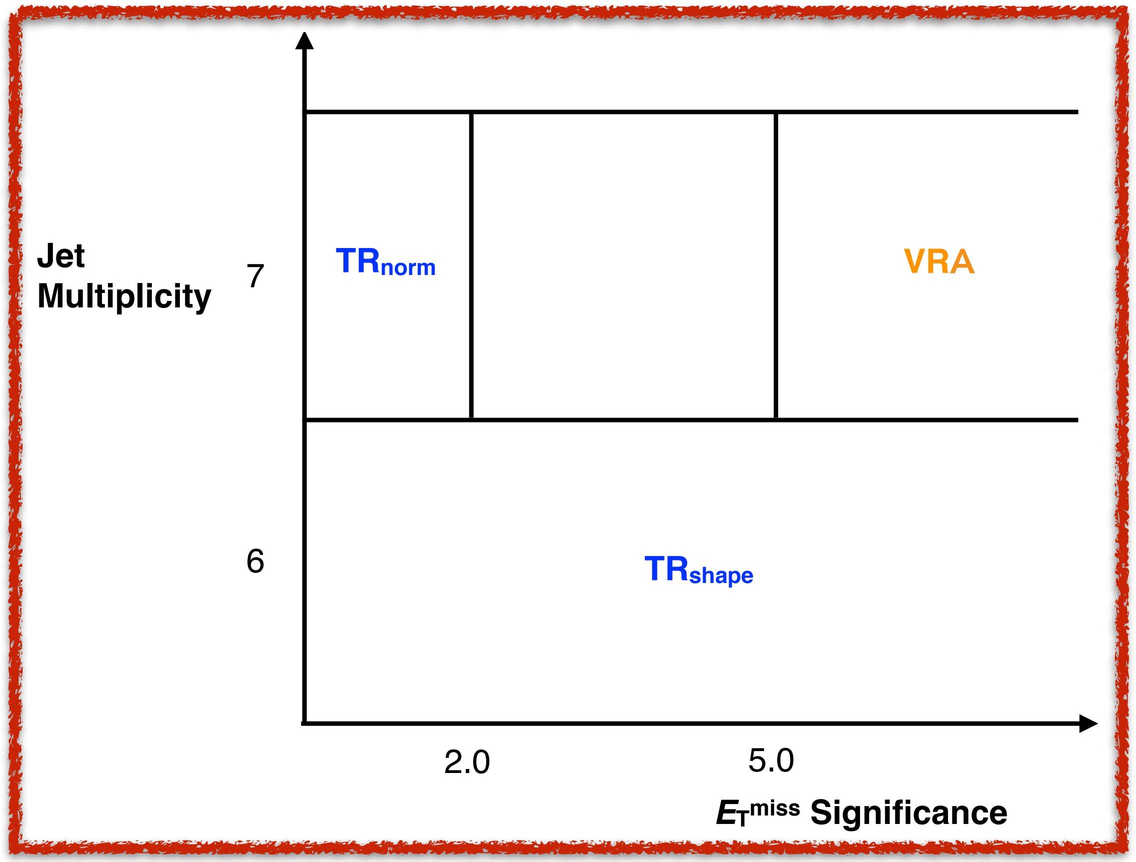
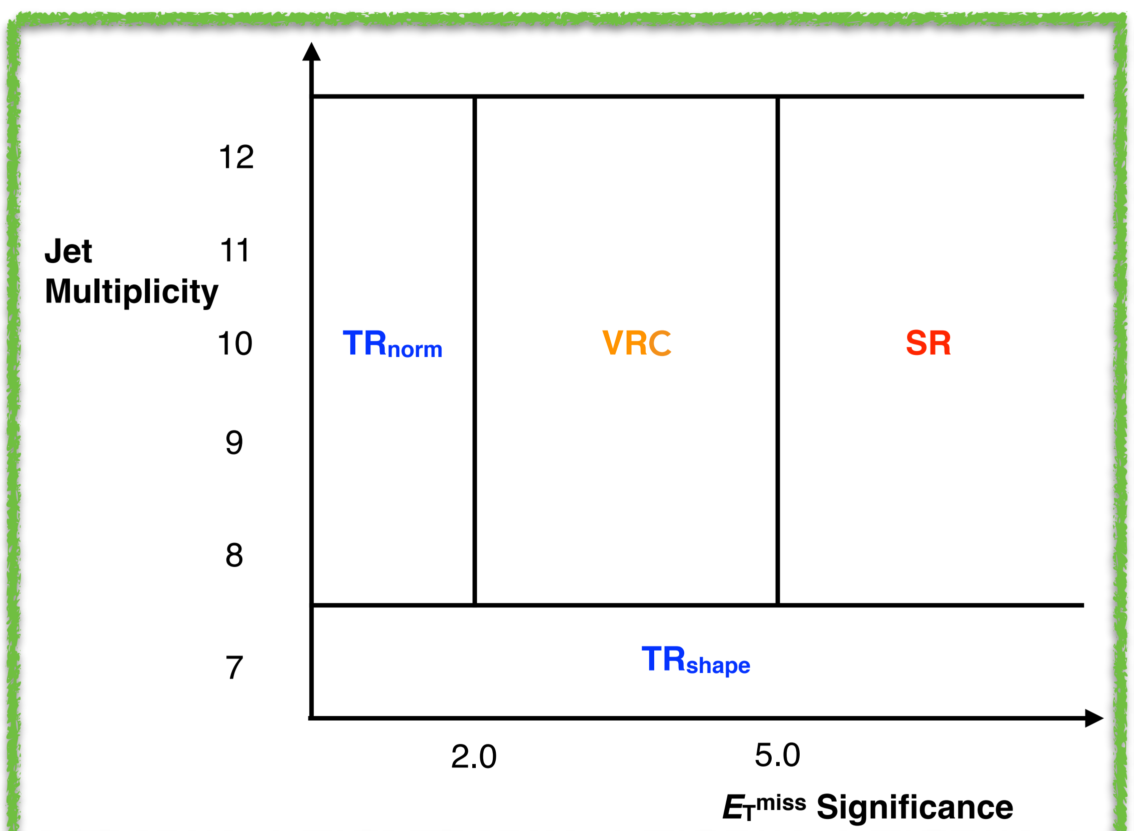
