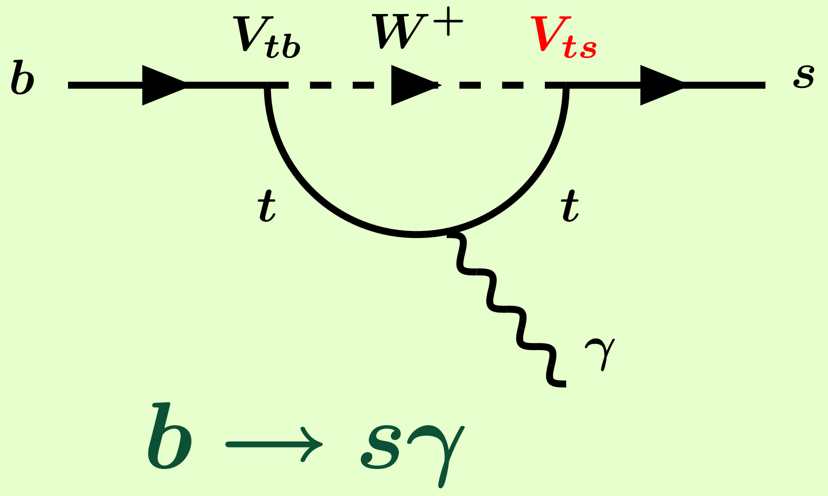
Radiative decays at Belle

- Radiative B Decays
- Belle
- Evidence for $b \longrightarrow d\gamma$
- CP asymmetry in $B \rightarrow X_s\gamma$
- Inclusive $b \longrightarrow s\gamma$ spectrum

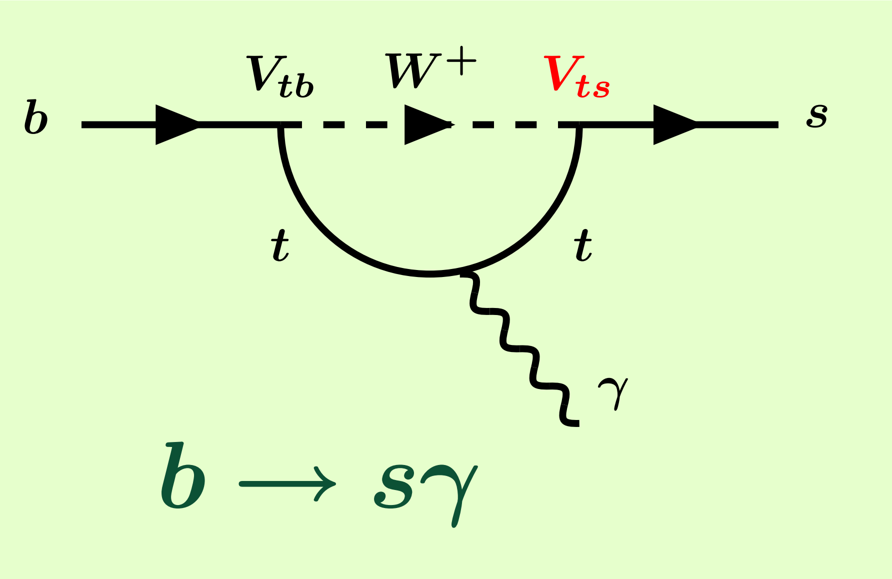
Short Introduction

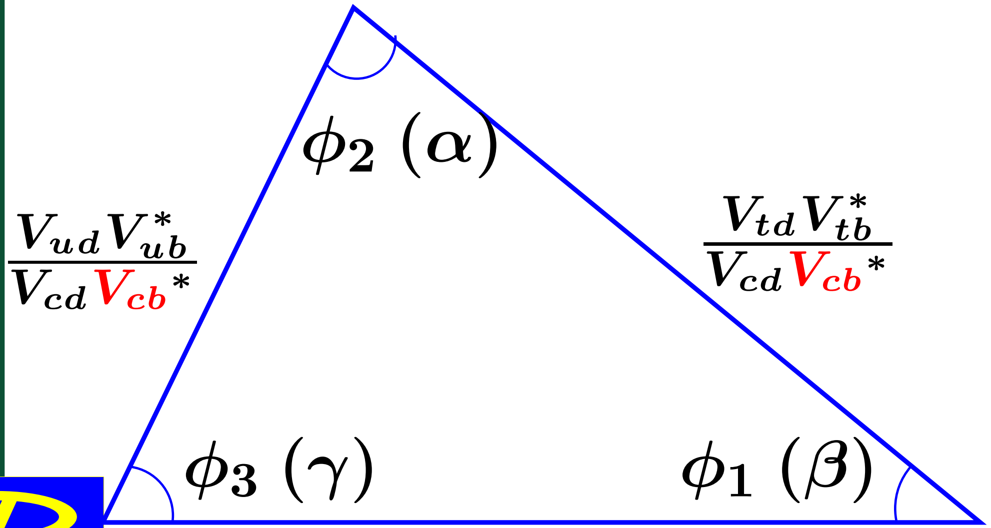


First observation of penguin decays 11 years ago by CLEO

- Used to be a hot candidate for New Physics ($|C_7|$)
- $\mathrm{BR} \simeq 3.3 \cdot 10^{-4}$ ($\simeq$ theory expectation)
- Today we enter the era of precision measurements
  - Many final states are visible (e.g. $B \to \phi K \gamma$)
  - Strong bounds on CP asymmetries ($\simeq 0$ in SM)

Short Introduction

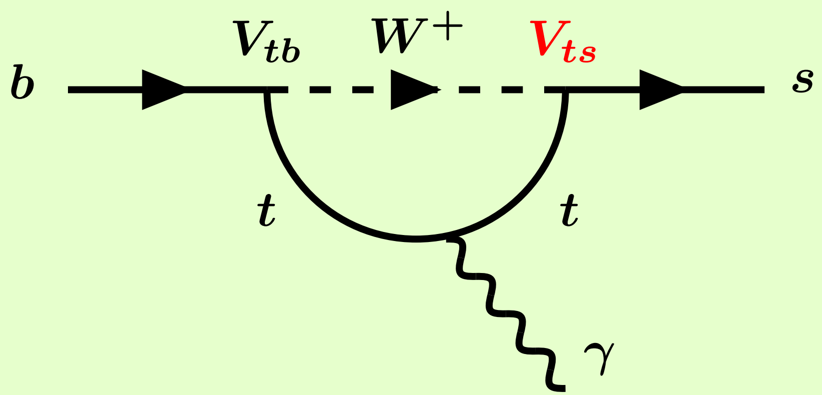




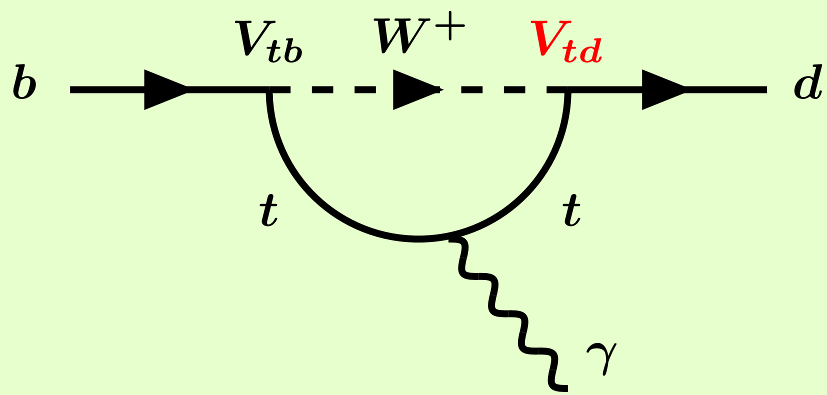
CKM-matrix:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Short Introduction



$$b \longrightarrow s\gamma$$



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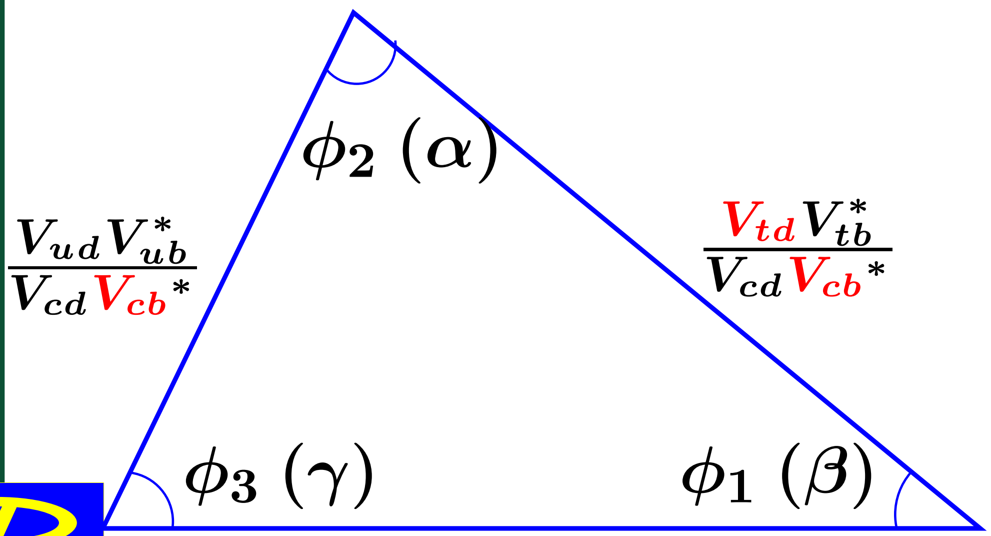

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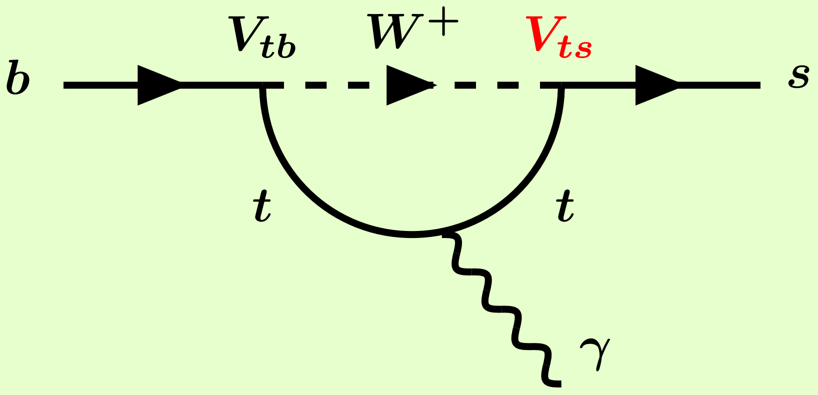
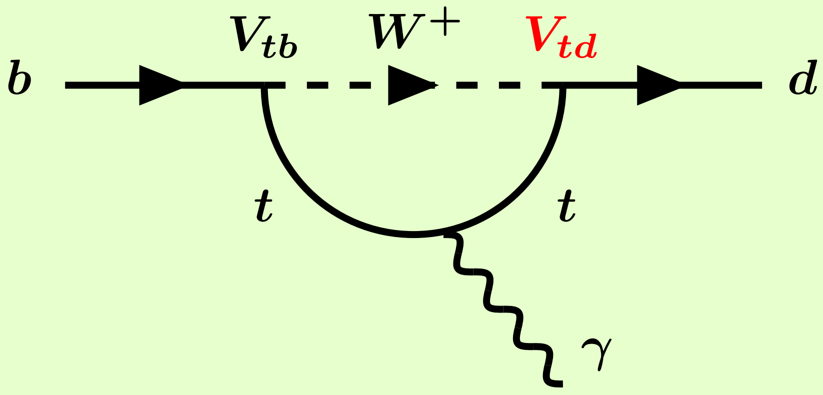


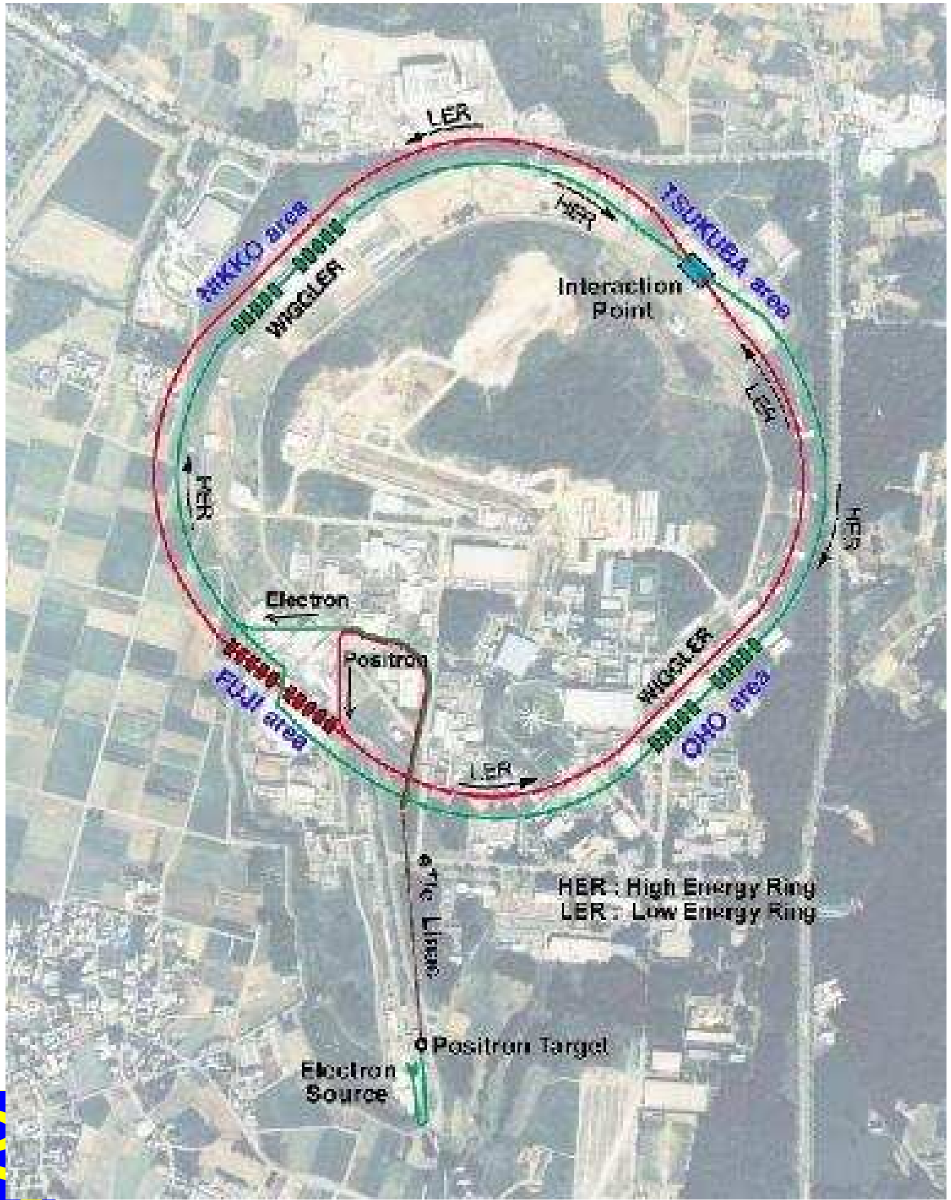
$b \to s\gamma$



$b \to d\gamma$

- Handle on $|V_{td}/V_{ts}|^2$
- Very rare (10^{-6}).

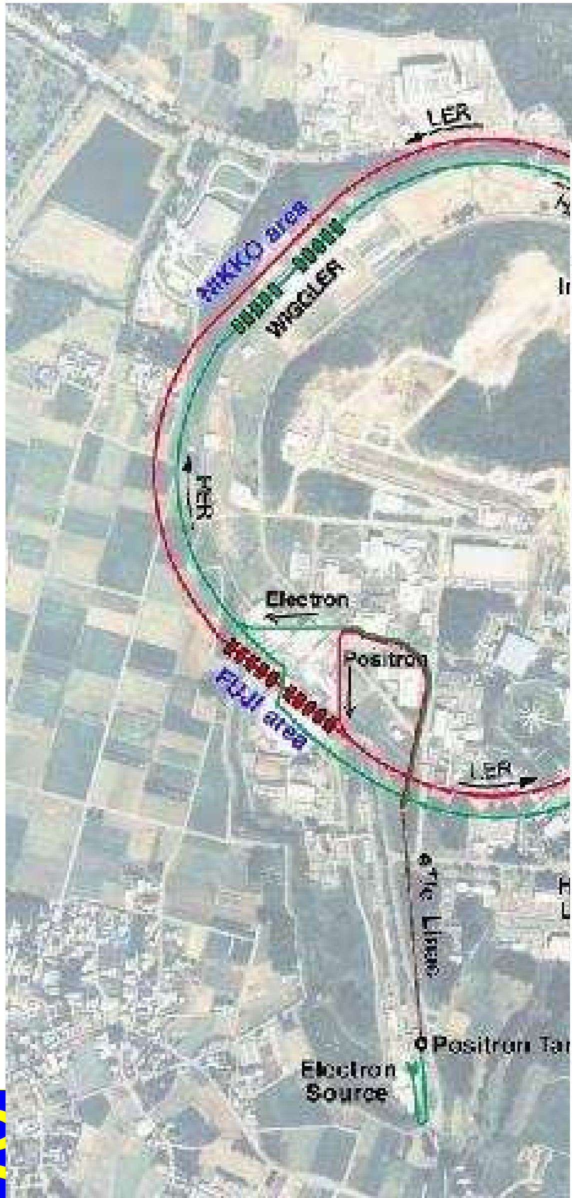
KEKB accelerator

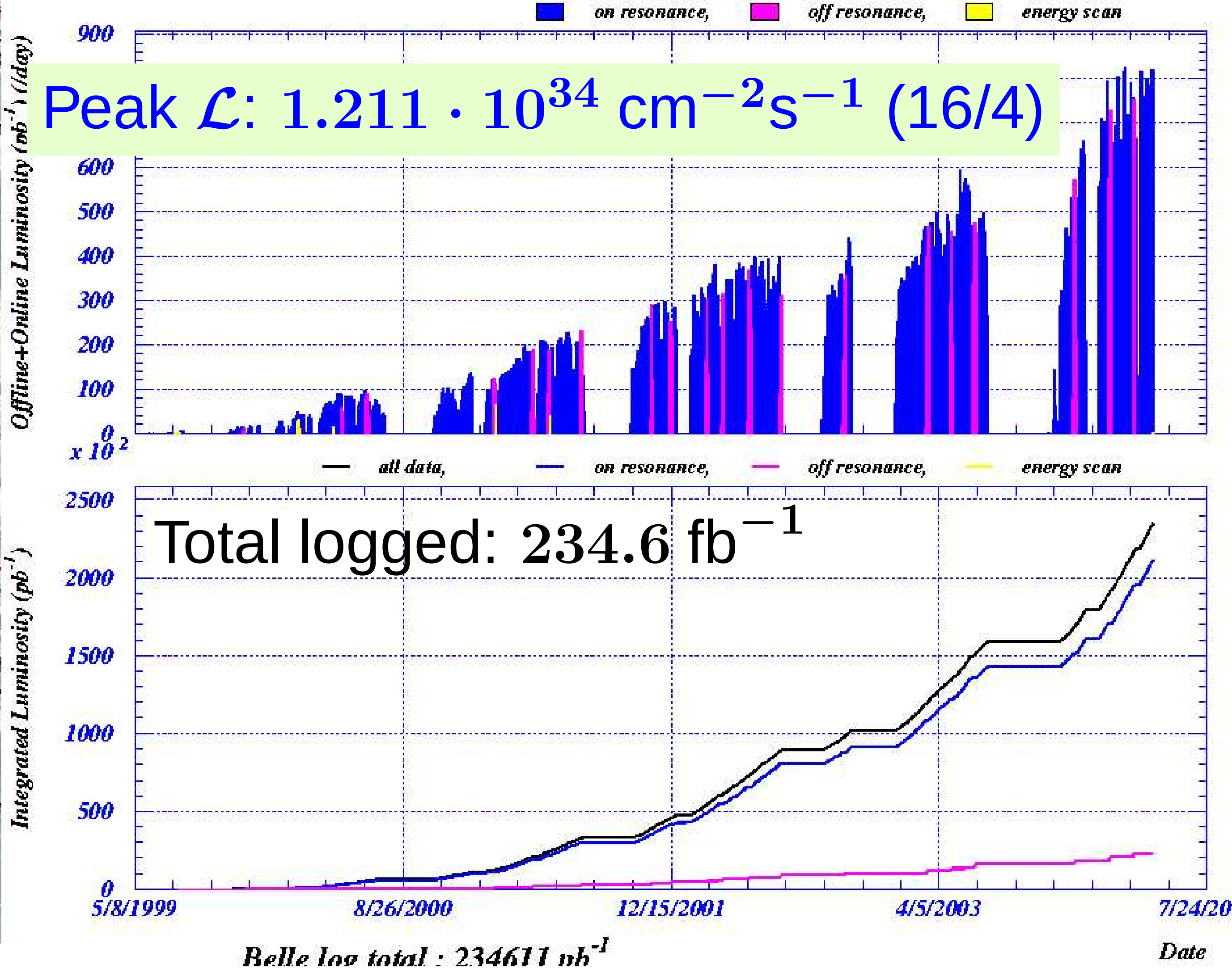


Asymmetric $(\mathbf{3.5 \oplus 8.0\,GeV})$ e^+e^- collider at the $\Upsilon(4S)$

KEKB accelerator

Asymmetric $(3.5 \oplus 8.0\ \mathrm{GeV})$
e^+e^- collider at the $\Upsilon(4S)$





Peak $\mathcal{L}$: $1.211 \cdot 10^{34}$ cm^{-2}s^{-1} (16/4)

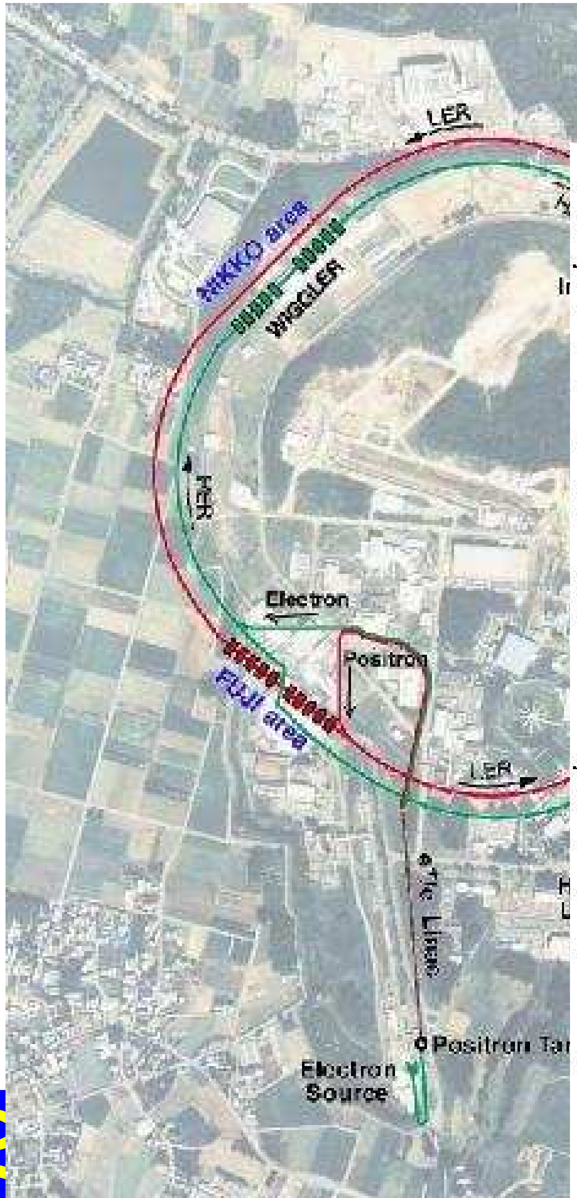
Total logged: 234.6 fb^{-1}

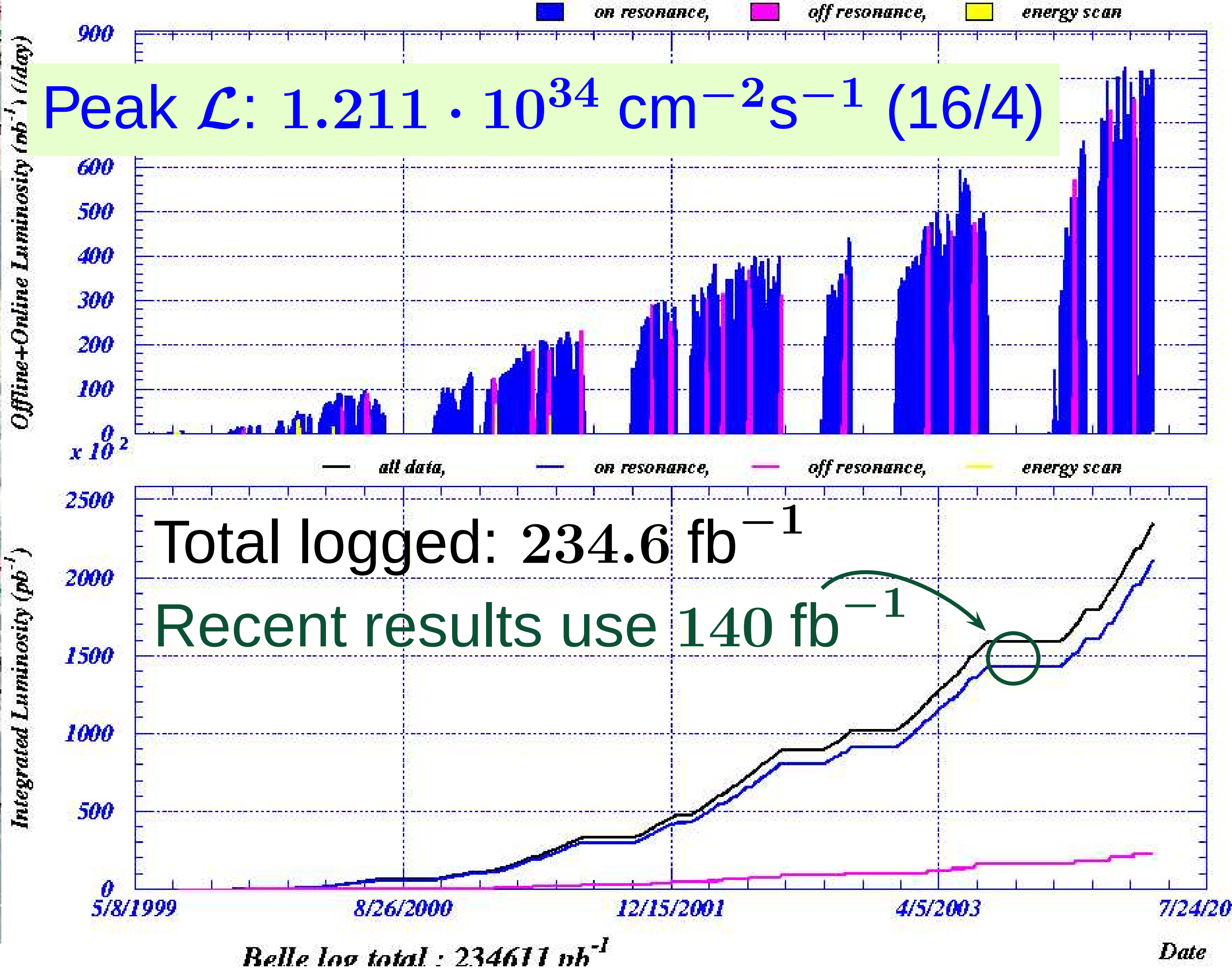
BELLE

P.Koppenburg

KEKB accelerator

Asymmetric $(3.5 \oplus 8.0\,\mathrm{GeV})$ e^+e^- collider at the $\Upsilon(4S)$



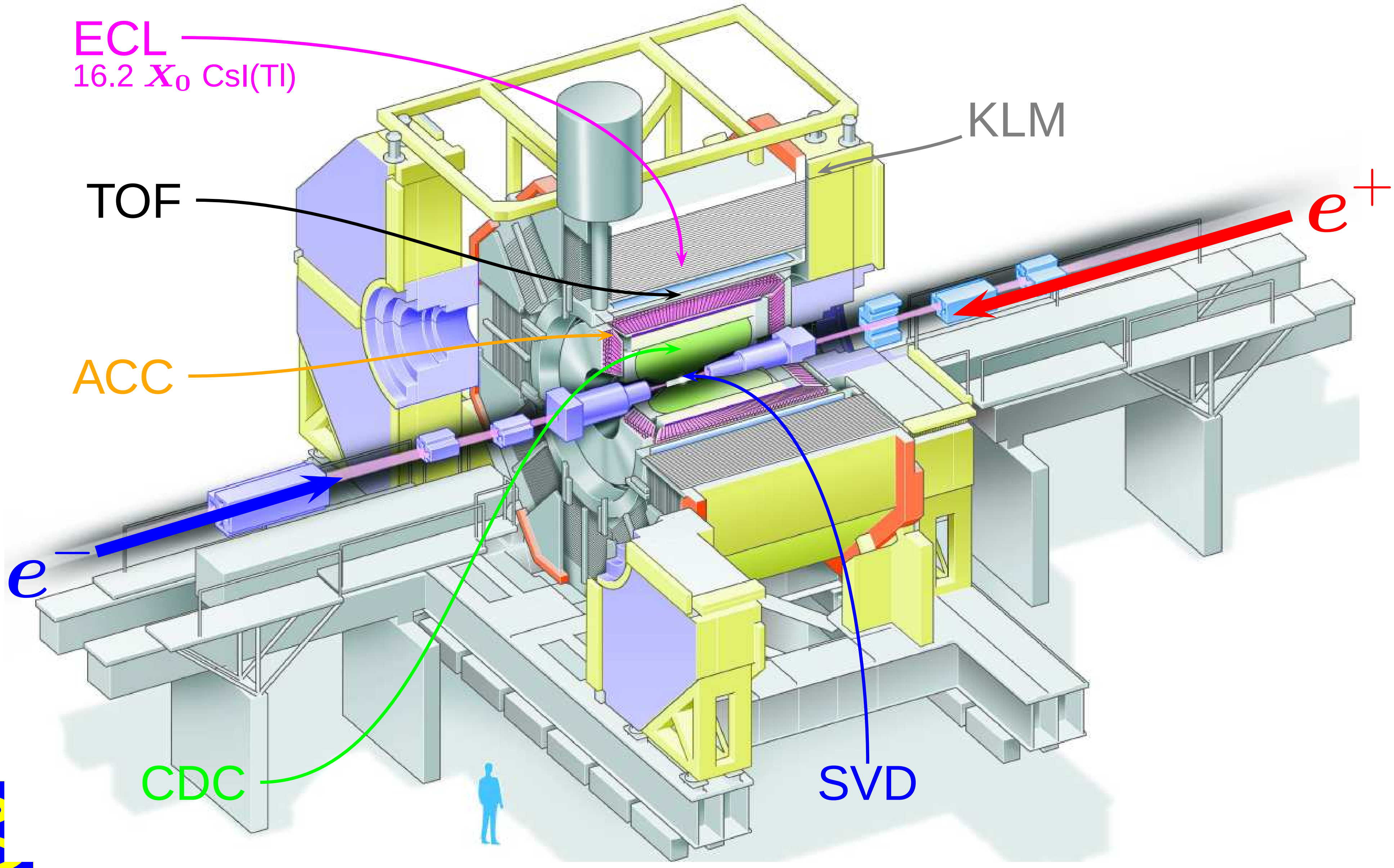


Peak $\mathcal{L}$: $1.211 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (16/4)

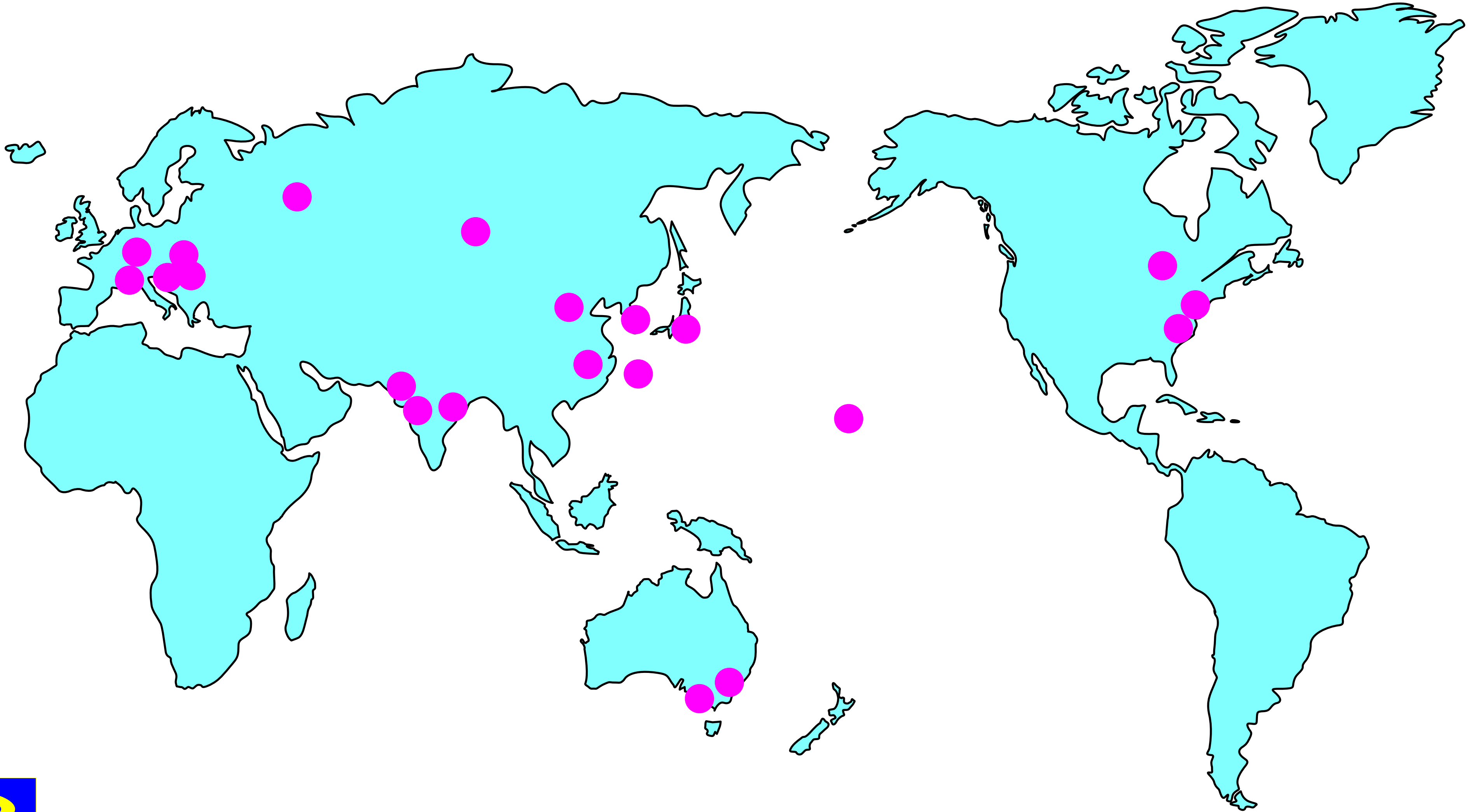
Total logged: $234.6\,\mathrm{fb}^{-1}$

Recent results use $140\,\mathrm{fb}^{-1}$

The Belle Experiment



The Belle Collaboration



Evidence for $b \longrightarrow d\gamma$

[Belle preliminary]

$B \to (\rho, \omega)\gamma$

Reconstruct and add:

- $B^0 \to \rho^0(\pi^+\pi^-)\gamma$,
- $B^+ \to \rho^+(\pi^+\pi^0)\gamma$,
- $B^0 \to \omega(\pi^+\pi^-\pi^0)\gamma$

