Alternative angular variables for QCD multijet background event suppression in SUSY searches at the LHC

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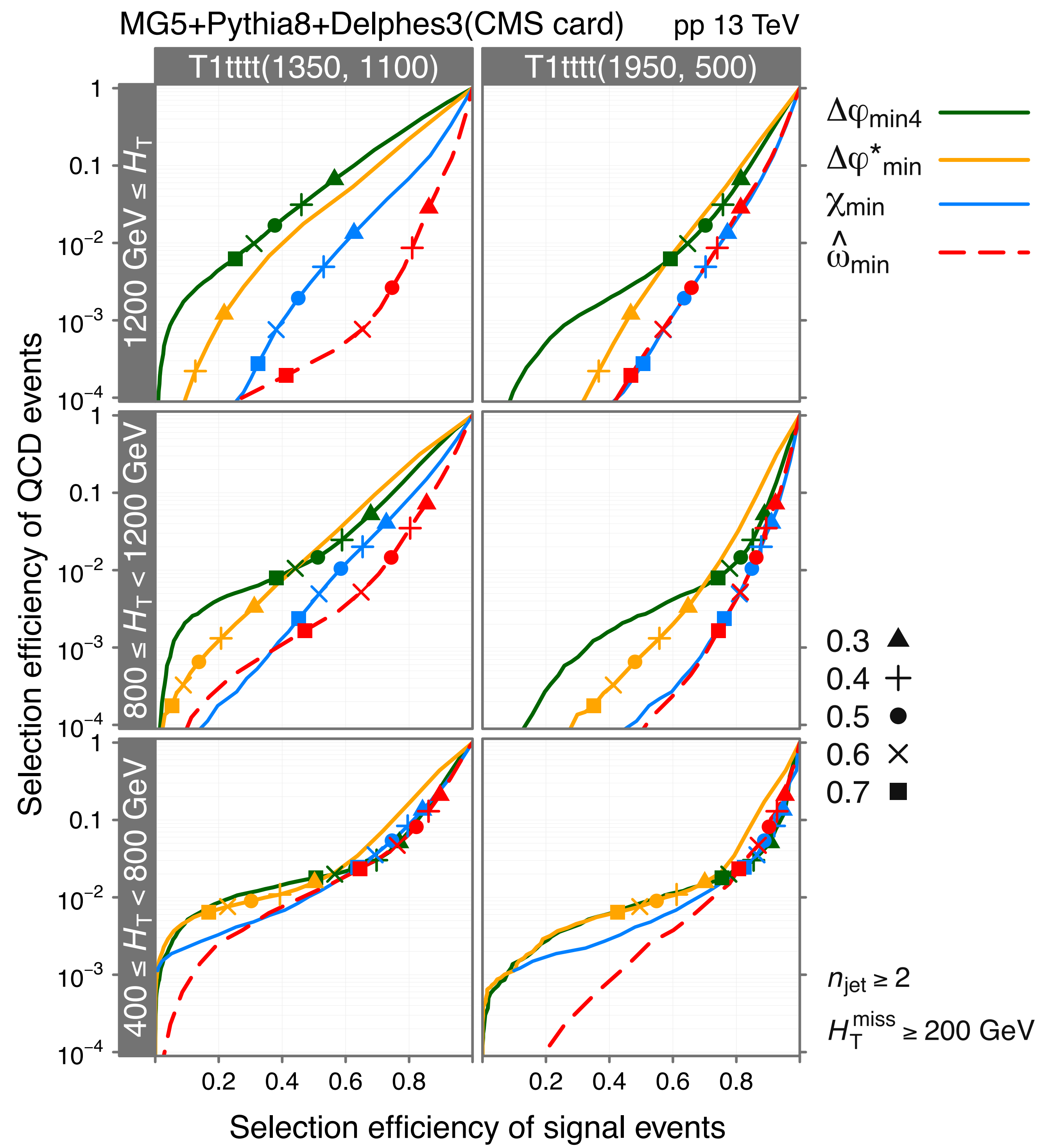
14 December 2017

SUSY 2017, TIFR, Mumbai

http://www.tifr.res.in/~susy17/



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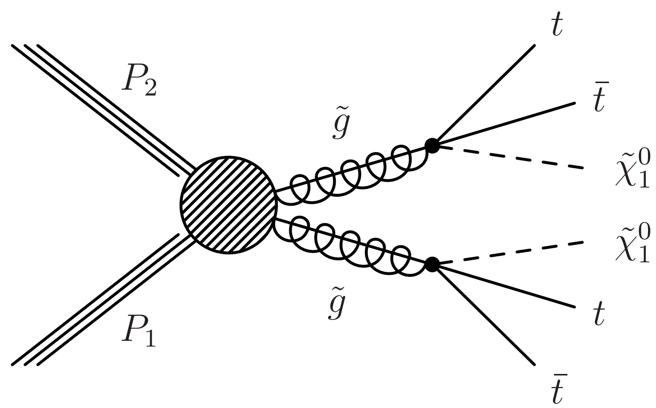
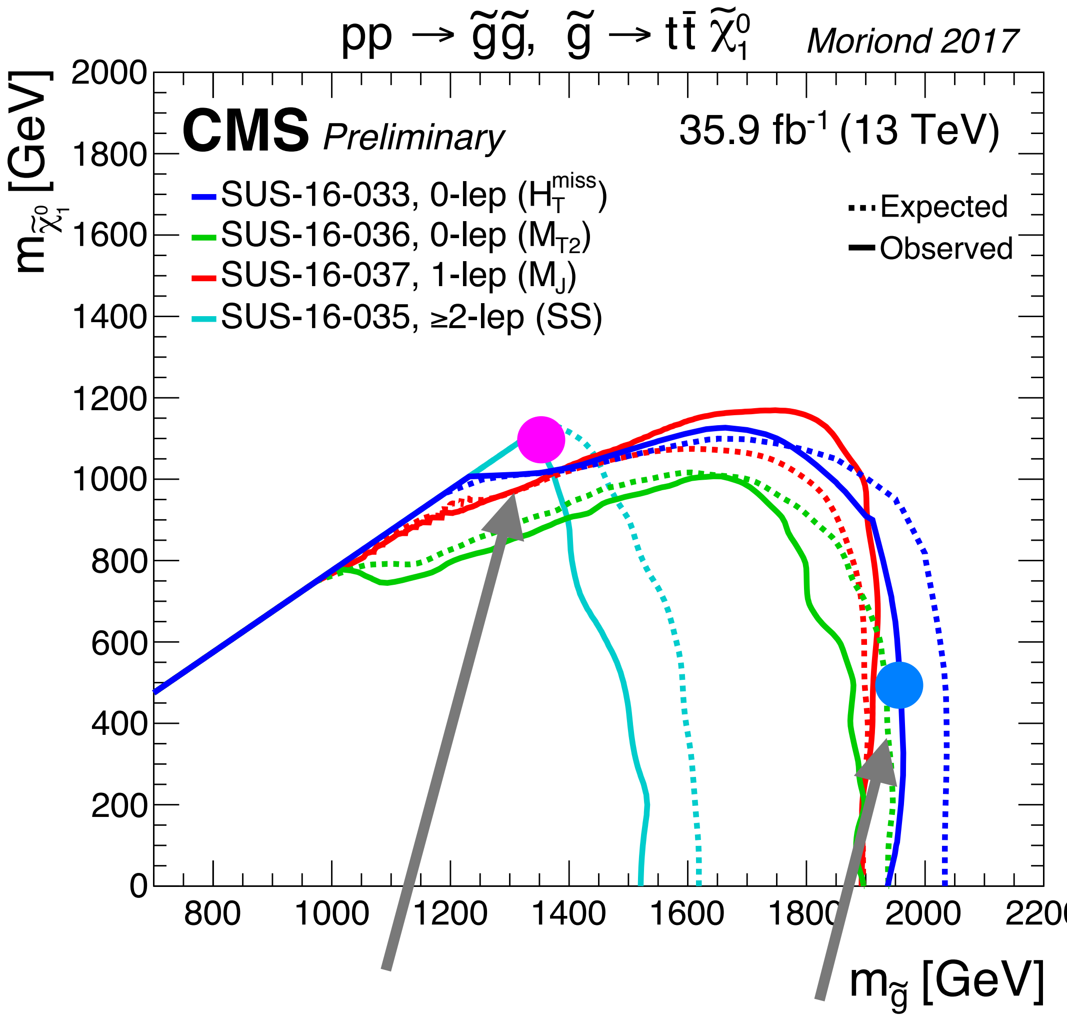
Benchmark signal models

2 mass points from **T1tttt** (**Gtt**) near the exclusion contour of recent results

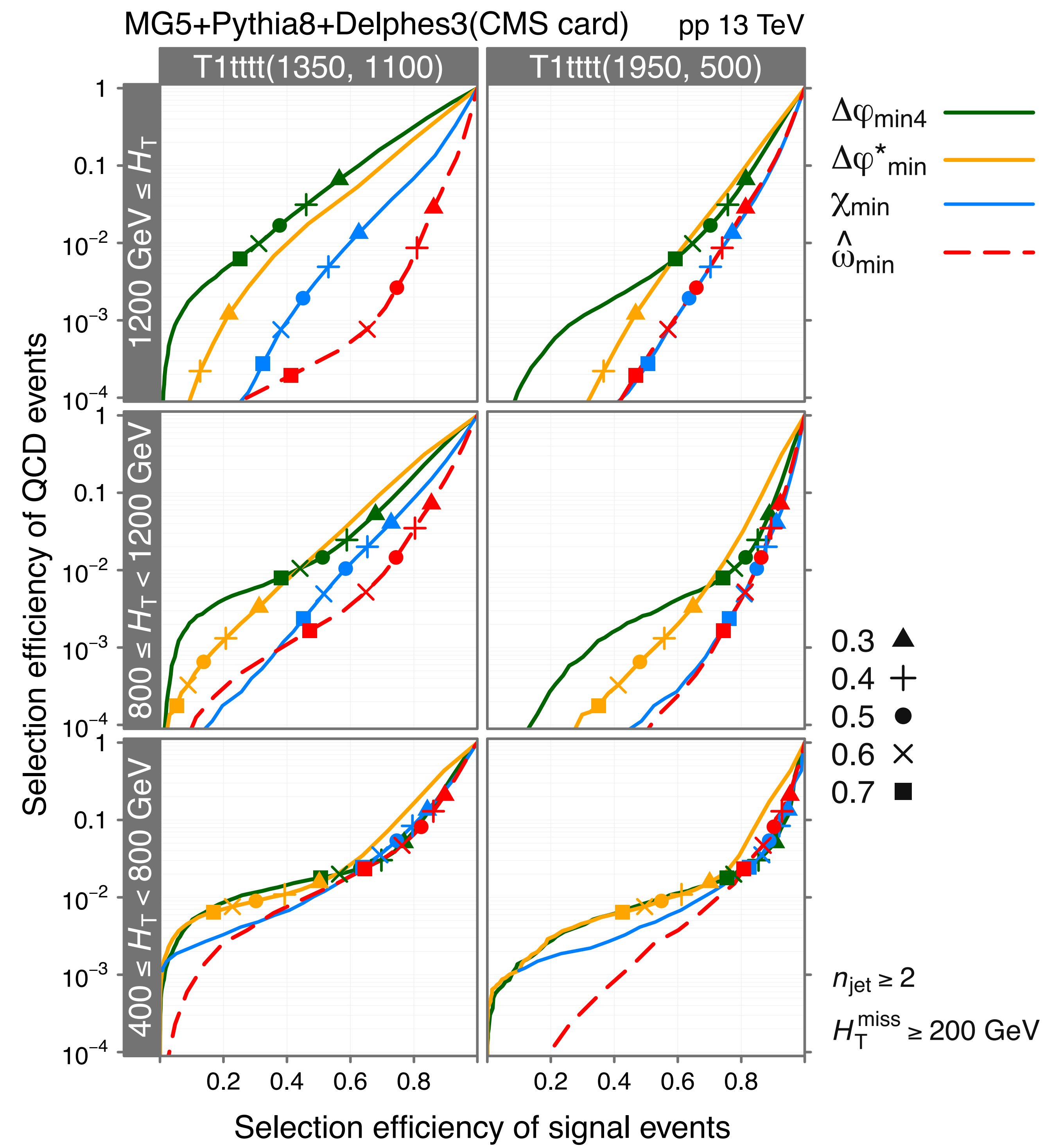
High jet multiplicity final state





compressed spectrum   high gluino mass

ROC curves



New variables: $\chi_{\min}$ $\hat{\omega}_{\min}$

HT: $H_{\mathrm{T}} \equiv \sum_{i\in\mathrm{jets}} |\vec{p}_{\mathrm{T}i}|$ MHT: $\vec{H}_{\mathrm{T}}^{\mathrm{miss}} \equiv -\sum_{i\in\mathrm{jets}} \vec{p}_{\mathrm{T}i}$

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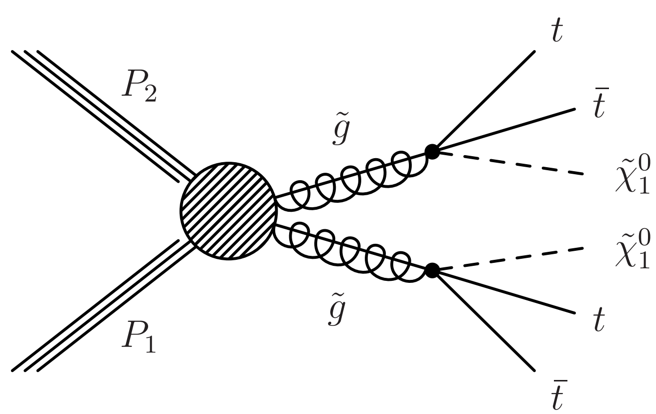

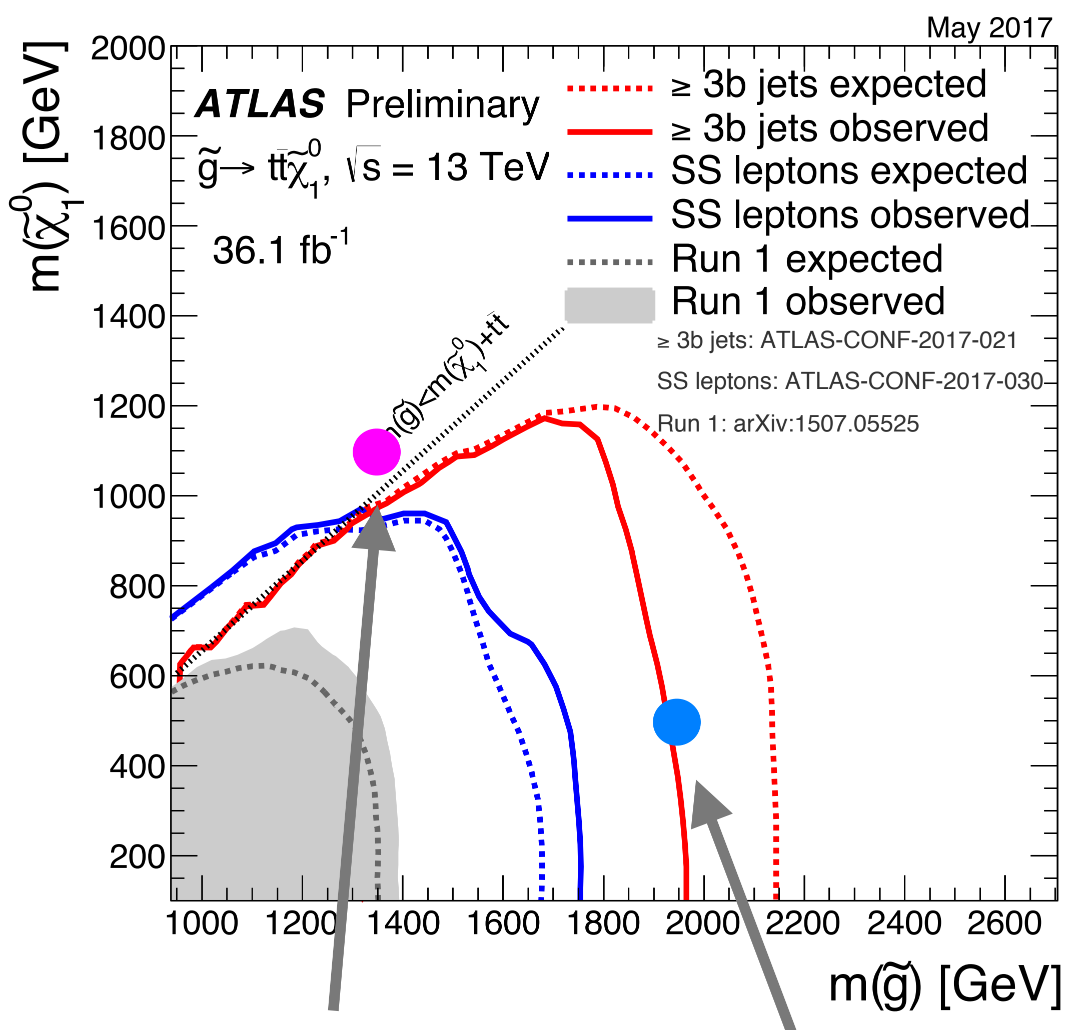

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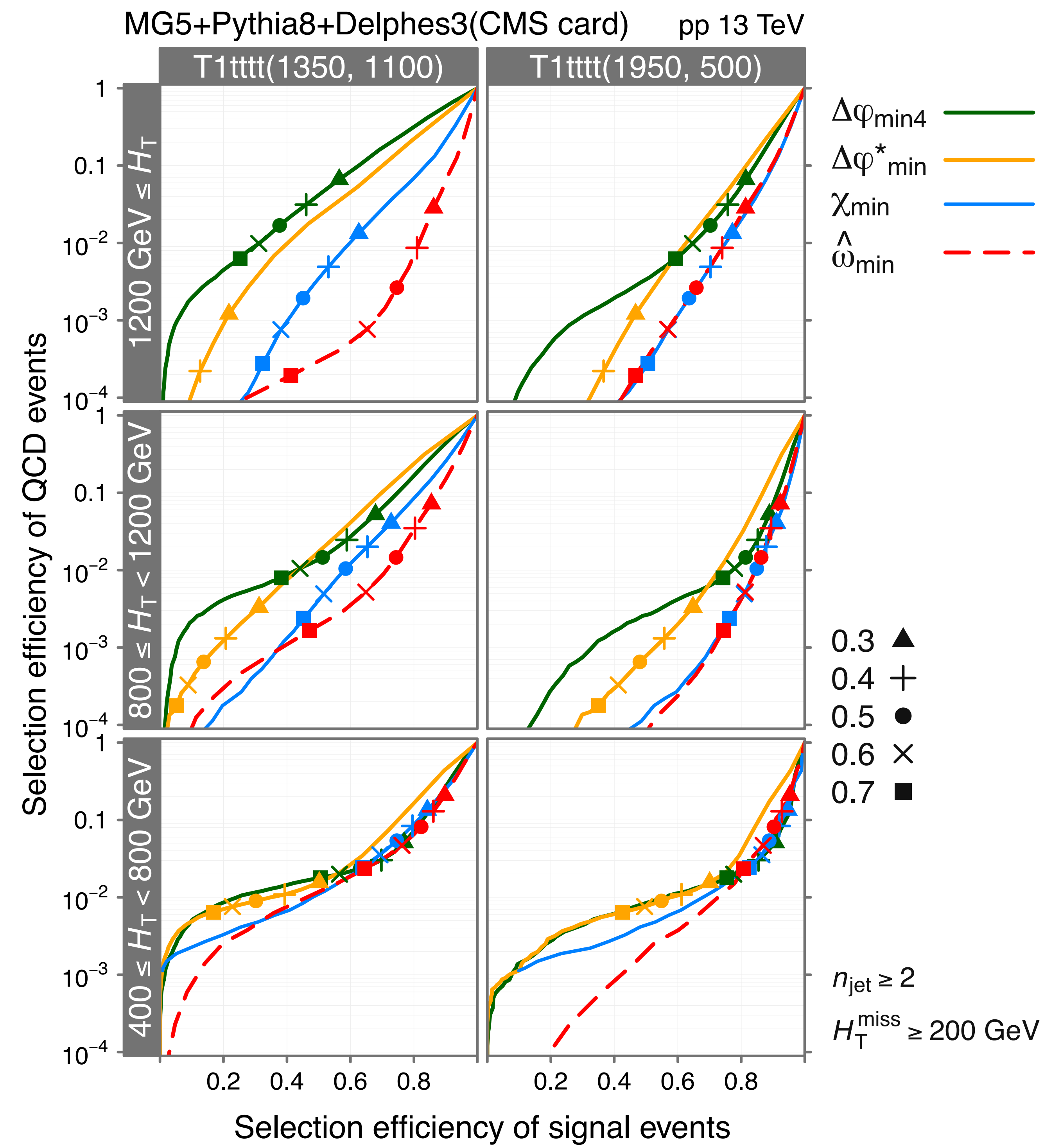

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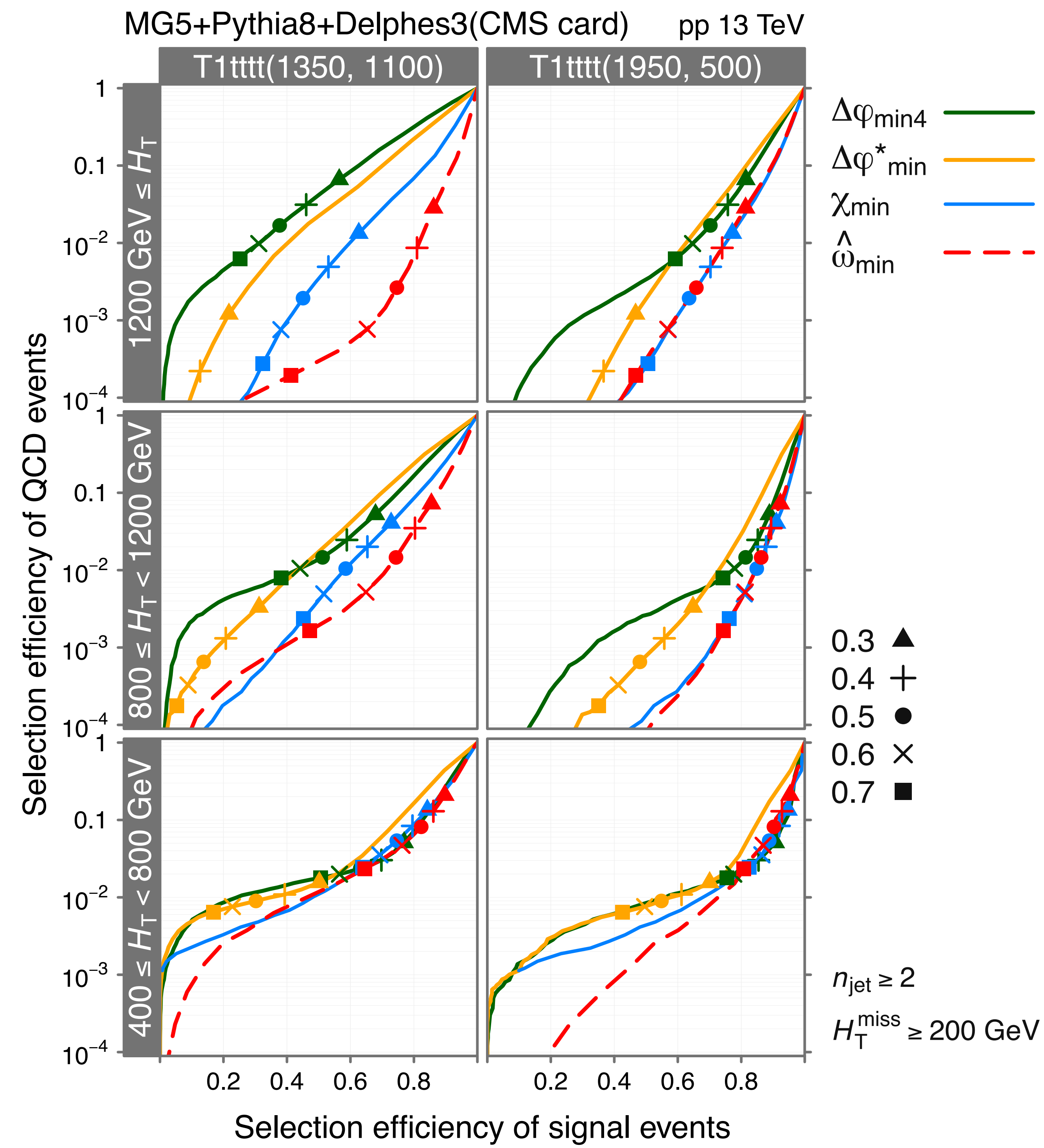
Contents

- QCD events with large MET (MHT)
- Review of $\Delta\varphi_i$ cut
- Review of $\Delta\varphi^{*}_{\mathrm{min}}$ cut
- Alternative angle ω_i
- New variables
- Performance in simulated events
- Summary
- Backup slides
  - simulated event sample
  - comparison of Delphes CMS and ATLAS cards



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QCD events with large MET (or MHT)

- Why do QCD events have large MET (or MHT)?

