Test of Lepton Flavour Universality using $D_{(s)}^+ \to \phi(\ell^+\ell^-)\pi^+$ decays

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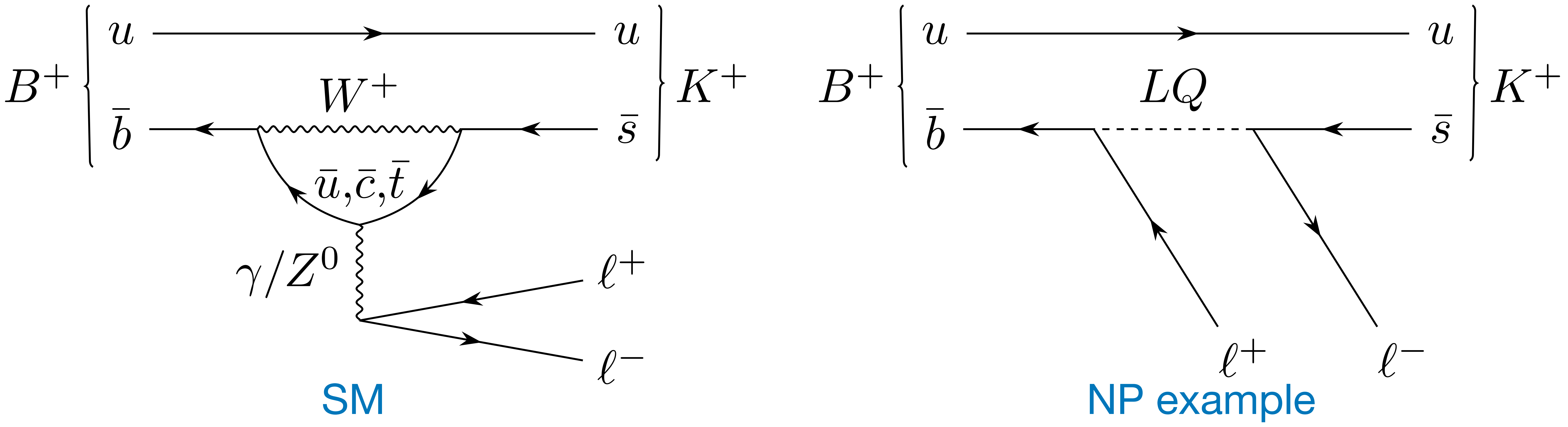
Rare decays as New Physics probes

- Rare $b \to s\ell\ell$ decays are sensitive New Physics (NP) probes since they are loop level and CKM suppressed.
- NP contributions could be of same size as the SM (e.g. enhancing/suppressing branching fractions, angular distributions).
- In the Standard Model (SM) couplings of vector bosons to leptons are flavour universal (LFU):

→any deviation from LFU is a clear NP indication.



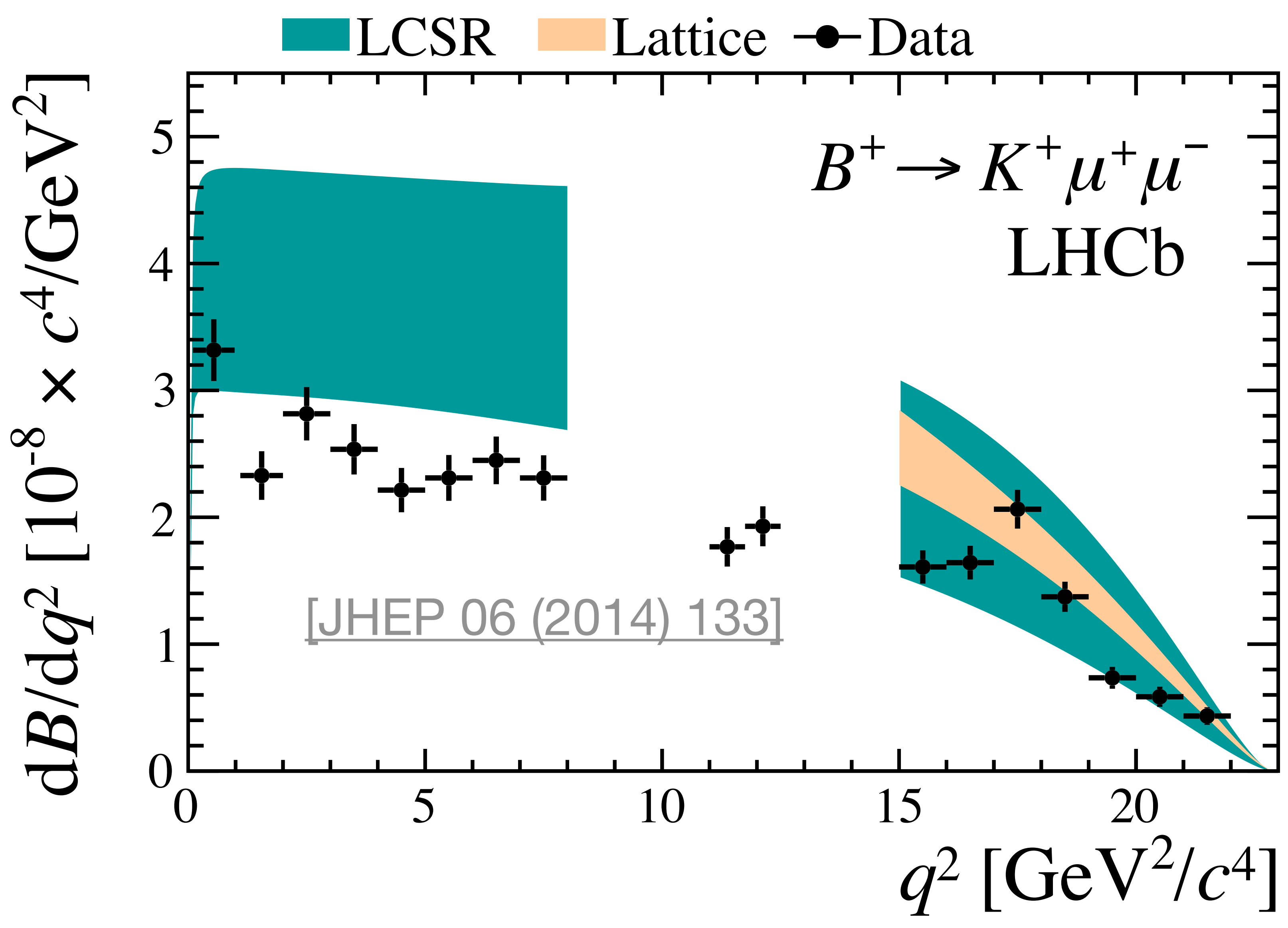
A coherent pattern?

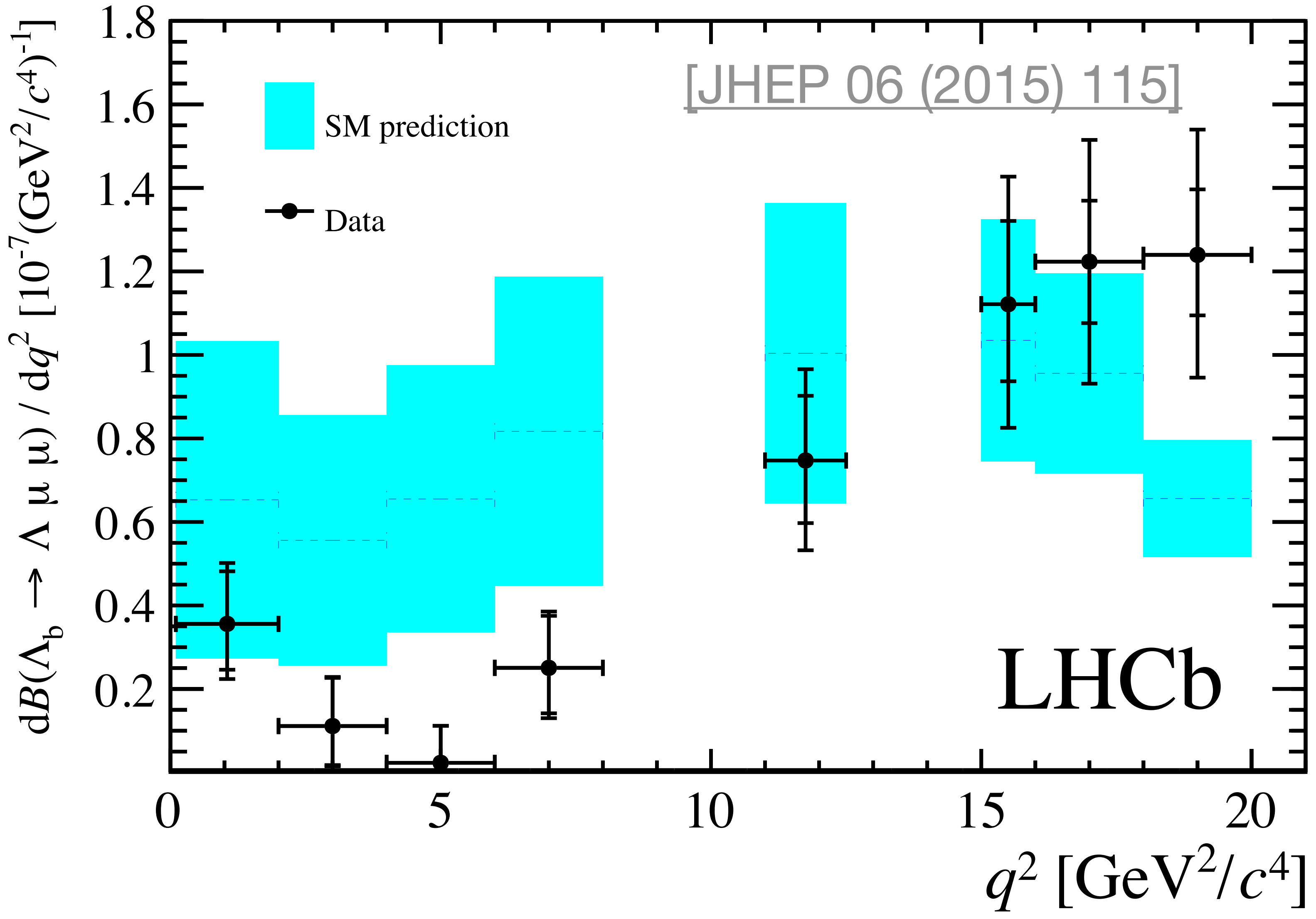
Over the past decade a coherent set of tensions with SM predictions has emerged in $b \to s\ell\ell$ transitions:

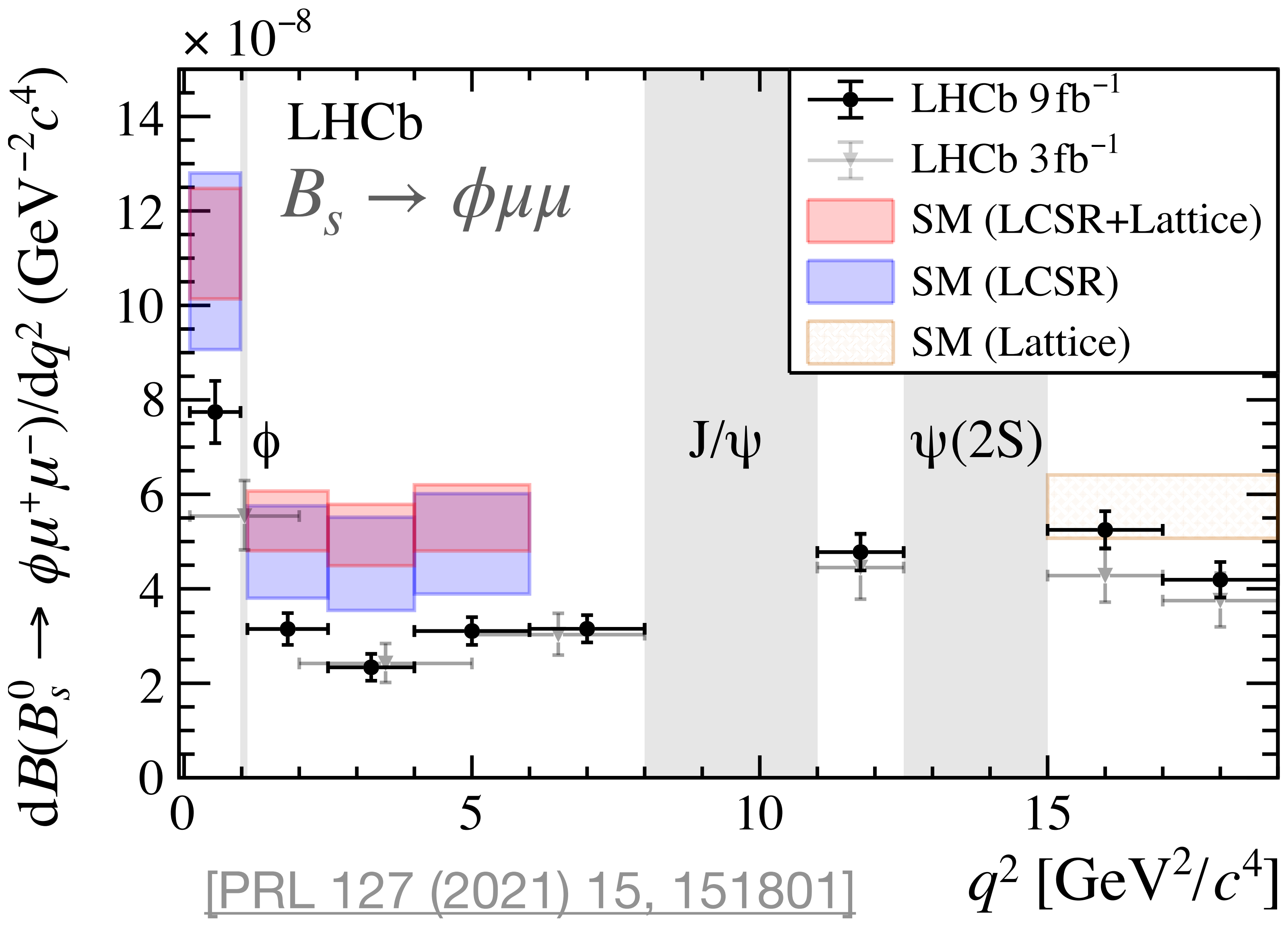
- Branching fractions (e.g. $B_s \to \phi\mu^+\mu^-$, $B \to K^{(*)}\mu^+\mu^-$).

- Optimised angular observables (e.g. P_5' in $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$).

$q^2 \stackrel{def}{=}$ dilepton invariant mass squared







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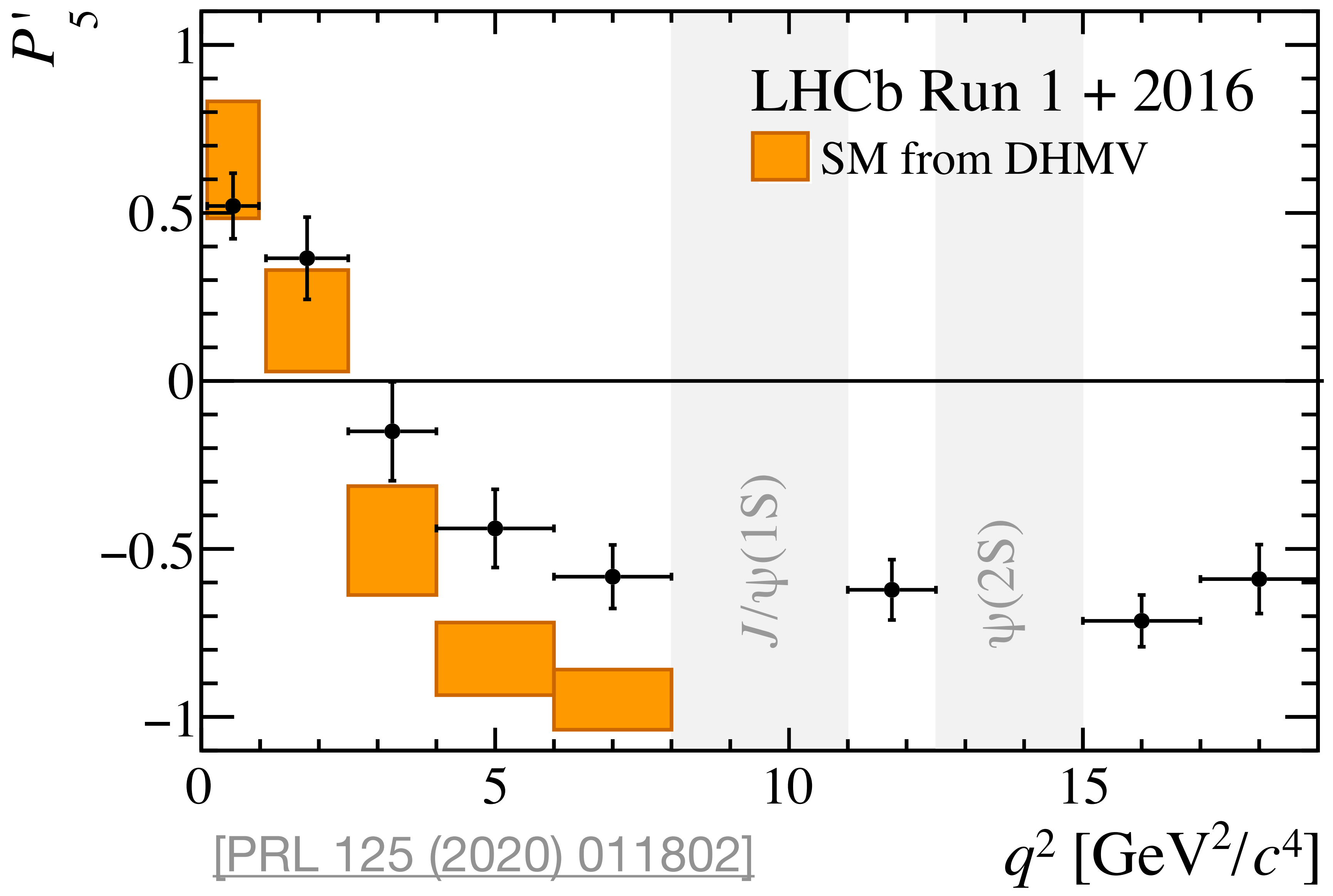
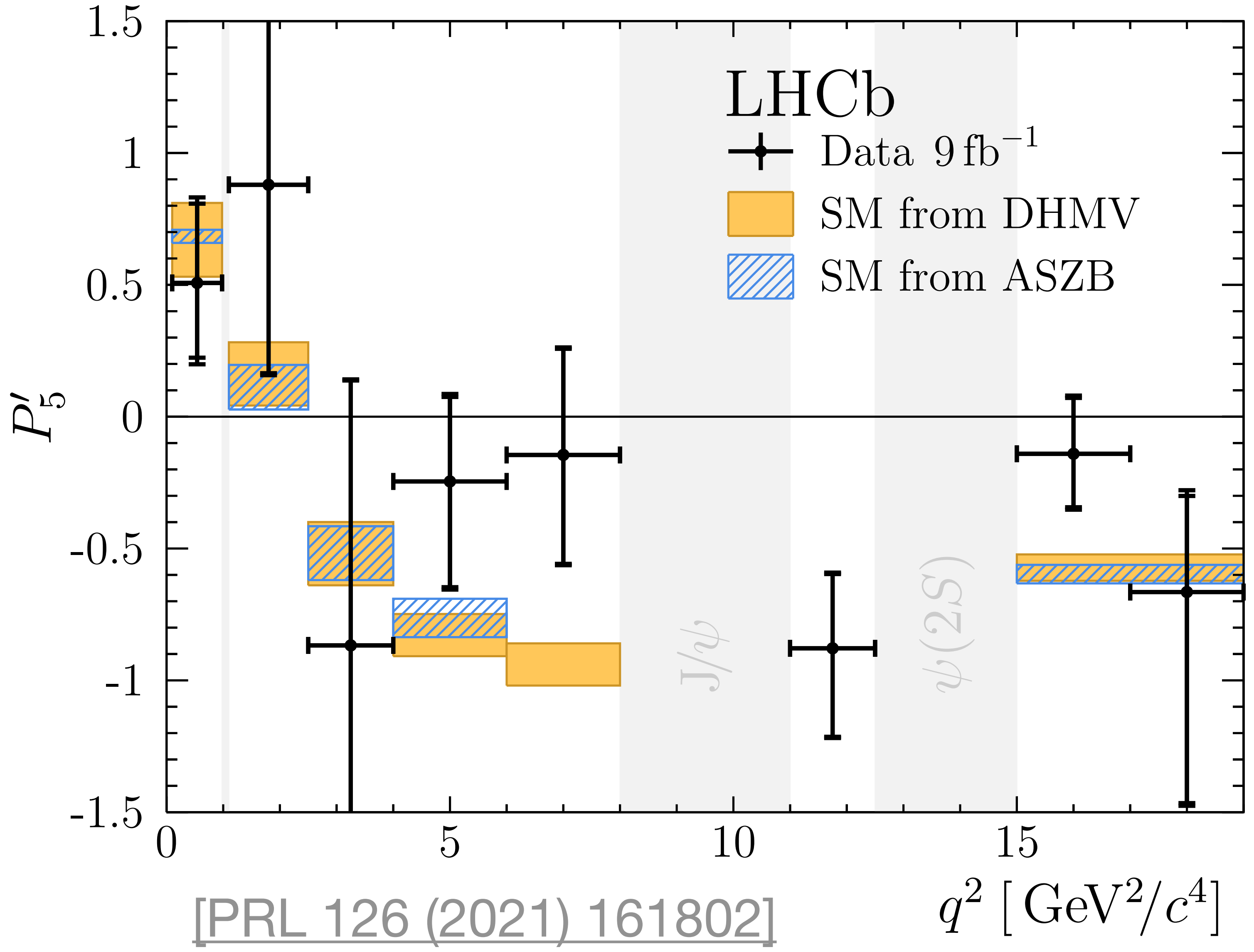
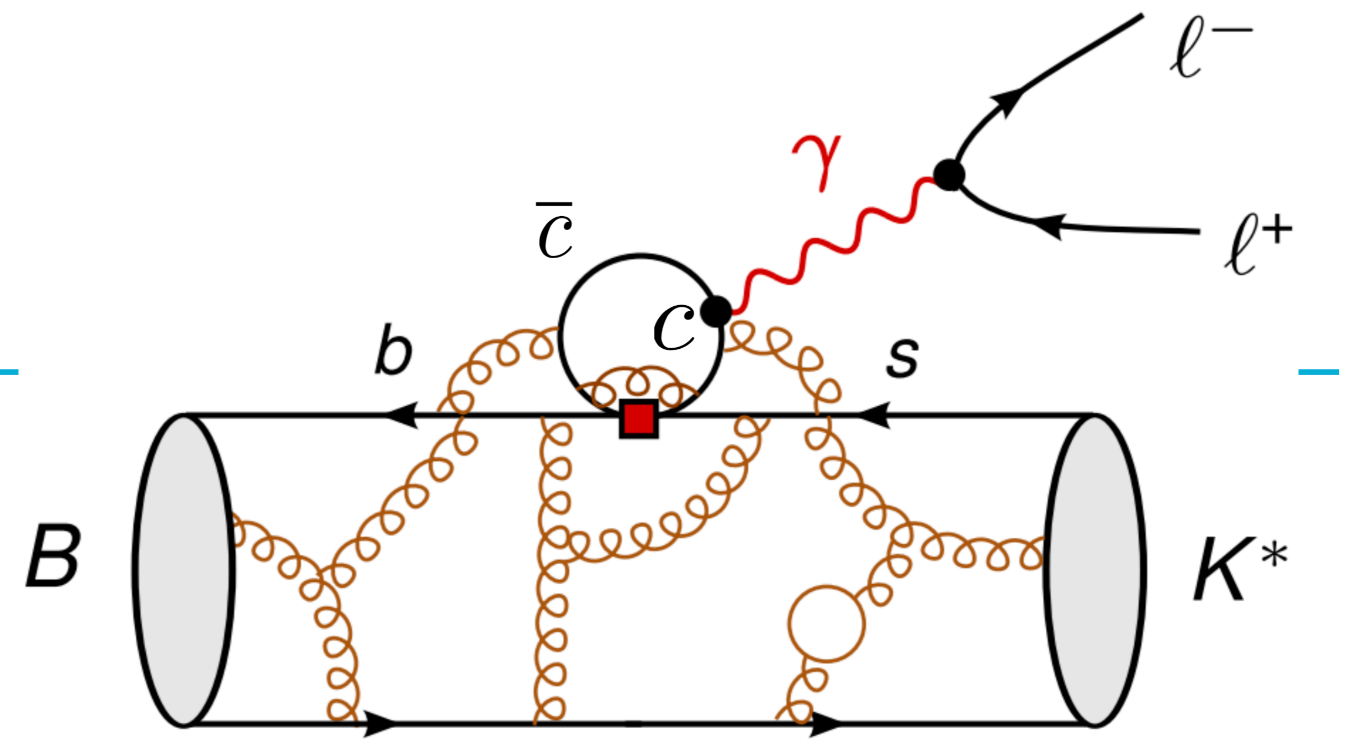


[PRL 125 (2020) 011802]



[PRL 126 (2021) 161802]

The R_H observables



- $B \to K^{(*)}\ell^+\ell^-$ BF and angular observables known to suffer from potentially underestimated hadronic uncertainties.

- Define a set of theoretically clean observables:

$q^2 \equiv$ momentum transfer to the pair of leptons

$$R_{H_s} = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B \to H_s \mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B \to H_s e^+e^-)}{dq^2} dq^2} \stackrel{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

QED

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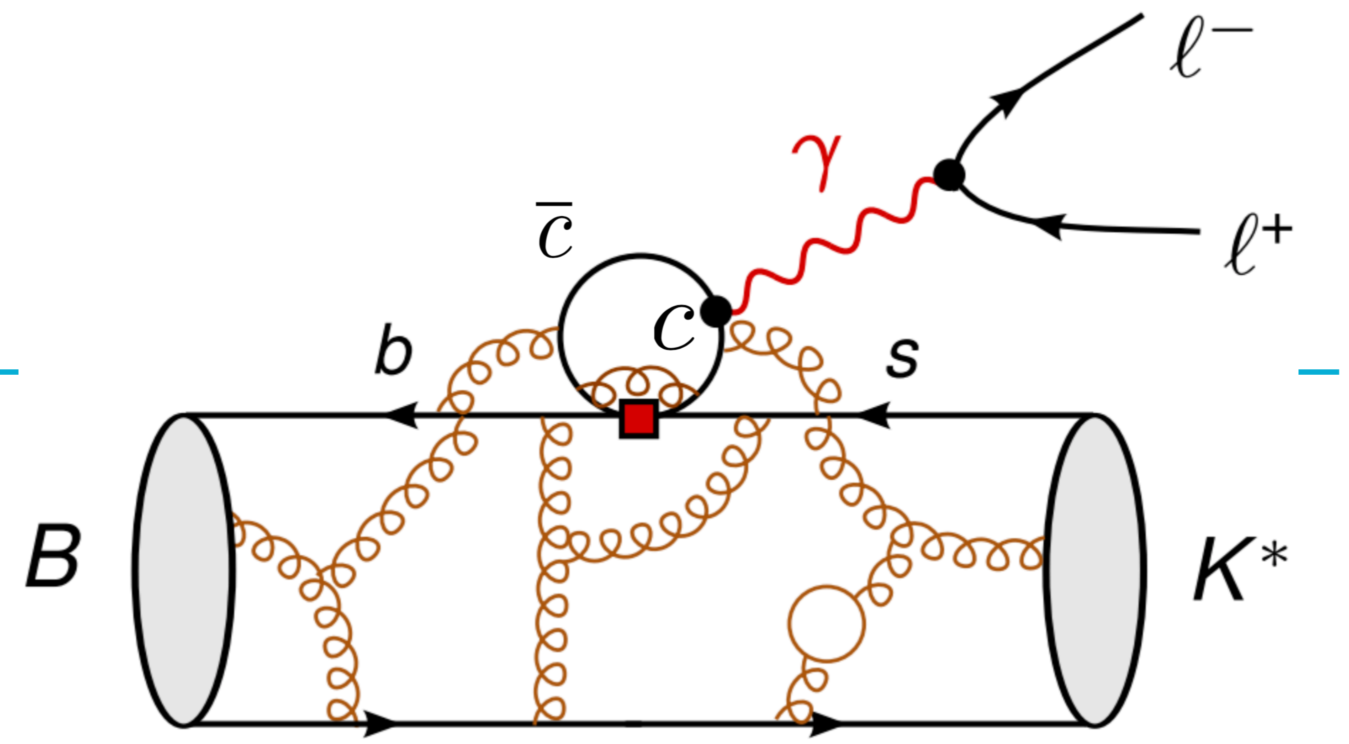

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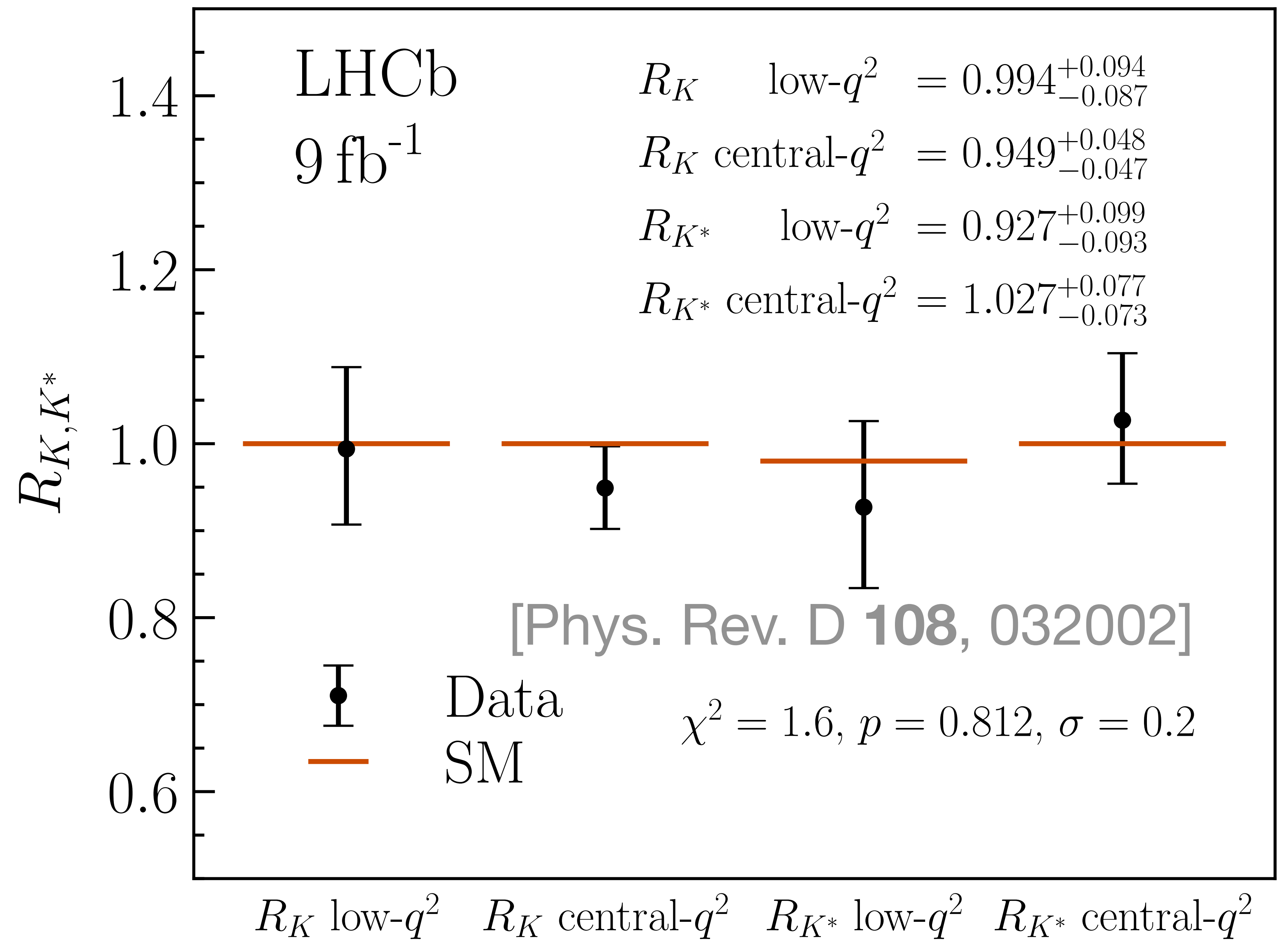
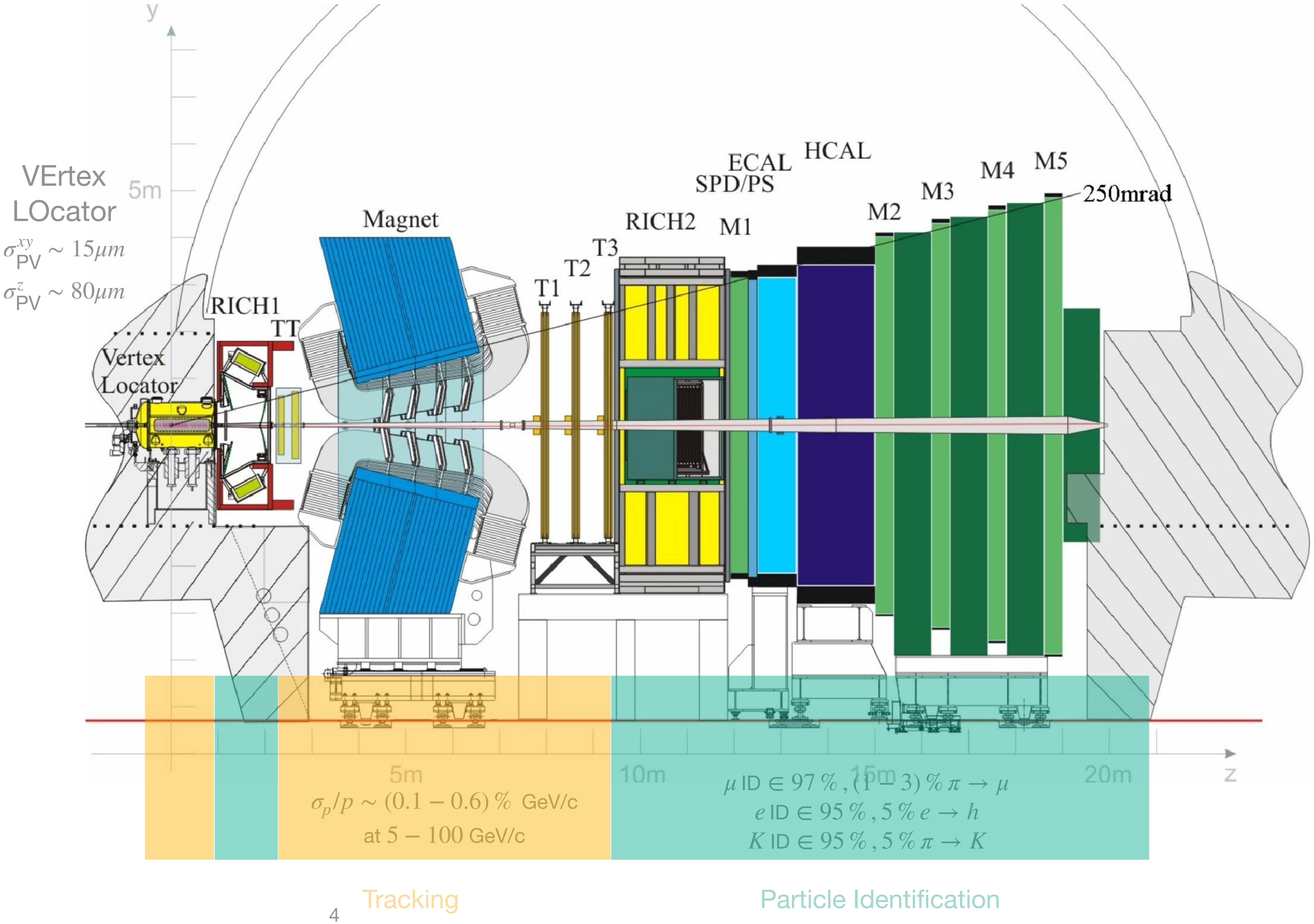
QED

- [2021 R_K], [2017 R_{K^*}] claims of LFUV evaporated after a more thorough study of misID $h \to e$ background sources



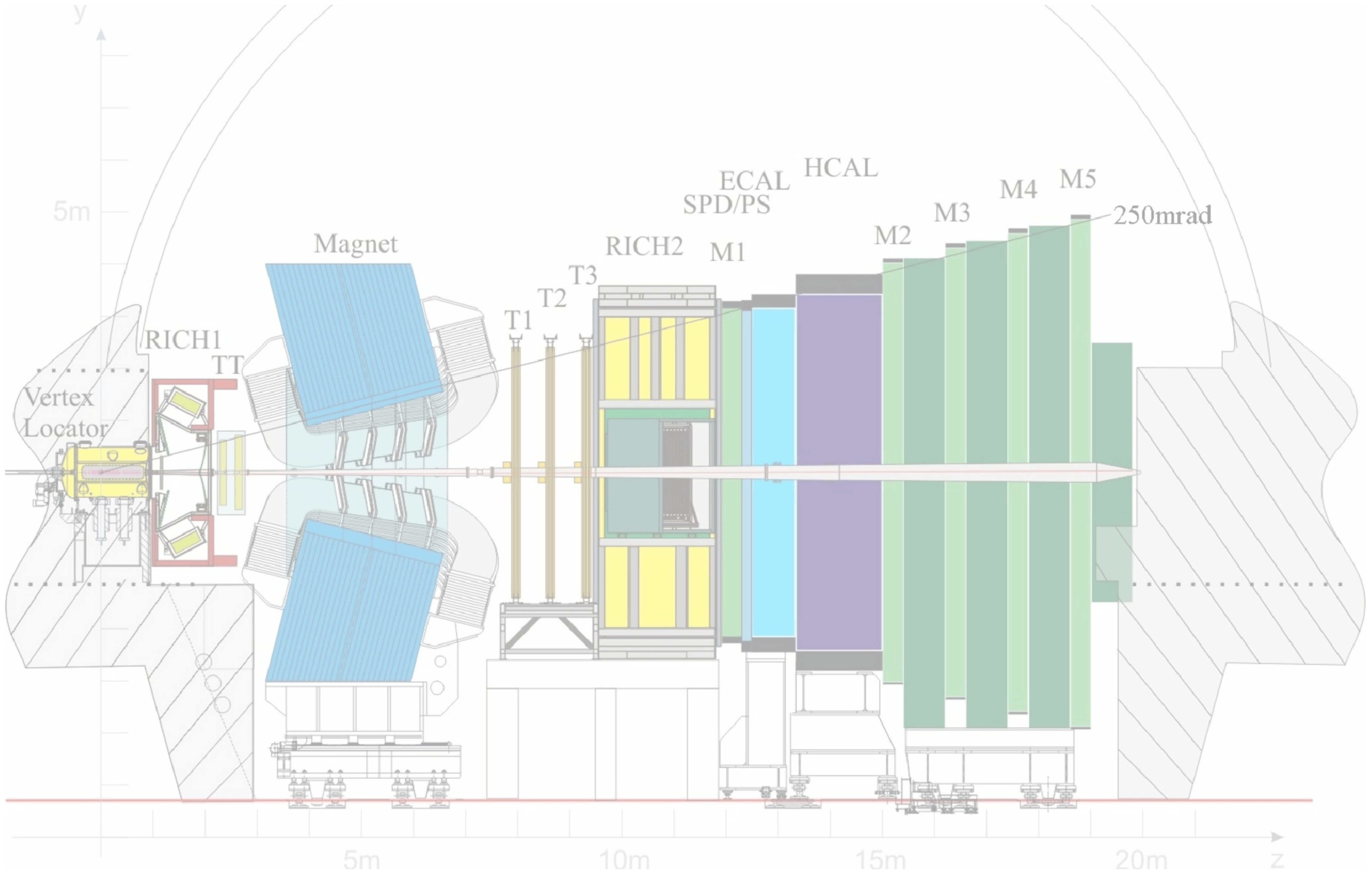
The LHCb experiment @ LHC

- Forward arm spectrometer designed for heavy flavour physics.
- Instrumented in the forward region where $\sigma(pp \to b\bar{b}X)$ is maximal.
- Excellent vertexing and PID capabilities to identify displaced (few mm) $b-$hadron vertices and rare decays.
- 100 thousand $b\bar{b}$ pairs per second produced in LHCb acceptance.



