AUSTRIAN ACADEMY OF SCIENCES

SMI – STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS

Tau anomalous magnetic moment measurements in ultra-peripheral collisions with ALICE at the LHC

SMI retreat 2023

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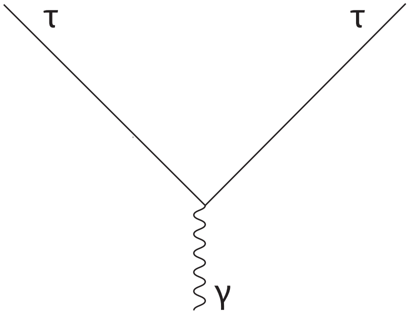
Anomalous magnetic moment

- Magnetic dipole moment μ:

$$\boldsymbol{\mu} = g \frac{e}{2\,m} \boldsymbol{s}.$$

g - gyromagnetic factor, e - elementary charge, m - mass, $\boldsymbol{s}$ - spin

- Under Dirac assumption (point-like particle, spin 1/2) $g = 2$.



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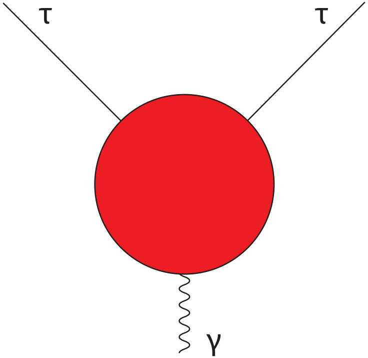

- Anomalous magnetic moment:

$$a = \frac{g-2}{2}.$$

- Standard Model prediction:

$$a = a^{\mathrm{QED}} + a^{\mathrm{EW}} + a^{\mathrm{Hadron\ loops}}$$

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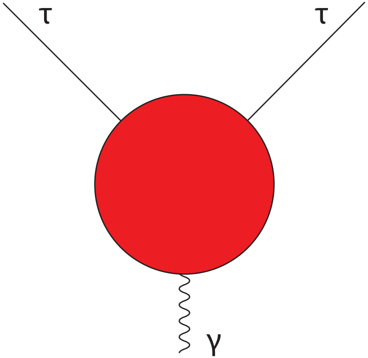

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- Standard Model prediction:

$$a = a^{\mathrm{QED}} + a^{\mathrm{EW}} + a^{\mathrm{Hadron\ loops}} + a^{???}$$

QED contribution

- Photon and (l)epton loops (three (f)lavours).

$$a^{\text{QED}} = A_1 + A_2\left(\frac{m_{l,f=1}}{m_{l,f=2}}\right) + A_2\left(\frac{m_{l,f=1}}{m_{l,f=3}}\right) + A_3\left(\frac{m_{l,f=1}}{m_{l,f=2}}, \frac{m_{l,f=1}}{m_{l,f=3}}\right)$$

- A_1 - only photon loops (no mass and flavour dependency).
- Expansion as power series in α/π:

$$A_i = A_i^{(2)}\left(\frac{\alpha}{\pi}\right) + A_i^{(4)}\left(\frac{\alpha}{\pi}\right)^2 + \dots$$

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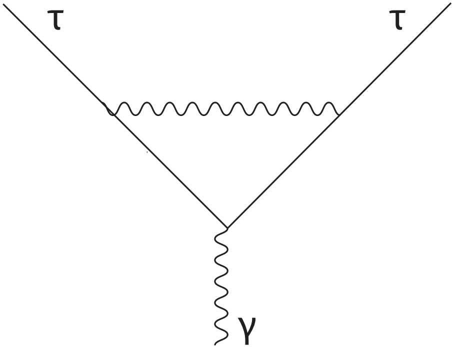

- Only one diagram in the lowest order.
- $A_1^{(2)} = 1/2$.
- Schwinger, Phys. Rev. 73, 416 (1948).

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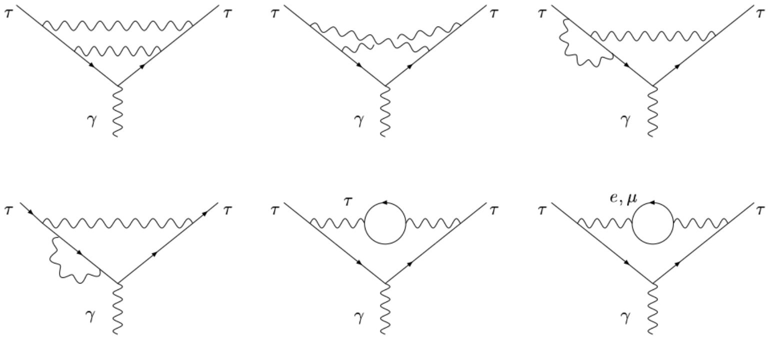
- $A_1^{(2)} = 1/2$.
- Schwinger, Phys. Rev. 73, 416 (1948).
- Very apprehensive wife.

