Soft photons with ALICE 3

EMMI Rapid Reaction Task Force (RRTF):
Real and virtual photon production at ultra-low transverse momentum and low mass at LHC

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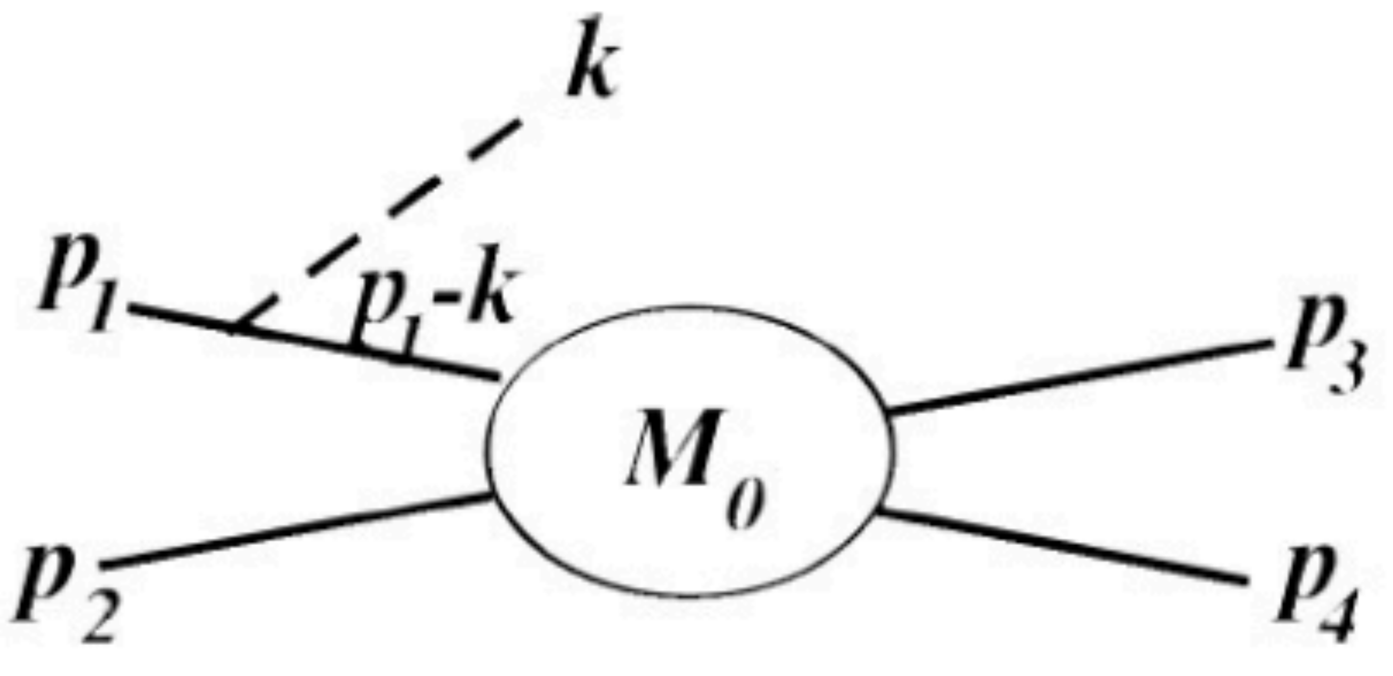
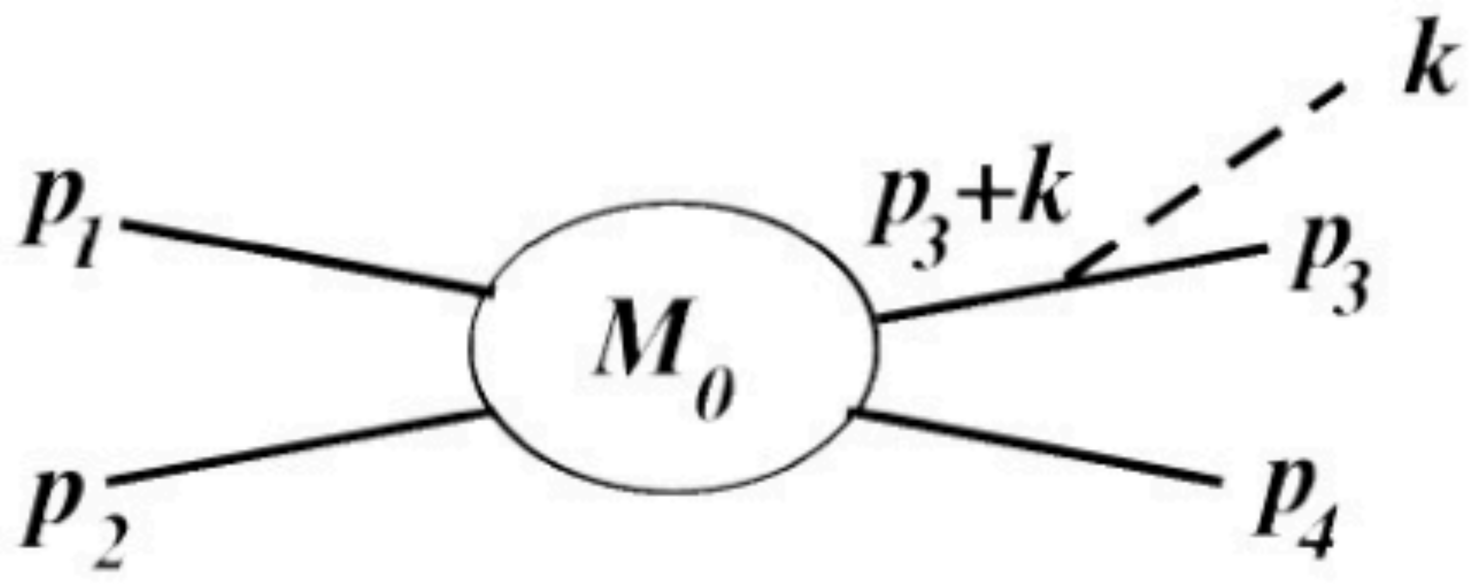
Why soft photons?

Expect soft photon production in hadronic collisions to be described by QED (inner bremsstrahlung as calculated according to Low's theorem)



Several experiments found a factor 4 (or so) excess above inner bremsstrahlung signal ("soft photon puzzle")

False measurements or interesting fundamental phenomenon?



Can resolve this long-standing puzzle with ALICE 3

Formula for inner bremsstrahlung as used by experiments

$$\frac{dN_\gamma}{d^3\vec{k}} = \frac{\alpha}{(2\pi)^2} \frac{-1}{E_\gamma} \int d^3\vec{p}_1 \ldots d^3\vec{p}_N \left(\sum_i \frac{\eta_i e_i P_i}{P_i K} \right)^2 \frac{dN_{\text{hadrons}}}{d^3\vec{p}_1 \ldots d^3\vec{p}_N}$$

$\sum_i$: sum over $N+2$ particles (2 incoming, N outgoing)

$K, \vec{k}$: photon four- and three momentum ($E_\gamma \equiv |\vec{k}|$)

$P_i, \vec{p}_i$: four- and three momentum of particle i

$e_i = 1$ for positive particle, $e_i = -1$ for negative particle

$\eta_i = 1$ for outgoing particle, $\eta_i = -1$ for incoming particle

Valid for long wavelengths with which one cannot resolve the temporal and spatial structure of the collision (only incoming and outgoing charged currents matter)

Francis E. Low, Phys.Rev.Lett. 110 (1958) 468
DELPHI, Eur. Phys. J. C 47, 273 (2006)
Belogianni et al. (WA102), Phys. Lett. B 548, 129 (2002)

Derivable from the Low paper

"Tree-level exact", i.e., there are no loop corrections in the limit $E_\gamma \to 0$

Coincides with formula obtained in classical electrodynamics

Possible approximation: Outgoing current defined by rapidity distribution $\rho(y)$ of outgoing charges

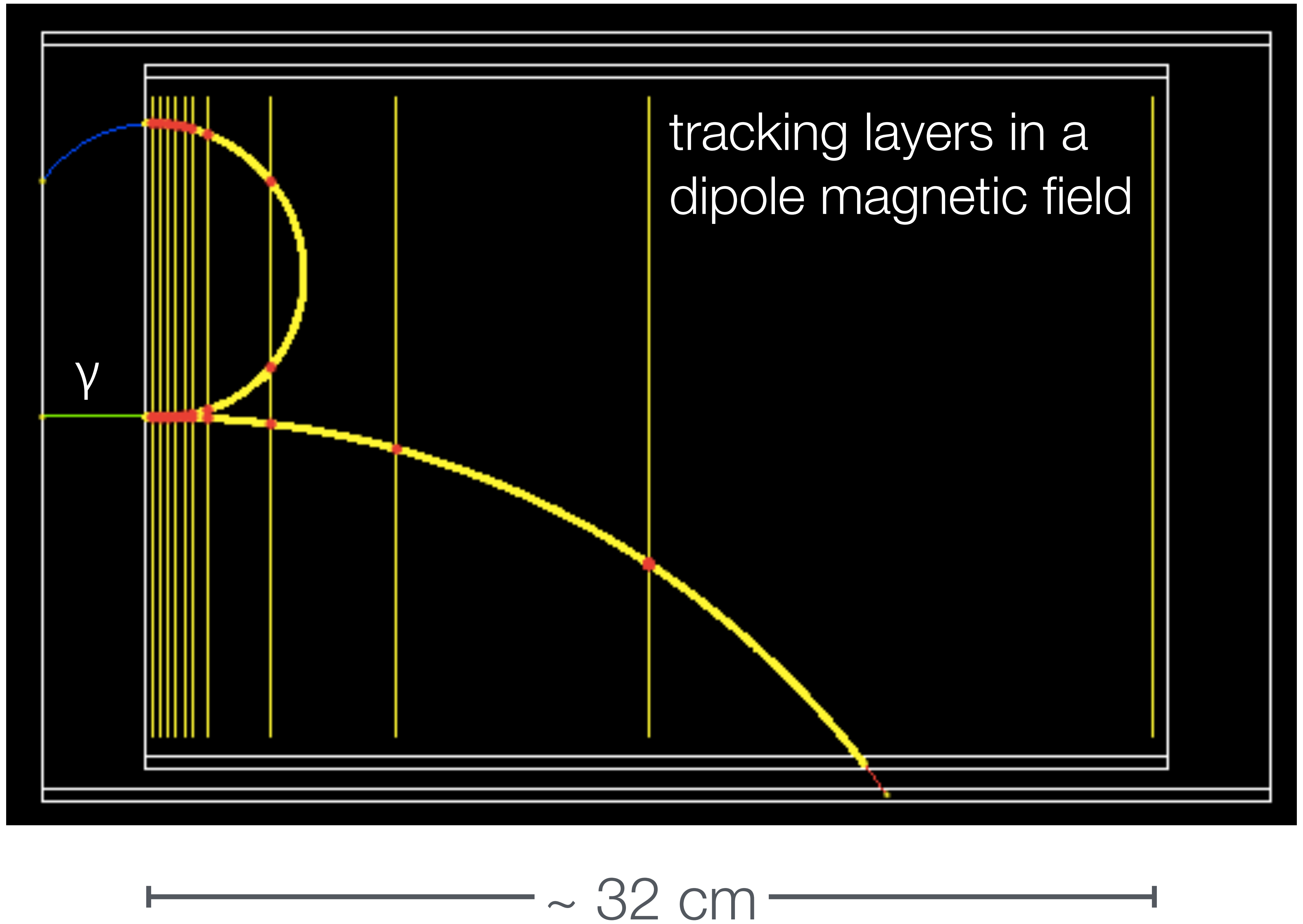
- Soft photons sensitive to different stopping scenarios (Landau, Bjorken, …)
- Park, Wiedemann, 2107.05129