- SM expectations: $\sim 1 \cdot 10^{-6}$
- Exp. limits: $\sim 1\text{–}2 \cdot 10^{-6}$

$\longrightarrow$ Around the corner

Assuming isospin invariance [Ali et al, ZPC 6, 437]:

$$\begin{aligned}
\mathrm{BR}(B \to (\rho,\omega)\gamma) &\doteqdot \mathrm{BR}(B^+ \to \rho^+\gamma) \\
&= 2\frac{\tau_{B^+}}{\tau_{B^0}}\mathrm{BR}(B^0 \to \rho^0\gamma) \\
&= 2\frac{\tau_{B^+}}{\tau_{B^0}}\mathrm{BR}(B^0 \to \omega\gamma)
\end{aligned}$$

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- $B^0 \to \omega(\pi^+\pi^-\pi^0)\gamma$

- SM expectations: $\sim 1 \cdot 10^{-6}$
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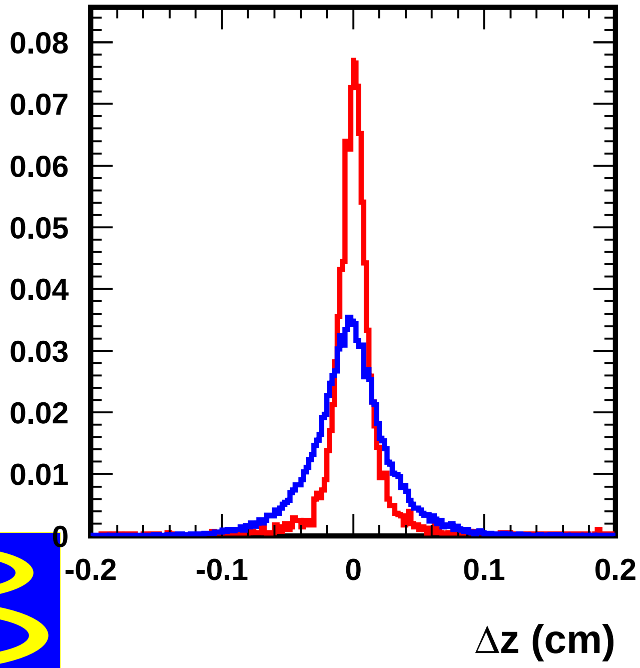
$\longrightarrow$ Around the corner

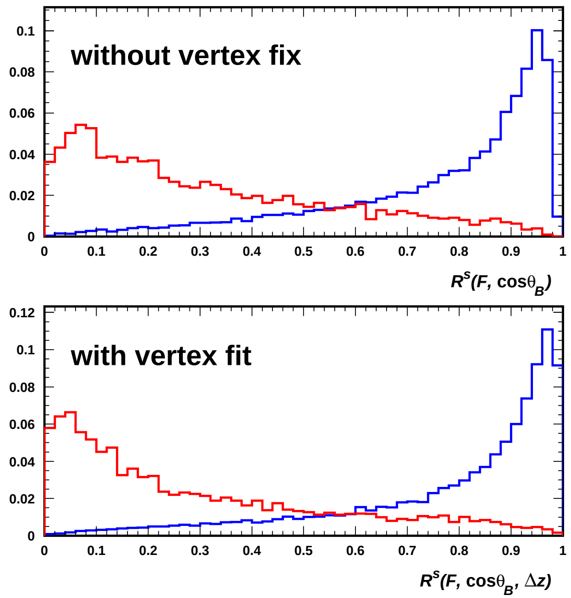
- Use isolated γ that don't form a π^0 or a η when combined with another photon
- Use charged tracks clearly identified as π
- $\pi^0 \to \gamma\gamma$ (within 3σ, forced to π^0 mass)

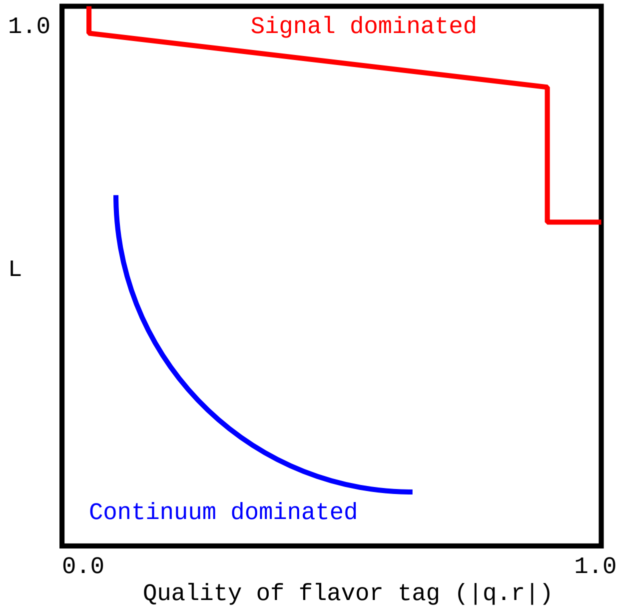
$B \to (\rho, \omega)\gamma$ continuum background

Continuum (u,d,s,c) background (75% at $\Upsilon(4S)$):

- events are more jetty $\longrightarrow$ Improved Super-Fox-Wolfram
- vertex position is more centred (B flight)
- quality of flavour tag is poorer



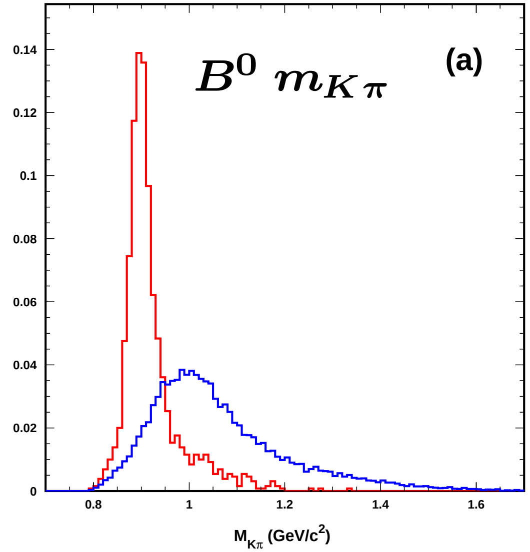


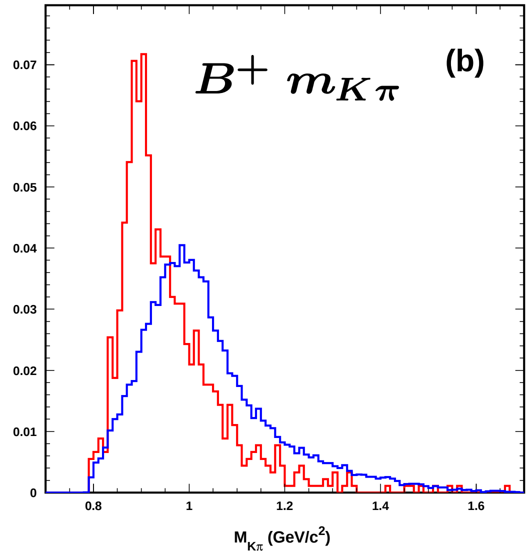


$B \to (\rho, \omega)\gamma$ specific backgrounds

$B \to \rho\gamma$ and $B \to K^*\gamma$ MC:

- $m_{K^+\pi^-} > 0.96\ \mathrm{GeV}/c^2$
- $m_{K^+\pi^0} > 0.92\ \mathrm{GeV}/c^2$





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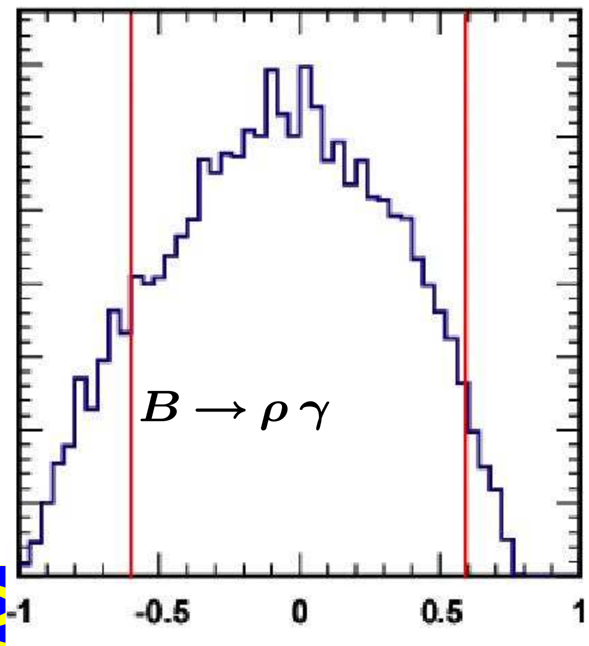
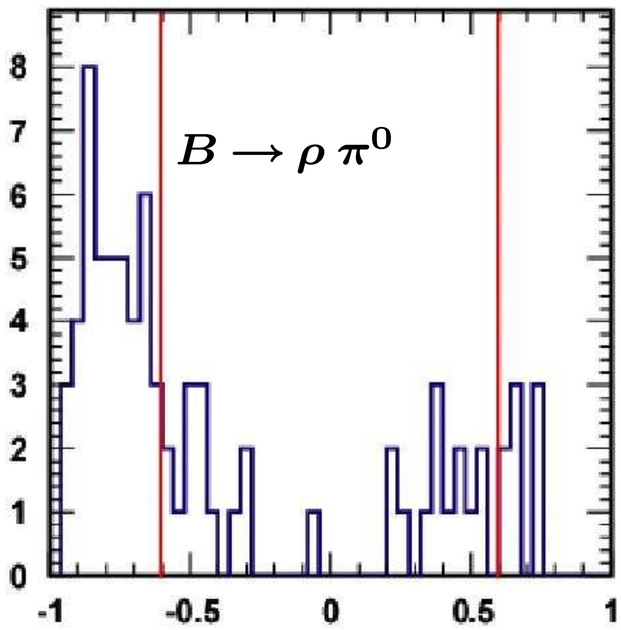
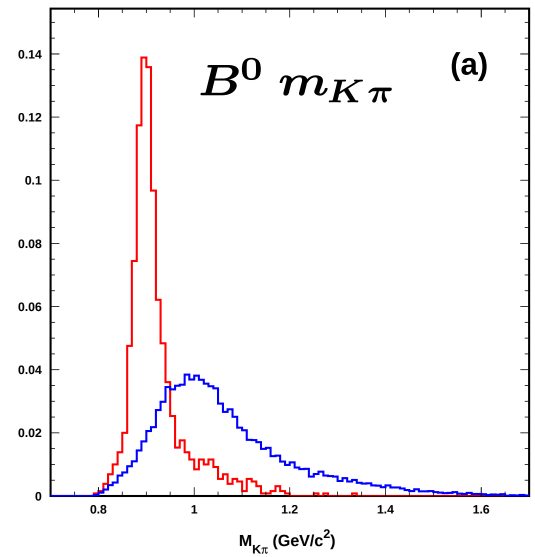
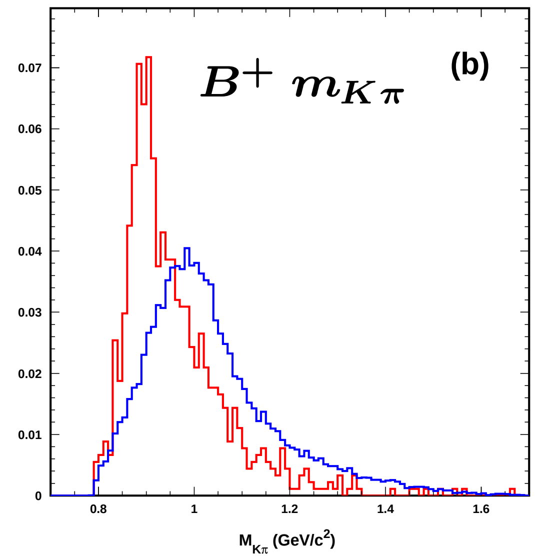
$B \to \rho\pi^0$: Apply helicity cut.

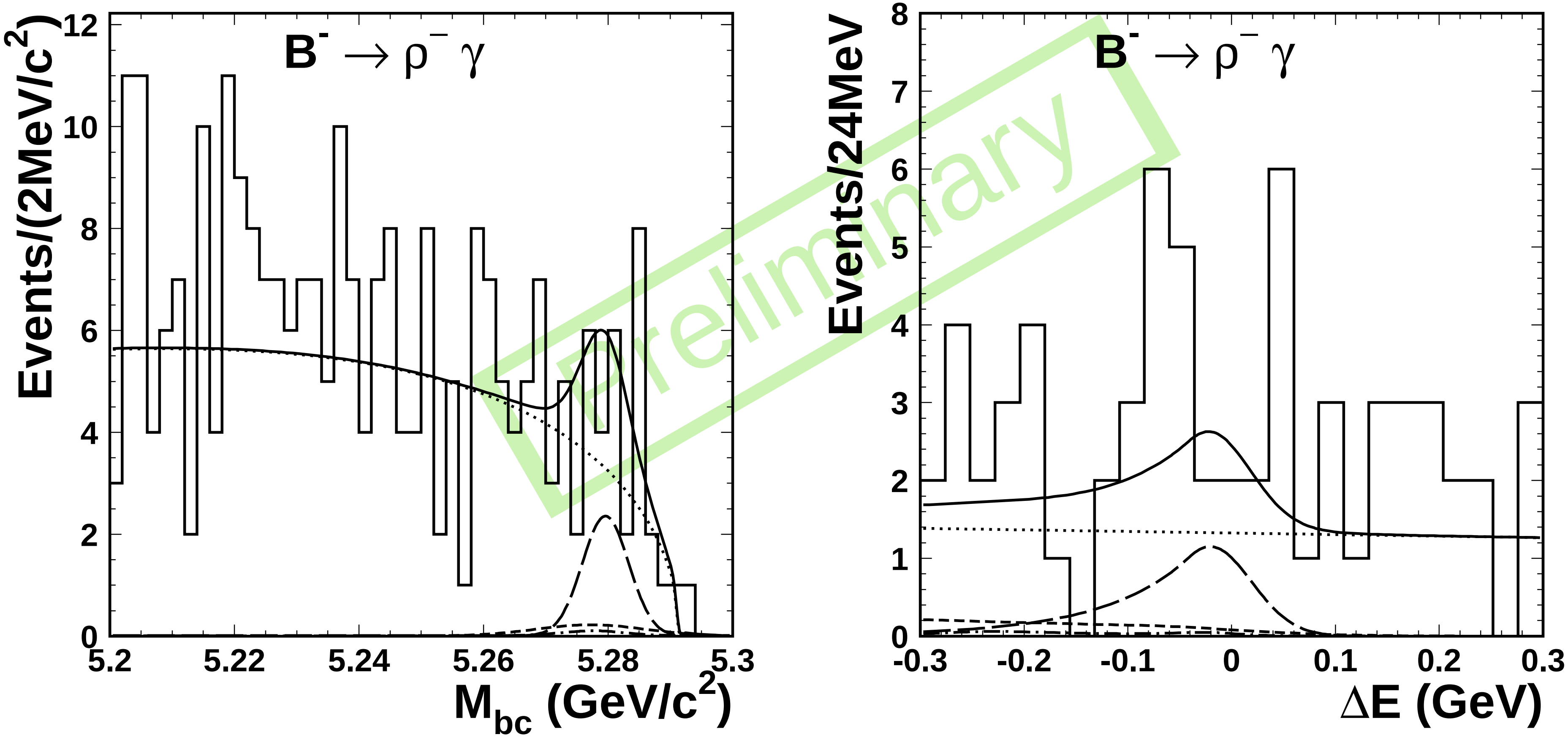








$B \to (\rho, \omega)\gamma$: Fit results



$$M_{\text{bc}} = \sqrt{{E^*_{\text{beam}}}^2 - p_B^2}$$
$$\Delta E = E^*_B - E^*_{\text{beam}}$$

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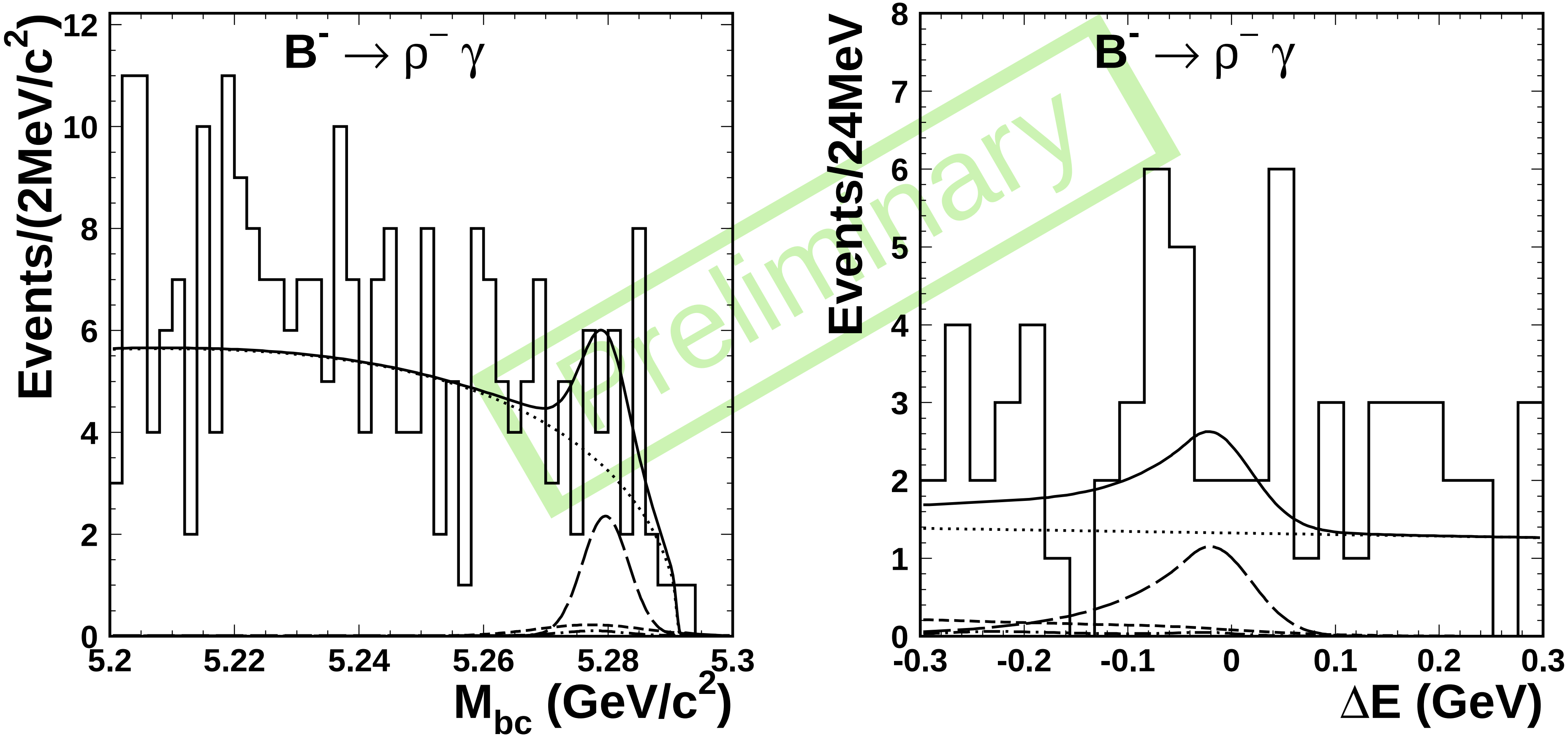
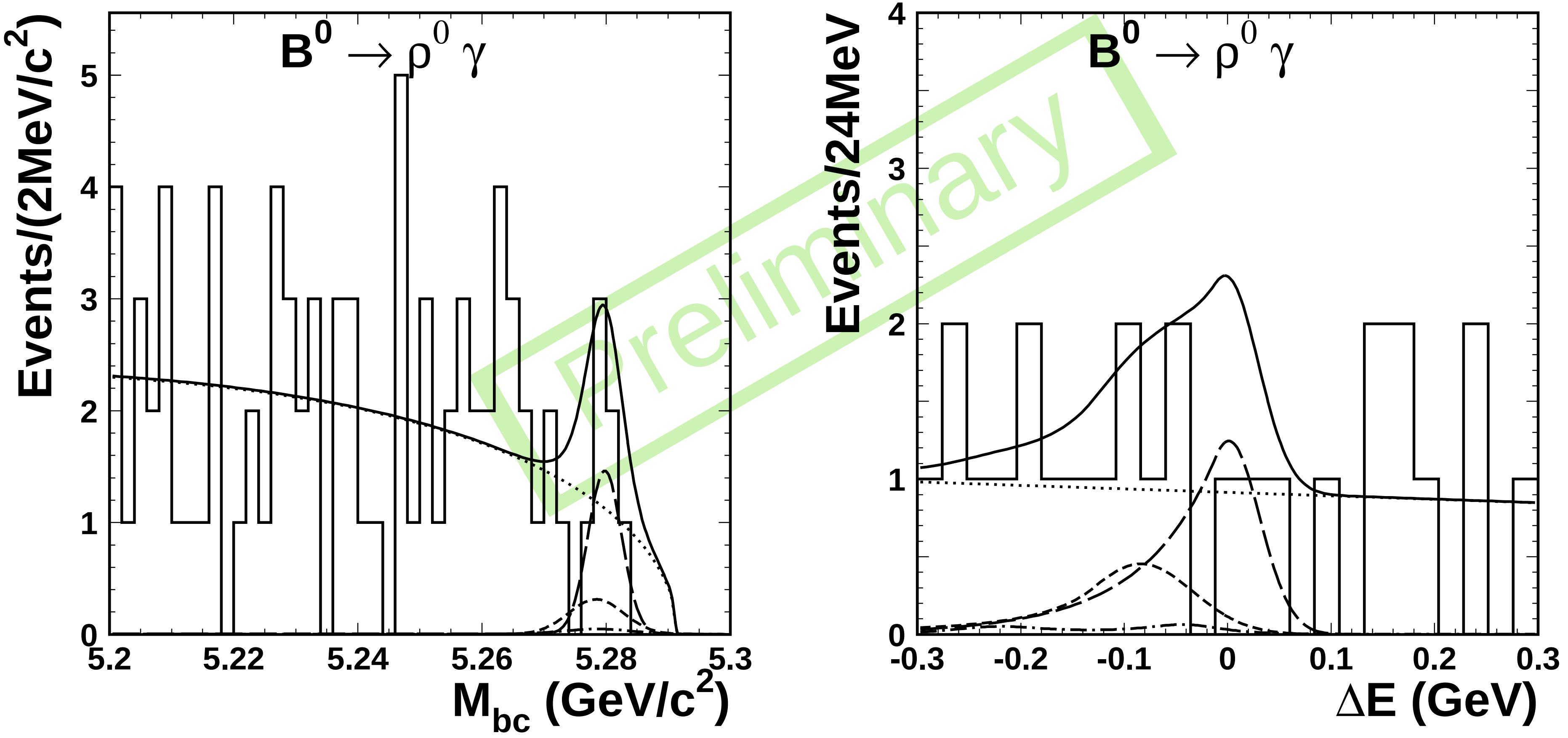


$B^+ \to \rho^+\gamma$

1D-projection of simultaneous 2D fit

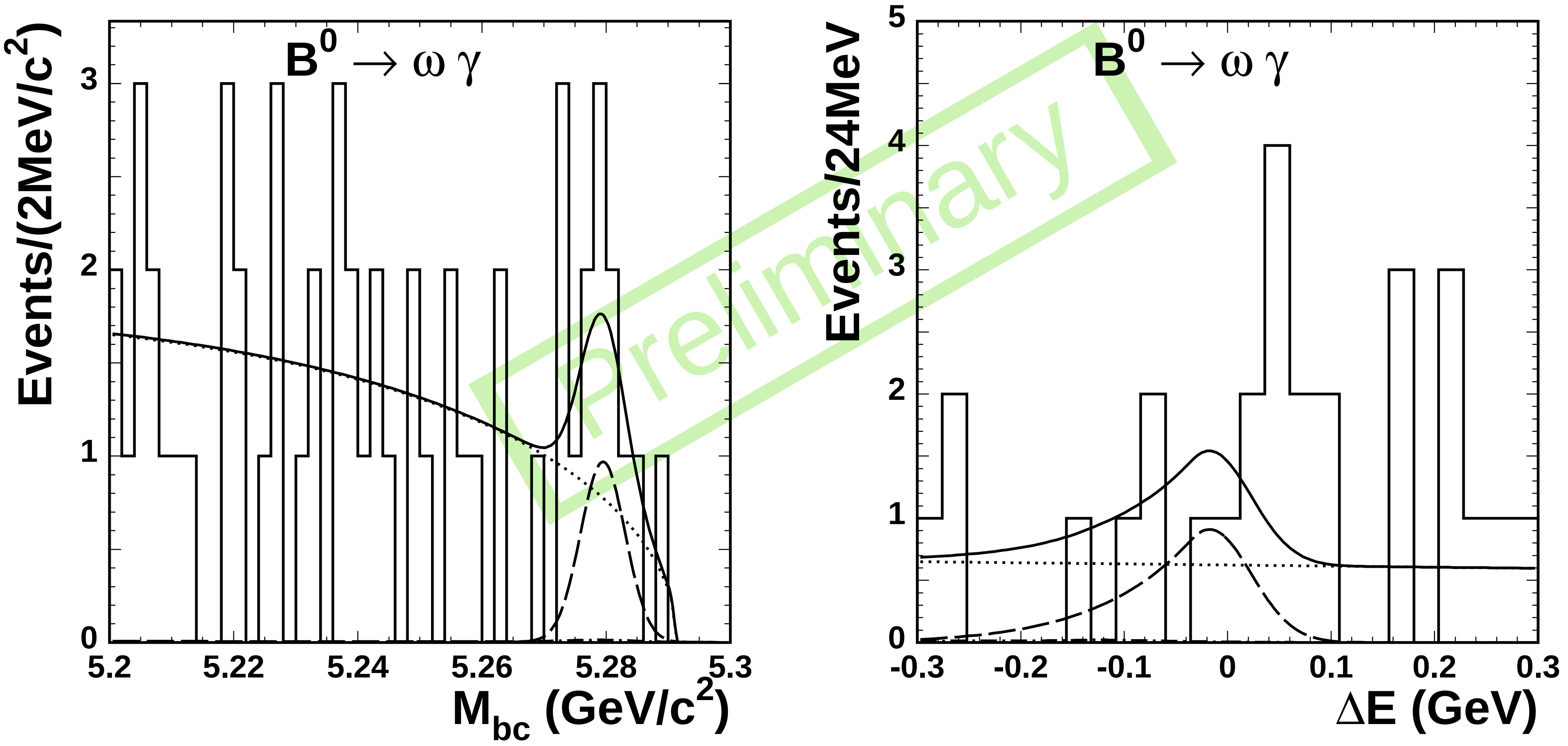
$B \to (\rho, \omega)\gamma$: Fit results



$B^0 \to \rho^0\gamma$

1D-projection of simultaneous 2D fit

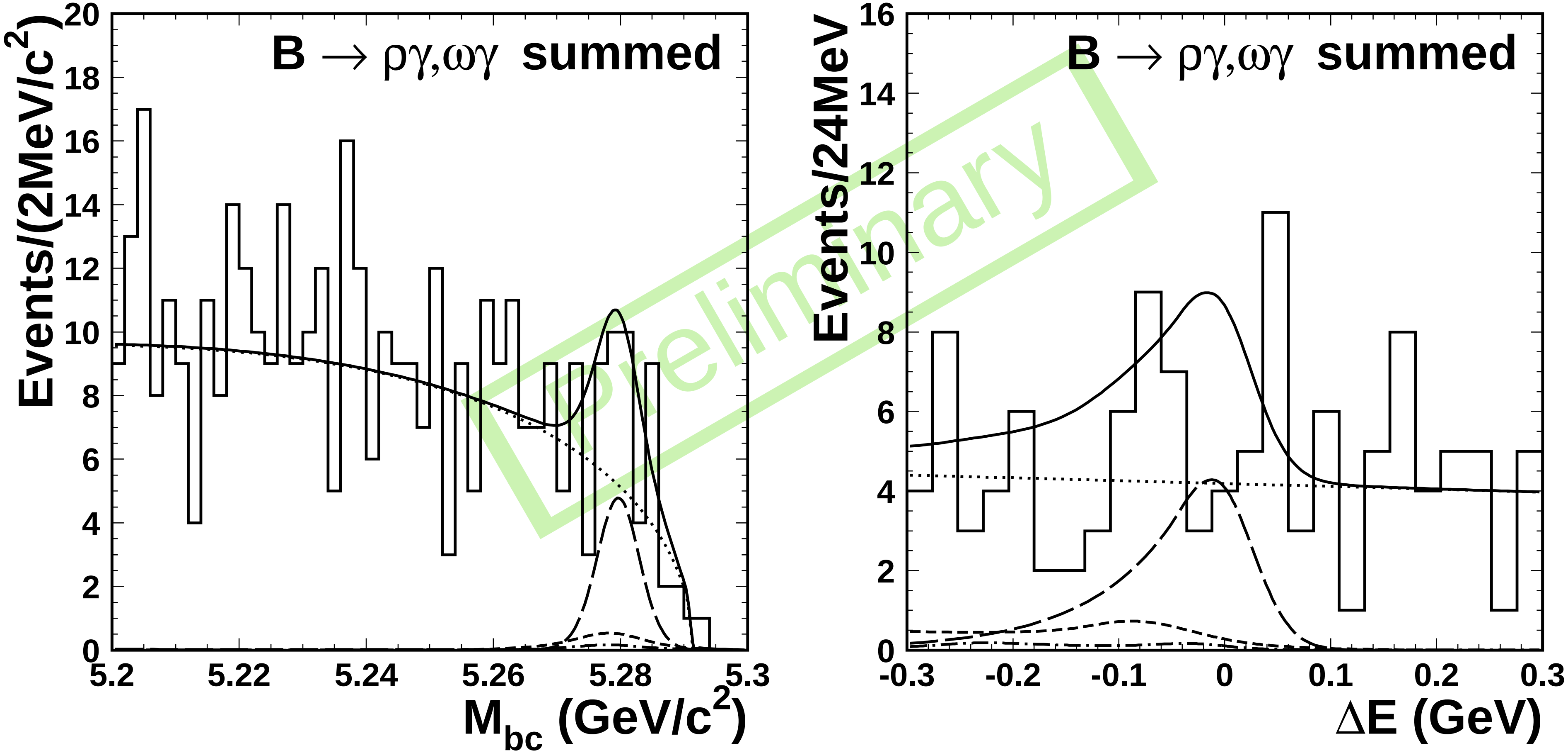
$B \to (\rho, \omega)\gamma$: Fit results



$$B^0 \to \omega\gamma$$

1D-projection of simultaneous 2D fit

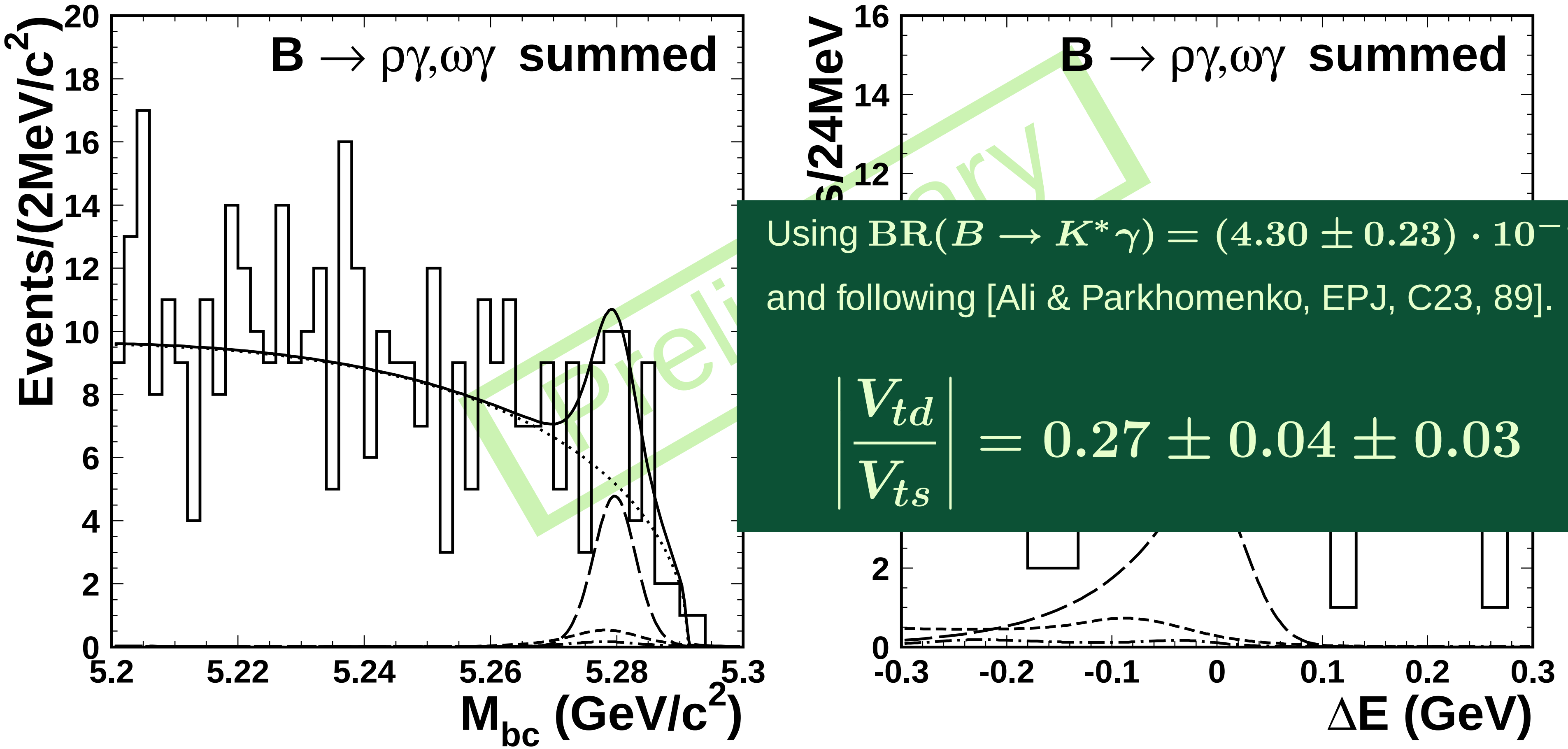
$B \to (\rho, \omega)\gamma$: Fit results



$$\mathrm{BR}(B \to (\rho, \omega)\gamma) = \left(1.8\,^{+0.6}_{-0.5} \pm 0.1\right) \cdot 10^{-6}$$

3.5σ evidence for $b \to d\gamma$!

$B \longrightarrow (\rho, \omega)\gamma$: Fit results



Using $\mathrm{BR}(B \to K^*\gamma) = (4.30 \pm 0.23) \cdot 10^{-5}$ and following [Ali & Parkhomenko, EPJ, C23, 89].