QED contribution

- The two-loop order example (8 diagrams in total):

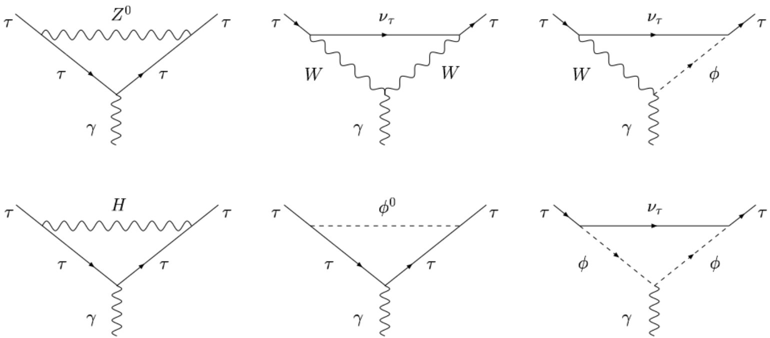


Eidelman, *et al.*: Phys. Lett. A 22 (2007) 159-179

- The three-loop order:
  - More than one hundred diagrams.
  - Analytic computations required three decades...

Electroweak contribution

- Loops with $W^{\pm}, Z, H$, goldstone bosones...

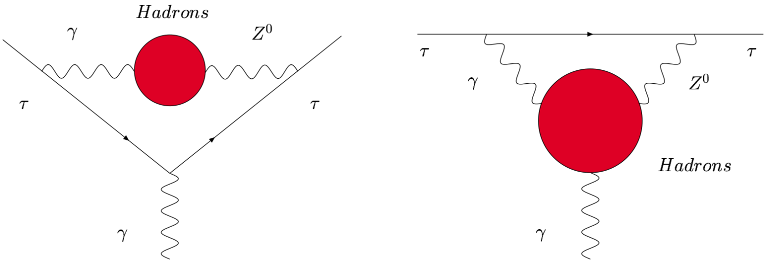


Eidelman, *et al.*: Phys. Lett. A 22 (2007) 159-179

- Wrt. QED, EW contribution is proportional to $\sim (m_l / m_W)^2$.
- For electron, this contribution is strongly suppressed!
- For tauon, on the level of the three-loop order.

Hadron contribution

- Hadronic vacuum polarization, light-by-light, higher orders loops...



(a) (b)

Eidelman, *et al.*: Phys. Lett. A 22 (2007) 159-179

- Calculations based on experimental results.
- For electron, again, this contribution is strongly suppressed!

Lepton family overview

	a_e	a_μ	a_τ
SM pred.	0.00115965218164(77)	0.00116591804(51)	0.00117721(5)
Exp. val.	0.00115965218073(28)	0.00116592061(41)	[-0.052, 0.013] (95%CL)

- Difference of Standard Model and observations:
  - Compositeness of leptons (hint at neutron inner structure)?
  - New physics Beyond Standard Model (BSM)?
- BSM scales with $(m^2_{\text{lepton}}/m^2_\Lambda)$, where m_Λ is the mass scale of BSM particles.
  - $e : \mu = 1 : 42750$
  - $\mu : \tau = 1 : 280$
- Higher mass of lepton $\rightarrow$ reaching lower scale $\rightarrow$ better sensitivity to BSM.

a_e experimental value: Hanneke *et al.*: Phys. Rev. A 83, 052122 (2011)

a_μ experimental value: Muon g-2: Phys. Rev. Let. 126, 141801 (2021)

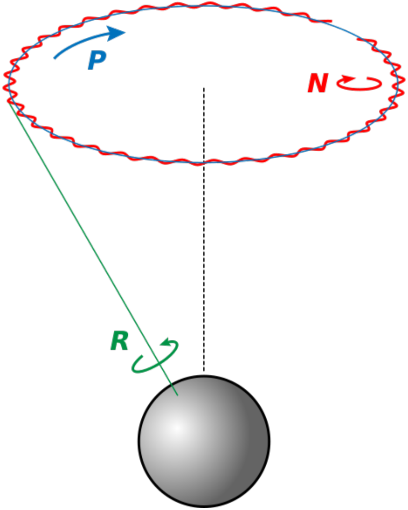
a_τ experimental value: DELPHI: Eur. Phys. J. C 35, 159-170 (2004)

Measurement method: Precession

- Three possible movements around Euler angles.
- Rotation R, precession P and nutation N.
- A magnetic dipole (particle with spin and momentum) in an external magnetic field $\vec{B} \to$ precession.

$$\vec{\omega}_a = -a_\mu \frac{q\,\vec{B}}{m}.$$

- Through precession frequency $\vec{\omega}_a$ you measure anomalous magnetic moment a_μ.
- Highly uniform magnetic field $\vec{B}$ needed!
- Penning traps, storage rings...
- Possible for electrons and muons (2×10^{-6}s), tauons have too short lifetime (3×10^{-13}s).