Light leptons at LHCb

- Since probability of bremsstrahlung emission $\propto E/m^2 \rightarrow$ electrons and muons interact differently with the detector, and exploit different subdetector systems



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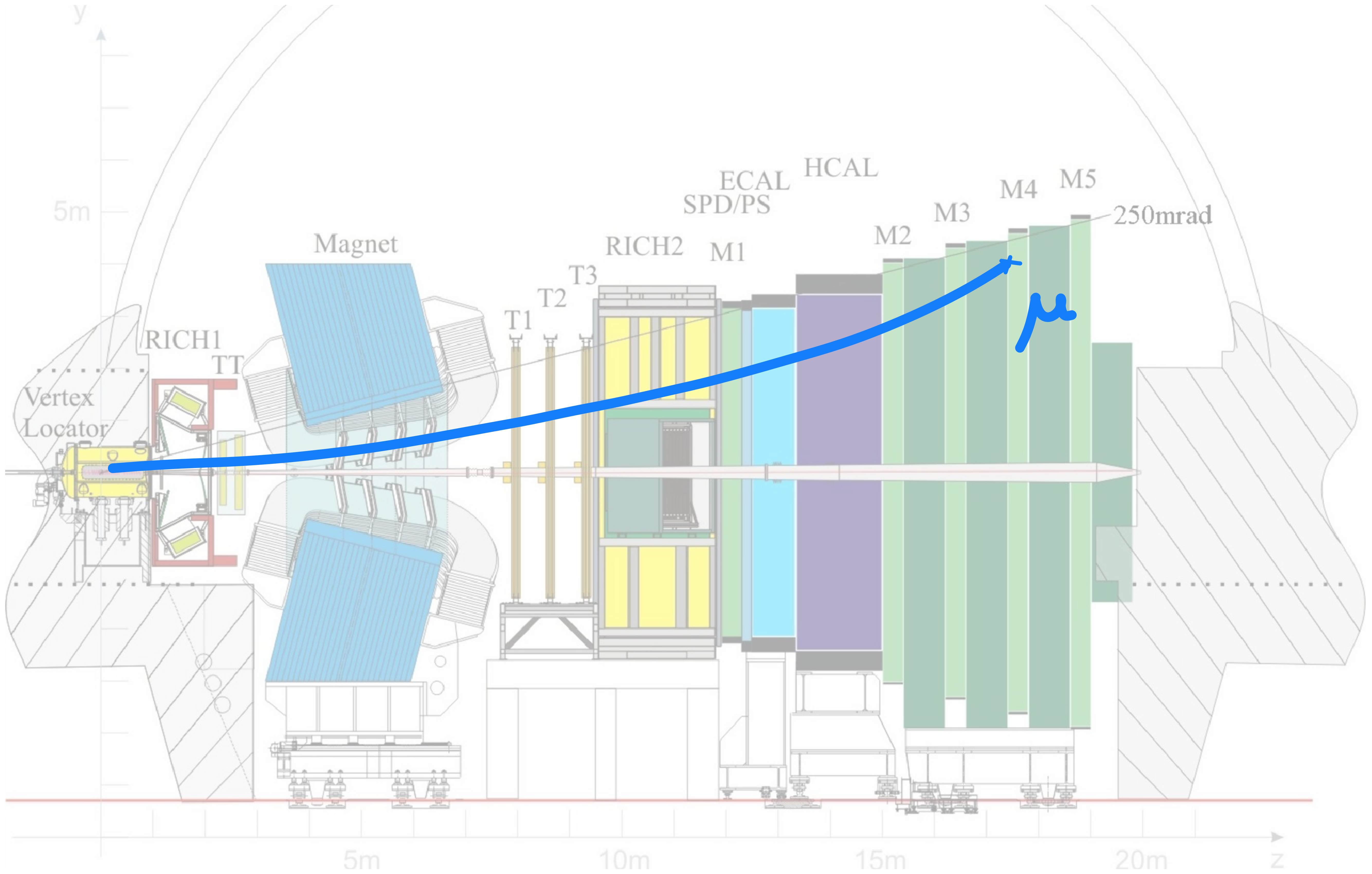

Light leptons at LHCb

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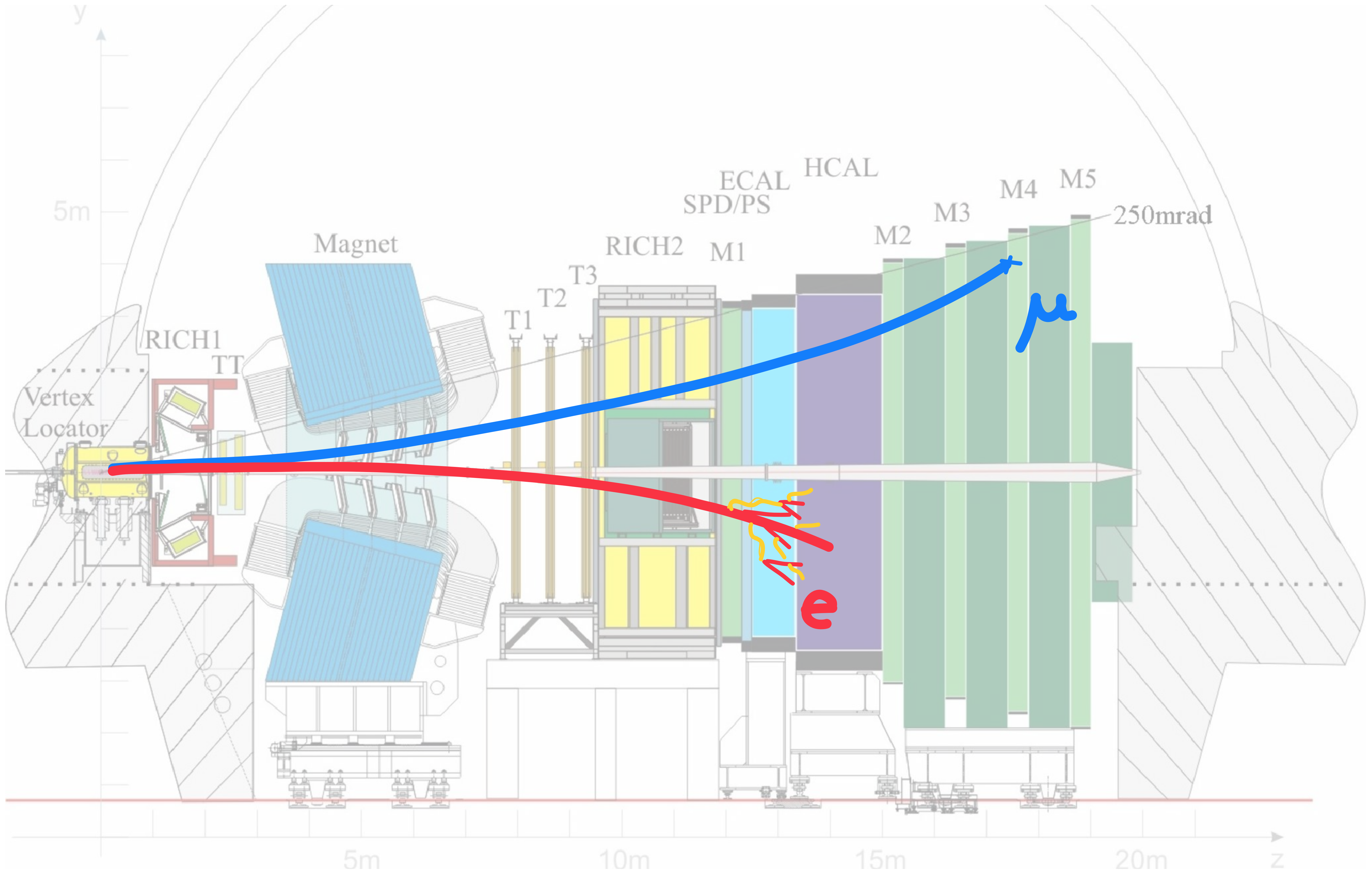
- Muons traverse the detector undisturbed

- Electrons lose significant amount of energy to bremsstrahlung radiation:
  - Poorer mass resolution and reconstruction efficiency than muons.
  - Effect mitigated by bremsstrahlung recovery algorithm.

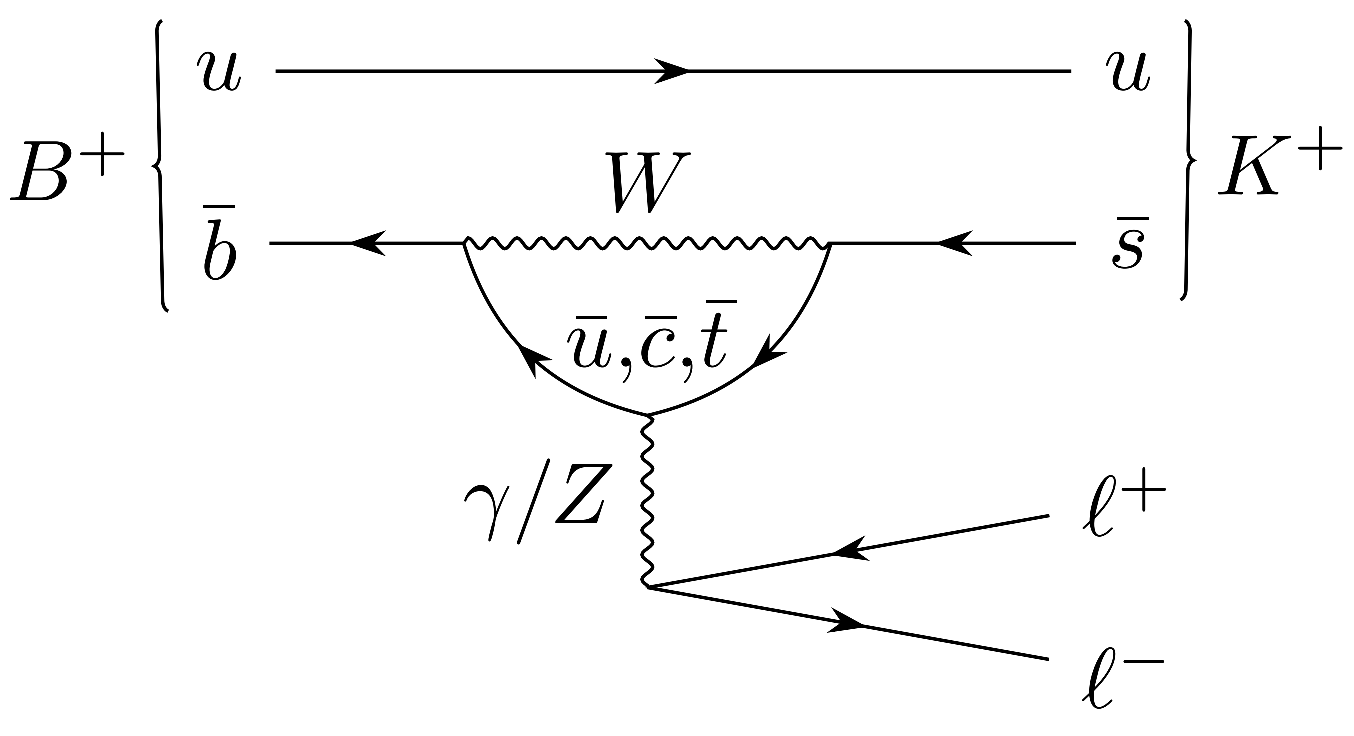


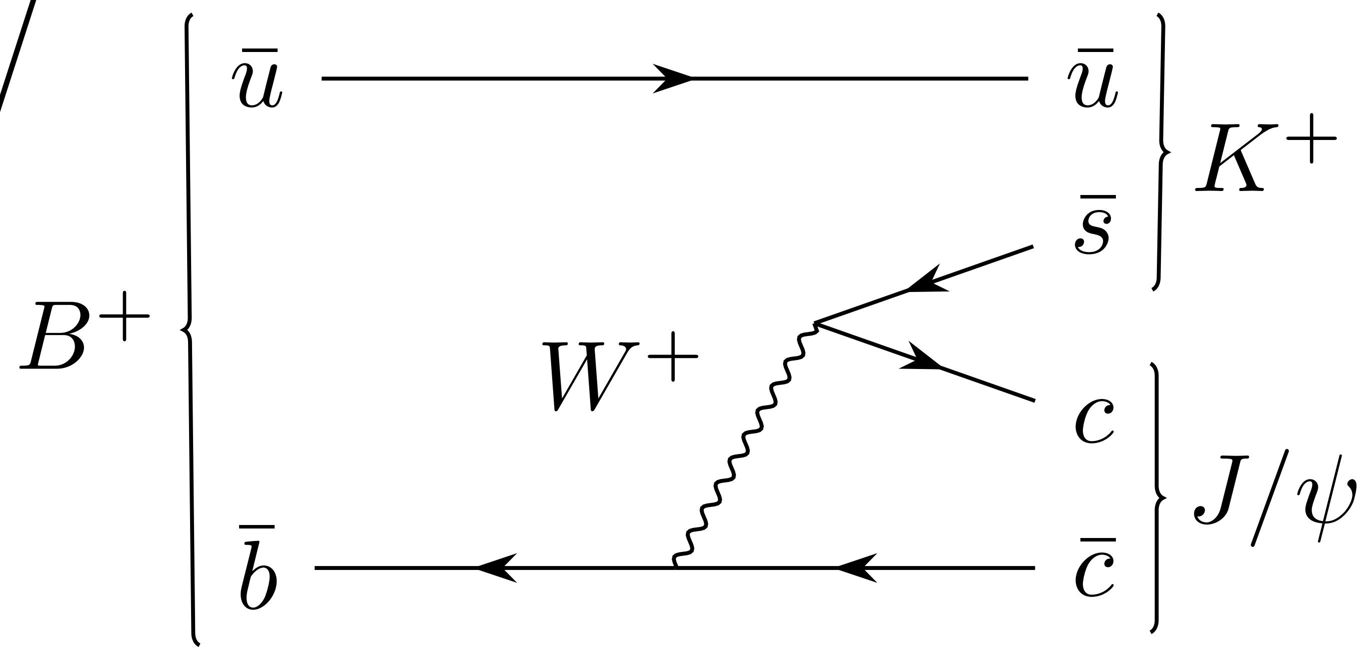
The double ratio strategy

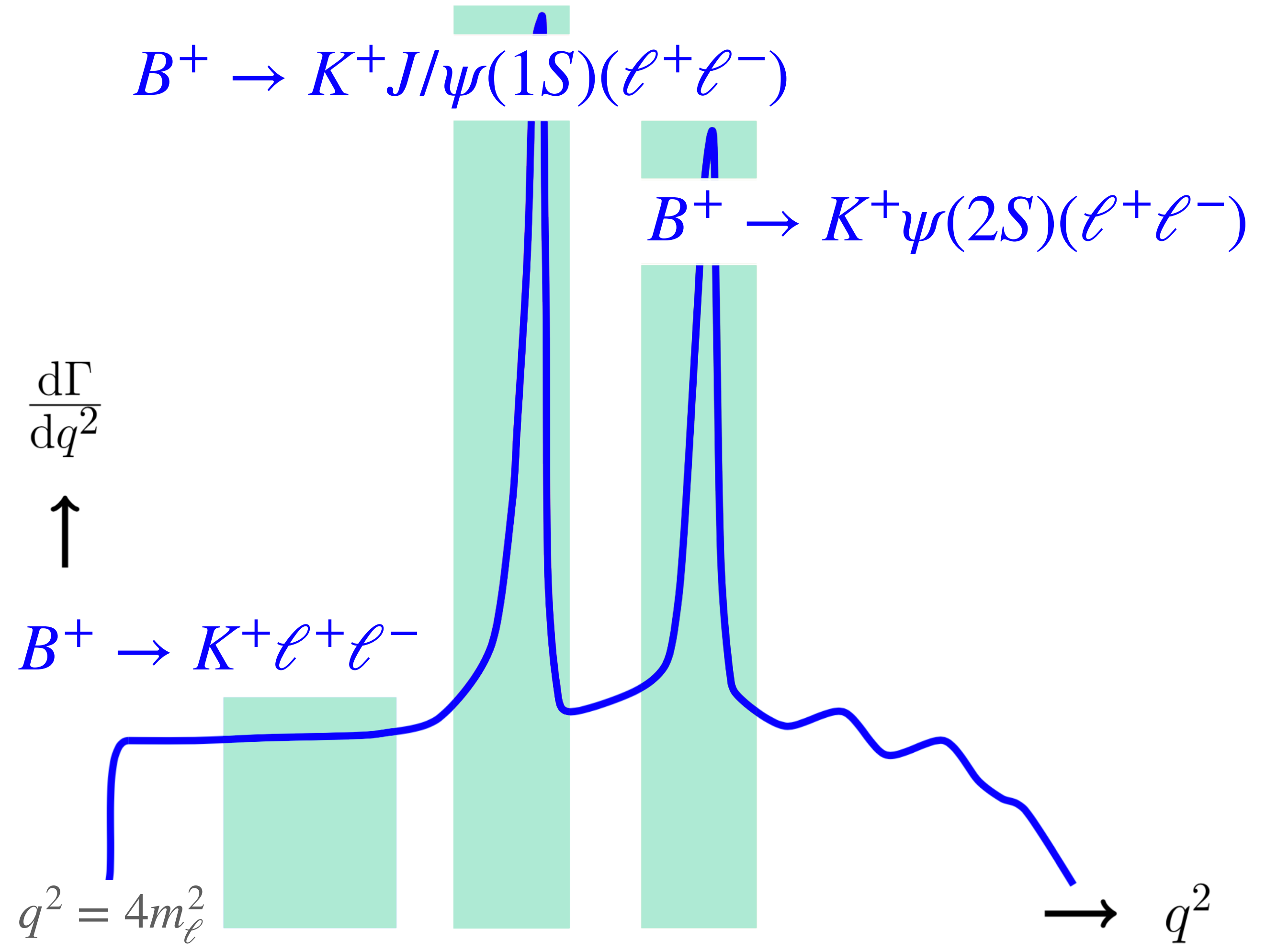
- Control electron-muon differences using double ratio between nonresonant $B^+ \to K^+\ell^+\ell^-$ and resonant $B^+ \to K^+J/\psi(\ell^+\ell^-)$.

$$R_K = \frac{N(K^+\mu\mu)}{N(K^+J/\psi(\mu\mu))}\frac{\varepsilon(K^+J/\psi(\mu\mu))}{\varepsilon(K^+\mu\mu)} \Big/ \frac{N(K^+ee)}{N(K^+J/\psi(ee))}\frac{\varepsilon(K^+J/\psi(ee))}{\varepsilon(K^+ee)}$$

known to be LFU within 0.4% [PDG]





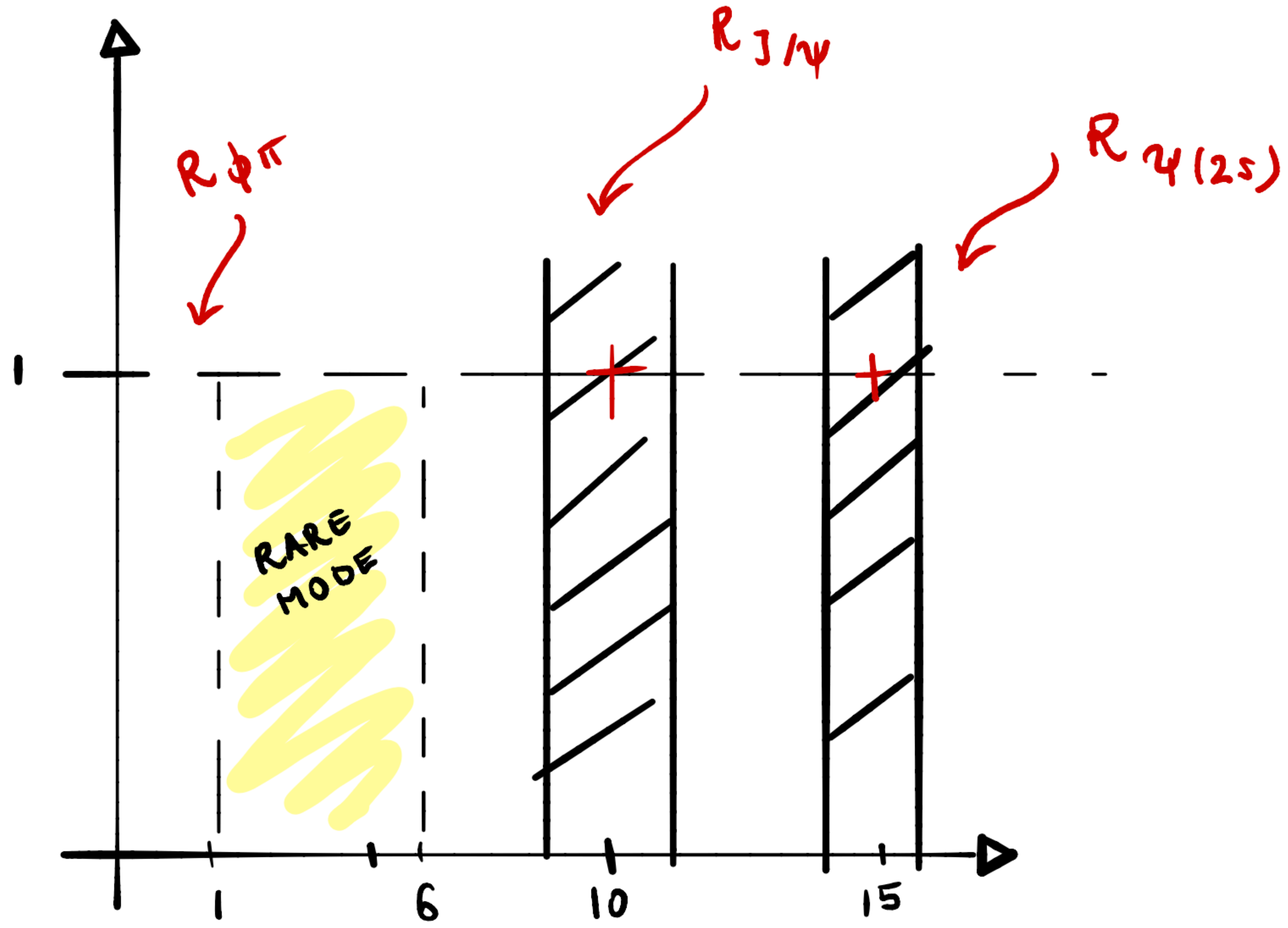


Definition of $R_{\phi\pi}$

- Resonant $D^+_{(s)} \to \phi(\ell^+\ell^-)\pi^+$ are ideal control channels in the low dilepton invariant mass region

- Allows to precisely verify $h \to e$ mis-ID rates estimation strategy

- Muon anomalous results still stand, important to check that we understand their detection efficiencies at low q^2 as well



$$R^{d(s)}_{\phi\pi} = \beta \cdot \frac{\mathcal{B}(D^+_{(s)} \to \phi(\mu\mu)\pi^+)}{\mathcal{B}(D^+_{(s)} \to \phi(ee)\pi^+)} \Big/ \frac{\mathcal{B}(B^+ \to J/\psi(\mu\mu)K^+)}{\mathcal{B}(B^+ \to J/\psi(ee)K^+)} = 1$$

where $\beta = \mathcal{B}(\phi \to e^+e^-)/\mathcal{B}(\phi \to \mu^+\mu^-) \sim \left(1 - \frac{4m_\mu^2}{m_\phi^2}\right)^{-1/2} \simeq 1.022$ ratio of phase space factors

Analysis Strategy overview

- Using $5.4\,\mathrm{fb}^{-1}$ of data collected in 2016, 2017 and 2018 measure:

$$R_{\phi\pi}^{d(s)} = \beta \cdot \frac{N(D_{(s)}^{+} \to \phi(\mu\mu)\pi^{+})}{N(D_{(s)}^{+} \to \phi(ee)\pi^{+})} \cdot \frac{\varepsilon(D_{(s)}^{+} \to \phi(ee)\pi^{+})}{\varepsilon(D_{(s)}^{+} \to \phi(\mu\mu)\pi^{+})} \Big/ r_{J/\psi}$$

Blindedd

1. Efficiency calculation:

- Eff. computed using simulated samples and corrected using control channels selected from the data (mother kinematics, trigger, PID).

2. Signal yield extraction:

- Perform separate maximum likelihood fits for each year of data taking and trigger category and combine as a direct sum.

3. Systematic uncertainties:

- Evaluated by taking the standard deviation of $R_{\phi\pi}^{d(s)}$ values when alternative strategies for yields extraction/efficiency calculation are employed.

Efficiencies

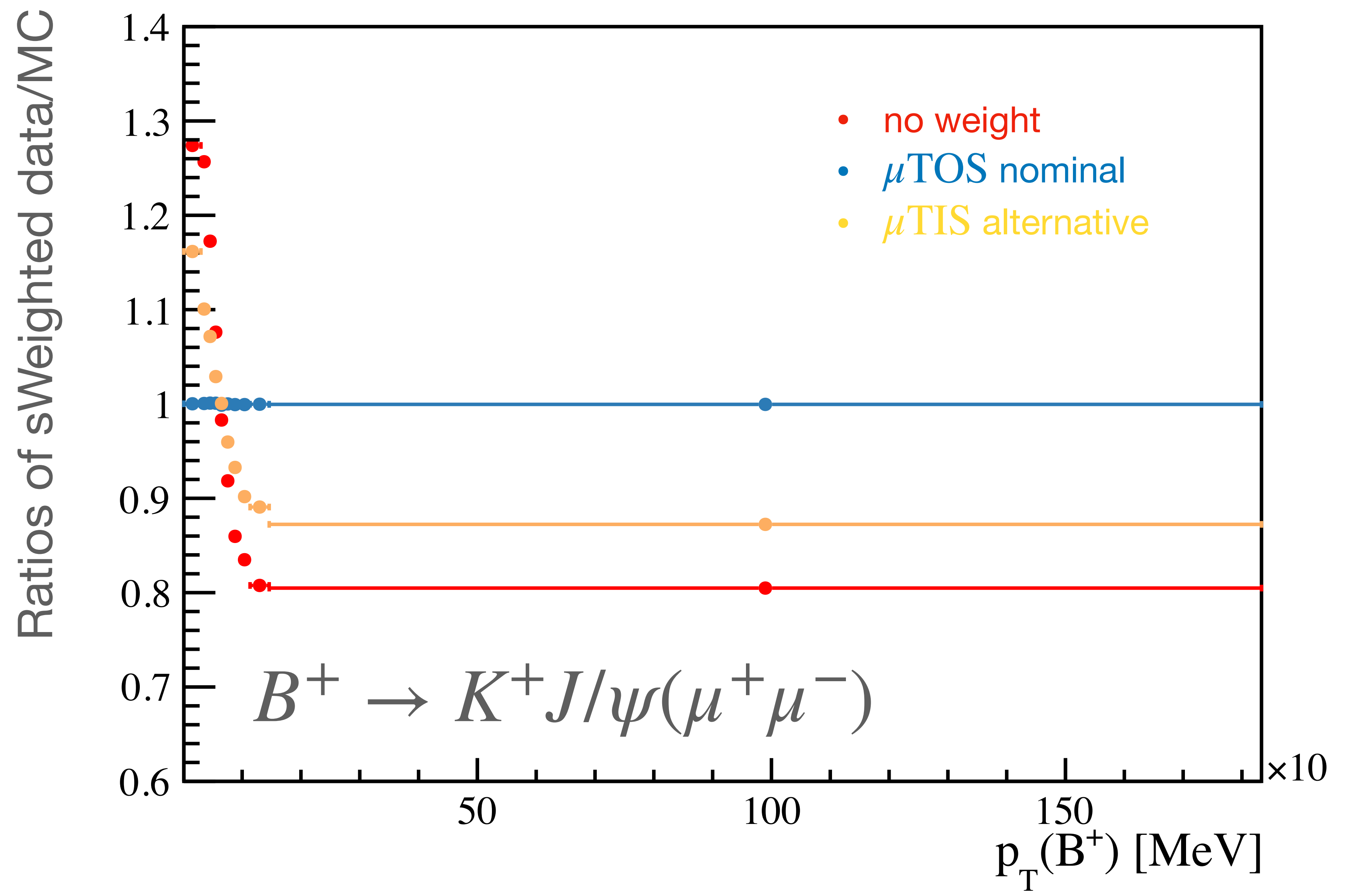
Corrections to simulated efficiencies

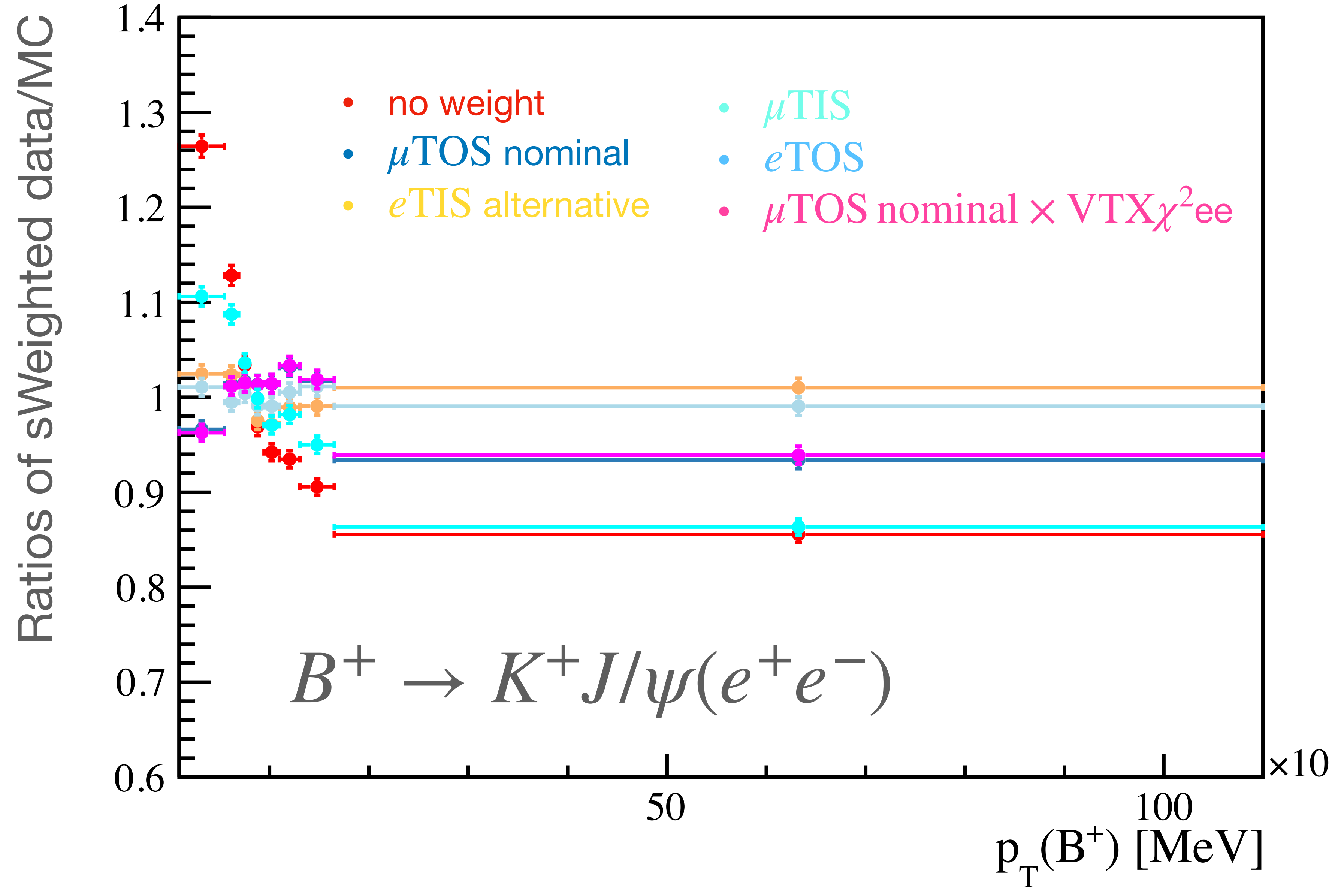
- Align the efficiencies correction strategy to [2021 R_K]
  - Calibration of $B^+/D^+_{(s)}$ kinematics
  - Particle identification efficiency corrections
  - Trigger corrections & fiducial cuts
  - Correction of imperfect resolution modelling

Kinematic corrections

- Align the efficiencies correction strategy to [2021 R_K]
  - Calibration of $B^+/D^+_{(s)}$ kinematics

    $\rightarrow$Simulation is reweighed to match the mother kinematic distributions observed in data
  - Particle identification efficiency corrections
  - Trigger corrections & fiducial cuts
  - Correction of imperfect resolution modelling



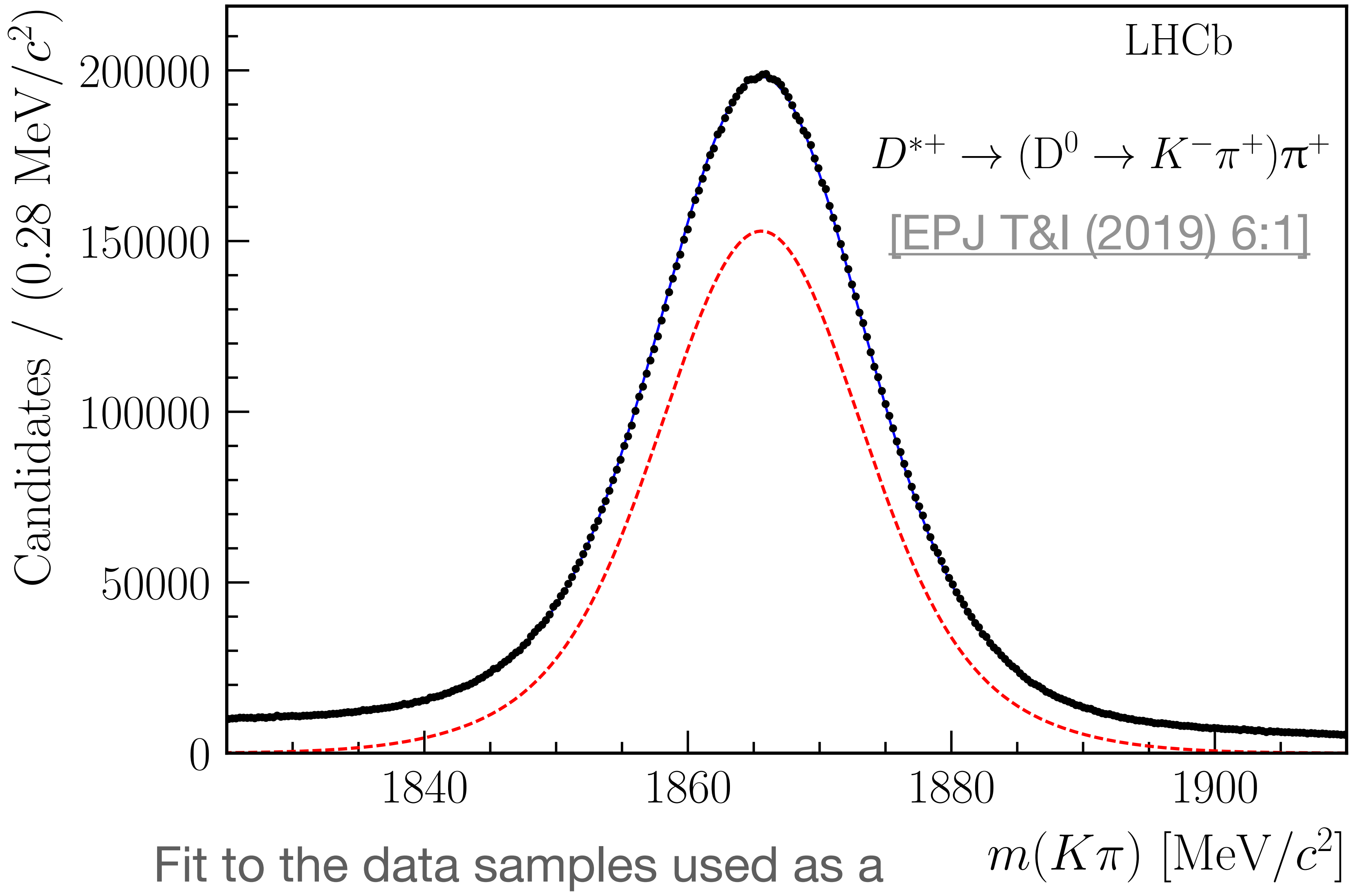


PID Calibration

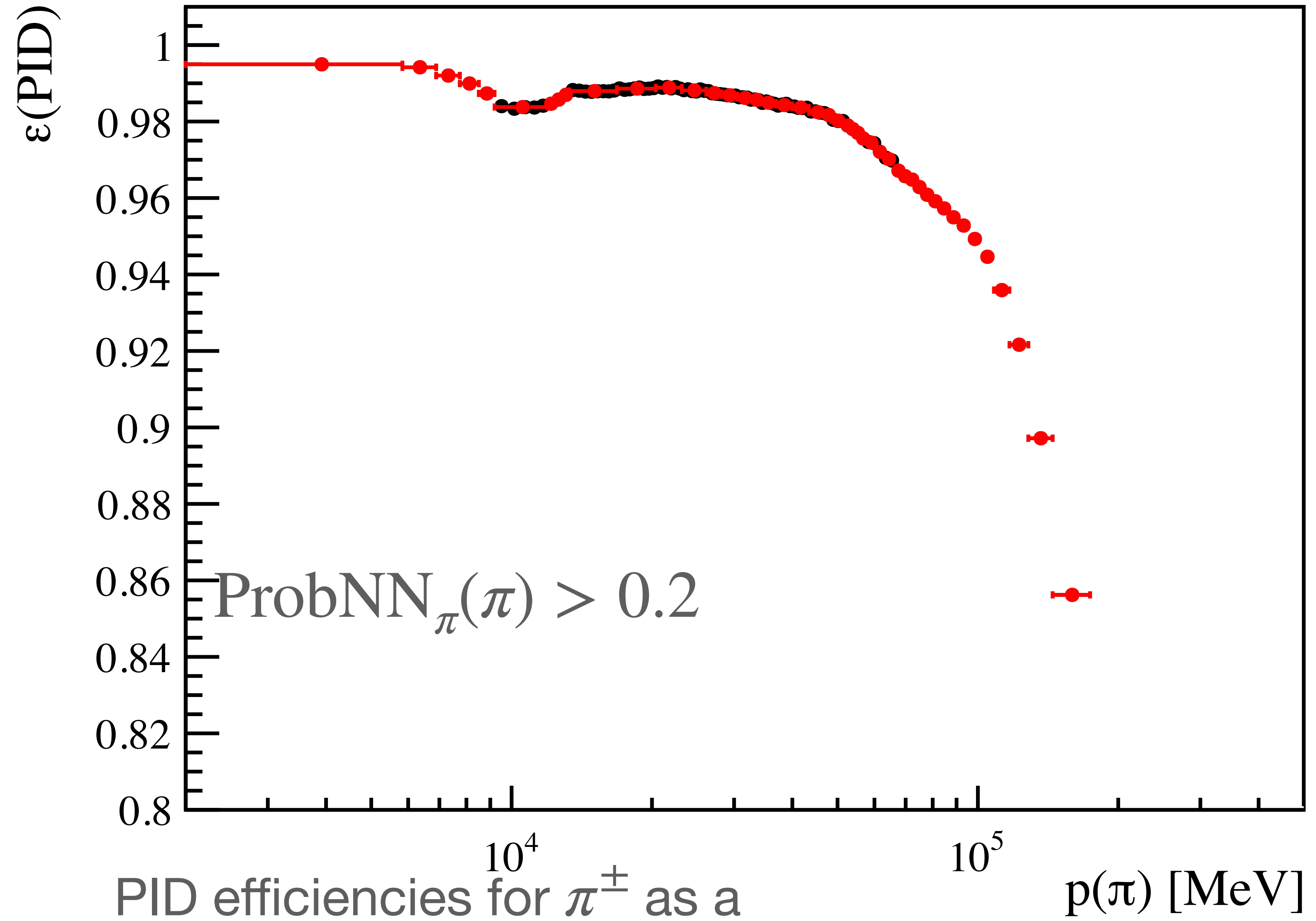
- Align the efficiencies correction strategy to [2021 R_K]
  - Calibration of $B^+/D^+_{(s)}$ kinematics
  - Particle identification efficiency corrections