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.27 \pm 0.04 \pm 0.03$$

$$\mathrm{BR}(B \longrightarrow (\rho, \omega)\gamma) = \left(1.8\,^{+0.6}_{-0.5} \pm 0.1\right) \cdot 10^{-6}$$

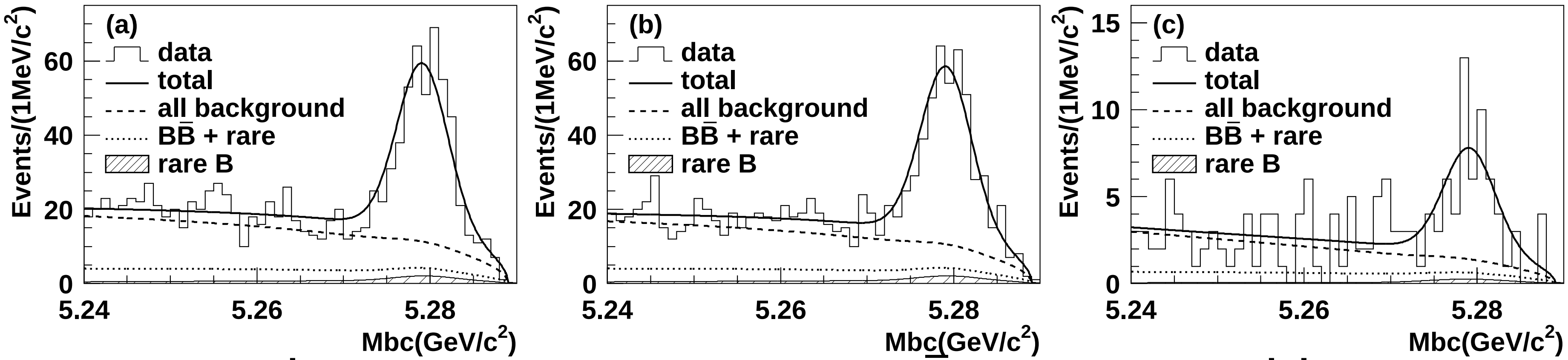
3.5σ evidence for $b \longrightarrow d\gamma$!

CP asymmetry in $B \longrightarrow X_s\gamma$ decays

[Nishida et al., hep-ex/0308038]

$A_{\rm CP}$ in $B \to X_s\gamma$

- Isolated photon, not from π^0, η
- $X_s = Kn\pi$ $(n = 1\ldots4)$, $\leq 1\ \pi^0$, or $X_s = 3K(\pi)$
- $m_{X_s} < 2.1\ \mathrm{GeV}/c^2$ (i.e $E_\gamma > 2.24\ \mathrm{GeV}$)



Tagged as b Tagged as $\bar{b}$ Ambiguous

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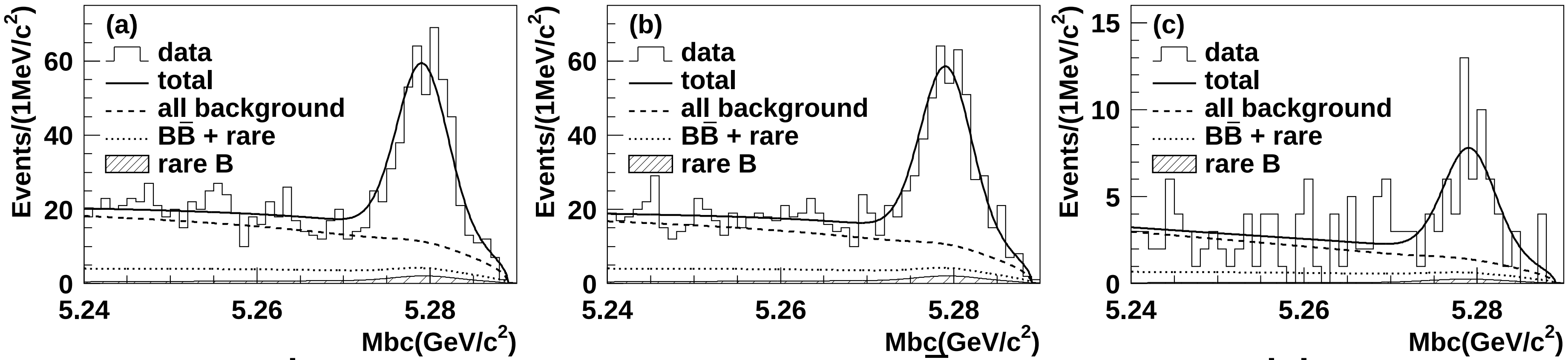

Tagged as b | Tagged as $\bar{b}$ | Ambiguous

Three states: b, $\bar{b}$, ambiguous $\longrightarrow$ three mis-tag rates

$$w_{b\leftrightarrow\bar{b}} = 0.0206 \pm 0.0027 \quad (K^+\pi^-\gamma \to K^0_S\pi^-\gamma)$$

$$w_{\mathrm{A}\to\mathrm{T}} = 0.248 \pm 0.020 \quad (K^0_S\pi^+\pi^-\gamma \to K^0_S\pi^+\pi^0\gamma)$$

$$w_{\mathrm{T}\to\mathrm{A}} = 0.0067 \pm 0.0013 \quad (K^0_S\pi^+\pi^0\gamma \to K^0_S\pi^+\pi^-\gamma)$$

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$$A_{\rm CP} = \underbrace{\frac{1 - w_{b\leftrightarrow\bar{b}} - w_{\mathsf{T}\to\mathsf{A}}}{(1 - w_{\mathsf{A}\to\mathsf{T}})(1 - 2w_{b\leftrightarrow\bar{b}} - w_{\mathsf{T}\to\mathsf{A}})}}_{\text{Dilution}} \underbrace{\frac{N_b - N_{\bar{b}}}{N_b + N_{\bar{b}} - \frac{w_{\mathsf{A}\to\mathsf{T}}}{1-w_{\mathsf{A}\to\mathsf{T}}} N_{\mathsf{A}}}}_{A_{\rm CP}^{\rm raw}}$$

Three states: b, $\bar{b}$, ambiguous $\longrightarrow$ three mis-tag rates

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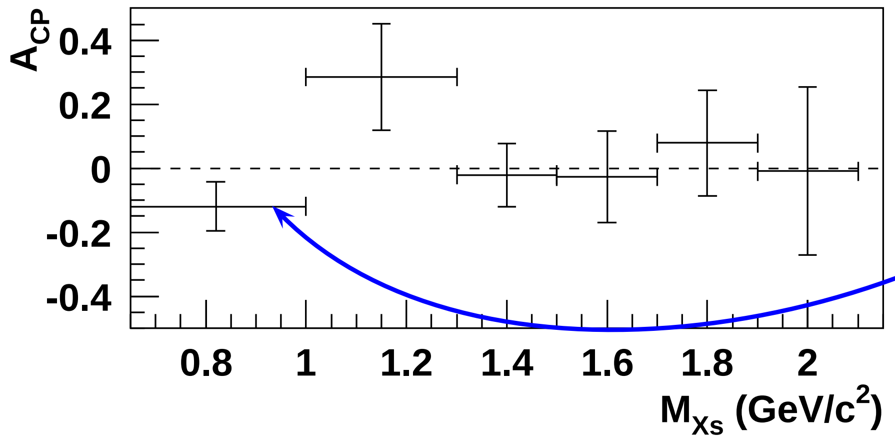
$$A_{\mathrm{CP}}(m_{X_s} < 2.1\ \mathrm{GeV}/c^2) = (0.2 \pm 5.0 \pm 3.0)\ \%$$



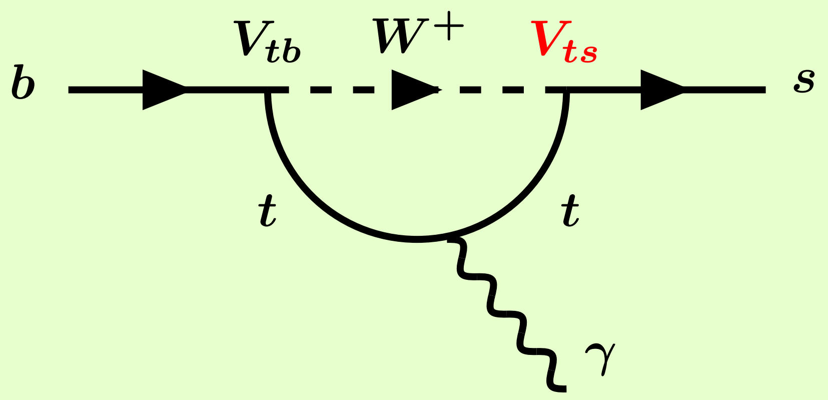
Consistent with $B \to K^*\gamma$

[Nakao et al., hep-ex/0402042]

Fully Inclusive $b \longrightarrow s\gamma$

[Koppenburg et al., hep-ex/0403004]

Introduction (reminder)



$$b \longrightarrow s\gamma$$

Inclusive decay

- Theoretically clean!
- BR very sensitive new physics.

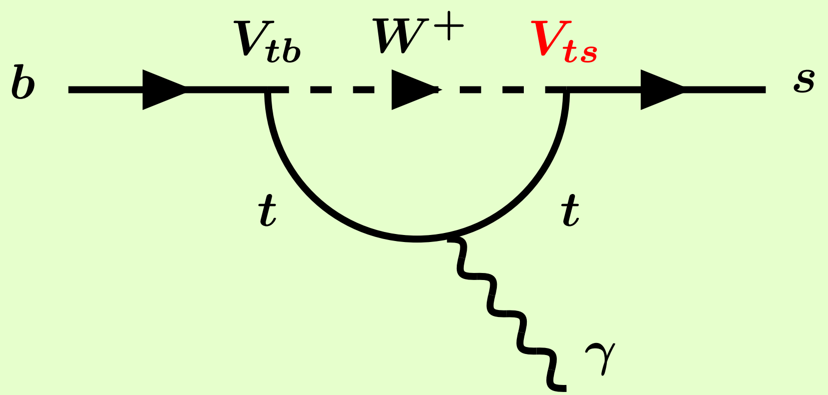
…but the experiment agrees very well with theory

$$\mathrm{BR(theory)} = \left(3.79\,{}^{+\,0.36}_{-\,0.53}\right) \cdot 10^{-}$$

[Hurth, Lunghi, Porod, hep-ph/0312260]

$$\mathrm{BR(PDG)} = (3.3 \pm 0.4) \cdot 10^{-4}$$

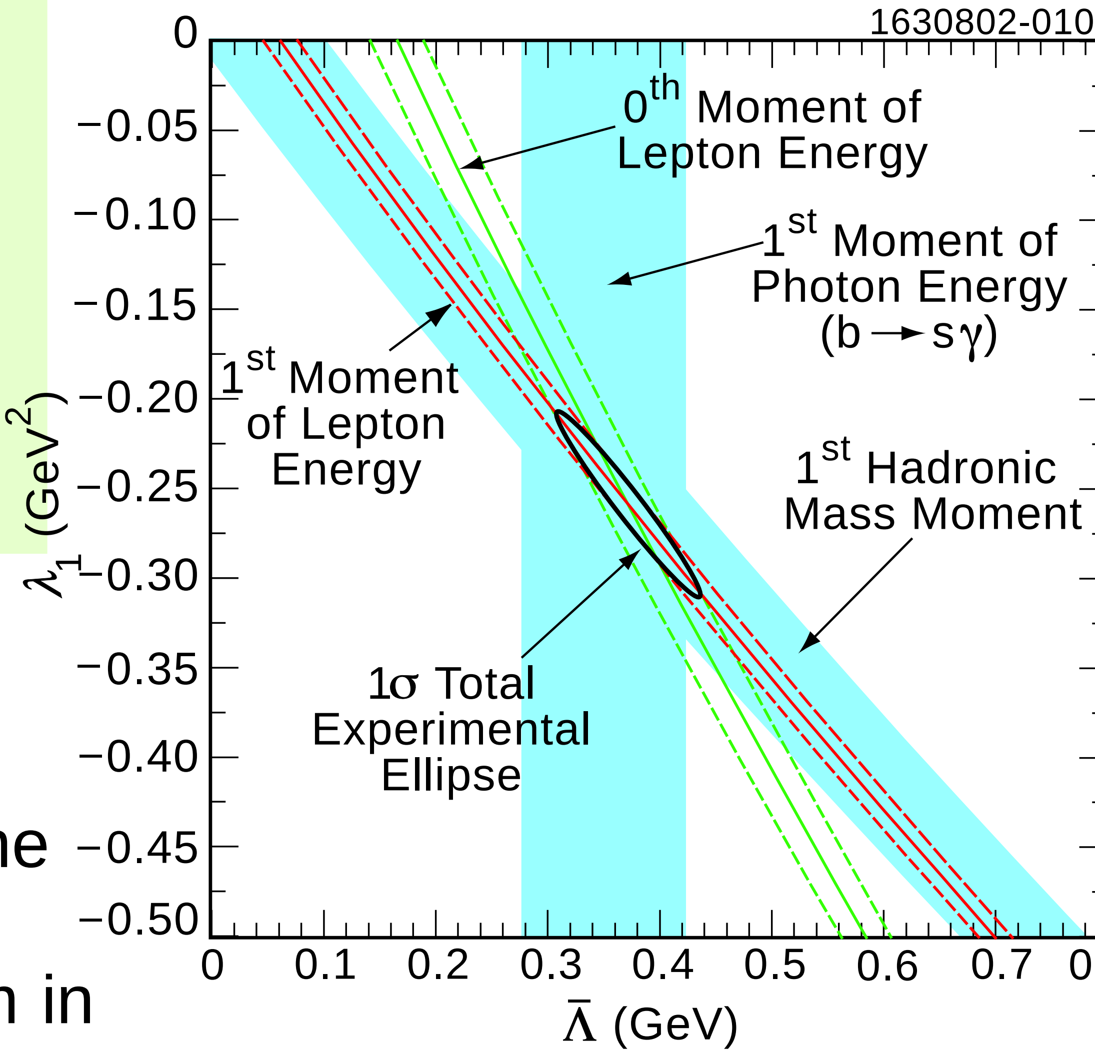
Introduction (reminder)



$b \to s\gamma$

- At parton-level it is a two-body decay.

$\longrightarrow$ QCD measurement of the B meson
$\longrightarrow$ Infer lepton spectrum in $b \to \ell\nu q \to V_{cb}$ and V_{ub}.



CLEO [Phys.Rev.D67:072001,2003]

Experimental motivation

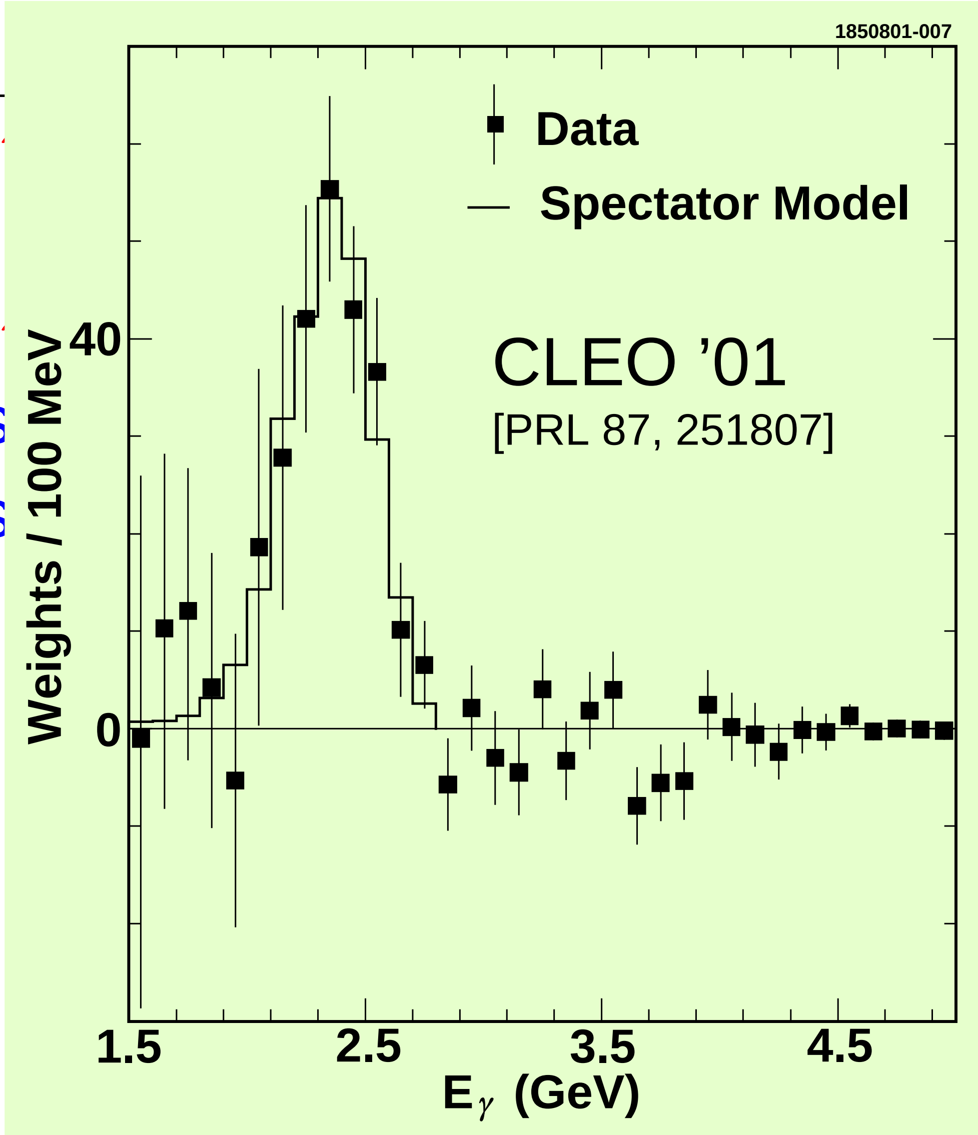
	$\int \mathcal{L}$	Method	$\mathrm{BR} \times 10^{-4}$
CLEO '95	$3\ \mathrm{fb}^{-1}$	$K n\pi$	$2.32 \pm 0.57 \pm 0.35$
Aleph '98	$Z \to b\bar{b}$		$3.11 \pm 0.80 \pm 0.72$
Belle '01	$6\ \mathrm{fb}^{-1}$	$K n\pi$	$3.36 \pm 0.53 \pm 0.42 \, ^{+0.50}_{-0.54}$
CLEO '01	$9\ \mathrm{fb}^{-1}$	Inclusive	$3.21 \pm 0.43 \pm 0.27 \, ^{+0.18}_{-0.10}$
(BaBar '02)	$54\ \mathrm{fb}^{-1}$	Inclusive	$3.88 \pm 0.36 \pm 0.37 \, ^{+0.43}_{-0.23}$

- Error is limited by systematics
- X_s from $K n\pi$ leads to large model errors
- 65% of the hadronic structure is unknown

$\longrightarrow$ Use Inclusive method

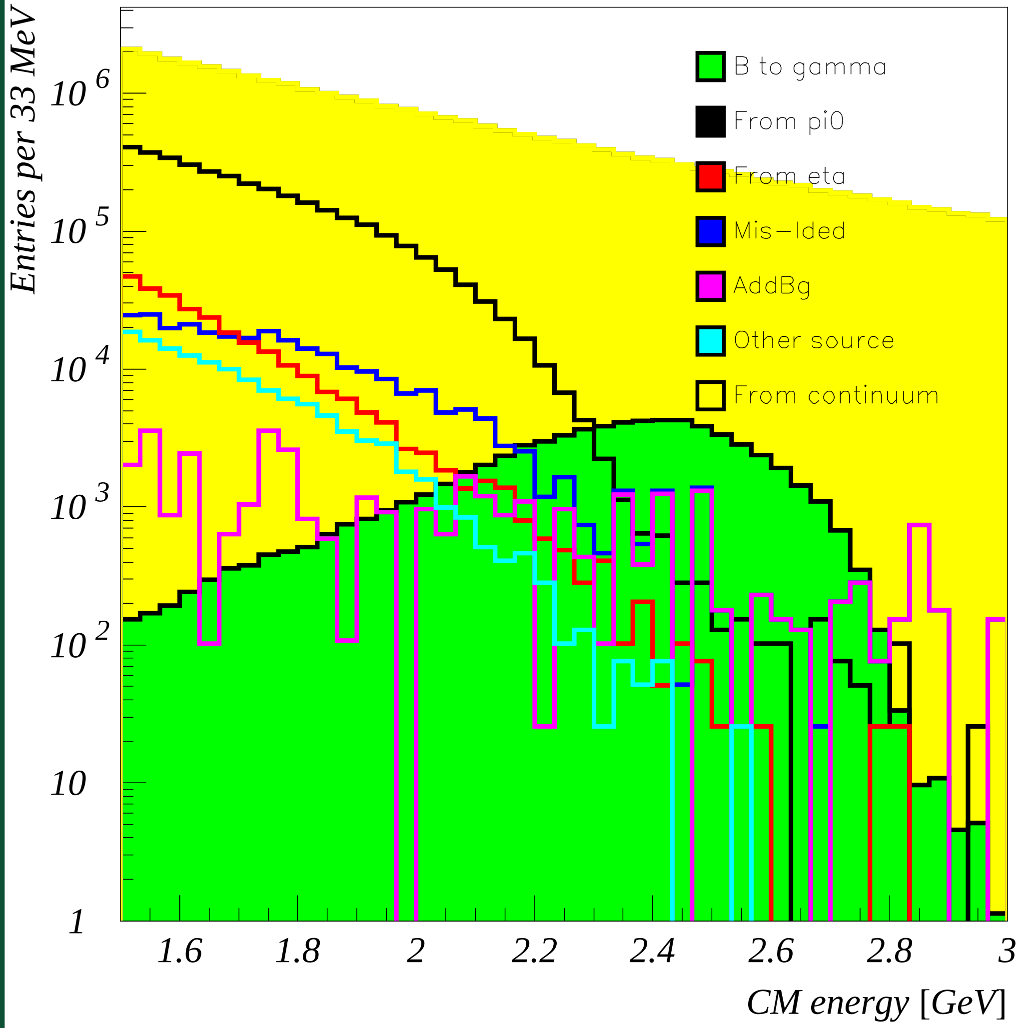
Experimental motivation

	$\int \mathcal{L}$	Meth
CLEO '95	$3\ \mathrm{fb}^{-1}$	*Kn*
Aleph '98	$Z \to b\bar{b}$	
Belle '01	$6\ \mathrm{fb}^{-1}$	*Kn*
CLEO '01	$9\ \mathrm{fb}^{-1}$	Inclus
(BaBar '02)	$54\ \mathrm{fb}^{-1}$	Inclus



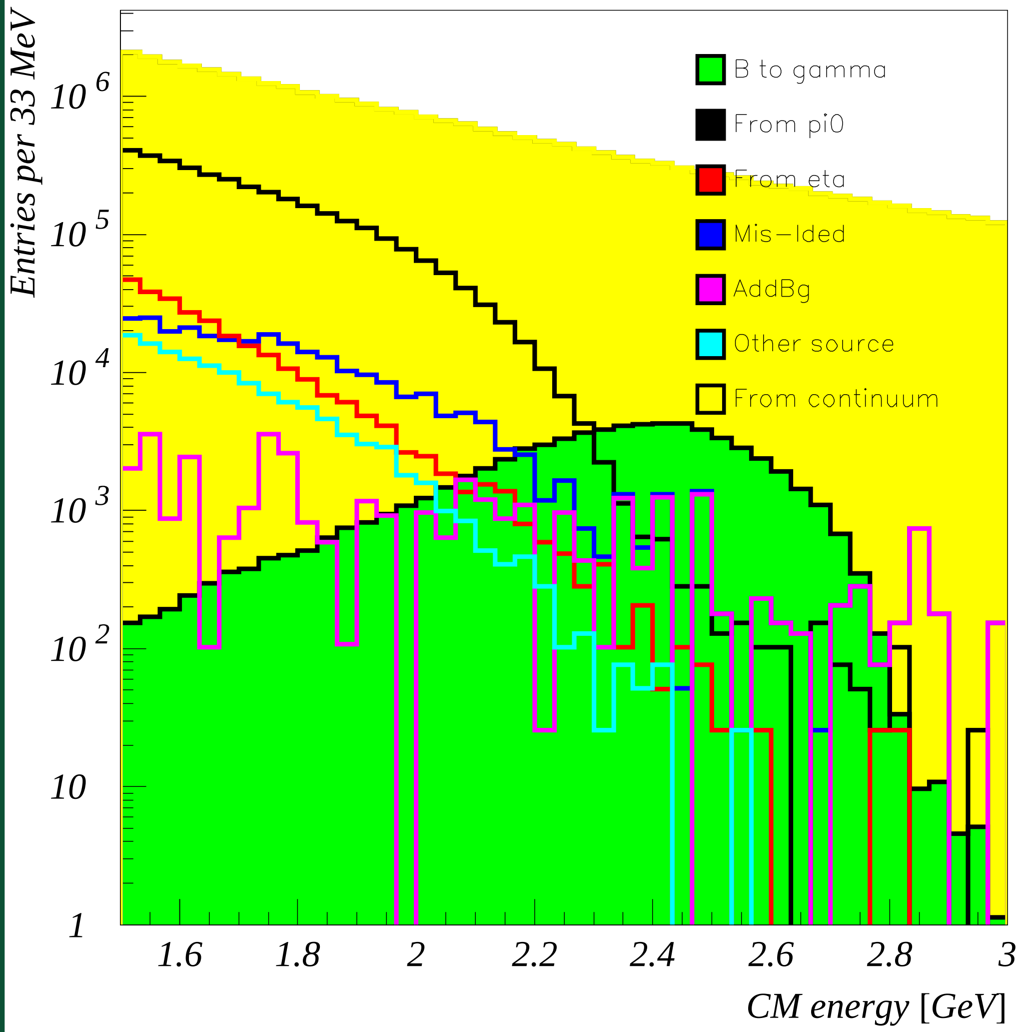
- $E^* > 2.0\ \mathrm{GeV}$
- With 15 times more data, Belle can reach $E^* > 1.8\ \mathrm{GeV}$

Strategy



B to gamma
From pi0
From eta
Mis−Ided
AddBg
Other source
From continuum
Entries per 33 MeV
10^6
10^5
10^4
10^3
10^2
10
1
1.6
1.8
2
2.2
2.4
2.6
2.8
3
CM energy [GeV]

Strategy



Data sets:

- 140 fb^{-1} ON-resonance
- 15 fb^{-1} OFF-resonance

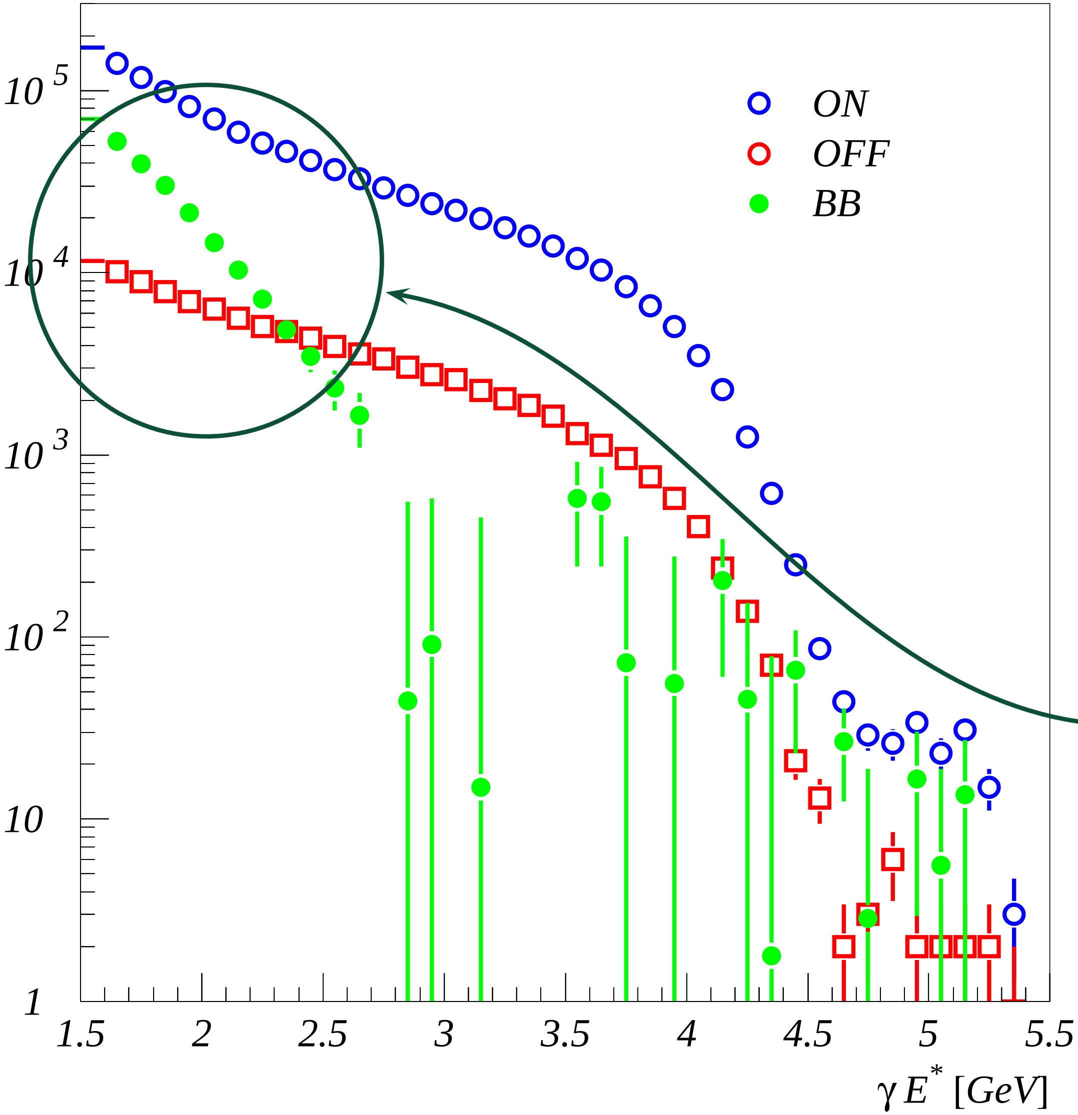
Event selection:

- Hadronic events with isolated photon(s) in ECL. $E^* > 1.5\,\mathrm{GeV}$.
- Veto γ from π^0 and η.
- Apply event shape cuts to suppress continuum background.

Optimise cuts to maximise statistical significance in $1.8 \leq E^* \leq 1.9\,\mathrm{GeV}$ bin

BELLE

OFF-resonance data subtraction

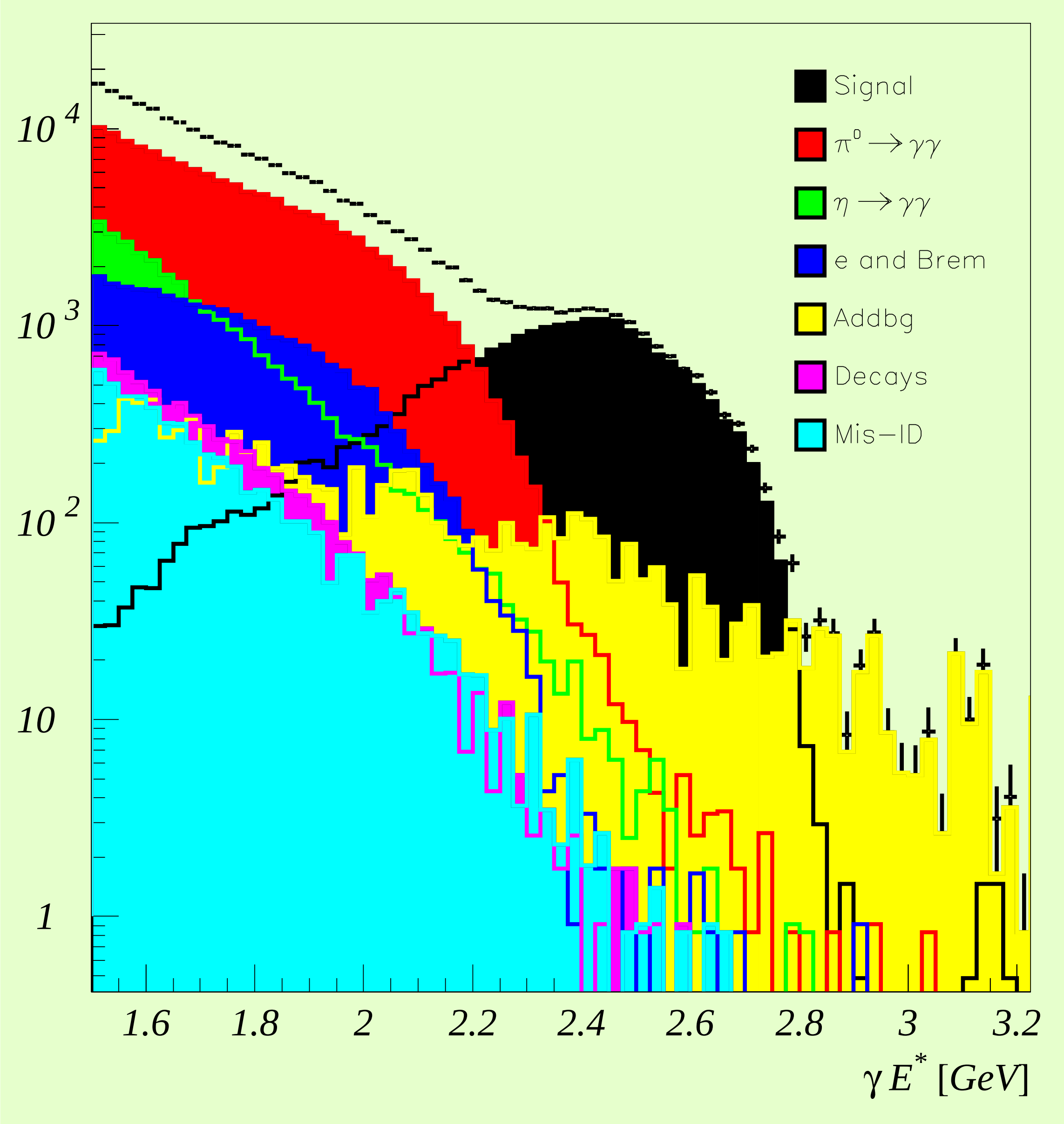


OFF-resonance data is scaled according to luminosities and subtracted from ON-resonance data

Still dominated by low-E^* γ background from B decays.