MHT

$$\vec{H}_{\mathrm{T}}^{\mathrm{miss}} \equiv -\sum_{i \in \mathrm{jets}} \vec{p}_{\mathrm{T}i}$$

note: in this talk, I will mostly use MHT instead of MET.

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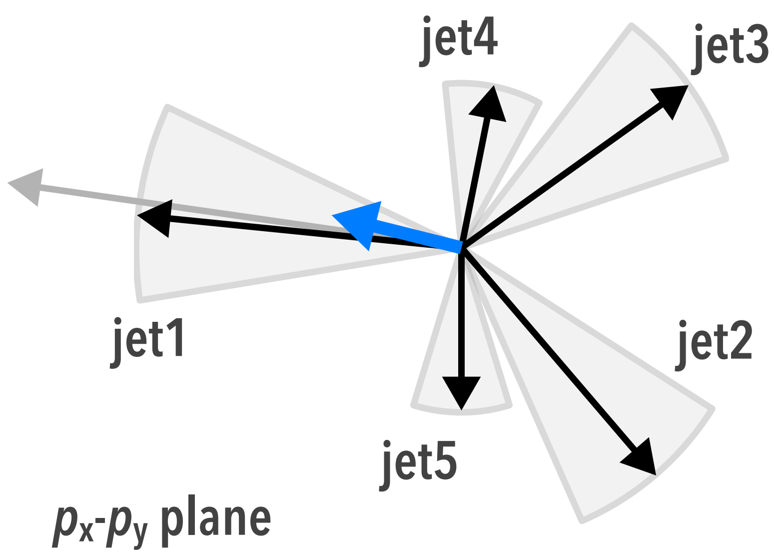

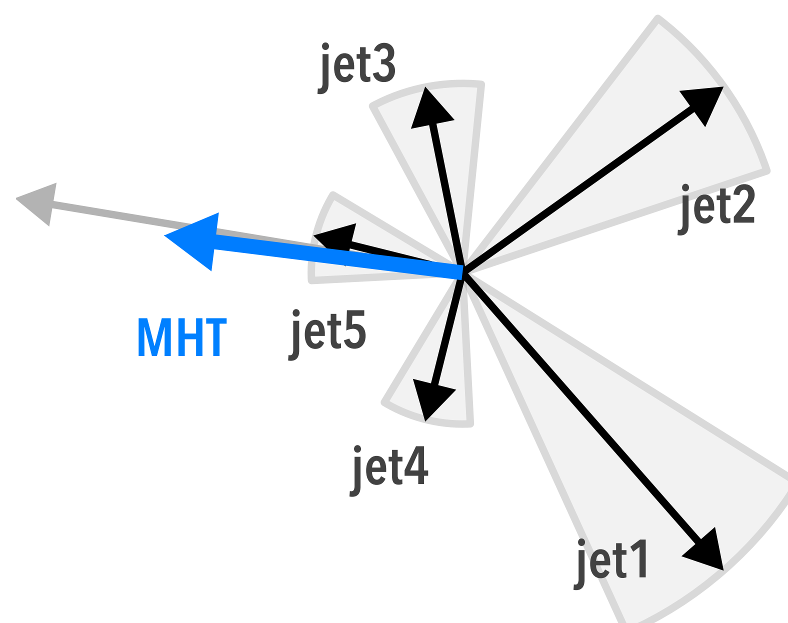

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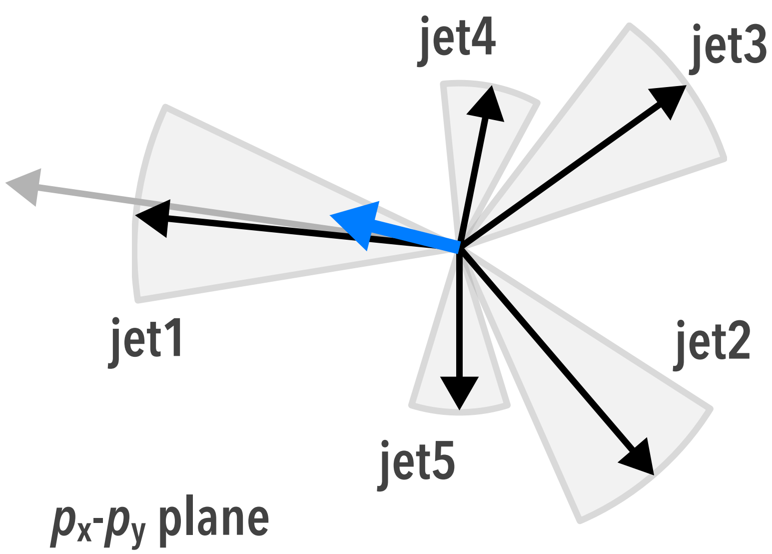

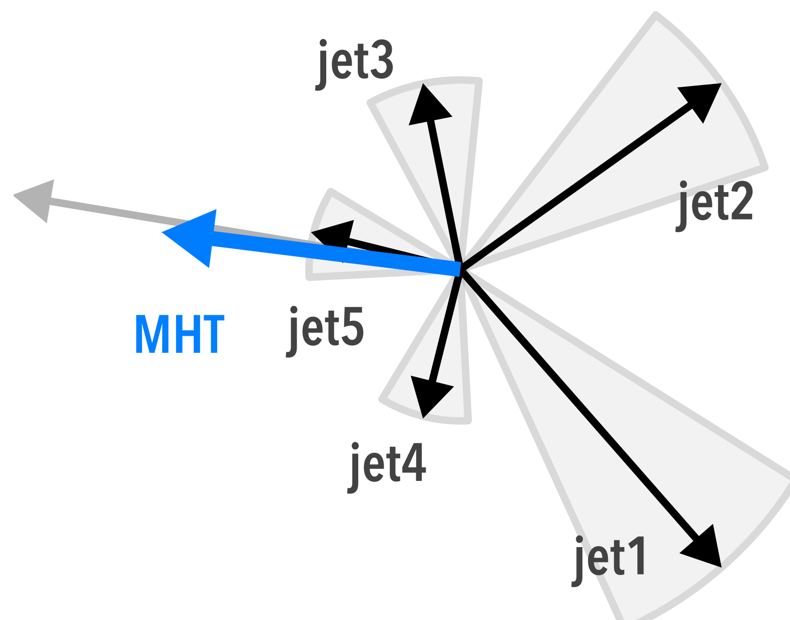

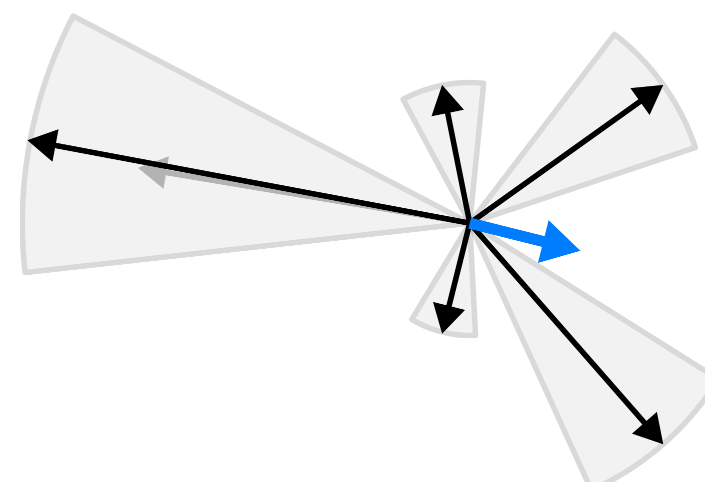

MHT

$$\vec{H}_T^{miss} \equiv -\sum_{i \in jets} \vec{p}_{Ti}$$

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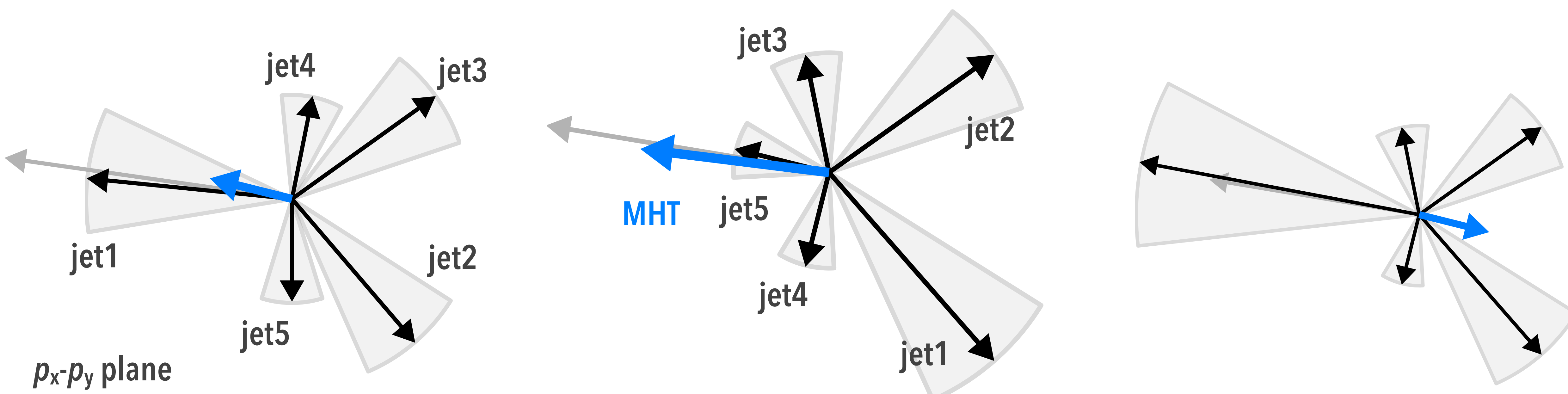


- How do you reject these QCD events without much reducing the signal acceptance?

MHT

$$\vec{H}_T^{\text{miss}} \equiv -\sum_{i \in \text{jets}} \vec{p}_{Ti}$$

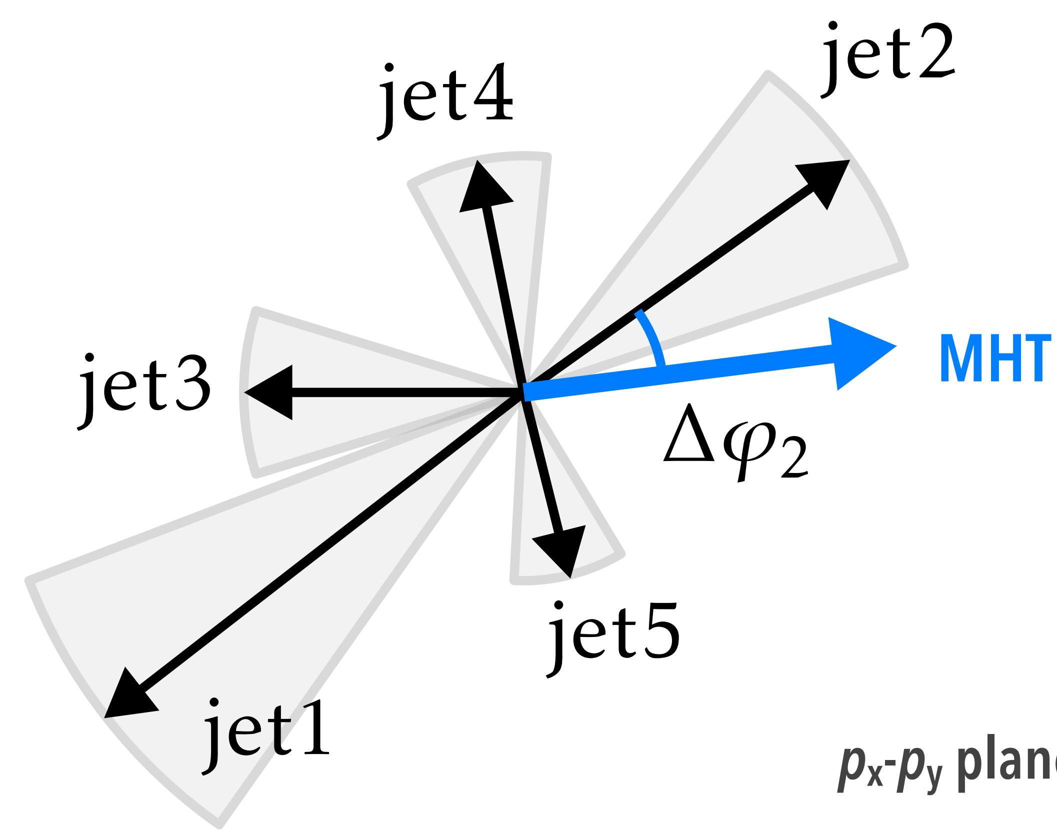
note: in this talk, I will mostly use MHT instead of MET.

The angle $\Delta\varphi_i$

- The angle $\Delta\varphi_i$ (delta phi)

$$\Delta\varphi_i \equiv \Delta\varphi(\vec{p}_{\mathrm{T}i}, \vec{H}_{\mathrm{T}}^{\mathrm{miss}})$$

  - widely used to reject QCD events with large MHT (MET) in **all-hadronic** SUSY searches in CMS and ATLAS



p_x-p_y **plane**

e.g., **CMS**, PRD96(2017)032003 (MHT), EPJC77(2017)710 (MT2), arXiv:1710.11188 (top tag), JHEP10(2017)005 (stop), arXiv:1707.07274 (sbottom), arXiv:1709.04896 (higgsino)

ATLAS, arXiv:1712.02332 (Meff), arXiv:1711.01901 (3b), arXiv:1708.09266 (sbottom), arXiv:1709.04183 (stop), arXiv:1710.11412 (WIMP)

jet *i*	jet with *i*-th highest p_{T}
MHT	$\vec{H}_{\mathrm{T}}^{\mathrm{miss}} \equiv -\sum_{i\in\mathrm{jets}} \vec{p}_{\mathrm{T}i}$

note: $\Delta\varphi_i$ is more commonly defined with MET rather than with MHT. In this talk, however, $\Delta\varphi_i$ is defined with MHT unless stated otherwise.

The $\Delta\varphi_i$ cut

- Typical requirement: $\Delta\varphi_i$ of a few highest-p_T jets in the event be wider than certain angles
  - e.g., $\Delta\varphi_{\min 4} \equiv \min_{i \in \{1,\cdots,4\}} \Delta\varphi_i \geq 0.4$ [arXiv:1711.01901 (ATLAS 3b)] ($\Delta\varphi_i$ defined with MET)

    $\Delta\varphi_1 \geq 0.5, \Delta\varphi_2 \geq 0.5, \Delta\varphi_3 \geq 0.3, \Delta\varphi_4 \geq 0.3$ [PRD96(2017)032003 (CMS MHT)]

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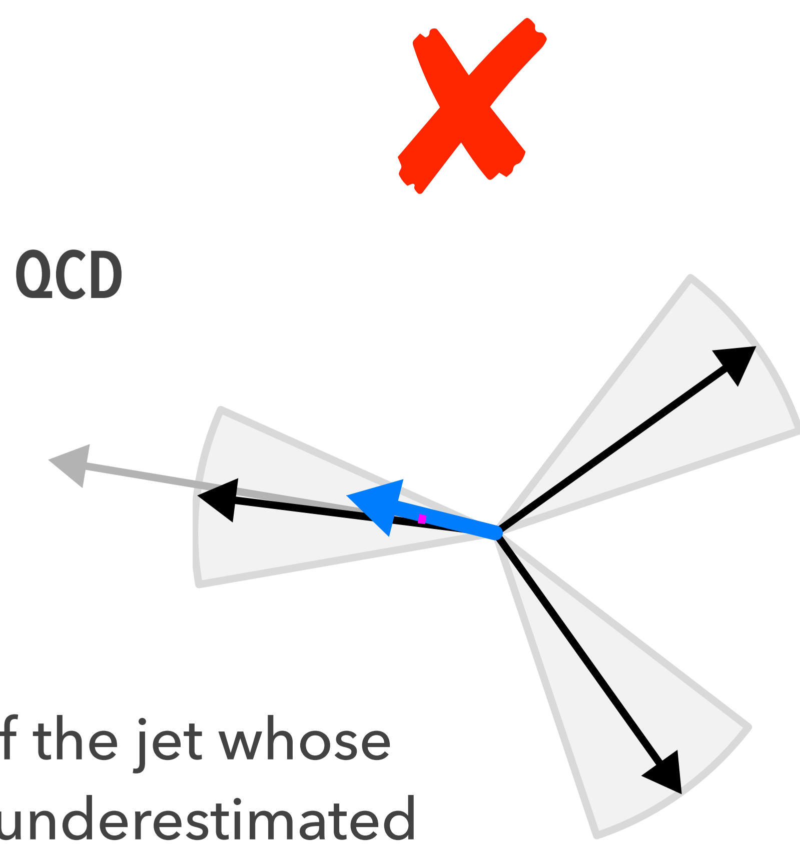
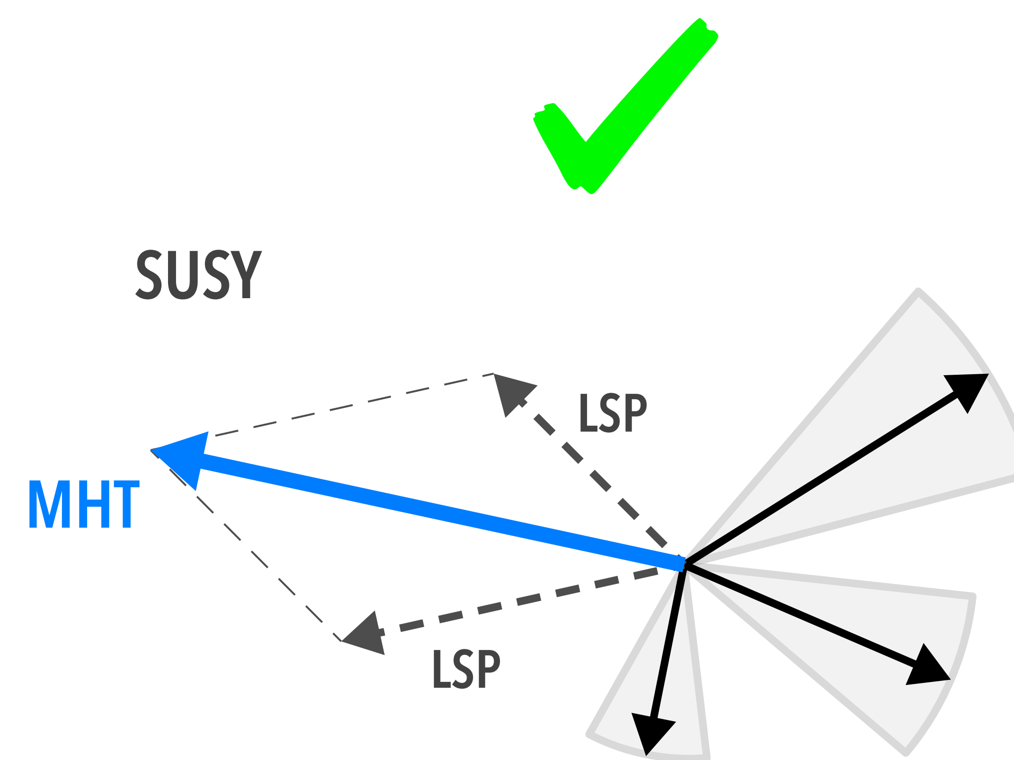


$\Delta\varphi_i$ of the jet whose p_T is underestimated is narrow



none of $\Delta\varphi_i$ is necessarily narrow

✗ rejected

✓ selected

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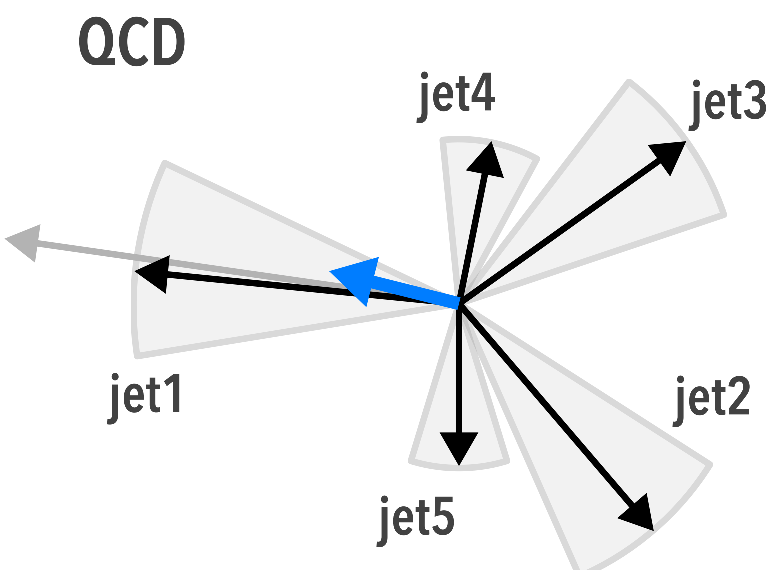
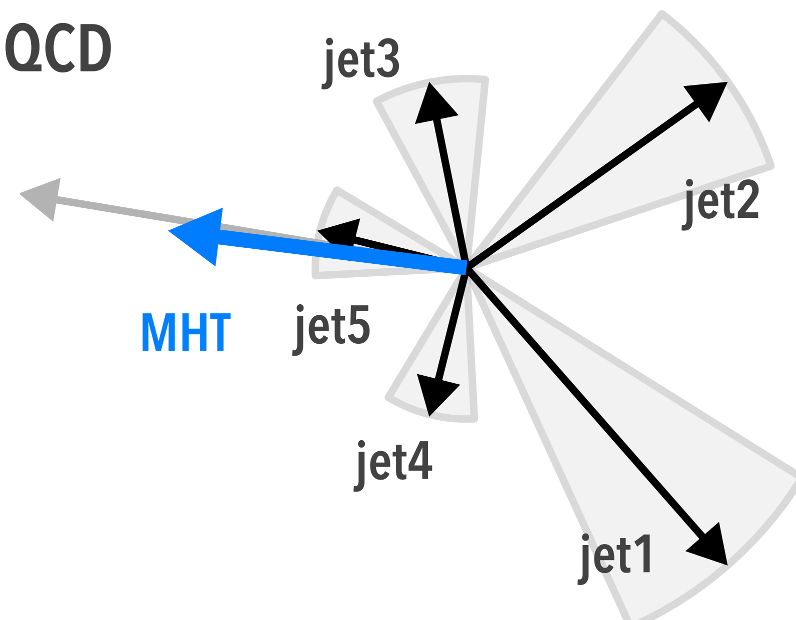
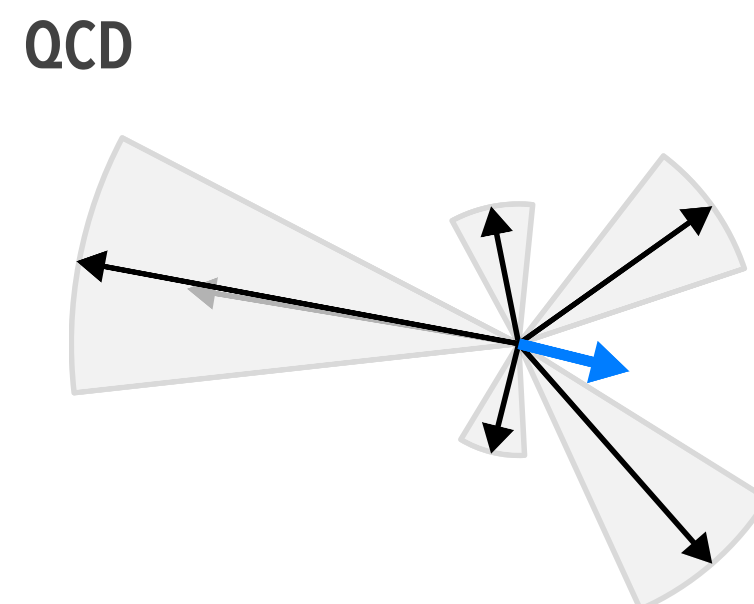