Anomalous soft photon production: signal > prediction in many experiments

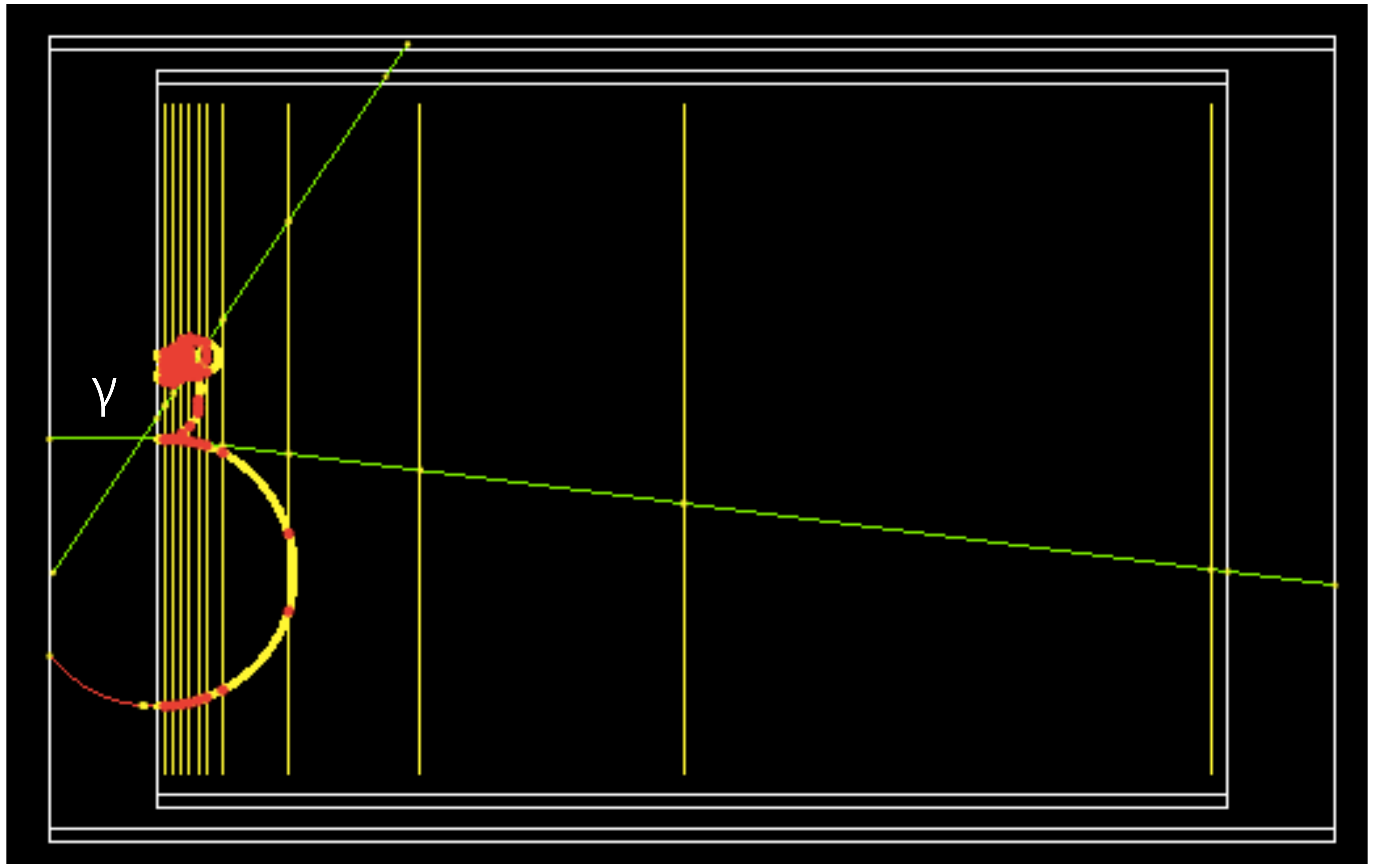
Experiment	Year	Collision energy	Photon p_T	Photon / Brems Ratio	Detection method	Reference (click to go to paper)
π^+p	1979	10.5 GeV	p_T < 30 MeV/c	1.25 ± 0.25	bubble chamber	Goshaw et al., Phys. Rev. Lett. 43, 1065 (1979)
K^+p WA27, CERN	1984	70 GeV	p_T < 60 MeV/c	4.0 ± 0.8	bubble chamber (BEBC)	Chliapnikov et al., Phys. Lett. B 141, 276 (1984)
π^+p CERN, EHS, NA22	1991	250 GeV	p_T < 40 MeV/c	6.4 ± 1.6	bubble chamber (RCBC)	Botterweck et al., Z. Phys. C 51, 541 (1991)
K^+p CERN, EHS, NA22	1991	250 GeV	p_T < 40 MeV/c	6.9 ± 1.3	bubble chamber (RCBC)	Botterweck et al., Z. Phys. C 51, 541 (1991)
π^-p, CERN, WA83, OMEGA	1993	280 GeV	p_T < 10 MeV/c (0.2 < E_γ < 1 GeV)	7.9 ± 1.4	calorimeter	Banerjee et al., Phys. Lett. B 305, 182 (1993)
p-Be	1993	450 GeV	p_T < 20 MeV/c	< 2	pair conversion, calorimeter	Antos et al., Z. Phys. C 59, 547 (1993)
p-Be, p-W	1996	18 GeV	p_T < 50 MeV/c	< 2.65	calorimeter	Lissauer et al., Phys.Rev. C54 (1996) 1918
π^-p, CERN, WA91, OMEGA	1997	280 GeV	p_T < 20 MeV/c (0.2 < E_γ < 1 GeV)	7.8 ± 1.5	pair conversion	Belogianni et al., Phys. Lett. B 408, 487 (1997)
π^-p, CERN, WA91, OMEGA	2002	280 GeV	p_T < 20 MeV/c (0.2 < E_γ < 1 GeV)	5.3 ± 1.0	pair conversion	Belogianni et al., Phys. Lett. B 548, 122 (2002)
pp, CERN, WA102, OMEGA	2002	450 GeV	p_T < 20 MeV/c (0.2 < E_γ < 1 GeV)	4.1 ± 0.8	pair conversion	Belogianni et al., Phys. Lett. B 548, 129 (2002)
$e^+e^- \to$ 2 jets CERN, DELPHI	2006	91 GeV (CM)	p_T < 80 MeV/c (0.2 < E_γ < 1 GeV)	4.0 ± 0.3 ± 1.0	pair conversion	DELPHI, Eur. Phys. J. C 47, 273 (2006)
$e^+e^- \to \mu^+\mu^-$ CERN, DELPHI	2008	91 GeV (CM)	p_T < 80 MeV/c (0.2 < E_γ < 1 GeV)	~ 1	pair conversion	DELPHI, Eur. Phys. J. C57, 499 (2008)

Measuring soft photons through conversion

E_γ = 100 MeV: easy

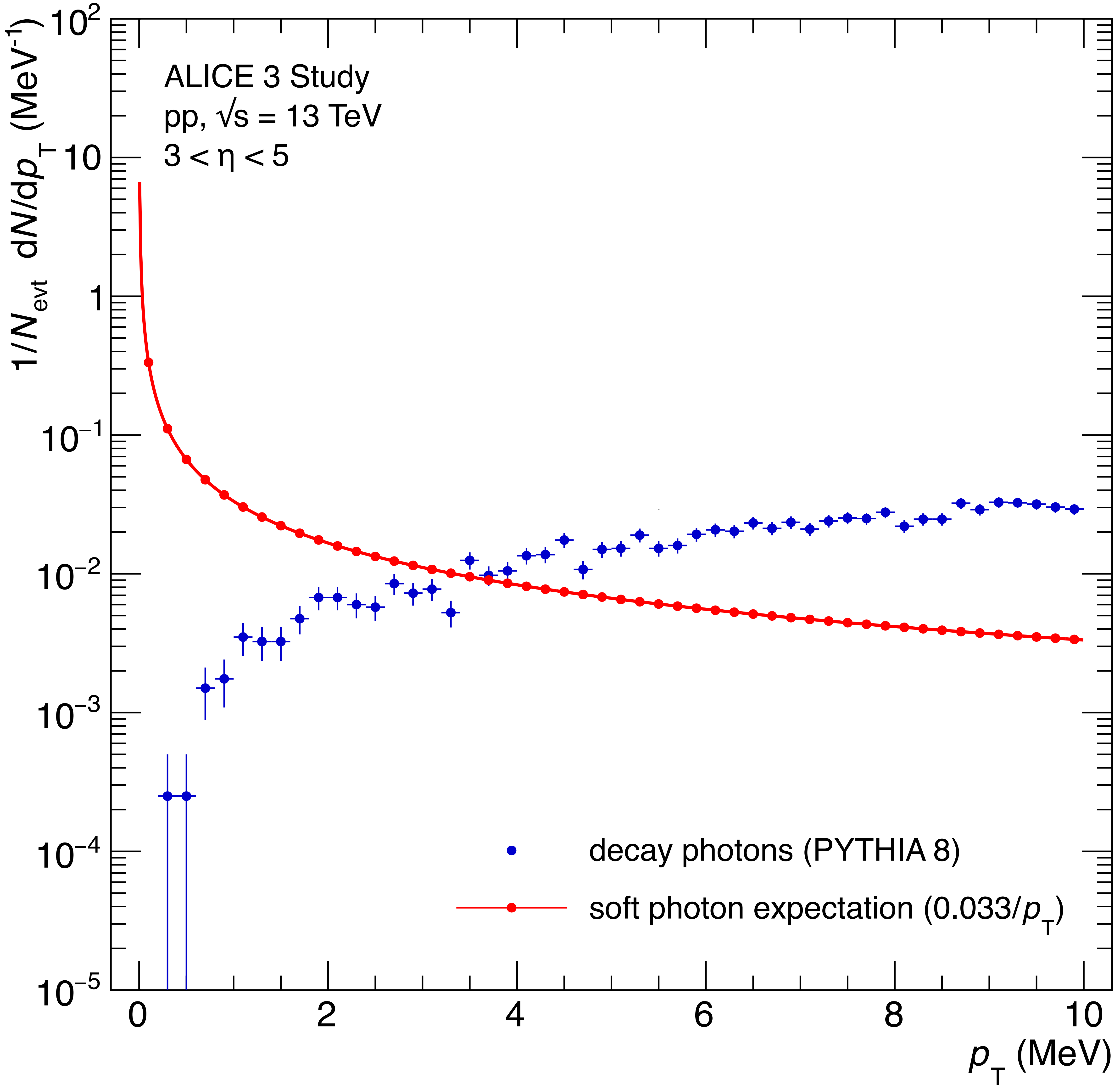


E_γ = 20 MeV: not so easy



Can measure photons through conversions down to E_γ = 50-100 MeV

Proton-proton collisions at the LHC: Bremsstrahlung signal larger than decay photon backgr. for $p_T \lesssim 4$ MeV/c



Decay photon background drops for $p_T < 10$ MeV/c

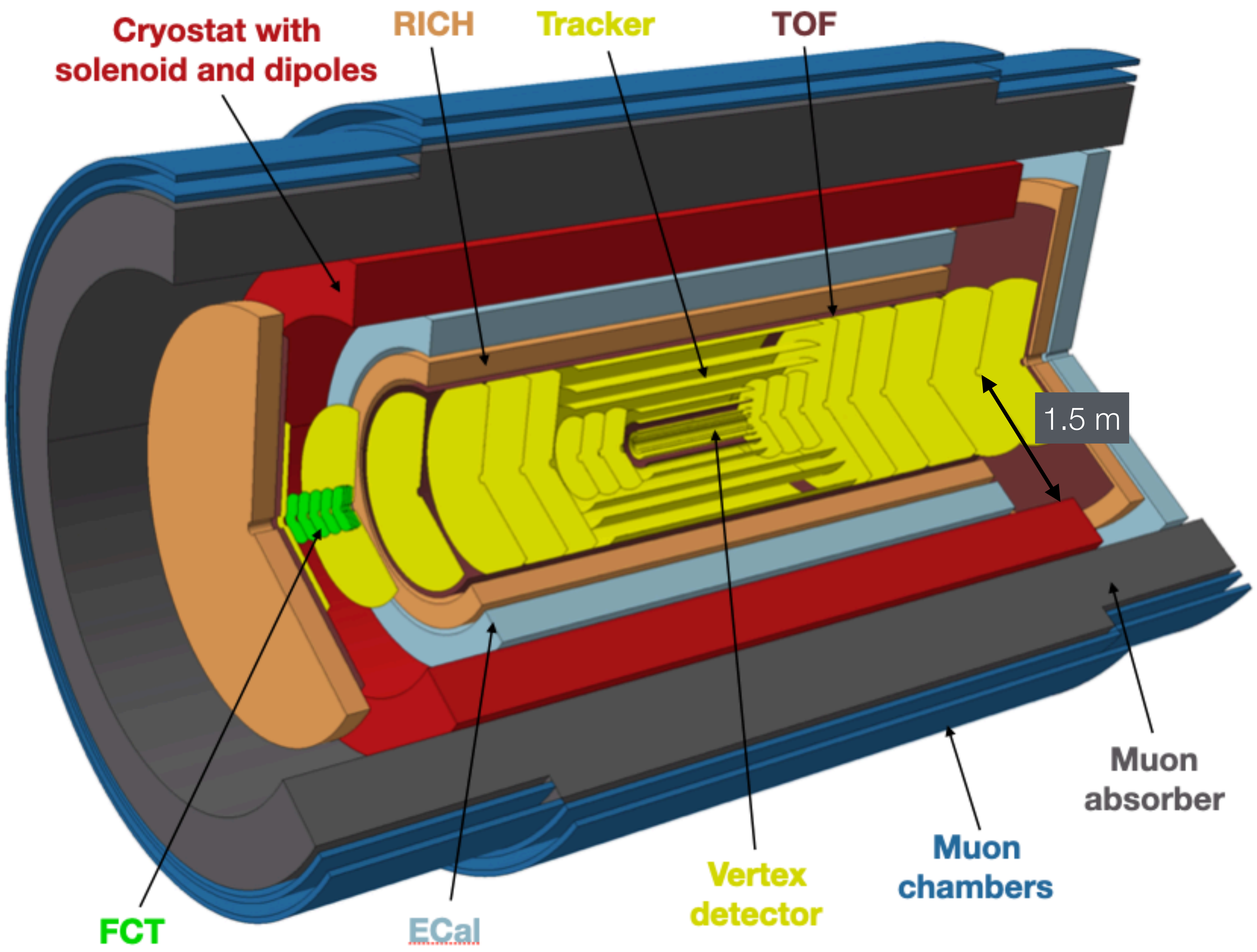
Region of special interest: $1 \lesssim p_T \lesssim 10$ MeV/c

$$p_T = \frac{E_\gamma}{\cosh \eta}, \quad \cosh \eta \approx 10,\ 27,\ 74 \text{ for } \eta = 3,\ 4,\ 5$$

