Constraining the tau lepton g-2 revisited: implementation in SuperChic

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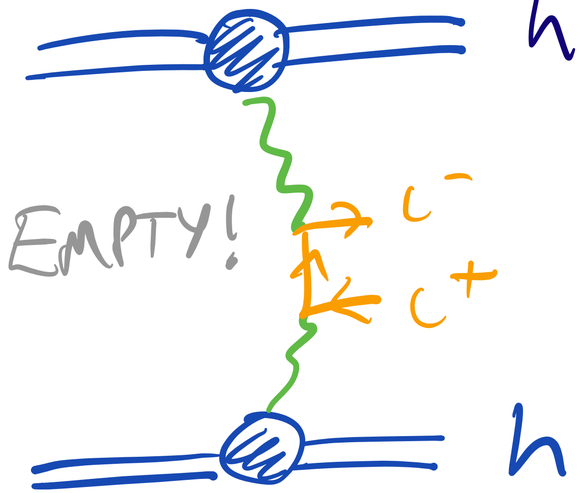
LHC Forward Physics WG meeting, CERN Dec 13

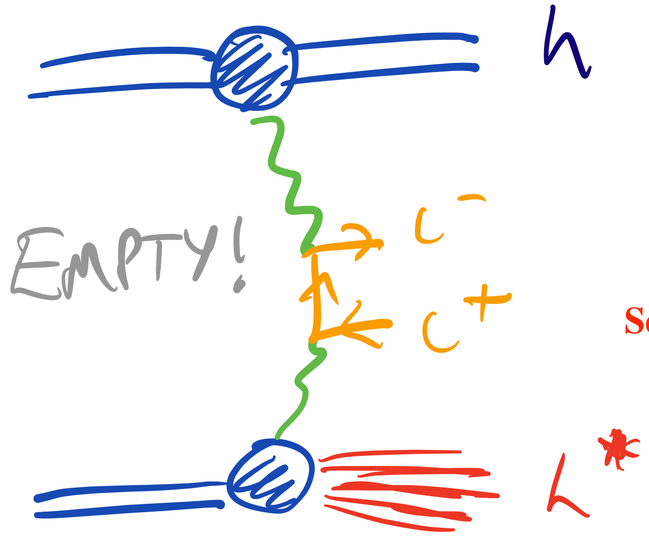
LHL, arXiv:2410.10978 (EPJC accepted)

Photon-Photon Physics

- Both protons and heavy ions can act as source of initial-state photons $\Rightarrow$ purely photon-initiated production possible.
- This allows for **exclusive/semi-exclusive** production: colour singlet photon naturally leads to events with intact protons/rapidity gaps in final state:

Exclusive



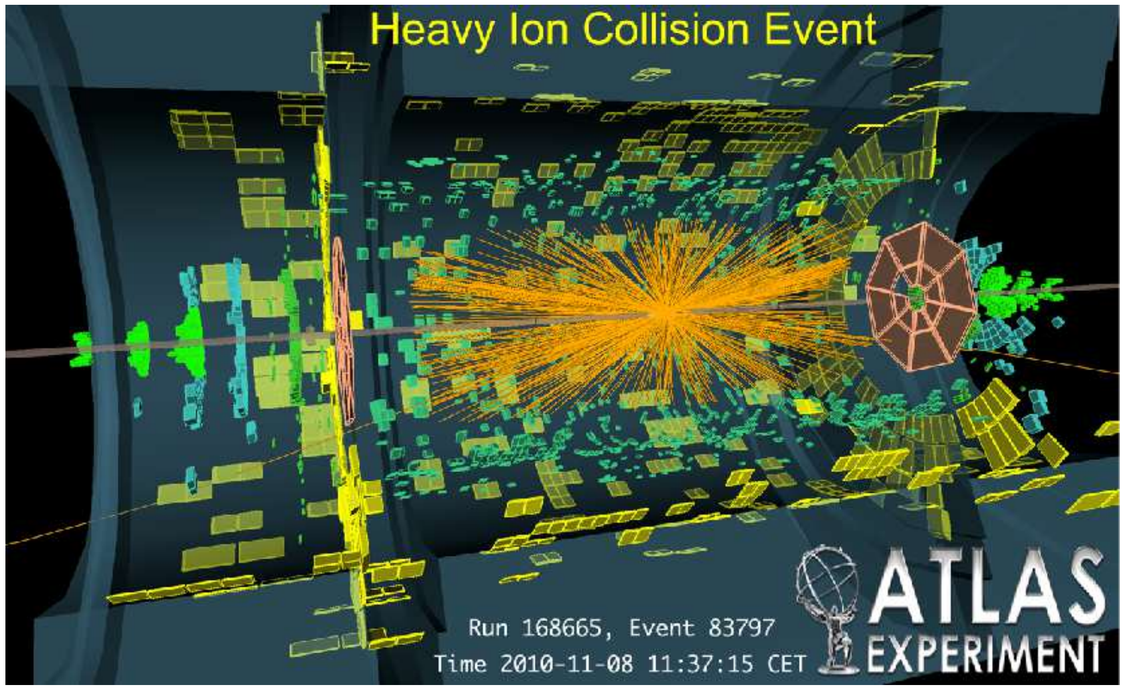


Semi-exclusive

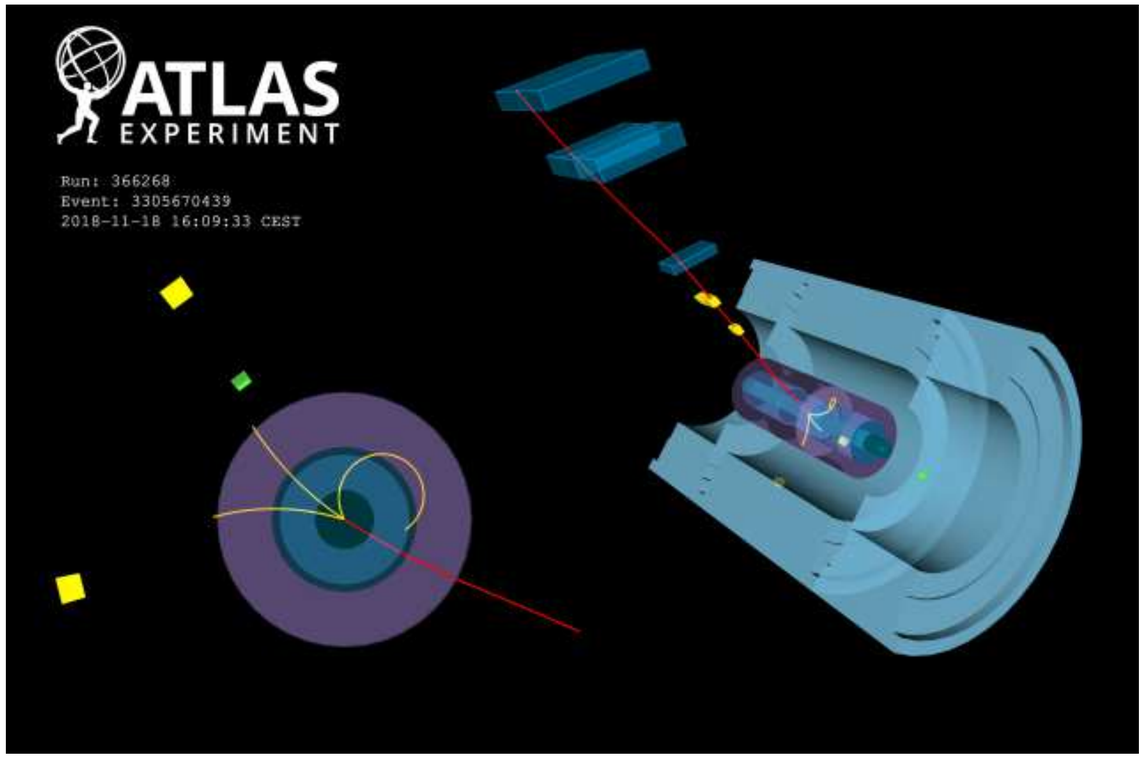
★ QCD interactions between hadrons can be largely ignored, i.e. ~ pure QED production

$\Rightarrow$ The LHC as a $\gamma\gamma$ collider! How does this differ from `standard' LHC collisions?

What does is it look like?

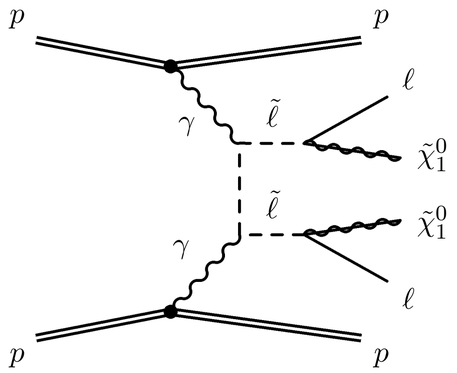


vs.



★ By dealing with ~ pure QED initial state, many studies of the EW sector and BSM modifications to it open up…

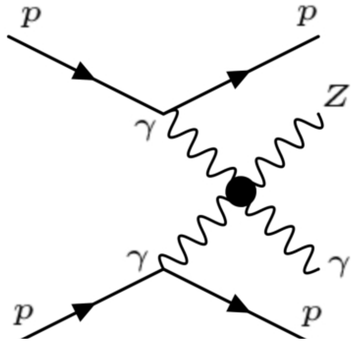
Compressed SUSY



LHL et al., JHEP 1904 (2019) 010

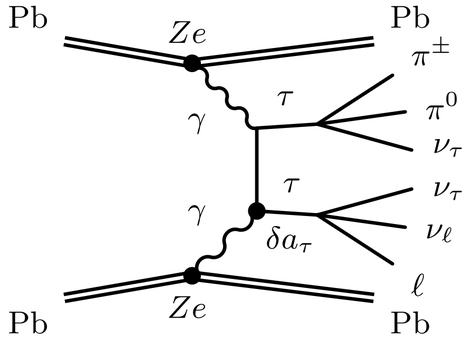
L. Beresford and J. Liu, PRL 123 (2019) no.14

Anomalous couplings



C. Baldenegro et al, JHEP 12 (2020) 165, JHEP 06 (2017) 142

tau g-2



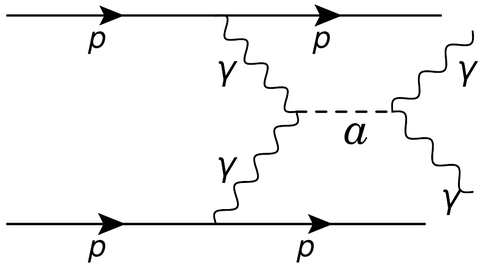
L. Beresford and J. Liu, PRD 102 (2020) 11, 113008

M. Dyndal et al., PLB 809 (2020) 135682

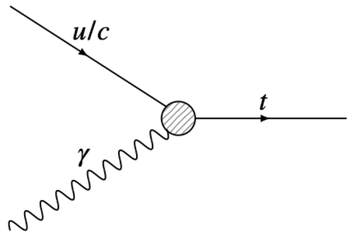
Axion-like Particles

LHL and M. Tasevsky, arXiv:2208.10526

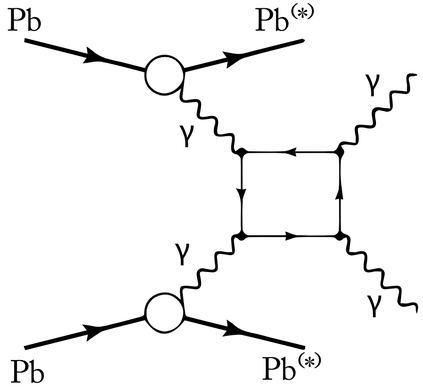
C. Baldenegro et al., *JHEP* 06 (2018) 131