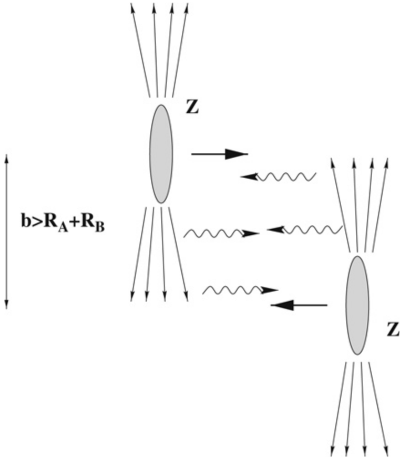
Wikimedia Commons

Heavy-ion tool

- Ultra-peripheral collisions (UPCs).
  - Impact parameter $b > R_A + R_B$.
  - Strong interaction suppressed.
  - EM interaction remains.

- EM field of ultra-relativistic electrically charged particle $\sim$ flux of photons.
  - Interaction intensity increasing with Z^2.

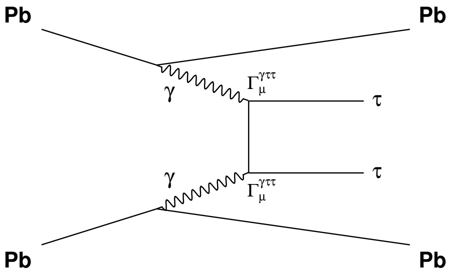
- Many measurements at ALICE already.
  - Photon used as a probe to inner structure of hadrons/ions.
  - Appreciate addition to HERA/EIC.
  - Proof of usefulness of this tool.



Baltz *et al.*: Phys.Rept. 458 (2008) 1-171

Measurement method: Differential cross section of τ production

- $\gamma\tau\tau$ vertex is sensitive to a_τ.
- Two vertices = enhanced sensitivity.
- Different options like $e^+e^- \to \tau\tau(e^+e^-)$ and $Z \to \tau\tau\gamma$...
- ...or employ UPCs!
  - Great source of photons at hadron colliders.
  - $q^2 \to 0$ is ideal.

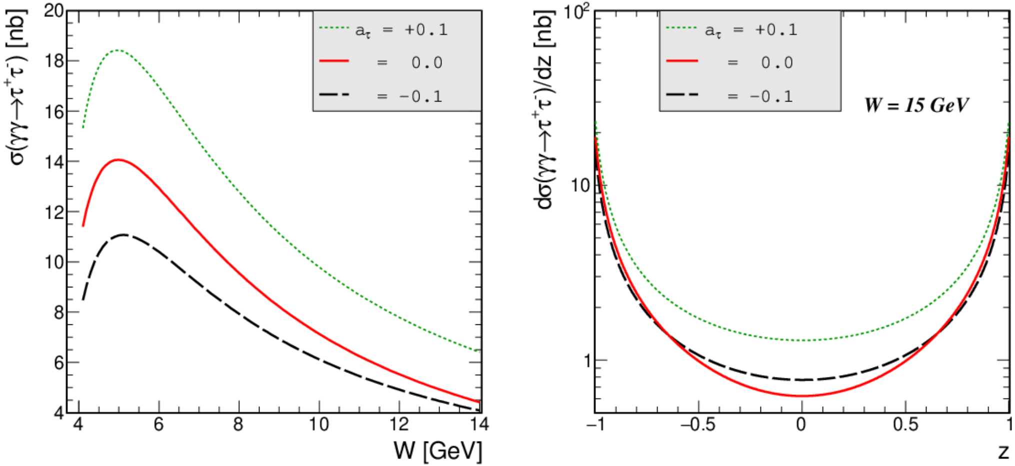


- Proposed for LHC (and SSC) in 1991, del Aguilla *et al.*: Phys. Lett. B 271 (1991) 256.
- SM effective field theory (SMEFT), Bereford *et al.*: Phys. Rev. D 102, (2020) 113008.
- Direct calculation, Dyndal *et al.*: Phys. Lett. B 809, (2020) 135682.

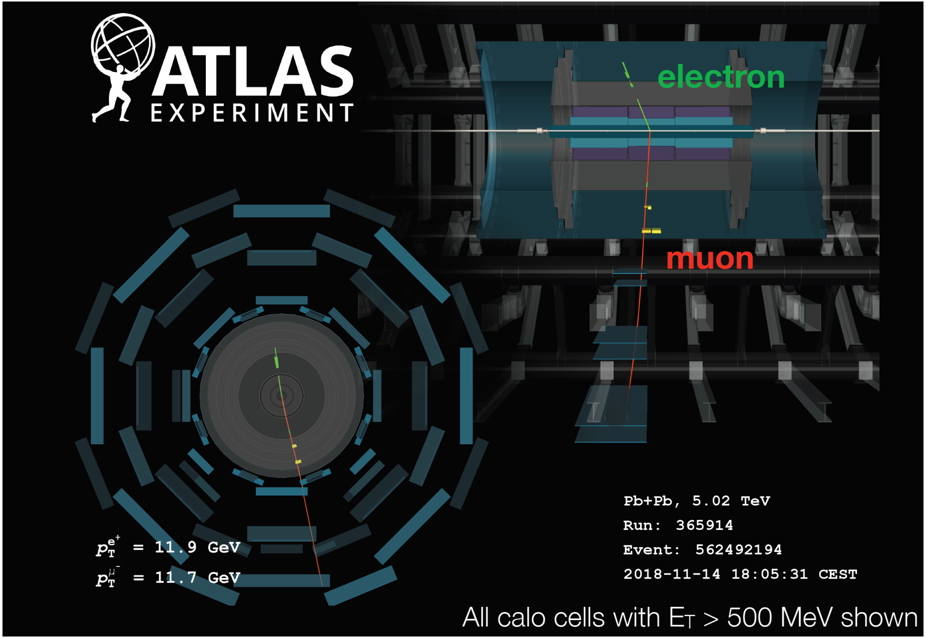
$$i\Gamma_\mu^{(\gamma\tau\tau)}(q) = -ie\left[\gamma_\mu F_1(q^2) + \frac{i}{2m_\tau}\sigma_{\mu\nu}q^\nu F_2(q^2) + \frac{1}{2m_\tau}\gamma^5\sigma_{\mu\nu}q^\nu F_3(q^2)\right] \qquad F_2(q^2 \to 0) = a_\tau$$

