THE IMPORTANCE OF BEING TRANSVERSE

EVENT RECONSTRUCTION AND SUSY SEARCHES AT ATLAS AND THE LHC

TENG JIAN KHOO

UNIVERSITÉ DE GENÈVE

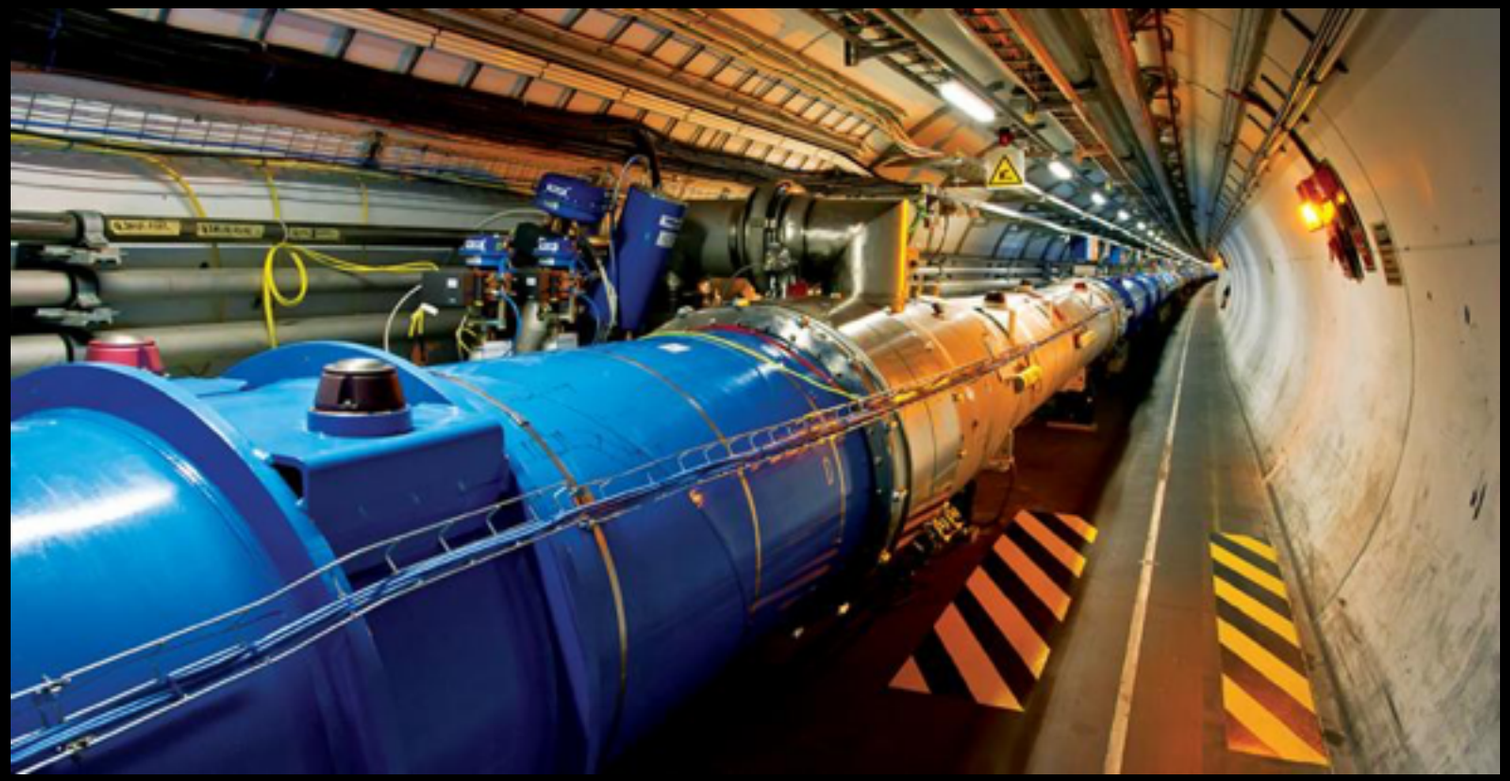
ATLAS EXPERIMENT

OUTLINE

- Hadron collider physics and momentum conservation
- ATLAS event reconstruction and missing transverse momentum performance
- Transverse mass variables
- Supersymmetry searches

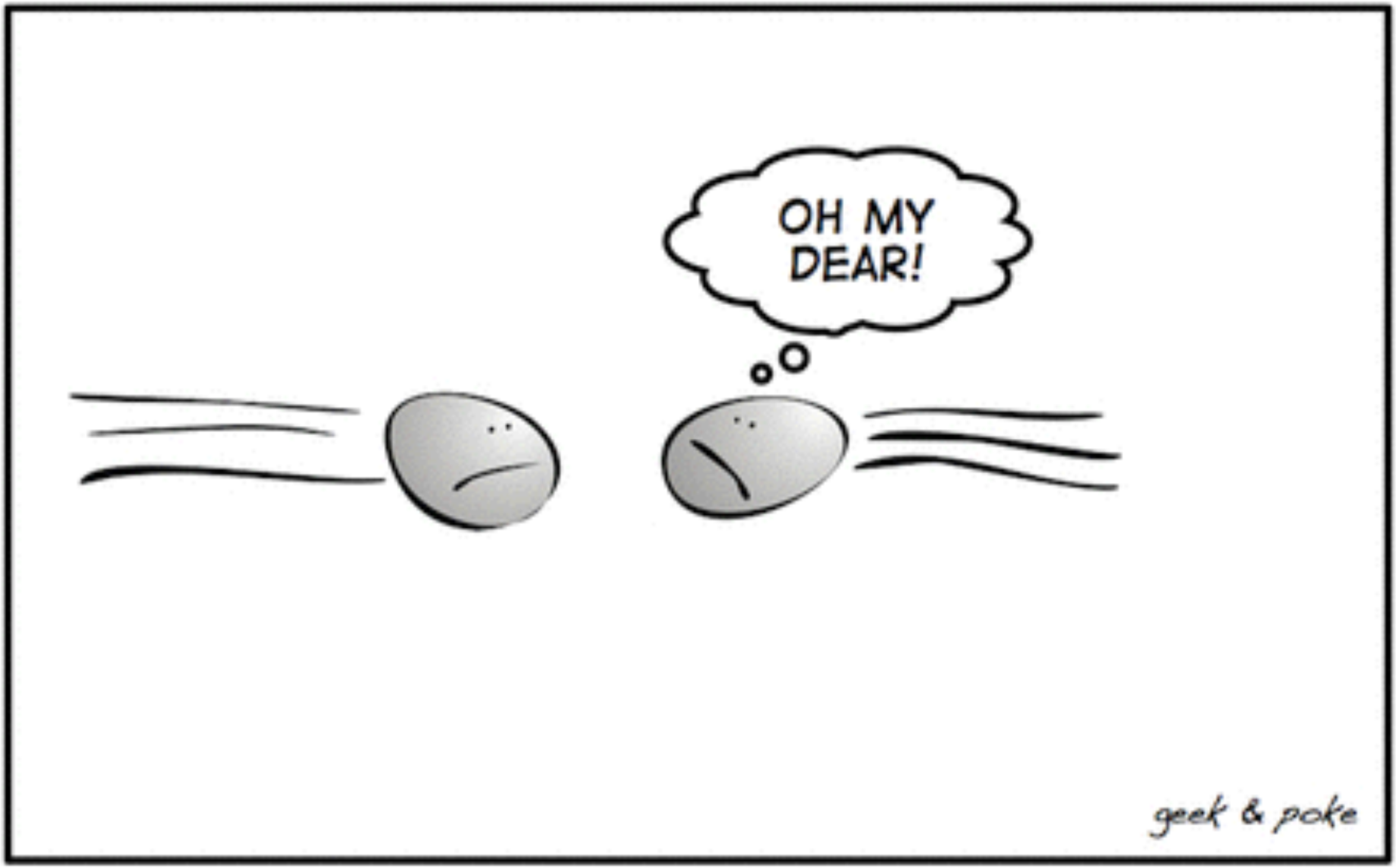
HADRON COLLIDER PHYSICS

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

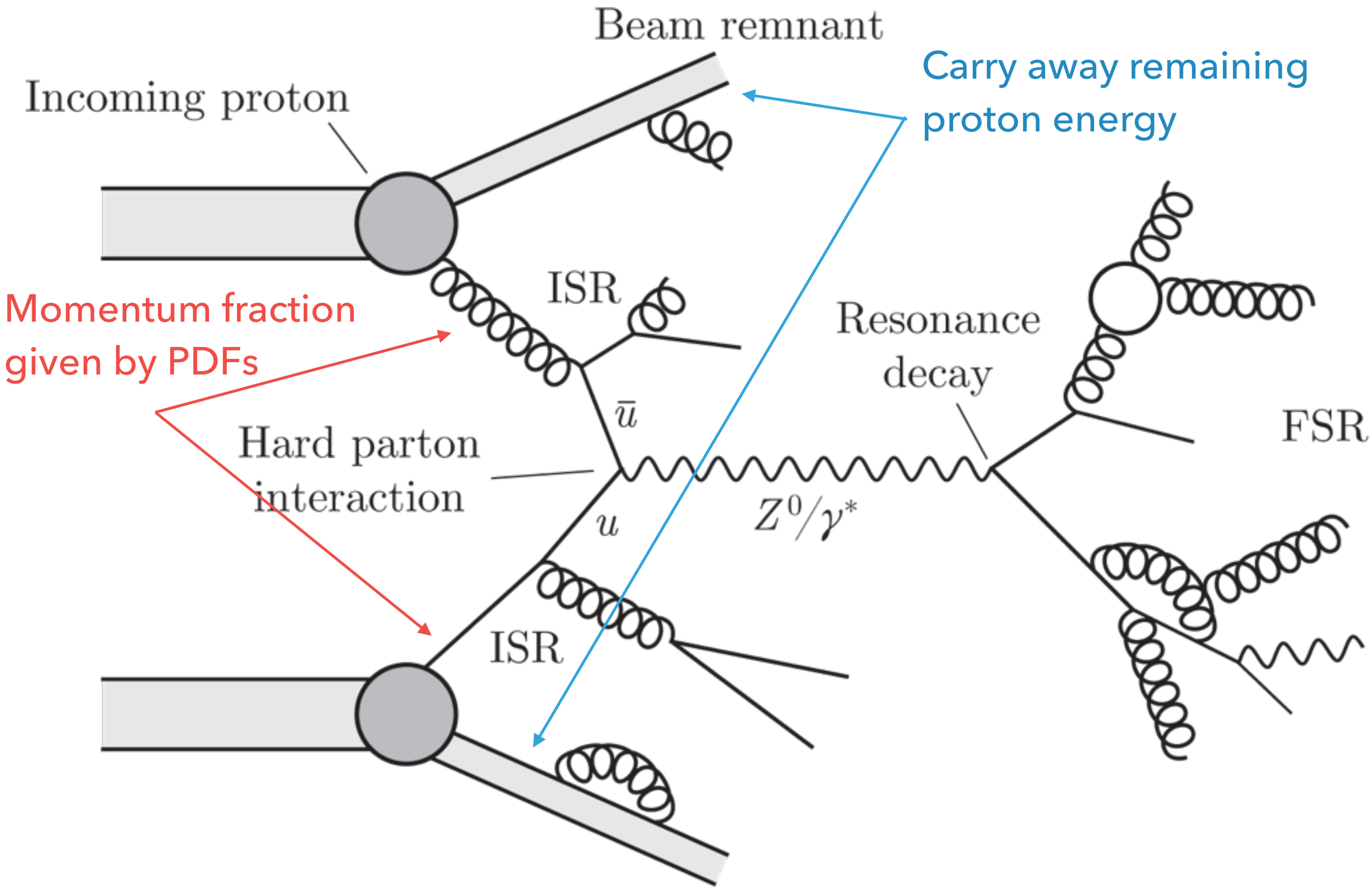


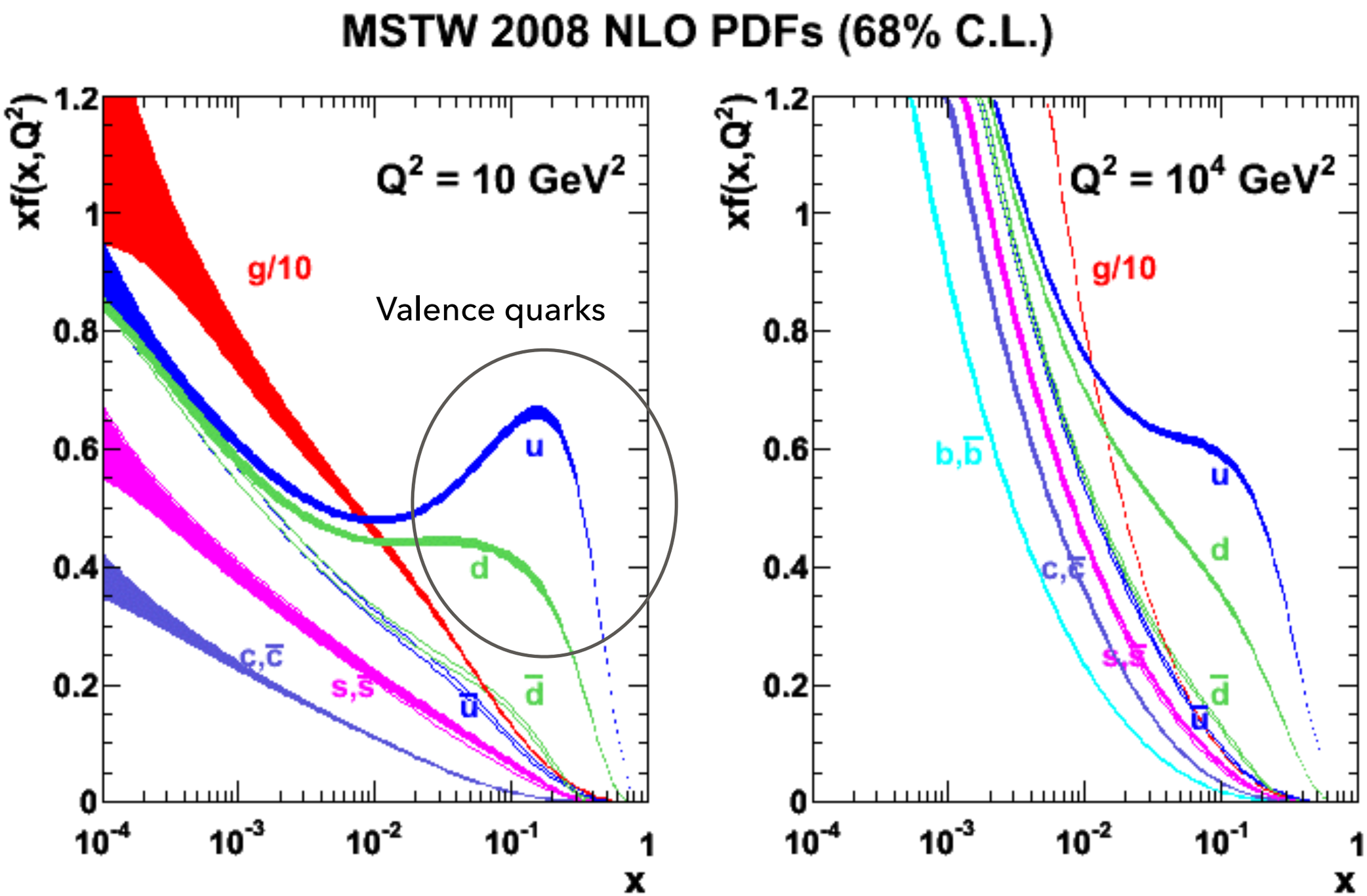
HADRON COLLIDER PHYSICS

- LHC collides protons at energy scales beyond that needed to probe proton structure.
- Centre-of-mass proton collision energy $\sqrt{s} = 13\ \mathrm{TeV}$.
- Effectively functions as a parton collider (gluons & quarks interact directly). Parton COM energy $\sqrt{\hat{s}} \leq 13\ \mathrm{TeV}$.
- Parton distribution functions describe energy fractions carried by colliding partons.

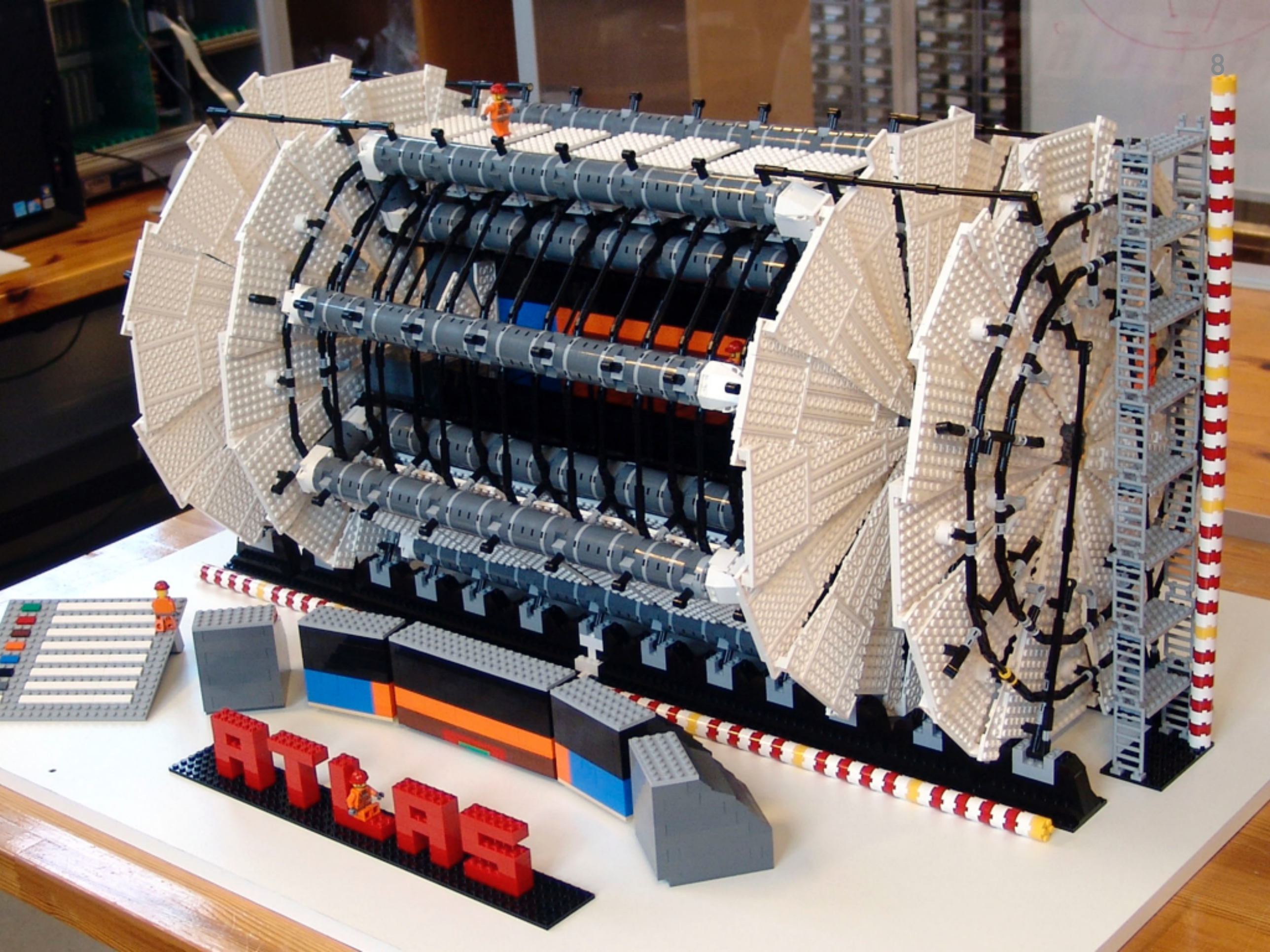


LATELY INSIDE THE LHC:
2 PROTONS 0.000000000000000000001 SEC BEFORE THE COLLISION


Beam remnant
Incoming proton
Carry away remaining proton energy
ISR
Momentum fraction given by PDFs
Resonance decay
$\bar{u}$
FSR
Hard parton interaction
u
Z^0/γ^*
ISR



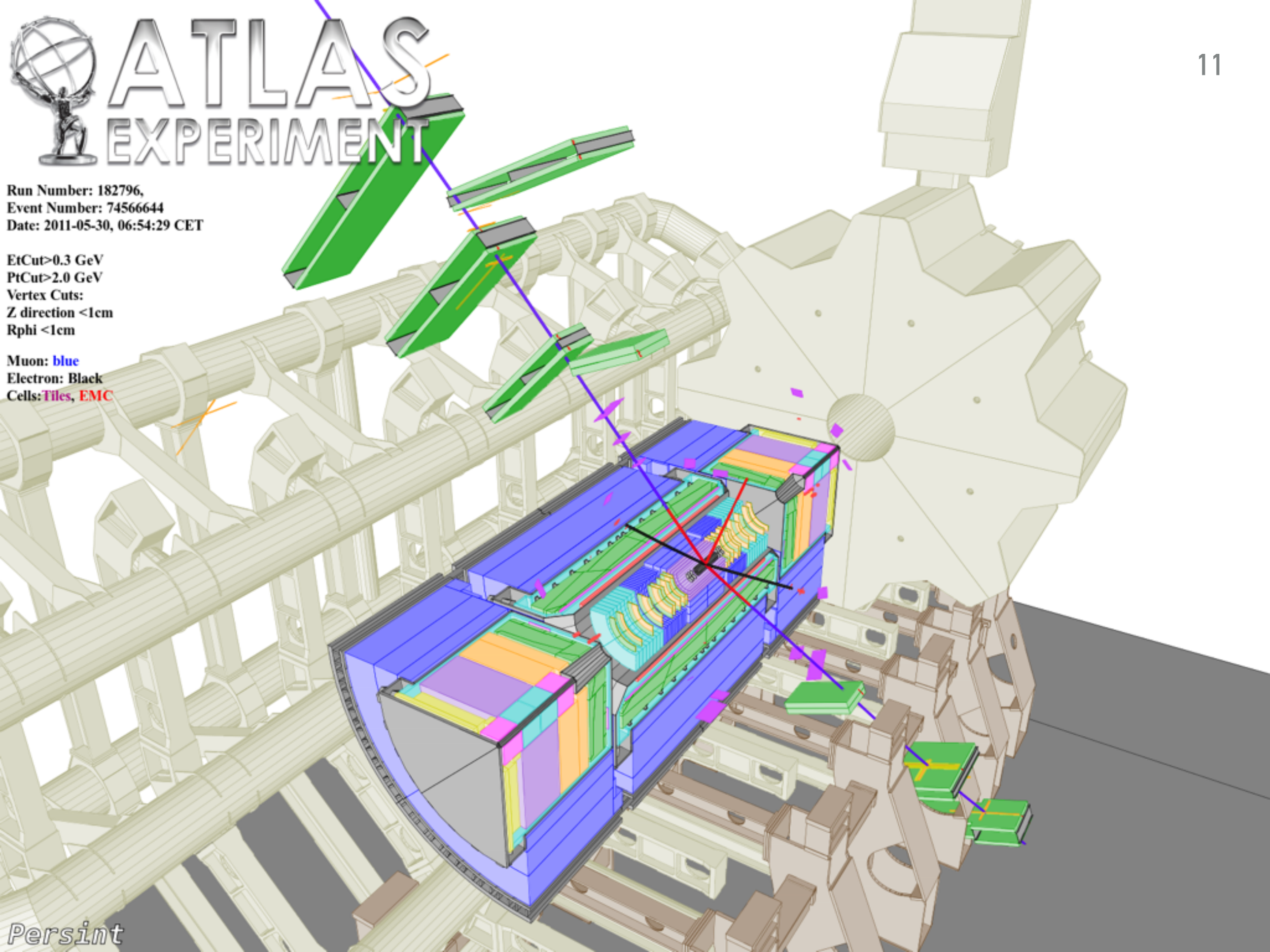
Eur.Phys.J. C63 (2009) 189-285

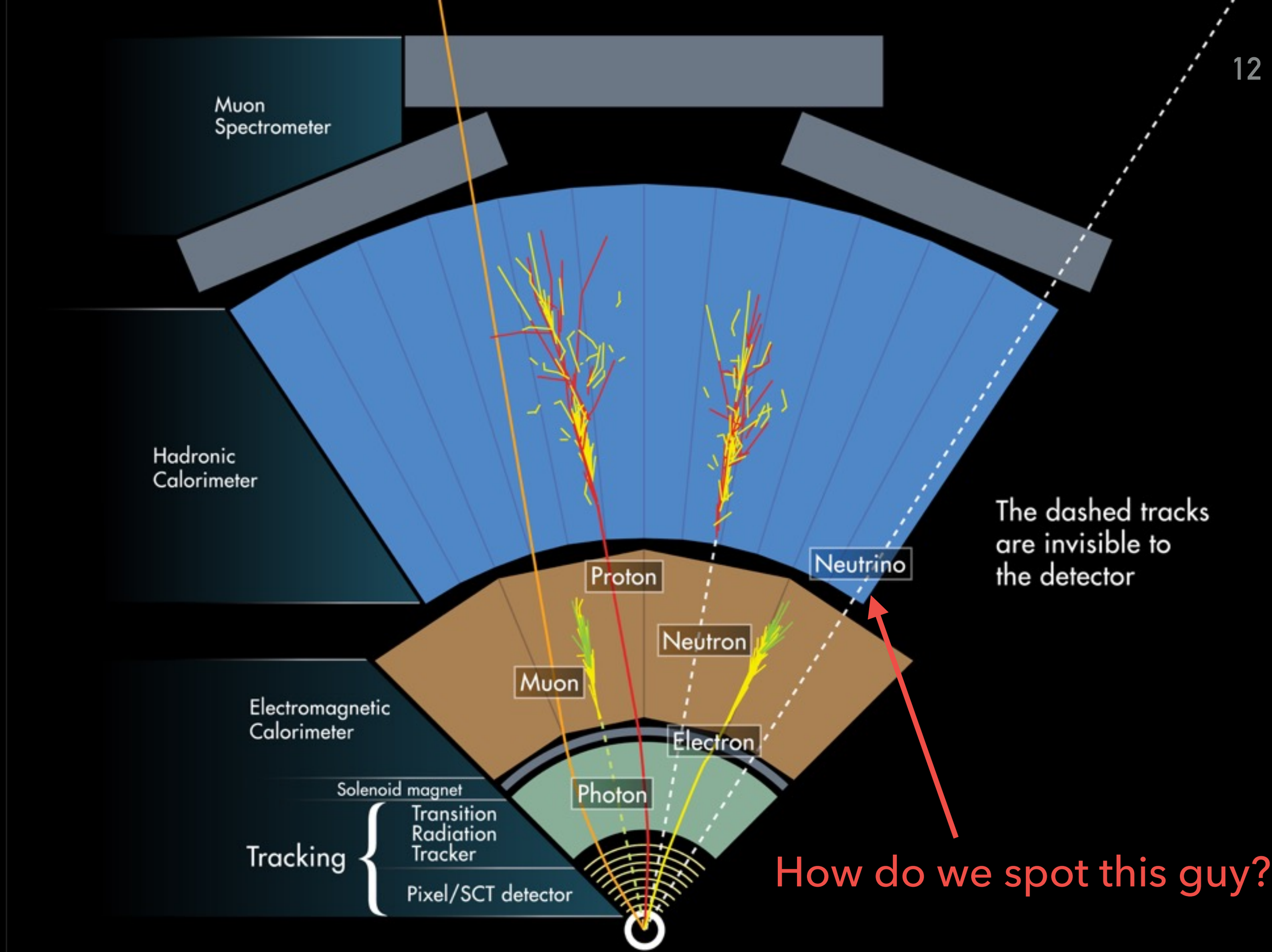

ATLAS

PIECES OF ATLAS

A Toroidal LHC ApparatuS


ATLAS
EXPERIMENT
Run Number: 165591, Event Number: 42994023
Date: 2010-09-22 20:45:21 EDT


ATLAS
EXPERIMENT
Run Number: 182796,
Event Number: 74566644
Date: 2011-05-30, 06:54:29 CET
EtCut>0.3 GeV
PtCut>2.0 GeV
Vertex Cuts:
Z direction <1cm
Rphi <1cm
Muon: blue
Electron: Black
Cells:Tiles, EMC
Persint


Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks are invisible to the detector
How do we spot this guy?

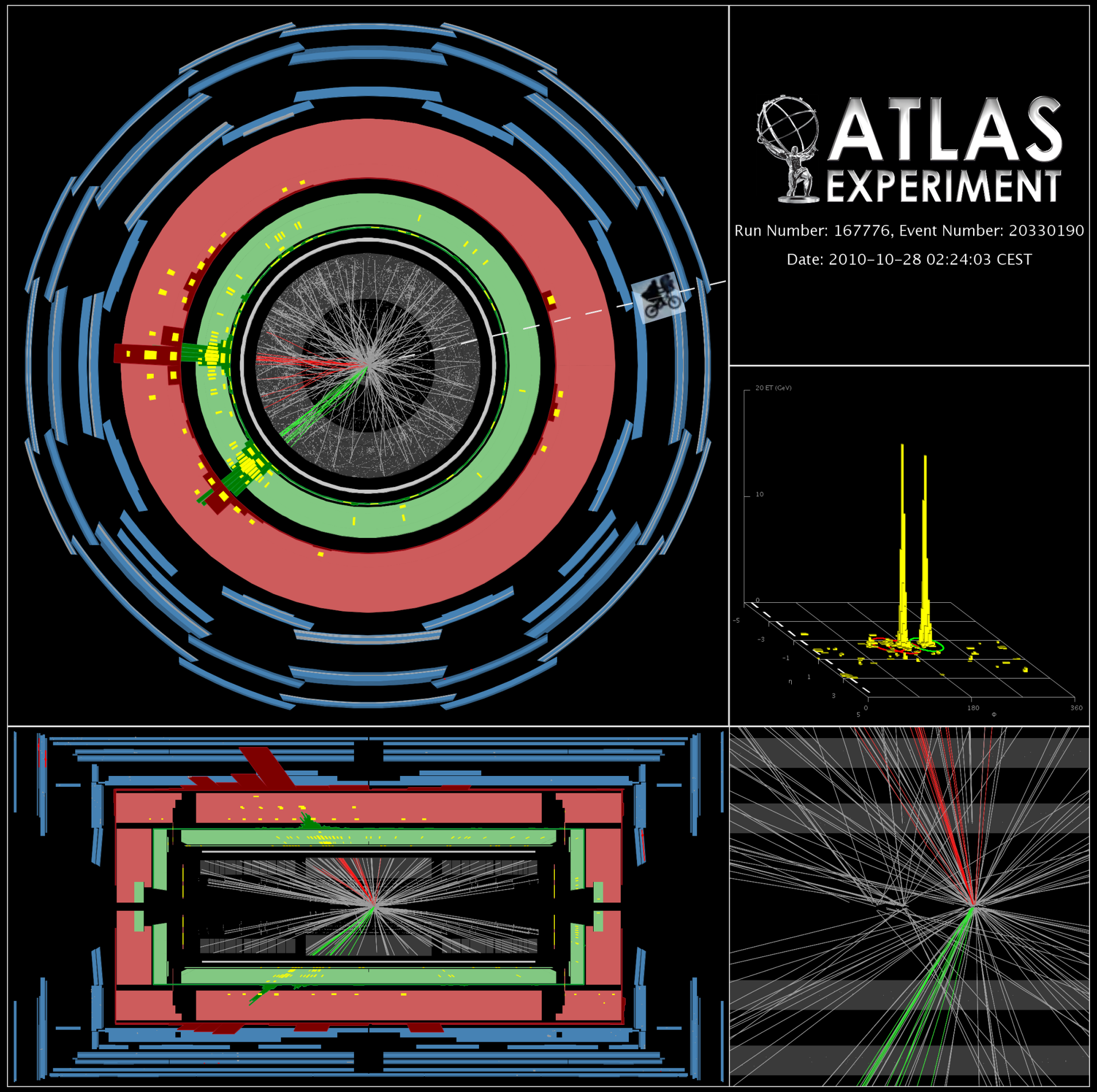
INVISIBLE PARTICLES — WHAT AND WHY?