2. a jet p_{T} underestimate (jet p_{T} ranking: low)



3. a jet p_{T} overestimate



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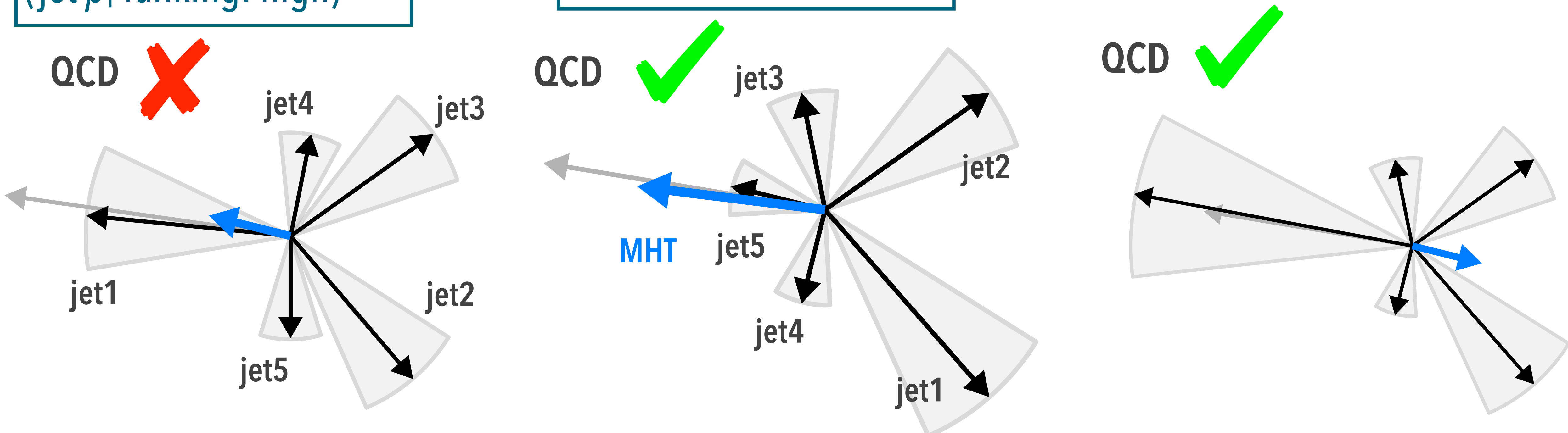

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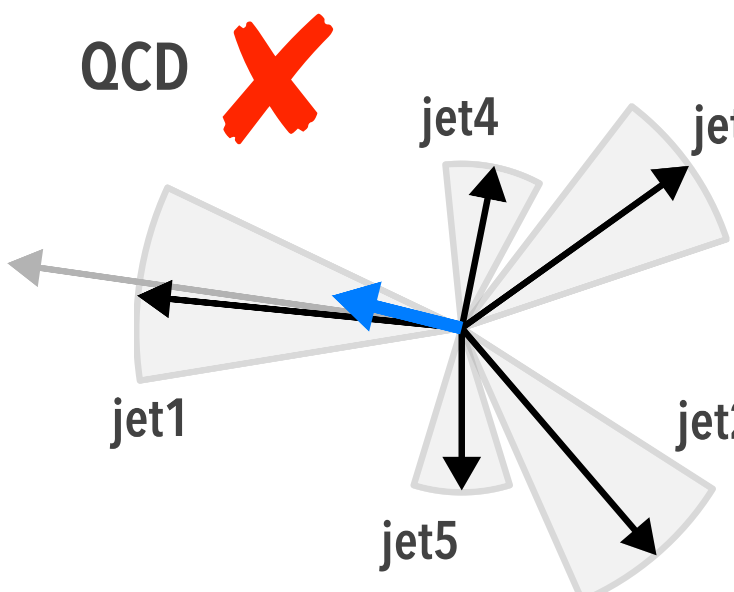
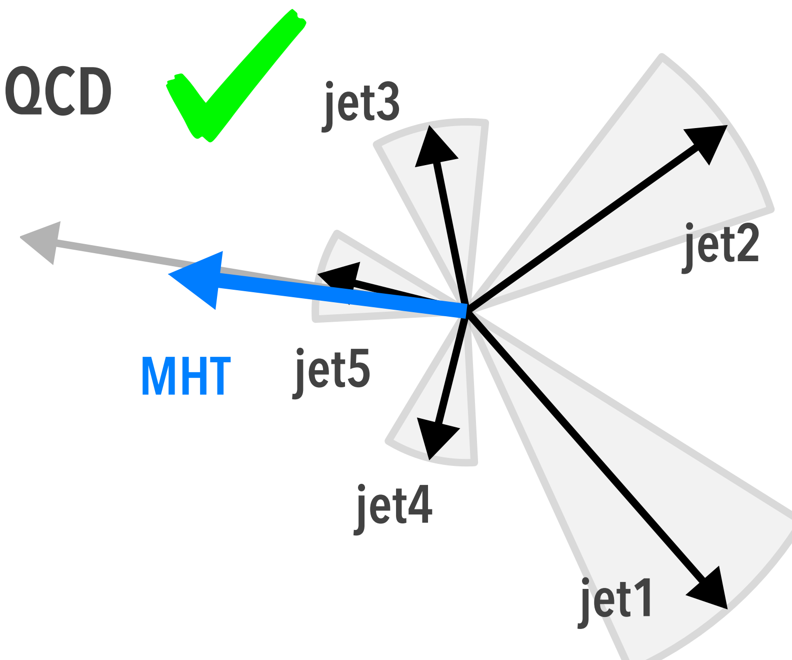


2. a jet p_T underestimate (jet p_T ranking: low)



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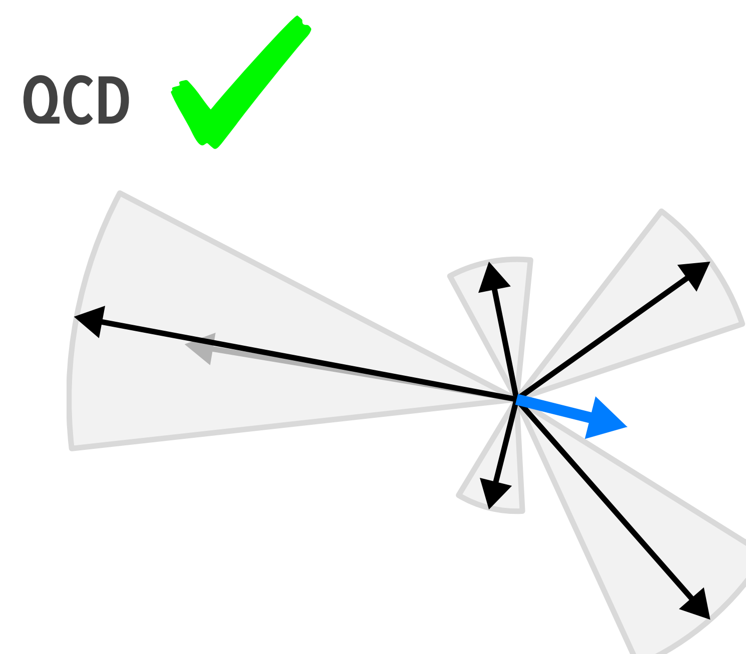
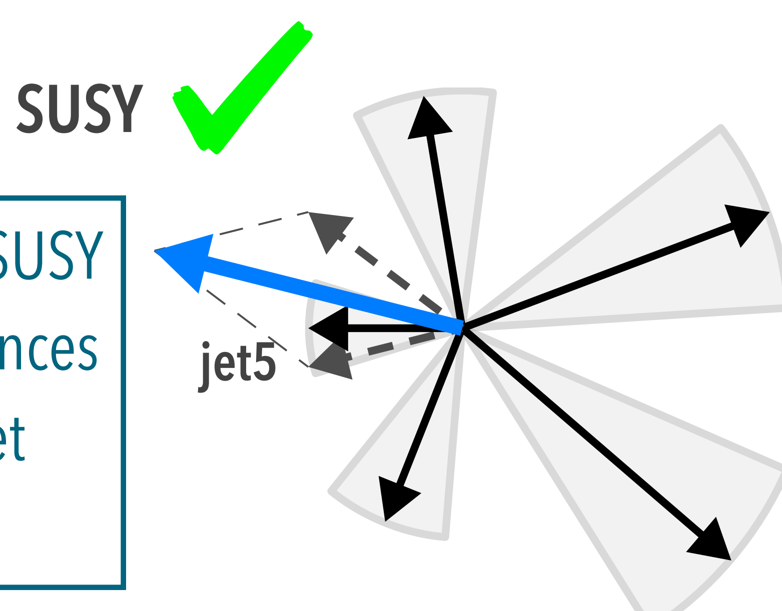
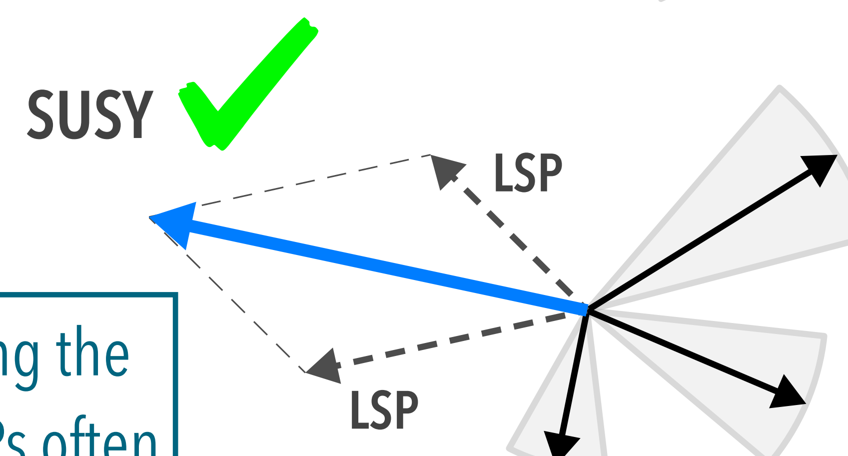


High jet multiplicity SUSY events have high chances to have at least one jet with narrow $\Delta\varphi_i$



Jets receiving the recoil of LSPs often have wide $\Delta\varphi_i$

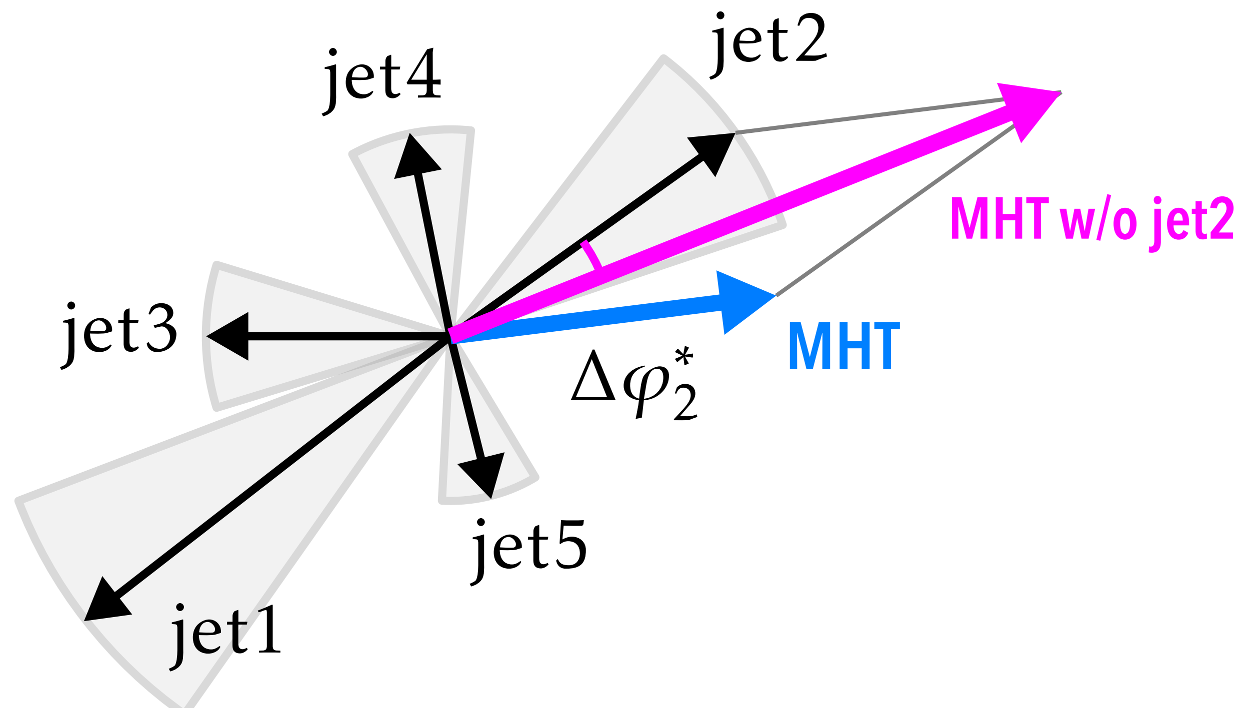


The angle $\Delta\varphi_i^*$

- The angle $\Delta\varphi^*_i$ (delta phi star)

$$\Delta\varphi_i^* \equiv \Delta\varphi(\vec{p}_{\mathrm{T}i}, \vec{H}_{\mathrm{T}}^{\mathrm{miss}} + \vec{p}_{\mathrm{T}i})$$

The azimuthal angle between a jet *i* and MHT calculated without the jet



- first appeared before Run 1 in [PAS-SUS-09-001, PAS-SUS-10-001 (CMS)]
- used, in early Run 1 analysis, to identify large MHT caused by masked region of calorimeter [PLB698(2011)196 (CMS α_{T})]
- used, in recent Run 2 results, to suppress QCD background to a negligible level [EPJC77(2017)294, PAS-SUS-16-016 (CMS α_{T})]

MHT w/o jet *i*

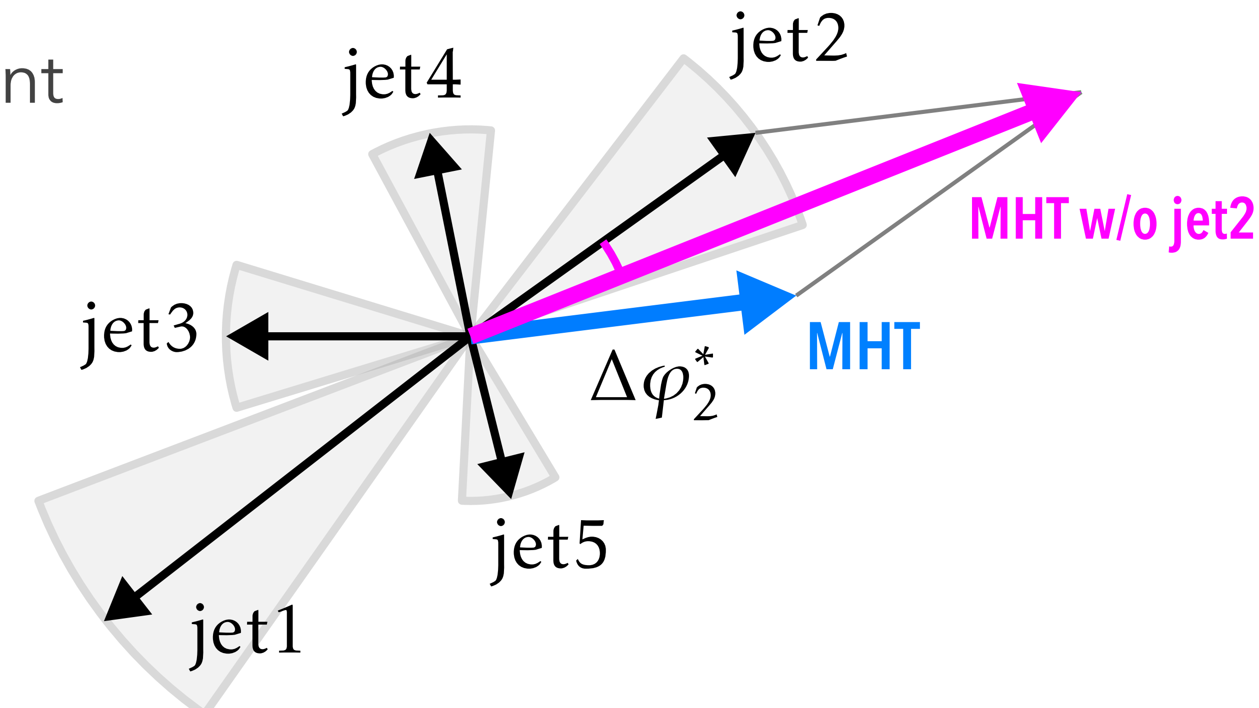
$$-\sum_{\substack{j\in\mathrm{jets}\\ j\neq i}} \vec{p}_{\mathrm{T}j} = -\sum_{j\in\mathrm{jets}} \vec{p}_{\mathrm{T}j} + \vec{p}_{\mathrm{T}i}$$

$$= \vec{H}_{\mathrm{T}}^{\mathrm{miss}} + \vec{p}_{\mathrm{T}i}$$

The angular variable $\Delta\varphi^*_{\text{min}}$

- The minimum $\Delta\varphi^*_i$ of all jets in the event

$$\Delta\varphi^*_{\text{min}} \equiv \min_{i \in \text{jets}} \Delta\varphi^*_i$$



- The $\Delta\varphi^*_{\text{min}}$ cut

$$\Delta\varphi^*_{\text{min}} \geq \gamma_0$$

e.g., $\gamma_0 = 0.5$ [EPJC77(2017)294, PAS-SUS-16-016 (CMS α_T)]

- can suppress QCD background to a negligible level while keeping the signal acceptance wide enough to carry out the search
- but does largely reduce the signal acceptance

Event selection	Benchmark model (m_{SUSY}, m_{LSP})					
	T1bbbb (1500, 100)	T1bbbb (1000, 800)	T1tttt (1300, 100)	T1tttt (800, 400)	T1ttbb (1300, 100)	T1ttbb (1000, 700)
Before selection	100	100	100	100	100	100
Event veto for muons and electrons	99	98	41	42	61	64
Event veto for single isolated tracks	94	91	31	32	51	54
Event veto for photons	93	91	30	32	50	54
Event veto for forward jets ($\lvert\eta\rvert > 3.0$)	82	79	27	27	44	47
$n_{\text{jet}} \geq 2$	82	78	27	27	44	47
$p_{\text{T}}^{\text{j}_1} > 100\,\text{GeV}$	82	69	27	25	44	43
$\lvert\eta^{\text{j}_1}\rvert < 2.5$	82	68	27	25	44	42
$H_{\text{T}} > 200\,\text{GeV}$	82	66	27	25	44	42
$H_{\text{T}}^{\text{miss}} > 130\,\text{GeV}$	79	48	25	15	41	32
$H_{\text{T}}^{\text{miss}} / E_{\text{T}}^{\text{miss}} < 1.25$	77	43	24	11	38	26
H_{T}-dependent α_{T} requirements ($H_{\text{T}} < 800\,\text{GeV}$)	77	29	24	8.3	38	19
$\Delta\phi^*_{\text{min}} > 0.5$	23	17	5.6	1.3	9.5	8.8
Four most sensitive n_{jet} event categories	23	12	5.6	1.3	9.5	7.4

http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-15-005/index.html

additional table for EPJC77(2017)294 (CMS α_{T})

The angle $\Delta\varphi_i^*$

The angle $\Delta\varphi^*{}_i$

$$\Delta\varphi_i^* = \Delta\varphi(\vec{p}_{\mathrm{T}i}, \vec{H}_{\mathrm{T}}^{\mathrm{miss}} + \vec{p}_{\mathrm{T}i})$$

with the law of cosine

$$\cos\Delta\varphi_i^* = \frac{\vec{p}_{\mathrm{T}i} \cdot \left(\vec{H}_{\mathrm{T}}^{\mathrm{miss}} + \vec{p}_{\mathrm{T}i}\right)}{\left|\vec{p}_{\mathrm{T}i}\right| \left|\vec{H}_{\mathrm{T}}^{\mathrm{miss}} + \vec{p}_{\mathrm{T}i}\right|}$$

which can be written as

$$\cos\Delta\varphi_i^* = \frac{f_i + \cos\Delta\varphi_i}{\sqrt{1 + f_i^2 + 2 f_i \cos\Delta\varphi_i}}$$

$$f_i \equiv \frac{p_{\mathrm{T}i}}{H_{\mathrm{T}}^{\mathrm{miss}}}$$

$\Delta\varphi^*{}_i$ is a function of two dimensionless variables $\Delta\varphi_i$ and f_i

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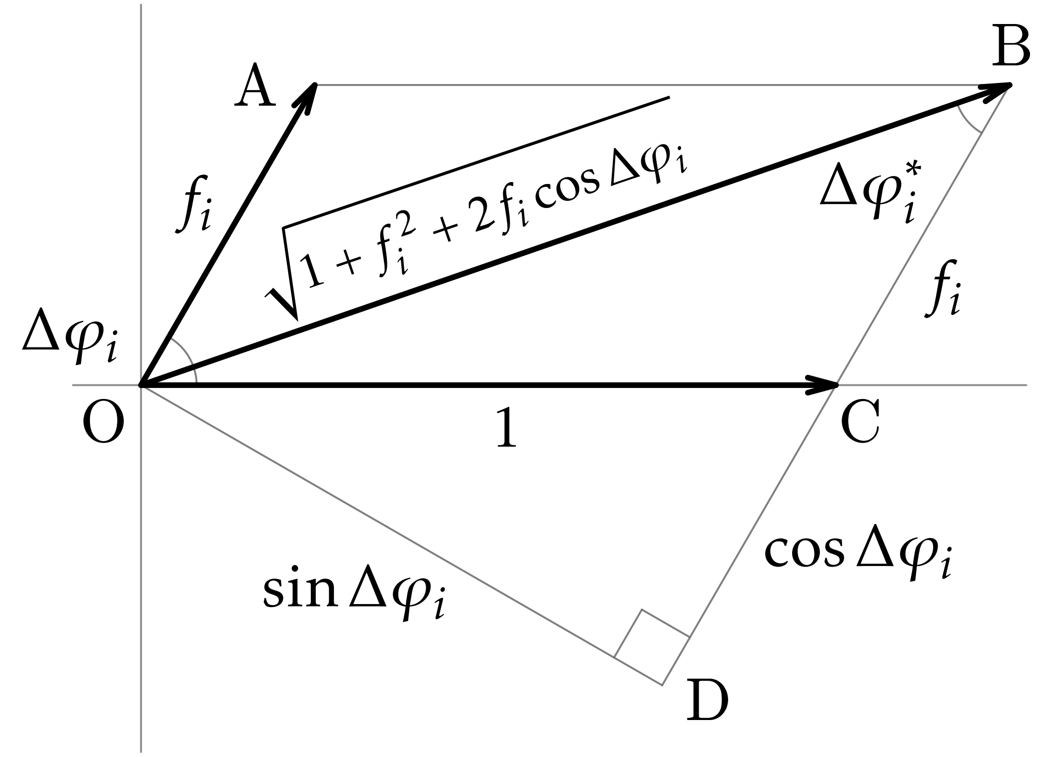