What remains in $B\overline{B}$ events

Signal	25%
Decays of π^0	52%
Decays of η	6%
e and Hadrons	8%
Bremsstrahlung	2%
Beam-gas	5%
Decays of $\omega(783)$	1%
Decays of J/ψ	1%
Other decays	1%



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What remains in $B\overline{B}$ events

Signal	25%		
Decays of π^0	52%	—	Measured spectrum
Decays of η	6%	—	Measured spectrum
e and Hadrons	8%	—	Scaled MC
Bremsstrahlung	2%	—	Scaled MC
Beam-gas	5%	—	Random triggers
Decays of $\omega(783)$	1%	—	Scaled MC
Decays of J/ψ	1%	—	Scaled MC (thanks to M. Misiak)
Other decays	1%	—	Scaled MC

Updated

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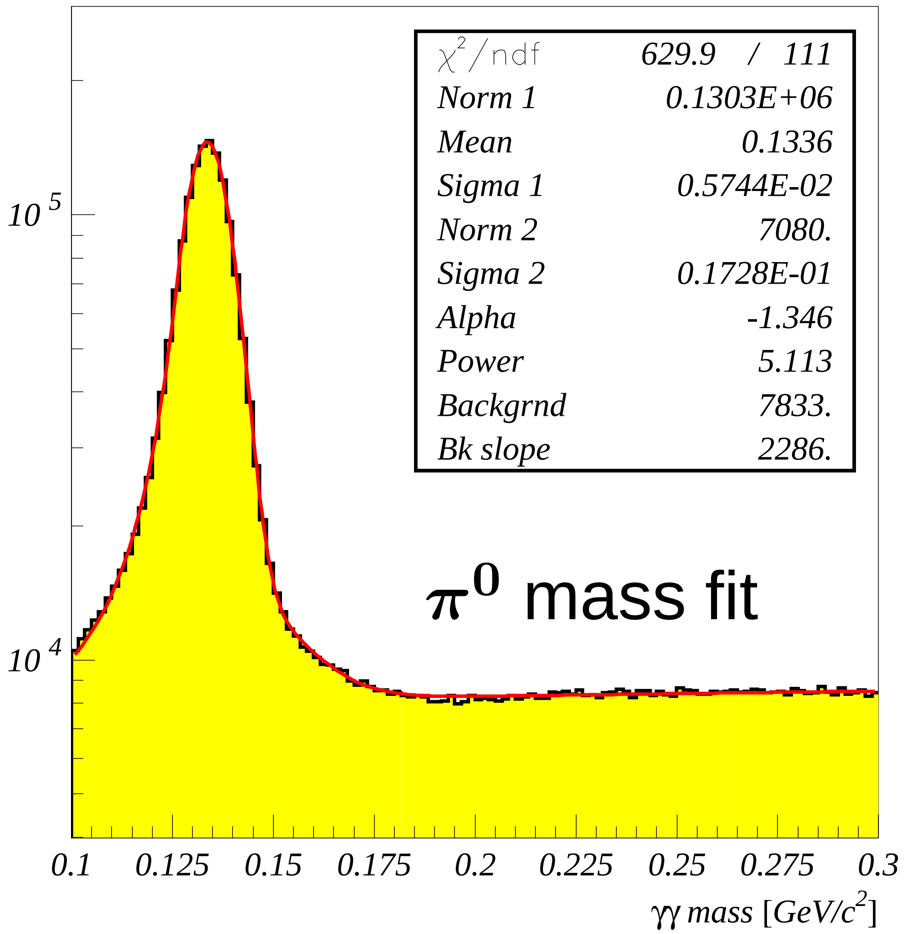
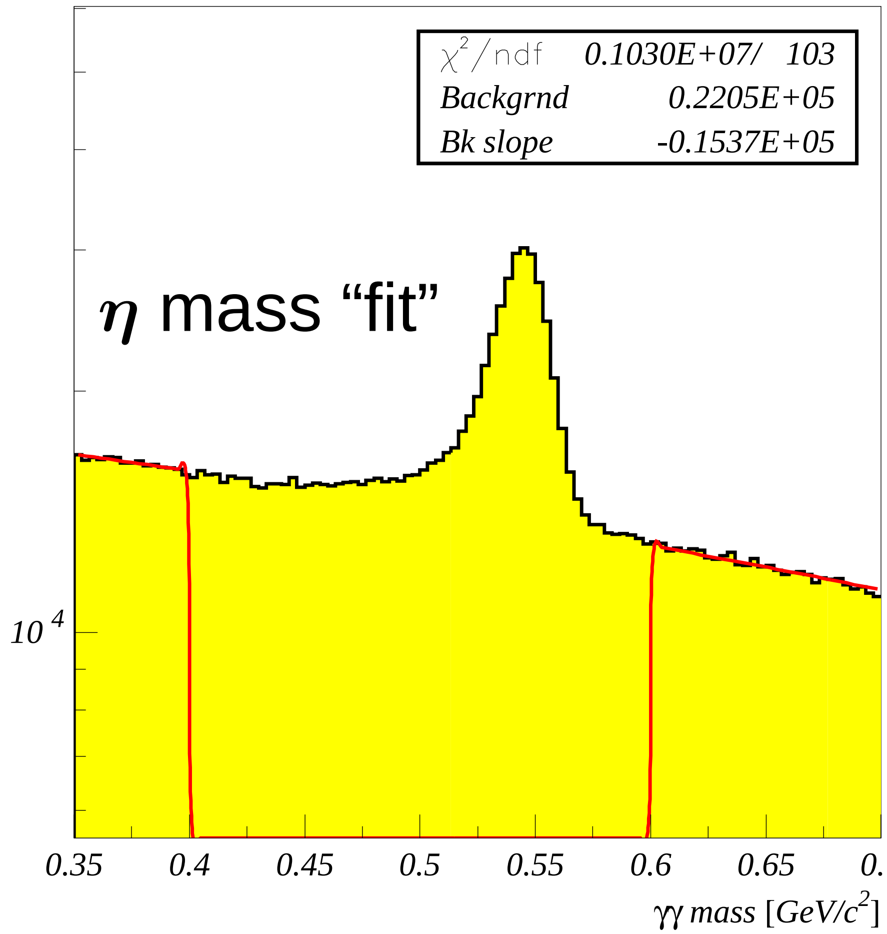
π^0 and η data mass peaks

All 2γ pairs with helicity angle $\mathrm{abs}(\cos\alpha) < 0.5$





Bin at $E^* = 1.775 \pm 0.025$ GeV

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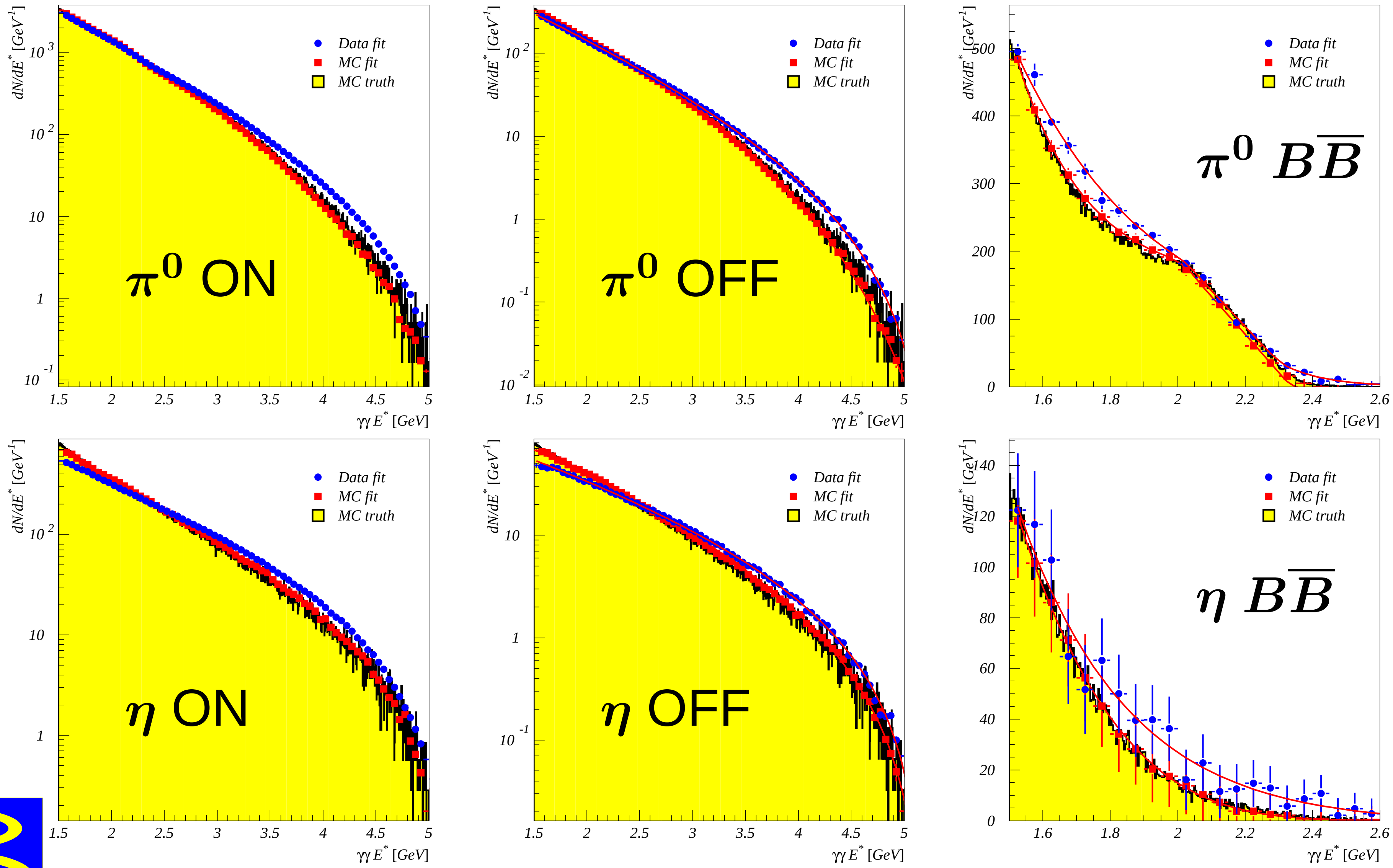
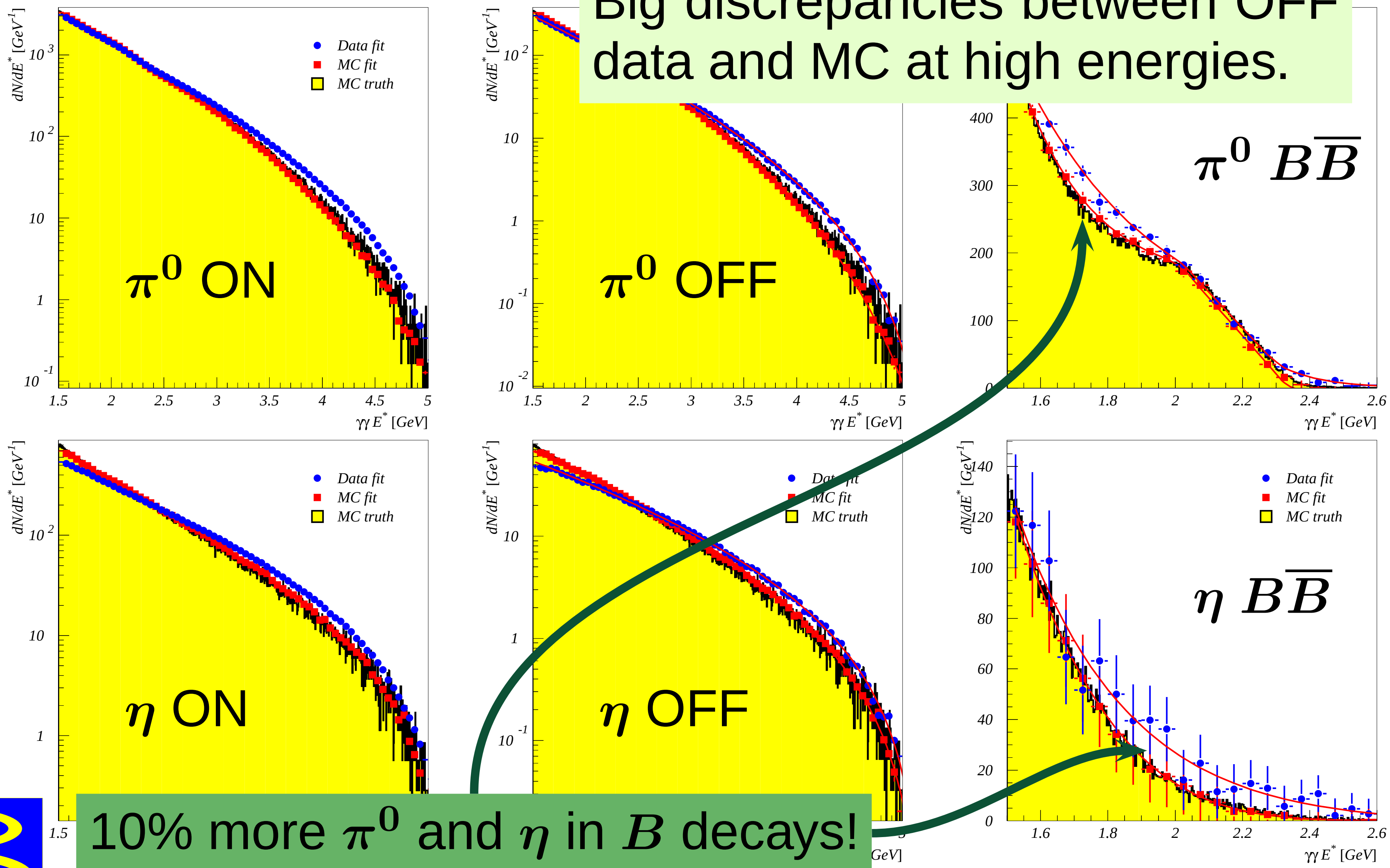
π^0, η spectra in MC and data



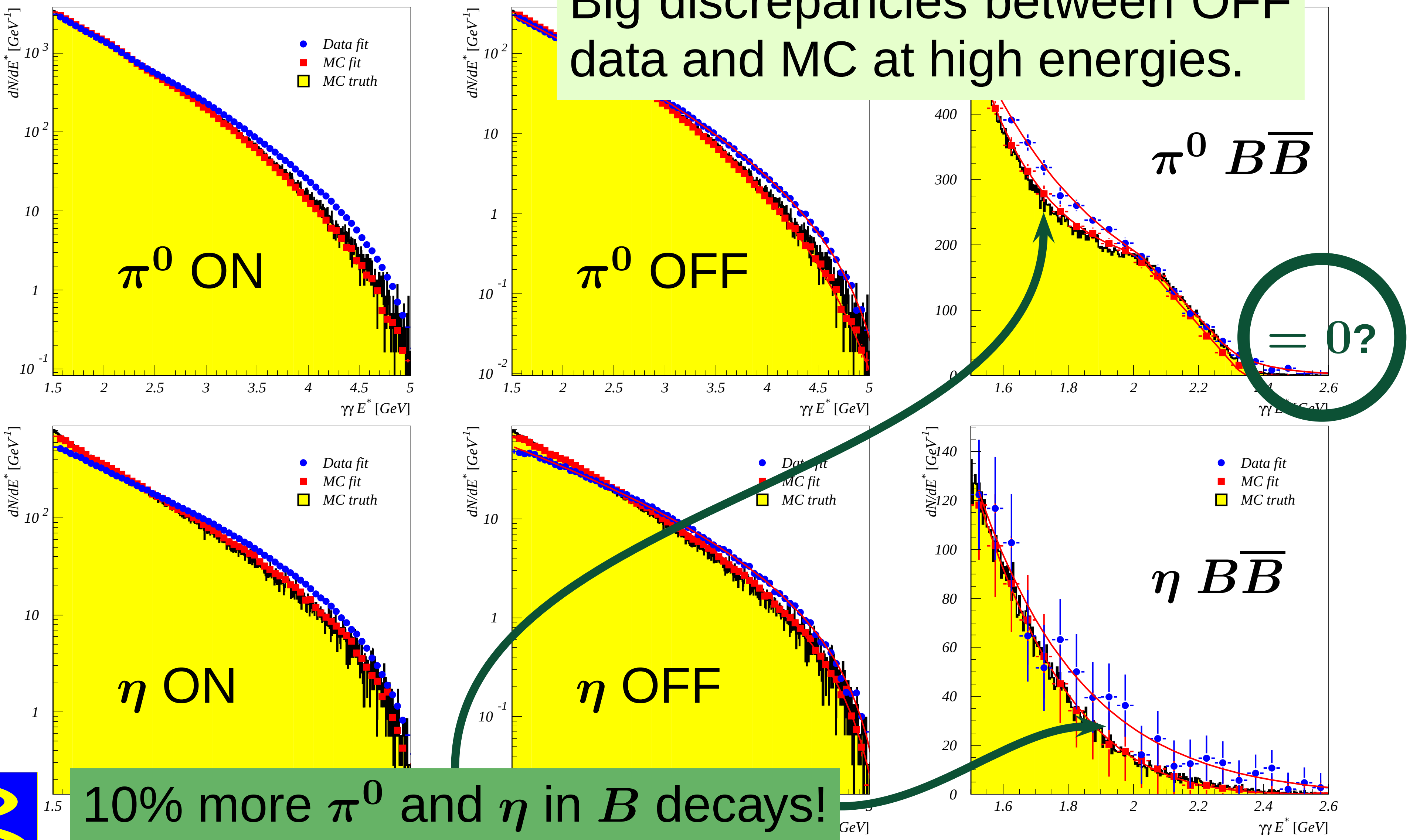
π^0, η spectra in MC and data



Big discrepancies between OFF data and MC at high energies.

10% more π^0 and η in B decays!

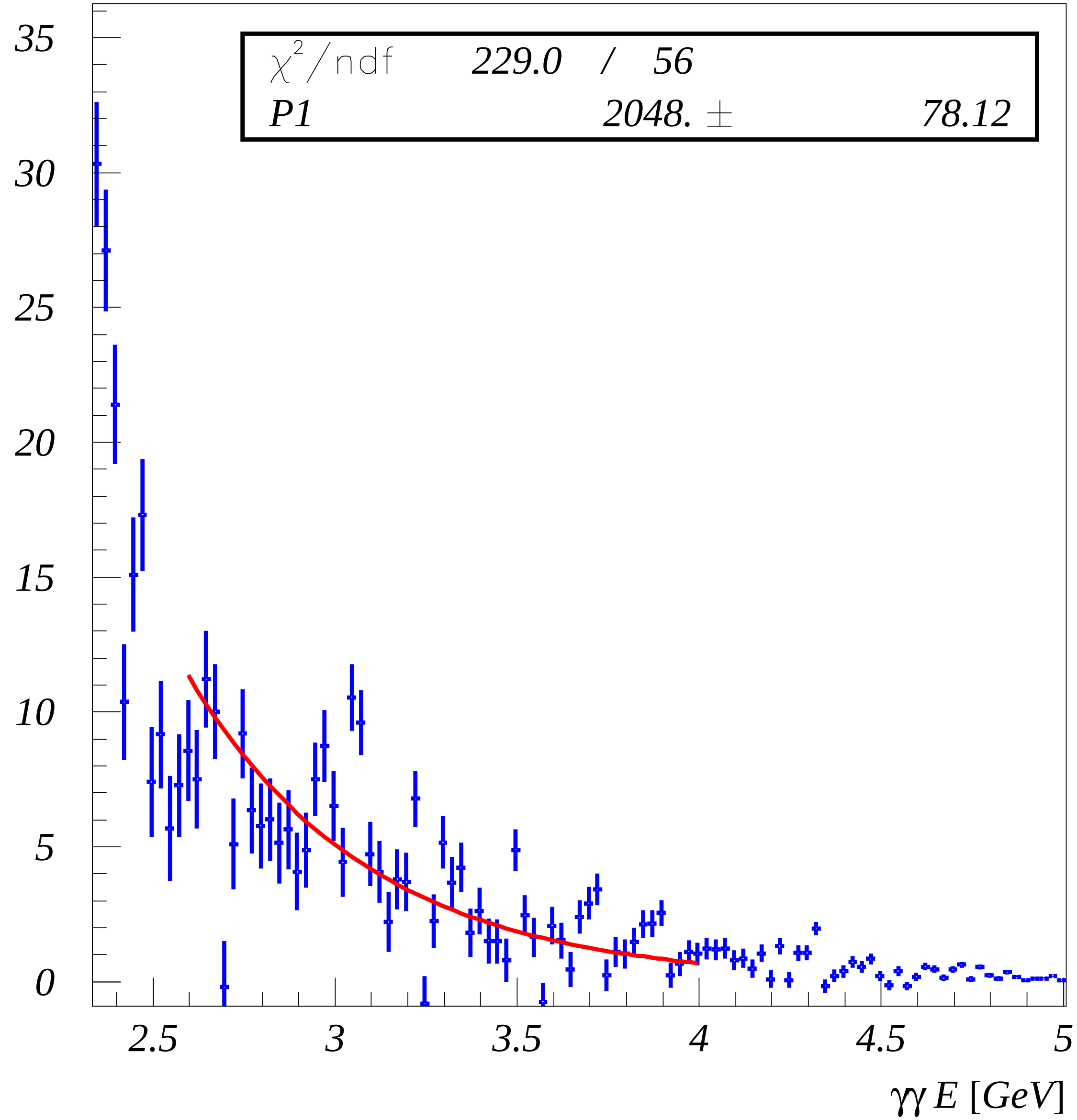
π^0, η spectra in MC and data



Big discrepancies between OFF data and MC at high energies.

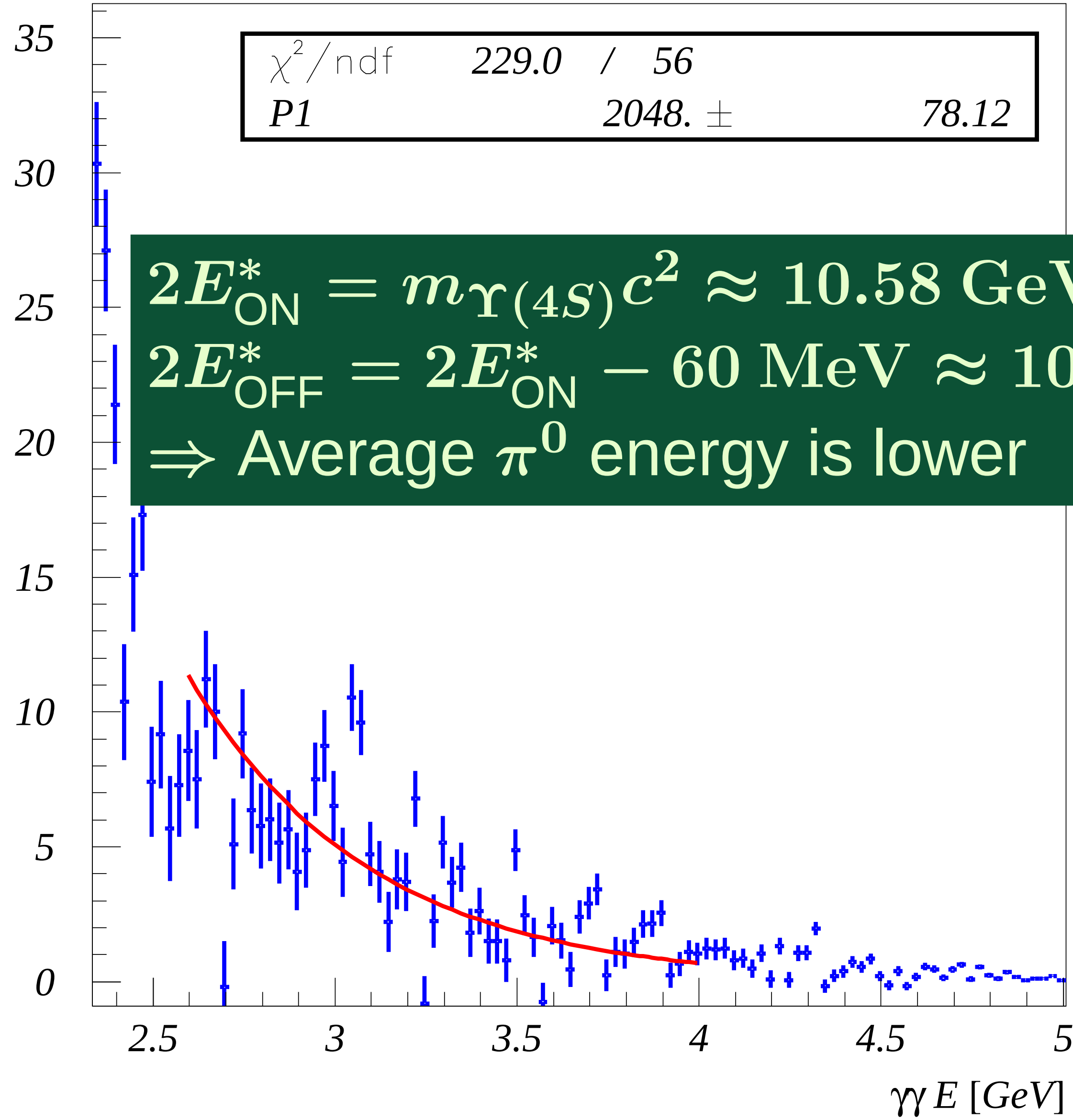
10% more π^0 and η in B decays!

$B\overline{B}\ \pi^0$ spectrum after endpoint



Exponential fit with fixed slope (from ON fit) in the $\boldsymbol{E}$ range above endpoint, but before threshold effects: $\mathbf{2.6\text{–}4.0\ GeV}$

$B\overline{B}\,\pi^0$ spectrum after endpoint



$2E^*_{\text{ON}} = m_{\Upsilon(4S)}c^2 \approx 10.58\ \text{GeV}$
$2E^*_{\text{OFF}} = 2E^*_{\text{ON}} - 60\ \text{MeV} \approx 10.52\ \text{GeV}$
$\Rightarrow$ Average π^0 energy is lower

Exponential fit with fixed slope (from ON fit) in the E range endpoint, but threshold ef- .6–4.0 GeV

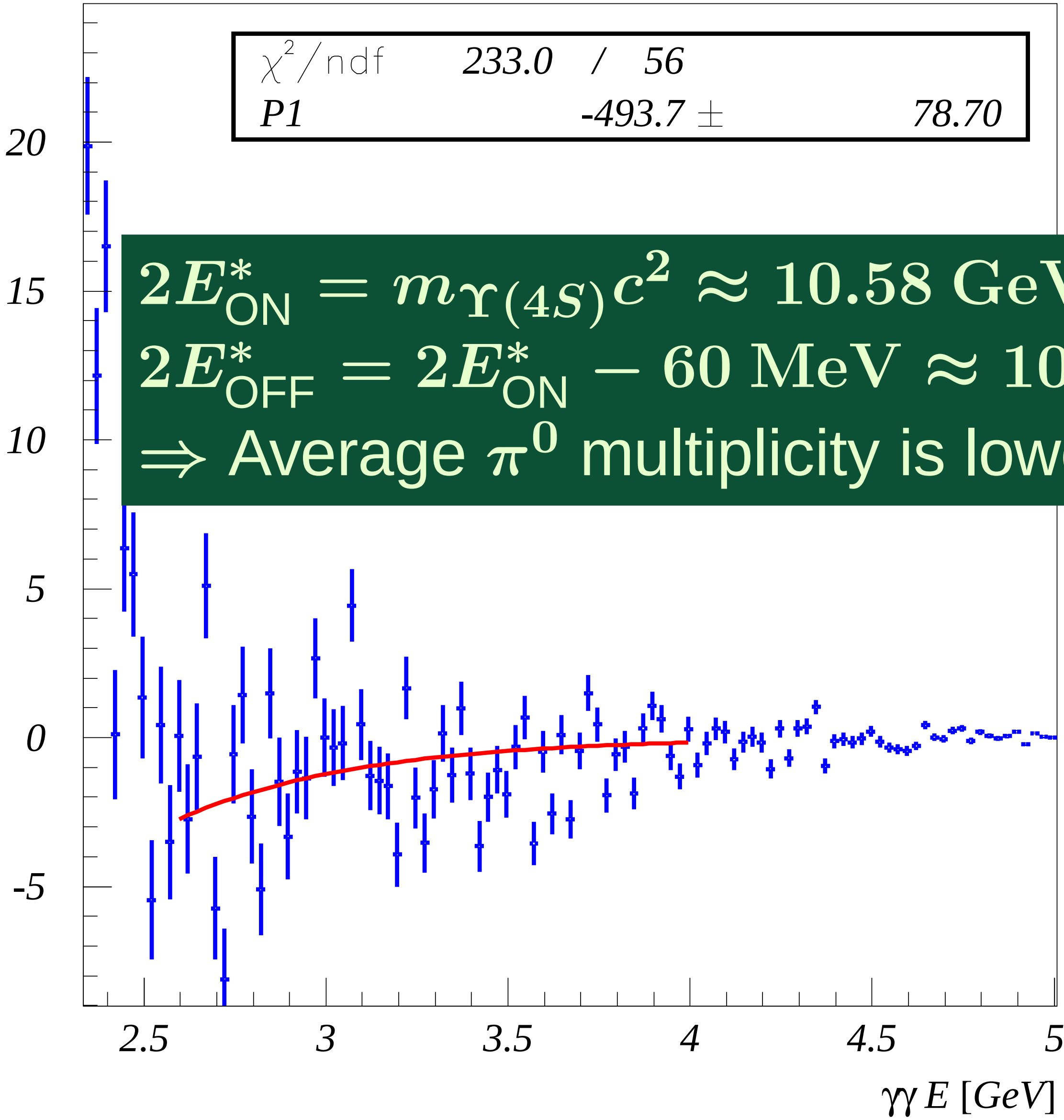
$$E^*_{\text{corr}} = E^*$$

No correction of OFF energies

25σ effect!

$\longrightarrow$ Correct OFF energy!

$B\overline{B}\ \pi^0$ spectrum after endpoint



$2E^*_{\mathrm{ON}} = m_{\Upsilon(4S)}c^2 \approx 10.58\ \mathrm{GeV}$
$2E^*_{\mathrm{OFF}} = 2E^*_{\mathrm{ON}} - 60\ \mathrm{MeV} \approx 10.52\ \mathrm{GeV}$
$\Rightarrow$ Average π^0 multiplicity is lower

Exponential fit with fixed slope (from ON fit) in the E range endpoint, but threshold ef- $.6$–4.0 GeV

$$E^*_{\mathrm{corr}} = \frac{E_{\mathrm{ON}}}{E_{\mathrm{beam}}} E^*$$

Proportional correction

(-6σ)

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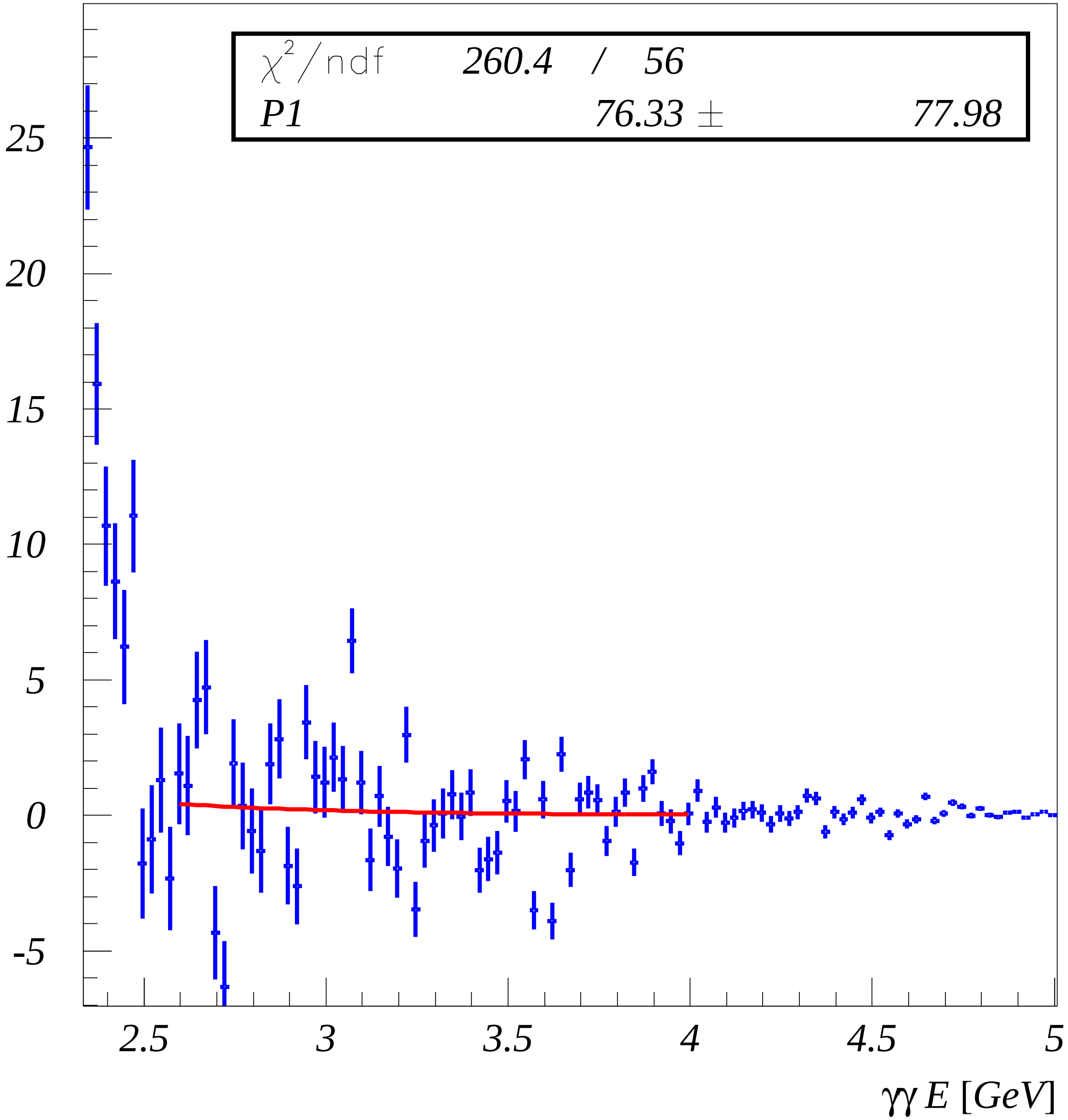
$B\overline{B}$ π^0 spectrum after endpoint



Exponential fit with fixed slope (from ON fit) in the E range above endpoint, but before threshold effects: $\mathbf{2.6–4.0\ GeV}$

$$E^*_{\text{corr}} = 1.0042E^*$$

Then scale by 1.0004.

Values obtained from generator-level Pythia study

What remains in $B\overline{B}$ events

				Background category
Signal	25%			γ
Decays of π^0	52%	—	Measured spectrum	π^0
Decays of η	6%	—	Measured spectrum	η
e and Hadrons	8%	—	Scaled MC	Mis-ID
Beam-gas	5%	—	Random triggers	Data
Bremsstrahlung	2%	—	Scaled MC	γ
Decays of $\omega(783)$	1%	—	Scaled MC	γ
Decays of J/ψ	1%	—	Scaled MC (thanks to M. Misiak)	γ
Other decays	1%	—	Scaled MC	γ

Background subtraction

For each of the 5 background categories and for each set of cuts, we correct the MC efficiency using data control samples.