Top quarks



LbyL scattering/ALPS



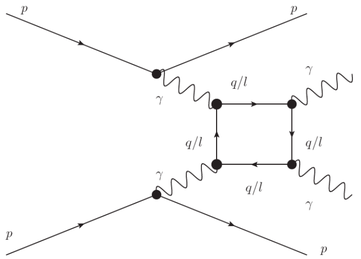
C. Baldenegro et al, JHEP 06 (2018) 131, S. Knapen et al, PRL 118 (2017) 17, 171801, D. d'Enterria, G. da Silveira, PRL 116 (2016) 12

V. Goncalves et al., *Phys.Rev.D* 102 (2020) 7, 074014

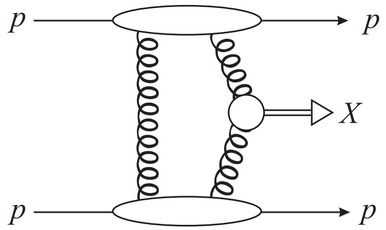
J. Howarth, arXiv:2008.04249

SuperChic MC Implementation

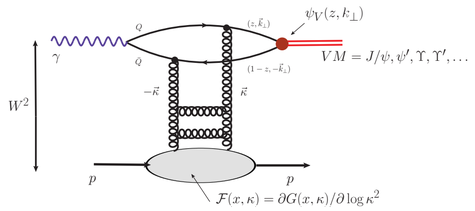
- A MC event generator for CEP processes.
  Common platform for:
  - QCD-induced CEP.
  - Photoproduction.
  - Photon-photon induced CEP.



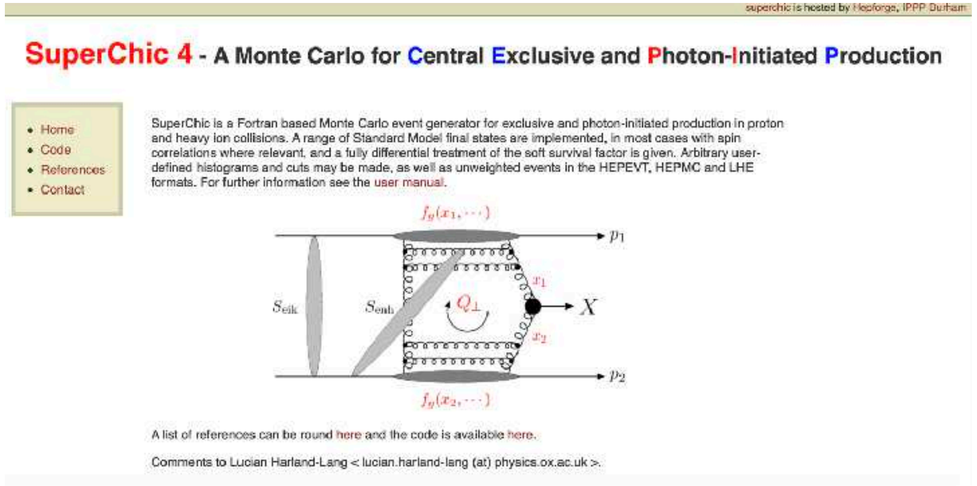
Photon-induced



QCD-induced



Photoproduction



- For **pp**, **pA** and **AA** collisions. Weighted/unweighted events (LHE, HEPMC) available- can interface to Pythia/HERWIG etc as required.

LHL et al., *Eur.Phys.J.C* 80 (2020) 10, 925

SuperChic 5 - MC Implementation

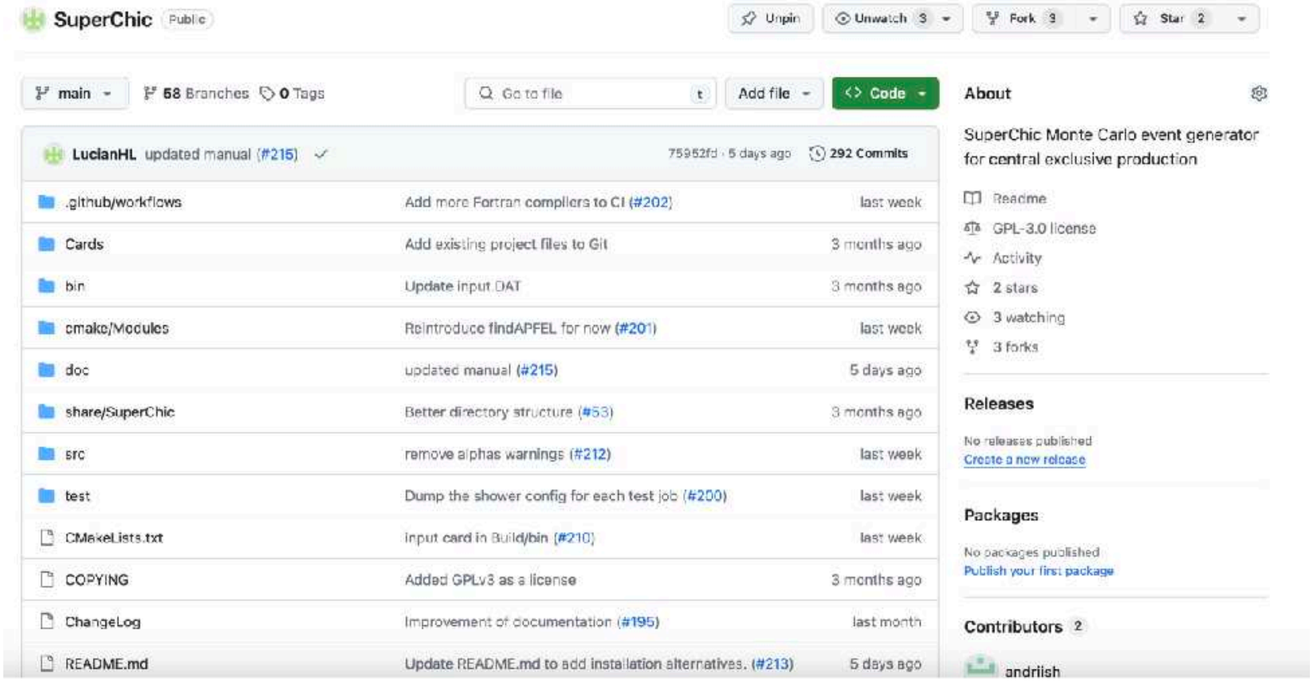
- Version 5 now released. Significant updates to code:

★HepMC output now properly supported.

★Full testing suite added + cmake build system.

★Various bug fixes + code improvements.

★ Future releases will be via github. Collaboration/PRs welcome!



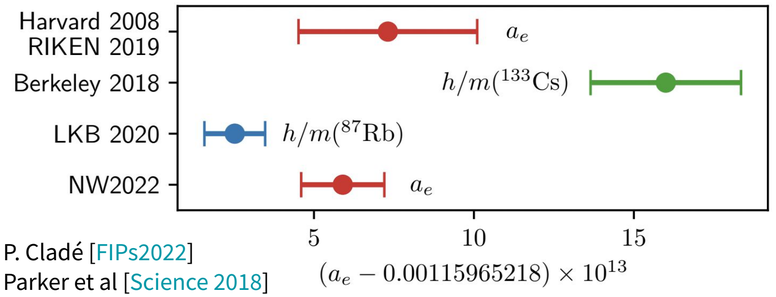
https://github.com/LucianHL/SuperChic

The tau lepton g-2

⋆ Probing the tau g-2:

- While experimental situation for lighter leptons well developed…

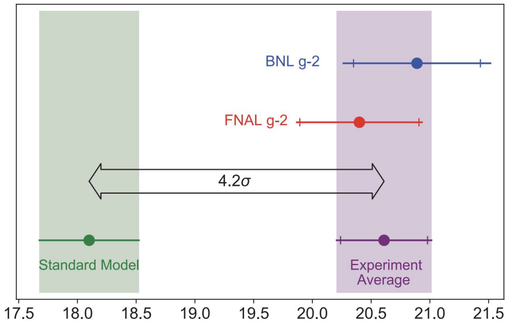
Electron $g-2$ (–2.5σ?)



P. Cladé [FIPs2022]
Parker et al [Science 2018]
Morel et al [Nature 2022], Fan et al [2209.13084]

0.2 parts per billion

Muon $g-2$ (+4.2σ?)



0.5 parts per million

- For the tau lepton surprisingly little is known!

$$a_\tau^{\mathrm{exp}} = -0.018\,(17)$$

DELPHI [hep-ex/0406010]

(Pre - LHC)

$$a_{\tau,\,\mathrm{SM}}^{\mathrm{pred}} = 0.001\,177\,21\,(5)$$

Eidelman, Passera [hep-ph/0701260]

- Does not even probe 1-loop QED:

$$\alpha/2\pi = 0.001162$$

Schwinger [1948]

- Sensitivity to BSM unprobed:

$$\delta a_\ell \sim m_\ell^2/M_{\mathrm{SUSY}}^2 \qquad m_\tau^2/m_\mu^2 \sim 280$$

Martin, Wells [hep-ph/0103067]

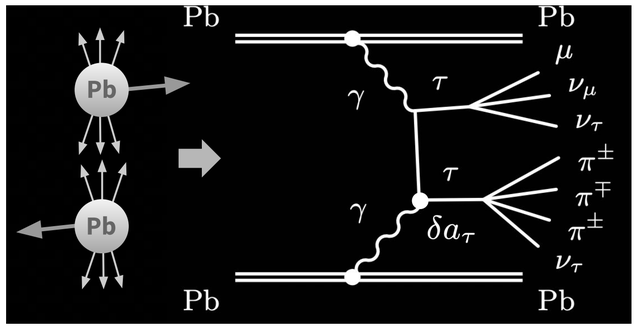
Figures curtesy of J. Liu

The tau lepton g-2 in PI production

- By measuring $\gamma\gamma \to \tau^+\tau^-$ production - sensitive to tau g-2.