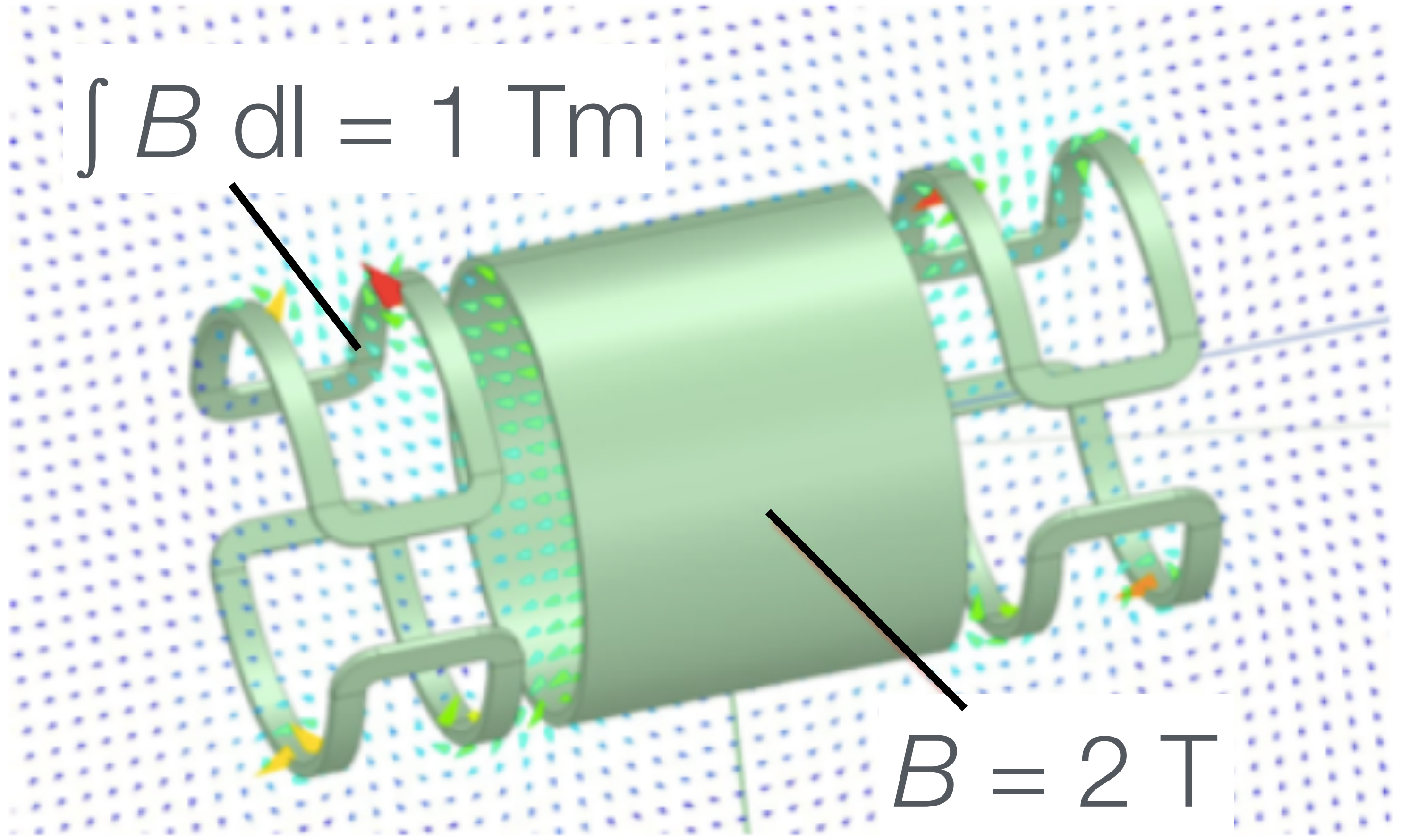
$$p_T = 10,\ 3.7,\ 1.3\,\mathrm{MeV}/c$$
$$\text{for } \eta = 3,\ 4,\ 5 \text{ and } E_\gamma = 100\,\mathrm{MeV}$$

Need to measure soft photons at forward rapidities

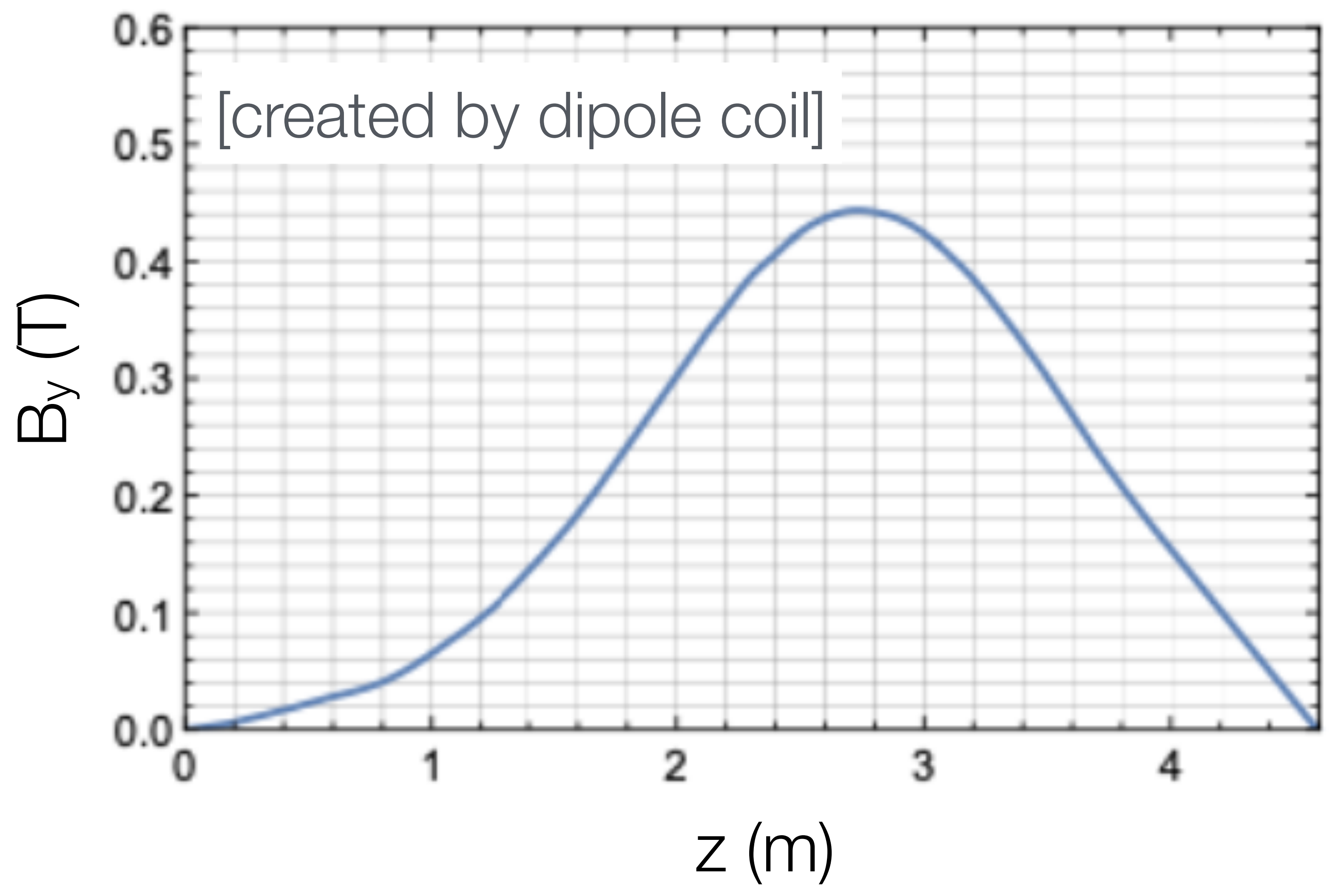
Soft photons with ALICE 3: Forward Conversion Tracker (FCT)



Solenoid + dipole coils

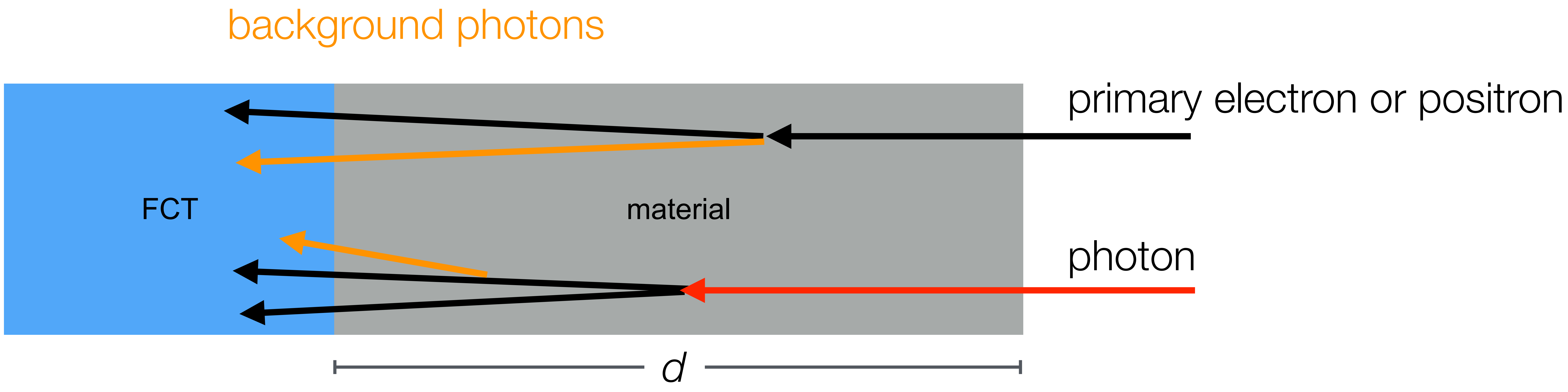


Magnetic field B_y along beam axis



Tracking of electrons/positrons from photon conversions directly in front FCT in dipole field

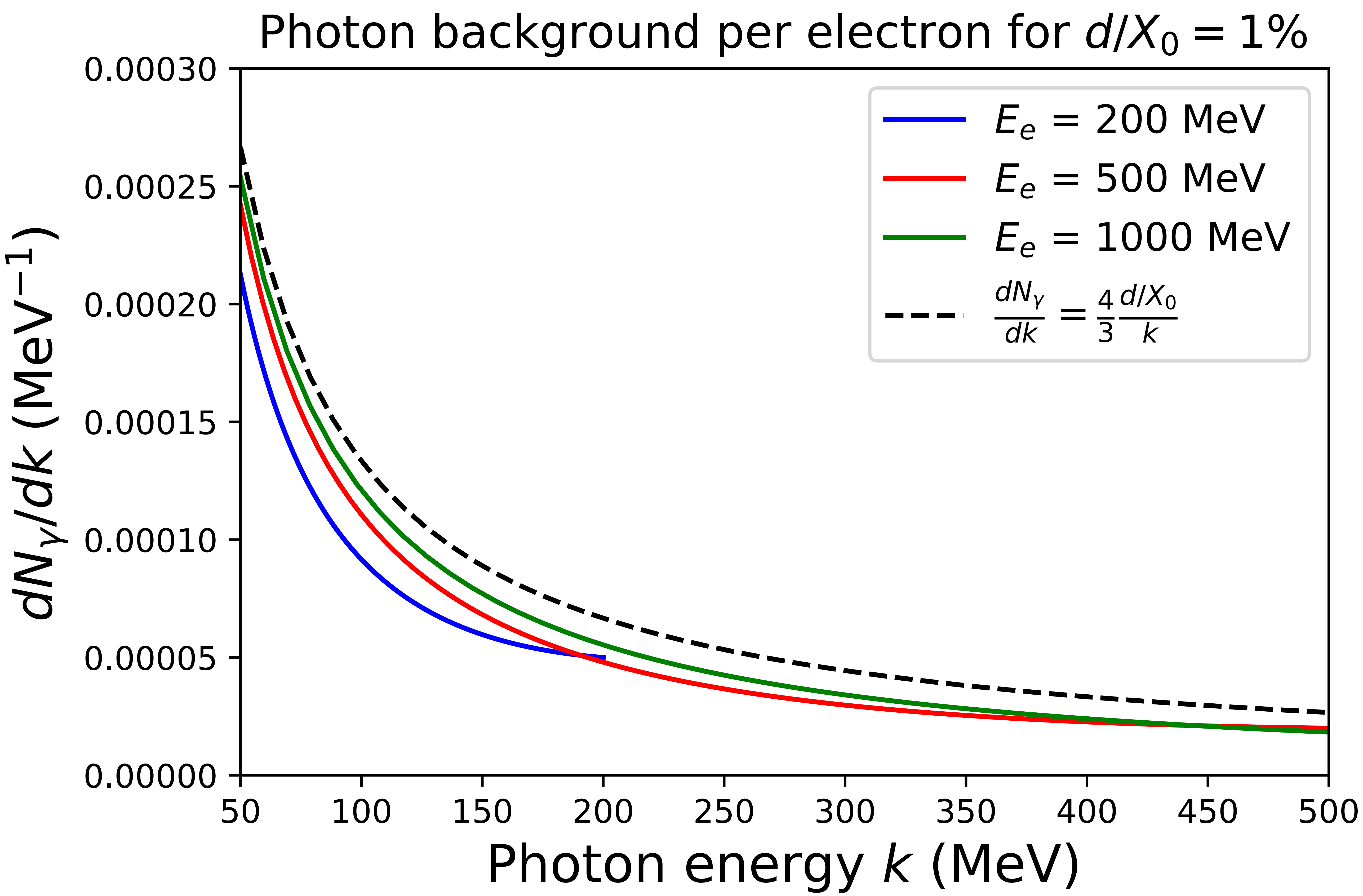
Key issue in soft photon measurement:
Background of bremsstrahlung photons produced in front of the detector



General strategy: minimize material in front of FCT

Avoid crossing of beampipe at shallow angles ($d = d_{\perp} \cosh \eta$)

Analytical insights into external bremsstrahlung background: Bremsstrahlung spectrum



Energy spectrum of bremsstrahlung photons (from particle data book):

$$\frac{dN_\gamma^{\text{bck. per electron}}}{dk} = \frac{4}{3}\frac{d}{X_0}\left(\frac{1}{k} - \frac{1}{E_e} + \frac{3}{4}\frac{k}{E_e^2}\right)$$

$$\approx \frac{4}{3}\frac{d}{X_0}\frac{1}{k} \quad \text{for } k \ll E_e$$

photon energy (k), electron energy (E_e)

Assume that each electron contributes to the background as if its energy was infinite (should be a conservative estimate)

Analytical insights into external bremsstrahlung background: Bremsstrahlung from primary electrons and conversion electrons

Bremsstrahlung background from primary electrons (mostly from Dalitz decays):

$$\frac{dN_\gamma^{\text{bck, e, prim}}}{dk_T\, d\eta} = \frac{dN^{\text{e, prim}}}{d\eta} \frac{d}{X_0} \frac{4}{3} \frac{1}{k_T}$$

linear in d/X_0

Bremsstrahlung background from conversion electrons:

$$\frac{dN_\gamma^{\text{bck, e, conv}}}{dk_T\, d\eta} \approx \frac{1}{2} \times \frac{dN^{\text{e, conv}}}{d\eta} \frac{d}{X_0} \frac{4}{3} \frac{1}{k_T}$$