- Do not interact via electromagnetic or strong nuclear forces.
  Do not decay within detector.
- Standard Model:
  Neutrino – produced in W,Z and top decays
- Supersymmetry (SUSY) with R-parity conservation:
  – Lightest supersymmetric particle (LSP) e.g. neutralino, gravitino
- Extra dimensional models:
  – Kaluza-Klein graviton/photon
- Generic dark matter candidates


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

Missing transverse momentum

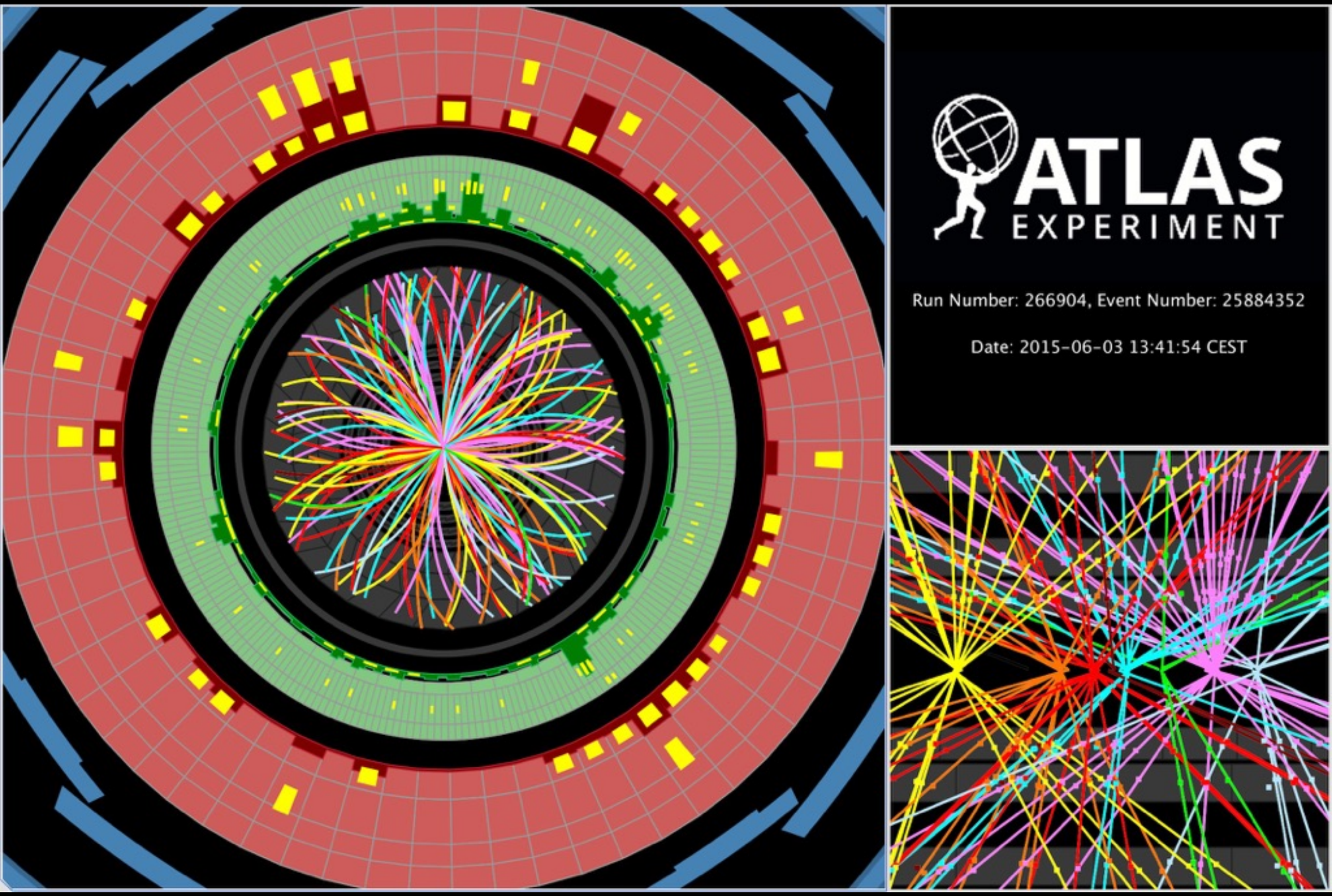
— not energy!


ATLAS
EXPERIMENT
Run Number: 167776, Event Number: 20330190
Date: 2010-10-28 02:24:03 CEST
20 ET (GeV)
10
0
-5
-3
-1
η
1
3
5
0
180
360
Φ

MISSING TRANSVERSE MOMENTUM RECONSTRUCTION

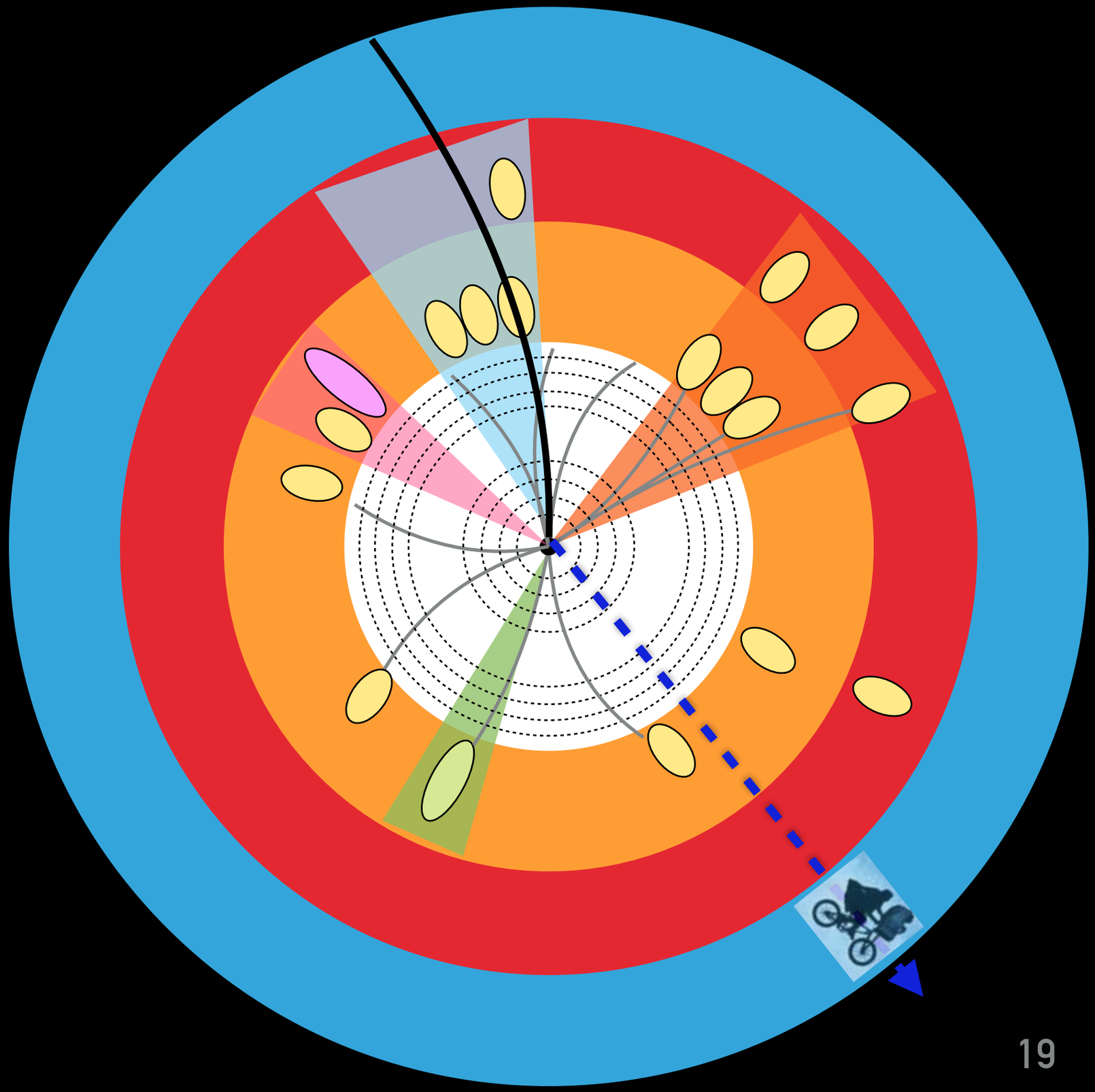
- Parton collision rest-frame should have ~0 transverse momentum, although boost along beam-pipe unknown.
- Sum up transverse momenta of detected particles.
- Invisible particles carrying transverse momentum –> apparent non-conservation.
- Susceptible to object mismeasurement/miscalibration.

8 reconstructed vertices. Mean in 2012 was ~20!



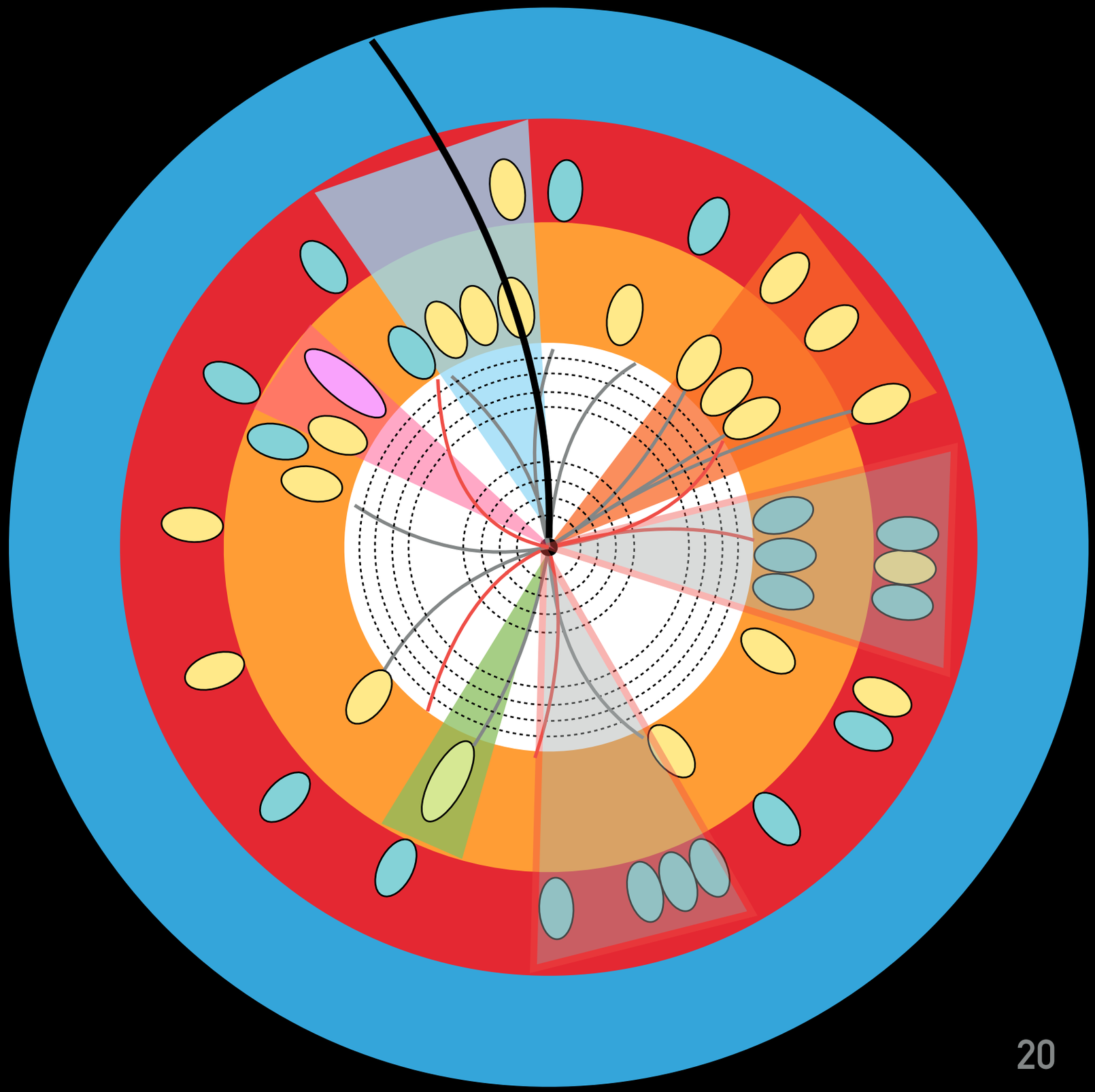
A SUM OF PARTS

- Well-calibrated reconstructed particles (e,γ,μ,τ)
- High-pT jets
- Soft particle contributions (clusters / tracks)



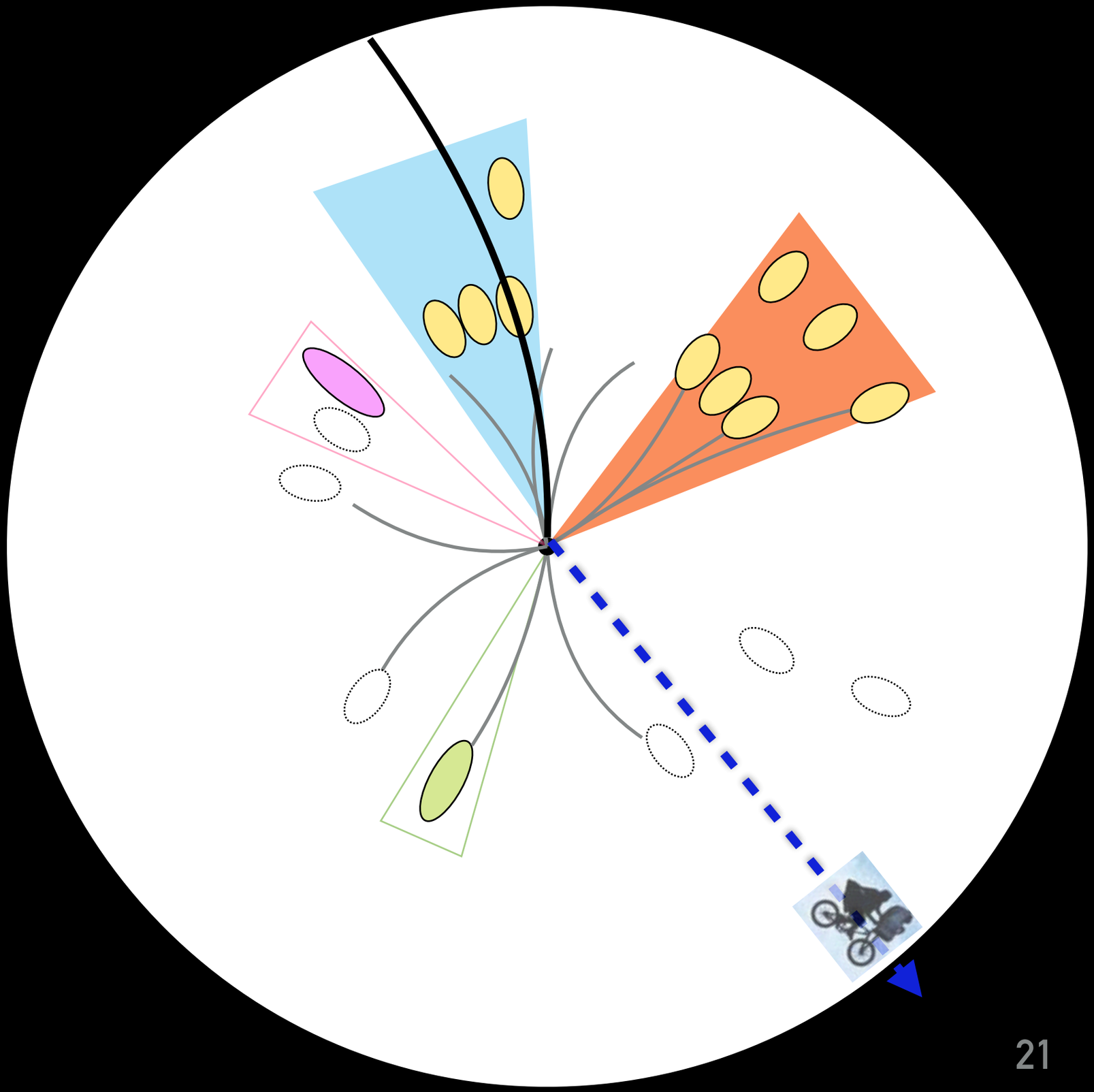
A SUM OF PARTS

- Pileup causes fluctuations
- Cannot separate calo signals from different vertices
- Can distinguish pileup tracks



A SUM OF PARTS

- Pileup causes fluctuations
- Cannot separate calo signals from different vertices
- Can distinguish pileup tracks



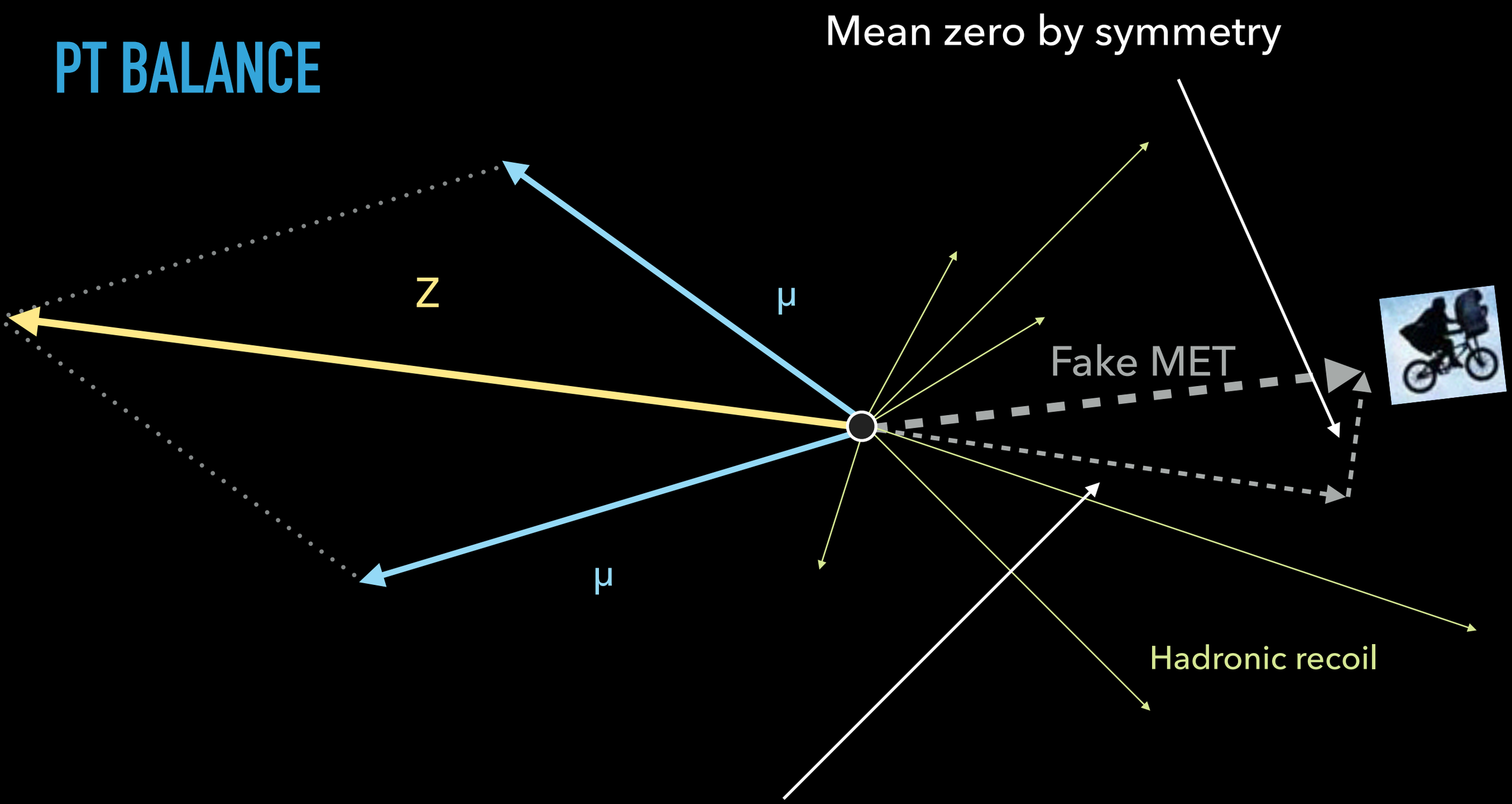
INVISIBLE IMPROVEMENT

- Pileup robustness:
  - Inherit suppression techniques pioneered by jets – track-based discriminants, area-based subtraction, constituent subtraction
  - Require adaptation for application to soft component: calorimeter occupancy/granularity pileup event shapes and detector-shaping reconstruction efficiency of soft particles

PERFORMANCE

- Analyses use MET to:
  - Reconstruct event – need accurate determination of magnitude and direction: good **resolution** and **scale**.
  - Identify signals with energetic invisibles – must **eliminate tails** from detector effects.
- Assess performance from **p_T balance** in pure event sample with clean reference particle and zero intrinsic MET.
  - Chiefly focus on $Z \to \mu\mu$ + jets.

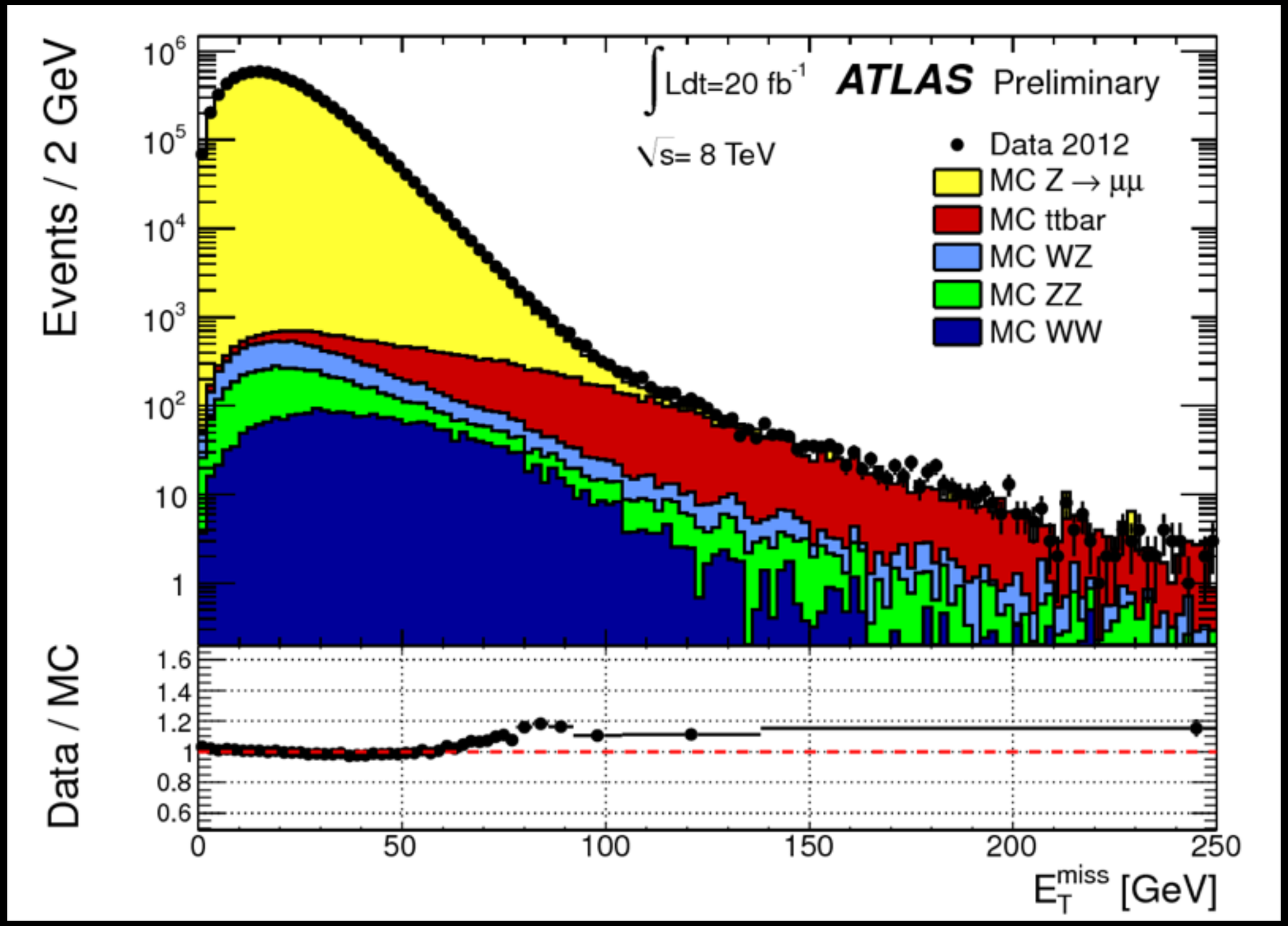
PT BALANCE

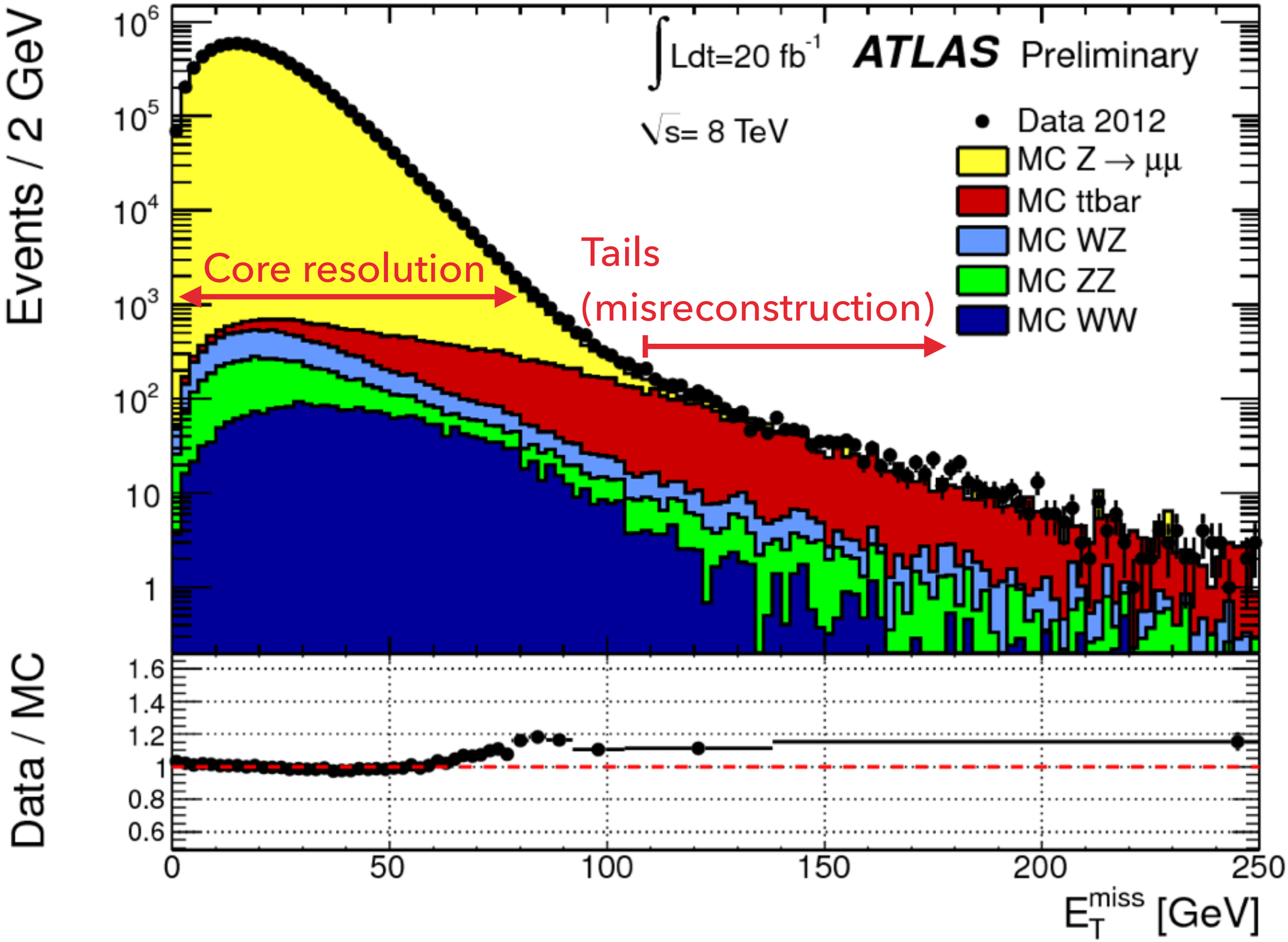


Non-zero mean indicates imbalance

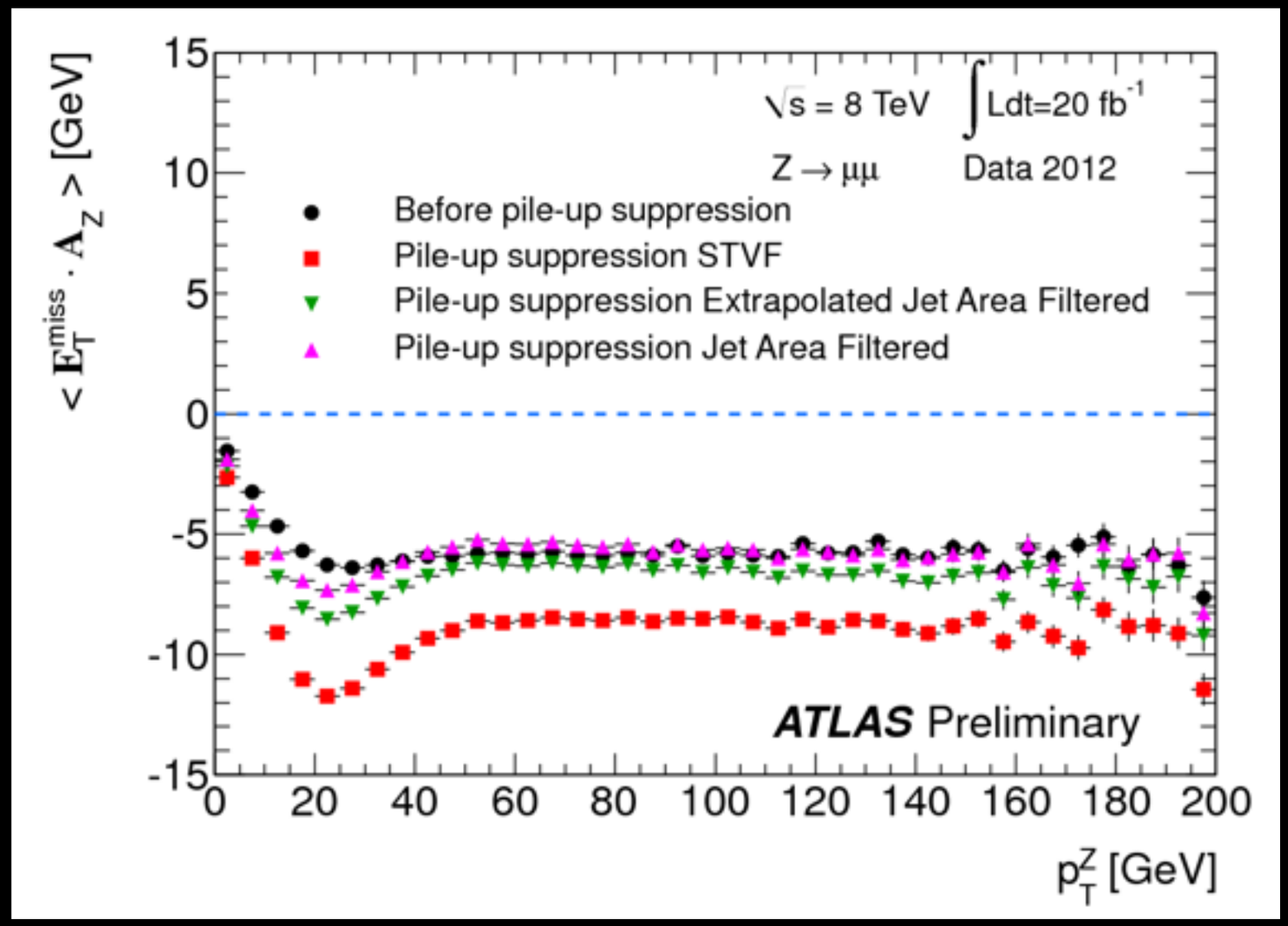
Resolution components not a priori correlated.