a_τ connection to cross section

- Non-trivial, but observable dependency on W, $z = \cos\theta$ (in $\gamma\gamma$ CM frame).

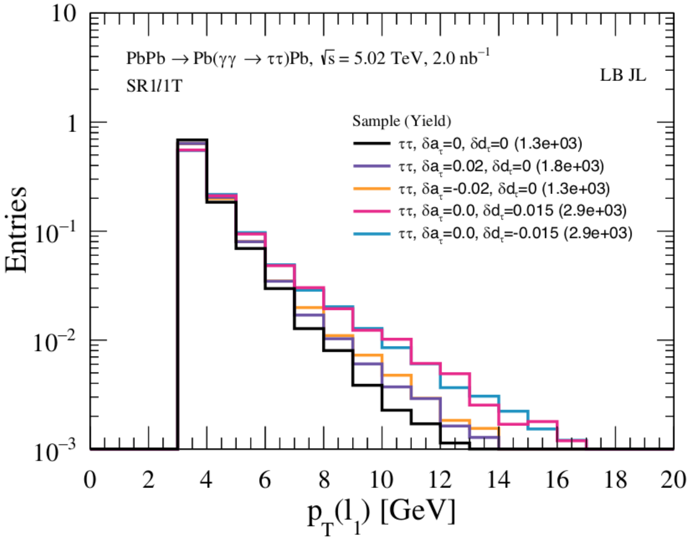


Dyndal *et al.*: Phys. Lett. B 809, (2020) 135682.

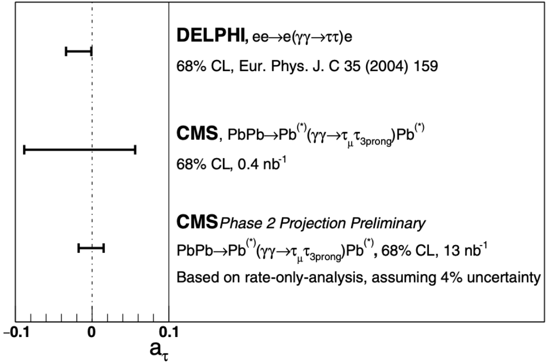

ATLAS
EXPERIMENT
electron
muon
$p_T^{e^+}$ = 11.9 GeV
$p_T^{\mu^-}$ = 11.7 GeV
Pb+Pb, 5.02 TeV
Run: 365914
Event: 562492194
2018-11-14 18:05:31 CEST
All calo cells with E_T > 500 MeV shown

p_T-spectrum sensitivity to a_τ

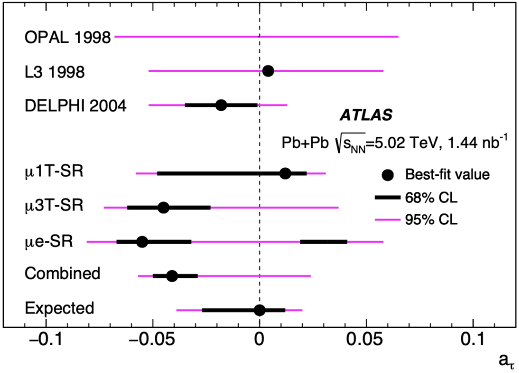
Bereford *et al.*: Phys. Rev. D 102, (2020) 113008.



New possible limits by ATLAS/CMS and its comparison to current values



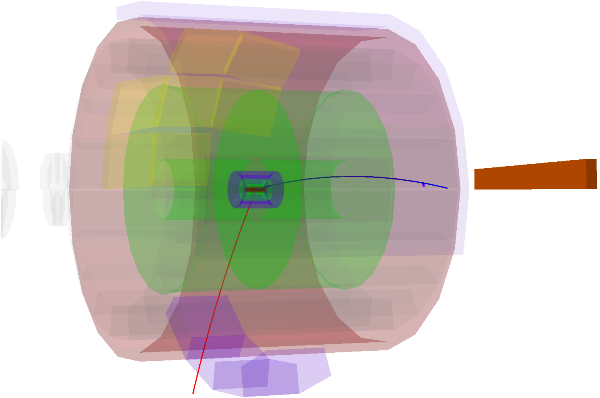
EPJ Web Conf. 276 (2023) 06003.

