GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN, 21/06/2019

BEYOND CALORIMETRY

CHALLENGES AND OPPORTUNITIES IN HADRONIC RECONSTRUCTION ON ATLAS

TENG JIAN KHOO

UNIVERSITÉ DE GENÈVE

ATLAS EXPERIMENT

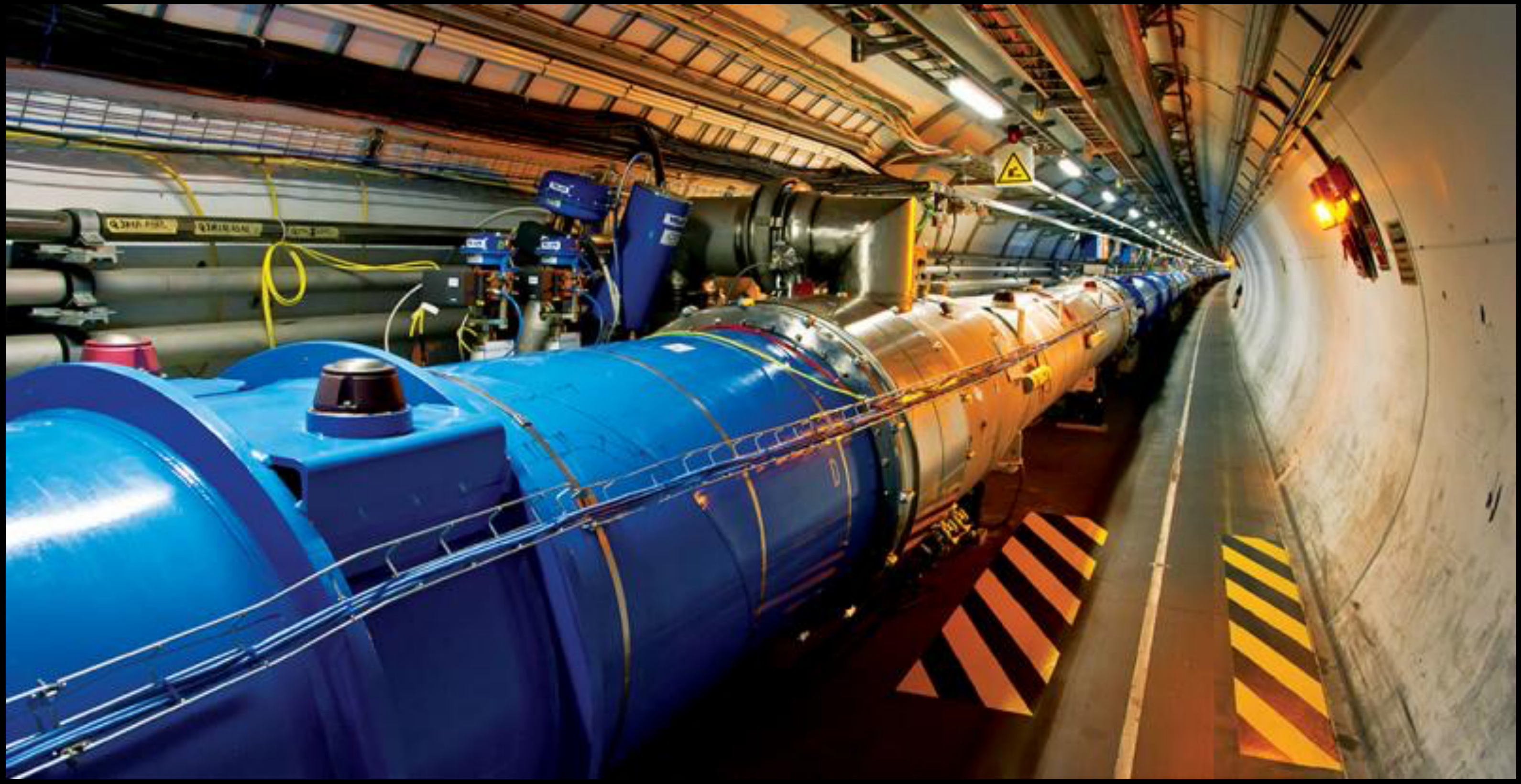
OUTLINE

- Motivation:
  - Hadronic observables – what & why?
  - Hadronic reconstruction – how?
- Challenges & current solutions
- (Re)constructing an analysis
- Future prospects

COLLIDING PROTONS

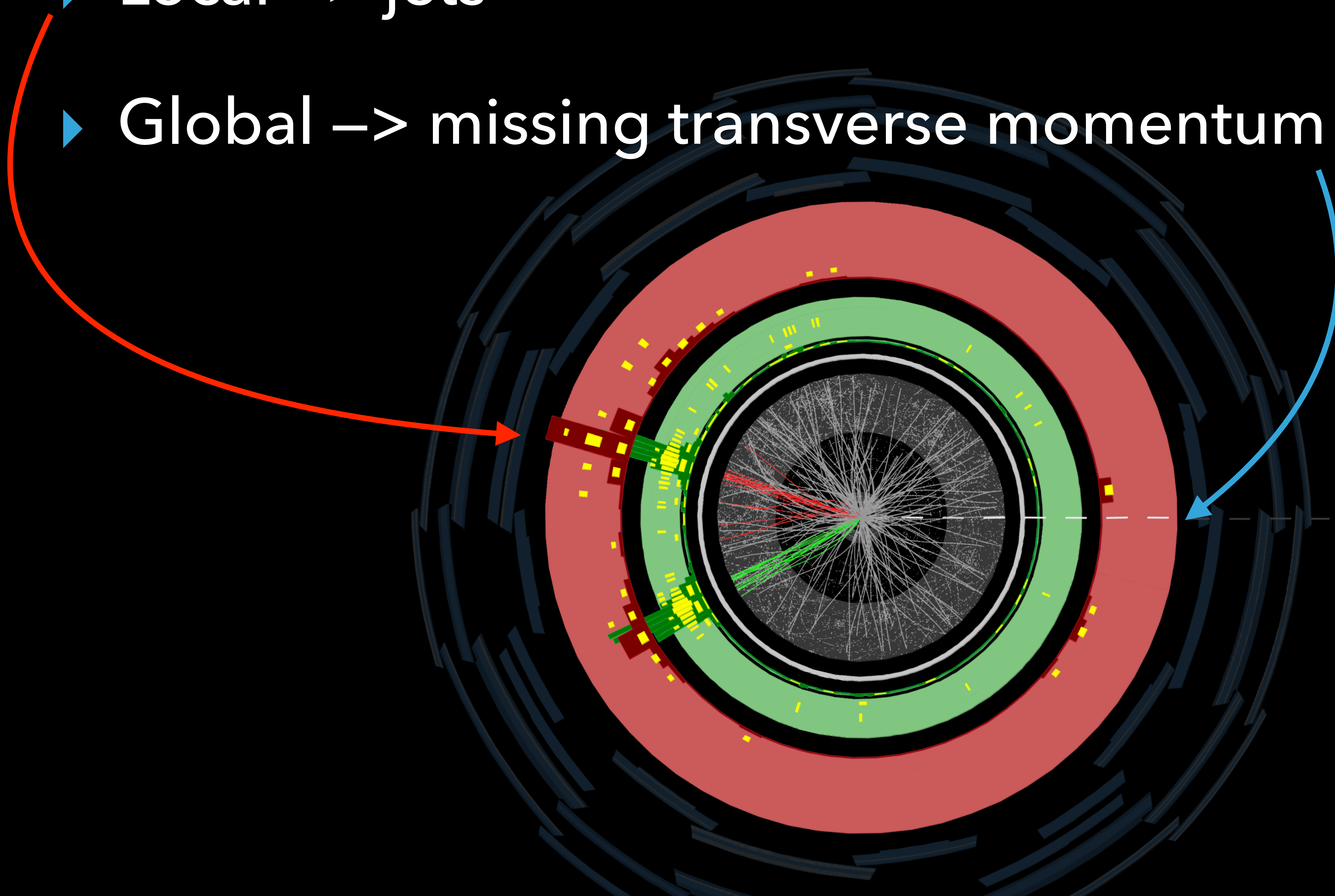
HADRON COLLIDER PHYSICS

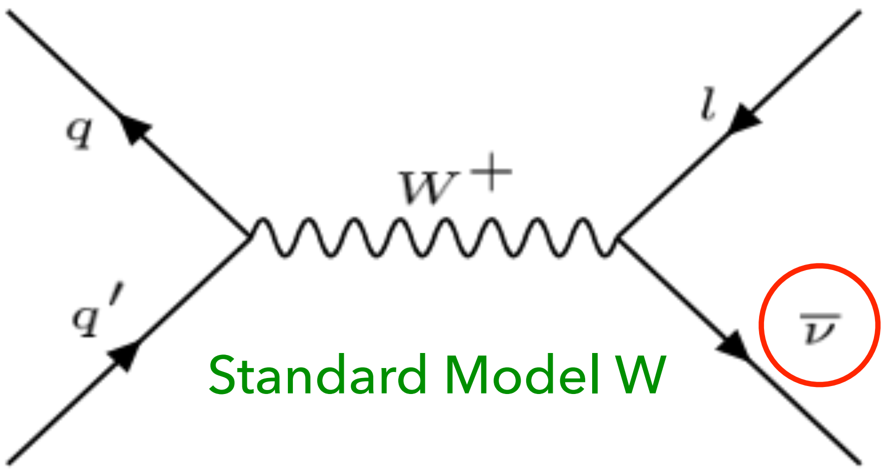
- LHC collides protons at energy scales beyond that needed to probe proton structure.
- Centre-of-mass proton collision energy $\sqrt{s} = 13\,\mathrm{TeV}$.

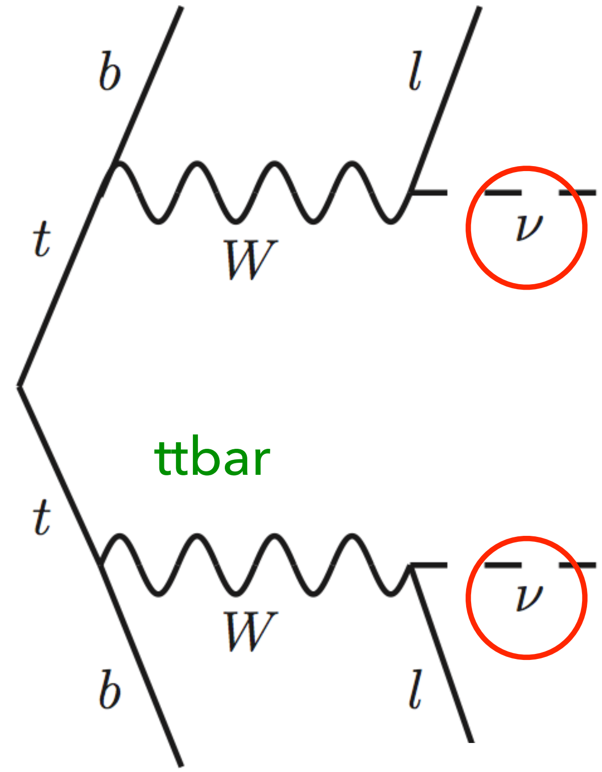


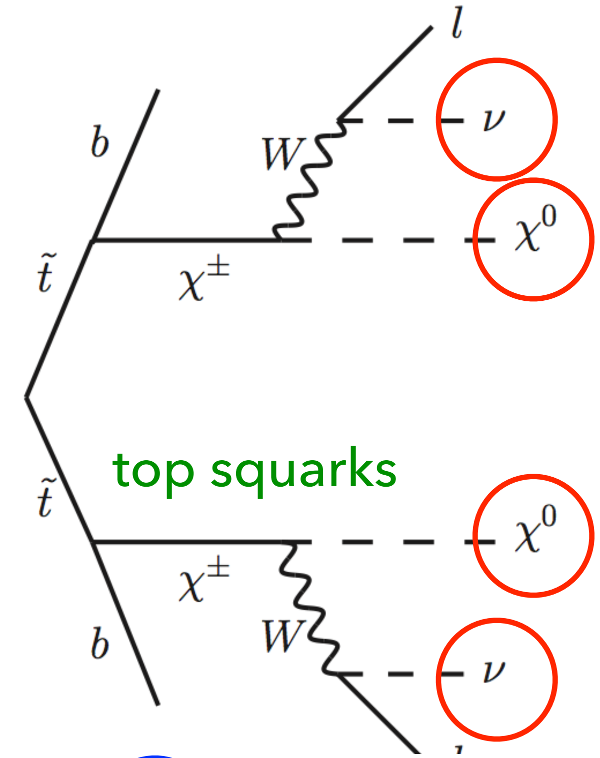
"HADRONIC OBSERVABLES"

- Observables describing collective flow of hadrons
  - Local –> jets
  - Global –> missing transverse momentum *(event shapes)*