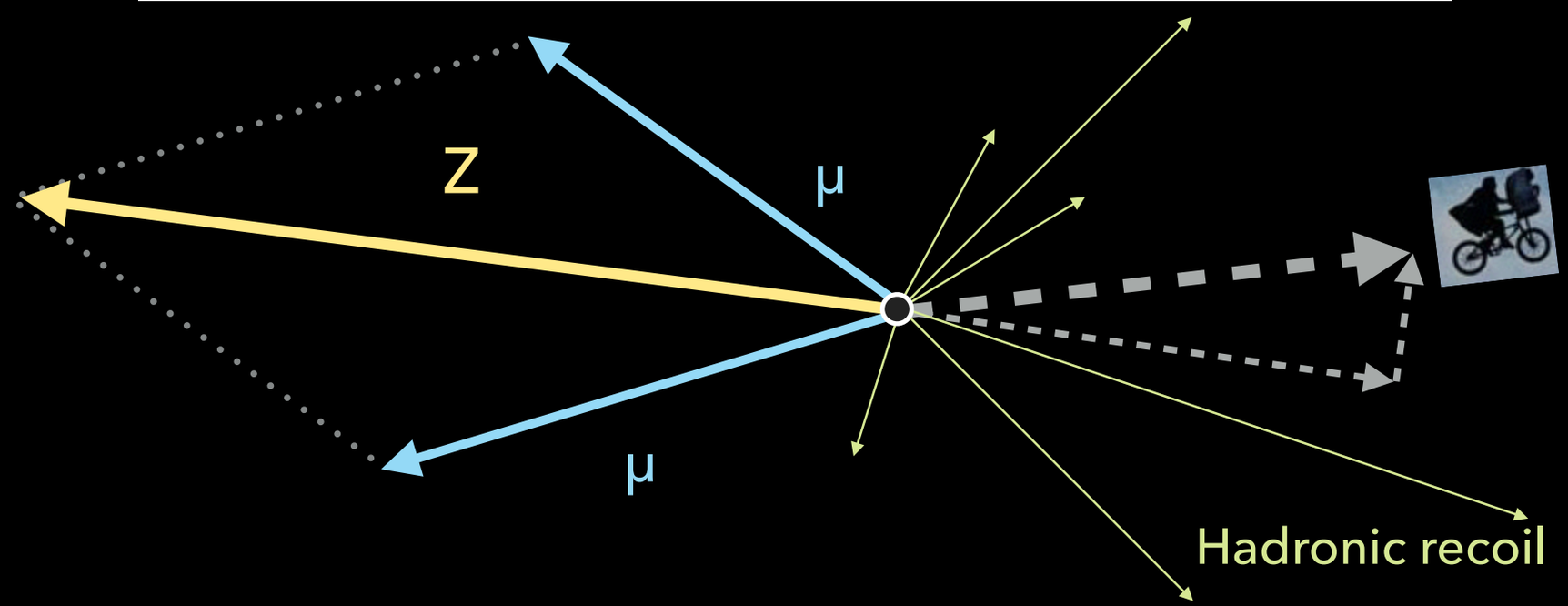
ATLAS-CONF-2013-082



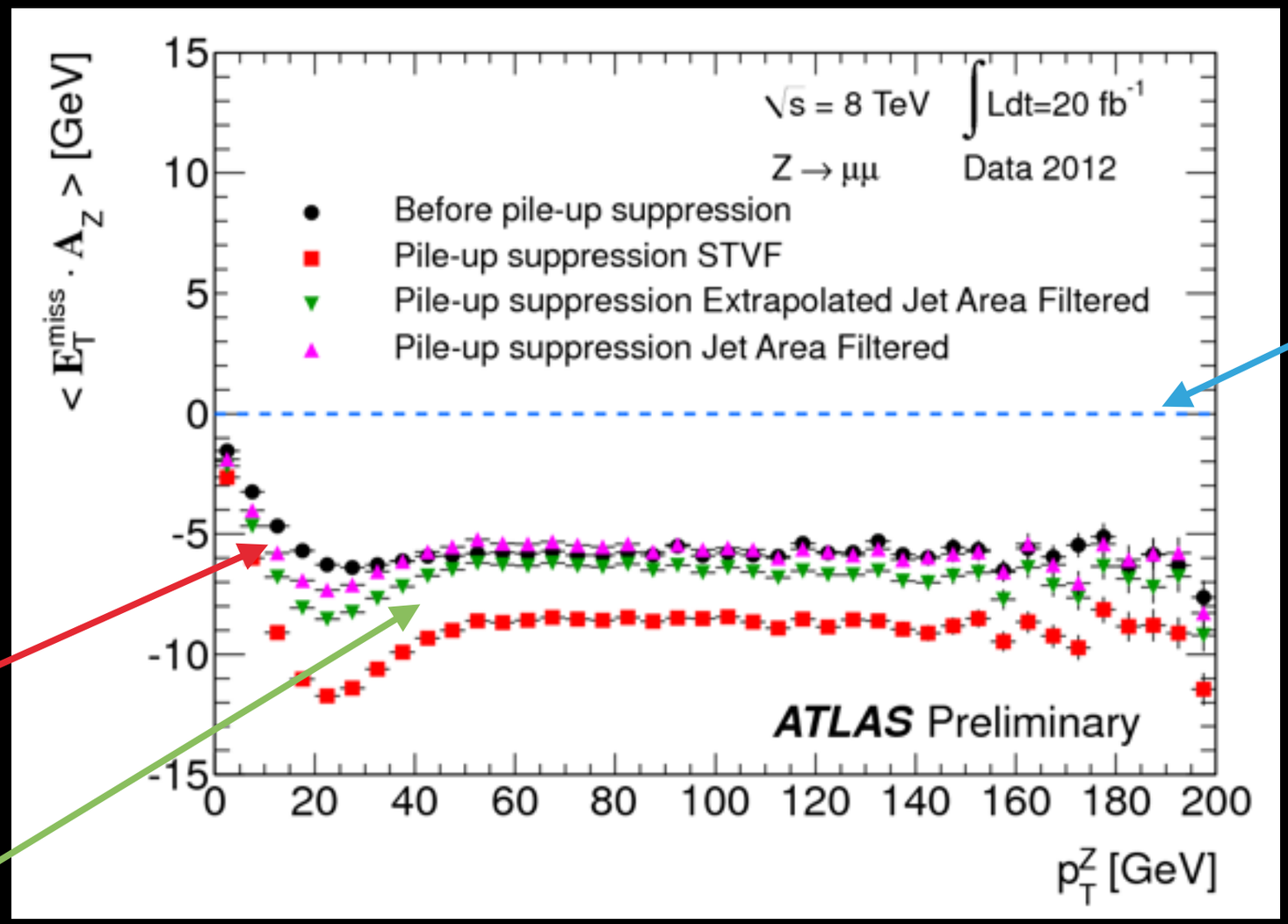

Events / 2 GeV
$\int$ Ldt=20 fb^{-1}
ATLAS Preliminary
$\sqrt{s}$= 8 TeV
Data 2012
MC Z → μμ
MC ttbar
MC WZ
MC ZZ
MC WW
Core resolution
Tails
(misreconstruction)
Data / MC
E_T^{miss} [GeV]

ATLAS-CONF-2013-082





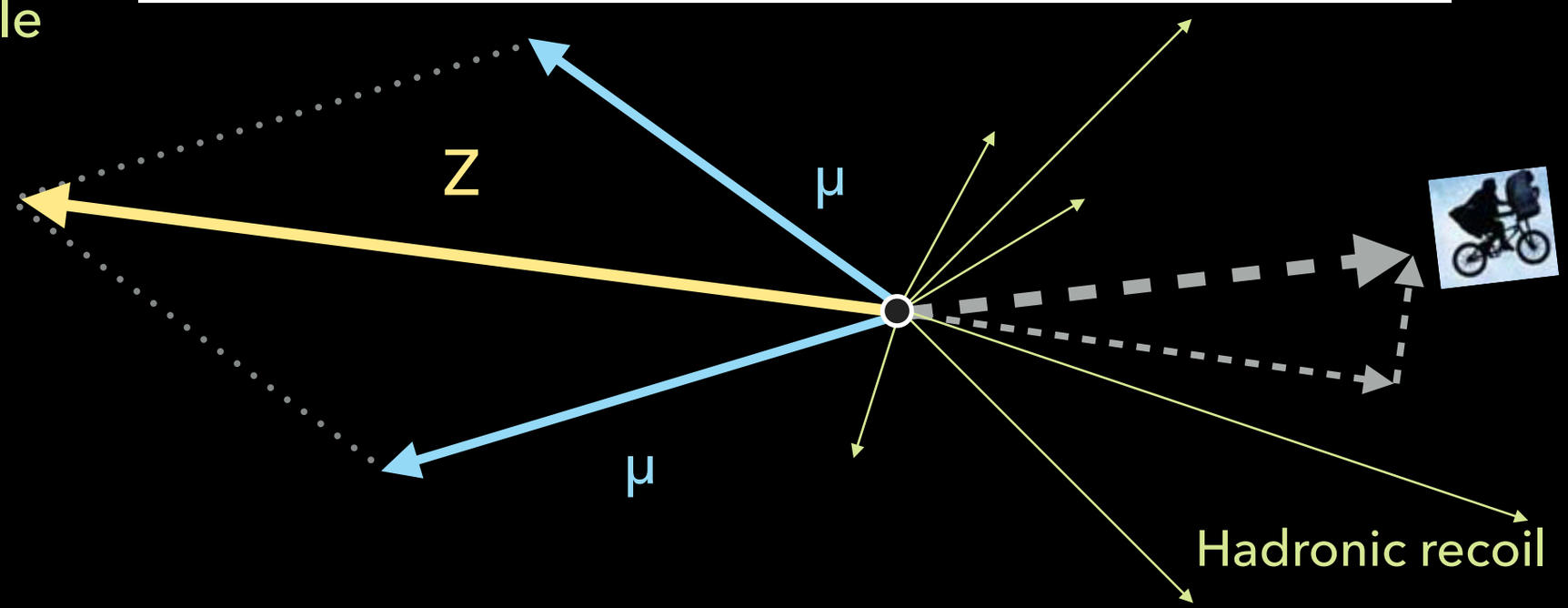
ATLAS-CONF-2013-082



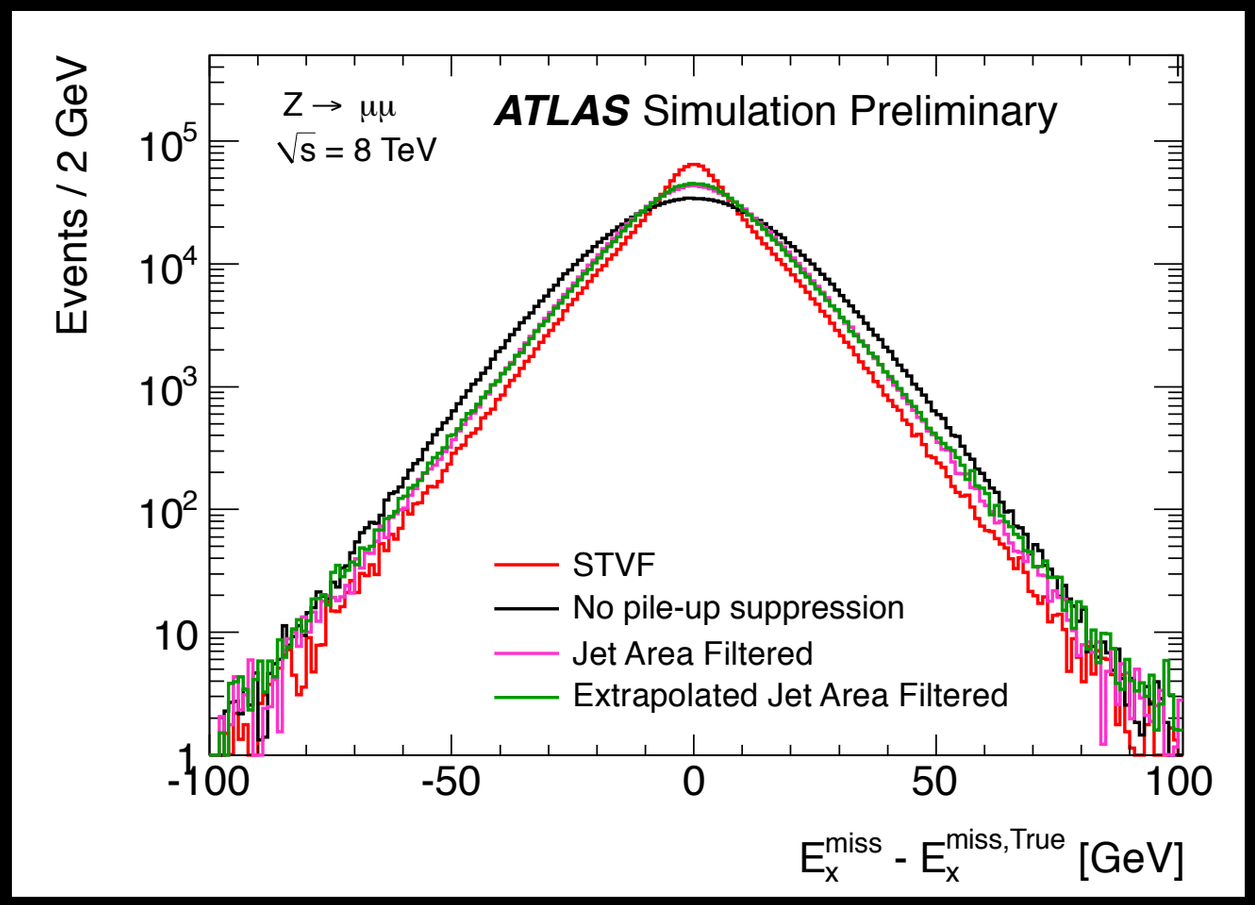
Perfect balance

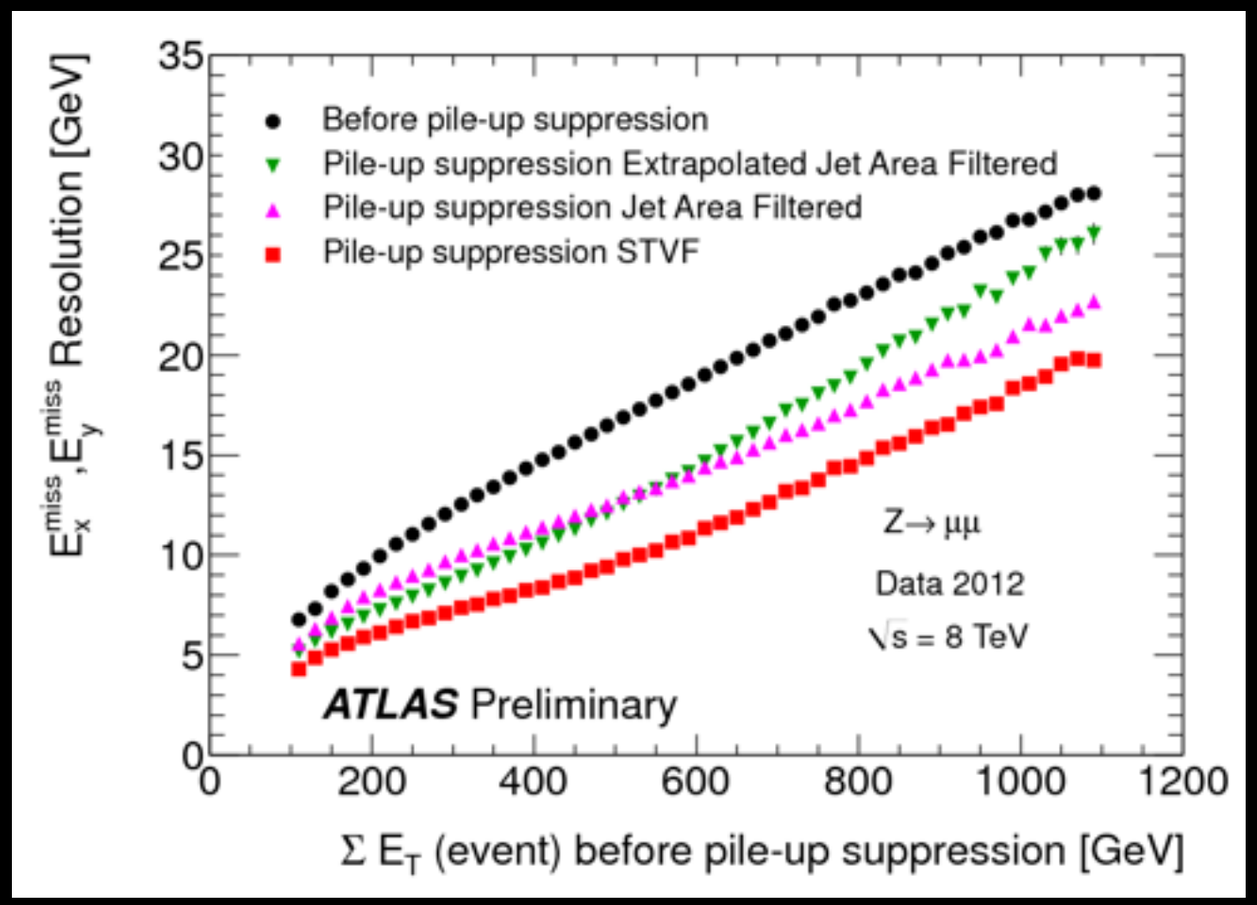
Soft component underestimated

Jet calibration restores scale



ATLAS-CONF-2013-082





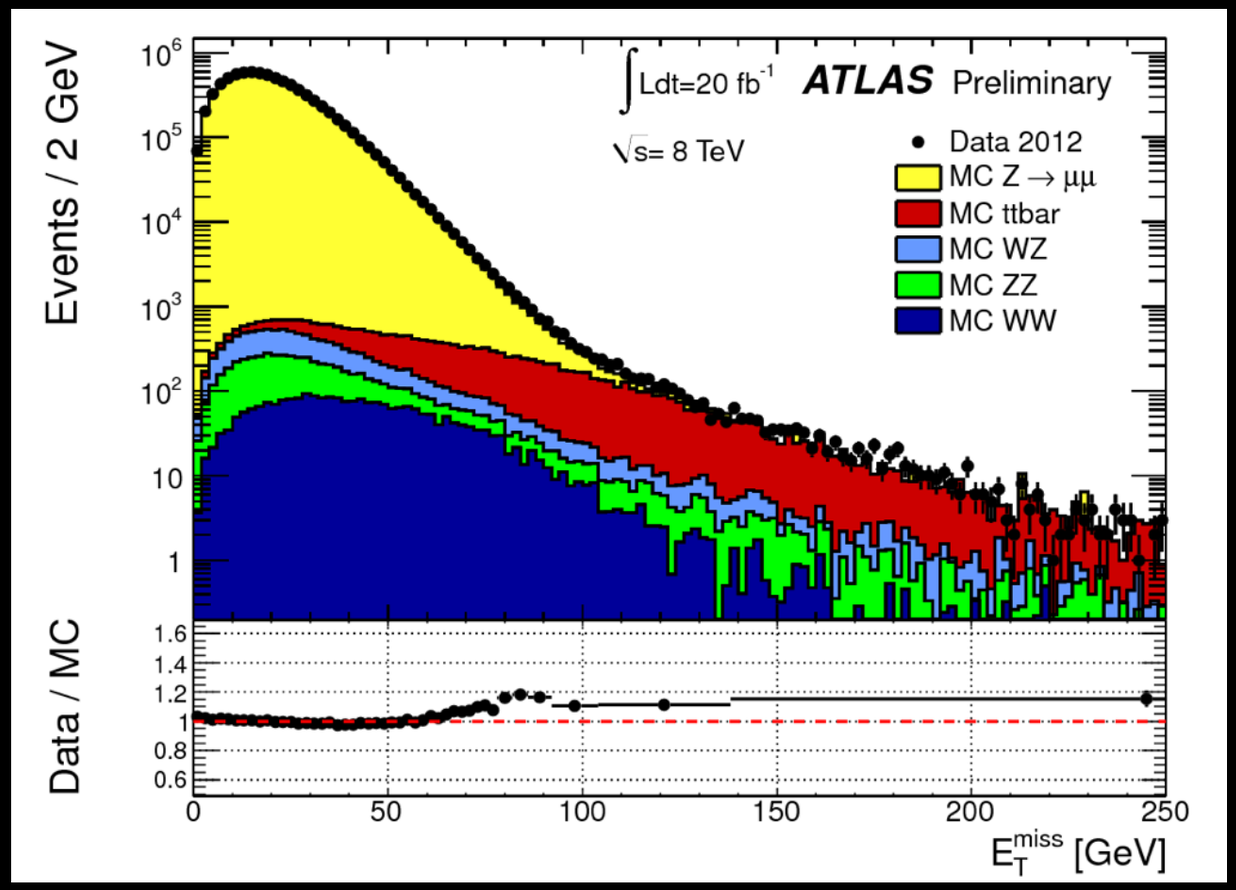
Samples with no intrinsic MET (neutrinos)

True value is spike at 0

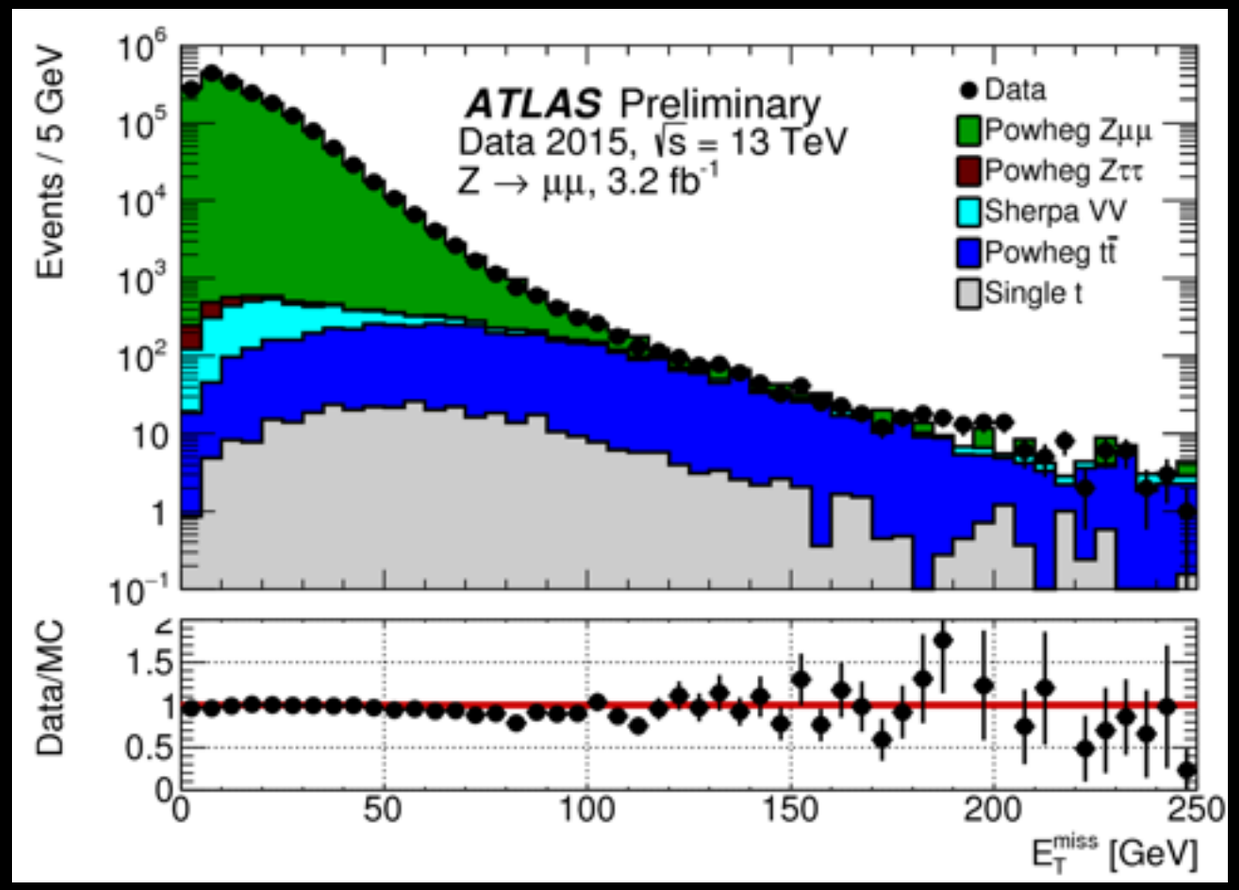
Width defines resolution, driven by fluctuations

