



Anomalous soft photons: Status and perspectives

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WEINBERG'S SOFT THEOREM — FROM PREDICTION TO MEASUREMENT

Kai Schweda (GSI/CERN)

Unlocking the QCD Phase Diagram
Darmstadt, Germany, September 7 - 9, 2026

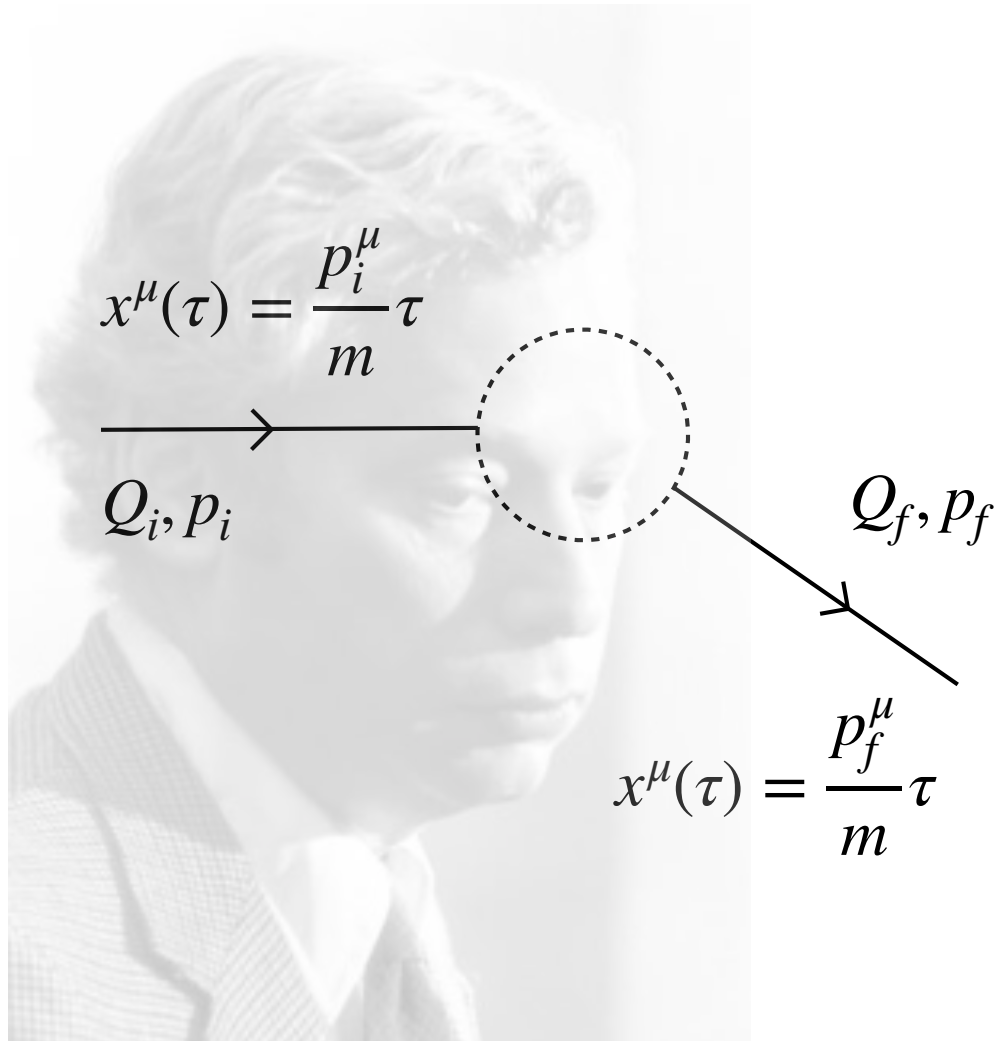
International Workshop dedicated to celebrating
the 80th birthday of Prof. Peter Braun-Munzinger



Peter Johanna me

August 1 - 5, 2022, GSI

WHY SOFT PHOTONS?



Massless photon $\rightarrow$ EM field has **infinite range**

Charged **asymptotic states** carry long-range
Coulomb fields

Scattering changes $p_i \rightarrow p_f$

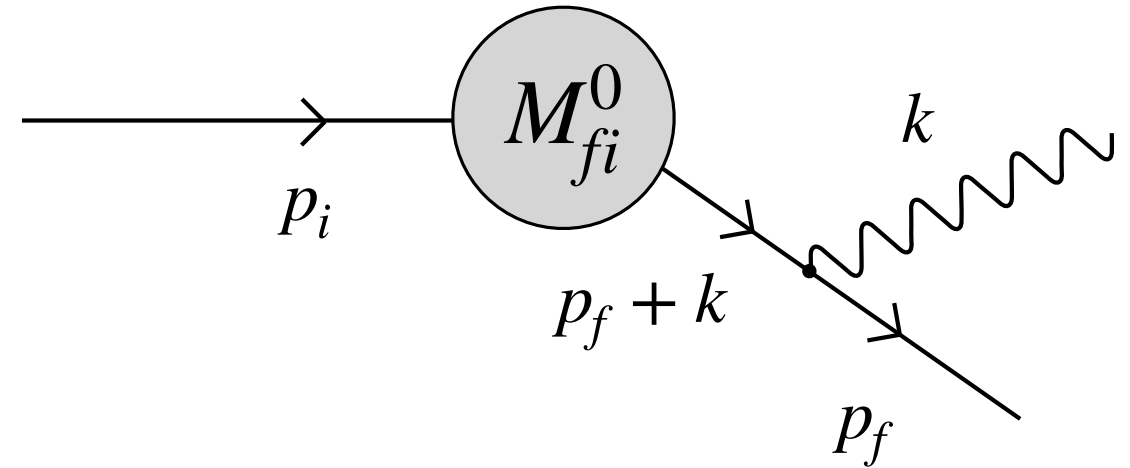
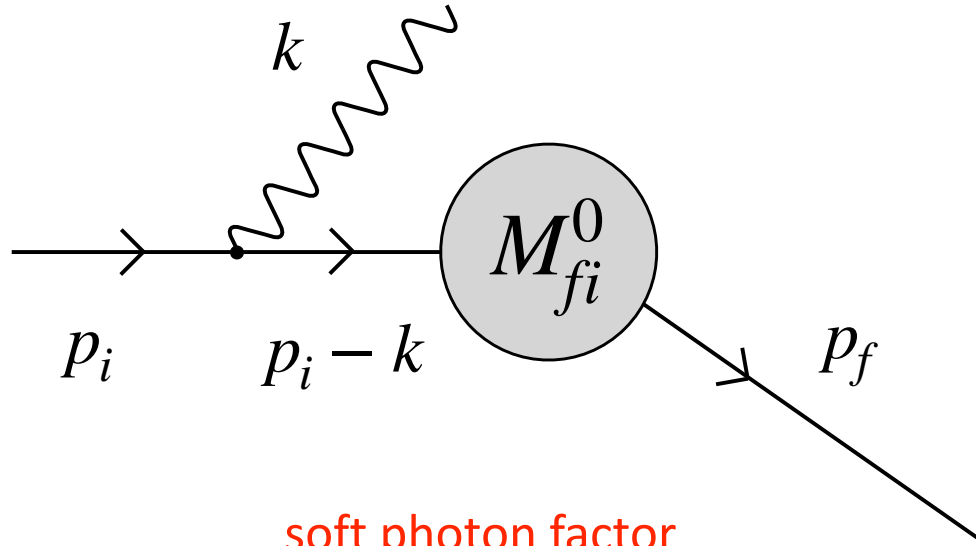
$\rightarrow$ **EM fields differ**

Their **difference** contains a **radiation field**

Real photons with $E_\gamma \rightarrow 0$

$\rightarrow$ **soft photons**

SOFT PHOTON FACTOR



soft photon factor

$$M_{\gamma}^{\text{soft}} \simeq eQ \left(\frac{p_f \cdot \varepsilon^*}{p_f \cdot k} - \frac{p_i \cdot \varepsilon^*}{p_i \cdot k} \right) M_{fi}^0$$