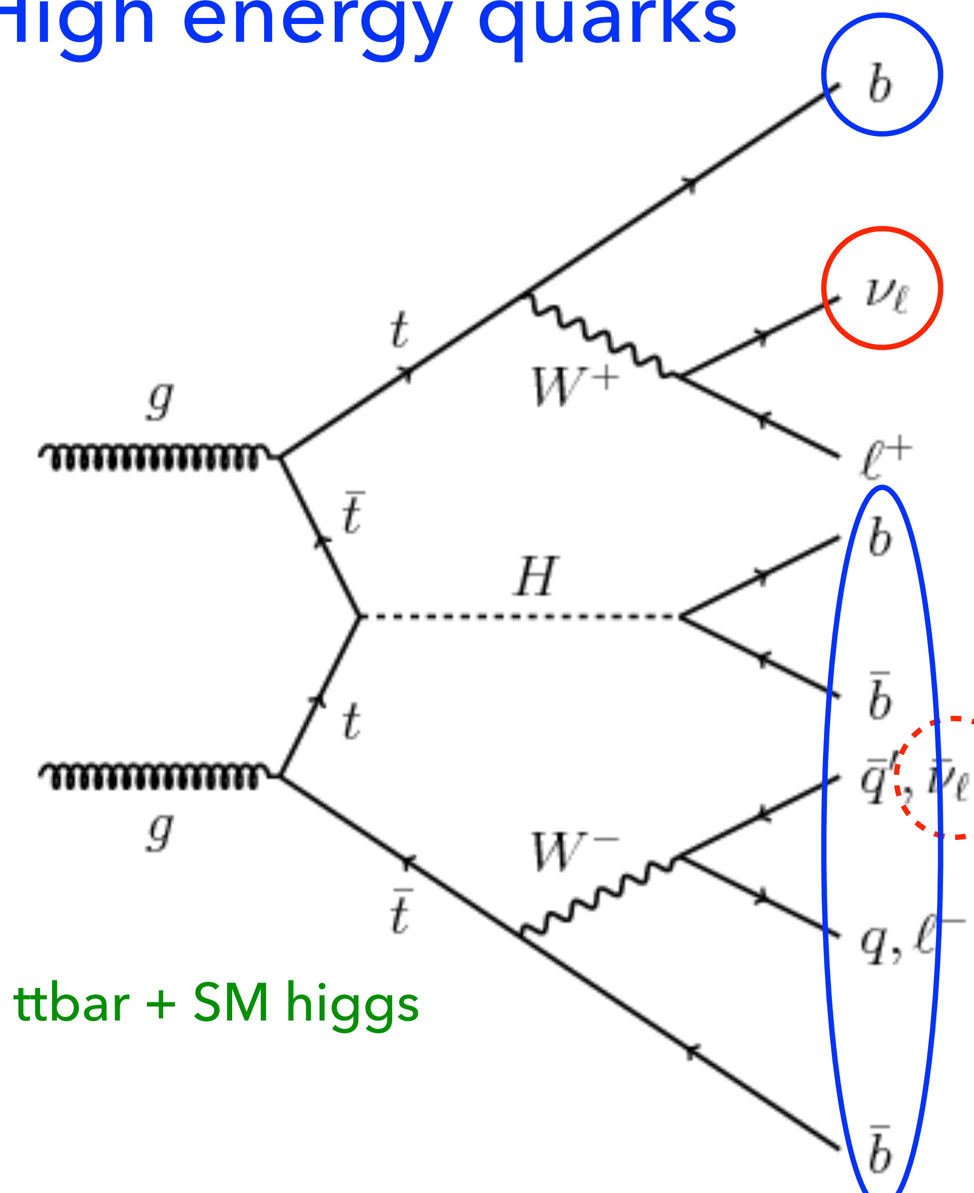


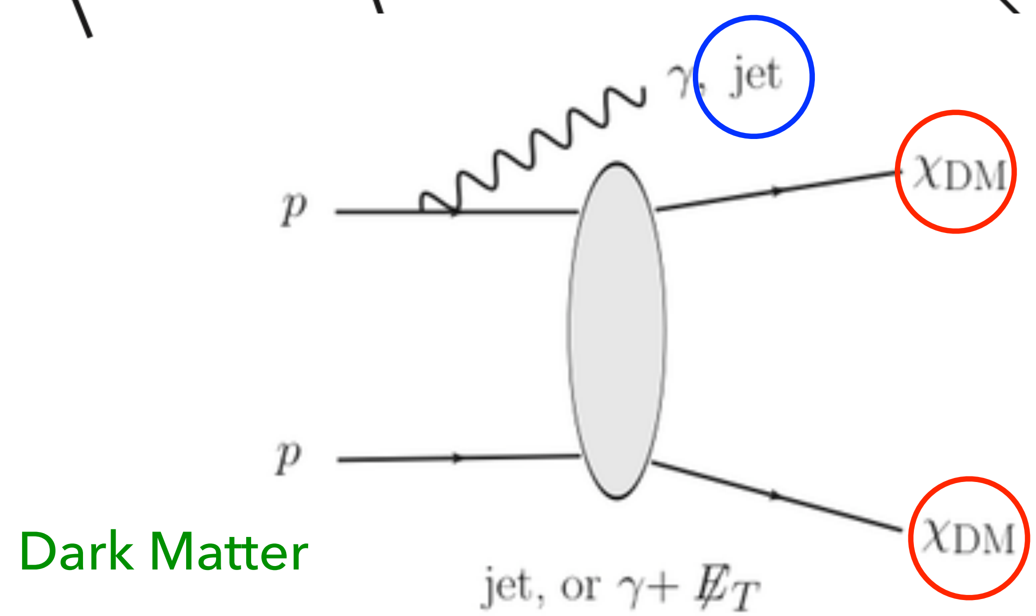


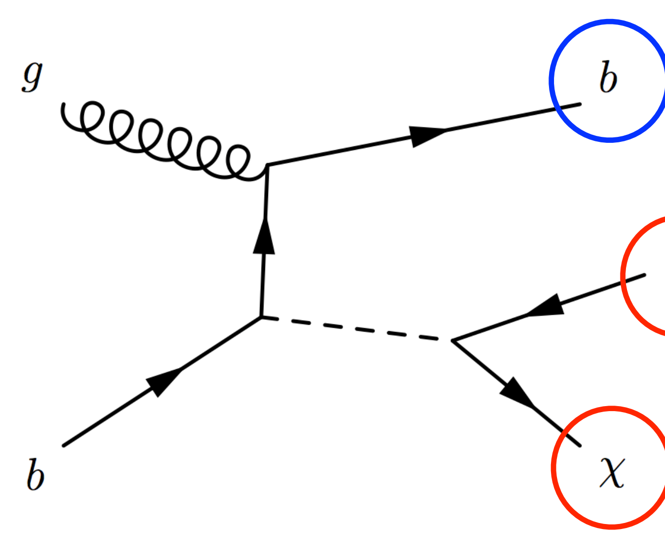


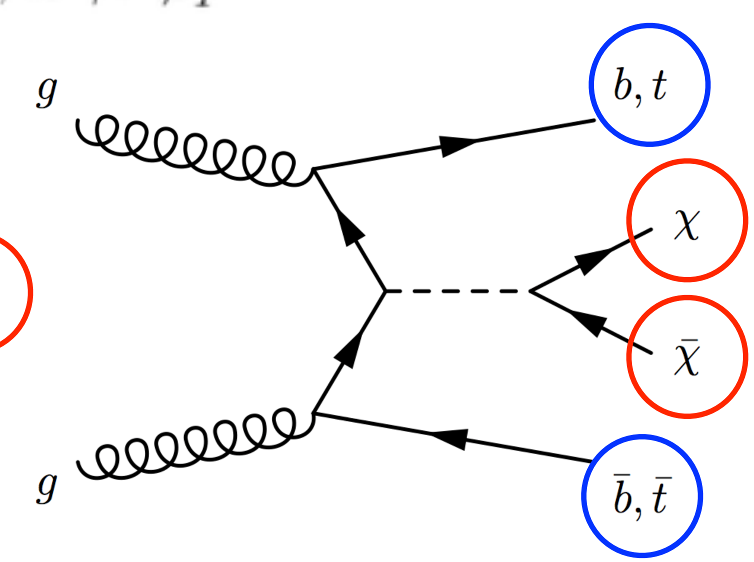
Noninteracting particles

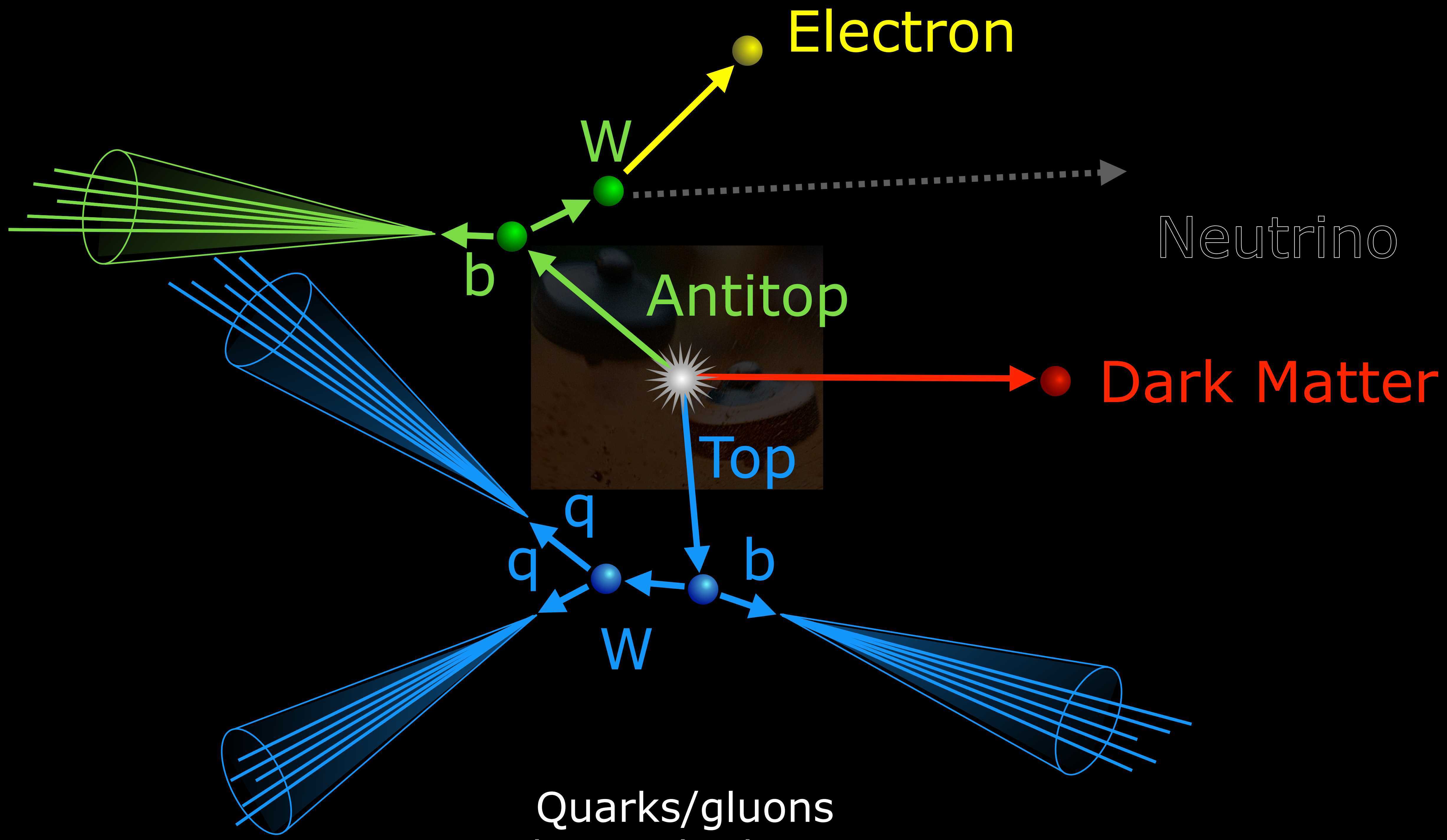
High energy quarks



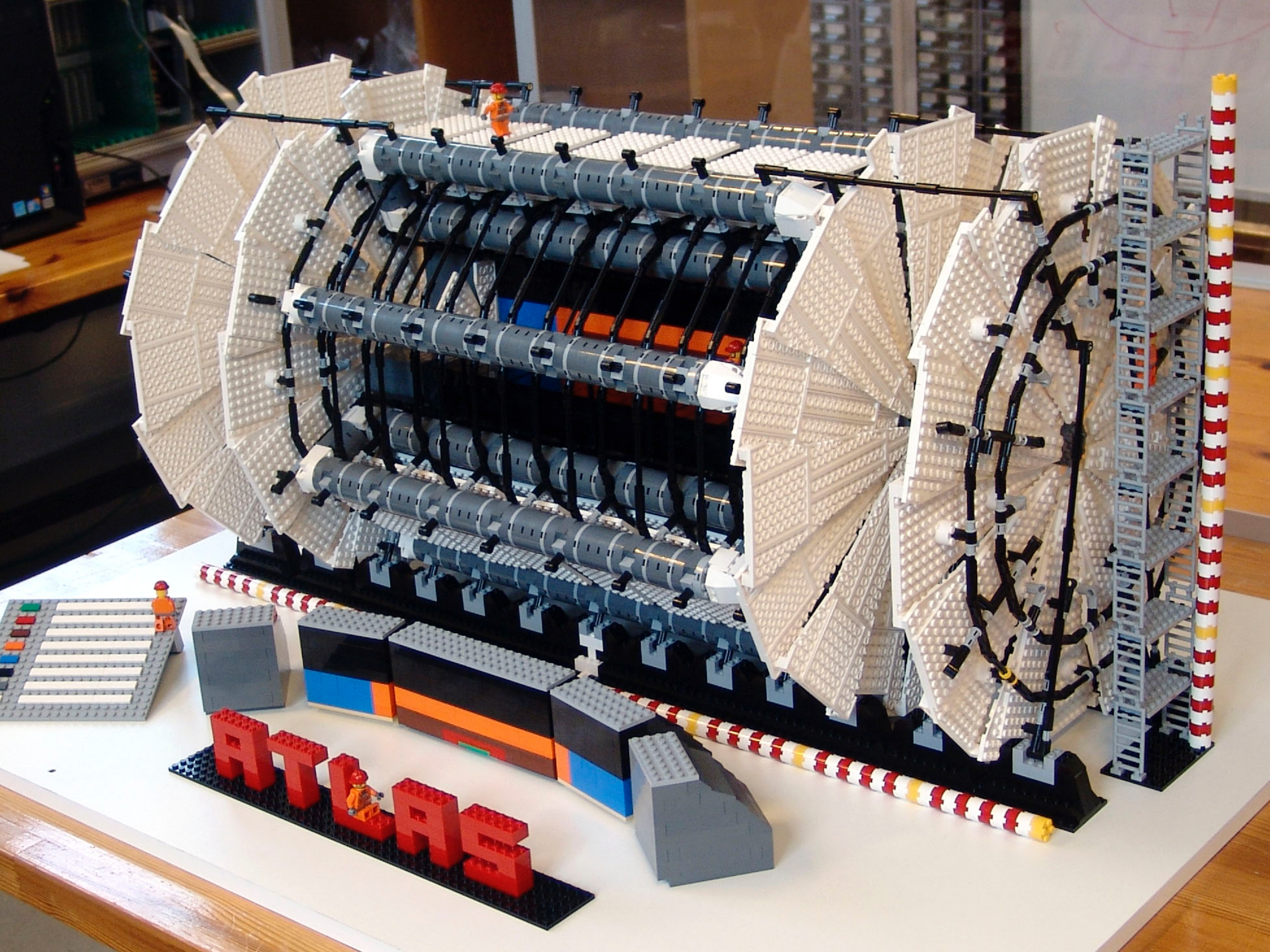


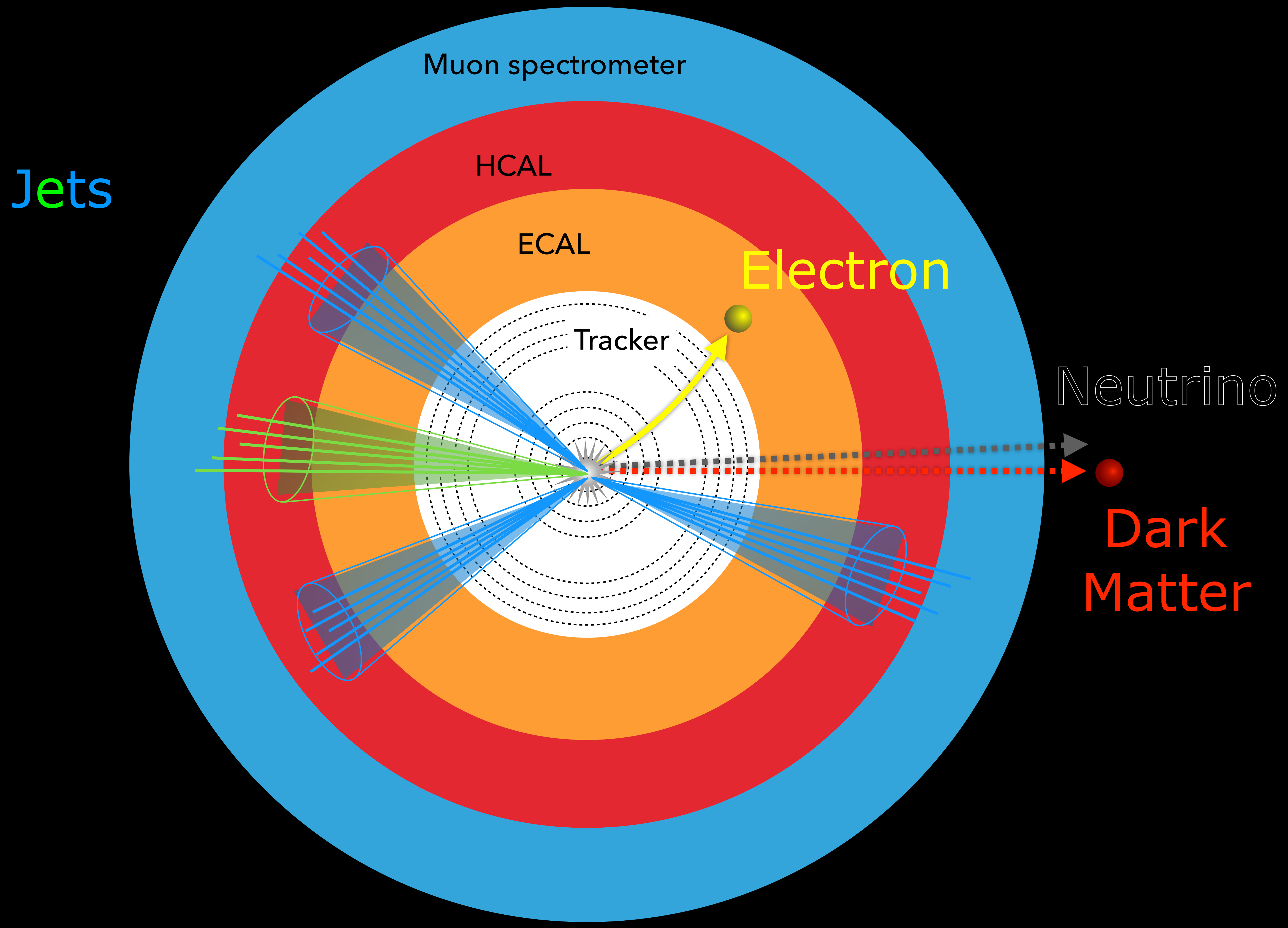




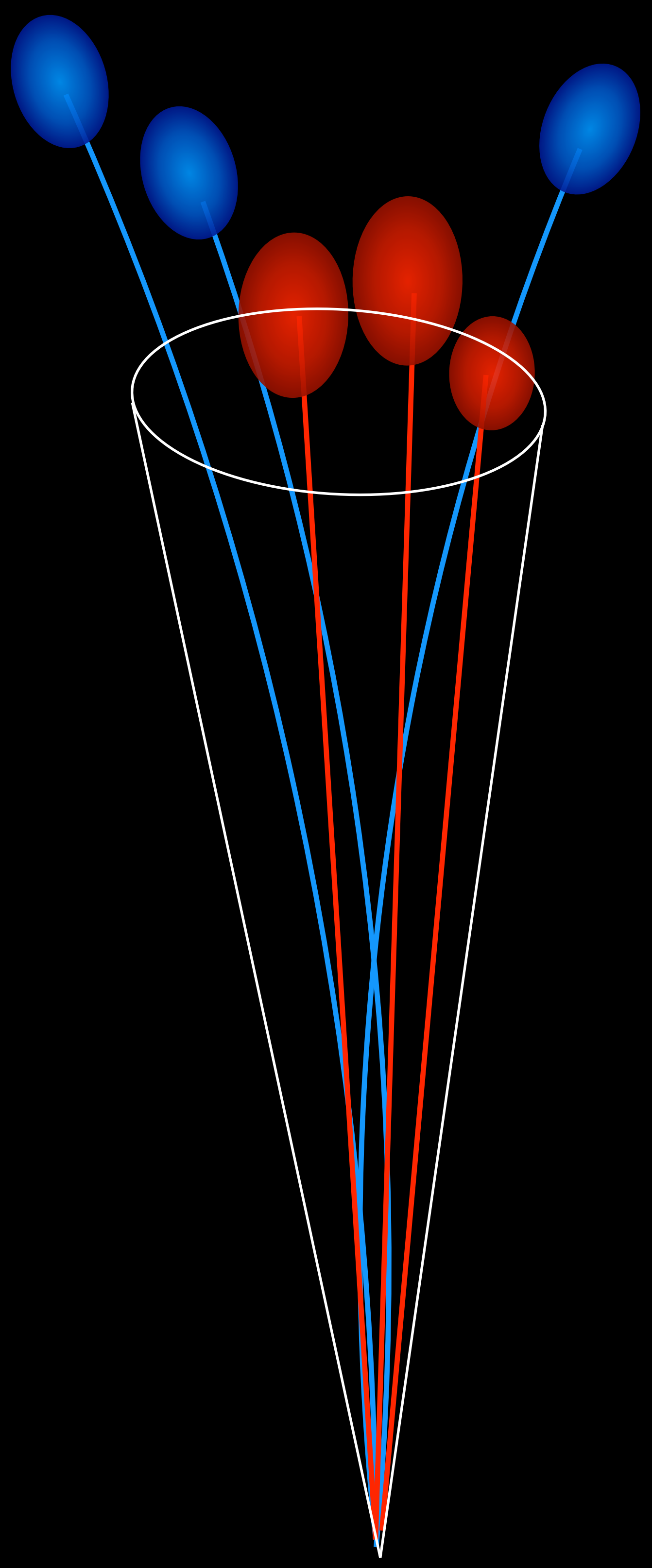


Quarks/gluons radiate & hadronise, producing "jets" of hadrons


ATLAS


Jets
Muon spectrometer
HCAL
ECAL
Electron
Tracker
Neutrino
Dark Matter

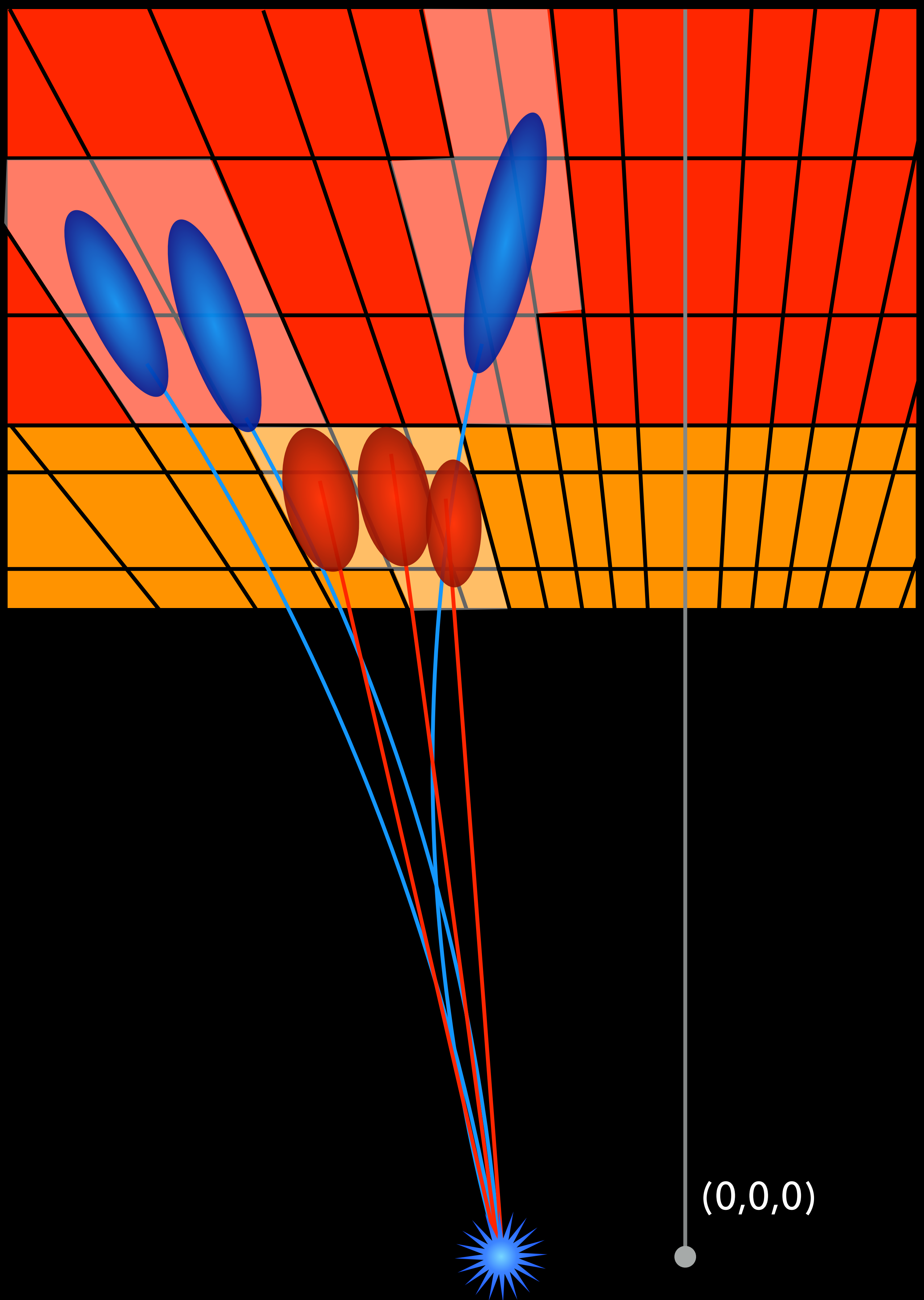
JET: RECONSTRUCTION & CALIBRATION



- Proxy for high-energy partons
- Mixture of charged & neutral hadrons
  - Stable particles reaching calorimeter:
    65% $h^{\pm}$
    25% $\pi^0 \rightarrow \gamma\gamma$
    10% other neutral hadrons
    occasional neutrinos
- Measurement mainly depends on calorimetry, tracks important for refinement

JET-FINDING

1. Cluster local energy deposits with noise suppression cuts

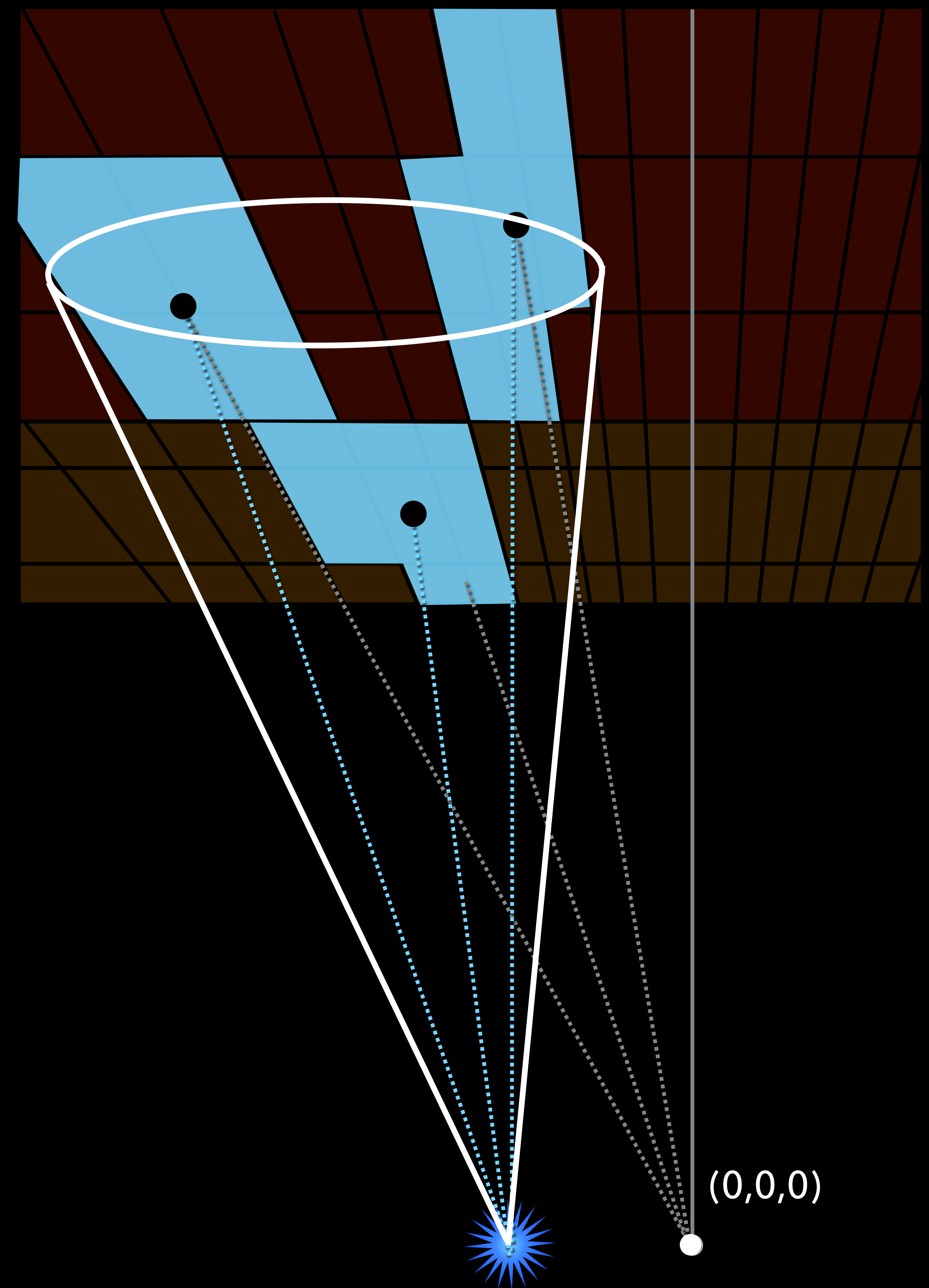


JET-FINDING

1. Cluster local energy deposits with noise suppression cuts

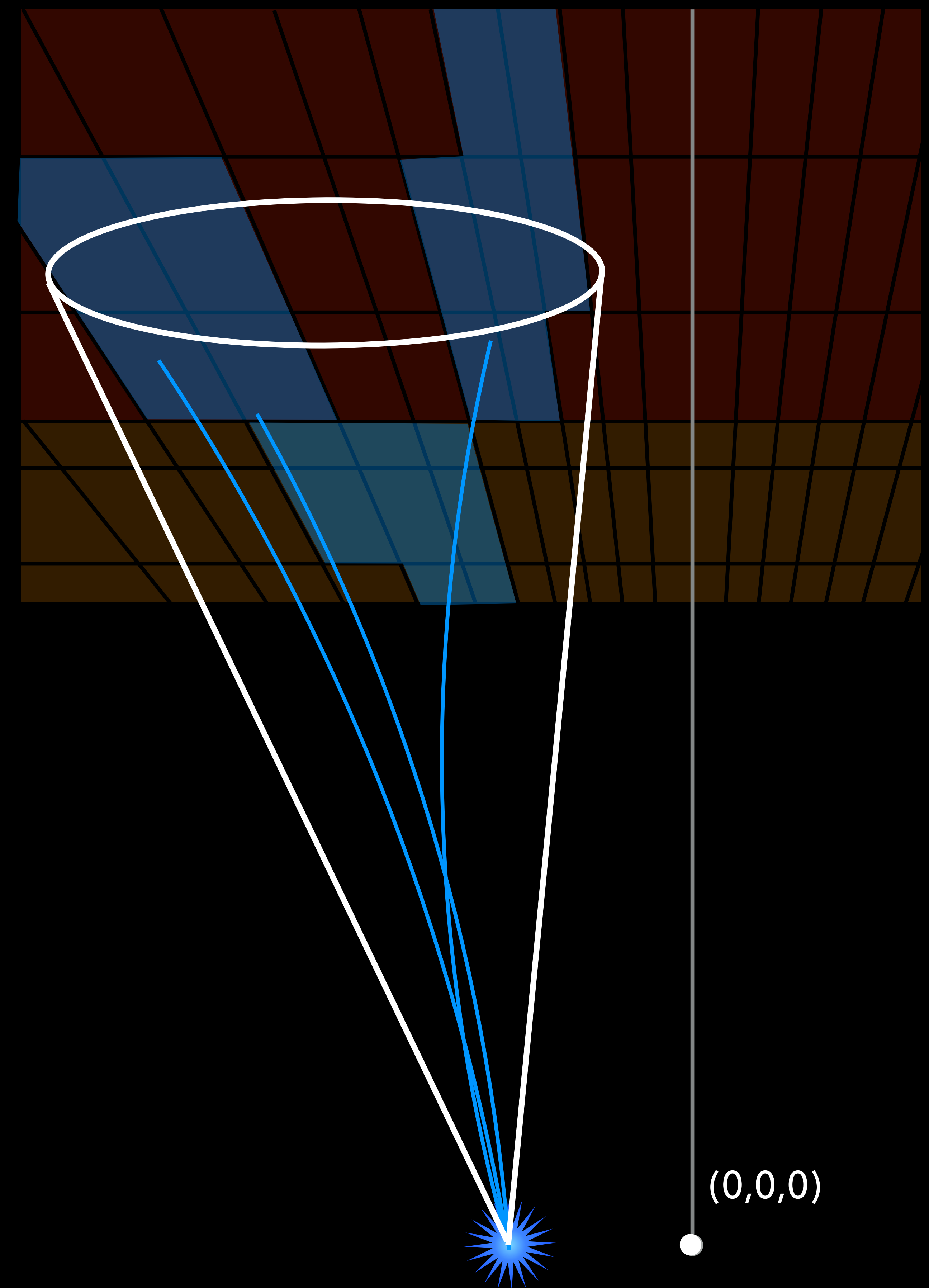
2. Point clusters to nominal hard scatter vertex (improve angular resolution)

3. Run jet clustering with fastjet (typically anti-kt algorithm)



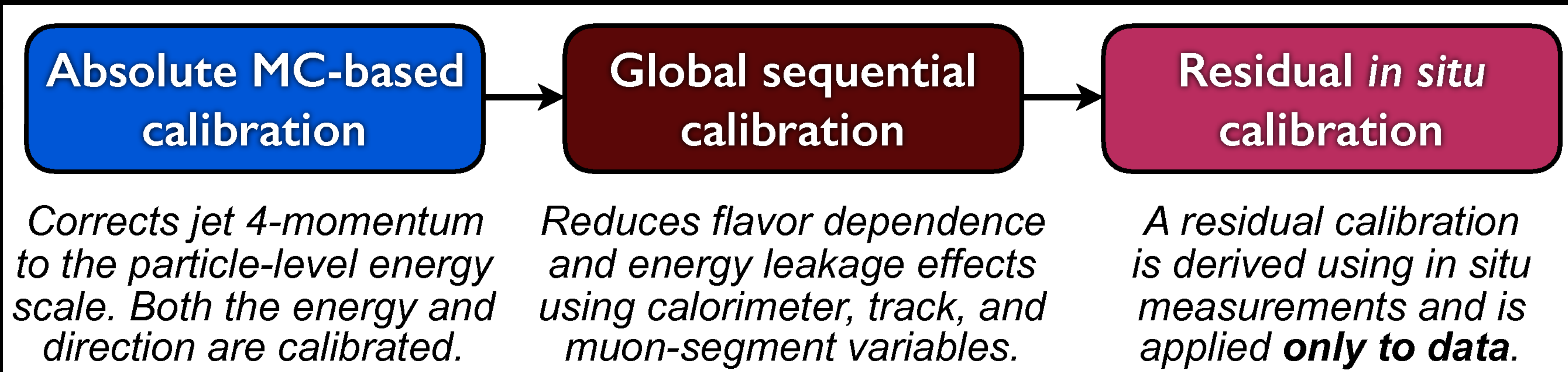
JET-FINDING

1. Cluster local energy deposits with noise suppression cuts
2. Point clusters to nominal hard scatter vertex (improve angular resolution)
3. Run jet clustering with fastjet (typically anti-kt algorithm)
4. Associate charged-particle tracks from ID
5. Calibrate & filter

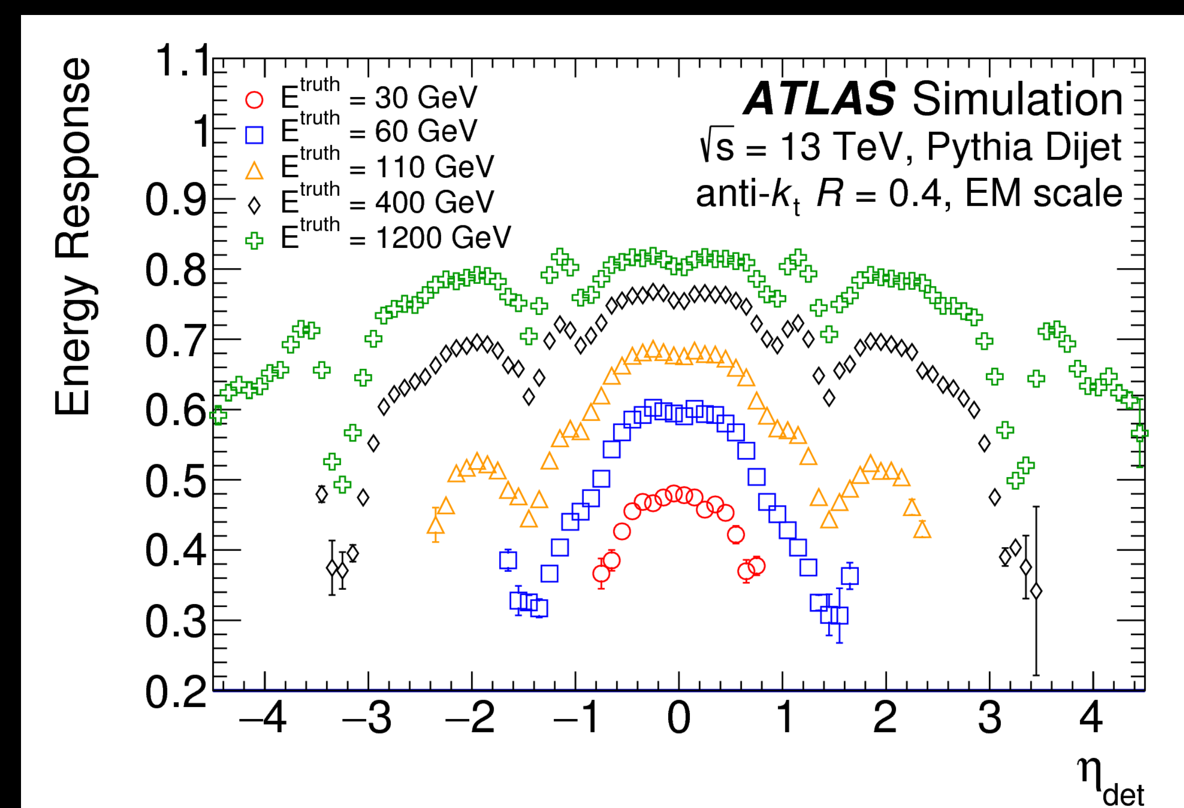


[Phys Rev D 96 072002]

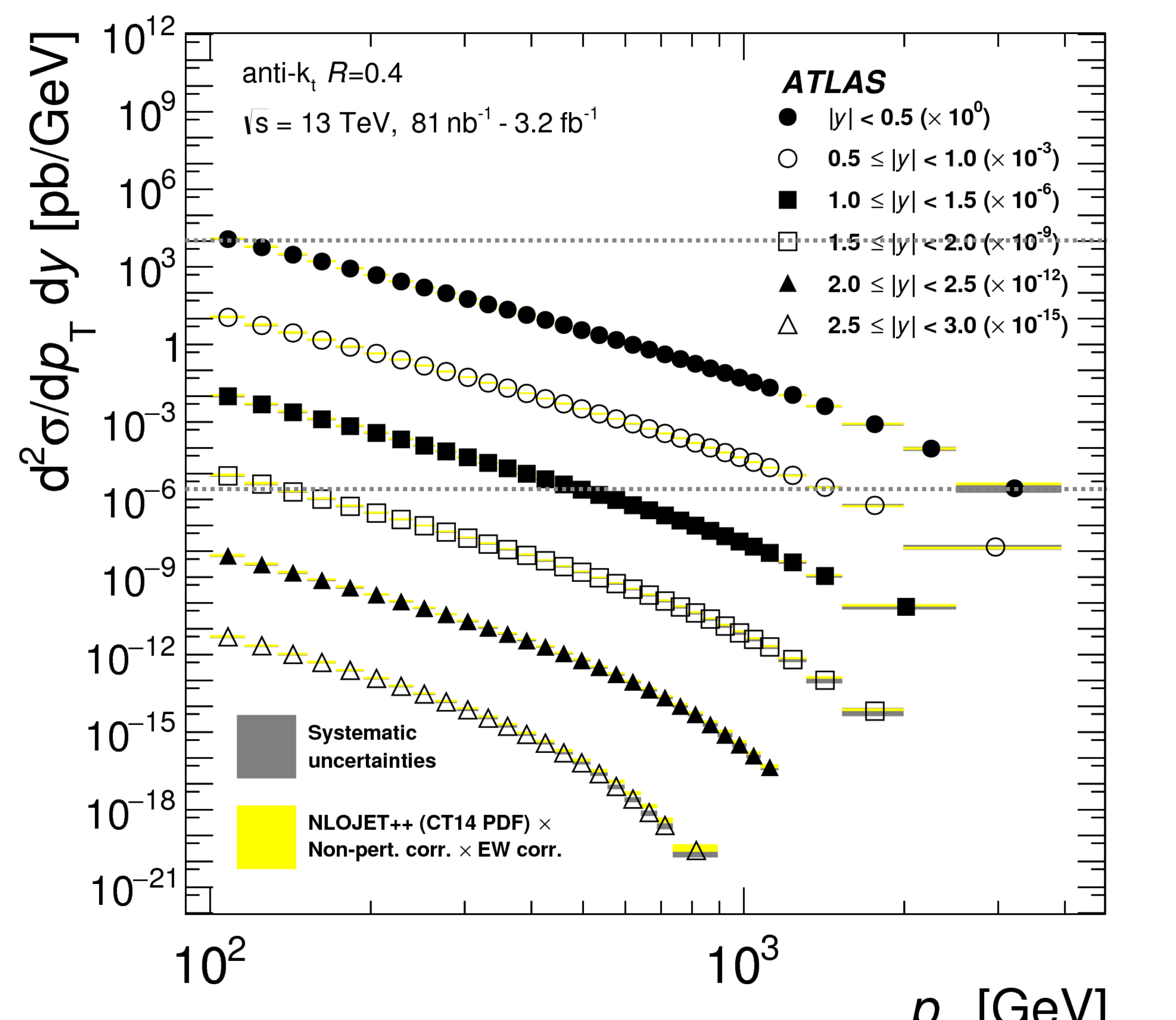
JET CALIBRATION



- Raw jets are at appropriate scale for electrons/photons, not hadrons
- Calibrate using simulated jets as reference four-momentum
- *Data is calibrated to match Monte Carlo simulation*

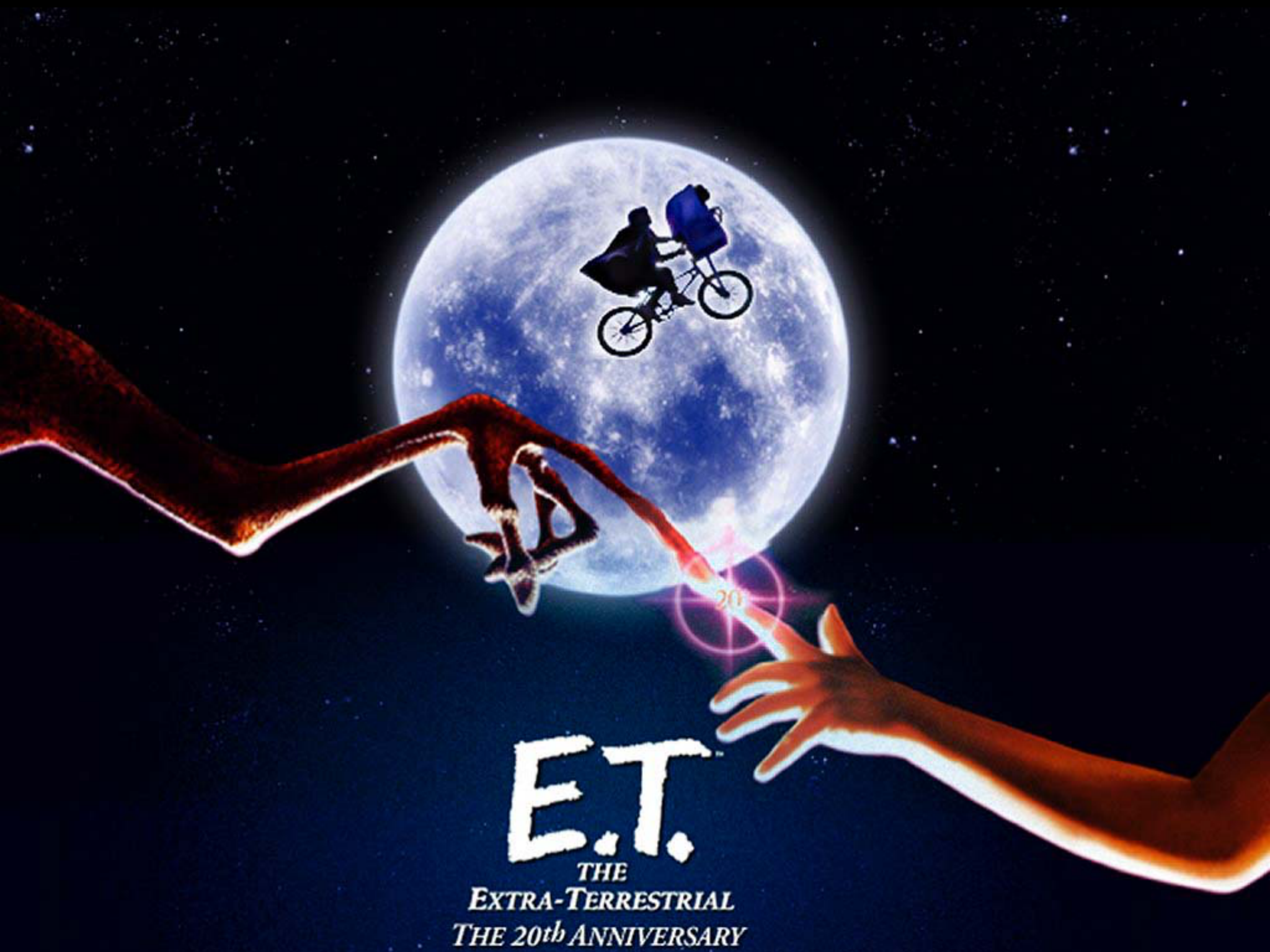


JETS IN ATLAS DATA

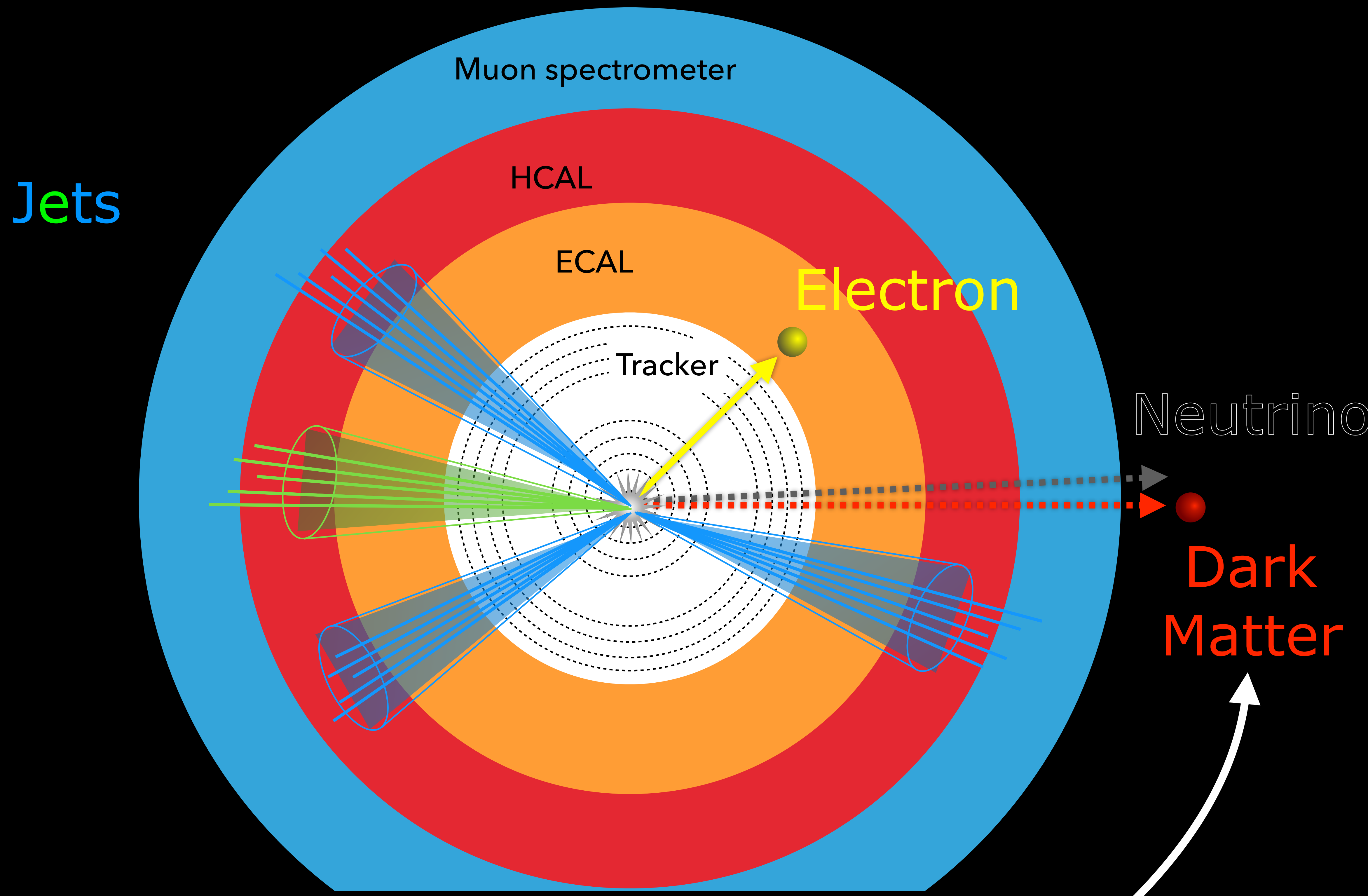


JHEP09 (2017) 020

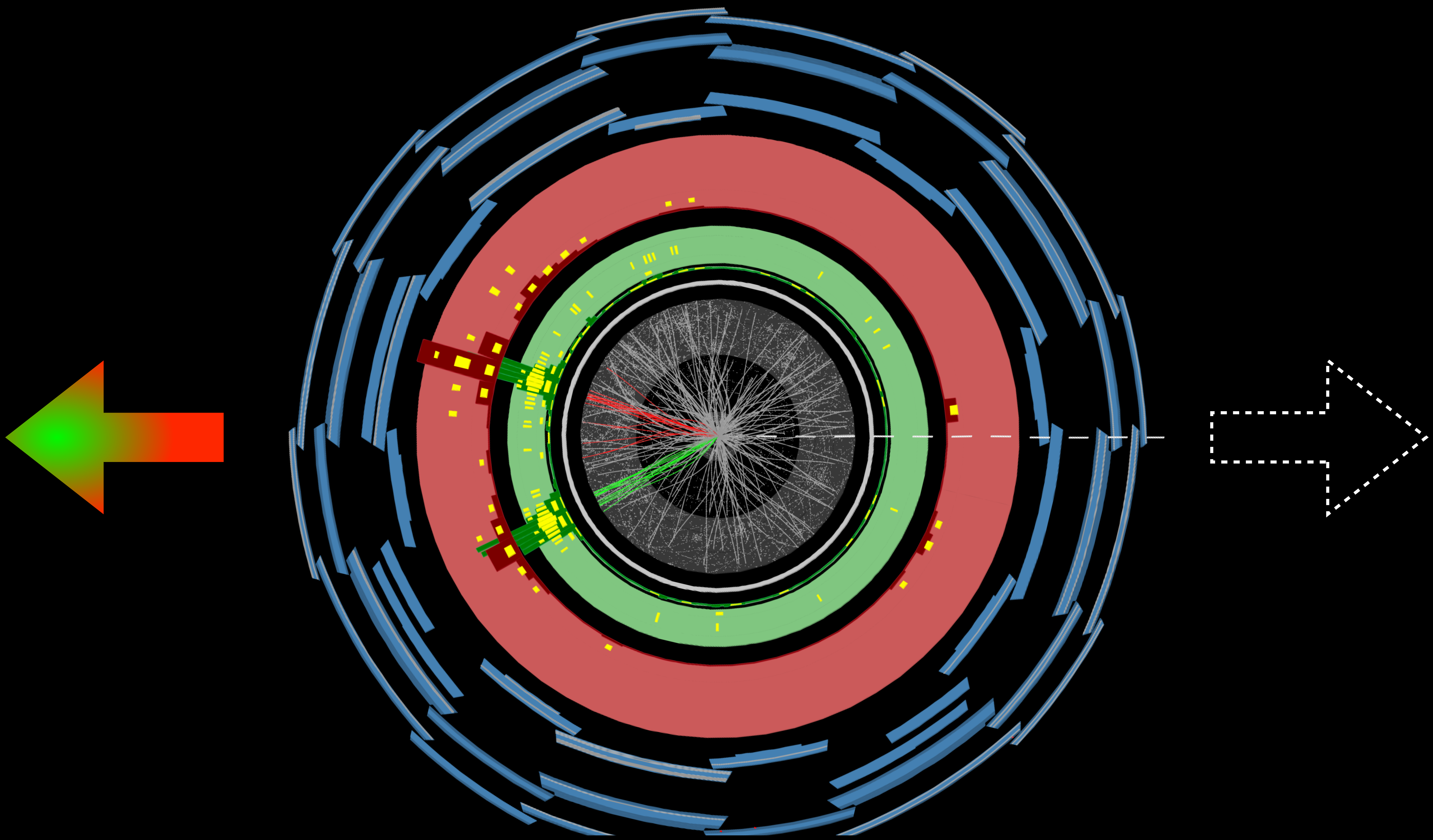
Cross-sections for inclusive jet production vs transverse momentum spanning 9 orders of magnitude