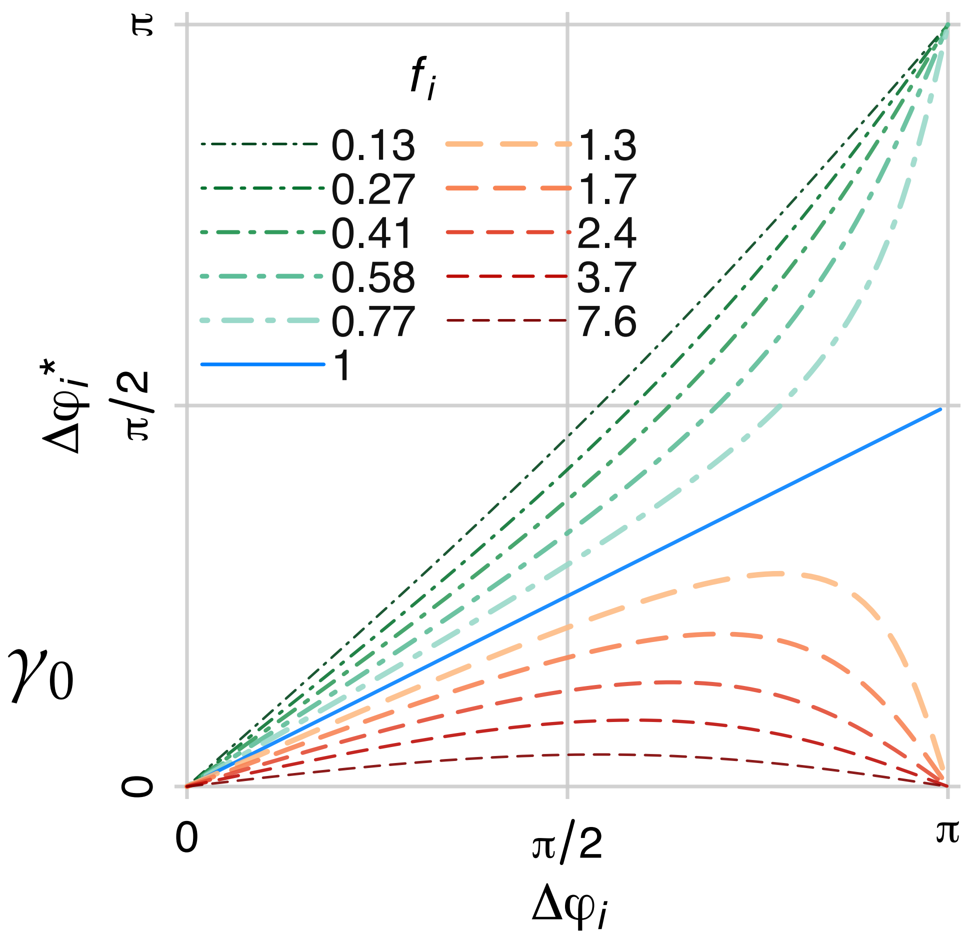
The normalized p_T plane: the p_x-p_y plane that is rotated and scaled such that MHT points horizontally to the right with unit length. The plane is flipped if necessary so that $0 \le \Delta\varphi_i \le \pi$.

$$\overrightarrow{\mathrm{OC}} = \vec{H}_\mathrm{T}^\mathrm{miss}$$

$$\overrightarrow{\mathrm{OA}} = \vec{p}_{\mathrm{T}i}$$

The angle $\Delta\varphi_i^*$

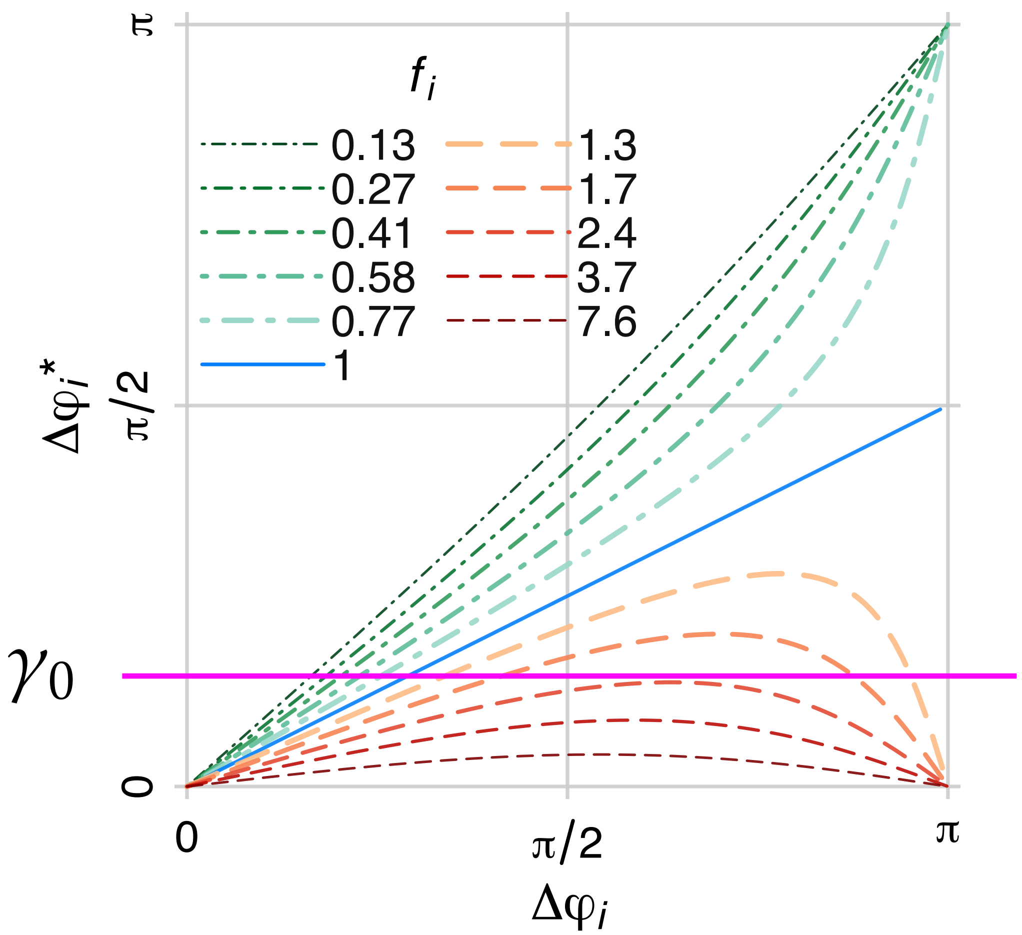
$\Delta\varphi^*_i$ as function of $\Delta\varphi_i$ and f_i



$\Delta\varphi_i \equiv \Delta\varphi(\vec{p}_{\mathrm{T}i}, \vec{H}_{\mathrm{T}}^{\mathrm{miss}}) \qquad f_i \equiv \frac{p_{\mathrm{T}i}}{H_{\mathrm{T}}^{\mathrm{miss}}}$

The angle $\Delta\varphi_i^*$

$\Delta\varphi^*_i$ as function of $\Delta\varphi_i$ and f_i



The $\Delta\varphi^*_{\text{min}}$ cut:

$$\Delta\varphi^*_{\text{min}} \geq \gamma_0$$

rejects every event with at least one jet with $\Delta\varphi^*_i < \gamma_0$

$$\Delta\varphi_i \equiv \Delta\varphi(\vec{p}_{\mathrm{T}i}, \vec{H}_{\mathrm{T}}^{\text{miss}}) \qquad f_i \equiv \frac{p_{\mathrm{T}i}}{H_{\mathrm{T}}^{\text{miss}}}$$

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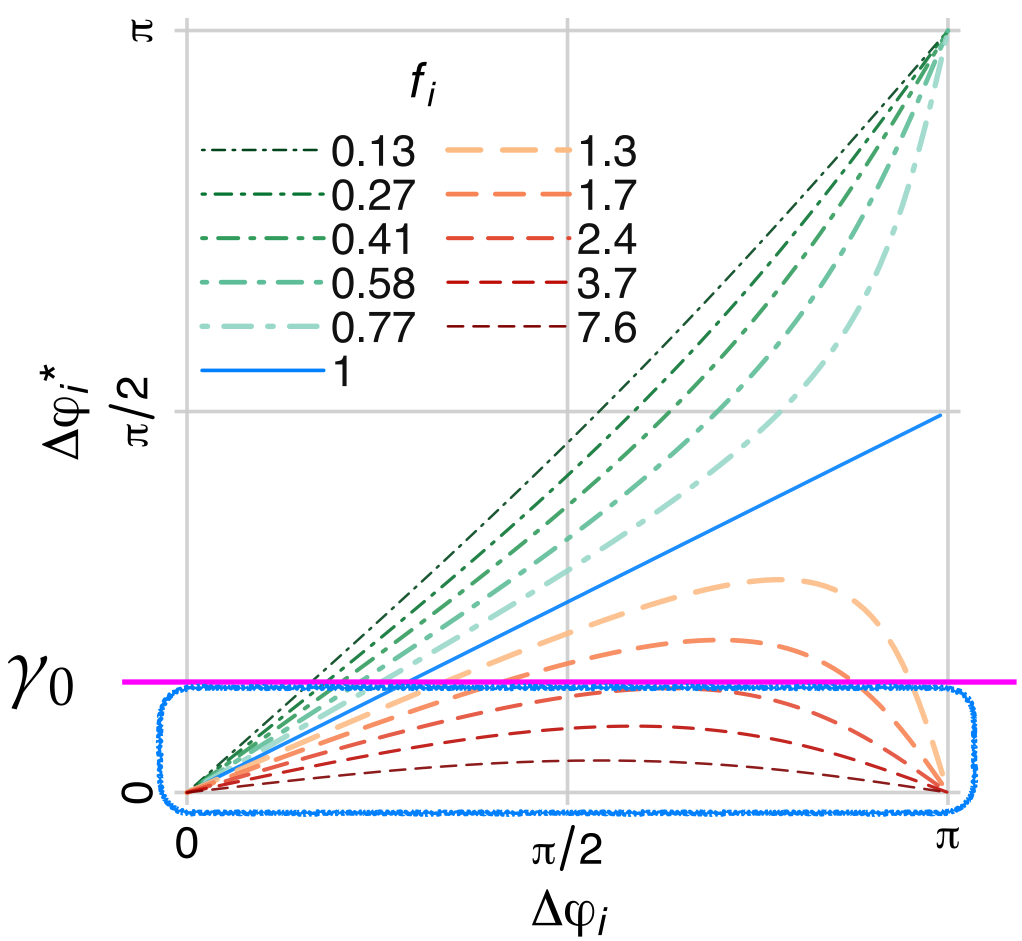

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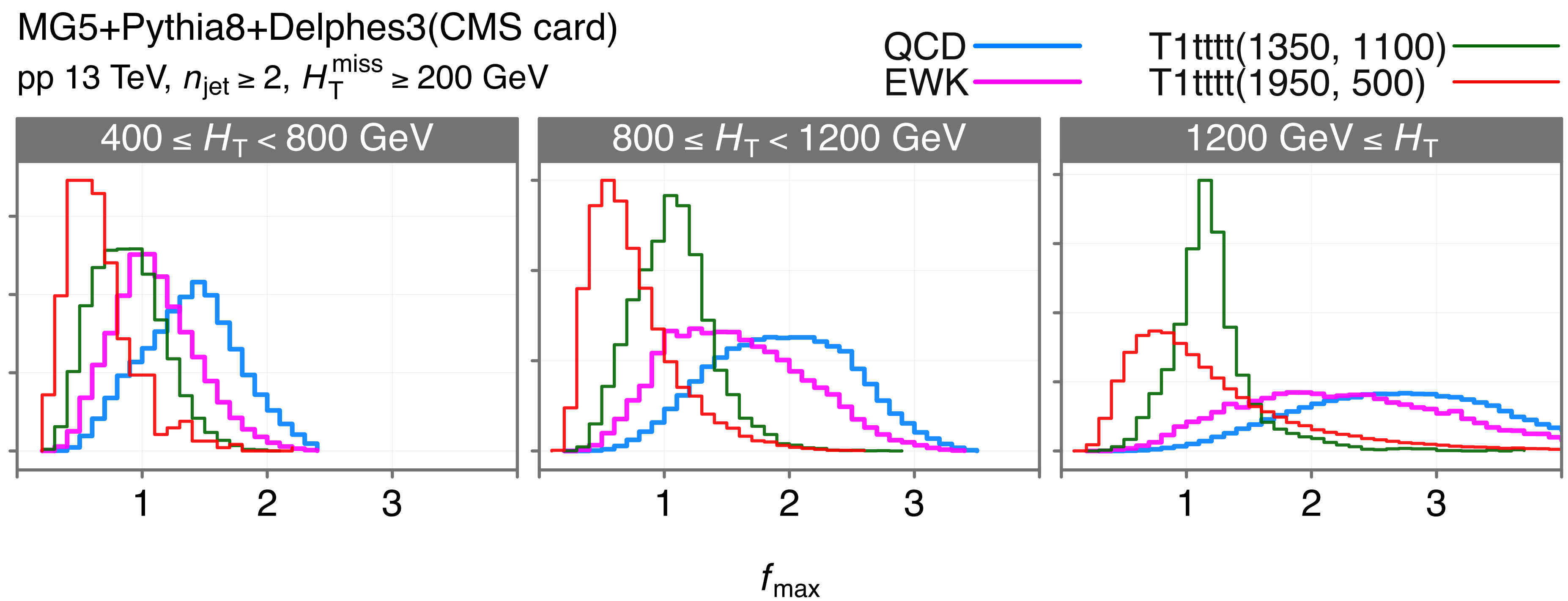
large f_i | wide $\Delta\varphi_i$ | narrow $\Delta\varphi_i$

The $\Delta\varphi^*_{\text{min}}$ cut rejects any event with one jet with large f_i (f_i larger than $1/\sin\gamma_0$)

For example, if $\gamma_0 = 0.5$, the $\Delta\varphi^*_{\text{min}}$ cut rejects all events with one jet with p_{T} at least 2.09 times larger than MHT

This feature might appear to needlessly reduce the signal acceptance.

Signal events don't normally have a jet with large f_i



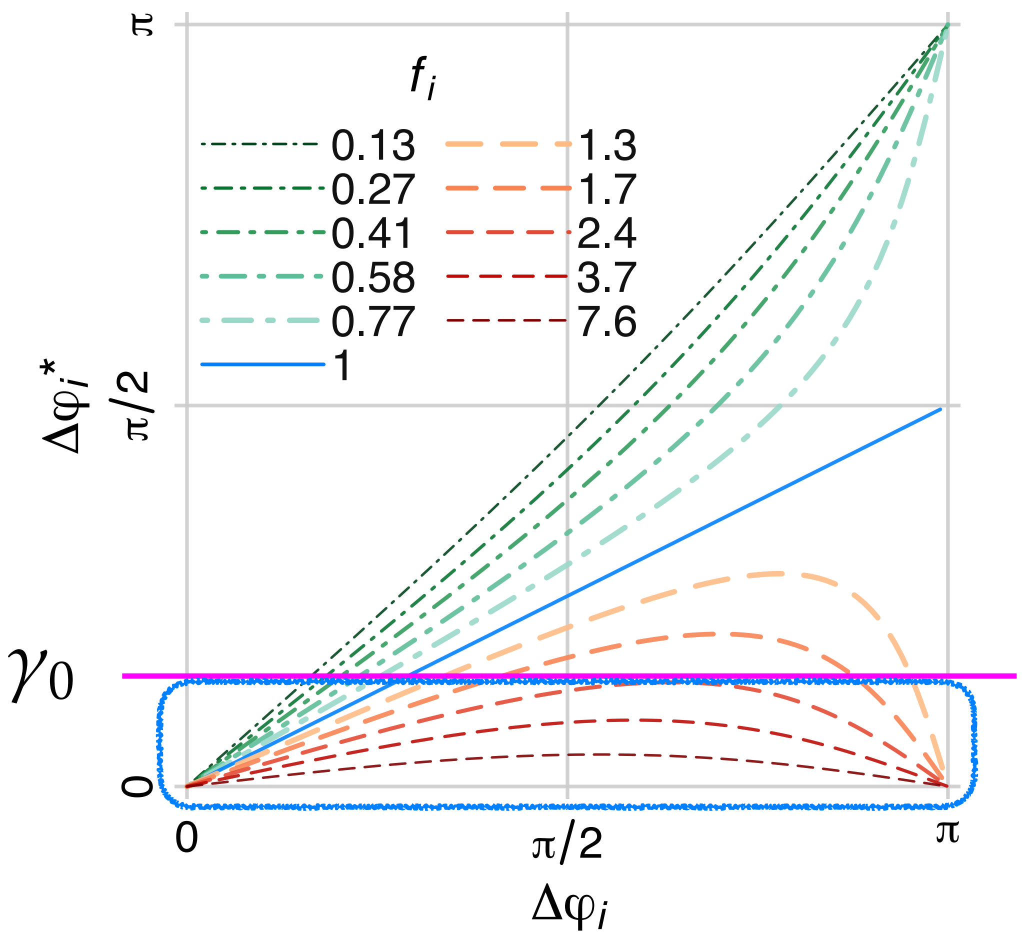
$$f_{\mathrm{max}} \equiv \max_{i \in \mathrm{jets}} f_i \qquad f_i \equiv \frac{p_{\mathrm{T}i}}{H_{\mathrm{T}}^{\mathrm{miss}}}$$

EWK: tt+jets, W+jets, Z($\rightarrow \nu\nu$)+jets

Incidentally, f_{max} can be potentially useful for offline and online preselection

The angle $\Delta\varphi_i^*$

$\Delta\varphi^*_i$ as function of $\Delta\varphi_i$ and f_i



The $\Delta\varphi^*_{\min}$ cut:

$$\Delta\varphi^*_{\min} \geq \gamma_0$$

rejects every event with at least one jet with $\Delta\varphi^*_i < \gamma_0$

$$\Delta\varphi_i \equiv \Delta\varphi(\vec{p}_{\mathrm{T}i}, \vec{H}_{\mathrm{T}}^{\mathrm{miss}}) \qquad f_i \equiv \frac{p_{\mathrm{T}i}}{H_{\mathrm{T}}^{\mathrm{miss}}}$$

large f_i | wide $\Delta\varphi_i$ | narrow $\Delta\varphi_i$

The $\Delta\varphi^*_{\min}$ cut rejects any event with one jet with large f_i (f_i larger than $1/\sin\gamma_0$)

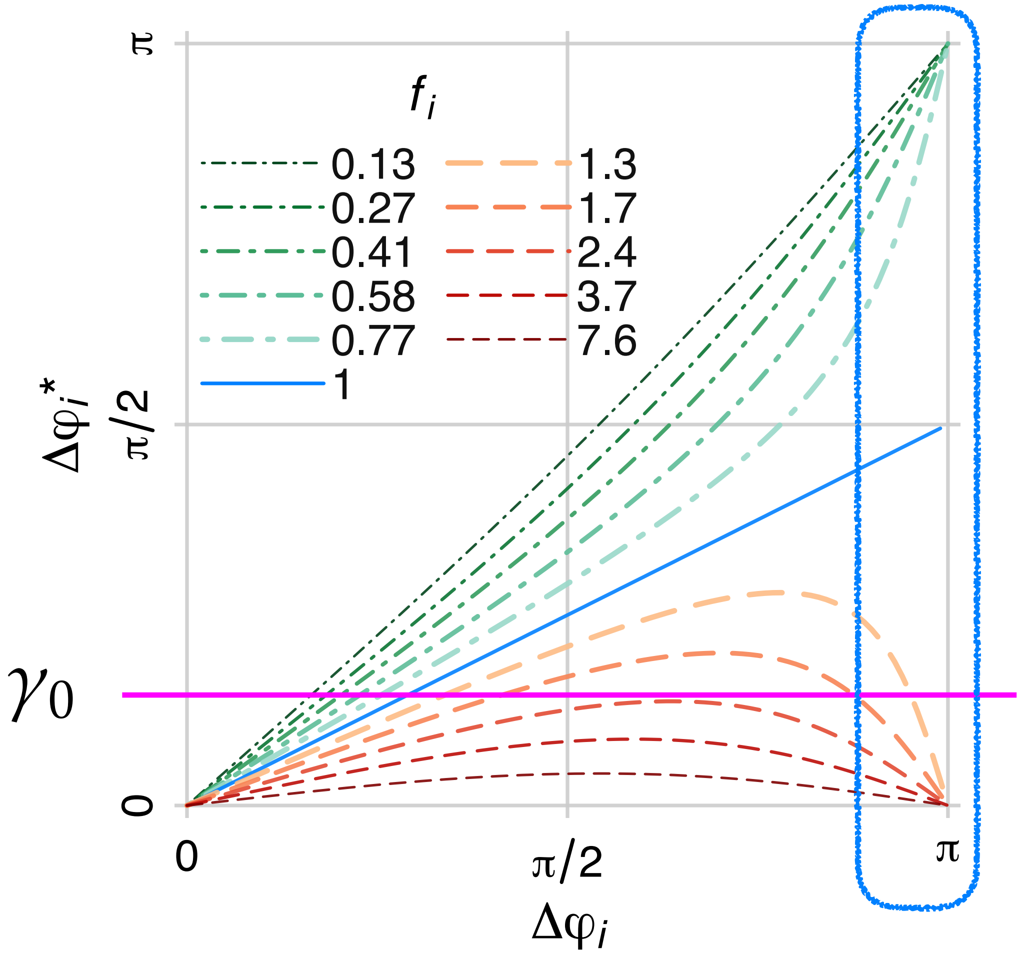
For example, if $\gamma_0 = 0.5$, the $\Delta\varphi^*_{\min}$ cut rejects all events with one jet with p_{T} at least 2.09 times larger than MHT

This feature might appear to needlessly reduce the signal acceptance.

On the contrary, this feature effectively reduce QCD events without much reducing the signal acceptance.