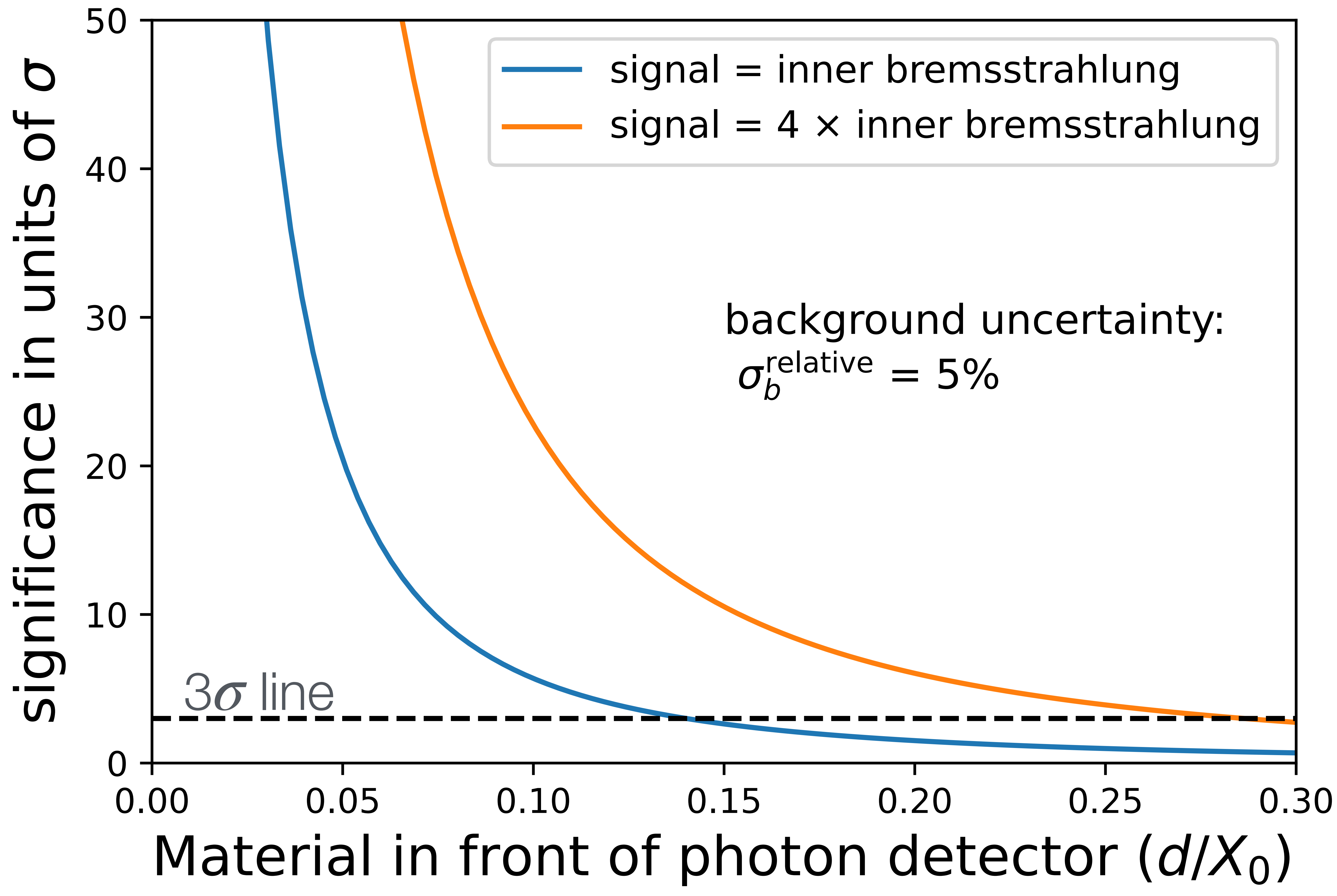
$$\frac{dN^{\text{e, conv}}}{d\eta} = 2 \times p_c \times \frac{dN_\gamma}{d\eta} = 2 \times \frac{7}{9} \frac{d}{X_0} \times 2 \frac{dN^{\pi^0}}{d\eta}$$

quadratic in d/X_0

produced electrons and positrons approximately pass through half of the material

Equal contribution for $d/X_0 \approx 1.3\%$, for larger material thickness conversion background dominates

Analytical insights into external bremsstrahlung background: Significance of the soft photon signal



Inner bremsstrahlung (pp, 13 TeV, based on charged particles from PYTHIA 8):

$$\frac{dN_{\text{signal}}}{dk_T} = \frac{a_\eta^{\text{signal}}}{k_T}$$

[Martin Völkl]

$$a_\eta^{\text{signal}} = \begin{cases} 0.018 & \text{for } 3 < \eta < 4 \\ 0.016 & \text{for } 4 < \eta < 5 \\ 0.034 & \text{for } 3 < \eta < 5 \end{cases}$$

Signal = background for $\frac{d}{X_0} \approx 5\,\%$

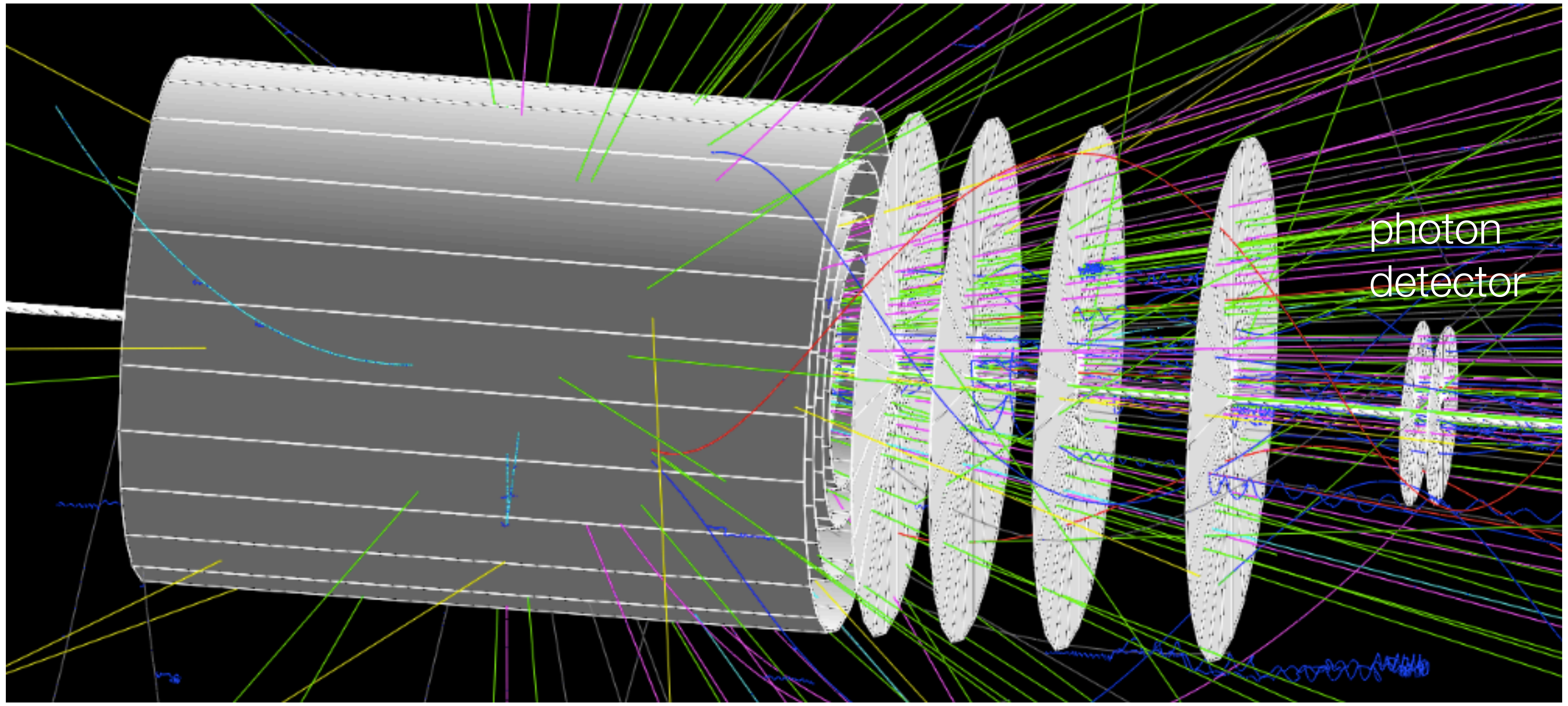
Significance (background subtraction):

$$\text{significance} = \frac{s}{\sigma_b^{\text{relative}} \cdot b}$$

On the save side with material budget of less than 10% X_0

Geant simulation of background photons

[Tim Rogoschinski]



Track particles produced in pp at 13 TeV through detector setup (g4me toolkit)

Setup

- standard beampipe (not optimized for soft photon measurement)
- barrel tracking layers
- forward disks

Compare background photons for two cases

- all events
- events without electrons/positrons in pseudorapidity range of the FCT

Fraction of events without an electrons or positron in the given pseudorapidity range:

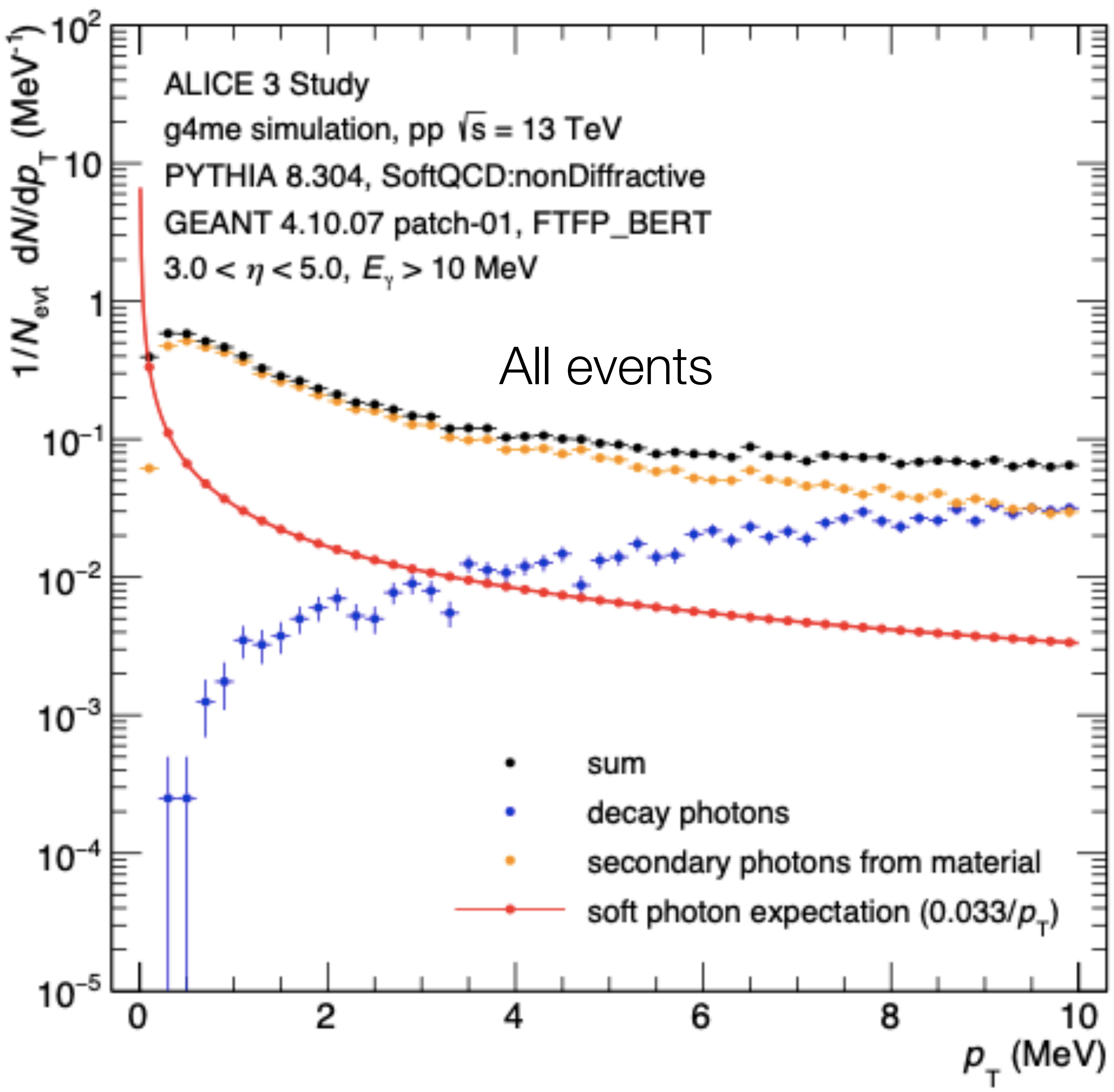
$3 < \eta < 5$: 1413 / 20000 ≈ 7.1%

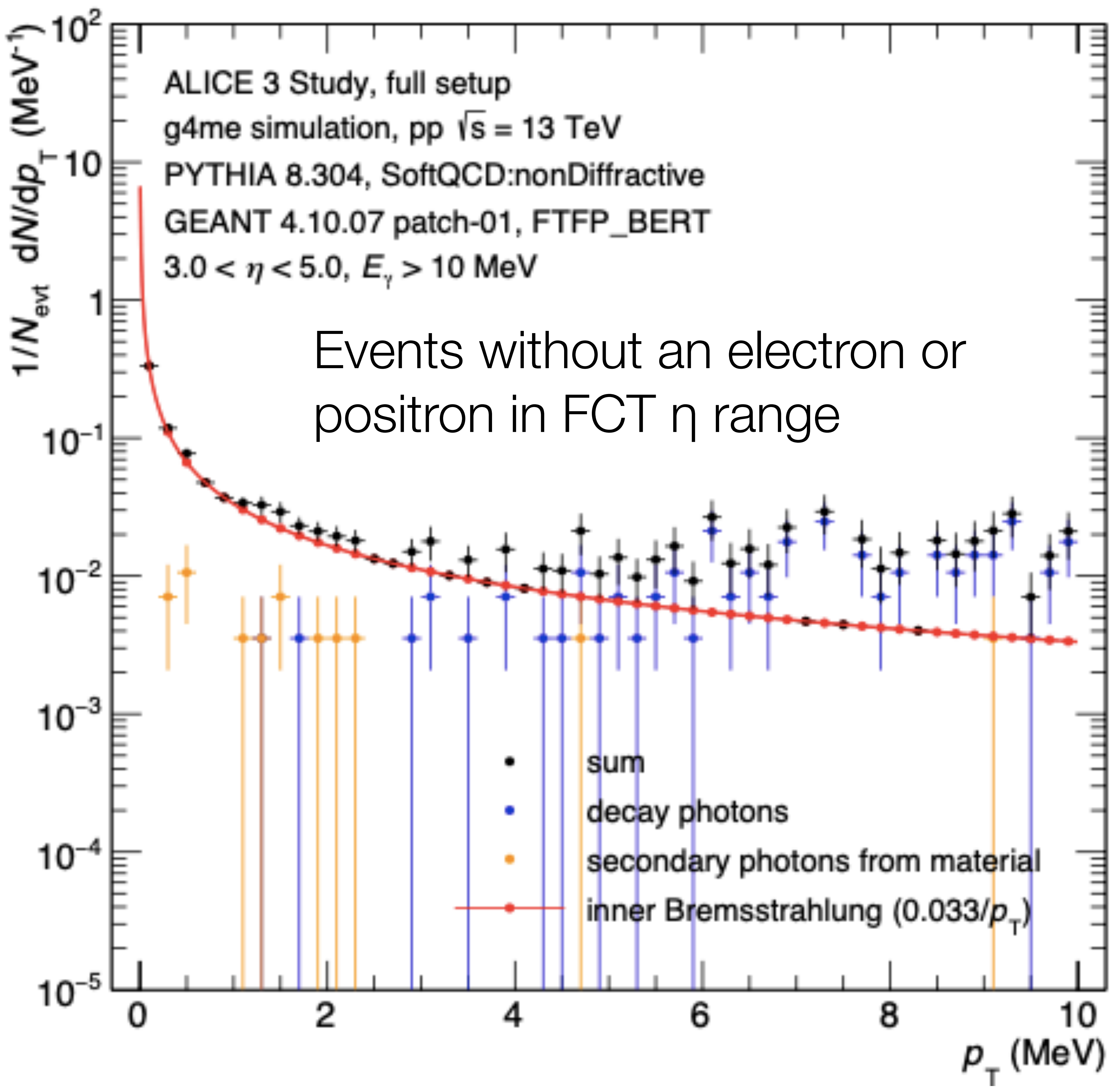
$3 < \eta < 4$: 2115 / 20000 ≈ 10.5%

$4 < \eta < 5$: 6029 / 20000 ≈ 30.1%

Background photons for all events and for events without and electron in the pseudorapidity range of the FCT ($3 < \eta < 5$)

[Tim Rogoschinski]

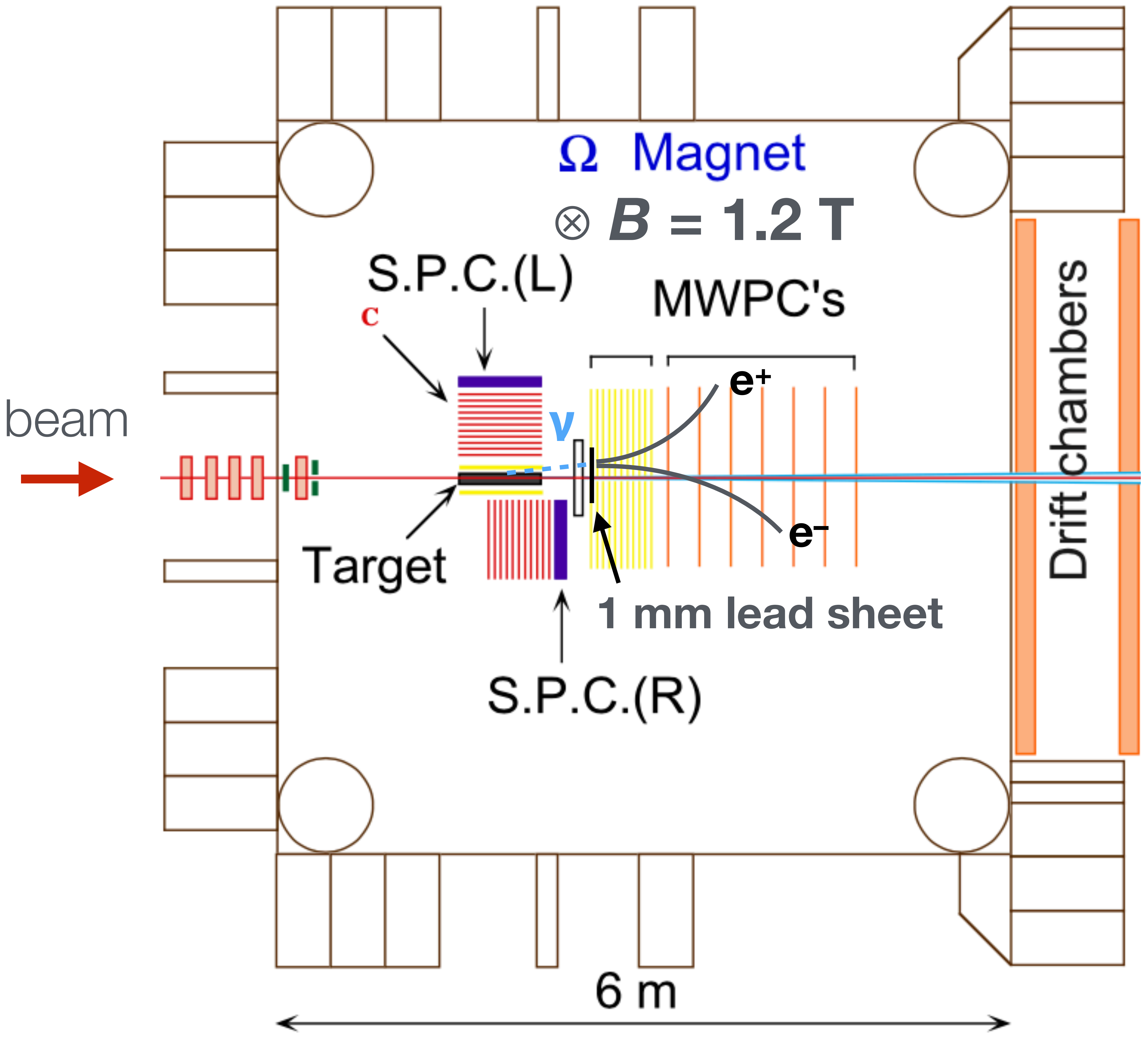




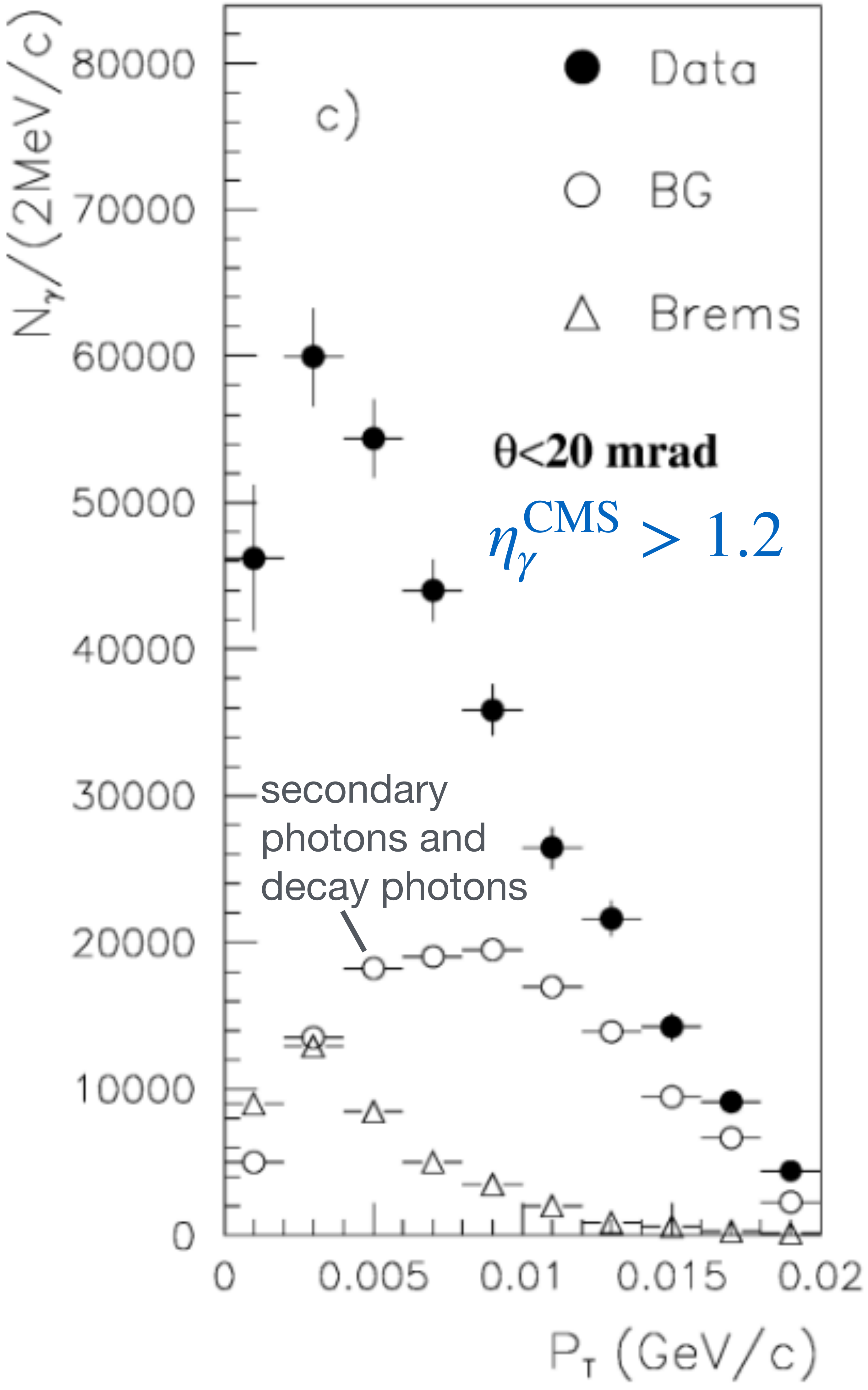
Key element of measurement strategy:
identify and reject events with an electron or positron in the η range of the FCT

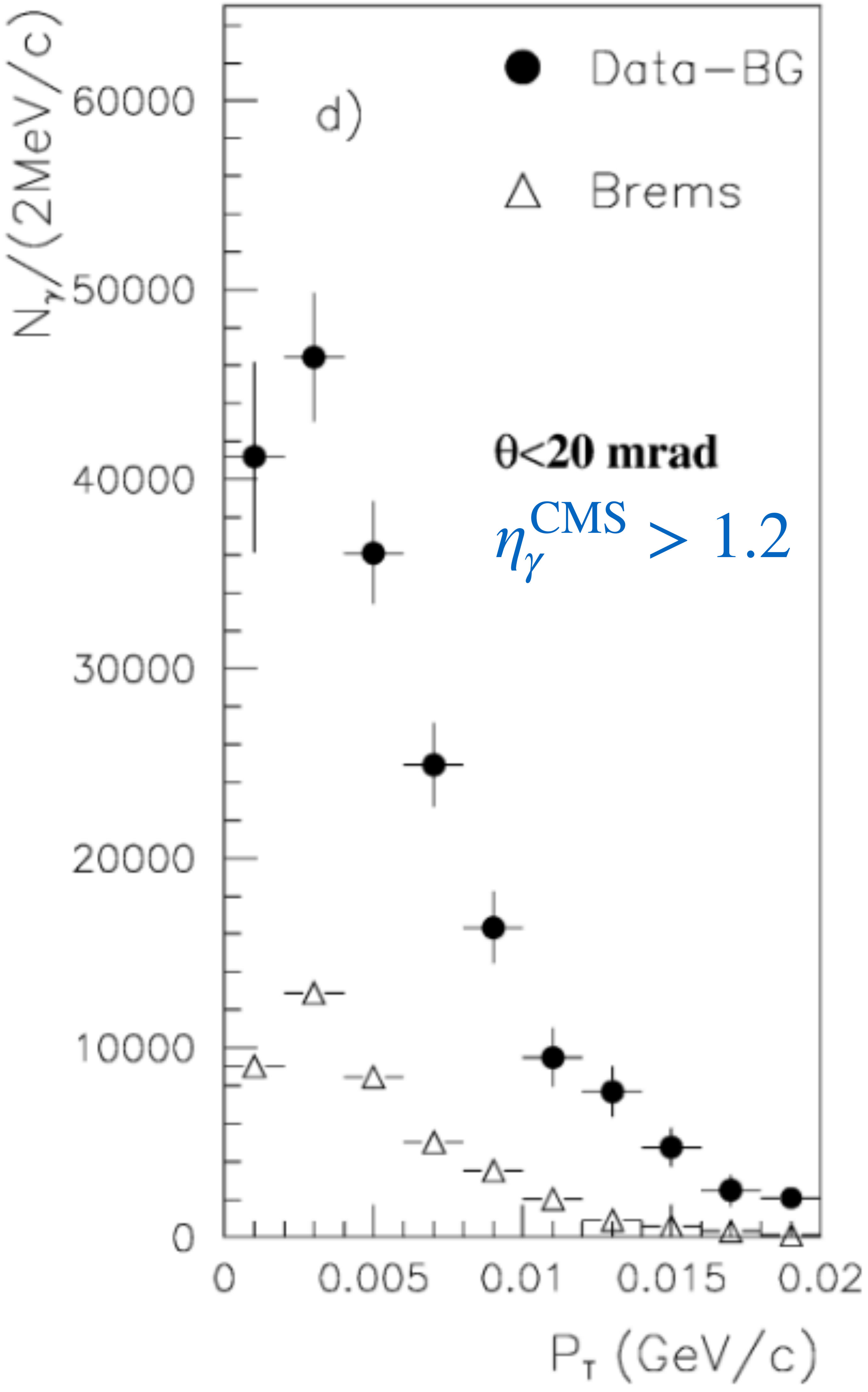
Omega spectrometer – WA102

p+p fixed target experiment at p_{beam} = 450 GeV/c



4×10⁶ events (with less than 8 charged tracks)