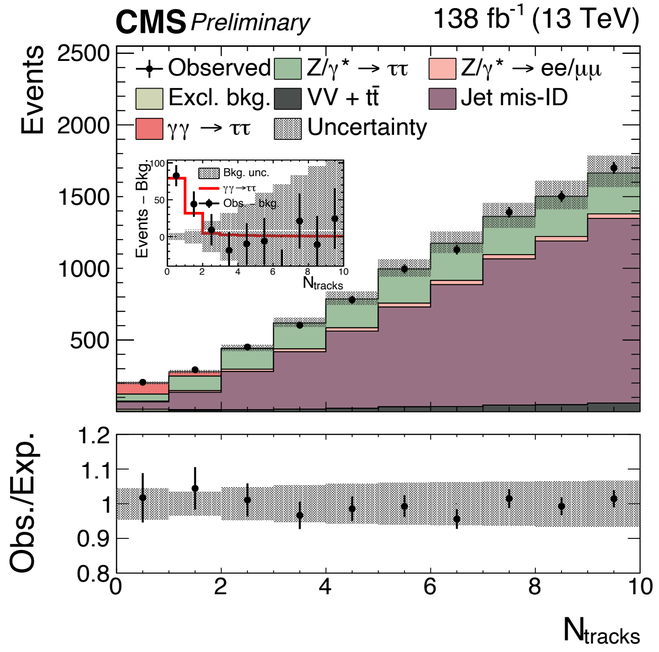
$$a_{\tau,\,\mathrm{SM}}^{\mathrm{pred}} = 0.001\,177\,21\,(5)$$

Eidelman, Passera [hep-ph/0701260]

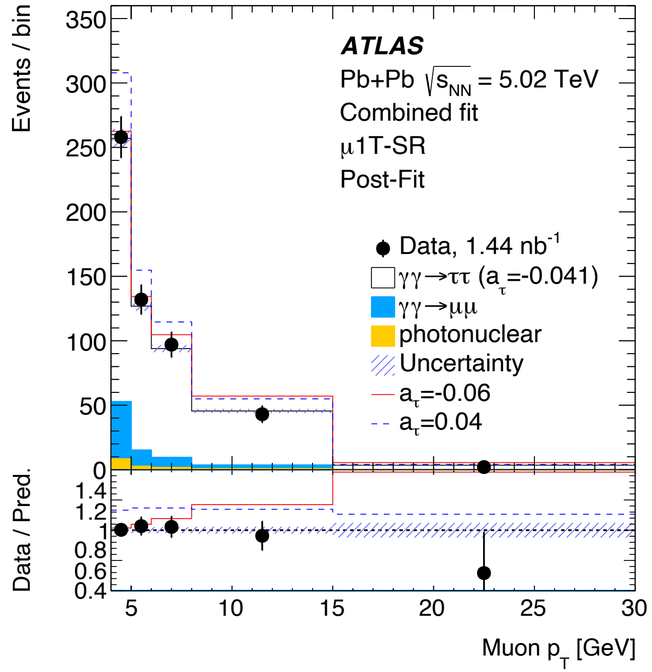


- Sensitivity via differential cross section has already set **new limits**.

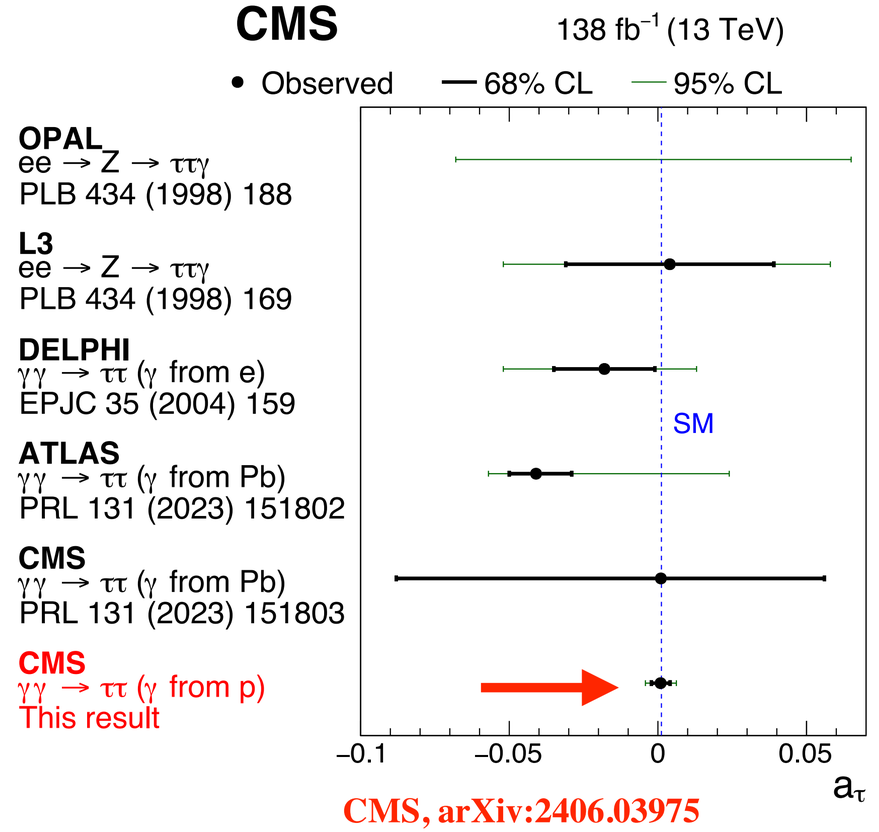
$$-0.0042 < a_\tau < 0.0062$$



CMS, arXiv:2406.03975



ATLAS, arXiv:2204.13478



CMS, arXiv:2406.03975

What is missing?

- Non-zero modifications $\delta a_\tau, \delta d_\tau$ induce change in $\tau\tau\gamma$ vertex:

$$V^{\mu}_{\tau\tau\gamma} = ie\gamma^{\mu} - \left[\delta a_\tau \frac{e}{2m_\tau} + i\delta d_\tau \gamma_5\right] \sigma^{\mu\nu} q_\nu \ ,$$

- Note in particular differing kinematic structure (additional q_ν).

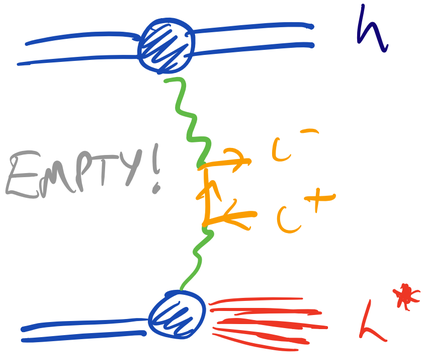
- Leads to well known increase in effect of $\delta a_\tau, \delta d_\tau$ with increasing scale. But also:

  ⋆ Survival factor.

  ⋆ Proton dissociation (EL vs. SD vs. DD).

- Will also be different between the LO and $\delta a_\tau, \delta d_\tau$ terms.
- This difference is not accounted for in current theoretical approaches, or in LHC analyses!

Proton Dissociation



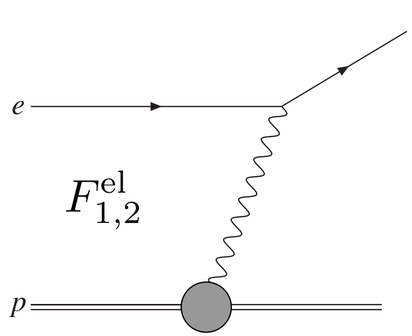
- PI cross section calculated in `structure function' (SF) approach:

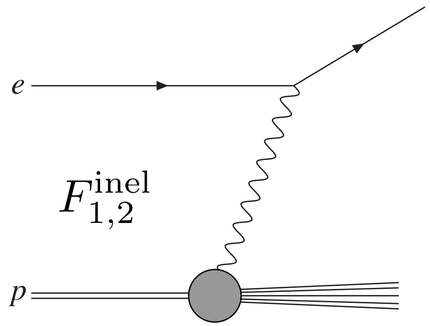
$$\sigma_{pp} = \frac{1}{2s}\int \mathrm{d}x_1 \mathrm{d}x_2\, \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp}\, \mathrm{d}\Gamma\, \alpha(Q_1^2)\alpha(Q_2^2) \frac{\rho_1^{\mu\mu'}\rho_2^{\nu\nu'} M^*_{\mu'\nu'} M_{\mu\nu}}{q_1^2 q_2^2} \delta^{(4)}(q_1 + q_2 - p_X)\ ,$$

Photon x, Q^2 ; $\gamma^* p \to X$; $\sim \sigma(\gamma^*\gamma^* \to X)$

- Key point (without details) for us - $\gamma p \to X$ vertex given in terms of (elastic/inelastic) proton SFs, taken from experiment.

$$W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x, Q^2) + \frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q} F_2(x, Q^2)$$

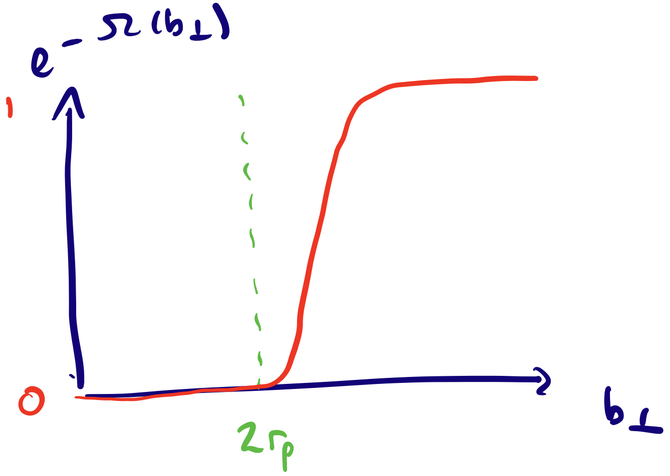




- Elastic SF (i.e. form factor) falls much faster with photon $Q^2 \Rightarrow$ differing impact wrt $\delta a_\tau, \delta d_\tau$ (recall factor of q_ν).

$$V^\mu_{\tau\tau\gamma} = ie\gamma^\mu - \left[\delta a_\tau \frac{e}{2m_\tau} + i\delta d_\tau \gamma_5\right] \sigma^{\mu\nu} q_\nu\ ,$$

Survival Factor



- Probability of no inelastic hadron-hadron interactions. Schematically:

$$\sigma = \int \mathrm{d}^2 b_{1\perp}\, \mathrm{d}^2 b_{2\perp} |\tilde{M}(\vec{b}_{1\perp}, \vec{b}_{2\perp}, ...)|^2 e^{-\Omega(\vec{b}_{1\perp} - \vec{b}_{2\perp})}$$

in impact parameter space.

$e^{-\Omega(\vec{b}_{1\perp} - \vec{b}_{2\perp})}$: **survival factor** - probability for no additional particle production at impact parameter $b_\perp = |\vec{b}_{1\perp} - \vec{b}_{2\perp}|$. Roughly:

- Key point - not a constant! Depends on kinematic and process:

$$\int \mathrm{d}^2 b_{1\perp}\, \mathrm{d}^2 b_{2\perp} |\tilde{M}(\vec{b}_{1\perp}, \vec{b}_{2\perp})|^2 e^{-\Omega(\vec{b}_{1\perp} - \vec{b}_{2\perp})} \quad \overset{b_\perp \leftrightarrow q_\perp}{\longleftrightarrow} \quad \int \mathrm{d}^2 q_{1\perp}\, \mathrm{d}^2 q_{2\perp} |M^{\text{inc. } S^2}(\vec{q}_{1\perp}, \vec{q}_{1\perp})|^2$$

Kinematics — Process

- Again recall differing impact wrt $\delta a_\tau, \delta d_\tau$ (recall factor of q_ν).