The angle $\Delta\varphi_i^*$

$\Delta\varphi^*_i$ as function of $\Delta\varphi_i$ and f_i



The $\Delta\varphi^*_{\text{min}}$ cut:

$$\Delta\varphi^*_{\text{min}} \geq \gamma_0$$

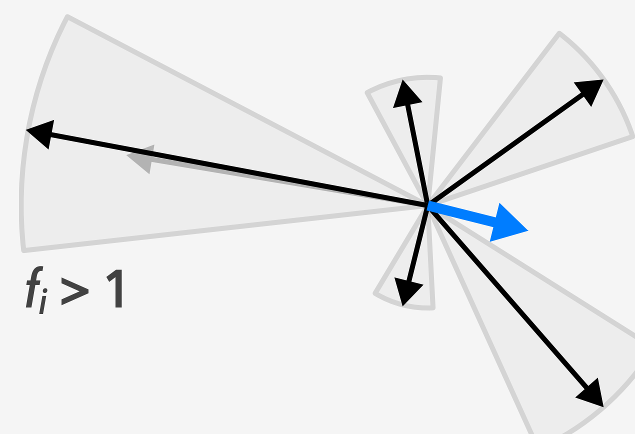
rejects every event with at least one jet with $\Delta\varphi^*_i < \gamma_0$

$$\Delta\varphi_i \equiv \Delta\varphi(\vec{p}_{\mathrm{T}i}, \vec{H}_{\mathrm{T}}^{\text{miss}}) \qquad f_i \equiv \frac{p_{\mathrm{T}i}}{H_{\mathrm{T}}^{\text{miss}}}$$

large f_i | **wide $\Delta\varphi_i$** | narrow $\Delta\varphi_i$

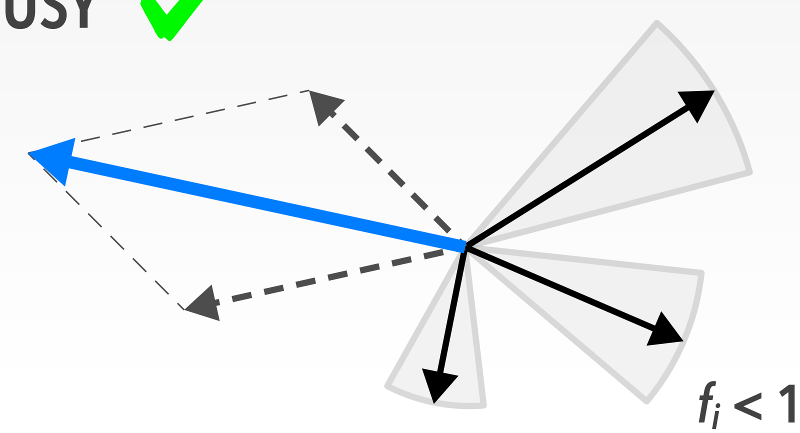
The $\Delta\varphi^*_{\text{min}}$ cut rejects QCD events with large MHT caused by jet p_{T} overestimate without needlessly reducing the signal acceptance

QCD ✗



The jet whose p_{T} is overestimated has $p_{\mathrm{T}} >$ MHT

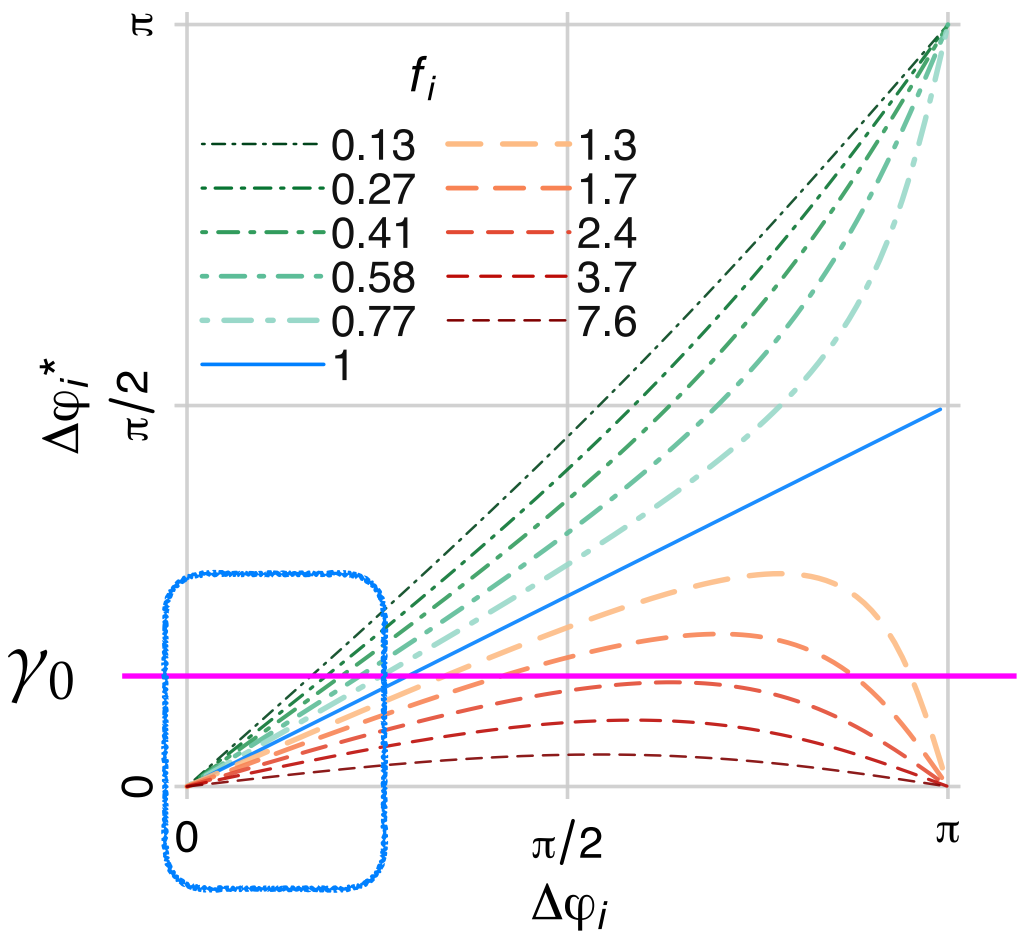
SUSY ✓



Jets receiving the recoil of LSPs can have $p_{\mathrm{T}} <$ MHT

The angle $\Delta\varphi_i^*$

$\Delta\varphi^*_i$ as function of $\Delta\varphi_i$ and f_i



The $\Delta\varphi^*_{\text{min}}$ cut:

$$\Delta\varphi^*_{\text{min}} \geq \gamma_0$$

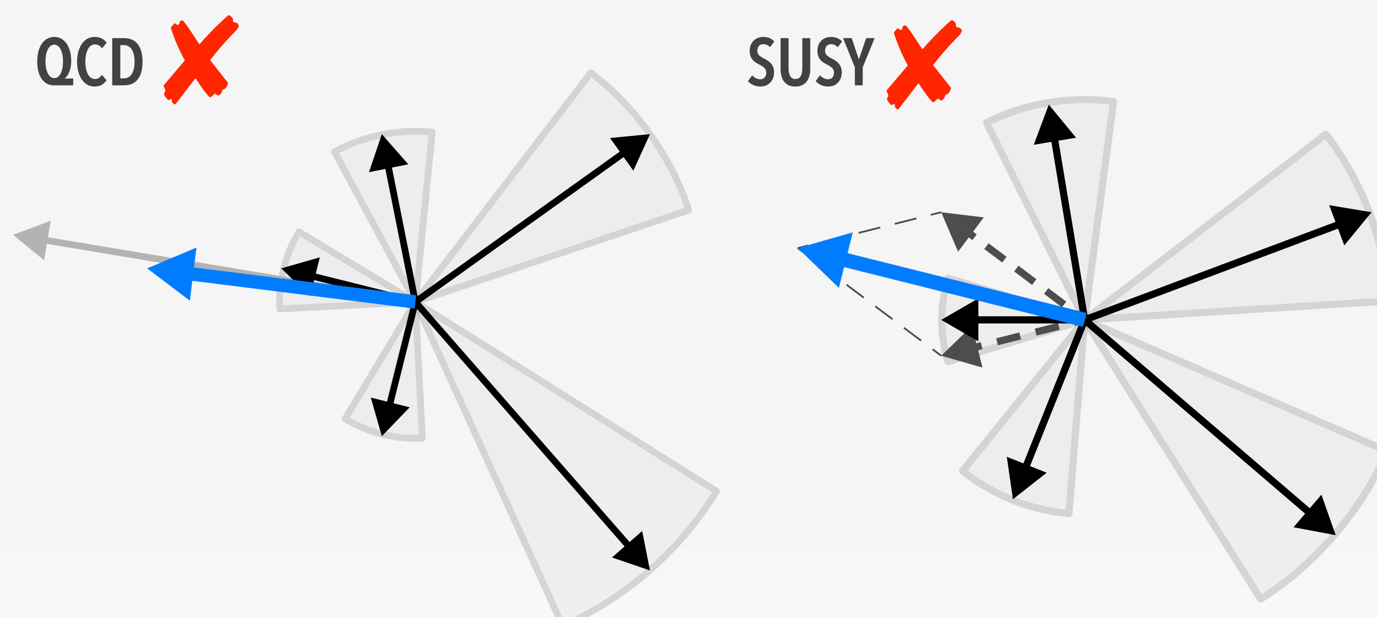
rejects every event with at least one jet with $\Delta\varphi^*_i < \gamma_0$

$\Delta\varphi_i \equiv \Delta\varphi(\vec{p}_{\mathrm{T}i}, \vec{H}_{\mathrm{T}}^{\text{miss}})$ $\qquad f_i \equiv \dfrac{p_{\mathrm{T}i}}{H_{\mathrm{T}}^{\text{miss}}}$

large f_i | wide $\Delta\varphi_i$ | narrow $\Delta\varphi_i$

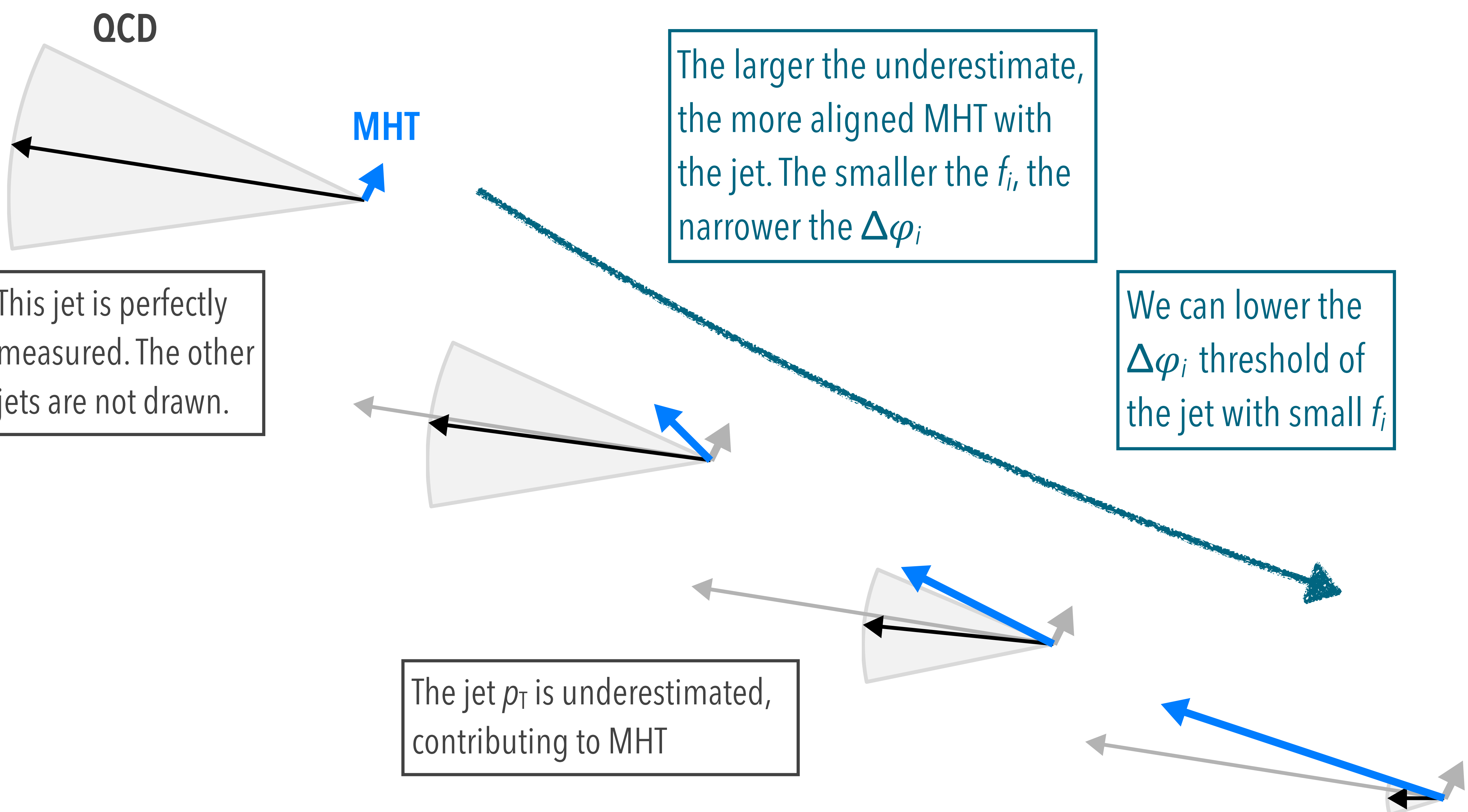
By definition, $\Delta\varphi^*_i \leq \Delta\varphi_i$

The $\Delta\varphi^*_{\text{min}}$ cut rejects every event with at least one jet with $\Delta\varphi_i < \gamma_0$



Here, there is room for improvement

The relation between $\Delta\varphi_i$ and f_i of the jet whose p_T is underestimated



This jet is perfectly measured. The other jets are not drawn.

The larger the underestimate, the more aligned MHT with the jet. The smaller the f_i, the narrower the $\Delta\varphi_i$

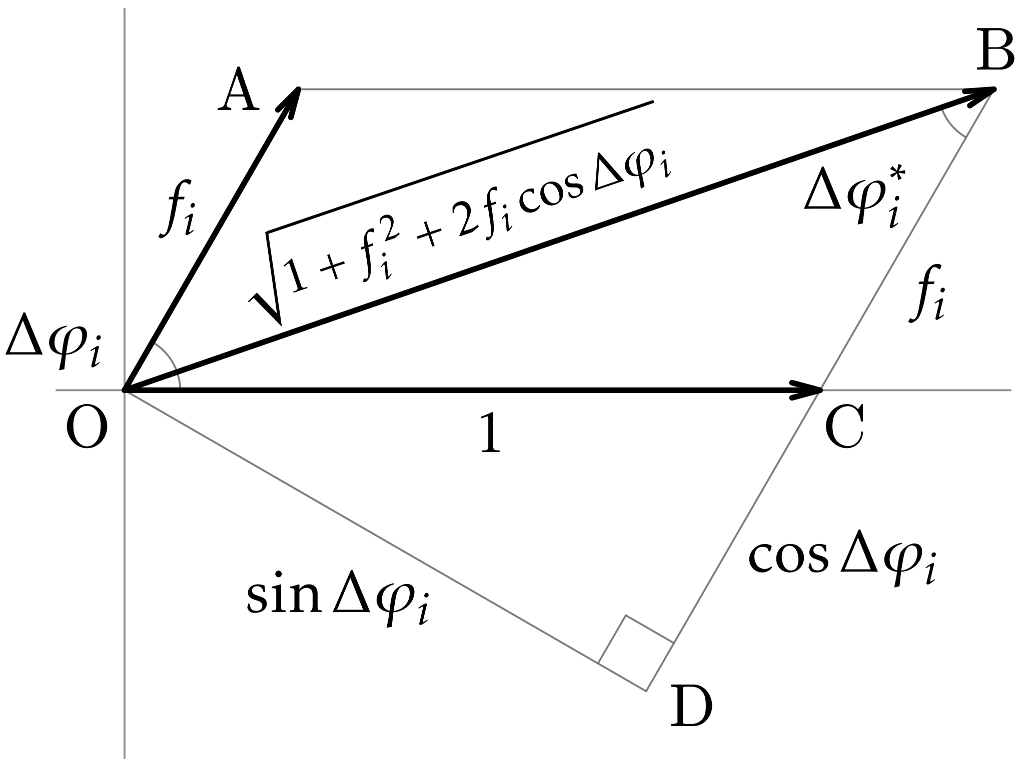
We can lower the $\Delta\varphi_i$ threshold of the jet with small f_i

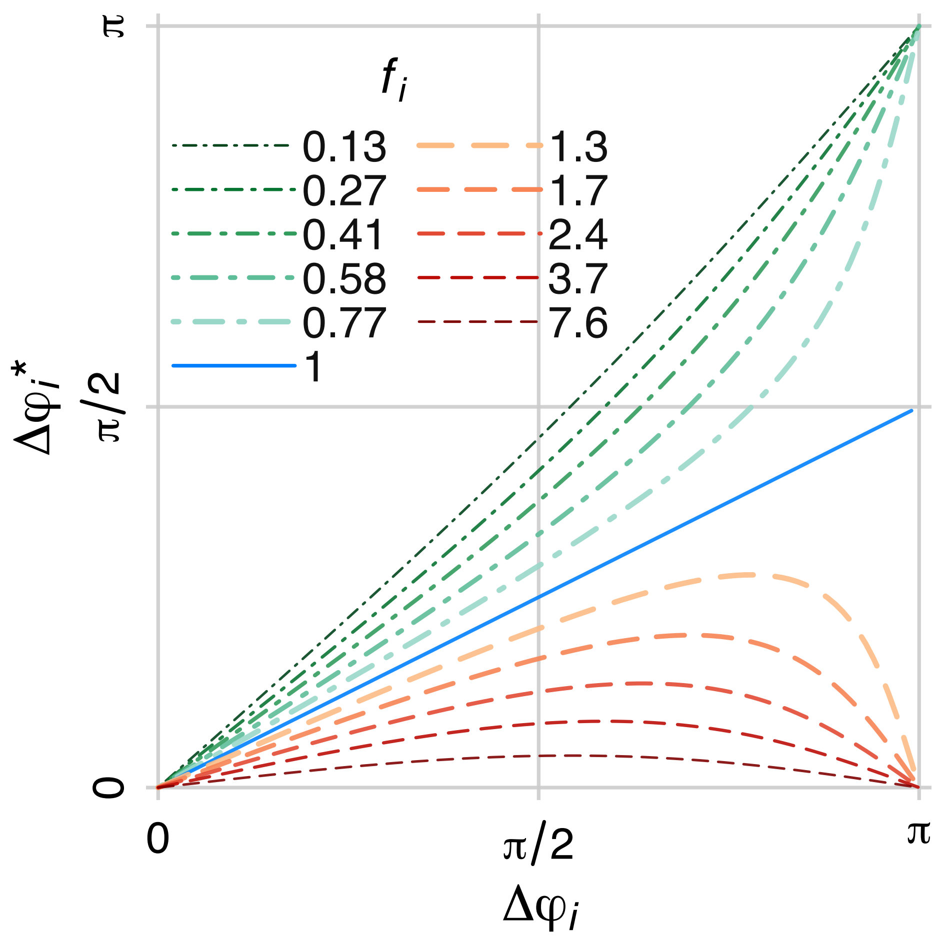
The jet p_T is underestimated, contributing to MHT

A large jet p_T underestimate

note: The argument here ignores a secondary counter effect whereby the larger the underestimate, the more deflected the jet is likely to be from the "true" jet

$$\tan \Delta\varphi_i^* = \frac{\sin \Delta\varphi_i}{f_i + \cos \Delta\varphi_i}$$





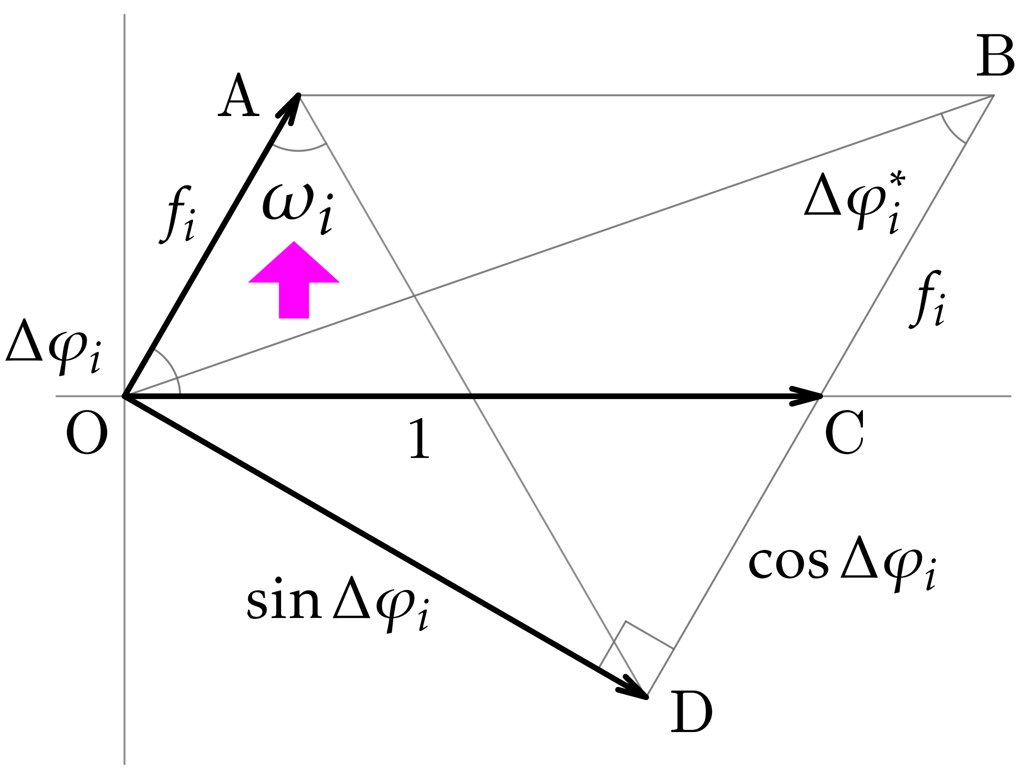
The normalized p_{T} plane

$$\overrightarrow{\mathrm{OC}} = \vec{H}_{\mathrm{T}}^{\mathrm{miss}}$$

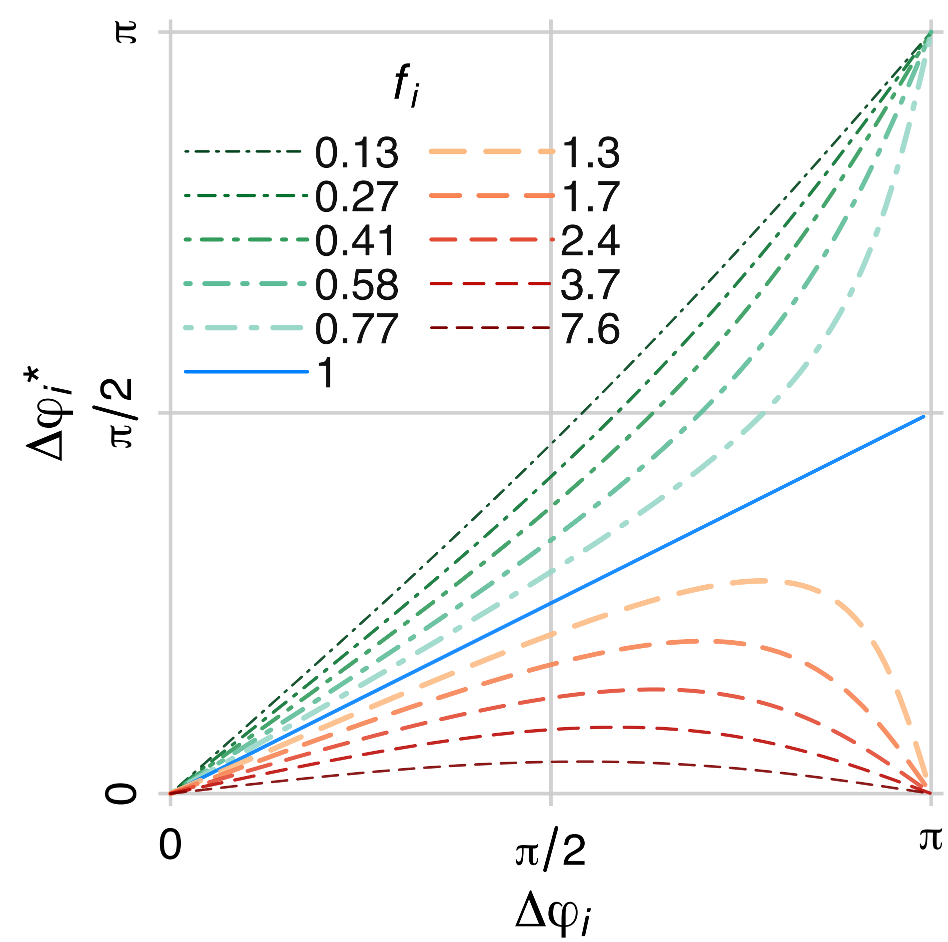
$$\overrightarrow{\mathrm{OA}} = \vec{p}_{\mathrm{T}i}$$

