ETH zürich

CMS

Performance of missing transverse momentum reconstruction at the CMS detector in 13 TeV data

Leonora Vesterbacka on behalf of the CMS collaboration

ICHEP2018 SEOUL

ICHEP2018 SEOUL

XXXIX INTERNATIONAL CONFERENCE ON high Energy PHYSICS

JULY 4 - 11, 2018

COEX, SEOUL

all results presented are from JME-17-001

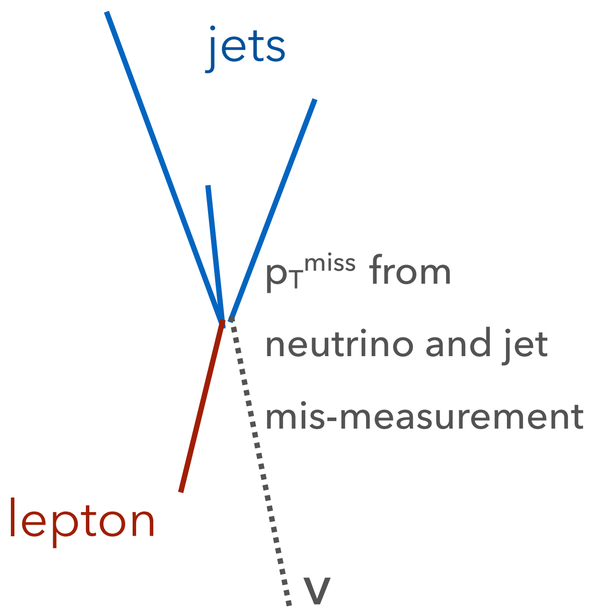
introduction: p_T^{miss}

neutrinos and other weakly interacting particles leave no signal in the detector

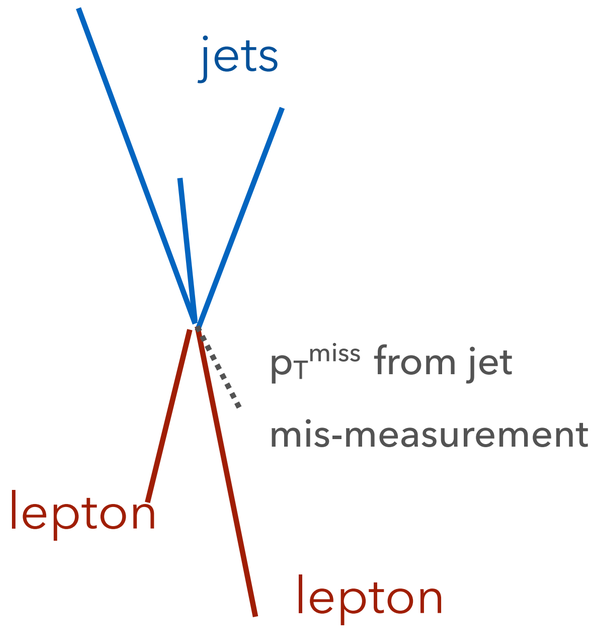
- momentum imbalance in the transverse plane
- crucial in SM, Higgs and BSM physics

	PF	PF + Puppi
$\vec{p}_T^{miss} =$	$-\sum_{i \in PF} \vec{p}_T^{\,i}$	$-\sum_{i \in PF} w^i \vec{p}_T^{\,i}$

Single lepton ($W \to \ell\nu$)



Double lepton ($Z \to \ell\ell$)



Particle Flow p_T^{miss} (PF):

- used in majority of CMS analyses

PUPPI p_T^{miss}:

- developed to provide a p_T^{miss} calculation that is robust against **pileup**

introduction: p_T^{miss} calibration

improve p_T^{miss} performance by propagating the JECs to the p_T^{miss}: Type 1 corrections

- correct jets if
  - $p_T > 15$ GeV
  - EM fraction < 0.9
  - no muon overlapping
- Type 1 corrected p_T^{miss} is used throughout this talk

$$\text{Type 1}\, p_{\mathrm{T}}^{\mathrm{miss}} = p_{\mathrm{T}}^{\mathrm{miss}} - \sum_{\mathrm{jets}} (\vec{p}_{\mathrm{T,jet}}^{\mathrm{corr}} - \vec{p}_{\mathrm{T,jet}}).$$

uncertainties :

- **jet energy scale:** ~ 3% (1-12%) inside (outside) tracker acceptance *
- **unclustered energy:** depends on the class of the objects
- **muons, electrons, photons and taus scale:** negligible compared to jets and unclustered energy.

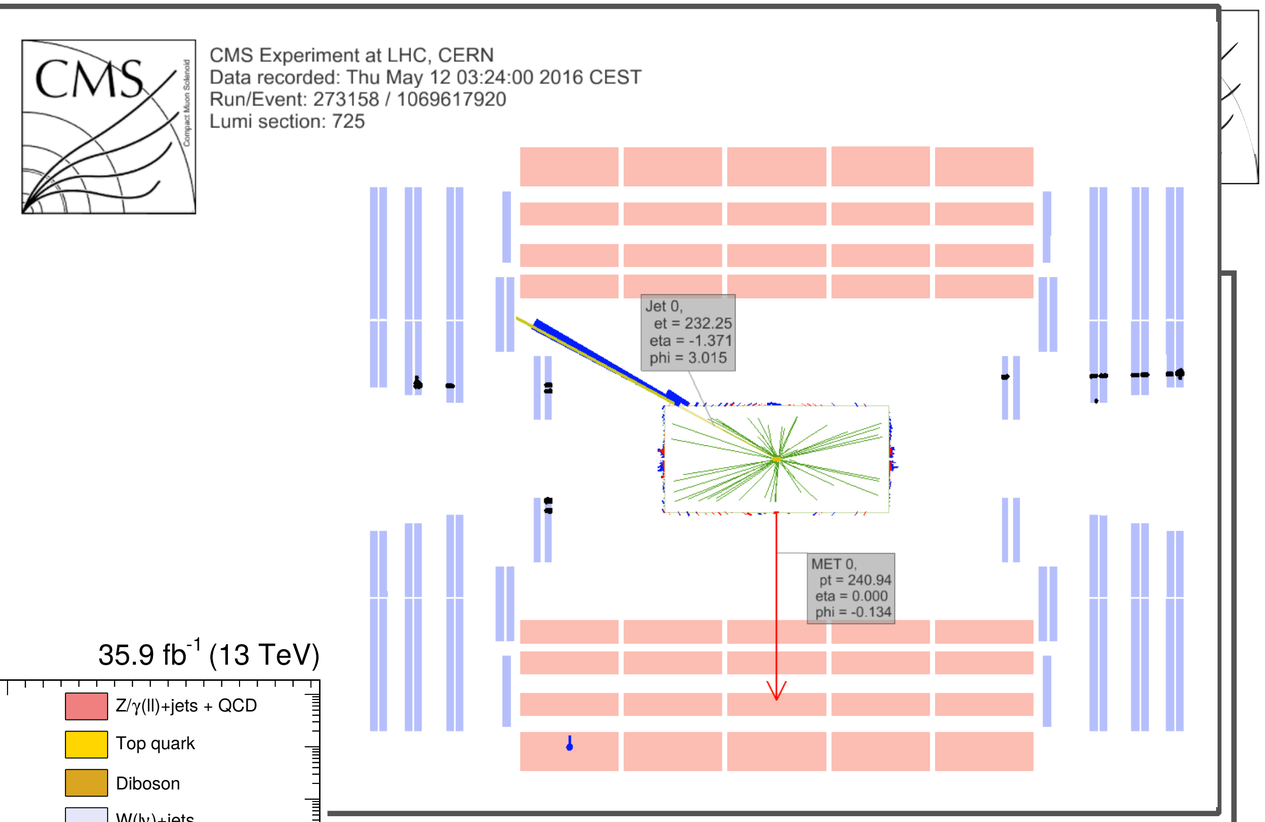
the uncertainties are represented by a grey band and contain jet energy scale/resolution, unclustered energy up/down variations and MC statistics

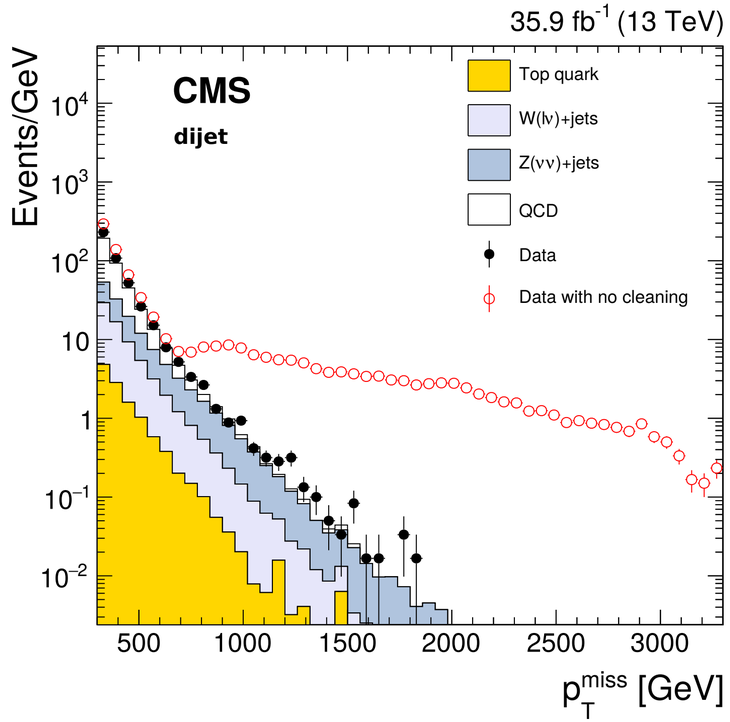
*Jet energy scale and resolution performance

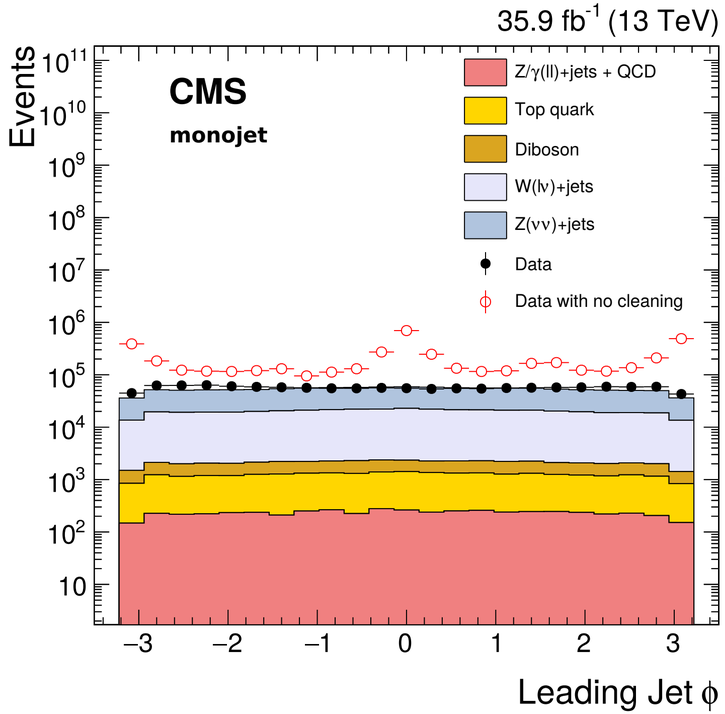
anomalous p_T^{miss}

event cleaning algorithms and p_T^{miss} filters

- p_T^{miss} distribution in di-jet events
- leading jet ϕ in mono-jet events
- cleaning and jet-id applied



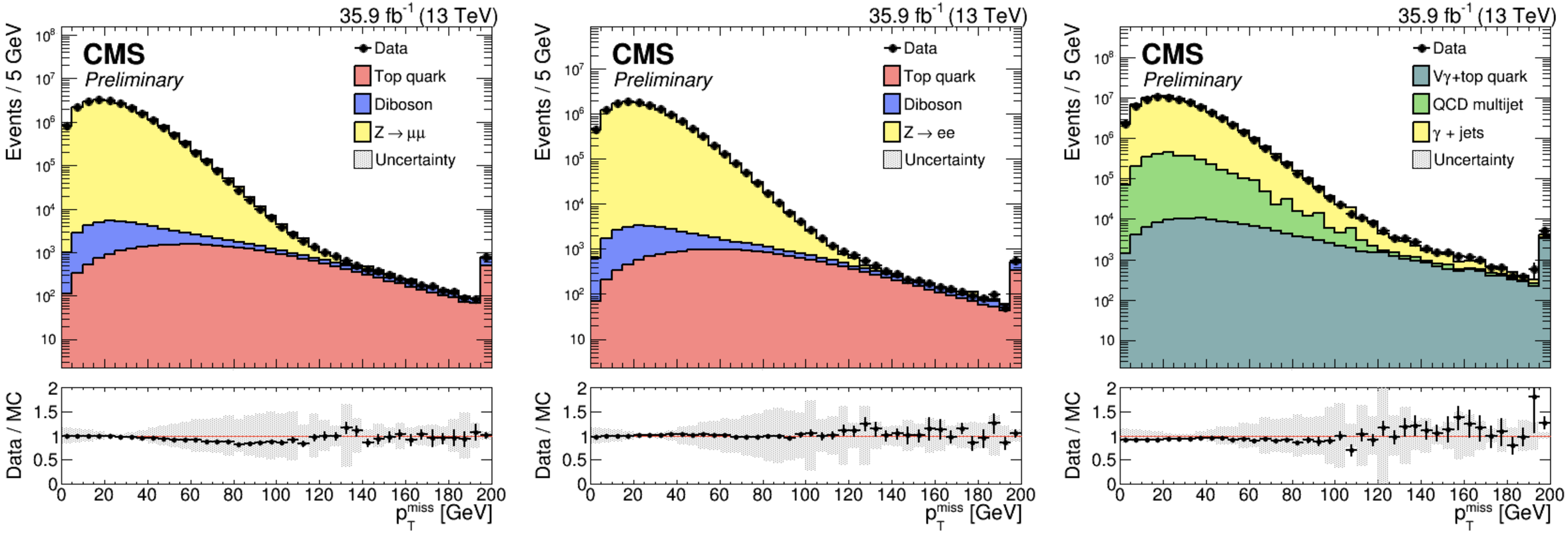




PF p_T^{miss} performance in 2016 data

PF performance in events with no intrinsic p_T^{miss}

Z→ℓℓ/γ+jets events used to study the detector response

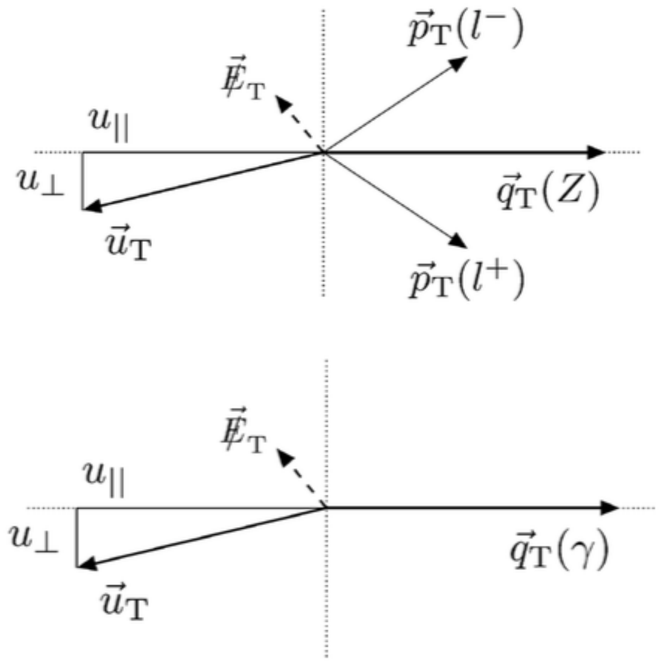


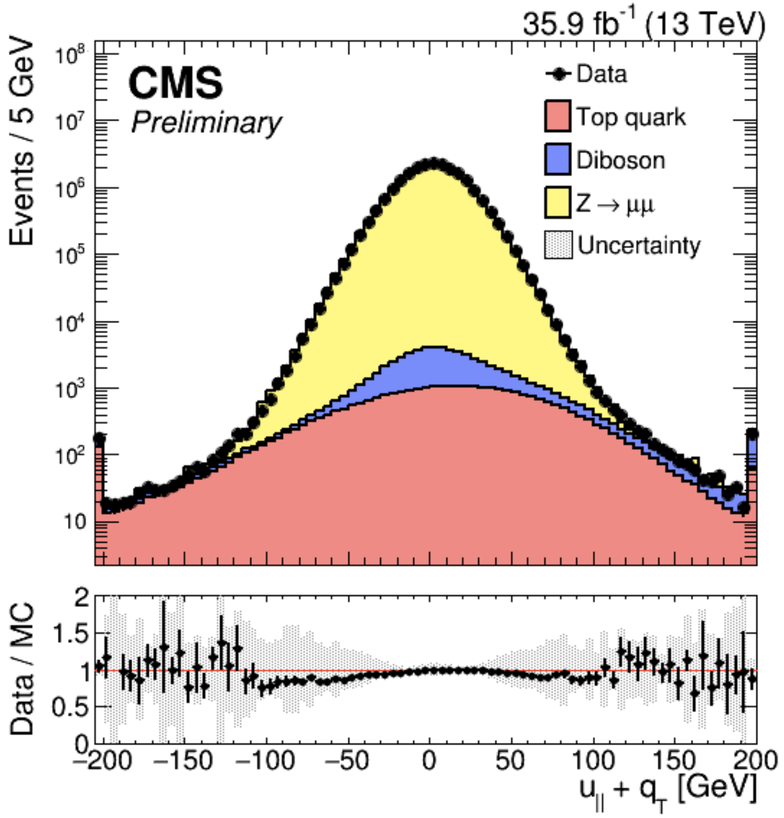
Z→μμ Z→ee γ+jets

PF performance in events with no intrinsic p_T^{miss}

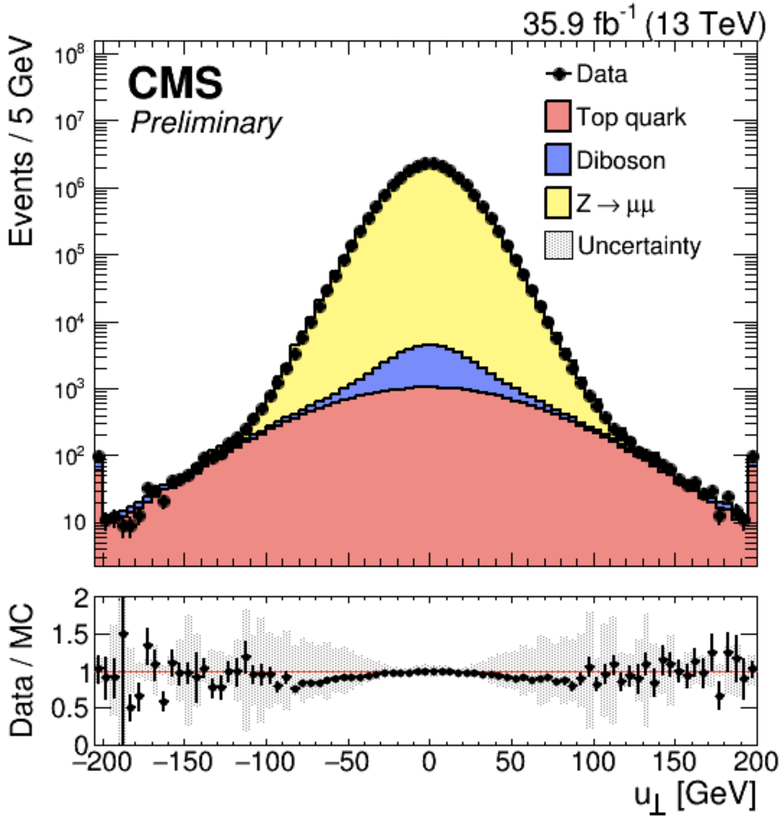
Z→ℓℓ/γ+jets events used to study the detector response