Most of the excess above inner bremsstrahlung at $\eta_\gamma^{CMS} \gtrsim 1$

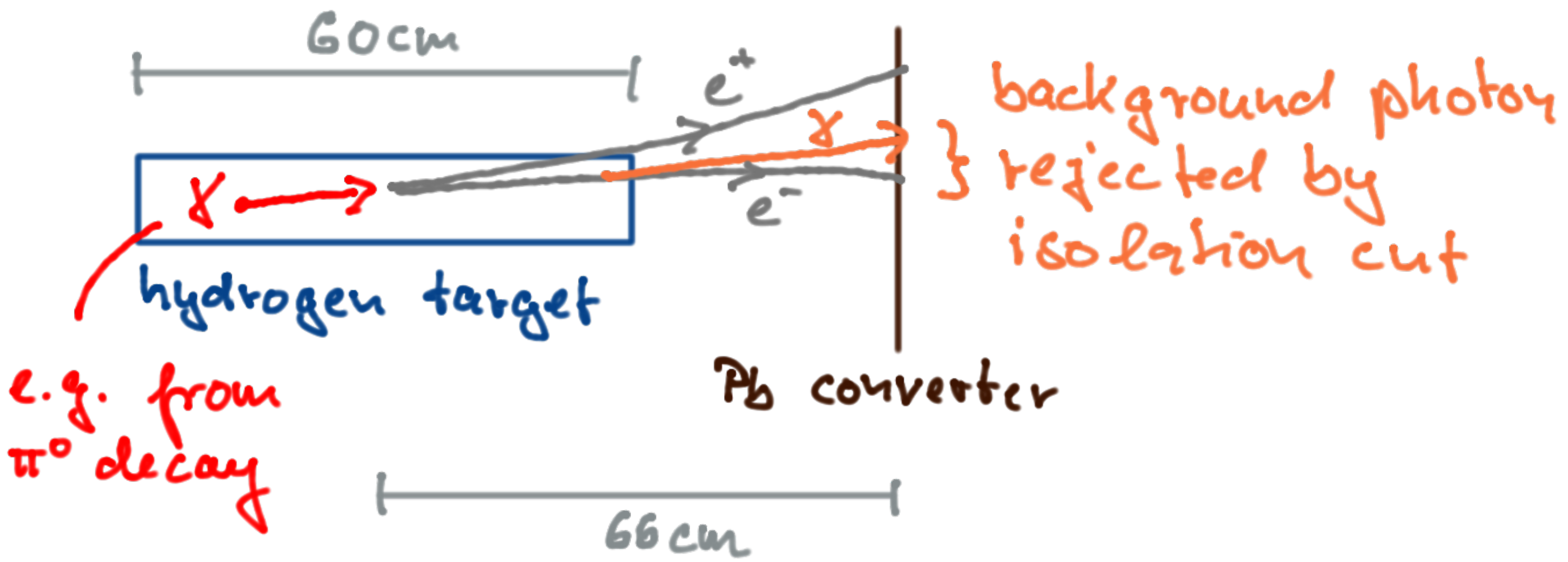
Importance of the photon isolation cut in WA102

Table 1
Calculated soft gamma yields ($0.2 < E_\gamma < 1$ GeV, $\theta < 20$ mrad). The quoted errors are statistical. The systematic errors for background calculations are estimated to be 10%, and for inner bremsstrahlung 5%

	Source (see text for definitions)	Number of γ per event (%) corrected for conversion probability
(a)	Inner bremsstrahlung	1.16 ± 0.02
(b)	γ's from hadronic decays	1.70 ± 0.03
(c)	Dalitz pairs	0.05 ± 0.01
(d)	Knock-on electrons	0.008 ± 0.003
(e)	Spurious γ's	$(1 \pm 1) \times 10^{-3}$
(f)	Secondary γ's	1.25 ± 0.03
(g)	Beam halo γ's	0.08 ± 0.08
(h)	γ's from secondary interactions	< 0.7 (95% C.L.)
	Sum over sources (b) to (g) (full non-direct photon background)	3.09 ± 0.09

Inner bremsstrahlung signal
≈ secondary γ background

Secondary γ's:



"Additionally, pairs from photons of $E_\gamma > 1$ GeV converted in the lead sheet can degrade to energies below 1 GeV due to bremsstrahlung. The latter process represents the major part of this background source after the application of the isolation cut"

Background photon rejection in the DELPHI measurement: Only jets without an electron or a positron considered

Photon range:

$$0.2 < E_\gamma < 1\,\mathrm{GeV}$$

$$p_T < 80\,\mathrm{MeV}/c$$

Observation:

$$(69.1 \pm 4.5 \pm 15.7) \times 10^{-3}\,\gamma/\mathrm{jet}$$

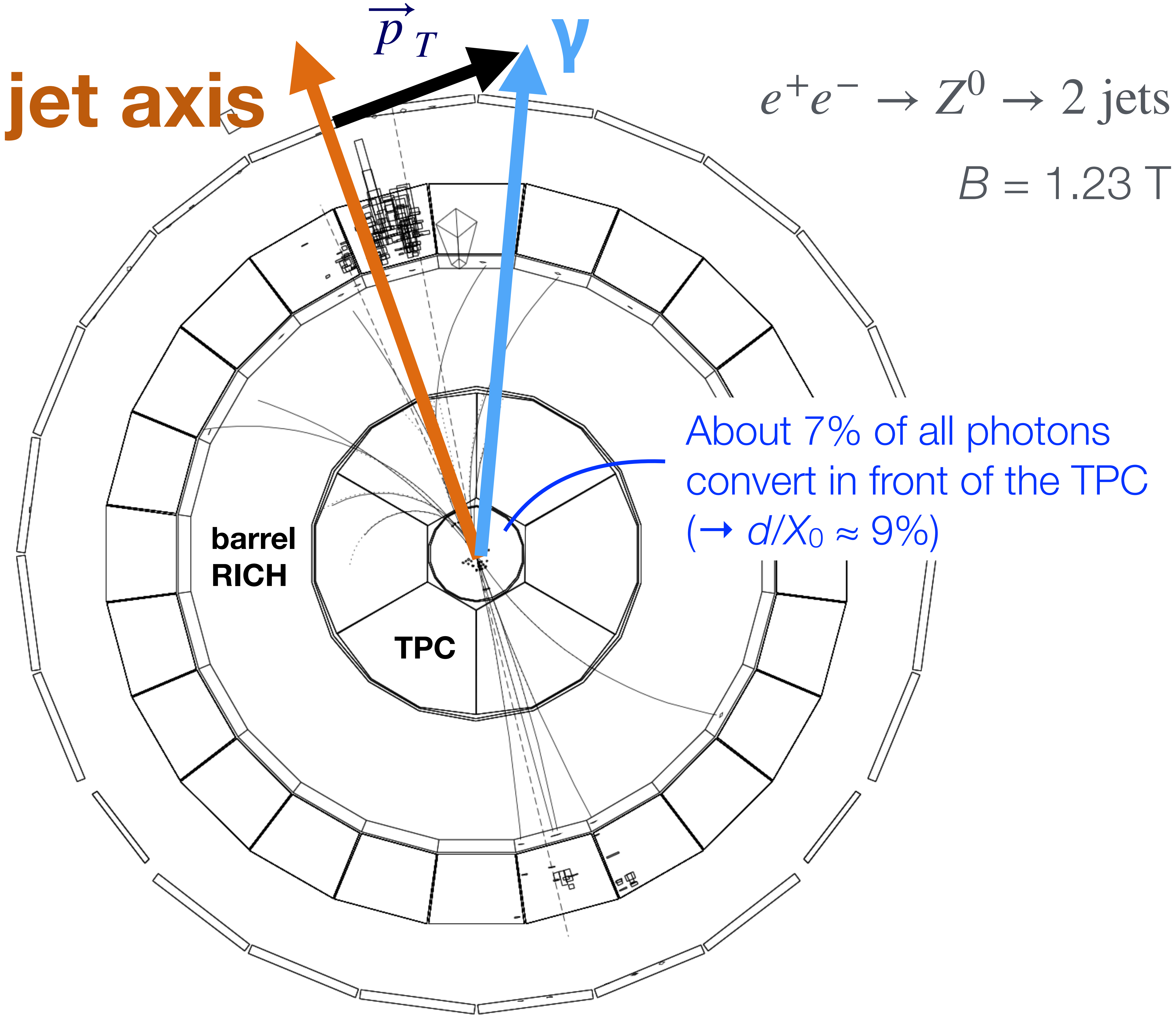
[→ probably very hard to do analysis in pp or AA due to underlying event]

Expected from inner bremsstrahlung:

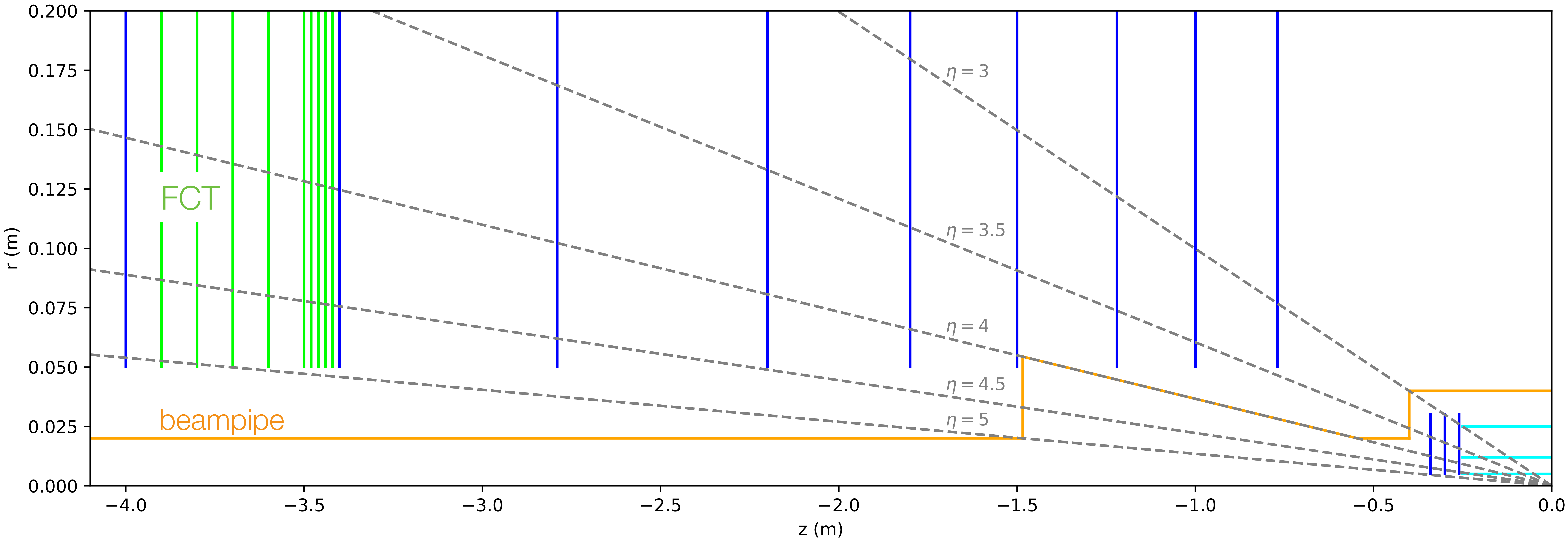
$$(17.1 \pm 0.01 \pm 1.21) \times 10^{-3}\,\gamma/\mathrm{jet}$$

Ratio:

$$4.0 \pm 0.3 \pm 1.0$$

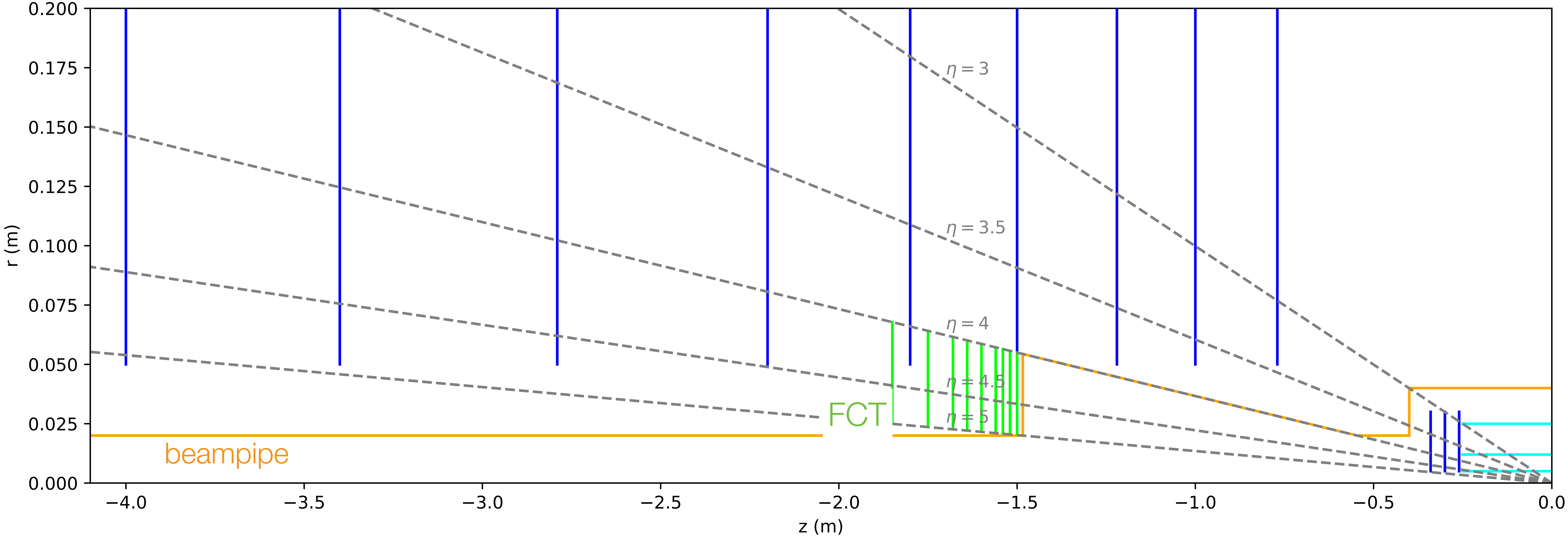


Ideas for the FCT and beampipe layout in ALICE 3 (1)



