

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

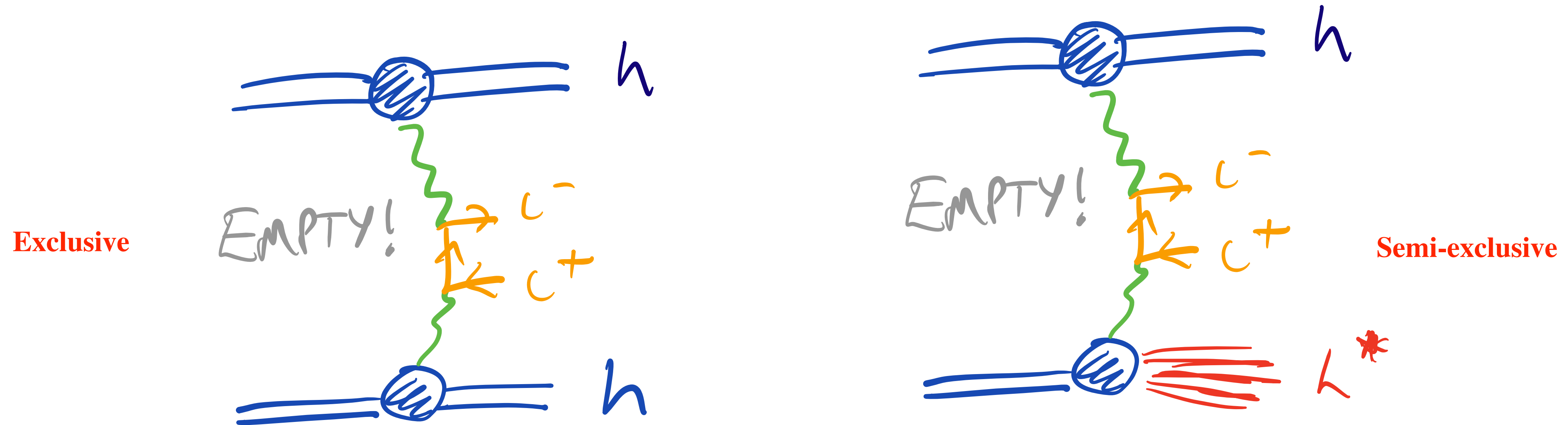
Lucian Harland-Lang, University College London

Low x 2024, Trabia, Sicily, Sep 11 2024



Photon-Photon Physics

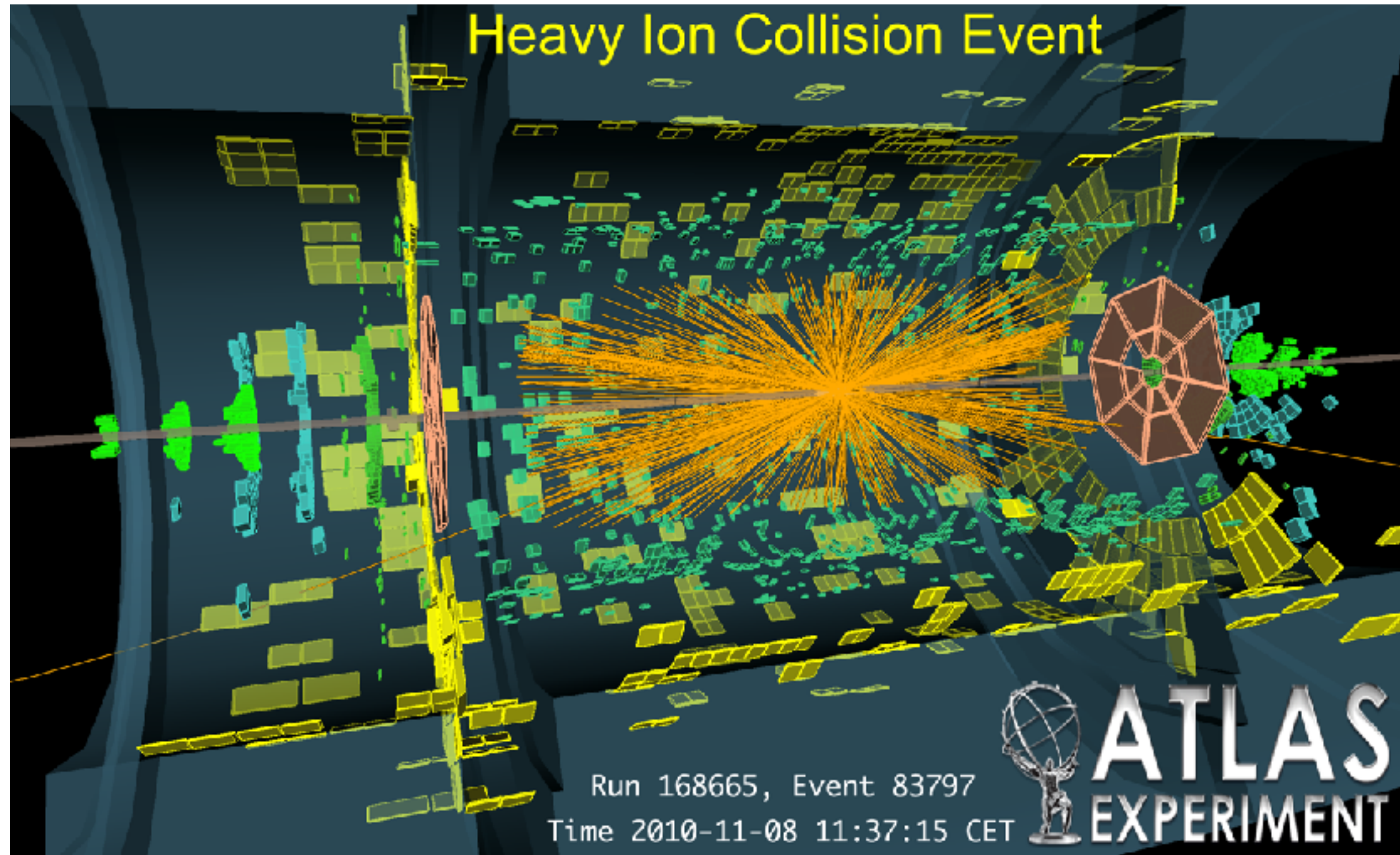
- Both protons and heavy ions can act as source of initial-state photons \Rightarrow purely photon-initiated production possible.
- This allows for **exclusive/semi-exclusive** production: colour singlet photon naturally leads to events with intact protons/rapidity gaps in final state:



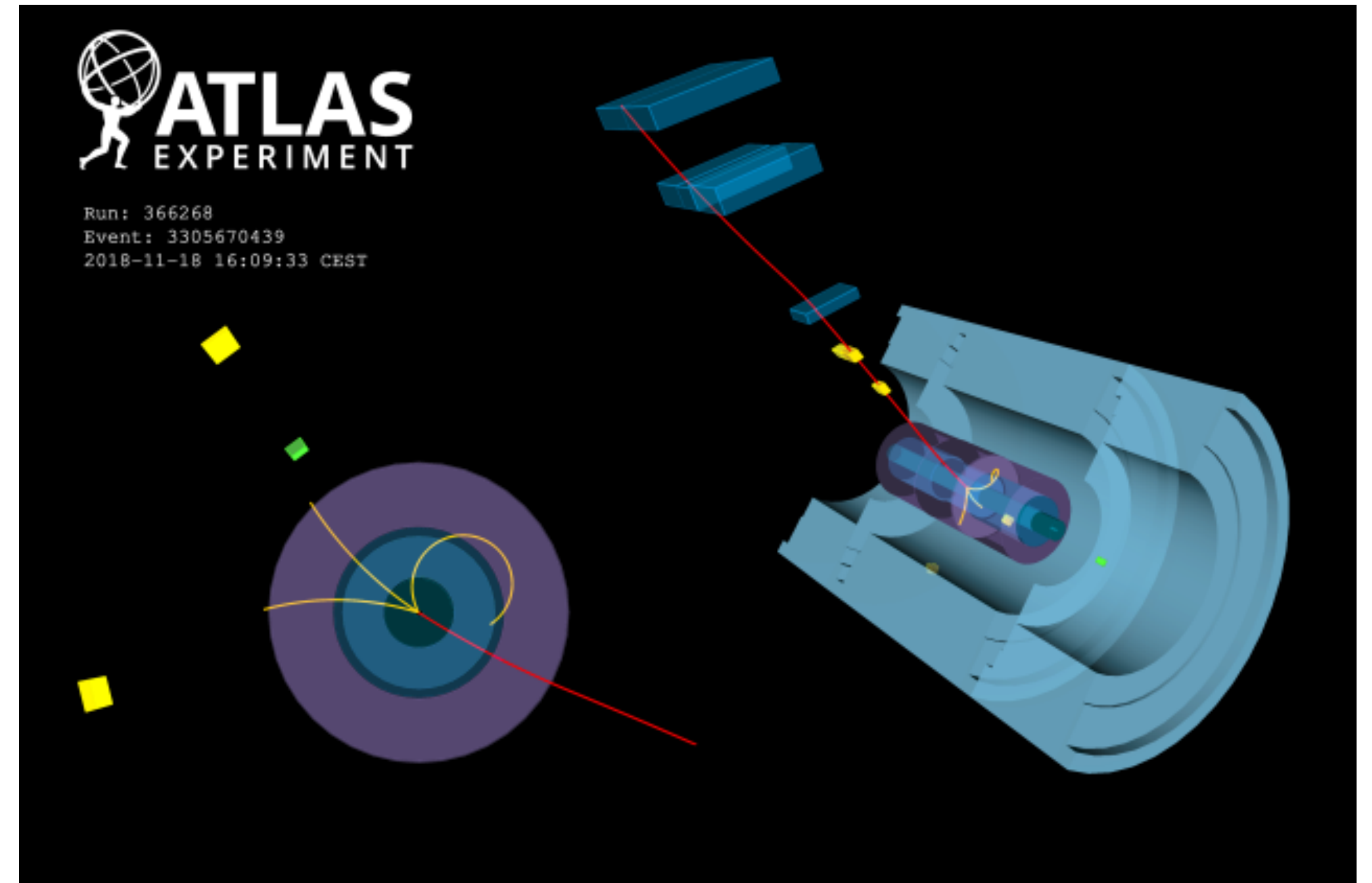
★ QCD interactions between hadrons can be largely ignored, i.e. \sim pure QED production

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

What does it look like?

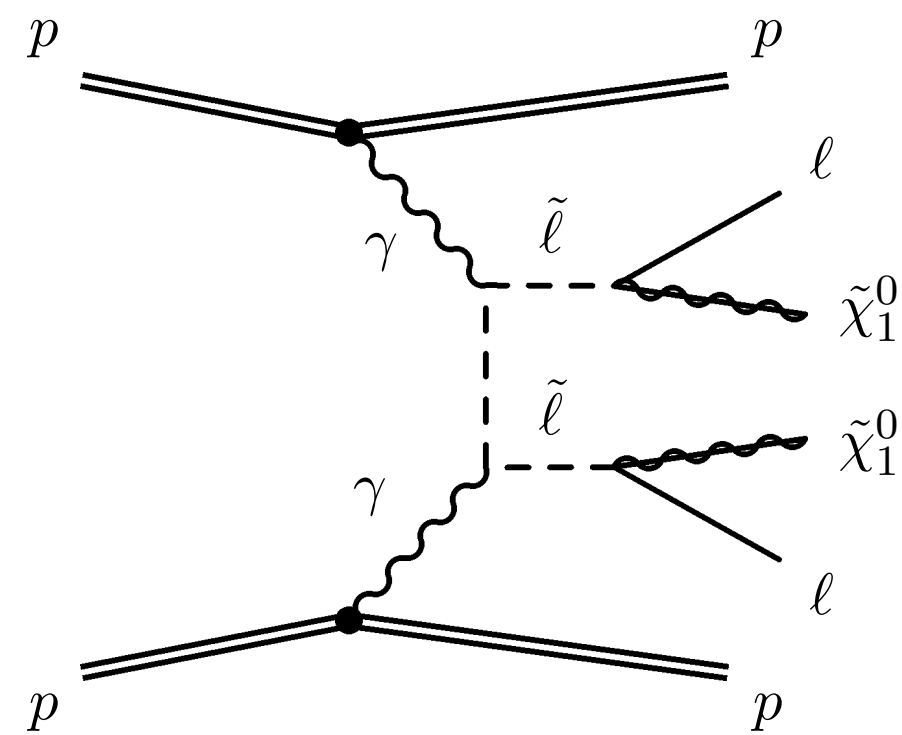


VS.