Control samples:

- Main stream (i.e. all events passing cuts)
- π^0 anti-veto (almost pure γ from π^0)
- Partially reconstructed $D \to K\pi\pi^0$ (pure γ from π^0)
- γ from symmetric π^0 decays, with other γ screened (to force random combinations)

For each sample, we have ON, OFF $\to B\overline{B}$

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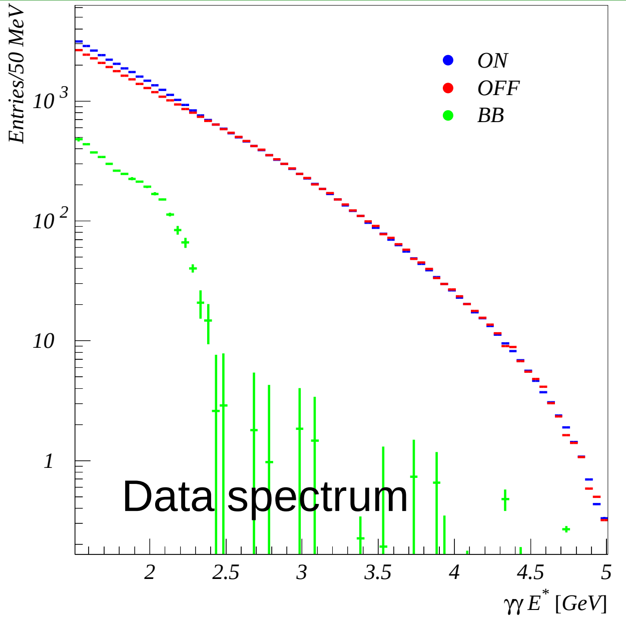
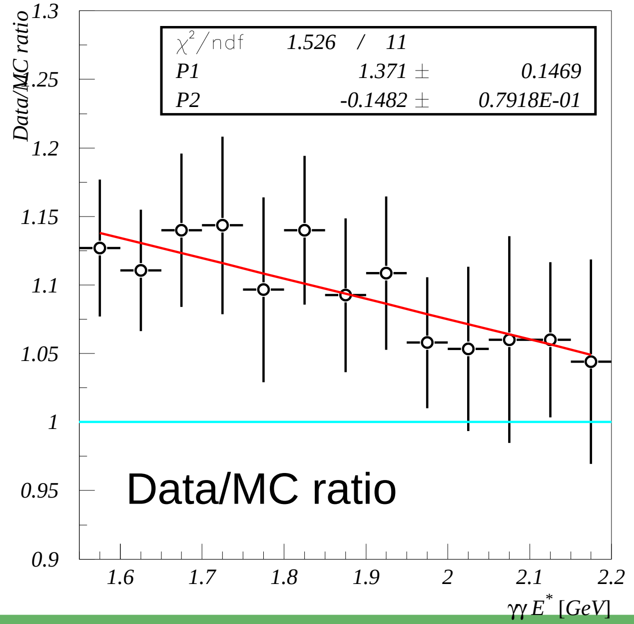
Yields and Efficiency corrections

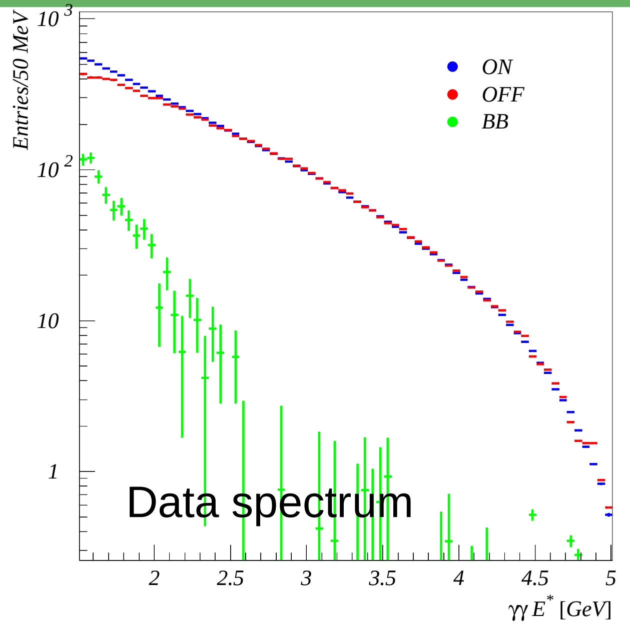
- $B \to \pi^0$ yields from data

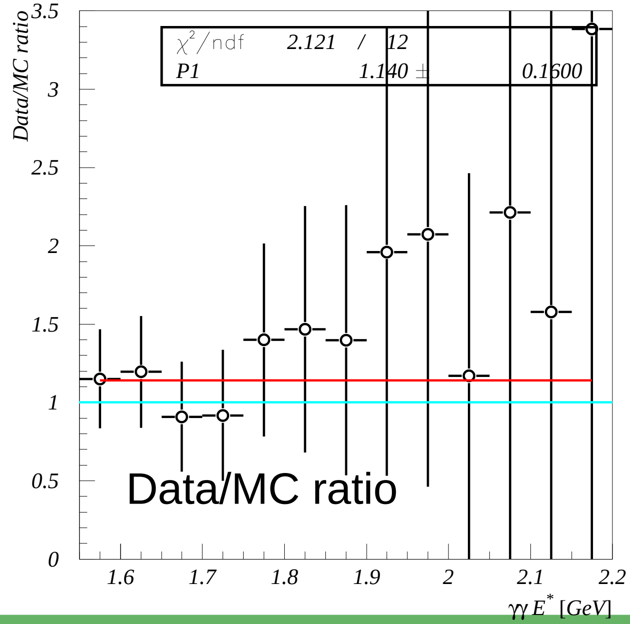




Yields and Efficiency corrections

- $B \to \pi^0$ yields from data
- $B \to \eta$ yields from data





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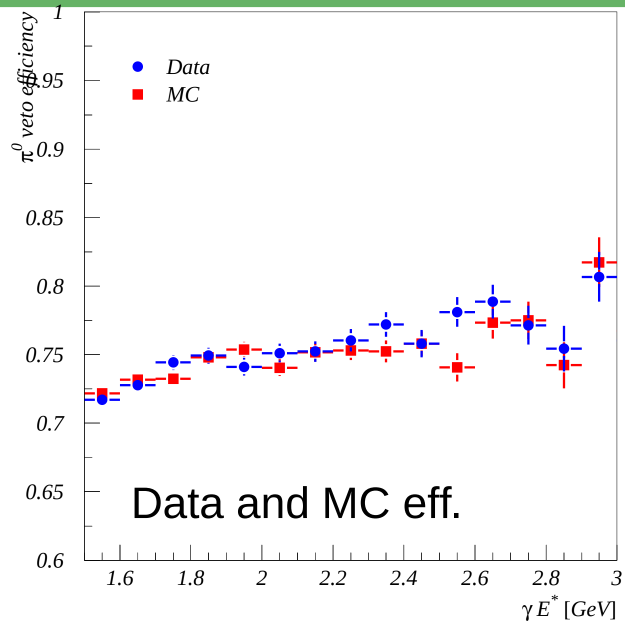
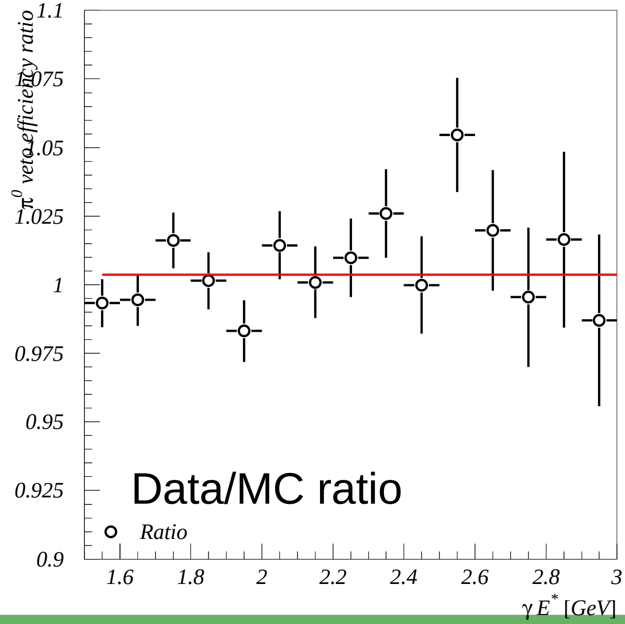
Yields and Efficiency corrections

- $B \to \pi^0$ yields from data
- $B \to \eta$ yields from data
- π^0 veto for $\pi^0 \to$ partial D sample





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Yields and Efficiency corrections

- $B \to \pi^0$ yields from data
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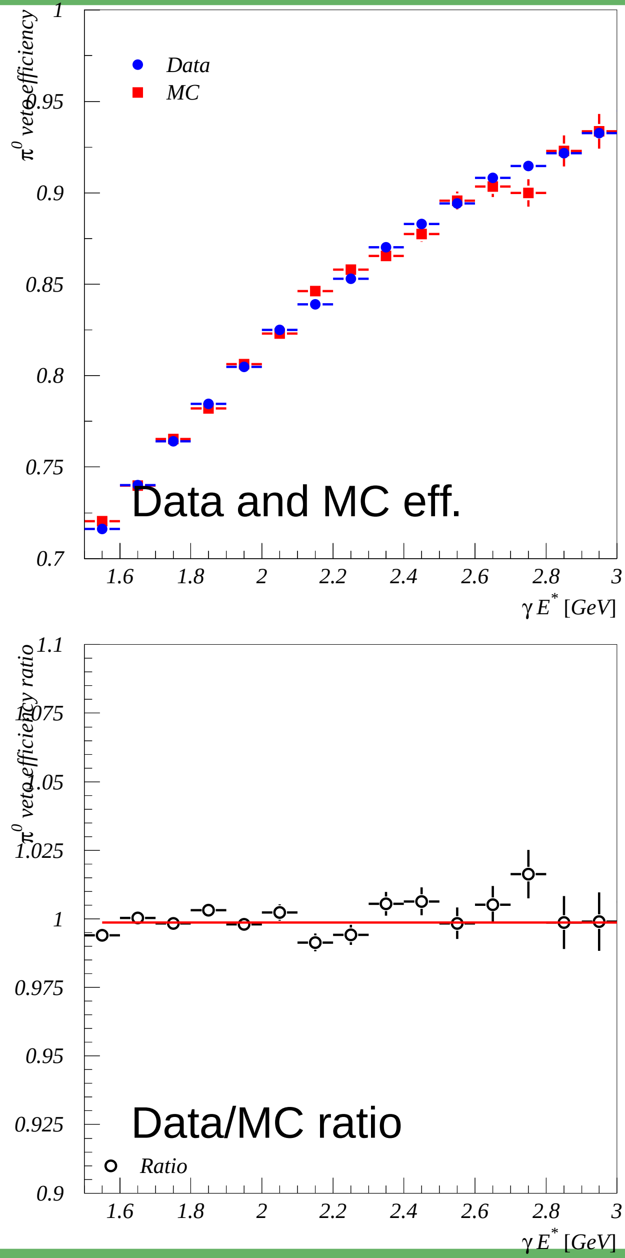
- π^0 veto for $\pi^0 \to$ partial D sample
- π^0 veto for others $\to$ screened π^0



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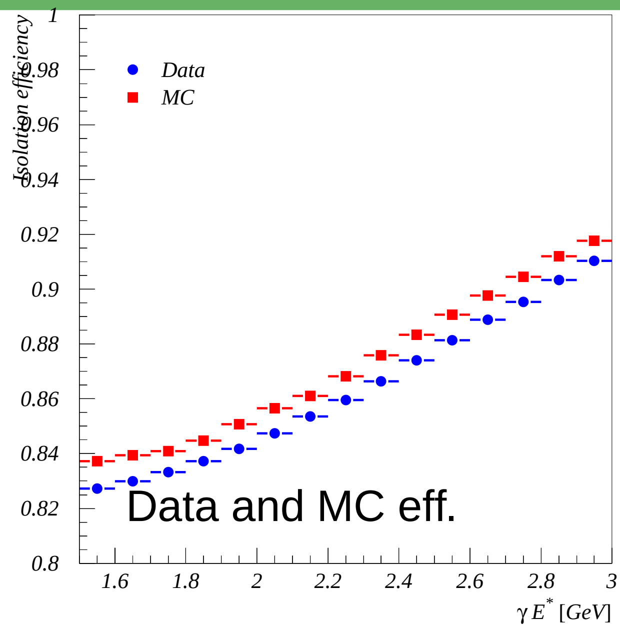
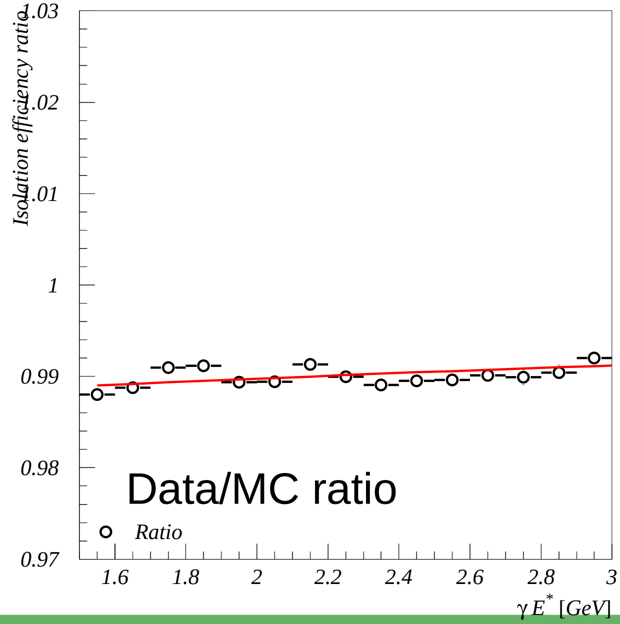
- Isolation cut efficiencies $\to$ main stream





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Yields and Efficiency corrections

- $B \to \pi^0$ yields from data
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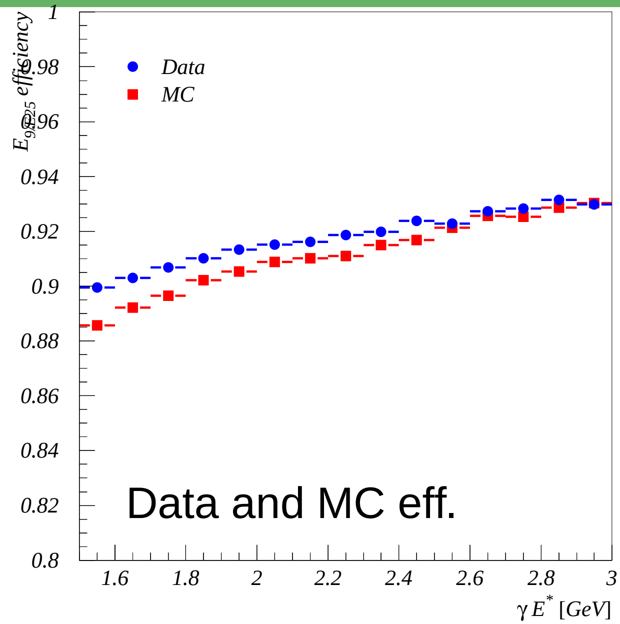
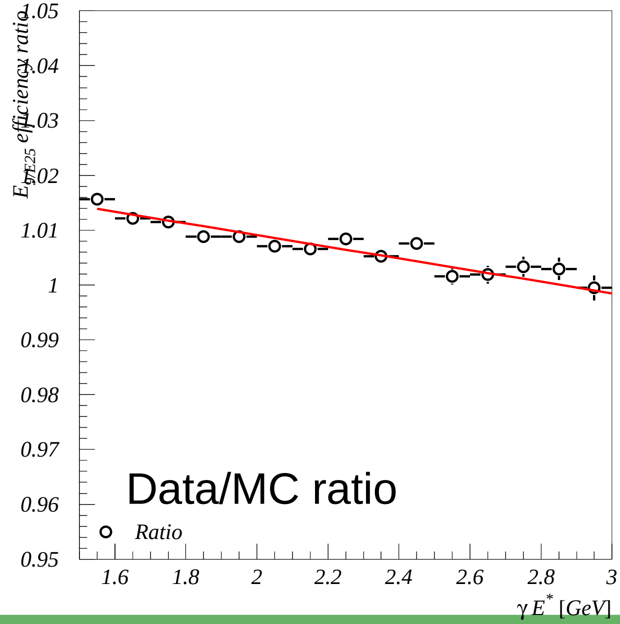
- Isolation cut efficiencies $\to$ main stream
- Calo cluster shapes for photons from anti-veto π^0





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Yields and Efficiency corrections

- $B \to \pi^0$ yields from data
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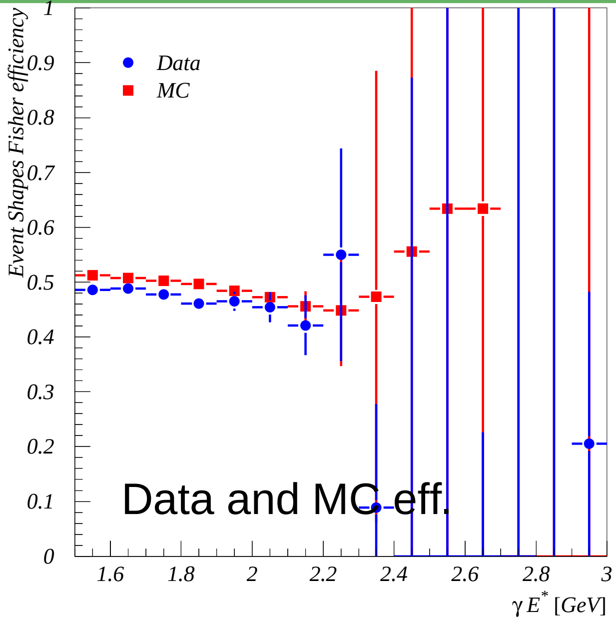
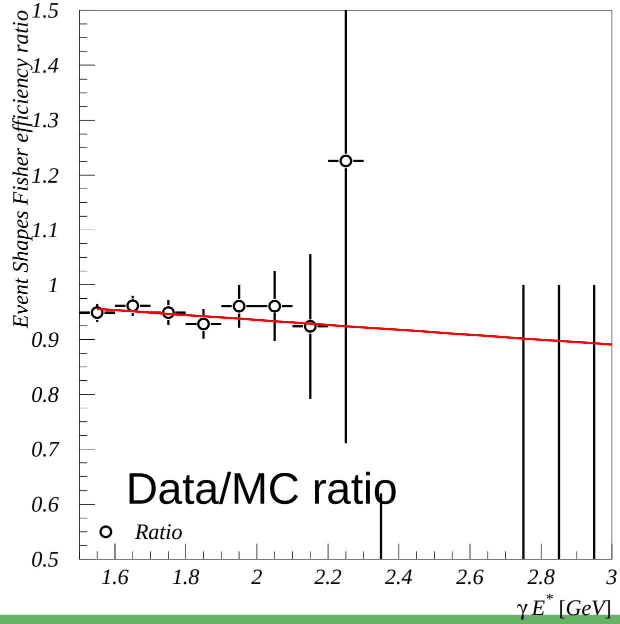
- Event shapes: π^0 anti-veto $B\overline{B}$ data (checked with other samples).





Yields and Efficiency corrections

- $B \to \pi^0$ yields from data
- $B \to \eta$ yields from data
- π^0 veto for $\pi^0 \to$ partial D sample
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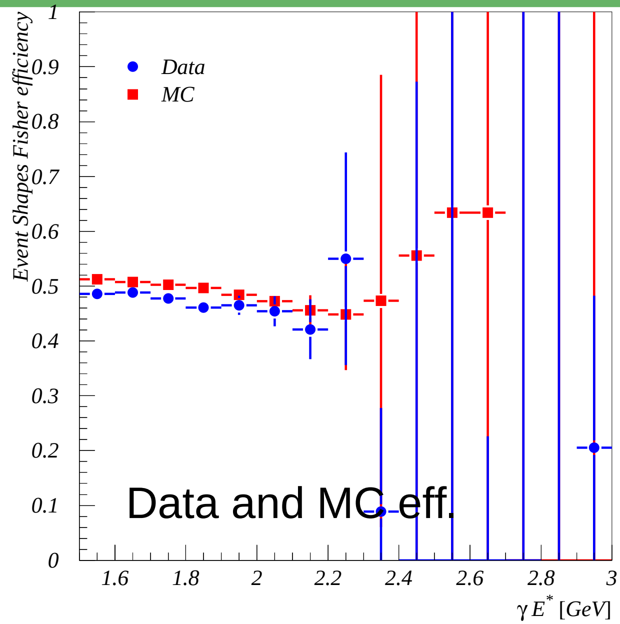
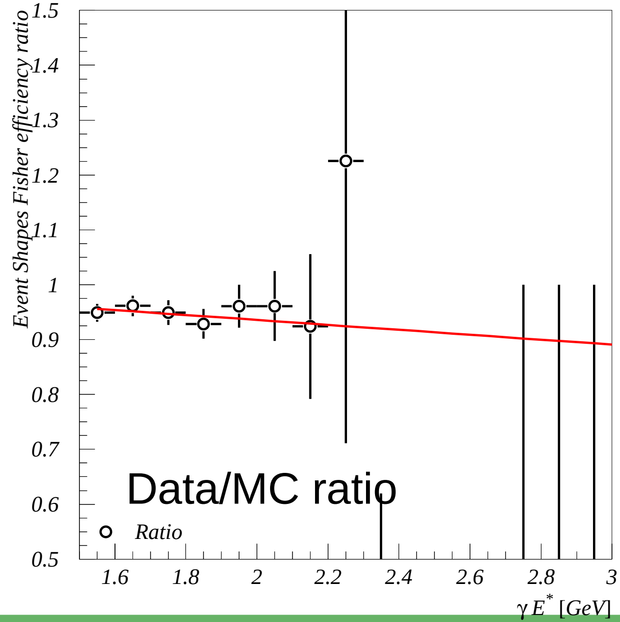
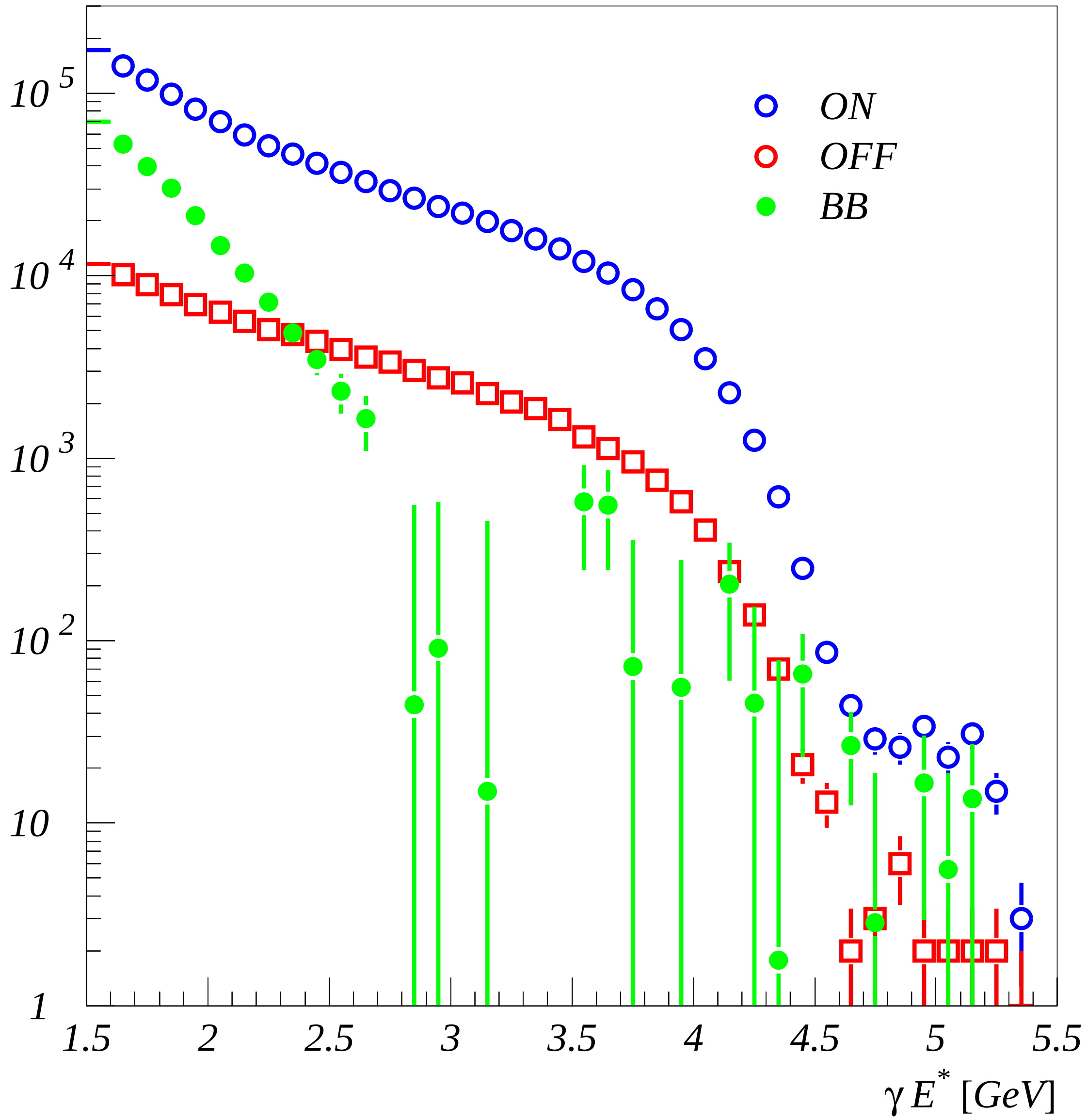
- Isolation cut efficiencies $\to$ main stream
- Calo cluster shapes for photons from anti-veto π^0
- Event shapes: π^0 anti-veto $B\overline{B}$ data (checked with other samples).
- ...and more and more ...



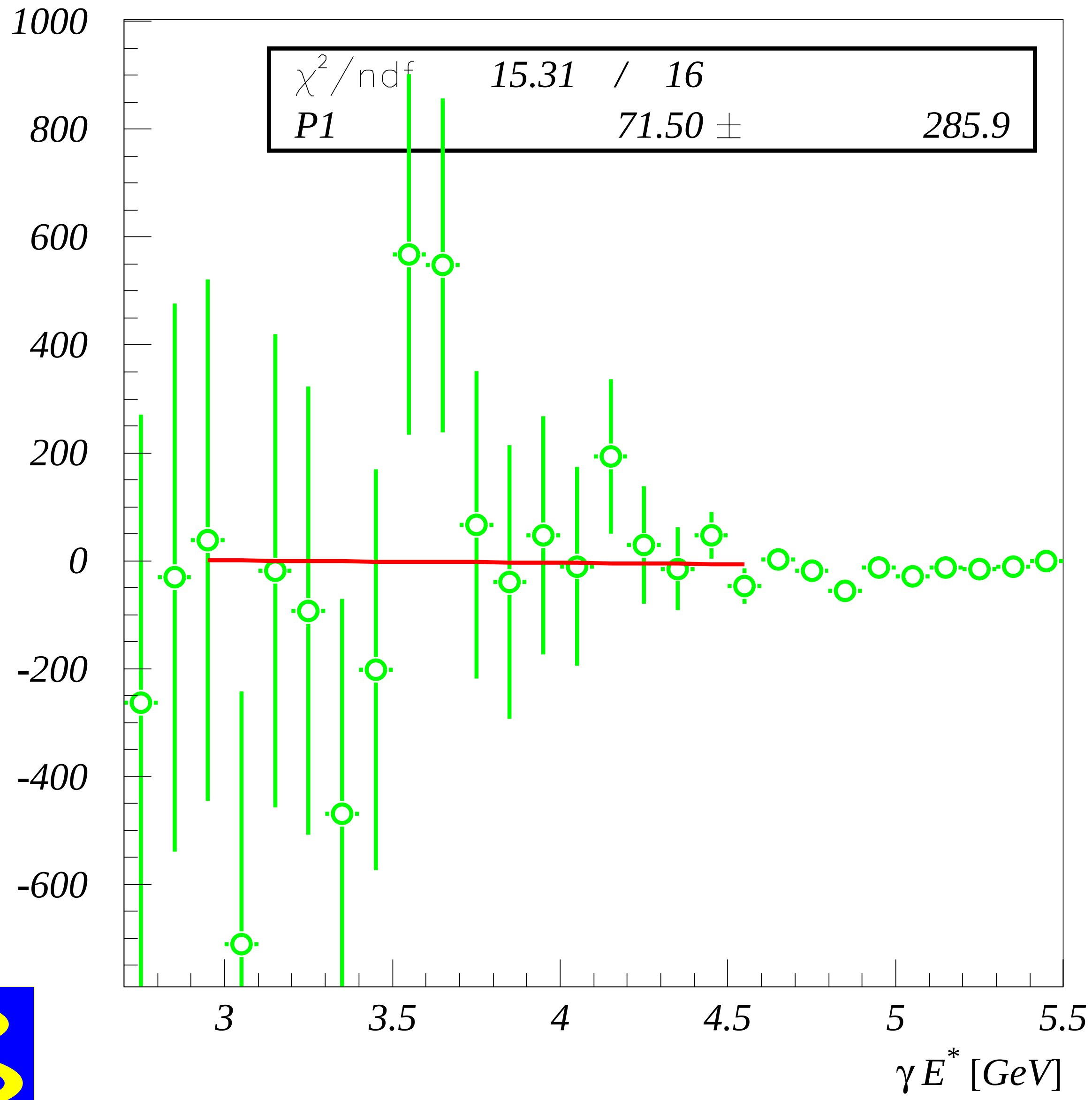


The spectrum



ON, OFF and $B\overline{B}$

The spectrum



Endpoint check:

No significant deviation from 0

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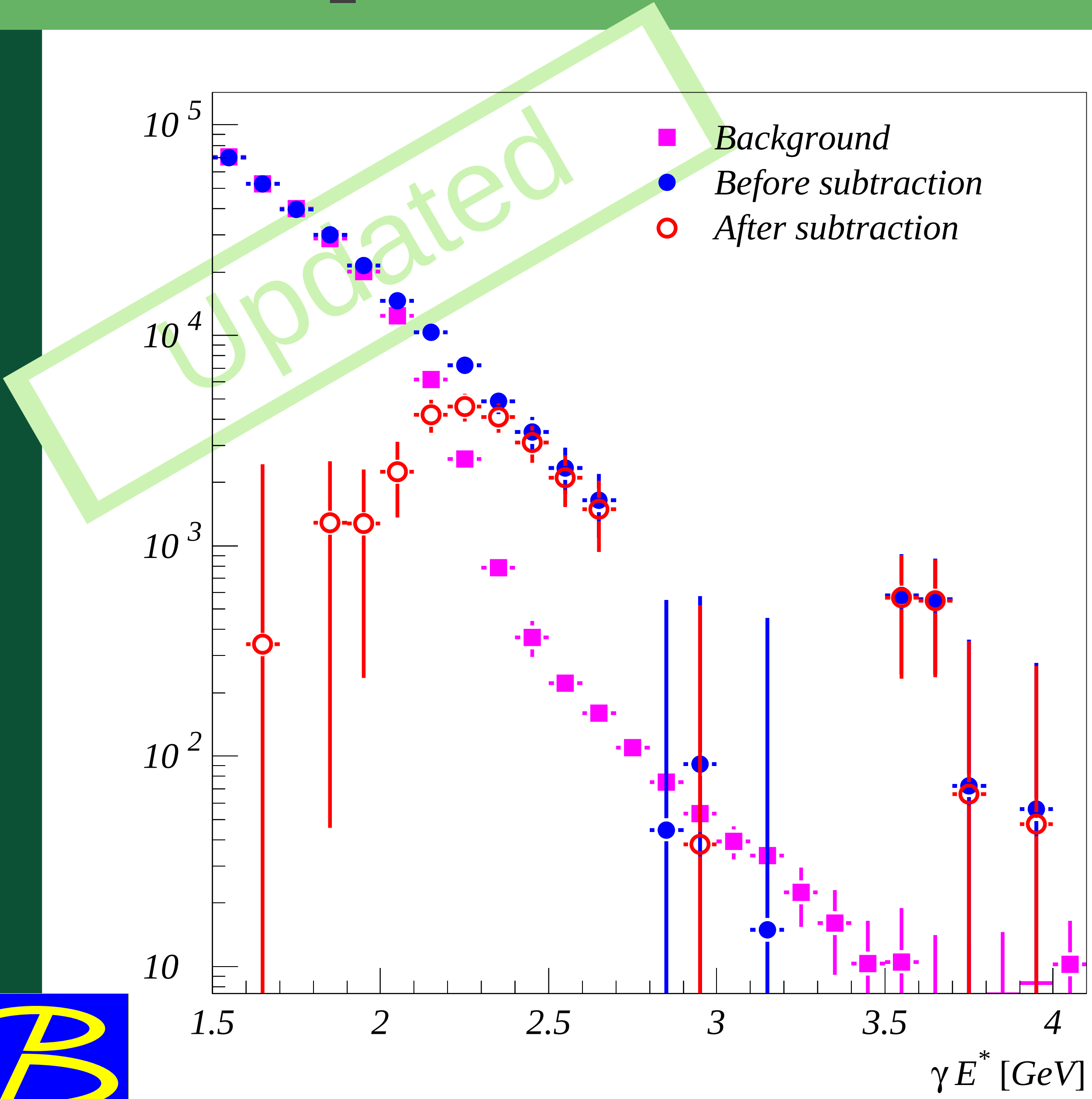
The spectrum



$B\overline{B}$ subtraction.

Using MC and applying all efficiency and yield corrections.

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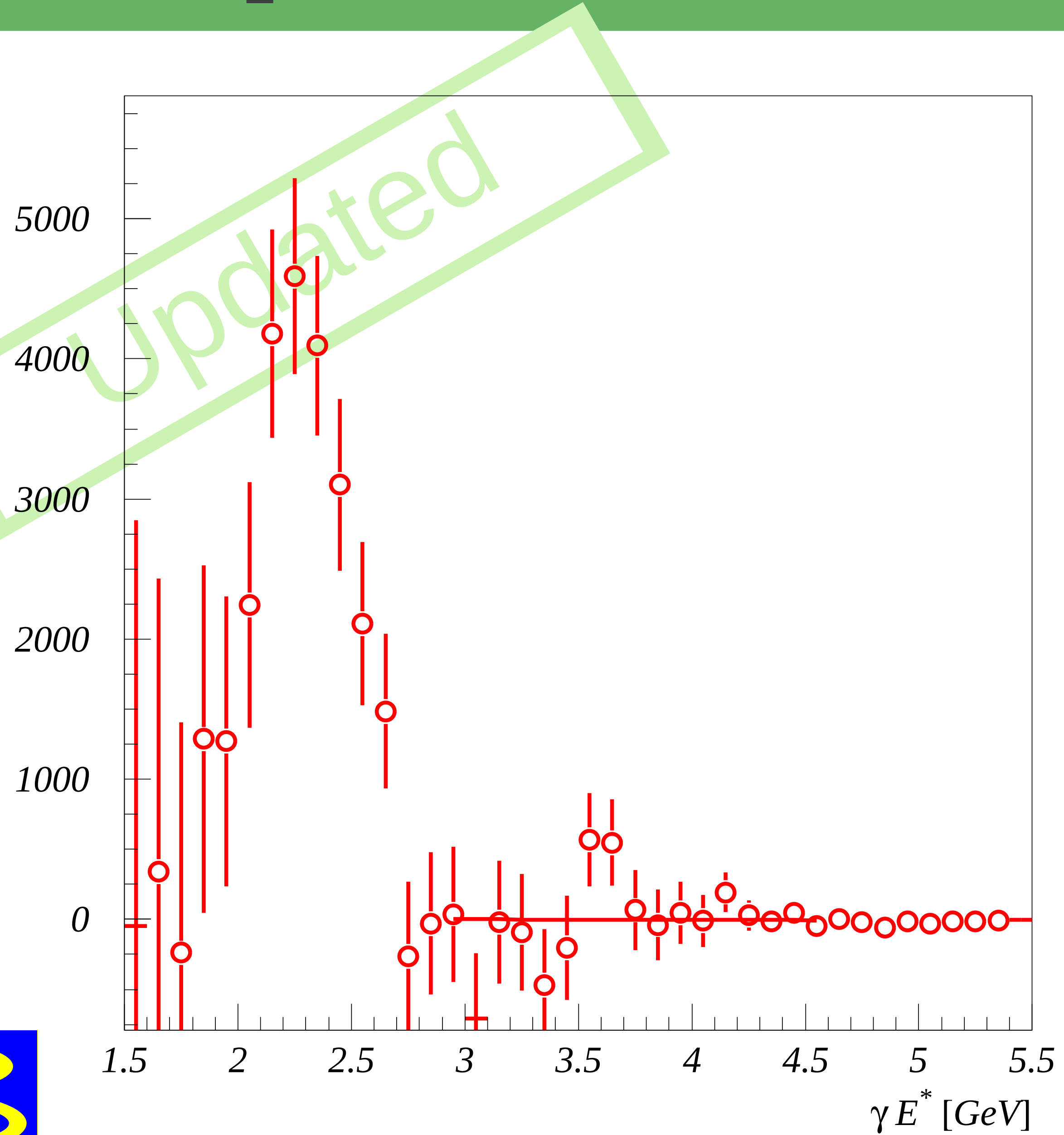
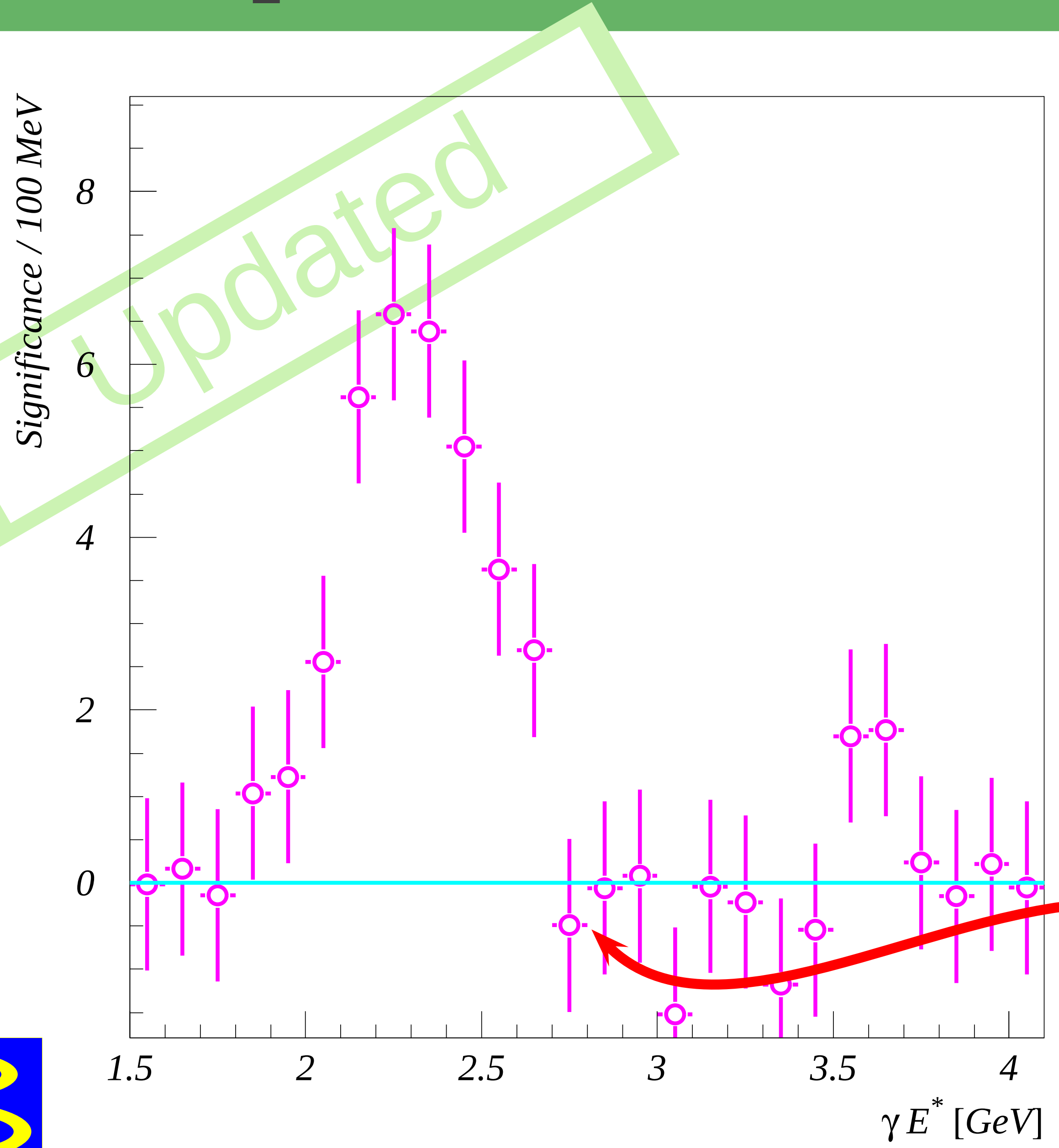
The spectrum



Raw spectrum after all cuts and background corrections

Signal yield:
$\mathbf{24100 \pm 2200}$ events.