Survival factor will be different between these!

$$V^\mu_{\tau\tau\gamma} = ie\gamma^\mu - \left[\delta a_\tau \frac{e}{2m_\tau} + i\delta d_\tau \gamma_5\right] \sigma^{\mu\nu} q_\nu \,,$$

SMEFT implementation

• In all cases anomalous $\delta a_\tau, \delta d_\tau$ in SC5.0 using matrix elements from MadGraph_5_aMC@NLO via `SMEFTsim_general_alphaScheme_UFO` package.

$$\mathcal{L}_{\text{SMEFT}} = \left(C_{\tau B}/\Lambda^2\right) \bar{L}_\tau \sigma^{\mu\nu} \tau_R H B_{\mu\nu} \quad \Longrightarrow \quad \delta a_\tau = \frac{2m_\tau}{e} \frac{\text{Re}\left[C_{\tau B}\right]}{M}, \quad \delta d_\tau = \frac{\text{Im}\left[C_{\tau B}\right]}{M},$$

In the vertex:

$$V^\mu_{\tau\tau\gamma} = ie\gamma^\mu - \left[\delta a_\tau \frac{e}{2m_\tau} + i\delta d_\tau \gamma_5\right] \sigma^{\mu\nu} q_\nu \ ,$$

So that $\gamma\gamma \to \tau^+\tau^-$ amplitude can be written as:

$$\mathcal{M}_{\mu\nu} = \mathcal{M}^{0,0}_{\mu\nu} + a_\tau \mathcal{M}^{1,0}_{\mu\nu} + d_\tau \mathcal{M}^{0,1}_{\mu\nu} + a_\tau d_\tau \mathcal{M}^{1,1}_{\mu\nu} + a^2_\tau \mathcal{M}^{2,0}_{\mu\nu} + d^2_\tau \mathcal{M}^{0,2}_{\mu\nu} \ ,$$

Results

- (Differential) cross section can be written as:

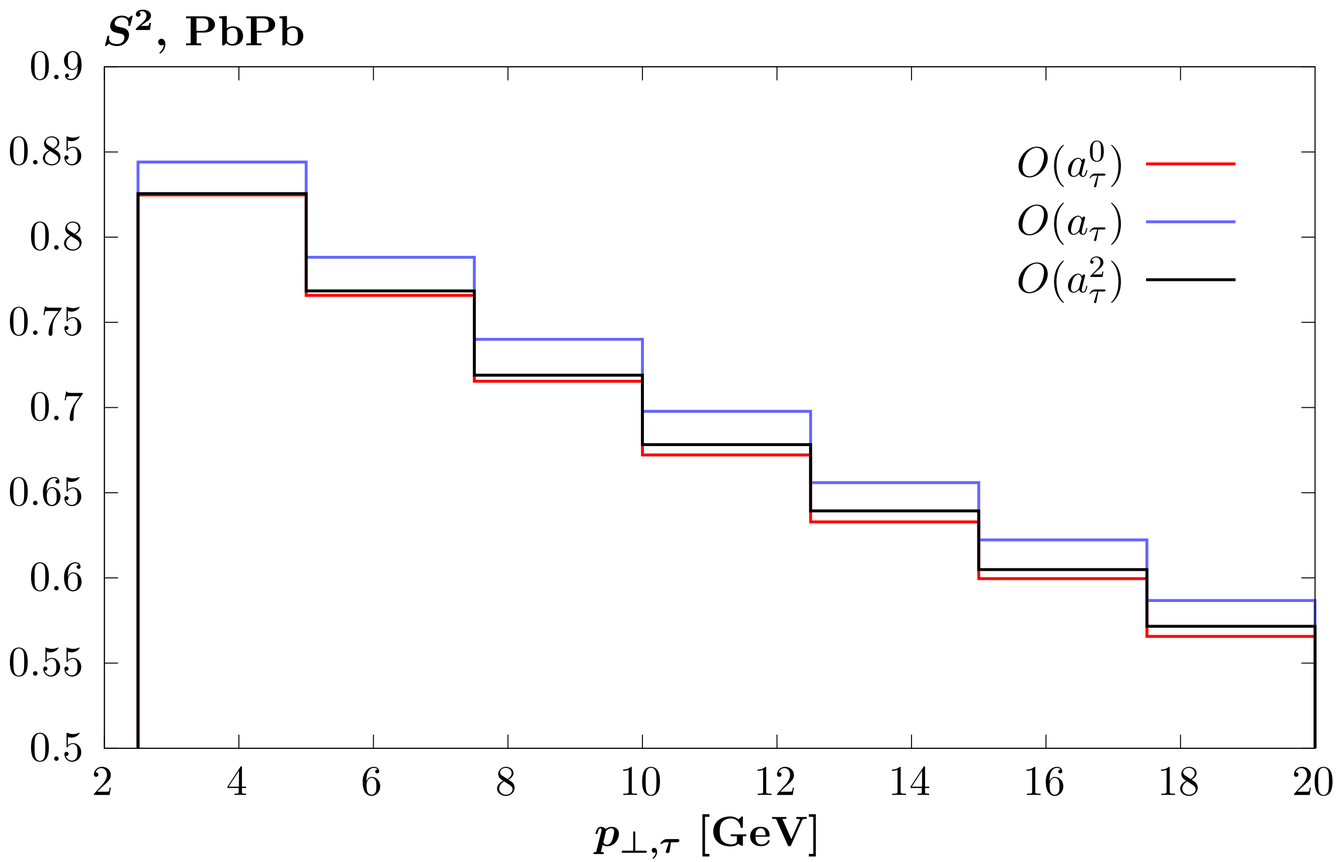
$$\mathrm{d}\sigma = \sum_{i=0}^{4} (a_\tau)^i \mathrm{d}\sigma_i \ , \qquad d_\tau = 0 \text{ for simplicity here}$$

- **Key point:** each individual term $\mathrm{d}\sigma_i$ can be evaluated in SC independent of particular value of a_τ
- Avoids any need to recalculate cross sections/observables for different values of a_τ
- Will show results with respect to tau level pseudo-observables ($p_{\perp,\tau}, m_{\tau\tau}$) to highlight relevant effects, but SC implementation allow for unweighted events, i.e. tau decays via external tool.
- Will only show results for a_τ here, but d_τ qualitatively similar.
- Start with PbPb case…

$$V^{\mu}_{\tau\tau\gamma} = ie\gamma^{\mu} - \left[\delta a_{\tau}\frac{e}{2m_{\tau}} + i\delta d_{\tau}\gamma_5\right]\sigma^{\mu\nu}q_{\nu} \ ,$$

PbPb

$$\mathrm{d}\sigma = \sum_{i=0}^{4}(a_{\tau})^{i}\mathrm{d}\sigma_{i} \ ,$$

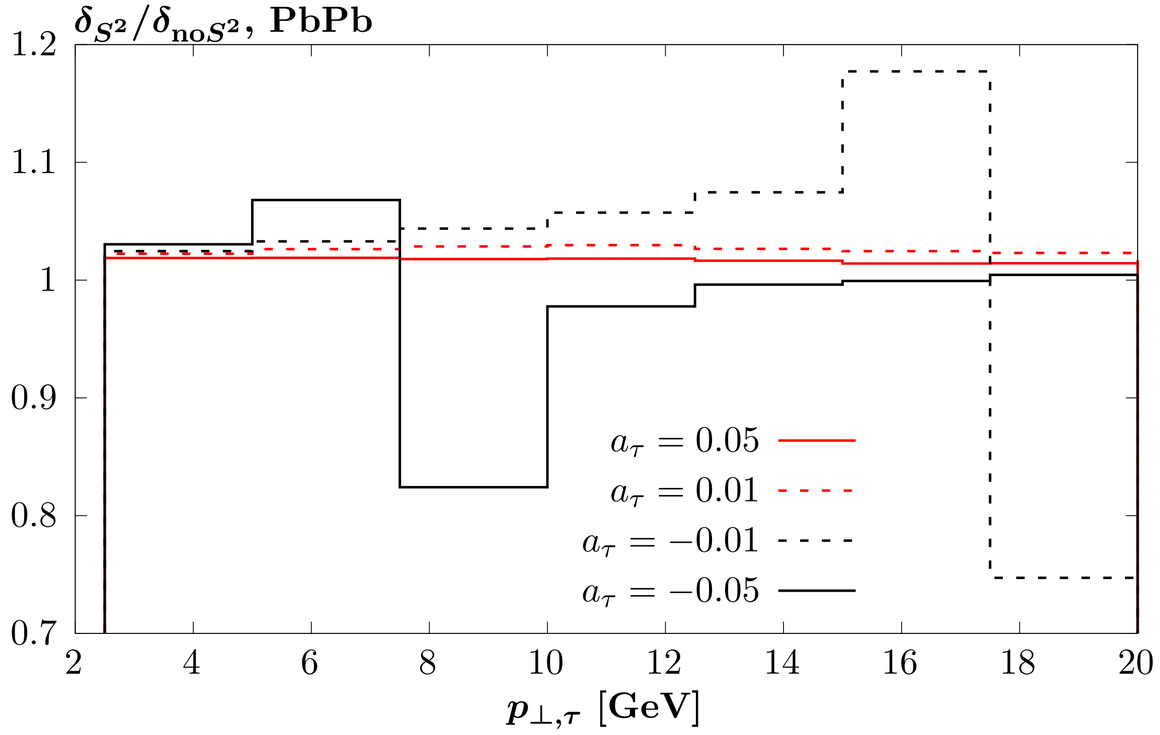


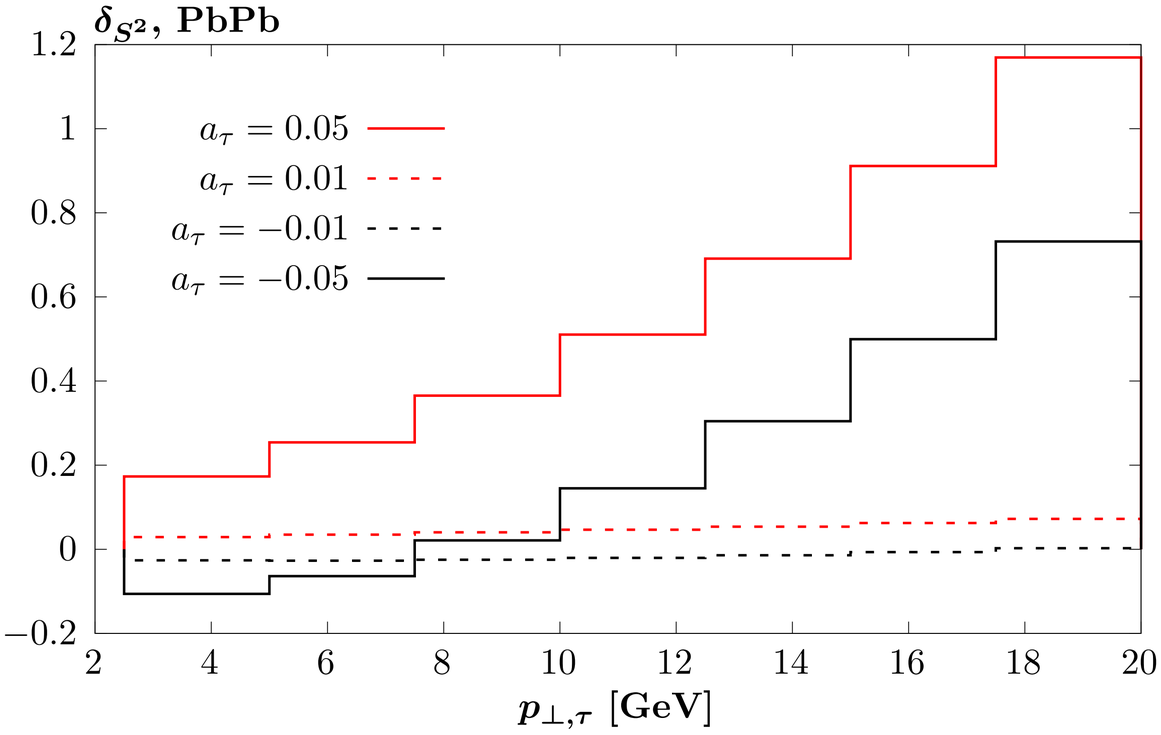
- Plot **survival factor** for dominant $O(a_\tau, a_\tau^2)$ contribution and the LO ($O(a_\tau^0)$) one.
- Not individually observable but demonstrates differences. Can see that there is indeed a different between the $O(a_\tau, a_\tau^2)$ and $O(a_\tau^0)$ though for the dominant $O(a_\tau^2)$ correction difference very **mild**.