ATLAS EXPERIMENT

ATLAS-CONF-2013-082

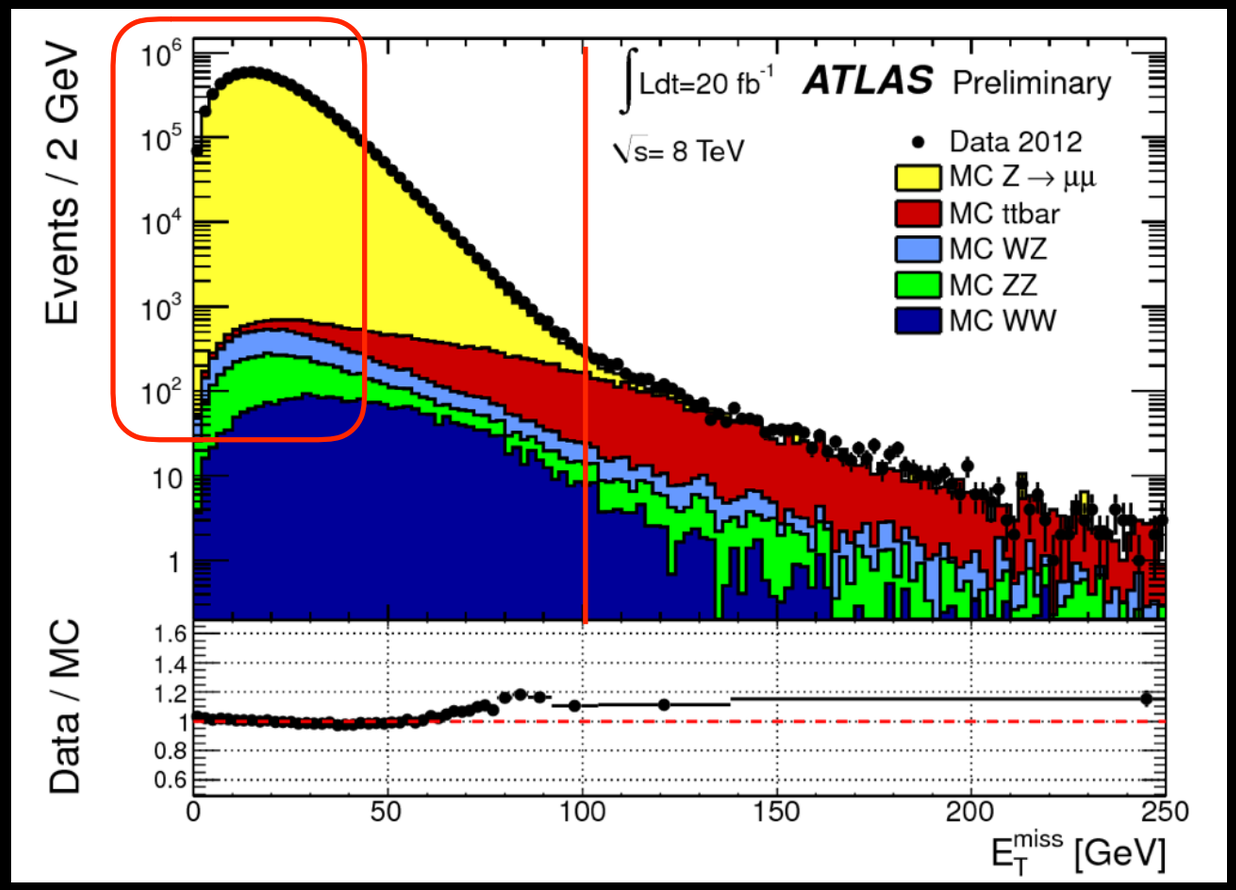


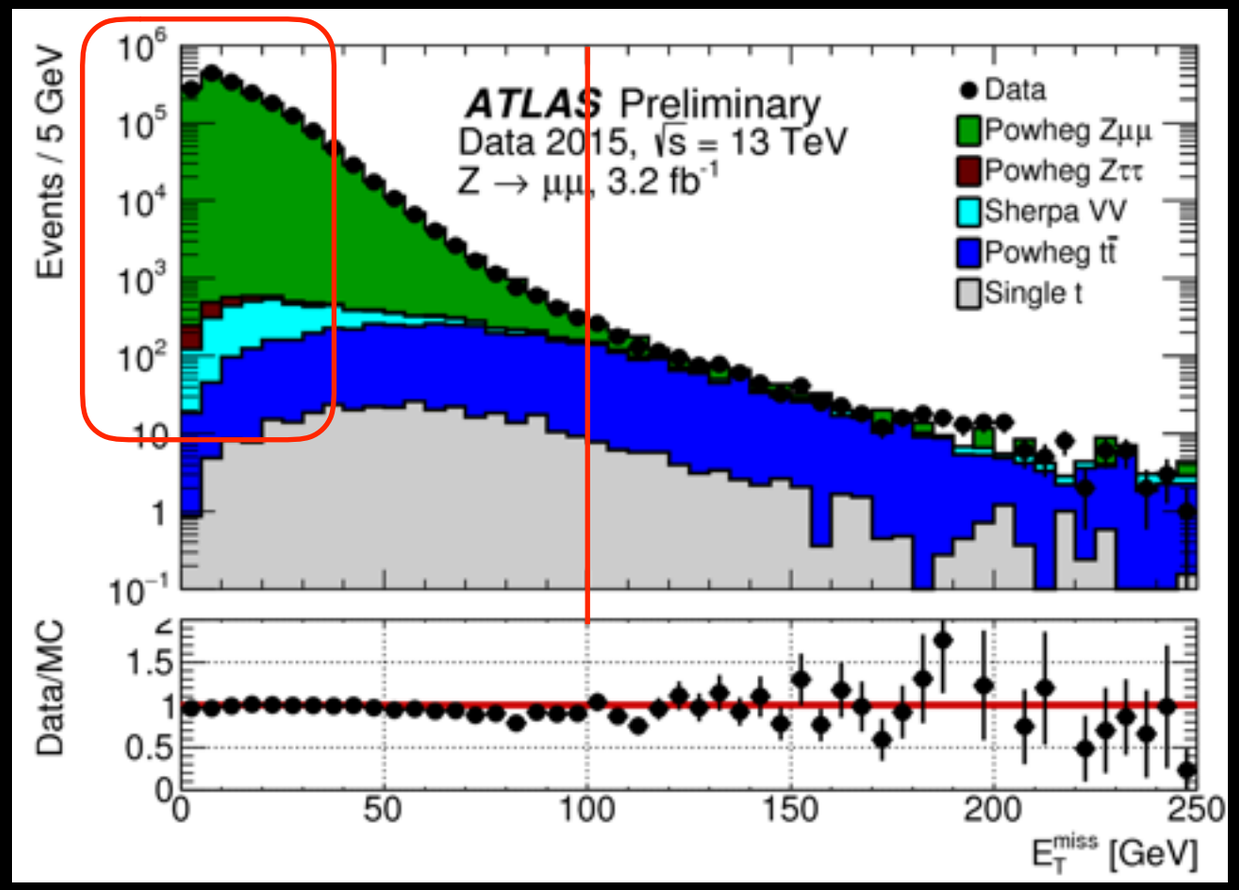
JETM-2016-003



2012 → 2015

New challenges
New tools

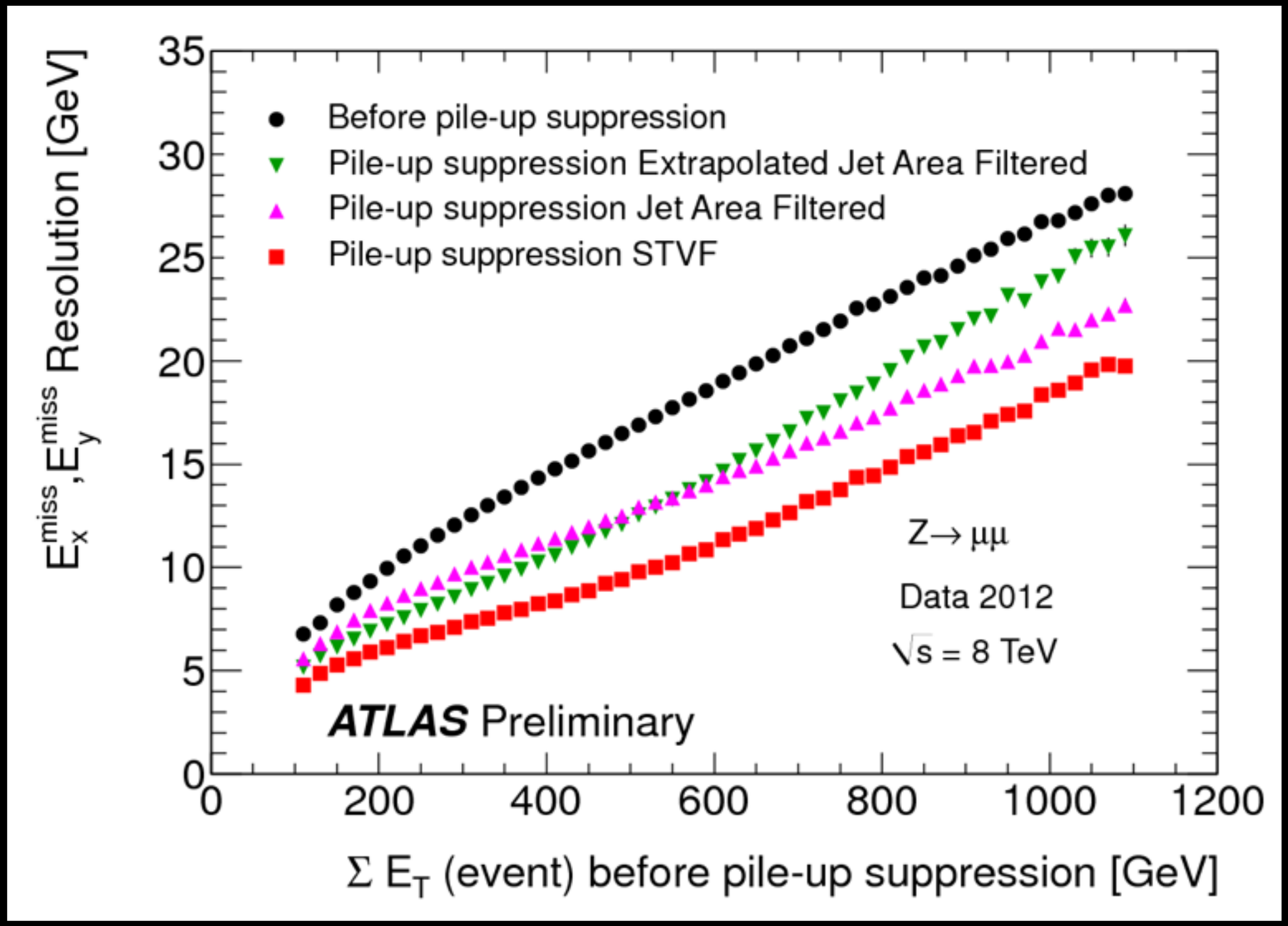




Core resolution improved without effect on tails

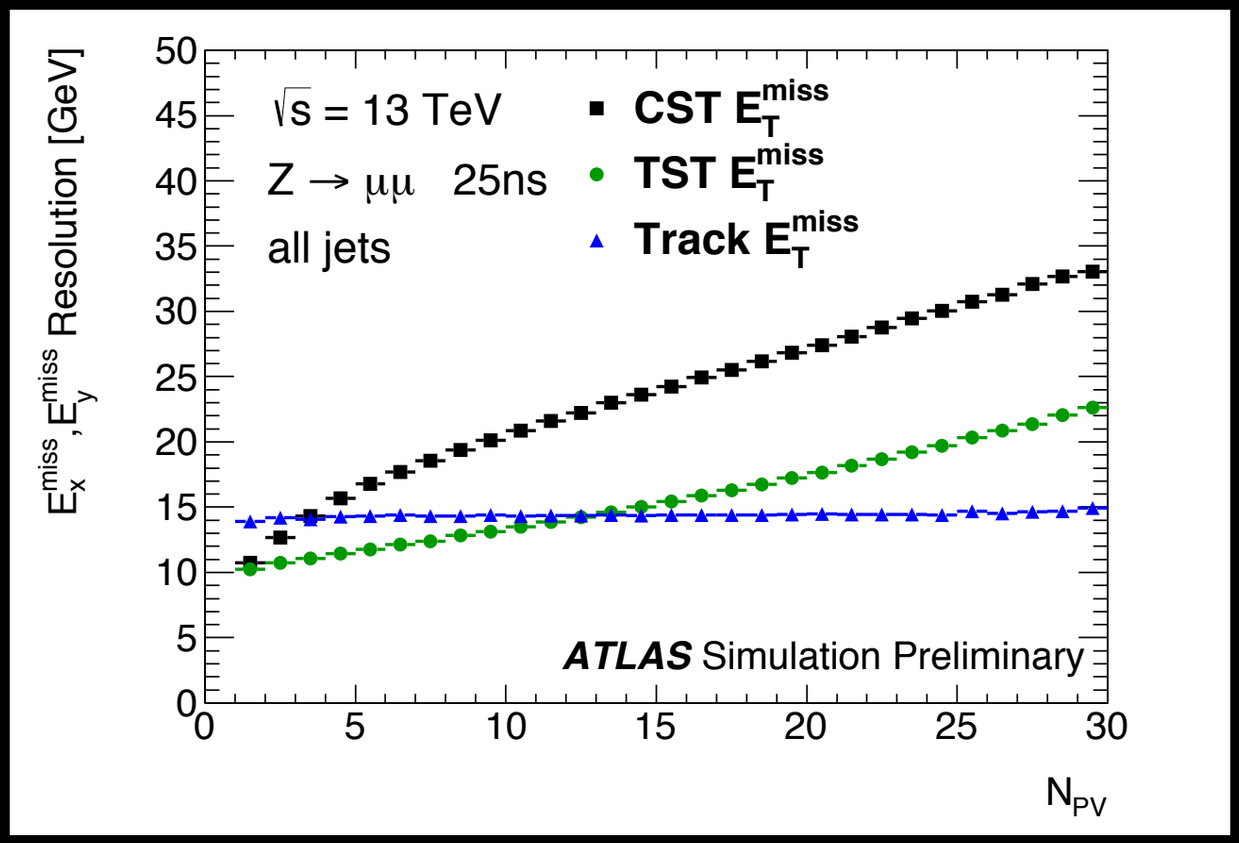
ATLAS-CONF-2013-082

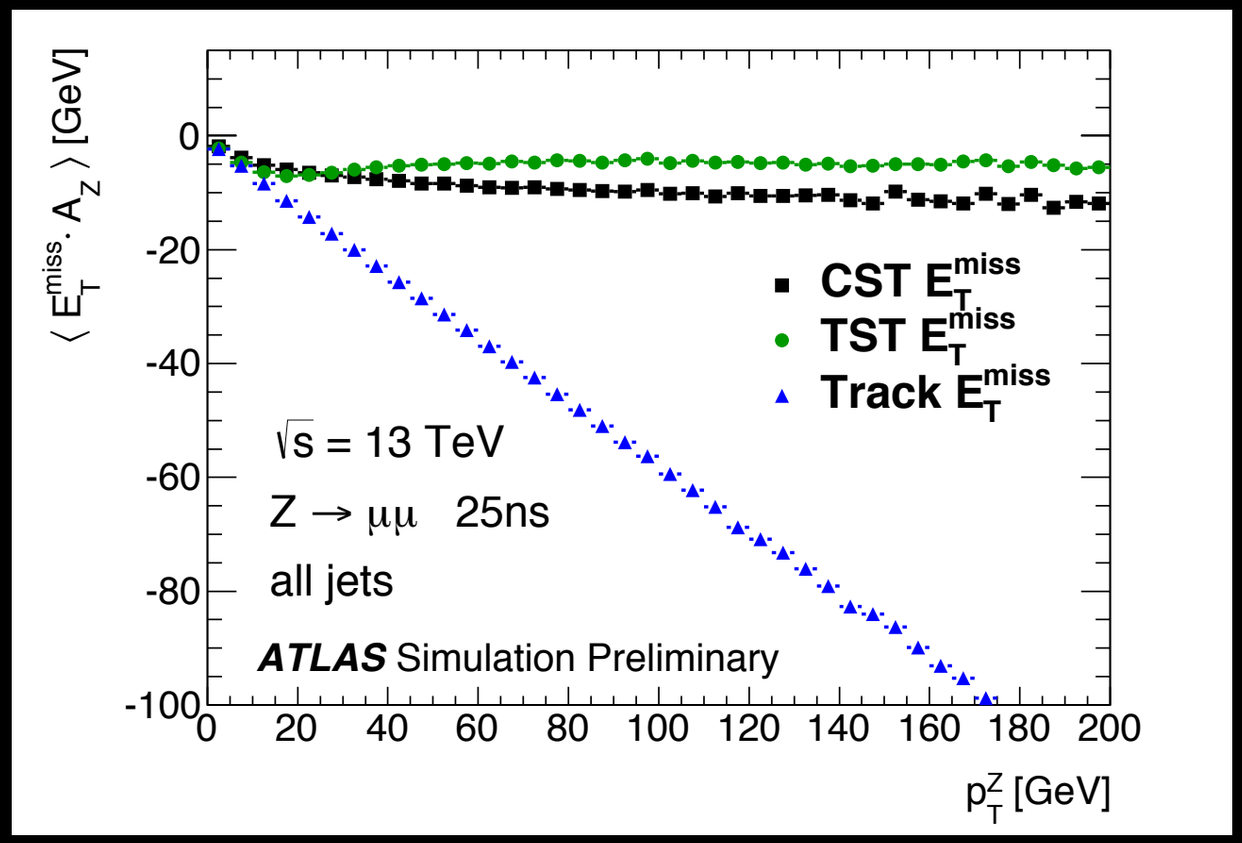
PILEUP CORRECTIONS — 2012



ATLAS-CONF-2013-082

PILEUP CORRECTIONS — 2015





Soft component not negligible
Pileup-sensitivity drives resolutions
Neutral information in energetic jets critical

Barr, Khoo, Konar, Kong, Lester, Matchev, Park
Phys.Rev. D84 (2011) 095031

MASSING AROUND WITH INVISIBLES

- Standard resonant signal: invariant mass peak
  – requires identification of all daughter four-momenta

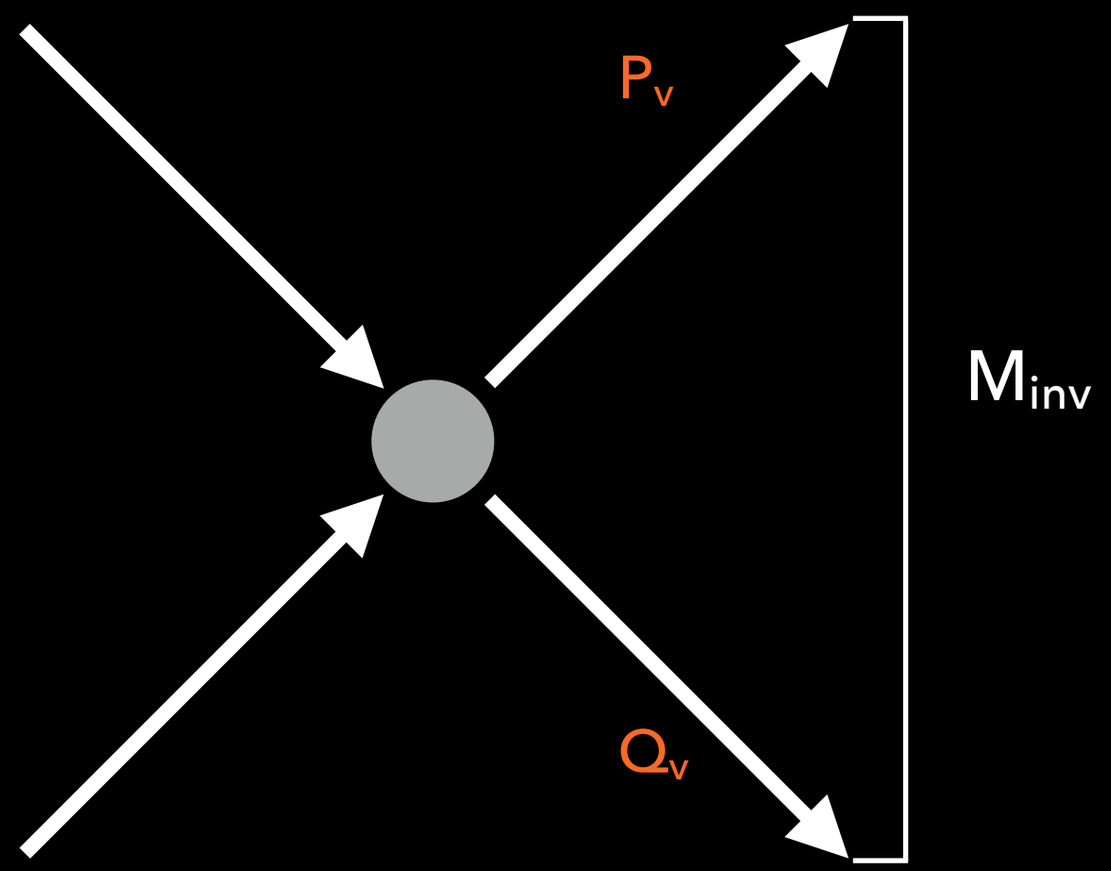
- MET reconstruction permits constraint on total invisible transverse momenta only:

$$\sum_{i \in \text{invis}} p_{x,y} = E^{\text{miss}}_{x,y}$$

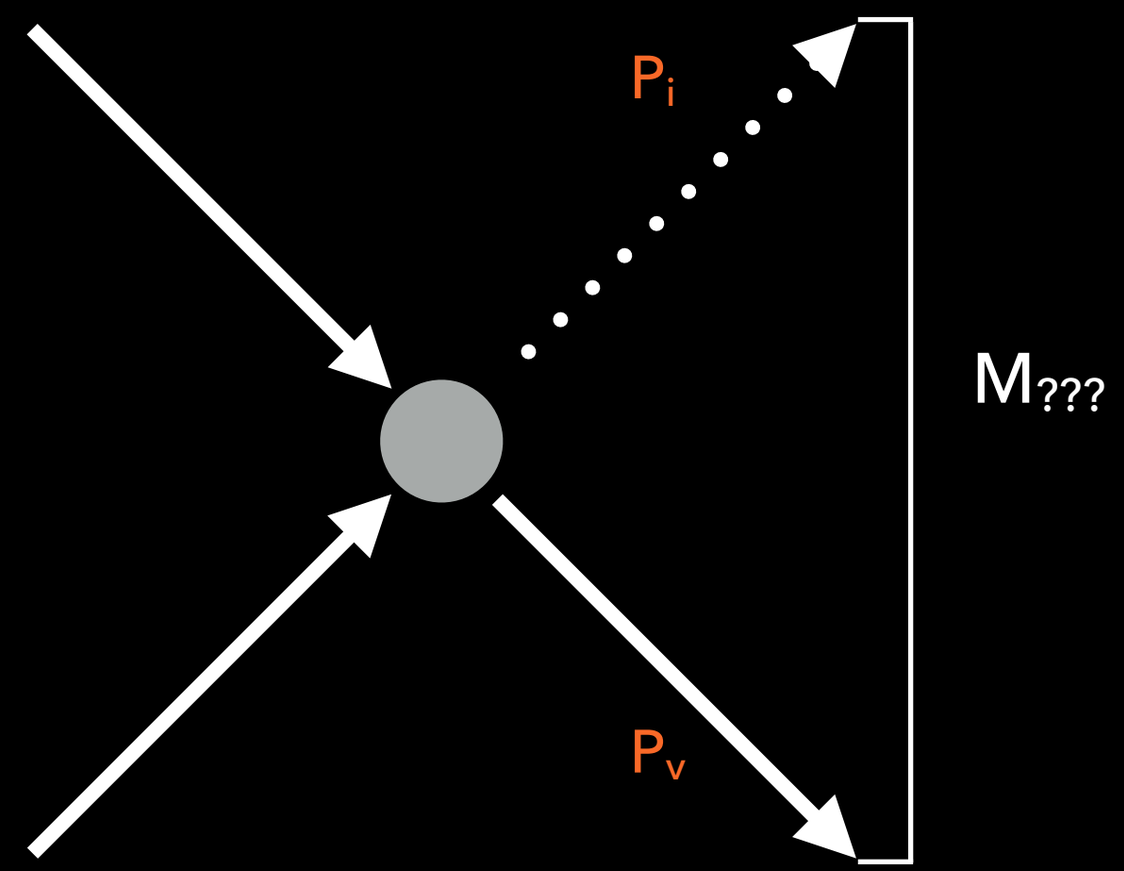
  Invisible mass and z-momentum unconstrained.

- Partial reconstruction of *semi-invisible* decays possible given appropriate assumptions about decay chain.

ONE TO TWO



Fully visible decay



Semi-invisible decay

Konar, Kong, Matchev
JHEP 0903:085,2009

LOSING WEIGHT: MASSES VIA MINIMISATION

- Want to compute something like an invariant mass.

3+1D vector

$$
\begin{aligned}
M_{\text{inv}}^2 &= (P_v^\mu + P_i^\mu)^2 \\
&\geq \min_{p_z^i} (P_v^\mu + P_i^\mu)^2 \\
&= \min_{y^i} (P_v^\mu + P_i^\mu)^2 \\
&= \left(p_{\text{T,v}}^\alpha + p_{\text{T,i}}^\alpha\right)^2 = m_{\text{T}}^2
\end{aligned}
$$

Minimise over unknown z-component

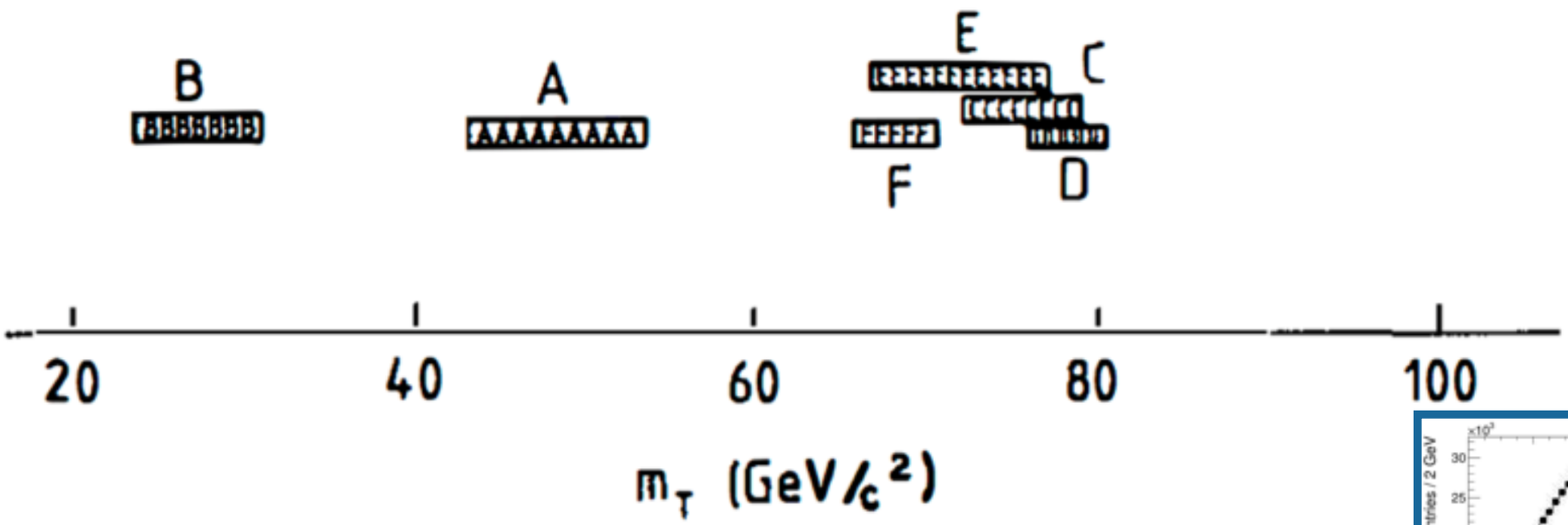
Equivalent to minimising over rapidity

2+1D vector

Result: make $y_{vis} = y_{invis}$, boost to frame where both are 0
Equivalently, ignore all longitudinal momenta.

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

The UA1 Collaboration



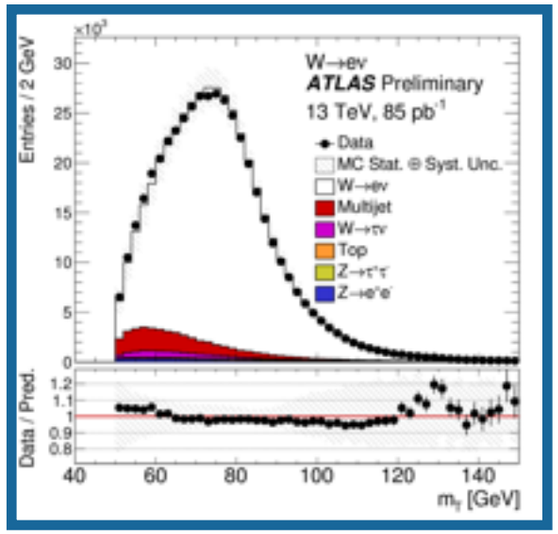


Fig. 9

The distribution of the transverse mass derived from the measured electron and neutrino vectors of the six electron events.

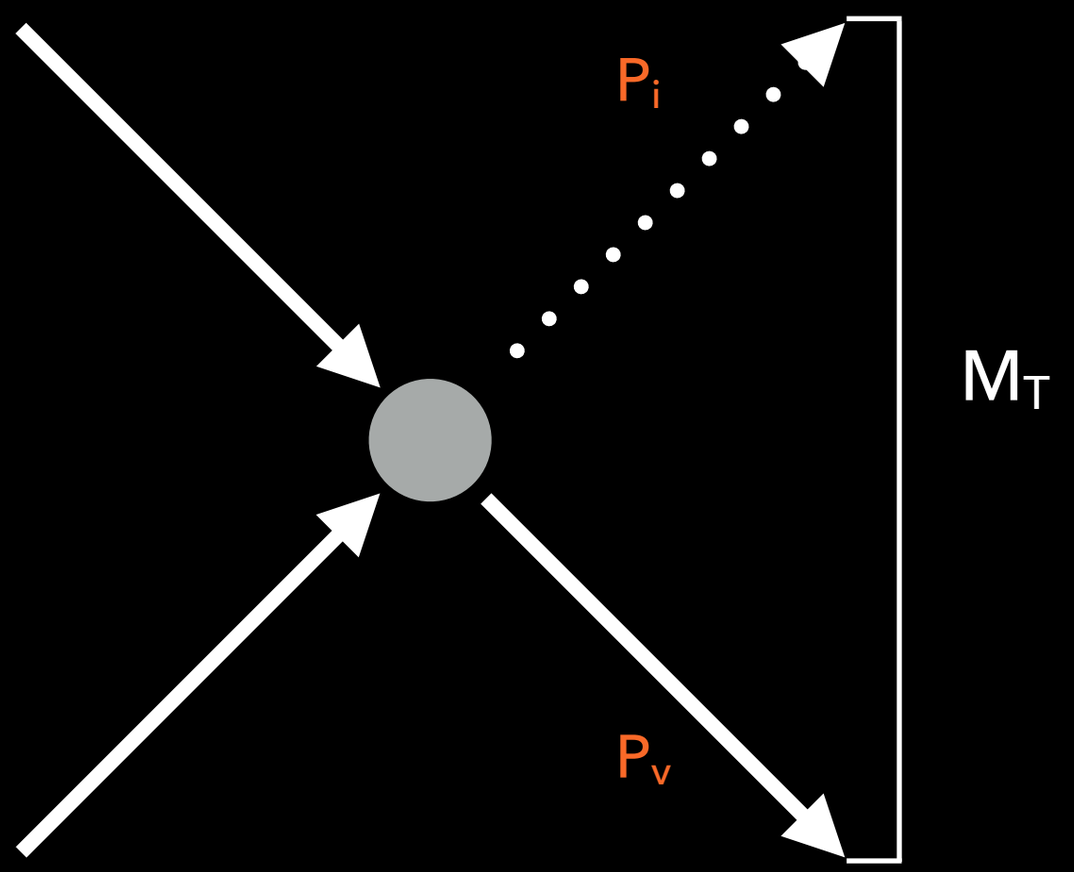
TRANSVERSE MASSES — A STORM IN A `T'-CUP

- Transverse mass m_T – classically used for W discovery.
- Simplification for ~massless daughters:

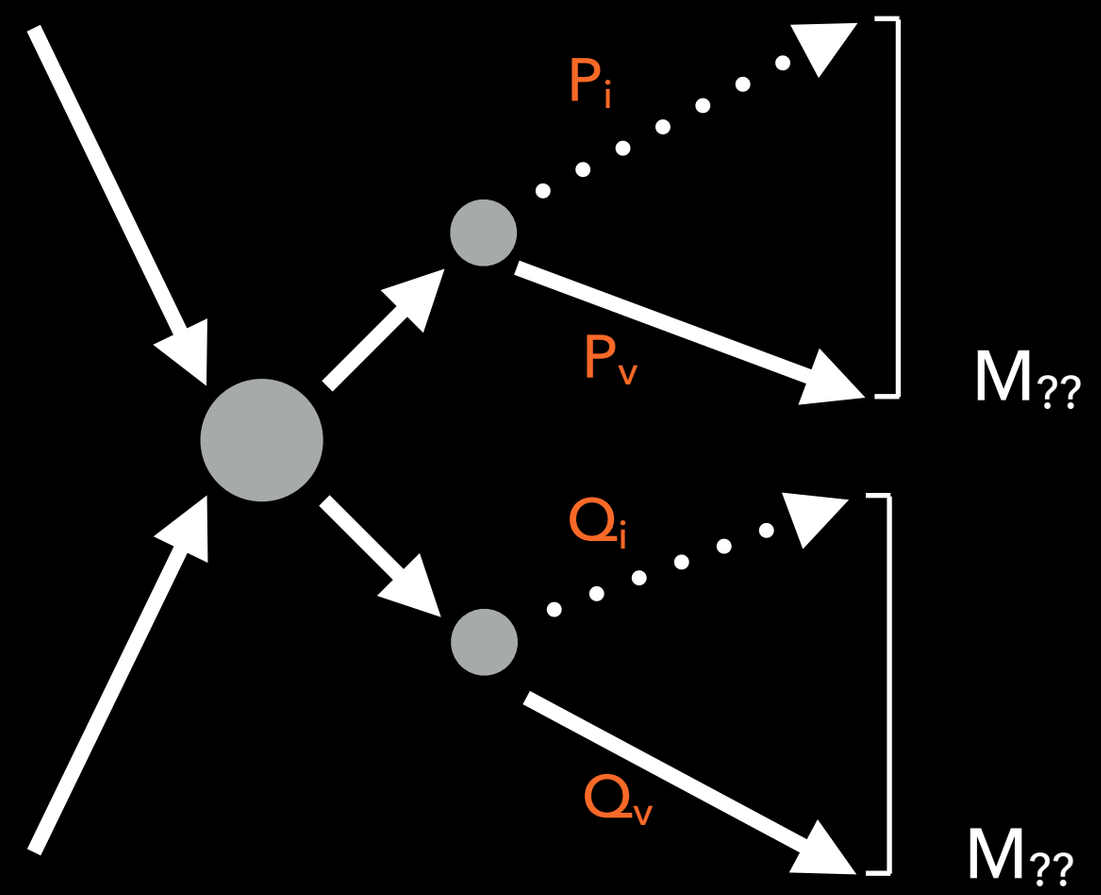
$$m_{\mathrm{T}}^2 = m_i^2 + m_v^2 + 2\left(E_{\mathrm{T}}^v E_{\mathrm{T}}^i - \vec{p}_{\mathrm{T}}^v \cdot \vec{p}_{\mathrm{T}}^i\right)$$
$$\simeq 2|p_{\mathrm{T}}^v||p_{\mathrm{T}}^i|\left(1 - cos(\Delta\phi_{v,i})\right)$$

- Inequality: every event produces lower bound on true mass, distribution has endpoint at invariant mass.
- Can generalise to N-body decay, sum visible four-momenta, then apply *transverse projection* to 2+1D.
- How to generalise to N parent decays?