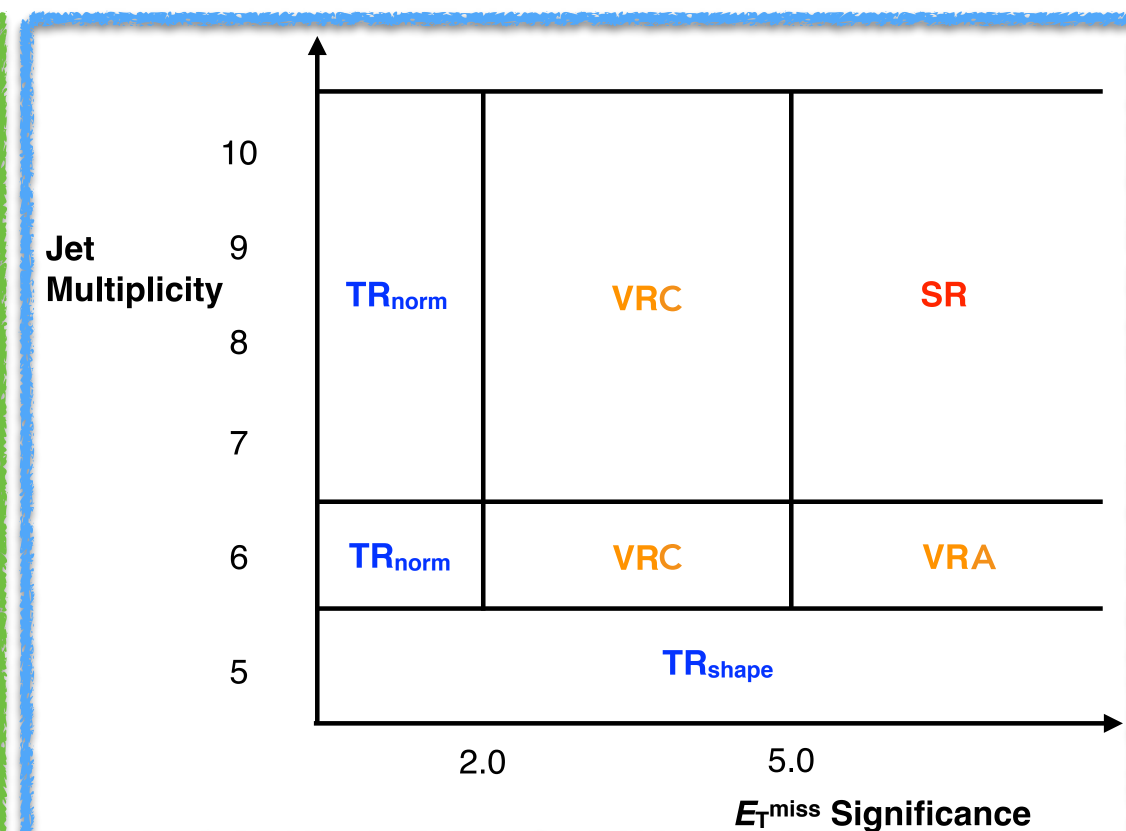