20
E.T.
THE
EXTRA-TERRESTRIAL
THE 20th ANNIVERSARY

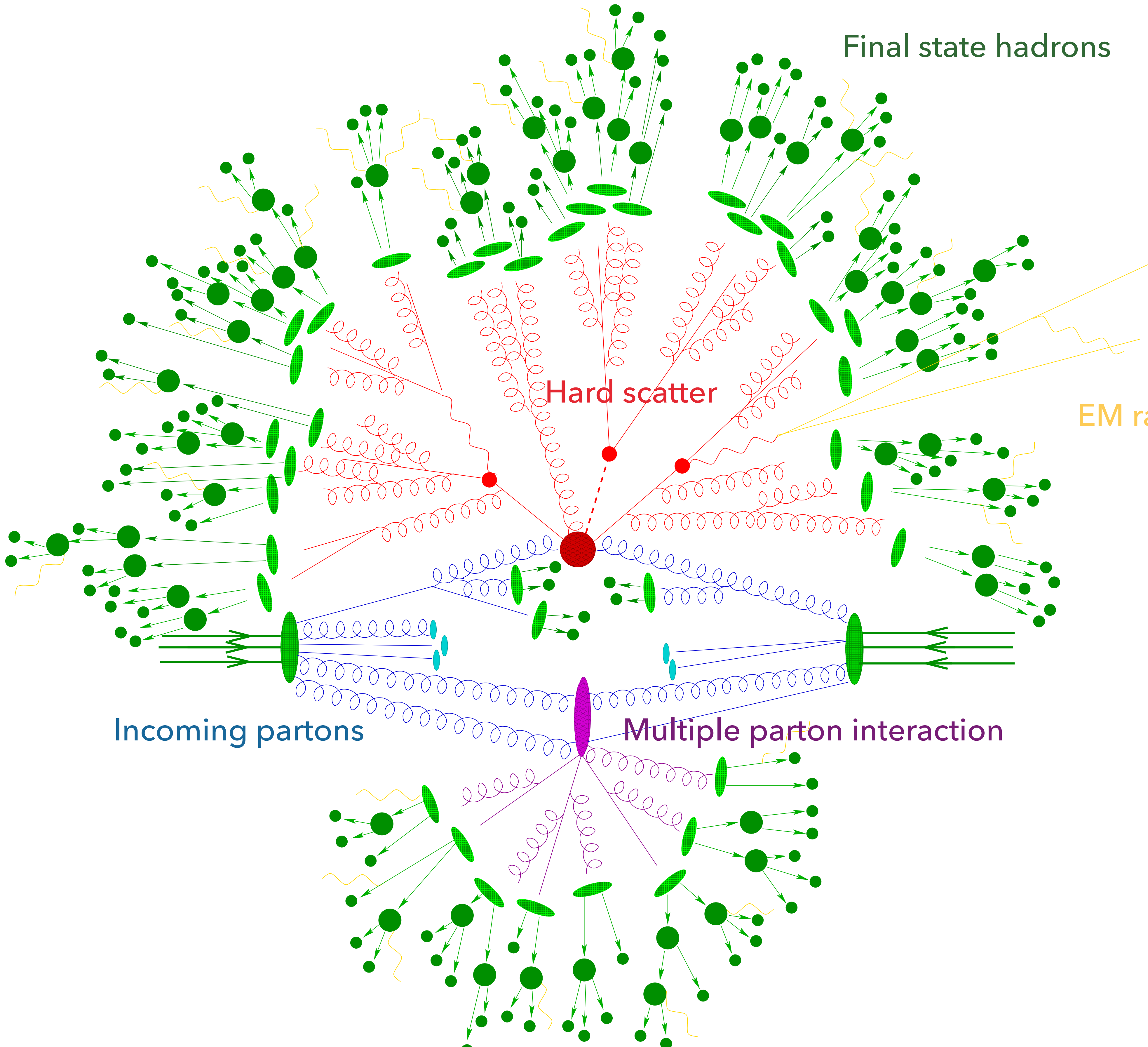
Missing transversE momenTum



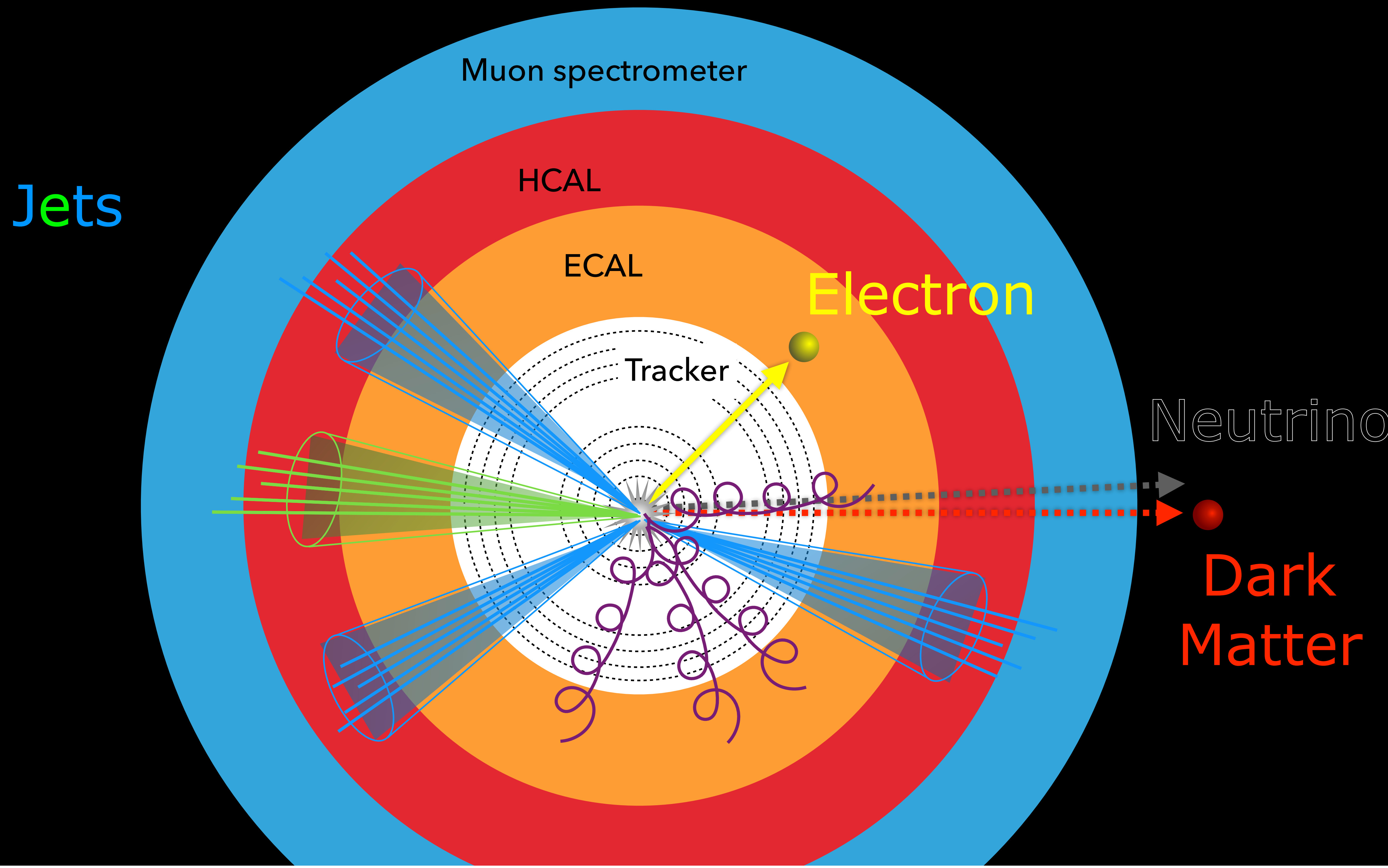
CONSERVE (TRANSVERSE) MOMENTUM!



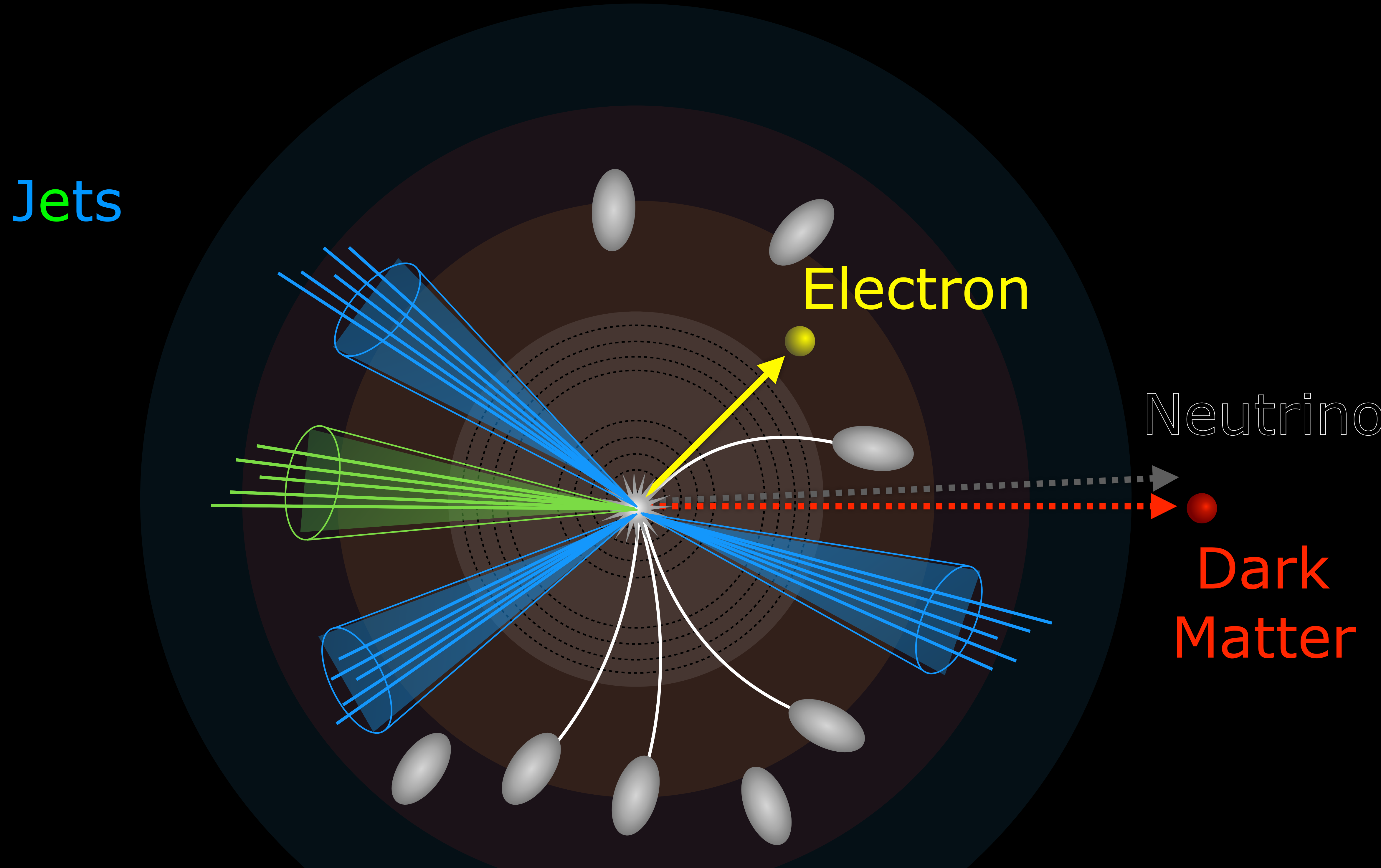
CONSERVE (TRANSVERSE) MOMENTUM!



From S. Höche, [arXiv 1411.4085]



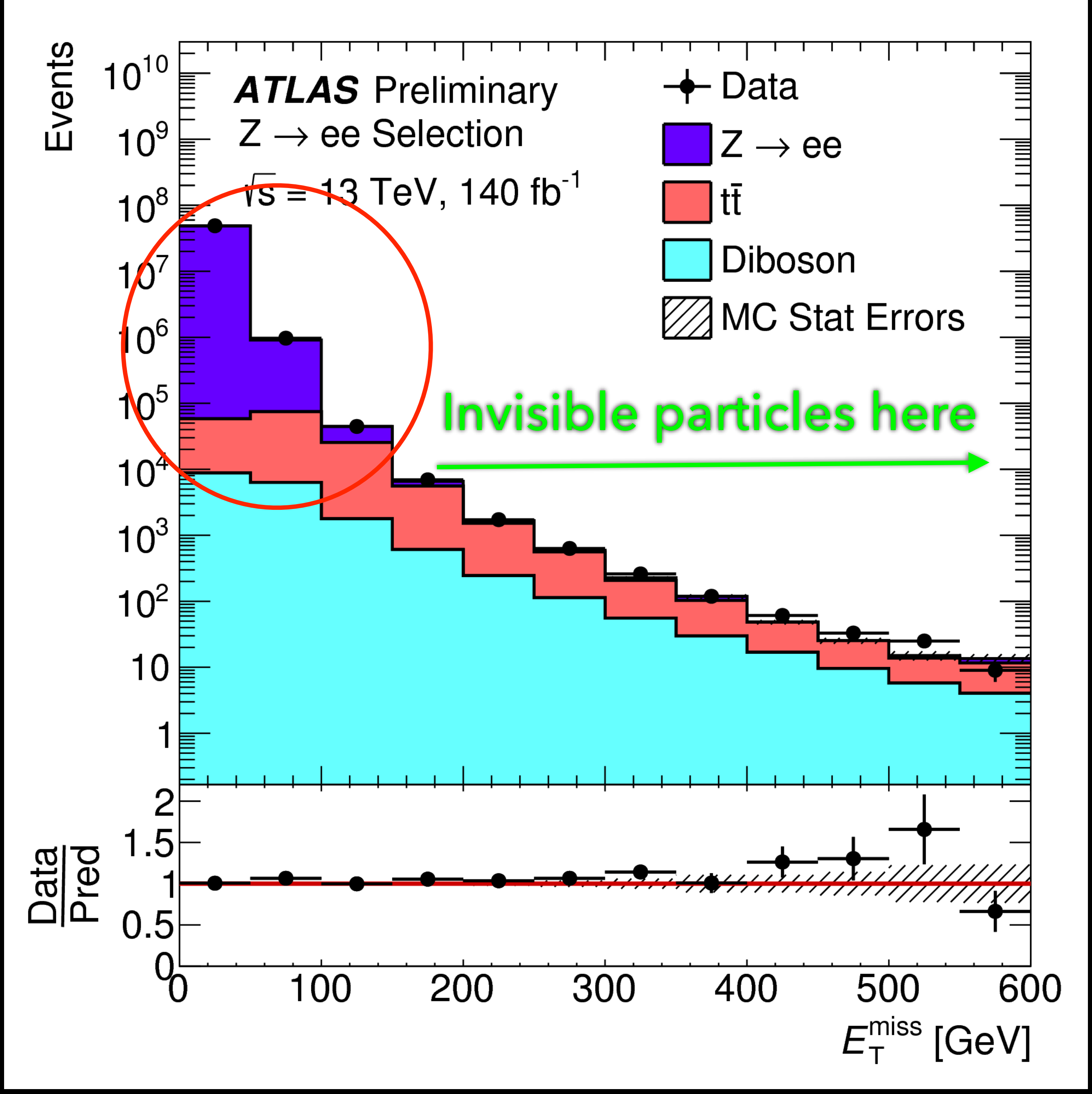
SOFT RADIATION COMPLICATES MEASUREMENT OF INCLUSIVE OBSERVABLES



AUGMENT "HARD" MET TERMS WITH SUMS OVER UNASSOCIATED CLUSTERS/TRACKS

MISSING TRANSVERSE MOMENTUM IN ATLAS DATA

No neutrinos, only mismeasurement

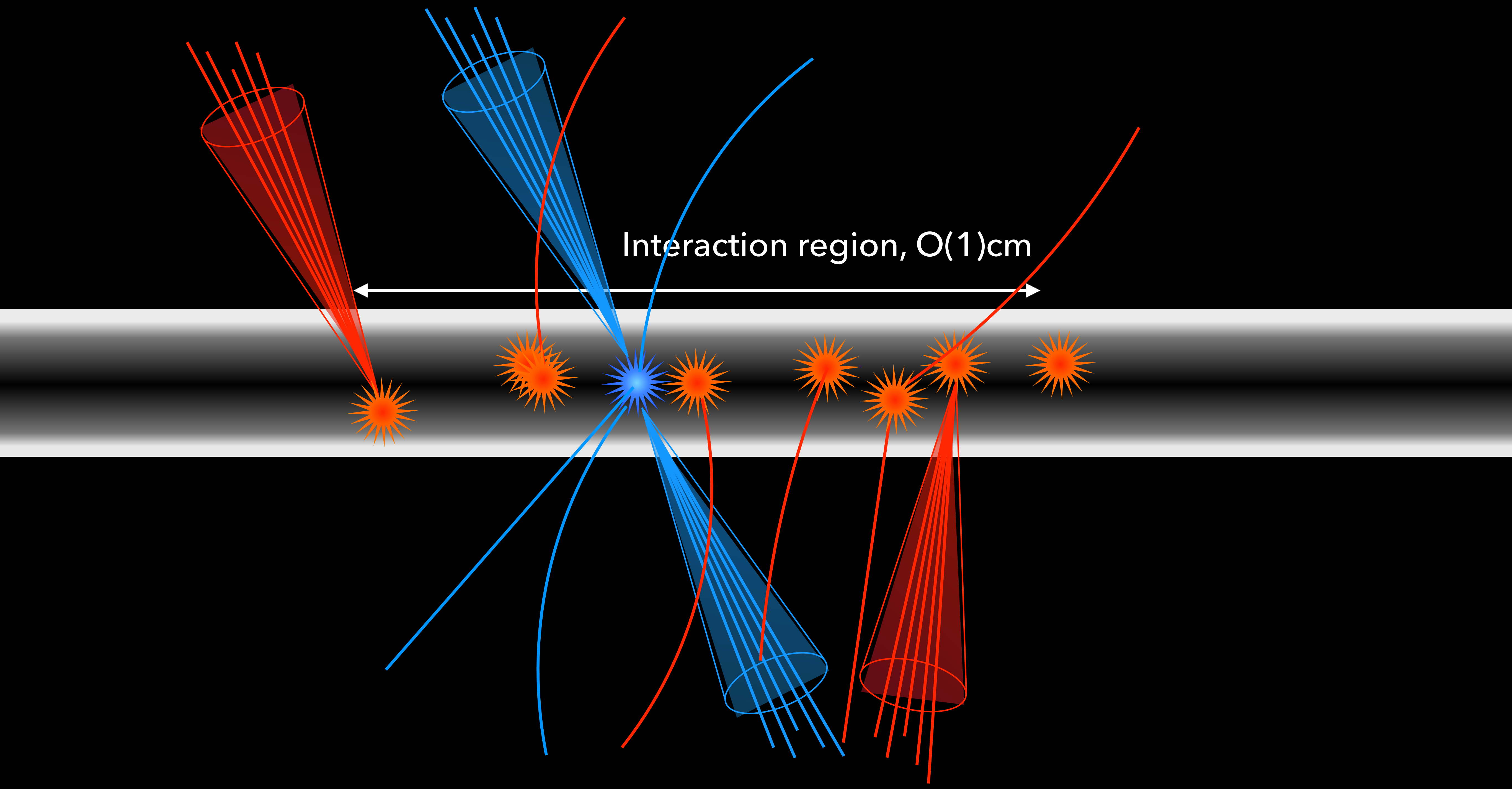


SOFTWARE PLUG

- ATLAS software would cost 500M CHF to develop at professional rates per line of code
- Performance studies translate into physics results only after many hours of dedicated programming
- Flexibility & intelligent software design has allowed the breadth of experimentation in analyses
  - ca 30 MET variants in Run 1 —> analysis-customisable MET reconstruction in Run 2
  - Fast optimisation and response to issues

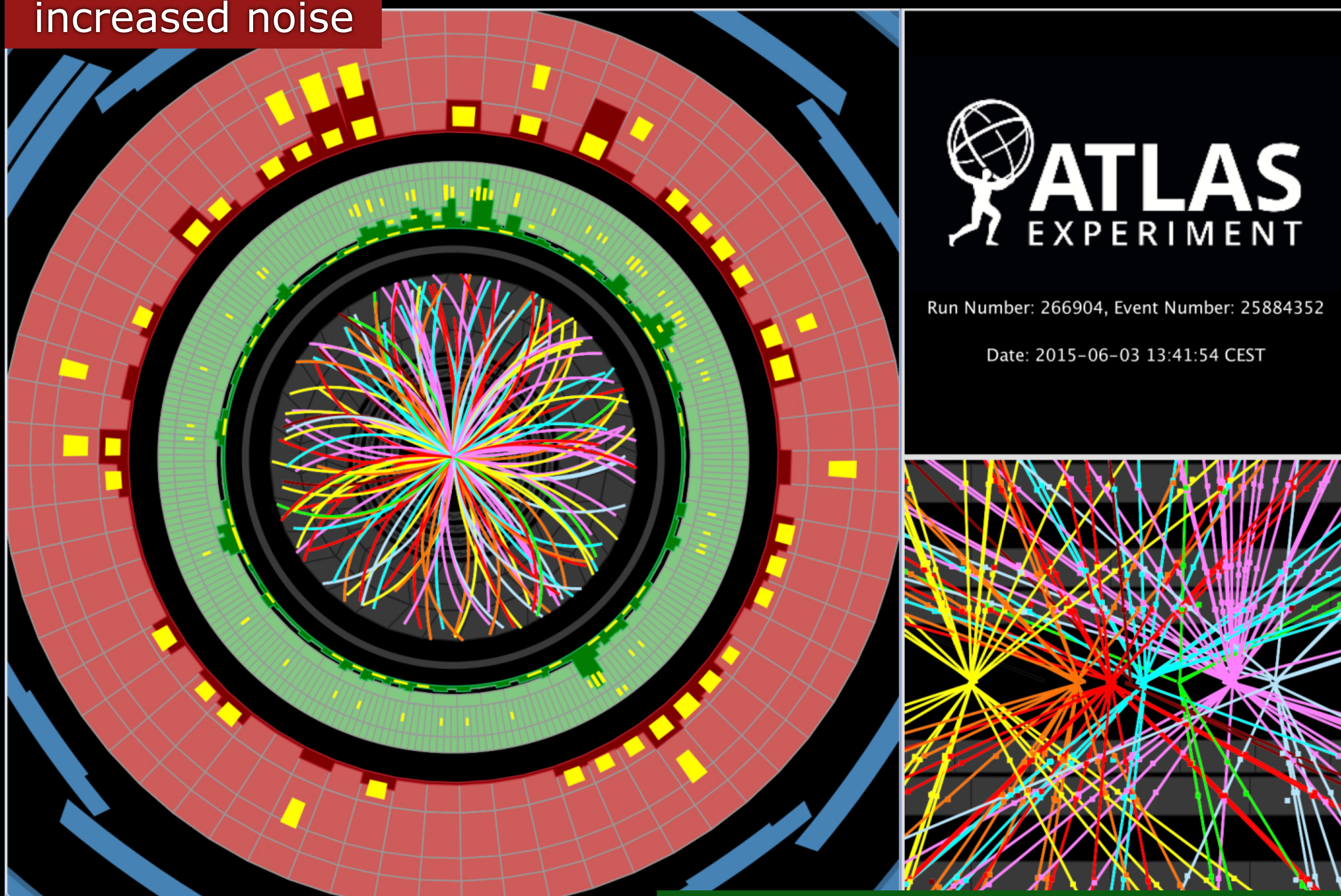
PILEUP (PUNTING)

PILEUP (LHC)



Every "event" contains many visible collisions

Calorimeter sees increased noise



Tracker sees distinct interactions

2021: 60 mean

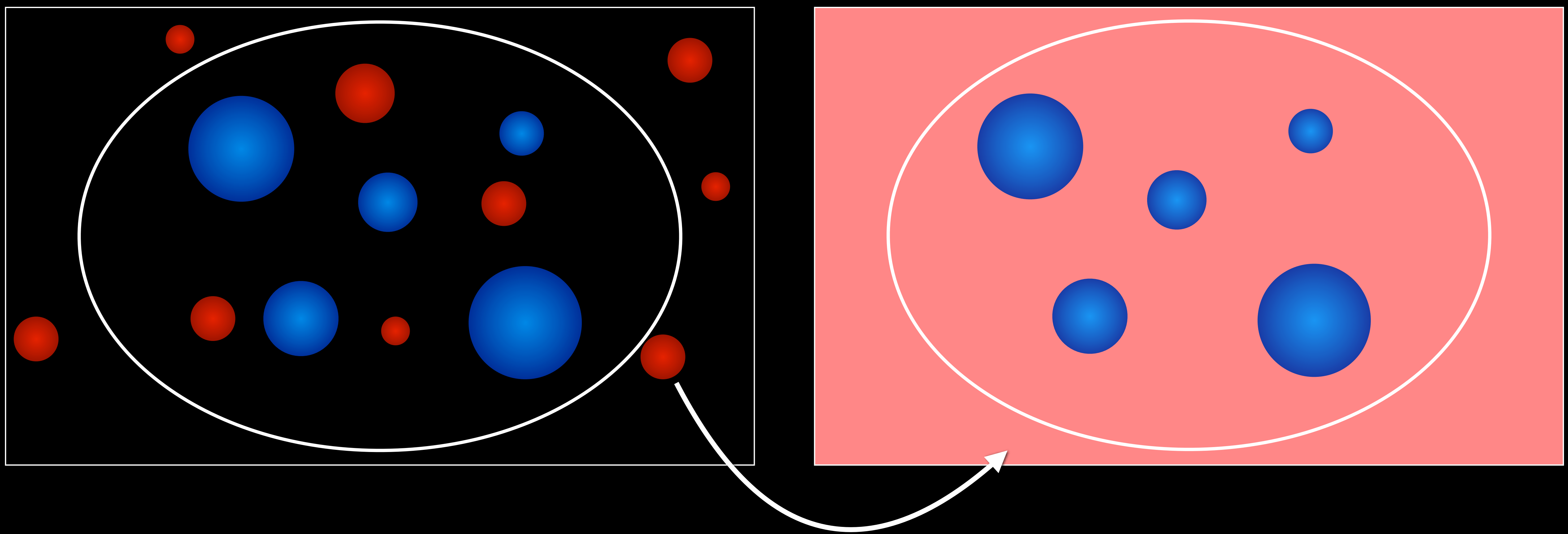
2018: 60 peak

LHC design

2012: 20

2009: <1

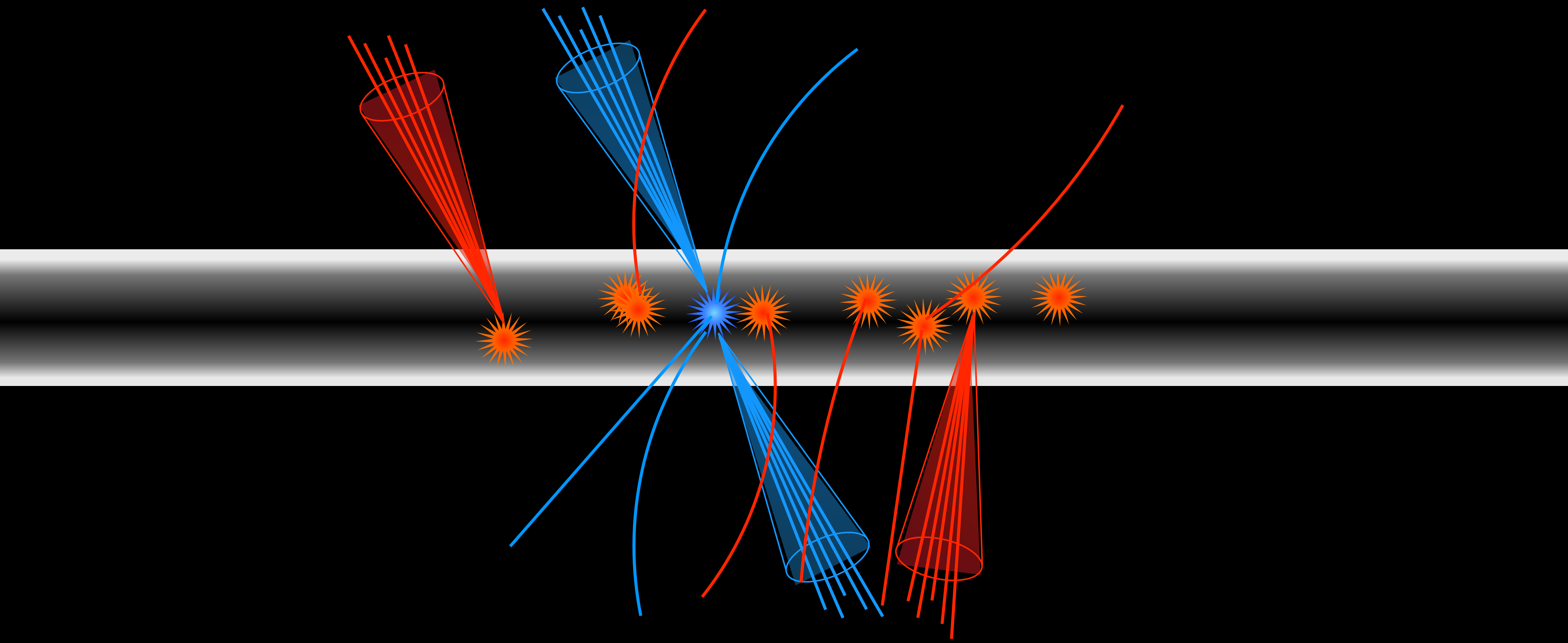
PILEUP IN JETS - ENERGY CORRECTION



Model as diffuse energy permeating calorimeter

Measure pileup energy density (median) and subtract jet area times energy density $A \cdot \rho$

PILEUP IN JETS — FAKE JET REJECTION



Assign tracks to pileup vertices or hard scatter vertex

Match tracks to jets & compute pileup discriminants
– based on fraction of hard scatter track pt

PILEUP IN JETS — FAKE JET REJECTION

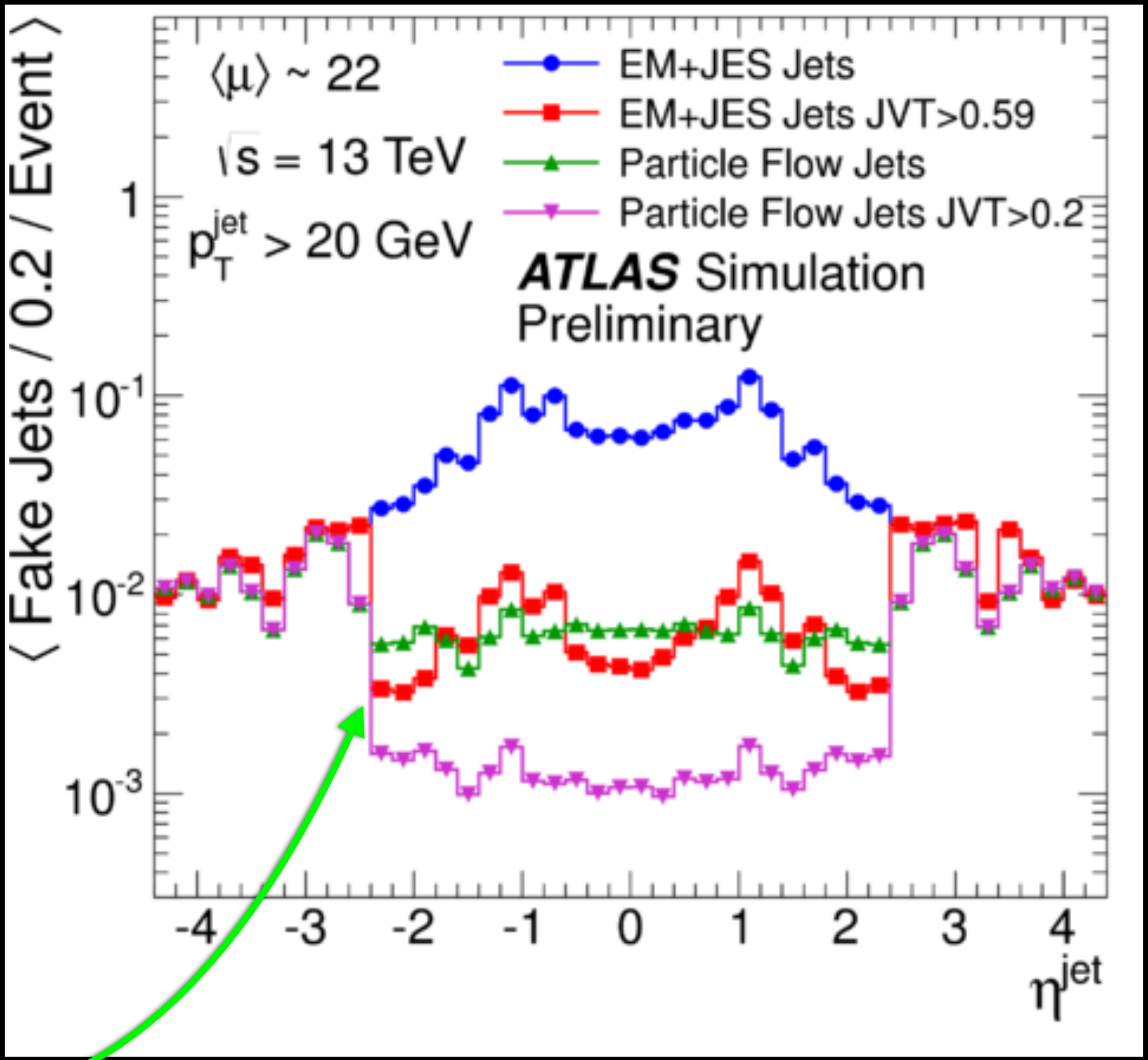
$$R_{\mathrm{pT}} = \frac{\sum_k p_{\mathrm{T},k}^{\mathrm{track}}(\mathrm{PV}_0)}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

HS track /calibrated p_T ratio

Penalise for tracks from pileup vertices, but scale penalty to total PU tracks to maintain stable efficiency wrt NPV

$$\mathrm{corrJVF} = \frac{\sum_m p_{\mathrm{T},m}^{\mathrm{track}}(\mathrm{PV}_0)}{\sum_l p_{\mathrm{T},l}^{\mathrm{track}}(\mathrm{PV}_0) + \frac{\sum_{n\geq 1}\sum_l p_{\mathrm{T},l}^{\mathrm{track}}(\mathrm{PV}_n)}{(k \cdot n_{\mathrm{track}}^{\mathrm{PU}})}}$$