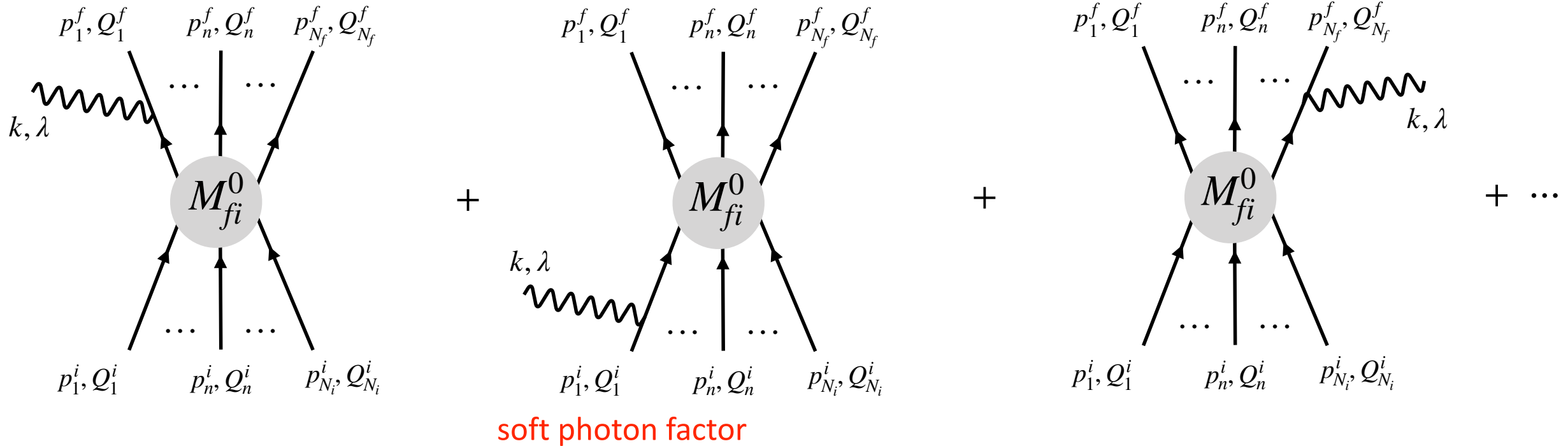
$$k^0 \rightarrow 0 \quad \Rightarrow \quad p \cdot k \rightarrow 0 \quad \Rightarrow \quad M_{\gamma}^{\text{soft}} \sim \frac{1}{p \cdot k} \sim \frac{1}{k^0}$$

soft photon emission

divergent with

$$1/k^0 = 1/E_{\gamma}$$

UPCOMING EVENTS



$$dI = \frac{\alpha}{(2\pi)^2} \frac{d^3\mathbf{k}}{\omega_k} \sum_{n,m=1}^{N_i+N_f} \eta_n Q_n \eta_m Q_m \frac{-p_n \cdot p_m}{(k \cdot p_n)(k \cdot p_m)} |M_{fi}^0|^2$$

soft photon couples universally to every charged external leg
contributions interfere coherently

COLLINEAR EMISSION — DEAD CONE

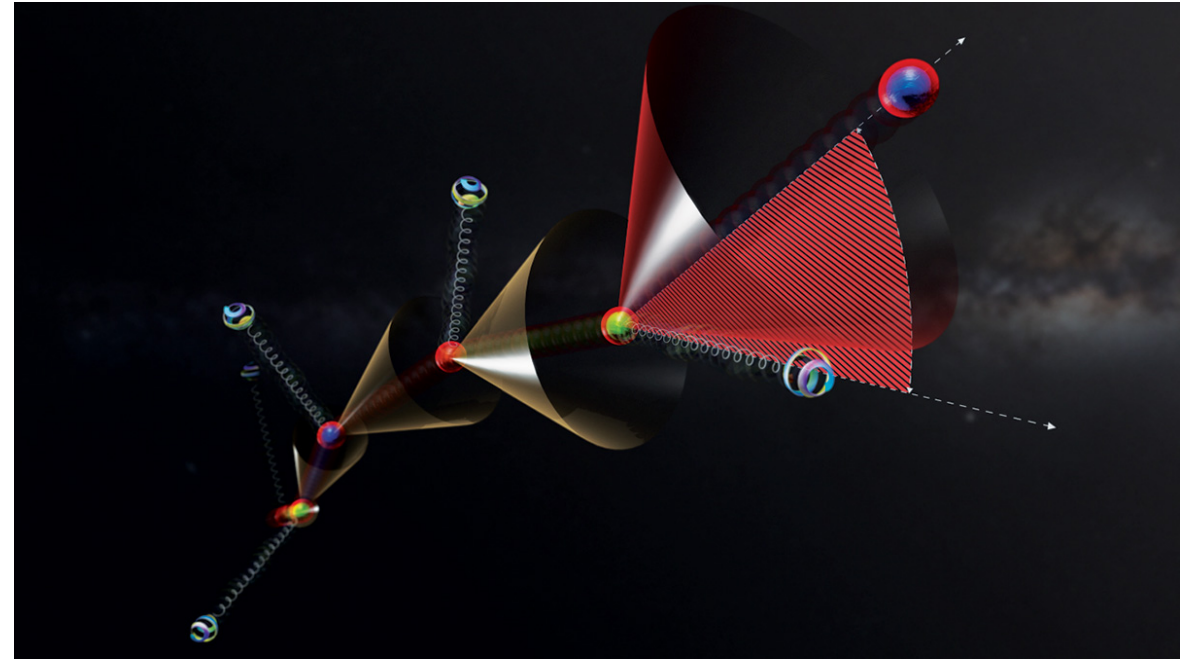
$$dI = \alpha Q^2 \frac{d\omega_k}{\omega_k} \frac{d\theta}{2\pi} \frac{4\theta^3}{[\theta^2 + \theta_0^2]^2} |M_{fi}^0|^2$$

small angle **radiation** is
suppressed in the **dead cone**

$$\theta_0 = 1/\gamma$$

small angle **radiation** reaches
maximum

$$\theta_0 = \sqrt{3}/\gamma$$



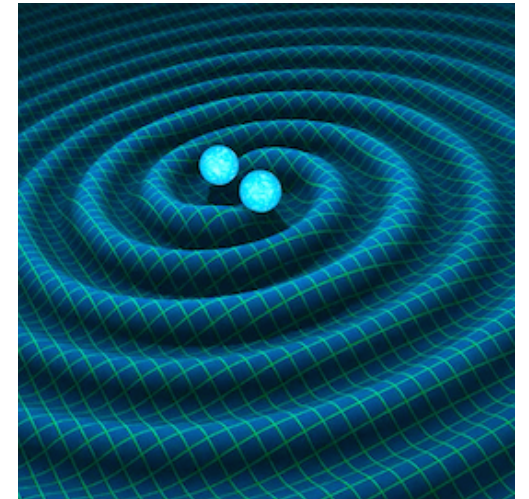
[Nature, 605 \(2022\) 440](#)