- Suggests impact will be small. To check, consider cross section modification: $\delta = \frac{1}{\mathrm{d}\sigma_0}\sum_{i=1}^{4}(a_\tau)^i \mathrm{d}\sigma_i$,

- Plot ratio including S^2 to that without to gauge impact of full treatment. Also shown is absolute modifications as guide of size of corrections.

- Very roughly $\delta_{S^2}/\delta_{\mathrm{no}\,S^2} \sim$ fractional change will induce in extracted a_τ (limit on it). This is indeed small - at percent level.

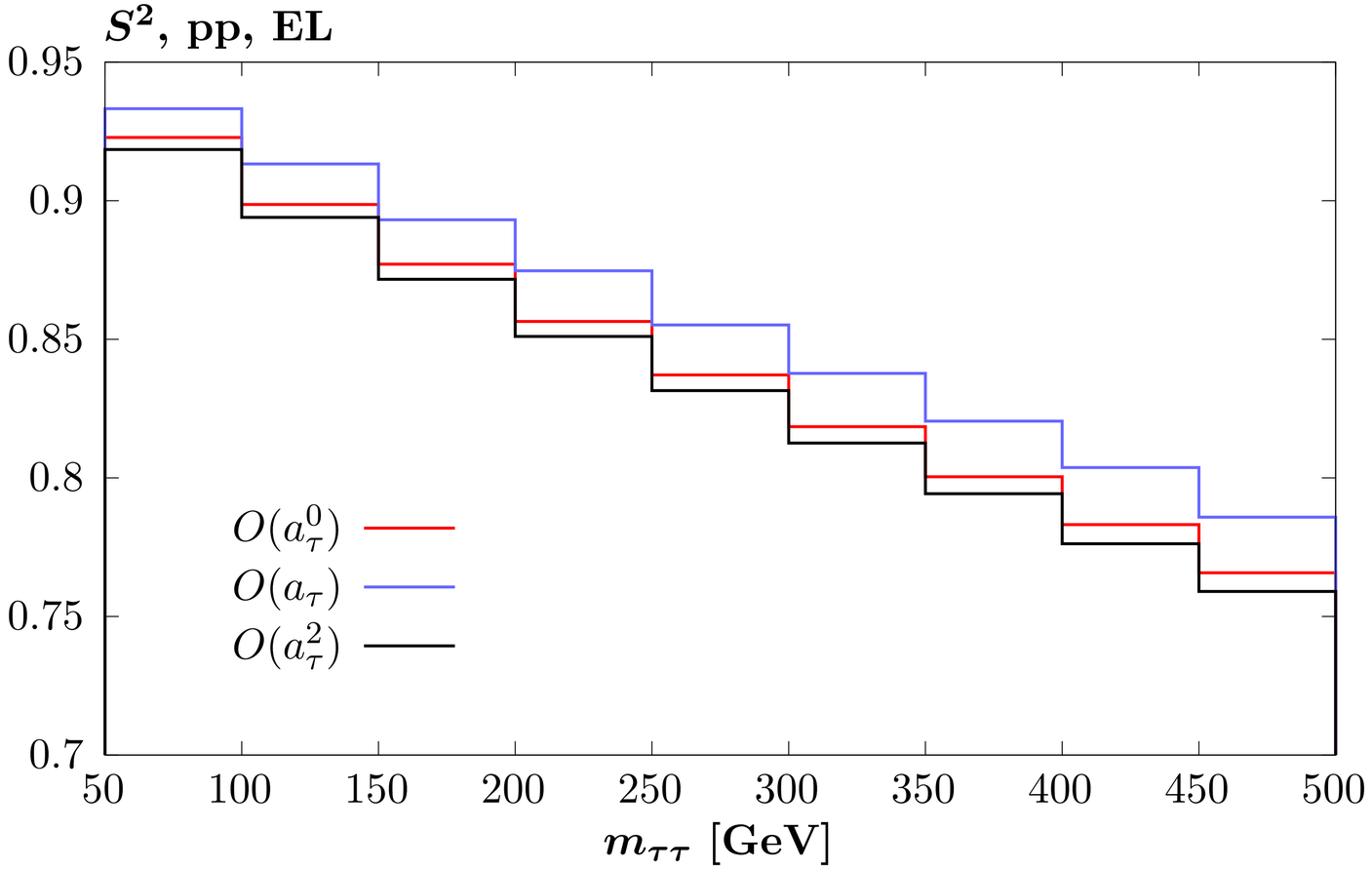




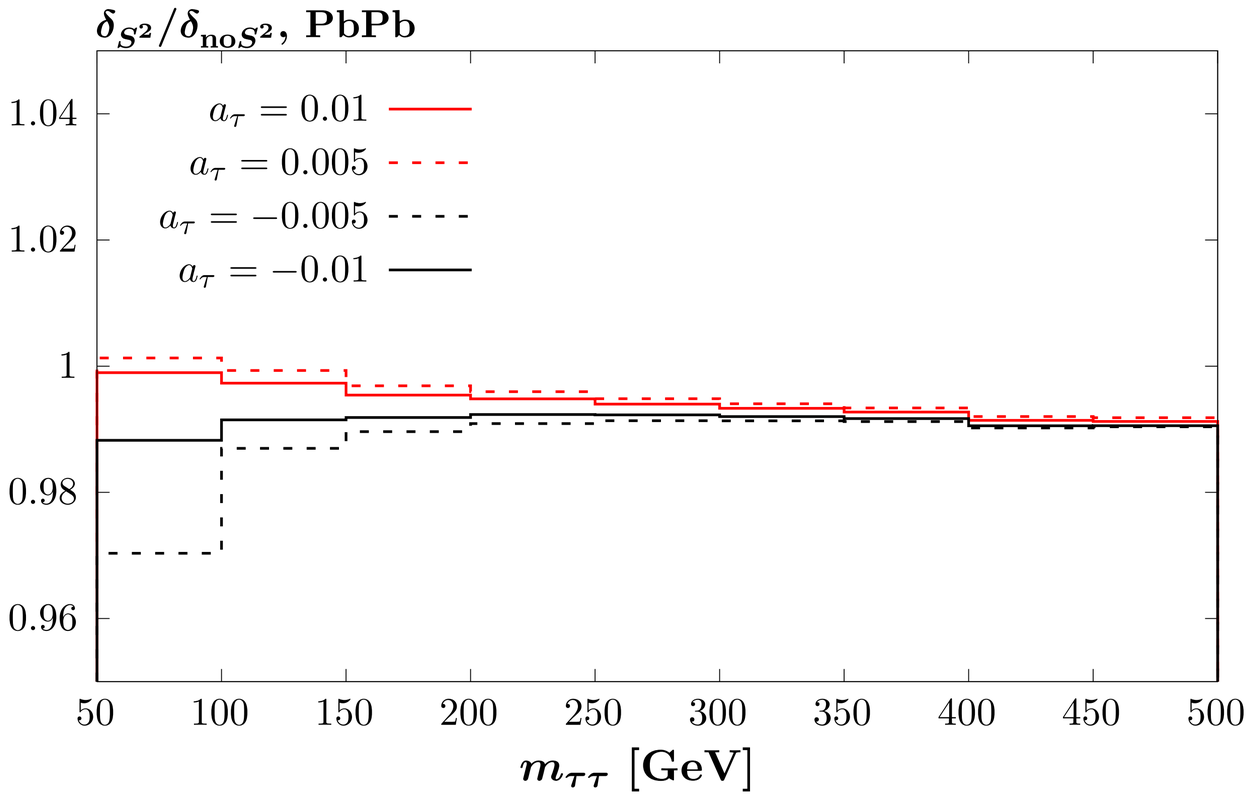
$$V^{\mu}_{\tau\tau\gamma} = ie\gamma^{\mu} - \left[\delta a_{\tau}\frac{e}{2m_{\tau}} + i\delta d_{\tau}\gamma_5\right]\sigma^{\mu\nu}q_{\nu} \ ,$$