Measurement in $3 < \eta < 5$, large distance to interaction point presumably makes photon isolation cut less efficient

Ideas for the FCT and beampipe layout in ALICE 3 (2)



Measurement only in $4 < \eta < 5$,
presumably isolation cut more efficient

$$d/X_0 \approx O(\text{a few }\%) + \underbrace{0.1\% \times \cosh \eta}_{7.4\%}$$

Conclusions

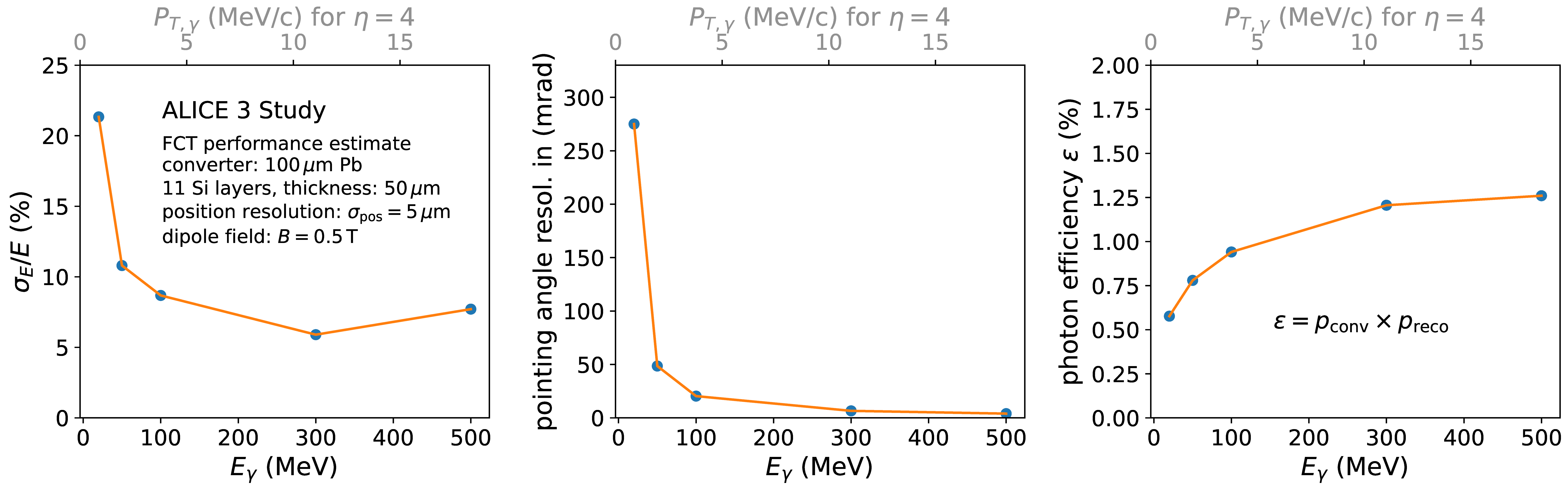
- Motivation for ultra-soft photons with ALICE 3:
  - Bremsstrahlung as calculated according to Low's theorem is a robust theoretical prediction
  - Confirm or refute earlier measurements showing strong excess above prediction from Low's theorem
  - Resolve the puzzle!

- Dominant background:
  - External bremsstrahlung produced by electrons and positrons (mostly from photon conversions)
  - Importance of rejecting events with electrons/positron tracks and/or photon isolation cut

- With a material budget of not more than 10% X_0 in front of the FCT an experimental test of Low's theorem is feasible with ALICE 3

Extra slides

FCT performance estimate:
Energy resolution, pointing resolution and efficiency



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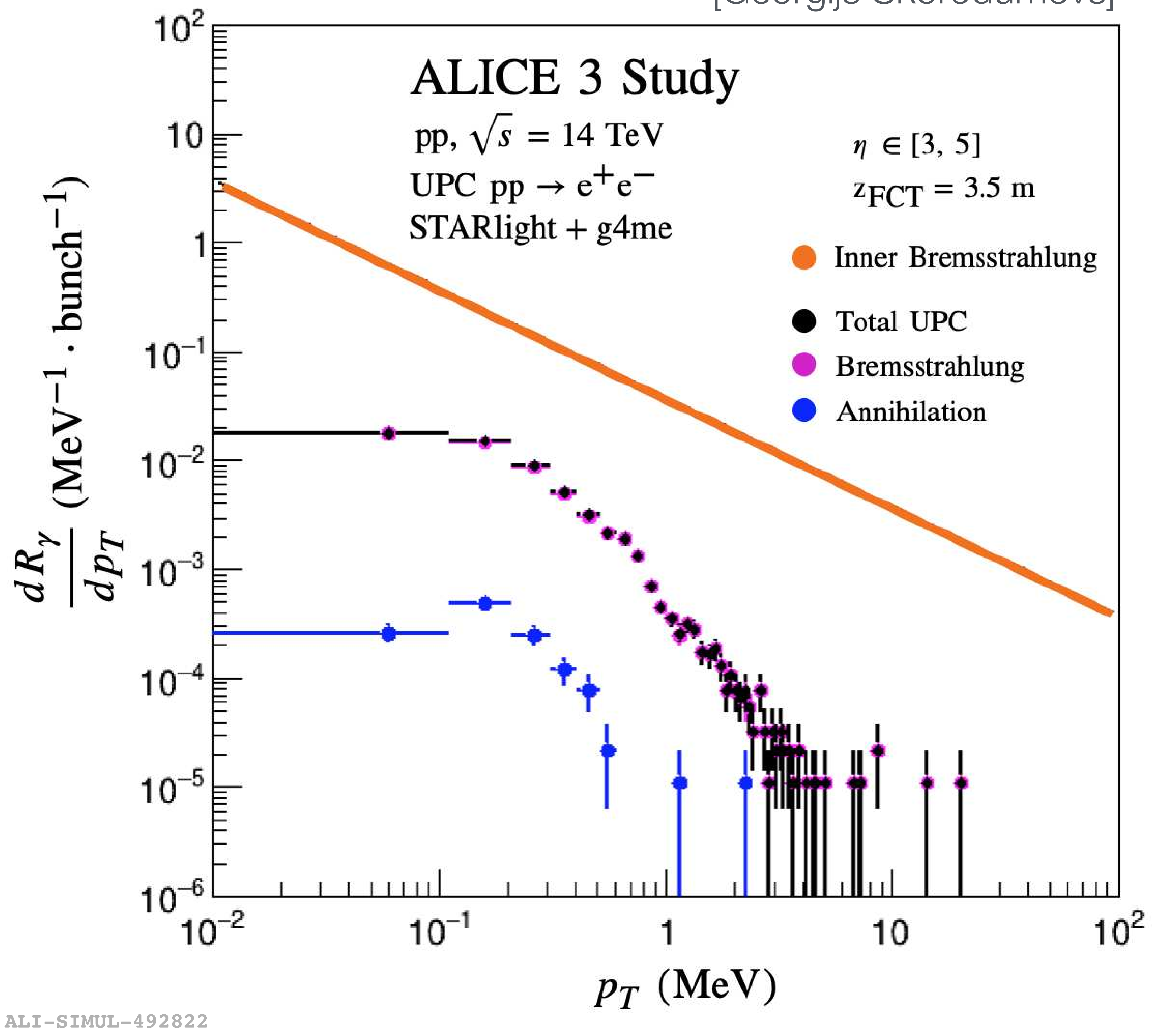
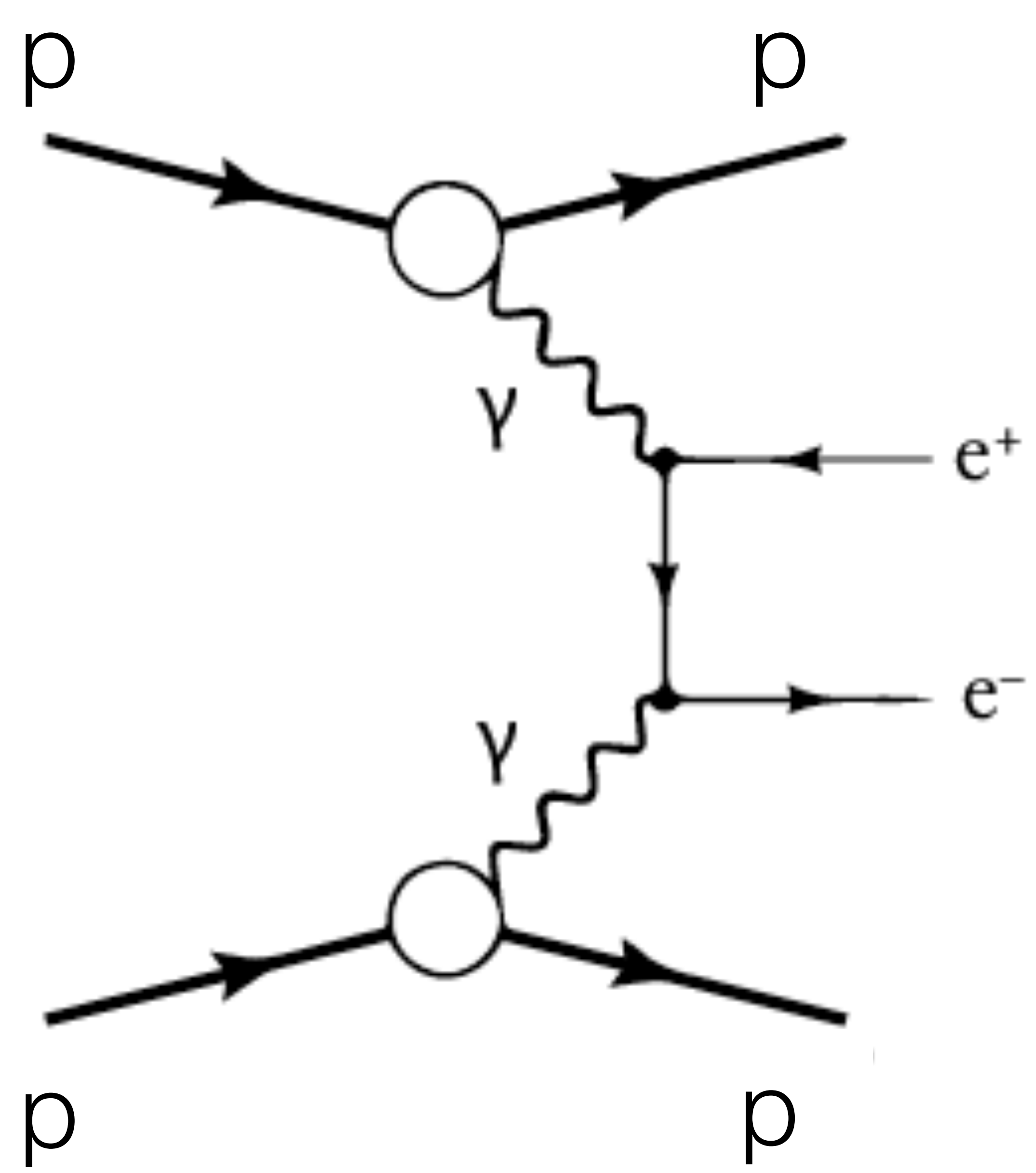
Background from e^+e^- pairs produced in electromagnetic processes

[Georgijs Skorodumovs]