COLLINEAR DIVERGENCE

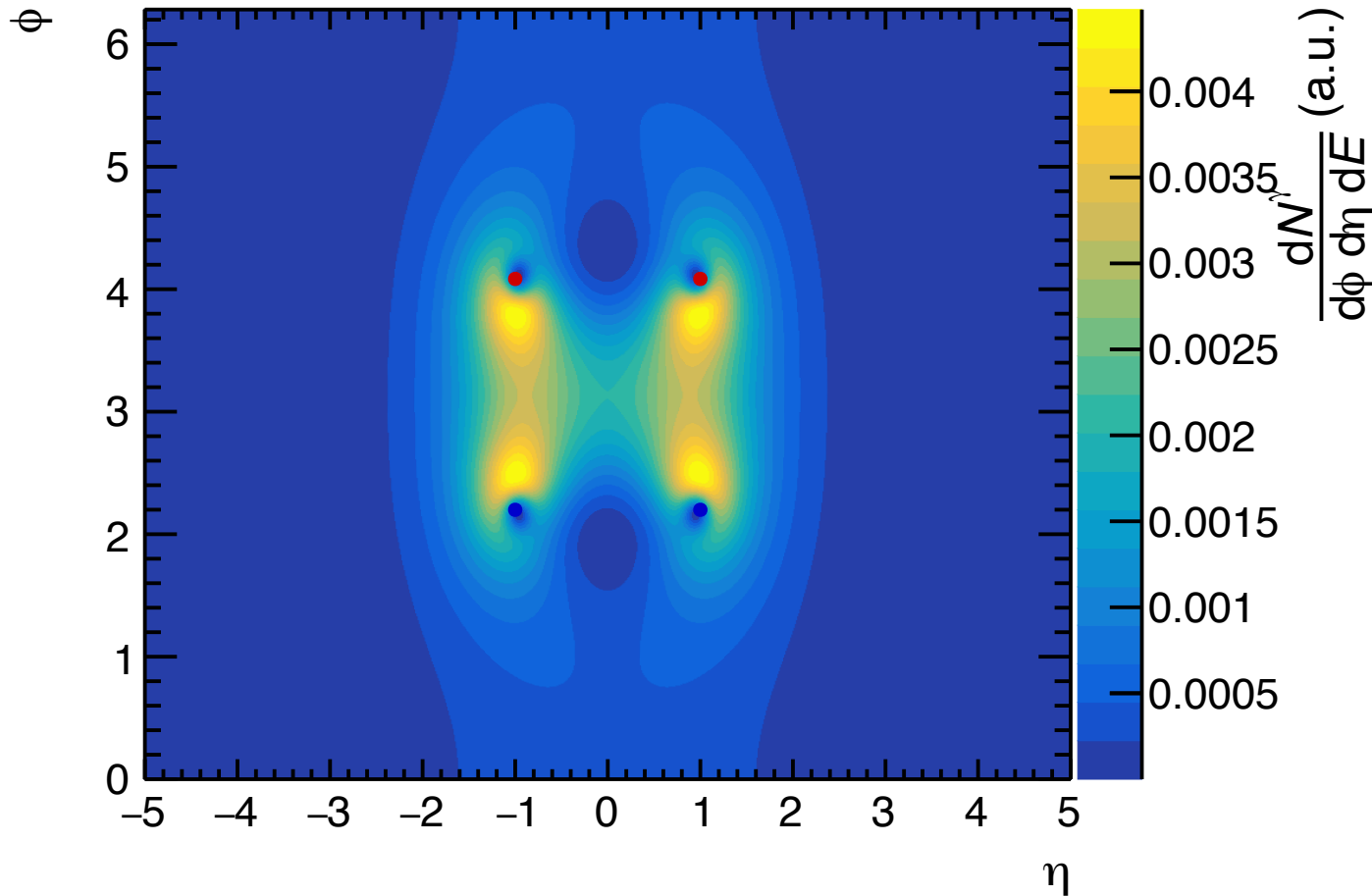
The **dead cone** regulates the **collinear divergence** in QED

There are **no massless charged particles** — thank God!

Gravity is **doubly special**: its coupling vanishes at low energy, and its spin-2 structure eliminates the collinear divergence
→ **no collinear divergence**



SOFT RADIATION: COHERENCE AND INTERFERENCE



Four charged external legs:

$Q_f = \pm 1$, with **(2+)** and **(2-)**

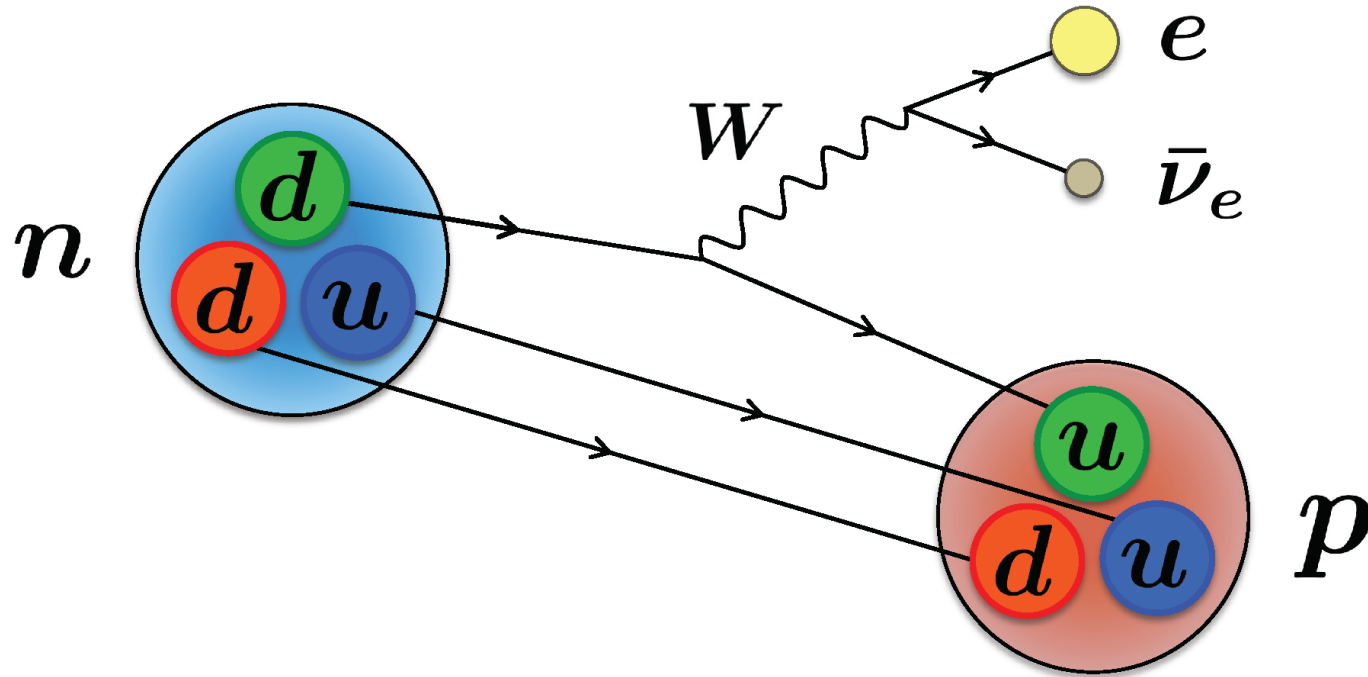
Dead cone: collinear radiation suppressed for massive charges