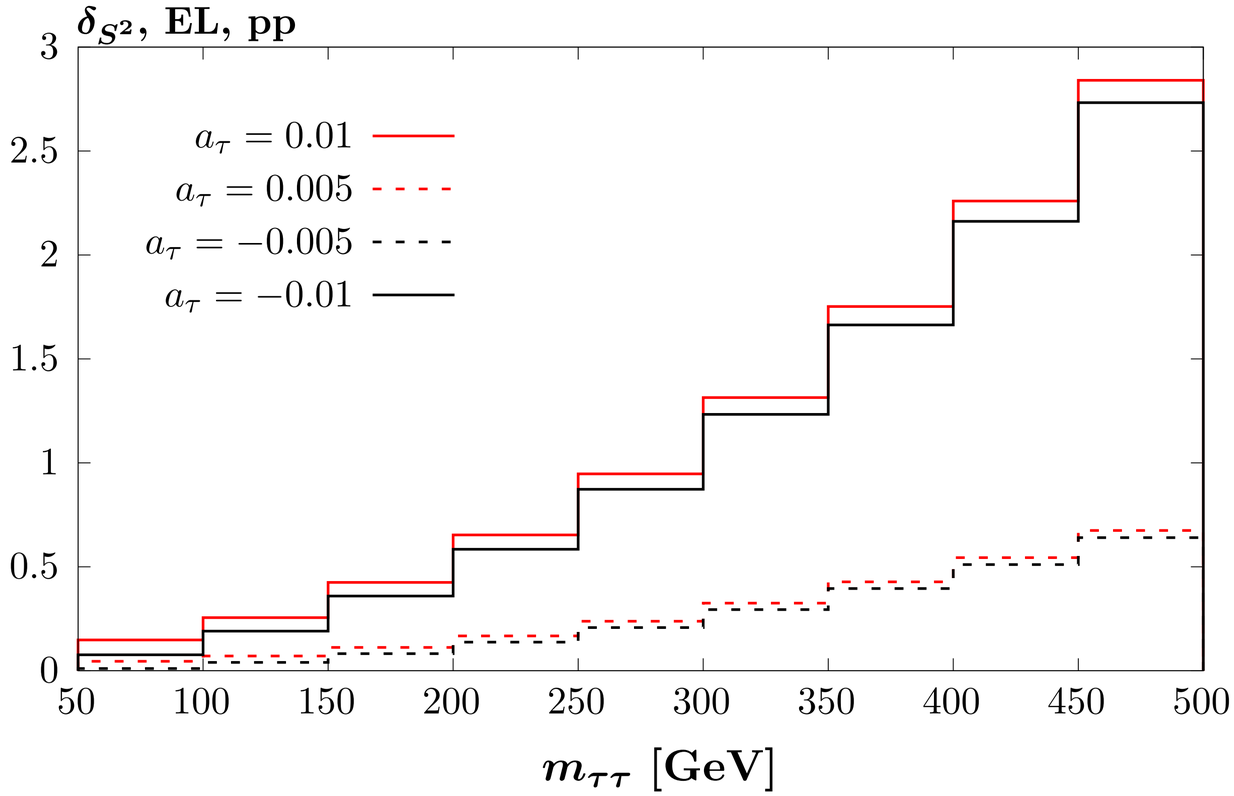
pp

$$\mathrm{d}\sigma = \sum_{i=0}^{4}(a_{\tau})^{i}\mathrm{d}\sigma_{i} \ ,$$



- Rather similar story to PbPb for **survival factor** effect…



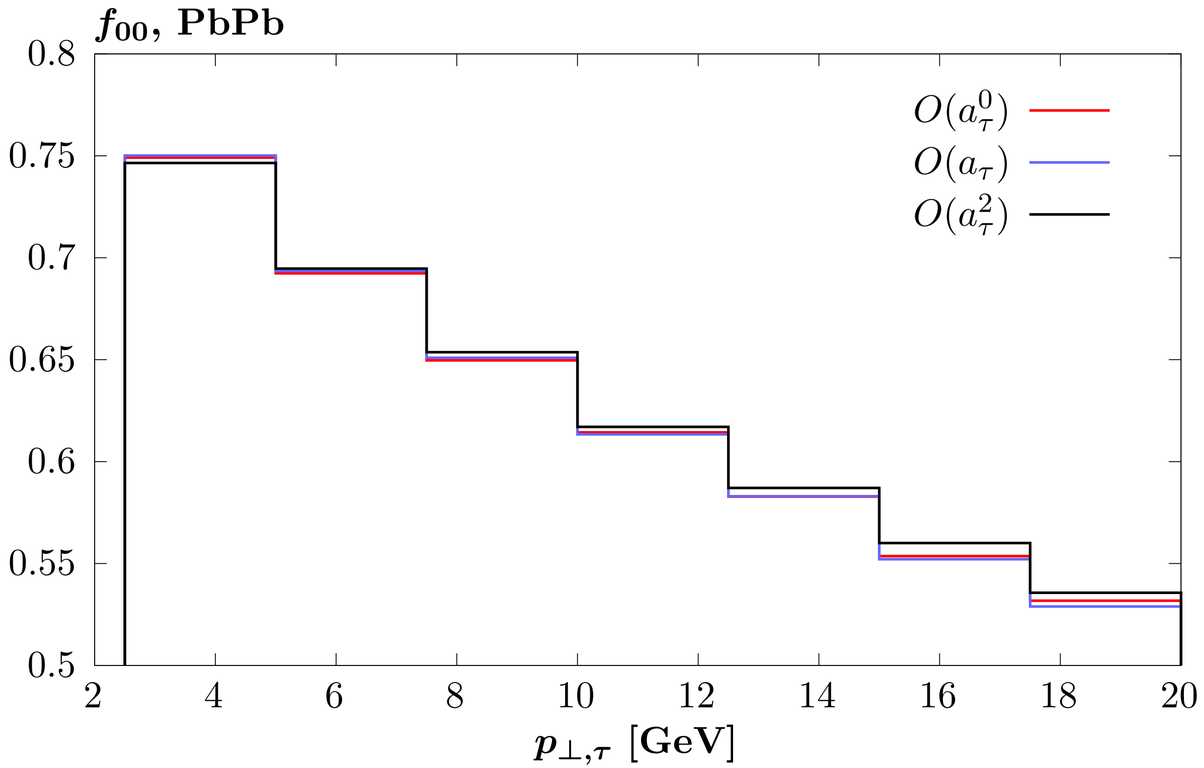


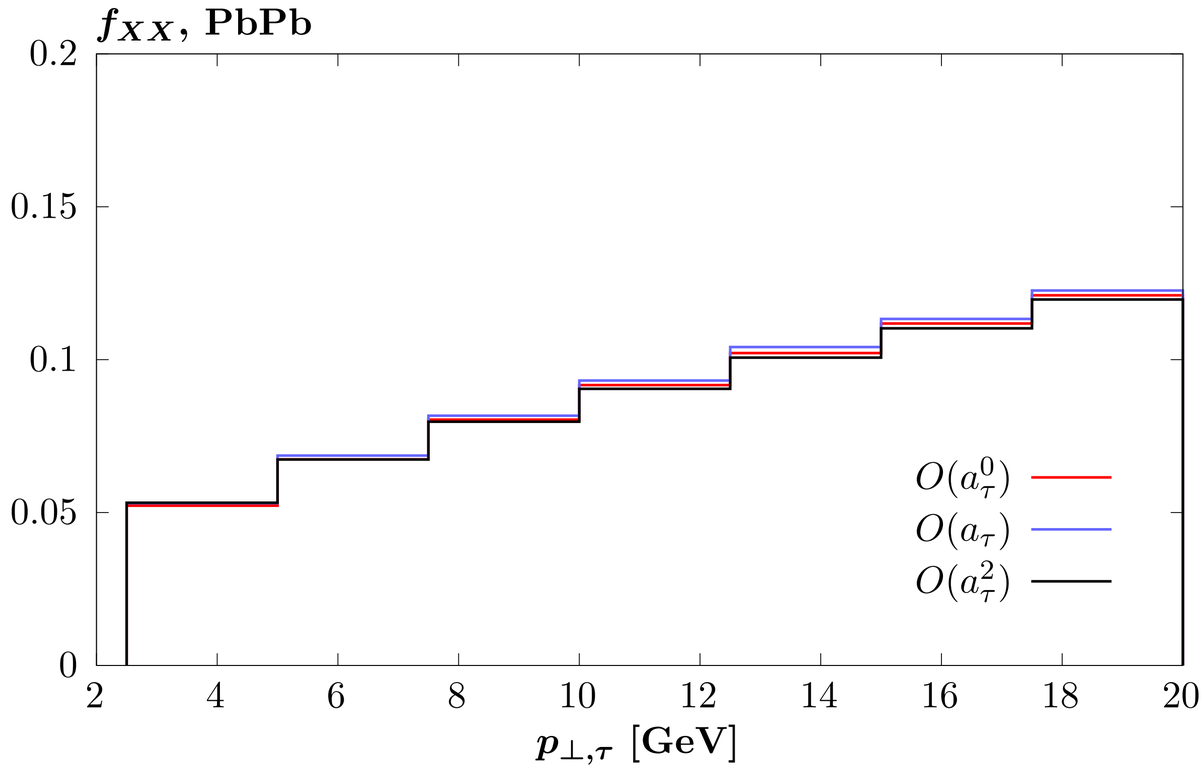
- …and similar percent level impact on a_τ determination/limit.

PbPb - dissociation

$$\mathrm{d}\sigma = \sum_{i=0}^{4} (a_\tau)^i \mathrm{d}\sigma_i \ ,$$

- Consider 0n0n and XnXn cross section fractions in ZDCs - i.e. with/without dissociation.
- Find dependence on a_τ very limited!