Alternative angle ω_i

$$\tan \Delta\varphi_i^* = \frac{\sin \Delta\varphi_i}{f_i + \cos \Delta\varphi_i} \qquad \tan \omega_i = \frac{\sin \Delta\varphi_i}{f_i}$$



The normalized p_{T} plane



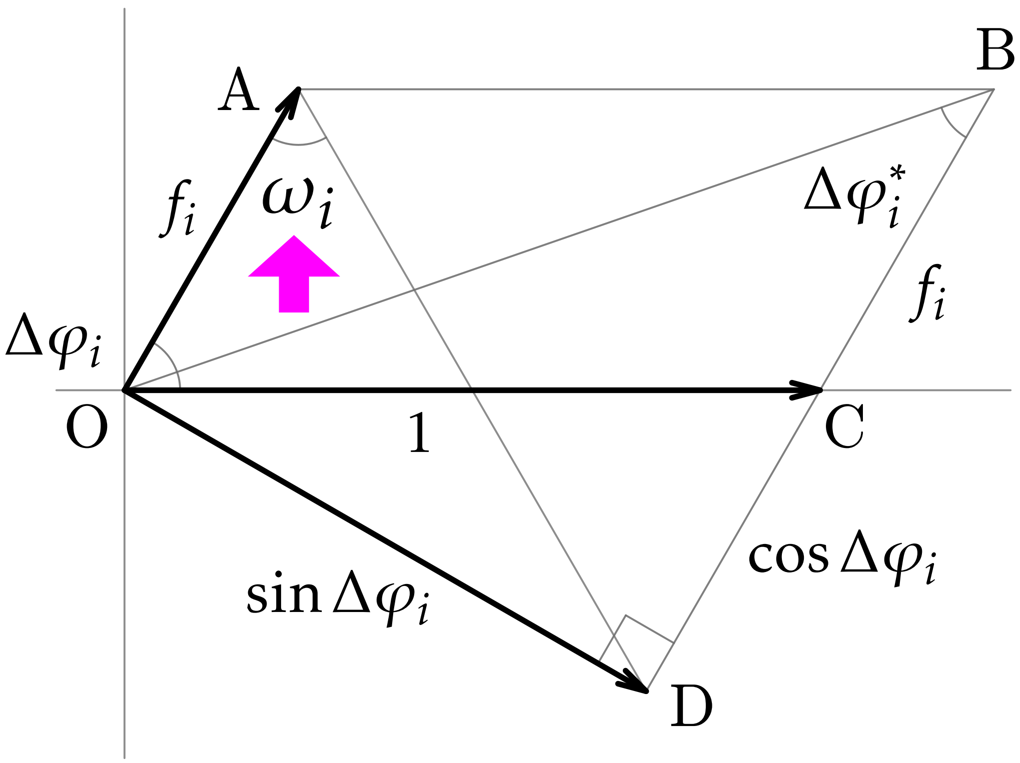
$\overrightarrow{\mathrm{OC}} = \vec{H}_{\mathrm{T}}^{\mathrm{miss}}$

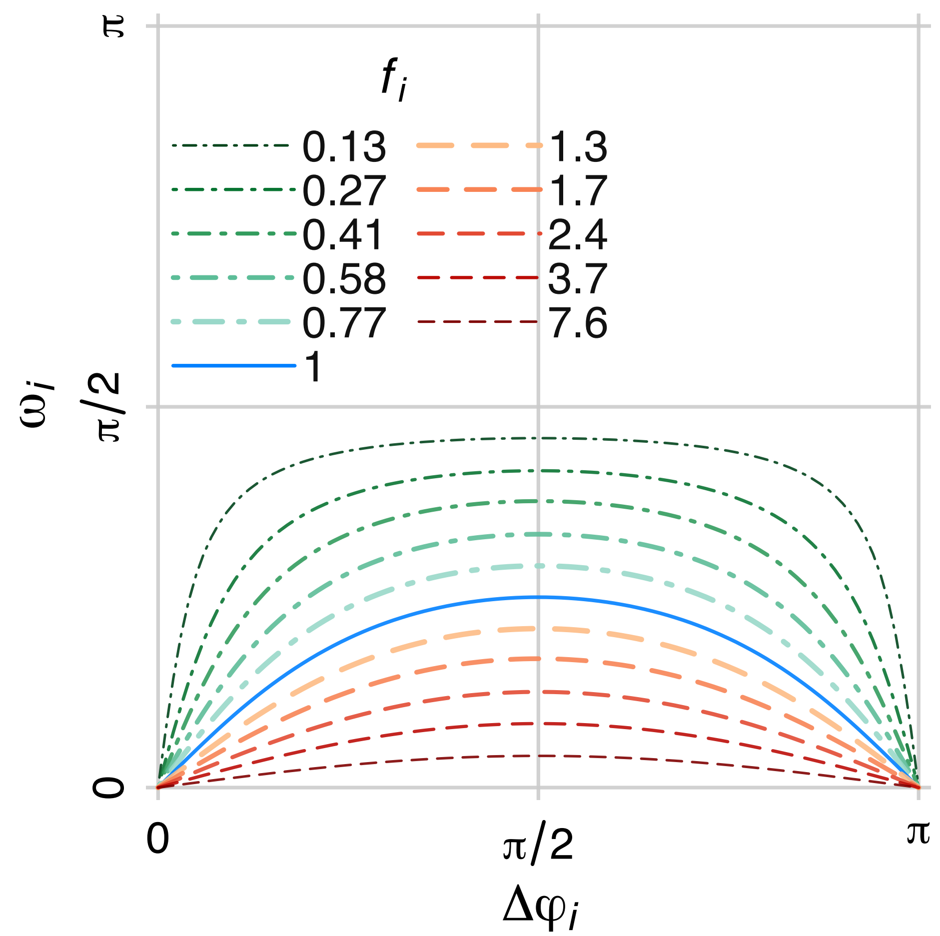
$\overrightarrow{\mathrm{OA}} = \vec{p}_{\mathrm{T}i}$

$\overrightarrow{\mathrm{OD}}$: minimized MHT

Alternative angle ω_i

$$\tan \Delta\varphi_i^* = \frac{\sin \Delta\varphi_i}{f_i + \cos \Delta\varphi_i} \qquad \tan \omega_i = \frac{\sin \Delta\varphi_i}{f_i}$$





The normalized p_T plane

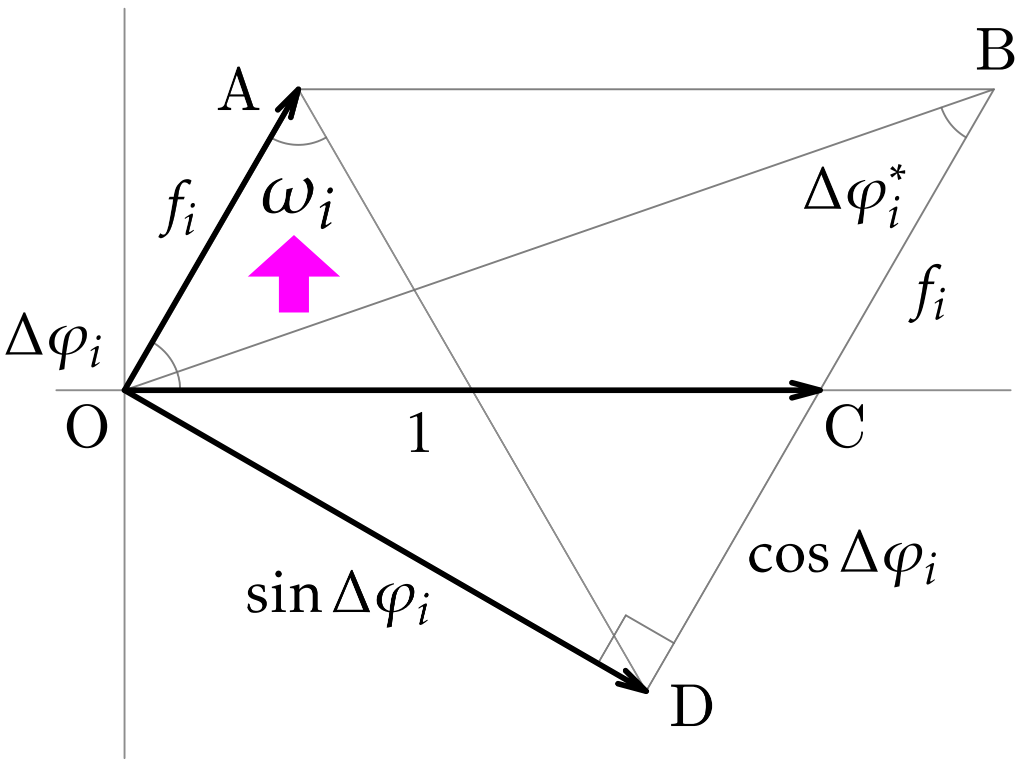
$$\overrightarrow{OC} = \vec{H}_T^{miss}$$

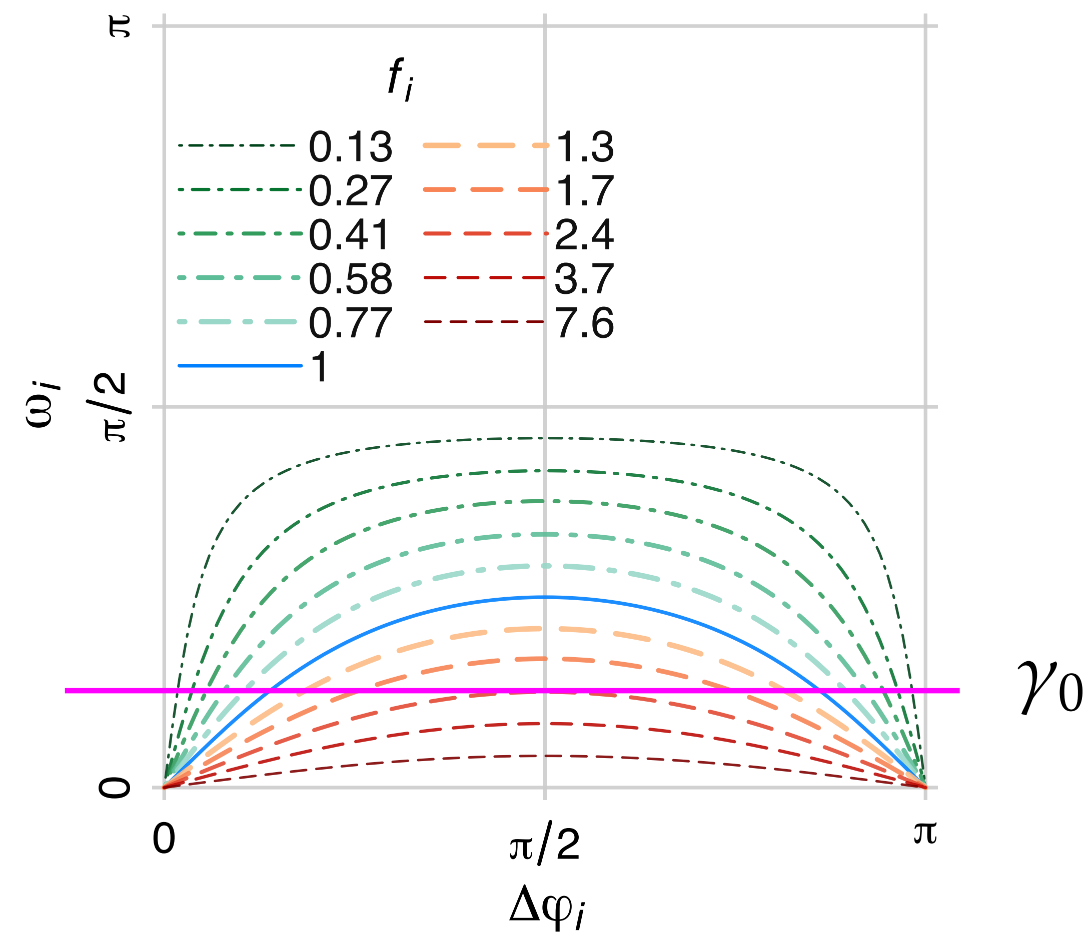
$$\overrightarrow{OA} = \vec{p}_{Ti}$$

$\overrightarrow{OD}$: minimized MHT

Alternative angle ω_i

$$\tan \Delta\varphi_i^* = \frac{\sin \Delta\varphi_i}{f_i + \cos \Delta\varphi_i} \qquad \tan \omega_i = \frac{\sin \Delta\varphi_i}{f_i}$$





The normalized p_T plane

$$\overrightarrow{OC} = \vec{H}_T^{miss}$$

$$\overrightarrow{OA} = \vec{p}_{Ti}$$

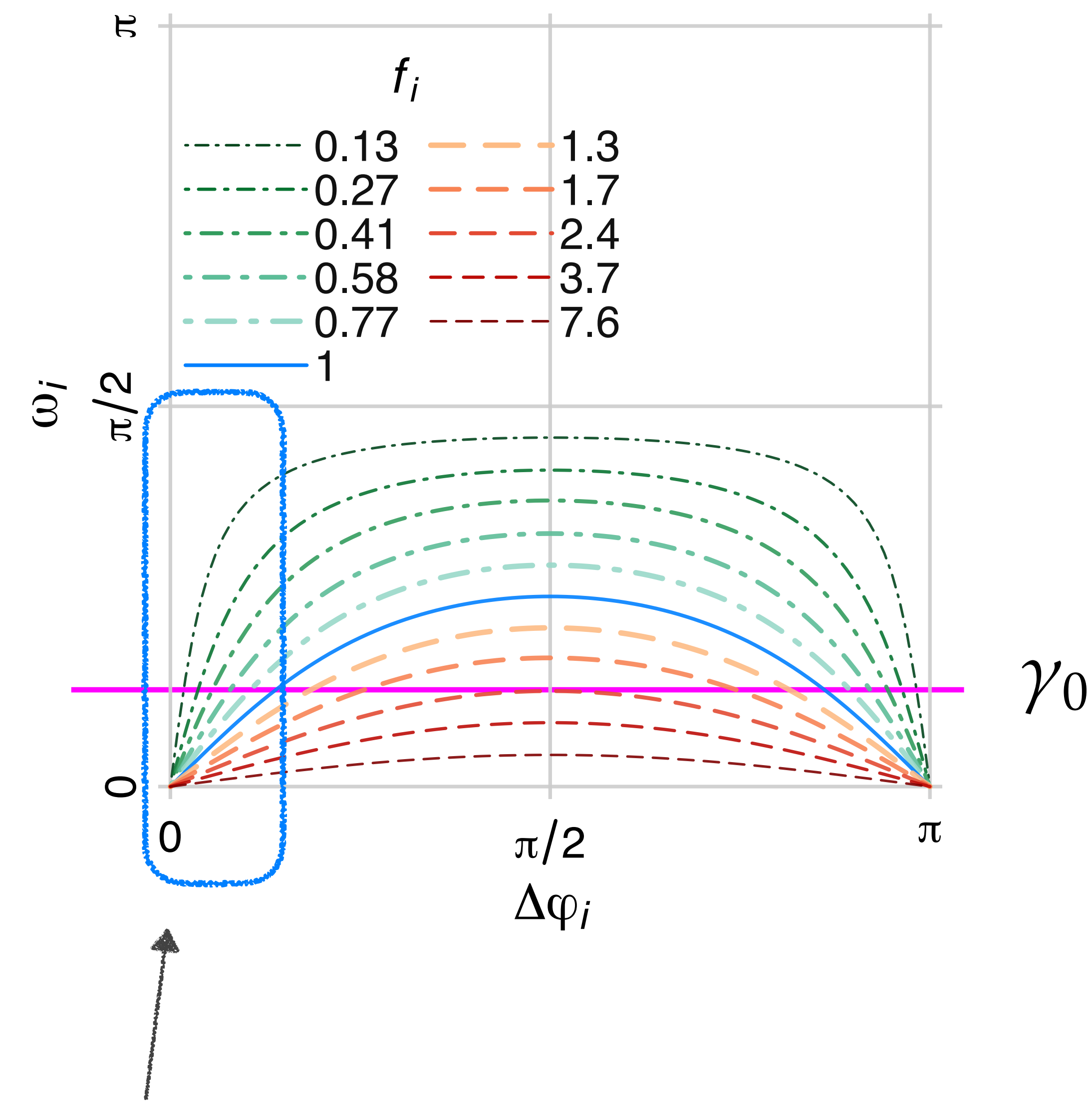
$\overrightarrow{OD}$: minimized MHT

Alternative angle ω_i

$$\tan \omega_i = \frac{\sin \Delta\varphi_i}{f_i}$$

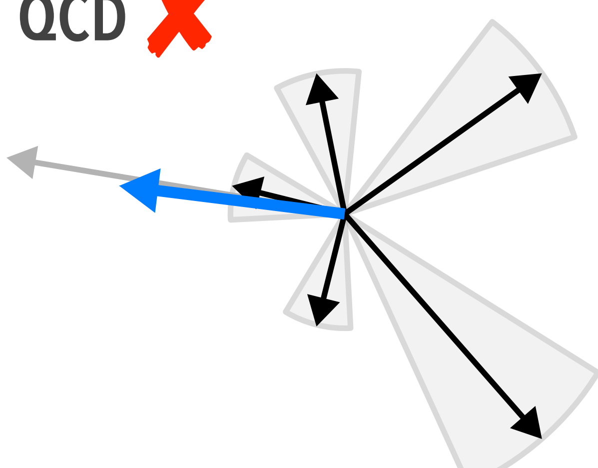
The angle ω_i

- can be wider than $\Delta\varphi_i$
- in the limit $f_i \to 0$, a step function of $\Delta\varphi_i$
  - ω_i can be wider than any acute angle if f_i is sufficiently small
  - no matter how small f_i is, ω_i can be narrower than any angle if $\Delta\varphi_i$ is sufficiently narrow

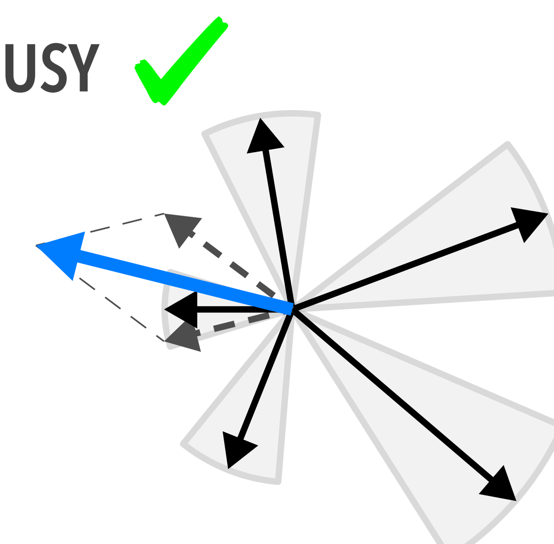


improved here

QCD



SUSY

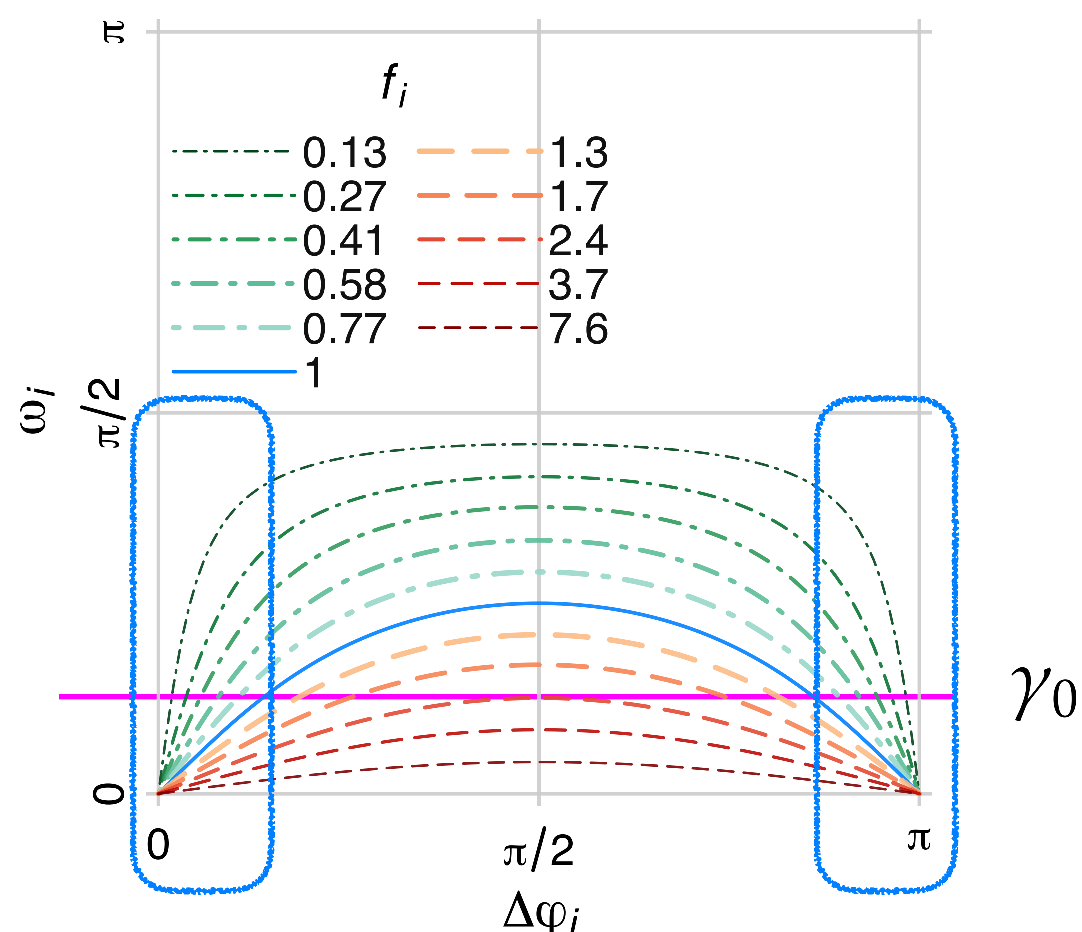


Alternative angle ω_i

$$\tan \omega_i = \frac{\sin \Delta\varphi_i}{f_i}$$

The angle ω_i

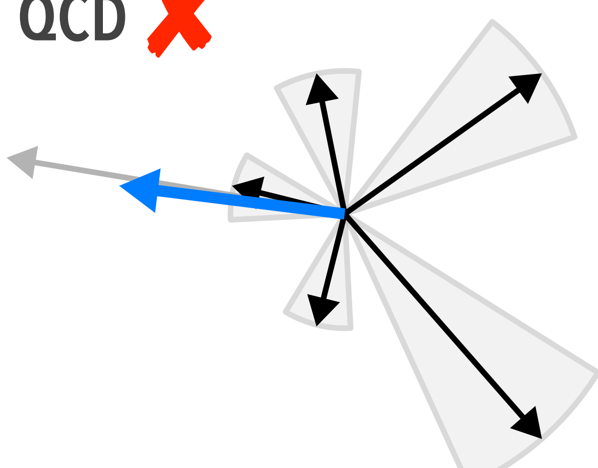
- can be wider than $\Delta\varphi_i$
- in the limit $f_i \to 0$, a step function of $\Delta\varphi_i$
  - ω_i can be wider than any acute angle if f_i is sufficiently small
  - no matter how small f_i is, ω_i can be narrower than any angle if $\Delta\varphi_i$ is sufficiently narrow