    →Correct for mismodelled particle ID efficiencies

    using PIDCalib for K, π and μ, fit&count for e
  - Trigger corrections & fiducial cuts
  - Correction of imperfect resolution modelling



Fit to the data samples used as a source of $\pi^\pm$ PID eff calibration



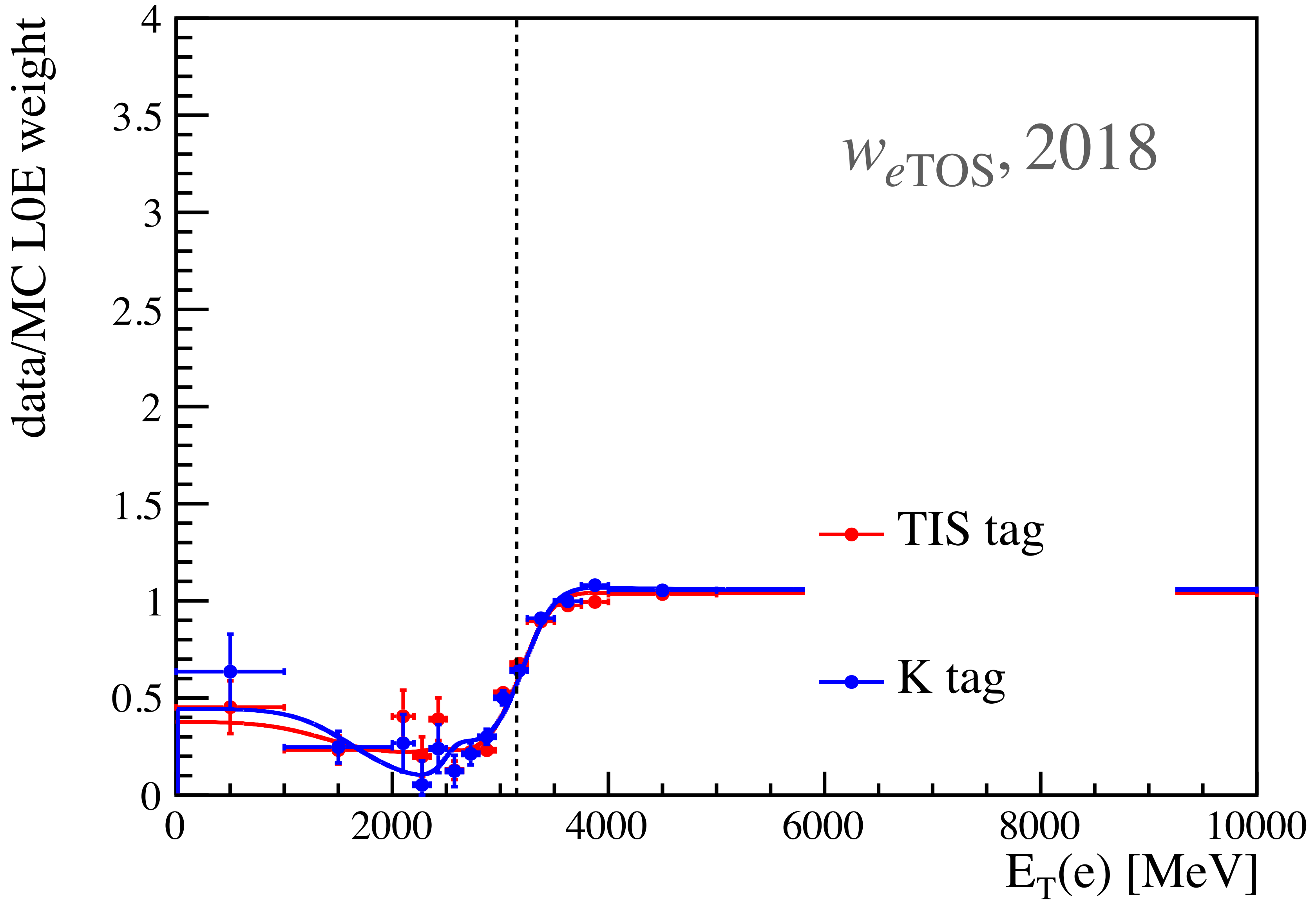
PID efficiencies for $\pi^\pm$ as a function of their momentum

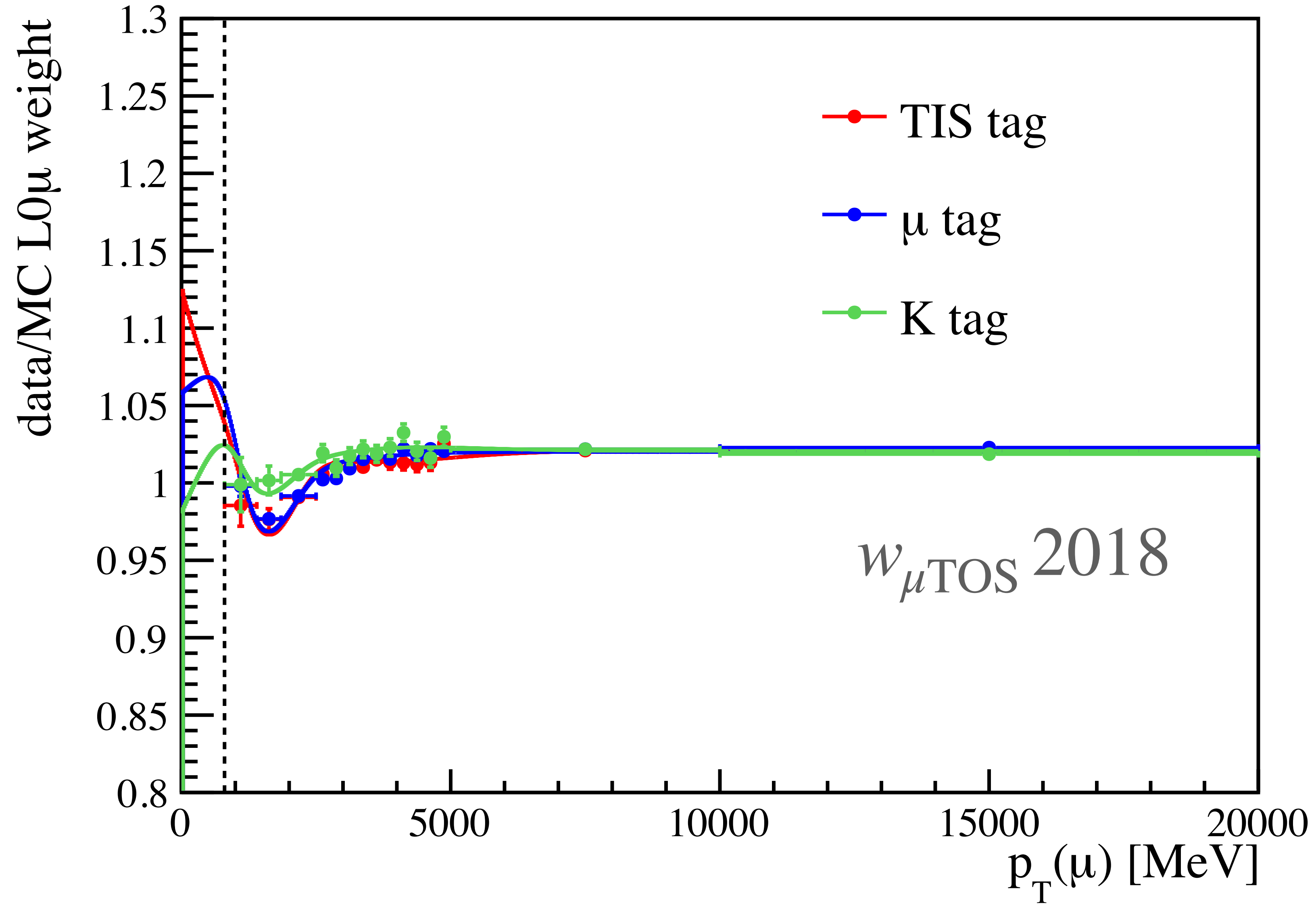
Trigger corrections

- Align the efficiencies correction strategy to [2021 R_K]
  - Calibration of $B^+/D^+_{(s)}$ kinematics
  - Particle identification efficiency corrections
  - Trigger corrections & fiducial cuts

    →Imperfect modelling of L0 efficiency in simulation

    corrected using $B^+ \to K^+ J/\psi(\ell^+\ell^-)$ data
  - Correction of imperfect resolution modelling



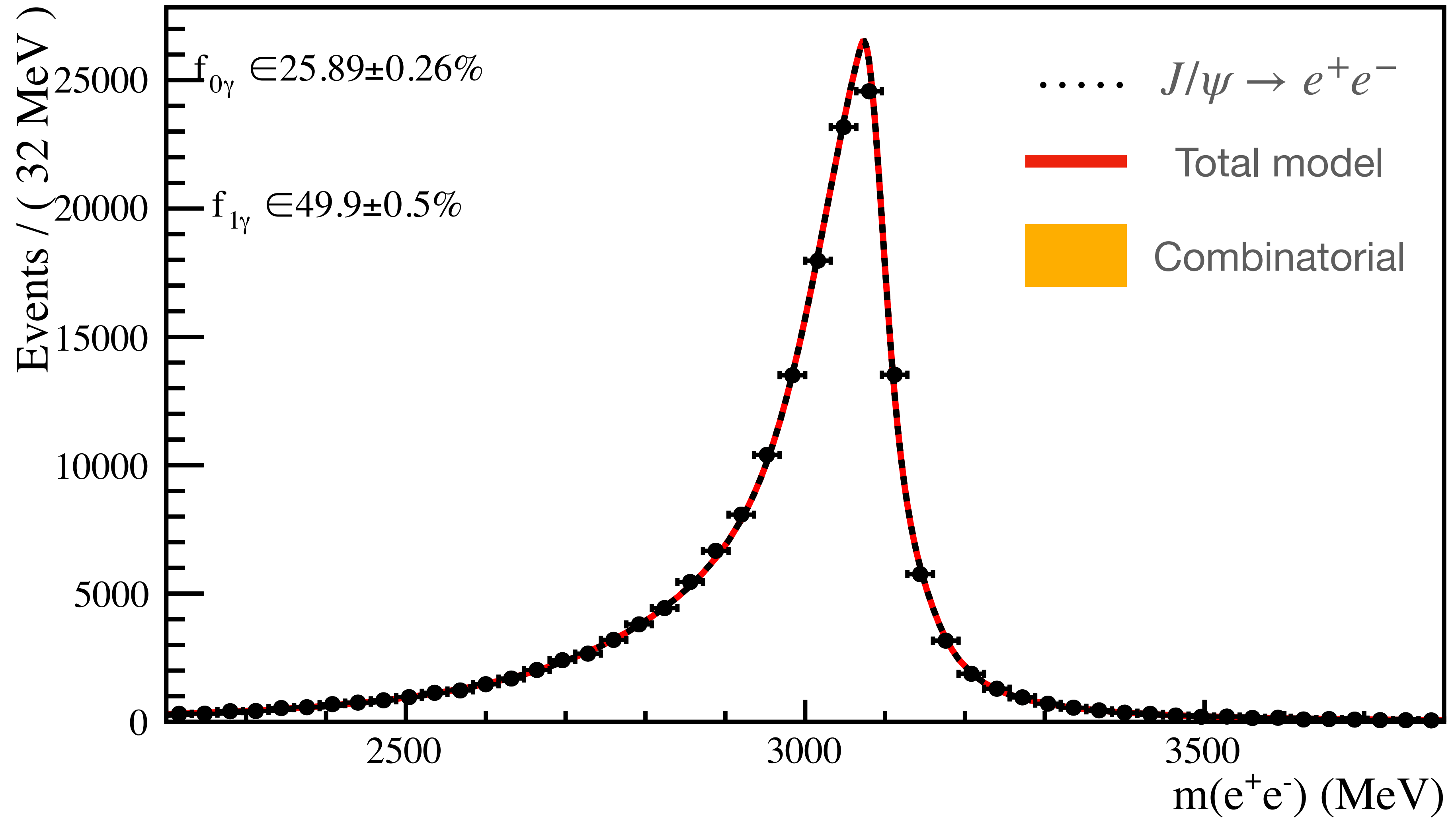


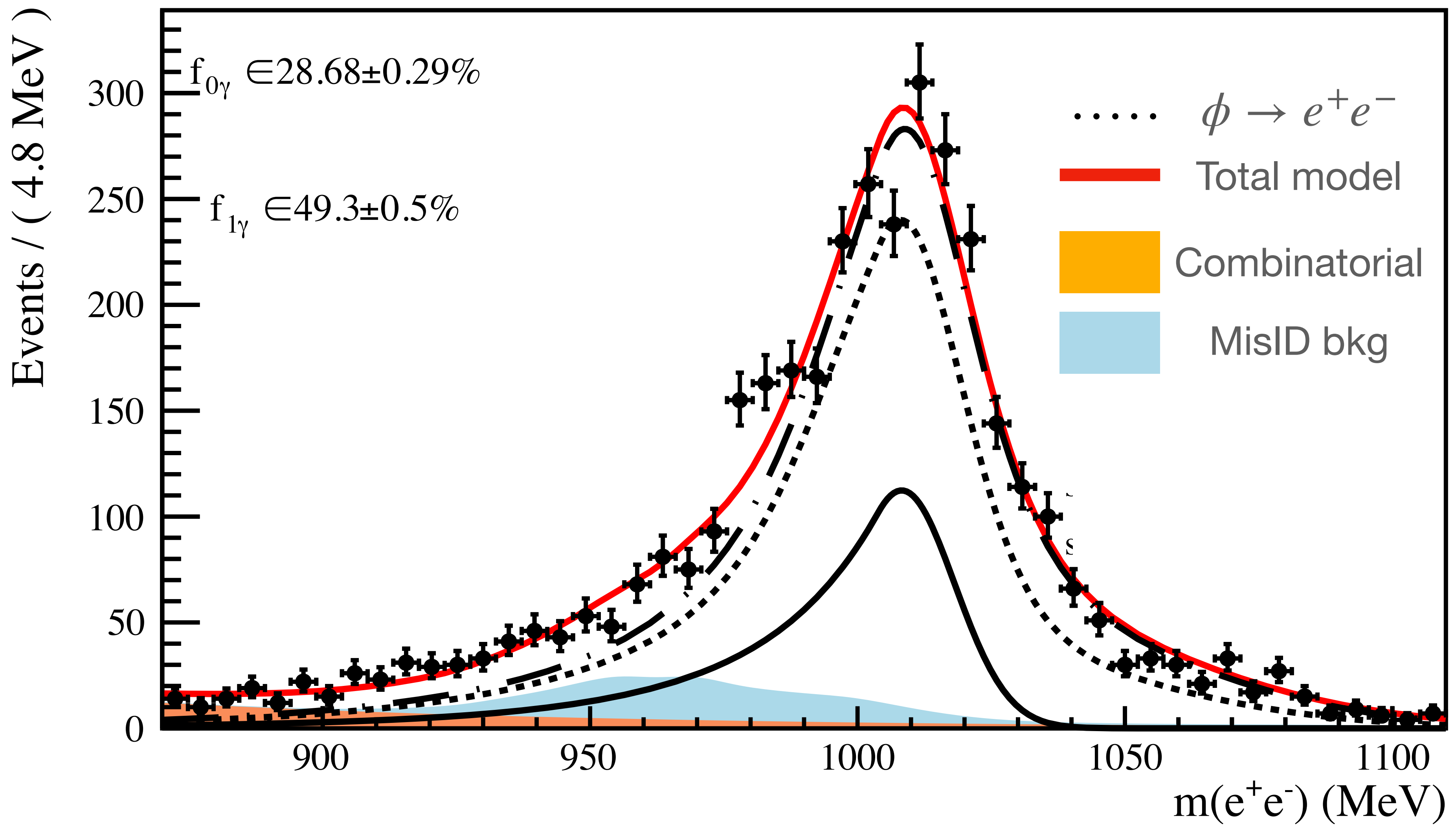
Vertical dashed lines: fiducial cuts veto regions where corrections to efficiencies are not well under control

Correction to resolution

- Align the efficiencies correction strategy to [2021 R_K]
    - Calibration of $B^+/D^+_{(s)}$ kinematics
    - Particle identification efficiency corrections
    - Trigger corrections & fiducial cuts
    - Correction of imperfect resolution modelling

→Extract resolution parameters from $B^+ \to K^+ J/\psi(\ell^+\ell^-)$ data and apply them to $D_s^+ \to \pi^+\phi(e^+e^-)$



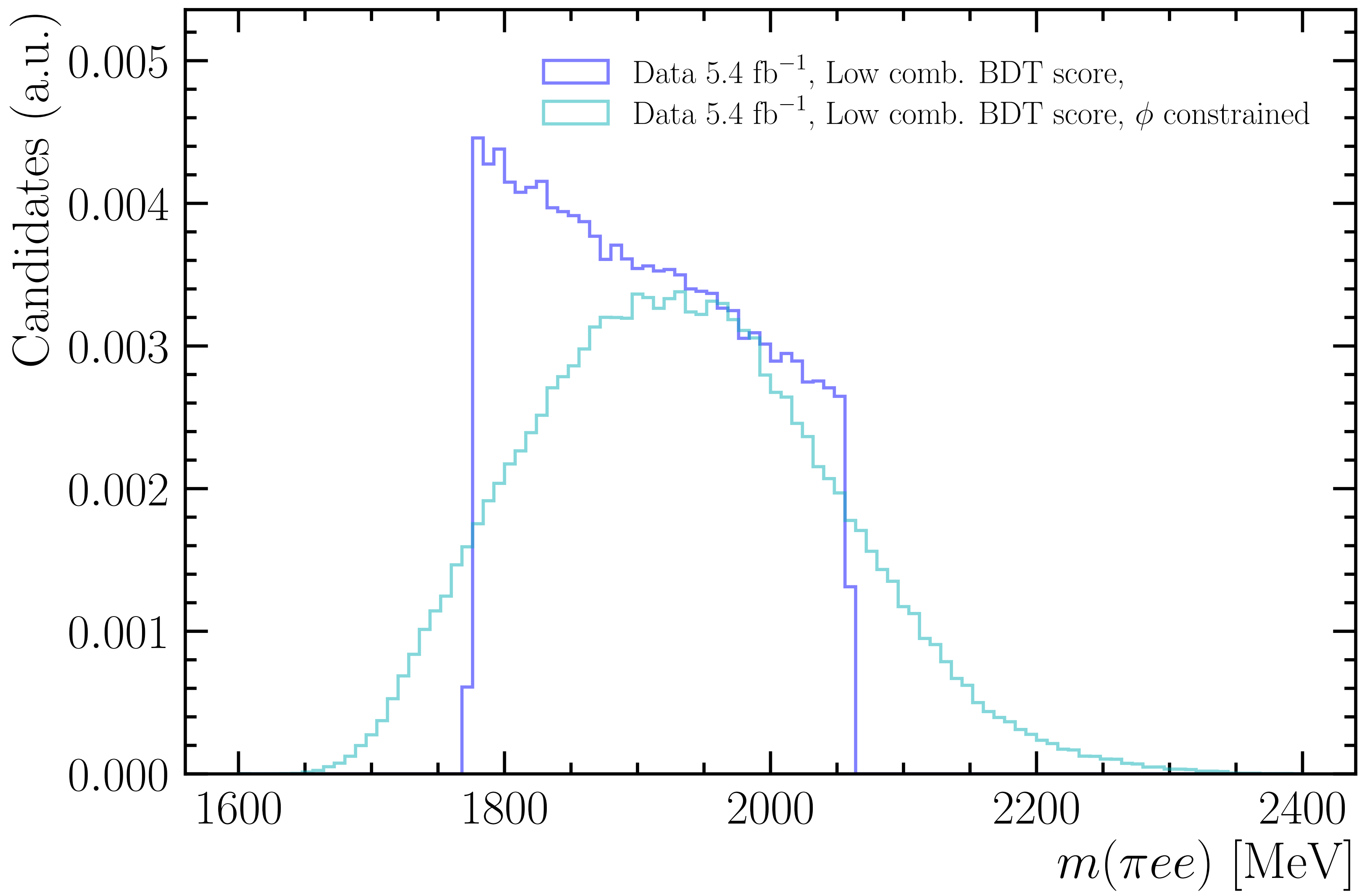


Signal yield extraction

Warping of the combinatorial background shape

- Tight cuts around the reconstructed D^+ mass at trigger level induce a strongly varying efficiency as a function of the ϕ-constrained D^+ mass

- Warps shape of all backgrounds $\rightarrow$ causes the combinatorial to have a bell shape instead of the usual falling exponential



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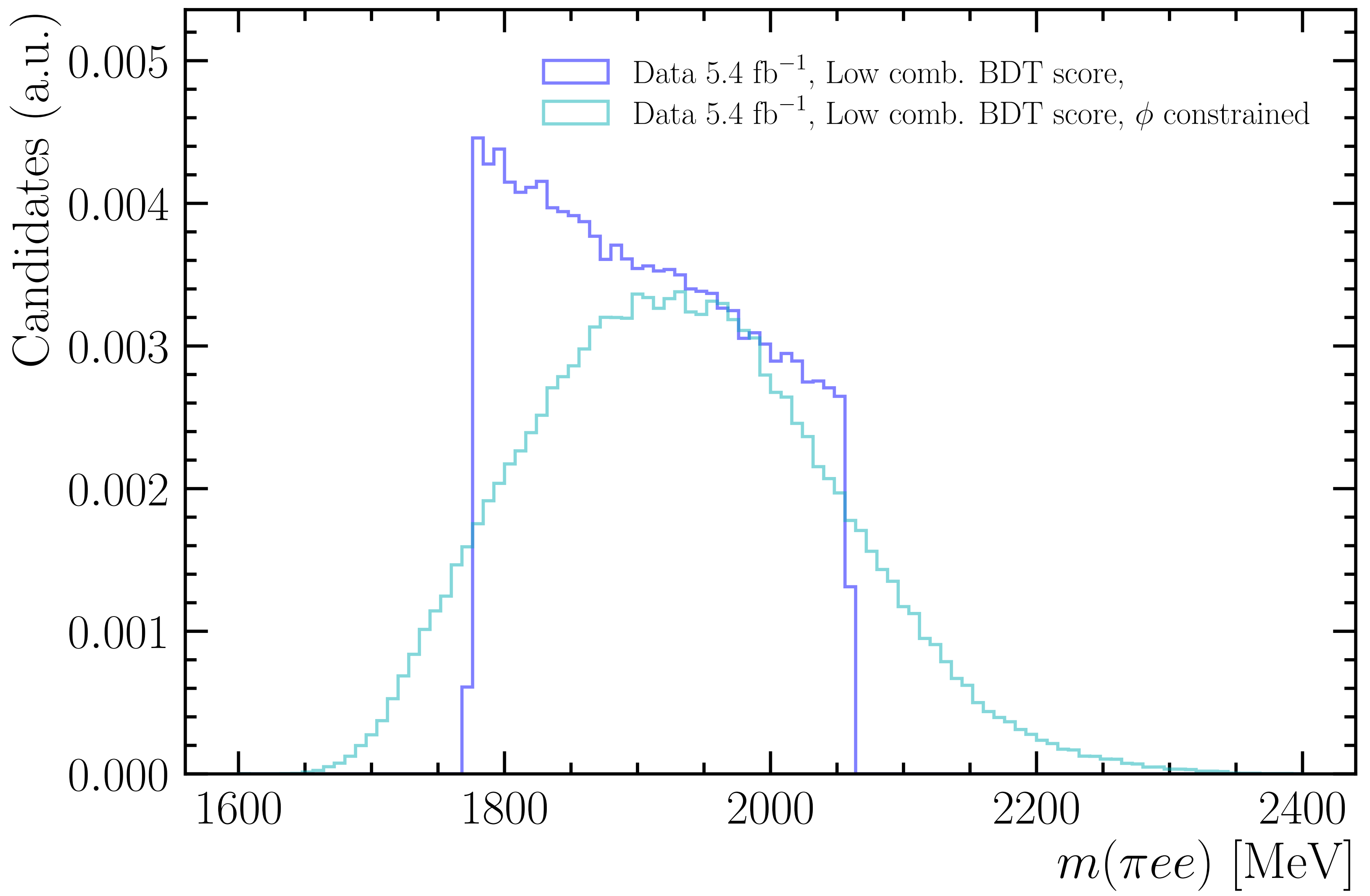
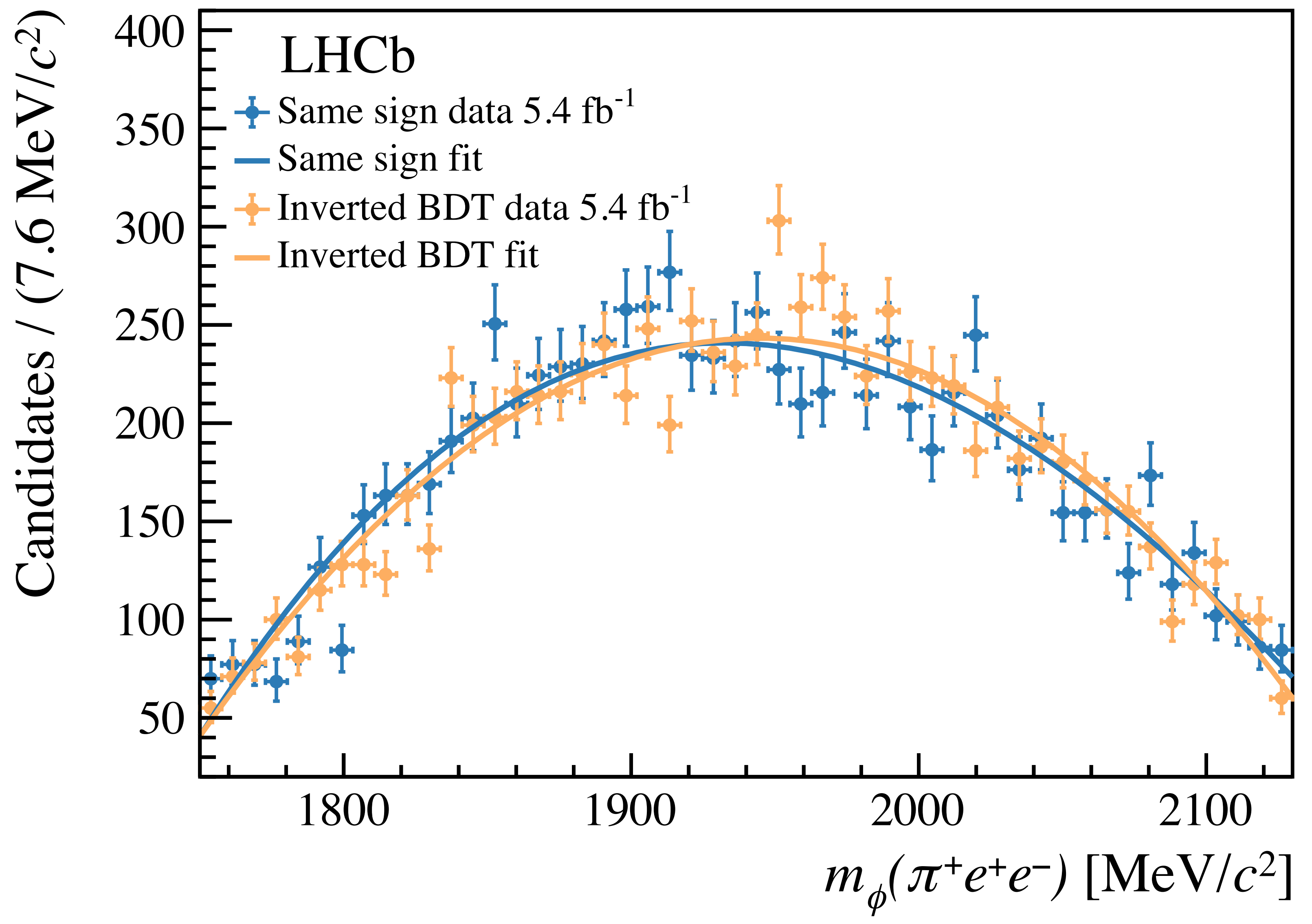
- Tight cuts around the reconstructed D^+ mass at trigger level induce a strongly varying efficiency as a function of the ϕ-constrained D^+ mass
- Warps shape of all backgrounds → causes the combinatorial to have a bell shape instead of the usual falling exponential
- Combinatorial modelled with a third order Chebychev polynomial → choice is validated against control samples
    - Sample with inverted BDT requirement
    - Sample obtained from selecting final states with electrons of same charge





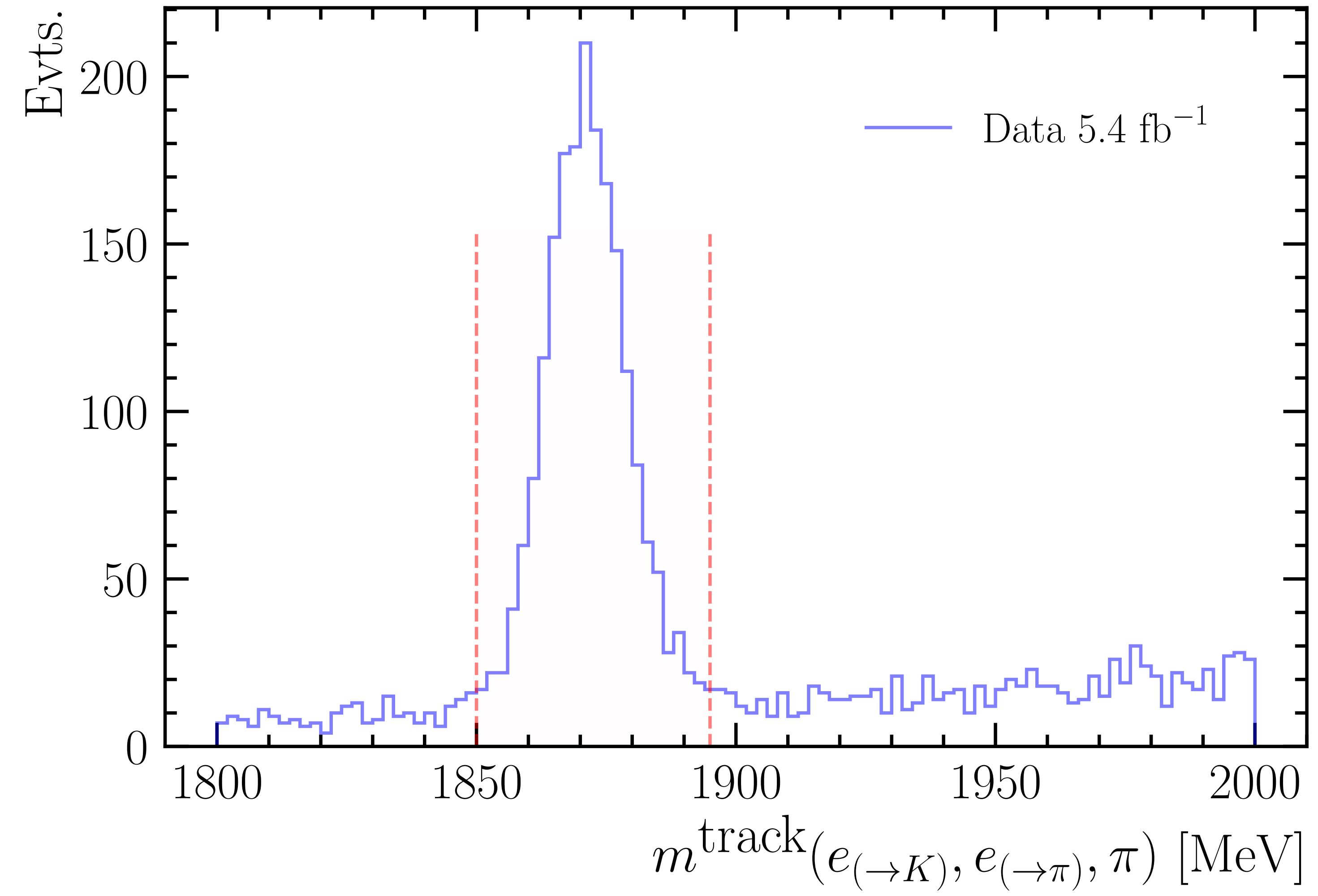
Peaking background sources: $D^+ \to K^-\pi^+\pi^+$

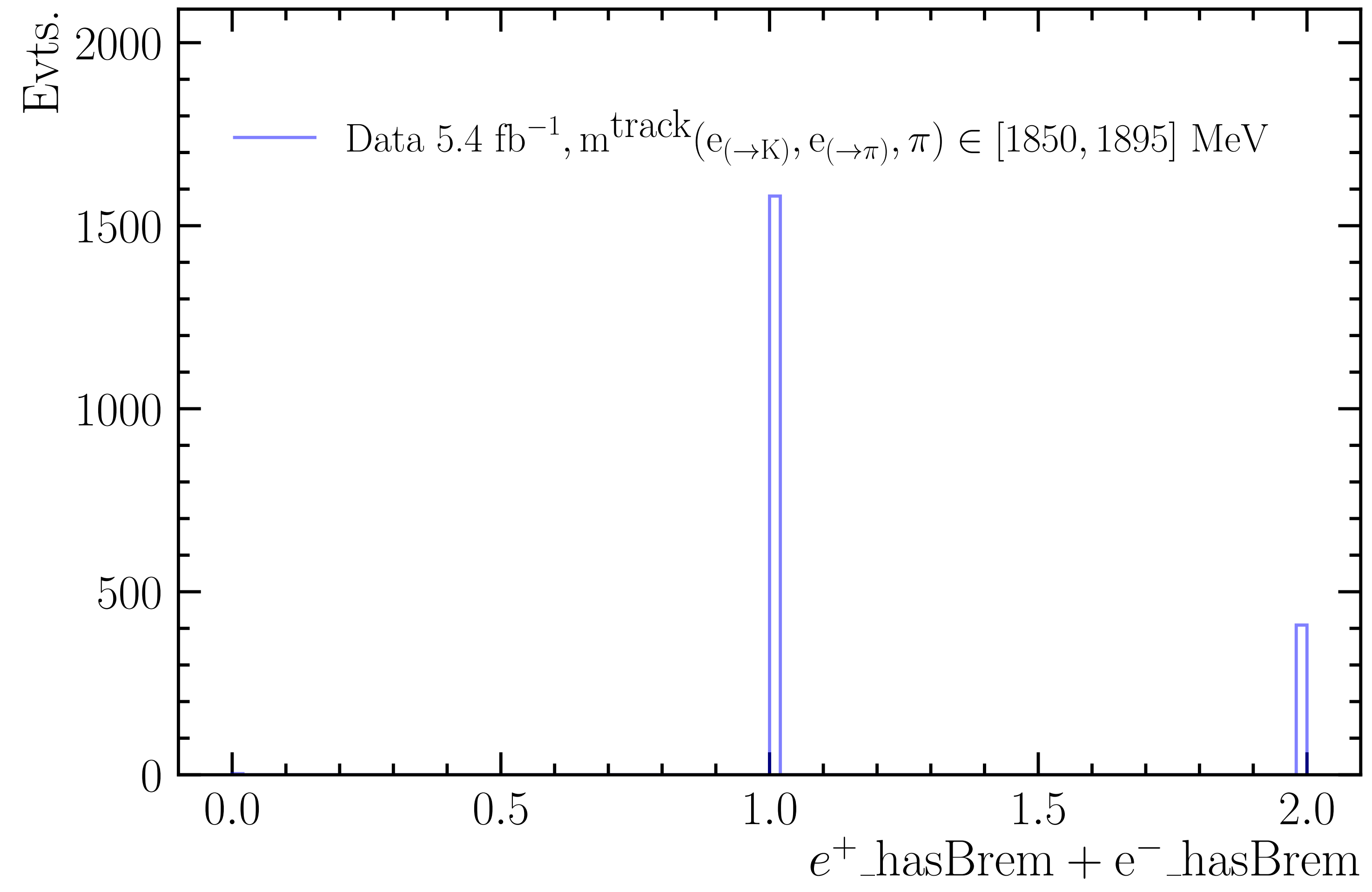
- Doubly misidentified $D^+ \to K^-\pi^+\pi^+$ were not expected to contaminate the signal region due to large $e - K$ mass difference

- Individuated a sizeable contribution of this source due to incorrectly added bremsstrahlung radiation, bringing background events back in the mass window

- Has non-trivial $m(e^+e^-)$ distribution and affects only D^+ channel due to charge of the final states and CKM suppression