Soft-photon **amplitudes interfere coherently**

(++ , --): destructive interference

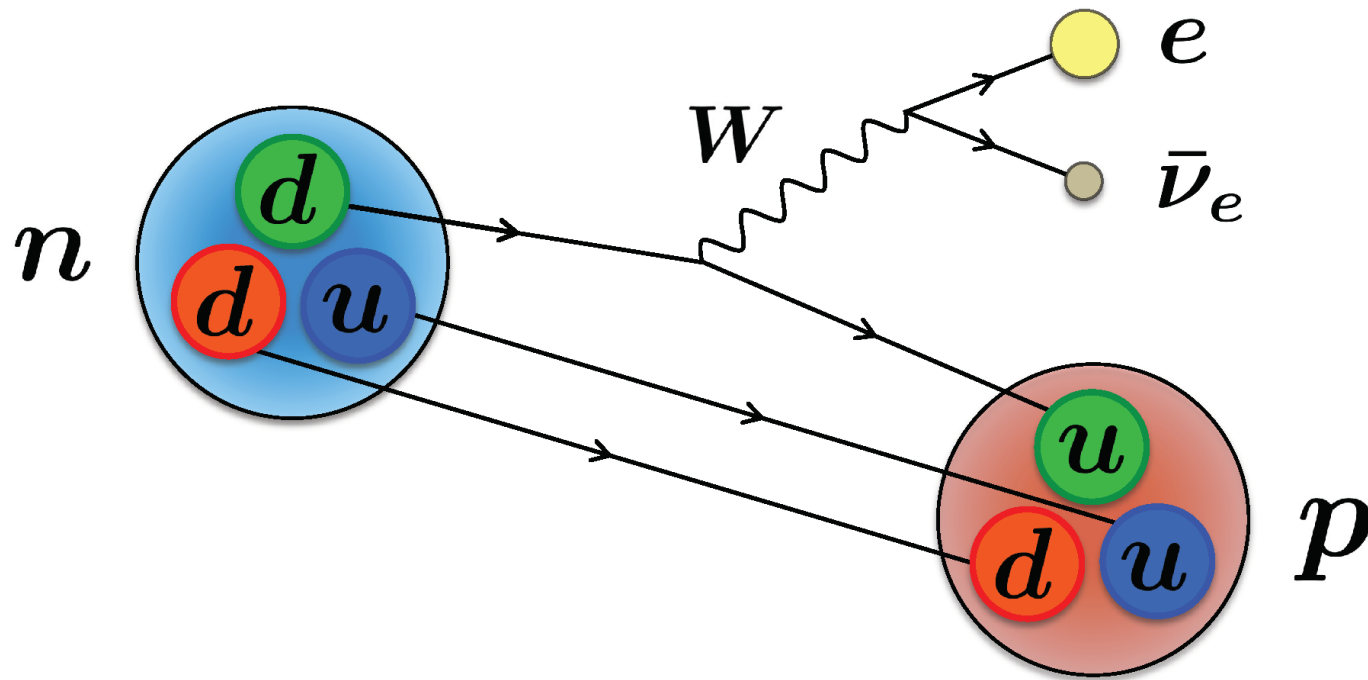
(+- , -+): constructive interference

NEUTRON RADIATIVE DECAY

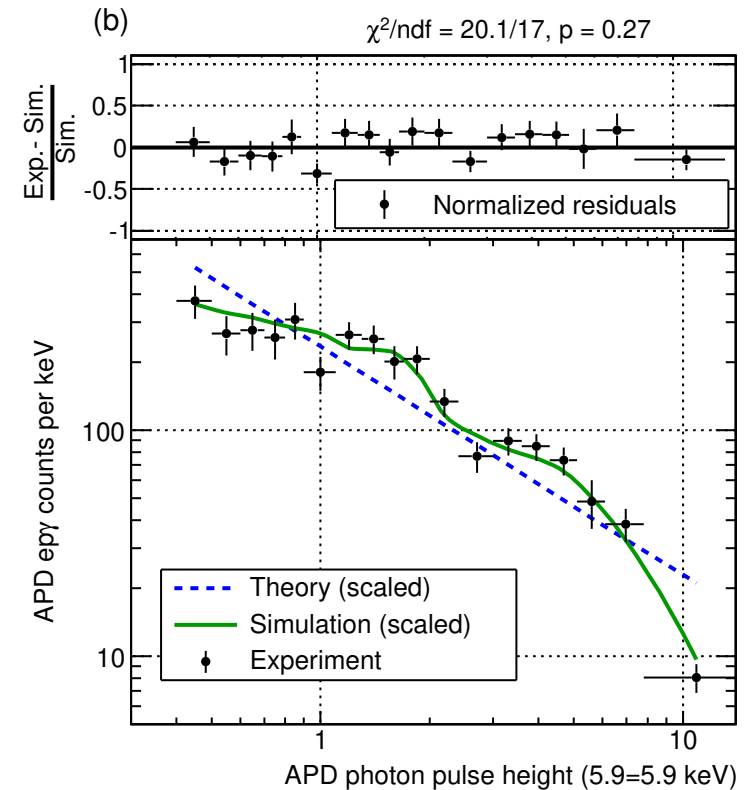


[Universe 2023, 9\(10\), 449](#)

NEUTRON RADIATIVE DECAY



[PRL 116, 242501 \(2016\)](#)



$$E_\gamma = 0.4 - 14 \text{ keV}$$

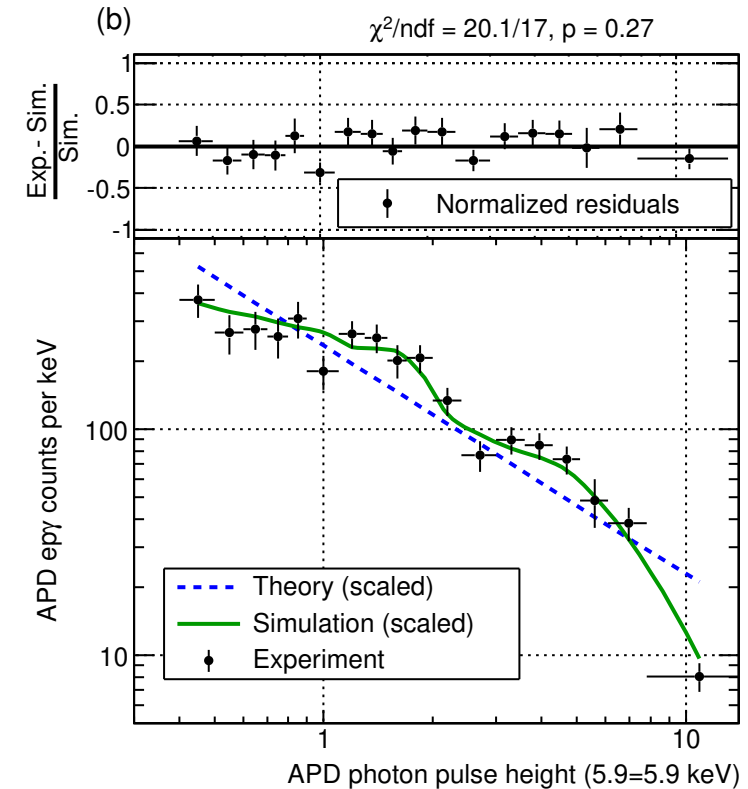
$$BR = 0.00582 \pm 0.00023 [\text{stat}] \pm 0.00062 [\text{syst}]$$

**Full QED reproduces the
universal leading soft behavior**

[Universe 2023, 9\(10\), 449](#)

NEUTRON RADIATIVE DECAY

[PRL 116, 242501 \(2016\)](#)