$$\vec{q}_T + \vec{u}_T + \vec{\not{E}}_T = 0$$





parallel component $u_{||} + q_T$



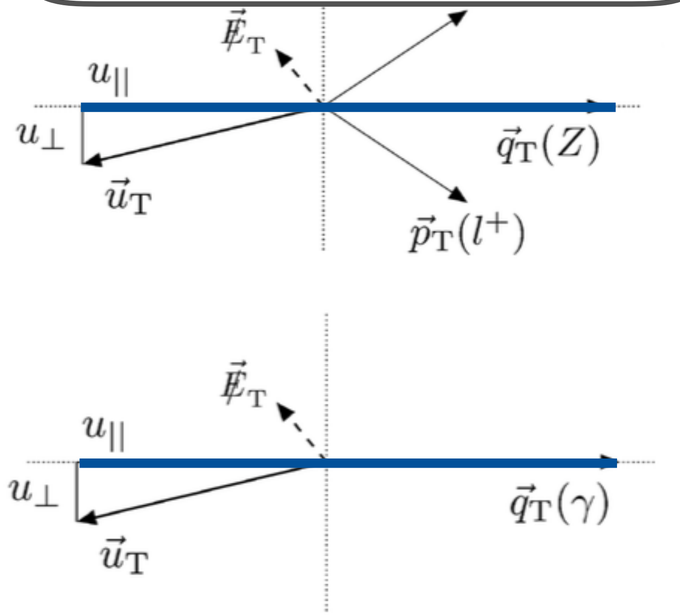
perpendicular component $u_\perp$

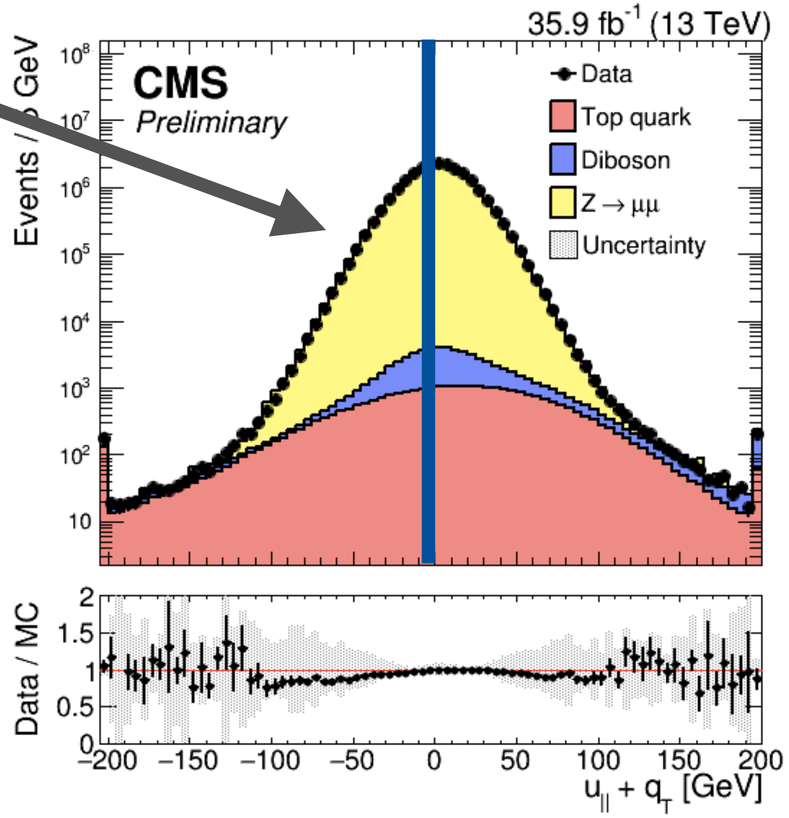
PF performance in events with no intrinsic p_T^{miss}

Z→ℓℓ/γ+jets events used to study the detector response

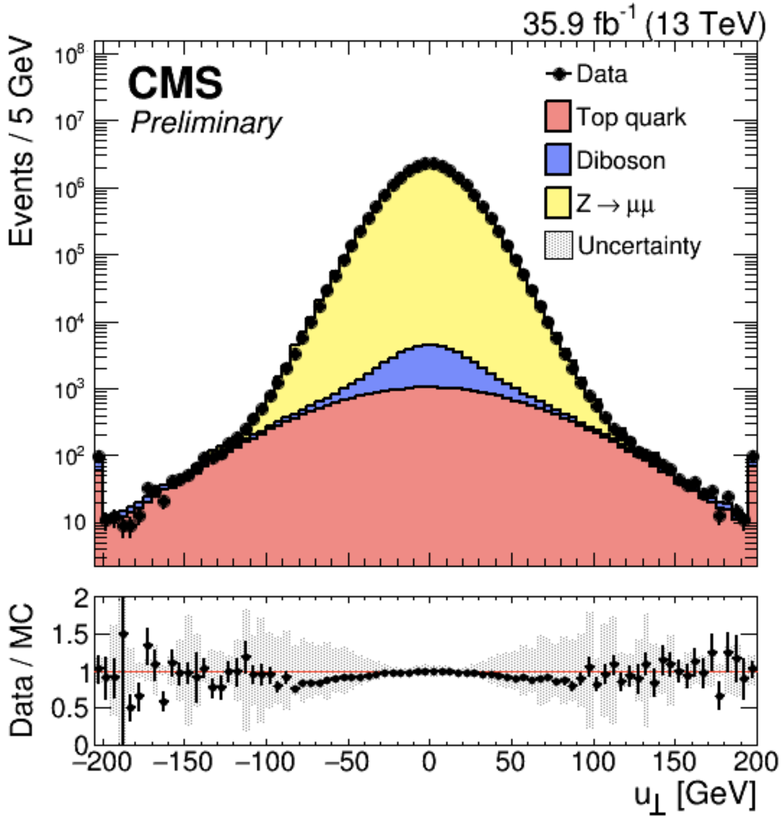
response:

$-\langle u_{||} \rangle / \langle q_T \rangle$





parallel component $u_{||} + q_T$

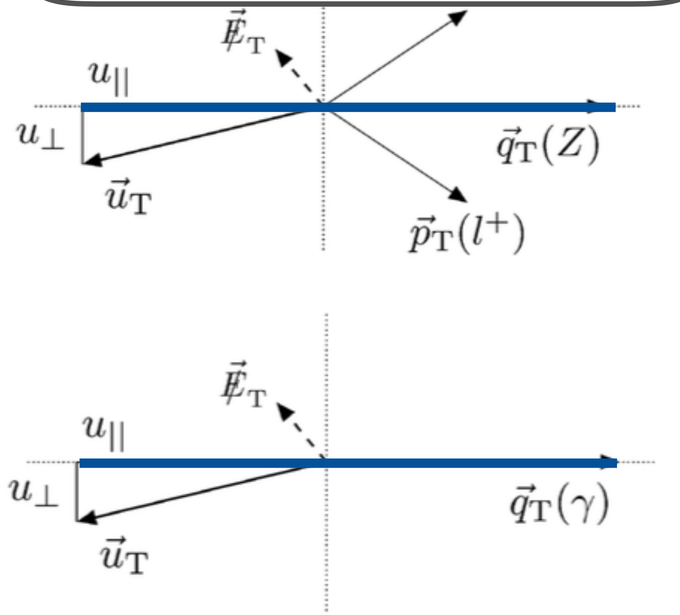


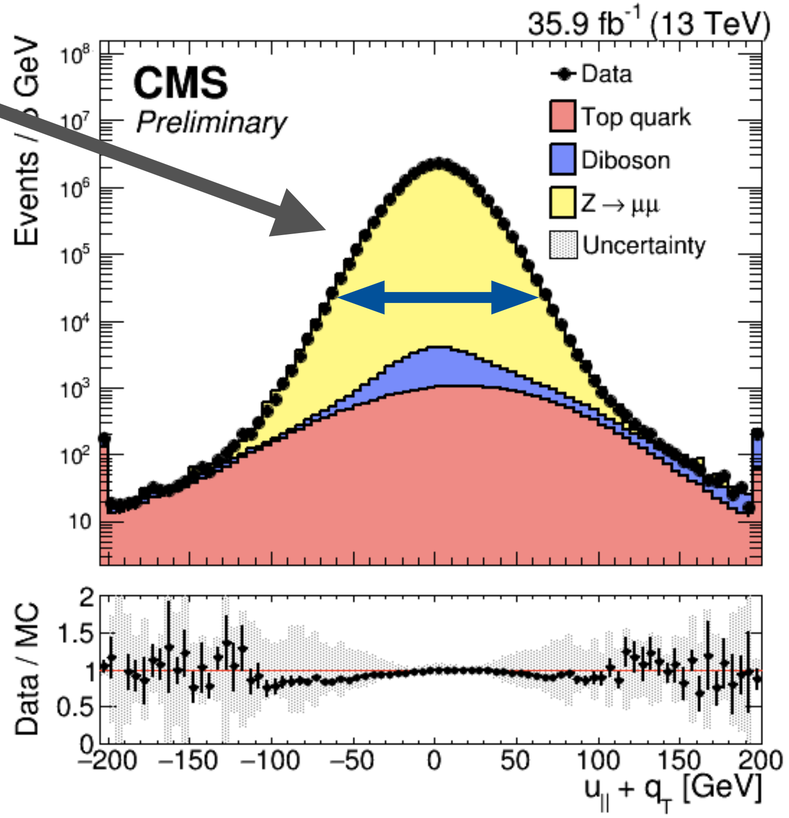
perpendicular component $u_\perp$

PF performance in events with no intrinsic p_T^{miss}

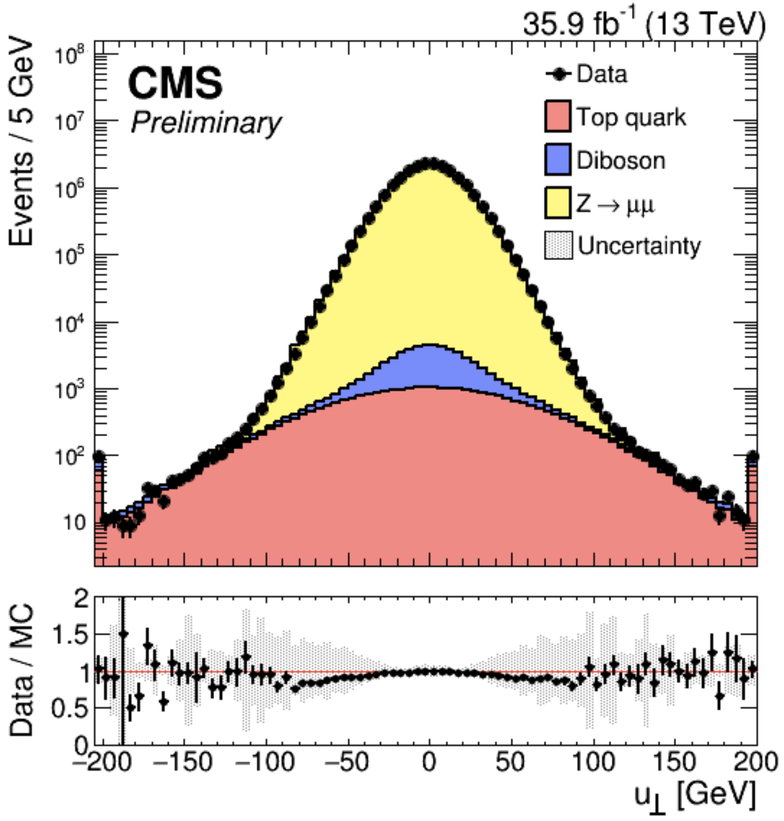
$Z \to \ell\ell/\gamma$+jets events used to study the detector response

resolution:
RMS of $u_{||} + q_T$





parallel component $u_{||} + q_T$

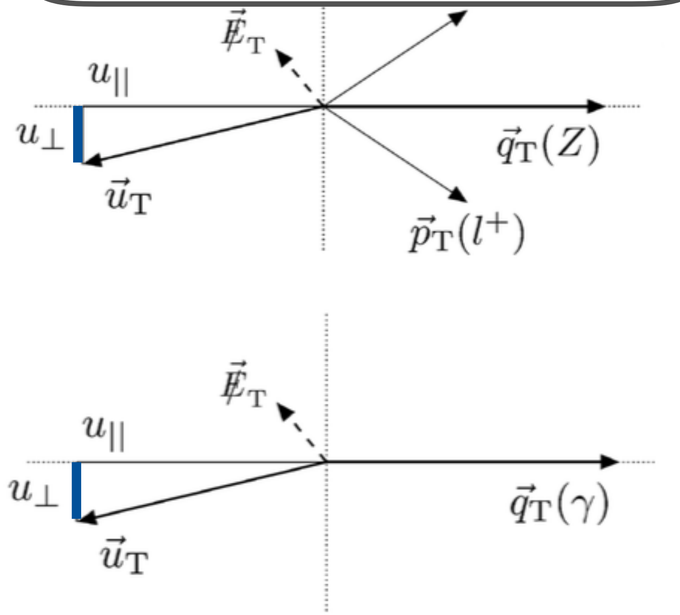


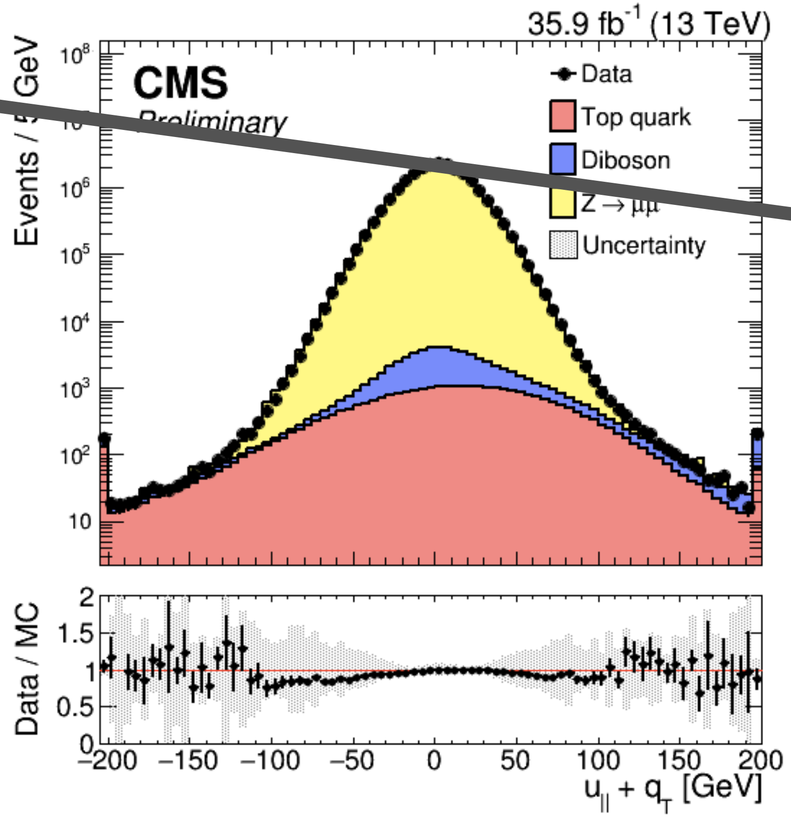
perpendicular component $u_\perp$

PF performance in events with no intrinsic p_T^{miss}

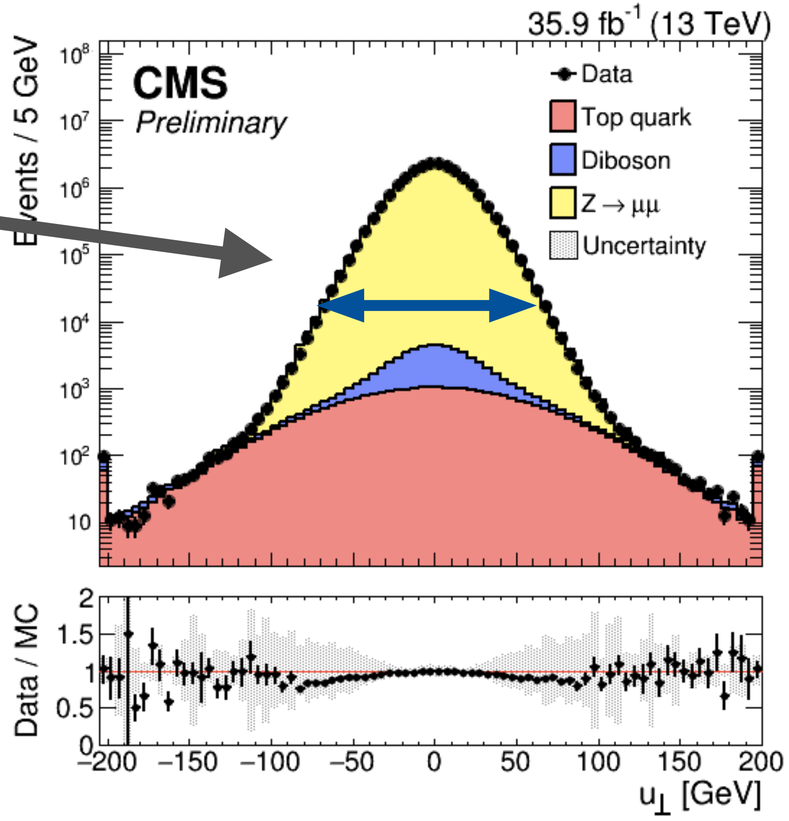
Z→ℓℓ/γ+jets events used to study the detector response