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

Compressed SUSY



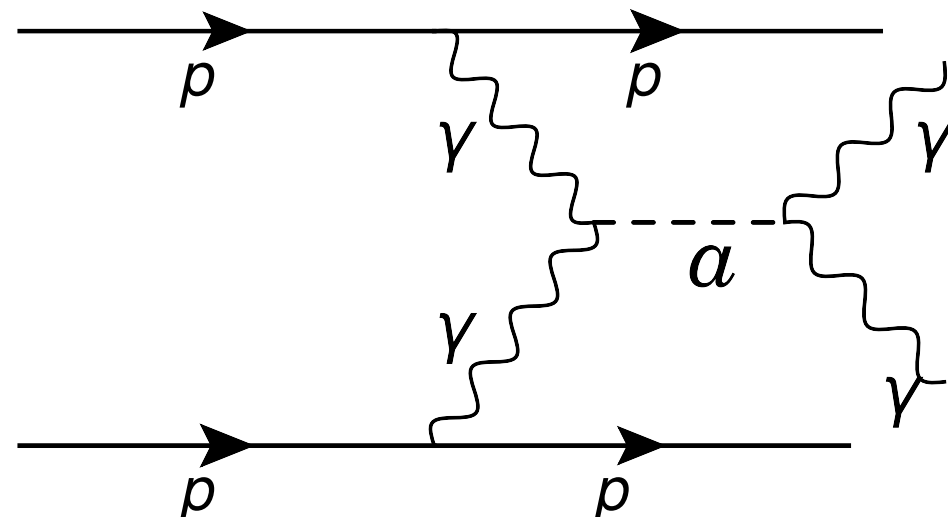
LHL et al., JHEP 1904 (2019) 010

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

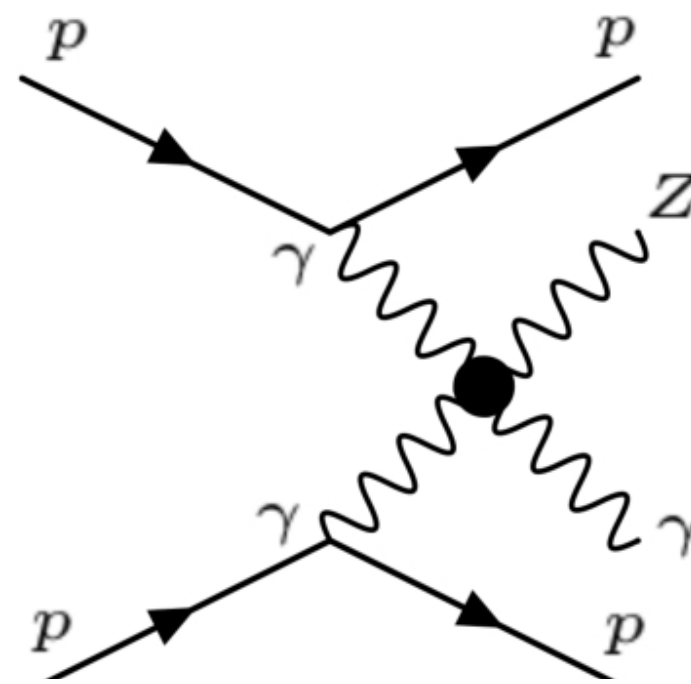
Axion-like Particles

LHL and M. Tasevsky, arXiv:2208.10526

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

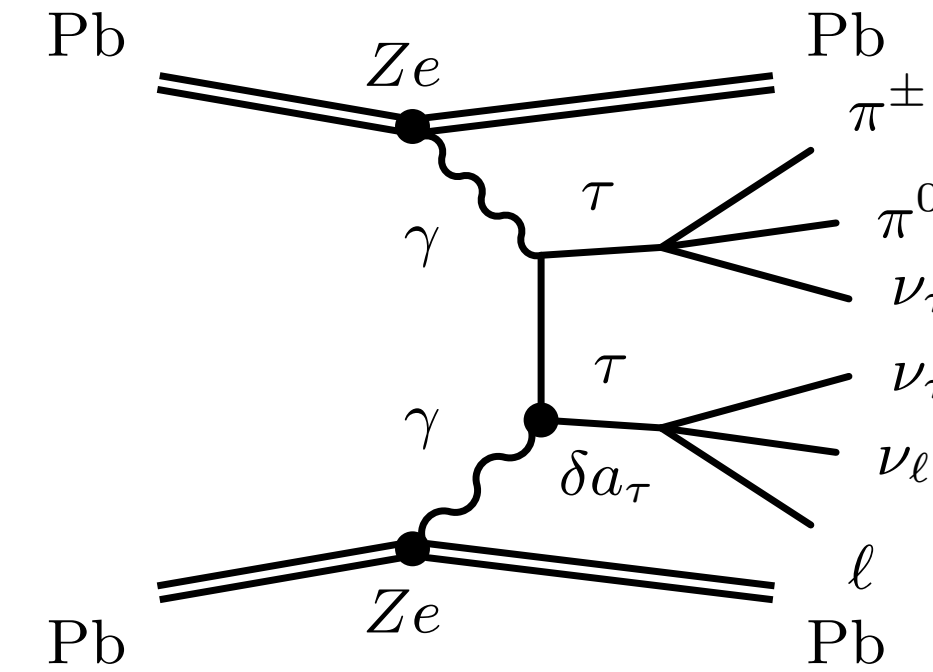


Anomalous couplings



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

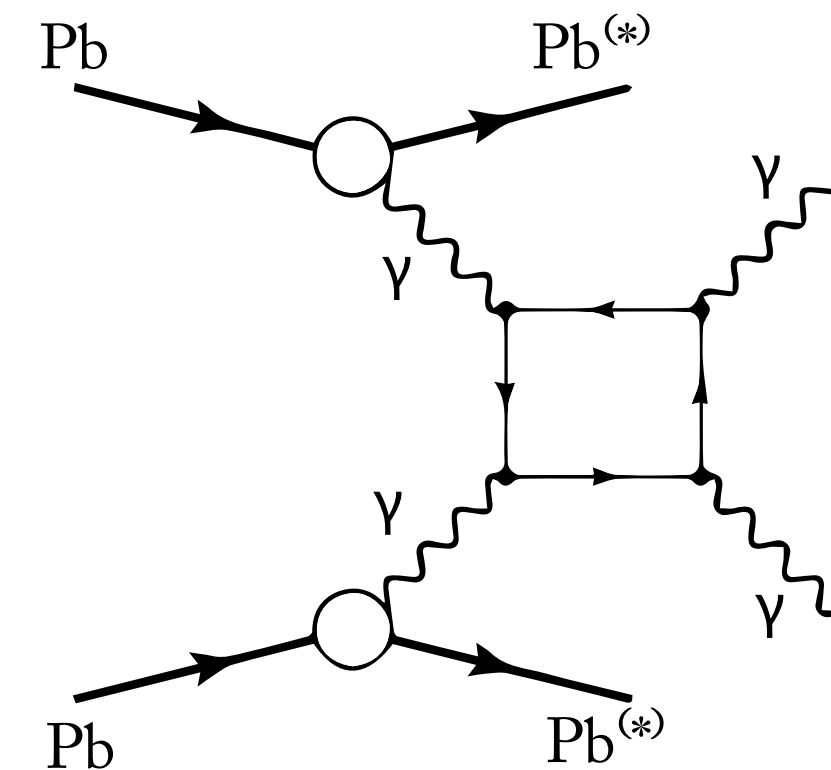
tau g-2



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

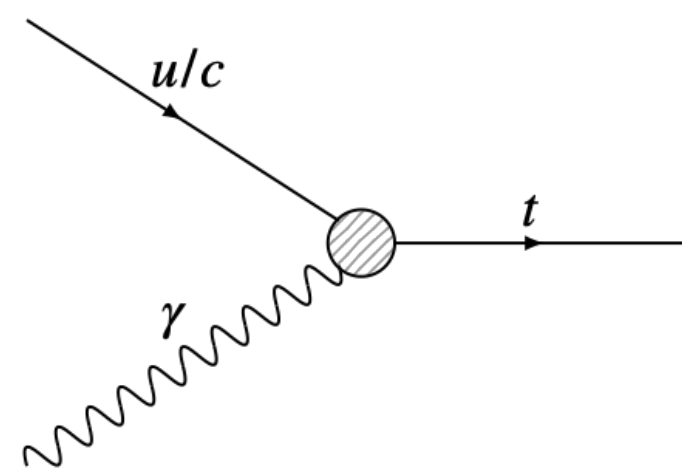
M. Dyndal et al., PLB 809 (2020) 135682

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

Top quarks



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

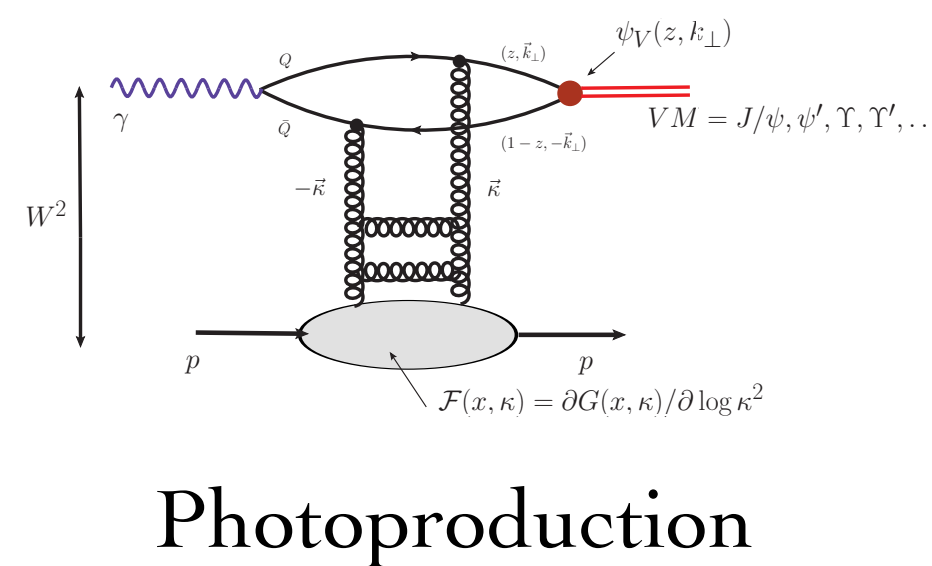
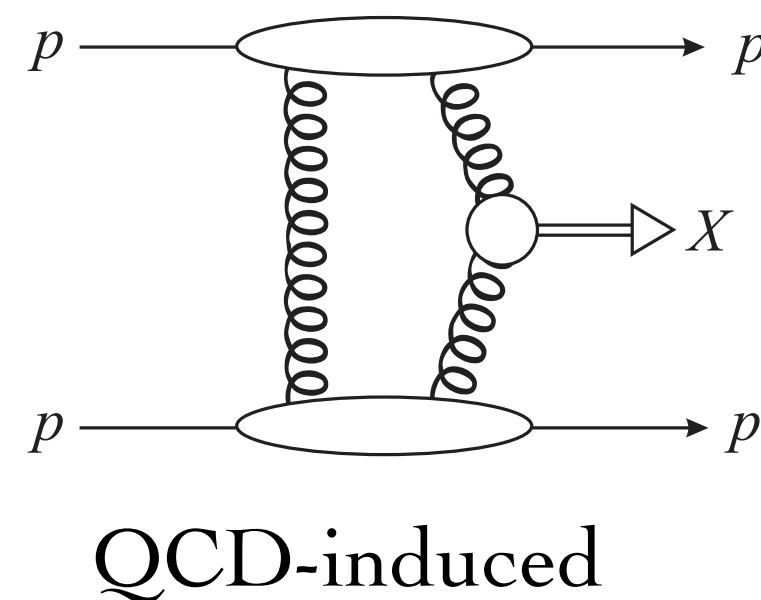
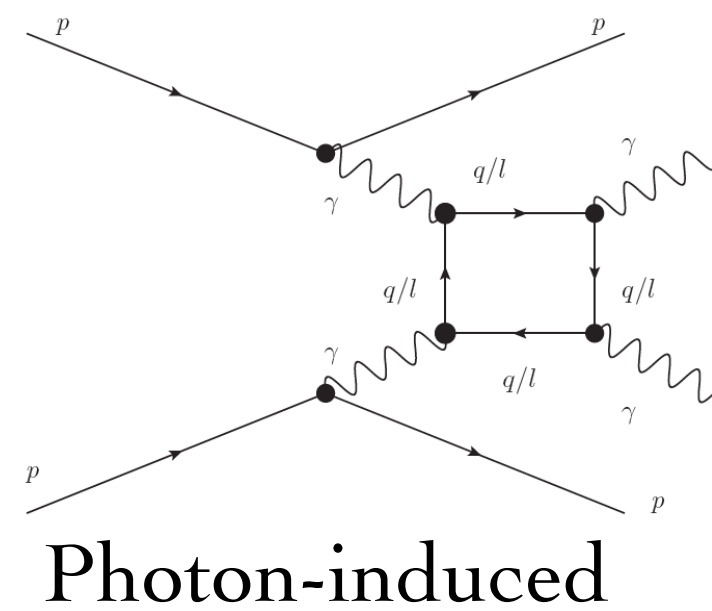
J. Howarth, arXiv:2008.04249

SuperChic MC Implementation

- A MC event generator for CEP processes.

Common platform for:

- ▶ QCD-induced CEP.
- ▶ Photoproduction.
- ▶ Photon-photon induced CEP.



superchic is hosted by Hepforge, IPPP Durham

SuperChic 4 - A Monte Carlo for Central Exclusive and Photon-Initiated Production

- [Home](#)
- [Code](#)
- [References](#)
- [Contact](#)

SuperChic is a Fortran based Monte Carlo event generator for exclusive and photon-initiated production in proton and heavy ion collisions. A range of Standard Model final states are implemented, in most cases with spin correlations where relevant, and a fully differential treatment of the soft survival factor is given. Arbitrary user-defined histograms and cuts may be made, as well as unweighted events in the HEPEVT, HEPMC and LHE formats. For further information see the [user manual](#).

A list of references can be found [here](#) and the code is available [here](#).

Comments to Lucian Harland-Lang < lucian.harland-lang (at) physics.ox.ac.uk >.

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

SuperChic 5 - MC Implementation

- Version 5 now released. Significant updates to code:

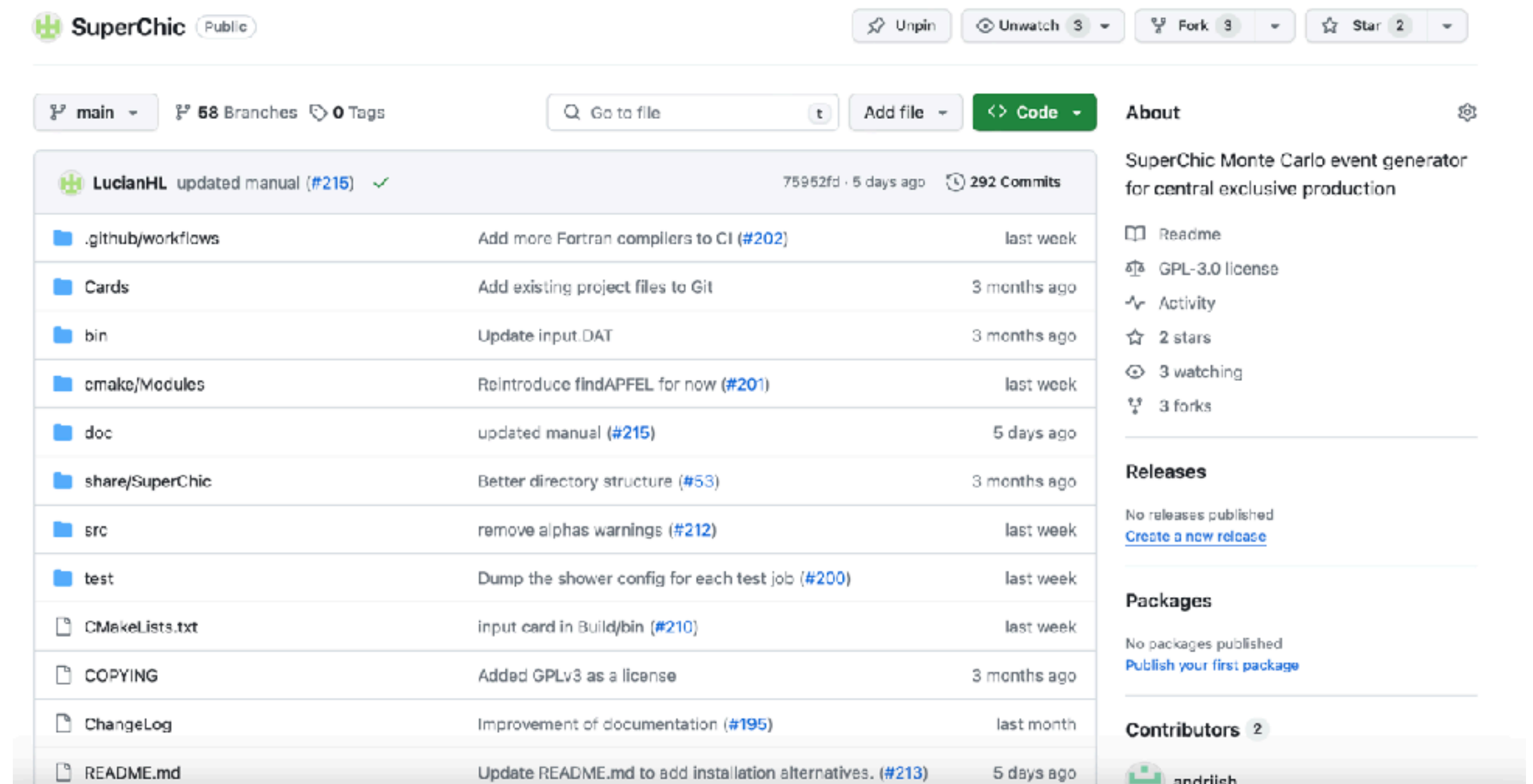
★HepMC output now properly supported.

★Full testing suite added + cmake build system.

★Various bug fixes + code improvements.

★ Future releases will be via github.

Collaboration/PRs welcome!



The screenshot shows the GitHub repository page for SuperChic. The repository is public and has 68 branches and 0 tags. The commit history is as follows:

Commit	Message	Time
LucianHL updated manual (#215) ✓		75952fd · 5 days ago · 292 Commits
.github/workflows	Add more Fortran compilers to CI (#202)	last week
Cards	Add existing project files to Git	3 months ago
bin	Update input.DAT	3 months ago
cmake/Modules	Reintroduce findAPFEL for now (#201)	last week
doc	updated manual (#215)	5 days ago
share/SuperChic	Better directory structure (#53)	3 months ago
src	remove alphas warnings (#212)	last week
test	Dump the shower config for each test job (#200)	last week
CMakeLists.txt	input card in Build/bin (#210)	last week
COPYING	Added GPLv3 as a license	3 months ago
ChangeLog	Improvement of documentation (#195)	last month
README.md	Update README.md to add installation alternatives. (#213)	5 days ago

Repository details on the right side:

- About: SuperChic Monte Carlo event generator for central exclusive production
- Readme
- GPL-3.0 license
- Activity
- 2 stars
- 3 watching
- 3 forks
- Releases: No releases published. [Create a new release](#)
- Packages: No packages published. [Publish your first package](#)
- Contributors: 2 (andriish)

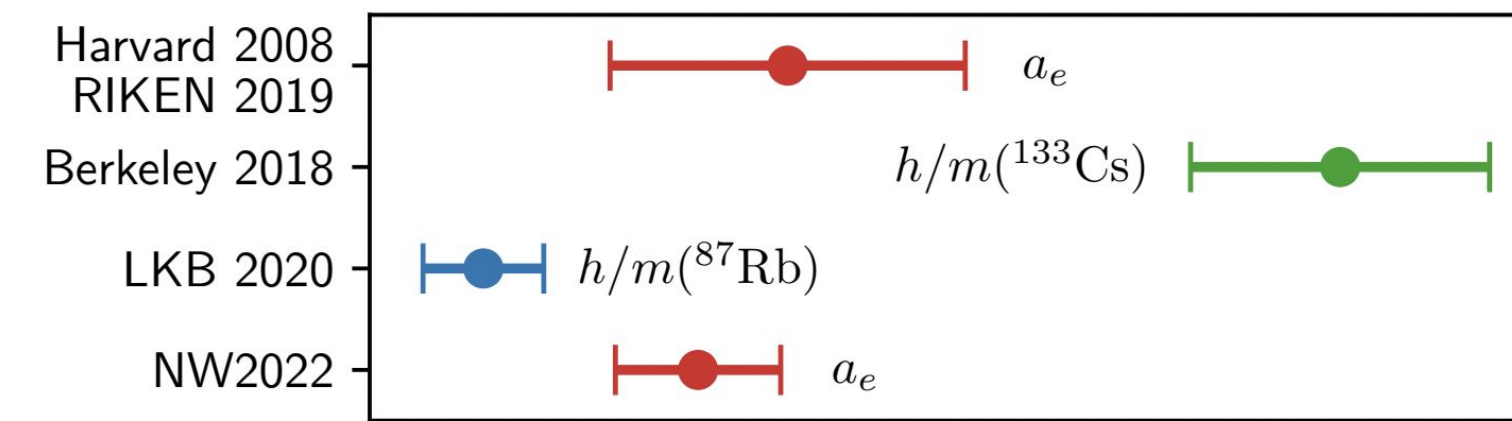
<https://github.com/LucianHL/SuperChic>

The tau lepton g-2

★ Probing the tau g-2:

- While experimental situation for lighter leptons well developed...