$\rightarrow$Vetoed this component





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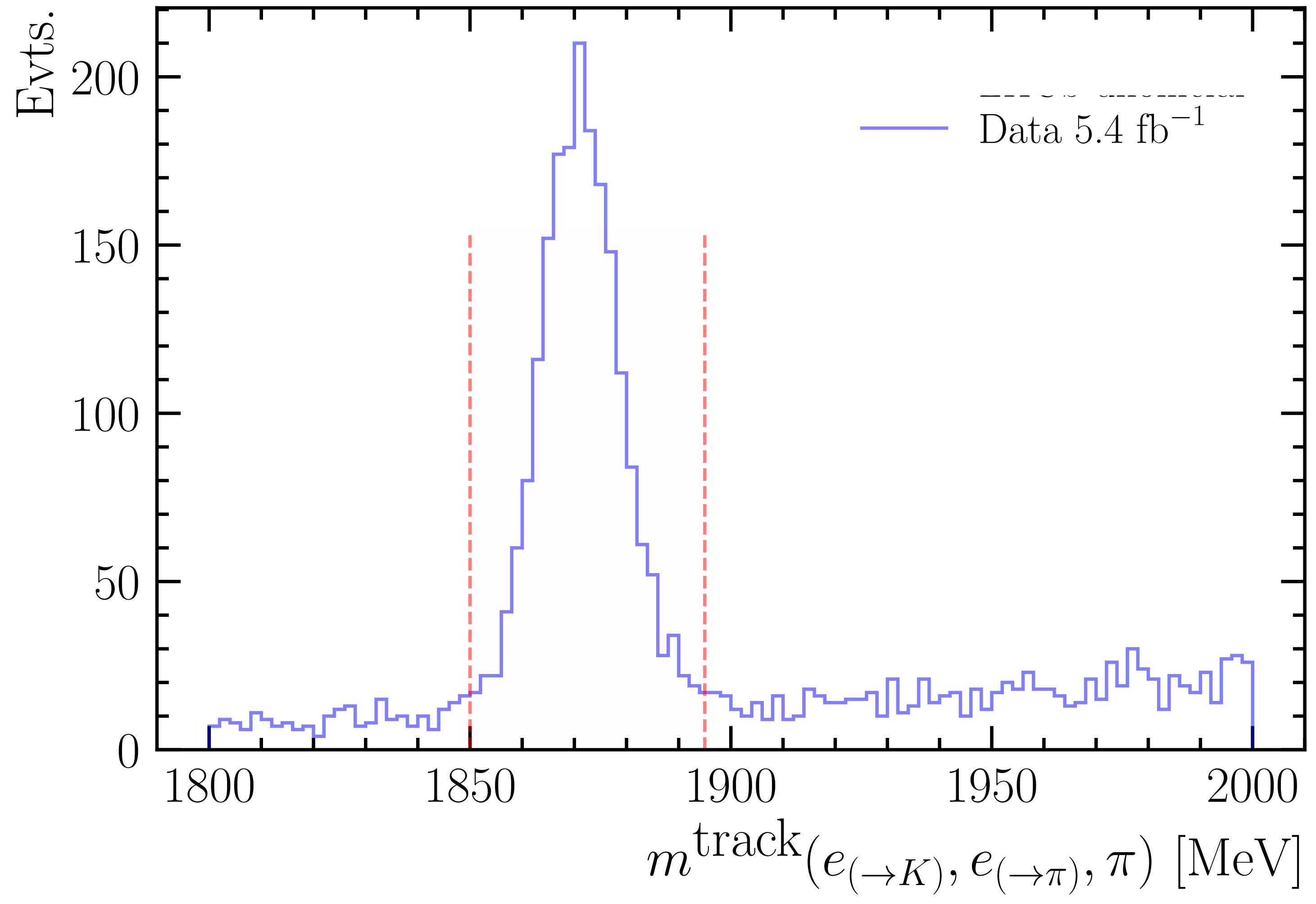
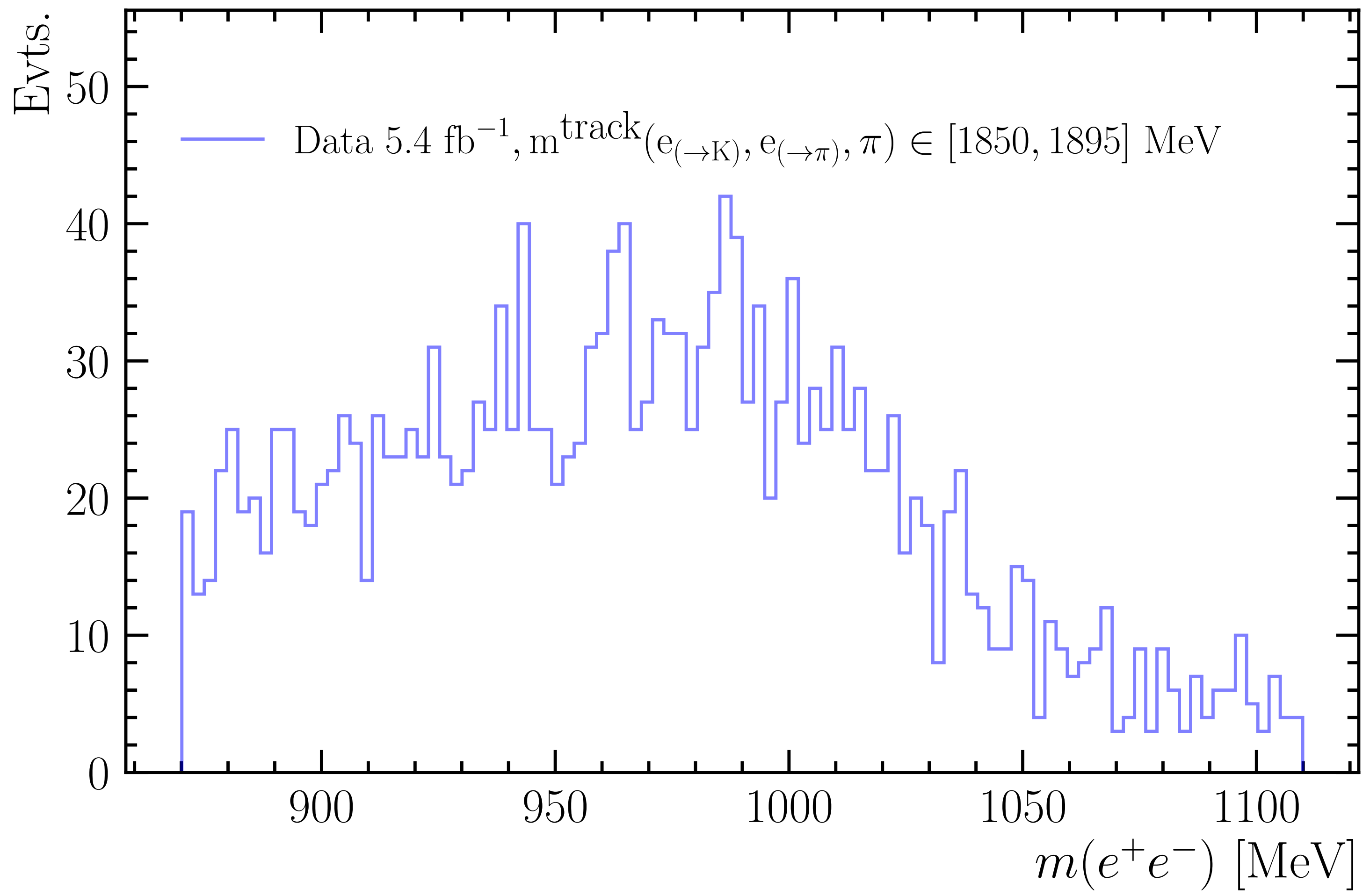
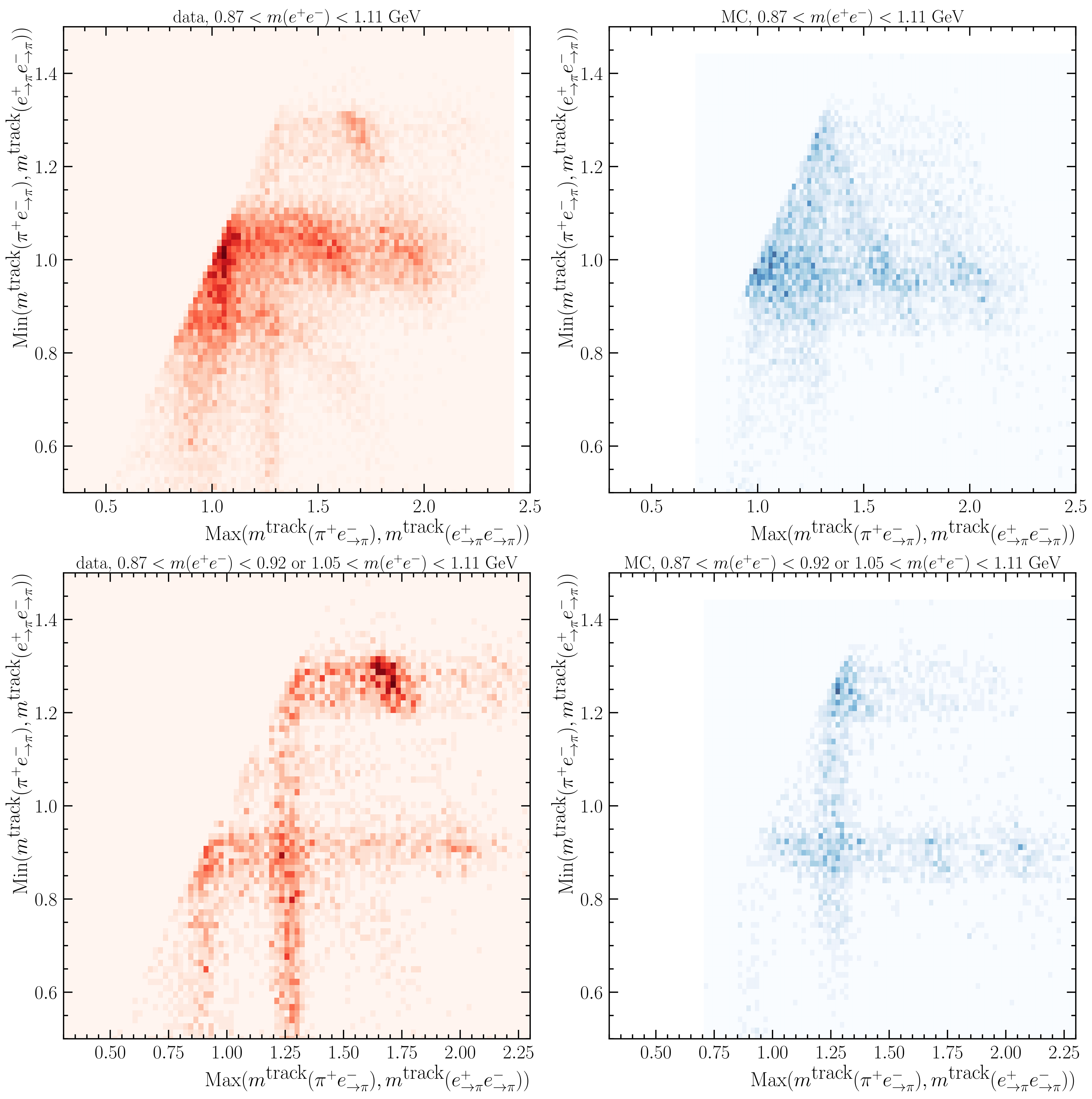




Peaking background sources: $D^+ \to \pi^+\pi^-\pi^+$

- Doubly misidentified $D^+ \to \pi^+\pi^-\pi^+$, sizeable irreducible background with non-trivial Dalitz distribution

- Important to properly take into account warping due to constraining the dilepton mass to the ϕ



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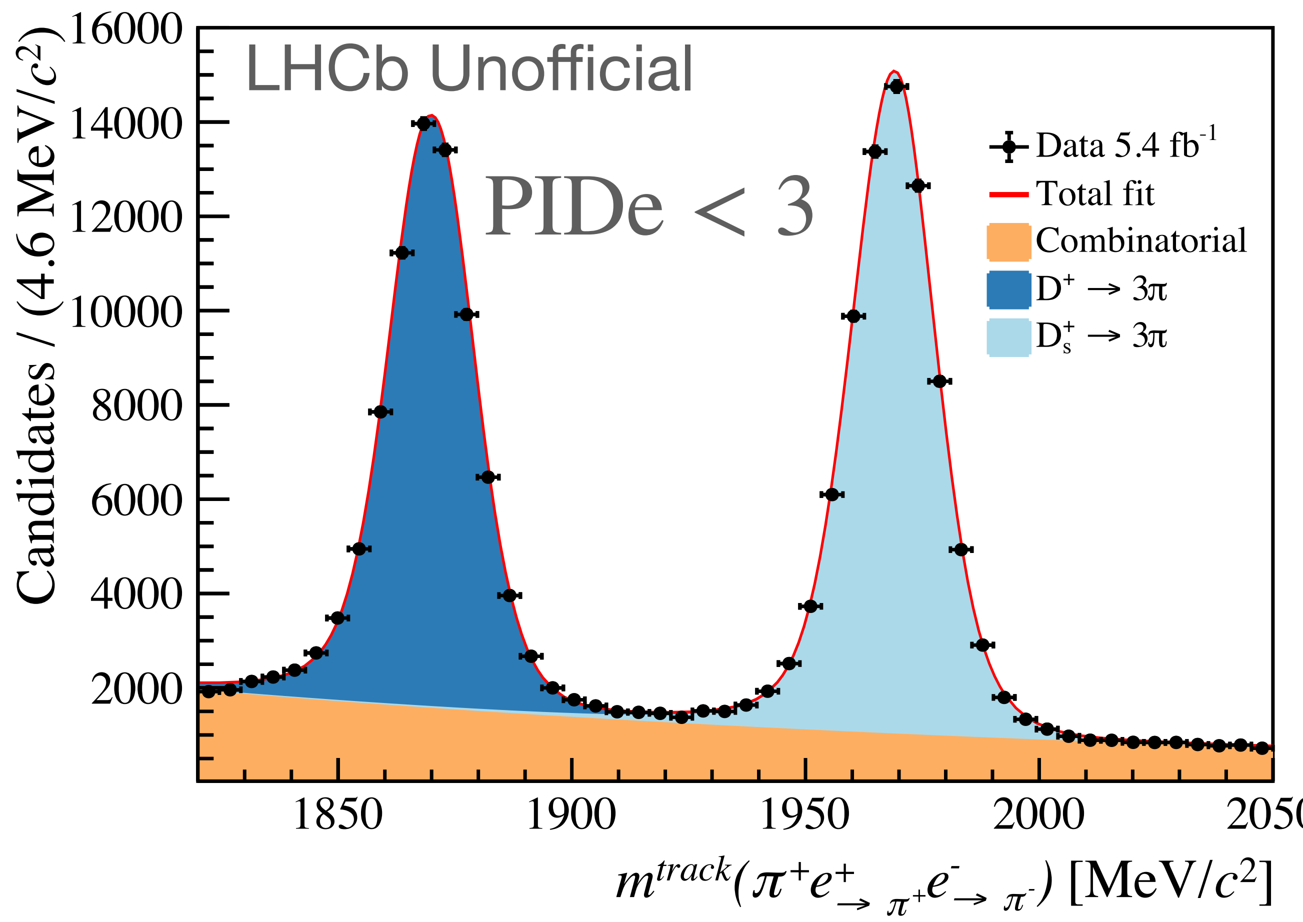
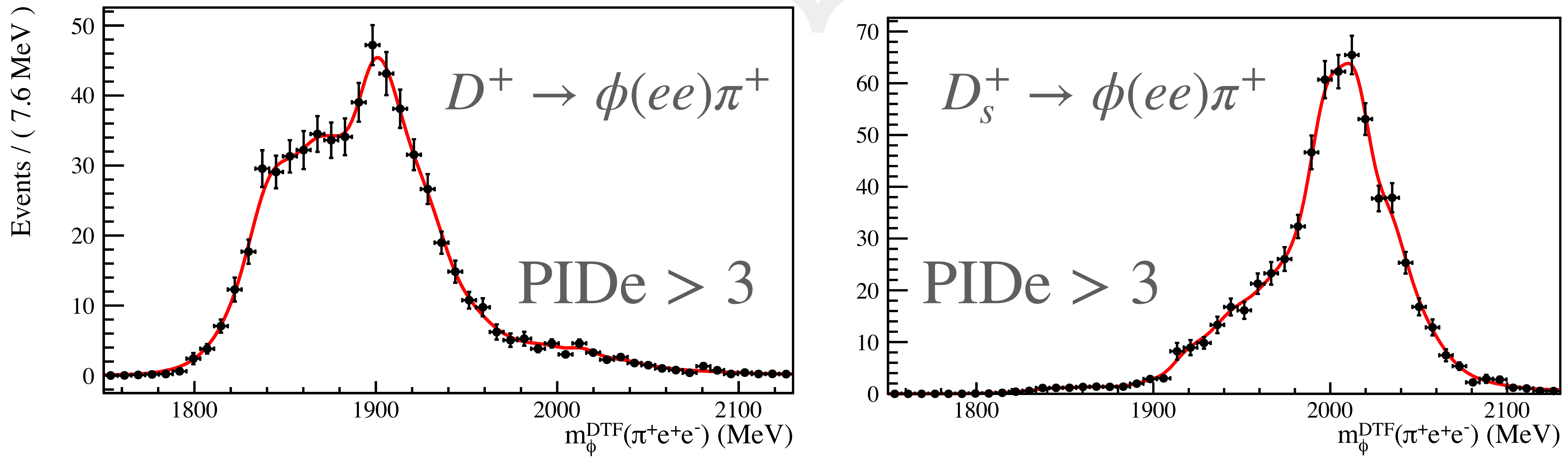
- Doubly misidentified $D^+ \to \pi^+\pi^-\pi^+$, sizeable irreducible background with non-trivial Dalitz distribution
- Important to properly take into account warping due to constraining the dilepton mass to the ϕ
- Use PID inversion technique to extract doubly $\pi \to e$ misidentified component from data:
  - Obtain sWeighted distribution in inverted selection PID region
  - Project into nominal selection PID region using transfer weights obtained from data



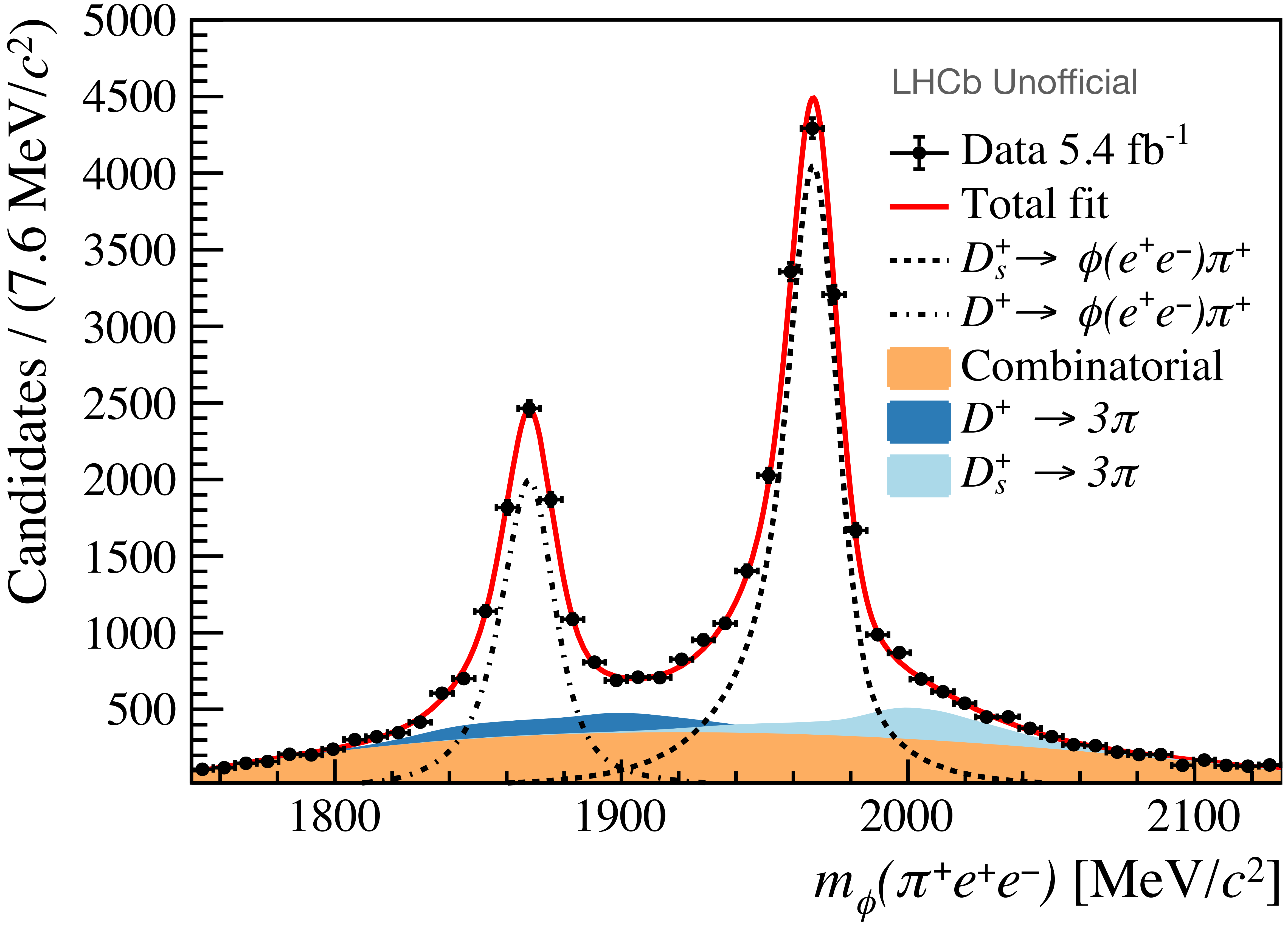
$$\mathrm{sWeight_i} \times w_i(p, \eta, \texttt{L0Electron})$$

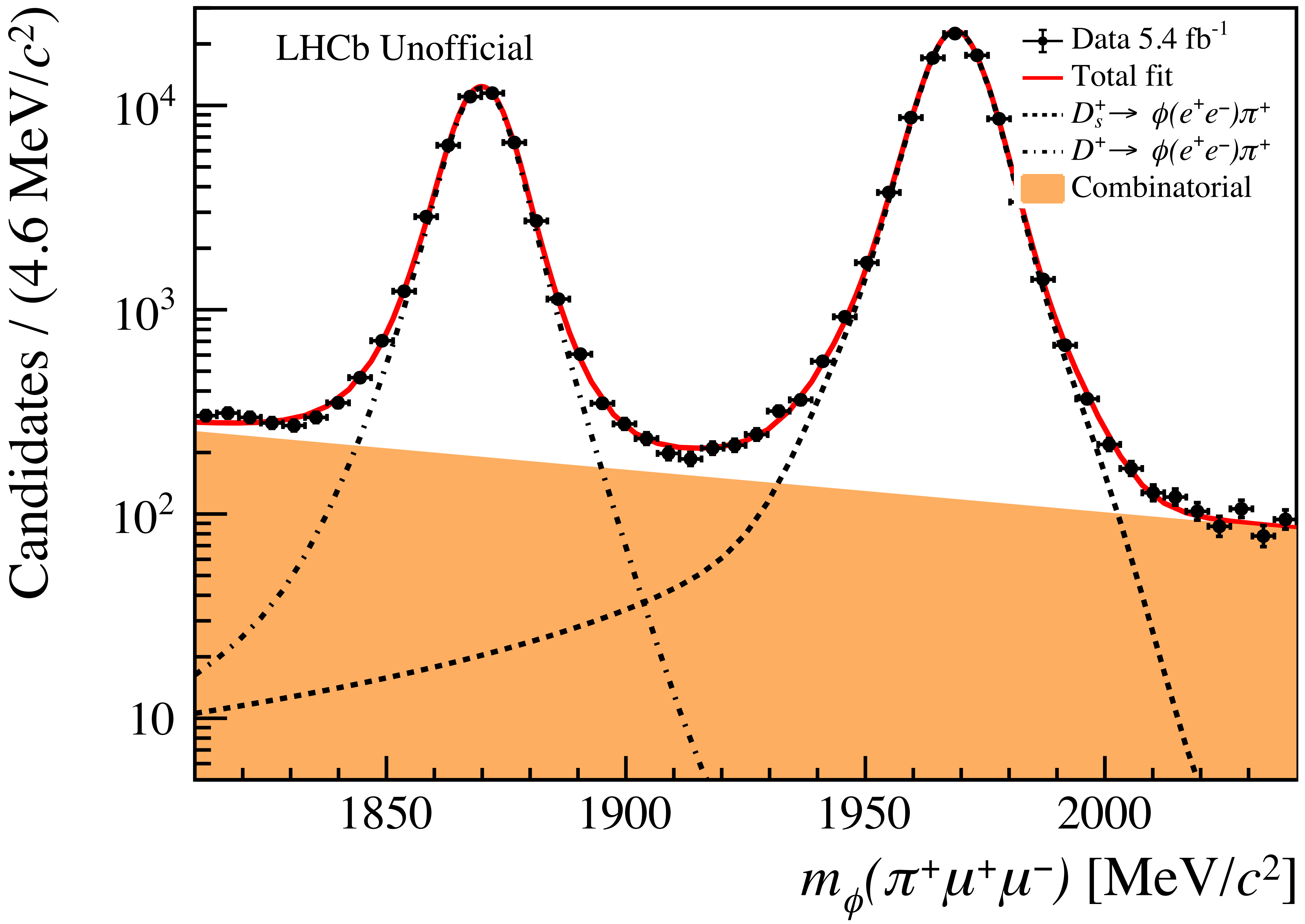


$$w_i(p, \eta, \texttt{L0Electron}) = \frac{w_{\mathrm{PID}}^{\mathrm{invt}}(e^+)_i \cdot w_{\mathrm{PID}}^{\mathrm{invt}}(e^-)_i}{w_{\mathrm{PID}}^{\mathrm{norm}}(e^+)_i \cdot w_{\mathrm{PID}}^{\mathrm{norm}}(e^-)_i}$$

Signal yield extraction

The signal yields are extracted separately in each year of data taking and trigger category

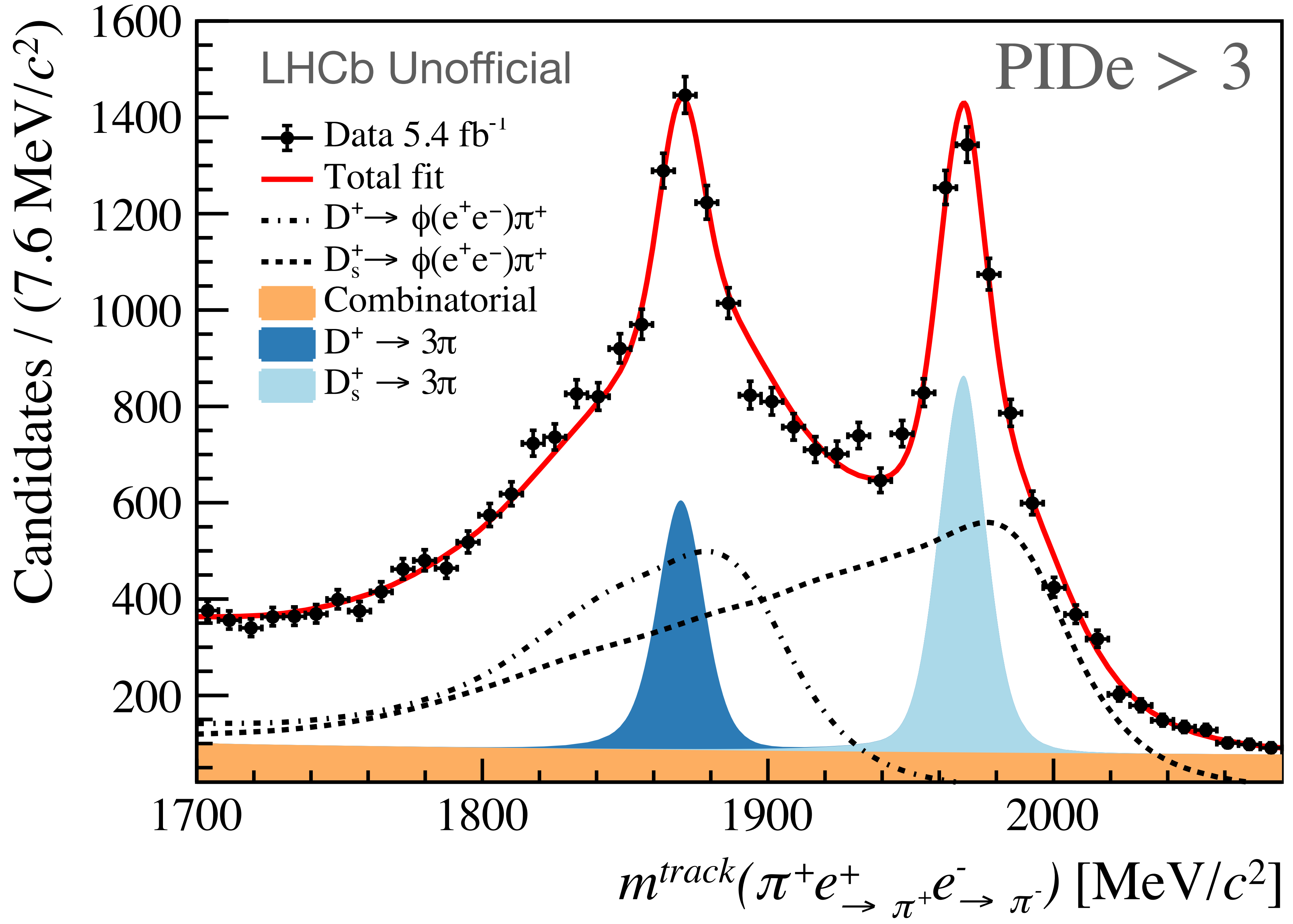


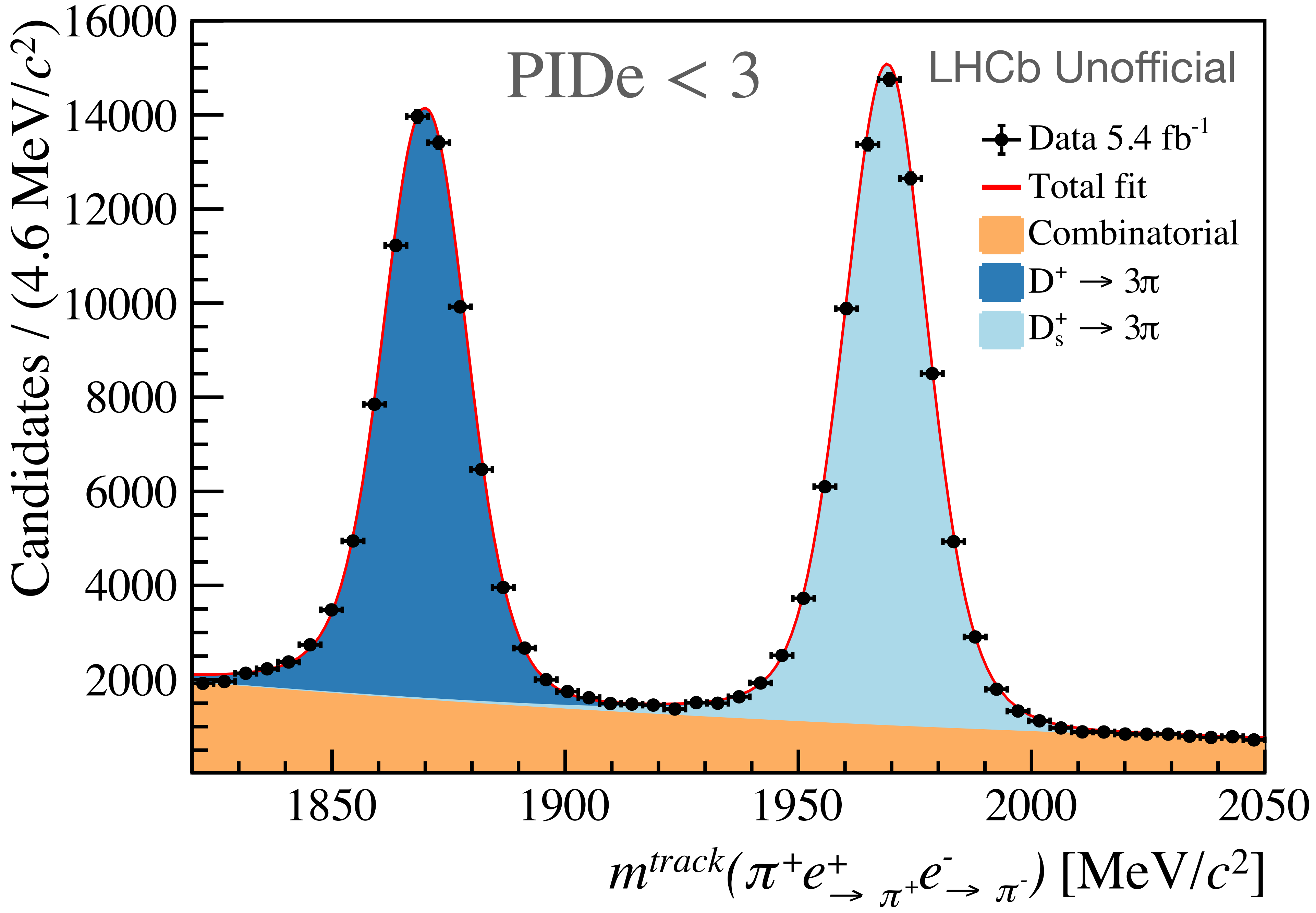


Systematic uncertainties

Peaking backgrounds systematics: $D^+ \to \pi^+\pi^-\pi^+$

- Deployed technique enables important cross check of data driven approach by comparing different mass fits in orthogonal regions of PID variables





- Clear separation in the nominal PID region adopting π mass hypothesis

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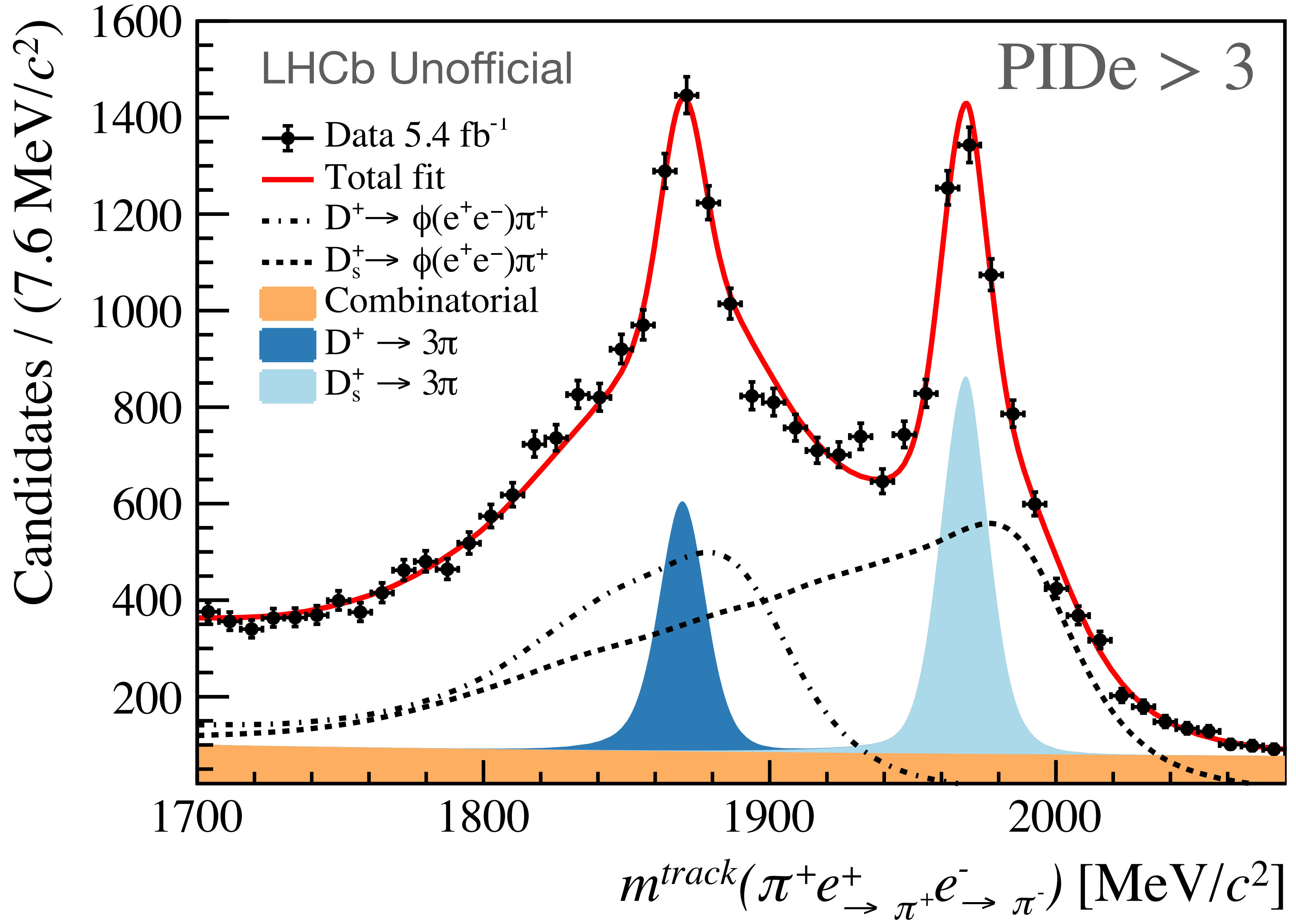
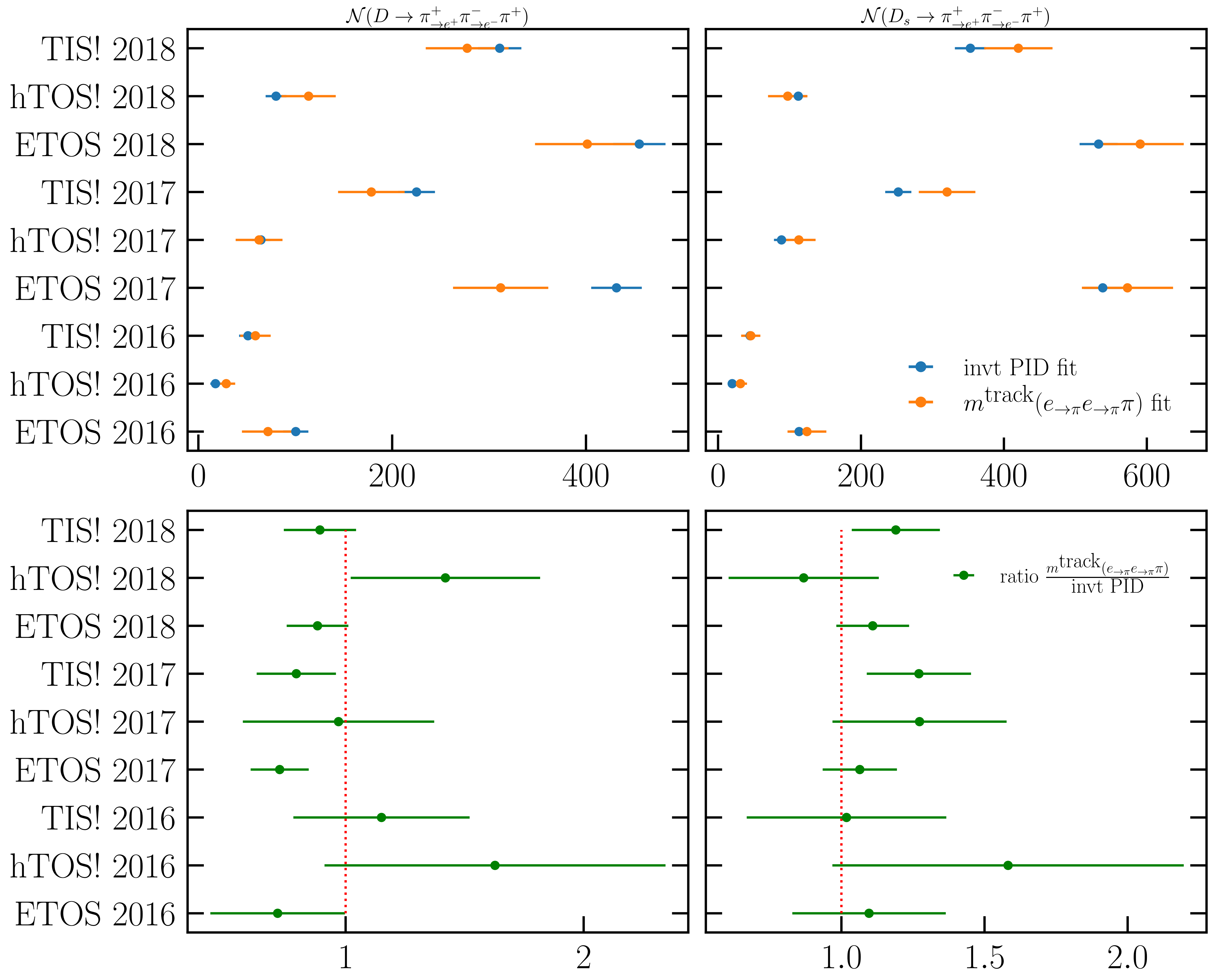




- Clear separation in the nominal PID region adopting π mass hypothesis

Summary of systematic uncertainties

- Evaluated by taking the standard deviation of $R_{\phi\pi}^{d(s)}$ values when alternative strategies for yields extraction/efficiency calculation are employed.