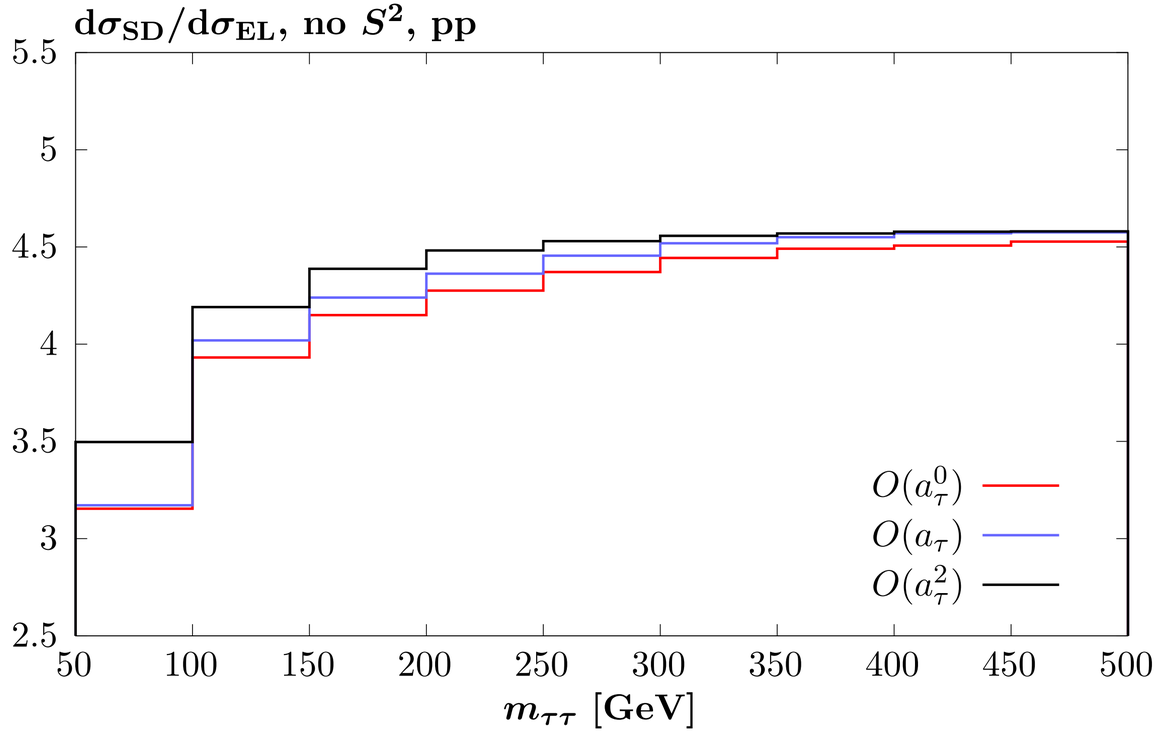
pp - dissociation

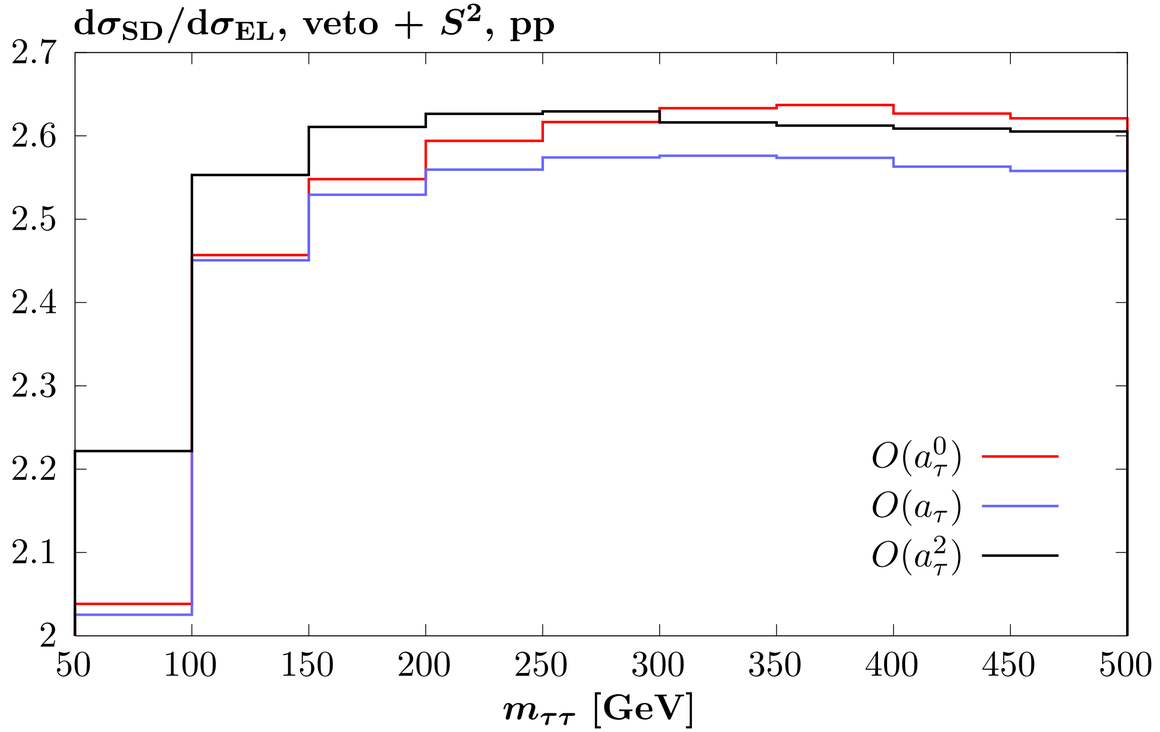
$$V^{\mu}_{\tau\tau\gamma} = ie\gamma^{\mu} - \left[\delta a_{\tau}\frac{e}{2m_{\tau}} + i\delta d_{\tau}\gamma_5\right]\sigma^{\mu\nu}q_{\nu} \ ,$$

$p_{\perp} > 0.5$ GeV and $|\eta| < 2.5$.

$$\mathrm{d}\sigma = \sum_{i=0}^{4}(a_{\tau})^{i}\mathrm{d}\sigma_{i} \ ,$$

- Now plot ratio of dissociative cross section to EL, with and without veto (latter relevant in end!).

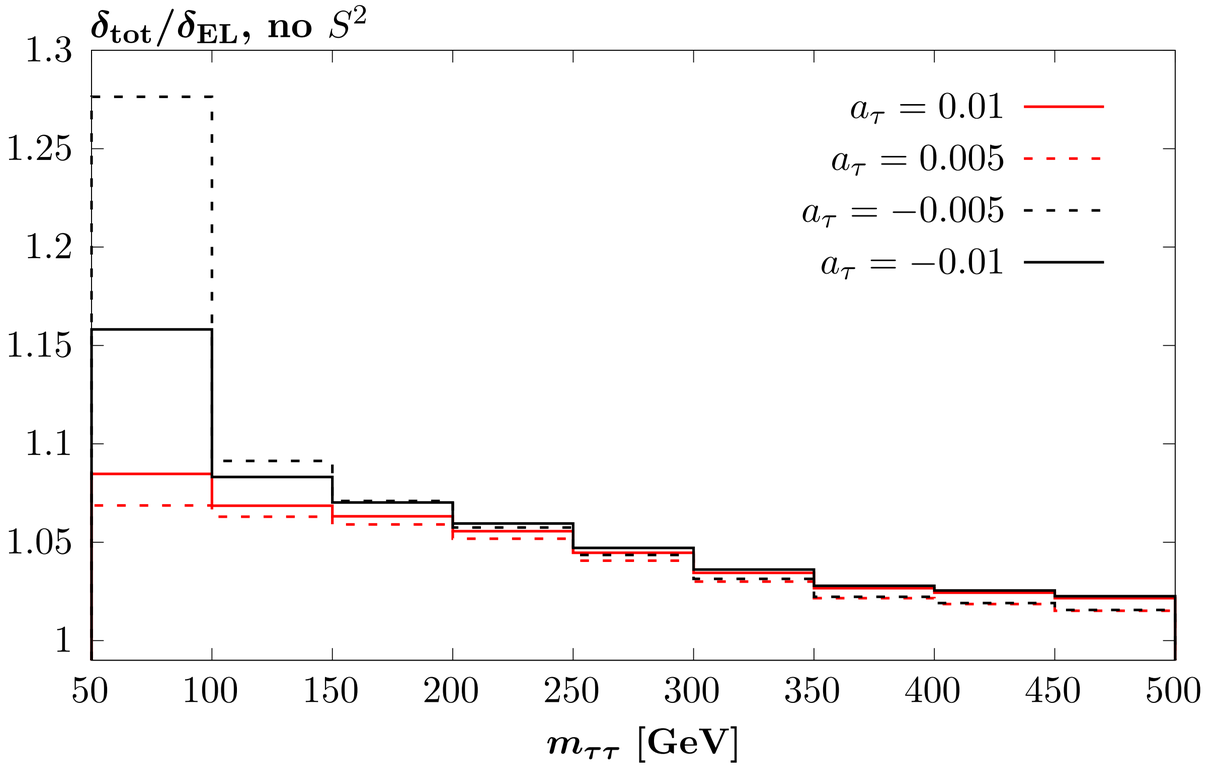


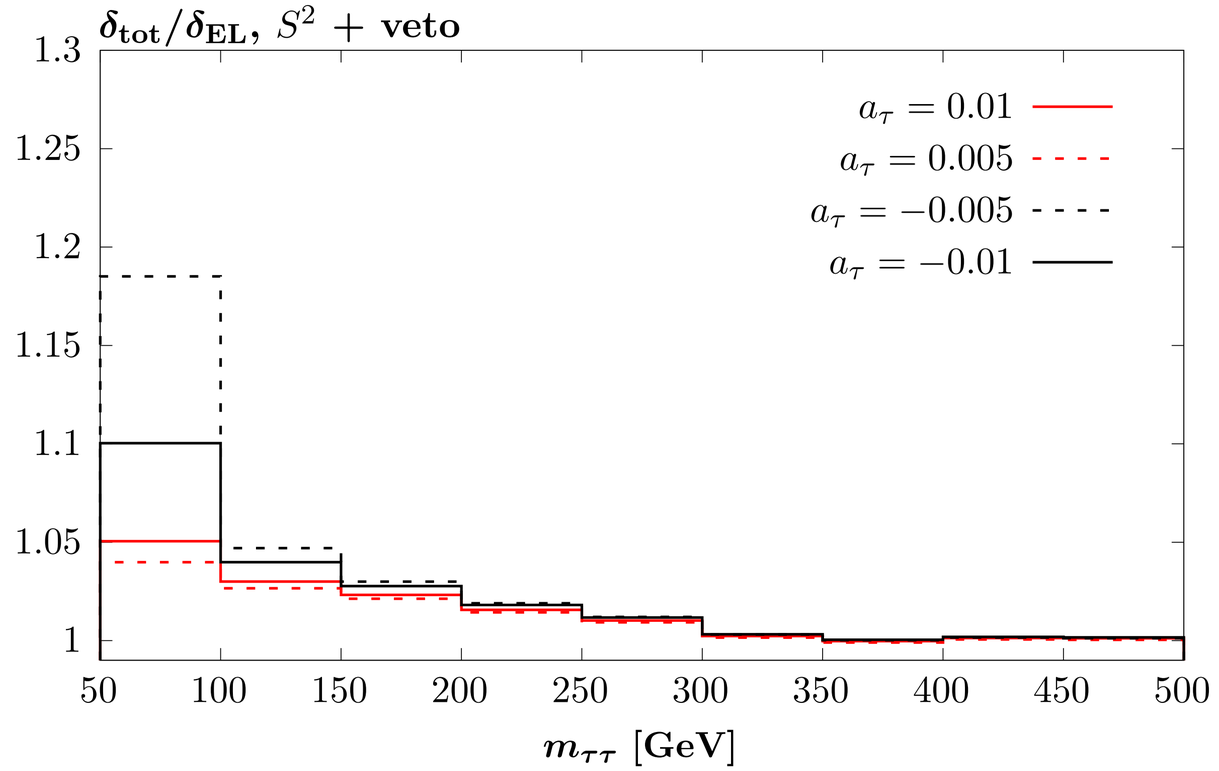


- Single dissociation (**SD)** dominant one - show here. Again see moderate differences in the SD/ EL fractions in the different terms. Pre-veto corrections prefers dissociation ($\Rightarrow$ higher Q^2).
- After veto differences remain, but reduced (higher Q^2 ~ removed).

$$\delta = \frac{1}{\mathrm{d}\sigma_0} \sum_{i=1}^{4} (a_\tau)^i \mathrm{d}\sigma_i \ ,$$

- Look at modifications in **total** (EL + SD + DD) cross section.
- In high $m_{\tau\tau}$ tail, where corrections largest again impact is very small in particular after **veto**.
- Differences appear larger at lower mass, but here absolute corrections small.
- Precise impact depend on how a_τ is extracted, decays etc but points to **percent level** again.