(Corrected) fraction of track p_T from HS vertex

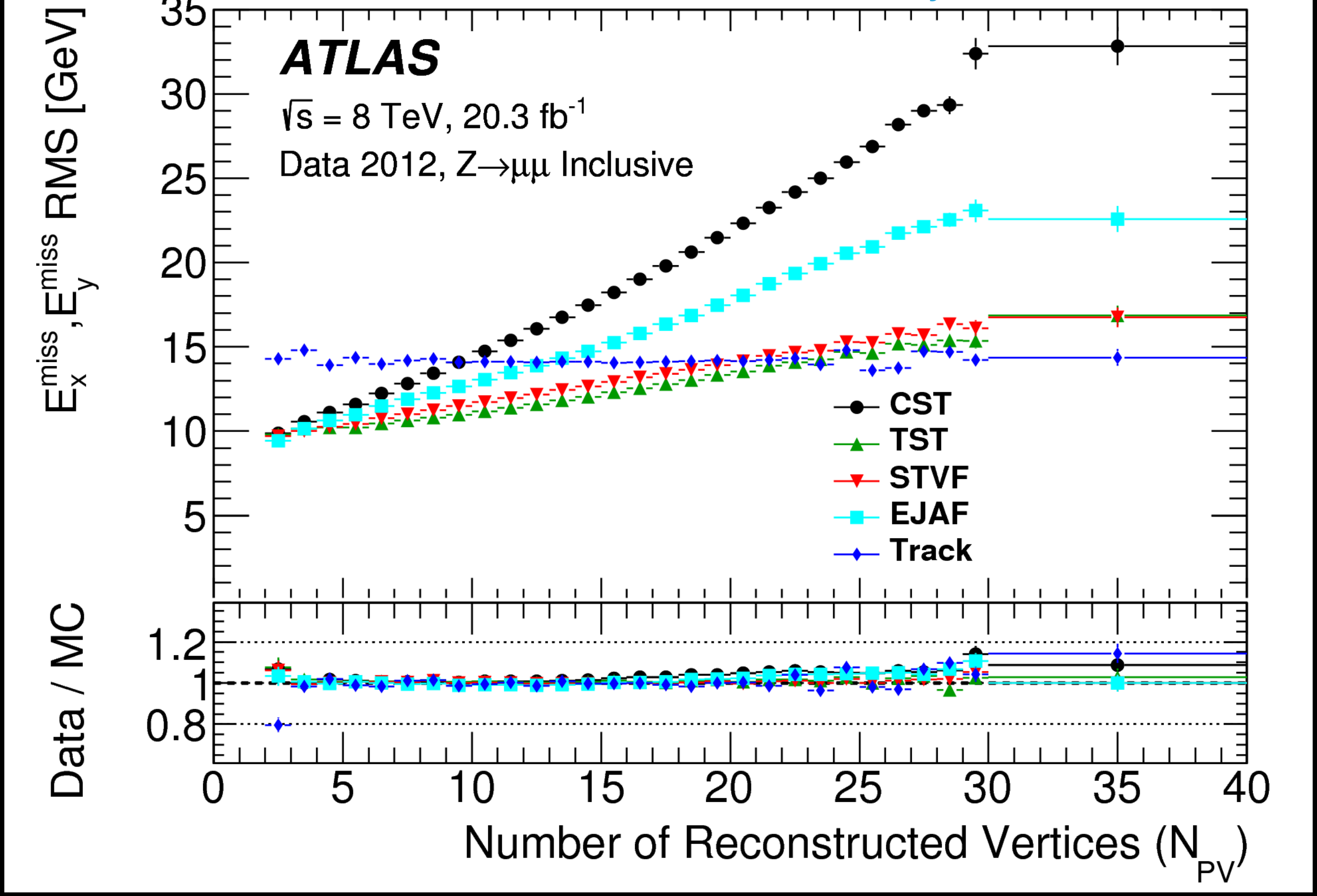


Form 2D likelihood for HS/PU jet discrimination

Eur. Phys. J. C (2016) 76:581

PILEUP IN MET — MITIGATION STRATEGIES

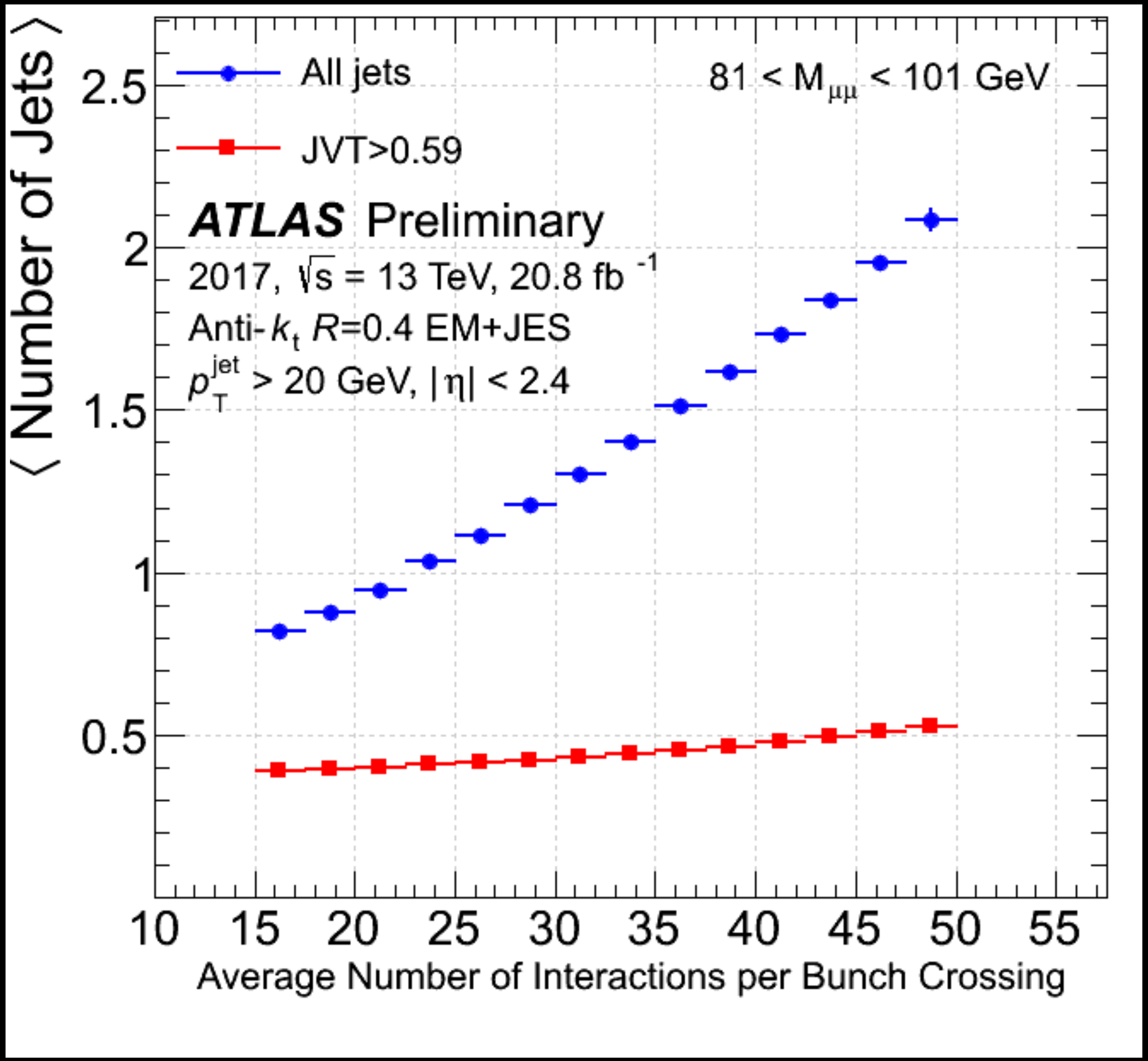
Eur. Phys. J. C77 (2017) 241

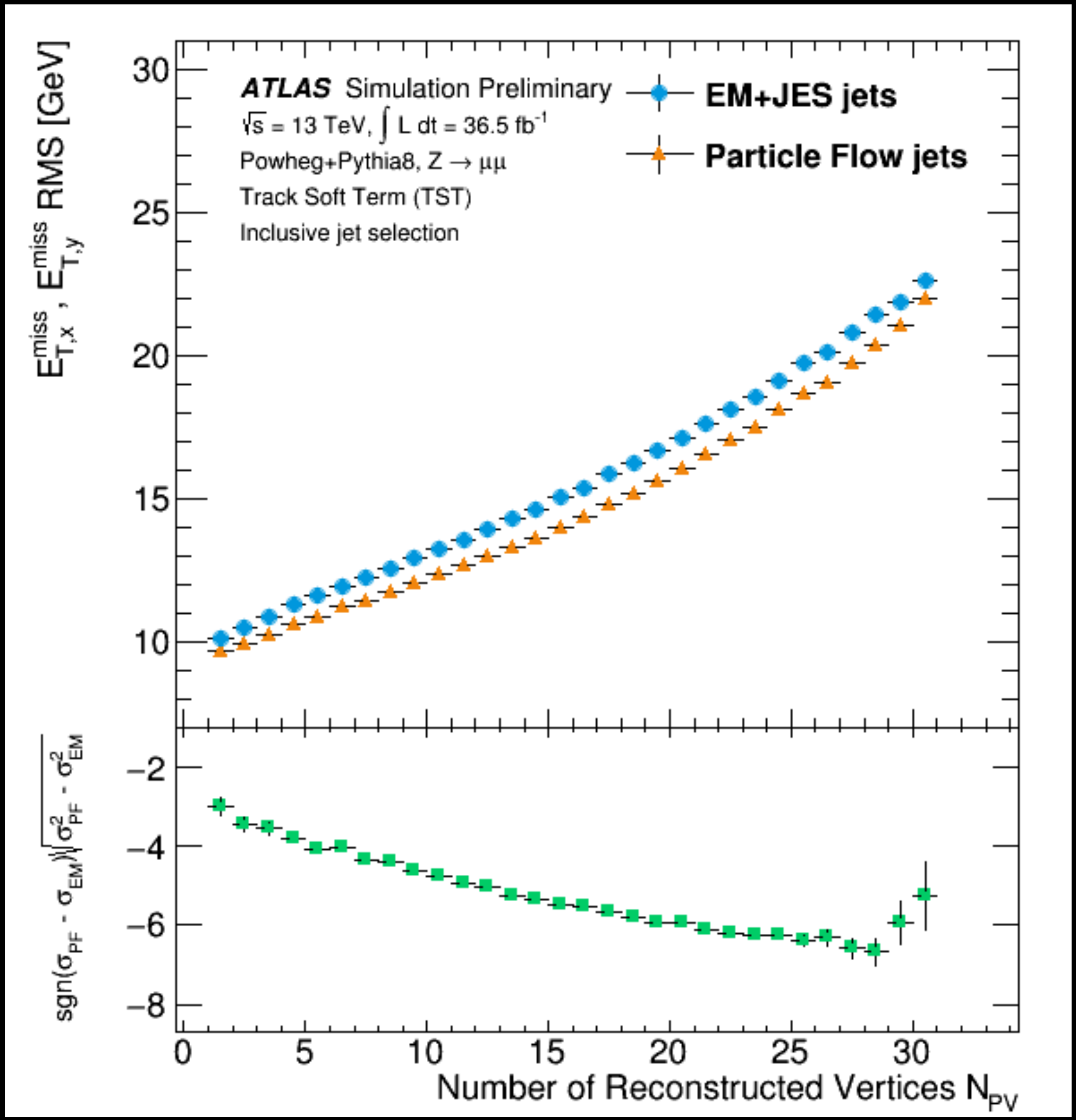


Tag & remove pileup jets

Build soft term from hard-scatter tracks

Penalty is incomplete reconstruction of hard scatter soft radiation

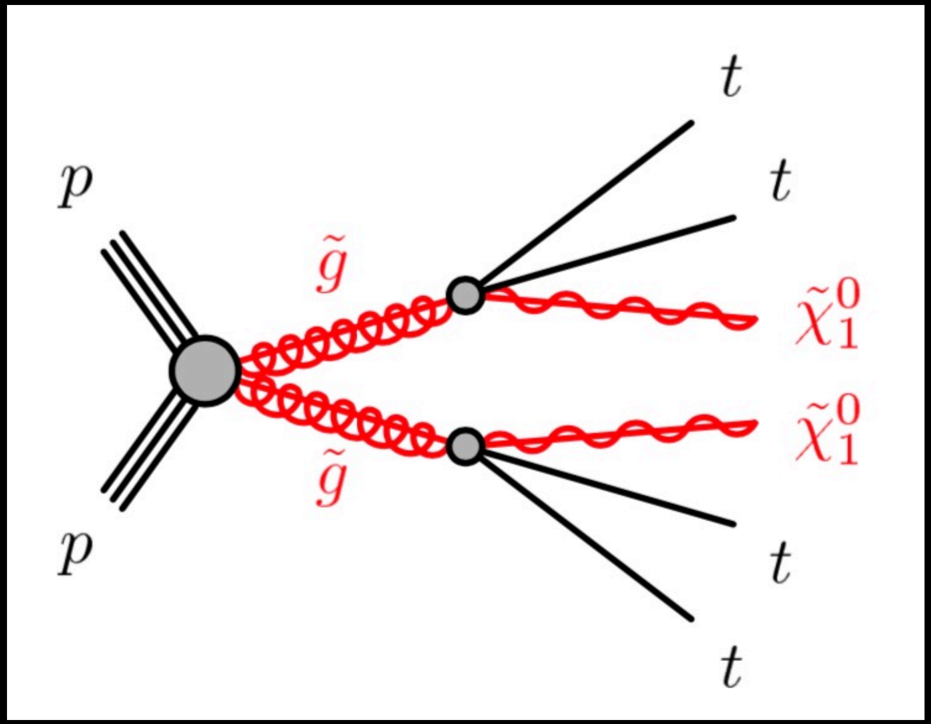


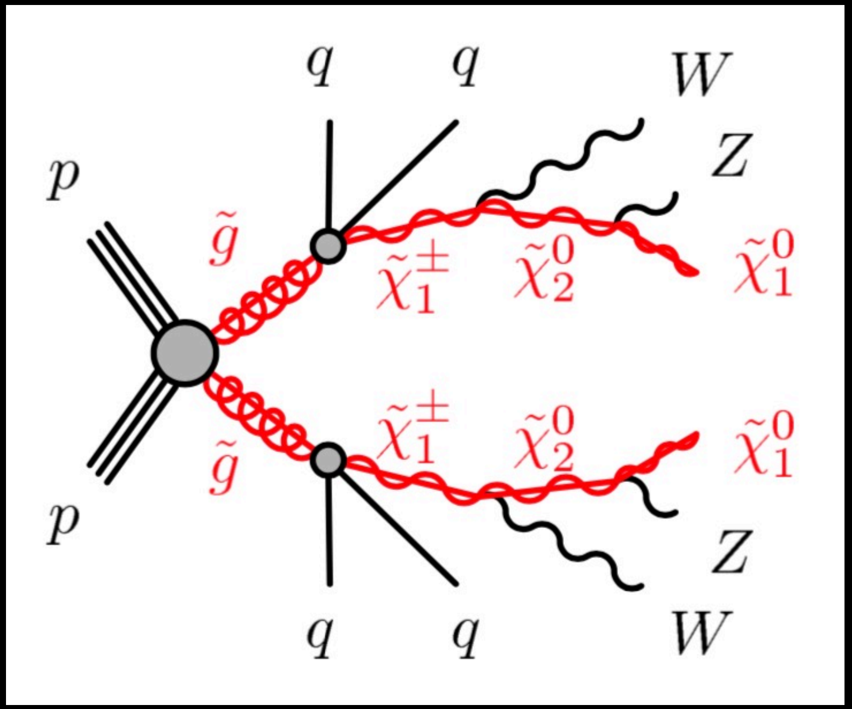


Large "fake" jet background without mitigation, mostly stable with PU tagger

MET resolution measured in Z events still grows due to fake jets

SUSY WITH JETS AND MET (AND MORE JETS)



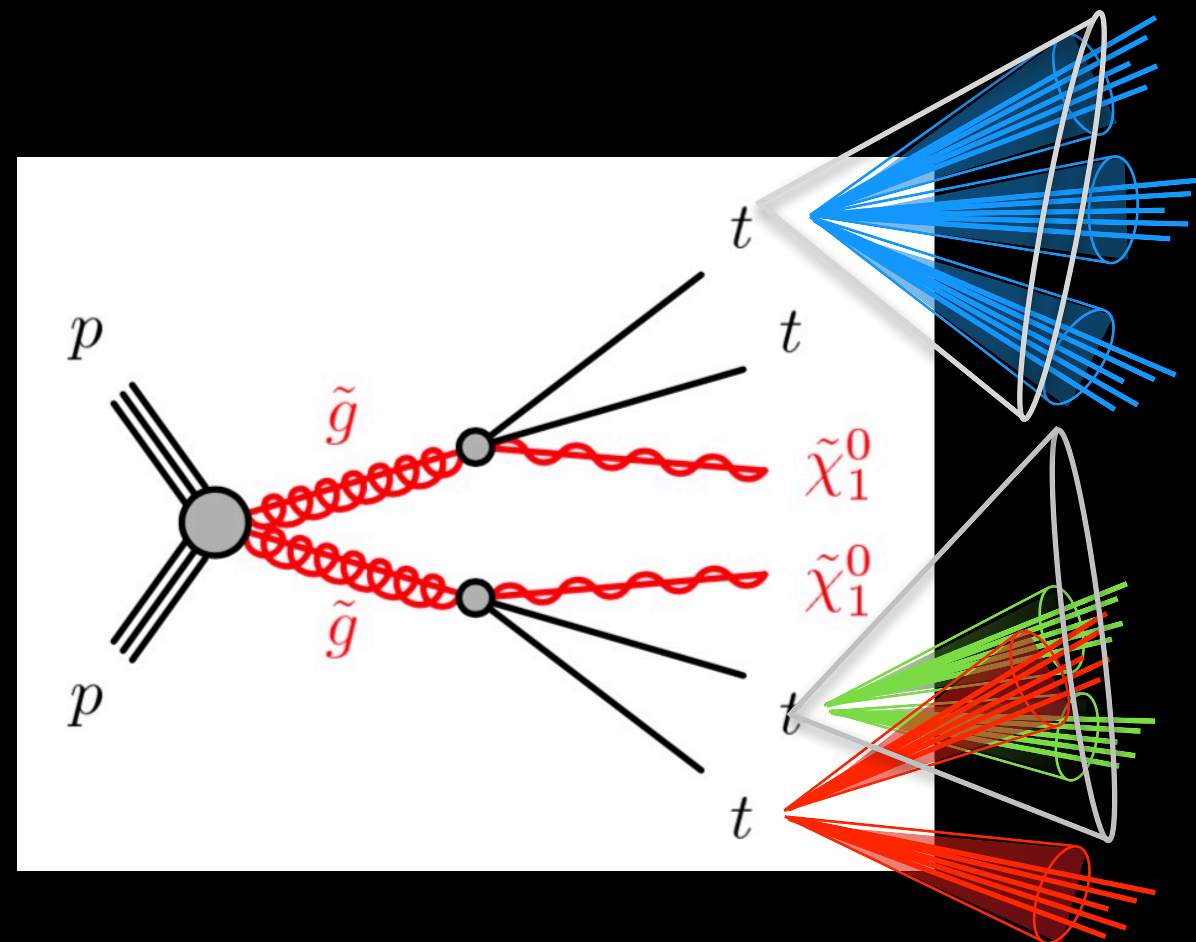


- New heavy particles (e.g. SUSY) could decay to many jets and MET. Long cascade decays reduce energy available to boost invisible particles.
- JHEP12(2017)034:
  - ≥8,9,10,11 jets with $p_T > 50$ GeV or ≥7,8,9 jets with $p_T > 80$ GeV
  - No leptons, significant" MET
  - Additional requirements of b-tagged jets and/or large jet masses

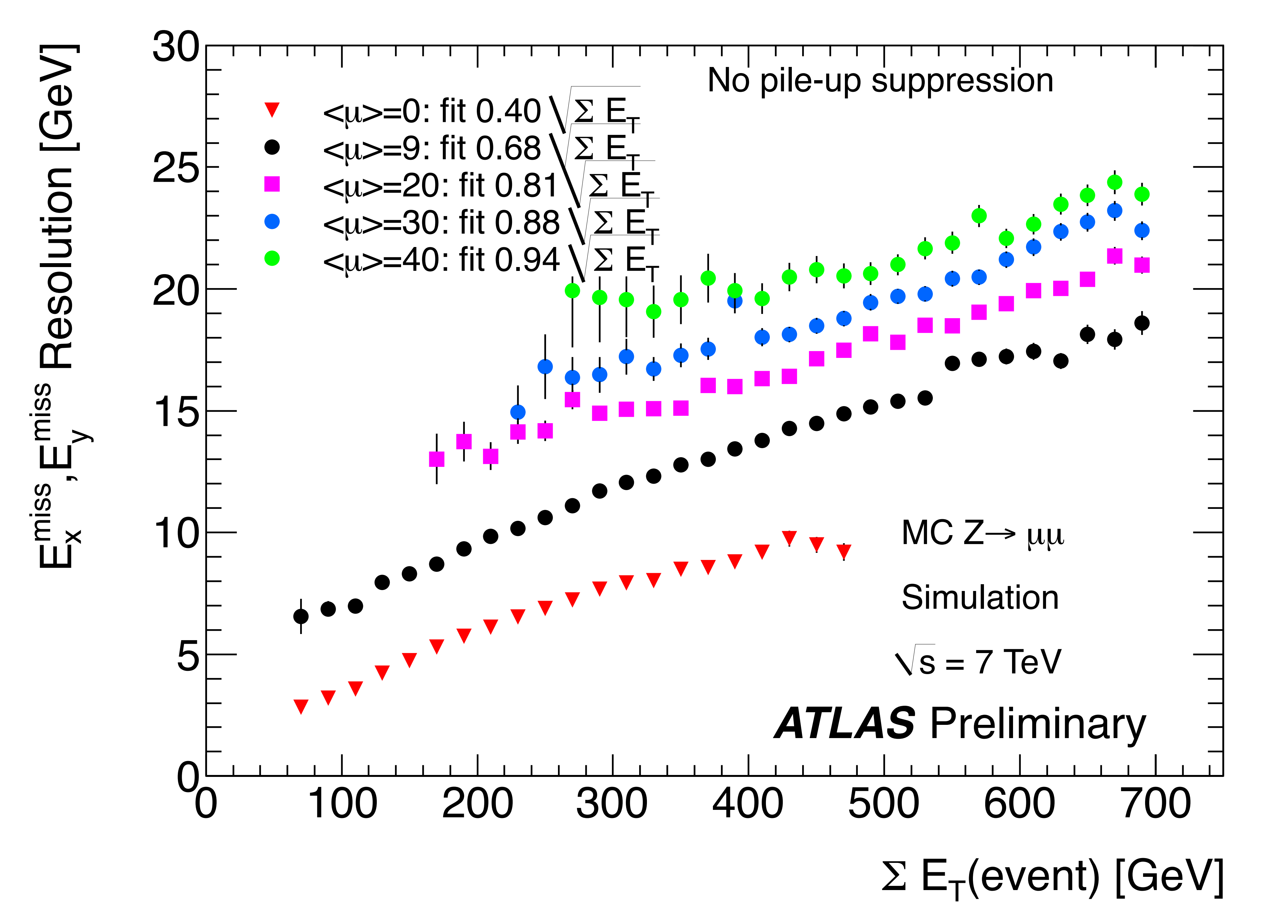
DISCRIMINATING VARIABLES

$$\frac{E_{\mathrm{T}}^{\mathrm{miss}}}{\sqrt{\sum E_{\mathrm{T}}}} \simeq \frac{E_{\mathrm{T}}^{\mathrm{miss}}}{\langle \sigma_{E_{\mathrm{T}}^{\mathrm{miss}}} \rangle} > 5$$

$$\sum_{\text{jets, R=1.0}} M_J > 340{,}500$$

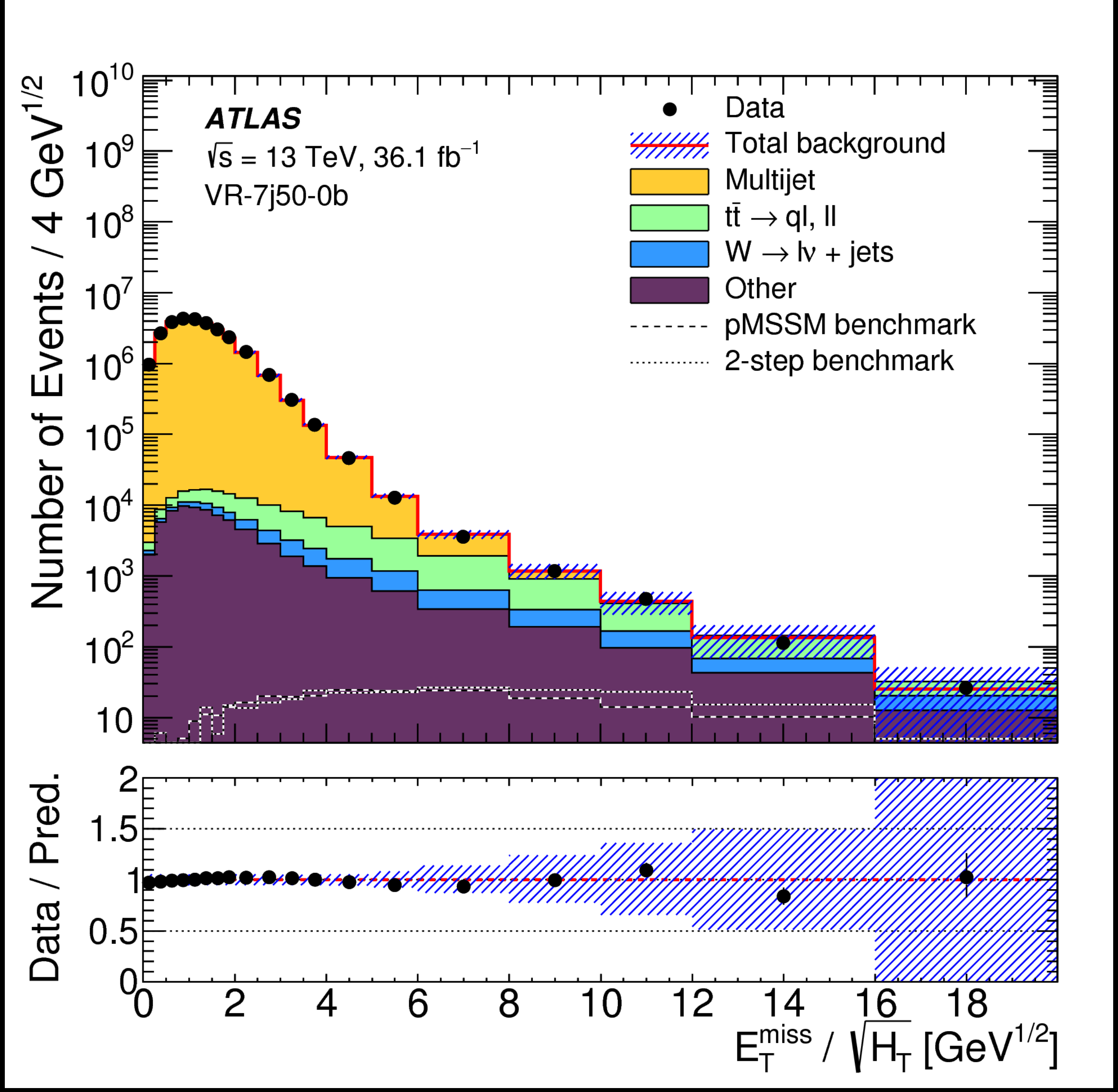


- Require moderate values of MET significance – incompatibility between measured MET and 0 hypothesis – uncorrelated with jet multiplicity
- Recluster jets with a larger radius in hope of capturing large mass groupings – does not require genuine resonant structure ("accidental substructure")



Calorimeter design resolution for central charged pions

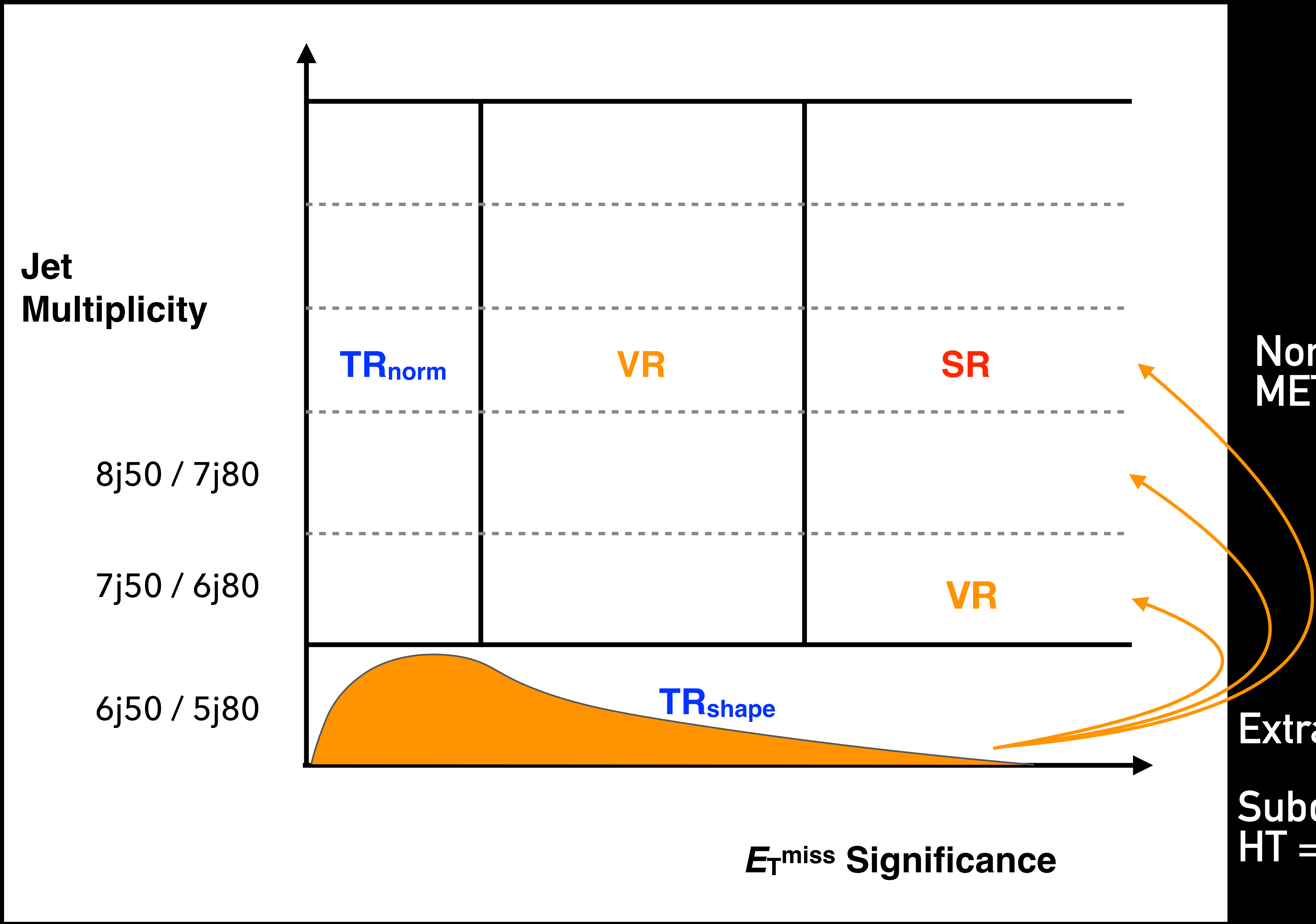
$$\frac{\sigma(E)}{E} = \frac{50\,\%}{\sqrt{E}} \oplus 3.4\,\% \oplus \frac{1\,\%}{E}$$



Dominant backgrounds:
Multijets
Top pairs+jets
W+jets

- Signals have wide MET distribution, buried at low jet multiplicities.
- Multijet background has huge cross-section, difficult to simulate – use data-driven prediction