  - Systematic error due to trigger, PID and tracking are of per-mille order

  - Fit model systematics due to assumptions in the backgrounds are at percent level

    → Important confirmation of the PID inversion method to estimate $\pi \to e$ misID at low q^2

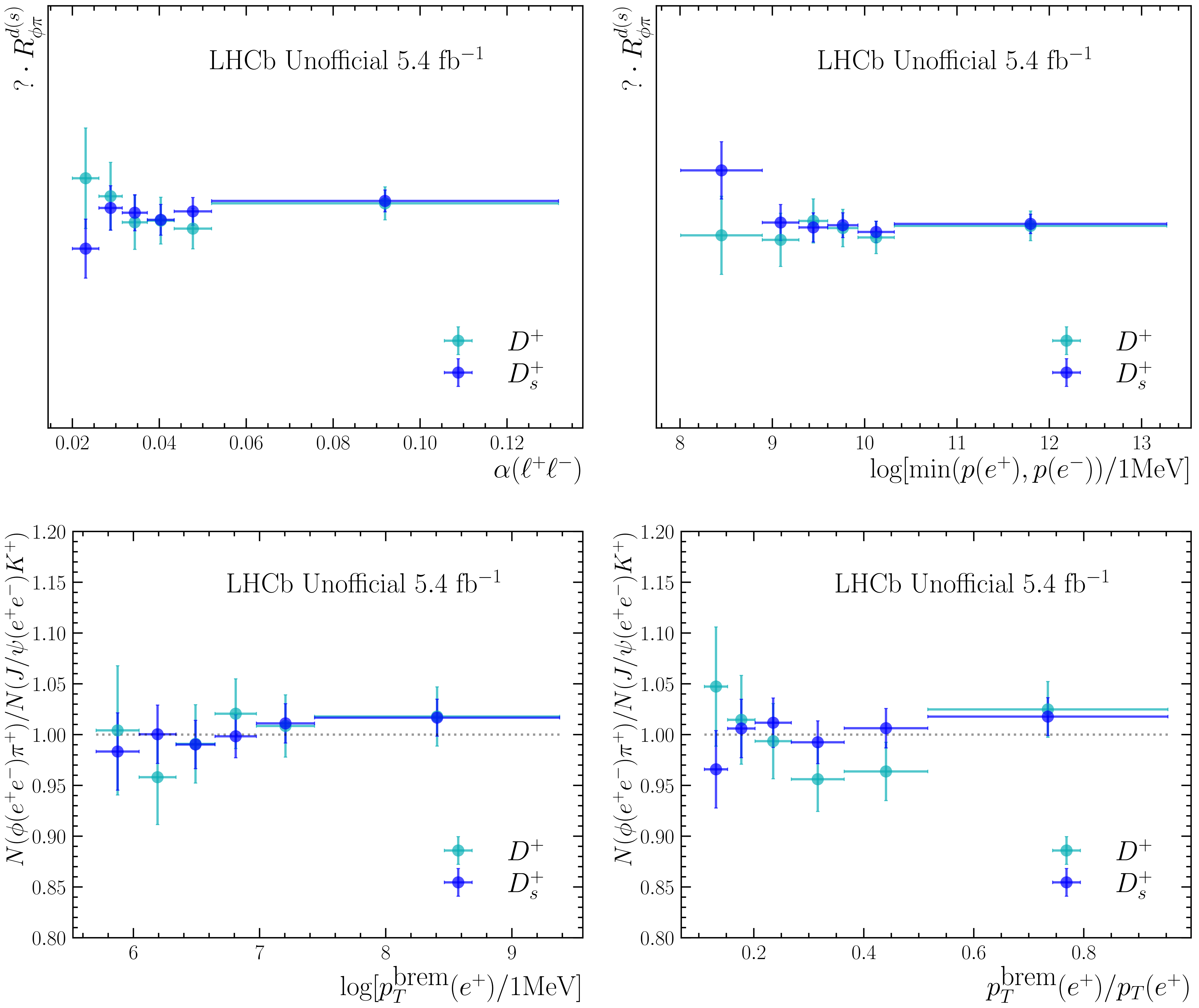
Source	$R_{\phi\pi}^{d}$	$R_{\phi\pi}^{s}$
q^2 resolution	3.71%	3.74%
Event multiplicity	2.61%	2.68%
Simulation reweighting	2.72%	2.22%
Combinatorial background shape parametrisation	1.51%	1.04%
Statistical uncertainties of control samples	0.79%	0.57%
PID	0.24%	0.28%
Trigger	0.27%	0.26%
Tracking	0.16%	0.14%
Background from doubly misidentified electrons	1.10%	0.04%

- Sources above the percent level are expected due to imperfect cancellation of mother meson kinematic corrections and relatively tight cuts around the D and ϕ masses for the electron signal mode

Results

Differential $R_{\phi\pi}^{d(s)}$

- As a cross check, $R_{\phi\pi}^{d(s)}$ is performed in bins of variables relevant to the detector response
- In each bin different years are combined as a weighted average, interbin correlations are not taken into account
- No significant trend is observed
- Important cross check of brem recovery algorithm at low dilepton invariant mass using data



Conclusions

- First cross check of LFU at low q^2 using $D^+_{(s)} \to \phi(\ell^+\ell^-)\pi^+$ decays will be public soon
- Challenging measurement, however it shows understanding of the portability of the corrections derived at $q^2 \sim m^2(J/\psi)$ to lower values:
    - Once the peculiarities arising from a different decay mother and type of backgrounds are taken into account
- Offers unique opportunity to cross check tools and techniques used by the collaboration:
    - Important check of reliability of $\pi \to e$ double misID contamination estimate with a control channel
    - Stability of the result as a function of bremsstrahlung variables is an important check of this tool at low dilepton invariant mass
    - Cementifies our confidence in light leptons detection efficiencies at low dilepton invariant mass

Thank you!

Backup

The selection chain

The selection is kept as aligned as possible between signal and control modes and consists of the following steps:

- Online selection:
    - Set of L0, HLT1 and HLT2 trigger requirements
- Offline selection:
    - Exploits the existing stripping lines for signal and control modes, introduces a filter for simulated signal samples to reduce disk usage
    - Fiducial cuts are applied offline to align data to the control samples and optimise eff. correction procedure
    - q^2 and mass(es) window and MVA techniques reduce contributions from partially reconstructed, misidentified and combinatorial background sources

Online selection: trigger requirements

- L0 and HLT1 lines are aligned between signal and control mode
- Exploit dedicated [HLT2 lines] that were introduced in Run2 for rare LFV charm searches. [*JHEP* 06 (2021) 044]
- These HLT2 trigger lines each use similar selections, most importantly:
  - `ALLSAMEBPV`
  - `ADAMASS(D+) < 200 MeV`

	Electron mode	**Muon mode**
	Signal mode	
L0	`L0Electron`(e) & $E_T(e) >$ threshold `L0Hadron`(π) & $E_T(\pi) >$ 3.5 GeV L0Electron ǁ L0Hadron ǁ L0Muon ǁ L0Photon (TIS)	`L0Muon`(μ) & $p_T(\mu) > 0.8$ GeV & $p_T^{\mathrm{L0}}(\mu) \geq$ threshold
$HLT1$	`Hlt1TrackMVA`(D)	`Hlt1TrackMVA`(D)
$HLT2$	`Hlt2RareCharmD2PiEEOSDecision`(D)	`Hlt2RareCharmD2PiMuMuOSDecision`(D)
	Control mode	
L0	`L0Electron`(e) & $E_T(e) >$ threshold `L0Hadron`(K) & $E_T(K) >$ 3.5 GeV L0Electron ǁ L0Hadron ǁ L0Muon ǁ L0Photon (TIS)	`L0Muon`(μ) & $p_T(\mu) > 0.8$ GeV & $p_T^{\mathrm{L0}}(\mu) \geq$ threshold
$HLT1$	`Hlt1TrackMVA`(B)	`Hlt1TrackMVA`(B)
$HLT2$	`Hlt2Topo[2,3]BodyBBDT`(B)	`Hlt2Topo[2,3]BodyBBDT`(B) `Hlt2TopoMu[2,3]BodyBBDT`(B)

Offline selection: stripping selection

- Stripping requirements are similar between signal and control modes, requiring a three track combination with a well-defined vertex significantly displaced from any PV
- Particle identification criteria are loosened in simulation, while transverse momenta are tightened by fiducial cuts

		D2XMuMuSS_Pi_EE_OSLine		D2XMuMuSS_PiOSLine	
$D_{(s)}$	$\mathrm{DOCA_{max}}\,(\mathrm{mm})$	$<$	0.15	$<$	0.15
	$\cos(\mathrm{DIRA})$	$>$	0.9999	$>$	0.9999
	χ^2_{IP}	$<$	25	$<$	25
	$\chi^2_{\mathrm{DV}}/\mathrm{ndof}$	$<$	5	$<$	5
	$m\,(\mathrm{GeV})$	$>$	1.763	$>$	1.763
	$\lvert m - m_{\mathrm{PDG}}(D^+)\rvert\,(\mathrm{MeV})$	$<$	200	$<$	200
$\ell\ell$	$m\,(\mathrm{MeV})$	$>$	250	$>$	250
ℓ	$p_T\,(\mathrm{MeV})$	$>$	300	$>$	300
	$p\,(\mathrm{MeV})$	$>$	2000	$>$	2000
	isMuon	—			true
all tracks	$\chi^2_{\mathrm{TrackFit}}$	$<$	5	$<$	5
	χ^2_{IP}	$>$	5	$>$	5
π	$p_{\mathrm{T}}\,(\mathrm{MeV})$	$>$	300	$>$	300
	$p\,(\mathrm{MeV})$	$>$	2000	$>$	2000

		Bu2LLKeeLine2		B2XMuMuLine	
B	$\chi^2_{to\ PV}$	$>$	100	$>$	121
	$\cos(\mathrm{DIRA})$	$>$	0.995	$>$	0.9999
	χ^2_{IP}	$<$	25	$<$	16
	$\chi^2_{\mathrm{DV}}/\mathrm{ndof}$	$<$	9	$<$	8
	$m\,(\mathrm{GeV})$	$>$	3.78	$>$	4.9
		$<$	6.78	$<$	7.0
$\ell\ell$	$\chi^2_{\mathrm{DV}\leftrightarrow\mathrm{PV}}$	$>$	16	$>$	9
	$\chi^2_{\mathrm{DV}}/\mathrm{ndof}$	$<$	9	$<$	12
ℓ	χ^2_{IP}	$>$	9	$>$	9
	$p_T\,(\mathrm{MeV})$	$>$	300	—	
	$\mathrm{PID}_{e,\mu}$	$>$	0	$>$	-3
	isMuon	—			true
all tracks	$\mathrm{prob_{ghost}}$	—		$<$	0.5
	$\chi^2_{\mathrm{TrackFit}}$	$<$	3	—	
K	χ^2_{IP}	$>$	9	$>$	6
	$p_{\mathrm{T}}\,(\mathrm{MeV})$	$>$	400	—	
event	nSPDHits	$<$	600	$<$	600

Offline selection: fiducial cuts and mass windows

- Signal and control modes are aligned to control data samples using fiducial cuts in order to optimise the efficiency correction procedure
- Signal is selected by requiring the dilepton invariant mass and the $\phi/J/\psi$ constrained D/B masses to lie within windows to maximise the signal yield
- Doubly misidentified backgrounds from $D^+ \to K^-\pi^+\pi^+$ decays in the electron mode are rejected by dedicated vetoes

	ee mode	$\mu\mu$ mode
signal mode	$0.76 < q^2 < 1.23\ \mathrm{GeV}^2$	$0.98 < q^2 < 1.10\ \mathrm{GeV}^2$
	$1.75 < m^{\phi}_{\mathrm{DTF}}(\pi^+e^+e^-) < 2.13\ \mathrm{GeV}$	$1.81 < m^{\phi}_{\mathrm{DTF}}(\pi^+\mu^+\mu^-) < 2.04\ \mathrm{GeV}$

Event quality

nSPDHits	$<$	450
$\mathrm{prob_{ghost}}(\pi, \mathrm{e})$	$<$	0.3
Clone veto		
$\cos(\pi^+e^+)$	$<$	0.99999
Double mis-ID vetoes		
$m^{\mathrm{track}}_{(e^+\to K^+, e^-\to\pi^-)}(\pi ee)$	$\notin$	$m(D^+) \pm 20$ MeV
Fiducial cuts		
$p_{\mathrm{T}}(e)$	$>$	0.5 GeV
$p(e)$	$>$	3 GeV
`hasRich`(π, e)	$=$	`true`
`hasCalo`(e)	$=$	`true`
$\lvert x_{ECAL}(e)\rvert$	$>$	363 mm
or $\lvert y_{ECAL}(e)\rvert$	$>$	282 mm
PID cuts		
$\mathrm{probNN}_{\pi}(\pi)$	$>$	0.2
$\mathrm{PID_e}(\pi)$	$<$	0
$\mathrm{PID_e}(\mathrm{e})$	$>$	3

Event quality

nSPDHits	$<$	450
Clone veto		
$\cos(\pi^+\mu^+)$	$<$	0.99999
$\mathrm{prob_{ghost}}(\pi, \mu)$	$<$	0.3
Fiducial cuts		
`hasRich`(π, μ)	$=$	`true`
$p_{\mathrm{T}}(\mu)$	$>$	0.8 GeV
PID cuts		
$\mathrm{probNN}_{\pi}(\pi)$	$>$	0.2
$\mathrm{PID}_{\mu}(\mu)$	$>$	-3
$\mathrm{isMuon}(\mu)$	$=$	`true`

Offline selection: multivariate classification

- A 10-fold MVA classifier based on GradientBoost is trained to distinguish signal simulation from sidebands

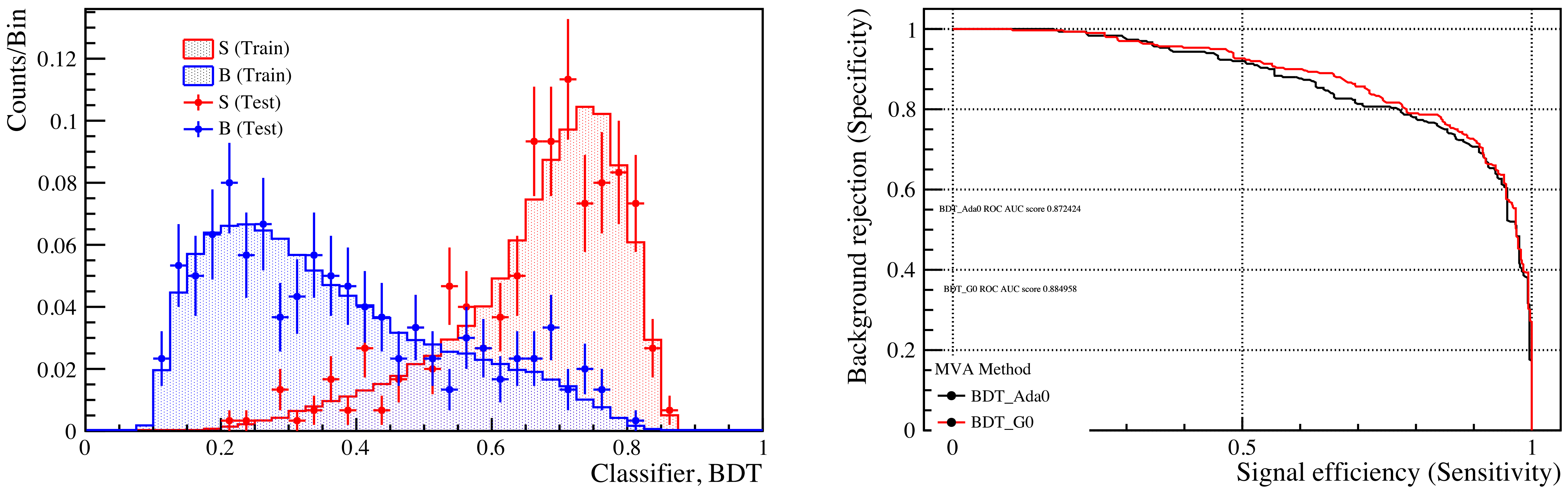
- Training variables are:

$B^+/D^+_{(s)}$	p_{T}, $\log\chi^2_{\mathrm{IP}}$, χ^2_{DV}, DIRA, $\chi^2_{\mathrm{DV}\leftrightarrow\mathrm{PV}}$
ll	p_{T}, $\log\chi^2_{\mathrm{IP}}$
K^+/π^+	p_{T}, $\log\chi^2_{\mathrm{IP}}$
l	min,max(p_{T}), min,max$(\log\chi^2_{\mathrm{IP}})$

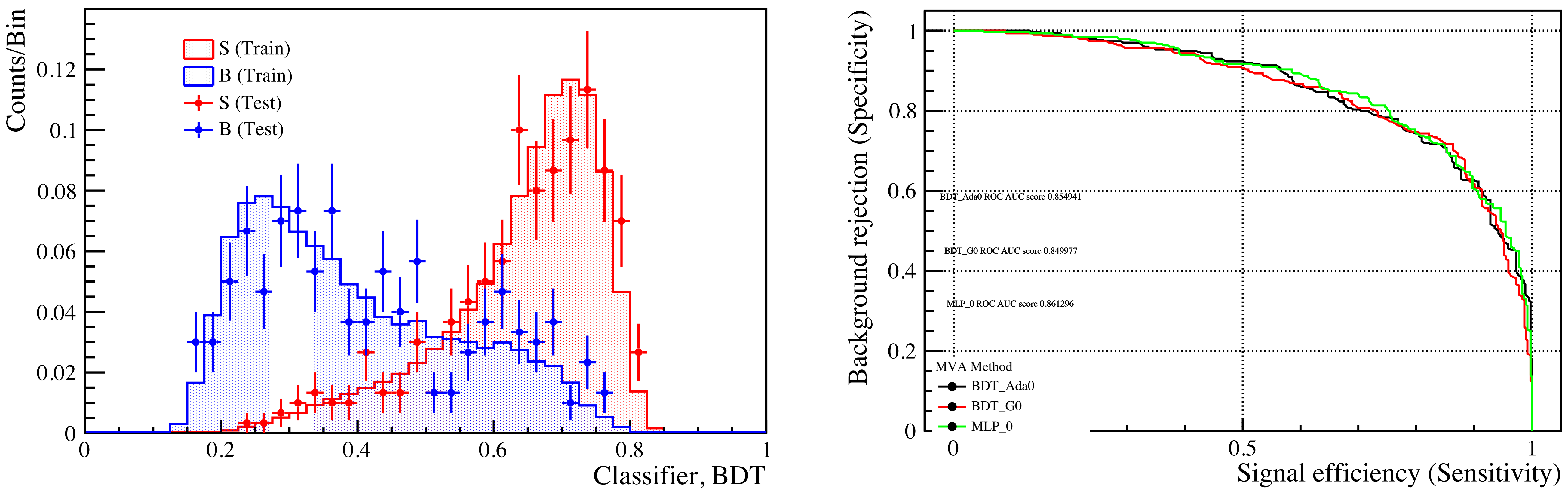
$\cos\theta_\ell$ (signal mode only)

- Optimised using $S/\sqrt{B}$ for all modes except the electron signal mode where the Punzi FOM is used with significance of 5σ

$D^+_{(s)} \to \phi(e^+e^-)\pi^+$



$D^+_{(s)} \to \phi(\mu^+\mu^-)\pi^+$



Offline selection: fiducial cuts and mass windows

- Fiducial, mass ranges and substituted mass cuts applied to the control mode

	ee mode	$\mu\mu$ mode
control mode	$6.00 < q^2 < 12.96\ \text{GeV}^2$	$8.68 < q^2 < 10.09\ \text{GeV}^2$
	$5.08 < m_{\text{DTF}}^{J/\psi}(K^+e^+e^-) < 5.68\ \text{GeV}$	$5.18 < m_{\text{DTF}}^{J/\psi}(K^+\mu^+\mu^-) < 5.60\ \text{GeV}$

Event quality		
nSPDHits	$<$	450
$\text{prob}_{\text{ghost}}(\text{K},\text{e})$	$<$	0.3
Cascade vetoes		
$m(K^+e^-)$	$>$	1885 MeV
$m_{e\to\pi}^{\text{track}}(K^+e^-)$	$\notin$	$m(D^0) \pm 40$ MeV
Fiducial cuts		
$p_{\text{T}}(e)$	$>$	0.5 GeV
$p(e)$	$>$	3 GeV
$\texttt{hasRich}(K,e)$	$=$	`true`
$\texttt{hasCalo}(e)$	$=$	`true`
$\lvert x_{ECAL}(e)\rvert$	$>$	363.6 mm
or $\lvert y_{ECAL}(e)\rvert$	$>$	282.6 mm
PID cuts		
$\text{probNN}_{\text{K}}(\text{K})$	$>$	0.2
$\text{PID}_{\text{e}}(\text{K})$	$<$	0
$\text{PID}_{\text{e}}(\text{e})$	$>$	3

Event quality		
nSPDHits	$<$	450
$\text{prob}_{\text{ghost}}(\text{K},\mu)$	$<$	0.3
Fiducial cuts		
$\texttt{inMuonAcc}(\mu)$	$=$	`true`
$\texttt{hasRich}(K,\mu)$	$=$	`true`
$p_{\text{T}}(\mu)$	$>$	0.8 GeV
PID cuts		
$\text{probNN}_{\text{K}}(\text{K})$	$>$	0.2
$\text{PID}_{\mu}(\mu)$	$>$	-3
$\text{isMuon}(\mu)$	$=$	`true`

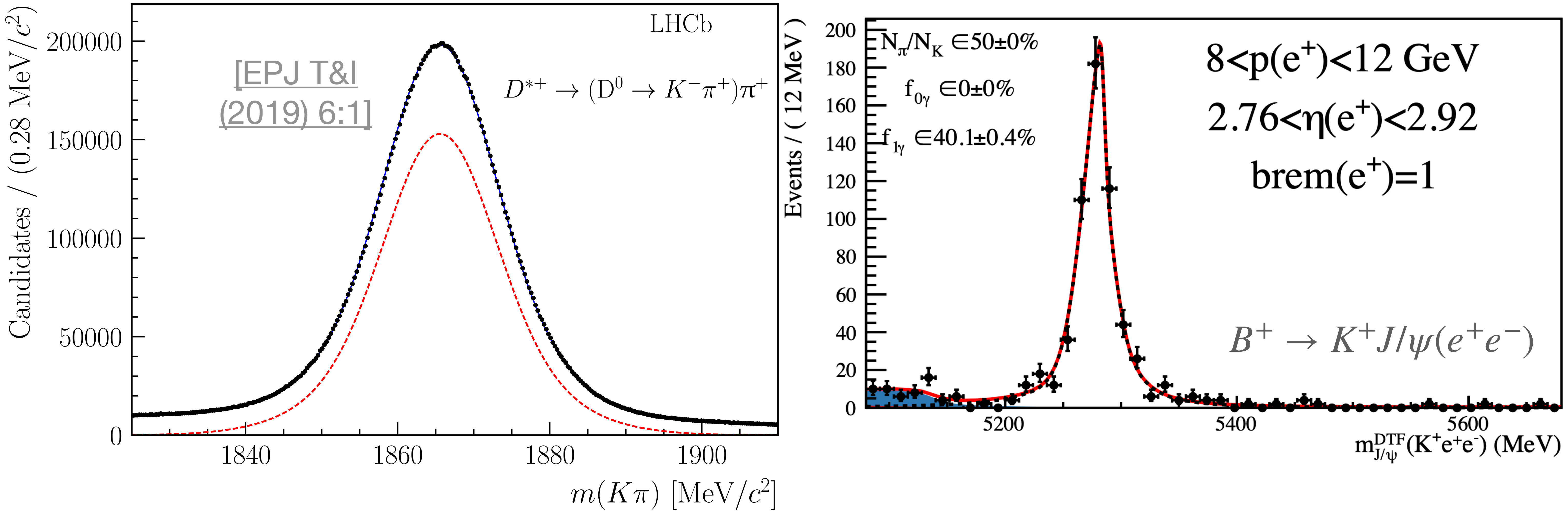
Efficiencies calculation

$$\varepsilon^{\text{tot}} = \varepsilon^{\text{geom}}(\cdot\varepsilon^{\text{filter}}) \cdot \varepsilon^{\text{rec,strip}} \cdot \varepsilon^{\text{presel}} \cdot \varepsilon^{\text{PID}} \cdot \varepsilon^{\text{trig}} \cdot \varepsilon^{\text{BDT}}$$

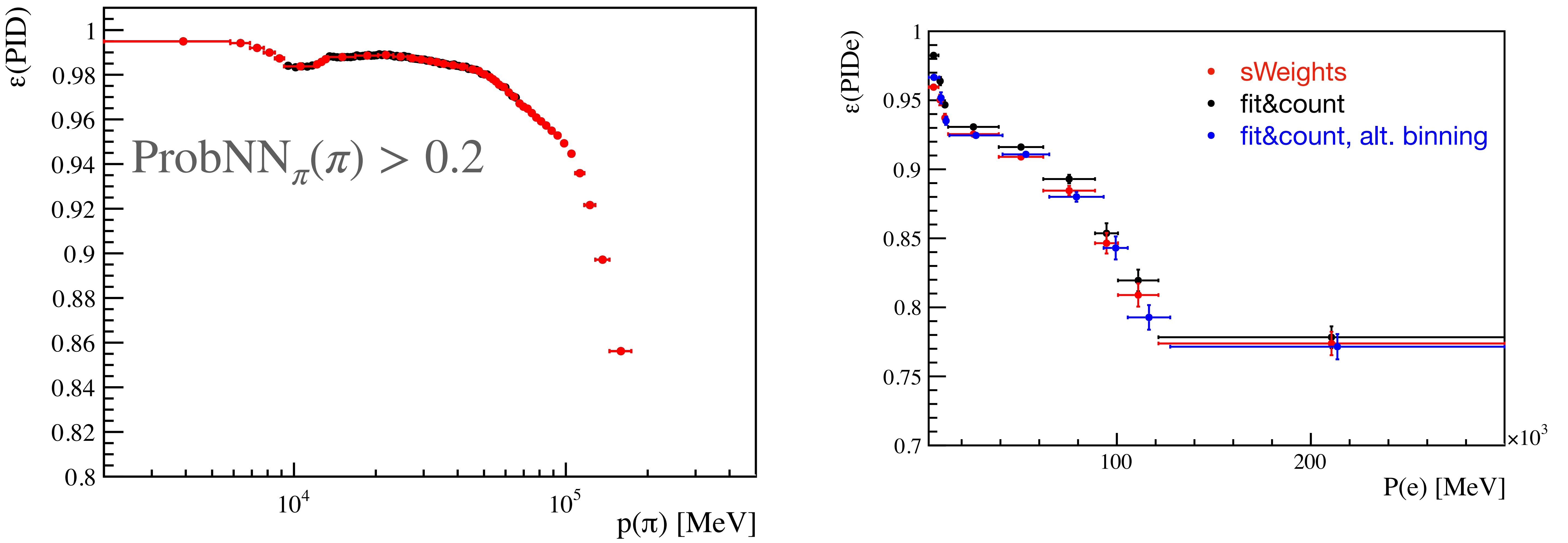
- Ghost computation:
  - Signal events which are misclassified as ghosts are taken into account
- PID efficiencies:
  - Use `PIDCalib` to extract μ, K, π efficiencies
  - e PID efficiencies obtained by fit and count procedure on $B^+ \to J/\psi(e^+e^-)K^+$ calibration data
  - Correction for electron PID factorisation bias
- Calibration of B/D kinematics:
  - Use $B^+ \to J/\psi(\ell^+\ell^-)K^+$ and $D^+_{(s)} \to \phi(\ell^+\ell^-)\pi^+$ selected data correct for remaining discrepancies between data and MC
- q^2 smearing:
  - Use parameters from a fit to $m(J/\psi)$ to better match q^2 resolution observed in data
- Electron tracking efficiency corrections:
  - Use the available WG tables to correct for inaccuracy of simulated track reconstruction

Corrections to Particle ID efficiencies

- Correct for mismodelled particle identification efficiencies using data:
  - *K*, *π* and *μ* (left): using efficiency histograms from `PIDCalib`
  - *e* (right): Dedicated calibration of ePID with fit&count method in bins of $(p(e^{\pm}), \eta(e^{\pm}), \text{hasBrem})$



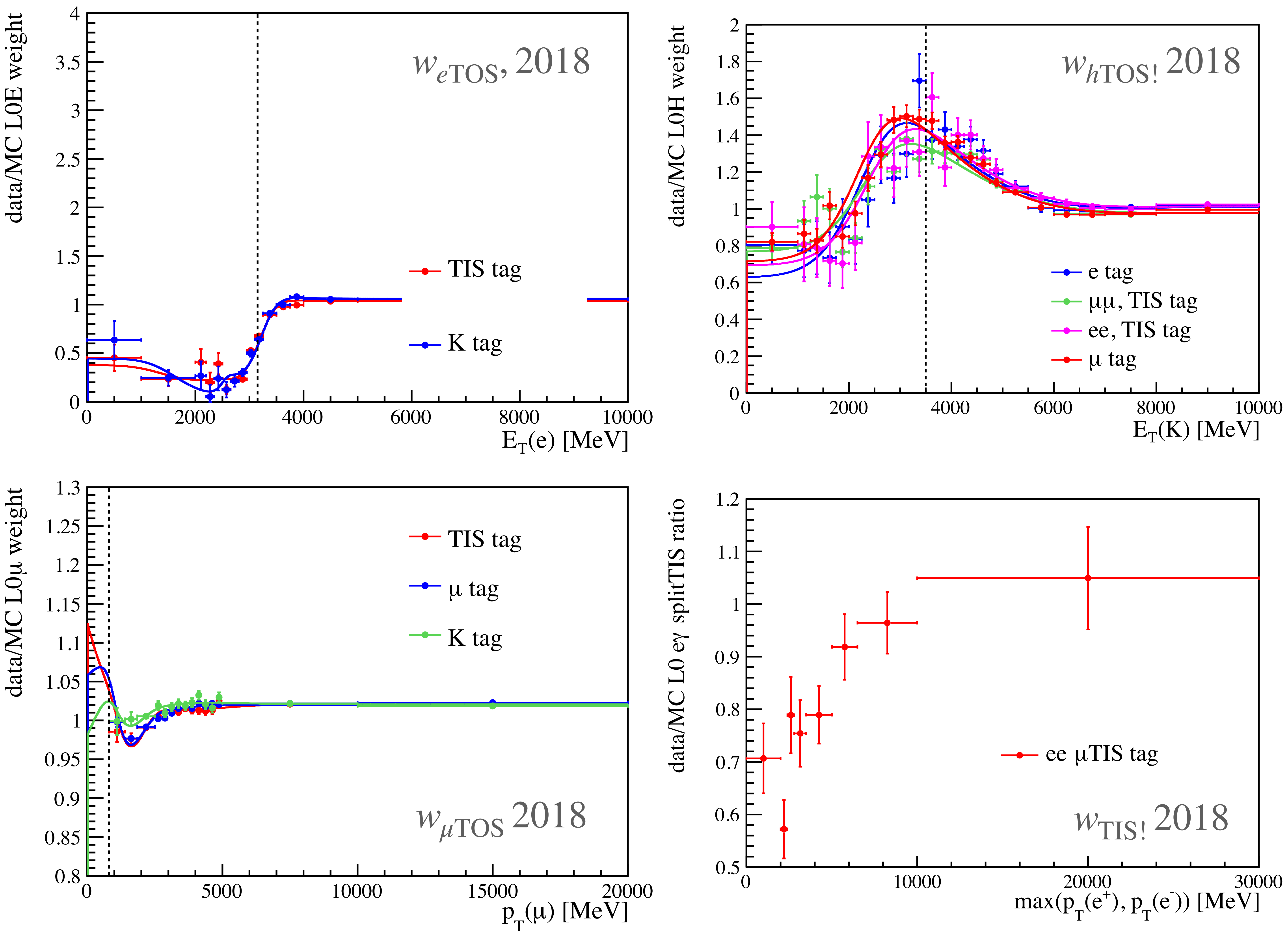
Fit to the data samples used as a source of $\pi^{\pm}$ (left) and $e^{\pm}$(right) PID eff calibration



PID efficiencies for $\pi^{\pm}$ (left) and $e^{\pm}$(right) as a function of their momenta

Trigger corrections

- Simulated trigger efficiencies are calibrated using sWeighted $B^+ \to J/\psi(\ell^+\ell^-)K^+$ data using a tag&probe approach
  - $\mu\mathrm{TOS}:\ \mathrm{p_T}(\mu)$
  - $e\mathrm{TOS}:\ \mathrm{E_T(e)}$
  - $h\mathrm{TOS!}:\ \mathrm{E_T(K)}$
  - $\mathrm{TIS!}:\ \max(\mathrm{p_T}(e^+), \mathrm{p_T}(e^-))$
- TIS tags are used to compute nominal weights, other tags are used for systematic

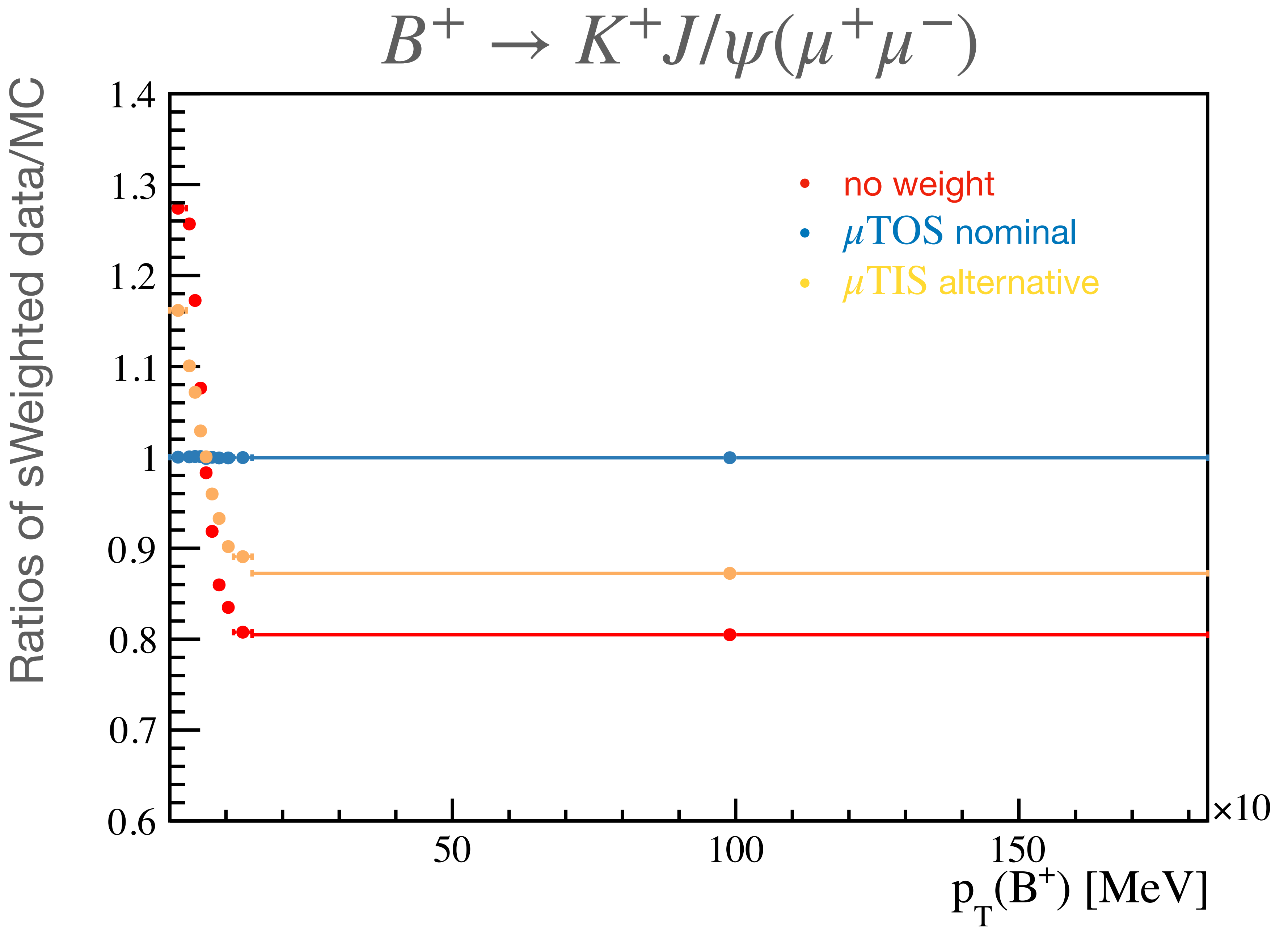


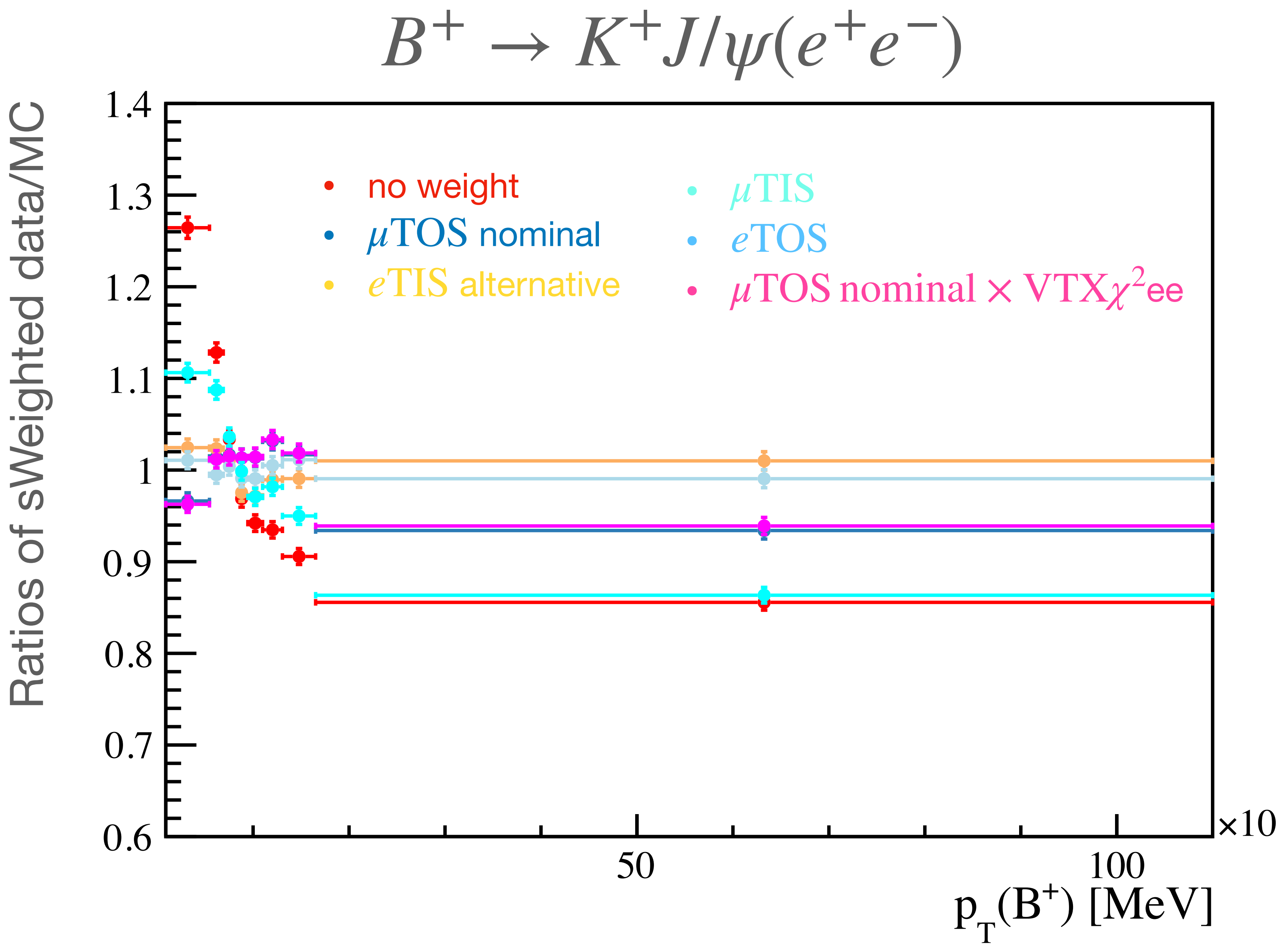
Kinematic corrections

- Use $B^+ \to K^+ J/\psi(\mu^+\mu^-)$, and $D^+_{(s)} \to \pi^+\phi(\mu^+\mu^-)$ to correct for B/D kinematics mismodeling in MC
- Simulation is reweighed to match the data distributions

$$(p_T(B/D) \times \eta(B/D), \chi^2_{\text{IP}}(B/D), \chi^2_{\text{DV}}(B/D))$$