resolution:
RMS of $u_\perp$





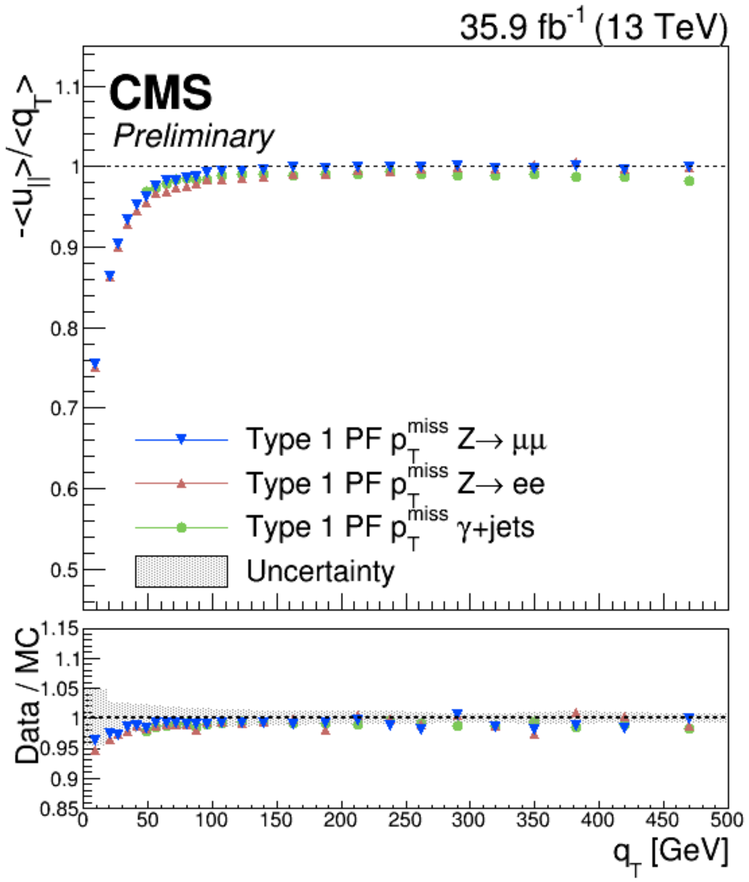
parallel component $u_{||} + q_T$



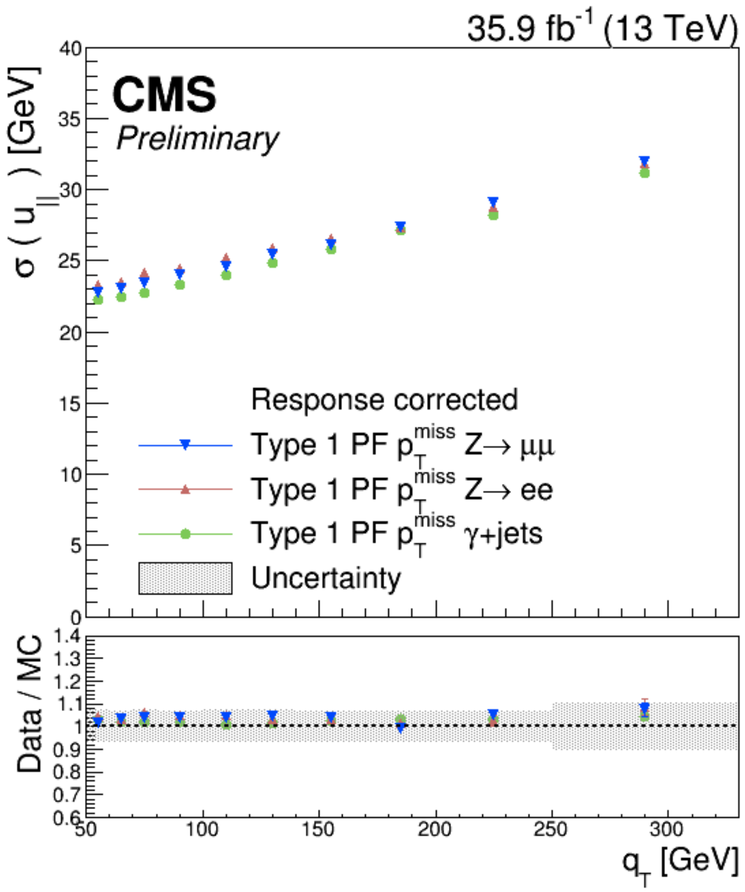
perpendicular component $u_\perp$

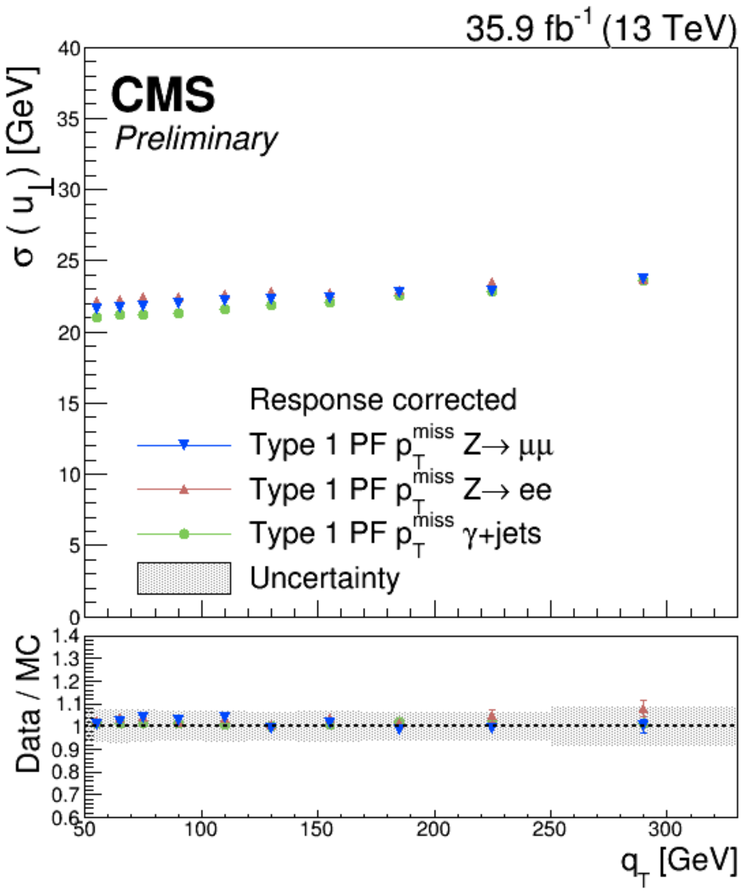
PF performance in events with no intrinsic p_T^{miss}

response: $-\langle u_{\parallel}\rangle / \langle q_T\rangle$



resolution as a function of q_T

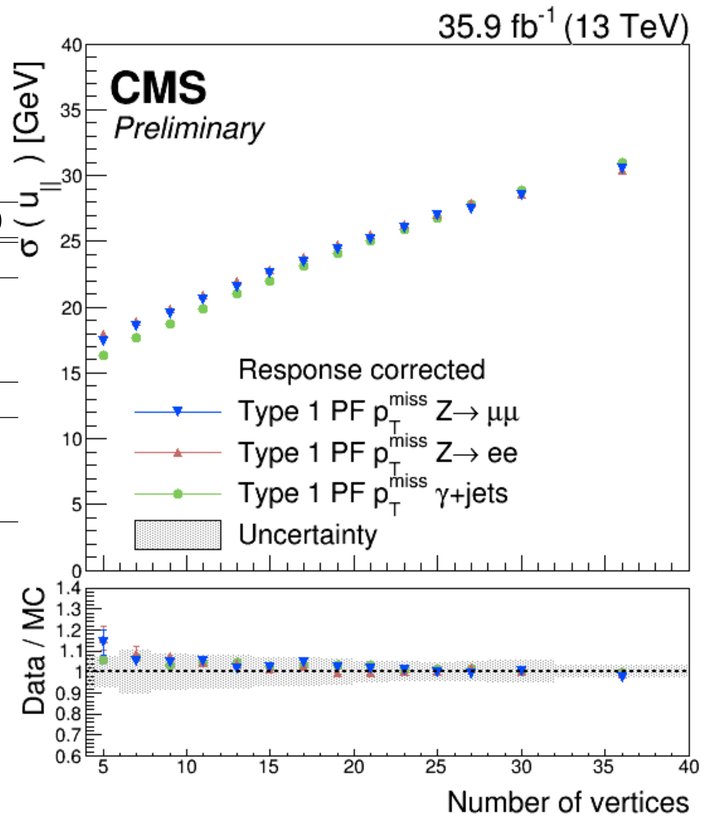


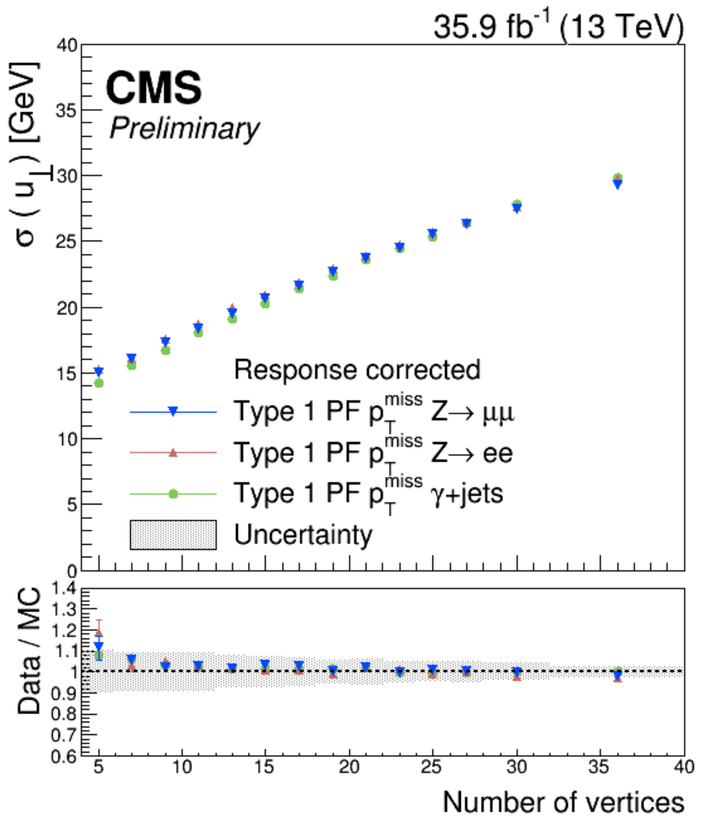


PF performance in events with no intrinsic p_T^{miss}

resolution as a function of number of vertices:

Process	σ_c(data)[GeV]	σ_c(MC)[GeV]	σ_{PU}(data)[GeV]	$R_r = \sigma_{PU}(data)/\sigma_{PU}(MC)$
		$u_{\parallel}$ component		
Z→ $\mu\mu$	13.9 ± 0.07	11.9 ± 1.53	3.82 ± 0.01	0.95 ± 0.04
Z→ ee	14.6 ± 0.09	12.0 ± 1.09	3.80 ± 0.02	0.95 ± 0.03
γ+jets	12.2 ± 0.10	10.2 ± 1.98	3.97 ± 0.02	0.97 ± 0.05
		$u_{\perp}$ component		
Z→ $\mu\mu$	10.3 ± 0.08	8.58 ± 2.2	3.87 ± 0.01	0.97 ± 0.04
Z→ ee	10.7 ± 0.10	8.71 ± 1.8	3.89 ± 0.01	0.96 ± 0.04
γ+jets	9.04 ± 0.11	6.93 ± 2.7	3.94 ± 0.01	0.97 ± 0.04



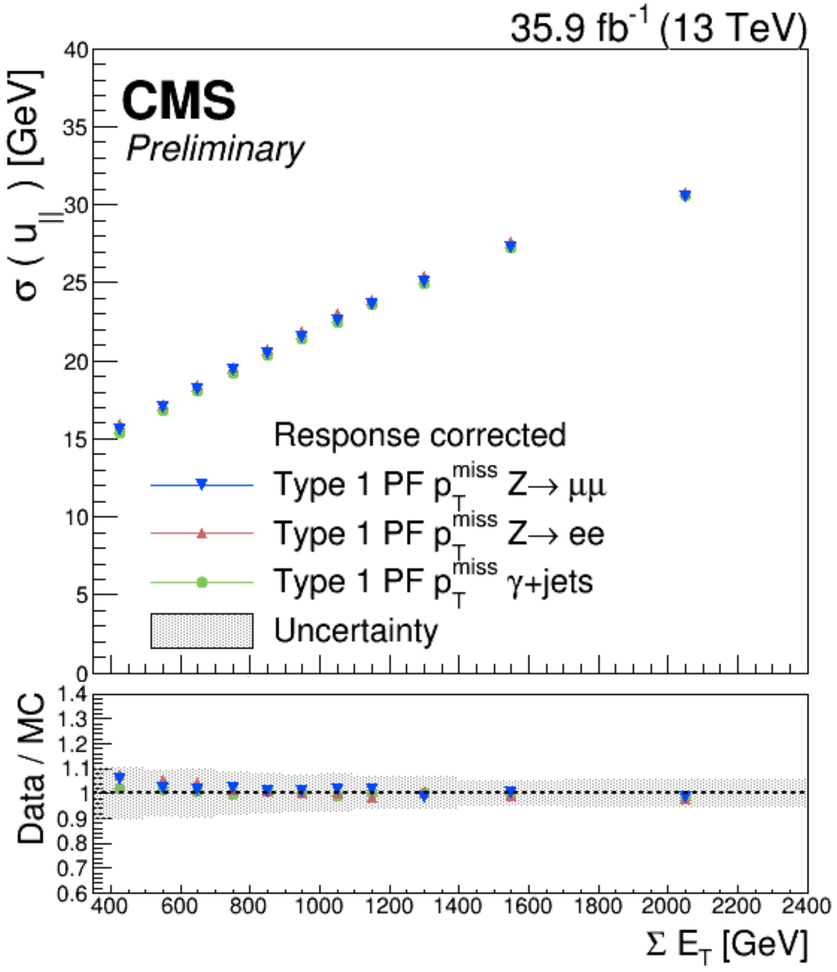


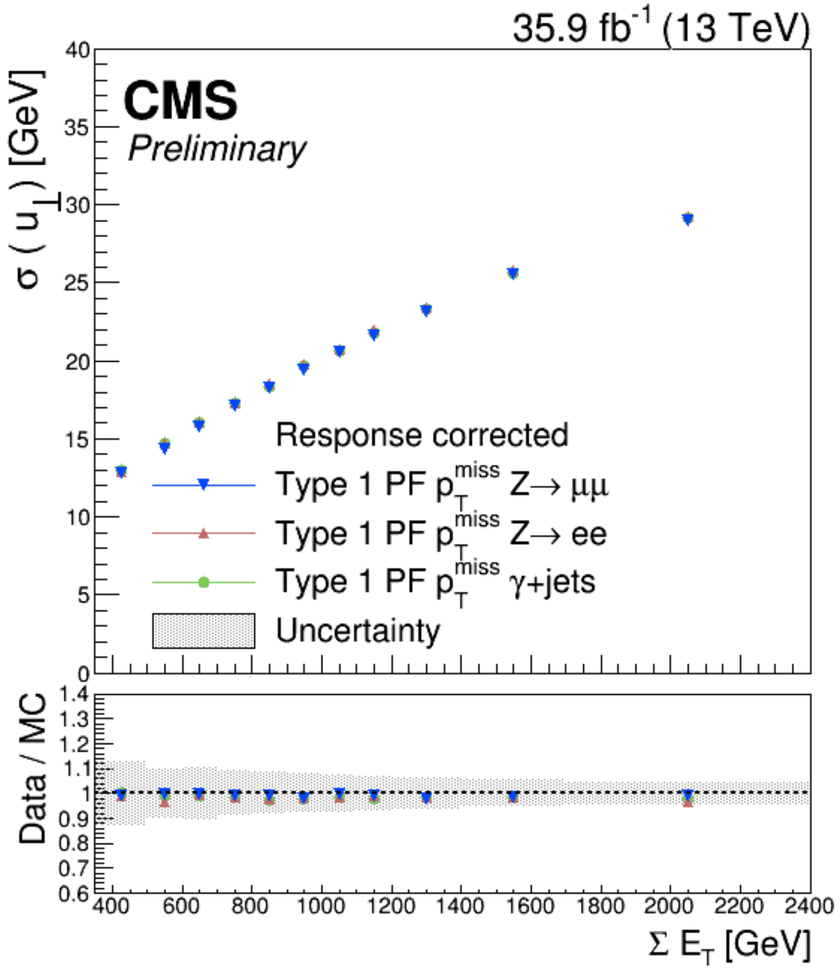
$$f(N_{vtx}) = \sqrt{\sigma_c^2 + \frac{N_{vtx}}{0.7}\sigma_{PU}^2}$$