TWO BY TWO



Semi-invisible decay, resonant production



Semi-invisible decay, pair production

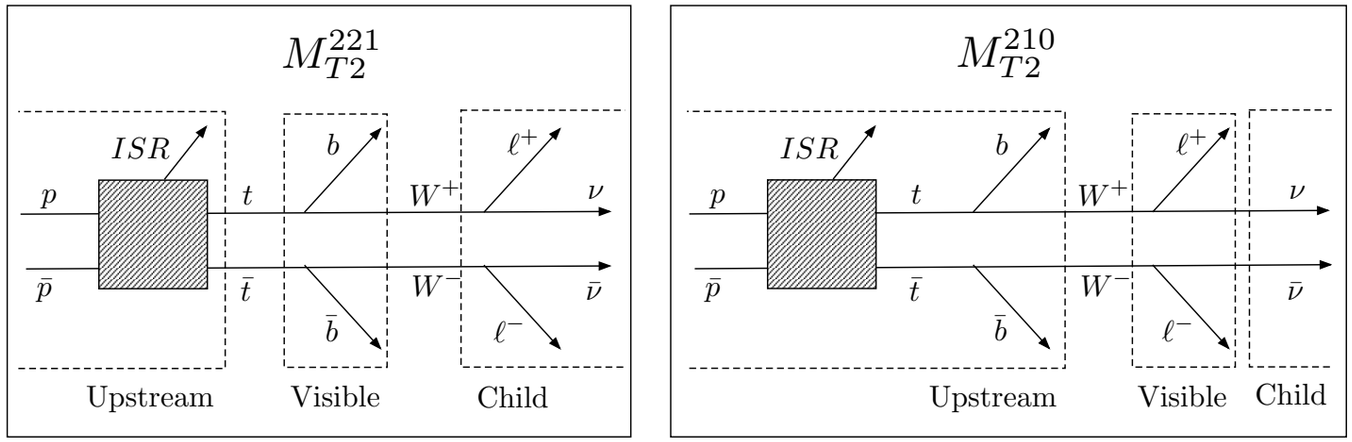
Lester, Summers Phys.Lett.B463:99-103,1999
Barr, Lester, Stephens J.Phys.G29:2343-2363,2003

MINIMISING MORE!

- Intuitively, we probably want an m_T for each of those legs. But how to partition invisible momenta?
- MET measurement constraint: $\vec{p}_{\mathrm{T}}^{\,i} + \vec{q}_{\mathrm{T}}^{\,i} = \vec{E}_{\mathrm{T}}^{\,\mathrm{miss}}$
- For any choice of P_{invis}, Q_{invis} satisfying constraint, can define m_T for corresponding parent particle.
- Assuming symmetric decay chains, $M_{\mathrm{parent}} \geq \max(m_{\mathrm{T}}^{P}, m_{\mathrm{T}}^{Q})$
- Define

$$m_{T2} = \min_{\vec{p}_T^{\,i} + \vec{q}_T^{\,i} = \vec{E}_T^{\,\mathrm{miss}}} \left[\max\left(m_T^P, m_T^Q \right) \right]$$

Eur. Phys. J. C 73 (2013) 2494



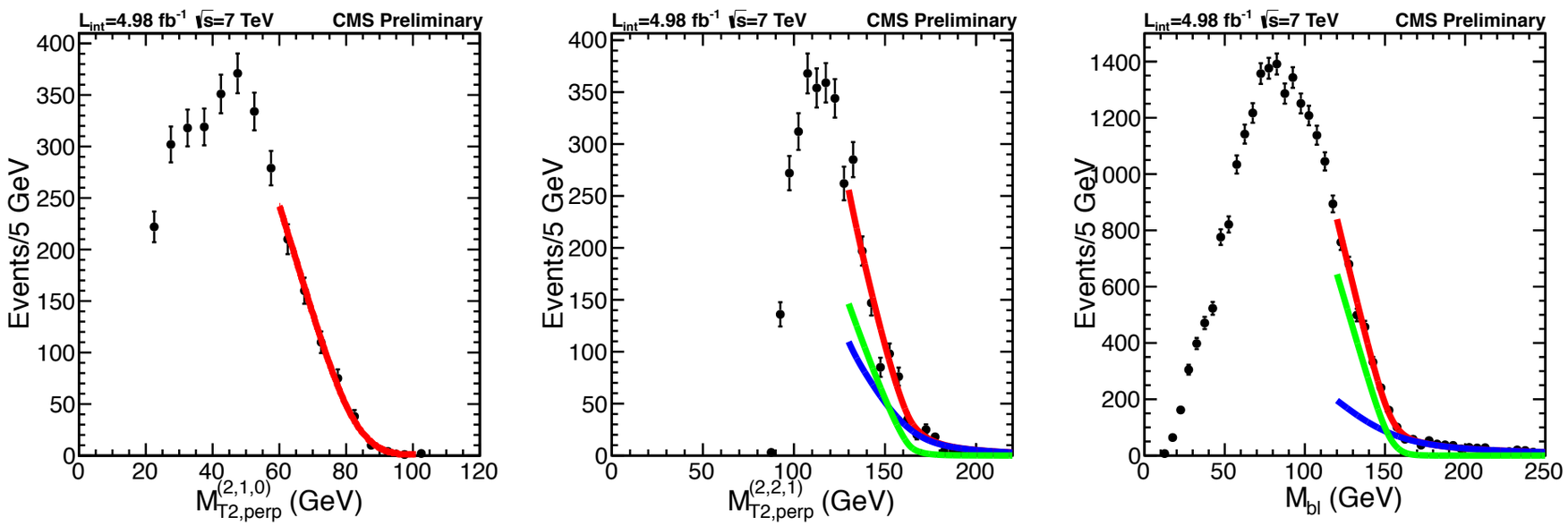
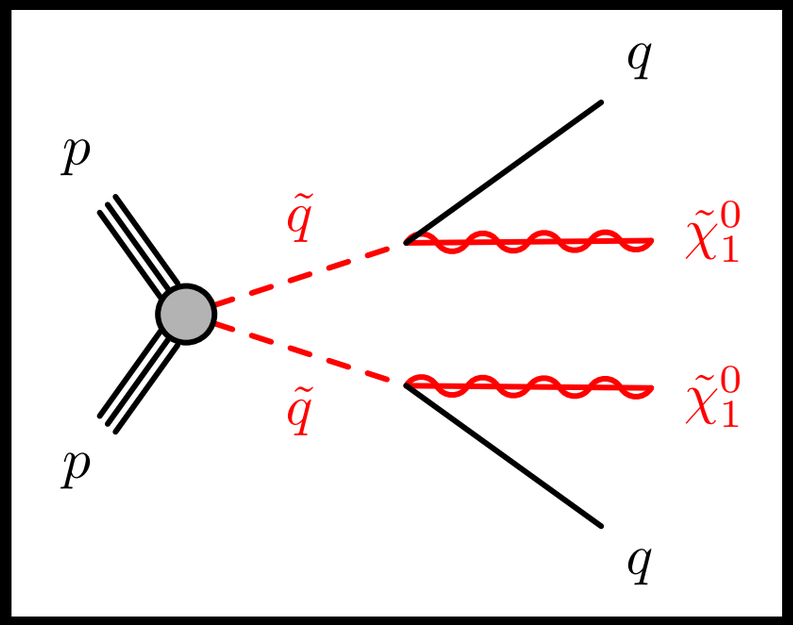
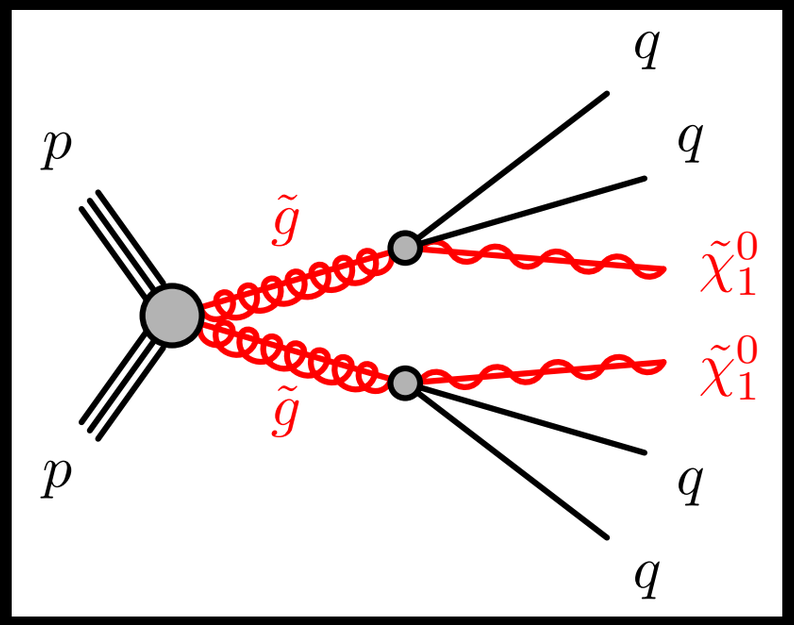


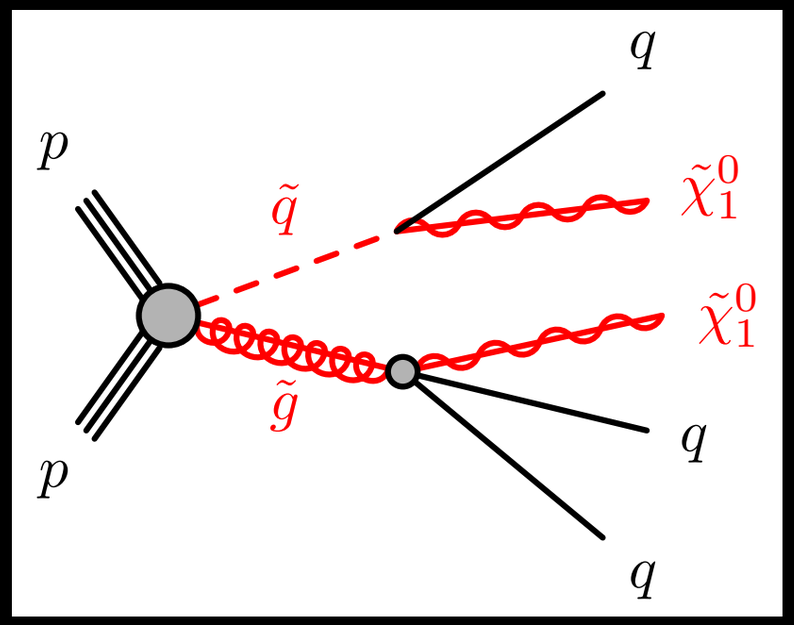
Table 4: Fit results from the three mass analyses with various levels of constraint. Errors are statistical (first) and systematic (second).

Fit Quantity	Constraint		
	None	$m_\nu = 0$	$m_\nu = 0$ and $M_W = 80.4$
m_ν^2 (GeV^2)	$-556 \pm 473 \pm 600$	(0)	(0)
M_W (GeV)	$72 \pm 7 \pm 9$	$80.7 \pm 1.1 \pm 1$	(80.4)
M_t (GeV)	$163 \pm 10 \pm 11$	$174.0 \pm 0.9 \pm 2$	$173.9 \pm 0.9^{+1.2}_{-1.8}$

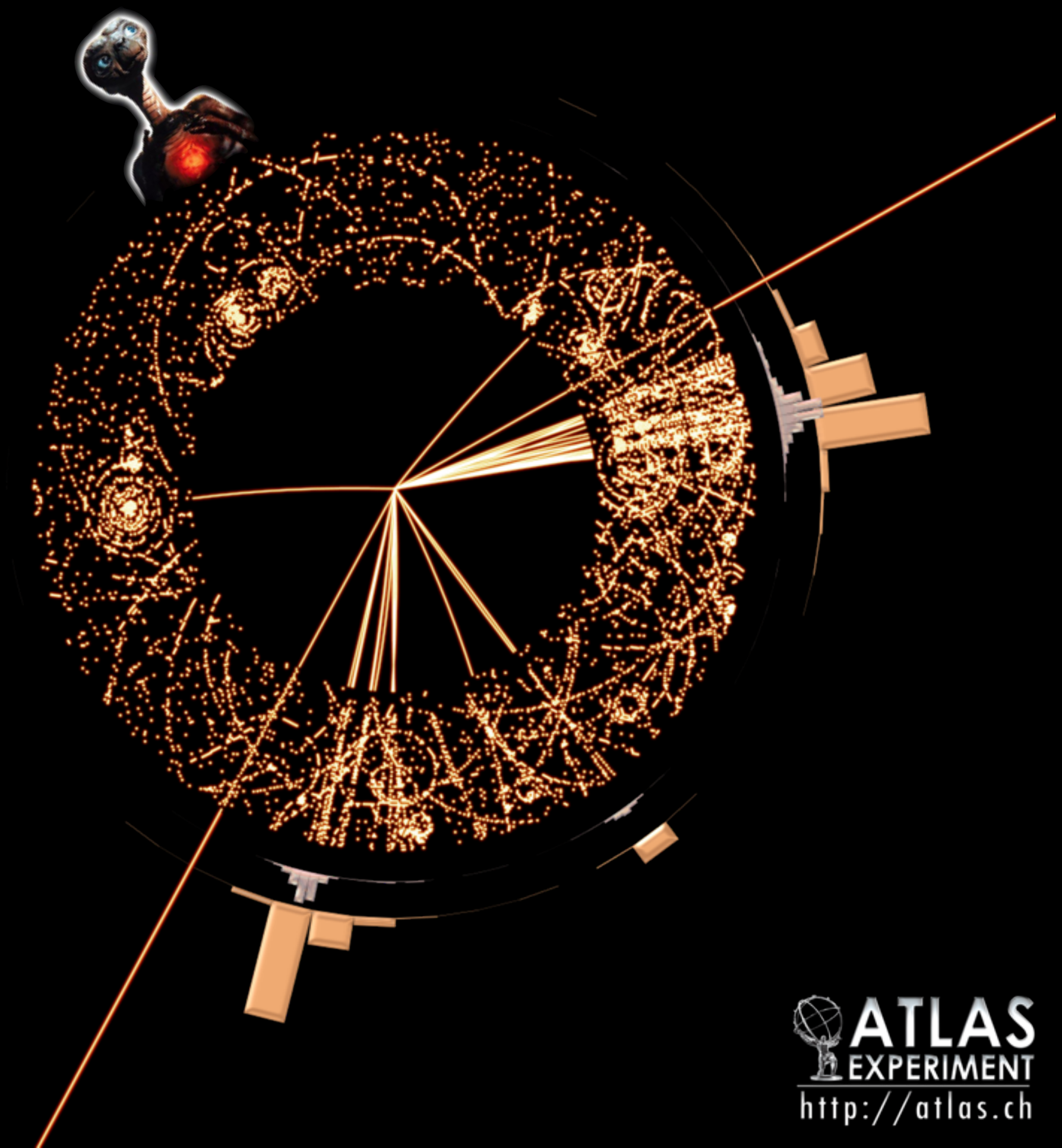
SUPER STRONG SIGNALS





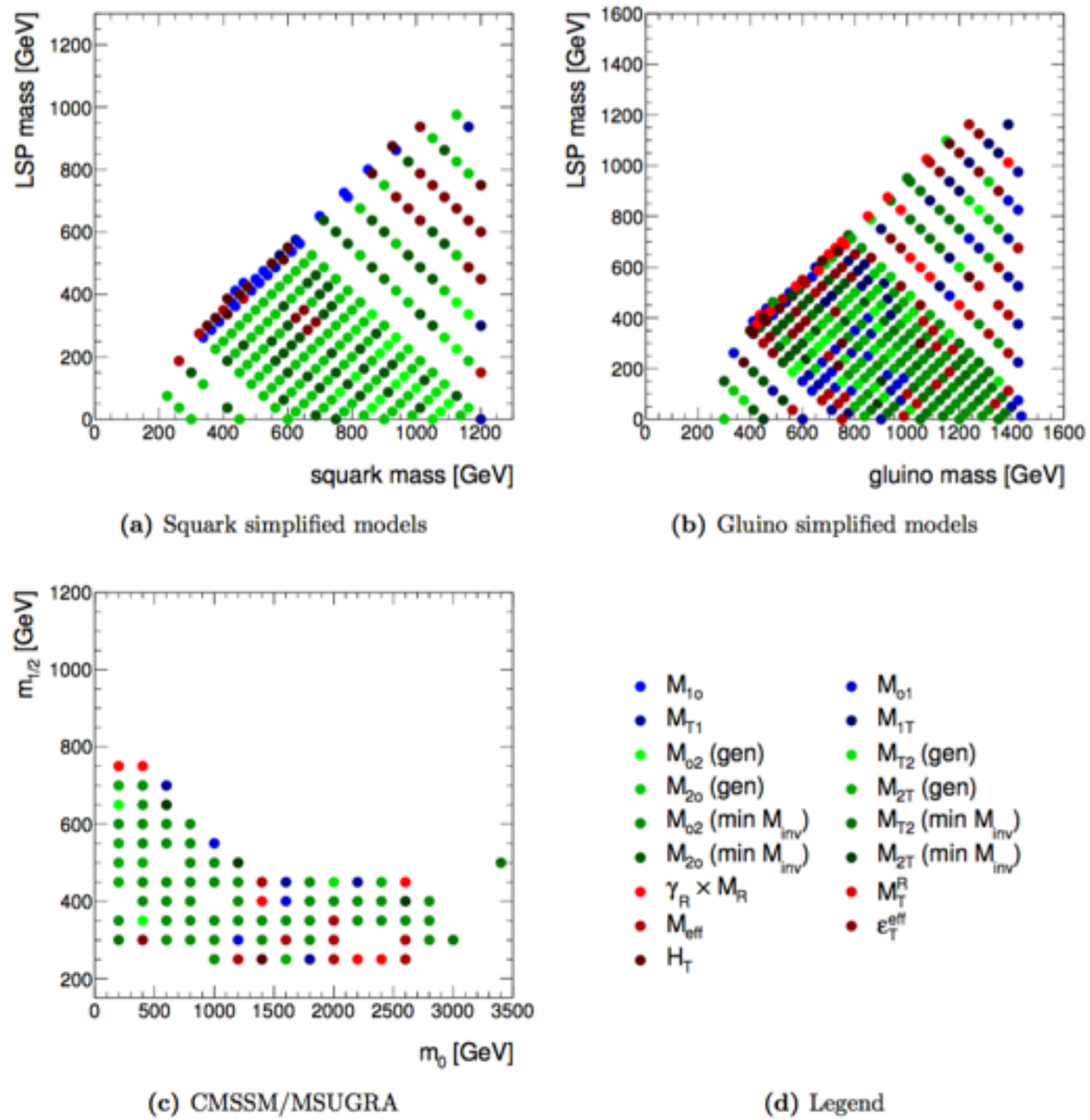


- Original motivation for MT2 definition:
  Measure masses of supersymmetric particles
- First step: discovery!
- Strongly produced SUSY with R-parity conservation
  Provides dark matter candidate – stable LSP
  Large production cross-sections, low (no) lepton multiplicity



ATLAS
EXPERIMENT
http://atlas.ch

CERN-THESIS-2013-037



(a) Squark simplified models

(b) Gluino simplified models

(c) CMSSM/MSUGRA

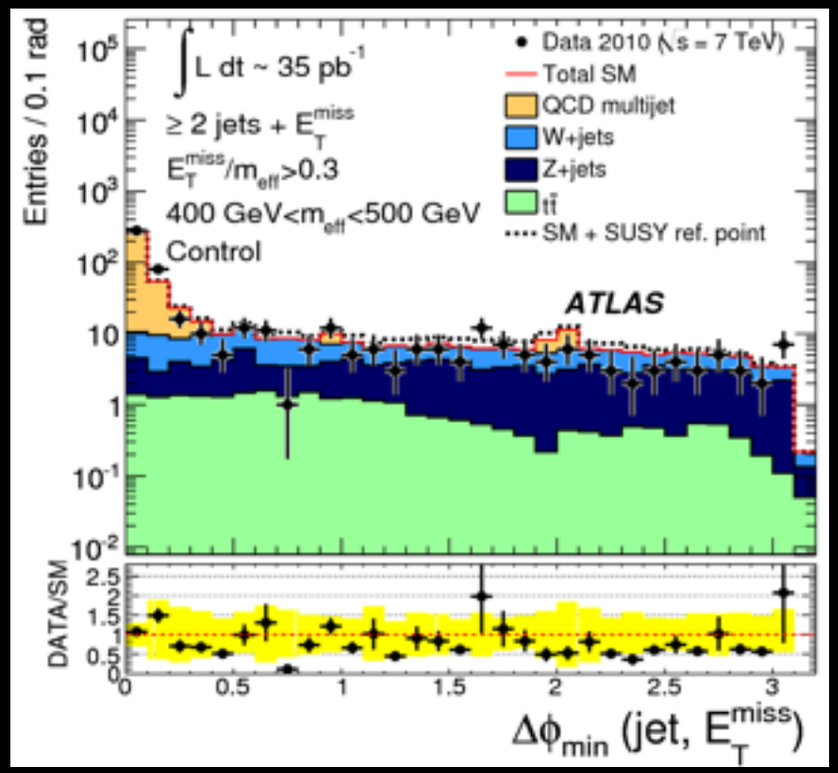
(d) Legend

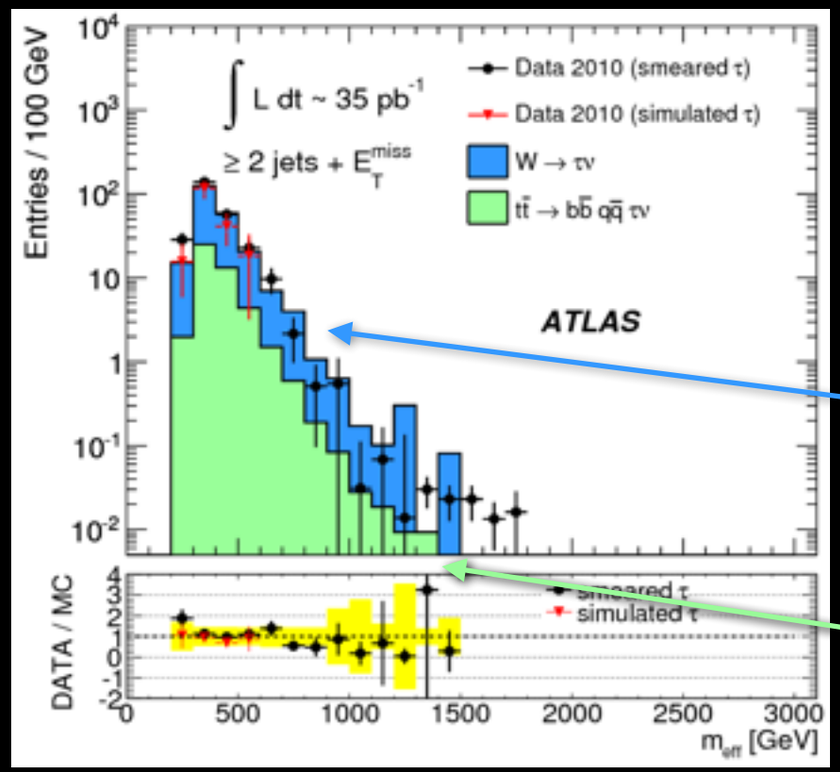
Figure 2.24: Preferred mass-like variables at each model point, having specified the p_T^{miss}-like variable to be M_T^R for the squark simplified models, M_{1o} for the gluino simplified models, and p_T^{miss} for the CMSSM models, based on the preference for p_T^{miss}-like variables identified in Figure 2.21. Classes of similar variables are distinguished by colour: blue labels the single-parent mass-bound variables; green labels the two-parent mass-bound variables; and red labels the variables that are not mass bounds.

0-LEPTON SEARCHES

- Dominant backgrounds by cross-section:
  - Multijet production – eliminate with cuts on mismeasured MET
  - $W_{\ell\nu}$+jets, top pairs – veto leptons, control regions
  - $Z_{\nu\nu}$+jets – irreducible, estimate with photon and leptonic control regions

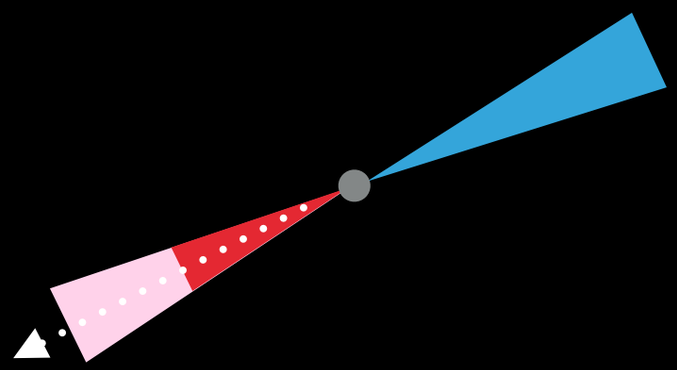
PLB 701 (2011) 186





B-jet requirement

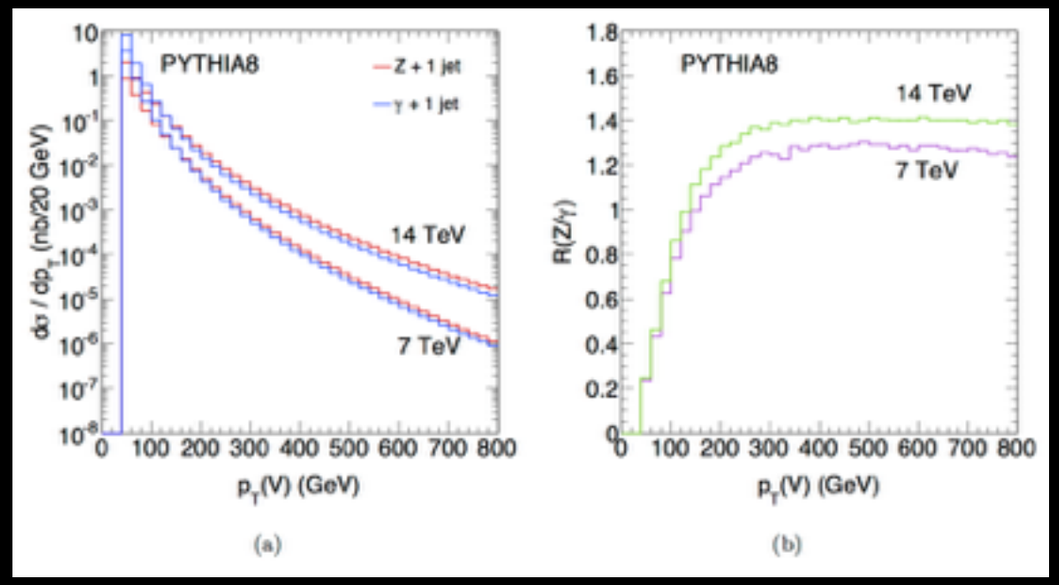
B-jet requirement



Mismeasured jets produce fake MET

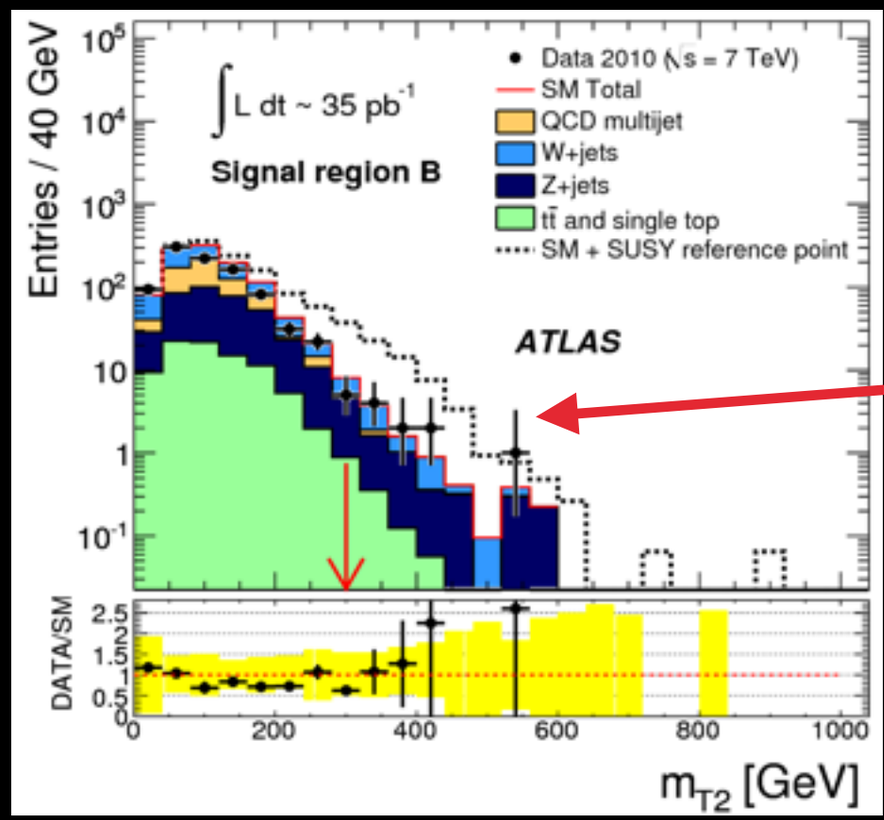
Estimate response and smear well-measured events