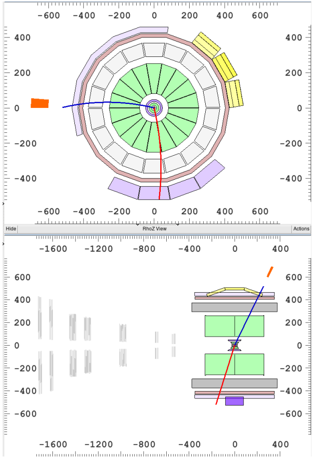


ATL-PHYS-PROC-2023-002

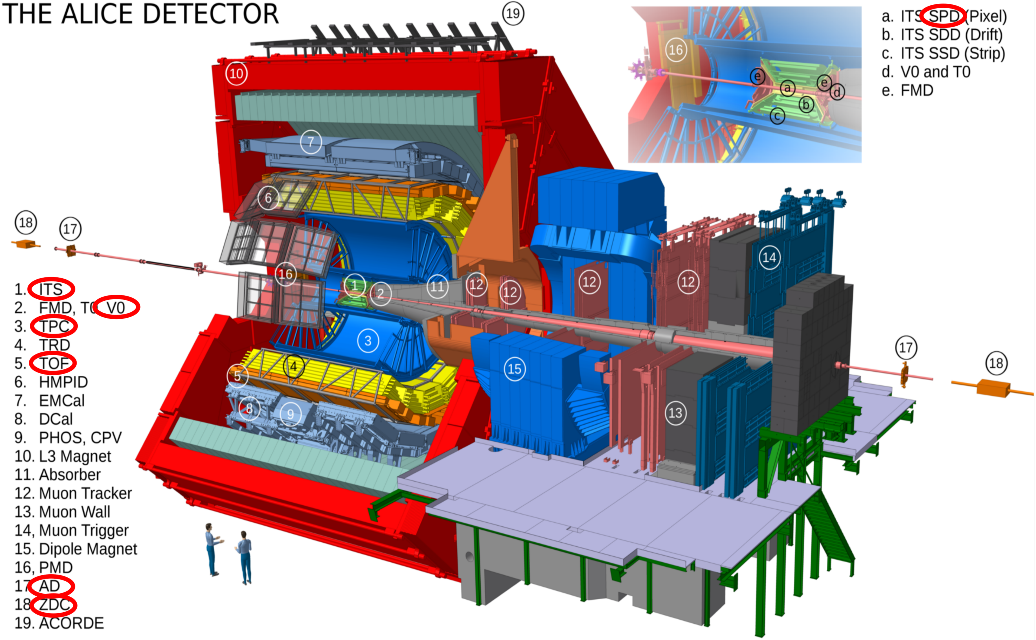
- ATLAS/CMS Run 2 statistics estimates: 1280 events (2 nb^{-1}).
- Systematics can strongly limits this measurement.

ALICE possibilities





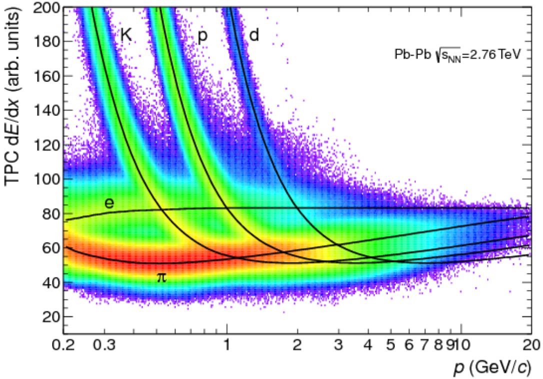
THE ALICE DETECTOR

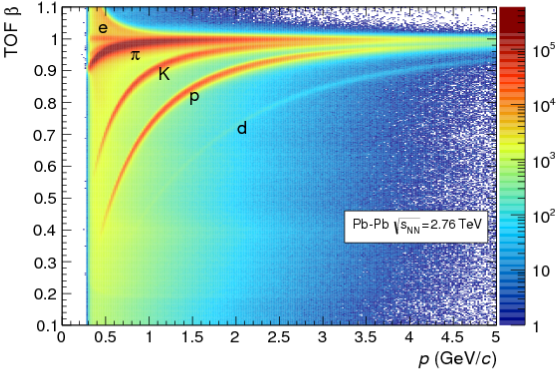


a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

PID

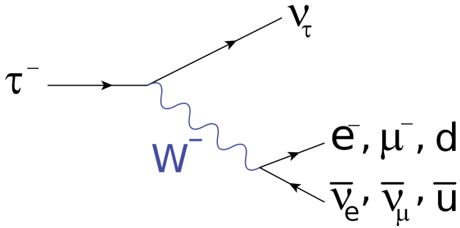




- Electron, μ/π, proton and kaon can be distinguished with TPC+TOF for $p_{\mathrm{T}} < 1.5$ GeV.
- TPC for electron and μ/π and TOF for electron/μ/π and proton and kaon.
- Not possible to distinguish μ/π.