- σ_c : resolution of hard scattering
- σ_{PU}: resolution degrades with 4 GeV per additional PU interaction
- 0.7 coefficient: accounts for the 2016 vertex reconstruction efficiency

PF performance in events with no intrinsic p_T^{miss}

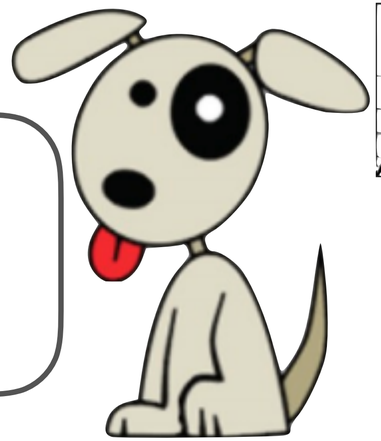
resolution as a function of $\sum E_T$:





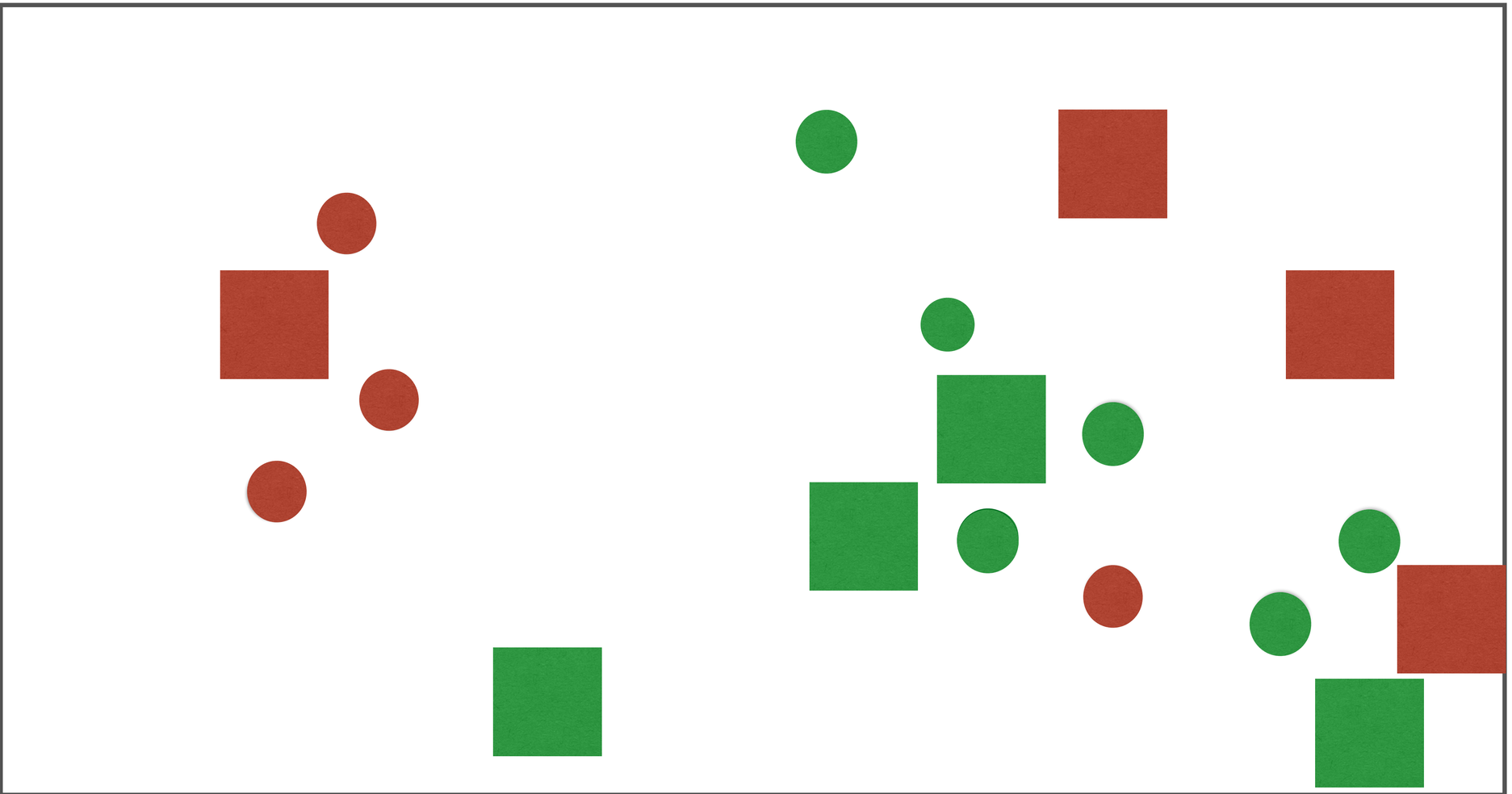
PUPPI p_T^{miss} performance in 2016 data

PUPPI



PUPPI algorithm

- 0. a typical event. Particle Flow algorithm can provide (within tracker volume) the following candidates



PU track

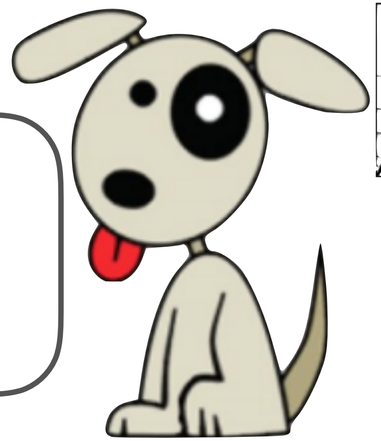
Good track

PU neutral

Good neutral

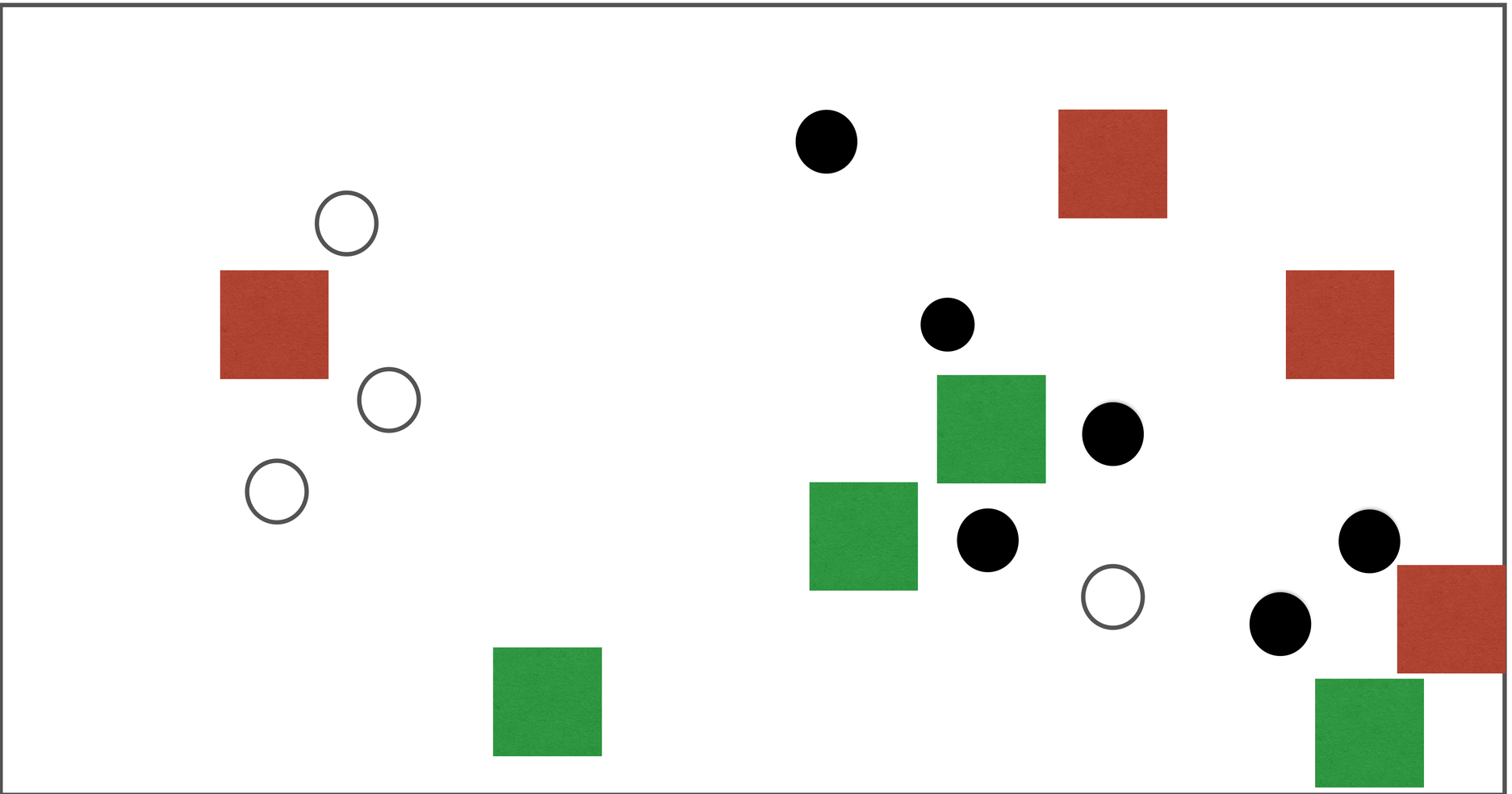
1407.6013

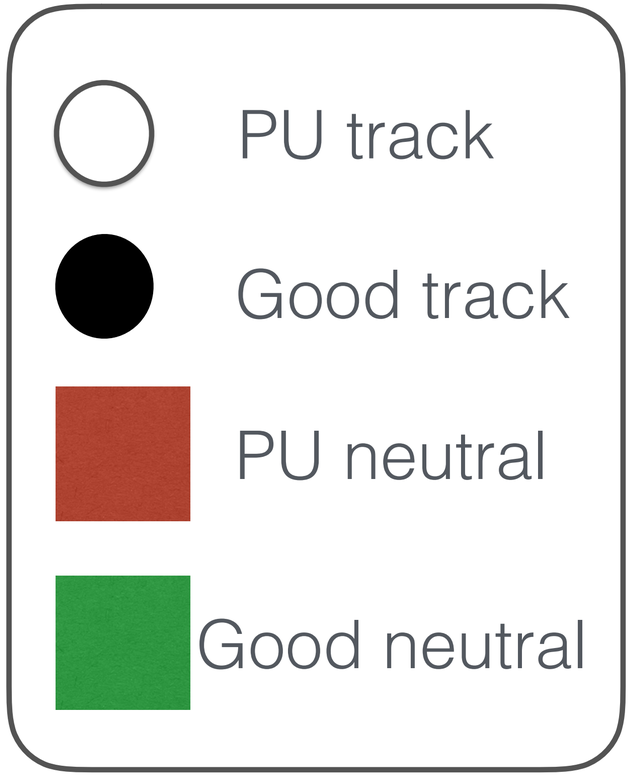
PUPPI



PUPPI algorithm

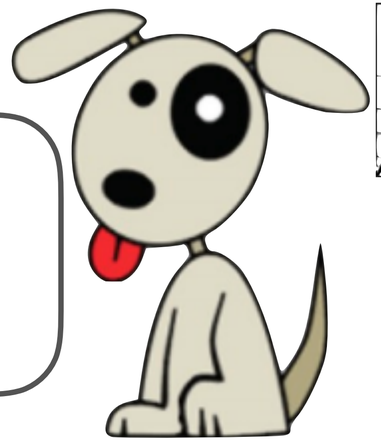
- 1. tracks can point to PU vertices, only keep charged tracks that come from the primary vertex