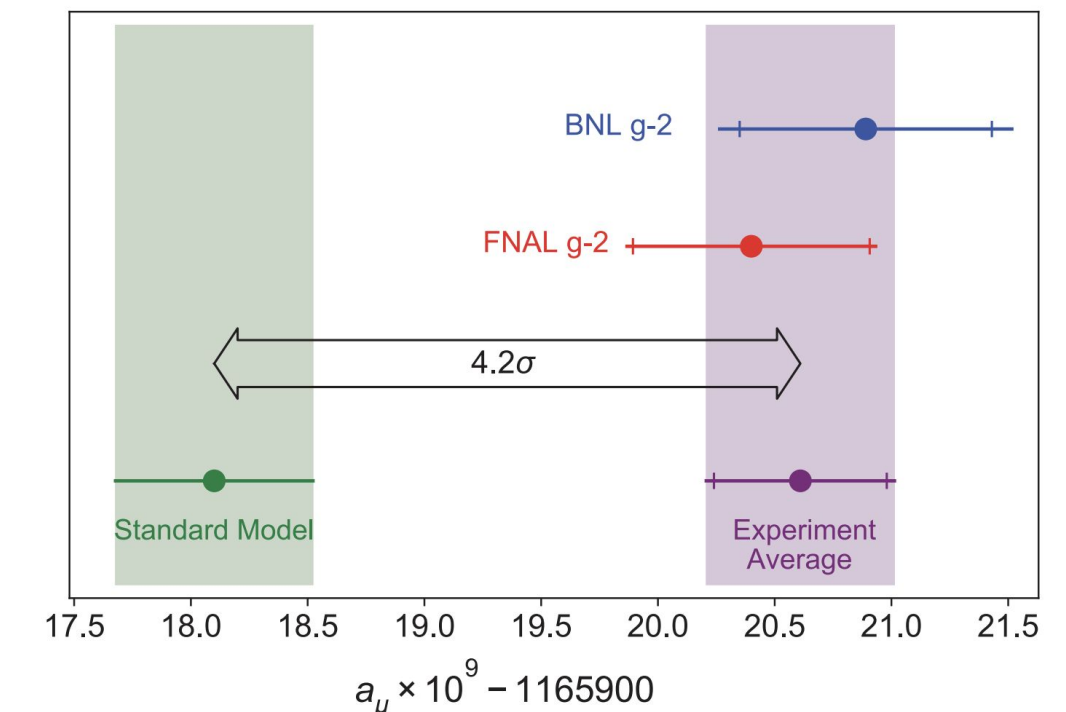
Electron g - 2 (-2.5σ?)



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!

$$a_{\tau}^{\text{exp}} = -0.018 (17) \quad \text{(Pre - LHC)}$$

DELPHI [hep-ex/0406010]

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

Eidelman, Passera [hep-ph/0701260]

- Does not even probe 1-loop QED:

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

Schwinger [1948]

- Sensitivity to BSM unprobed:

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

Martin, Wells [hep-ph/0103067]

The tau lepton g-2 in PI production

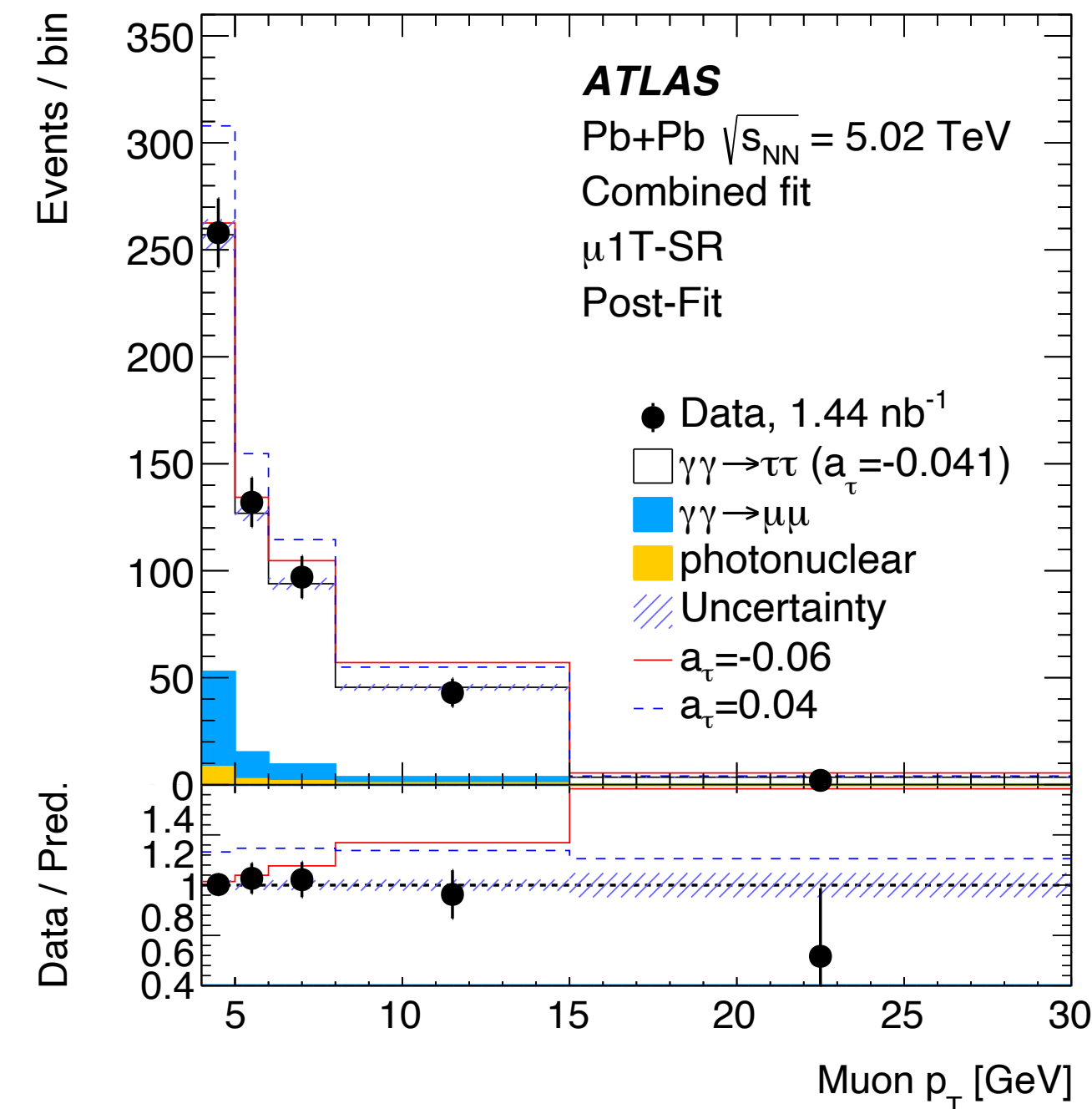
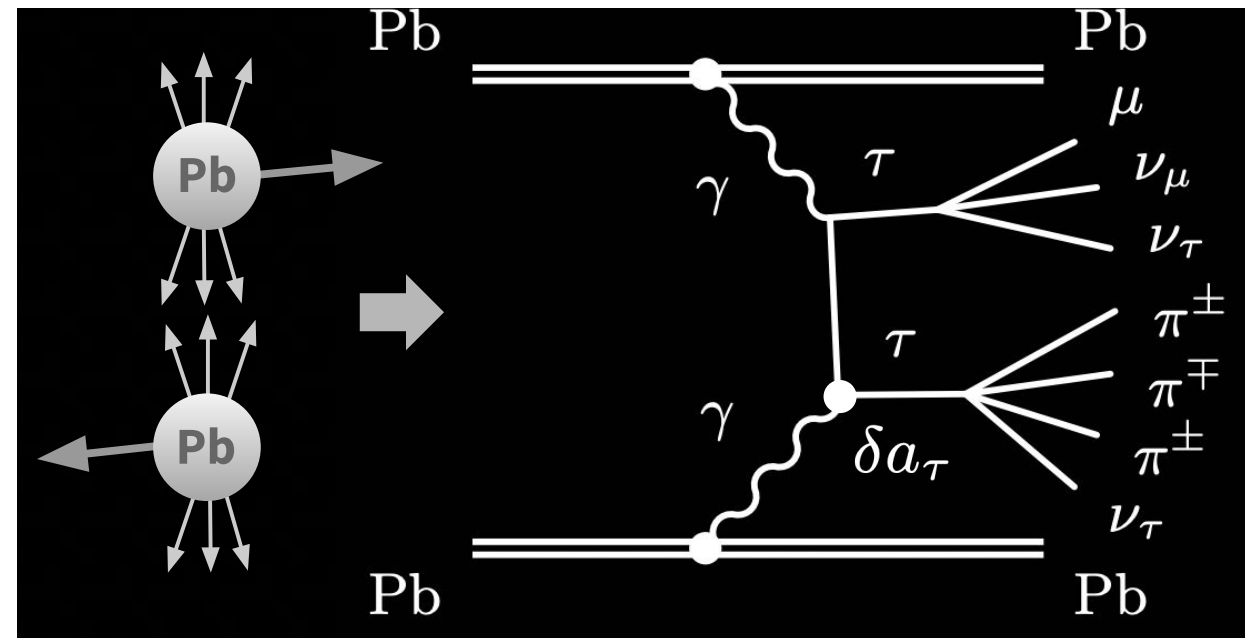
- By measuring $\gamma\gamma \rightarrow \tau^+\tau^-$ production - sensitive to tau g-2.