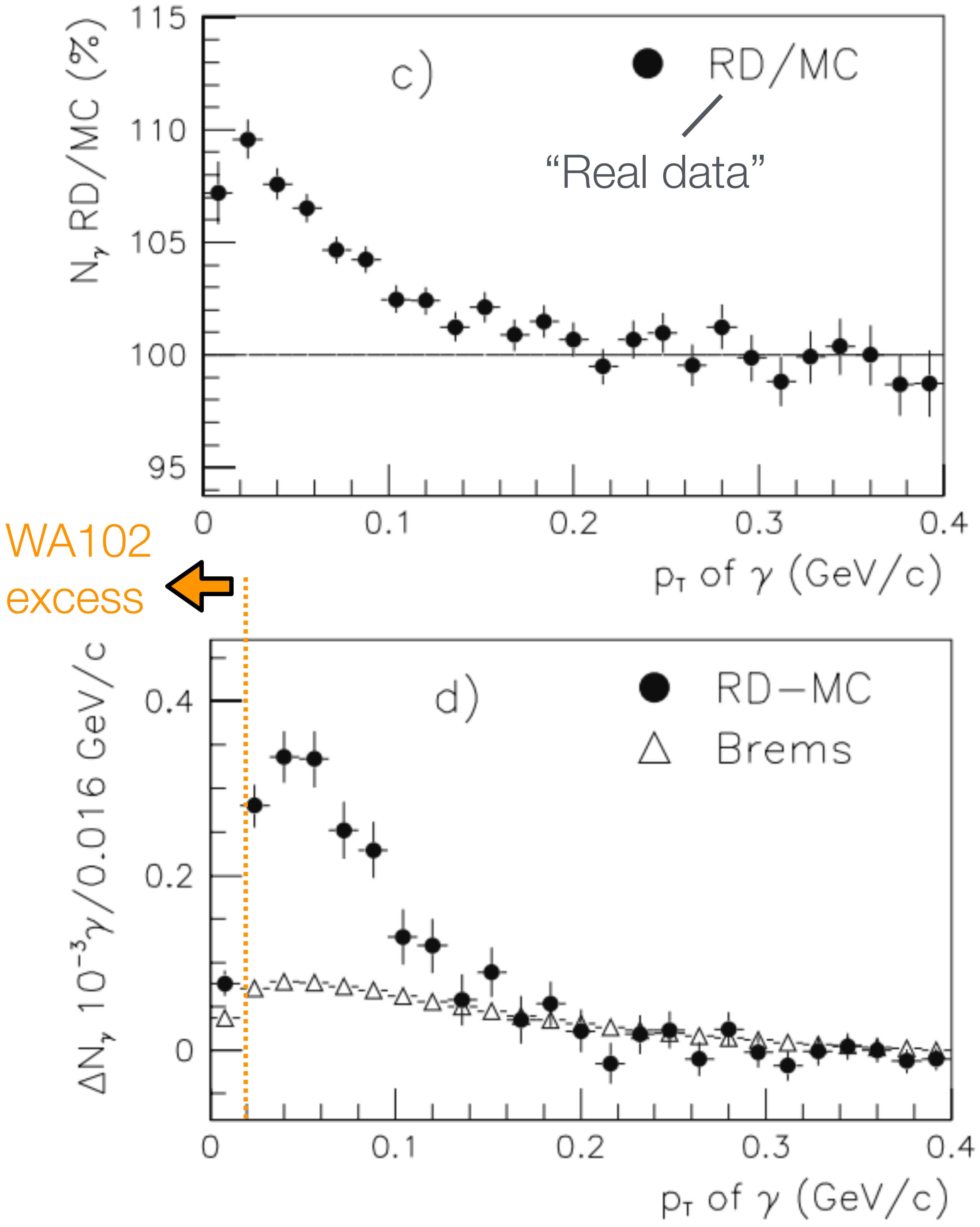
e^+e^- pairs created in e.m. processes create external bremsstrahlung in the detector material

Estimate based on STARlight and Geant4

Comparison is per bunch-crossing

Relatively small background

DELPHI soft photon excess above bremsstrahlung: Dependence on p_T w.r.t. jet axis



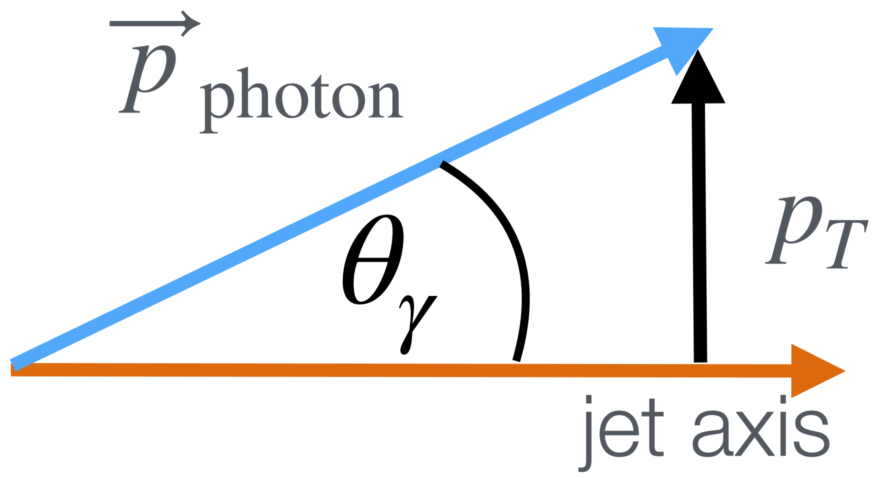
Excess extends to much larger p_T compared to WA102

Same origin as for WA102?

Inner bremsstrahlung signal (s_{IBS}) compared to background (benchmark for ALICE 3 design goals):

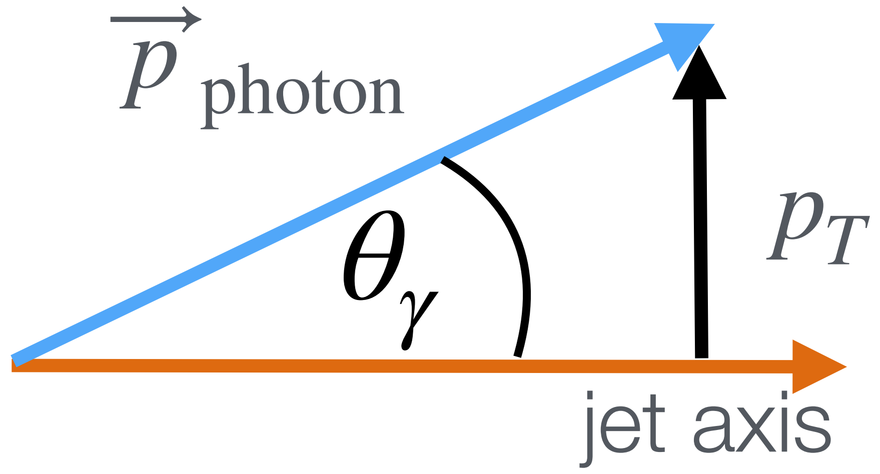
$$s = \mathrm{RD} - \mathrm{MC} \approx 0.1 \cdot \mathrm{MC} \equiv 0.1 \cdot b$$

$$s \approx 4 s_{\mathrm{IBS}} \quad \rightsquigarrow \quad \frac{s_{\mathrm{IBS}}}{b} \approx 2\text{–}3\%$$

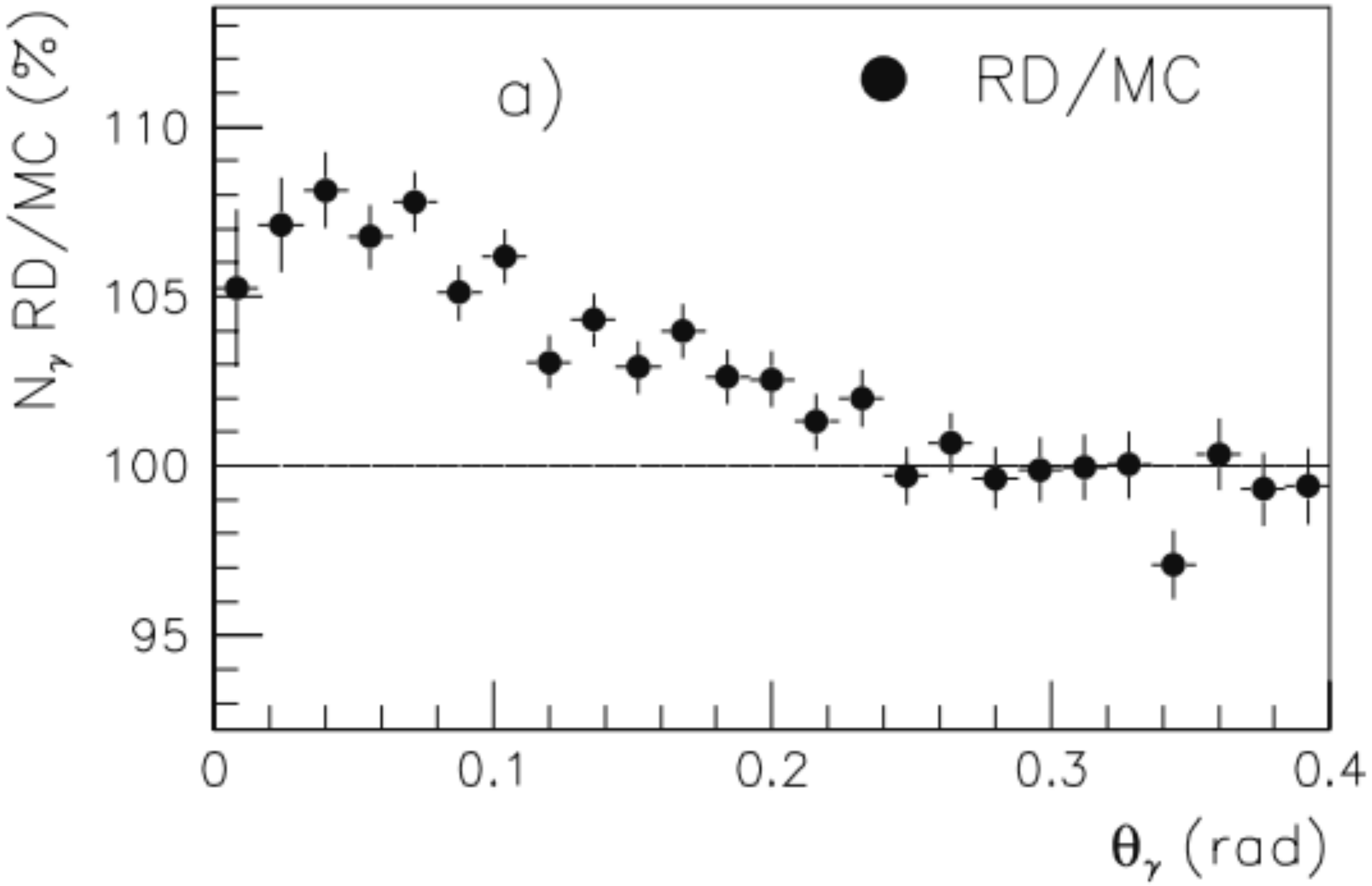


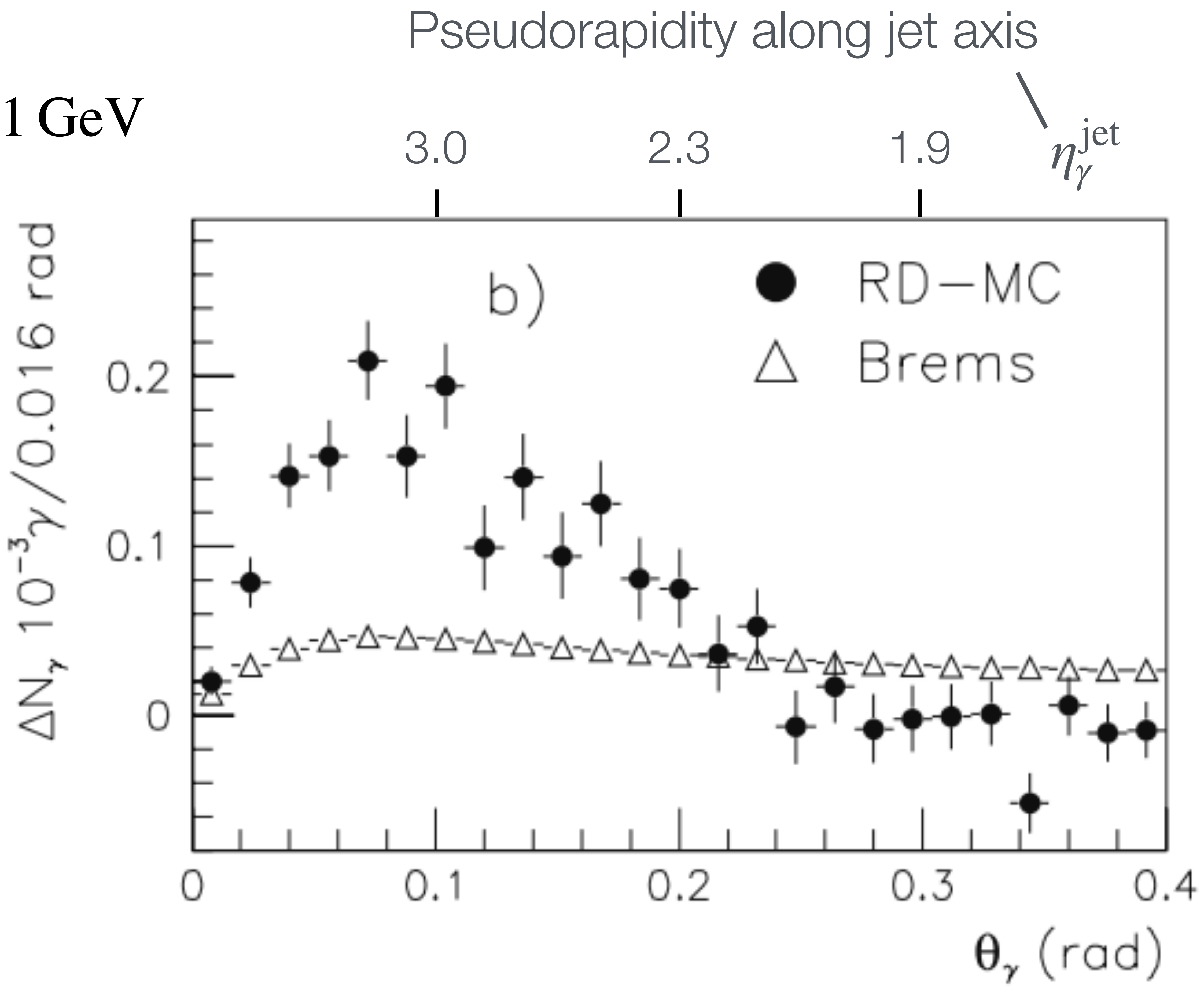
$$0.2 < E_\gamma < 1\,\mathrm{GeV}$$

DELPHI soft photon excess above bremsstrahlung: Dependence on polar angle w.r.t. jet axis



$0.2 < E_\gamma < 1\,\mathrm{GeV}$





Most of the excess above bremsstrahlung calc. at $\eta_\gamma^{jet} \gtrsim 2$