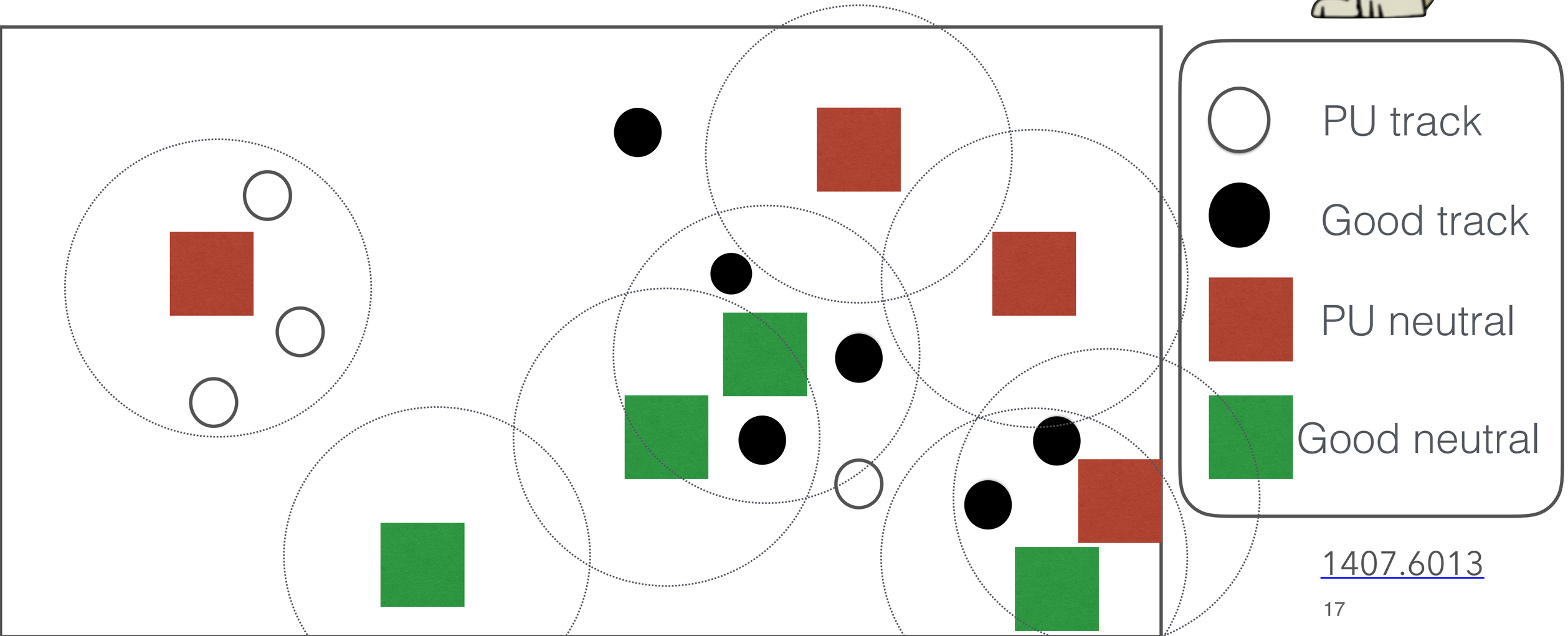
1407.6013

PUPPI



PUPPI algorithm

- 2. draw a cone around each neutral PF candidate

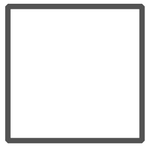


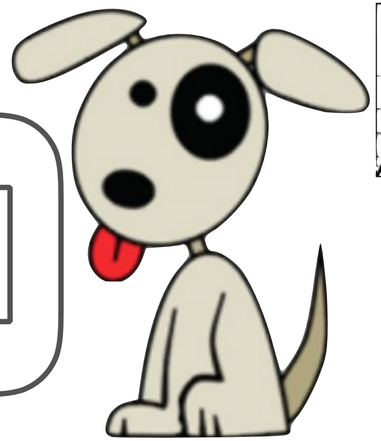
1407.6013

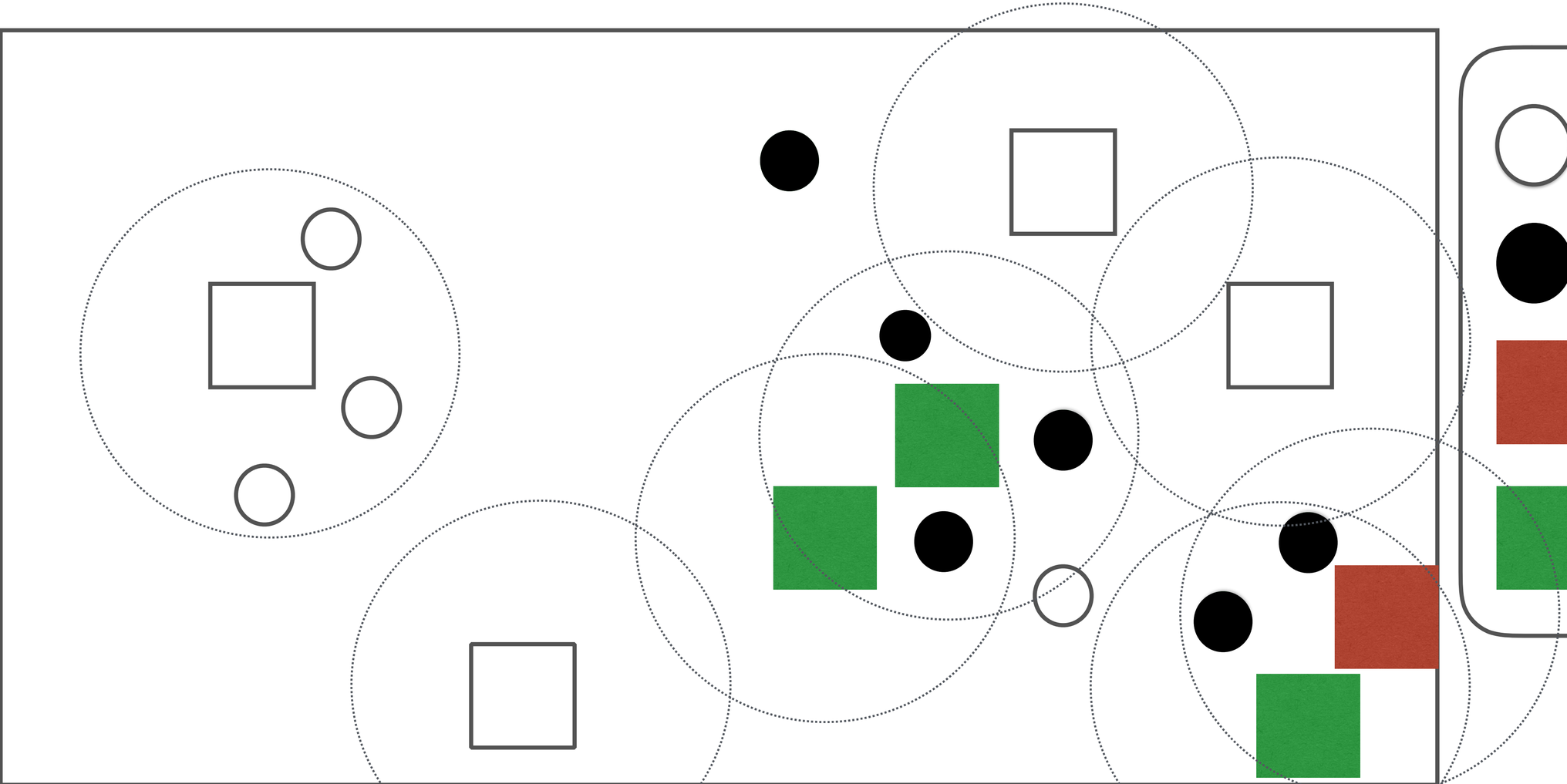
PUPPI

PUPPI algorithm

- 3. remove 0 weight contributions

$w(\alpha_{PU})$ x  = 





PU track

Good track

PU neutral

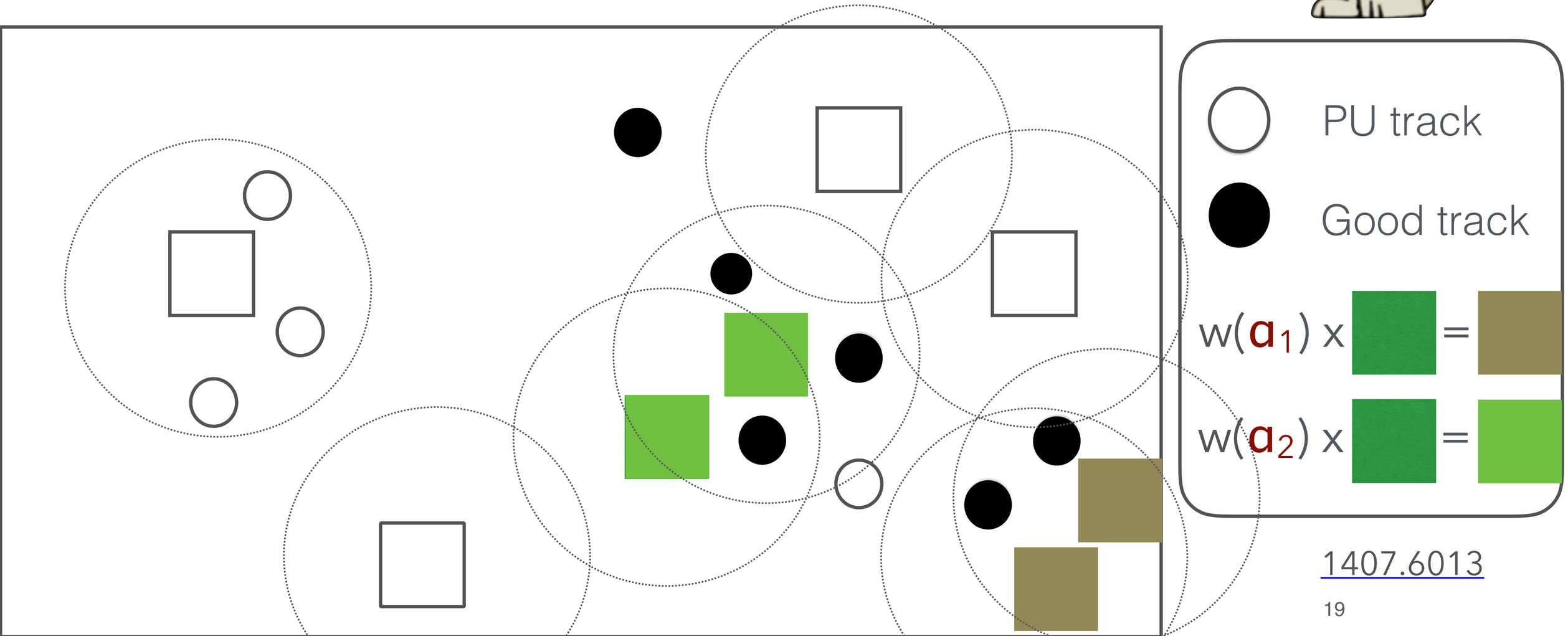
Good neutral

1407.6013

PUPPI

PUPPI algorithm

- 4. reweight neutrals

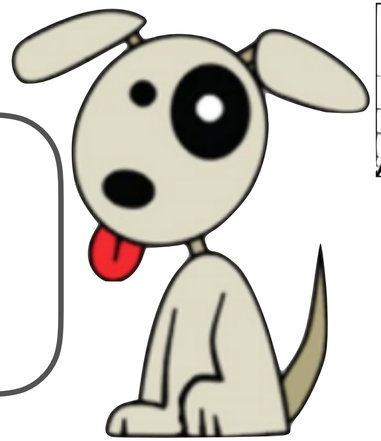


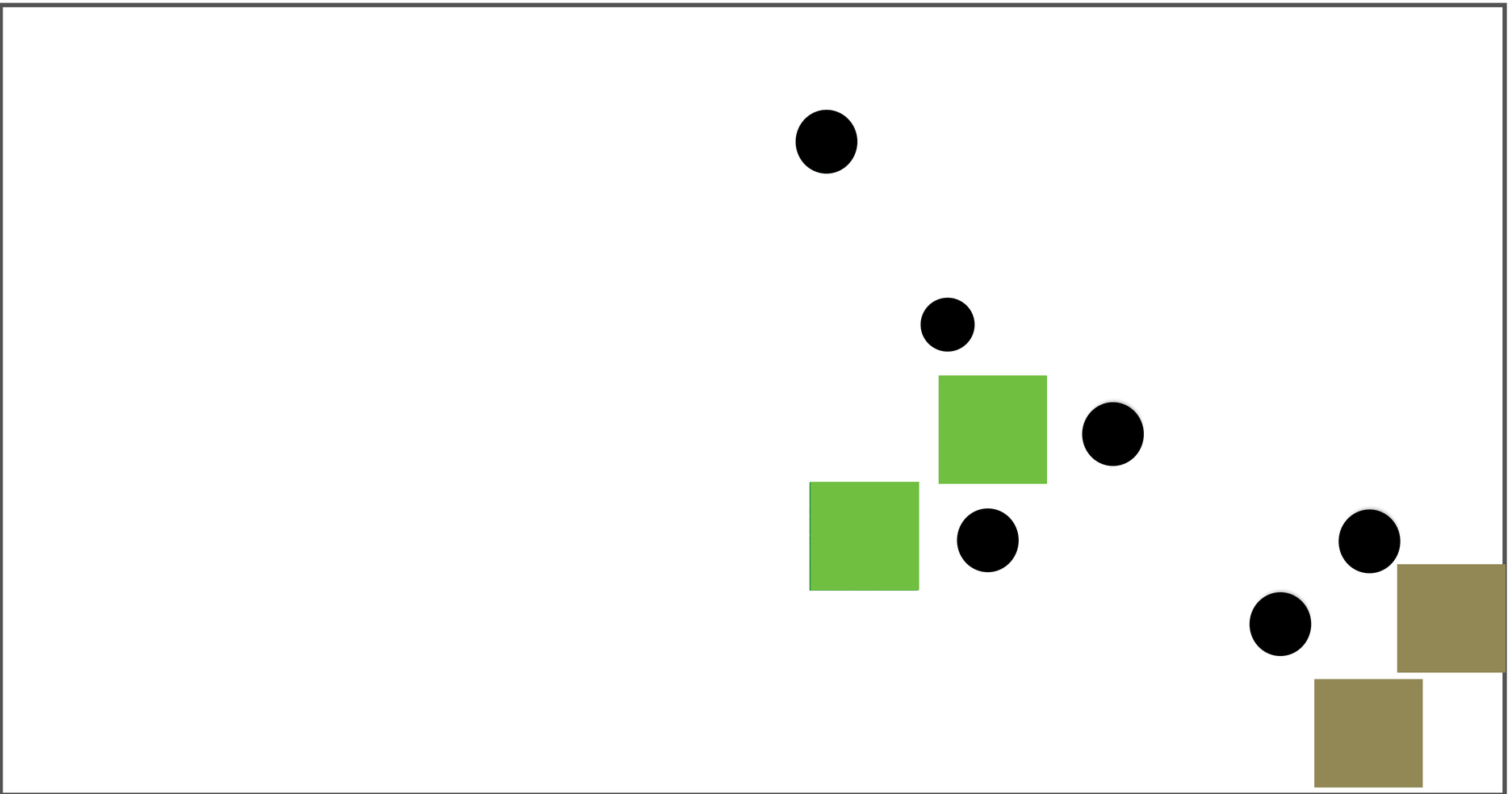
1407.6013

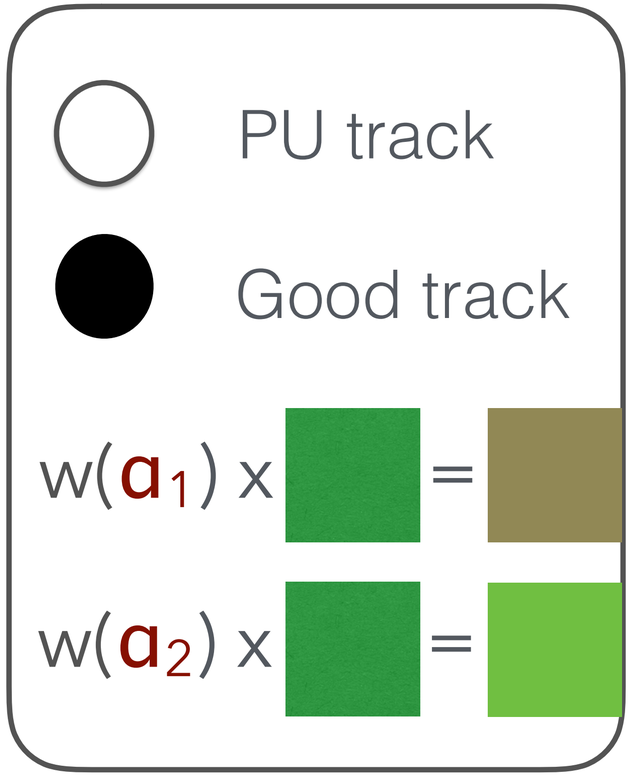
PUPPI

PUPPI algorithm

- 5. reinterpret the event





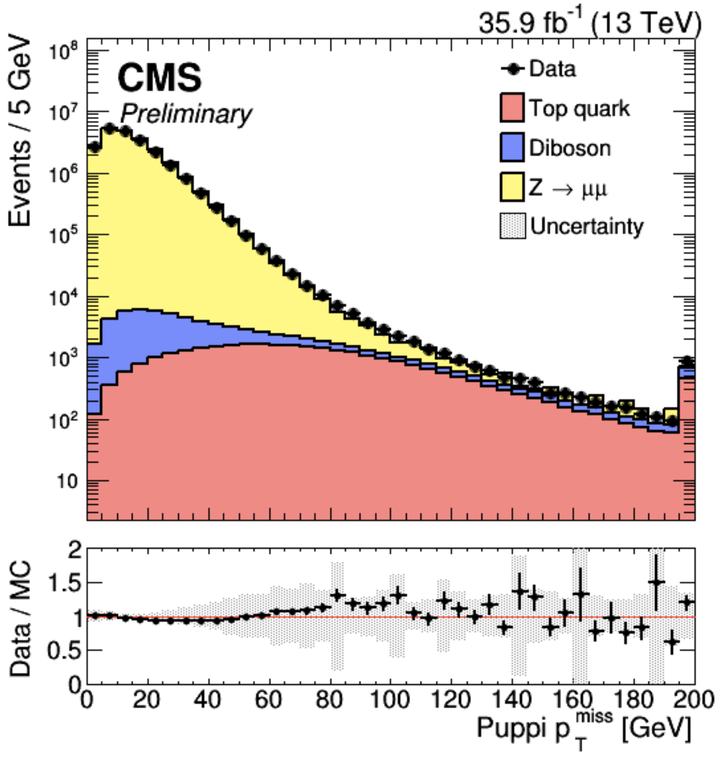


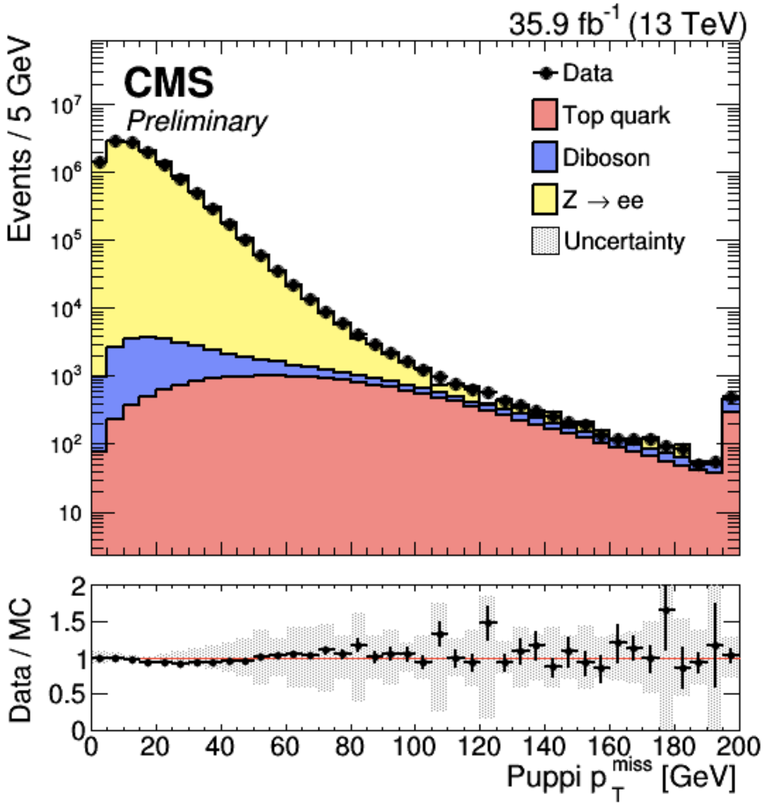
1407.6013

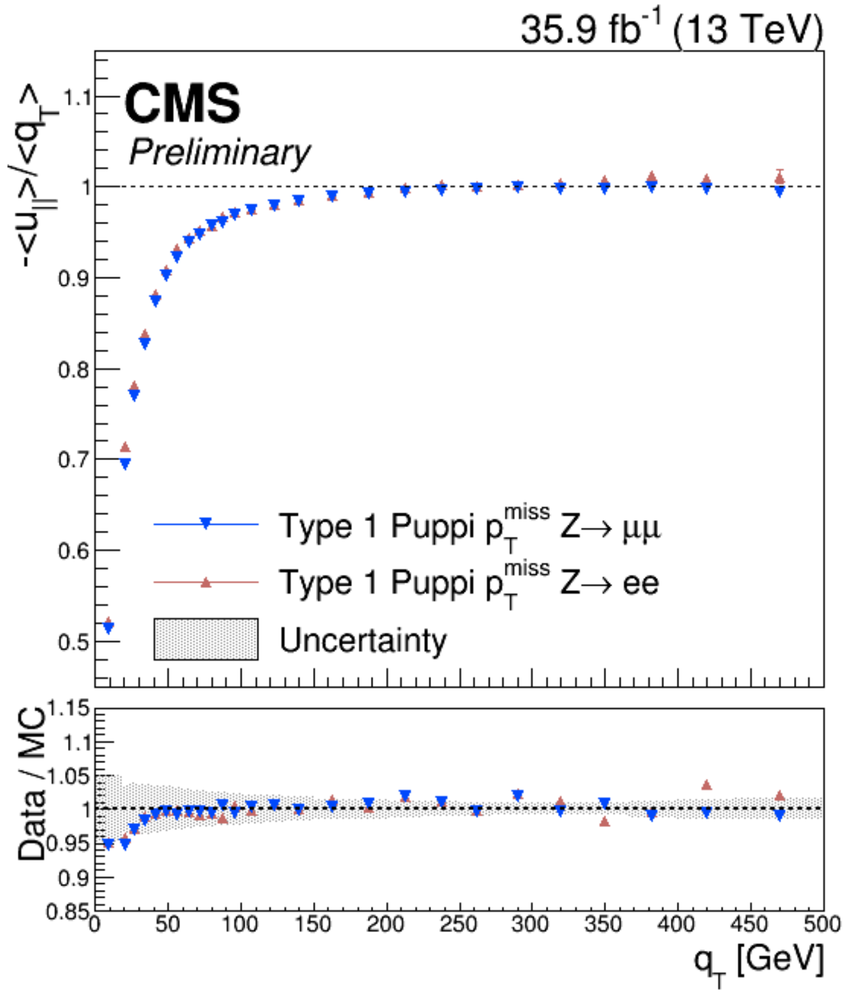
PUPPI performance in events with no intrinsic p_T^{miss}

Z→ℓℓ/γ+jets events used to study the detector response

	PF	PF + Puppi
$\vec{p}_T^{miss} =$	$-\sum_{i \in PF} \vec{p}_T^{\,i}$	$-\sum_{i \in PF} w^i \vec{p}_T^{\,i}$