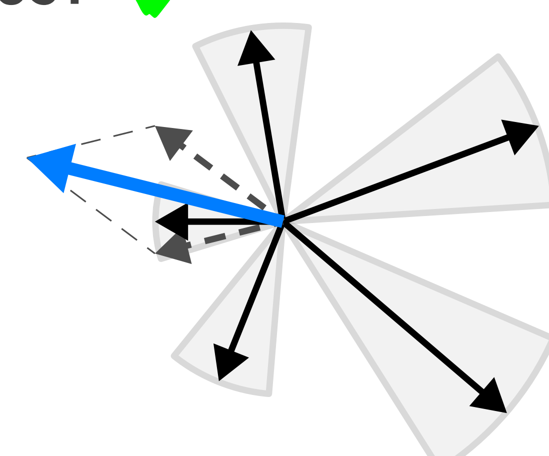
improved here

but lost advantage of $\Delta\varphi^*_i$ for wide $\Delta\varphi_i$

QCD ✗



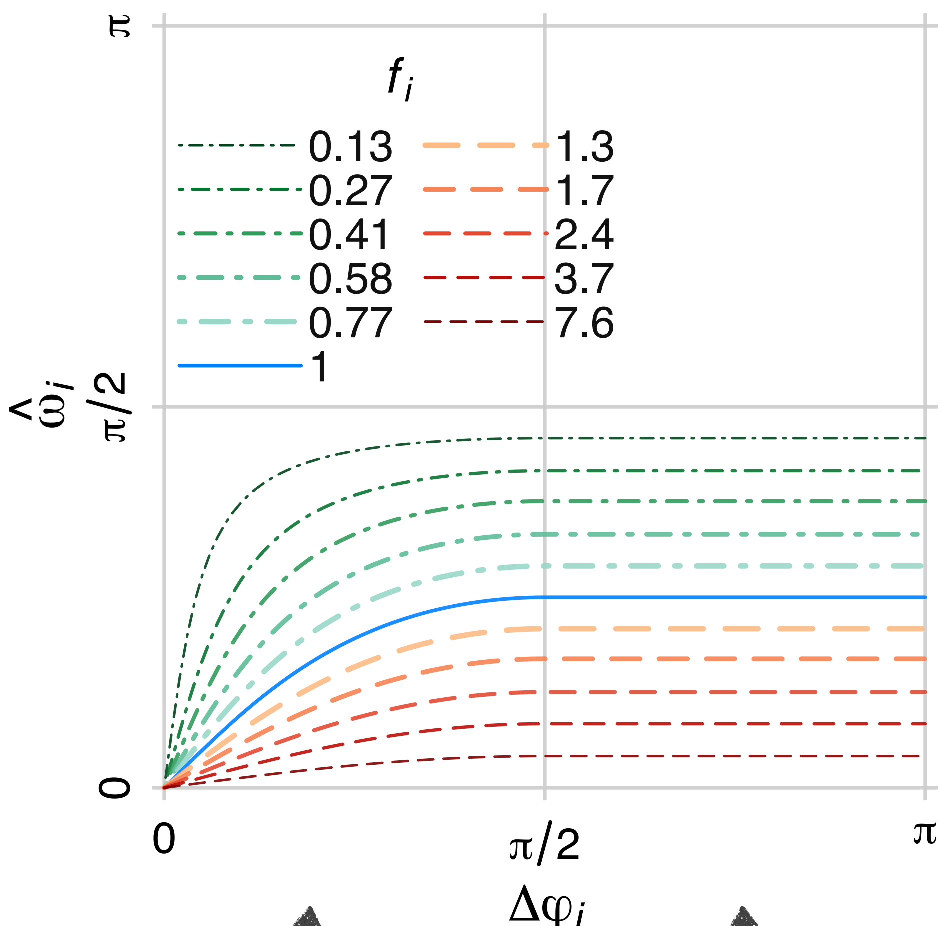
SUSY ✓



Variants of ω_i—recover the lost advantage

$\hat{\omega}_i$

$$\tan \hat{\omega}_i = \frac{\sin(\min(\Delta\varphi_i, \pi/2))}{f_i}$$

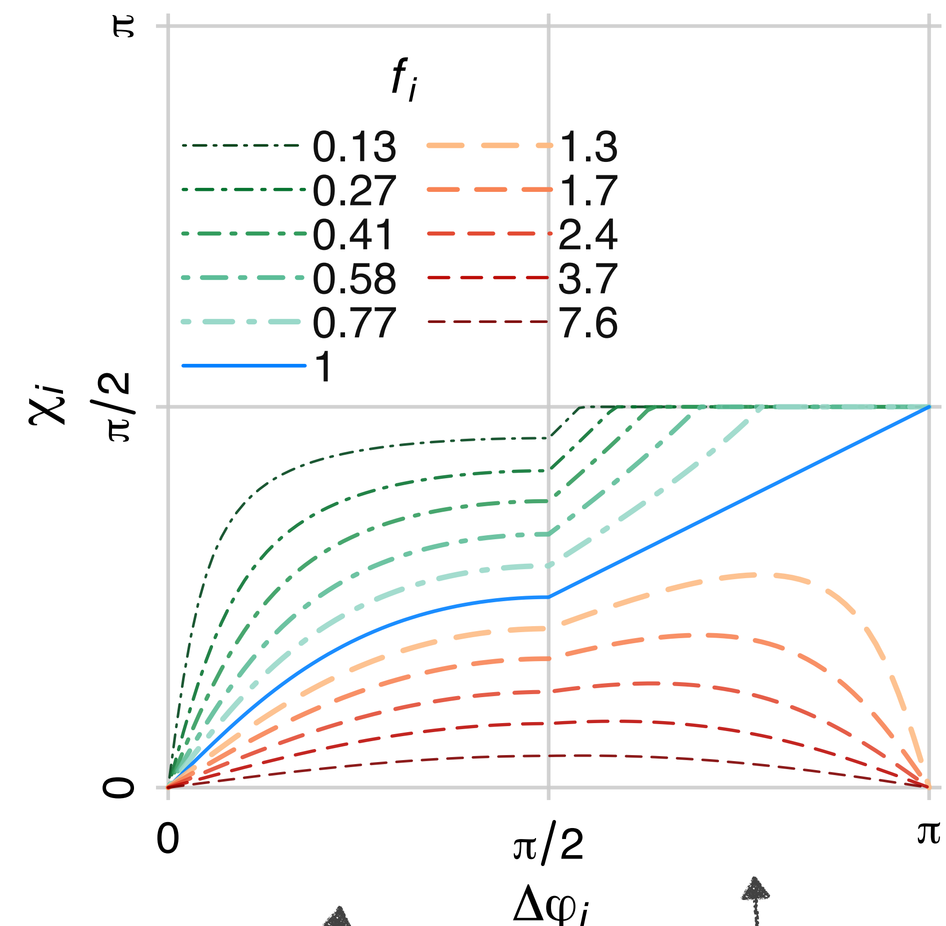


The same as ω_i for $\Delta\varphi_i \leq \pi/2$

no $\Delta\varphi_i$ dependency for $\Delta\varphi_i > \pi/2$

χ_i

$$\tan \chi_i = \frac{\sqrt{1 + (\min(f_i, -\cos\Delta\varphi_i))^2 + 2\min(f_i, -\cos\Delta\varphi_i)\cos\Delta\varphi_i}}{\min(f_i, \max(f_i + \cos\Delta\varphi_i, 0))}$$

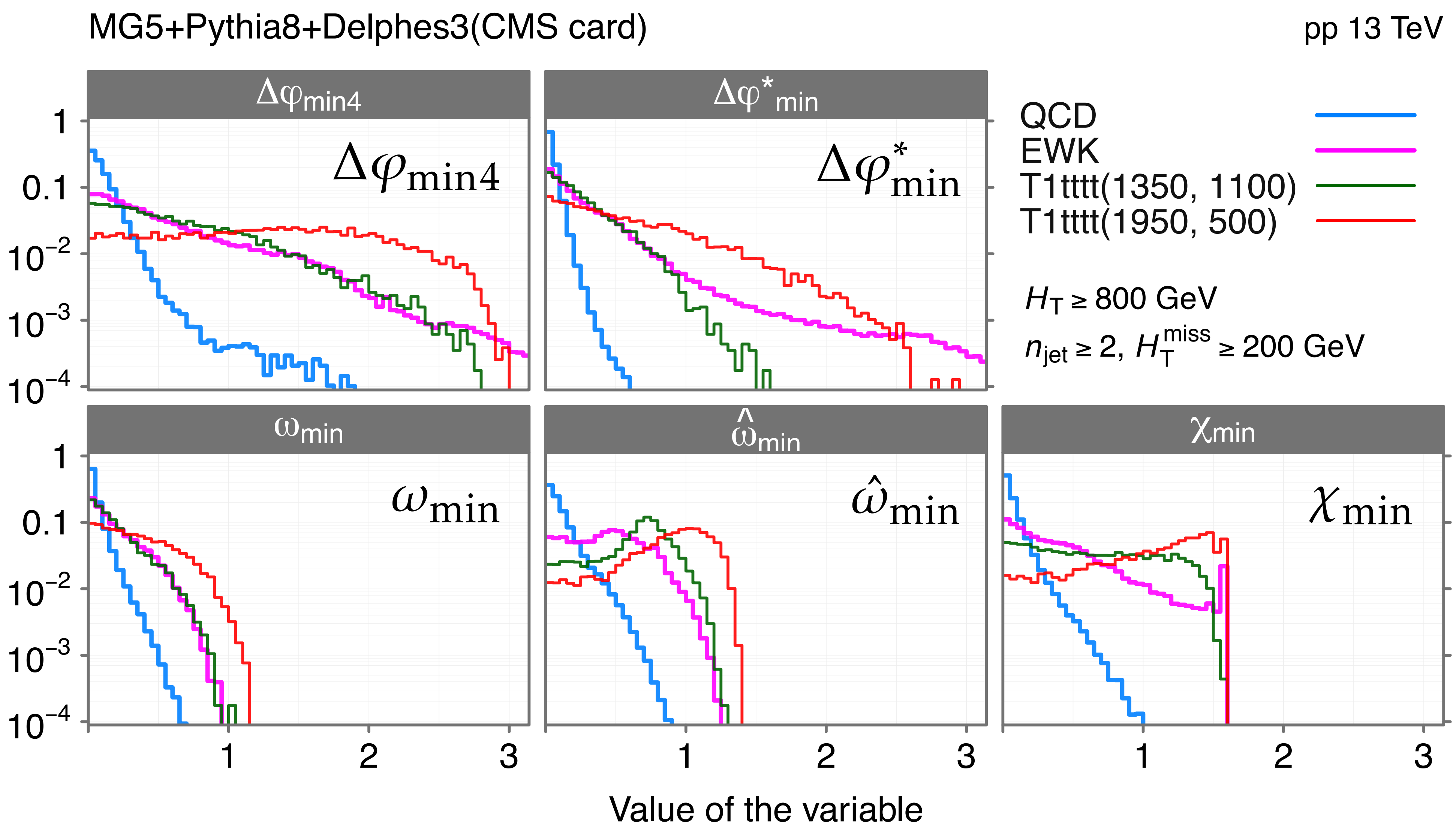


The same as ω_i for $\Delta\varphi_i \leq \pi/2$

The same as $\Delta\varphi^*_i$ for $\Delta\varphi_i > \pi/2$ except χ_i is capped at $\pi/2$

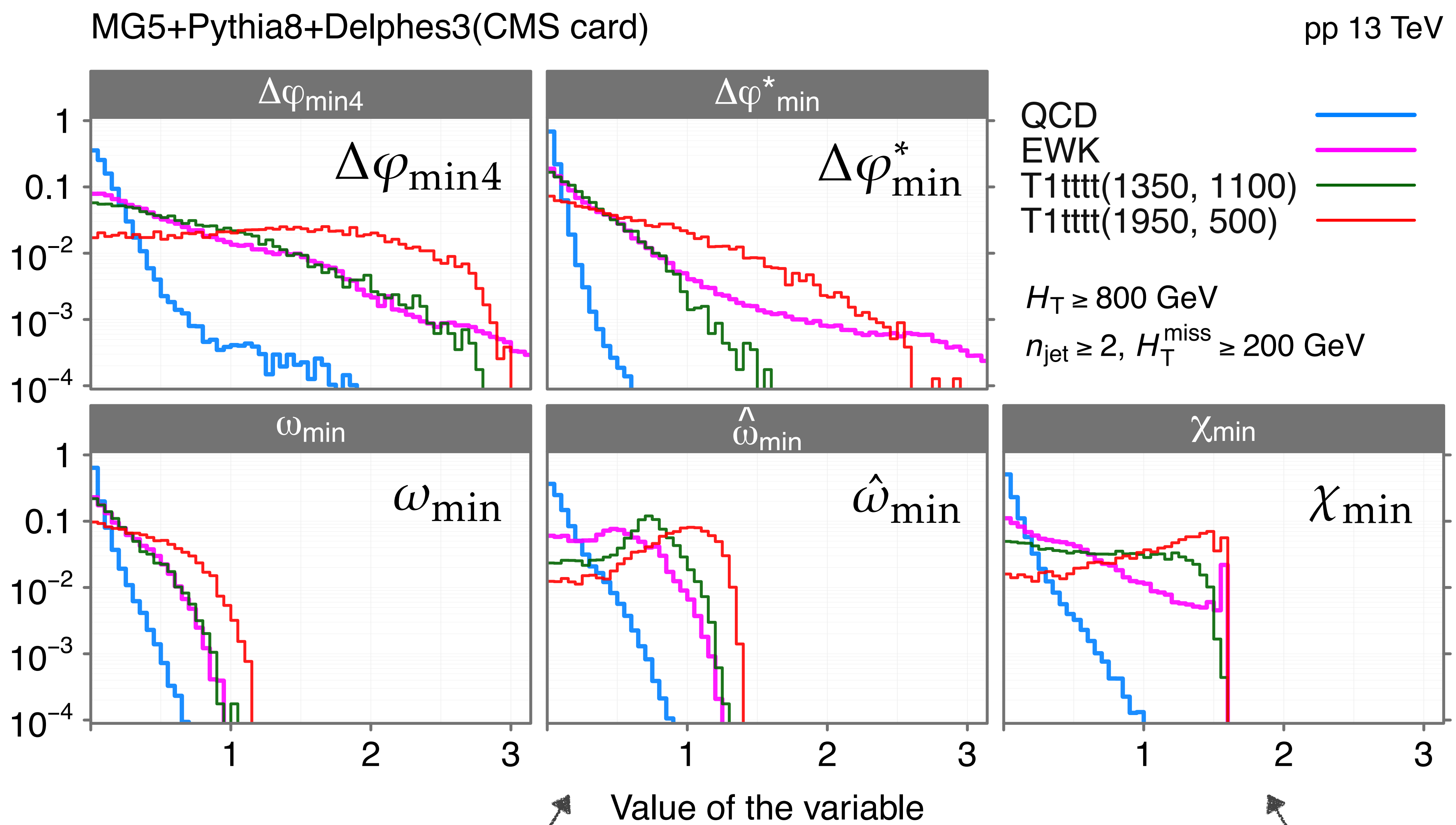
Event distributions

EWK: tt+jets, W+jets, $Z(\rightarrow\nu\nu)$+jets



Event distributions

EWK: tt+jets, W+jets, Z(→$\nu\nu$)+jets

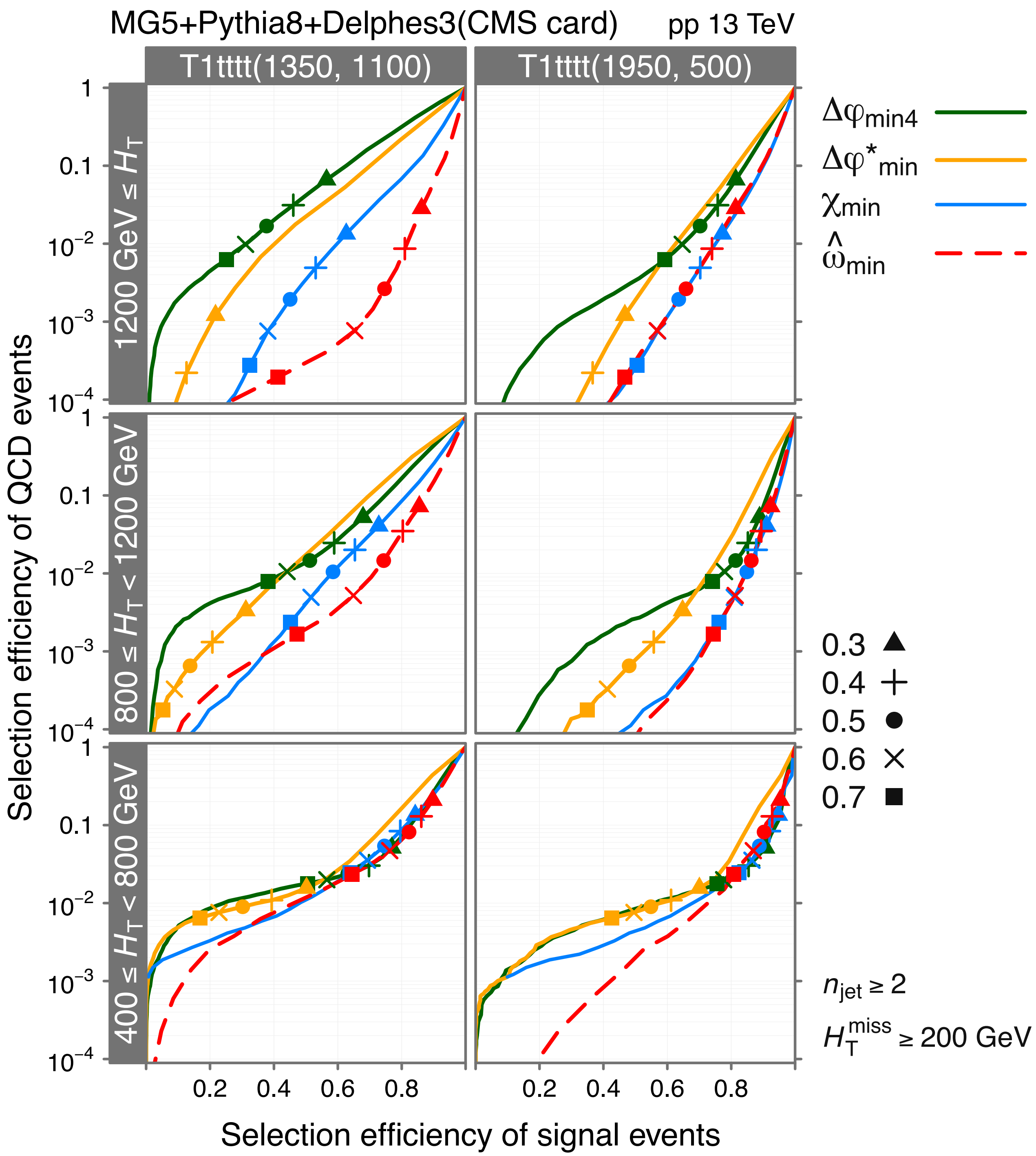


maxima at larger values for signal events

"ideal" distributions of $\Delta\varphi_i$ –exponential decrease for QCD, flat for signal events