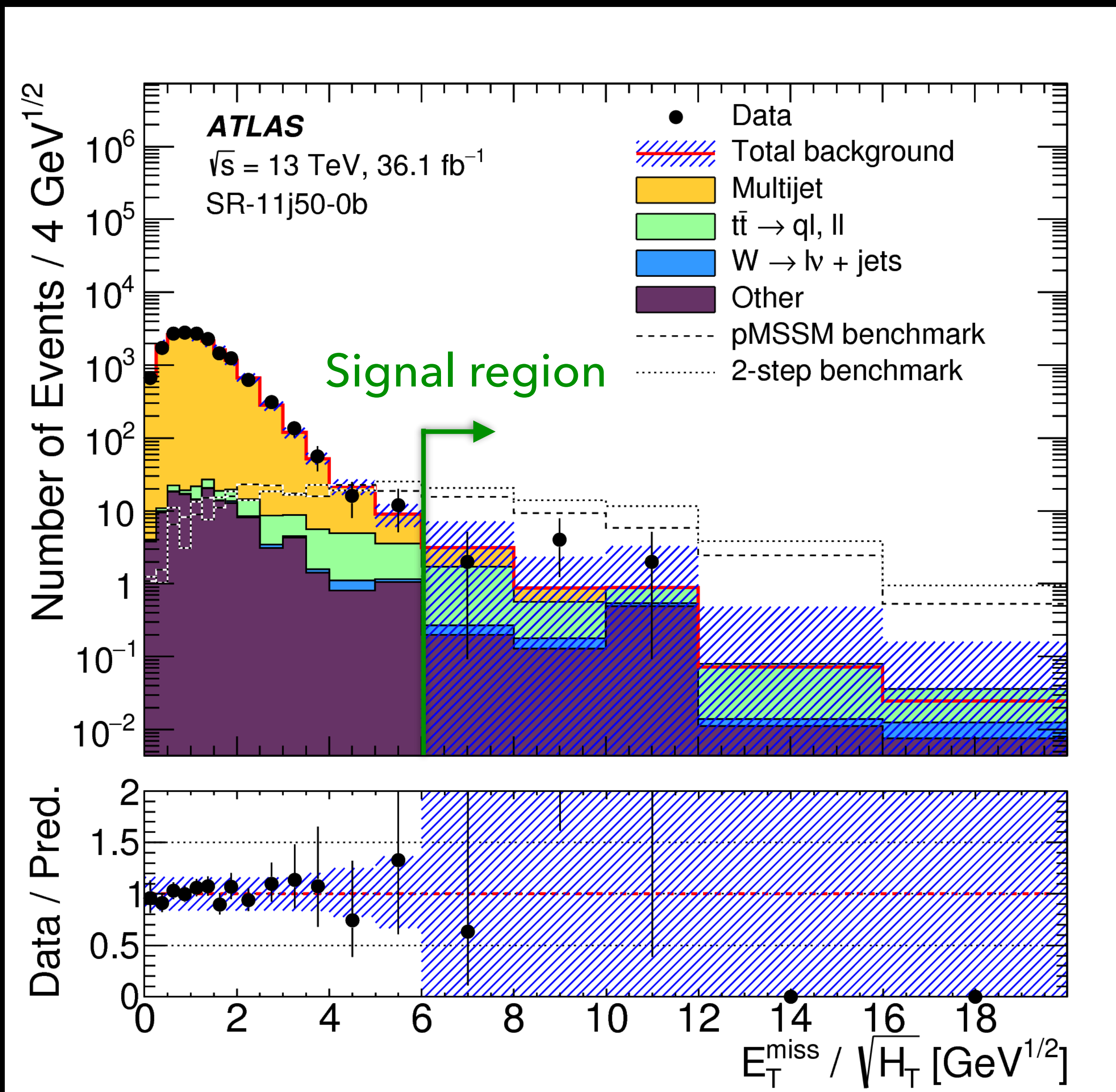
"MULTIJET TEMPLATE" METHOD

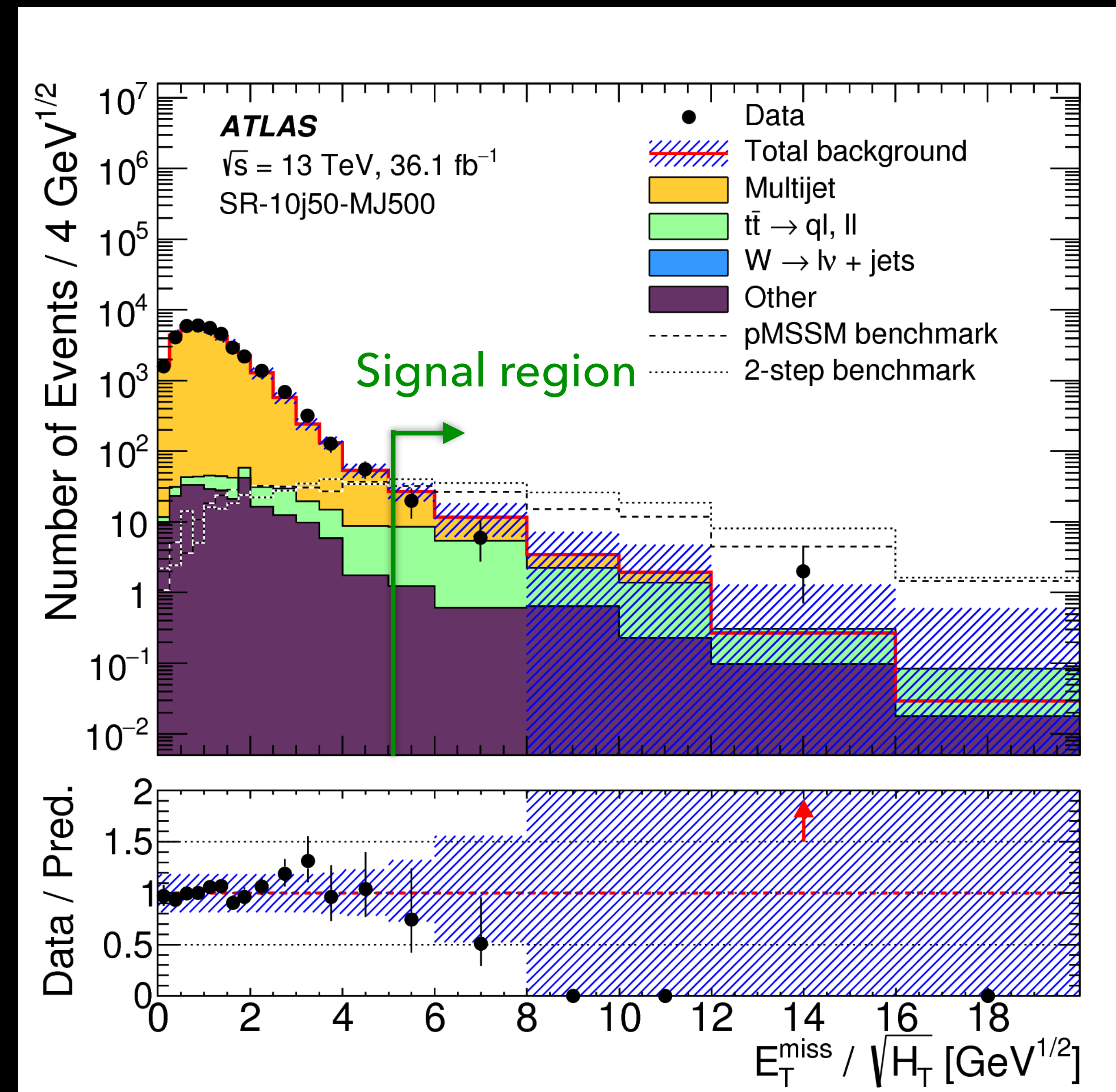


Normalise at low MET Significance

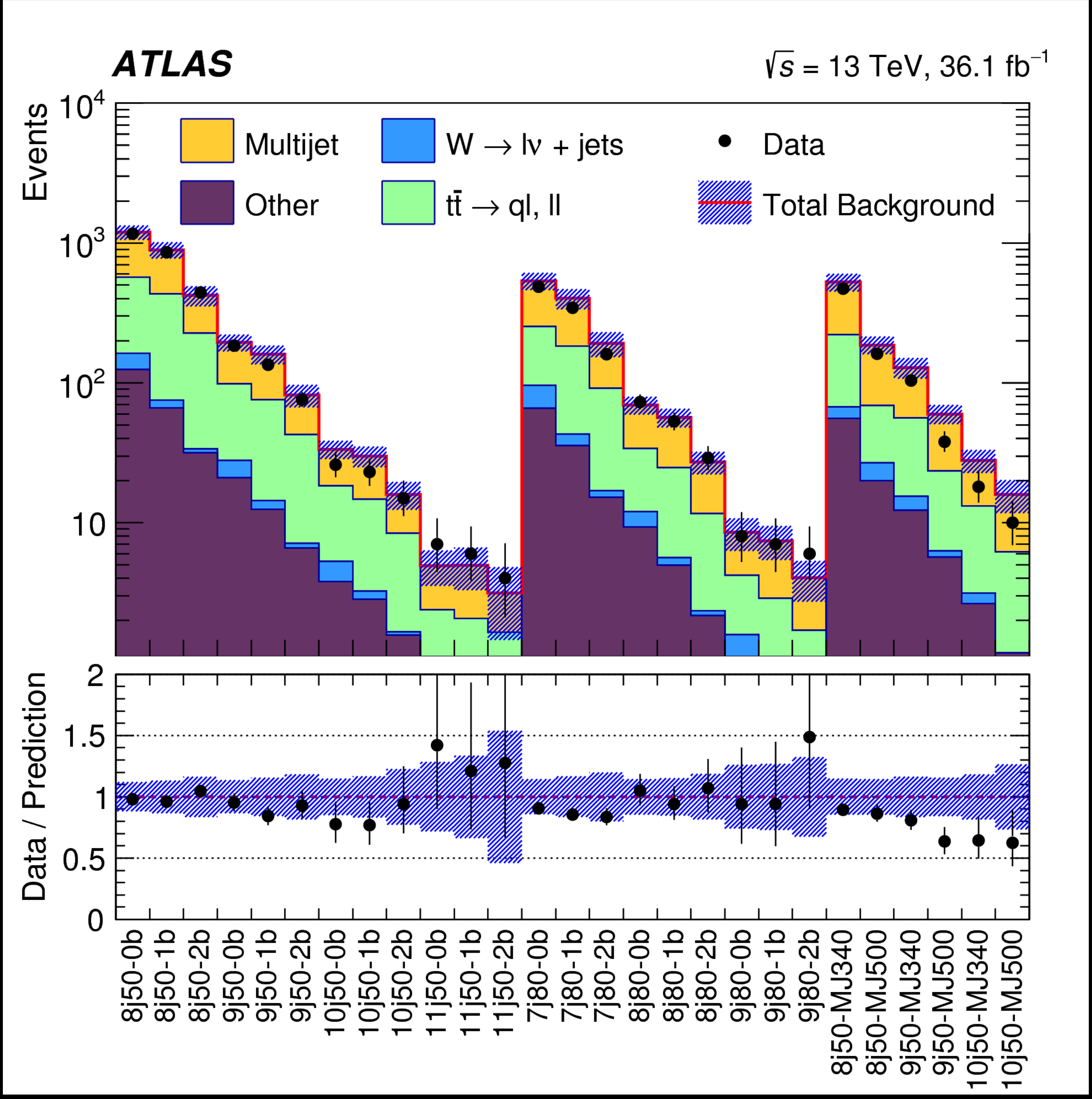
Extract from data - MC

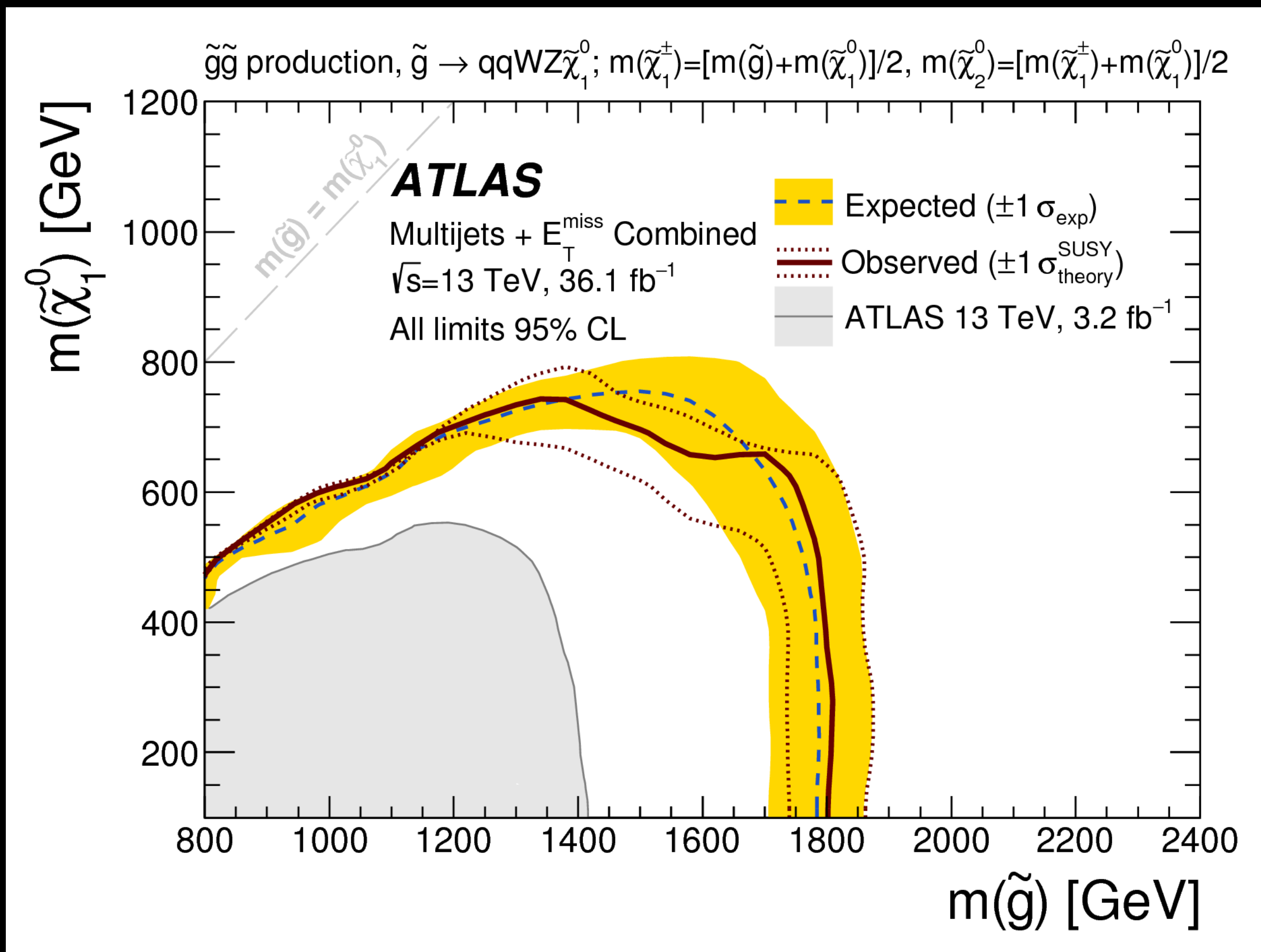
Subdivided in bins of HT $= \sum_{\text{jets}} p_{\mathrm{T}}$

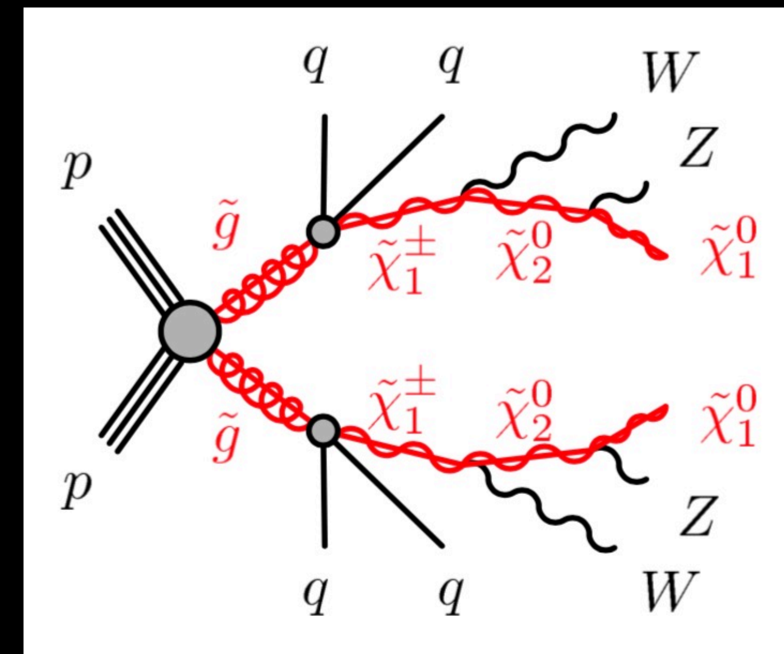


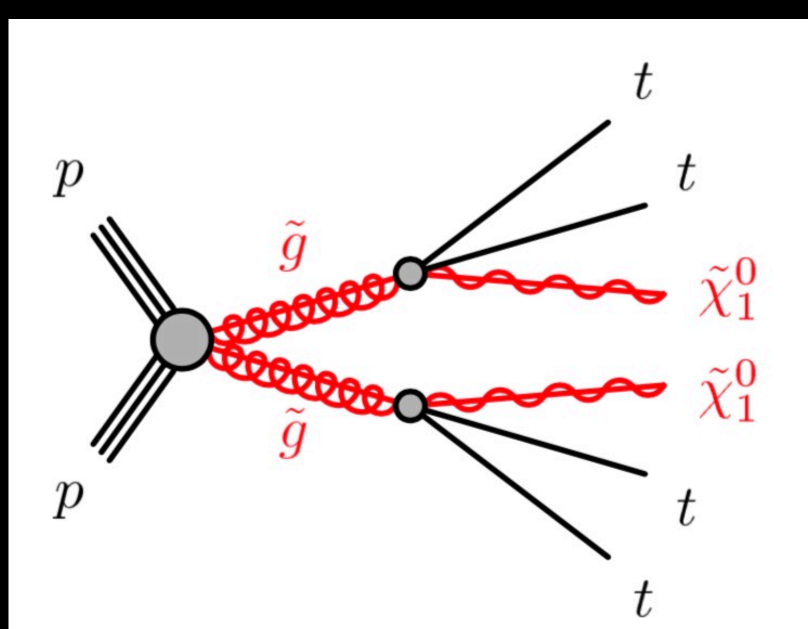


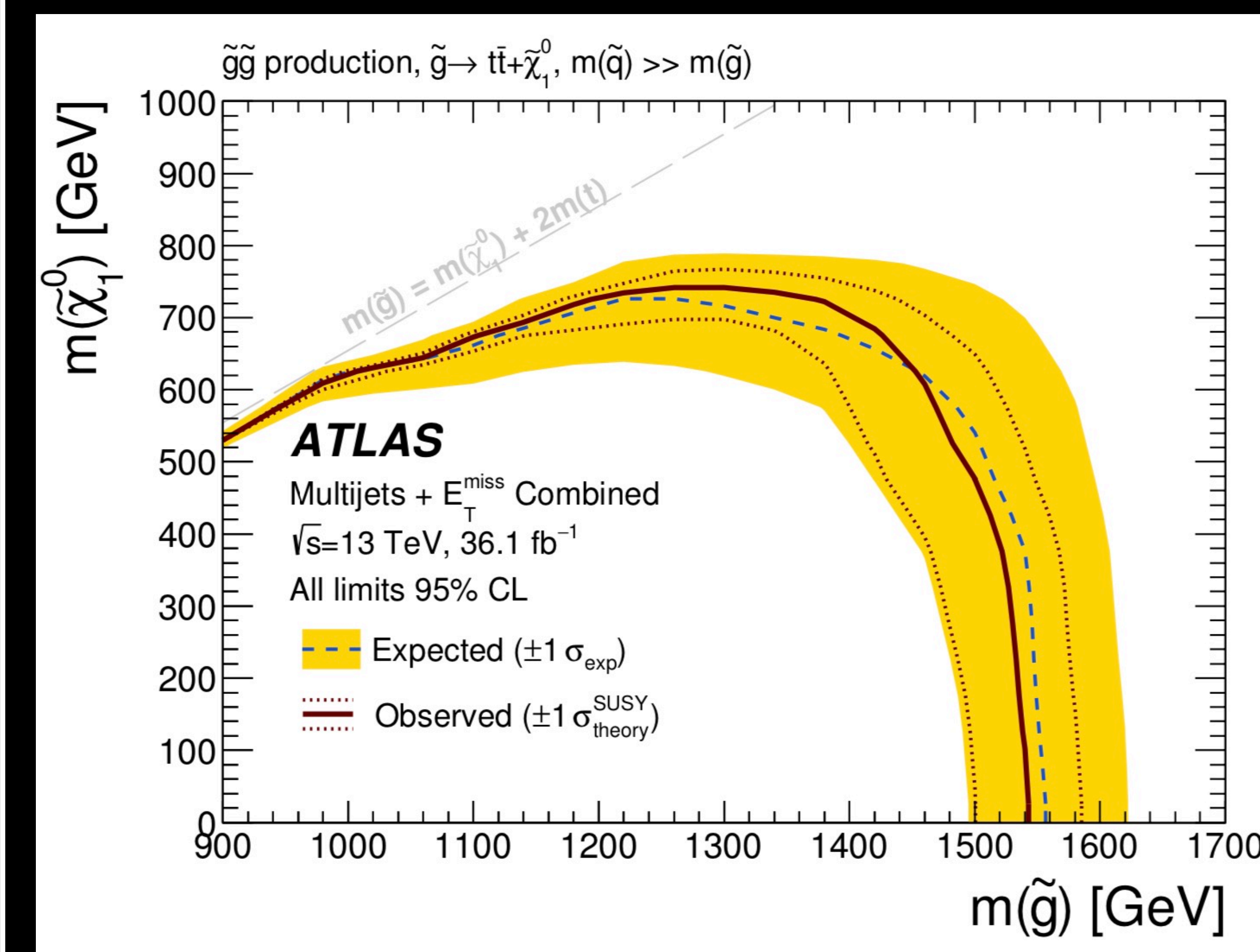
- Template prediction extends successfully across many jet bins with b-tagging and jet mass selection


ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Events
Multijet
W → lν + jets
Data
Other
tt̄ → ql, ll
Total Background
Data / Prediction
8j50-0b
8j50-1b
8j50-2b
9j50-0b
9j50-1b
9j50-2b
10j50-0b
10j50-1b
10j50-2b
11j50-0b
11j50-1b
11j50-2b
7j80-0b
7j80-1b
7j80-2b
8j80-0b
8j80-1b
8j80-2b
9j80-0b
9j80-1b
9j80-2b
8j50-MJ340
8j50-MJ500
9j50-MJ340
9j50-MJ500
10j50-MJ340
10j50-MJ500

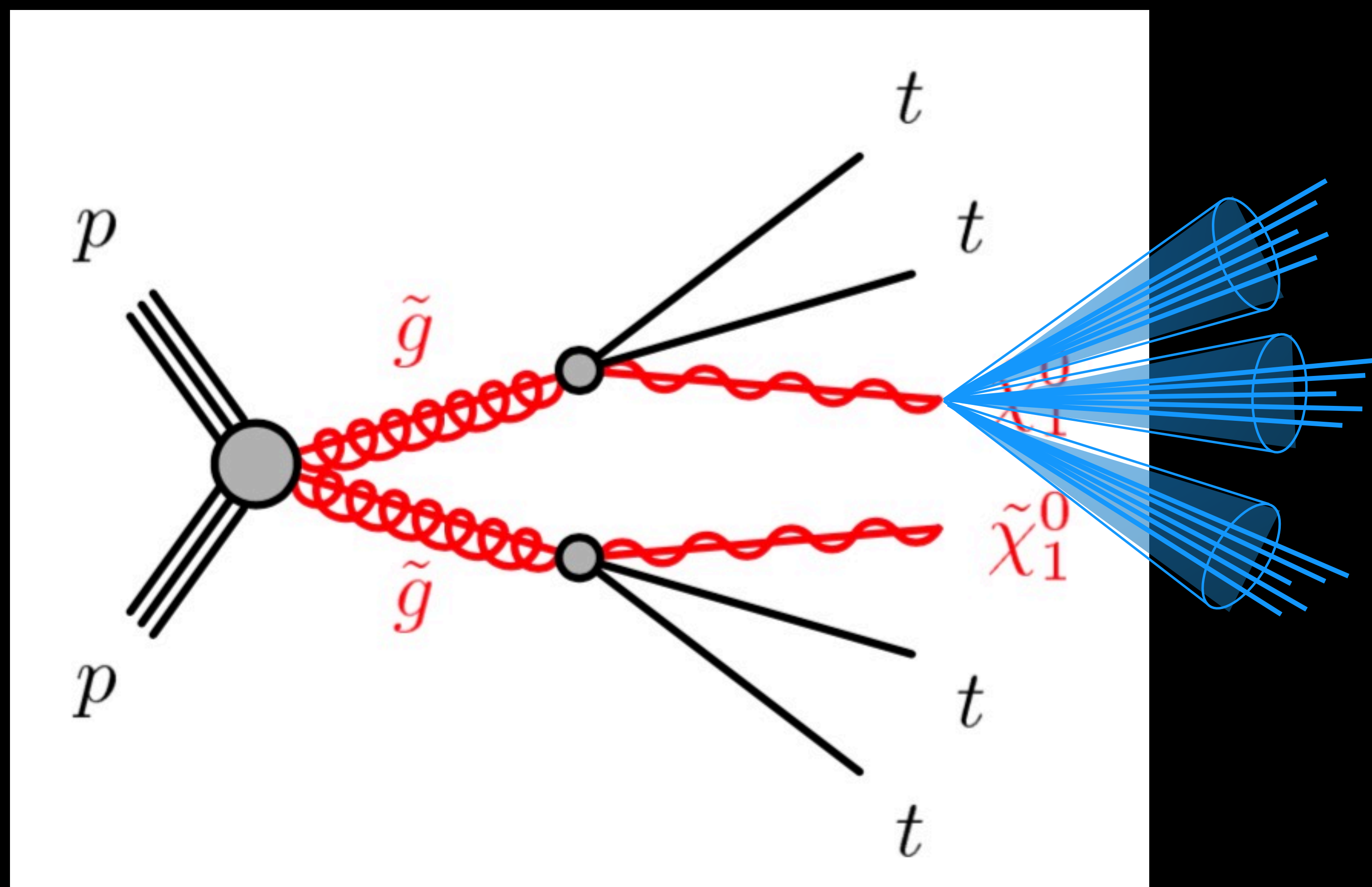

g̃g̃ production, g̃ → qqWZχ̃₁⁰; m(χ̃₁±)=[m(g̃)+m(χ̃₁⁰)]/2, m(χ̃₂⁰)=[m(χ̃₁±)+m(χ̃₁⁰)]/2
ATLAS
Multijets + E_T^miss Combined
√s=13 TeV, 36.1 fb⁻¹
All limits 95% CL
Expected (±1 σ_exp)
Observed (±1 σ_theory^SUSY)
ATLAS 13 TeV, 3.2 fb⁻¹
m(g̃) = m(χ̃₁⁰)
m(χ̃₁⁰) [GeV]
m(g̃) [GeV]
1200
1000
800
600
400
200
800
1000
1200
1400
1600
1800
2000
2200
2400


p
p
q
q
q
q
W
Z
Z
W
g̃
g̃
χ̃₁±
χ̃₂⁰
χ̃₁⁰
χ̃₁±
χ̃₂⁰
χ̃₁⁰


p
p
t
t
t
t
g̃
g̃
χ̃₁⁰
χ̃₁⁰

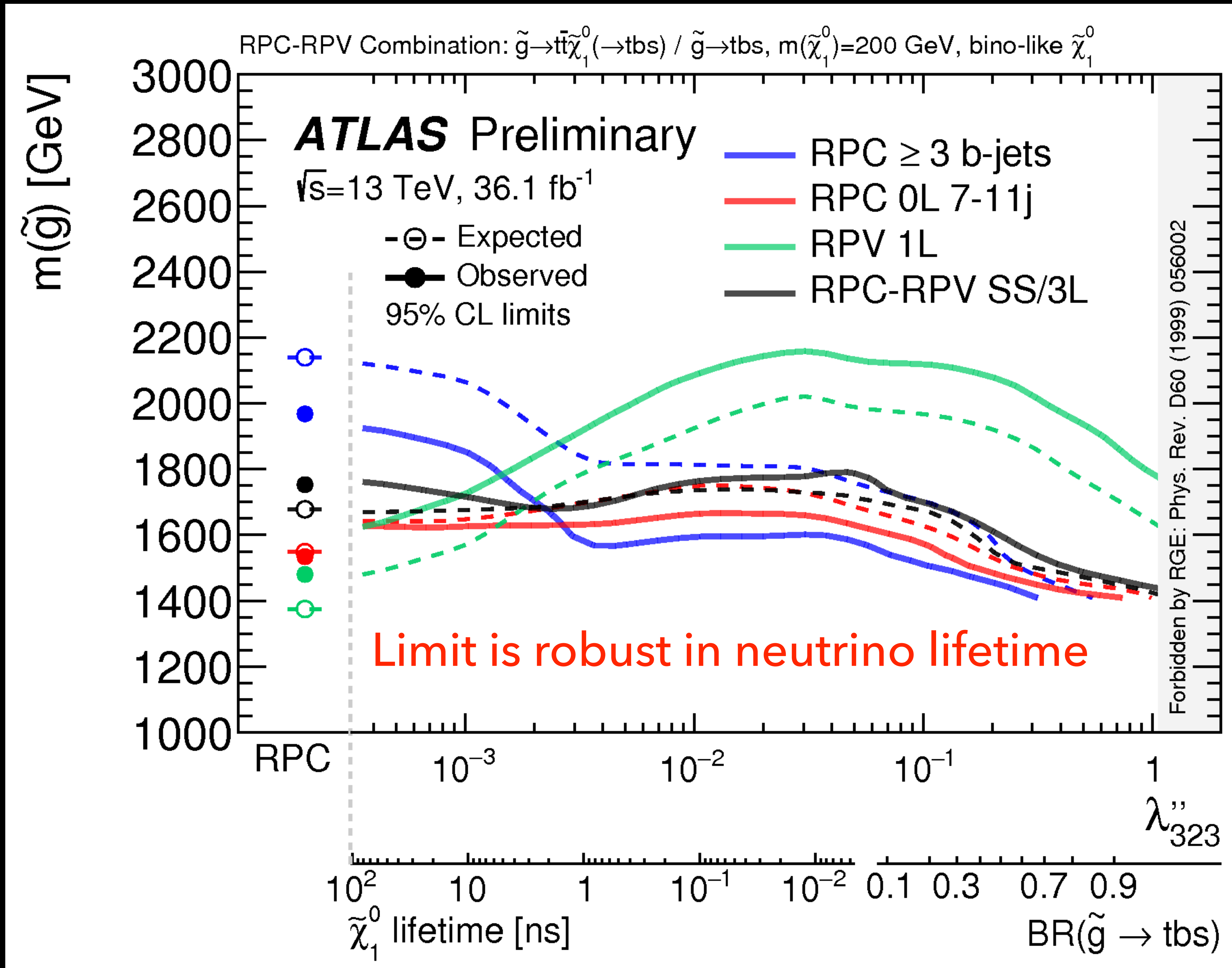

g̃g̃ production, g̃→ tt̄+χ̃₁⁰, m(q̃) >> m(g̃)
ATLAS
Multijets + E_T^miss Combined
√s=13 TeV, 36.1 fb⁻¹
All limits 95% CL
Expected (±1 σ_exp)
Observed (±1 σ_theory^SUSY)
m(g̃) = m(χ̃₁⁰) + 2m(t)
m(χ̃₁⁰) [GeV]
m(g̃) [GeV]
1000
900
800
700
600
500
400
300
200
100
0
900
1000
1100
1200
1300
1400
1500
1600
1700

R-PARITY VIOLATION



Drop assumption of R-parity conservation as protection against proton stability (can still be guaranteed by avoiding simultaneous baryon-number-violating and lepton-number-violating operators)

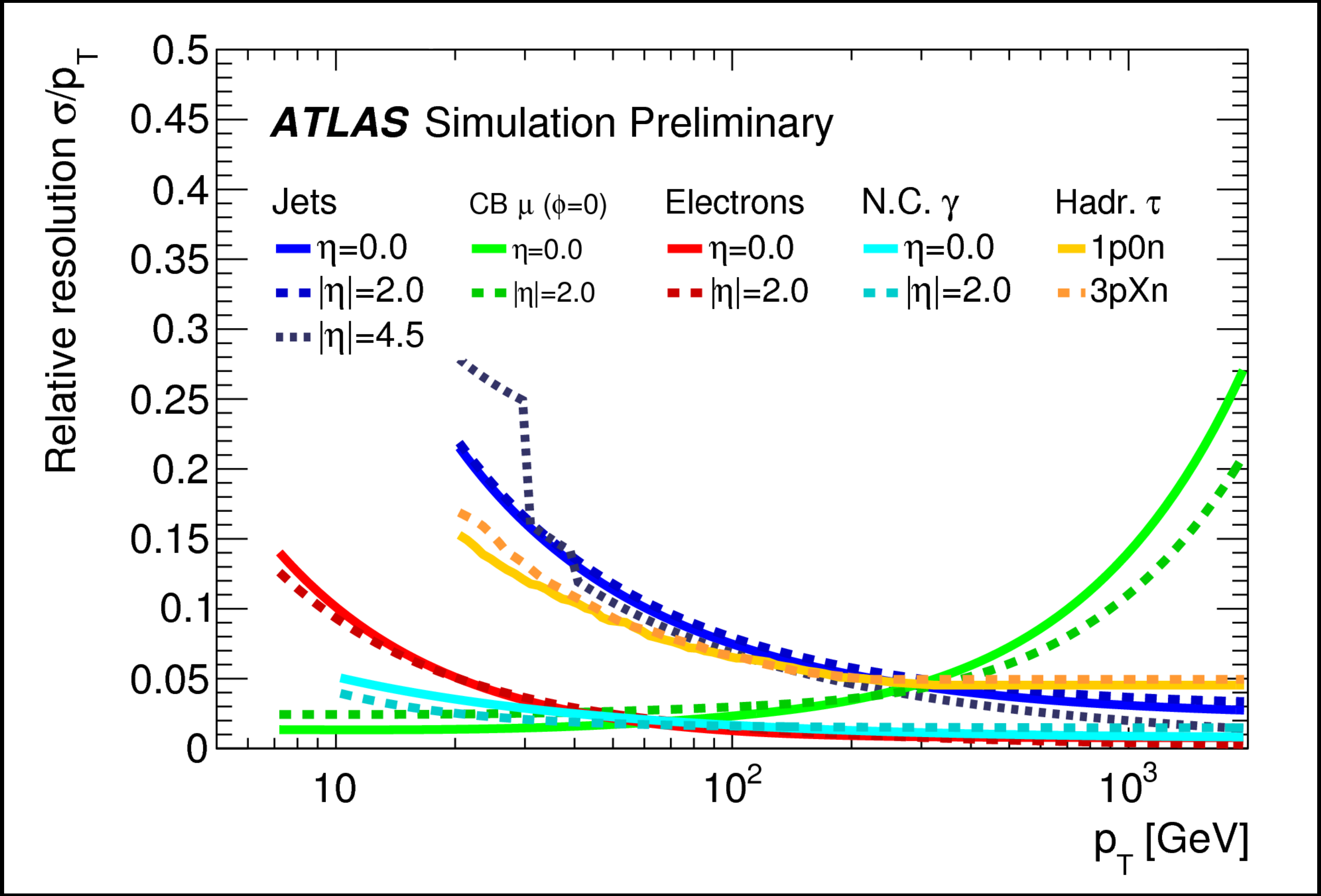
[ATLAS-CONF-2018-003]