PUPPI performance in events with no intrinsic p_T^{miss}

resolution as a function of number of vertices:

$$f(N_{vtx}) = \sqrt{\sigma_c^2 + \frac{N_{vtx}}{0.7}\sigma_{PU}^2}$$

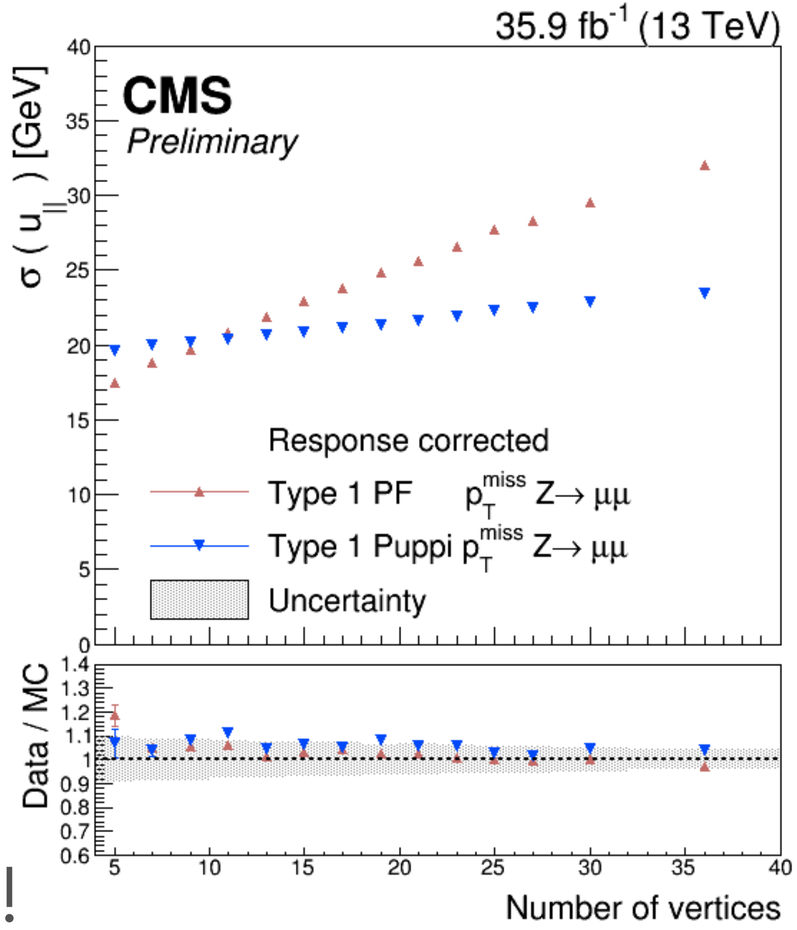
PF p_T^{miss}

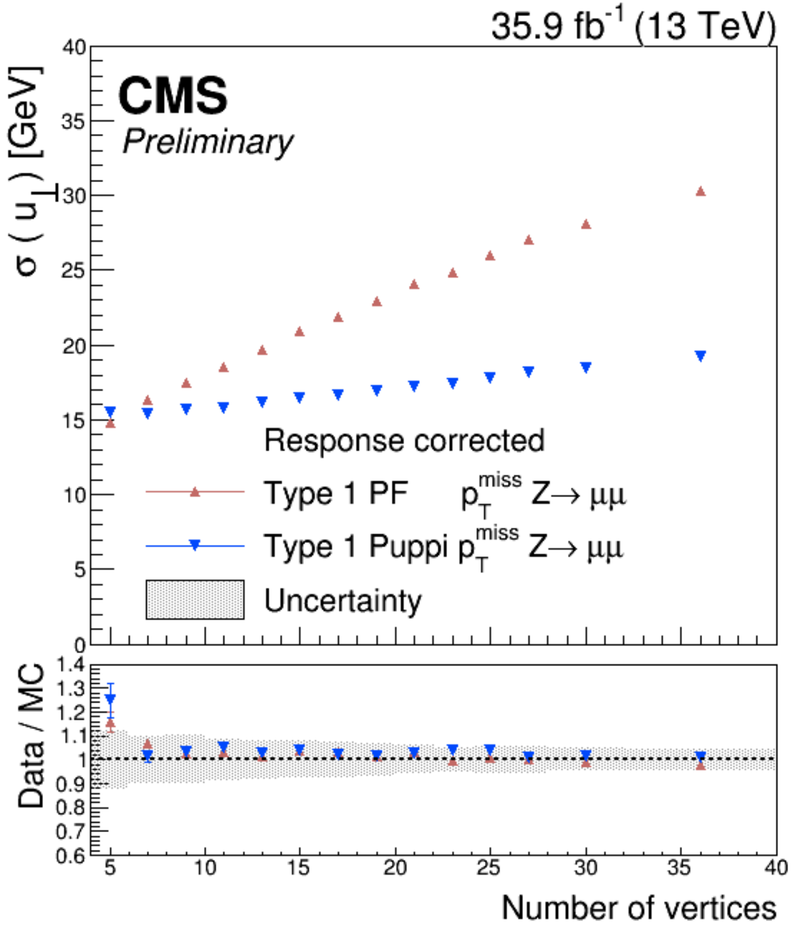
Process	σ_c(data)[GeV]	σ_c(MC)[GeV]	σ_{PU}(data)[GeV]
		$u_{\parallel}$ component	
$Z\to\mu\mu$	13.9 ± 0.07	11.9 ± 1.53	3.82 ± 0.01
$Z\to ee$	14.6 ± 0.09	12.0 ± 1.09	3.80 ± 0.02
γ+jets	12.2 ± 0.10	10.2 ± 1.98	3.97 ± 0.02
		$u_{\perp}$ component	
$Z\to\mu\mu$	10.3 ± 0.08	8.58 ± 2.2	3.87 ± 0.01
$Z\to ee$	10.7 ± 0.10	8.71 ± 1.8	3.89 ± 0.01
γ+jets	9.04 ± 0.11	6.93 ± 2.7	3.94 ± 0.01

PUPPI p_T^{miss}

Process	σ_c(data)[GeV]	σ_c(MC)[GeV]	σ_{PU}(data)[GeV]
		$u_{\parallel}$ component	
$Z\to\mu\mu$	18.9 ± 0.05	17.5 ± 0.74	1.93 ± 0.02
$Z\to ee$	18.9 ± 0.06	17.4 ± 0.79	1.94 ± 0.02
		$u_{\perp}$ component	
$Z\to\mu\mu$	14.2 ± 0.04	13.6 ± 0.59	1.78 ± 0.01
$Z\to ee$	14.3 ± 0.05	13.6 ± 0.56	1.8 ± 0.02

!!!

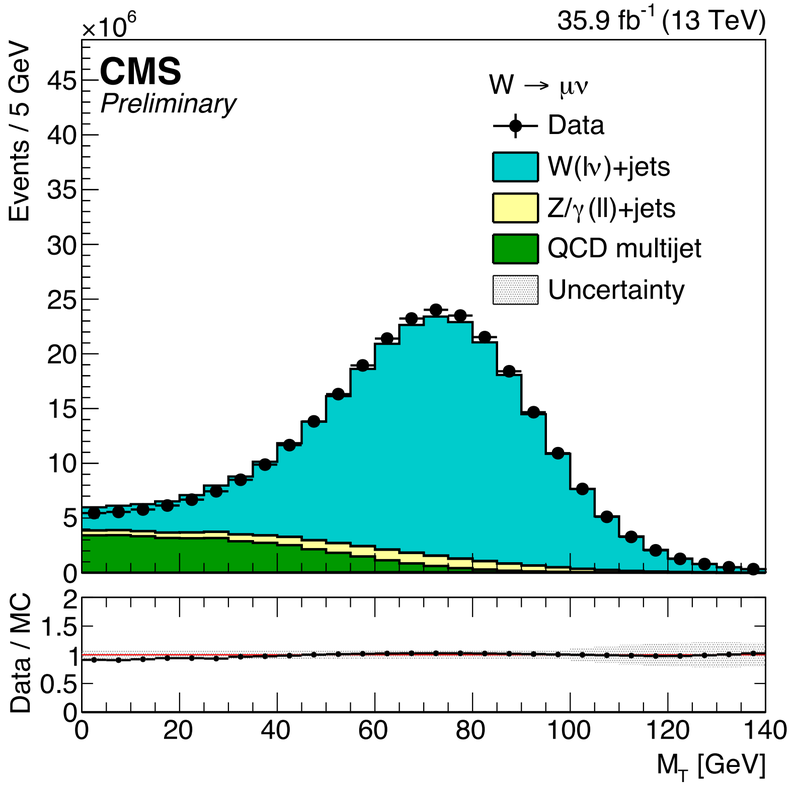


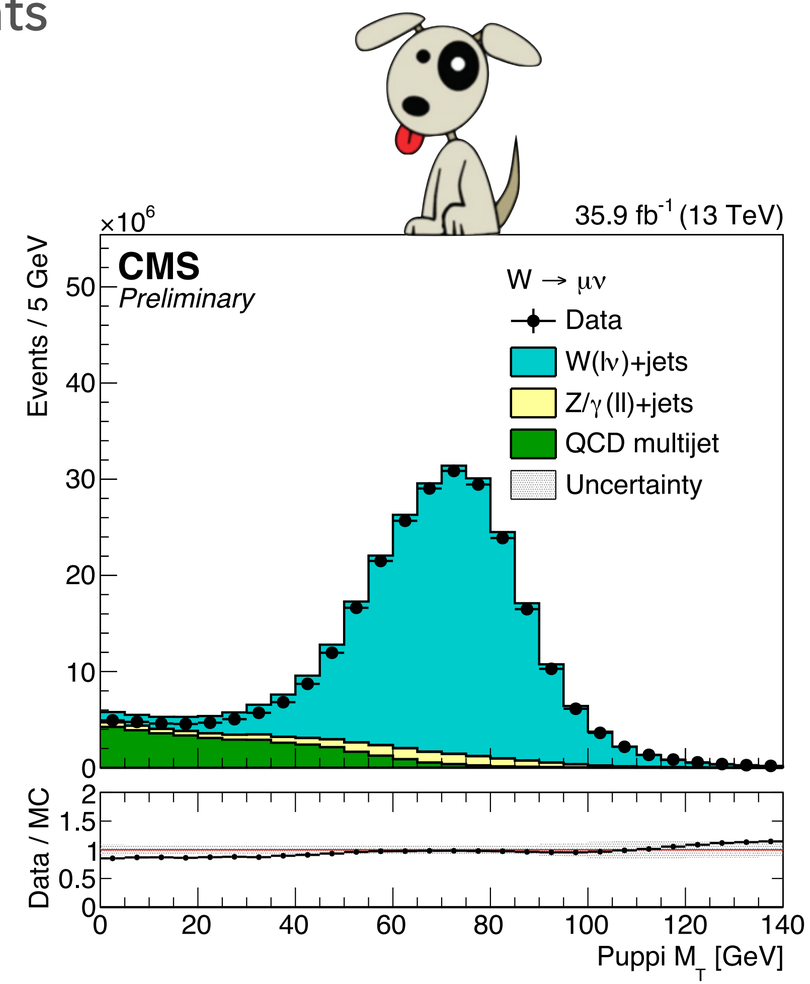


performance of PF and Puppi in genuine p_T^{miss} events

performance of PF and Puppi p_T^{miss} in W→μν events

$$M_T = \sqrt{2 p_T^{miss} p_T^{lepton} (1 - \cos\Delta\phi)}$$





p_T^{miss} significance in 2016 data

p_T^{miss} significance

p_T^{miss} significance

- quantifies the degree of compatibility of the p_T^{miss} with 0
- the significance is defined as a log-likelihood ratio

true p_T^{miss}

observed p_T^{miss}

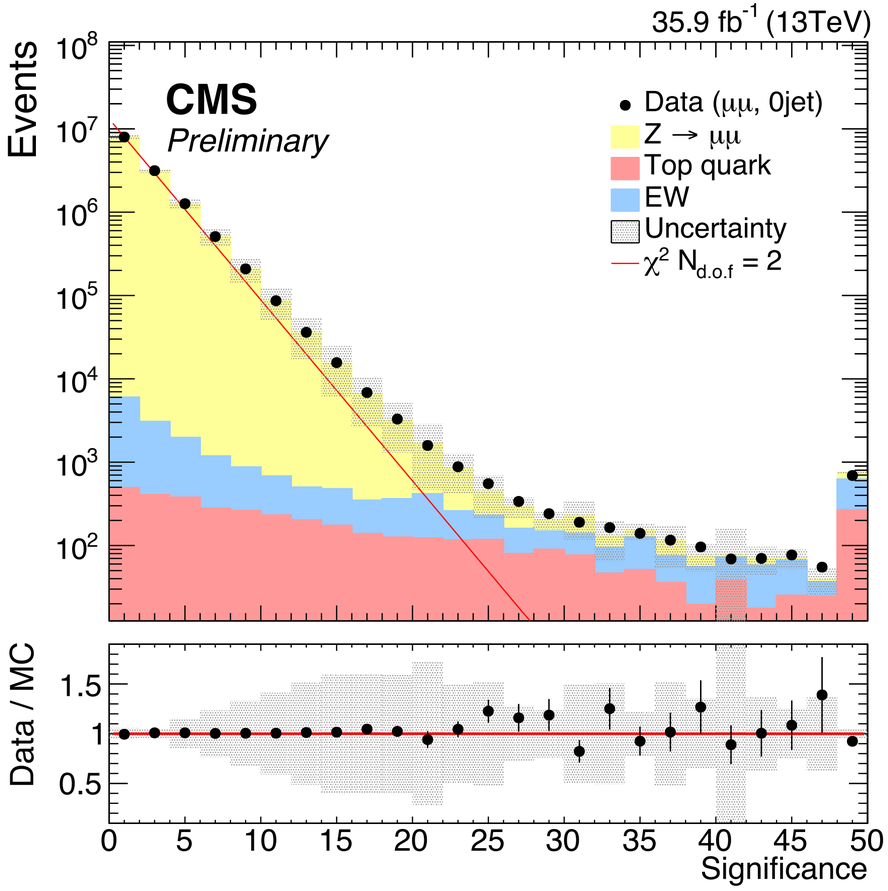
$$\mathcal{S} = 2 \ln \left(\frac{\mathcal{L}(\vec{\varepsilon} = \sum \vec{\varepsilon}_i)}{\mathcal{L}(\vec{\varepsilon} = 0)} \right)$$

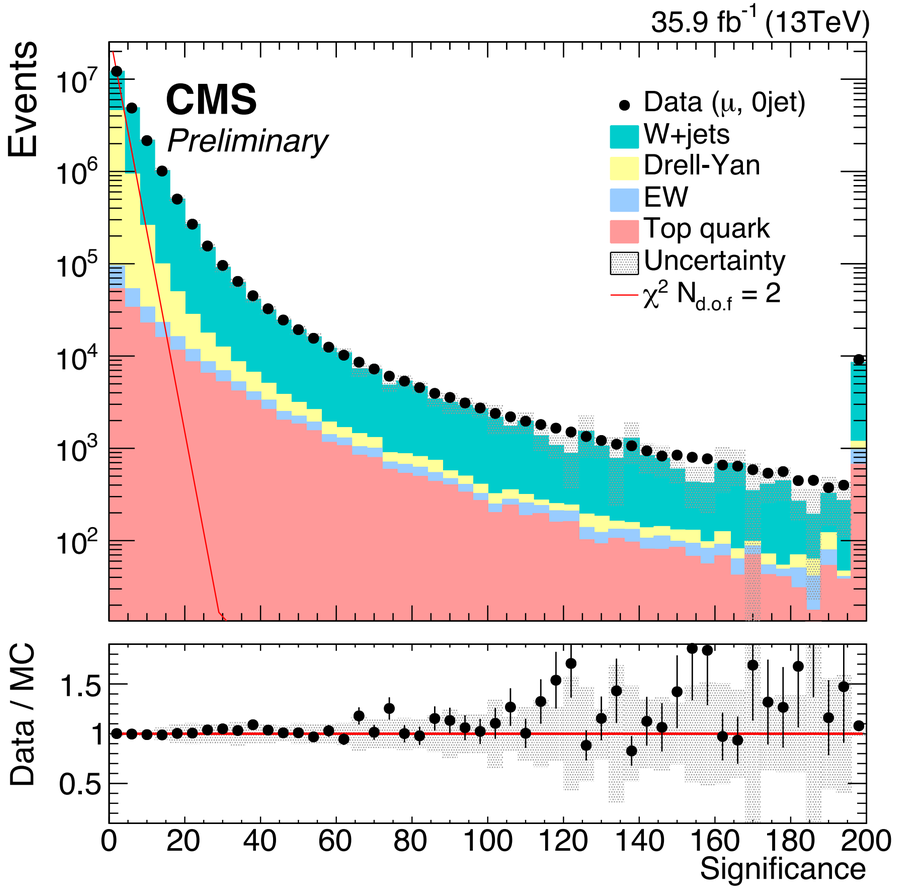
null hypothesis: true $p_T^{miss} = 0$

p_T^{miss} significance

performance of p_T^{miss} significance in Z→μμ/W→μν and no jets events

- χ^2 with 2 degrees of freedom follow the distribution with no genuine p_T^{miss}





summary

performance of missing transverse momentum at the CMS detector in 13 TeV data

- two algorithms used in CMS studied: **PF and Puppi p_T^{miss}**
  - the response and resolution of both algorithms is studied in **$Z \to \ell\ell/\gamma$+jets** events.
  - good agreement is found between the different samples and between data and simulation.
  - **Puppi p_T^{miss} is more stable than PF p_T^{miss} vs pileup**

backup

datasets

di-jet and mono-jet samples

- for p_T^{miss} filter studies
- collected using triggers on both $p_{T,trig}^{miss}$ and $H_{T,trig}^{miss}$

di-lepton and single photon samples

- used for PF and Puppi p_T^{miss} performance studies in fake p_T^{miss} events
- collected using triggers on leading and subleading muon/electron p_T, or using a set of isolated single photon triggers

single lepton samples

- used for PF and Puppi p_T^{miss} performance studies in genuine p_T^{miss} events
- collected using triggers on p_T and isolation on the electron/muon