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

Eidelman, Passera [[hep-ph/0701260](https://arxiv.org/abs/hep-ph/0701260)]

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

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

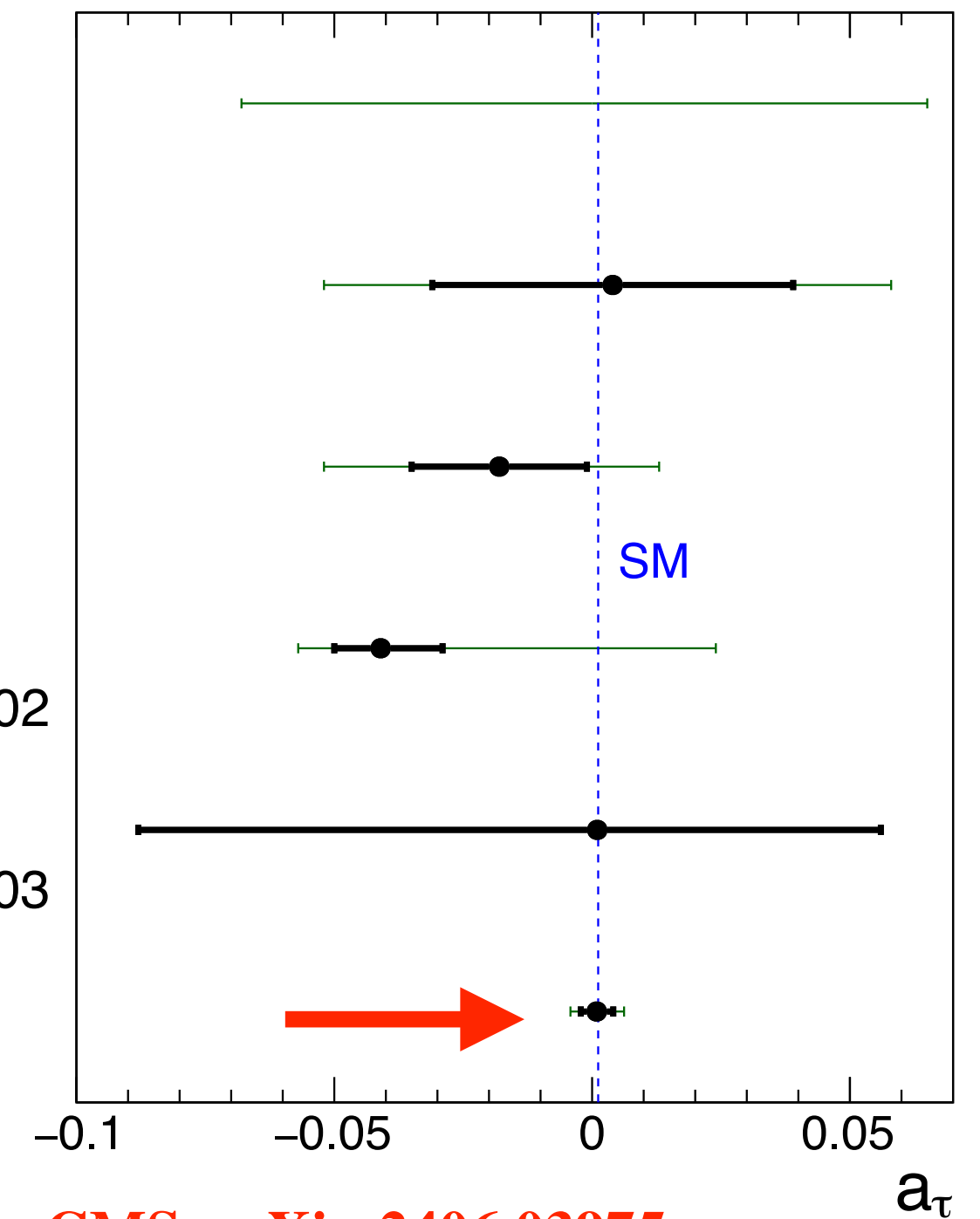


ATLAS, [arXiv:2204.13478](https://arxiv.org/abs/2204.13478)