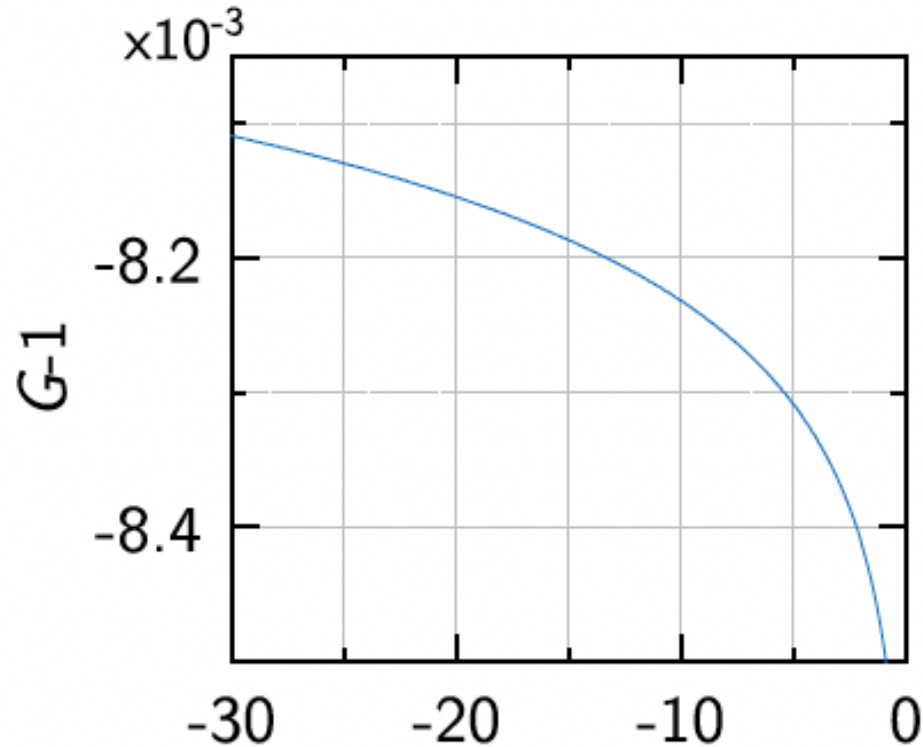


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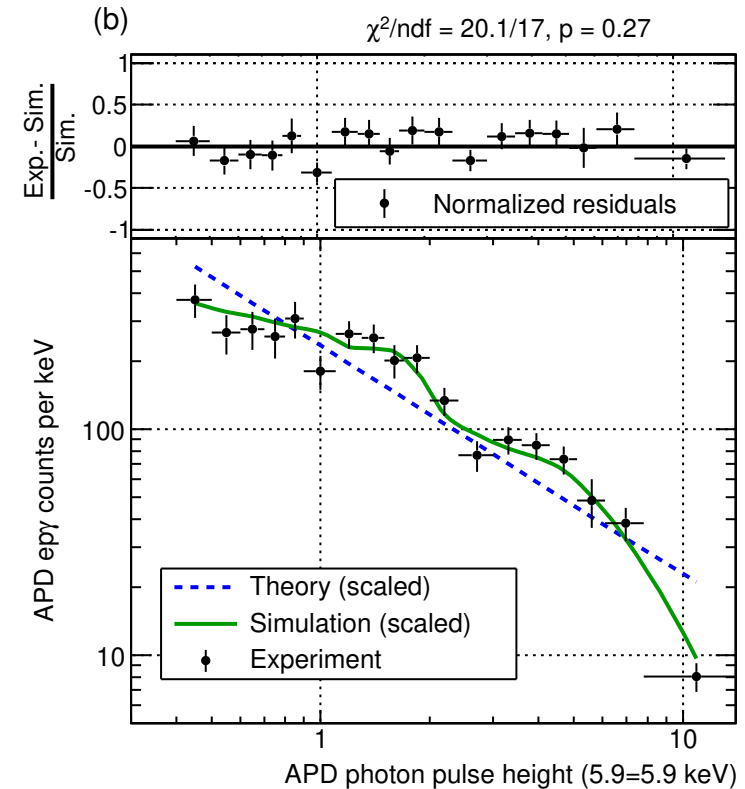
NEUTRON RADIATIVE DECAY



[Eur. Phys. J. C \(2019\) 79:204](#)

**KATRIN: radiative corrections
deplete the β spectrum
near the endpoint**

[PRL 116, 242501 \(2016\)](#)

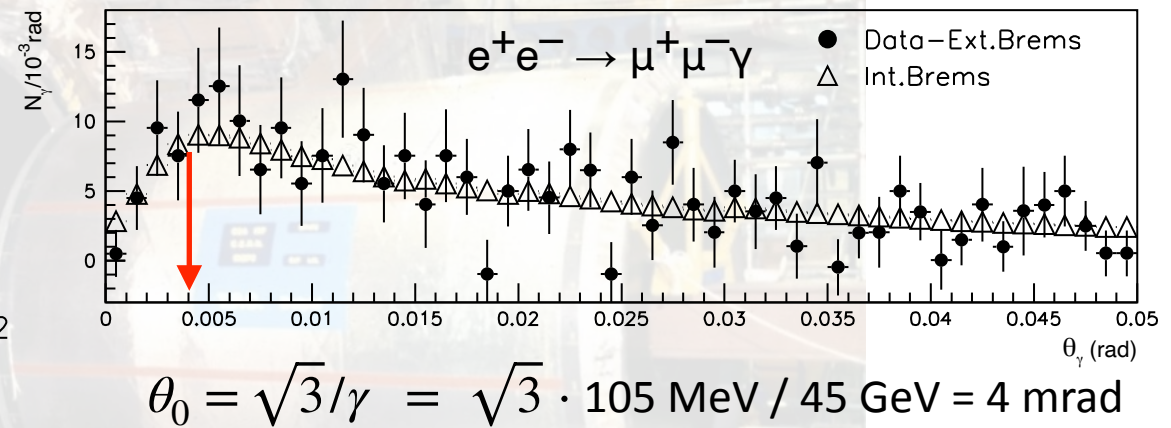
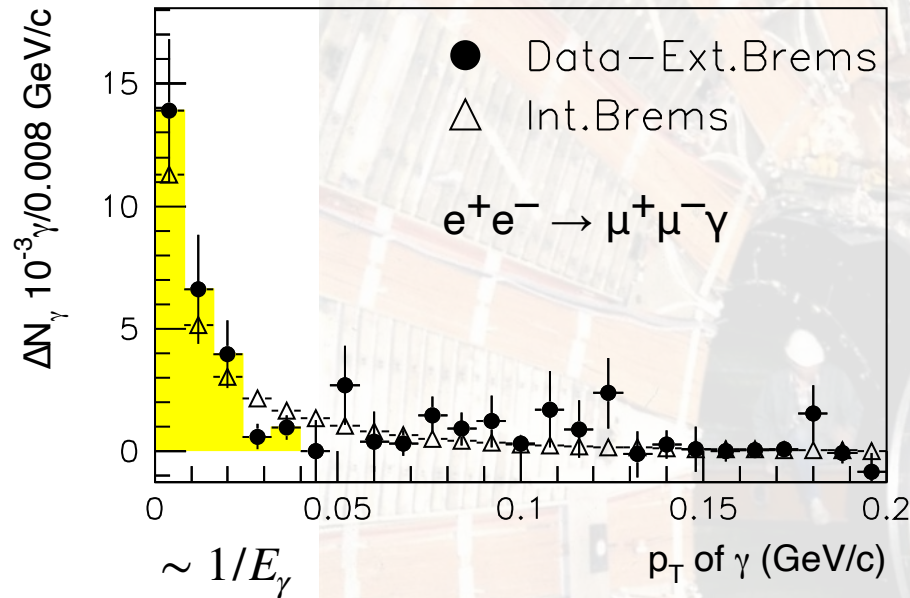


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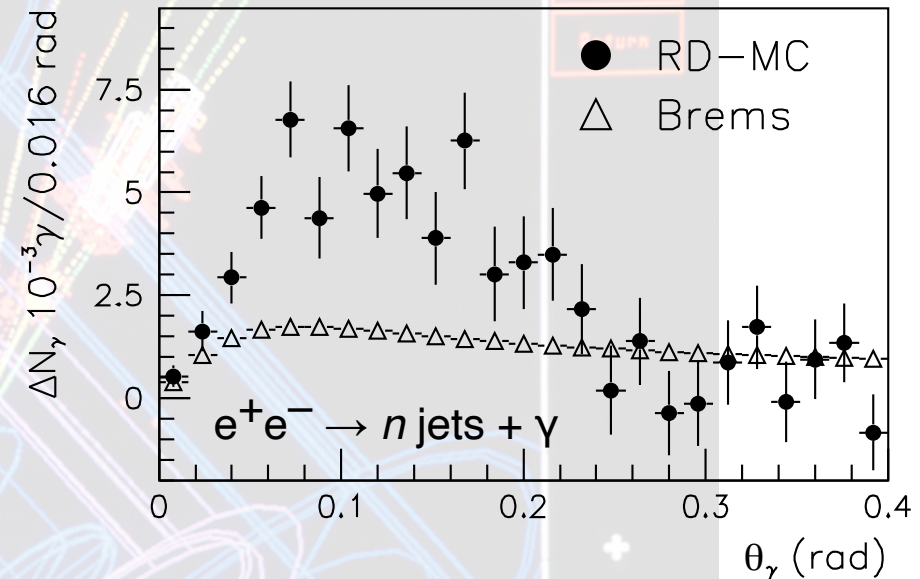
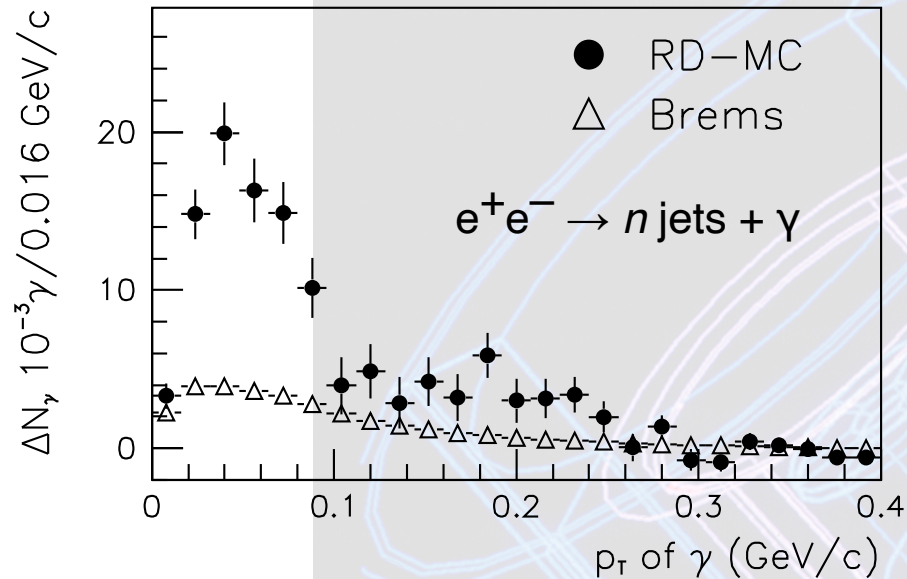
**Full QED reproduces the
universal leading soft behavior**