Event selection strategy

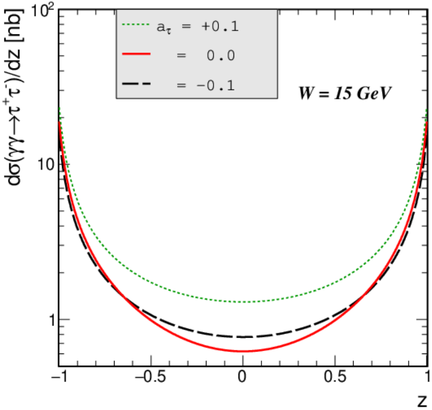
- 1-prong decay ($\sim$ 80%):
  - $\tau^{\pm} \rightarrow e^{\pm} + \bar{\nu}_{e/\tau} + \nu_{\tau/e}$ (17.8%)
  - $\tau^{\pm} \rightarrow \mu^{\pm} + \bar{\nu}_{\mu/\tau} + \nu_{\tau/\mu}$ (17.4%)
  - $\tau^{\pm} \rightarrow \pi^{\pm} + n\pi^{0} + \nu_{\tau}$ (45.6%)
- 3-prongs decay ($\sim$ 20%):
  - $\tau^{\pm} \rightarrow 3\pi^{\pm} + n\pi^{0} + \nu_{\tau}$

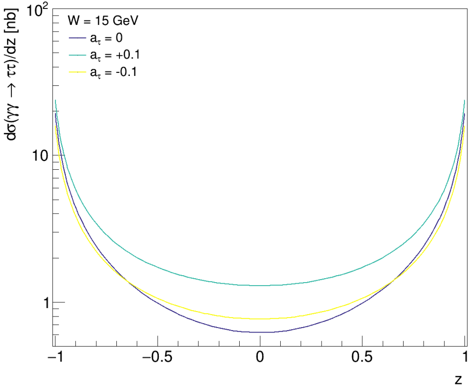


- ALICE strategy:
  - Exclusivity requirement: to avoid $\gamma\gamma \rightarrow q\bar{q}$ (or UPCs dipion), one decay is leptonic.
  - Midrapidity: Separation of μ and π with central barrel impossible $\rightarrow$ looking for electron(positron) + charged track (muon/pion).
  - Semi-forward rapidity: Forward muon + charged track in central barrel.
  - Forward rapidity: Only muon channel $\rightarrow$ suppressed to other cases.

Simulations: Run 3 2022 Pb–Pb collisions, 2.3nb^{-1}

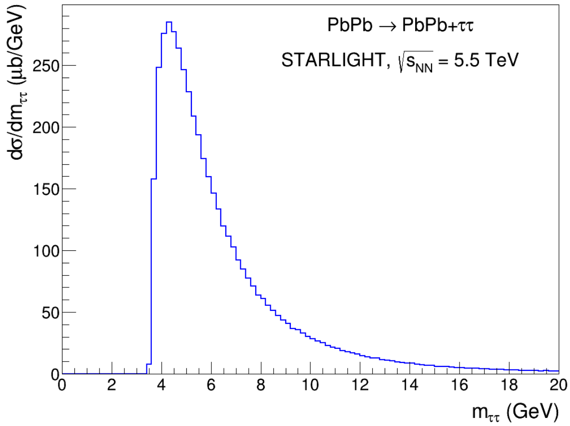
Dyndal *et al.*: Phys. Lett. B 809, (2020) 135682.

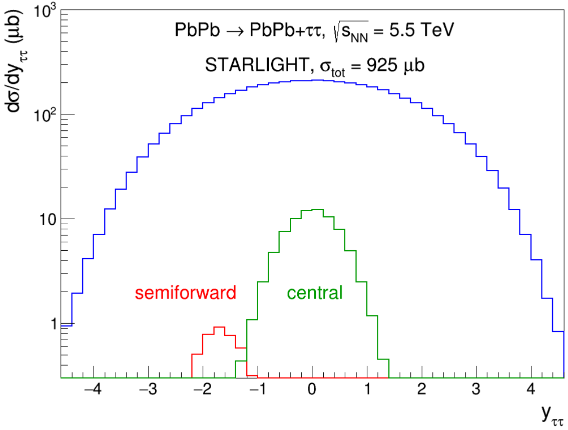




- Our simulations reproduce well those used for ATLAS/CMS.