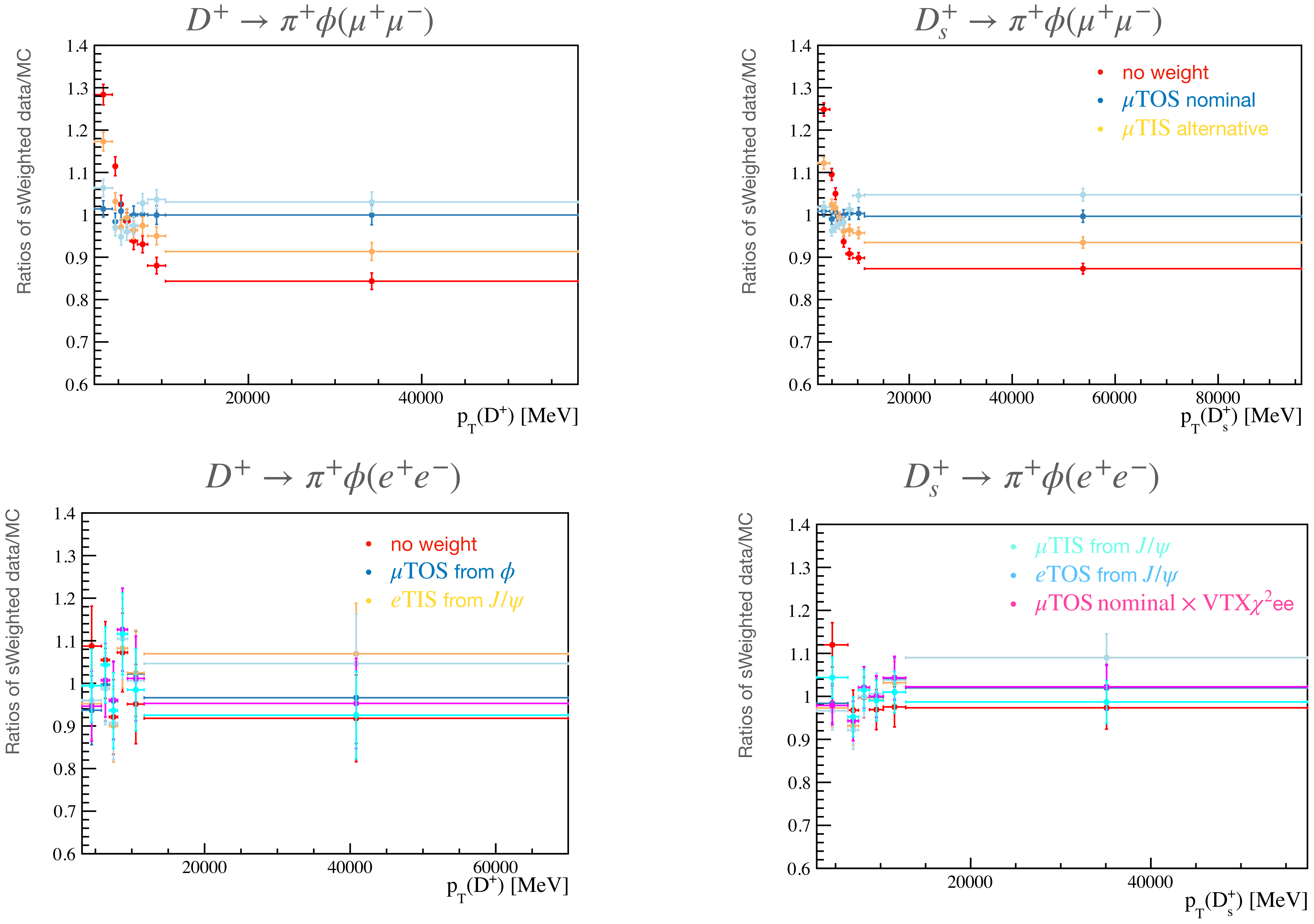
- Nominal approach uses sWeighted μTOS data
- Weights from $\mu\text{TIS!}$ tags or electron modes are used as systematics





Kinematic corrections

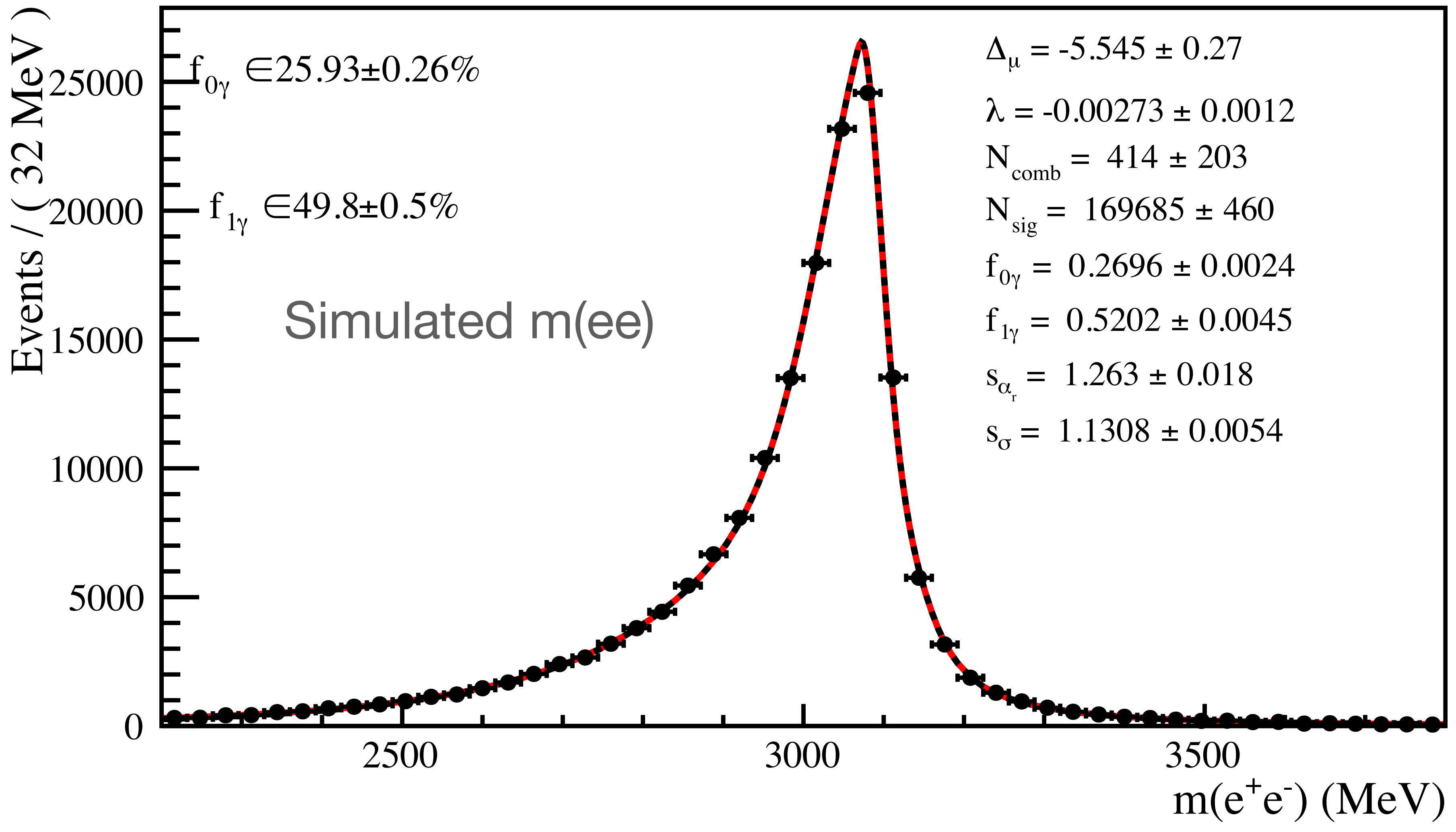
- Weights derived separately for D/D_s data
- Variance of alternative weights reduced by adopting J/ψ reweighting histograms due to low statistics of signal electrons

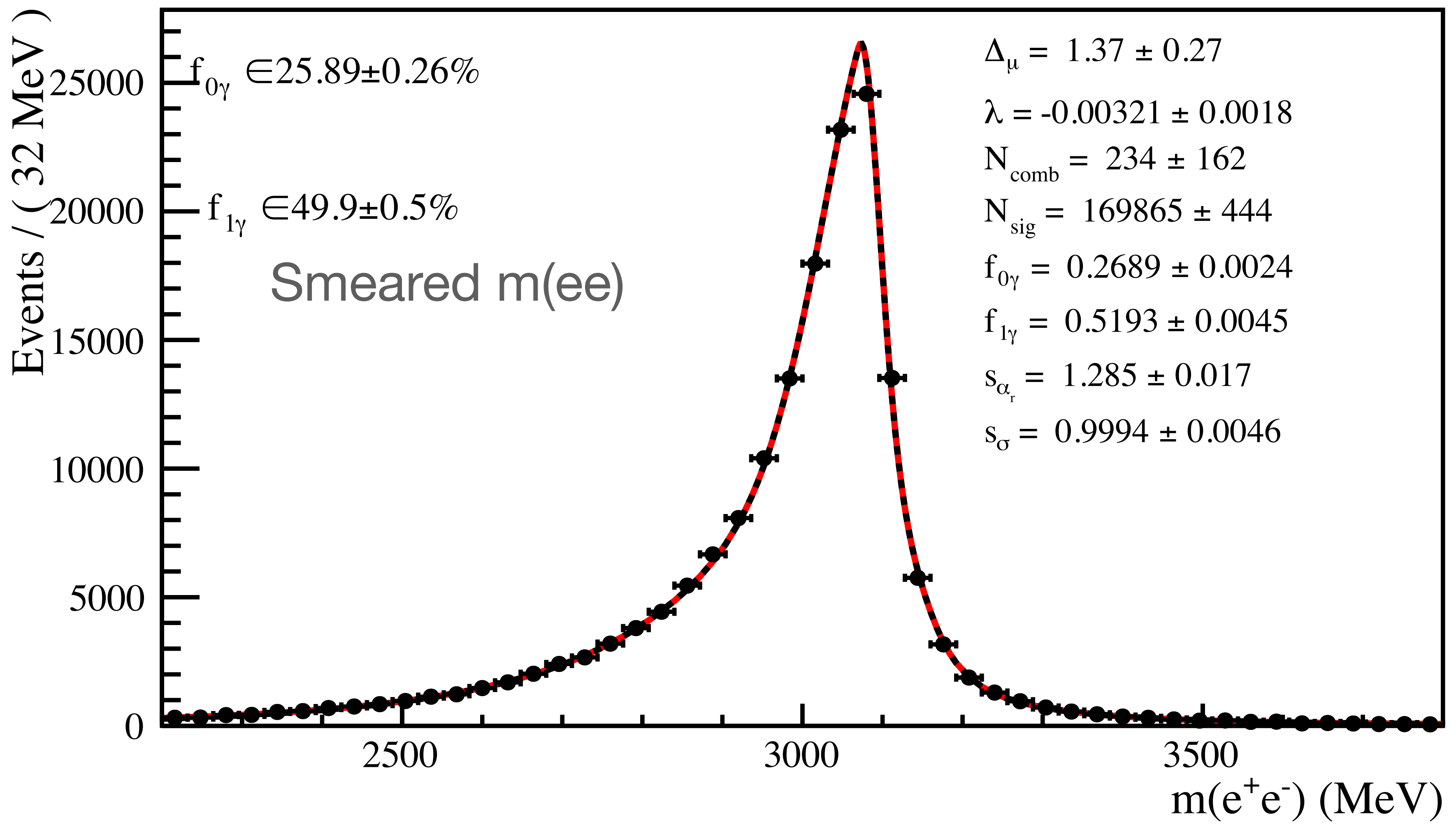


Di-electron mass smearing

- Simulated resolution is better than the one observed in data
- Extract smearing parameters from $B^+ \to K^+ J/\psi(e^+e^-)$

$$\mu^{\text{data}} = \mu^{MC} + \Delta\mu, \sigma^{data} = s_\sigma \cdot \sigma^{\text{MC}}$$





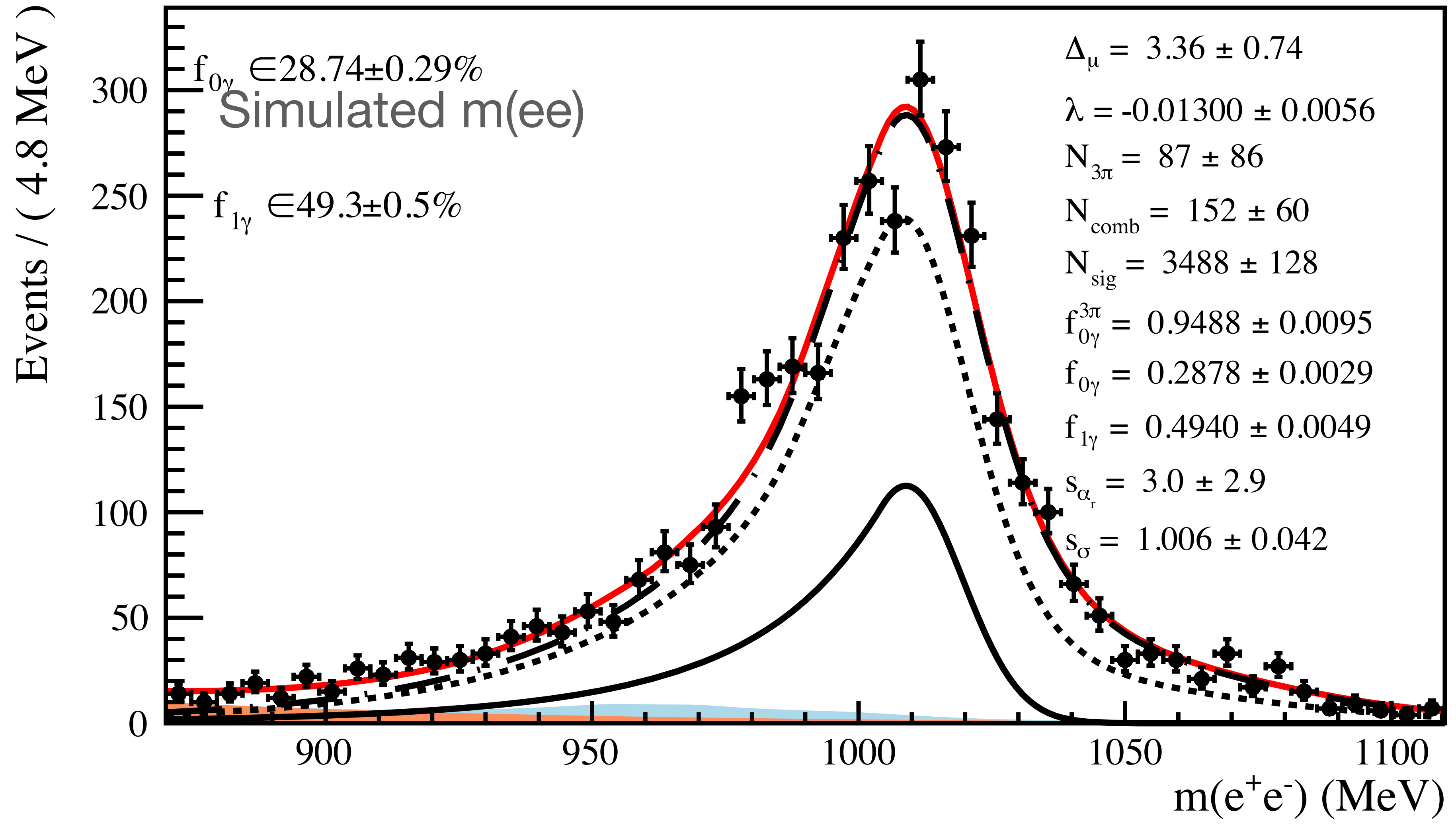
Di-electron mass smearing

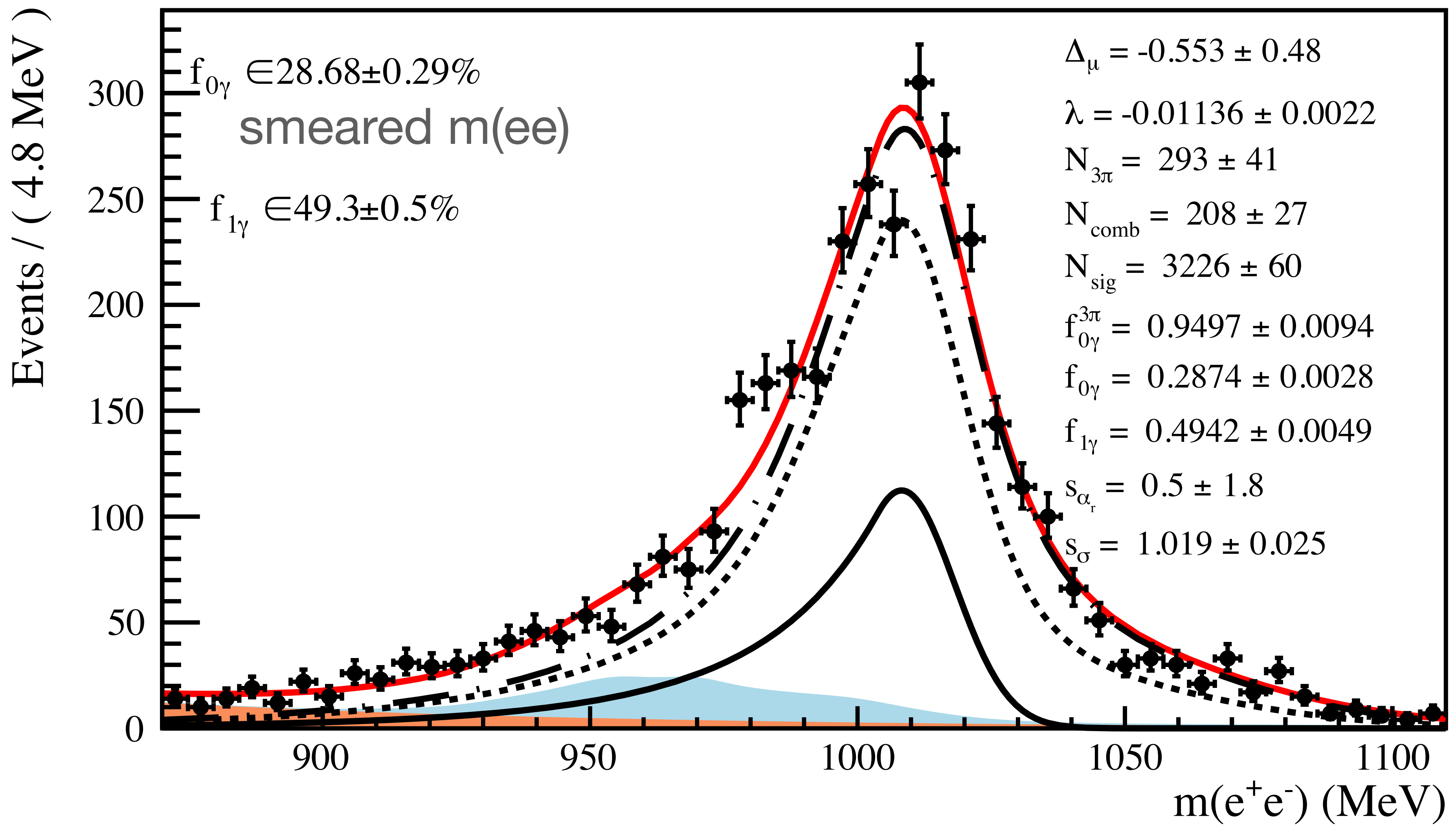
- Simulated resolution is better than the one observed in data
- Extract smearing parameters from $B^+ \to K^+ J/\psi(e^+e^-)$

$$\mu^{\text{data}} = \mu^{MC} + \Delta\mu, \sigma^{data} = s_\sigma \cdot \sigma^{\text{MC}}$$

- And correct simulated signal mode resolution according to:

$$m^{\text{smeared}} = m^{\text{true}} + s_\sigma(m - m^{\text{true}}) + \Delta\mu + (1 - s_\sigma)(\mu^{MC} - m(\phi))$$

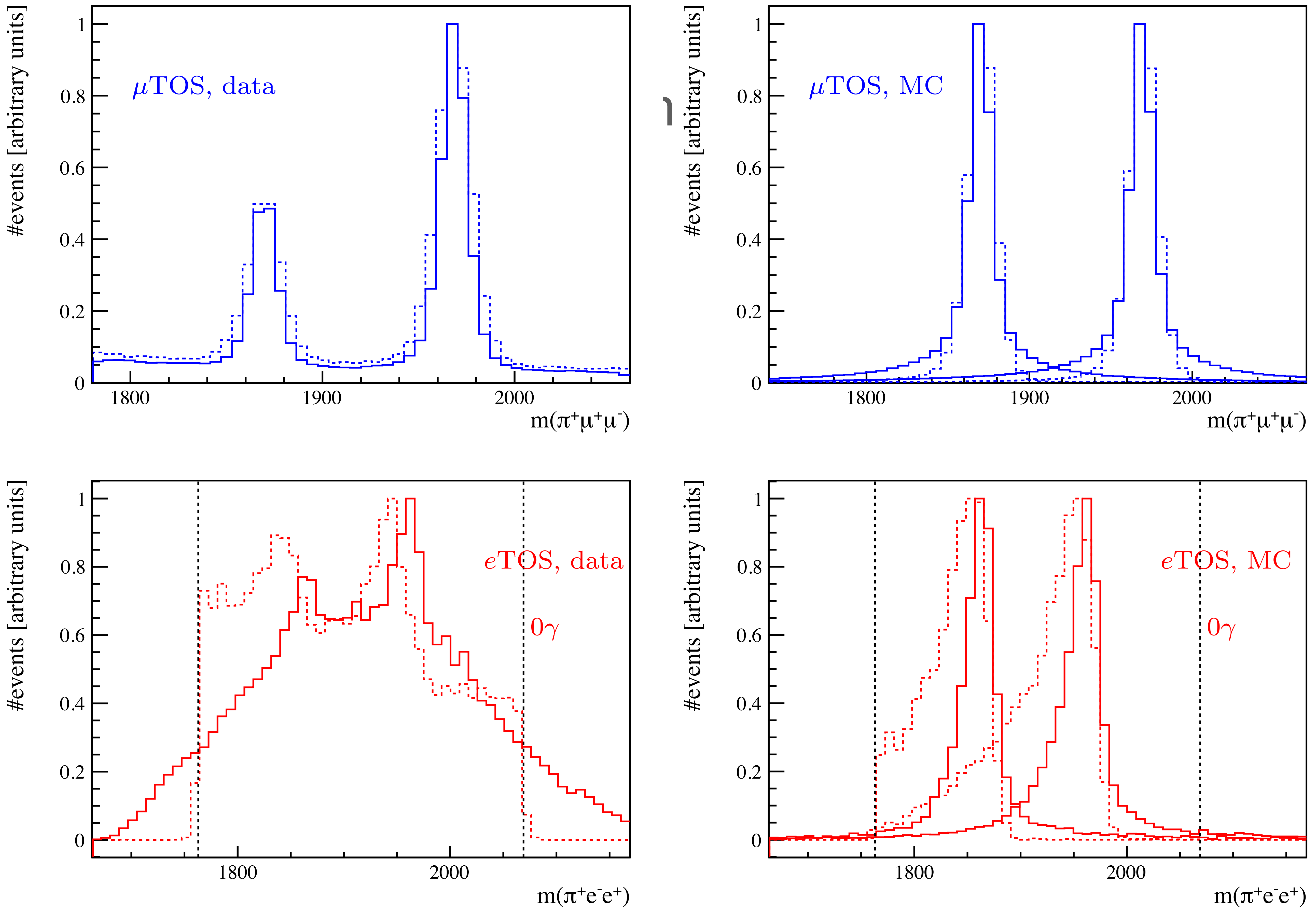




Warping of the combinatorial background shape

- The Standard Model (SM) of particle physics represents our best understanding of nature at the tiniest scales.
- It contains the building blocks of matte

- Strategic choice: use ϕ-constrained D^+ mass for the signal mode yield extraction to improve resolution
- However, we know what they say about free lunches…



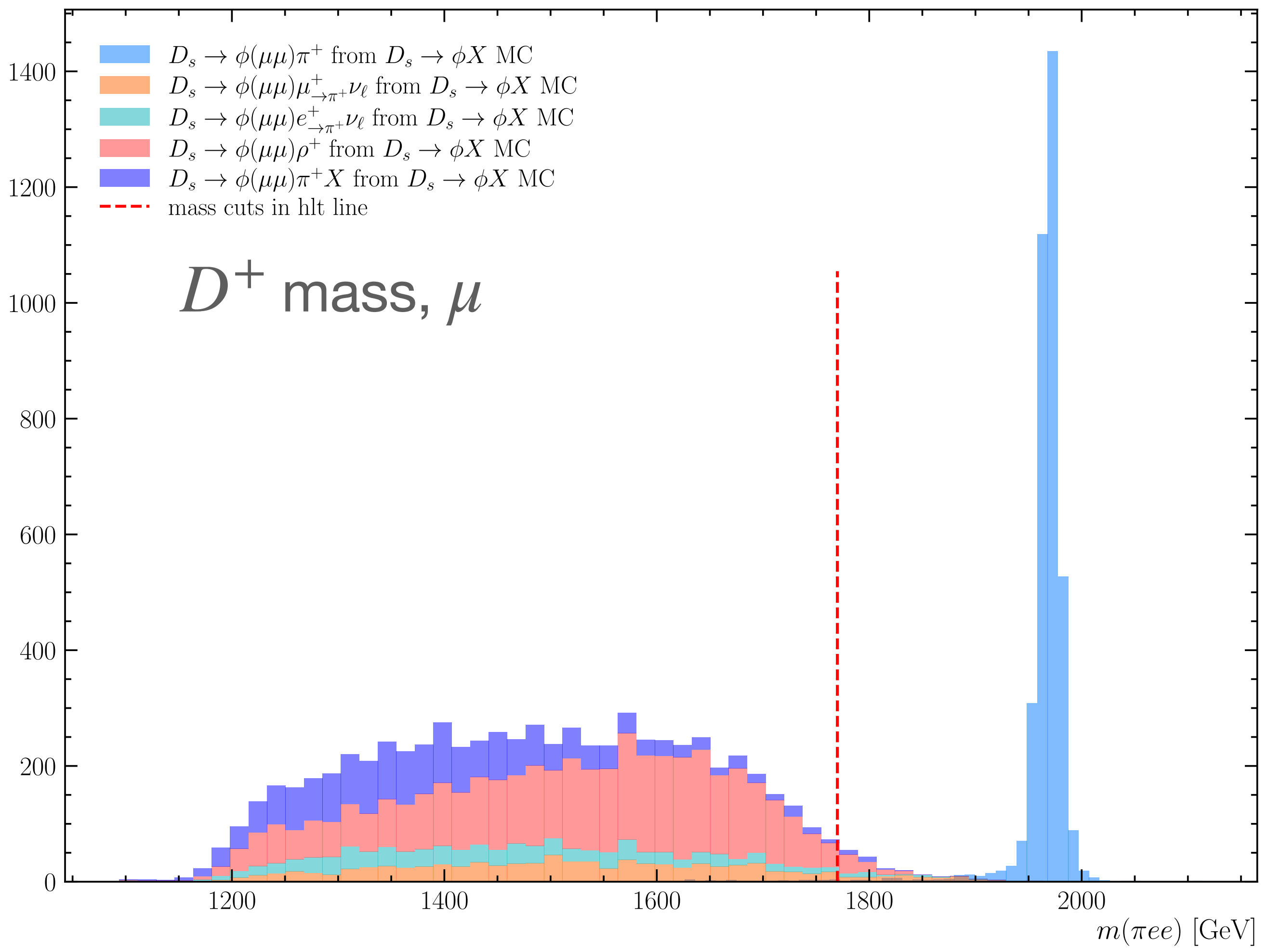
Peaking background sources

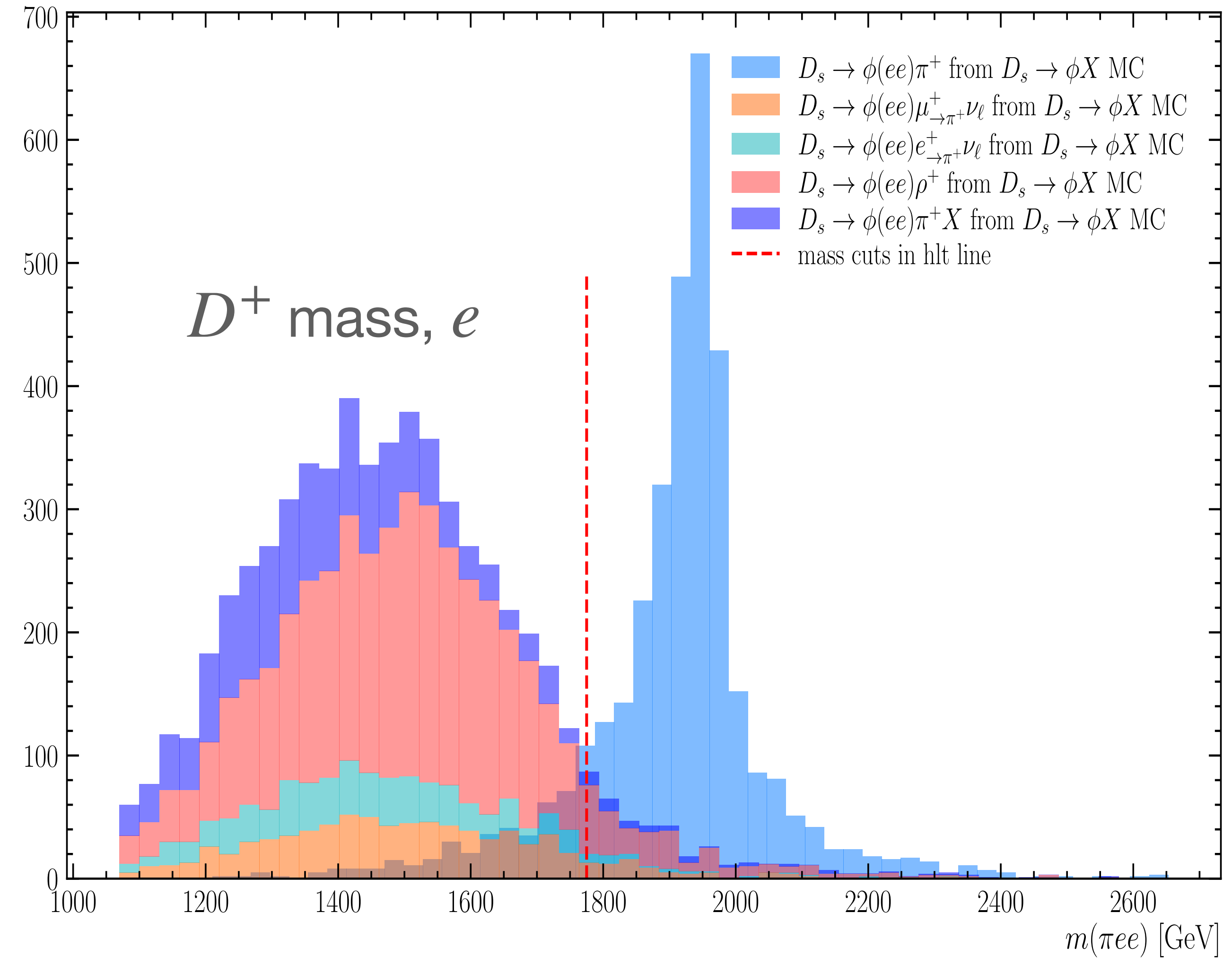
Several sources of peaking backgrounds affecting the signal channels are considered:

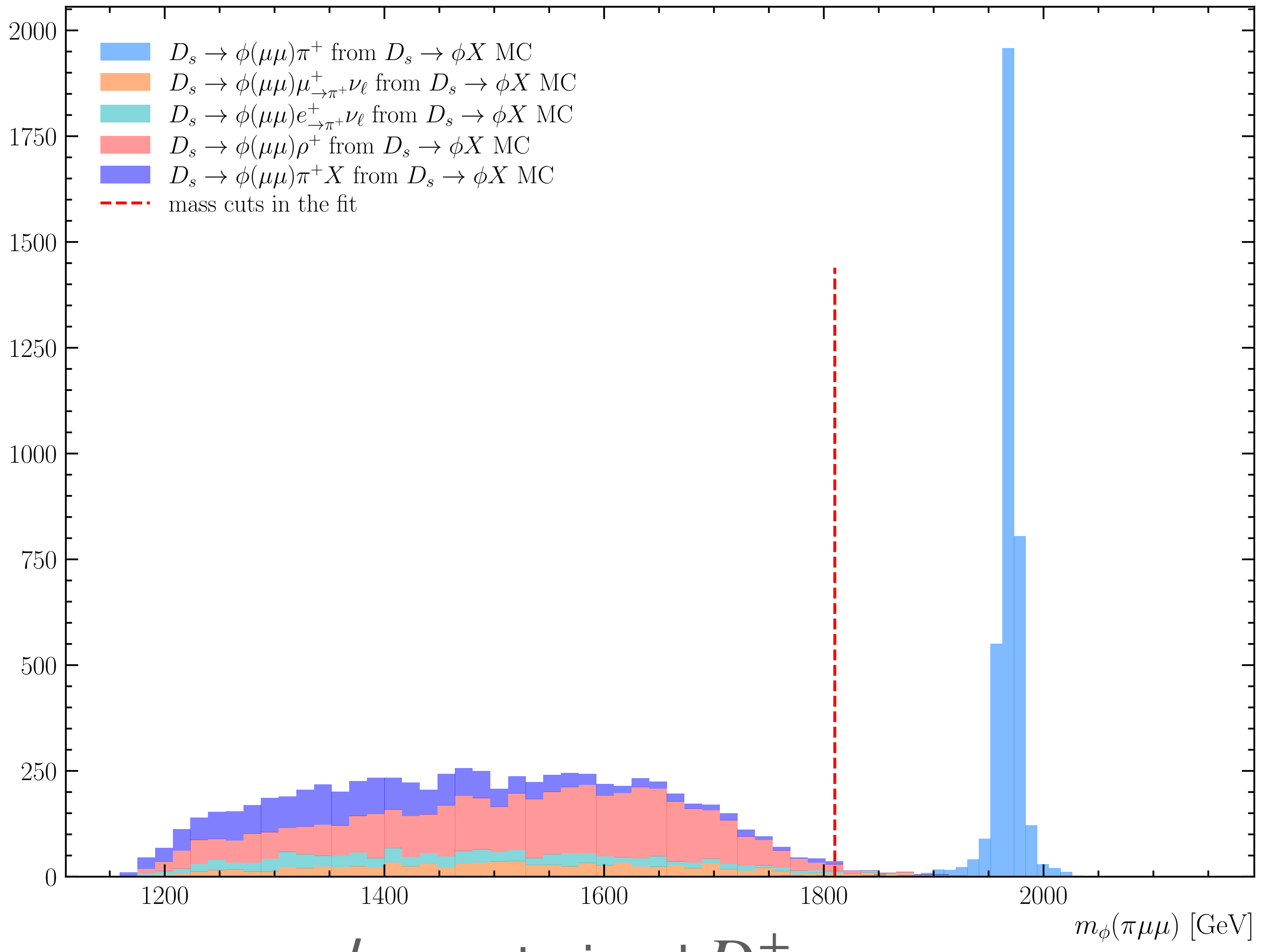
- Partially reconstructed and semileptonic backgrounds of the kind:

$$D \to \phi(\ell\ell)\rho(\pi^+\pi^0)$$
$$D \to \phi(\ell\ell)\ell_{\to\pi}\nu$$