The spectrum



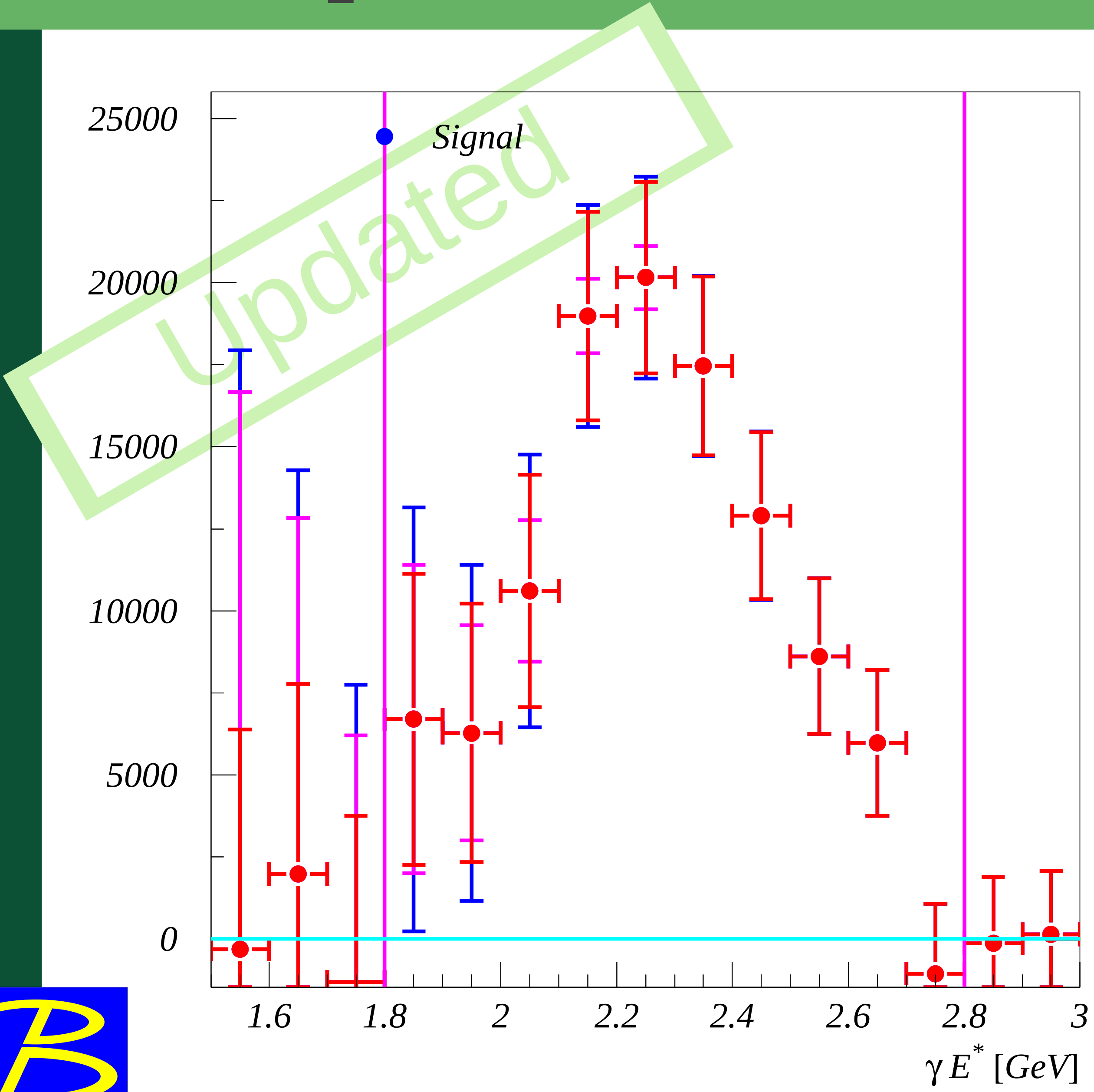
Statistical significance.

Up to 7σ at 2.25 GeV.

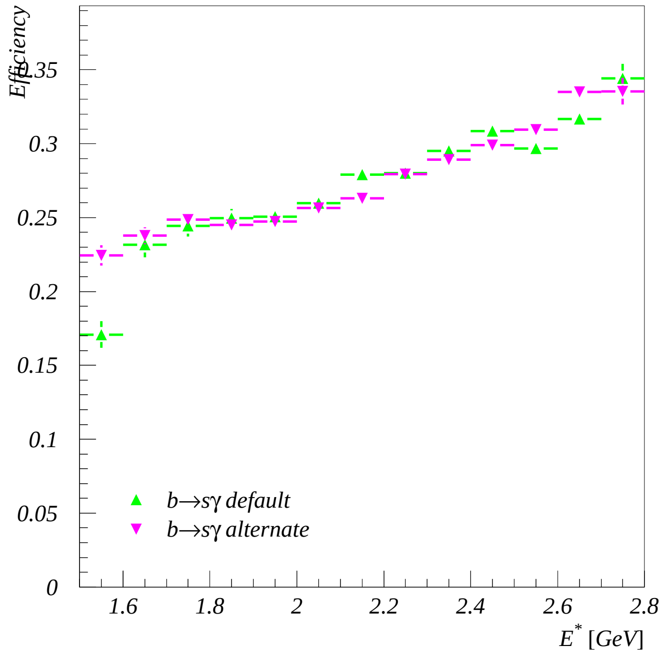
From MC we expect $> 1\sigma$ in 1.8–2.8 GeV.

OK.
Except undershooting in the 2.75 ± 0.05 bin.

The spectrum



Efficiency corrected spectrum.



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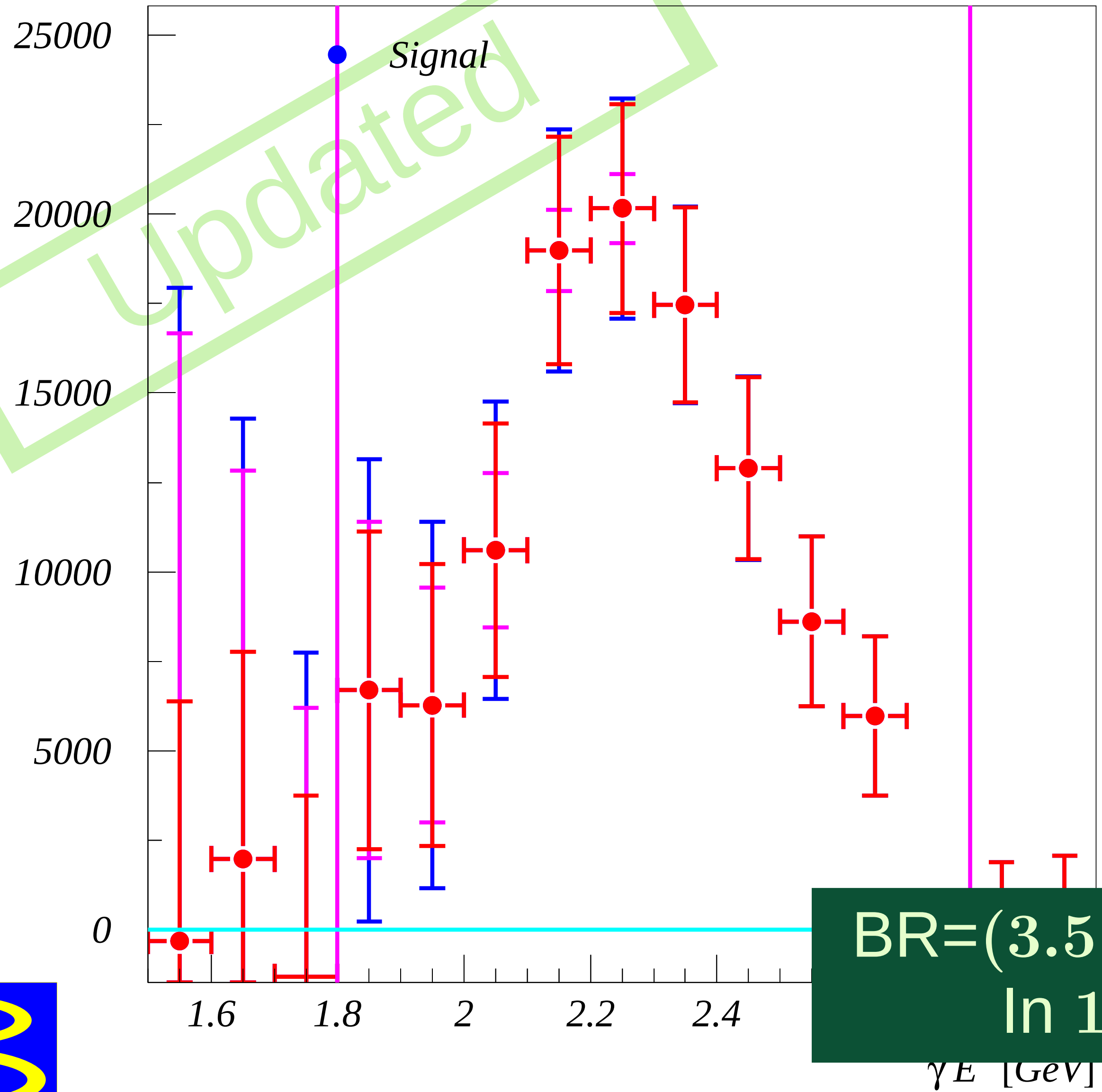
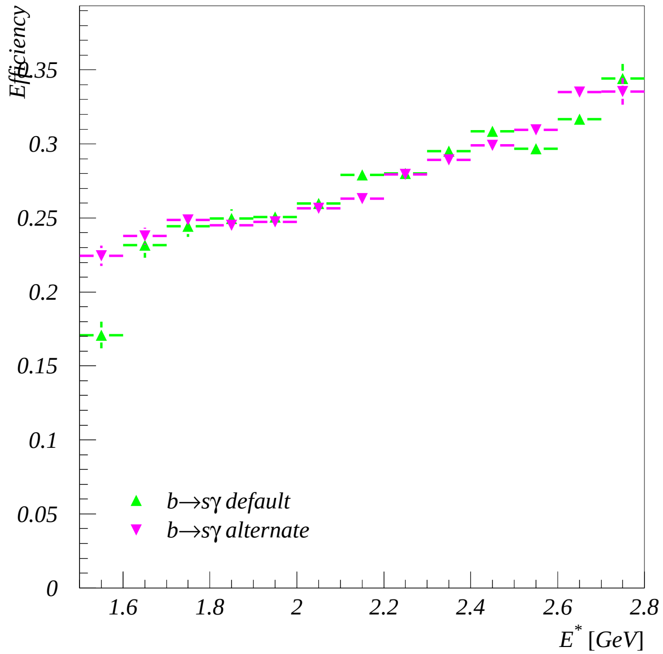
The spectrum



Efficiency corrected spectrum.



BR=$(3.51 \pm 0.32 \pm 0.29) \cdot 10^{-4}$
In 1.8–2.8 GeV range.

Systematics

Source of systematic error	$\times 10^{-4}$
Raw branching fraction	3.51 ± 0.32
Efficiency and yield scaling	± 0.21
Choice of fitting functions	± 0.048
Number of $B\bar{B}$-events $= (152.0 {}^{+0.6}_{-0.7}) \cdot 10^6$	${}^{+0.139}_{-0.160}$
ON-OFF data subtraction	± 0.026
Other $B\bar{B}$ photons	± 0.055
η veto on η	± 0.009
Signal MC	± 0.090
Photon detection efficiency	± 0.073
Energy leakage	${}^{+0.036}_{-0.000}$
Sum for partial $\mathcal{B}(b \to q\gamma)$	${}^{+0.29}_{-0.30}$

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Branching fraction

Raw $b \longrightarrow q\gamma$ in $\mathbf{1.8}$–$\mathbf{2.8}$ GeV: $\quad (\mathbf{3.51 \pm 0.32 \pm 0.29}) \cdot \mathbf{10^{-4}}$

Updated

Branching fraction

Raw $b \longrightarrow q\gamma$ in 1.8–2.8 GeV: $(3.51 \pm 0.32 \pm 0.29) \cdot 10^{-4}$

$\frac{V_{td}}{V_{ts}}$-Corrected [hep-ph/0312260]: $(3.38 \pm 0.31 \,{}^{+\,0.29}_{-\,0.30} \pm 0.02) \cdot 10^{-}$

BELLE

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Updated

Full spectrum:

Kagan-Neubert [PLB539:227]: $(\mathbf{3.53 \pm 0.32\, {}^{+0.30}_{-0.31}\, {}^{+0.11}_{-0.05}}) \cdot \mathbf{10^{-}}$

Bigi-Uraltsev [IJMP A17, 4709]: $(\mathbf{3.56 \pm 0.33\, {}^{+0.30}_{-0.31} \pm 0.04}) \cdot \mathbf{10}$

Gambino-Misiak [NP B611, 338]: $(\mathbf{3.55 \pm 0.32\, {}^{+0.30}_{-0.31}\, {}^{+0.11}_{-0.05}}) \cdot \mathbf{10^{-}}$

Branching fraction

Updated

Raw $b \longrightarrow q\gamma$ in 1.8–2.8 GeV: $(3.51 \pm 0.32 \pm 0.29) \cdot 10^{-4}$

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Gambino-Misiak [NP B611, 338]: $(3.55 \pm 0.32\,^{+\,0.30}_{-\,0.31}\,^{+\,0.11}_{-\,0.05}) \cdot 10^{-4}$

Combined: $(3.55 \pm 0.32\,^{+\,0.30}_{-\,0.31}\,^{+\,0.11}_{-\,0.07}) \cdot 10^{-4}$

We measure $\sim 95\%$ of the full spectrum.

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Comparison

	$\int \mathcal{L}$	Method	$\mathrm{BR} \times 10^{-4}$
CLEO '95	3 fb^{-1}	$K n\pi$	$2.32 \pm 0.57 \pm 0.35$
Aleph '98	$Z \to b\bar{b}$		$3.11 \pm 0.80 \pm 0.72$
Belle '01	6 fb^{-1}	$K n\pi$	$3.36 \pm 0.53 \pm 0.42 {}^{+0.50}_{-0.54}$
CLEO '01	9 fb^{-1}	Inclusive	$3.21 \pm 0.43 \pm 0.27 {}^{+0.18}_{-0.10}$
(BaBar '02)	54 fb^{-1}	Inclusive	$3.88 \pm 0.36 \pm 0.37 {}^{+0.43}_{-0.23}$
Belle '04	140 fb^{-1}	Inclusive	$3.55 \pm 0.32 {}^{+0.30}_{-0.31} {}^{+0.11}_{-0.07}$
Theory	[Hurth, Lunghi, Porod, hep-ph/0312260]		$3.79 {}^{+0.36}_{-0.53}$

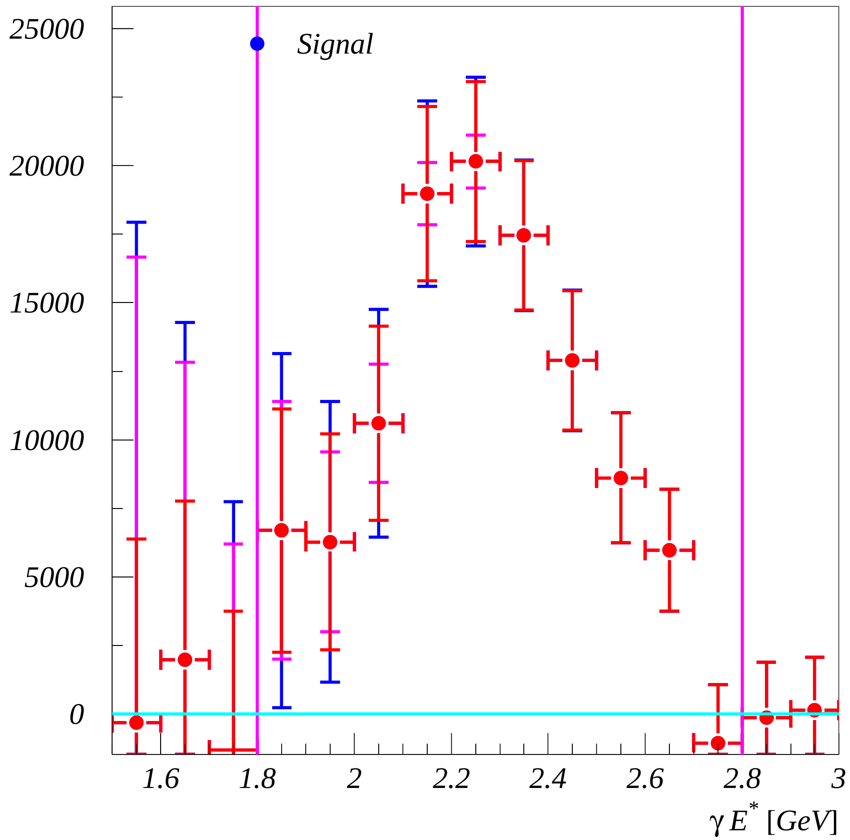
Moments

Raw:

$$\langle E_\gamma \rangle = 2.252 \pm 0.026 \pm 0.020\ \mathrm{GeV}$$
$$\left\langle E_\gamma^2 \right\rangle - \langle E_\gamma \rangle^2 = 0.0413 \pm 0.0074 \pm 0.0055\ \mathrm{GeV}^2$$

Correct for:

- Energy resolution (biases mean and broadens)
- B boost (shifts and broadens)
- $100\ \mathrm{MeV}$ binning (negligible)



Moments

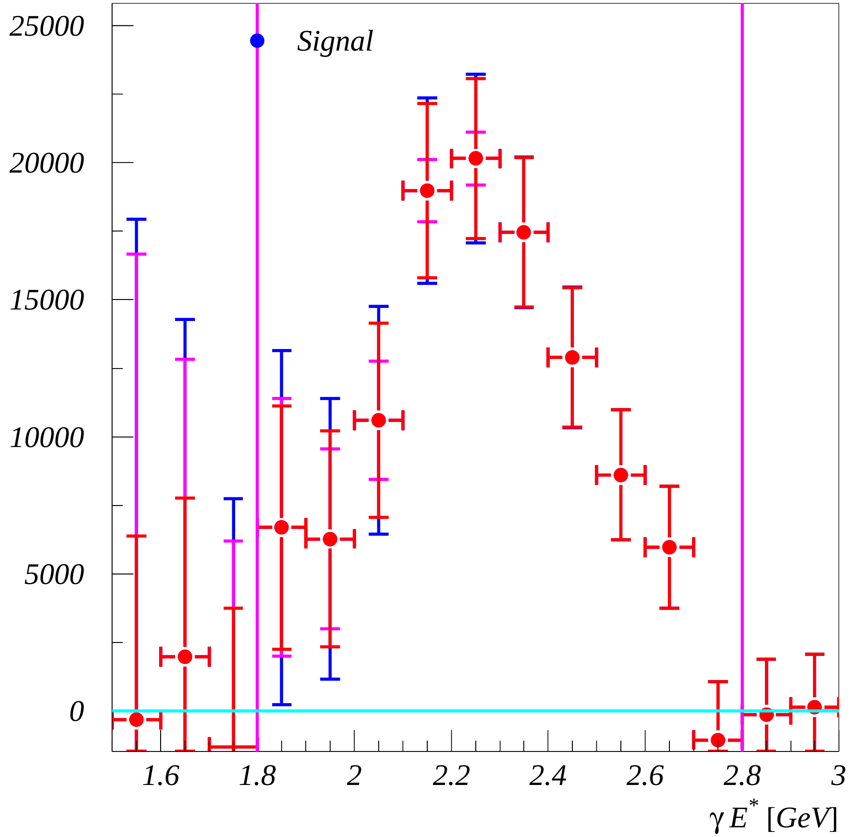
Belle:

$$\langle E_\gamma \rangle = 2.292 \pm 0.026 \pm 0.034 \text{ GeV}$$

$$\left\langle E_\gamma^2 \right\rangle - \langle E_\gamma \rangle^2 = 0.0305 \pm 0.0074 \pm 0.0063 \text{ GeV}^2$$

Correct for:

- Energy resolution (biases mean and broadens)
- B boost (shifts and broadens)
- 100 MeV binning (negligible)



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Moments

Belle:

$$\langle E_\gamma \rangle = 2.292 \pm 0.026 \pm 0.034 \text{ GeV}$$
$$\left\langle E_\gamma^2 \right\rangle - \langle E_\gamma \rangle^2 = 0.0305 \pm 0.0074 \pm 0.0063 \text{ GeV}^2$$

CLEO:

$$\langle E_\gamma \rangle = 2.346 \pm 0.032 \pm 0.011 \text{ GeV}$$
$$\left\langle E_\gamma^2 \right\rangle - \langle E_\gamma \rangle^2 = 0.0226 \pm 0.0066 \pm 0.0020 \text{ GeV}^2.$$

Conclusion

- Inclusive measurement of $b \longrightarrow s\gamma$ at Belle.
  - For the first time $E^* > 1.8\ \mathrm{GeV}$
  - BR: $\left(3.55 \pm 0.32\,{}^{+\,0.30}_{-\,0.31}\,{}^{+\,0.11}_{-\,0.07}\right) \cdot 10^{-4}$
  - Moments: $\langle E \rangle = 2.292 \pm 0.026 \pm 0.034\ \mathrm{GeV}$,
  - $\langle E^2 \rangle - \langle E \rangle^2 = 0.0305 \pm 0.0074 \pm 0.0063\ \mathrm{GeV}^2$

Conclusion

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  - For the first time $E^* > 1.8\ \mathrm{GeV}$
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  - $\langle E^2 \rangle - \langle E \rangle^2 = 0.0305 \pm 0.0074 \pm 0.0063\ \mathrm{GeV}^2$

- First evidence for $b \to d\gamma$
  - $\mathrm{BR}(B \to (\rho, \omega)\gamma) = \left(1.8\,^{+0.6}_{-0.5} \pm 0.1\right) \cdot 10^{-6}$

Conclusion

- Inclusive measurement of $b \longrightarrow s\gamma$ at Belle.
  - For the first time $E^* > 1.8\ \mathrm{GeV}$
  - BR: $\left(3.55 \pm 0.32\, {}^{+\,0.30}_{-\,0.31}\, {}^{+\,0.11}_{-\,0.07}\right) \cdot 10^{-4}$
  - Moments: $\langle E \rangle = 2.292 \pm 0.026 \pm 0.034\ \mathrm{GeV}$,
  - $\langle E^2 \rangle - \langle E \rangle^2 = 0.0305 \pm 0.0074 \pm 0.0063\ \mathrm{GeV}^2$
- First evidence for $b \longrightarrow d\gamma$
  - $\mathrm{BR}(B \longrightarrow (\rho, \omega)\gamma) = \left(1.8\, {}^{+0.6}_{-0.5} \pm 0.1\right) \cdot 10^{-6}$
- No CP violation in $B \longrightarrow X_s\gamma$
  - $A_{\mathrm{CP}}(m_{X_s} < 2.1\ \mathrm{GeV}/c^2) = (0.2 \pm 5.0 \pm 3.0)\ \%$

Conclusion

- Inclusive measurement of $b \to s$
  - For the first time $E^* >$
  - BR: $\big(3.55 \pm$
  - M
-
  - $\big(\; ^{+0.6}_{-0.5} \pm 0.1\big) \cdot 10^{-6}$
- No ion in $B \to X_s\gamma$
  - $A_{CP}(m_{X_s} < 2.1\,\mathrm{GeV}/c^2) = (0.2 \pm 5.0 \pm 3.0)\,\%$

These are results using $140\ \mathrm{fb}^{-1}$.

We have $235\ \mathrm{fb}^{-1}$ now...

and we'll have much more by this summer

Backup Slides

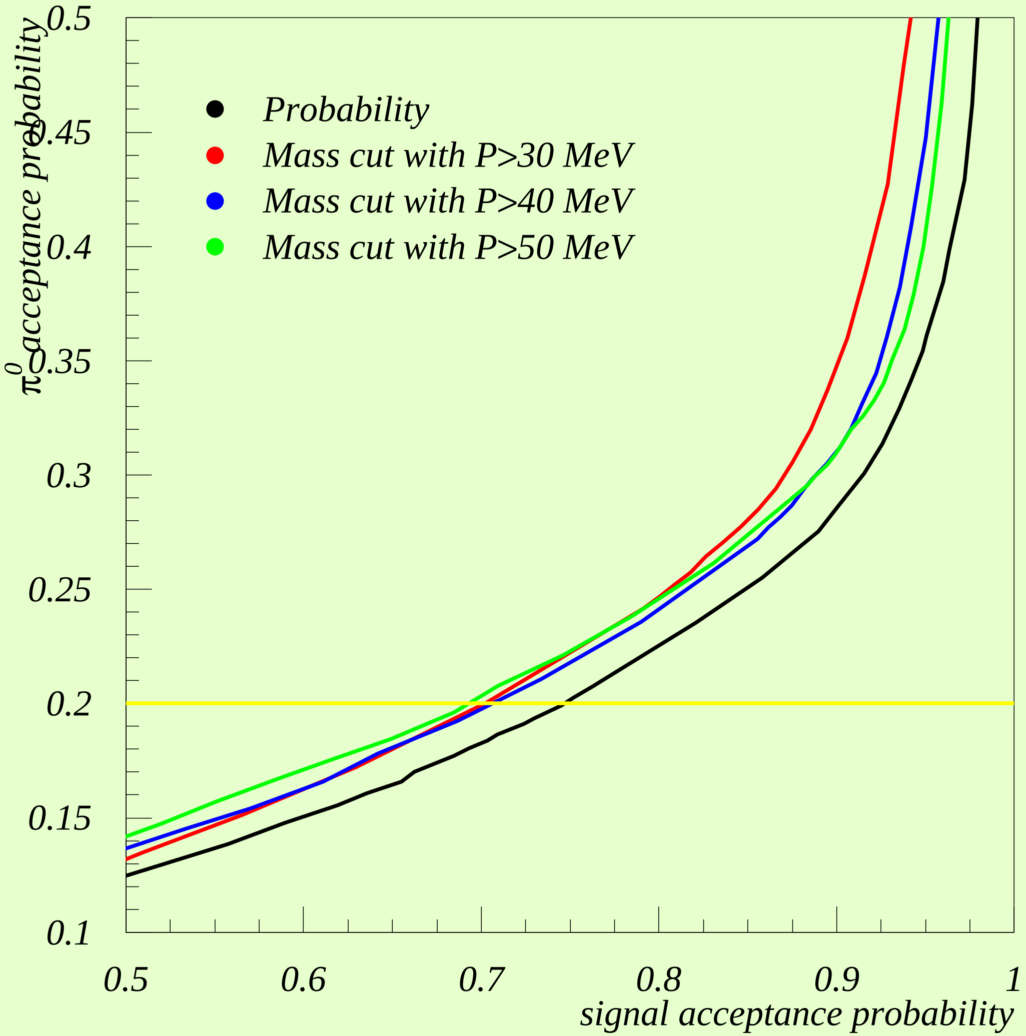
Fully Inclusive $b \longrightarrow s\gamma$

[Koppenburg et al., hep-ex/0403004]

Selection cuts

- Photons passing good_gamma with $\boldsymbol{E_9/E_{25} > 0.95}$
  - $\boldsymbol{E^* > 1.5\,\mathrm{GeV}}$ and $\boldsymbol{-0.5 < \cos\theta < 0.88}$

Selection cuts



A better π^0 veto

Based on 2D E_γ–$m_{\gamma\gamma}$ probabilities

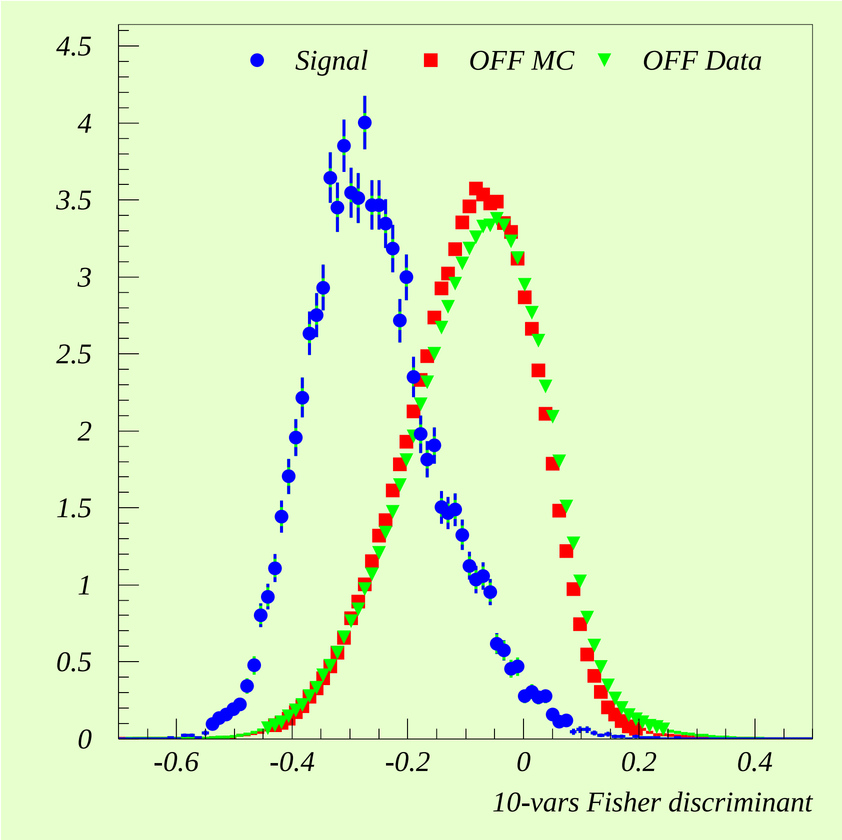
Code and documentation: see Belle Note 665.

Selection cuts

- Photons passing good_gamma with $\boldsymbol{E_9/E_{25} > 0.95}$
  - $\boldsymbol{E^* > 1.5\,\mathrm{GeV}}$ and $\boldsymbol{-0.5 < \cos\theta < 0.88}$
- $\boldsymbol{\pi^0}$, $\boldsymbol{\eta}$ veto: $\boldsymbol{\mathcal{P}_{\pi^0} < 0.10}$ and $\boldsymbol{\mathcal{P}_\eta < 0.20}$

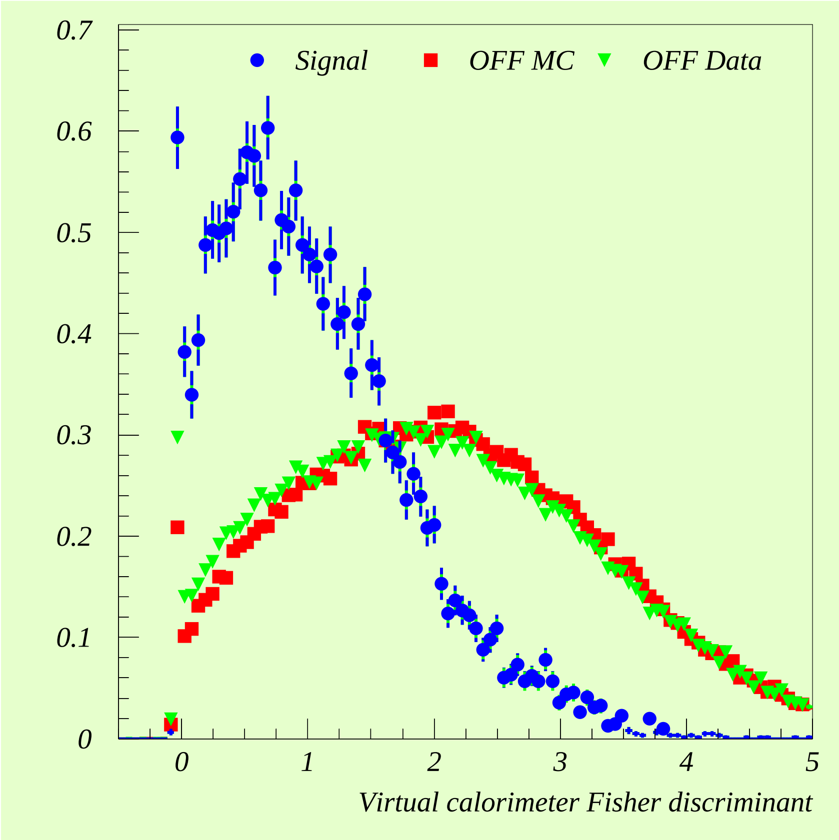
Selection cuts

- Photons passing good_gamma with $E_9/E_{25} > 0.95$
  - $E^* > 1.5\ \mathrm{GeV}$ and $-0.5 < \cos\theta < 0.88$
- π^0, η veto: $\mathcal{P}_{\pi^0} < 0.10$ and $\mathcal{P}_\eta < 0.20$
- Event Shapes: $F_{\mathrm{ES}} < -0.28$



Selection cuts

- Photons passing good_gamma with $E_9/E_{25} > 0.95$
  - $E^* > 1.5\ \mathrm{GeV}$ and $-0.5 < \cos\theta < 0.88$
- π^0, η veto: $\mathcal{P}_{\pi^0} < 0.10$ and $\mathcal{P}_\eta < 0.20$
- Event Shapes: $F_{\mathrm{ES}} < -0.28$
- Virtual Calo: $F_{\mathrm{VC}} < -2.0$



Selection cuts

- Photons passing good_gamma with $E_9/E_{25} > 0.95$
  - $E^* > 1.5\ \mathrm{GeV}$ and $-0.5 < \cos\theta < 0.88$
- π^0, η veto: $\mathcal{P}_{\pi^0} < 0.10$ and $\mathcal{P}_\eta < 0.20$
- Event Shapes: $F_{\mathrm{ES}} < -0.28$
- Virtual Calo: $F_{\mathrm{VC}} < -2.0$
- No lepton cuts!