Ask, Parker, Sandoval, Shea, Stirling, JHEP 1110 (2011) 058

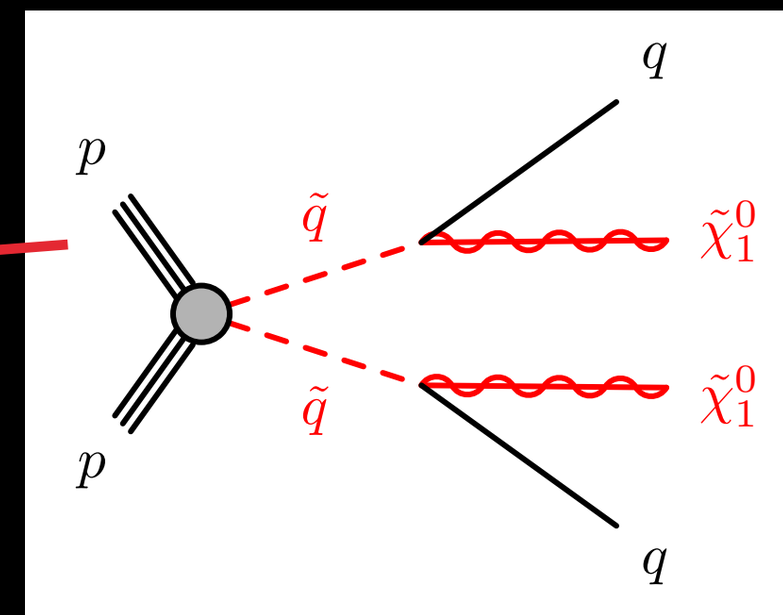


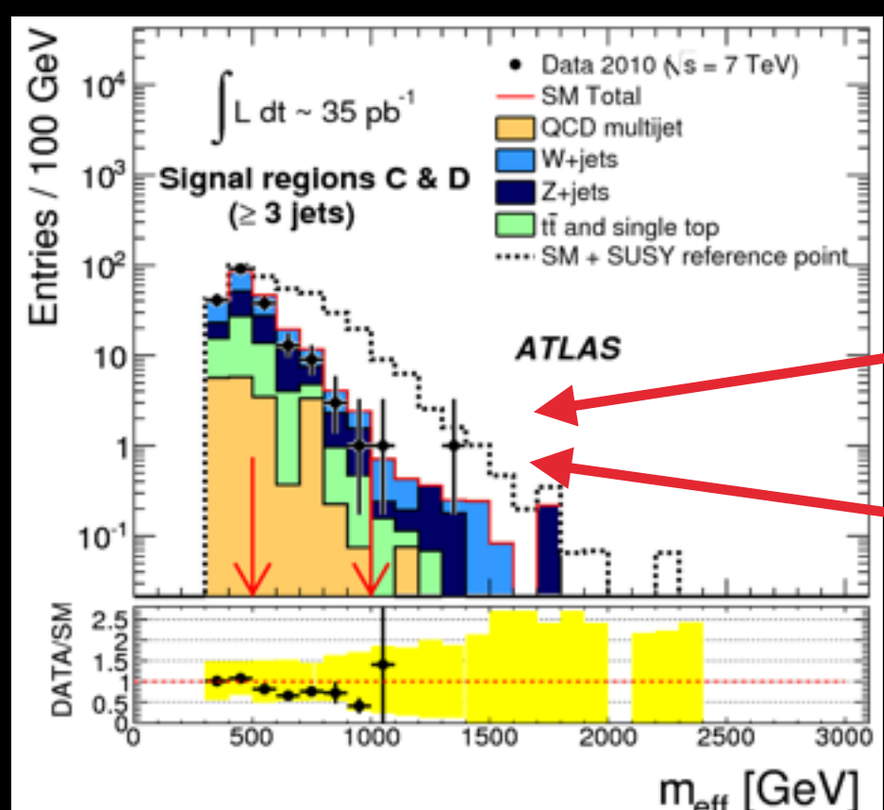
$$R_{Z_{\nu\nu}/\gamma} = \mathrm{BR}_{Z\to\nu\nu}\frac{\partial\sigma_Z/\partial p_\mathrm{T}}{\partial\sigma_\gamma/\partial p_\mathrm{T}}$$

PLB 701 (2011) 186

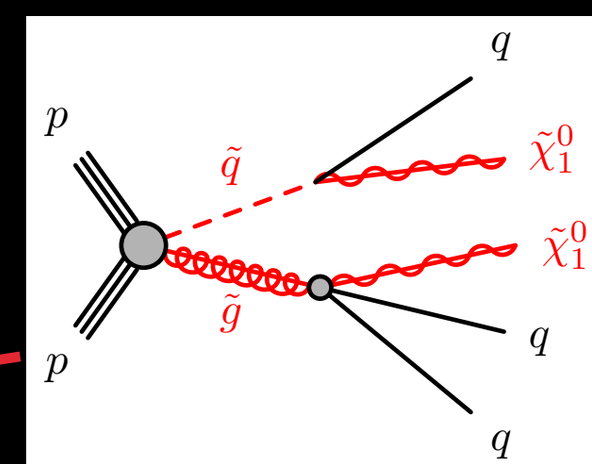


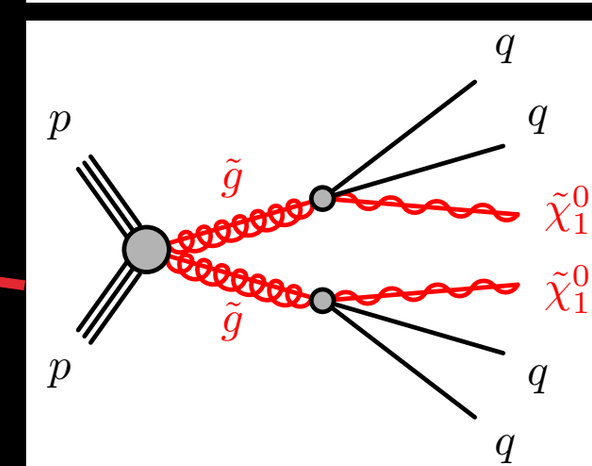
Signal-specific



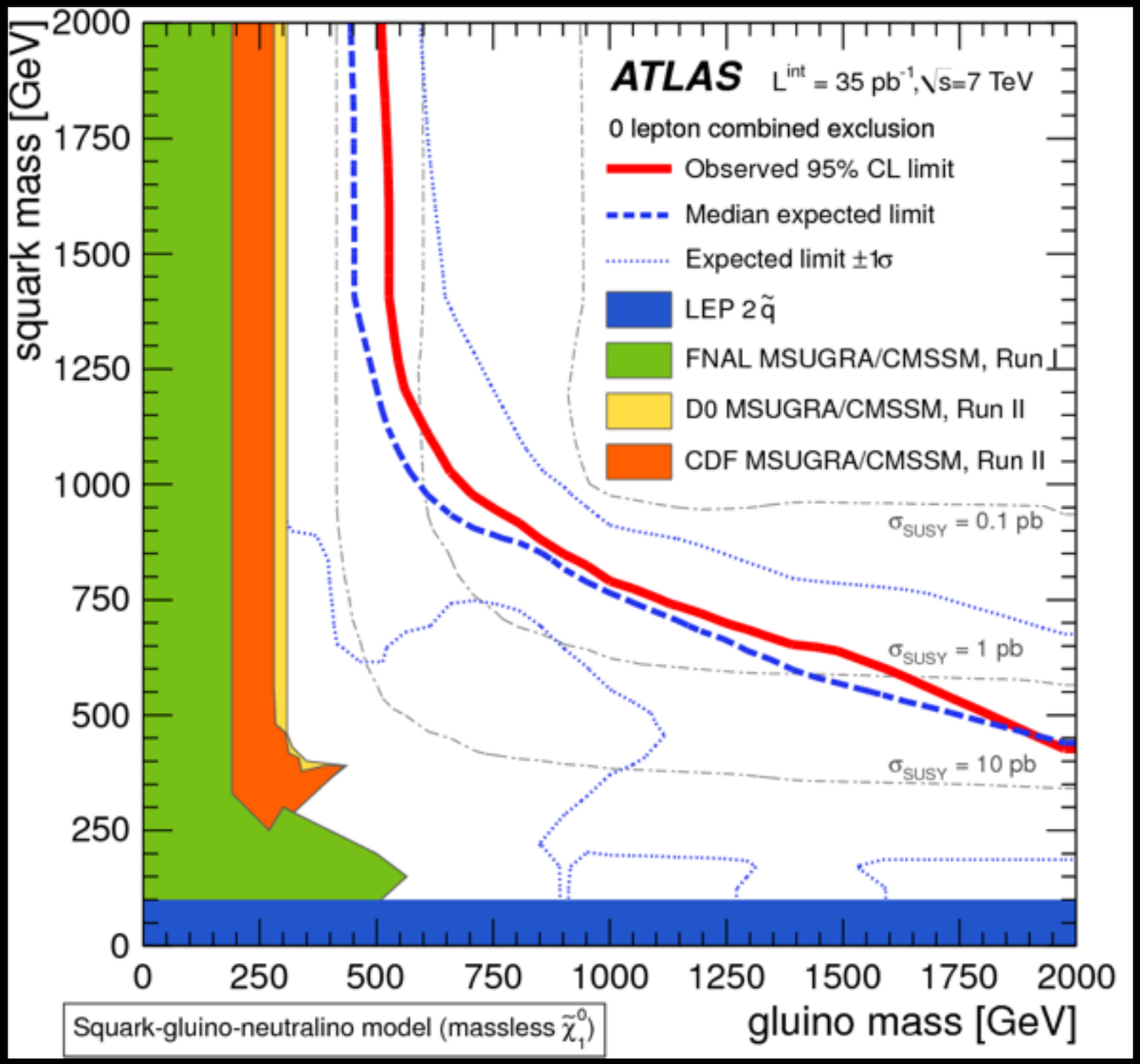


More generic

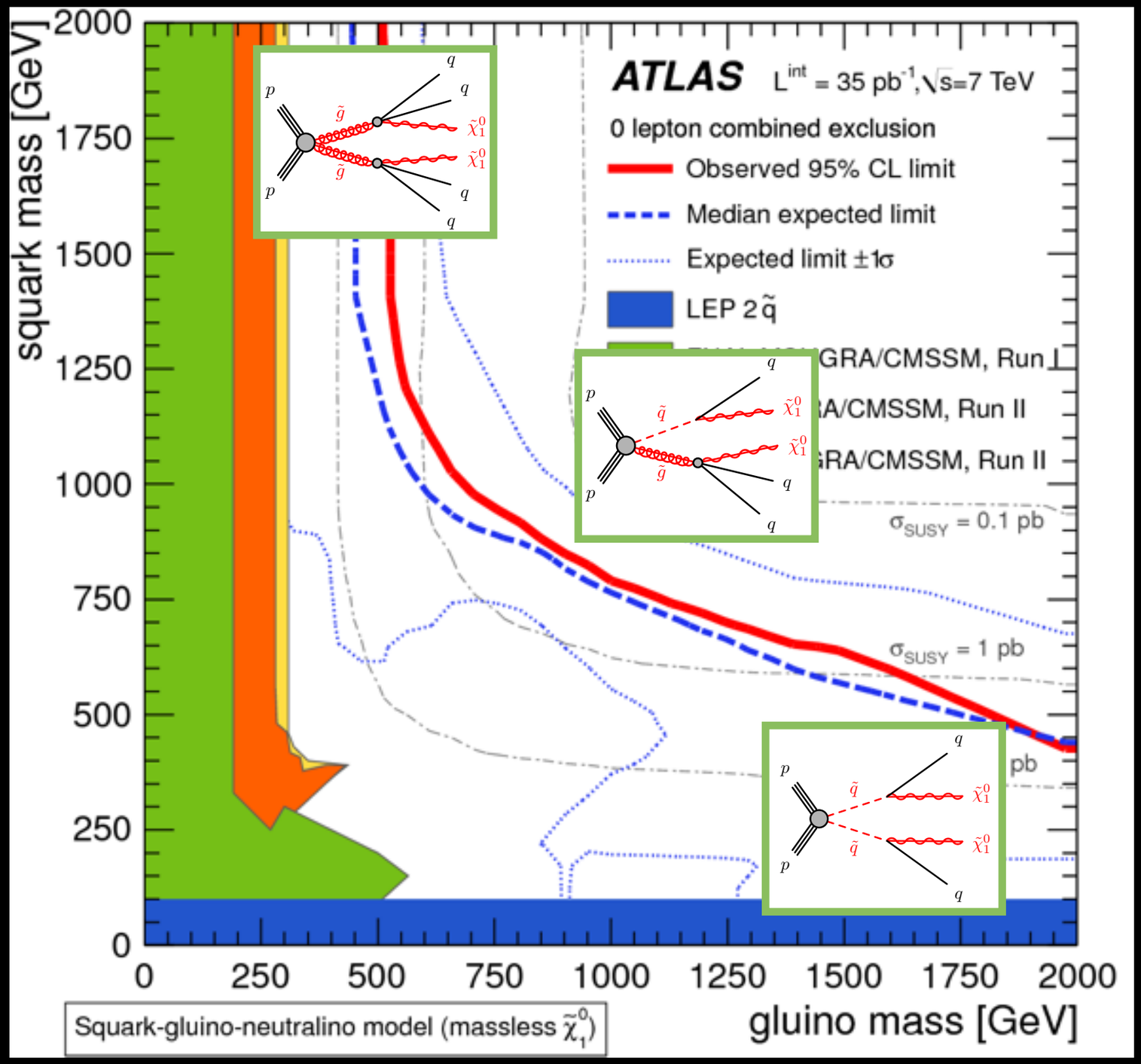




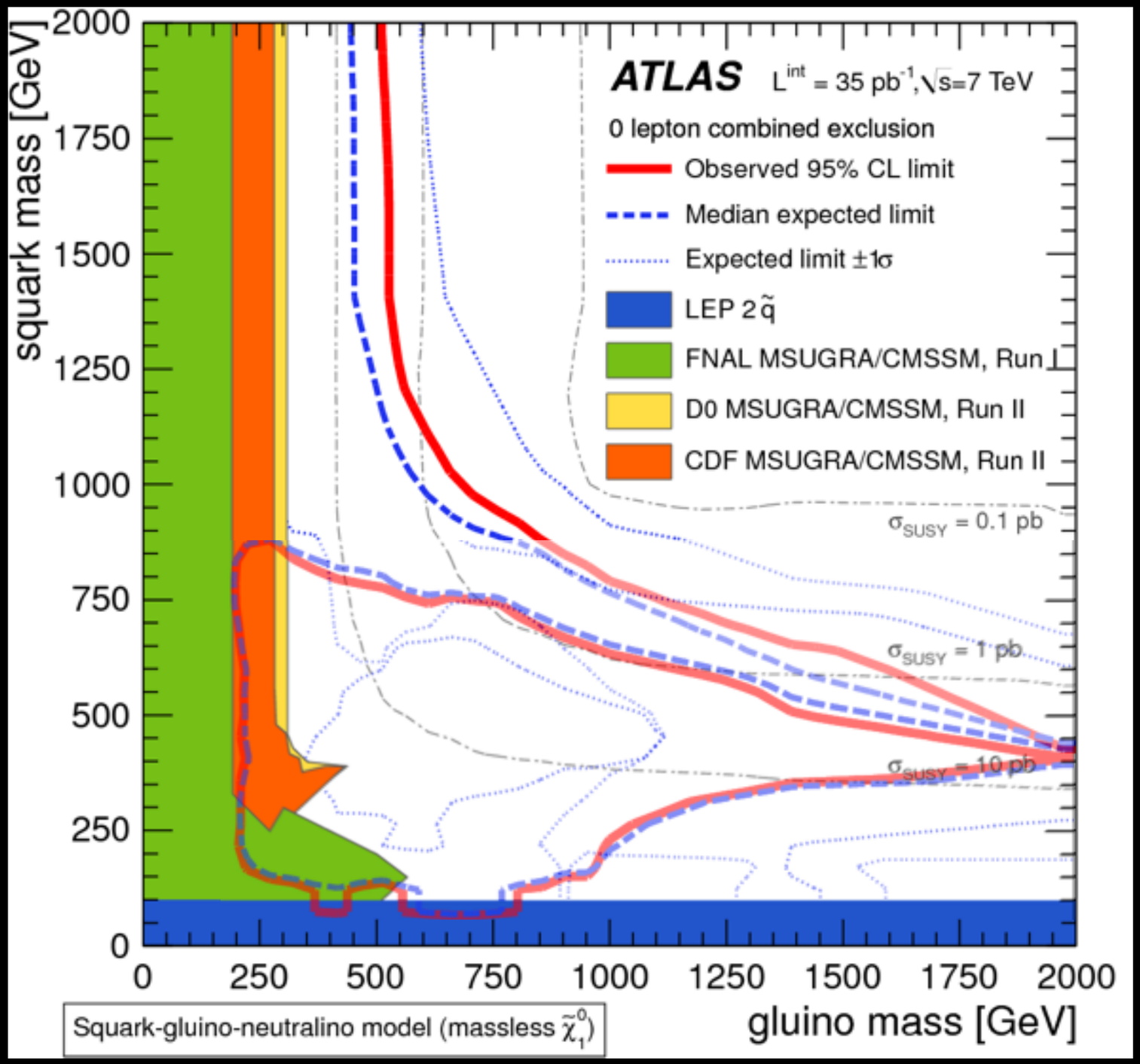
PLB 701 (2011) 186

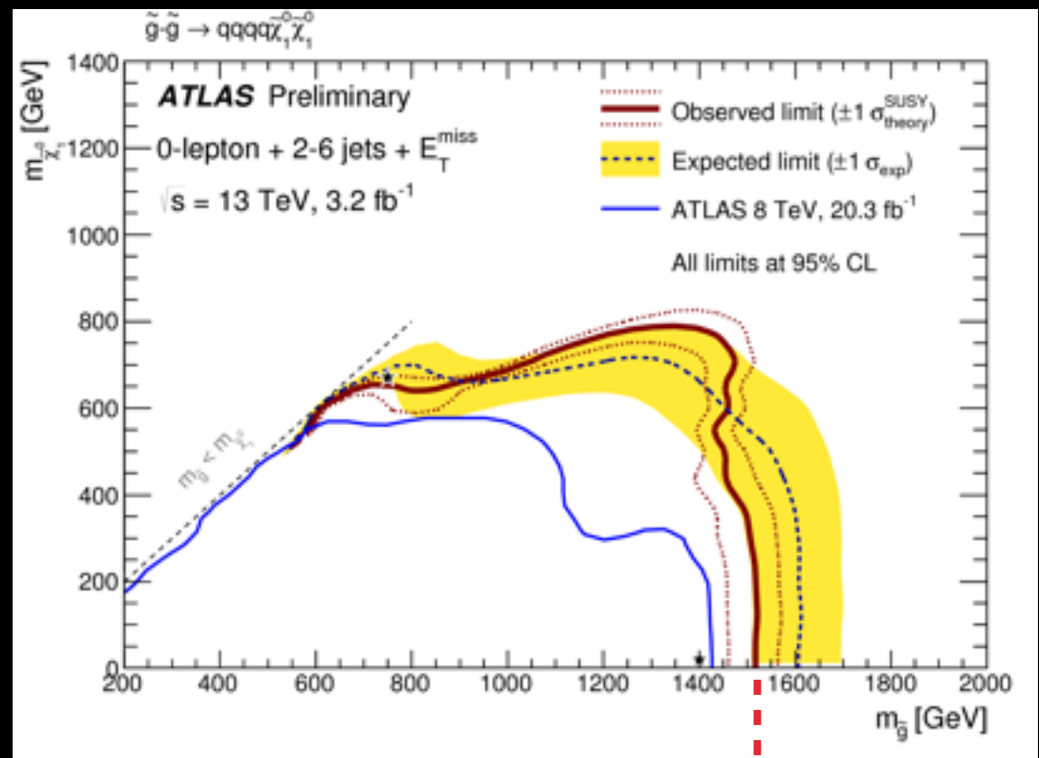


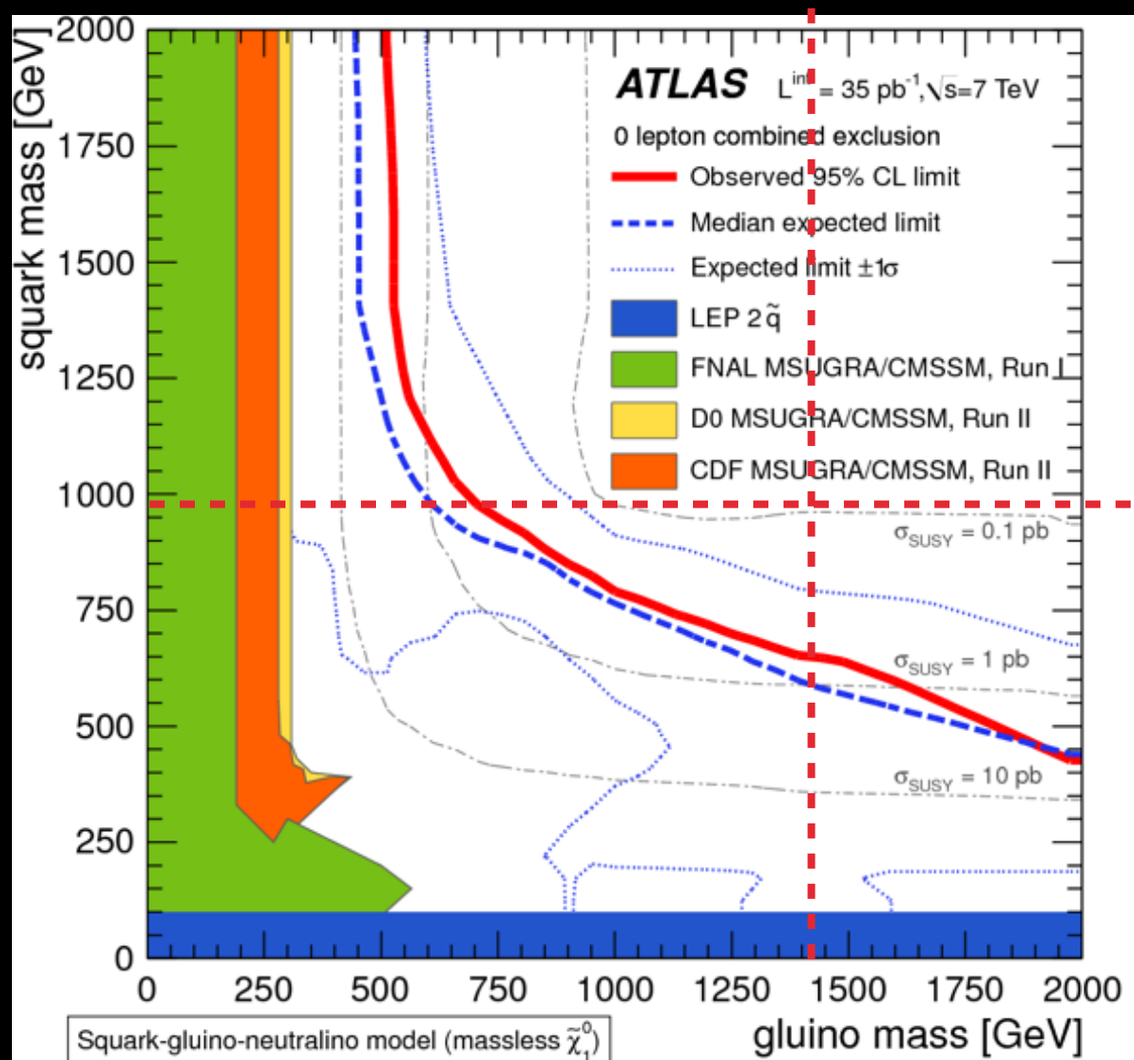
PLB 701 (2011) 186

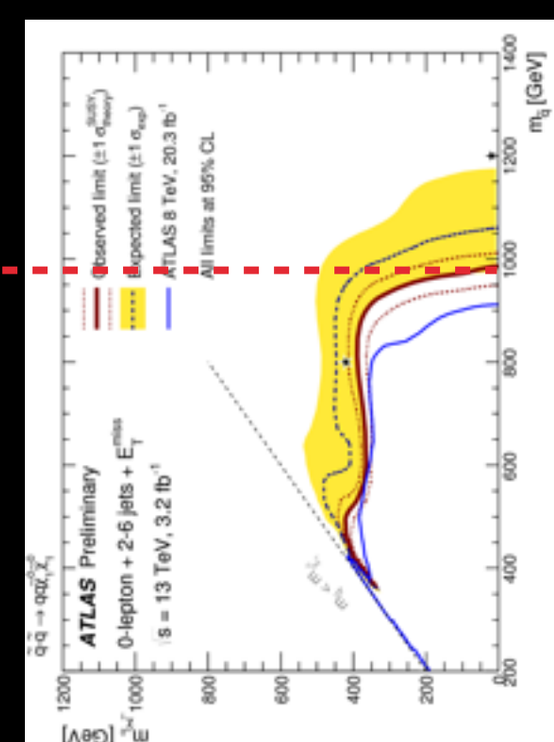


PLB 701 (2011) 186









PLB 701 (2011) 186

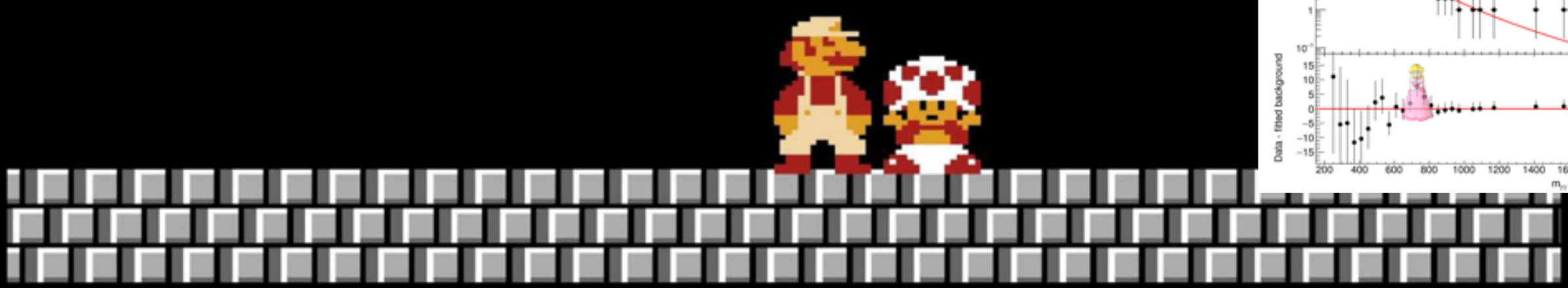
13 TeV

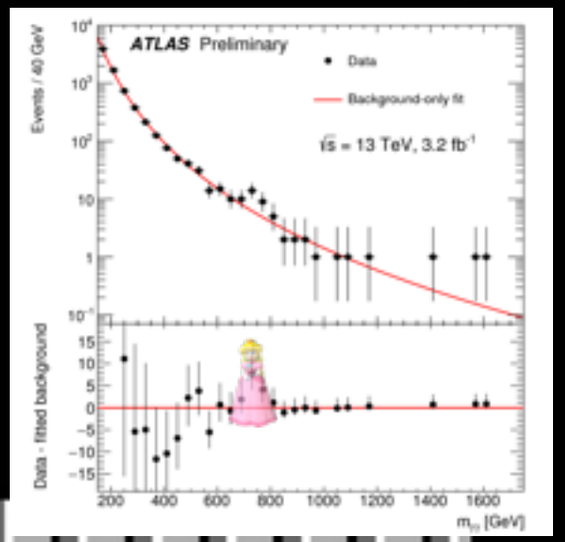
ATLAS-CONF-2015-062

THANK YOU MARIO!

BUT OUR PRINCESS IS IN

ANOTHER CHANNEL!





BONUS MATERIAL (IF TIME)

CERN-THESIS-2013-037

HOW WELL COULD WE WEIGH SUSY?