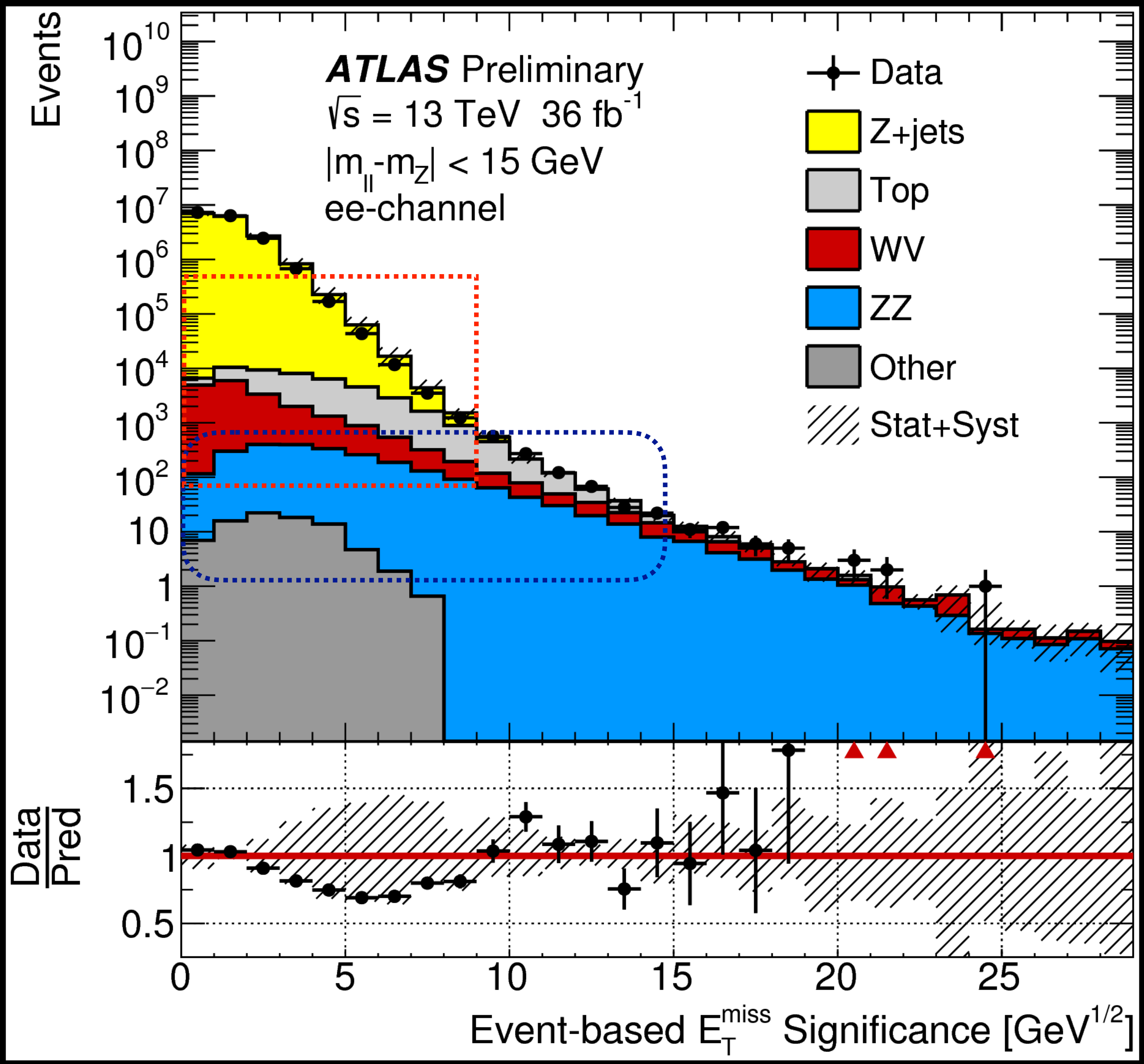
THE FUTURE

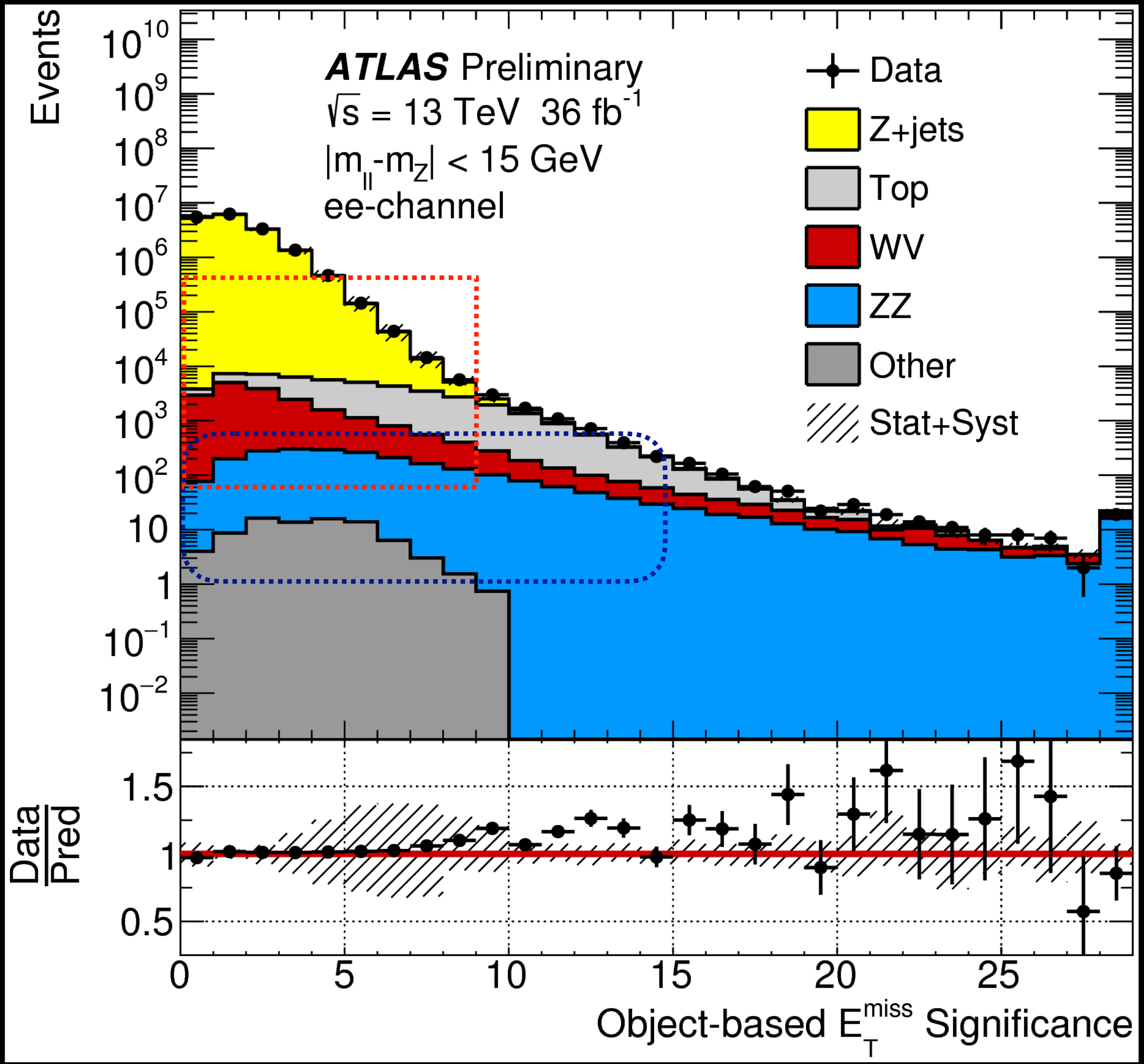

Resolutions
1.
2.

ATLAS-CONF-2018-038



MOVING BEYOND SQRT(SUMET)





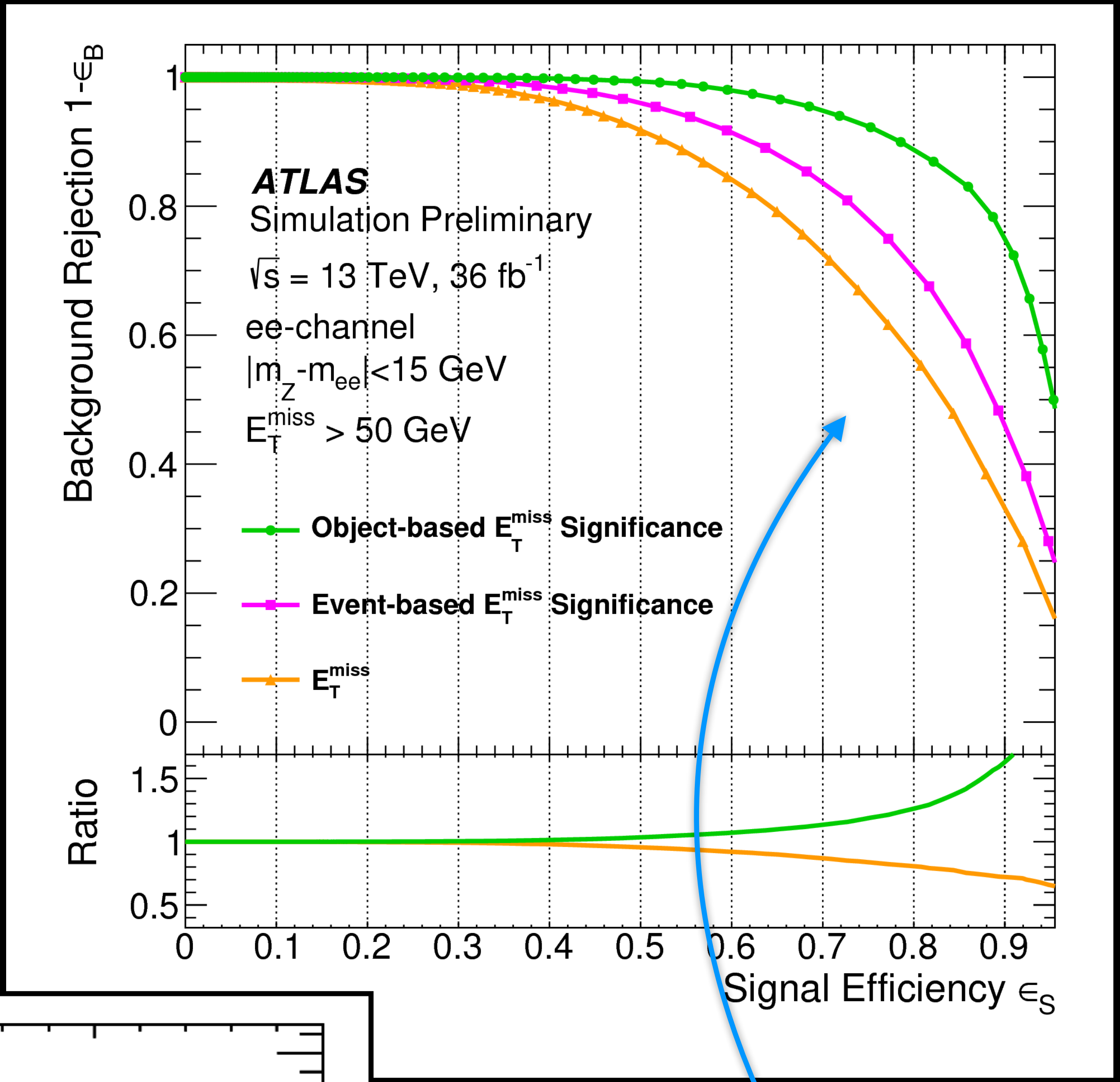
$$\frac{E_{\mathrm{T}}^{\mathrm{miss}}}{\sqrt{\sum E_{\mathrm{T}}}}$$

$$\frac{E_{\mathrm{T}}^{\mathrm{miss}}}{\langle \sigma_{E_{\mathrm{T}}^{\mathrm{miss}}} \rangle}$$

Propagate object resolutions to estimate total MET resolution

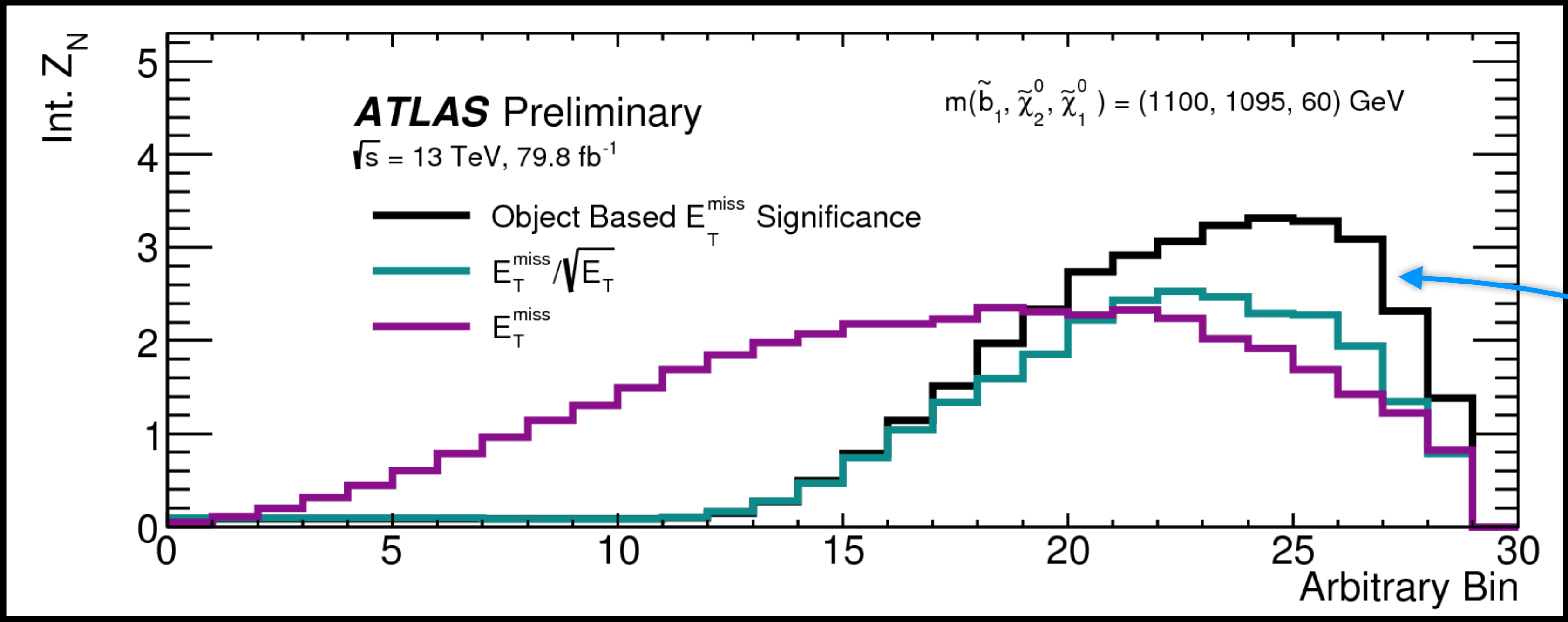
“Resolution” penalty for jets that may be from pileup

Object-based definition provides much better separation between real & fake MET sources – enhanced signal discrimination for searches



Z->ll+jets vs ZZ->llνν+jets

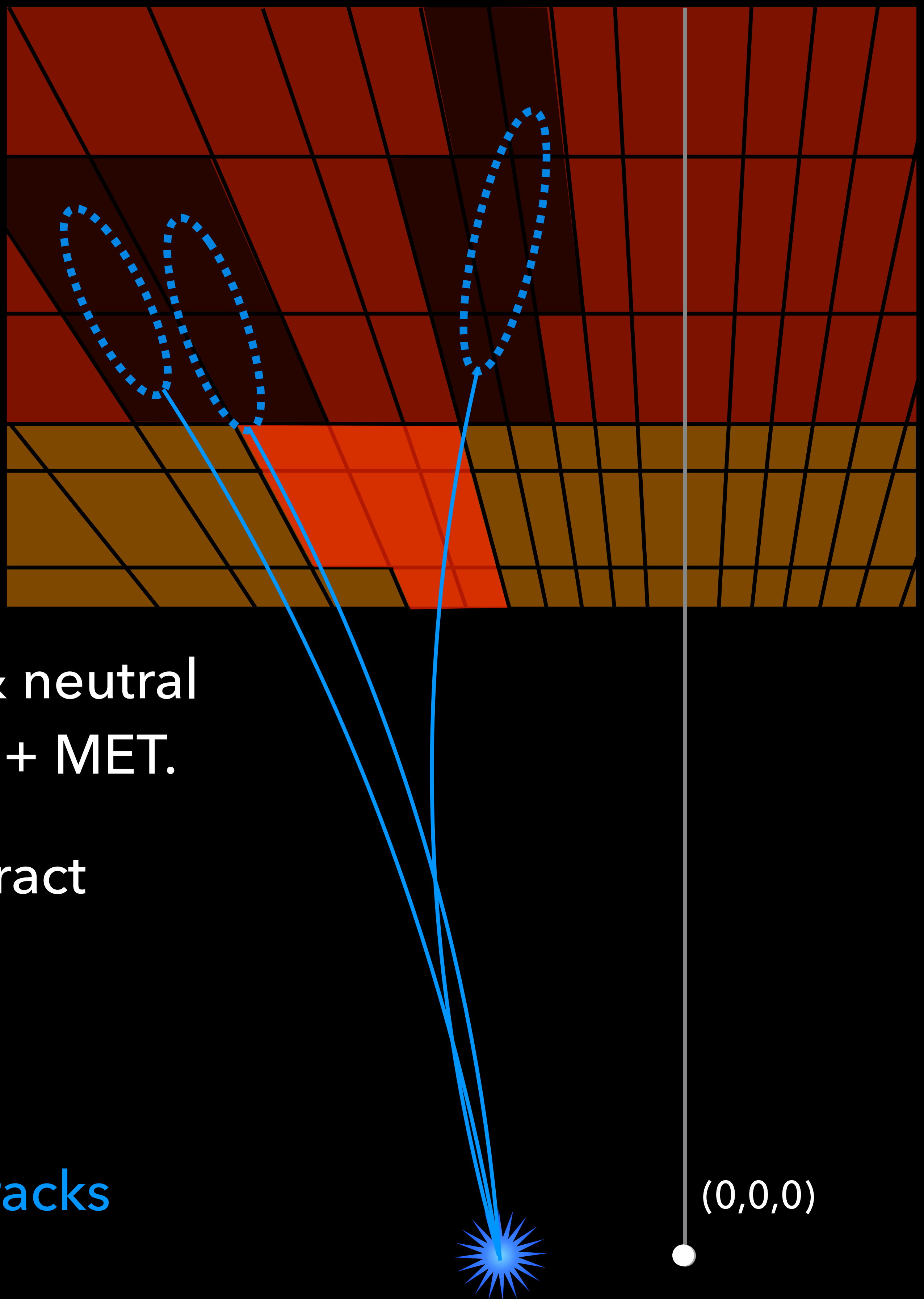
ATLAS-CONF-2018-040



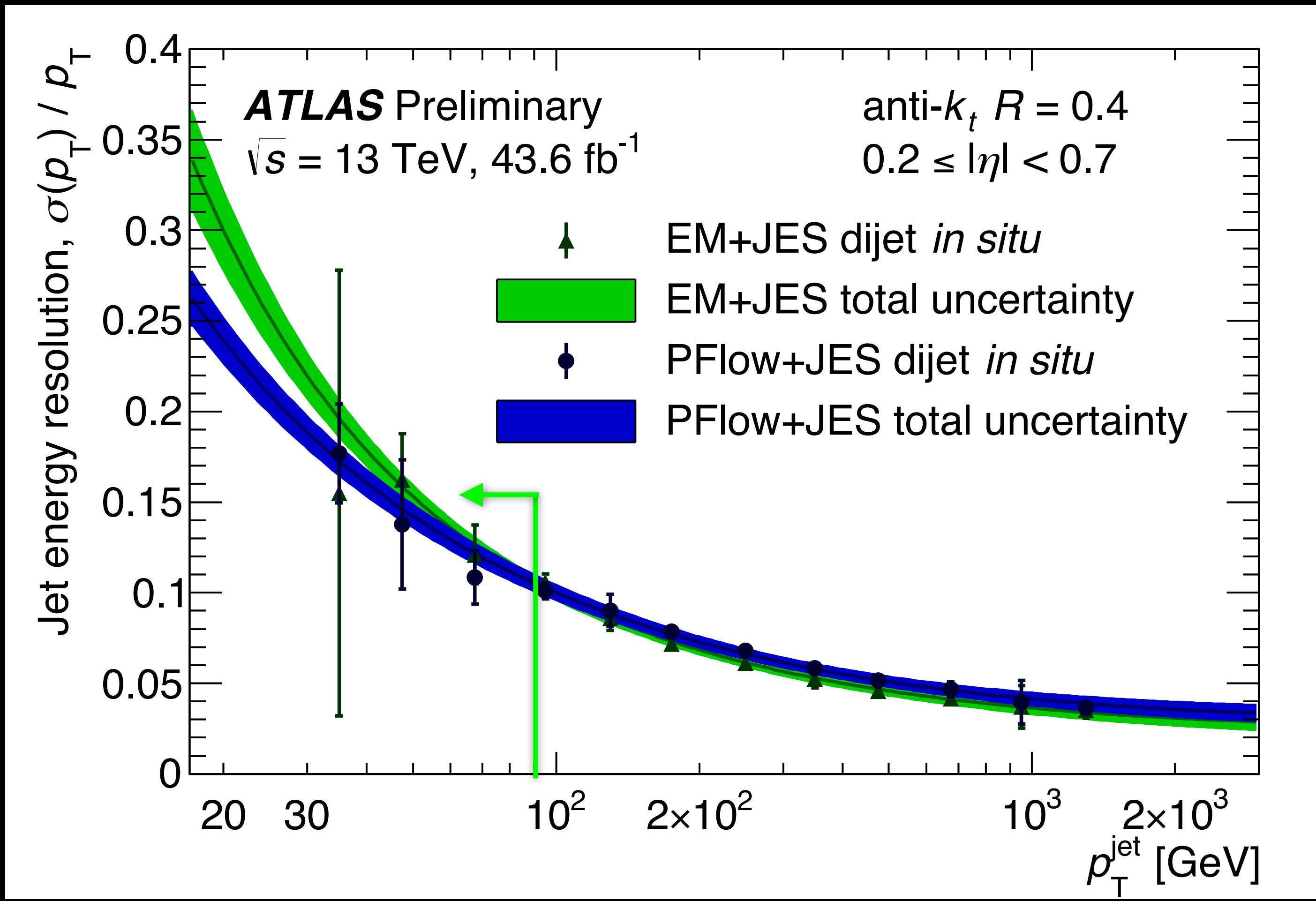
Discovery significance for superpartner of b quark

JETS WITH TRACKS

MORE PRECISION FOR YOUR PENNY: PARTICLE FLOW



- ATLAS variant: decompose charged & neutral calo energy and thereby improve jets + MET.
- Match tracks to topoclusters and subtract predicted energy deposits
- Discard pileup tracks *after subtraction*
- Build jets from neutral clusters & HS tracks