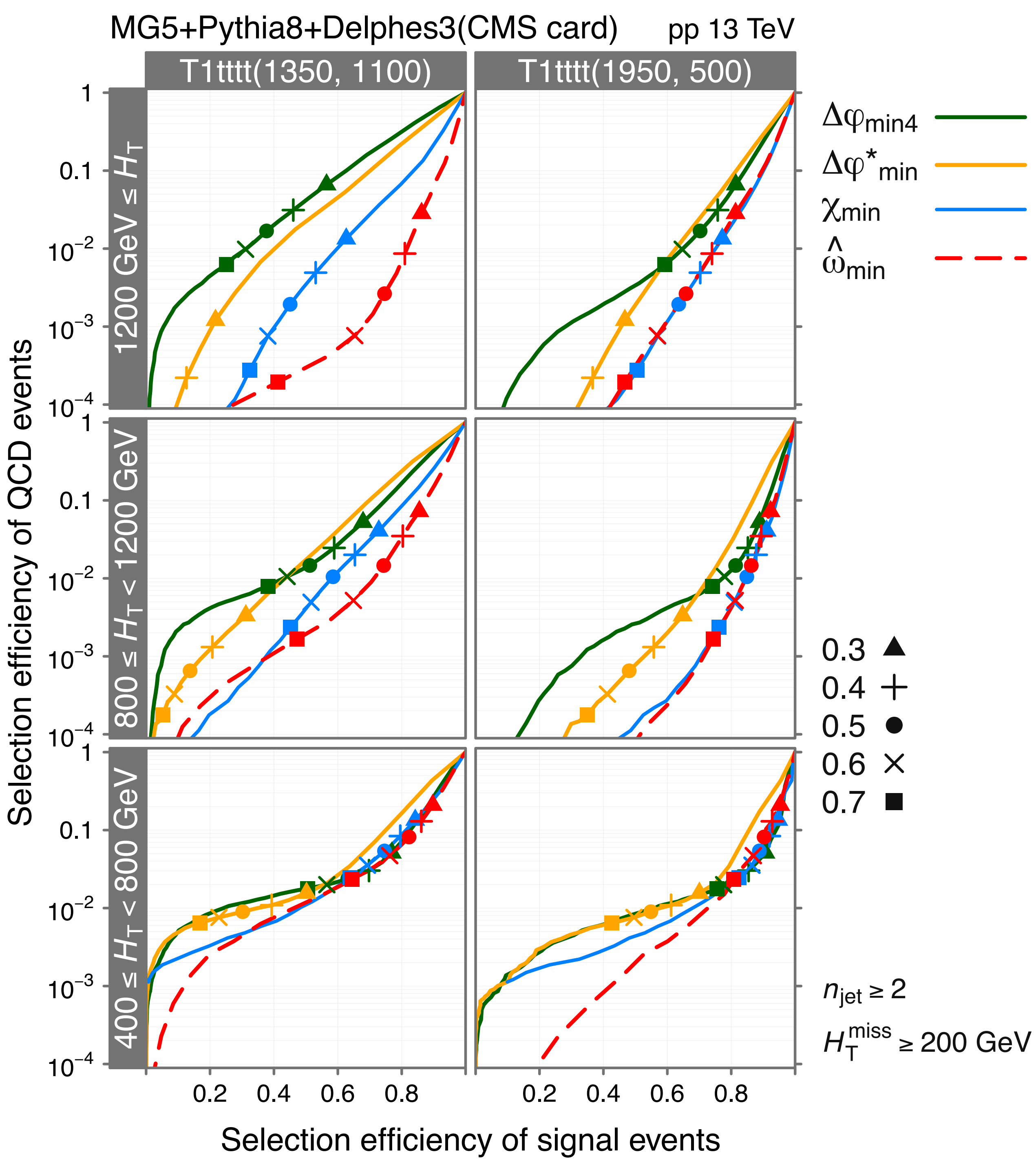
ROC curves

Against QCD multijet events

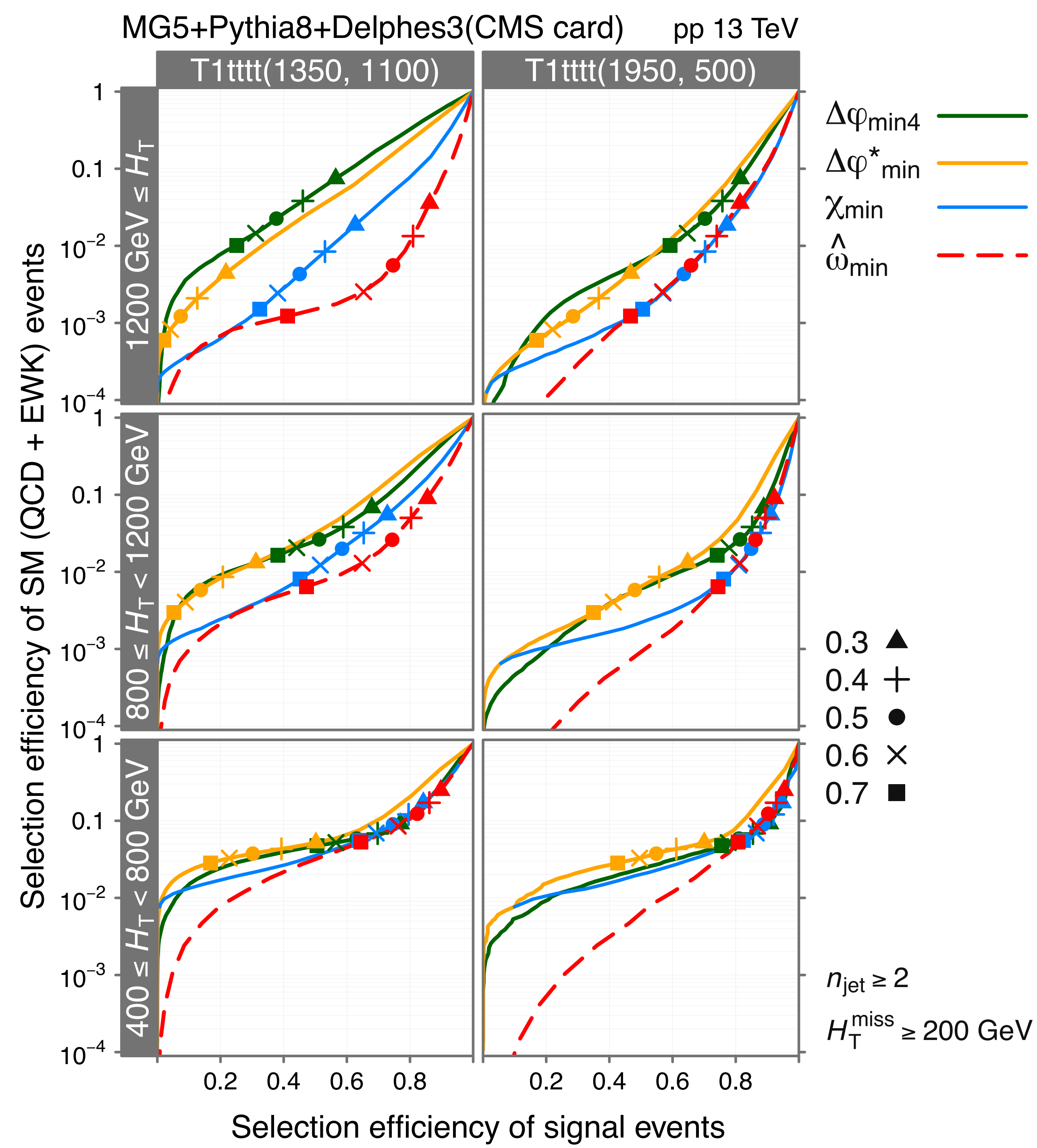


ROC curves

Against QCD multijet events

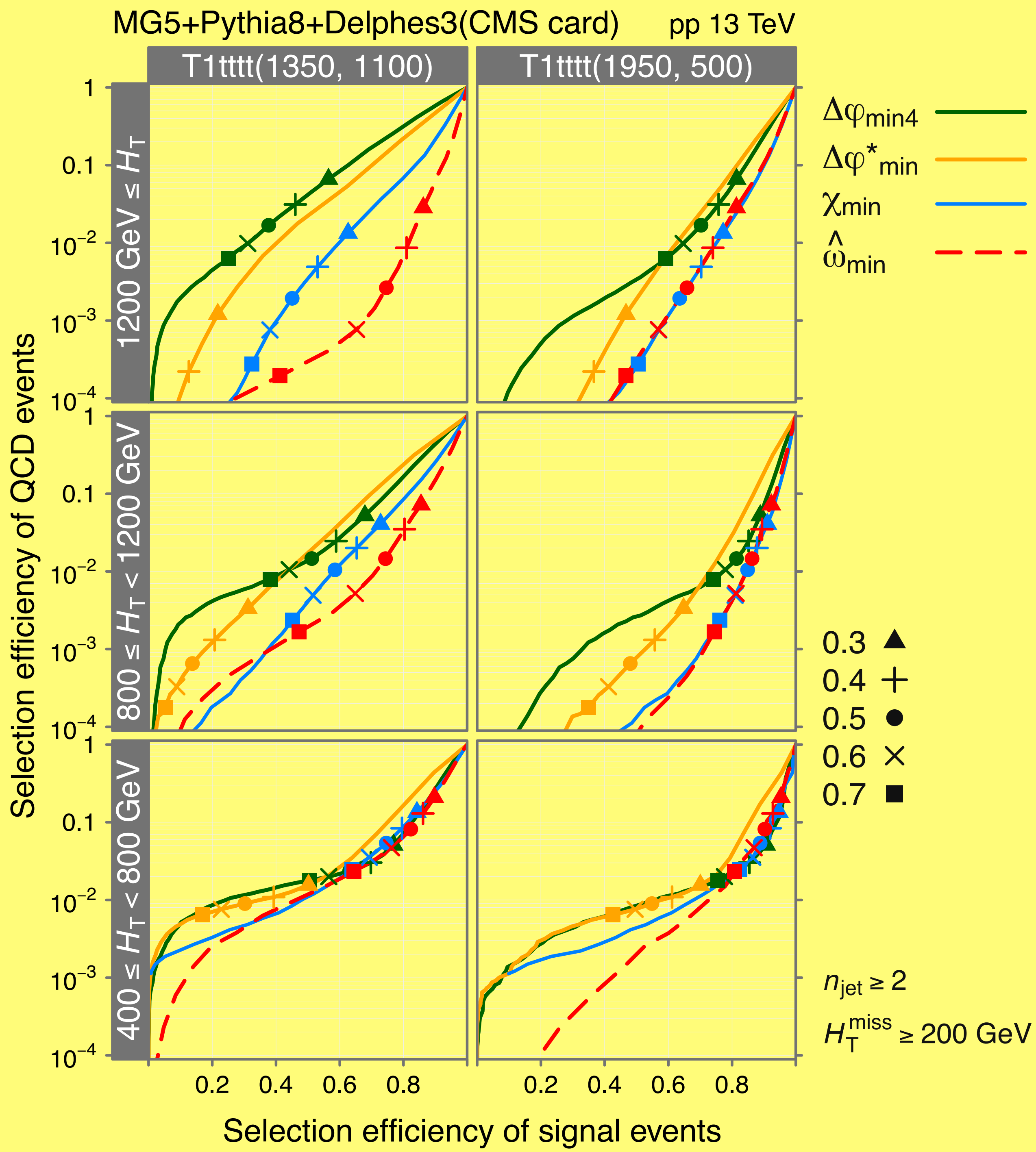


Against the total SM events
(QCD multijets, tt+jets, W+jets, Z($\to\nu\nu$)+jets)



Summary

- We have reviewed the $\Delta\varphi_i$ cut and $\Delta\varphi^{*}_{\mathrm{min}}$ cut for QCD multijet background event suppression in all-hadronic SUSY searches at LHC
- introduced alternative variables χ_{min} and $\hat{\omega}_{\mathrm{min}}$ and demonstrated that they perform better than the conventional variables in a simulated event sample
- planning to submit a paper in January (including more angular variables and variables with dimension)



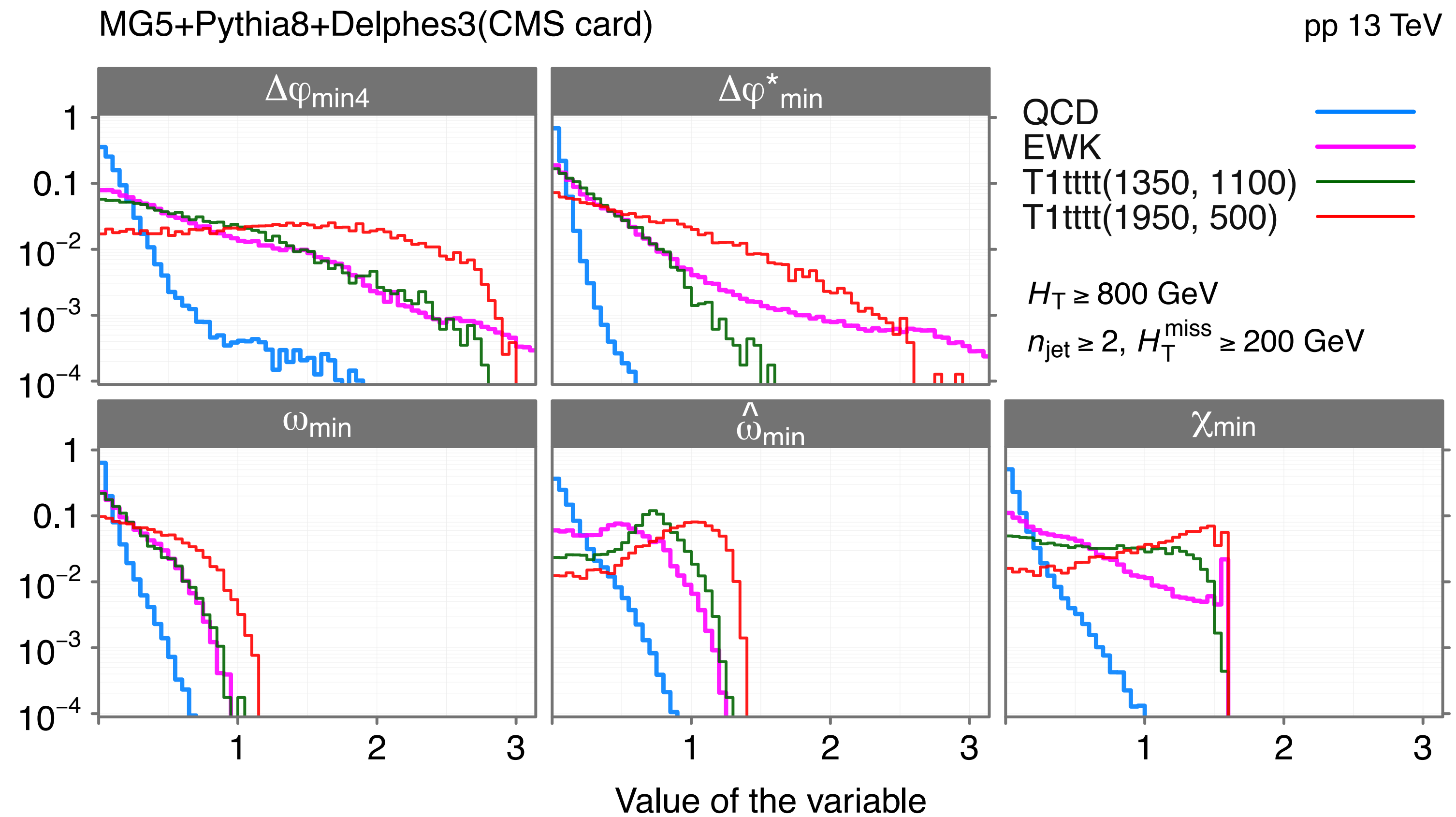
Backup slides

Simulated event sample

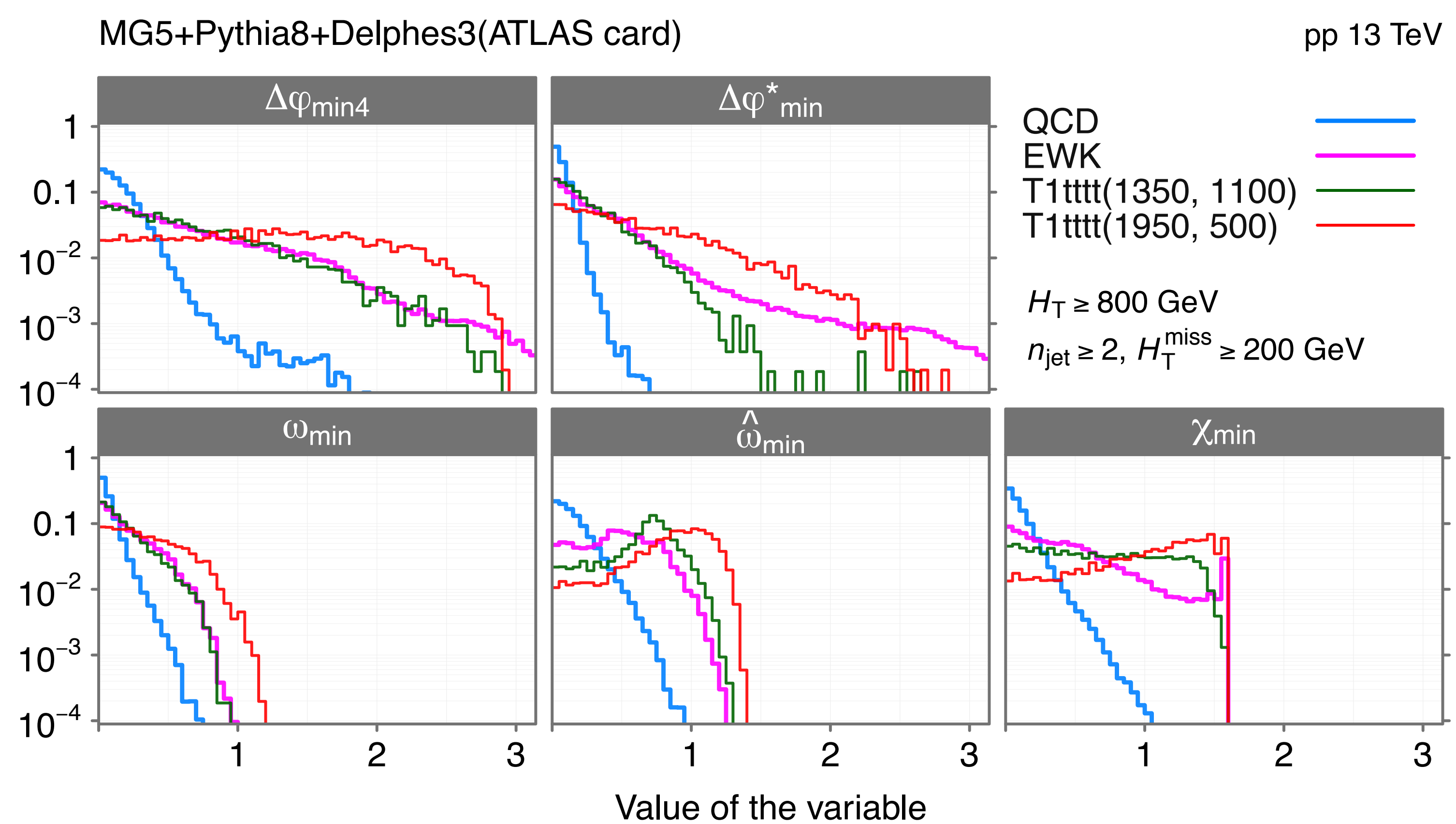
- MadGraph5_aMC@NLO 2.3.3 + Pythia 8.2
  - Leading order, NNPDF2.3LO, MLM matching
    - QCD multijet: up to 3 outgoing partons
    - tt+jets: up to 3 additional outgoing partons, MadSpin
    - W+jets, Z($\rightarrow\nu\nu$)+jets: up to 4 additional outgoing partons
    - T1tttt(1950, 500) , T1tttt(1350, 1100) : up to 2 additional outgoing partons
- Delphes 3.4.1
  - delphes_card_CMS(ATLAS)_PileUp.tcl with a slight modification
  - 23 pileup interactions on average
  - object reconstruction: jets, $e^{\pm}$, $\mu^{\pm}$, photons, MET
  - isolation variables, jet τ-tagging, jet pileup subtraction
- Jets
  - anti-kt (R=0.4) by FastJet run within Delphes
  - pT corrections - such that the peak location of pT distribution agrees with generated jets in ranges of pT and η
  - pT $\geq$ 30 GeV
- Generated Jets
  - anti-kt (R=0.4) by FastJet run within Delphes
  - particles after fragmentation, parton shower, and decay of certain short-lived particles
  - no neutrinos or neutralinos
- Event selection
  - vetos:
    - no isolated $e^{\pm}$, $\mu^{\pm}$, or photon
    - no forward jet ($|\eta|>3$) or τ-tagged jet
    - no jet that doesn't meet quality criteria
      - CMS card: Beta $\geq$ 0.14, NCharged > 0, PTD < 0.8, and MeanSqDeltaR < 0.1
      - ATLAS card: NNeutrals > 0 and 0.7 < EhadOverEem < 13
  - kinematic phase space:
    - njet $\geq$ 2, HT > 400 GeV
    - MHT > 200 GeV
    - MHT/MET < 1.25

Comparison of Delphes CMS and ATLAS cards: event distributions

CMS card

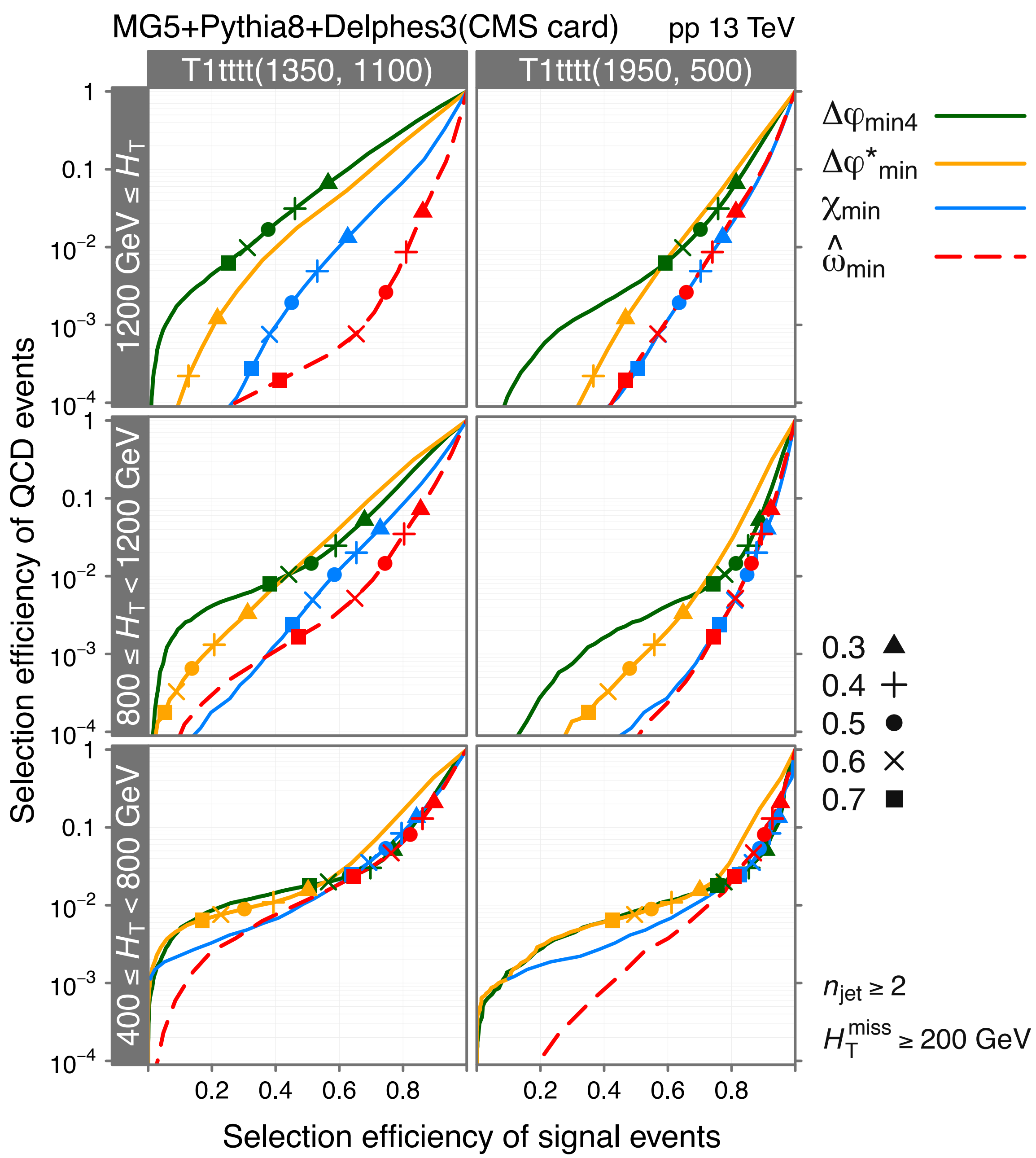


ATLAS card

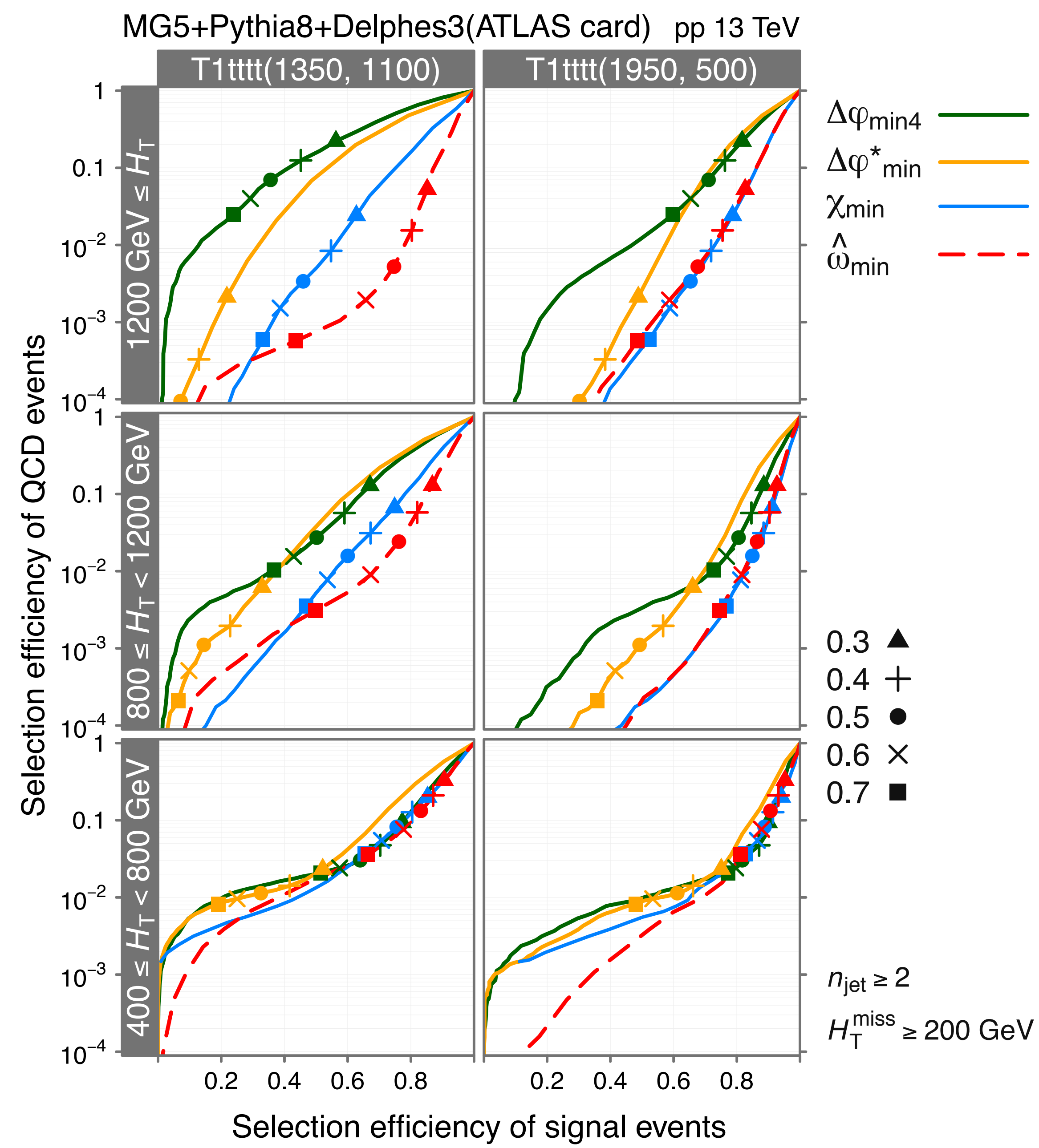


Comparison of Delphes CMS and ATLAS cards: ROC curves

CMS card



ATLAS card



End