- Neutralino LSP probably massive. Observed mass will need correction for mass difference.

$$M_{\mathrm{SUSY}}^{\mathrm{corr}} = \frac{M_{\mathrm{SUSY}}^2 - M_{\mathrm{LSP}}^2}{M_{\mathrm{SUSY}}}, \quad \text{where}$$

$$M_{\mathrm{SUSY}} = \sum_{p \text{ in sparticles}} M_p \cdot \frac{\sigma_p}{\sigma_{\mathrm{tot}}},$$

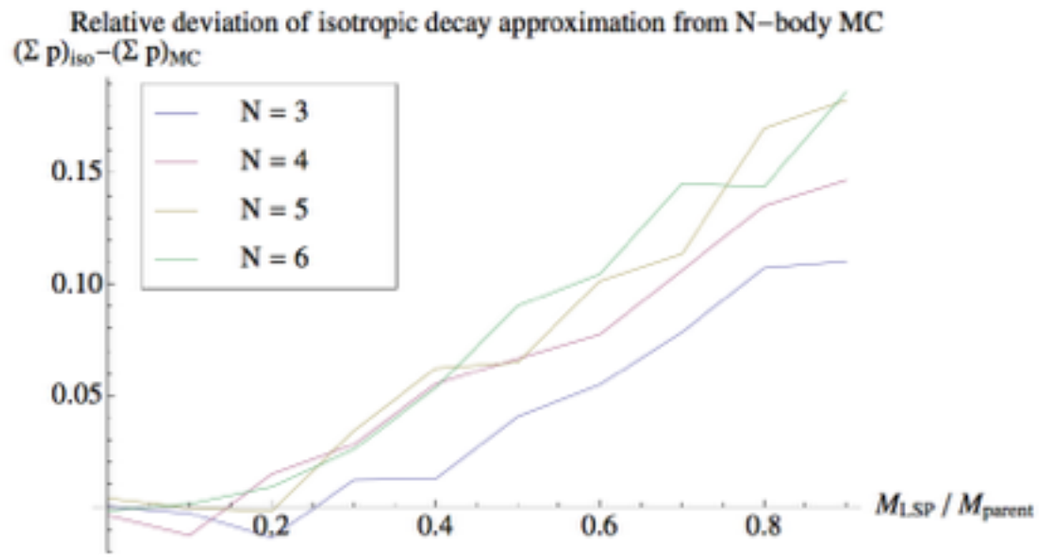
2-body decay expression,

Tovey, JHEP 0804 (2008) 034

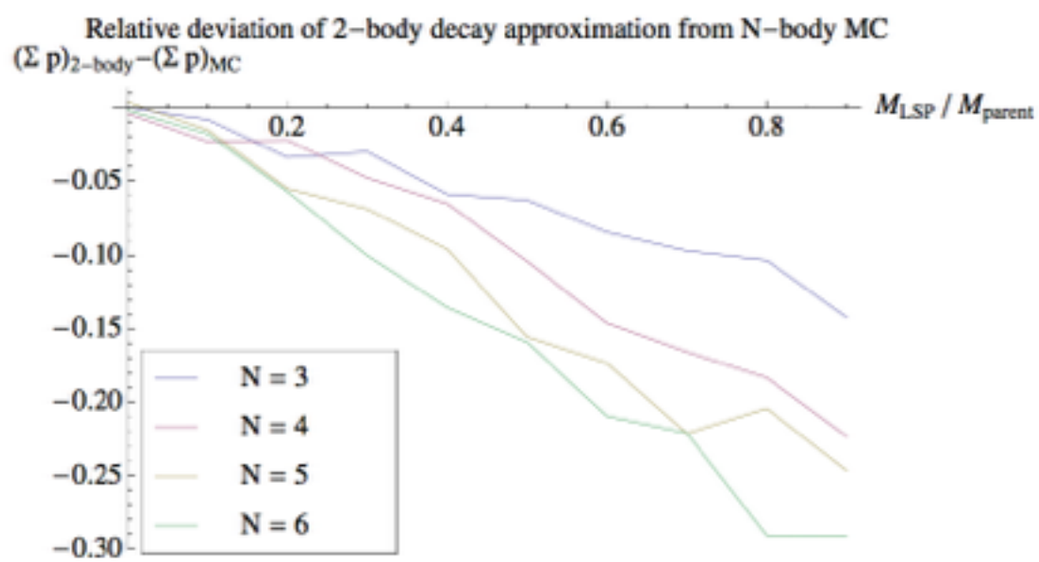
- Extend to N-body decay by assuming isotropic decay angles in a plane.

$$M_{\mathrm{SUSY}}^{\mathrm{corr}} = \frac{(N-1)M_{\mathrm{SUSY}} - \sqrt{M_{\mathrm{SUSY}}^2 + (N^2 - 2N)M_{\mathrm{LSP}}^2}}{N-2}.$$

CERN-THESIS-2013-037



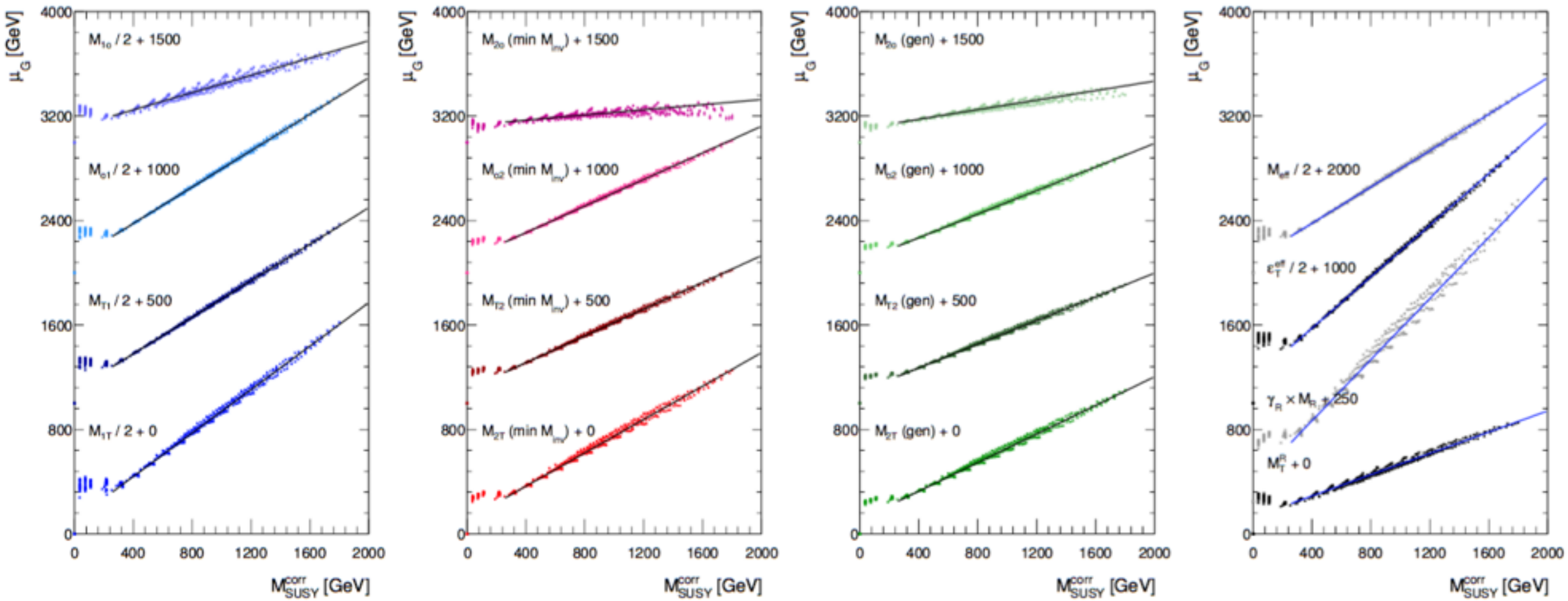
(a) Isotropic decay



(b) 2-body decay

Figure 2: Relative deviations between the isotropic decay and 2-body decay approximations to N-body Lorentz-invariant phase space MC, corresponding to $N = 3 - 6$ in Figure 3. The cases $N = 7, 8$ are omitted to aid distinguishability of the displayed curves, but obey the same trend.

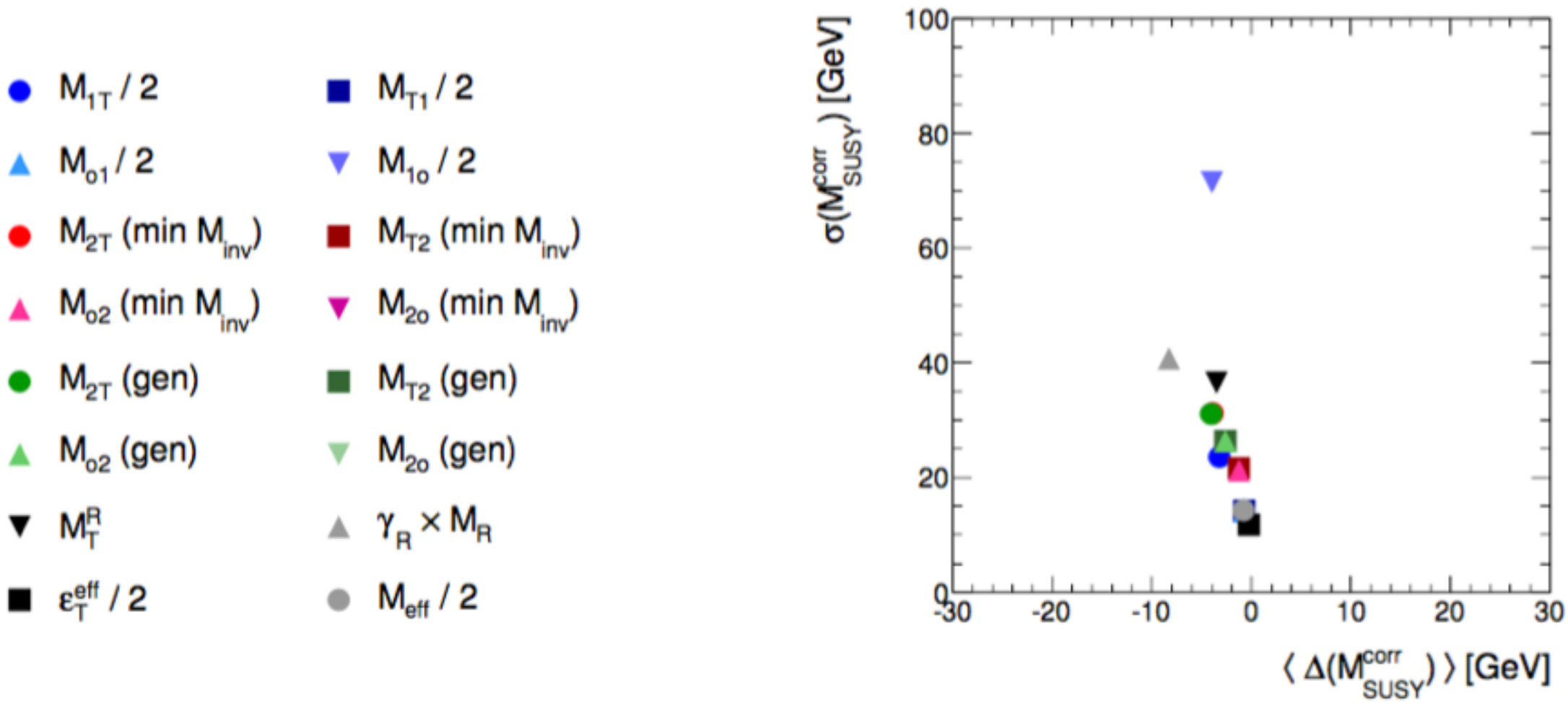
CERN-THESIS-2013-037



(a) 1-parent **(b)** 2-parent ($M_{\text{min}}^{\text{hemi}}$ association) **(c)** 2-parent ($m_{T\text{gen}}$ association) **(d)** Alternative mass variables

Figure 2.6: Fits to correlation plots of the peak position to the effective SUSY mass scale $M_{\text{SUSY}}^{\text{corr}}$, for a range of mass variables, in simplified models with only gluino production and decays to jets and neutralinos. The subfigures show: (a) single-parent mass bounds; (b) two-parent mass bounds, with jets partitioned into a pair of collections such that the sum of the invariant masses of the two collections is minimised; (c) two-parent mass bounds, with jets partitioned such that the value of the mass bound is minimised (i.e. using the $m_{T\text{gen}}$ procedure); (d) alternative mass variables not based on the transverse bound paradigm. In the case of the Razor variables, jets are partitioned such that the sum of the invariant masses of the two collections is minimised. An arbitrary offset is applied to the points in order to distinguish different variables, as labelled on each plot.

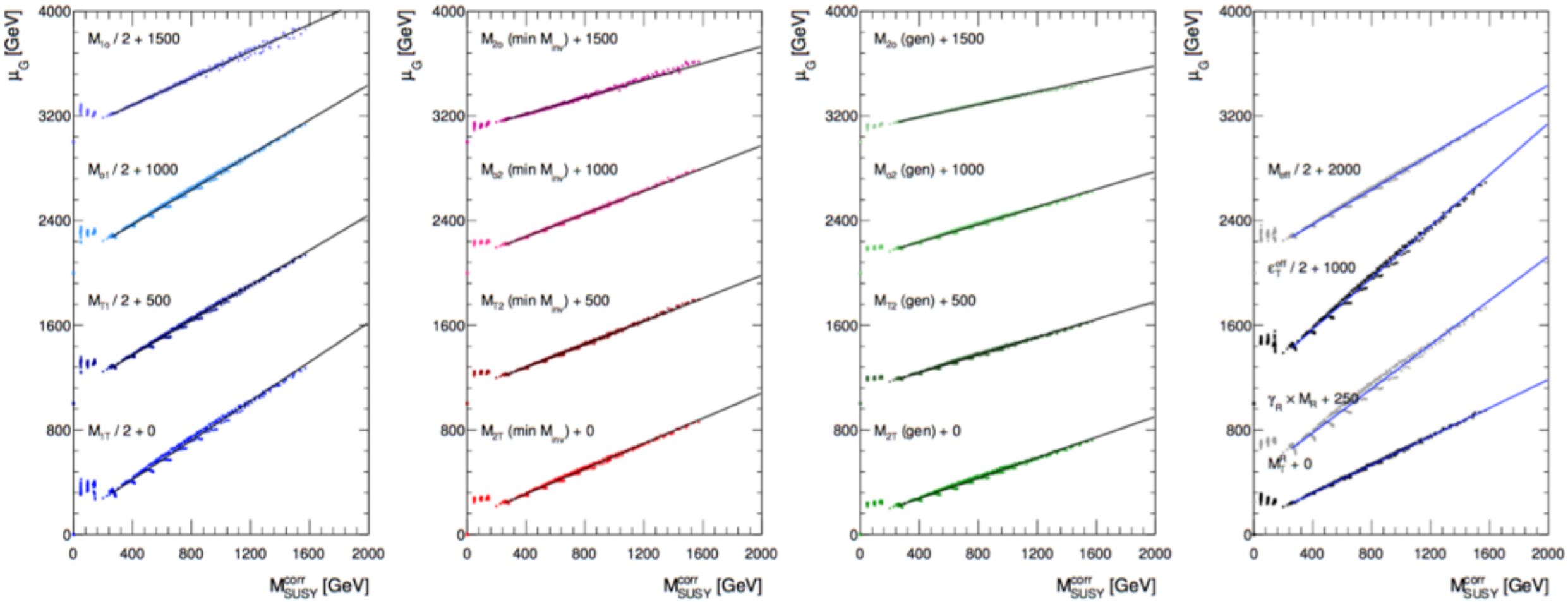
CERN-THESIS-2013-037



(a) Legend (b) Summary plot

Figure 2.7: Summary of the RMS deviations of the estimated and true values of $M_{\mathrm{SUSY}}^{\mathrm{corr}}$ from the linear fits versus the bias in the predictions for all variables, in simplified models with only gluino production and decays to jets and neutralinos.

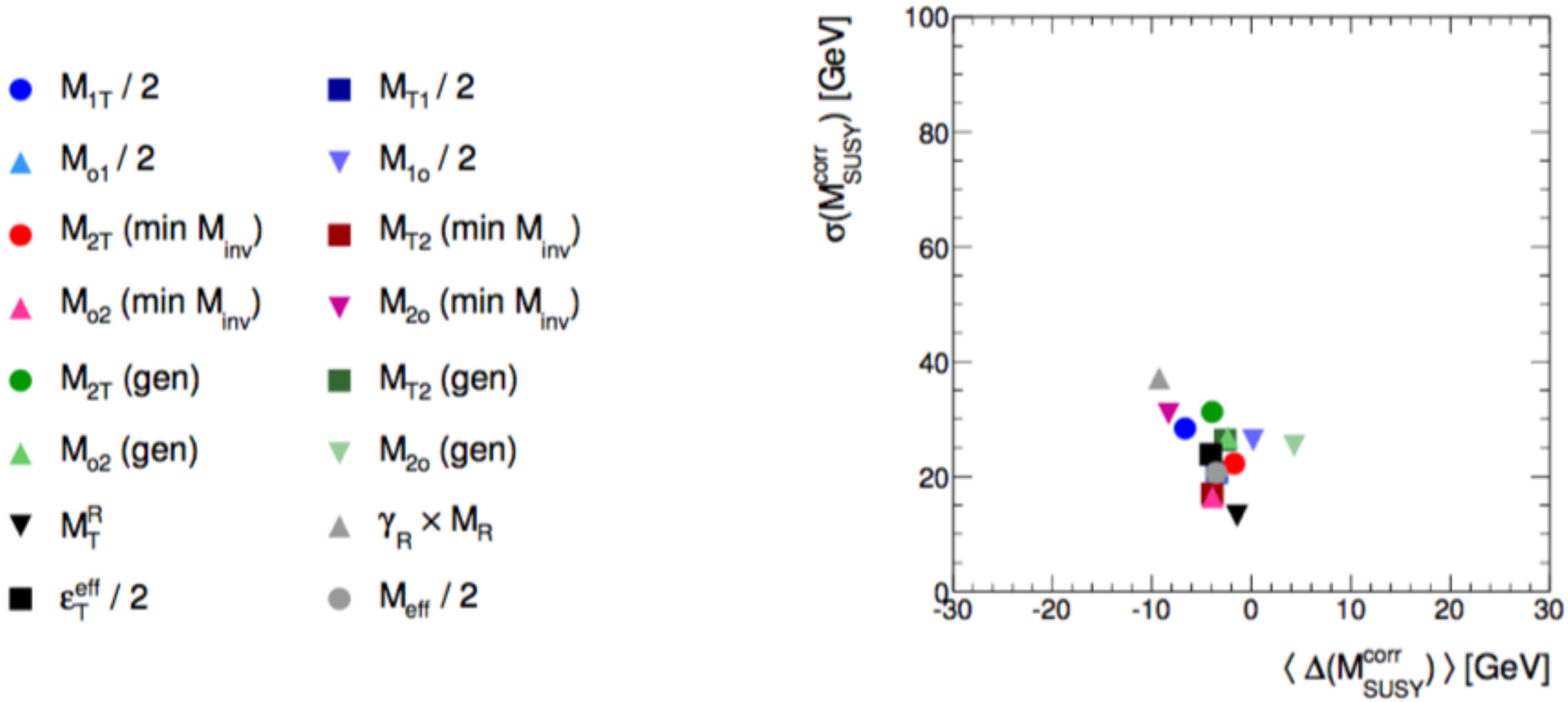
CERN-THESIS-2013-037



(a) 1-parent **(b)** 2-parent ($M_{\mathrm{min}}^{\mathrm{hemi}}$ association) **(c)** 2-parent ($m_{T\mathrm{gen}}$ association) **(d)** Alternative mass variables

Figure 2.4: Fits to correlation plots of the peak position to the corrected SUSY mass scale $M_{\mathrm{SUSY}}^{\mathrm{corr}}$, for a range of mass variables, in simplified models with only squark production and decays to jets and neutralinos. The subfigures show: (a) single-parent mass bounds; (b) two-parent mass bounds, with jets partitioned into a pair of collections such that the sum of the invariant masses of the two collections is minimised; (c) two-parent mass bounds, with jets partitioned such that the value of the mass bound is minimised (i.e. using the $m_{T\mathrm{gen}}$ procedure); (d) alternative mass variables not based on the transverse bound paradigm. In the case of the Razor variables, jets are partitioned such that the sum of the invariant masses of the two collections is minimised. An arbitrary offset is applied to the points in order to distinguish different variables, as labelled on each plot.

CERN-THESIS-2013-037

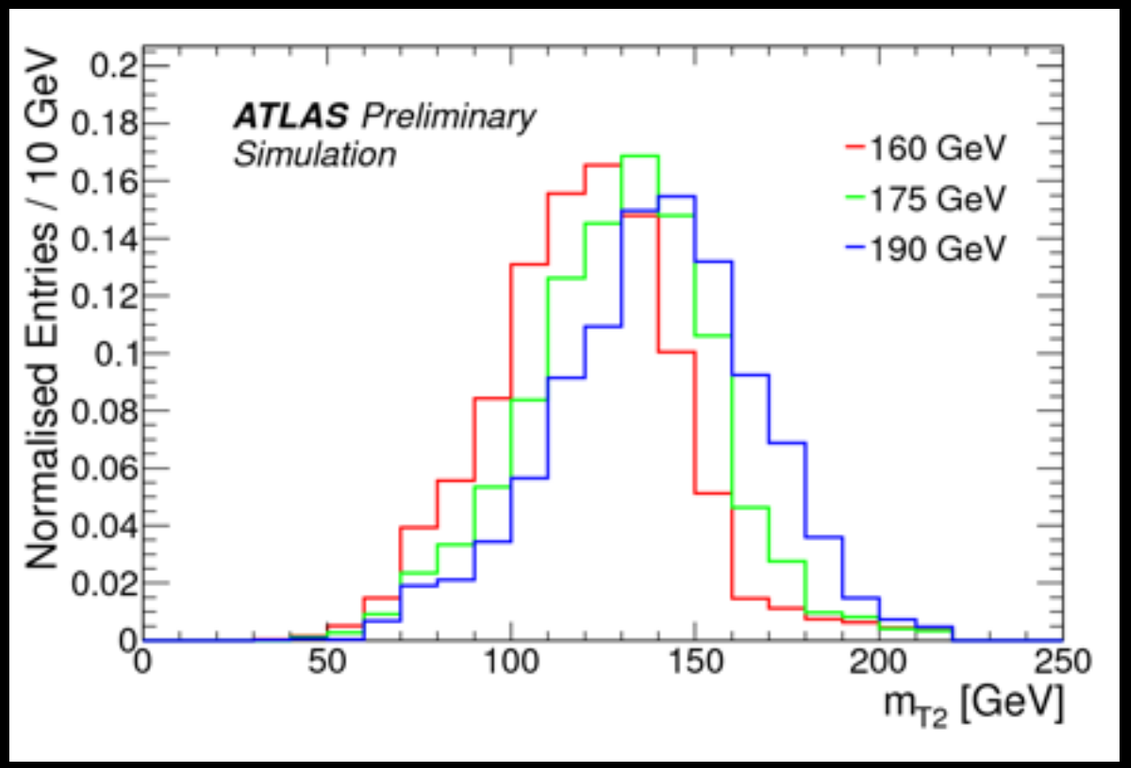


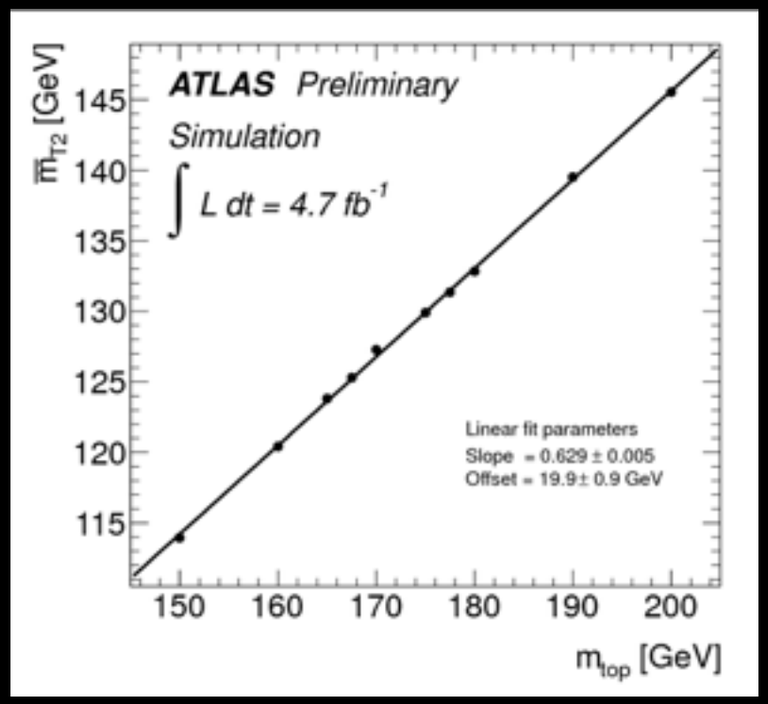
(a) Legend (b) Summary plot

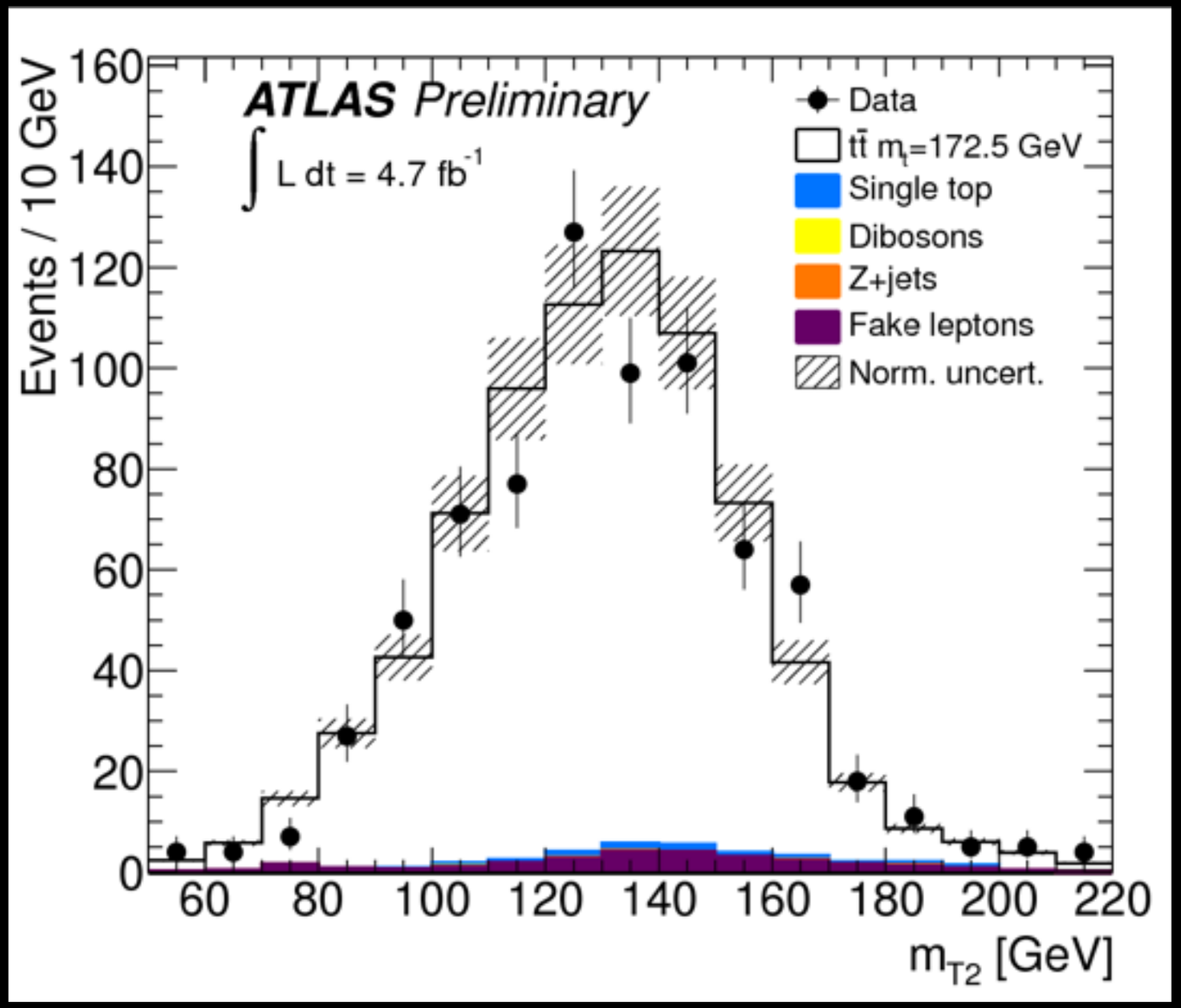
Figure 2.5: Summary of the RMS deviations of the estimated and true values of $M_{\mathrm{SUSY}}^{\mathrm{corr}}$ from the linear fits versus the bias in the predictions for all variables, in simplified models with only squark production and decays to jets and neutralinos.