Validation Regions (VR)

Signal Regions (SR) p_T > 50 GeV



Signal Regions (SR) p_T > 80 GeV



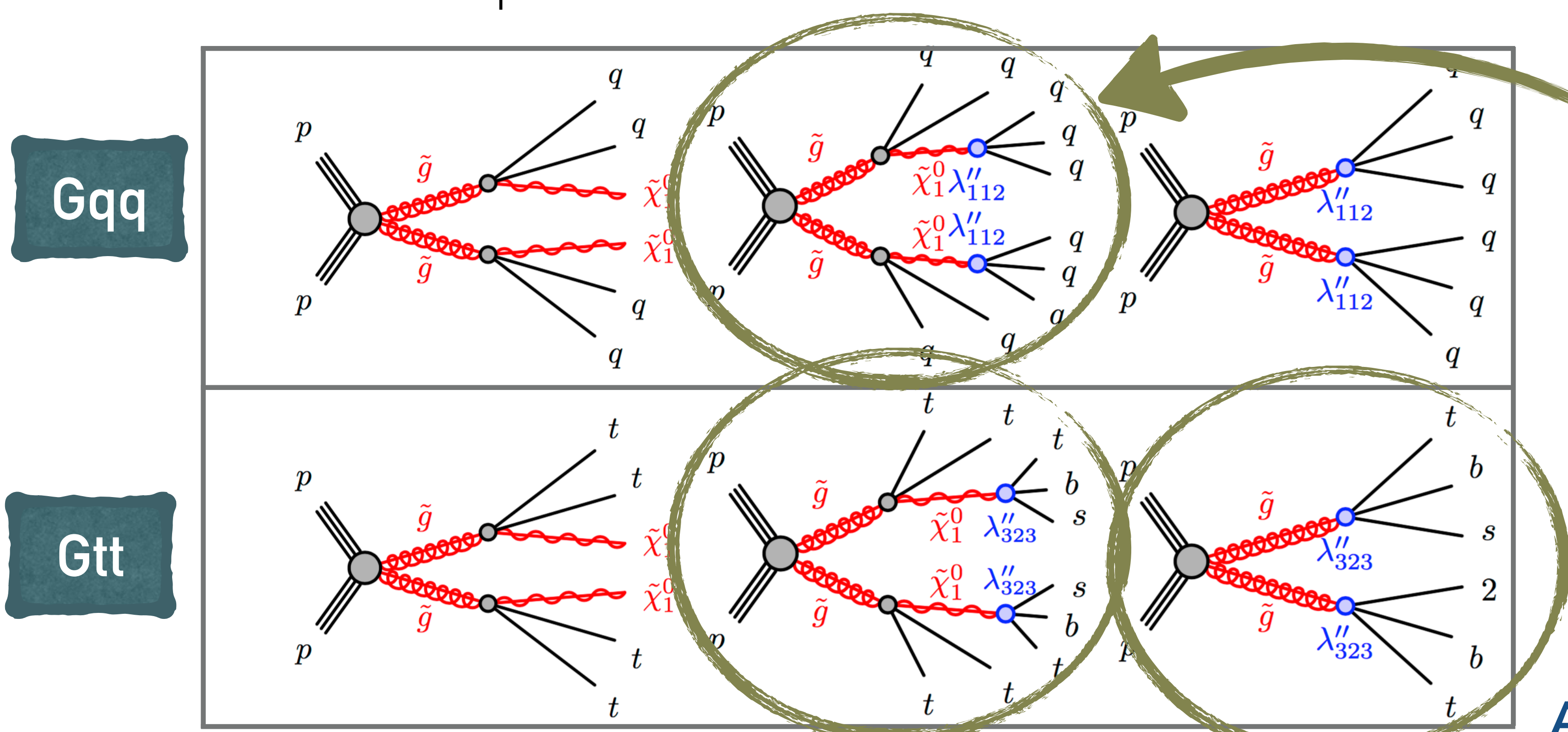
More on RPV reinterpretations

- R-parity violation (RPV): decay of the LSP (DM candidate) to SM particles.
- **Only a few ATLAS analysis are specifically targeting RPV signatures.** RPV is hard to target considering:
  - **Displaced tracking** in high pileup conditions (both online and offline).
  - **Poor background discrimination** due to low MET signals.
- Due to the low cut on MET significance, the 0-lepton Multijets analysis is well suited for RPV reinterpretations.

Leptonic number violation

$$W_{\mathrm{RPV}} = \frac{\lambda_{ijk}}{2} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{\lambda''_{ijk}}{2} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_u,$$

Baryonic number violation



Some sensitivity expected in the SUSY Multijet analysis (n_{jets} > 7)

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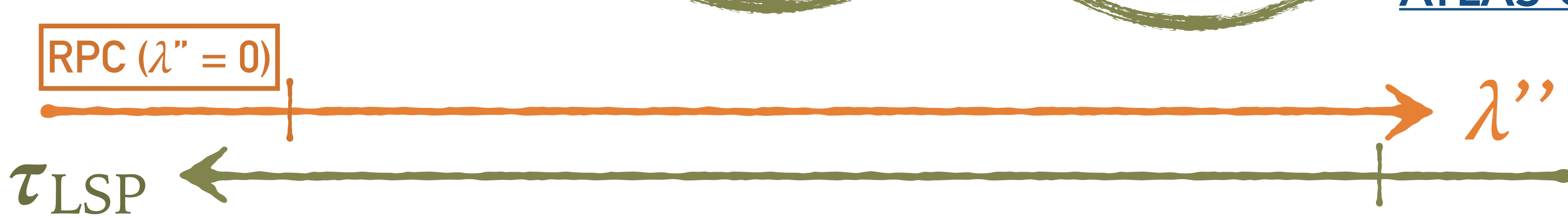

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