DELPHI: $e^+ + e^- \rightarrow Z^0 \rightarrow \mu^+ + \mu^- + \gamma$



DELPHI soft photons: $1/E_\gamma$, dead cone, yield: all as predicted

DELPHI: $e^+ + e^- \rightarrow Z^0 \rightarrow \text{hadrons} + \gamma$

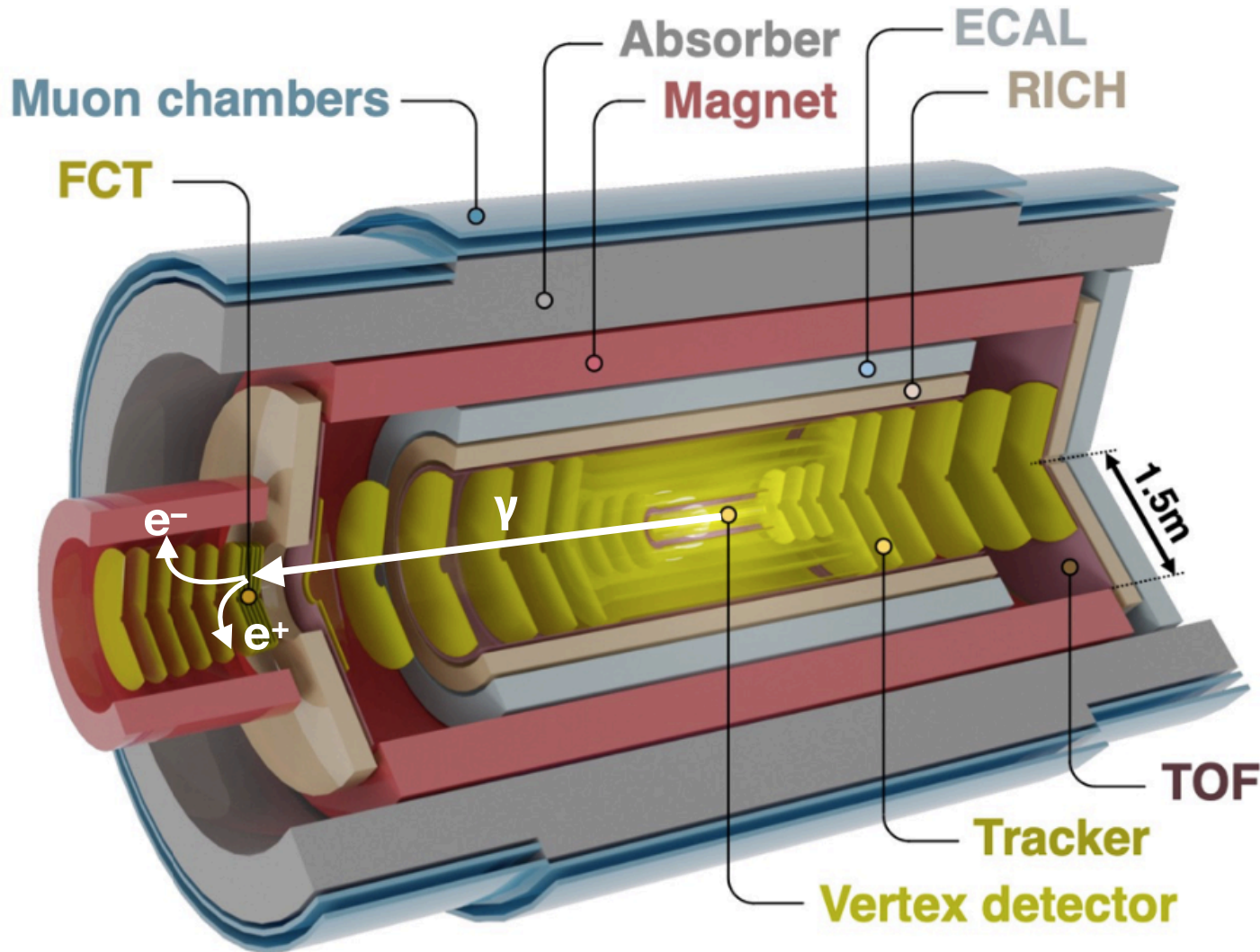


4x excess of soft photons in hadronic events — but hadronization involved

also seen in fixed-target experiments, yet no model gives a consistent description

The soft-photon puzzle!

ADDRESSING THE SOFT-PHOTON PUZZLE AT THE LHC



Ultra-soft photons:

Forward Conversion Tracker (FCT),
 $4 < \eta < 5$, $1 < p_T < 50 \text{ MeV}/c$

$$p_T = \frac{E_\gamma}{\cosh \eta}$$

η	3	4	5
$p_T \text{ (MeV}/c)$	10	3.7	1.3

**However, FCT was not included
in the approved version 3b**

Ultraperipheral collisions - QED processes

^{208}Pb

$$Z\alpha_{em} \approx 1$$

$$\text{photon flux} \propto Z^2$$

$$\text{photon luminosity}$$

$$\propto Z^4$$

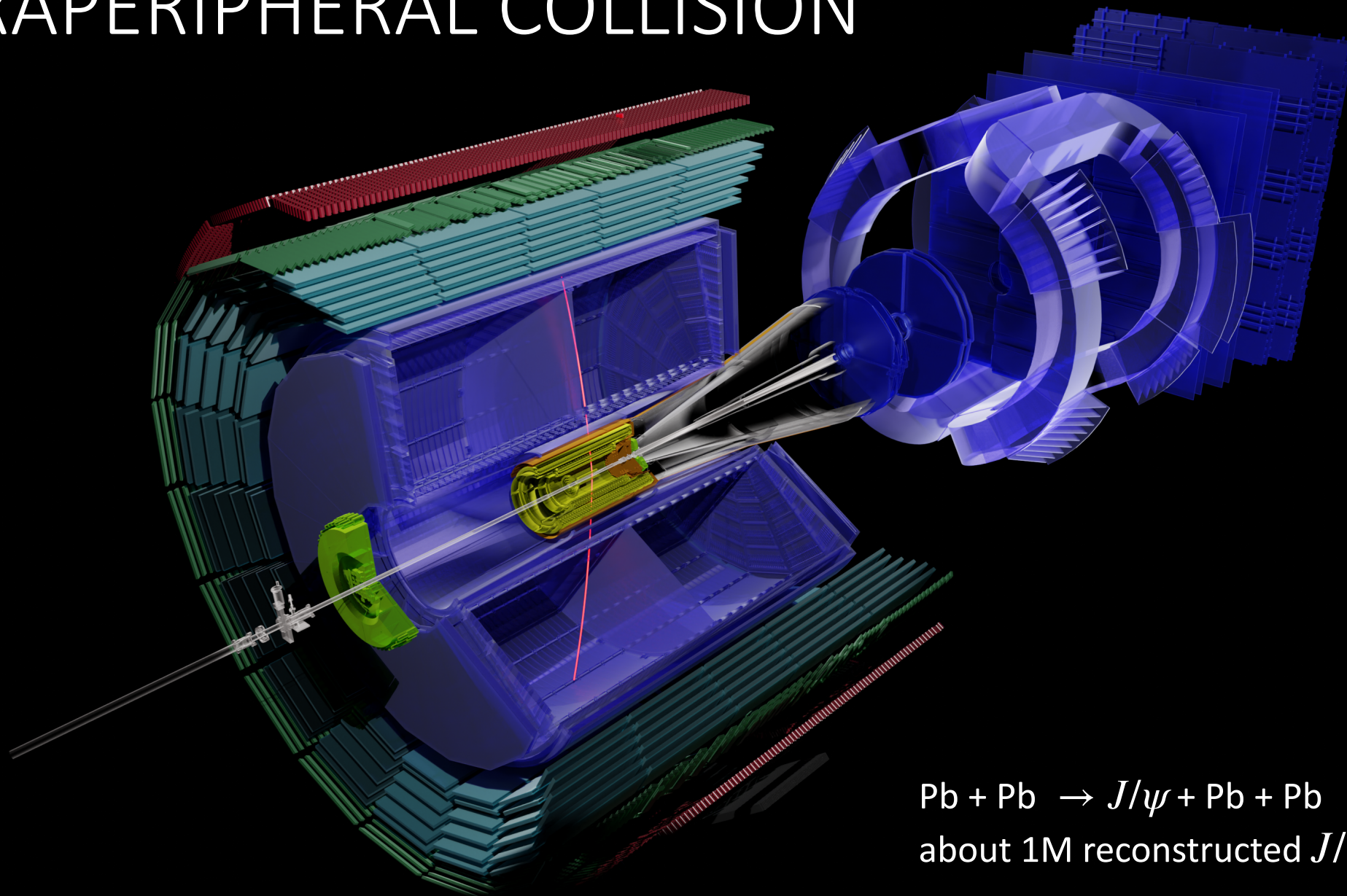
γ

Vector meson

Photon energy

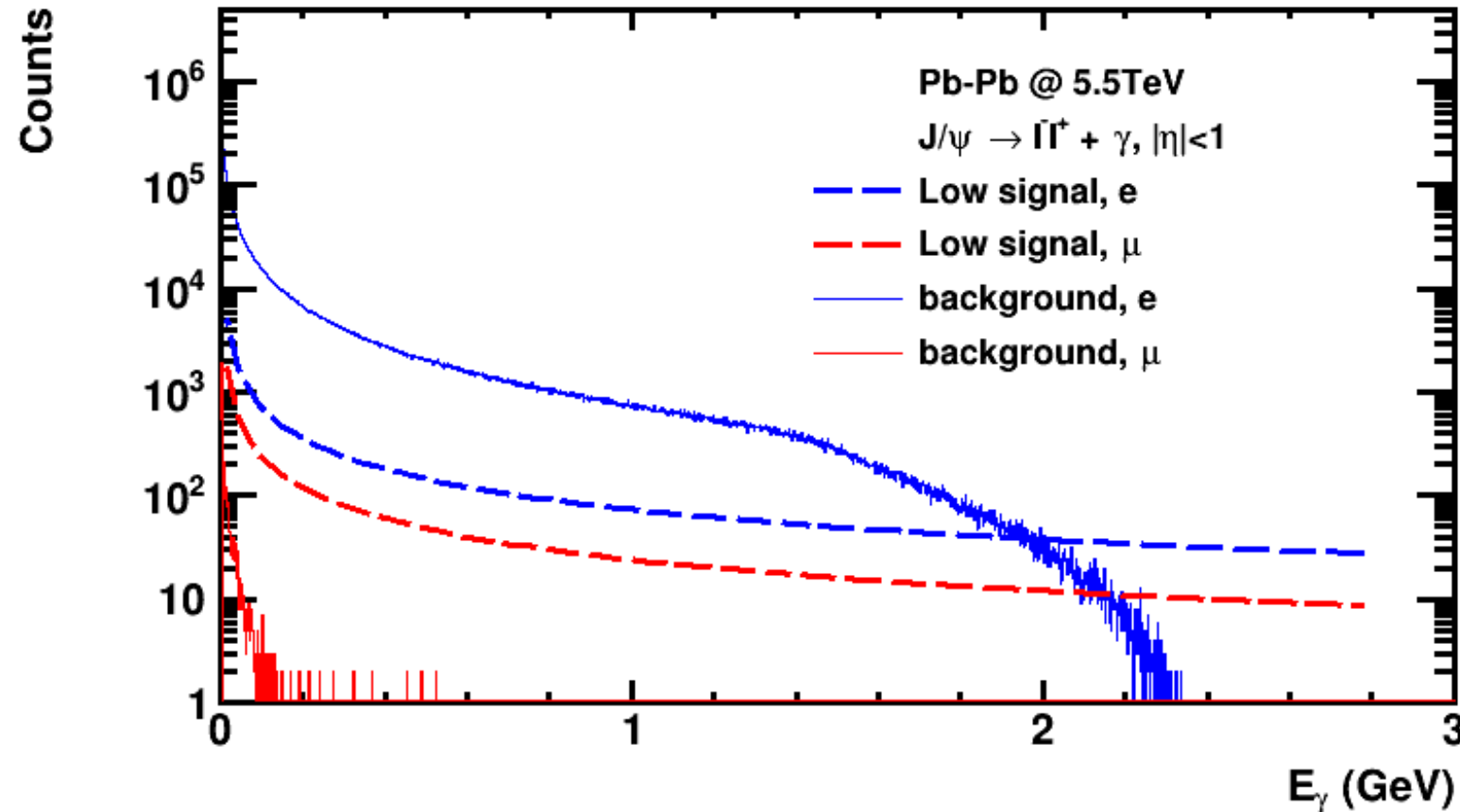
^{208}Pb

ULTRAPERIPHERAL COLLISION



$\text{Pb} + \text{Pb} \rightarrow J/\psi + \text{Pb} + \text{Pb}$
about 1M reconstructed J/ψ in Run 3