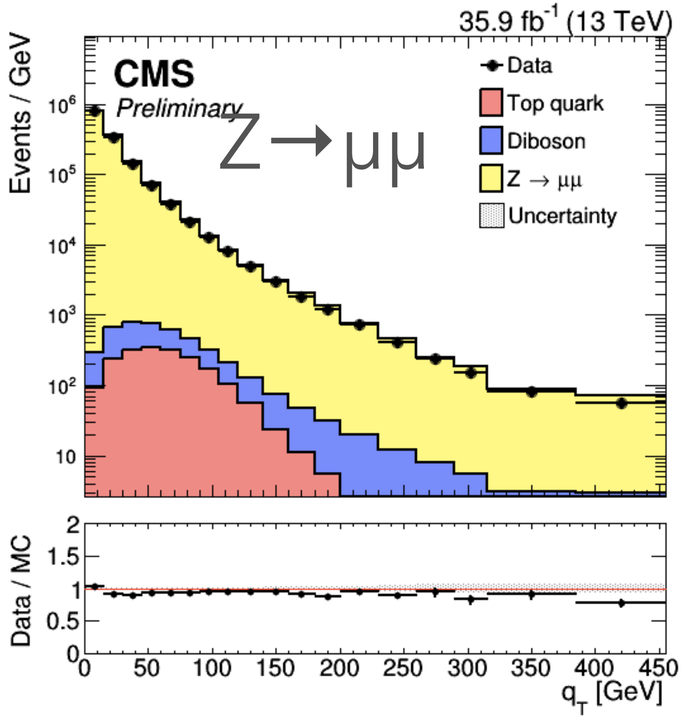
03Feb2017 re-reco of 2016 data

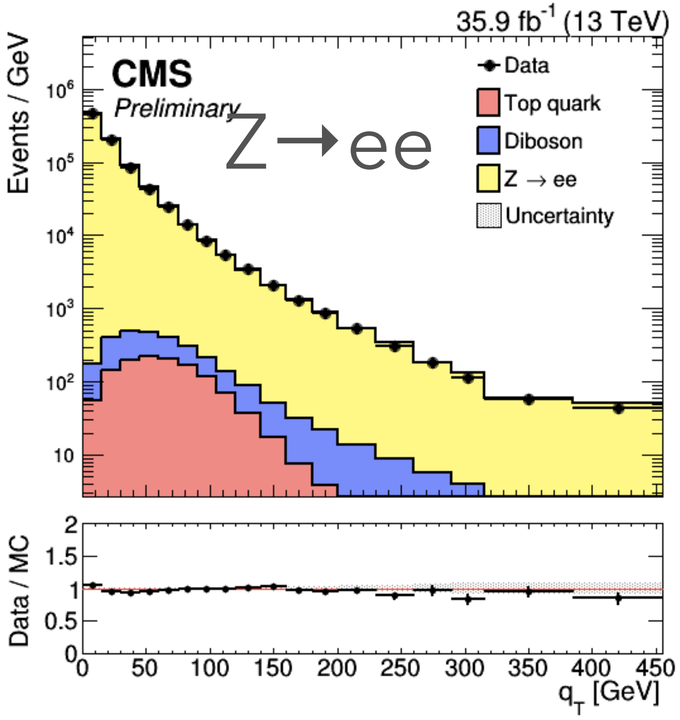
- JEC Summer16_23Sep2016V4
- MC reweighted to match data in number of vertices

selections

Z→ll for fake p_T^{miss} studies

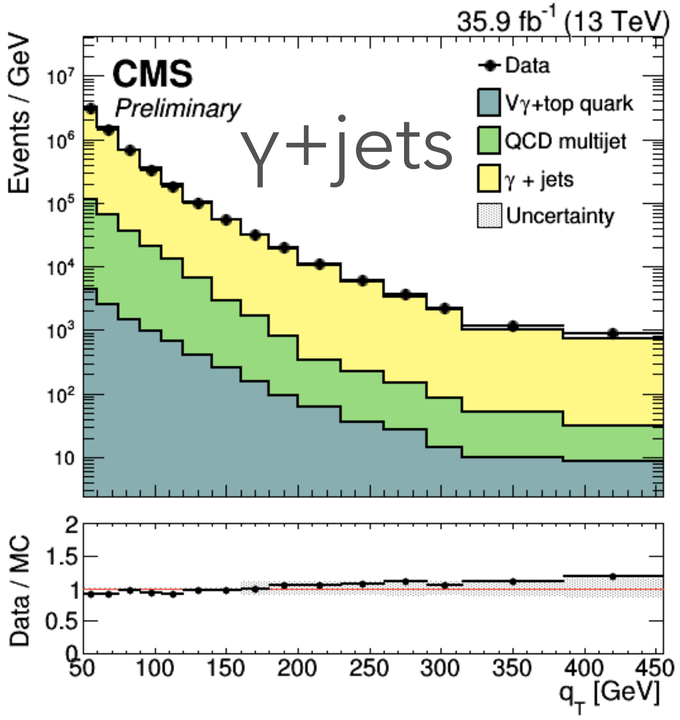
- muons: medium ID, p_T > 25, 20 GeV
- electrons: tight ID, p_T 25, 20 GeV
- compatible with Z boson mass (80 < m_{ll} < 100 GeV)
- additional leptons (p_T > 20 GeV) vetoed





γ+jets for fake p_T^{miss} studies

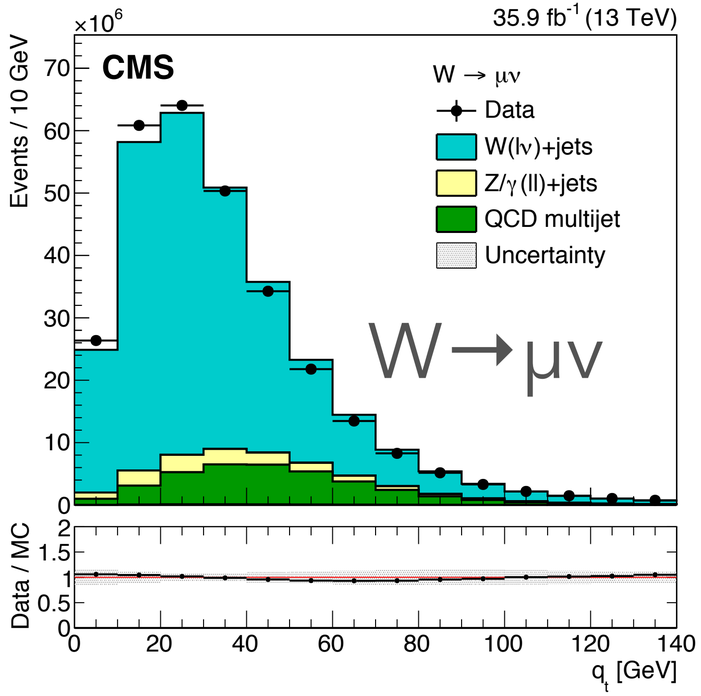
- photons: tight ID, p_T > 50 GeV
- at least 1 AK4 jet with p_T > 40 GeV
- leptons (p_T > 20 GeV) vetoed

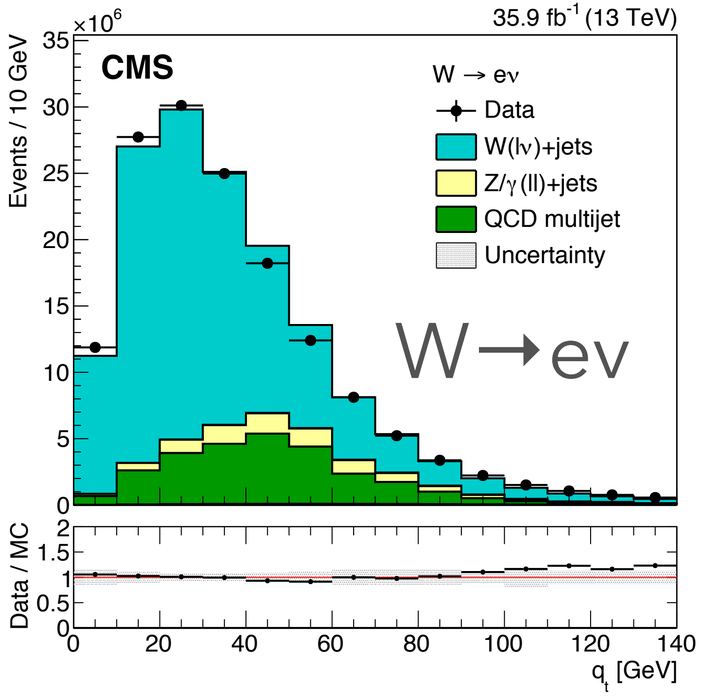


selections

W →lν for genuine p_T^{miss} studies

- single muons: tight ID, p_T > 25 GeV
- single electrons: tight ID, p_T > 26 GeV
- events with b-tagged jets or additional leptons (p_T > 10 GeV) rejected





mono-jet for p_T^{miss} filter studies

- leading AK4 jet p_T > 100 GeV
- p_T^{miss} > 250 GeV
- veto events with
  - electrons/muons with p_T > 10 GeV
  - taus with p_T > 18 GeV
  - photon with p_T >15 GeV
  - b-tagged jet with p_T > 20 GeV

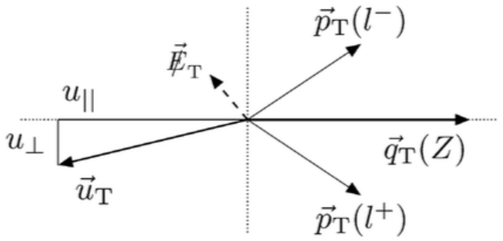
di-jet for p_T^{miss} filter studies

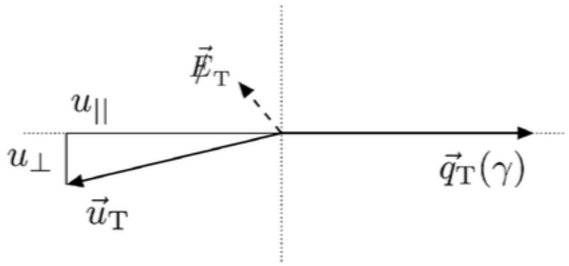
- leading AK4 jet p_T > 500 GeV
- trailing AK4 jet p_T > 200 GeV
- p_T^{miss} > 250 GeV
- same veto as mono-jet selection

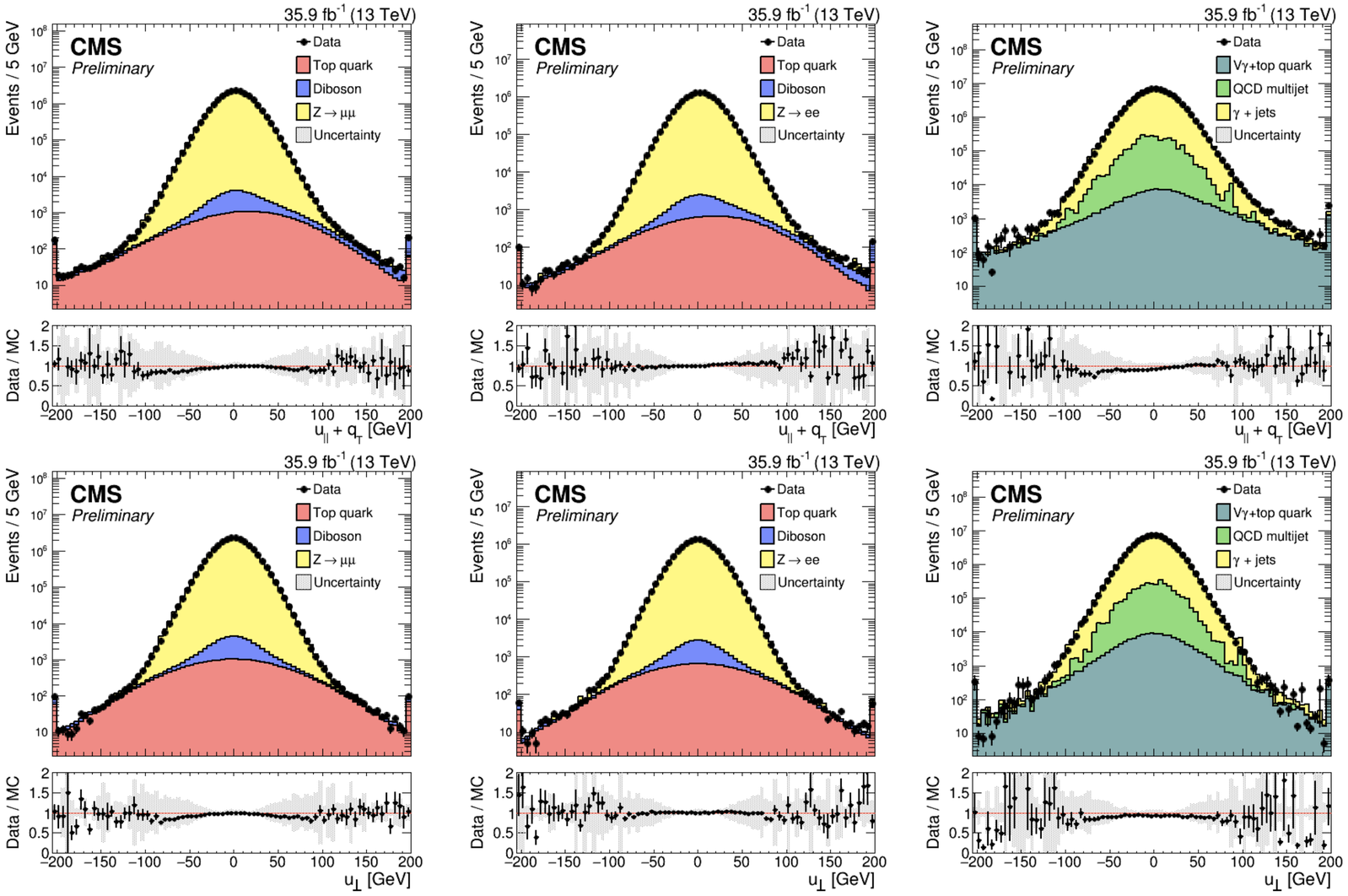
performance of PF p_T^{miss} algorithm

Projections of the hadronic recoil

- PF $u_{||}+q_T$ (top row)
- PF $u_\perp$ (bottom row)
- good data-simulation agreement







performance of PF p_T^{miss} algorithm

resolution as a function of number of vertices:

- FWHM vs. RMS: similar performance

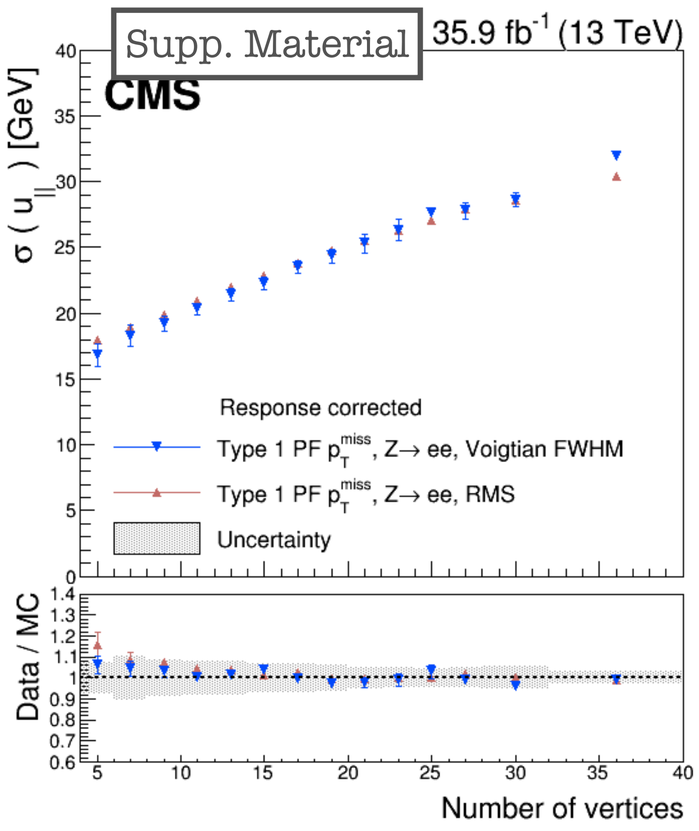
RMS

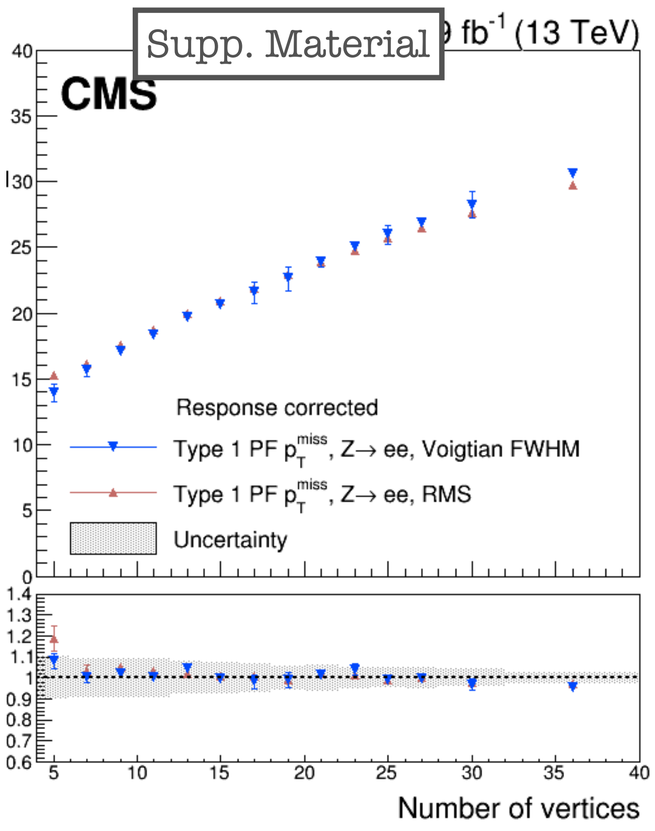
PAPER

Process	σ_c(data)[GeV]	σ_c(MC)[GeV]	σ_{PU}(data)[GeV]	$R_r = \sigma_{PU}(\text{data})/\sigma_{PU}(\text{MC})$
$u_{\|\|}$ component				
Z→ $\mu\mu$	13.9 ± 0.07	11.9 ± 1.53	3.82 ± 0.01	0.95 ± 0.04
Z→ ee	14.6 ± 0.09	12.0 ± 1.09	3.80 ± 0.02	0.95 ± 0.03
γ+jets	12.2 ± 0.10	10.2 ± 1.98	3.97 ± 0.02	0.97 ± 0.05
$u_\perp$ component				
Z→ $\mu\mu$	10.3 ± 0.08	8.58 ± 2.2	3.87 ± 0.01	0.97 ± 0.04
Z→ ee	10.7 ± 0.10	8.71 ± 1.8	3.89 ± 0.01	0.96 ± 0.04
γ+jets	9.04 ± 0.11	6.93 ± 2.7	3.94 ± 0.01	0.97 ± 0.04