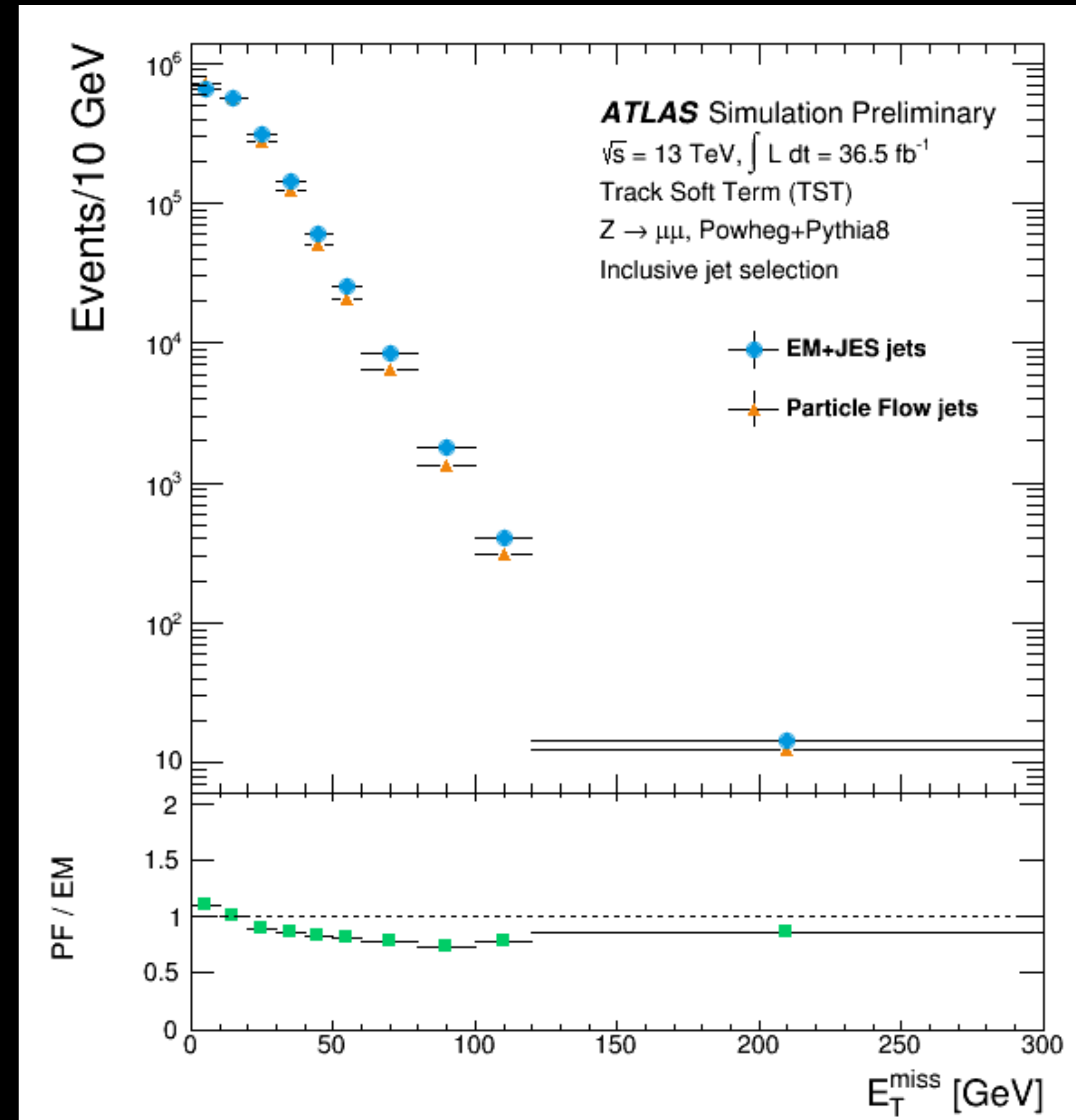


Jet resolution improved up to ~100 GeV

– sensitive to response differences between quarks and gluons

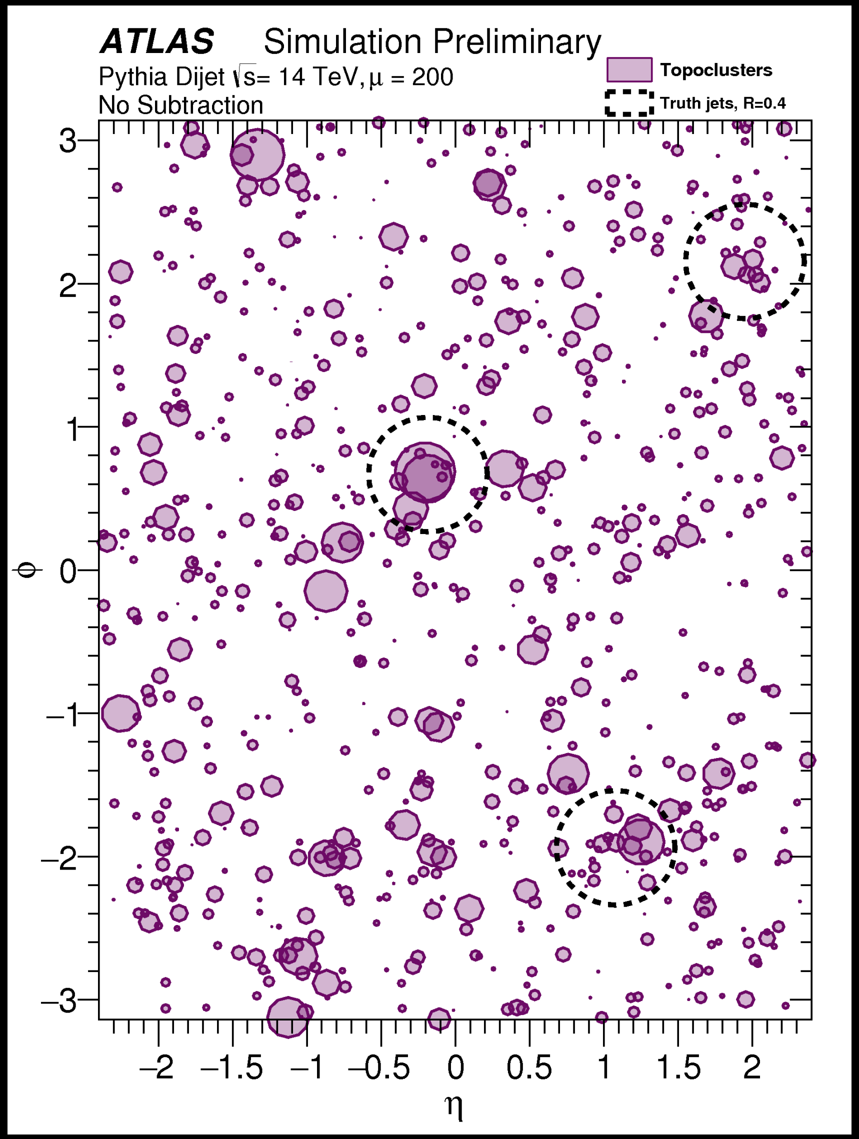
– low-p_t tracks better measured

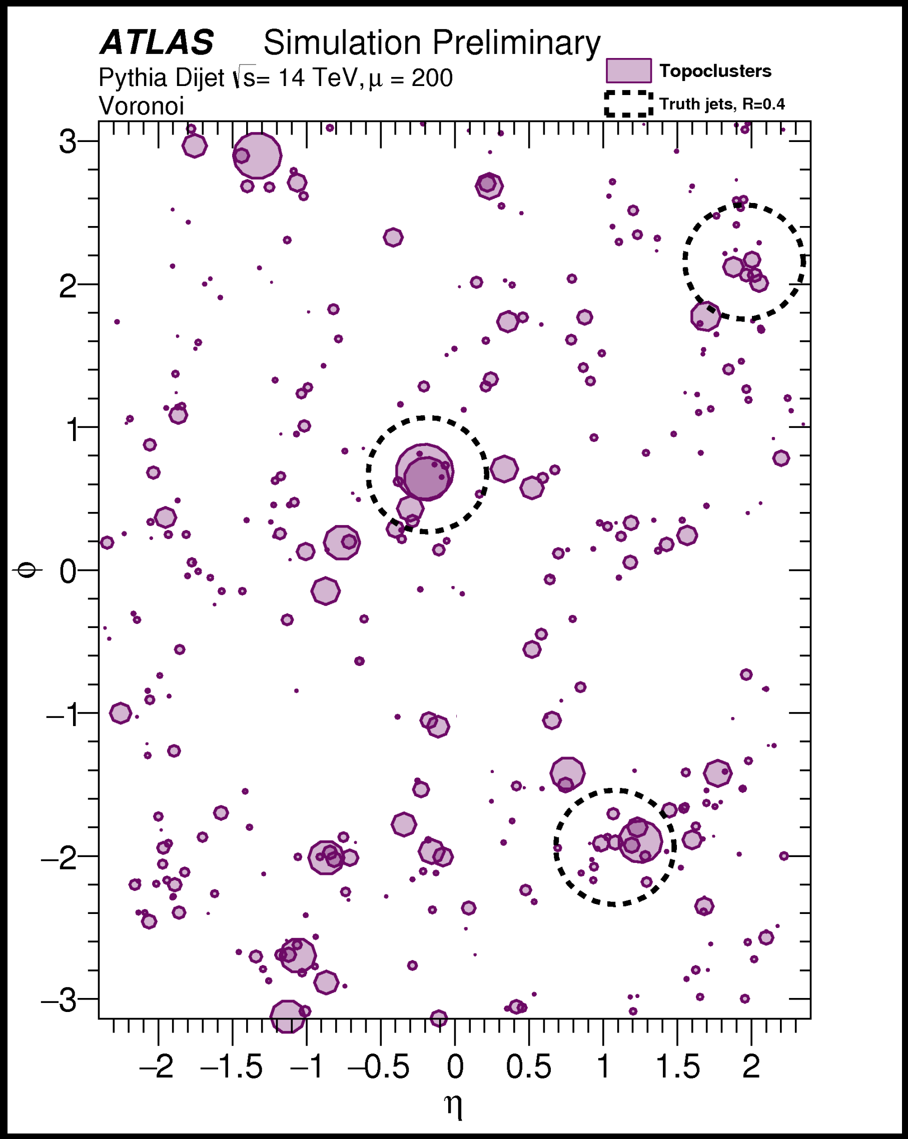
Smaller uncertainties

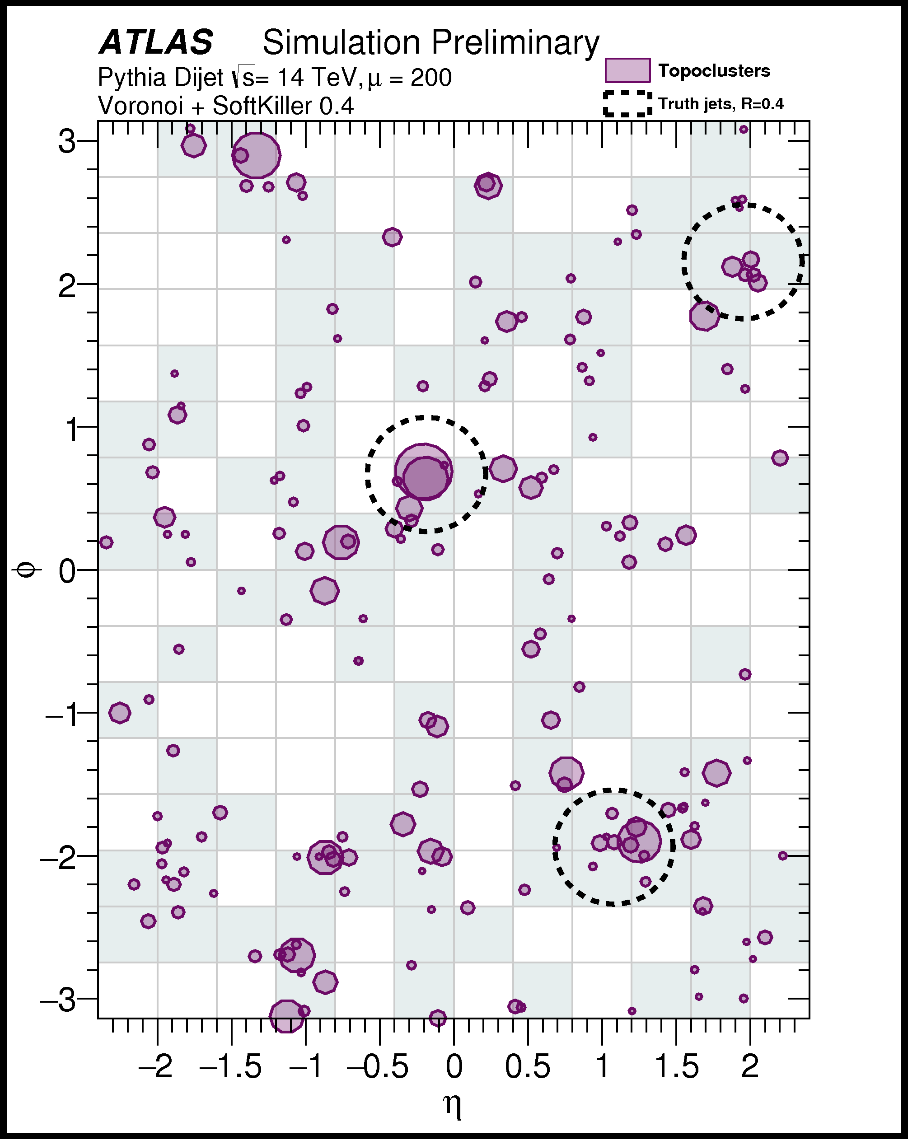


Improved core MET resolution and reduced tails from fake jets

CONSTITUENT-LEVEL PILEUP CORRECTIONS





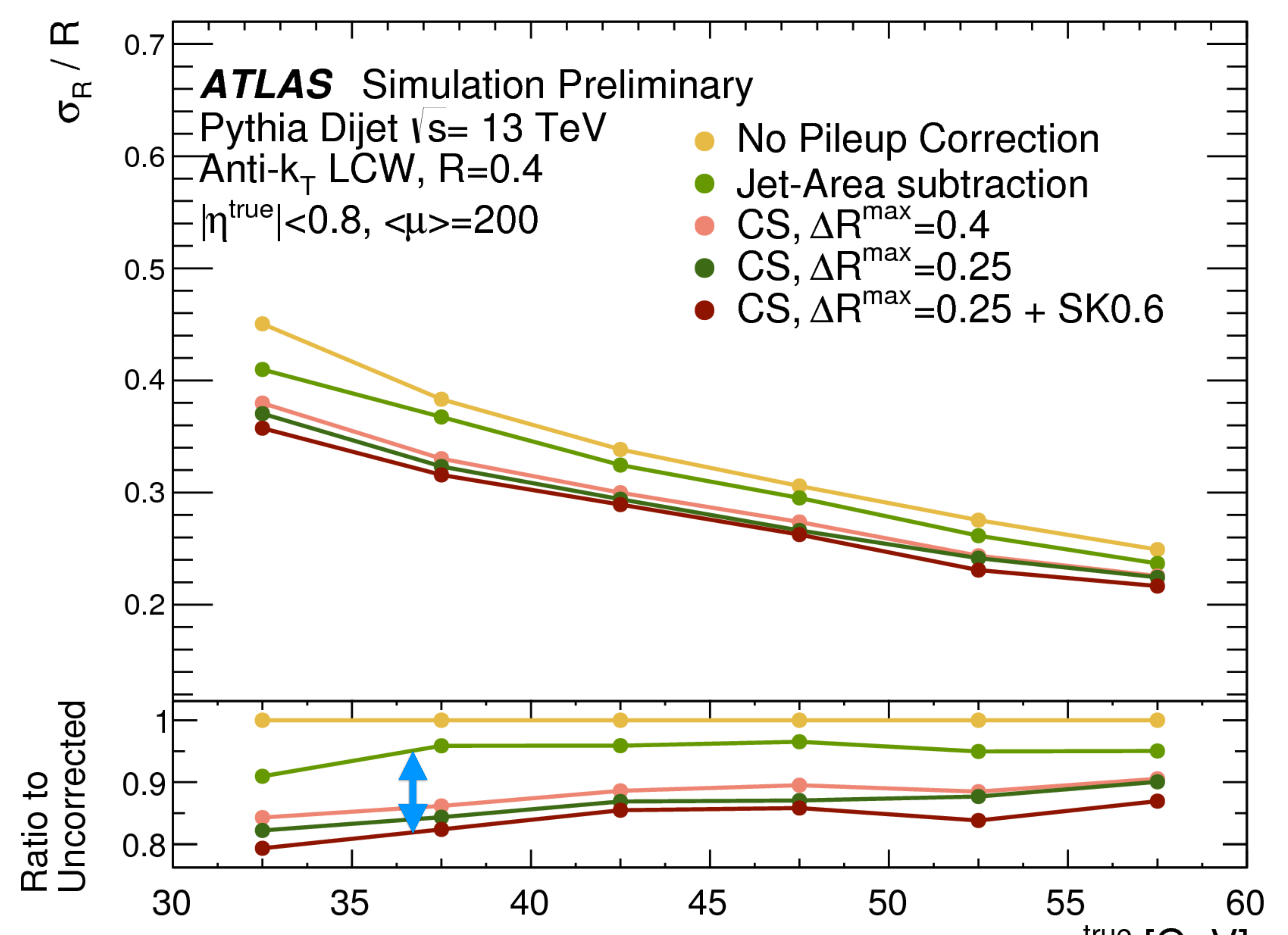


Raw topoclusters

Area-based correction
(median energy subtraction with Voronoi cells)

"SoftKiller" filter
(dynamic p_T cut based on grid occupancy)

Eur. Phys. J. C (2015) 75: 59



ATLAS-CONF-2017-065

Significant gain wrt jet area subtraction

Room for improvement with timing, ML

HARDER

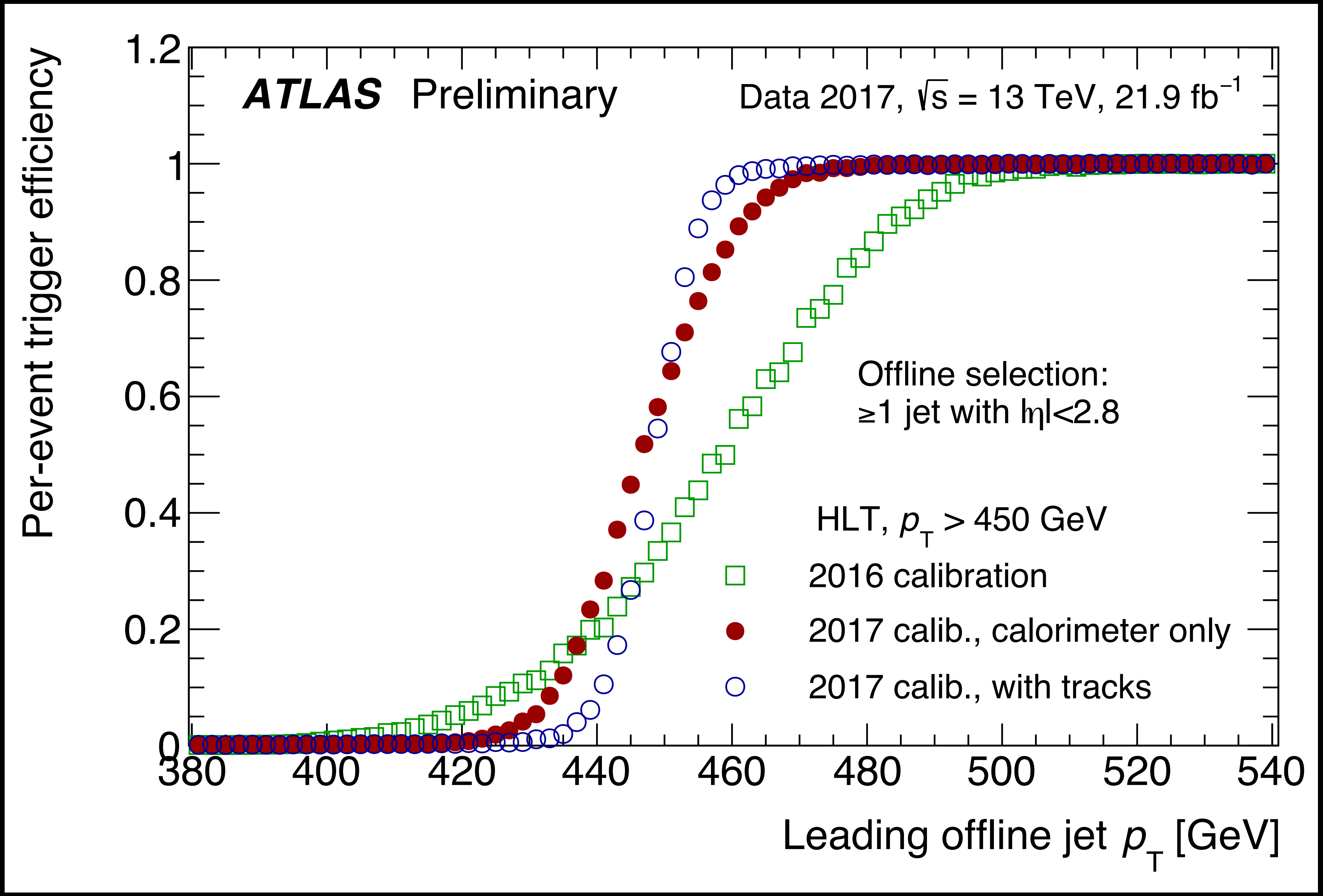
~~BETTER~~ ALMOST AS WELL

FASTER

~~STRONGER?~~

JET TRIGGERS

- HW selection: 40MHz -> 100kHz
- SW selection: 100kHz -> 1kHz
- Efficiency loss if offline/online reco not consistent.



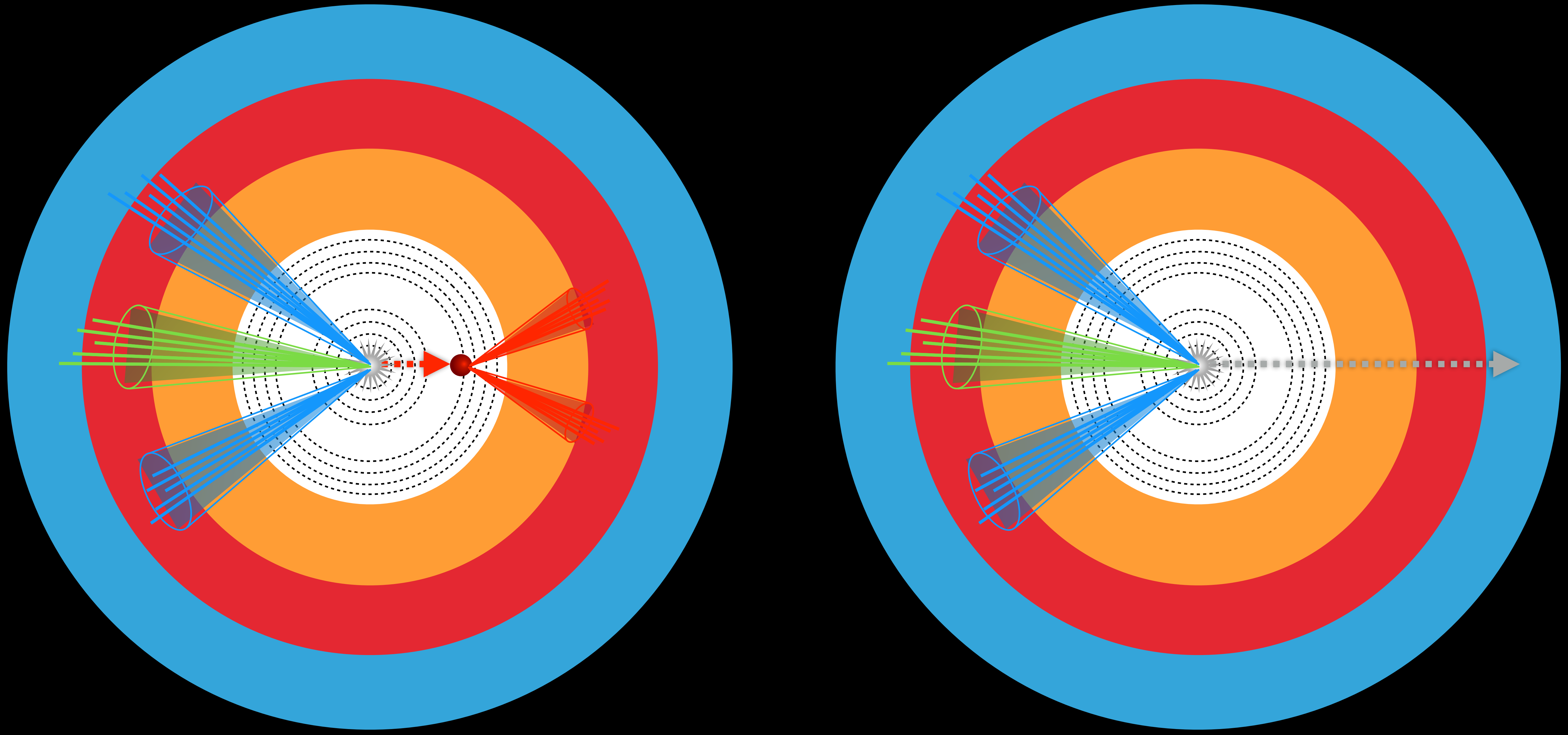
- Jet trigger pileup dependence severe due to lack of tracks
- Constituent pileup mitigation may help, but hope that new Fast TracKer module pulls through

IN SUMMARY

- Jets & Missing Transverse Momentum core observables in LHC physics analyses
- Large challenge from pileup mitigated successfully, but needs more powerful techniques for future datasets
  - Effective methods focus on suppressing pileup before jet reconstruction
- Thorough understanding of reconstruction performance allows innovative analysis design and improvement

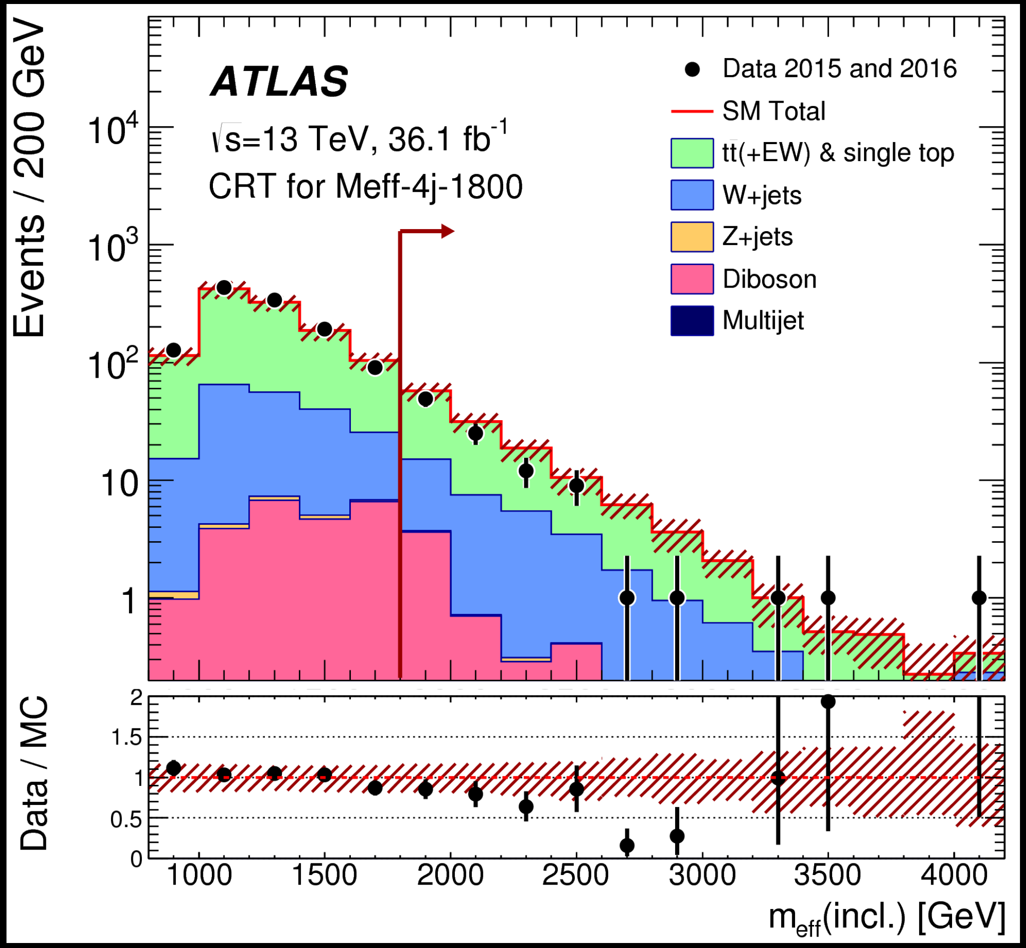
MORE ANALYSIS IDEAS

LONG-LIVED PARTICLES BY ACCIDENT



Delayed decay: jets discarded as pileup result in fake MET → Search for unbalanced events with displaced tracks in jets

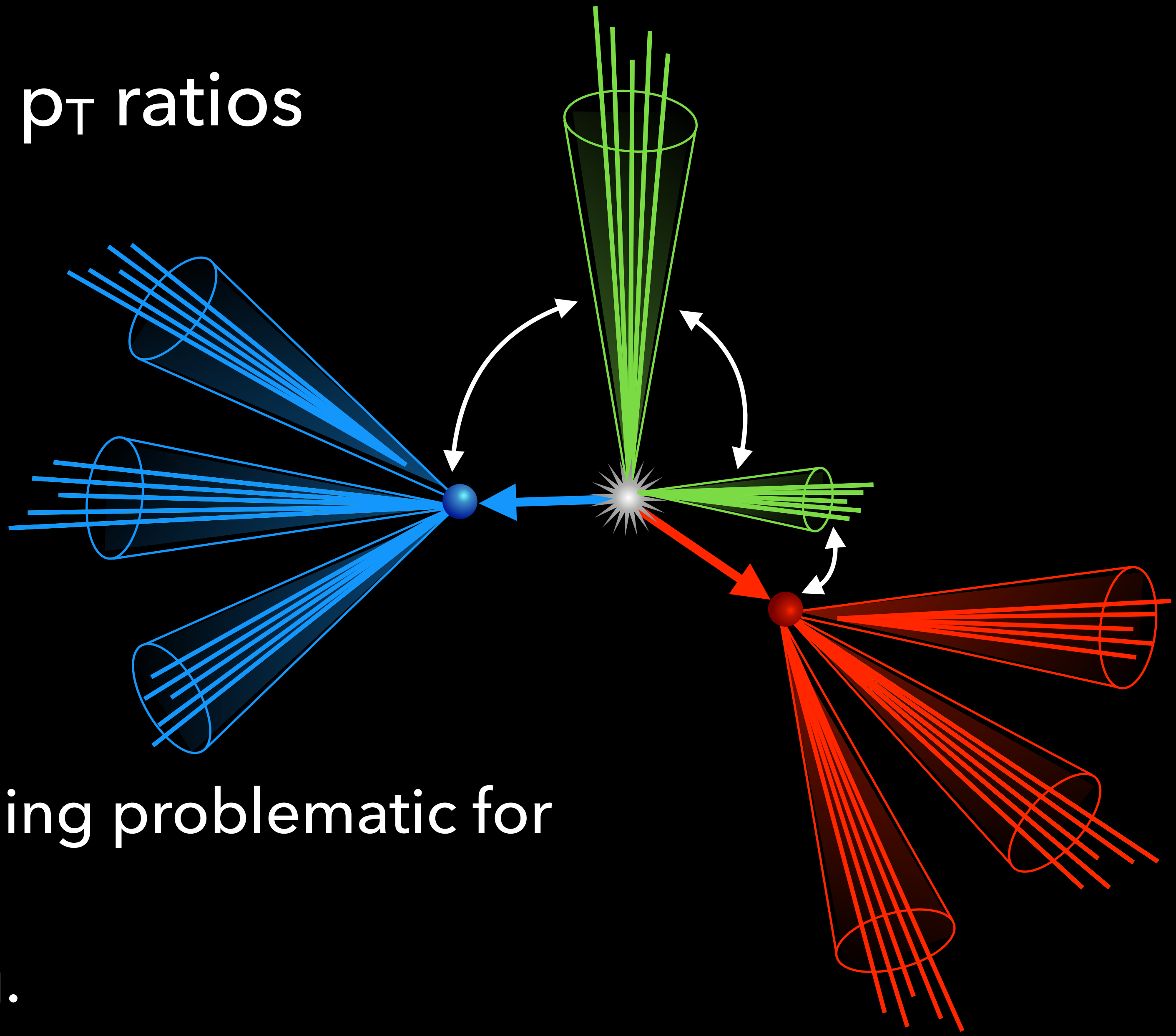
TOP-JET CORRELATIONS



Angular separations

Compare event scales

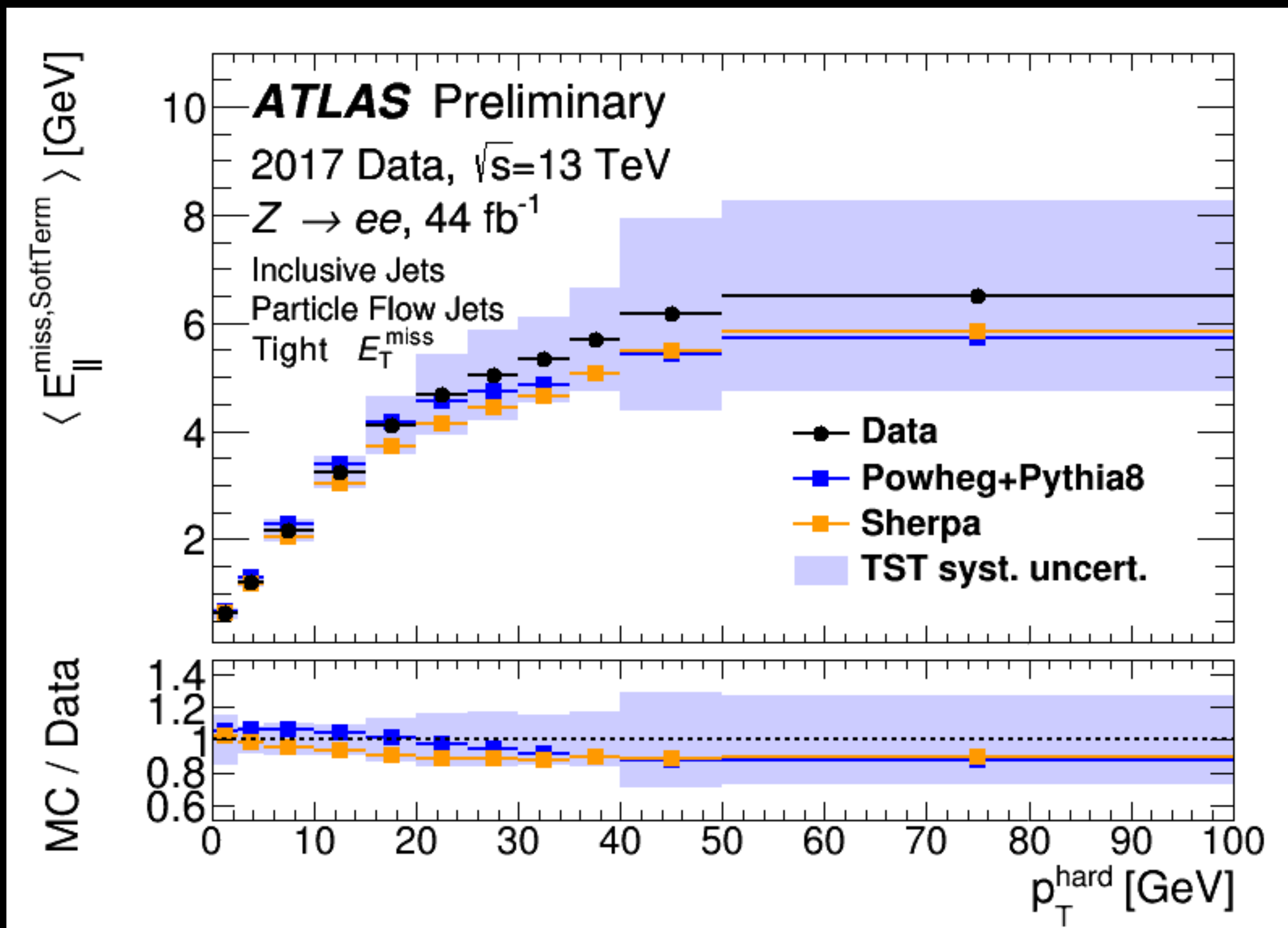
p_T ratios

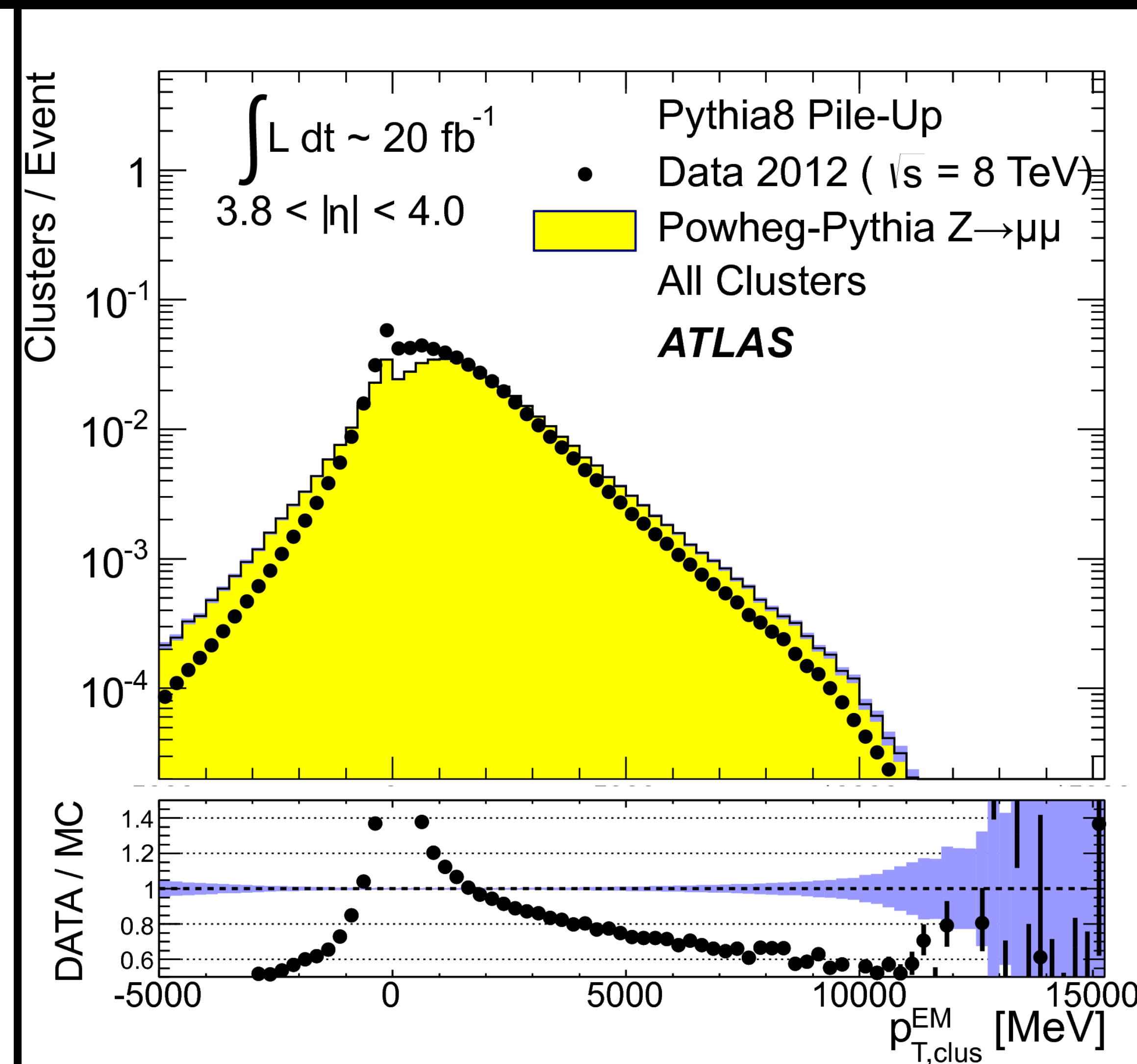


Large top uncertainties/mismodelling problematic for searches in extreme phase space.
Measure & improve MC modelling.

"Trigger-level analysis" for trigger-limited hadronic channels?

A SOFT ~~SPOT~~ MEASUREMENT FOR PILEUP

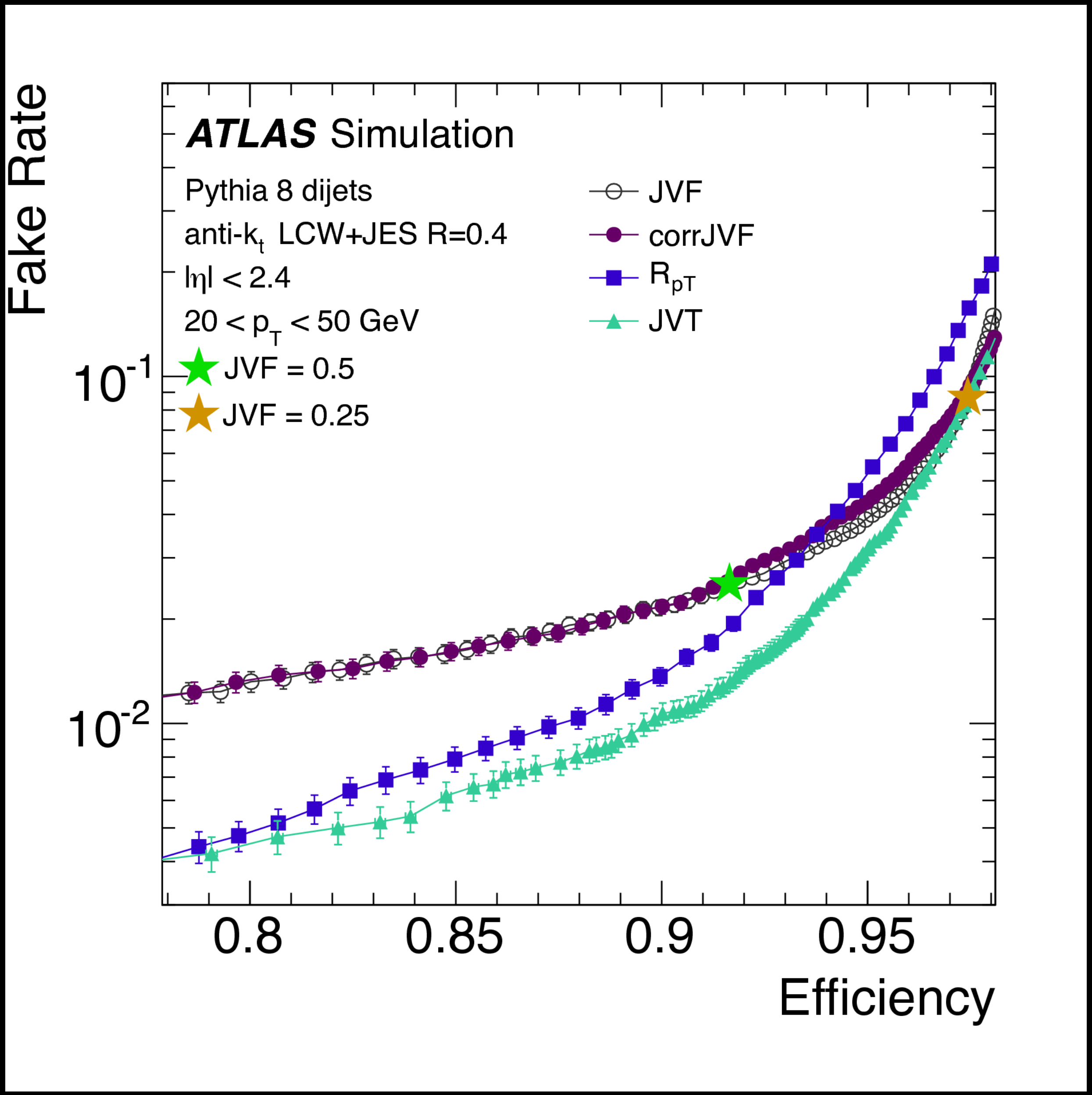


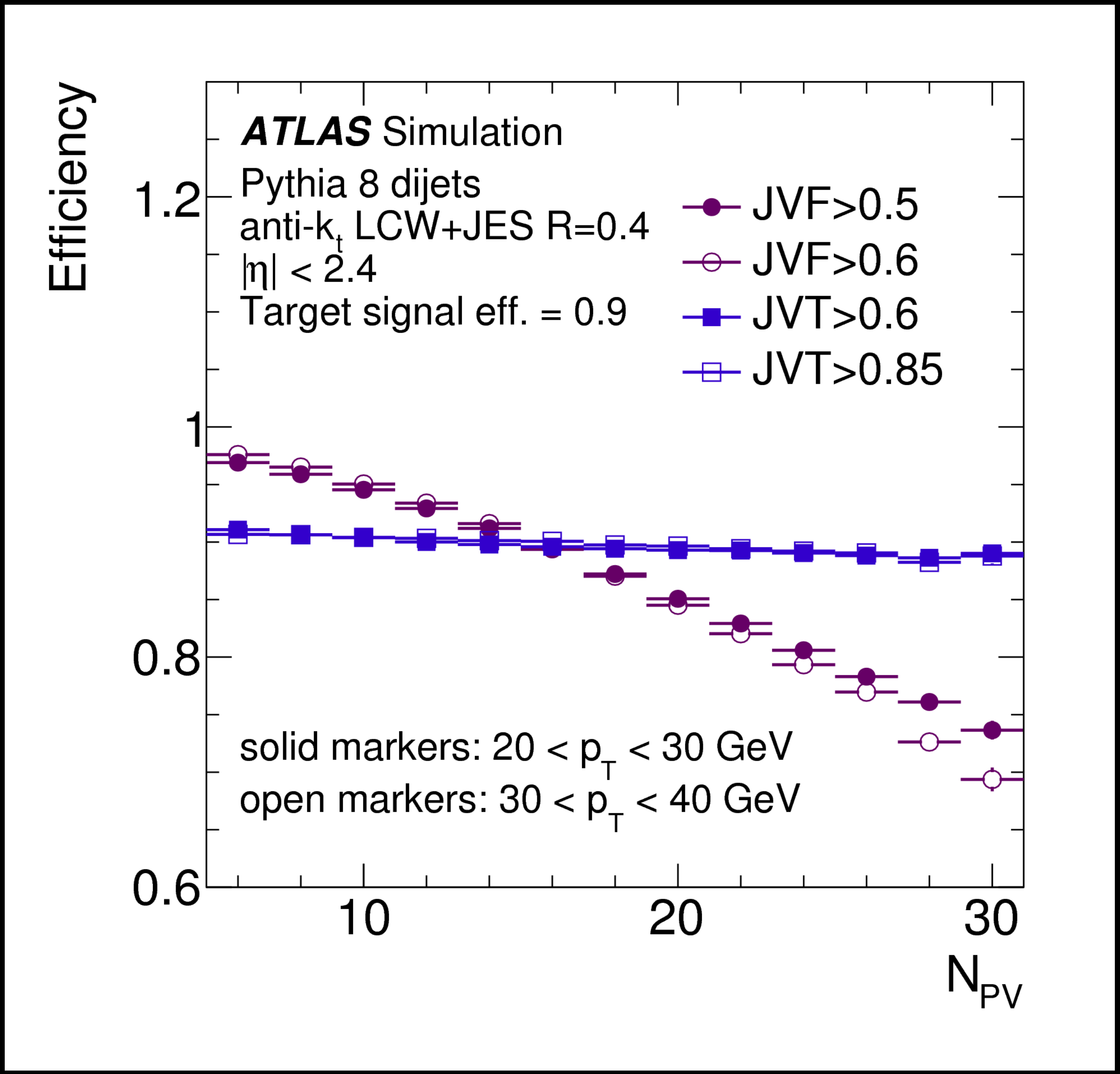


Soft QCD interactions poorly described, affecting simulated pileup and MET soft term.