BACKUPS

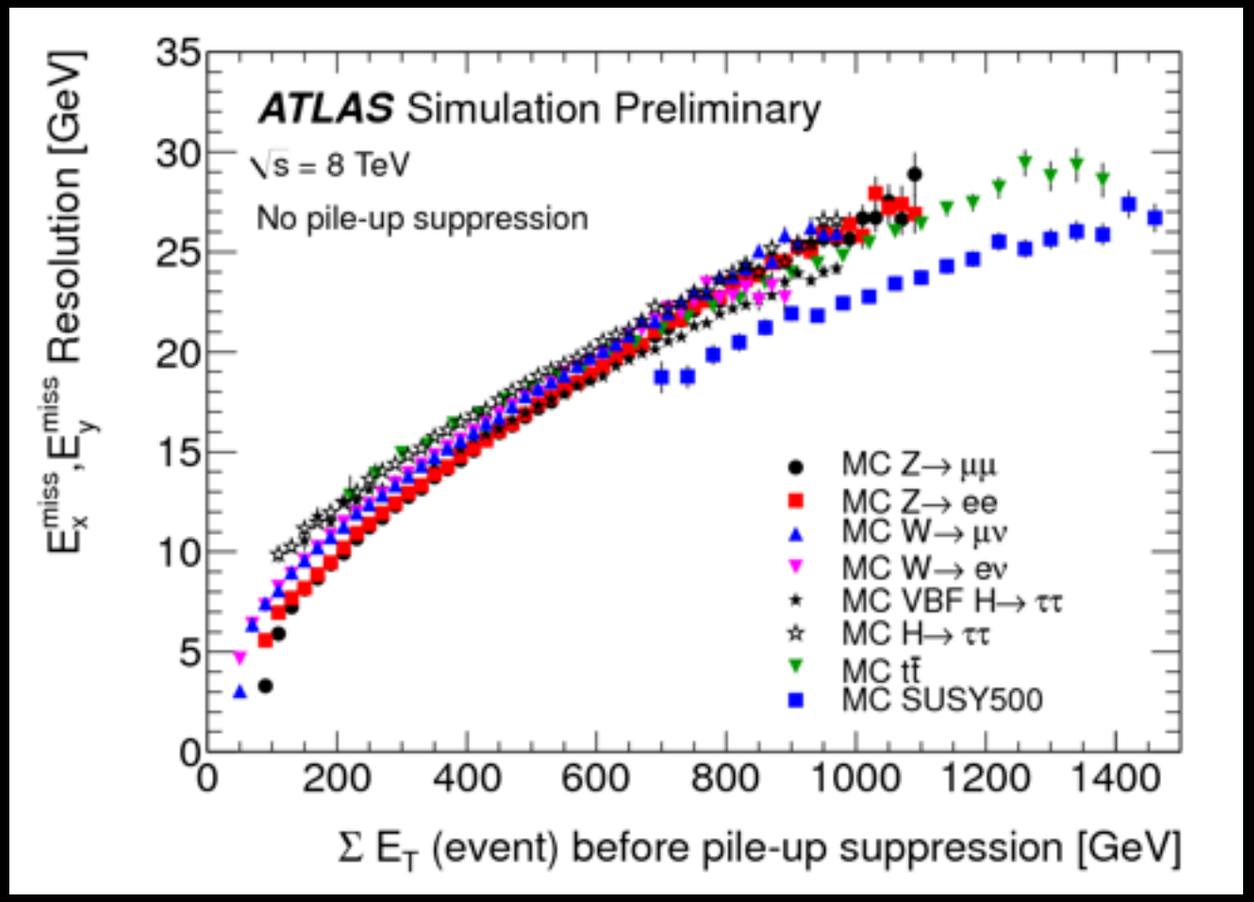
ATLAS-CONF-2012-082

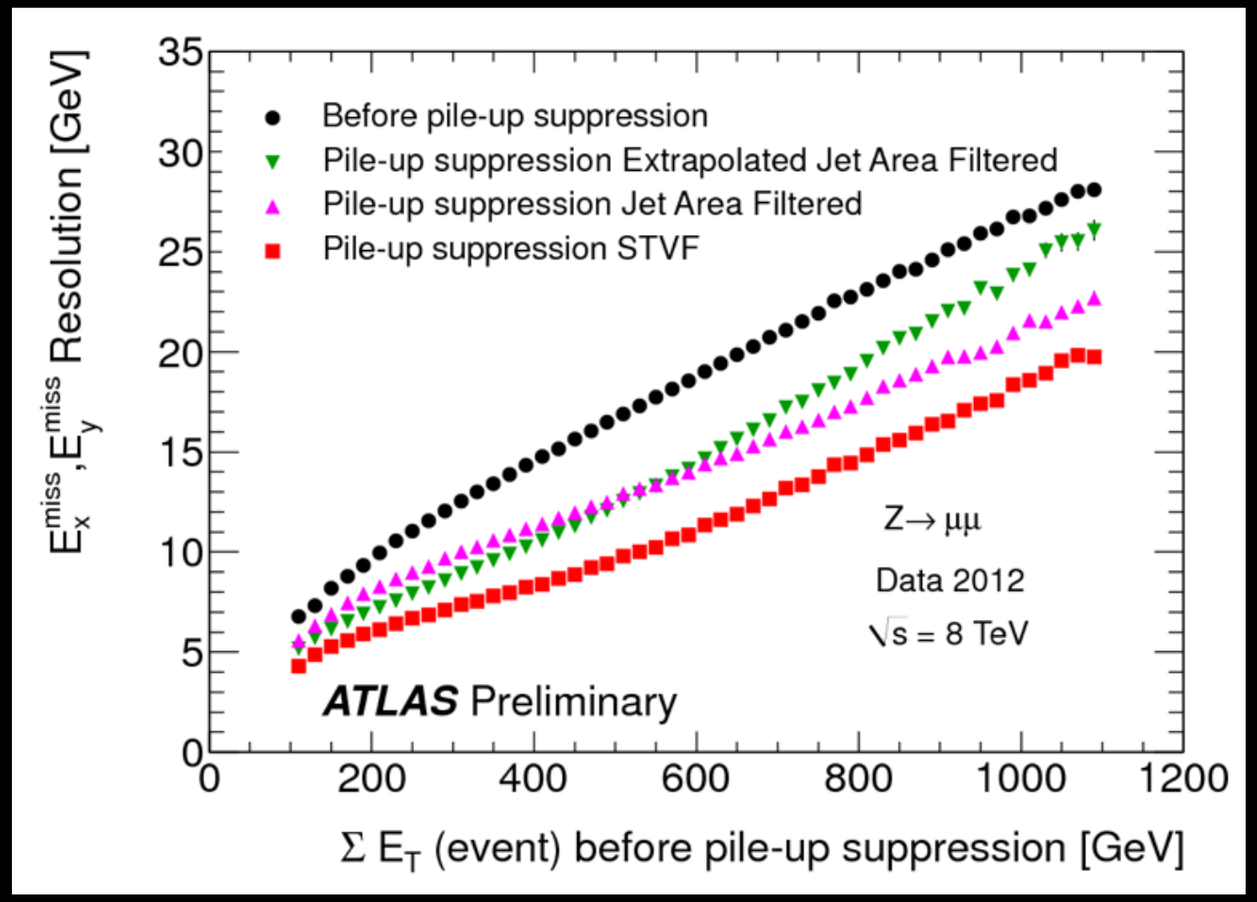






ATLAS-CONF-2013-082

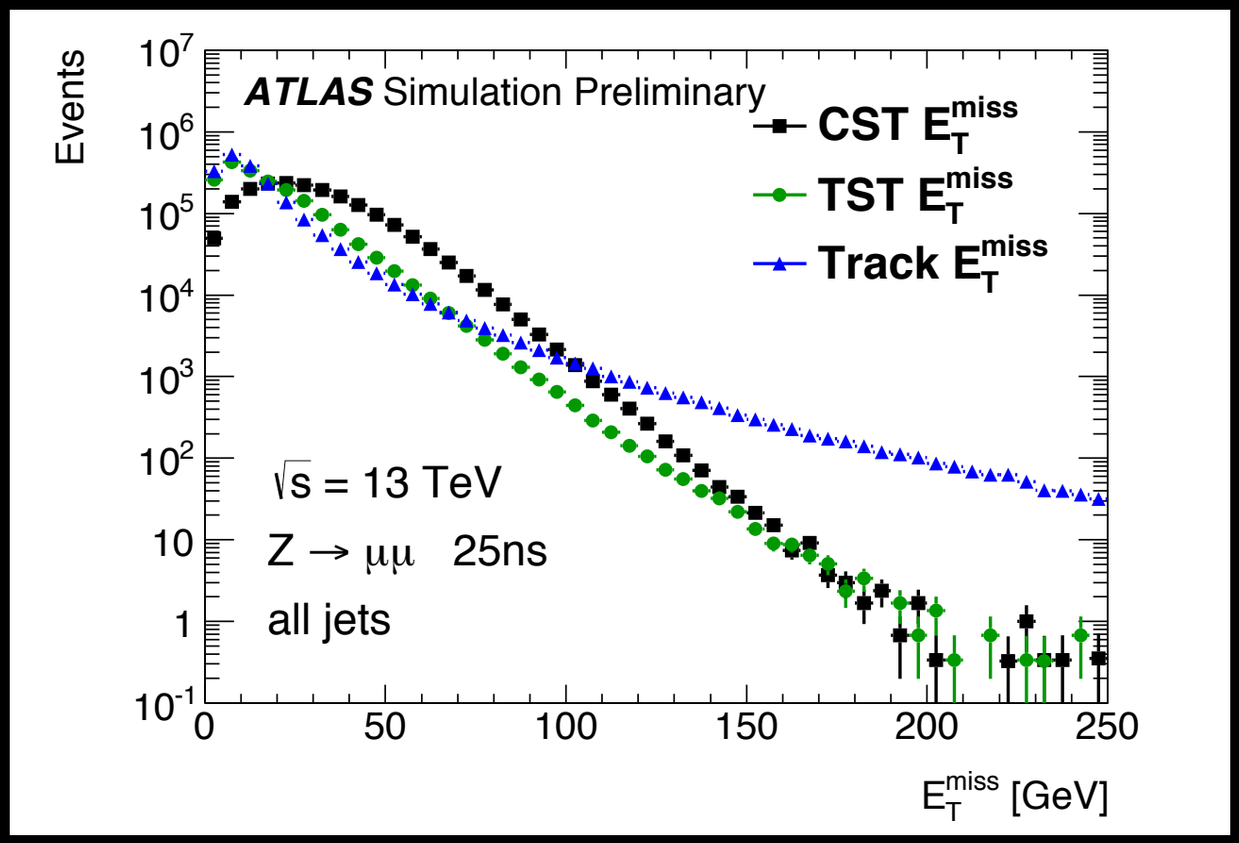


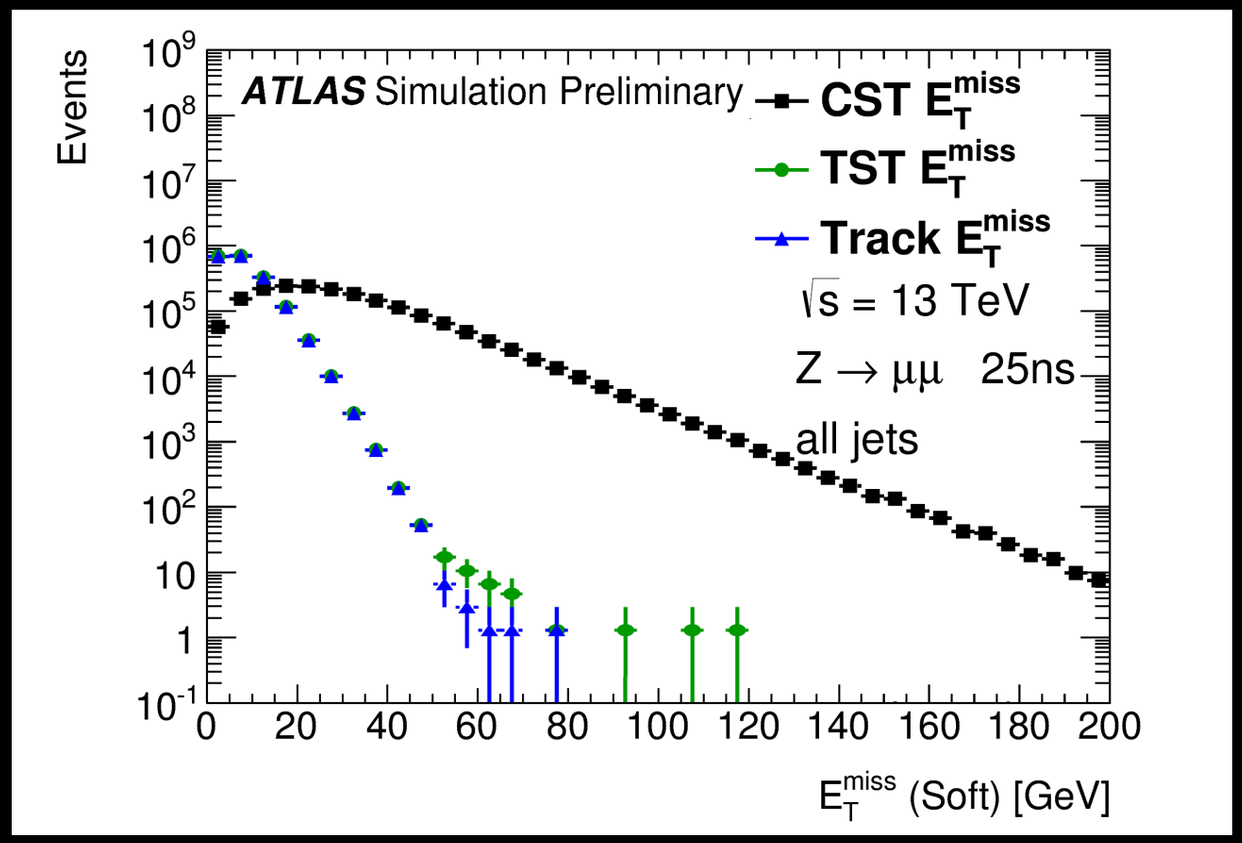


Process-dependent performance
- improve calibrations
- understand limitations

Combat pileup degradation
- refine corrections

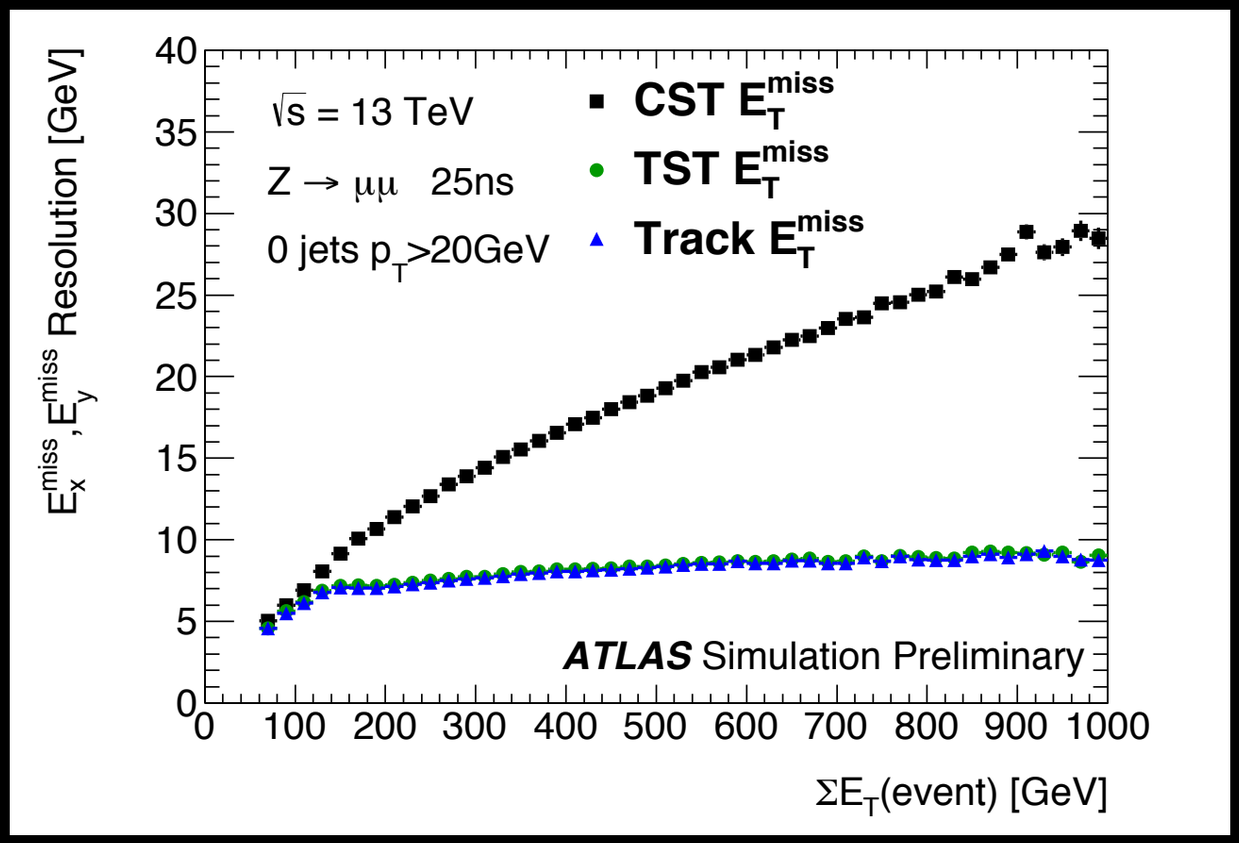
ATLAS-CONF-2013-082

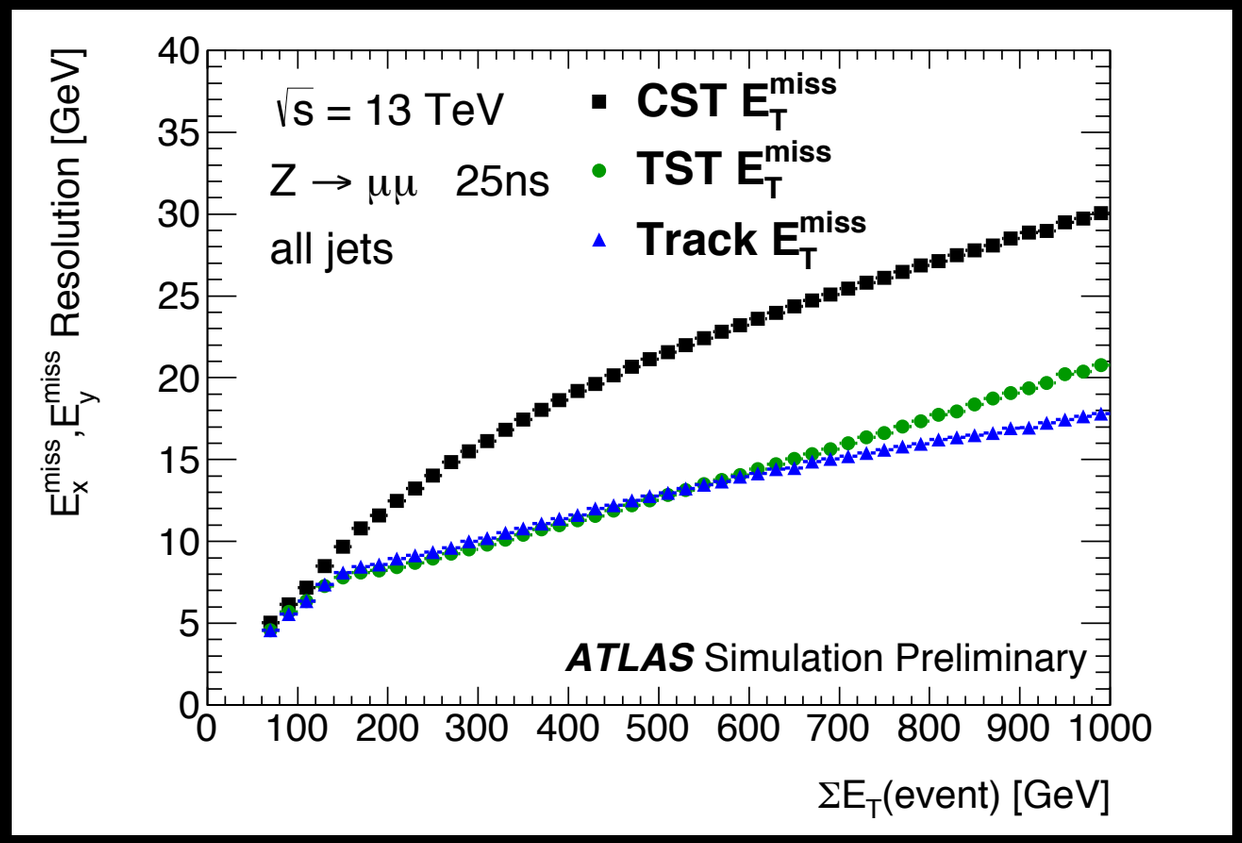




Soft component not negligible
Pileup-sensitivity drives resolutions
Neutral information in energetic jets critical

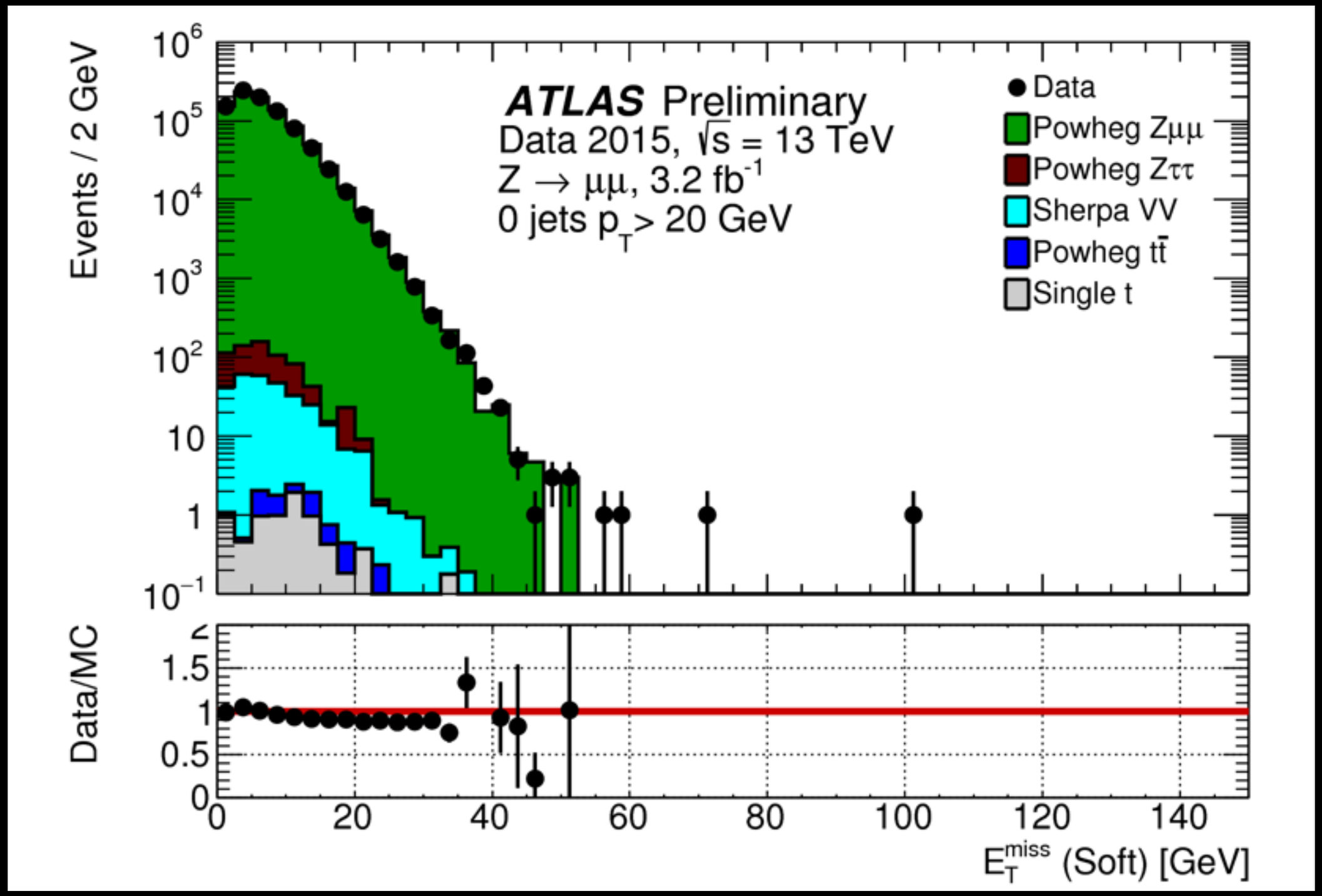
ATLAS-CONF-2013-082



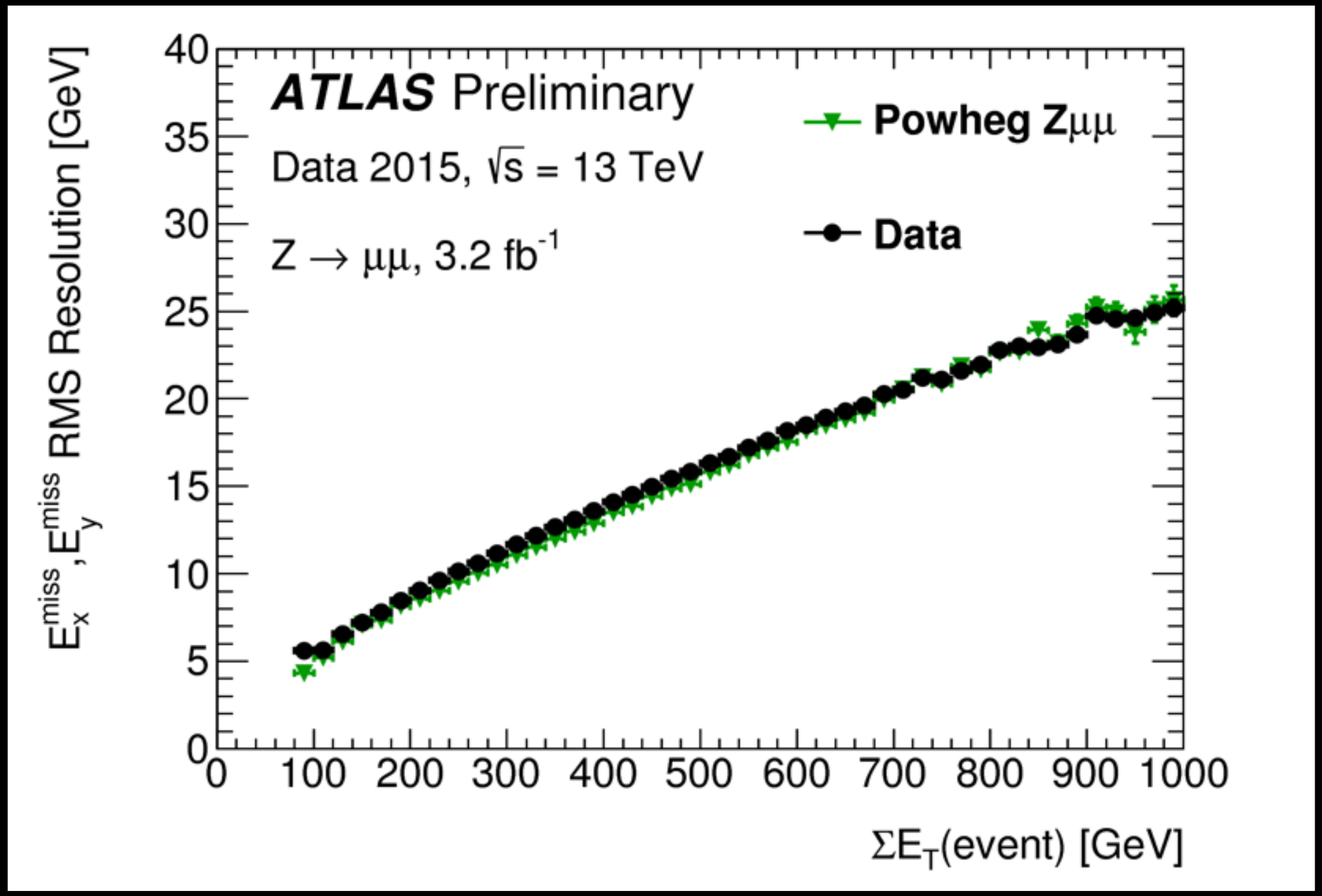


Soft component not negligible
Pileup-sensitivity drives resolutions
Neutral information in energetic jets critical

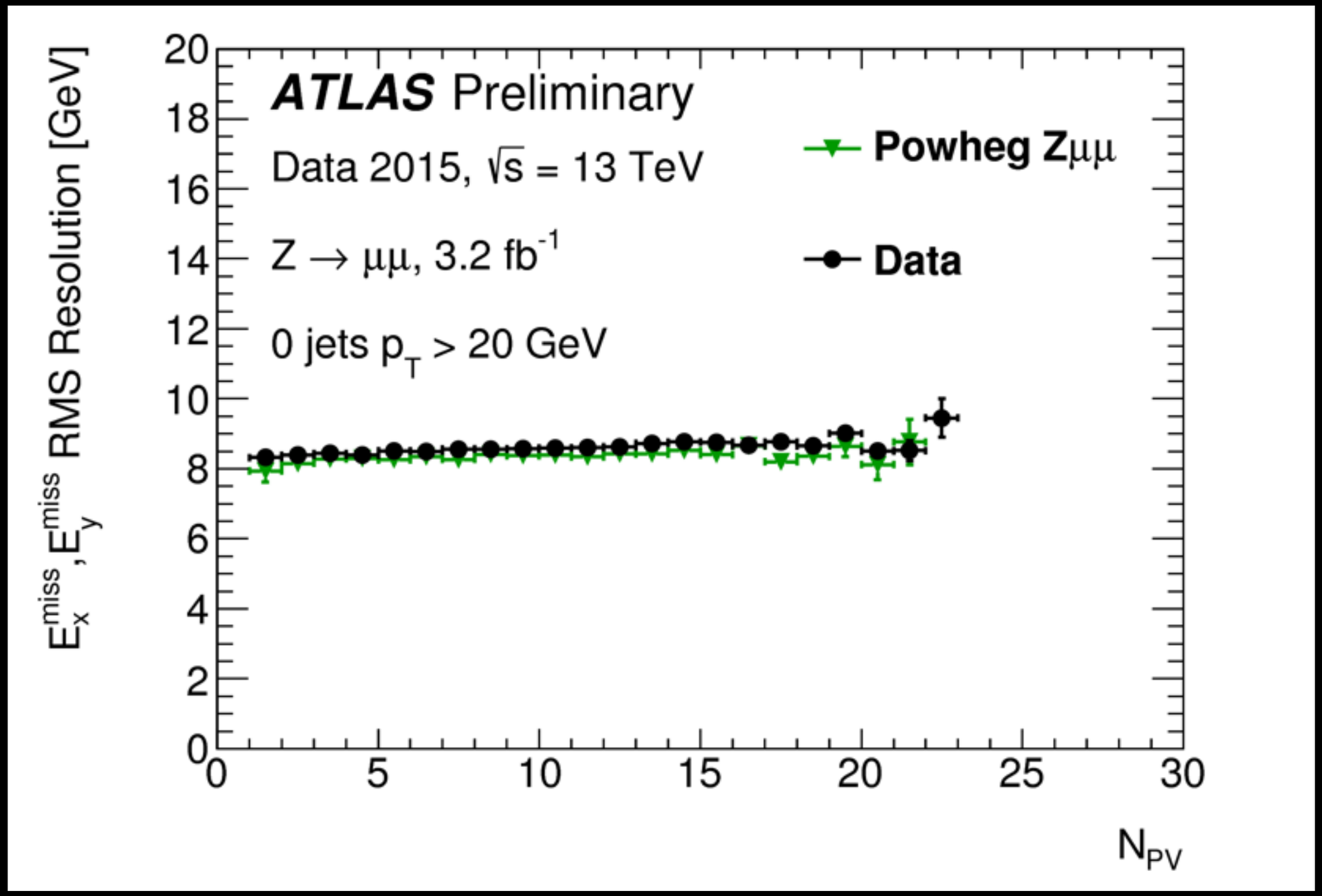
JETM-2016-003



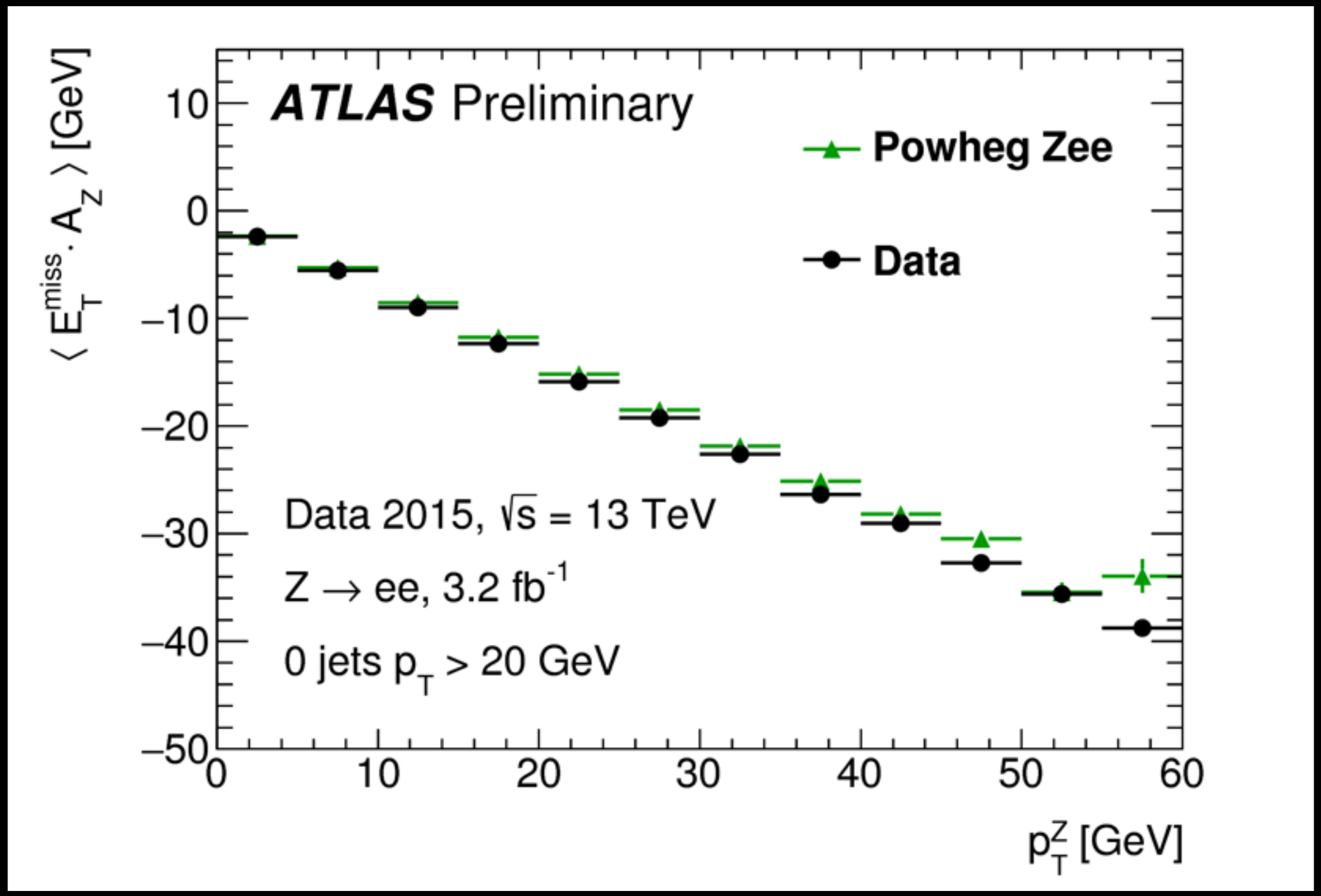
JETM-2016-003



JETM-2016-003



JETM-2016-003



ATLAS-CONF-2014-019