Selection cuts

- Photons passing good_gamma with $E_9/E_{25} > 0.95$
  - $E^* > 1.5\ \mathrm{GeV}$ and $-0.5 < \cos\theta < 0.88$
- π^0, η veto: $\mathcal{P}_{\pi^0} < 0.10$ and $\mathcal{P}_\eta < 0.20$
- Event Shapes: $F_{\mathrm{ES}} < -0.28$
- Virtual Calo: $F_{\mathrm{VC}} < -2.0$
- No lepton cuts!
- Isolation cuts

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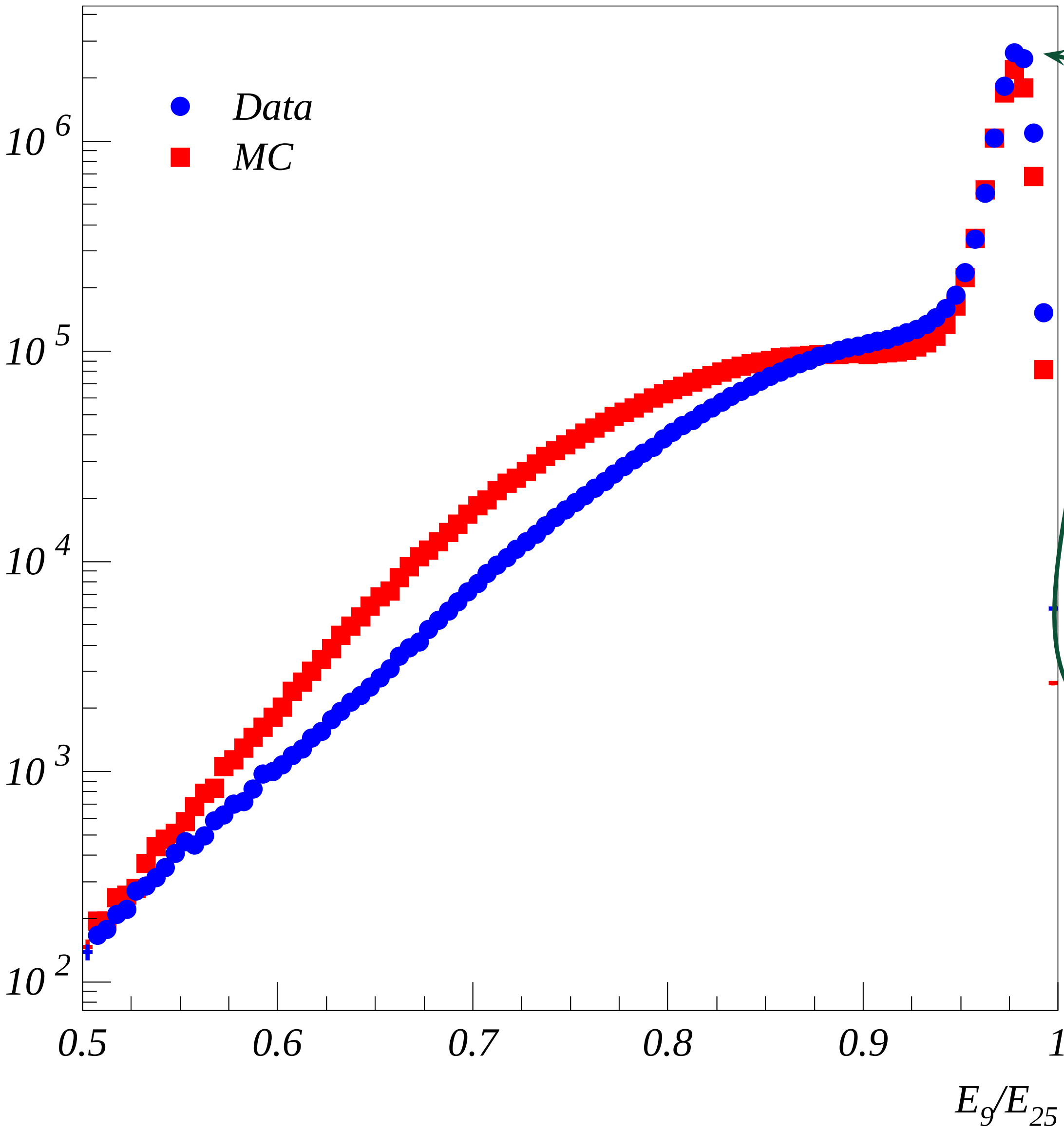
E_9/E_{25} Cluster shape

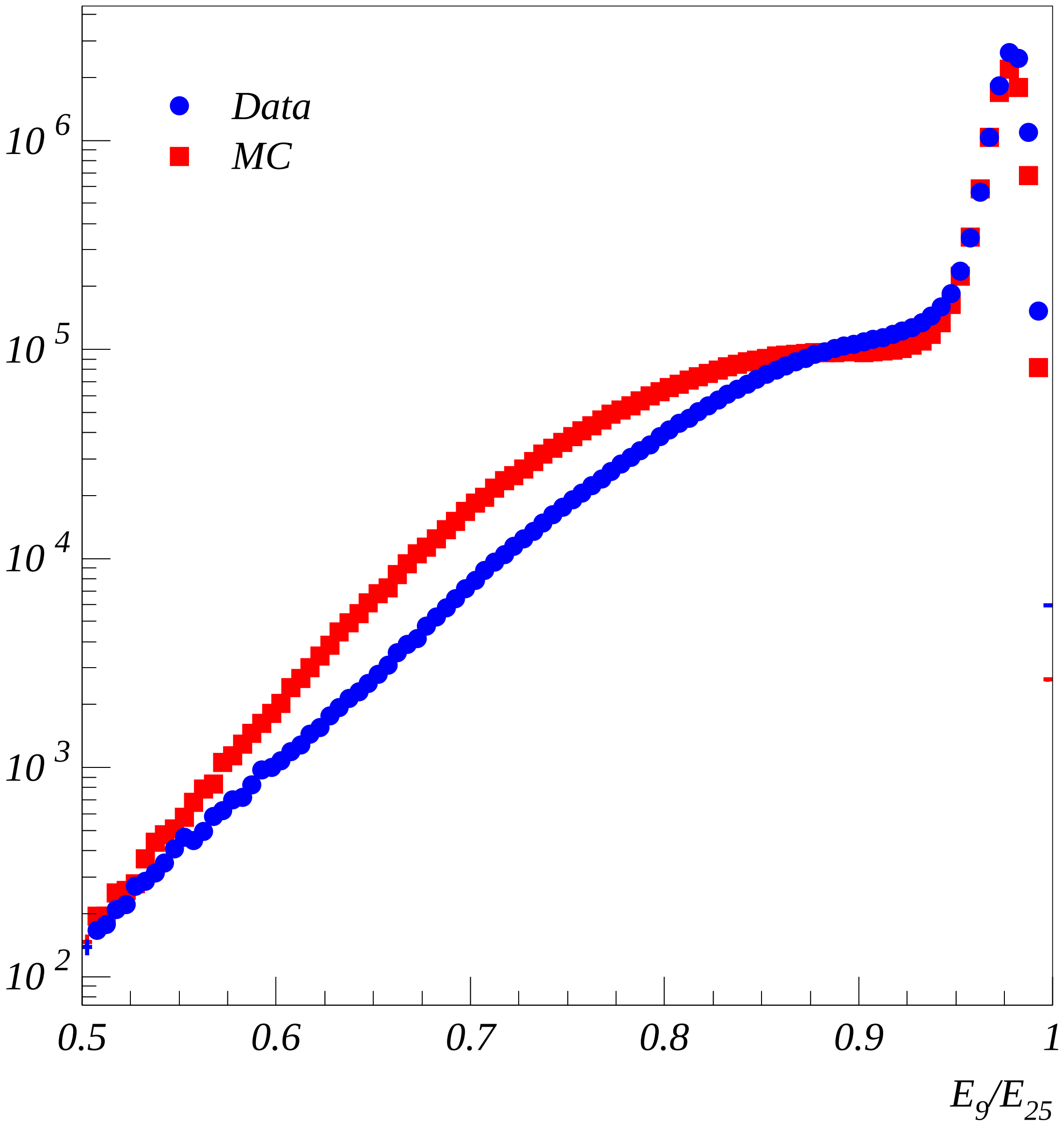


E_9: Energy deposited in 3×3 cells around cluster centre.

E_{25}: Energy deposited in 5×5 cells around cluster centre.

For photons, the ratio is close to 1.
Hence one requires $E_9/E_{25} > 0.95$.

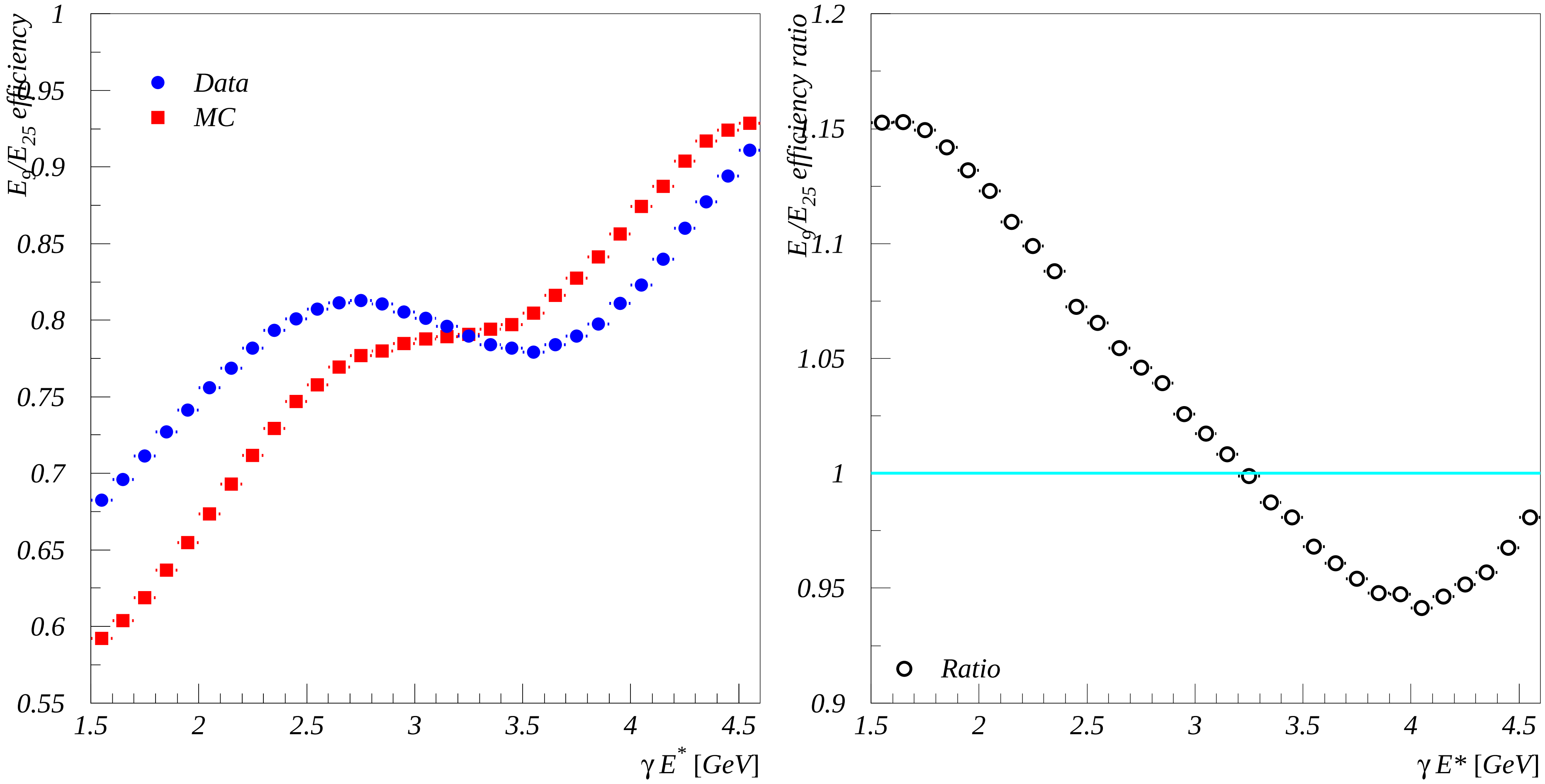
E_9/E_{25} Cluster shape



After π^0, η vetoes and isolation cuts

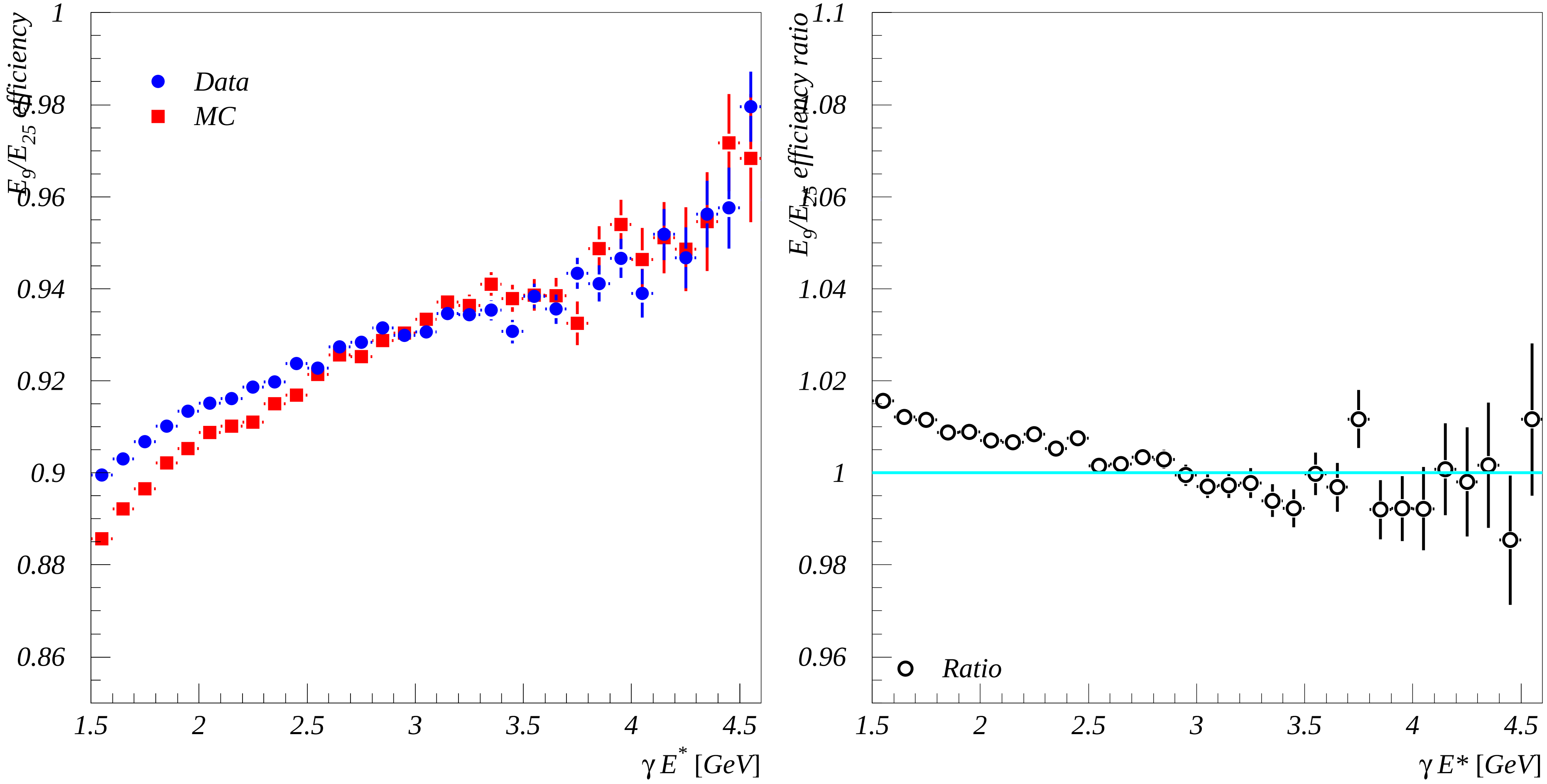
- The E_9/E_{25} distributions in data and MC are very different

E_9/E_{25} efficiency



E_9/E_{25} cut η in all ON events after isolation and vetoes

E_9/E_{25} efficiency



E_9/E_{25} cut η in π^0 anti-veto events

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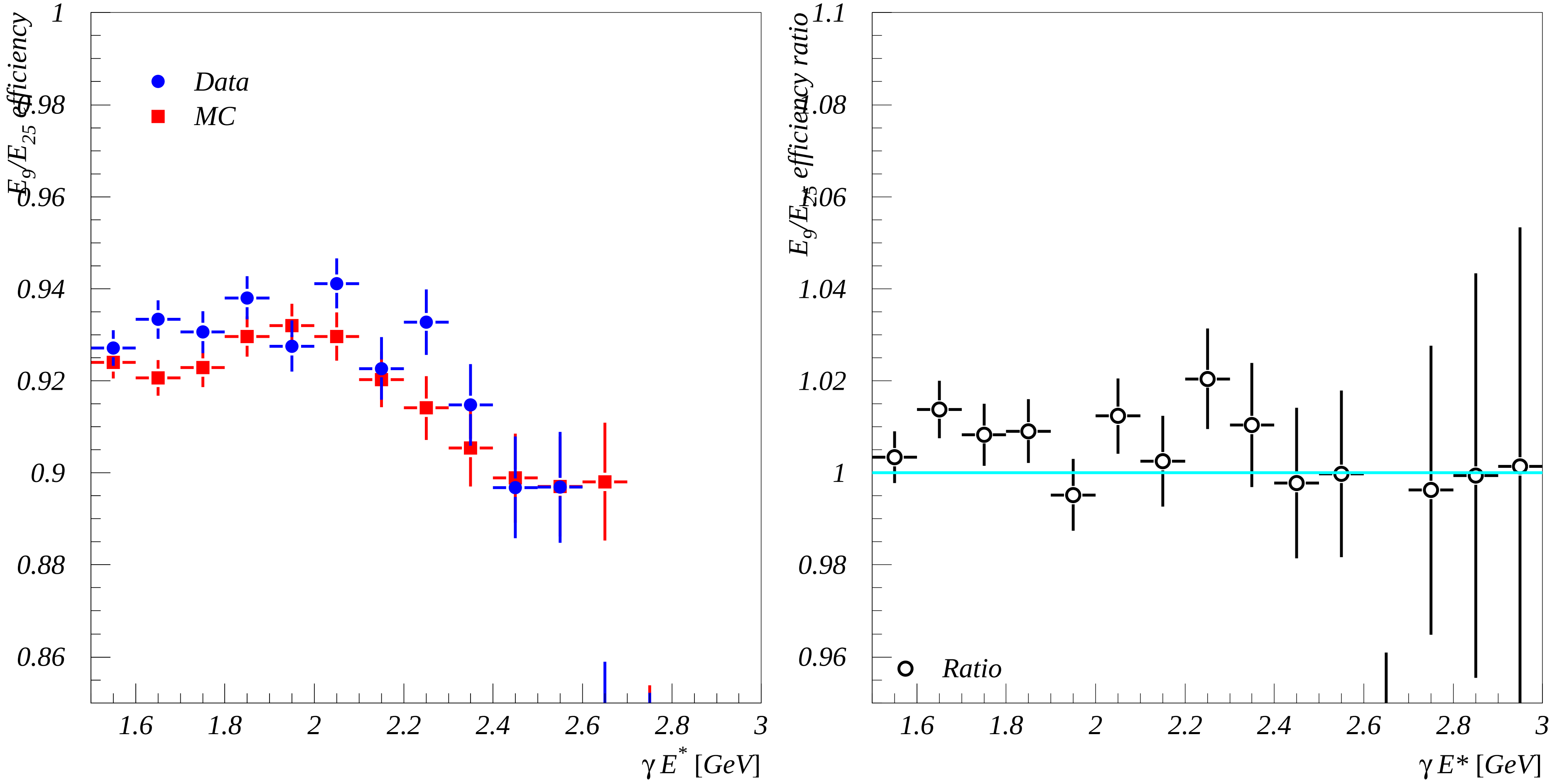
E_9/E_{25} efficiency



E_9/E_{25} cut η in partially reconstructed D events

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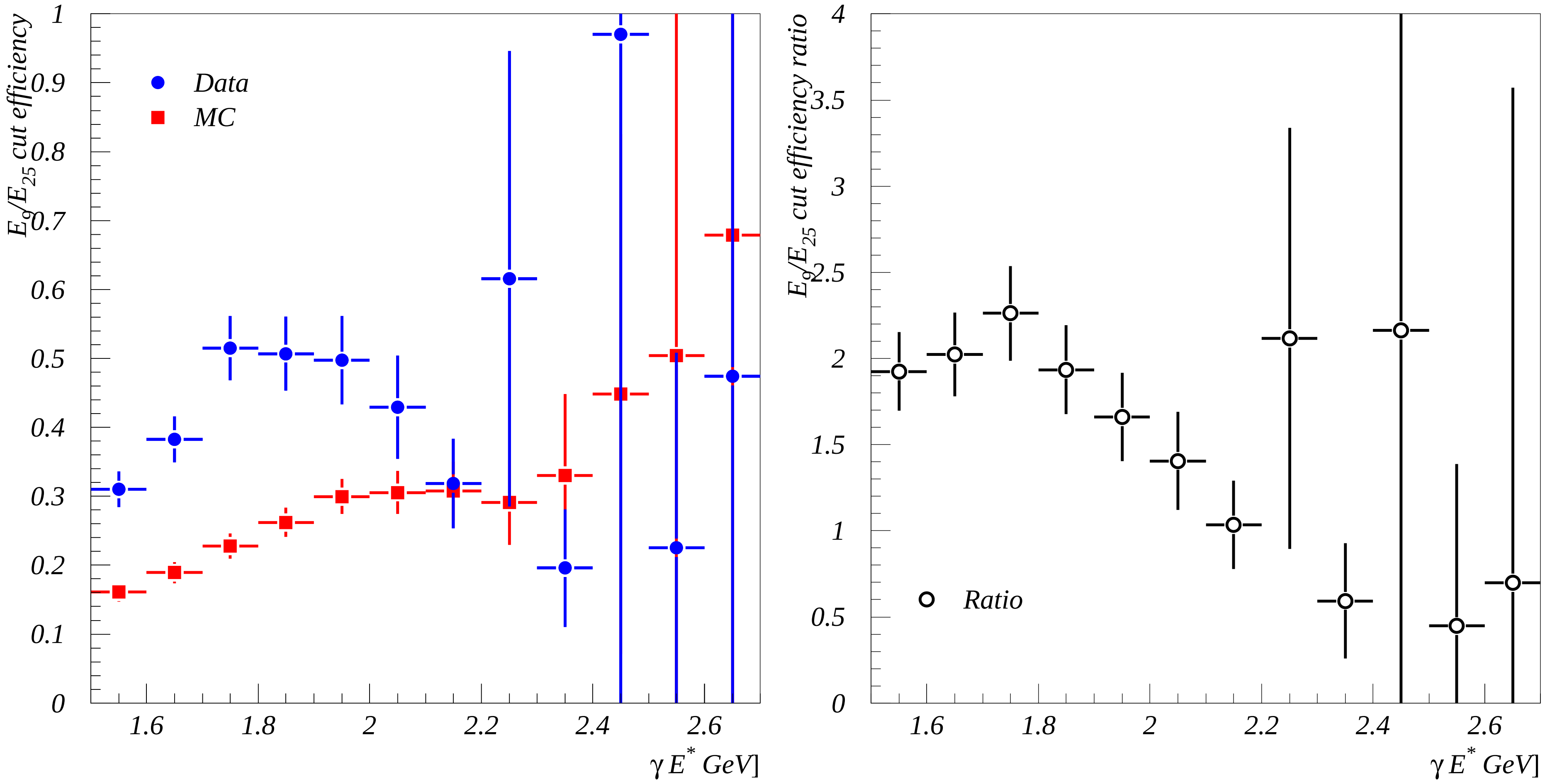
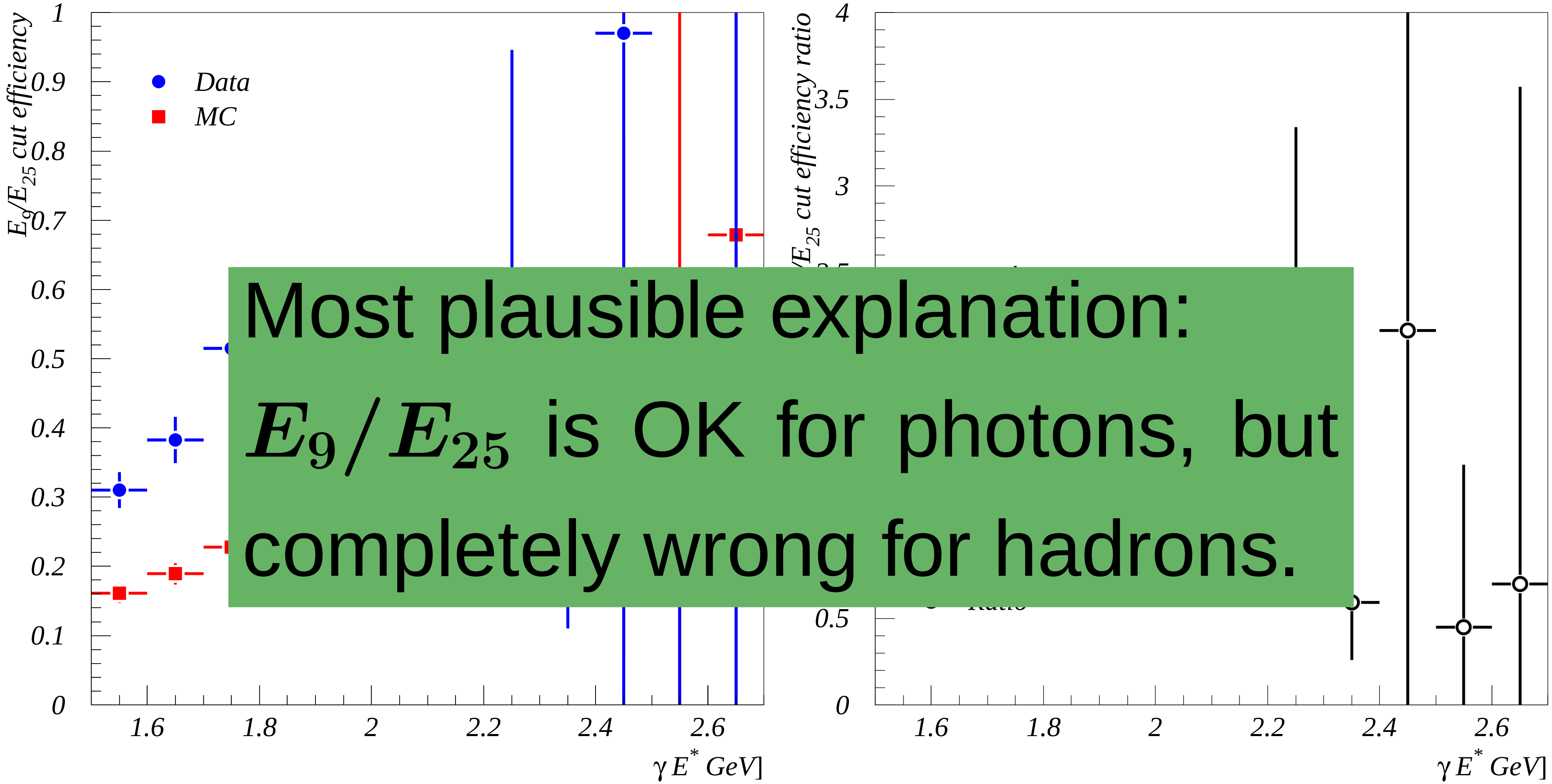
E_9/E_{25} efficiency



E_9/E_{25} cut η in γ-subtracted $B\overline{B}$ events

E_9/E_{25} efficiency



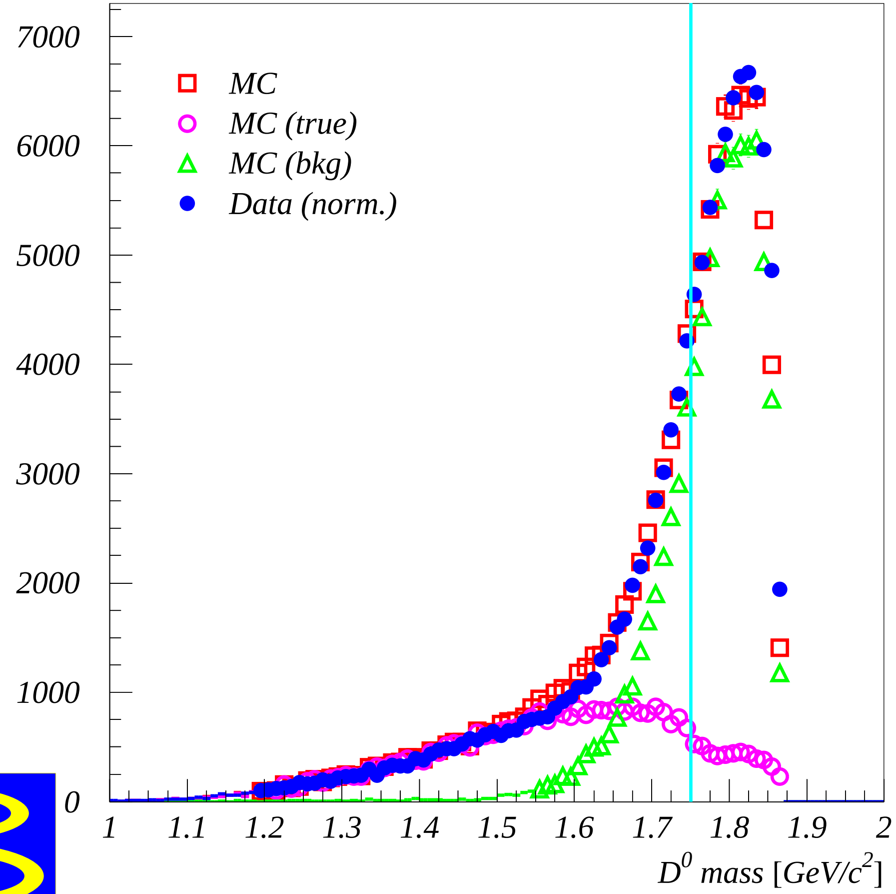
Most plausible explanation:
E_9/E_{25} is OK for photons, but completely wrong for hadrons.

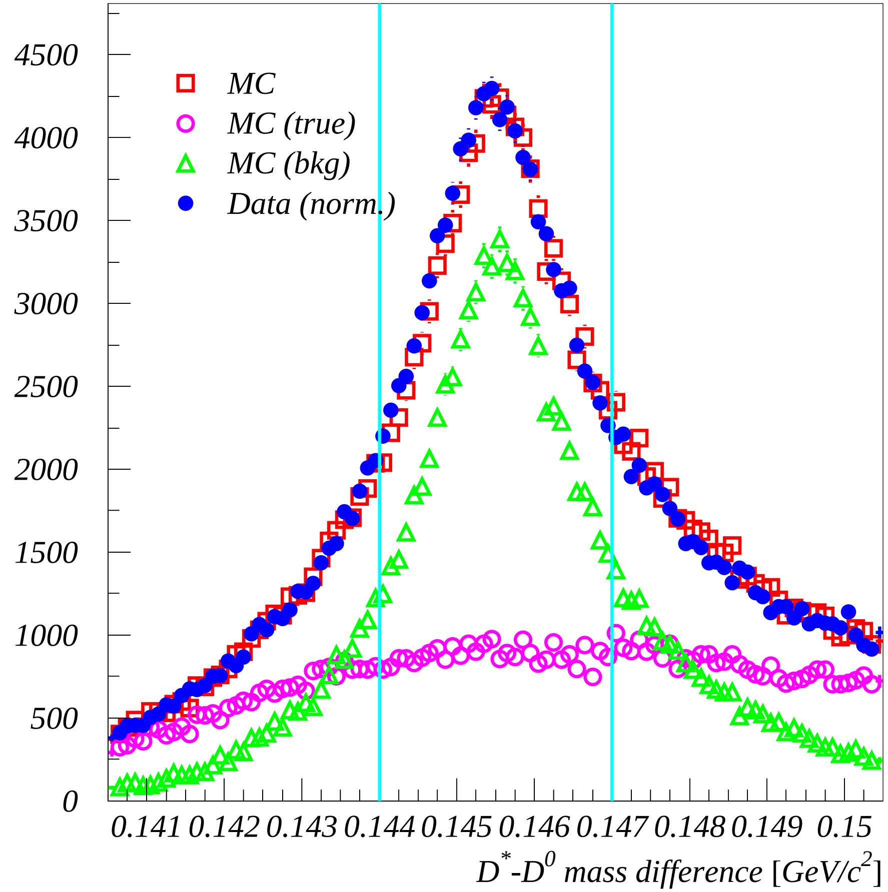
E_9/E_{25} cut η in γ-subtracted $B\overline{B}$ events

π^0 partial reconstruction

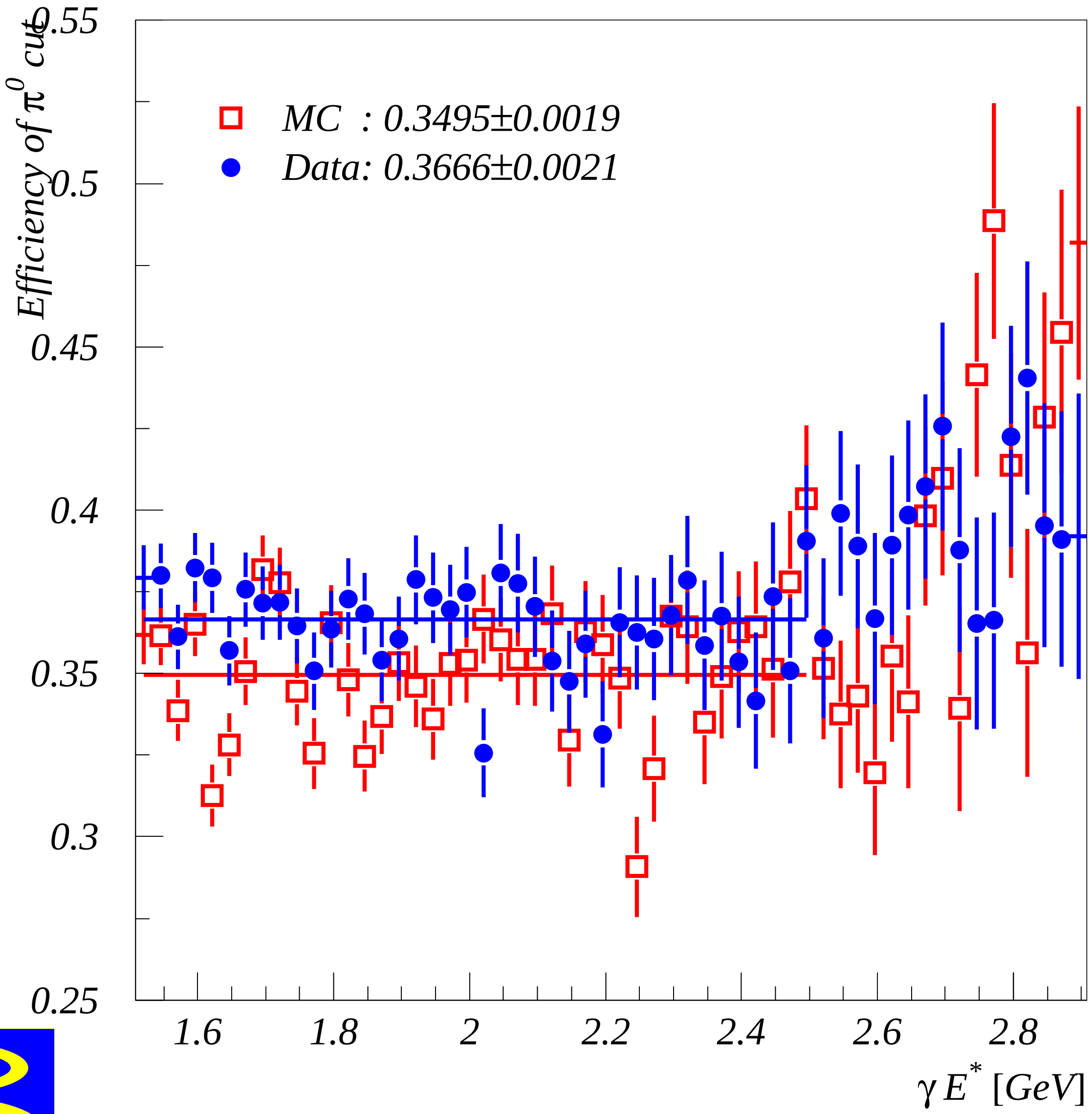
Decay chain $D^* \to \pi D^0$, $D^0 \to \pi^+ K^- \pi^0$ (BR=13%)
Partially reconstructed as $\pi^+\pi^+K^-\gamma$

Gets a too low D^0 mass. . . . . . but the right $D^* - D^0$ mass.