Voigtian FWHM

Process	σ_c(data)[GeV]	σ_c(MC)[GeV]	σ_{PU}(data)[GeV]	$R_r = \sigma_{PU}(\text{data})/\sigma_{PU}(\text{MC})$
$u_{\|\|}$ component				
Z→ $\mu\mu$	11.9 ± 0.40	10.2 ± 3.26	4.26 ± 0.03	0.97 ± 0.08
Z→ ee	12.6 ± 0.50	11.3 ± 3.26	4.23 ± 0.05	0.97 ± 0.07
γ + jets	12.1 ± 0.08	9.61 ± 3.04	4.09 ± 0.01	0.97 ± 0.06
$u_\perp$ component				
Z→ $\mu\mu$	8.51 ± 0.32	7.3 ± 2.57	4.23 ± 0.02	0.98 ± 0.05
Z→ ee	9.03 ± 0.43	5.9 ± 7.42	4.21 ± 0.03	0.96 ± 0.09
γ + jets	9.22 ± 0.08	6.5 ± 4.62	4.02 ± 0.01	0.96 ± 0.06



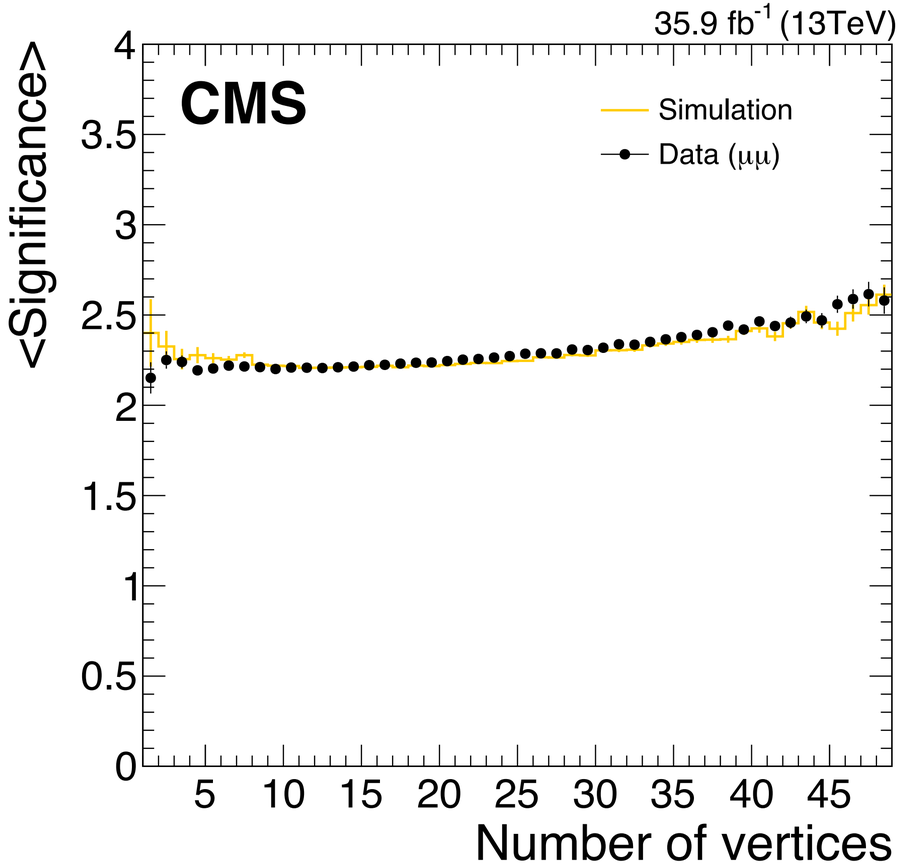


p_T^{miss} significance

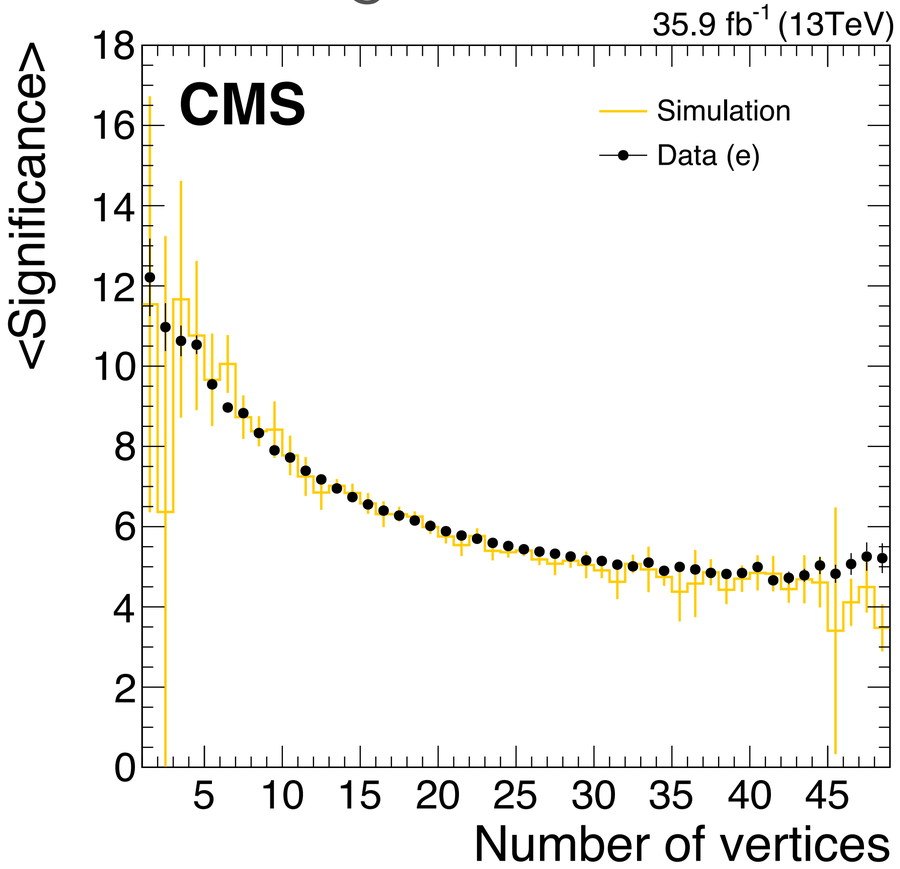
PAPER

robustness against pileup evaluated

di-muon



single electron



p_T^{miss} filters

- primary vertex filter
- beam halo filter
- HBHE noise filter
- HBHEiso noise filter
- ECAL TP filter
- ee badSC noise filter
- bad muon filter
- bad charged hadron filter
- twiki

anomalous p_T^{miss} arise from many sources

- Beam-halo
  - Real showers with non collision origins
  - Identified by matching hits in CSC and deposits in the calorimeters
- Noise in calorimeters
  - Noise in the hybrid photodiode and readout box of the HCAL
  - Direct particle interactions with the light guides and photomultipliers tubes of the forward calorimeter
  - ECAL super crystals producing anomalous pulses
  - absence of crystal level information in few ECAL towers
- Dead parts in the detector
- Object misreconstruction
  - in 2016, high p_T tracks misreconstructed as PF muons

Strategies to reject these events: cleaning at reconstruction level and filters at analysis level

How to get the weight factor for α_i

$$\alpha_i^C = \log\left[\sum_{j\in \mathrm{Ch,LV}} \frac{p_{T,j}}{\Delta R_{ij}}\,\Theta(R_0 - \Delta R_{ij})\right]$$

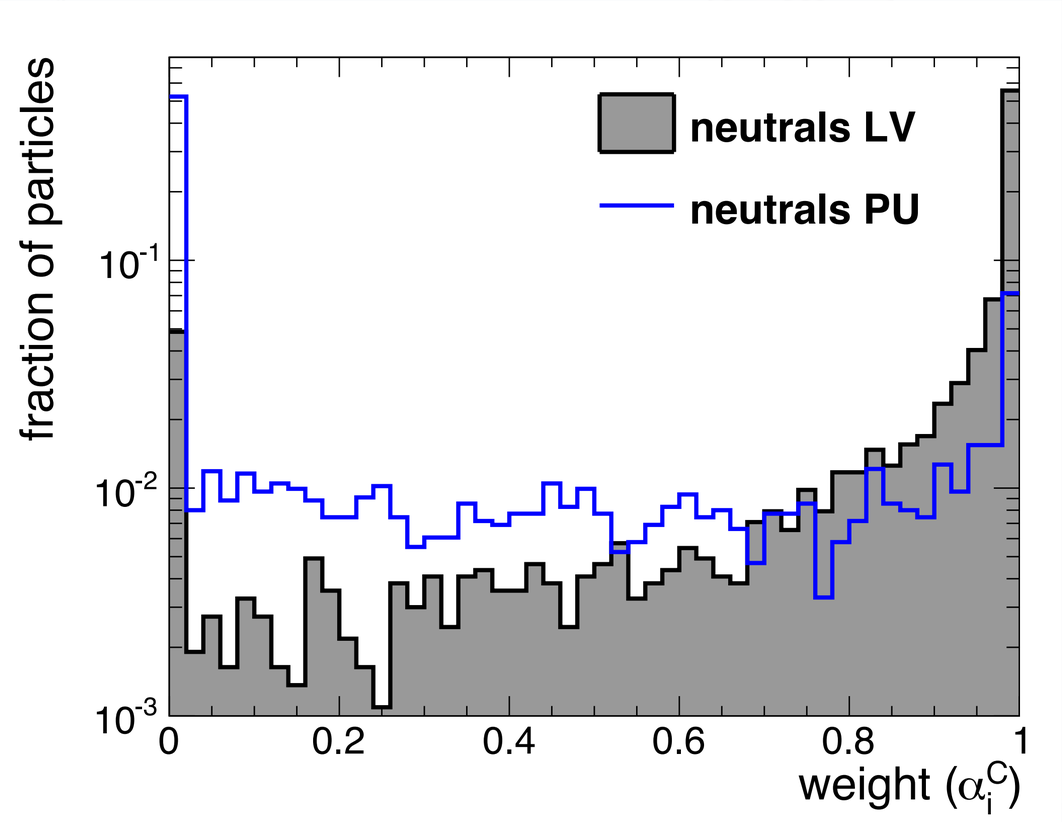
for a particle *i* with nearby particles *j*

1. define a local metric, α, that differs between pileup (PU) and leading vertex (LV)

2. using tracking information, define unique distributions of α for PU and LV

3. for the neutrals, ask "how PU-like is α for this particle?", compute a weight for how LV-like it is

4. reweight the four-vector of the particle by this weight



p_T^{miss} significance

true p_T^{miss} observed p_T^{miss}

$$\mathcal{S} = 2\ln\left(\frac{\mathcal{L}(\vec{\varepsilon} = \sum \vec{\varepsilon}_i)}{\mathcal{L}(\vec{\varepsilon} = 0)}\right)$$

null hypothesis: true $p_T^{miss} = 0$

p_T^{miss} significance

- quantifies the degree of compatibility of the p_T^{miss} with 0
- the significance is defined as a log-likelihood ratio
- a high value of S is an indication that the
  - p_T^{miss} observed in the event is not well explained by resolution smearing alone
  - suggesting that the event may contain unseen objects such as neutrinos or more exotic weakly interacting particles.
- to a good approximation, $\mathcal{L}(\vec{\varepsilon})$ has the form of a Gaussian distribution
  - → significance can be expressed in terms of a covariance matrix $\mathcal{S} = \left(\sum \vec{\varepsilon}_i\right)^{\mathrm{T}} \mathbf{V}^{-1} \left(\sum \vec{\varepsilon}_i\right)$
  - computed using all clustered objects and unclustered energy
  - two methods used to estimate the covariance matrix for the unclustered energy

p_T^{miss} significance

standard technique

- assuming resolution of unclustered PF candidates is isotropic in transverse plane

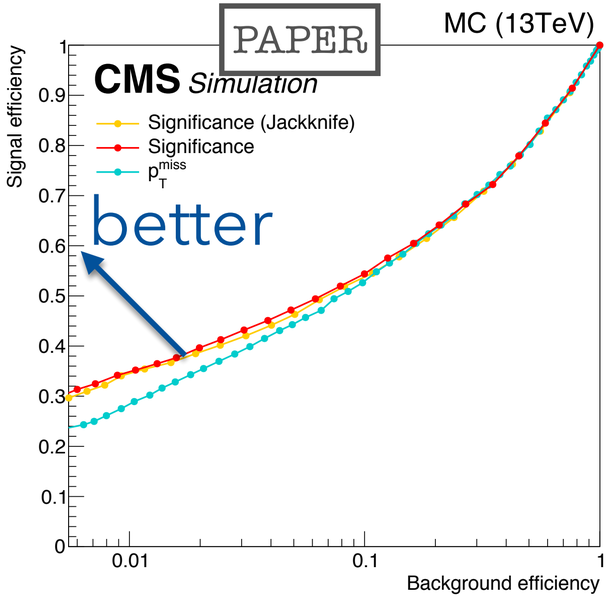
jackknife technique

- does not assume an isotropic covariance matrix including off-diagonal elements
- calculated using "delete-1" technique

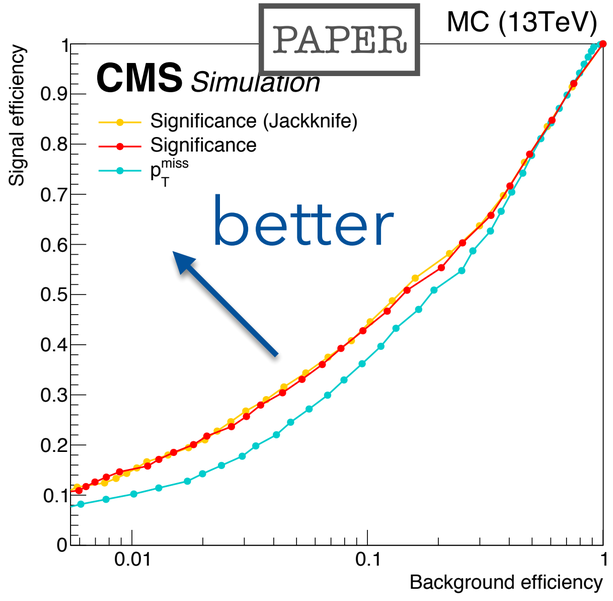
both techniques compared to p_T^{miss}

- background: processes with no intrinsic p_T^{miss}
- signal: processes with intrinsic p_T^{miss}
- similar performance
- improvement with respect to regular p_T^{miss}

di-muon



single electron

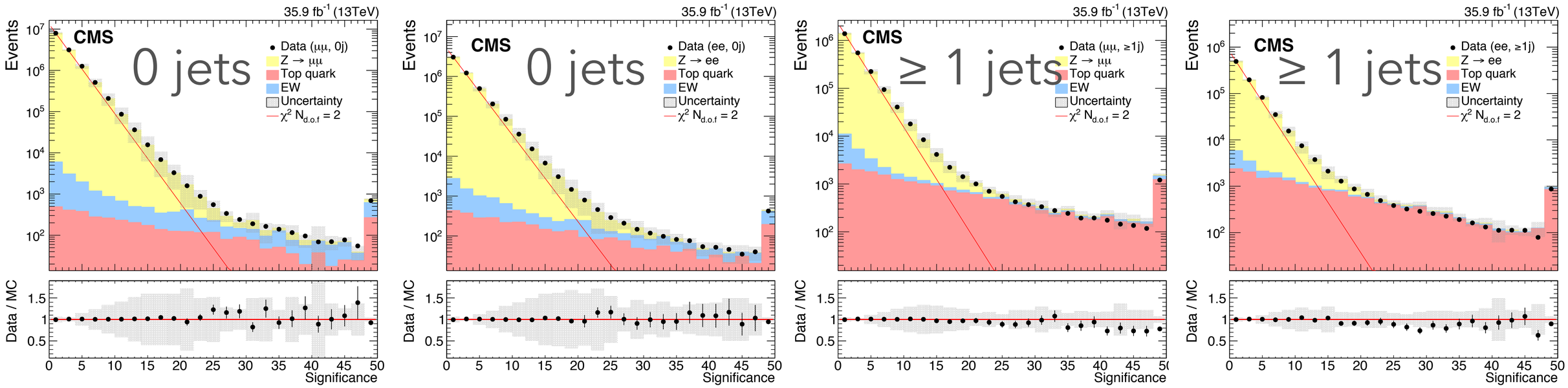


p_T^{miss} significance in Z→ll

performance of p_T^{miss} significance in instrumental p_T^{miss} events

$$\mathcal{S} = 2\ln\left(\frac{\mathcal{L}(\vec{\varepsilon} = \sum \vec{\varepsilon}_i)}{\mathcal{L}(\vec{\varepsilon} = 0)}\right)$$

- using standard method
- in Z→ll events, with no jets or ≥ 1 jets
  - 0 jet requirement to further enhance the fake p_T^{miss} contribution
- chi2 with 2 dof follow the distribution with no genuine p_T^{miss}



p_T^{miss} significance in W→lν

performance of p_T^{miss} significance in genuine p_T^{miss} events

$$\mathcal{S} = 2\ln\left(\frac{\mathcal{L}(\vec{\varepsilon} = \sum \vec{\varepsilon}_i)}{\mathcal{L}(\vec{\varepsilon} = 0)}\right)$$

- using standard covariance matrix estimation
- in W→lν events, with no jets or ≥ 1 jets
  - 0 jet requirement to enhance fake p_T^{miss} contribution
- chi2 with 2 dof follow the distribution with no genuine p_T^{miss}