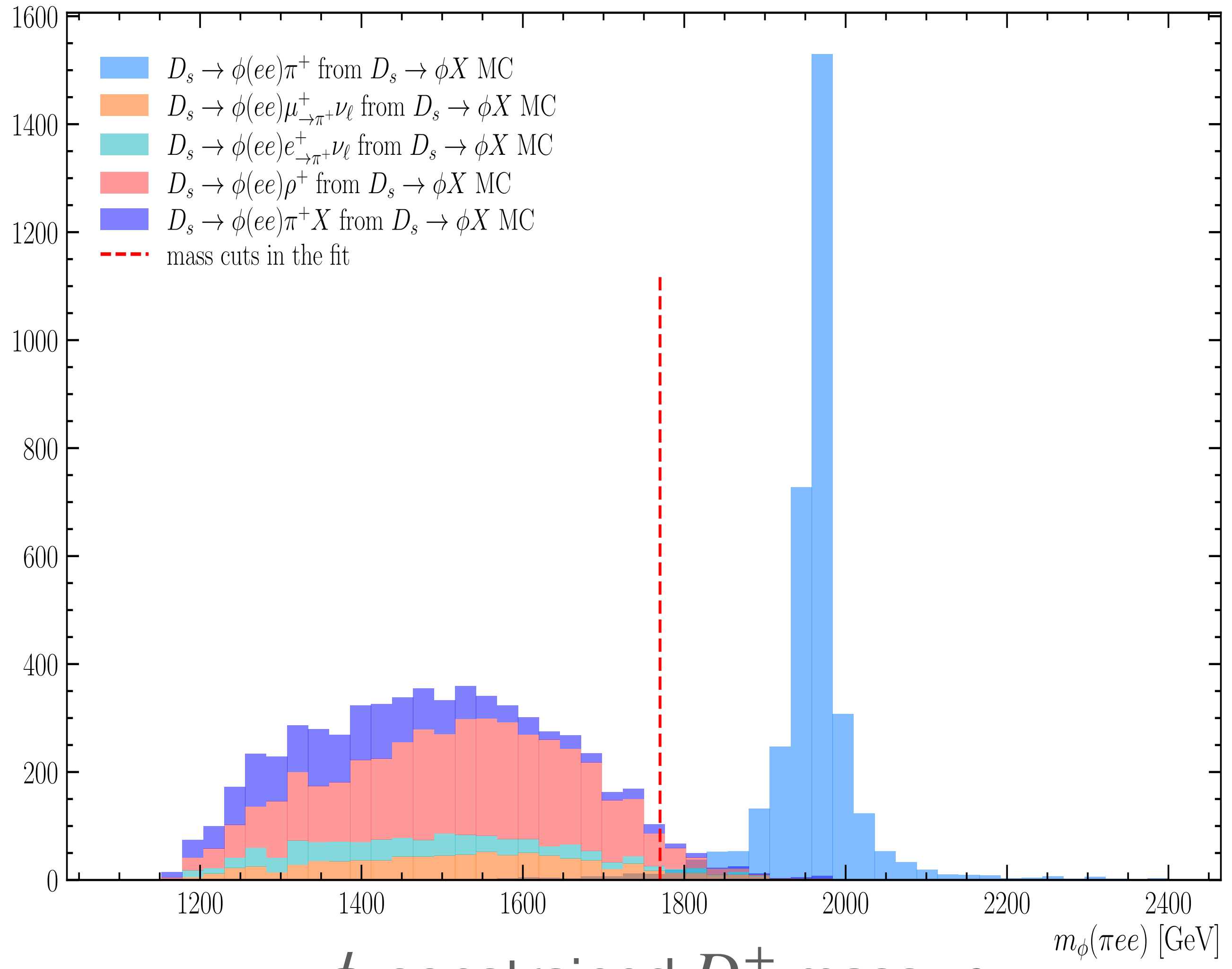
- Are checked with full simulation and reduced to a negligible level by the mass cuts







ϕ-constrained D^+ mass, μ



ϕ-constrained D^+ mass, e

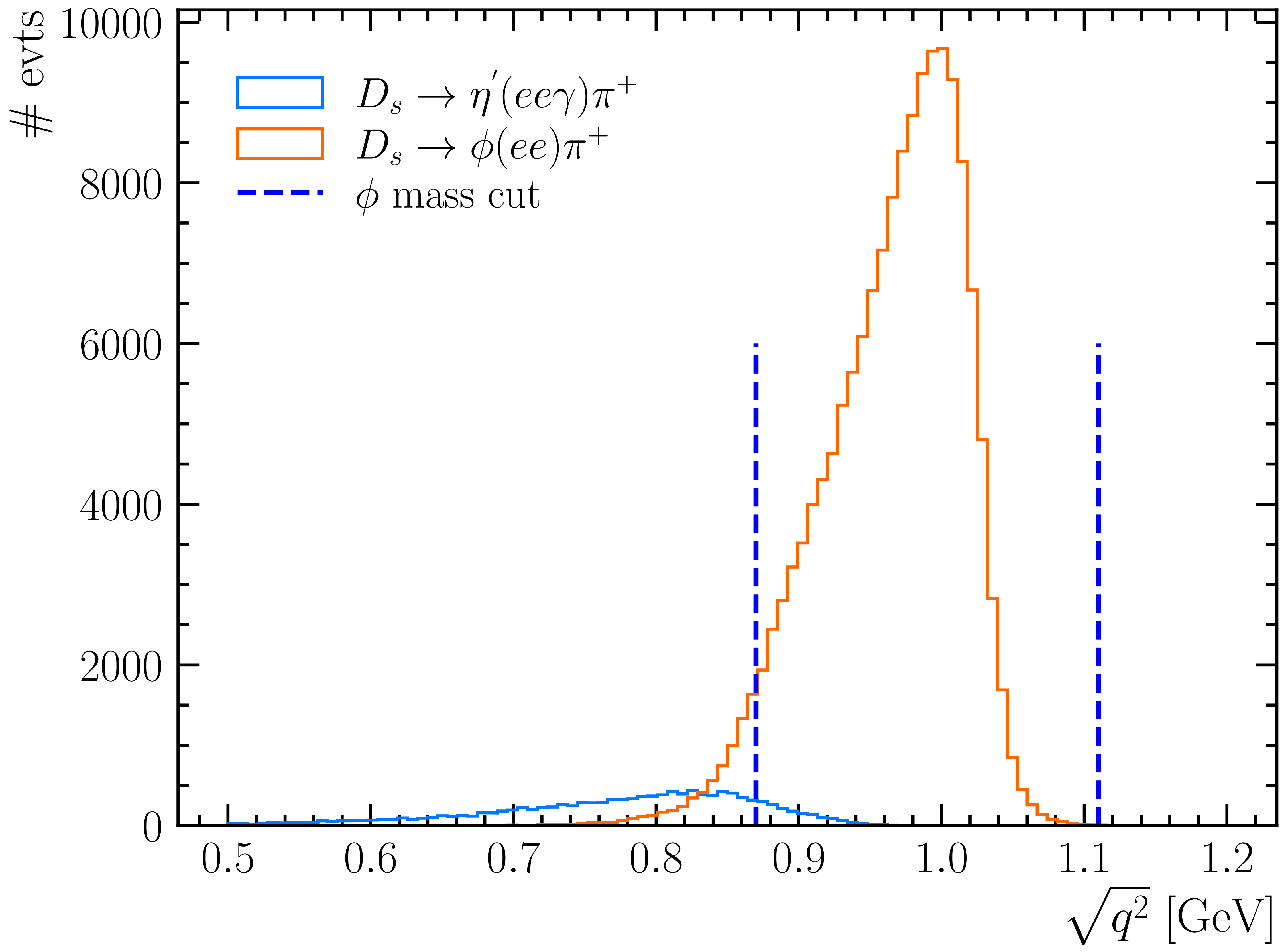
Peaking background sources

Several sources of peaking backgrounds affecting the signal channels are considered:

- It is checked using phase space only simulation (RapidSim + PHOTOS) that background sources of the kind:

$$D^+ \to \phi(\ell\ell)\eta'(ee\gamma)\pi^+$$

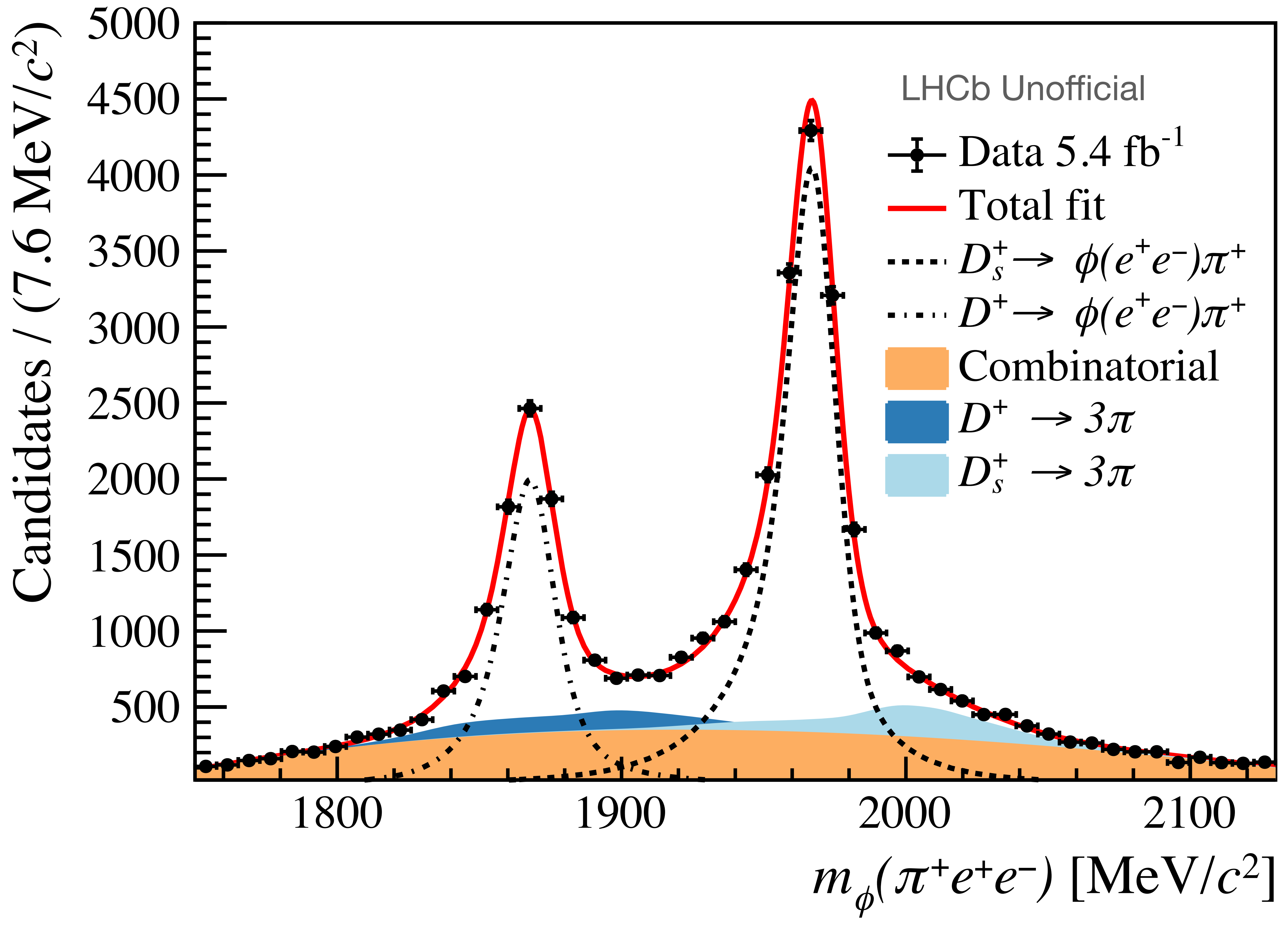
are reduced to percent level from acceptanc D mass window and lepton p, p_T cuts



Signal yield extraction: electrons

The signal yield is extracted separately in each year of data taking and trigger category

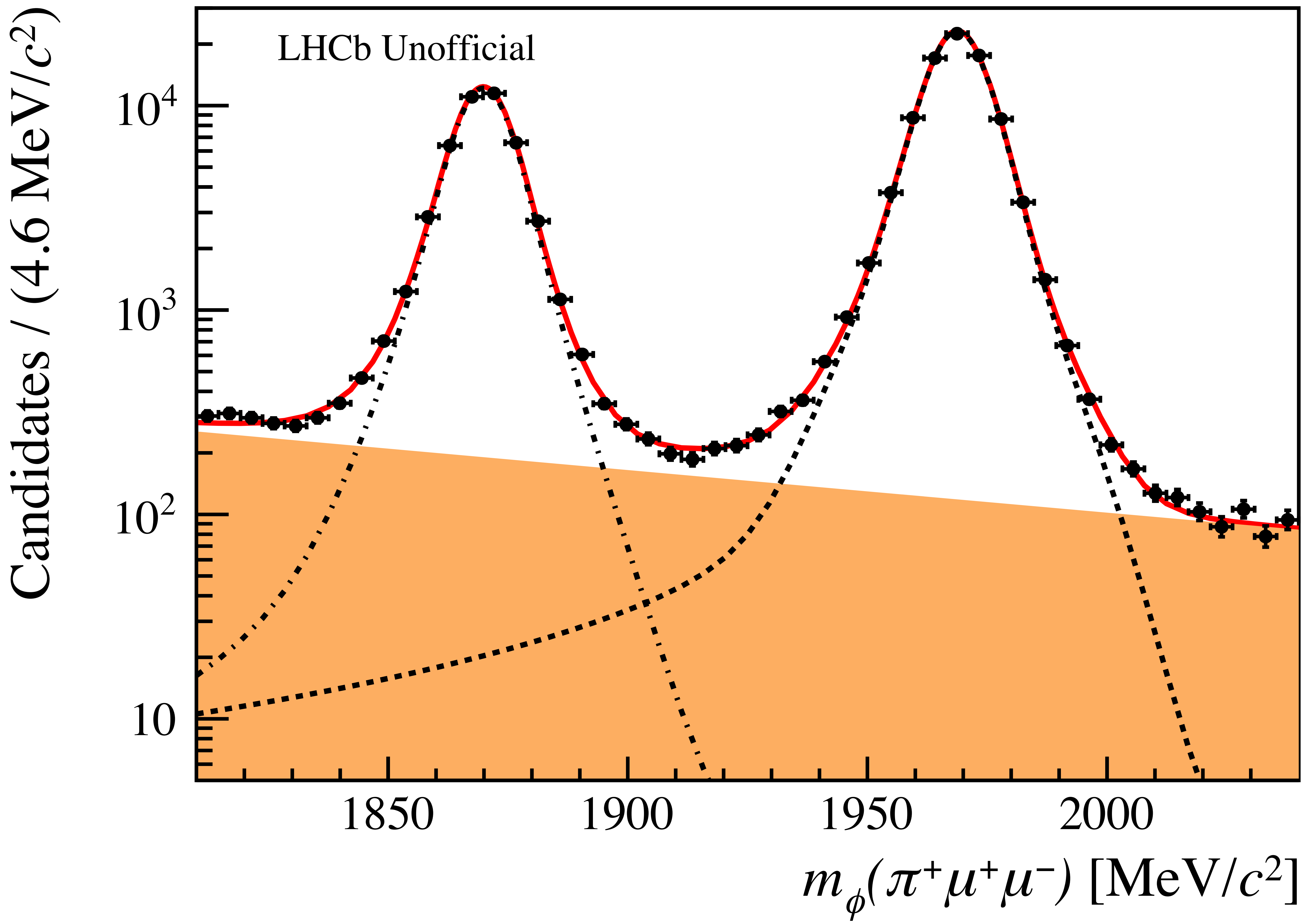
- Fit model for electron signal mode consists of:
  - Signal mode is parametrised as a sum of double crystal balls, one for each bremsstrahlung category with parameters obtained from simulation
  - Chebychev coefficients of combinatorial model are free to float in the nominal fit
  - Doubly misidentified $D^+ \to \pi^+\pi^-\pi^+$ background shape and yield are obtained from inverted PID sample



Signal yield extraction: muons

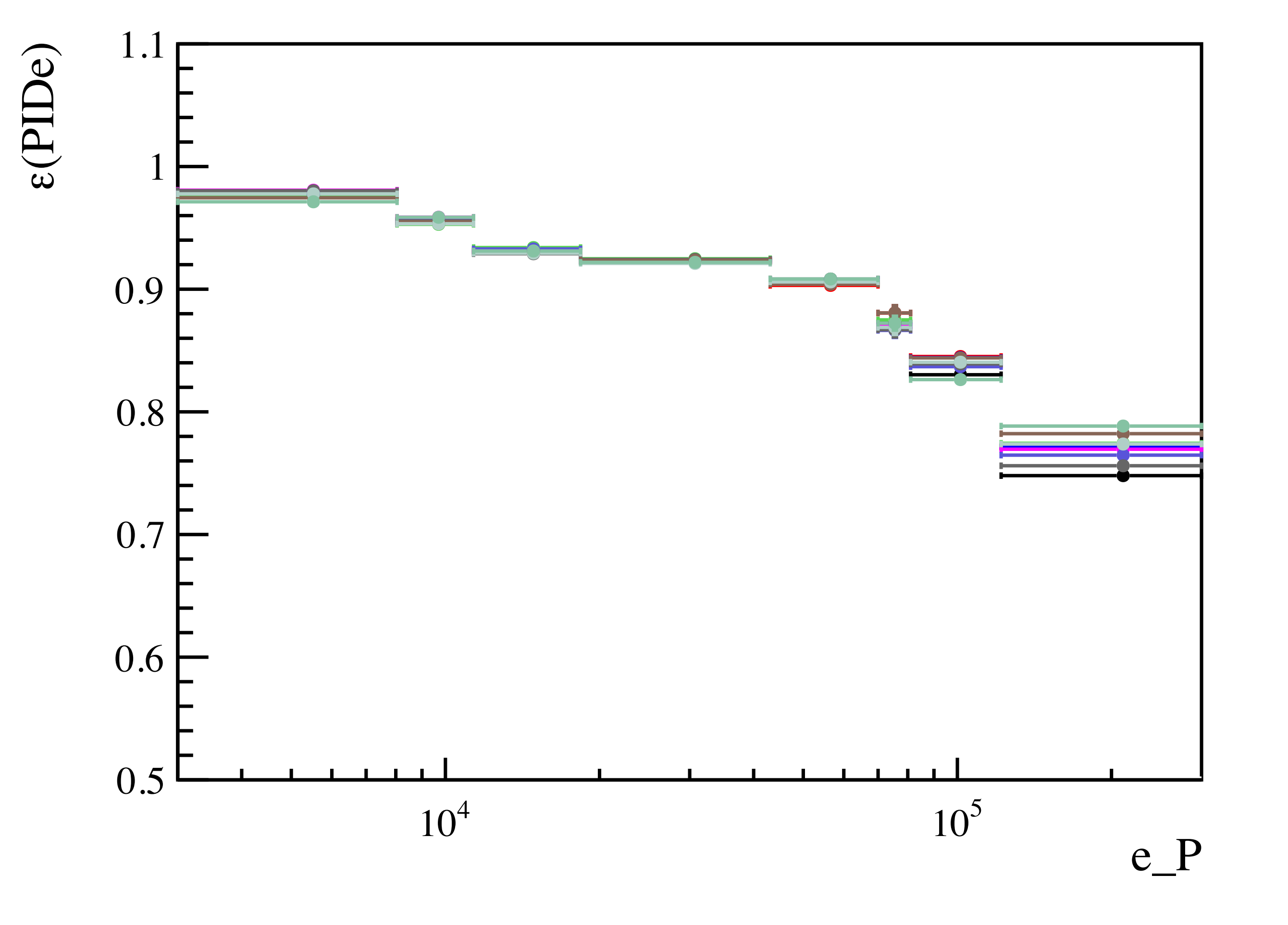
The signal yield is extracted separately in each year of data taking and trigger category

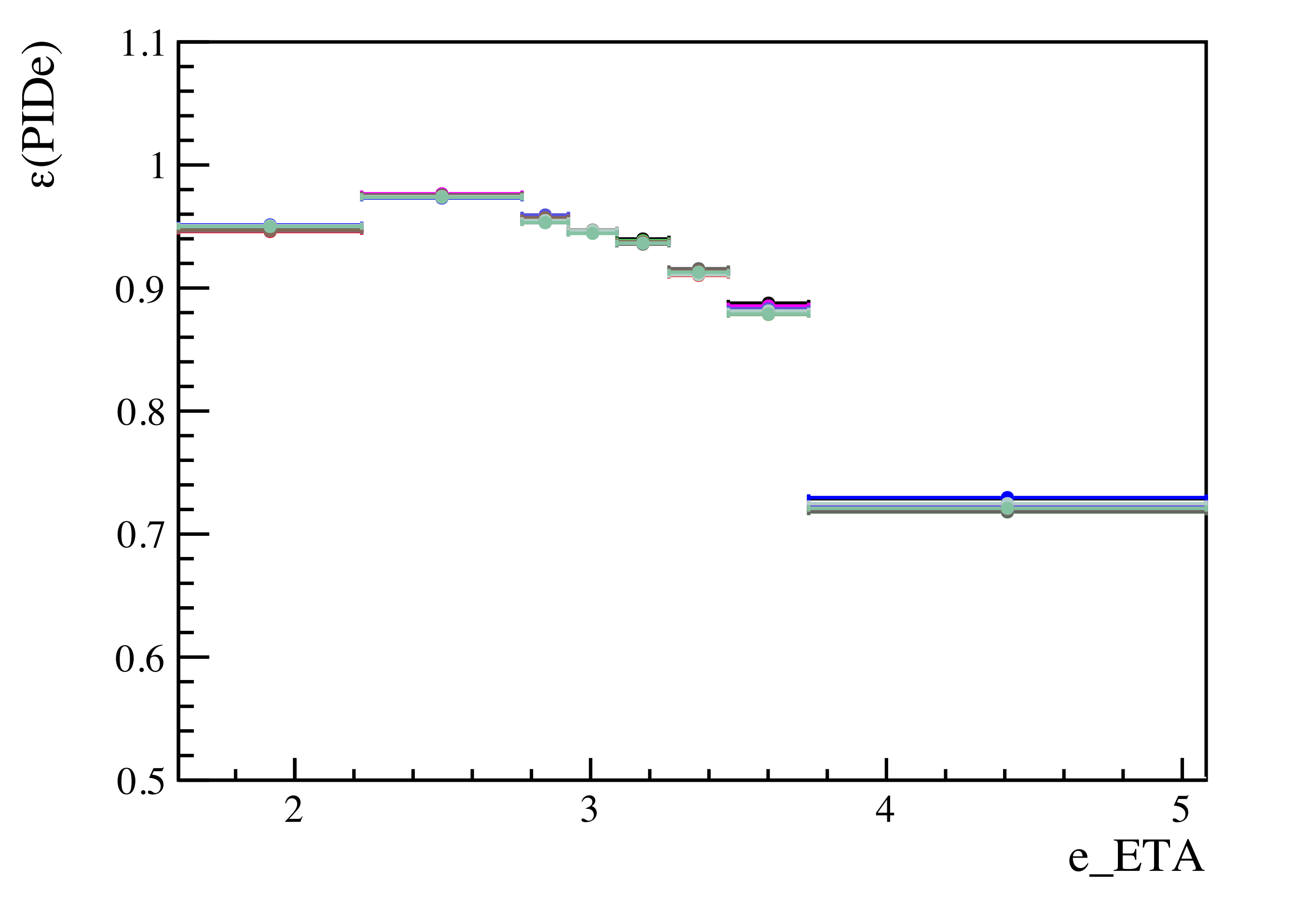
- Fit model for muon signal mode consists of:
  - Signal mode is parametrised as a double crystal ball with parameters obtained from simulation
  - Combinatorial model as falling exponential
  - Doubly misidentified $D^+ \to \pi^+\pi^-\pi^+$ background is negligible from PID and mass window cuts



Systematics

- Statistic of MC and calibration samples
  - Evaluated using bootstrapping method
- PID corrections
  - Choice of PID tables binning scheme or trigger bias evaluated requiring TIS on the probe electron
- Corrections to B/D kinematics:
  - Syst. related to the choice of reweighting scheme, evaluated varying the tags used to derive the kinematic corrections
- Occupancy systematics
  - Evaluated adding to the kinematic reweighting occupancy proxies (nPVs, nSPDHits, nTracks)
- q^2 smearing:
  - Uncertainties on the smearing parameters
- Fit model systematics
  - Variations on the model used to parametrise combinatorial events and misidentified backgrounds in the electron mode

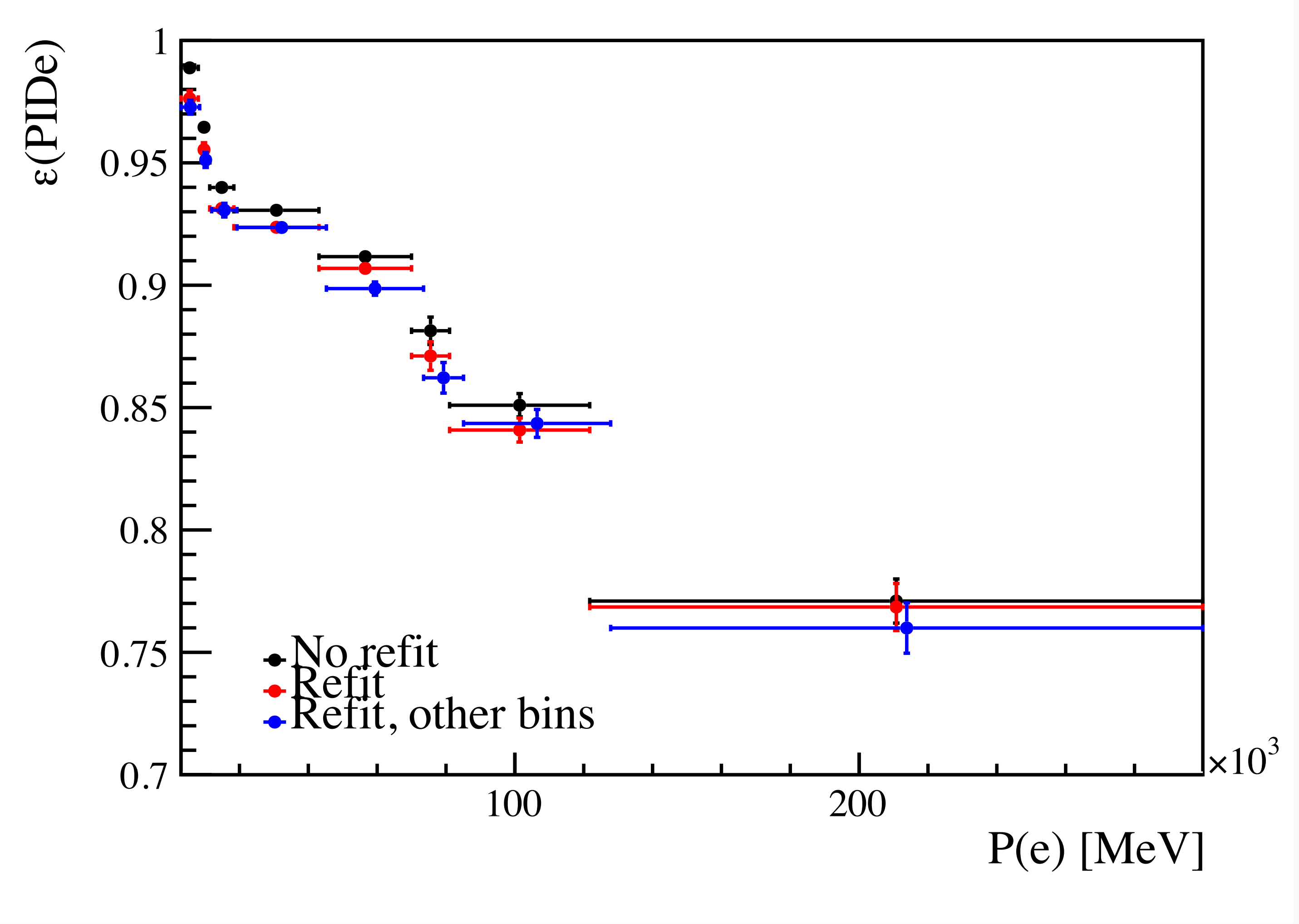


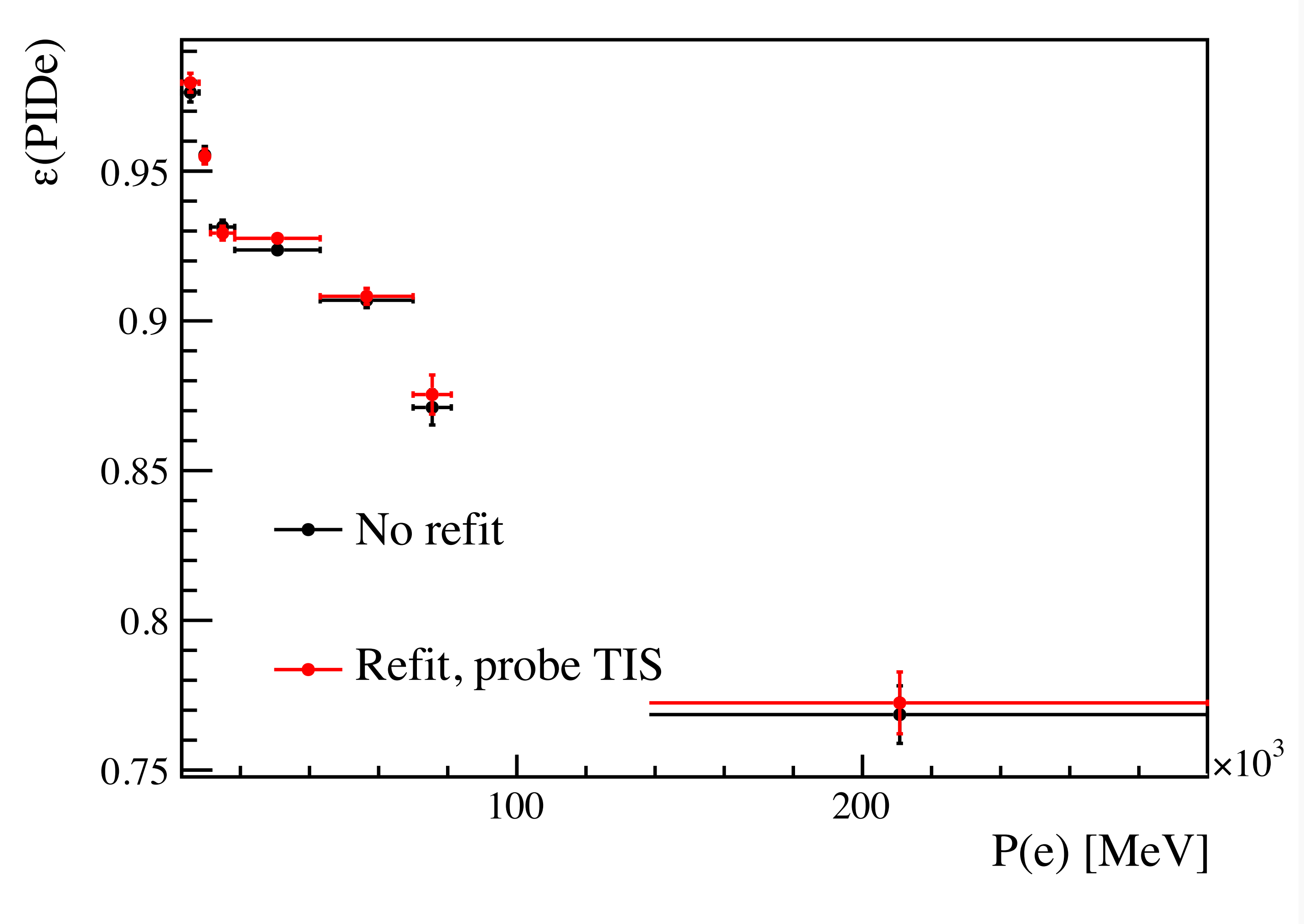


Applying bootstrap method to the calibration sample used to extract ePID efficiencies

Systematics

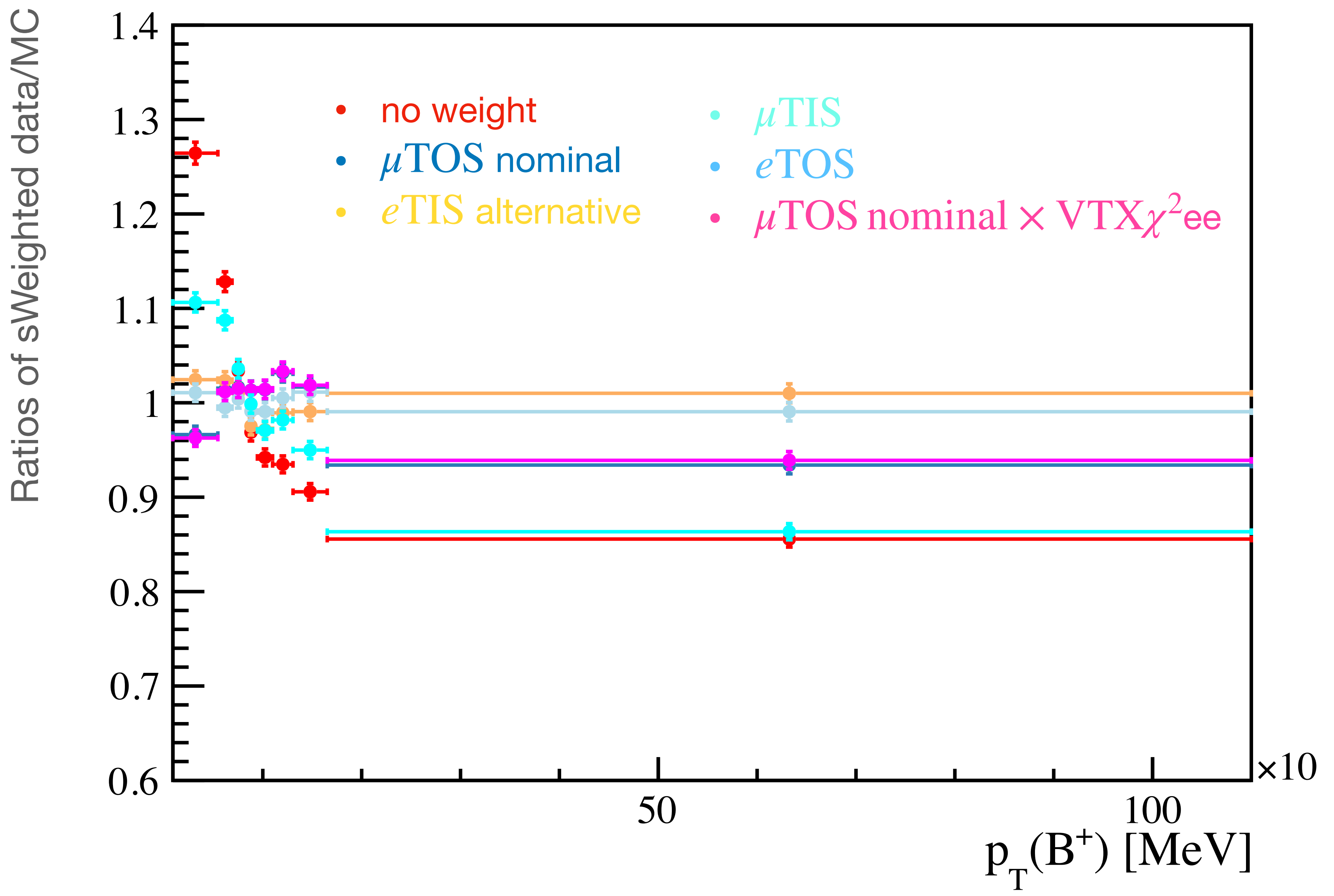
- Statistic of MC and calibration samples
    - Evaluated using bootstrapping method
- PID corrections
    - Choice of PID tables binning scheme or trigger bias evaluated requiring TIS on the probe electron
- Corrections to B/D kinematics:
    - Syst. related to the choice of reweighting scheme, evaluated varying the tags used to derive the kinematic corrections
- Occupancy systematics
    - Evaluated adding to the kinematic reweighting occupancy proxies (nPVs, nSPDHits, nTracks)
- q^2 smearing:
    - Uncertainties on the smearing parameters
- Fit model systematics
    - Variations on the model used to parametrise combinatorial events and misidentified backgrounds in the electron mode