π^0 partial reconstruction

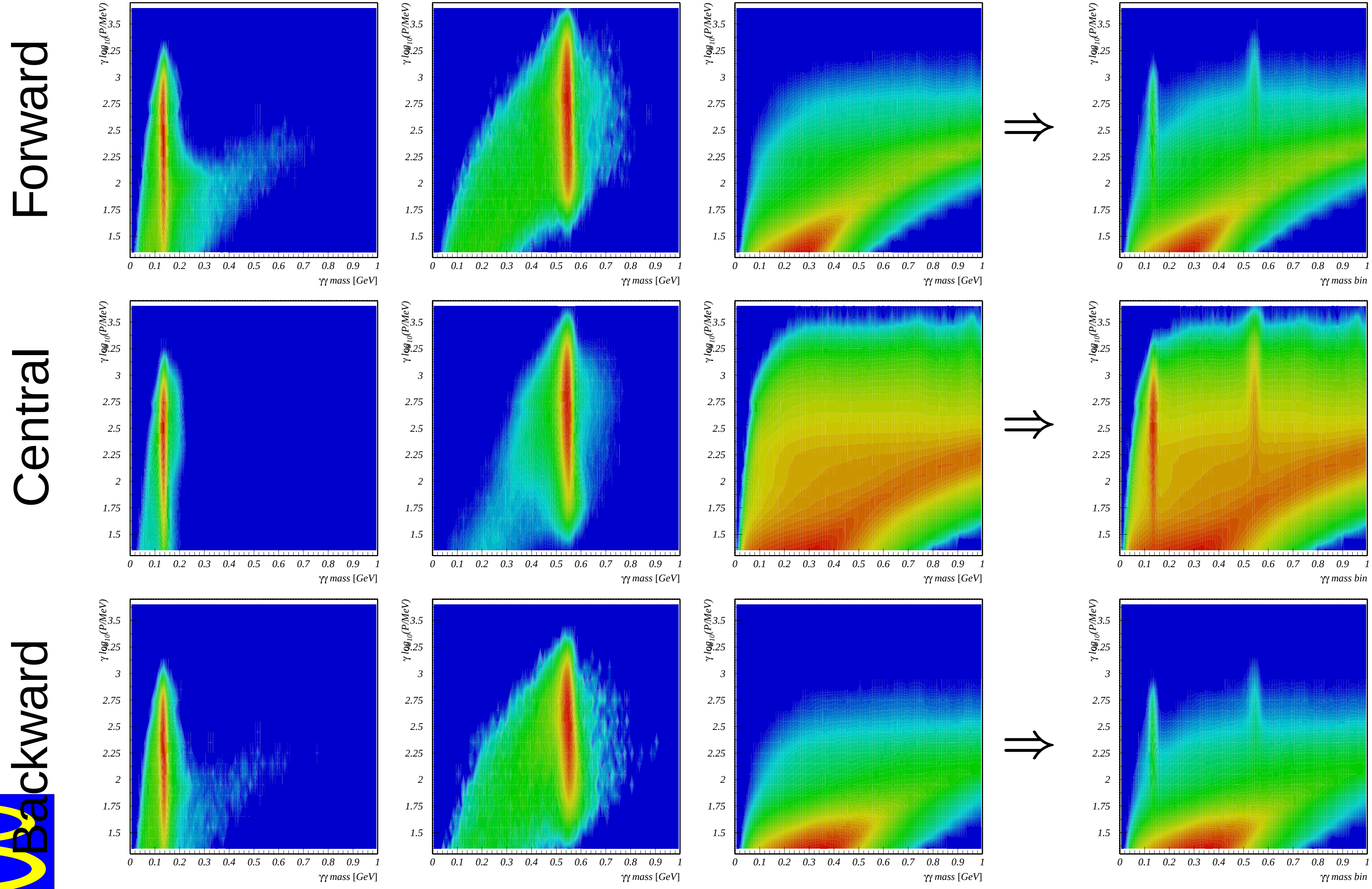


Clean $\pi^0 \to \gamma$ sample:

- The efficiency of the π^0 probability cut is flat versus the γ E^*
- there is a significant difference between data and MC.

$\Rightarrow$ ToyMC

π^0, η, background and sum densities



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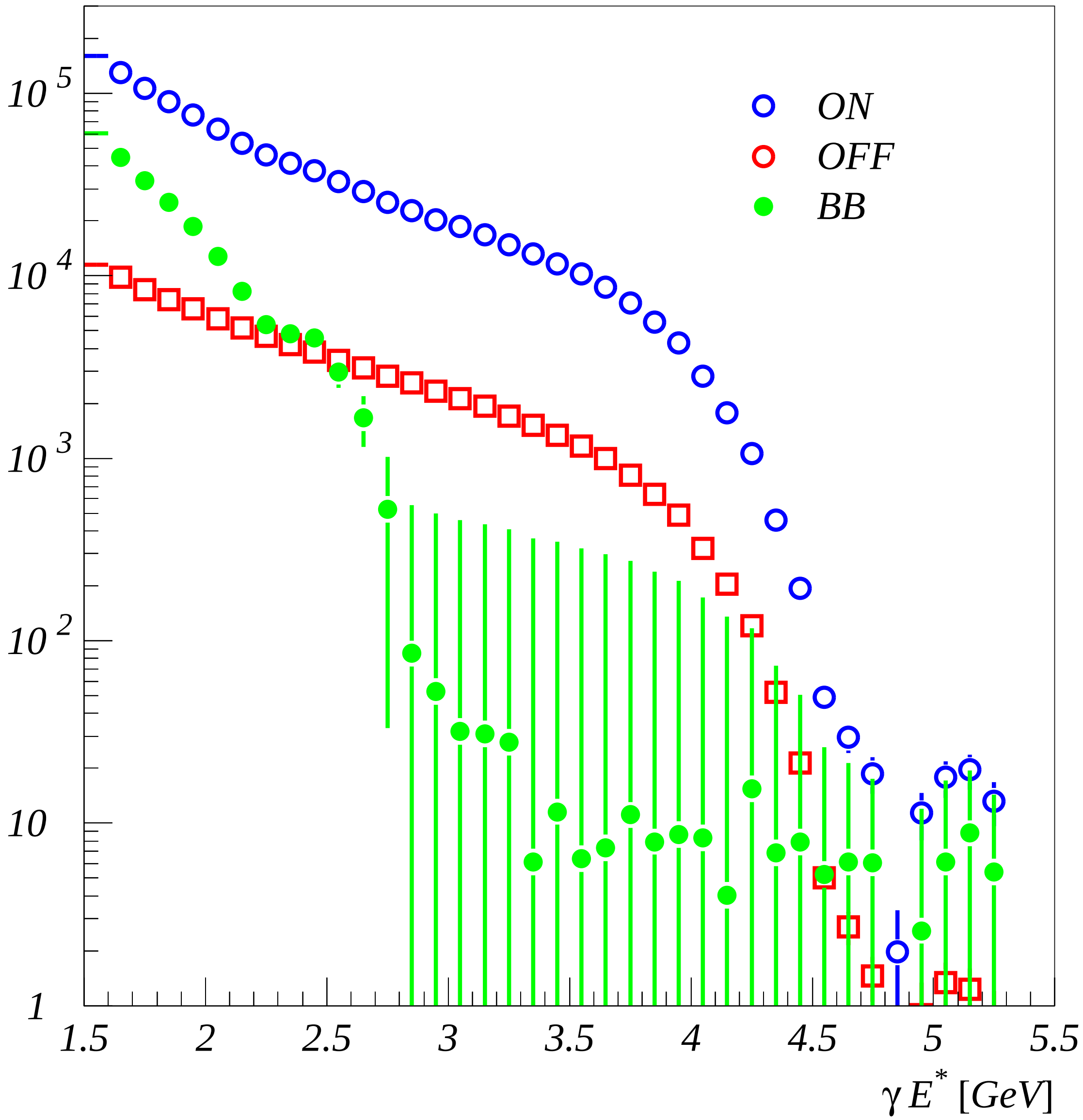
MC spectrum



ON, OFF and $B\overline{B}$ spectrum

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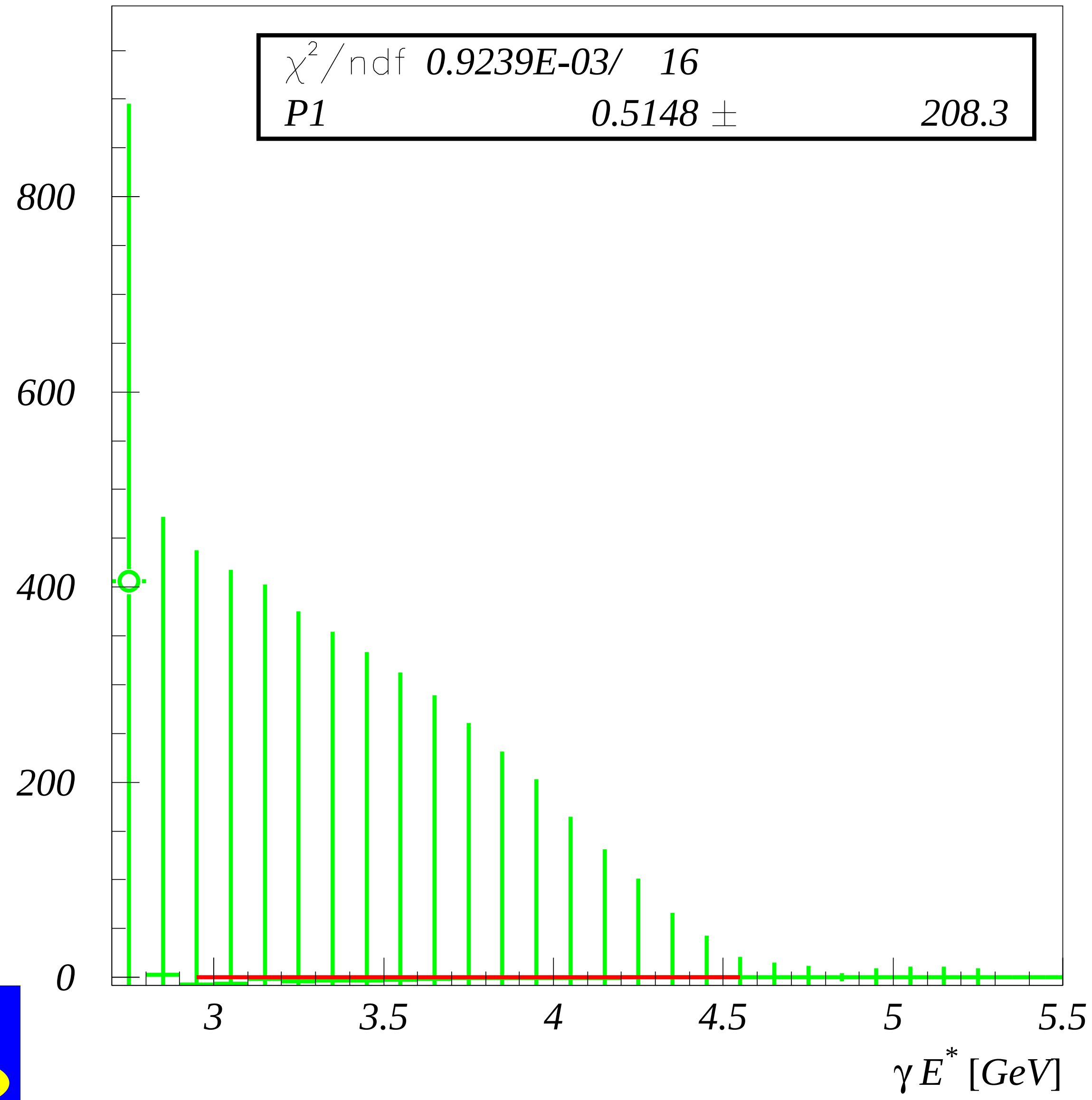
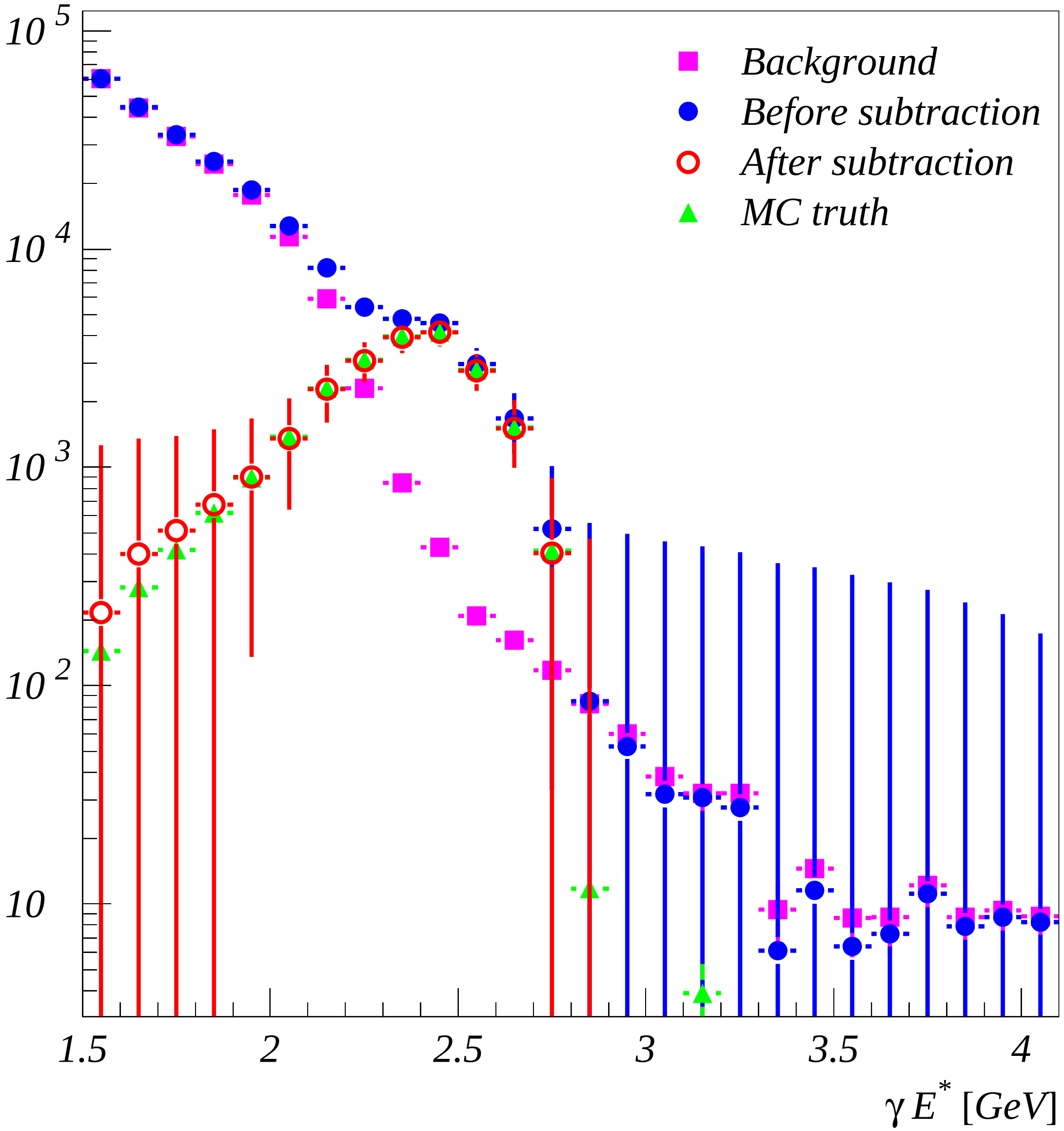
MC spectrum



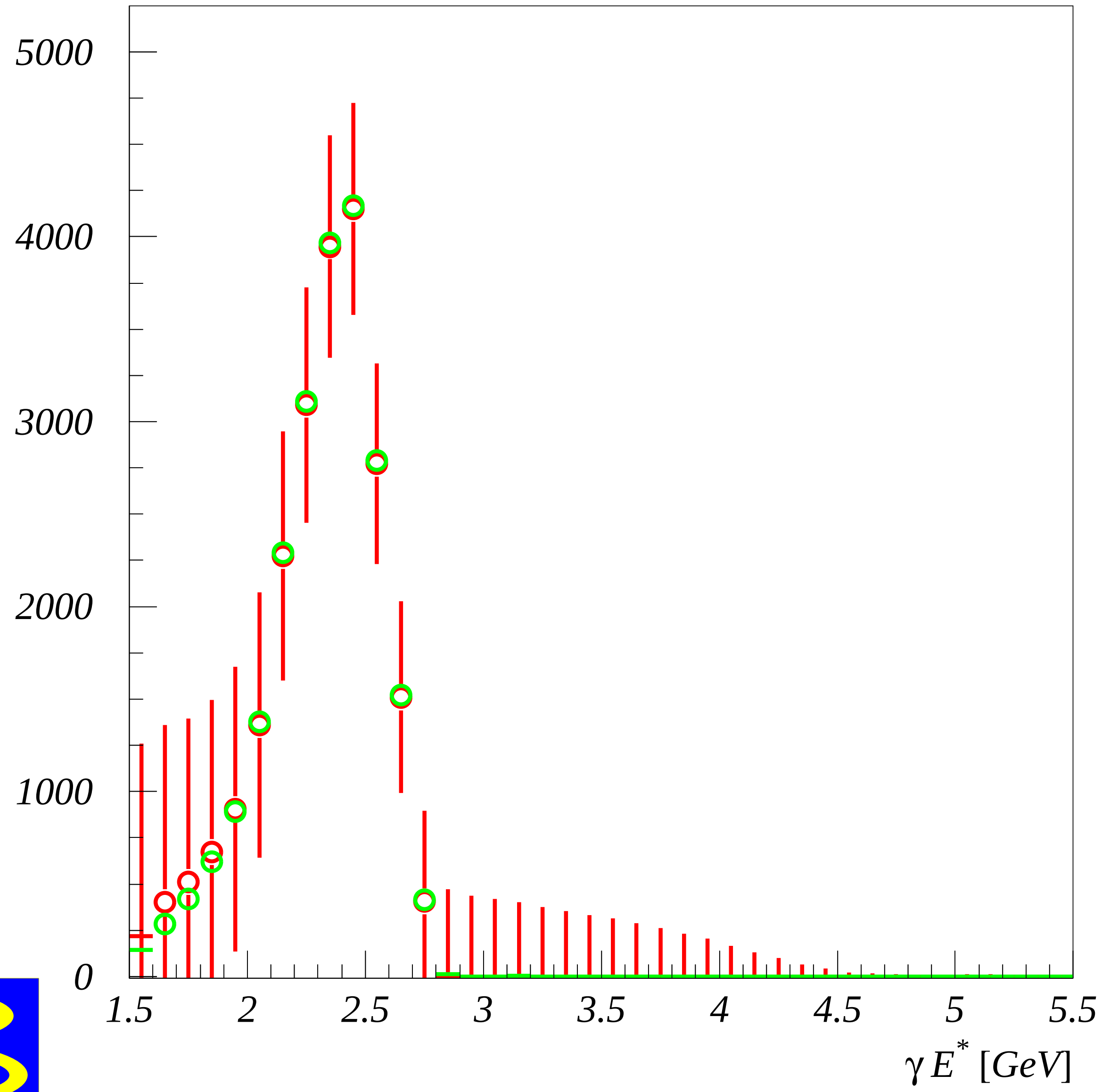
Endpoint check

MC spectrum



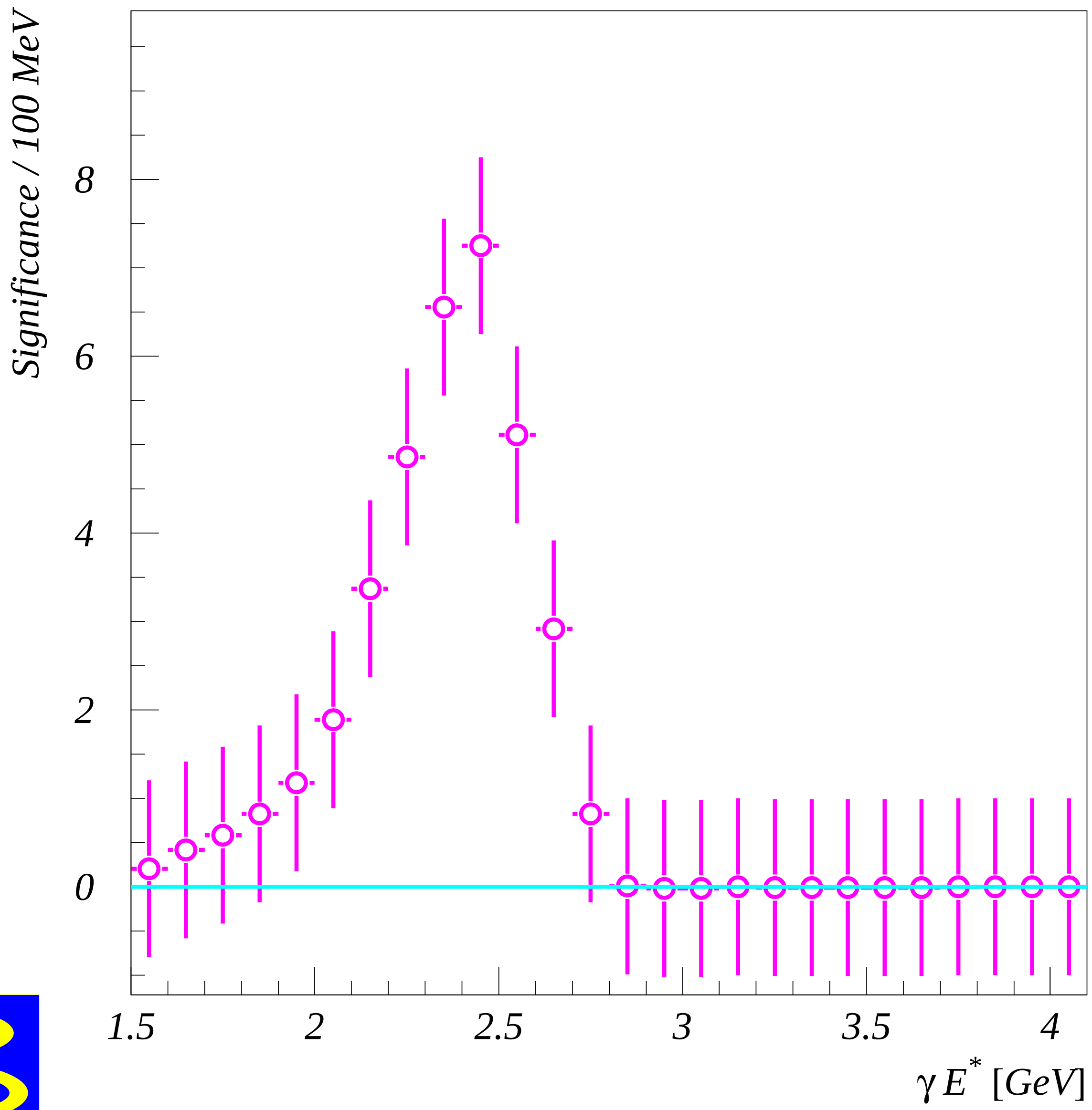
$B\overline{B}$ background subtraction

MC spectrum



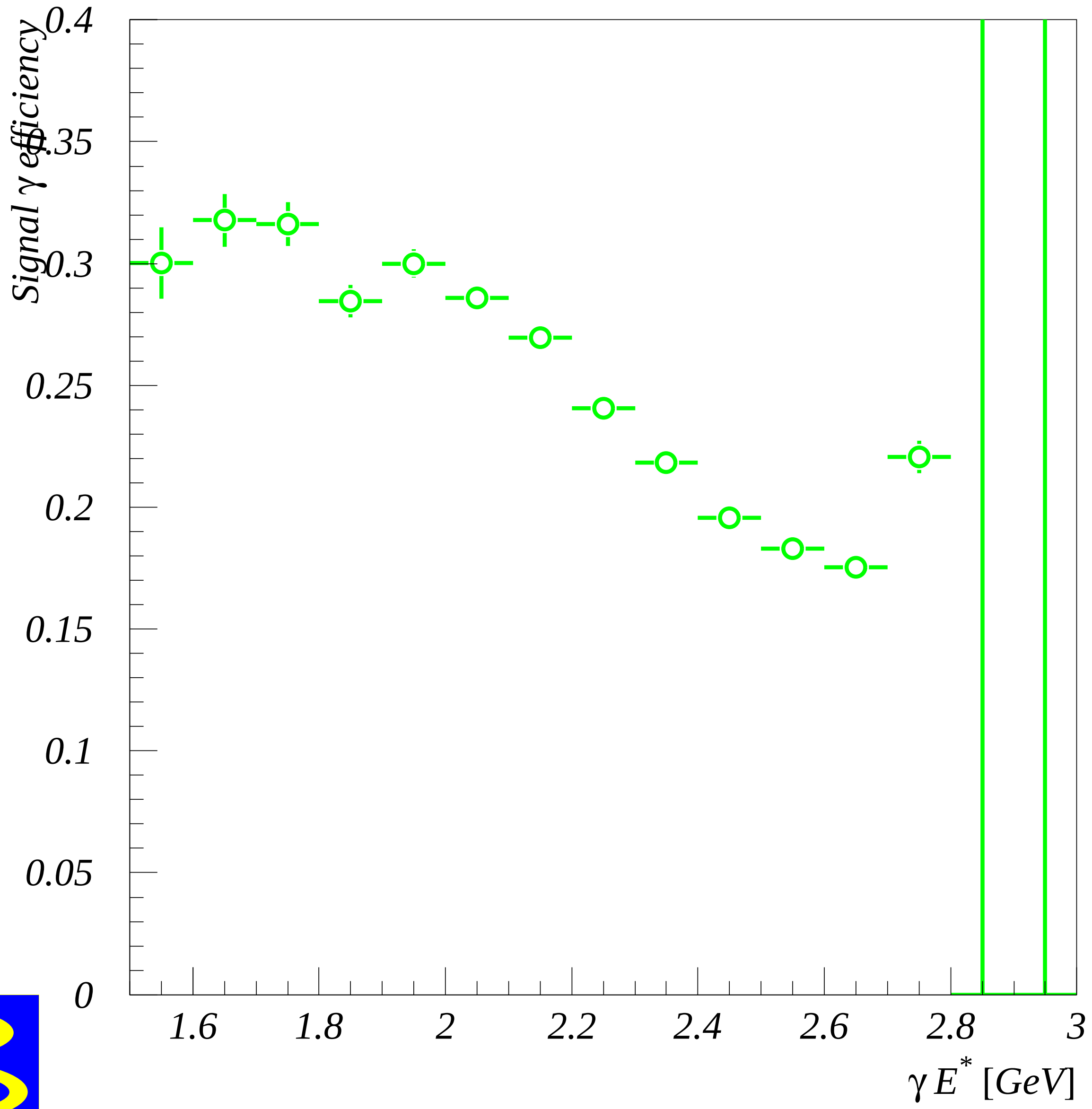
Raw $b \to s\gamma$ spectrum

MC spectrum



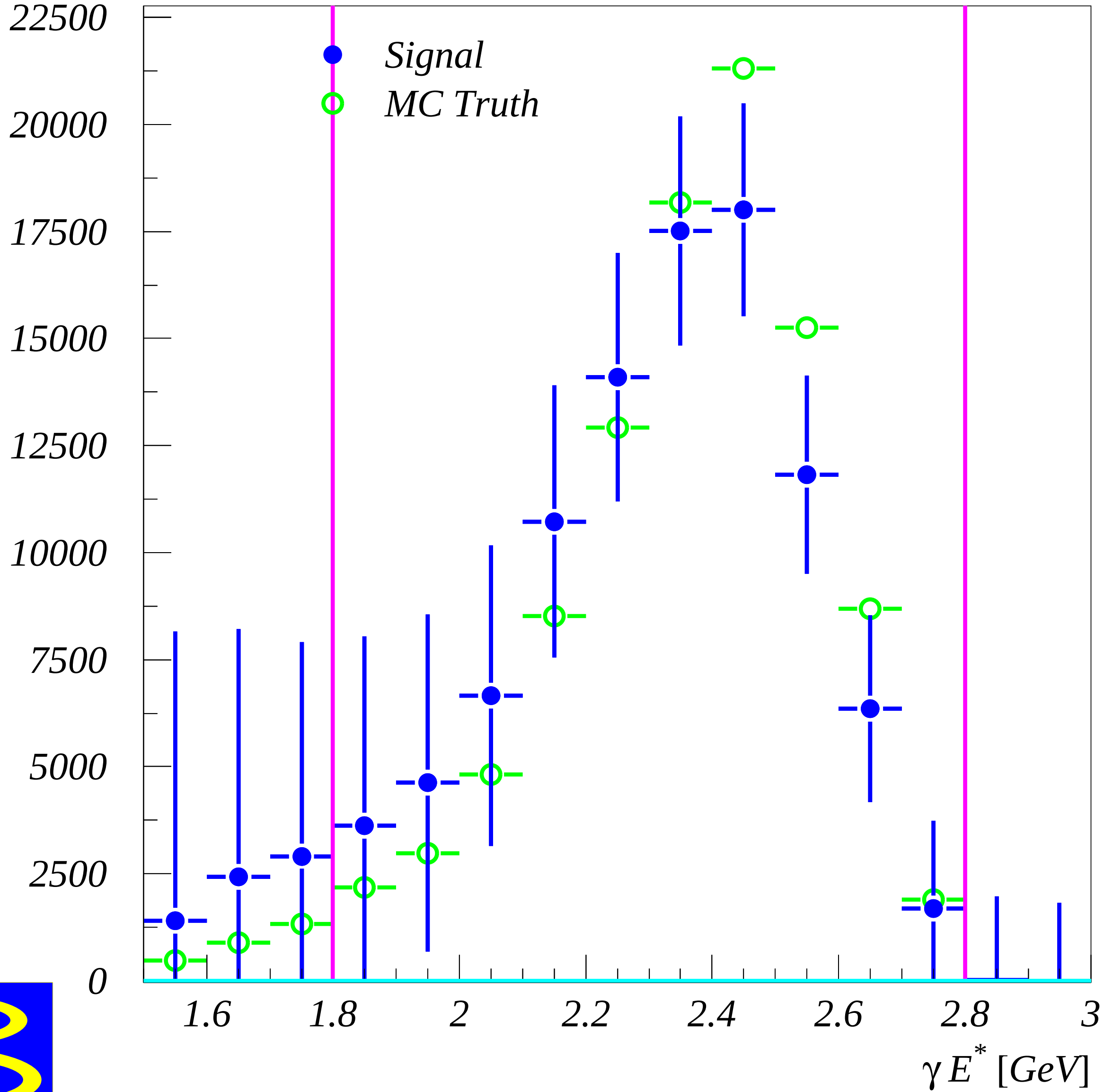
Expected statistical significance

MC spectrum



Efficiency correction function

MC spectrum



Efficiency corrected spectrum

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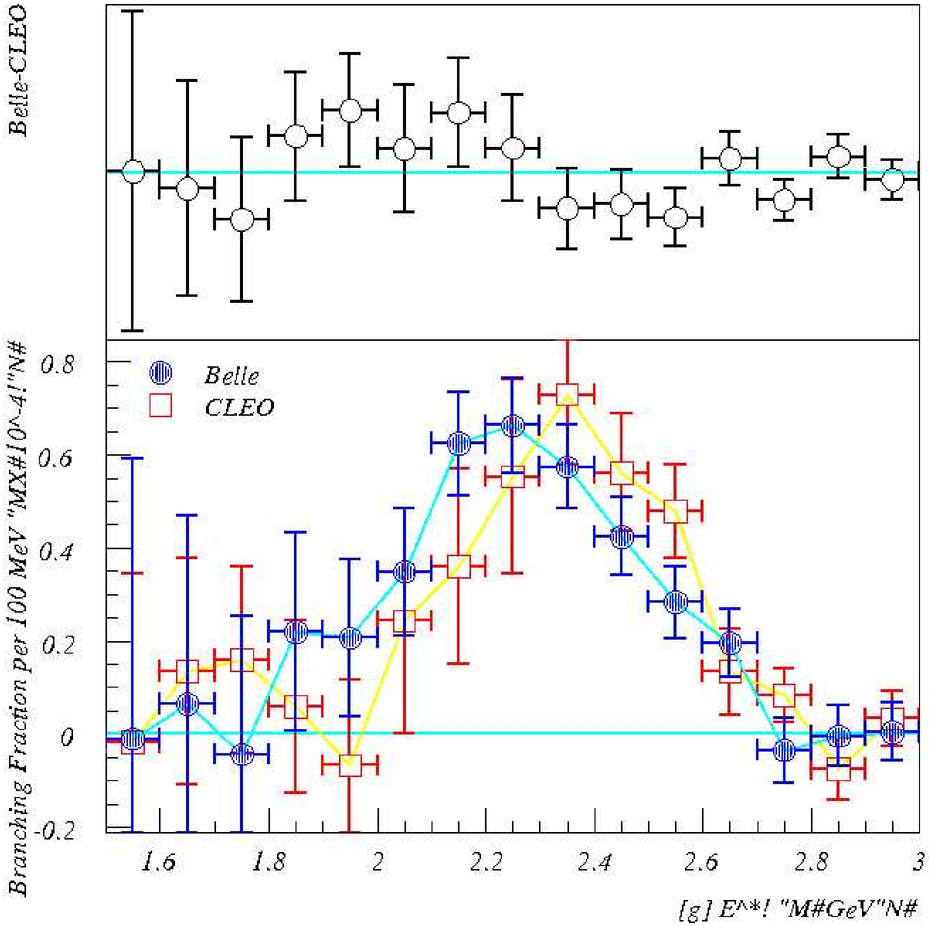
Compared to CLEO



In the energy range $2.0 < E^*_\gamma < 2.8$ GeV, CLEO quotes

$$(3.06 \pm 0.41 \pm 0.26) \cdot 10^{-4}$$

while we get

$$(3.08 \pm 0.26 \,{}^{+\,0.22}_{-\,0.24}) \cdot 10^{-4}.$$