Simulations: Run 3 2022 Pb–Pb collisions, 2.3nb^{-1}

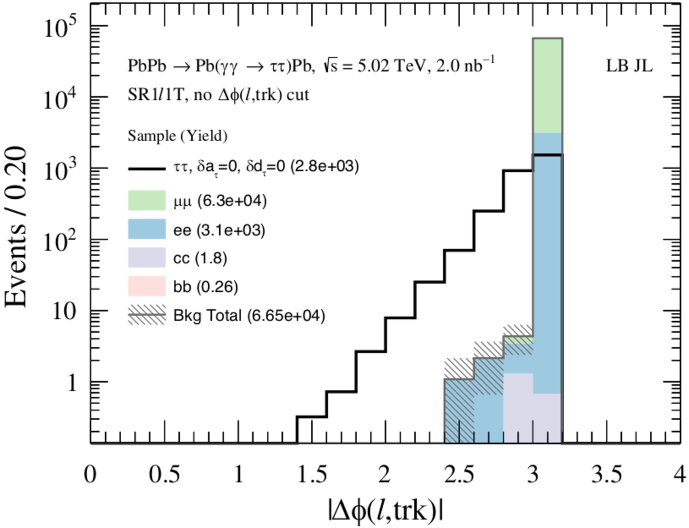




- 36 000 events in central barrel (electron + muon/pion).
- 2 000 events in semi-forward rapidity (two muons).

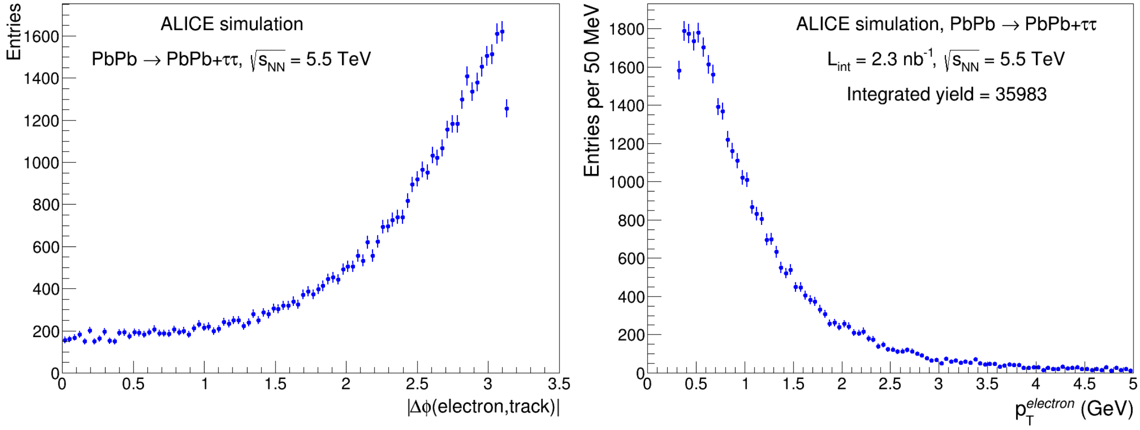
Suppressing background - acoplanarity cut

Bereford *et al.*: Phys. Rev. D 102, (2020) 113008.



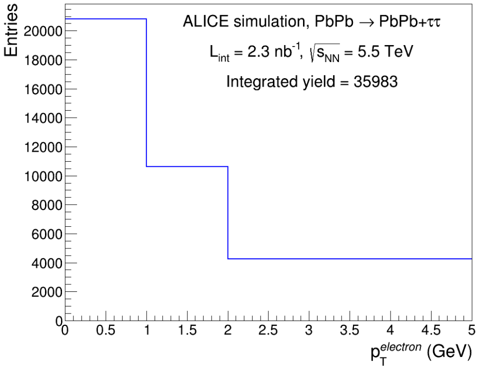
- Background from continuum.
- Avoiding back-to-back tracks.
- Run 2 trigger strategy did not favor such events.

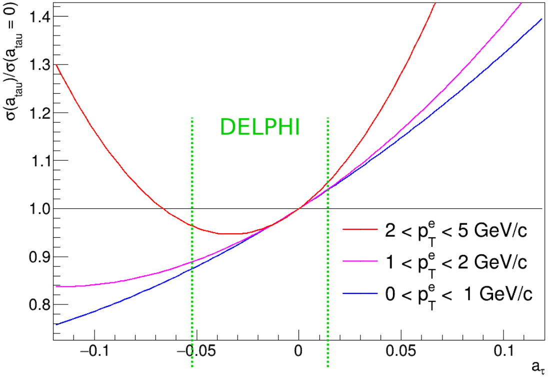
Simulations: Run 3 acoplanarity and p_T selection



- Still many events available after selection criteria.

Simulations: Run 3 a_τ and cross section ratio p_{T} dependency

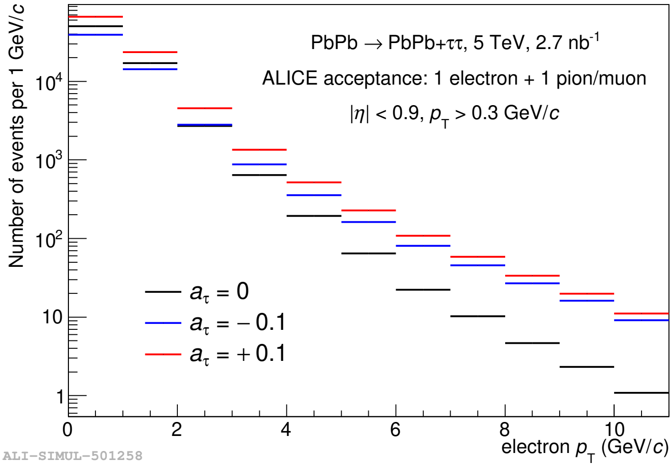




- Parabolic shape of ratio of electron p_{T}-differential cross sections in the vicinity of $a_\tau = 0$.
- Up to 15% variations of the yields within the range restricted by DELPHI limits.