Measure underlying event correlations more broadly than just in the transverse region?

LEFTOVERS

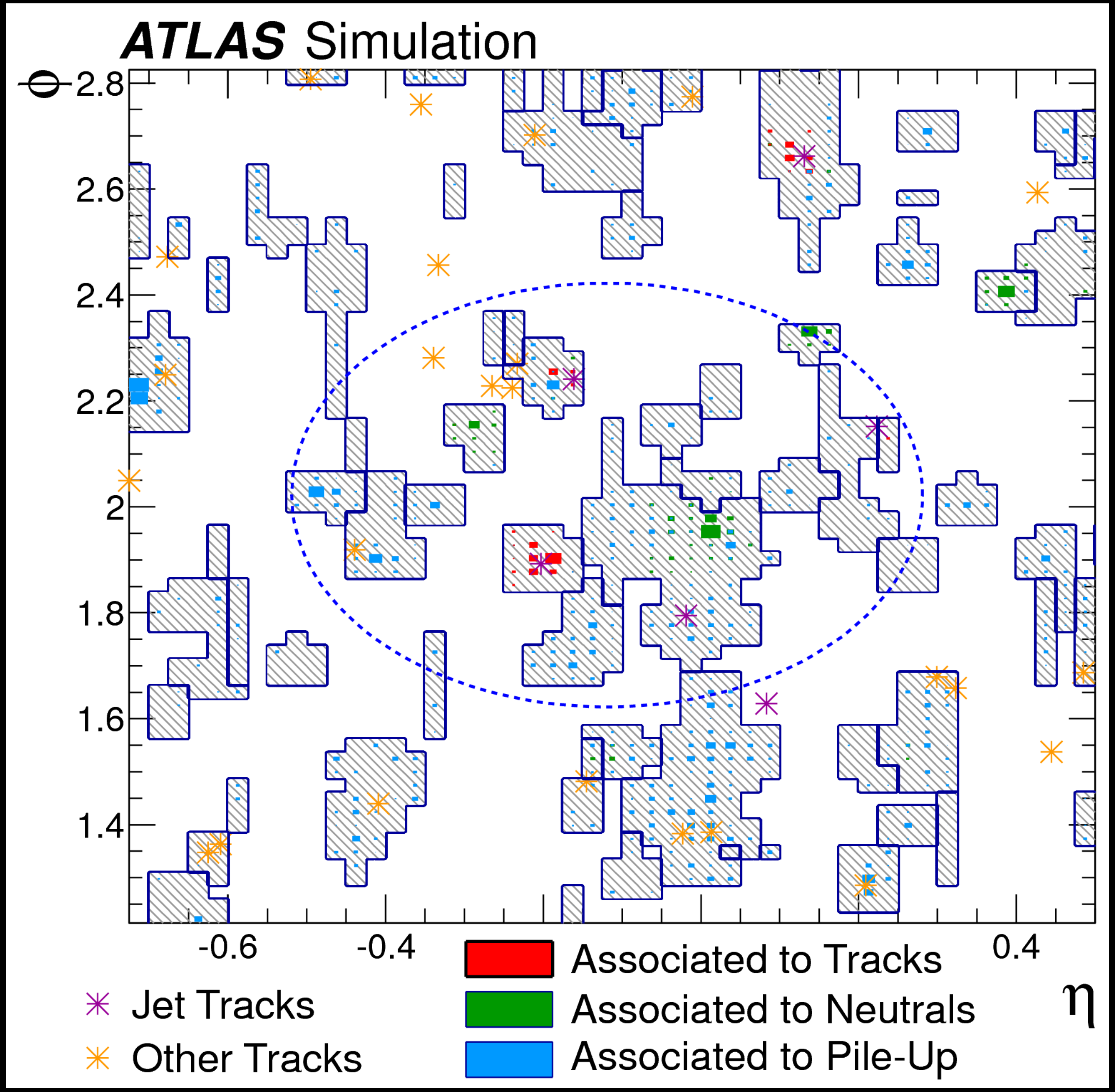


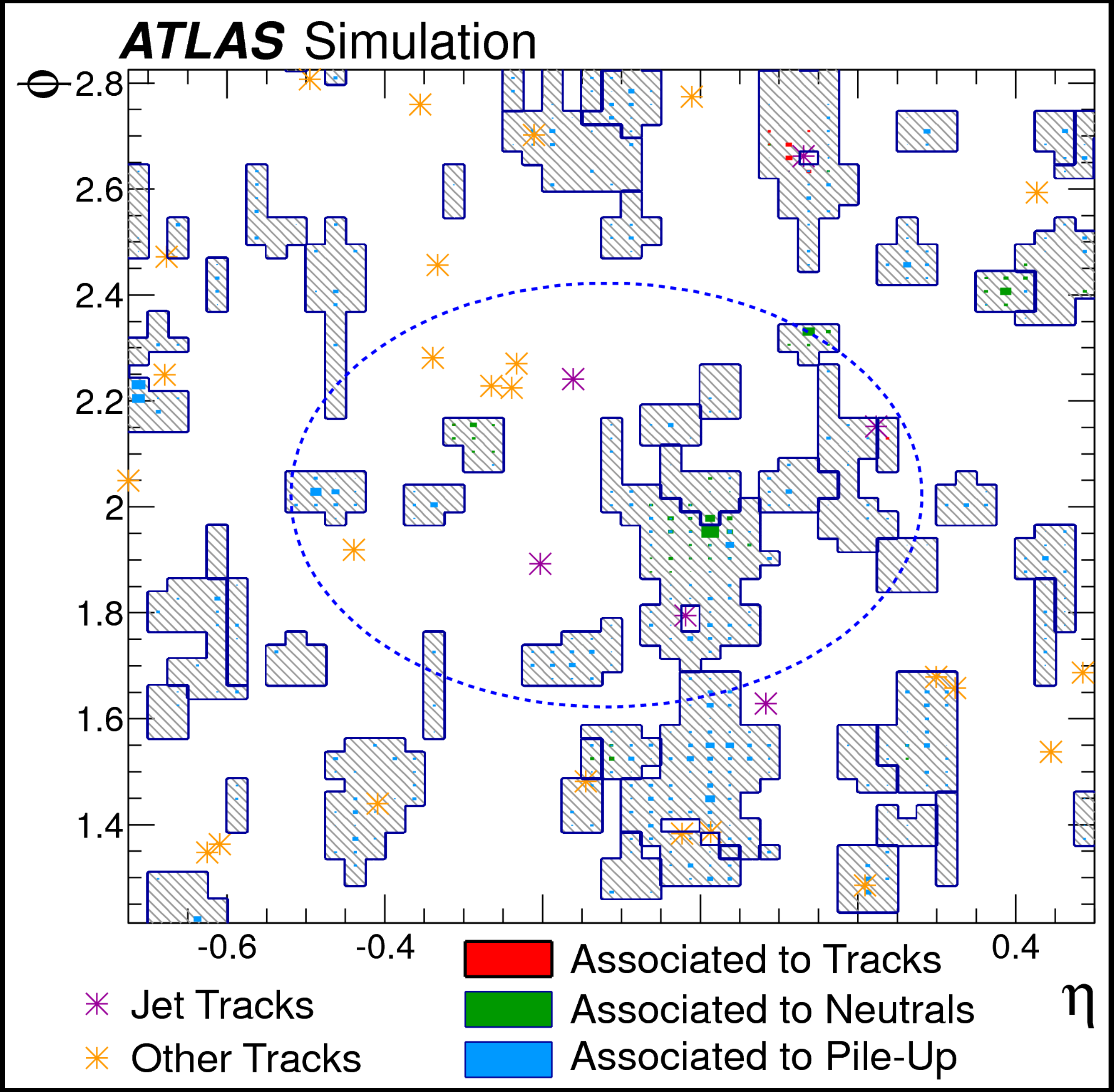


Combination of JVF and RpT produces significantly better pileup rejection

JVF correction term ensures stable efficiency vs pileup

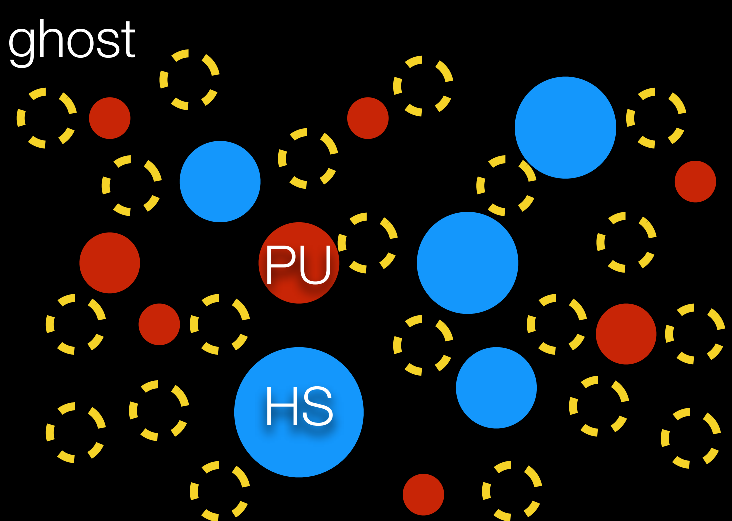
CARTOONS OF PARTICLE FLOW IN EVENT WITH PILEUP





CONSTITUENT-LEVEL PILEUP CORRECTIONS

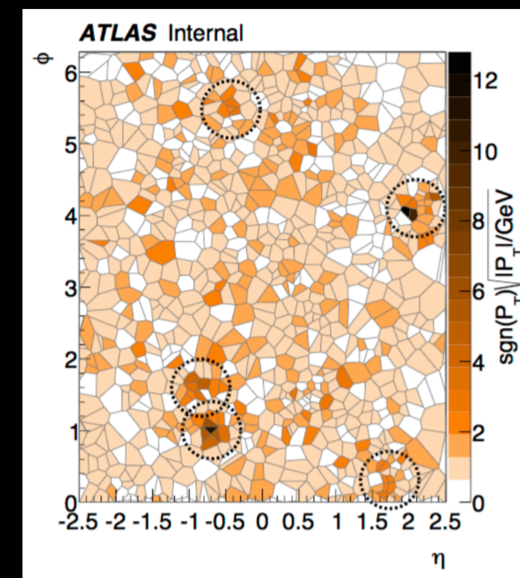
Constituent pileup subtraction



Distribute ghosts with negative pT to cancel median energy density

Match ghosts to nearby constituents and subtract.

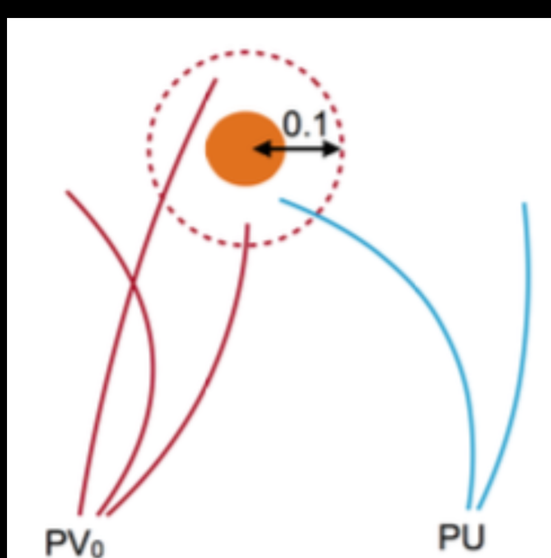
Voronoi area subtraction



Use Voronoi cells to determine area for each constituent, subtract ρ•A.

Further options for removal of soft or -ve E clusters.

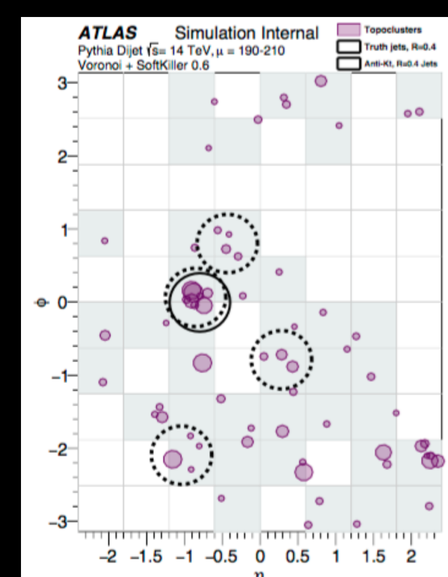
Track matching



Filter clusters using tracks to associate to pileup/primary vertices.

Extension of jet vertex fraction strategy

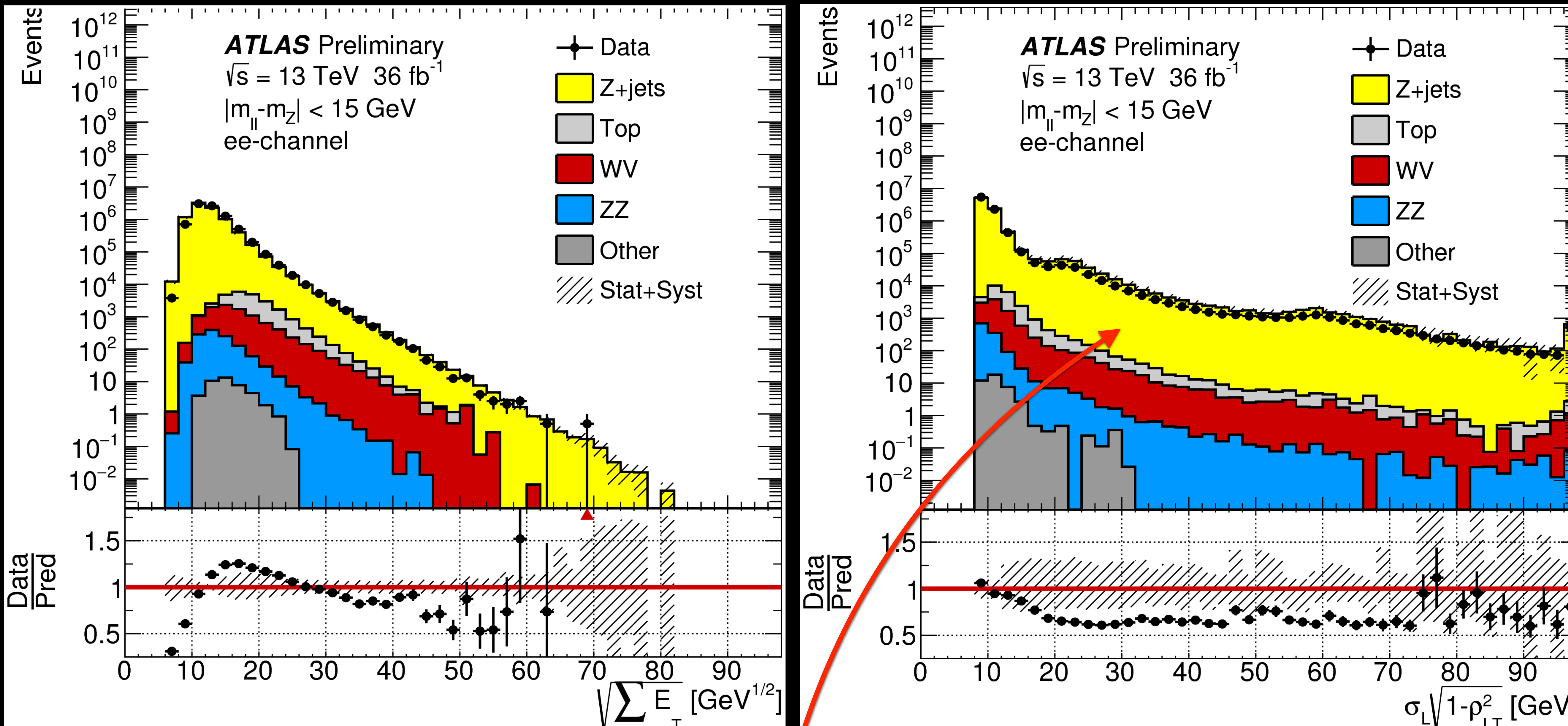
SoftKiller



Scan threshold on jet constituents to achieve a median ρ of 0.

“Equivalent” to subtracting ρ•A within a given jet.

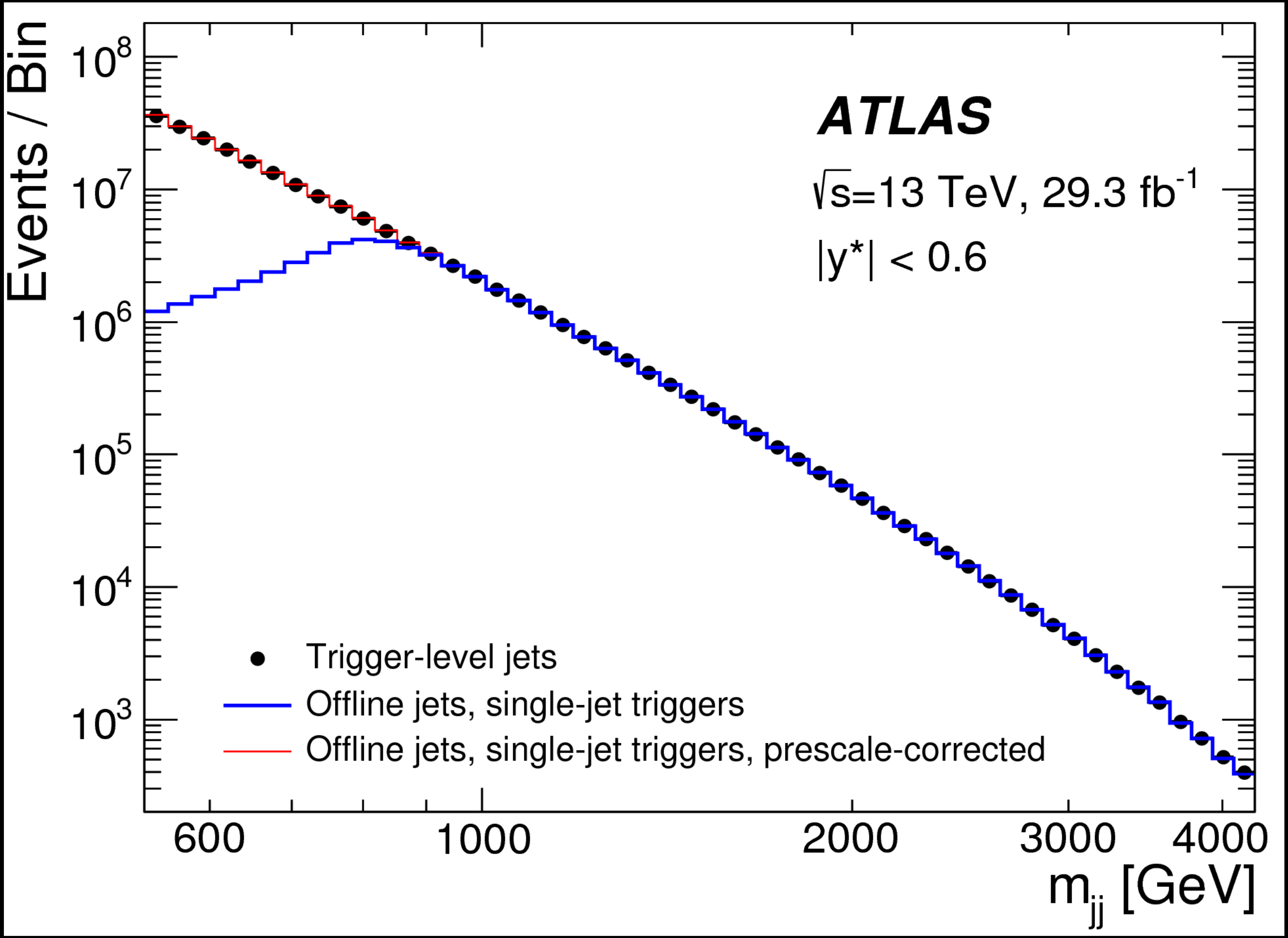
Filtering of caloclusters/towers or neutral PFOs not only improves pileup-resilience of jet four-momentum, but also of substructure & other moments.

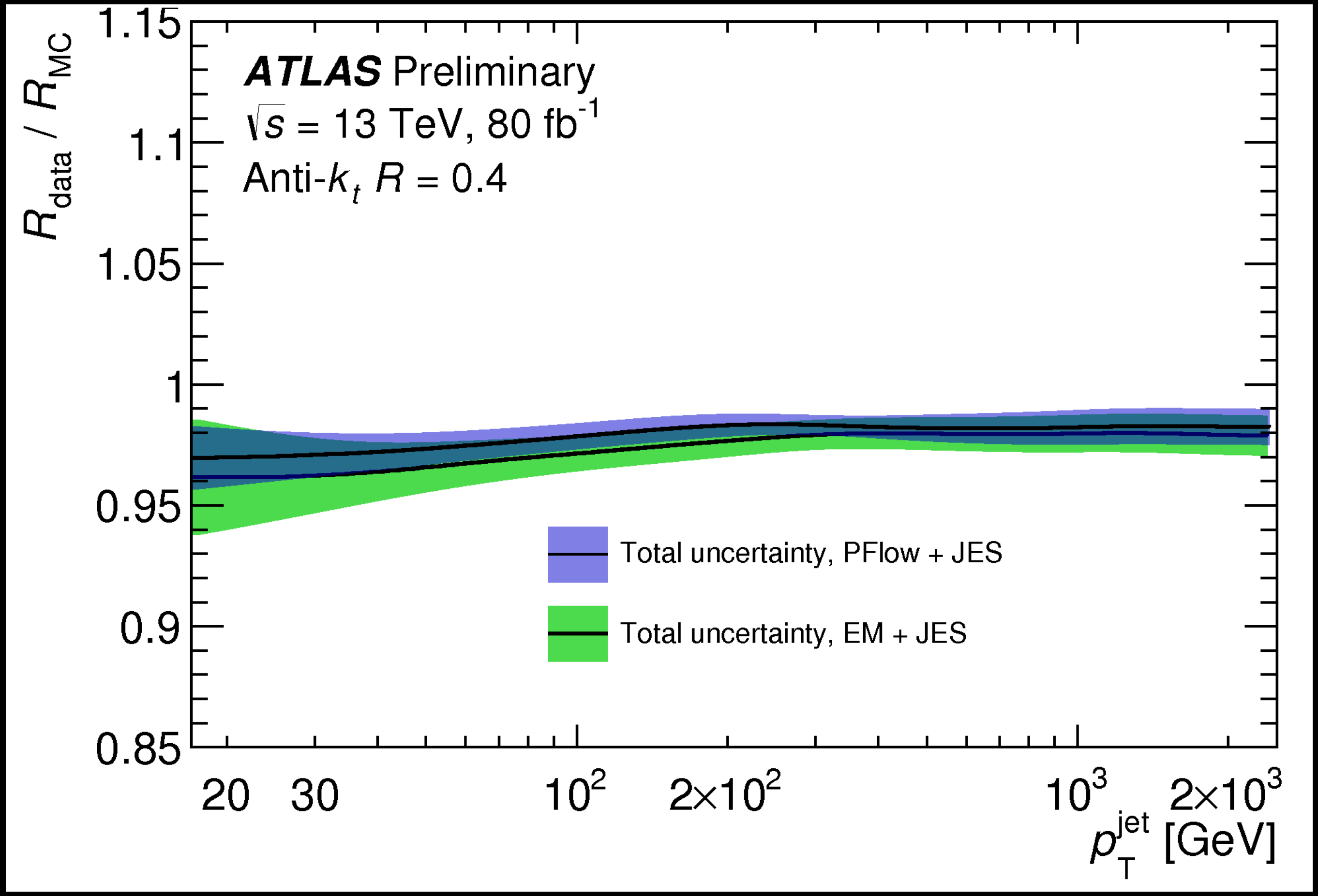


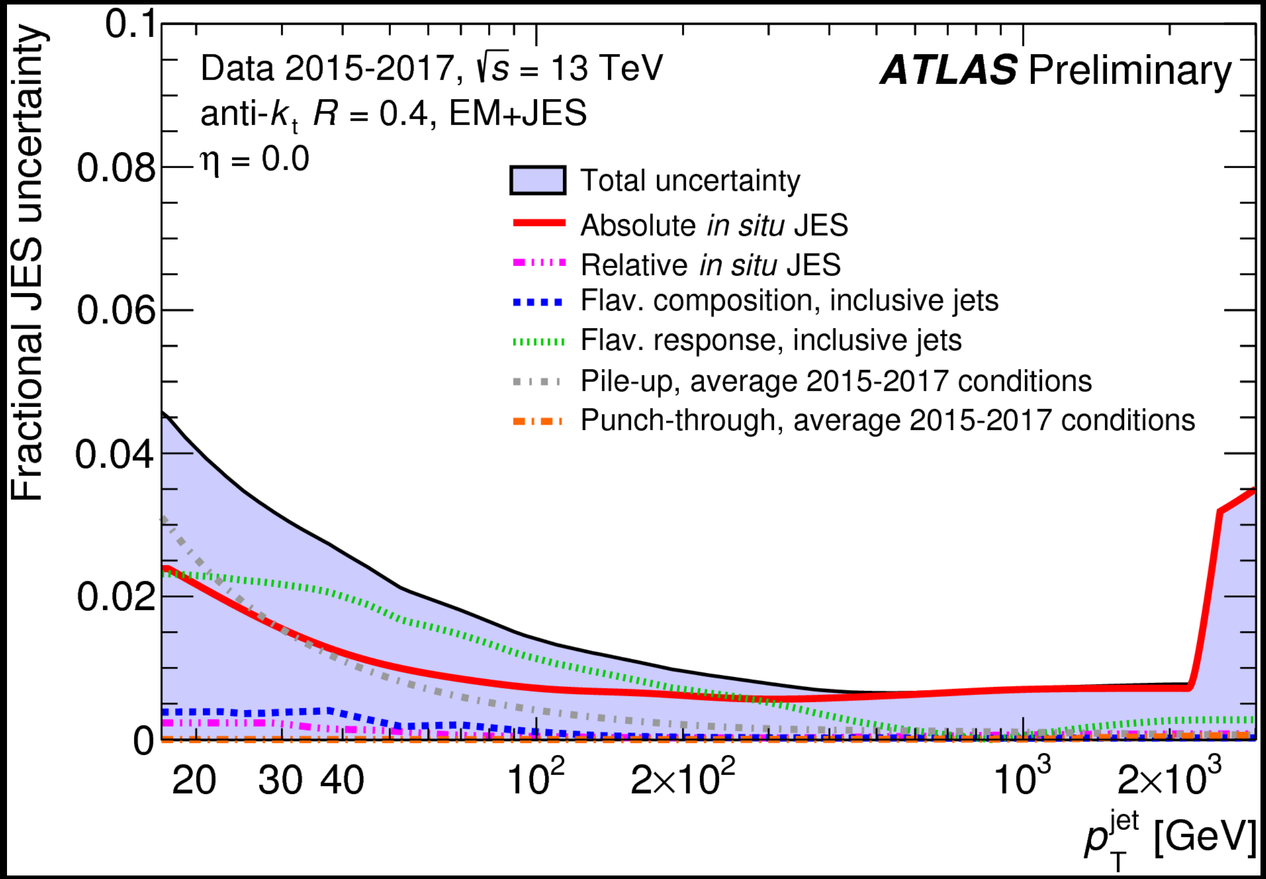
$$\sqrt{\sum E_\mathrm{T}}$$

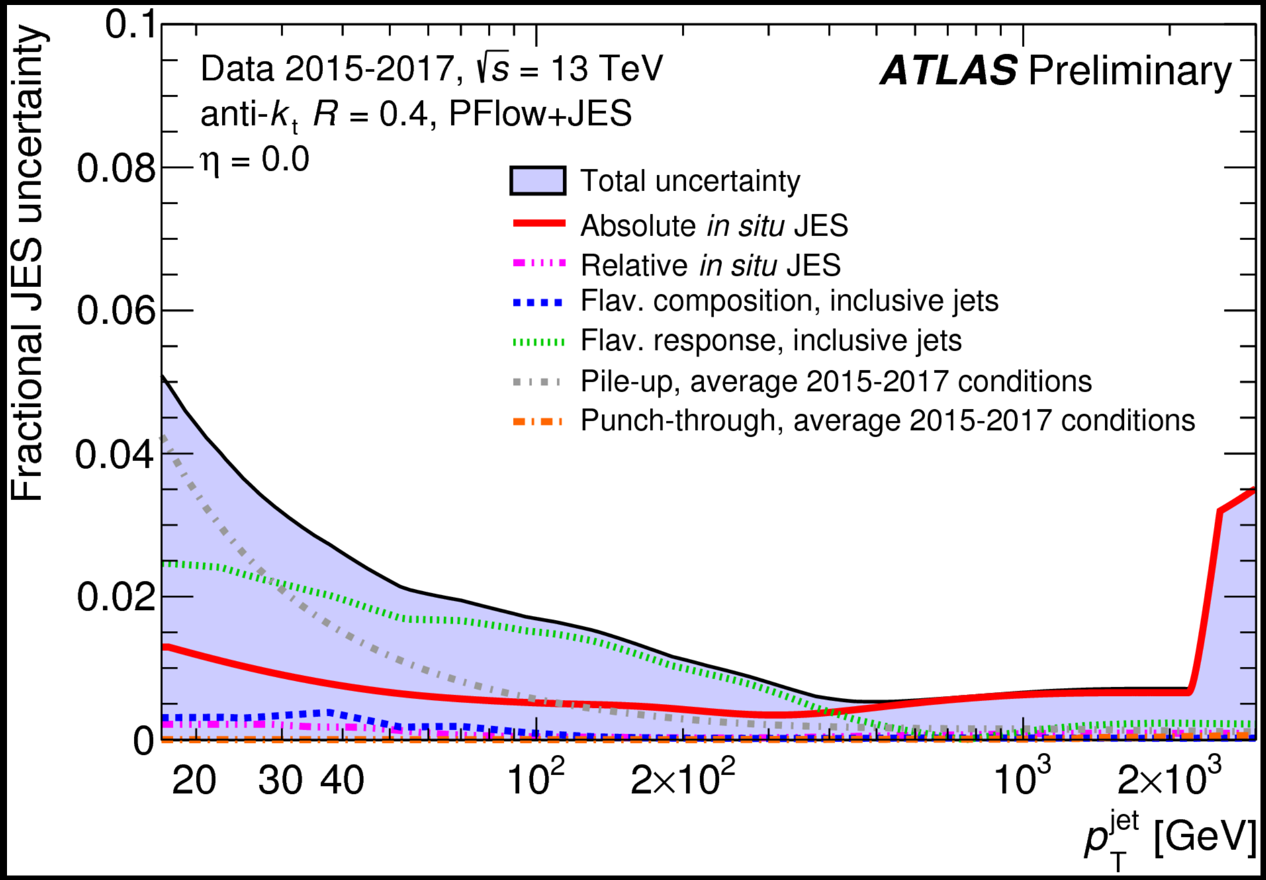
$$\langle \sigma_{E_\mathrm{T}^\mathrm{miss}} \rangle$$

"Resolution" penalty for jets that may be from pileup


ATLAS
√s=13 TeV, 29.3 fb-1
|y*| < 0.6
Events / Bin
10^8
10^7
10^6
10^5
10^4
10^3
600
1000
2000
3000
4000
m_jj [GeV]
Trigger-level jets
Offline jets, single-jet triggers
Offline jets, single-jet triggers, prescale-corrected







Significantly smaller uncertainties on jet energy scale

Data/MC correction systematics notably reduced at low p_T