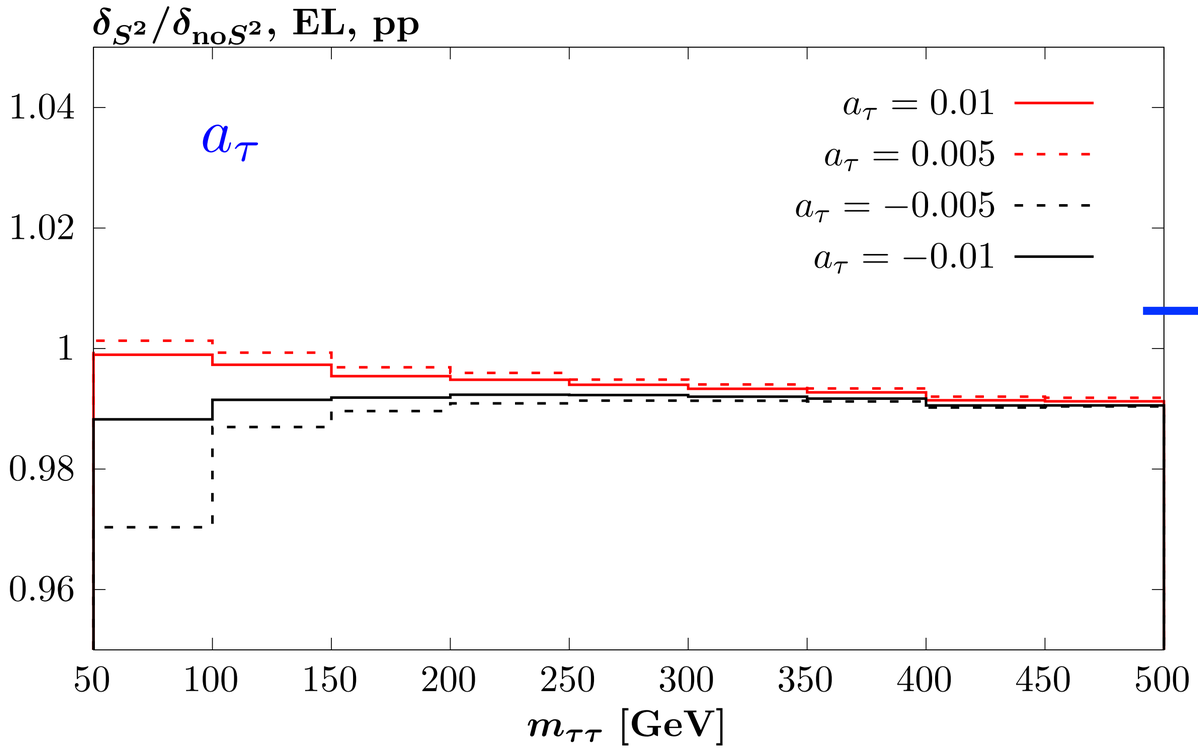


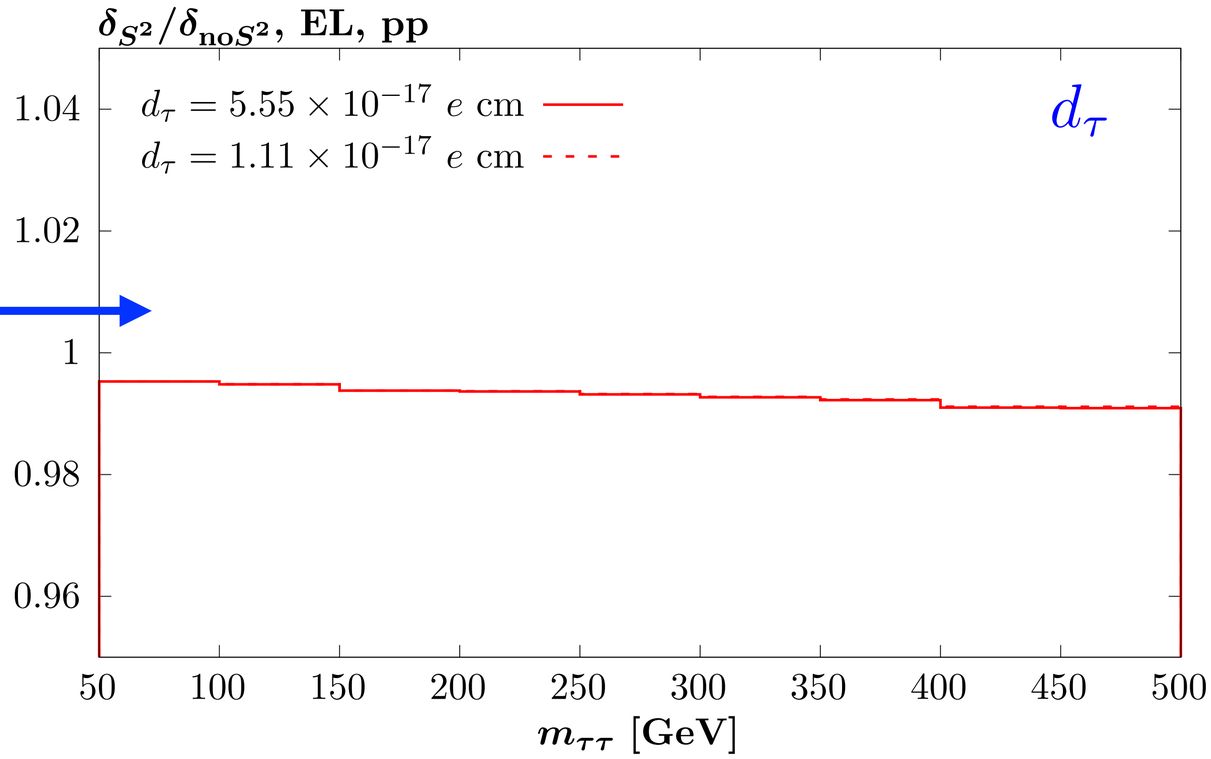


Electric Dipole Moment

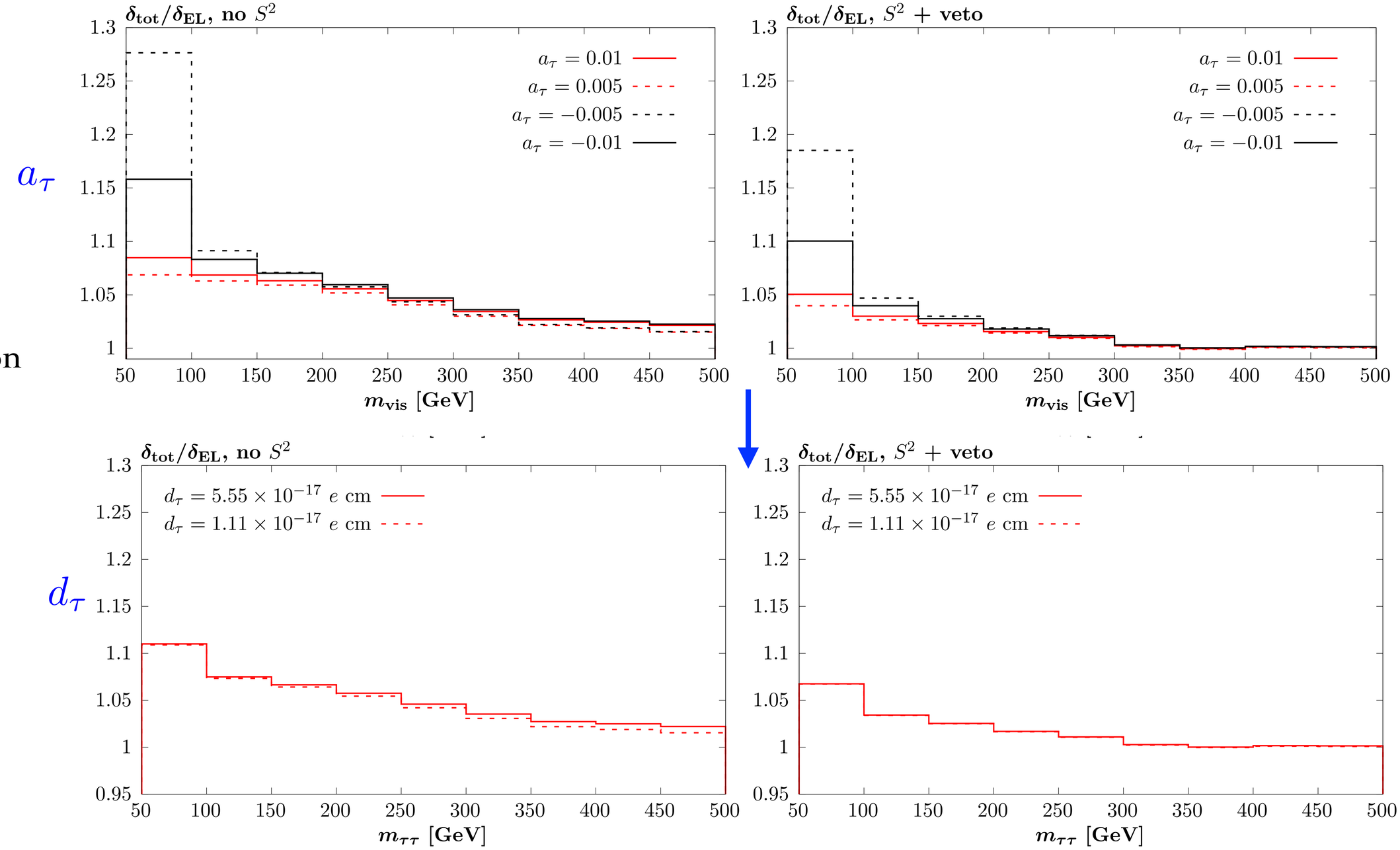
$$V^{\mu}_{\tau\tau\gamma} = ie\gamma^{\mu} - \left[\delta a_{\tau}\frac{e}{2m_{\tau}} + i\delta d_{\tau}\gamma_5\right]\sigma^{\mu\nu}q_{\nu}\ ,$$

- Very similar story for electric dipole moment.
- Survival factor in pp:





- Dissociation in pp:

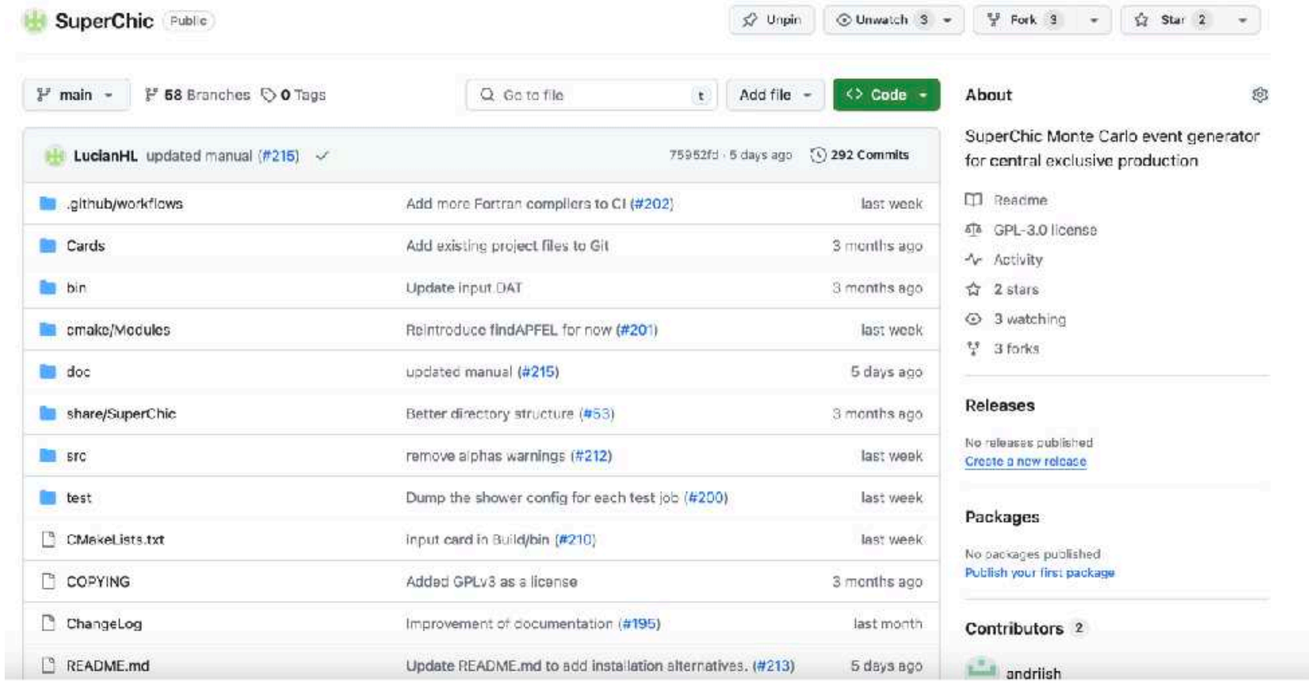


Summary/Outlook

★ Anomalous in a_τ, d_τ photon-initiated τ pair production included in SuperChic for first time, in pp and AA.

★ First complete treatment of **survival factor** and **proton dissociation**, and dependence on a_τ, d_τ.

★ Bottom line: impact of including this dependence small (percent level wrt a_τ, d_τ determination/limits).

★ Suggests existing LHC analyses already robust wrt this, but looking to the future we may care about these effects!

★ Proper treatment of proton dissociation also arguably mandatory (always there in pp) - now possible.