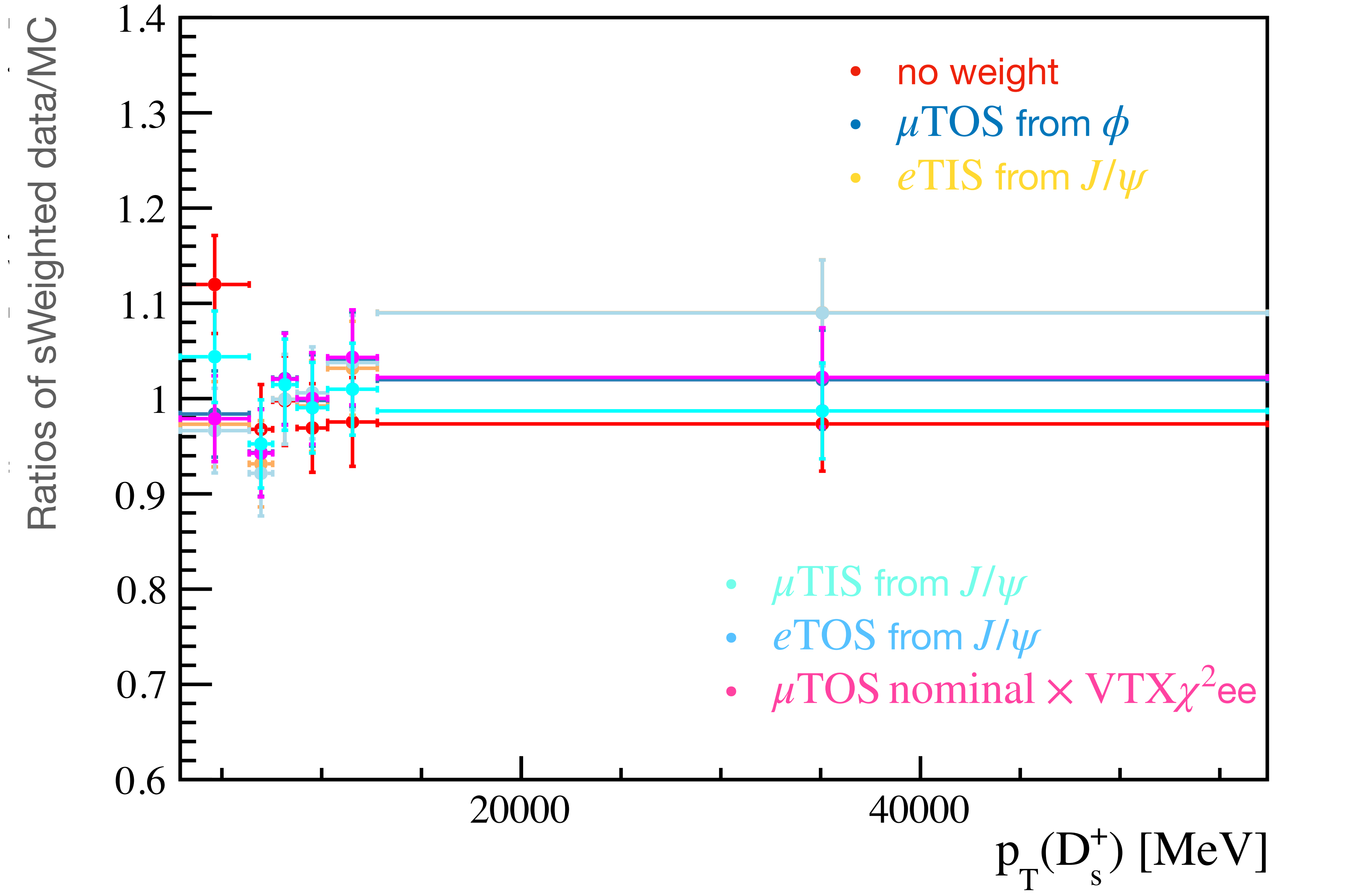




Systematics

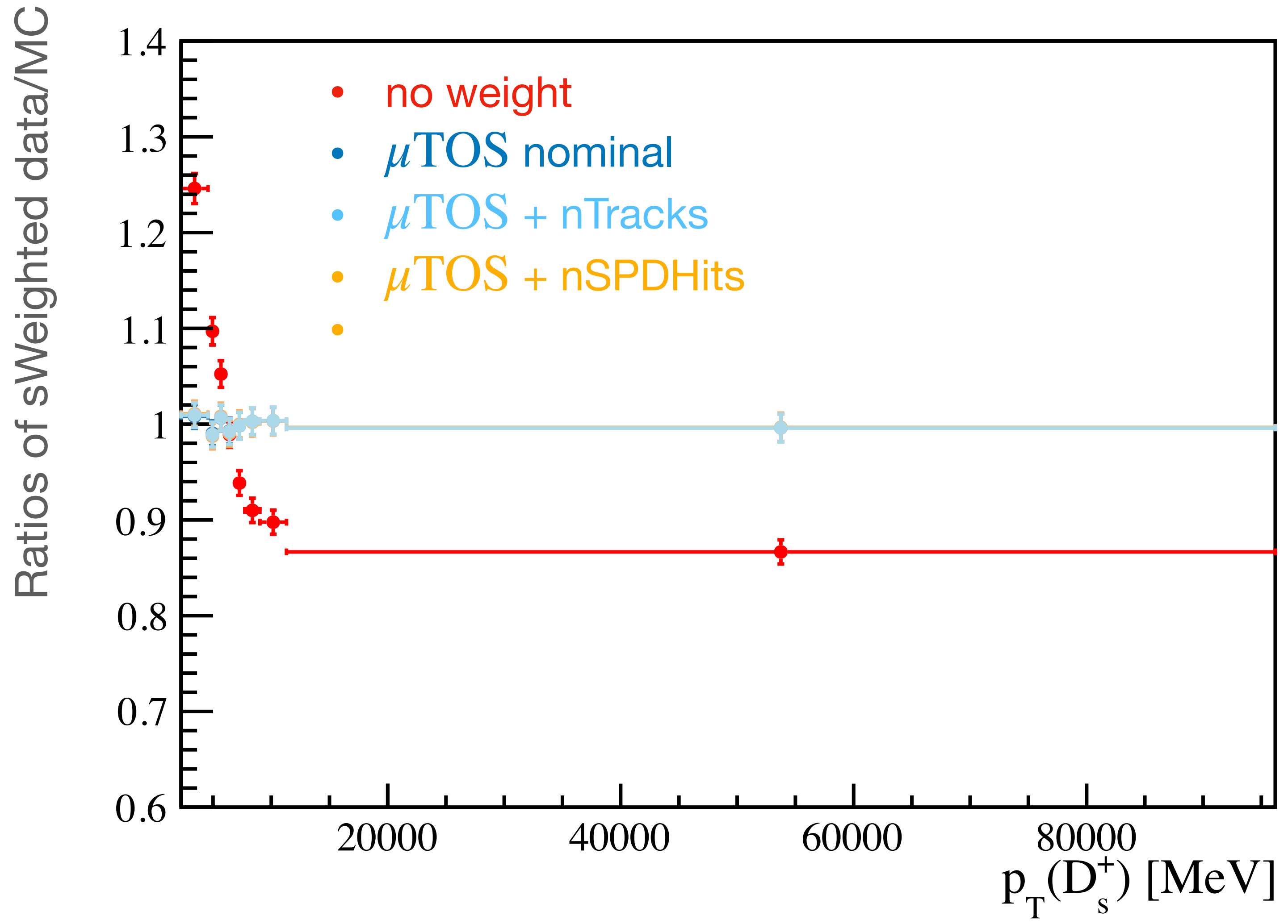
- Statistic of MC and calibration samples
  - Evaluated using bootstrapping method
- PID corrections
  - Choice of PID tables binning scheme or trigger bias evaluated requiring TIS on the probe electron
- Corrections to B/D kinematics:
  - Syst. related to the choice of reweighting scheme, evaluated varying the tags used to derive the kinematic corrections
- Occupancy systematics
  - Evaluated adding to the kinematic reweighting occupancy proxies (nPVs, nSPDHits, nTracks)
- q^2 smearing:
  - Uncertainties on the smearing parameters
- Fit model systematics
  - Variations on the model used to parametrise combinatorial events and misidentified backgrounds in the electron mode

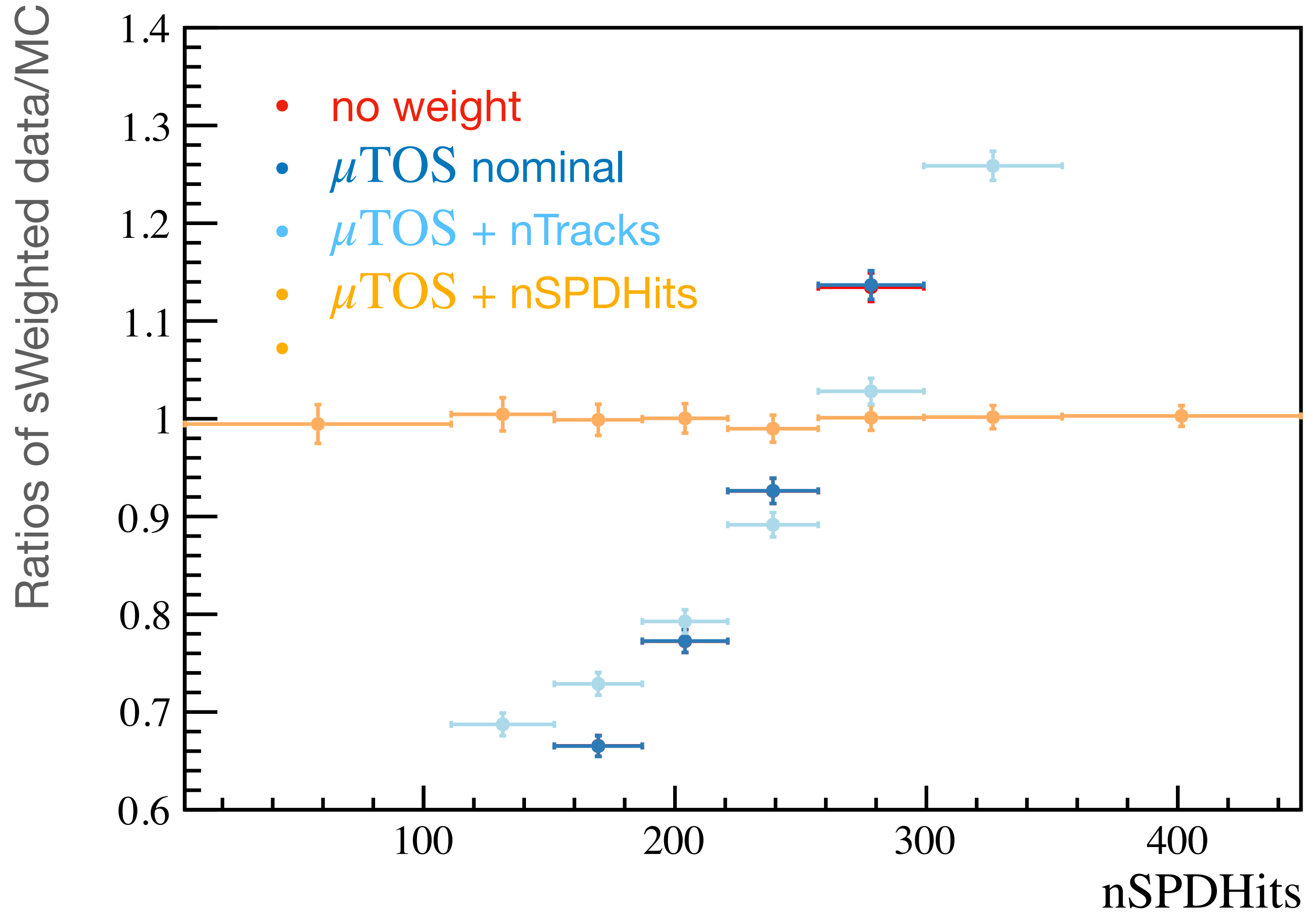




Systematics

- Statistic of MC and calibration samples
  - Evaluated using bootstrapping method
- PID corrections
  - Choice of PID tables binning scheme or trigger bias evaluated requiring TIS on the probe electron
- Corrections to B/D kinematics:
  - Syst. related to the choice of reweighting scheme, evaluated varying the tags used to derive the kinematic corrections
- Occupancy systematics
  - Evaluated adding to the kinematic reweighting occupancy proxies (nPVs, nSPDHits, nTracks)
- q^2 smearing:
  - Uncertainties on the smearing parameters
- Fit model systematics
  - Variations on the model used to parametrise combinatorial events and misidentified backgrounds in the electron mode

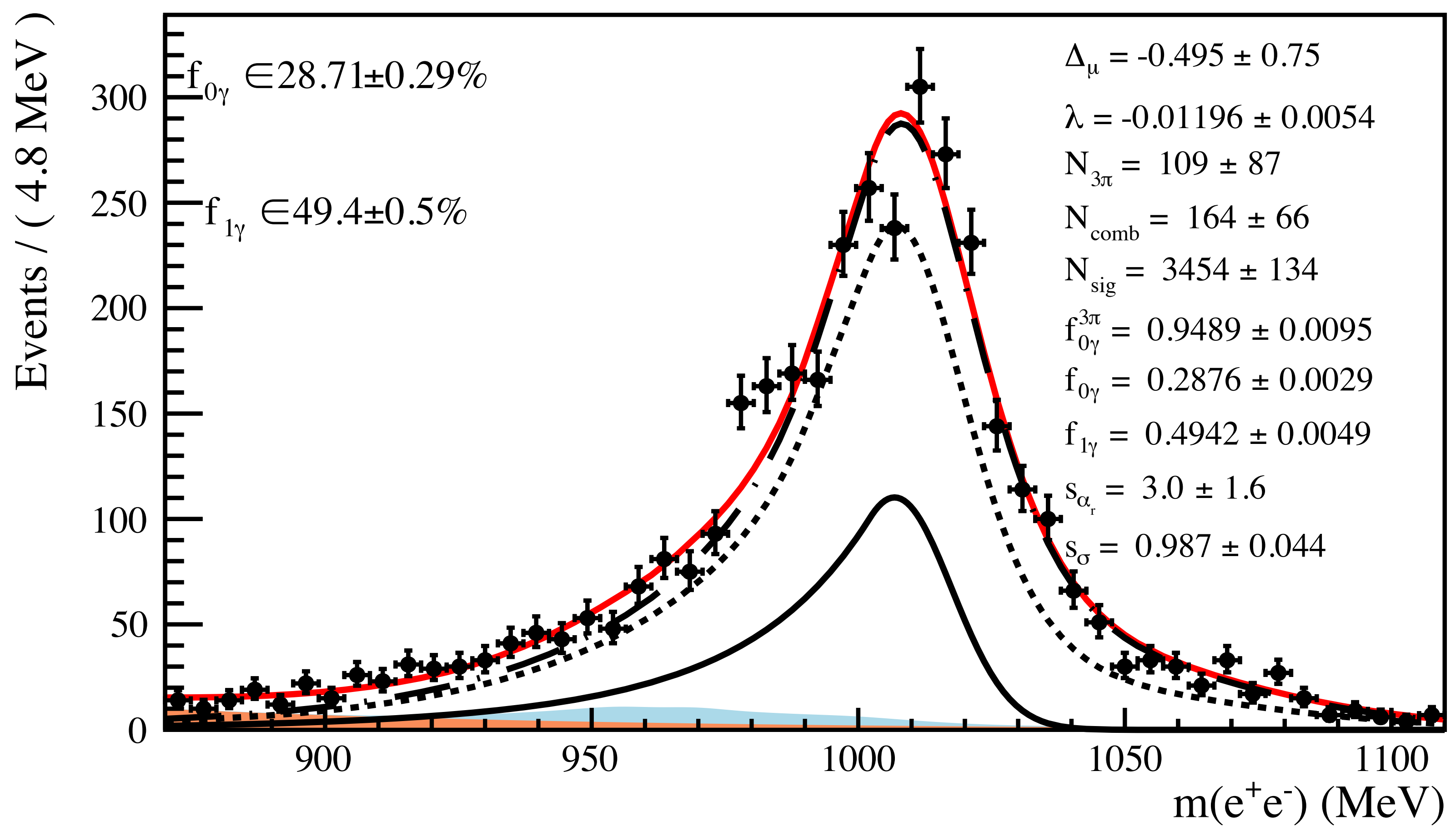




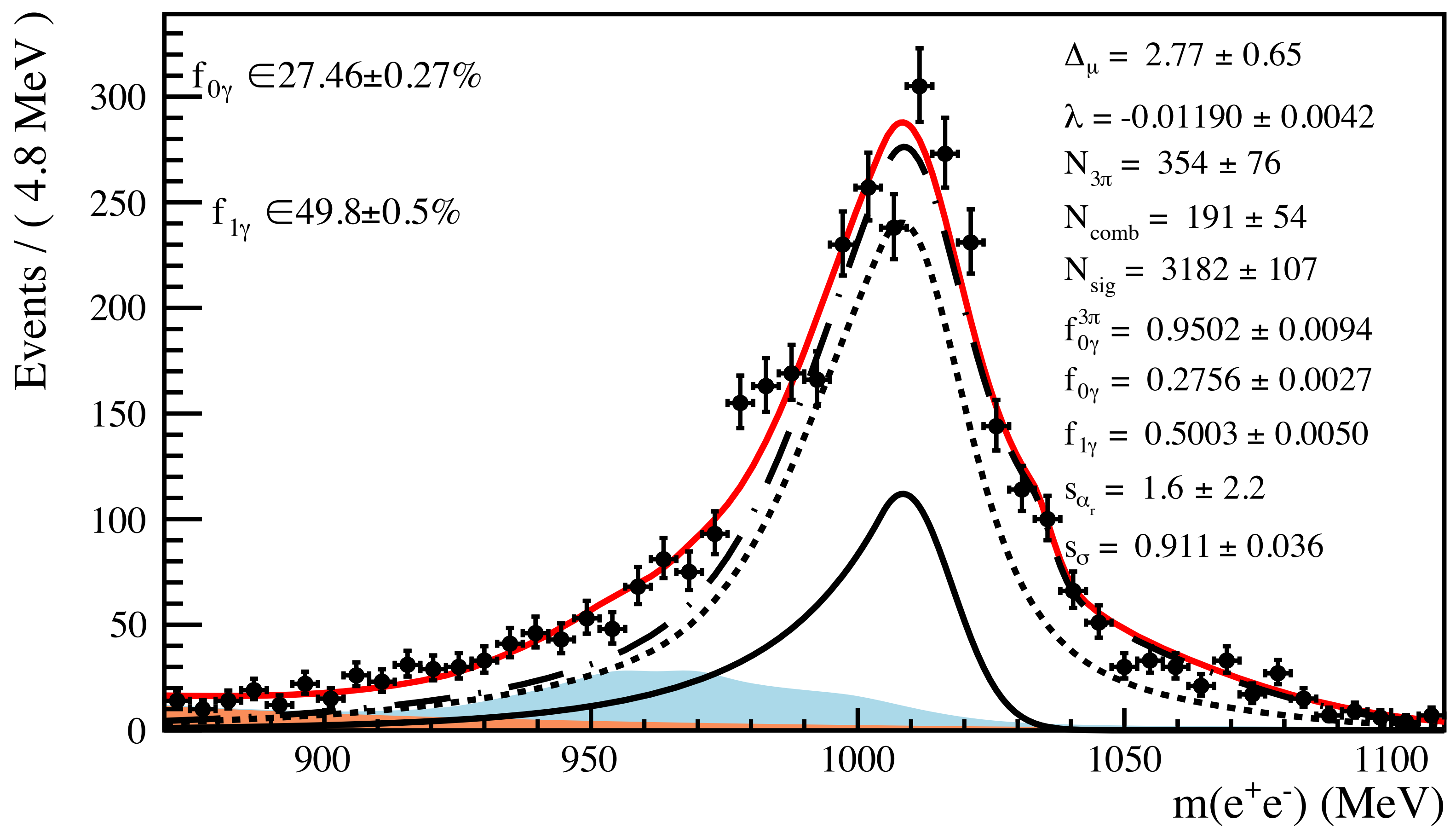
Systematics

- Statistic of MC and calibration samples
  - Evaluated using bootstrapping method
- PID corrections
  - Choice of PID tables binning scheme or trigger bias evaluated requiring TIS on the probe electron
- Corrections to B/D kinematics:
  - Syst. related to the choice of reweighting scheme, evaluated varying the tags used to derive the kinematic corrections
- Occupancy systematics
  - Evaluated adding to the kinematic reweighting occupancy proxies (nPVs, nSPDHits, nTracks)
- q^2 smearing:
  - Uncertainties on the smearing parameters, smearing parameters momentum dependent
- Fit model systematics
  - Variations on the model used to parametrise combinatorial events and misidentified backgrounds in the electron mode

nSPDHits dependent smearing



momentum dependent smearing



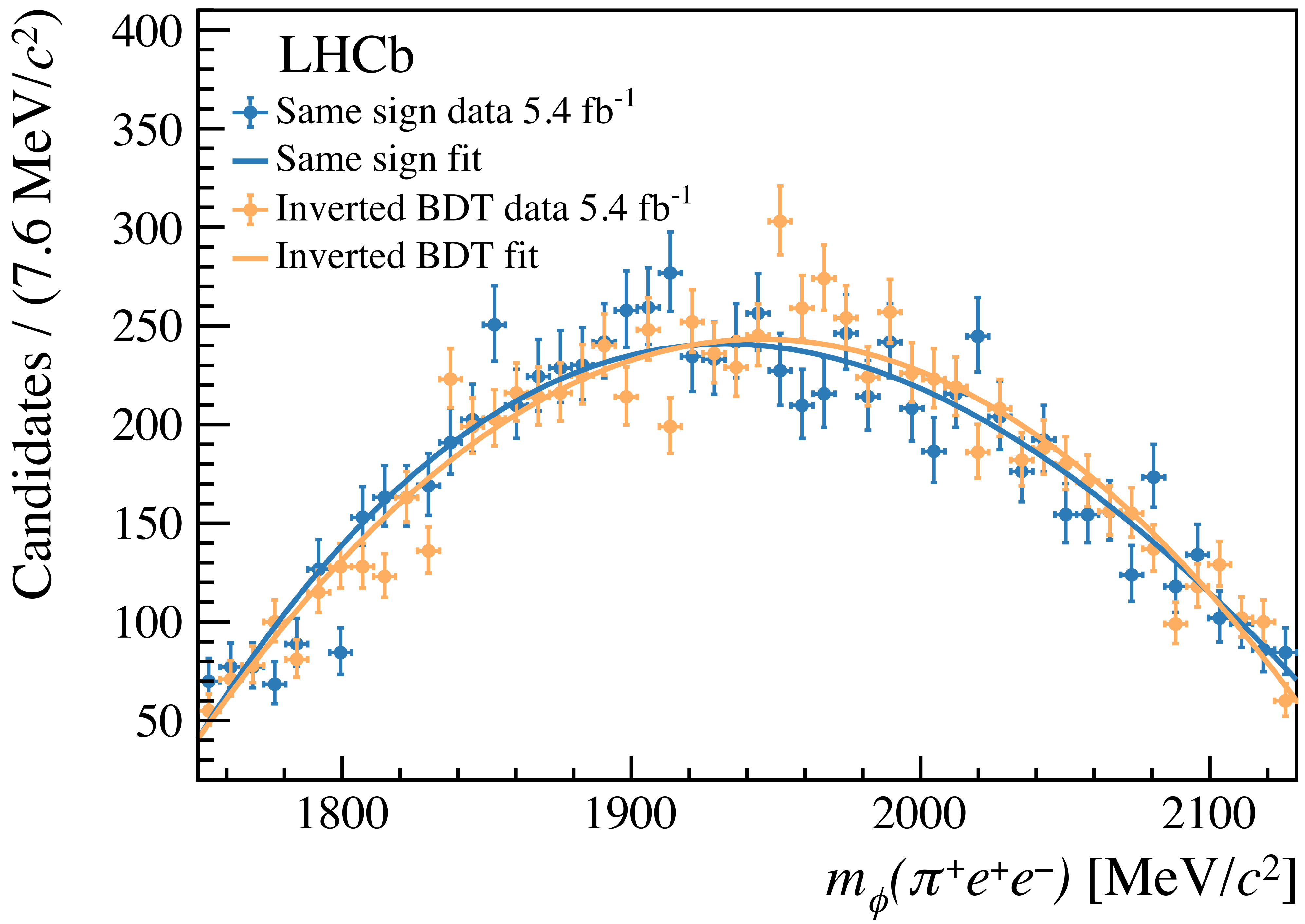
ϕ mass smearing using alternative procedures

Systematics

- Statistic of MC and calibration samples
  - Evaluated using bootstrapping method
- PID corrections
  - Choice of PID tables binning scheme or trigger bias evaluated requiring TIS on the probe electron
- Corrections to B/D kinematics:
  - Syst. related to the choice of reweighting scheme, evaluated varying the tags used to derive the kinematic corrections
- Occupancy systematics
  - Evaluated adding to the kinematic reweighting occupancy proxies (nPVs, nSPDHits, nTracks)
- q^2 smearing:
  - Uncertainties on the smearing parameters
- Fit model systematics
  - Variations on the model used to parametrise combinatorial events and misidentified backgrounds in the electron mode

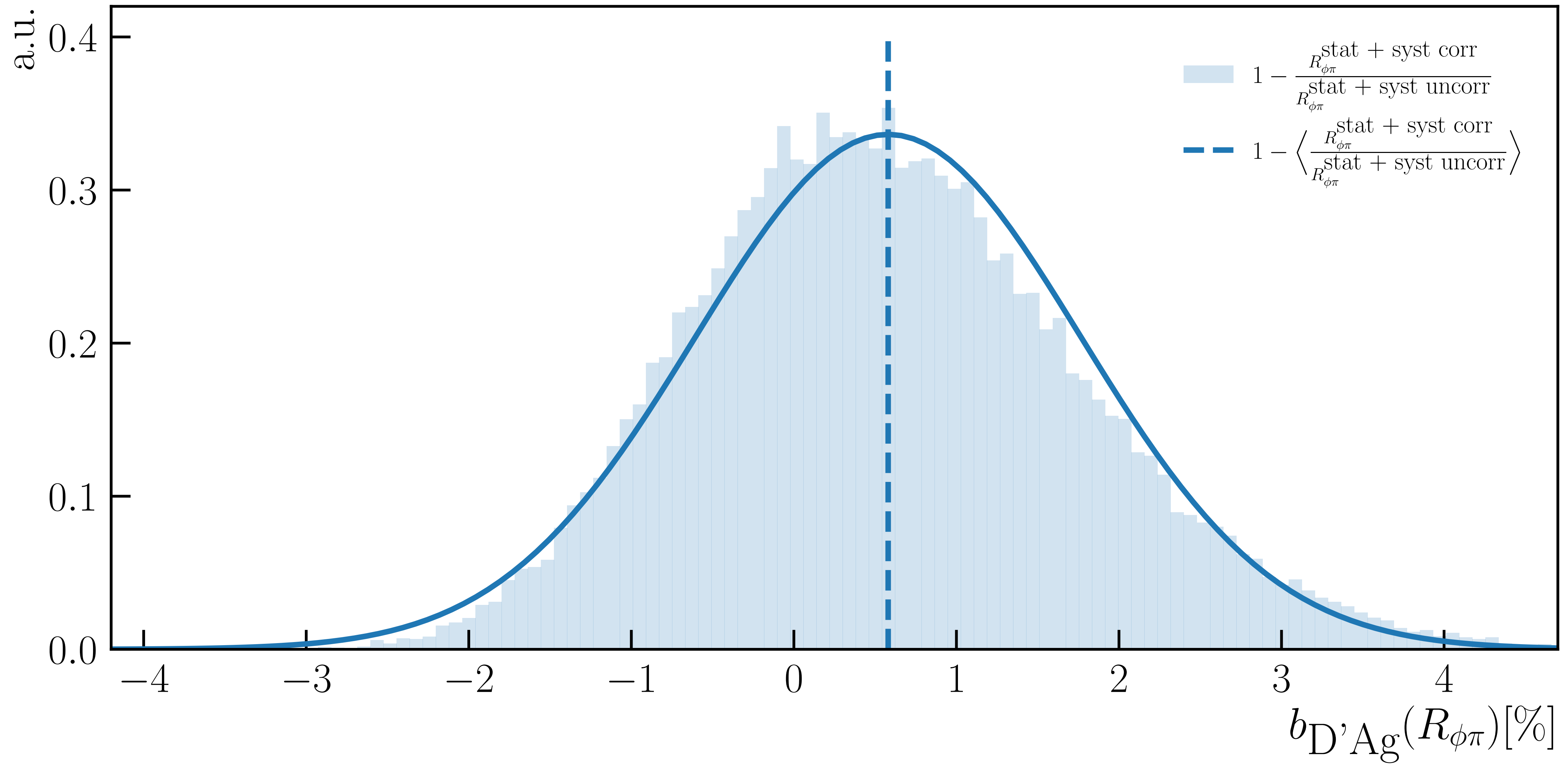
Combinatorial background systematic

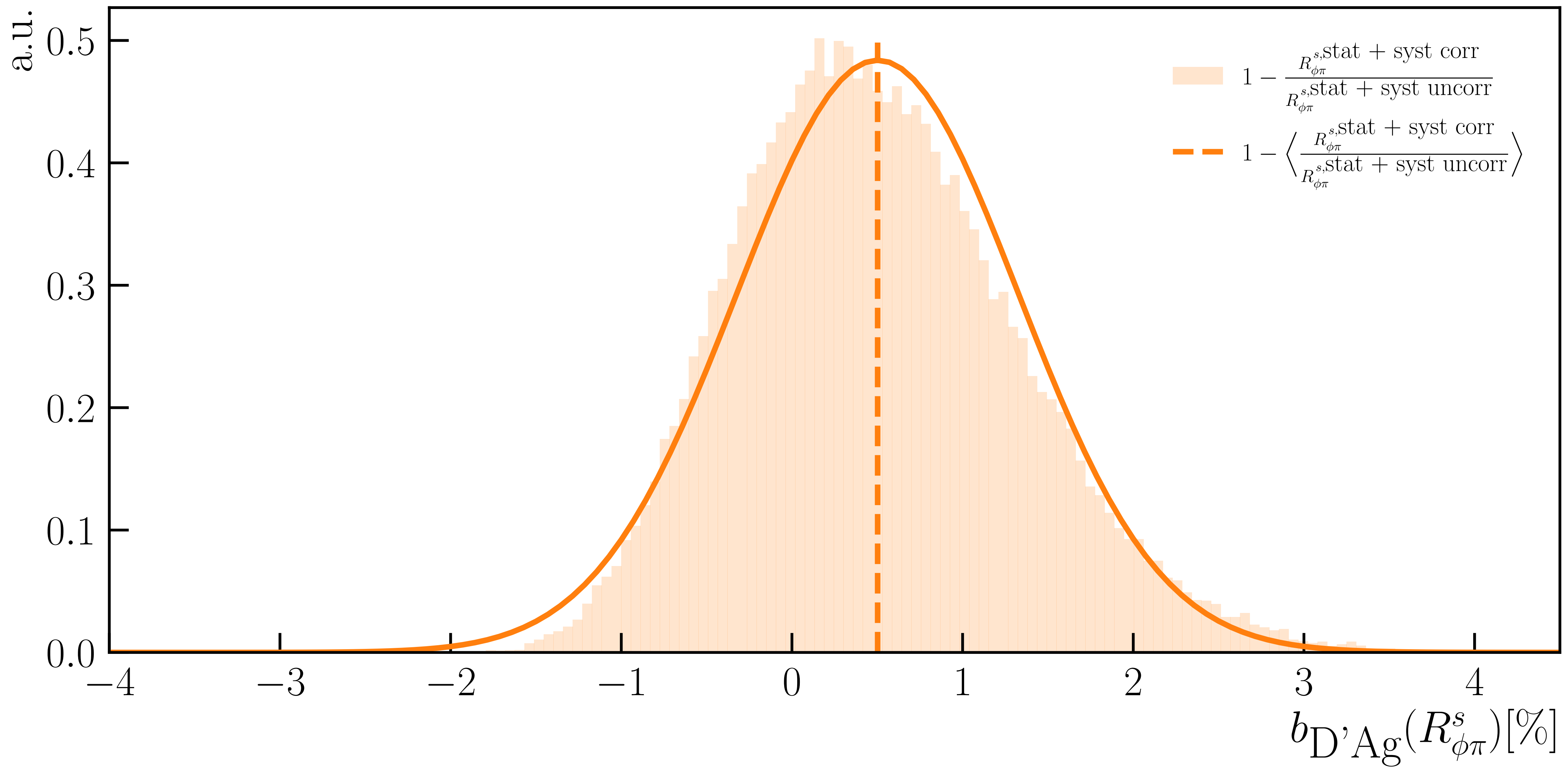
- Parametrise the combinatorial shape as a third-order Chebyshev polynomial, validated against:
    - Sample with inverted BDT requirement
    - Sample obtained from selecting final states with electrons of same charge
    - Extending the number of terms in the polynomial to 4



Combination method

- Even though measurement is not affected by D’Agostini bias, it is still systematically dominated
- Using the BLUE method to combine values in different categories yields a biased average
- This is because sizeable off diagonal matrix elements appear in the systematics covariance matrix

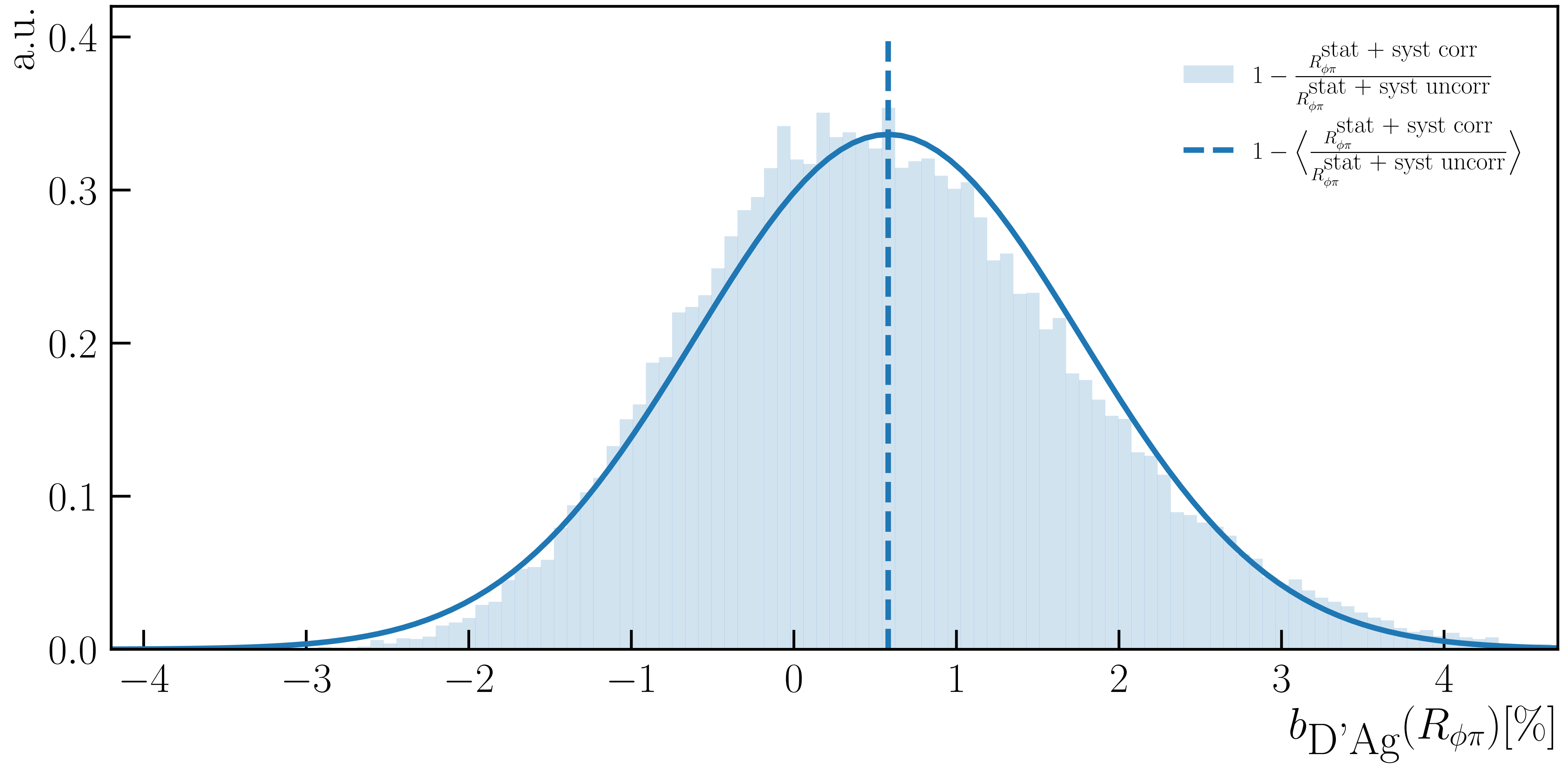


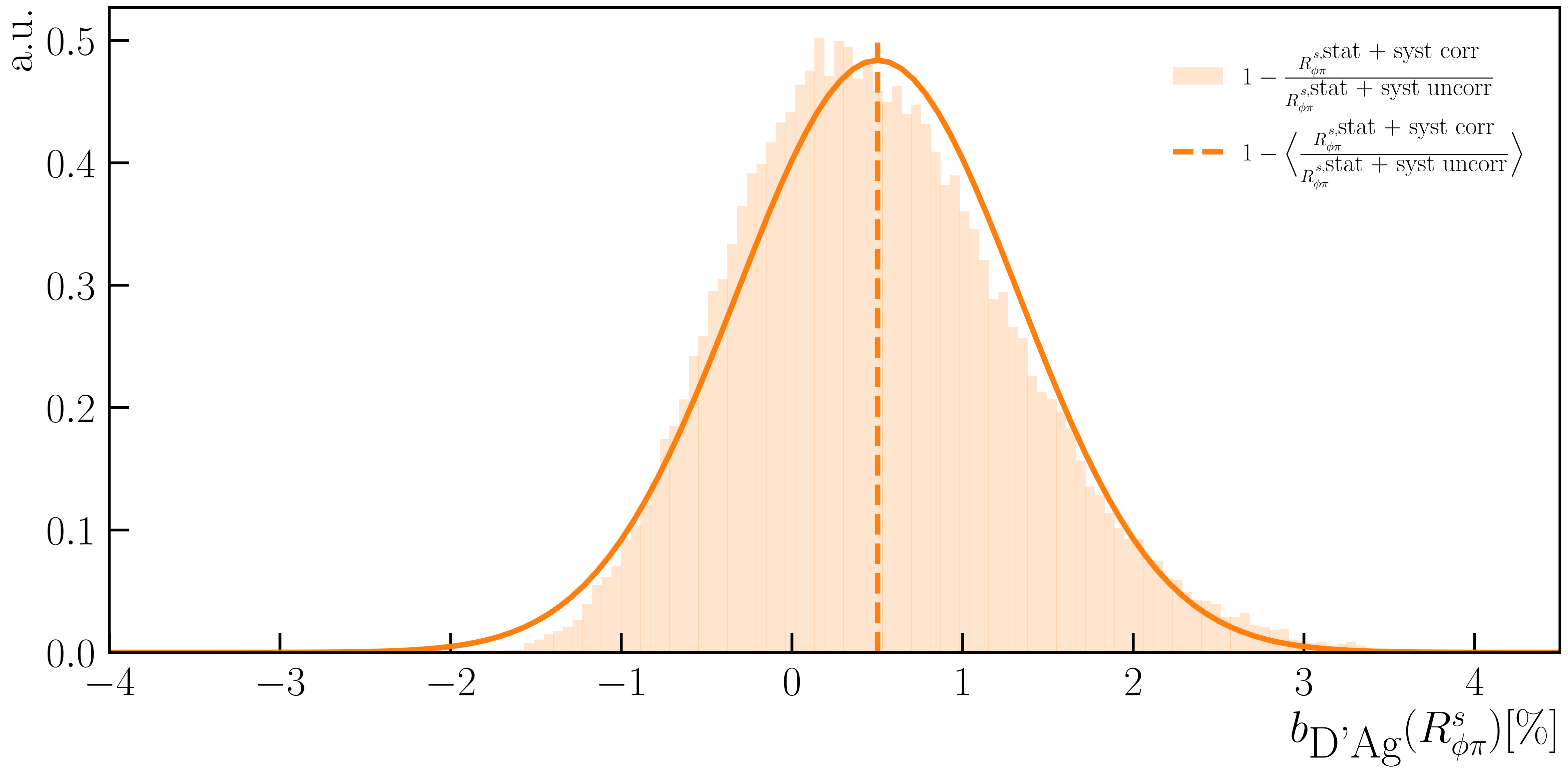


Combination method

- Even though measurement is not affected by D’Agostini bias, it is still systematically dominated
- Using the BLUE method to combine values in different categories yields a biased average
- This is because sizeable off diagonal matrix elements appear in the systematics covariance matrix

- $R_{\phi\pi}^{d(s)}$ is obtained as weighted average between the different categories
- Obtain systematic errors by averaging the combinations instead of BLUE method





Combination

- Even though measurement is not affected by D'Agostini bias, it is still systematically dominated
- Using the BLUE method to combine values in different categories yields a biased average
- This is because sizeable off diagonal matrix elements appear in the systematics covariance matrix
- Example of combination of two values of the same measurement using BLUE method