J/ψ RADIATIVE DECAY — CENTRAL BARREL



Electron channel: radiative decay

buried in **background**

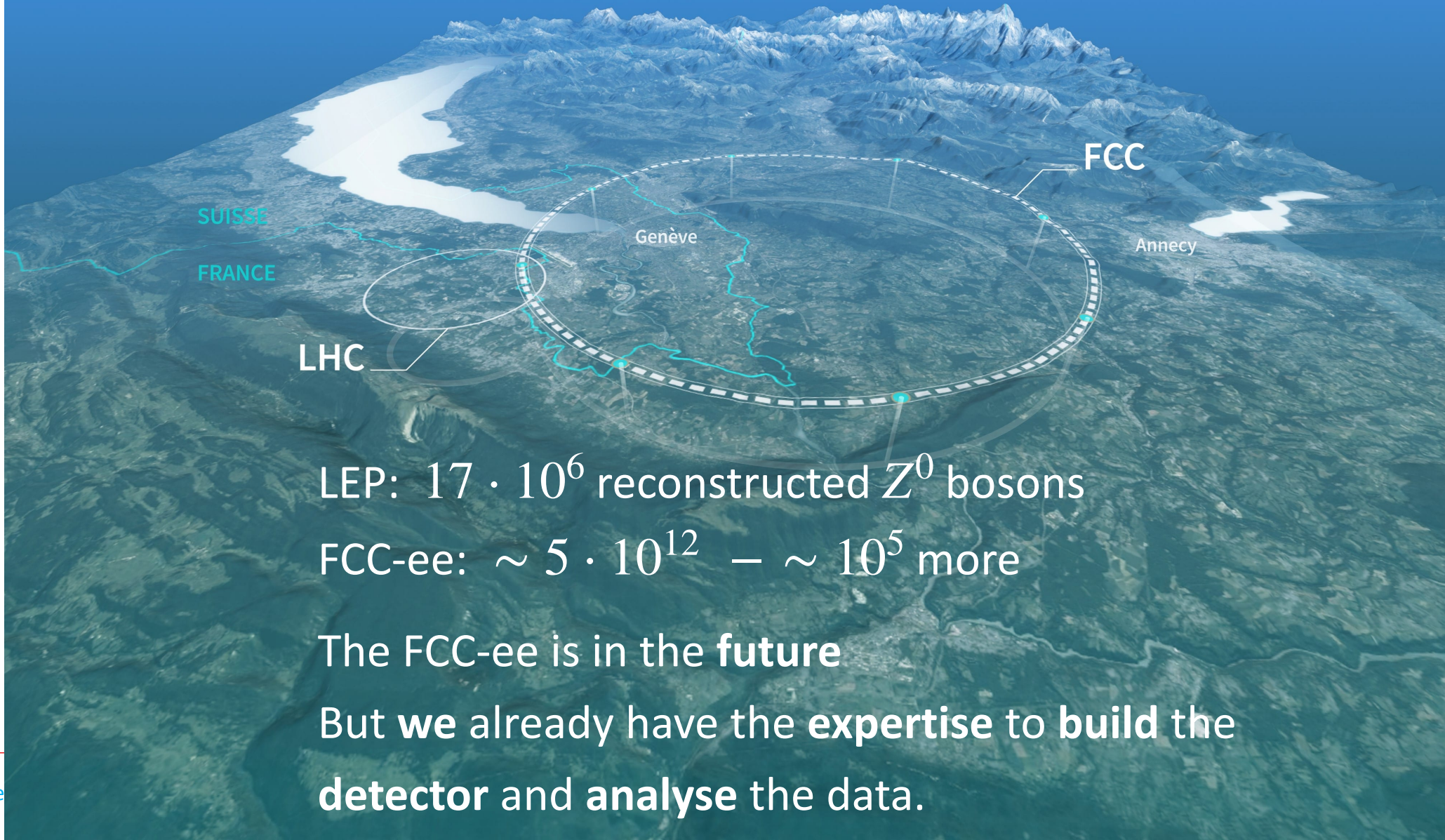
Muon channel: essentially

background-free

signal has explicit β dependence

— not just a mass effect

THE FUTURE CIRCULAR COLLIDER



LEP: $17 \cdot 10^6$ reconstructed Z^0 bosons

FCC-ee: $\sim 5 \cdot 10^{12}$ — $\sim 10^5$ more

The FCC-ee is in the **future**

But **we** already have the **expertise** to **build** the
detector and **analyse** the data.

SOME PERSONAL REMARKS

30 years — and still learning from you

1996 · Darmstadt · My PhD begins

2022 · Modern Aspects of Nuclear Physics · Finally your student — sort of!

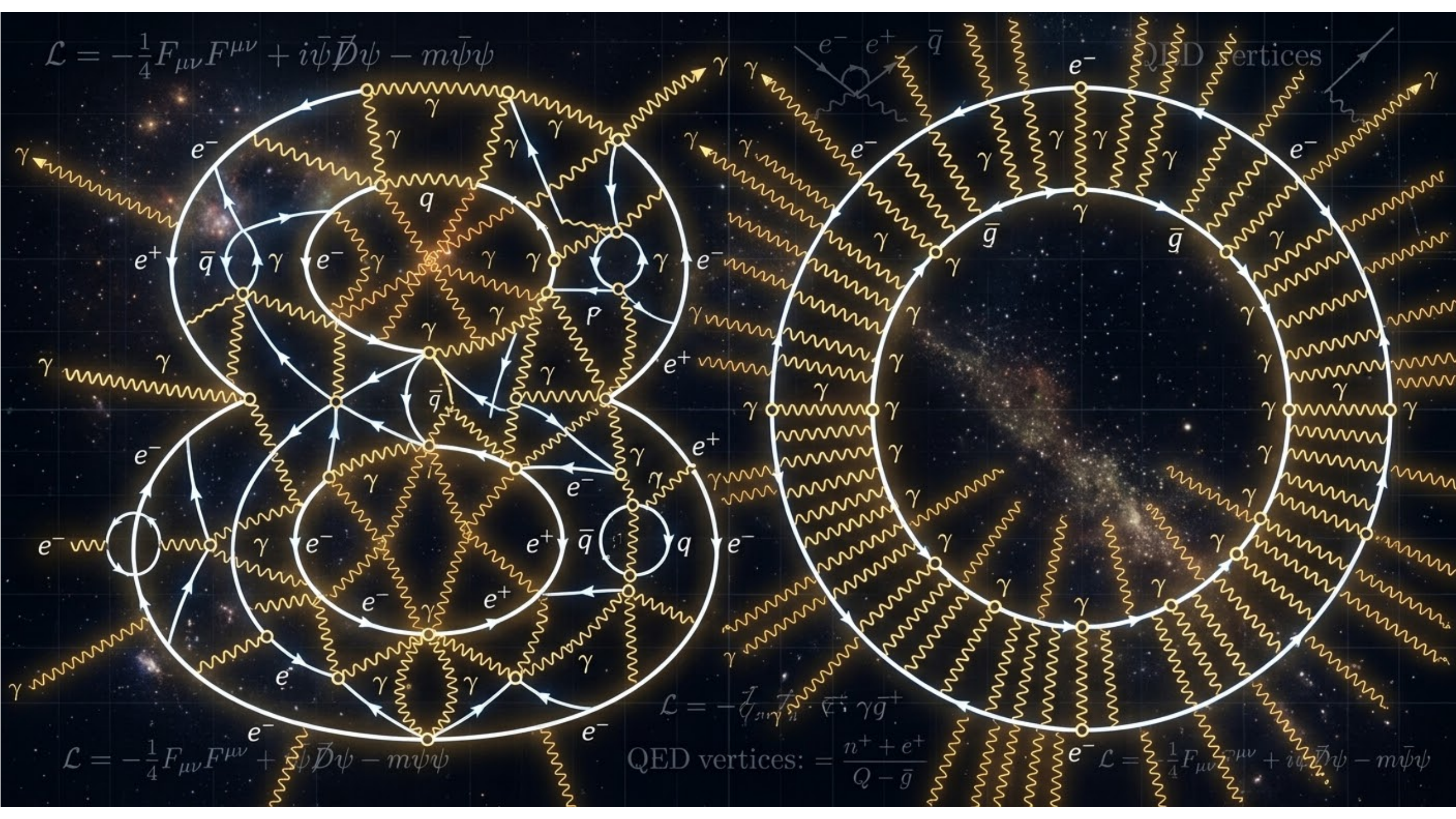
Your power of persuasion

Making us do things we would never do voluntarily — and making us enjoy it

Your scientific compass

Always pushing me towards questions that matter

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi - m\bar{\psi}\psi$$



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QED vertices: $= \frac{n^+ + e^+}{Q - \bar{g}}$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi - m\bar{\psi}\psi$$

BACKUP



SOFT-PHOTON YIELDS AT LEP

$$dI = \alpha Q^2 \frac{d\omega_k}{\omega_k} \frac{d\Omega_k}{(2\pi)^2} \frac{|\beta|^2 \sin^2 \theta}{(1 - |\beta| \cos \theta)^2} |M_{fi}^0|^2$$

$$\frac{dN_\gamma}{d^2\mathbf{k}_T d\eta d\phi} = \frac{\alpha}{(2\pi)^2} \int d^3\mathbf{p}_{\mu^+} d^3\mathbf{p}_{\mu^-} \sum_{n,m=1}^4 \eta_n Q_n \eta_m Q_m \frac{-(p_n \cdot p_m)}{(p_n \cdot k)(p_m \cdot k)} \frac{dN_{\mu^+\mu^-}}{d^3\mathbf{p}_{\mu^+} d^3\mathbf{p}_{\mu^-}}$$

$$\frac{dN_\gamma}{d^2\mathbf{k}_T d\eta d\phi} = \frac{\alpha}{(2\pi)^2} \int d^3\mathbf{p}_1 \dots d^3\mathbf{p}_{N_f} \sum_{n,m=1}^N \eta_n Q_n \eta_m Q_m \frac{-(p_n \cdot p_m)}{(p_n \cdot k)(p_m \cdot k)} \frac{dN_{\text{hadrons}}}{d^3\mathbf{p}_1 \dots d^3\mathbf{p}_{N_f}}$$

ELECTRON VS MUON SEPARATION IN TPC