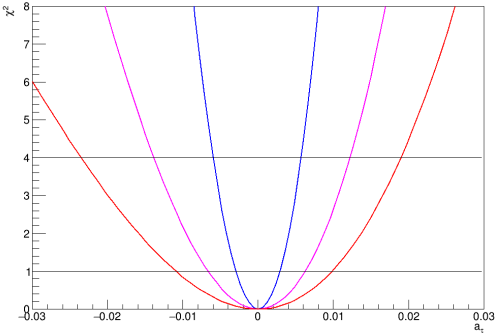
Simulations: Run 3 differential p_{T}-spectrum

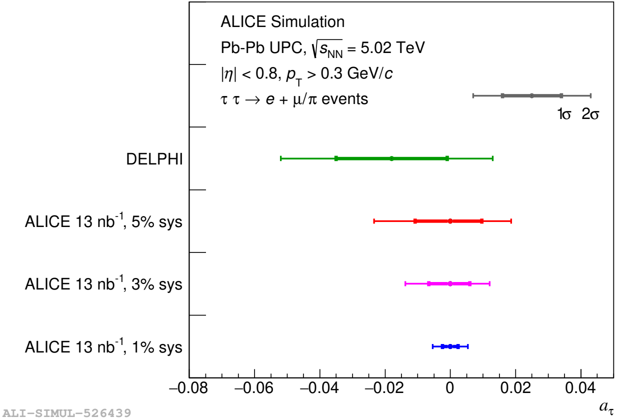
- We can also try to perform p_{T}-differential measurement.
- A lot of low-p_{T} events, where ALICE has a good sensitivity.
- Positive a_{τ} cross sections above Standard Model.
- Negative a_{τ} p_{T}-differential cross section distribution steeper than Standard Model.



Simulations: Run 3+4 a_τ limits from p_T-differential measurement

- Combining the cross section ratios of different p_T intervals.
- Using χ^2 sum of 10 p_T intervals.
- Uncorrelated systematics.
- Limits improvement looks feasible.





Summary

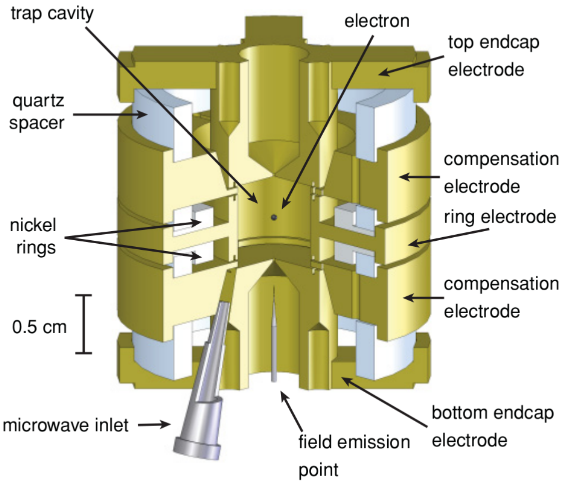
- Determination of anomalous magnetic moment is a powerful check of Standard Model.
- Heavy weight of tau-lepton provides the best sensitivity.
- LHC beams together with the ALICE detector with good low-momentum resolution provides us a unique opportunity for a competitive measurement.
- Pb–Pb collisions in upcoming Run 3+4 will deliver enough luminosity to try to improve the current experimental limits 2-8$\times$.
- There is still some work to do before 2022 data-taking:
  - Fine-tune our simulations to have a great control on possible systematic effects.
  - Understanding the background in detail.
  - Identifying the best selection criteria.

Time for your questions, please

back up

Electron and fine-structure constant α

- Electron trapped in cyclotron.
- You only need to measure the spin and cyclotron frequency.
- QED contribution dominates.
- a^{QED} proportional to α.
- Measurement of electron anomalous magnetic moment allows us a direct access to fine-structure constant!
- Measured with an accuracy to 12 digits.
- The most precise measurement of a constant in the history of physics.
- $\alpha^{-1} = 137.035999084(51)$



Hanneke *et al.*: Phys. Rev. A 83, 052122 (2011)

Muon and the latest evidence of BSM

- Example: Fermilab Muon $g-2$ Collaboration, details: Phys. Rev. D 103, 072002 (2021).
- (Almost) exclusively $\mu^{\pm} \to e^{\pm} + \bar{\nu}_{e/\mu} + \nu_{\mu/e}$, $\gamma \approx 30 \to \bar{\tau}_{\tau} = 60 \times 10^{-6}$s.
- Measurement of the positron energy spectrum.
- Muon spin and momentum aligned = spectrum easiest.
- Muon spin and momentum anti-aligned = spectrum steepest.
- N events in certain energy interval is changing with time.
- Modulation frequency = $\vec{\omega}_a$.
- 4.2σ strong evidence!
- Other explanation within QCD: arXiv:2002.12347