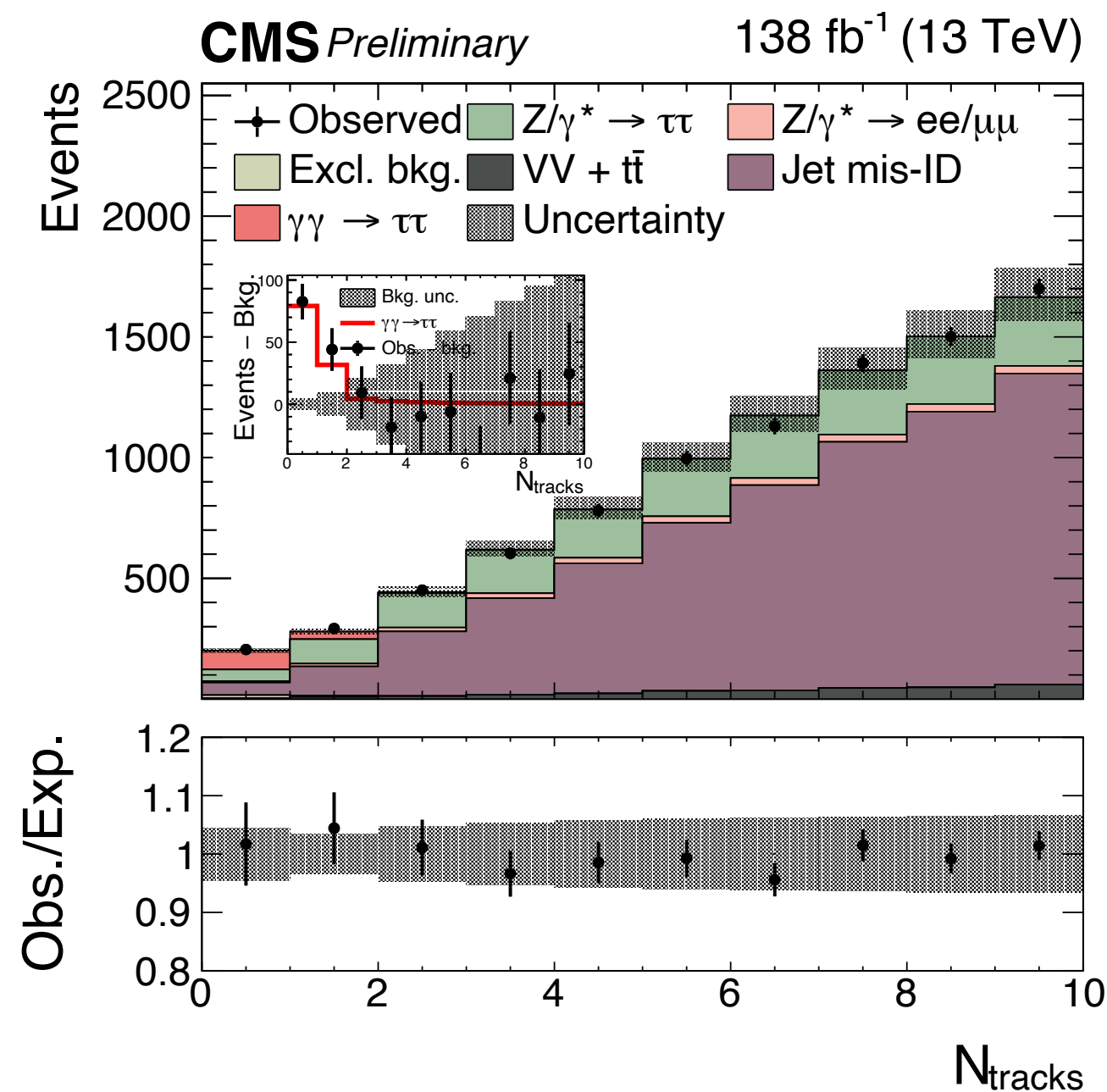
CMS

138 fb^{-1} (13 TeV)

- Observed
- 68% CL
- 95% CL



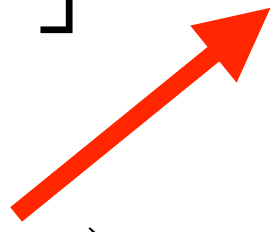
CMS, [arXiv:2406.03975](https://arxiv.org/abs/2406.03975)



CMS, [arXiv:2406.03975](https://arxiv.org/abs/2406.03975)

What is missing?

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

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


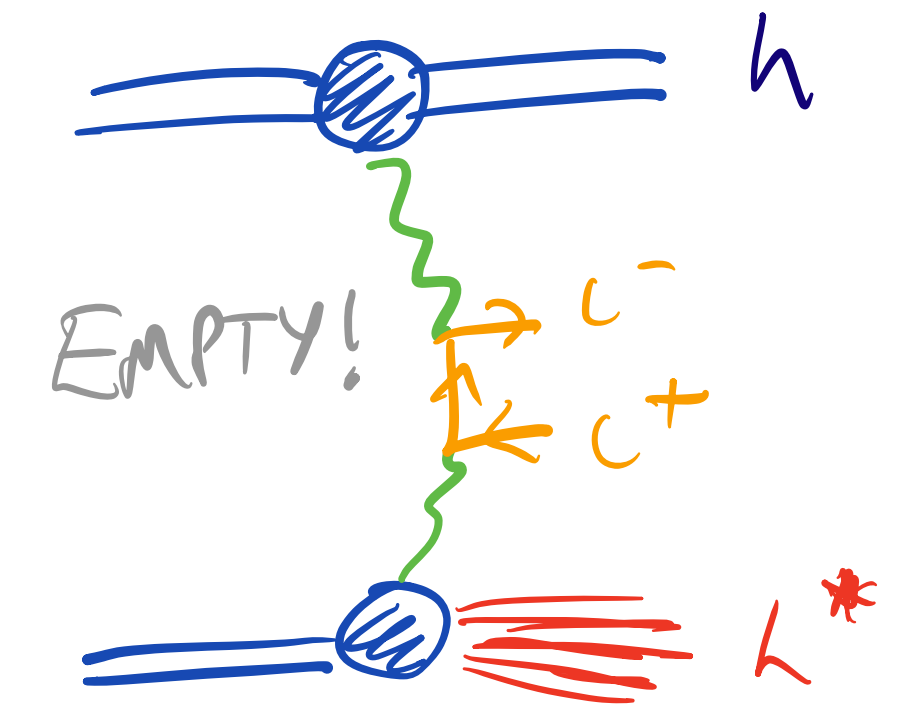
- Note in particular differing kinematic structure (additional q_ν).
- Leads to well known increase in effect of $\delta a_\tau, \delta d_\tau$ with increasing scale. But also:
 - ★ Survival factor.
 - ★ Proton dissociation (EL vs. SD vs. DD).
- Will also be different between the LO and $\delta a_\tau, \delta d_\tau$ 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:

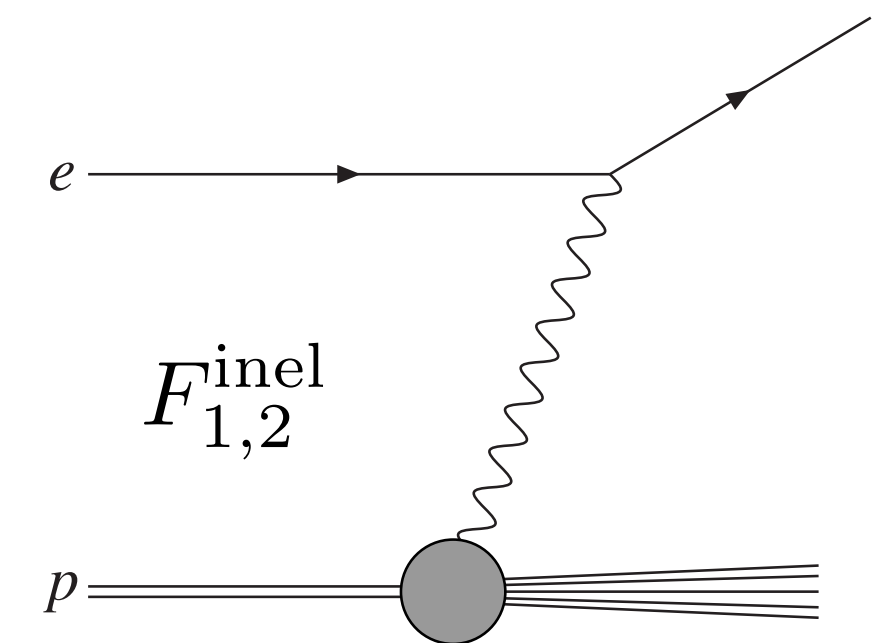
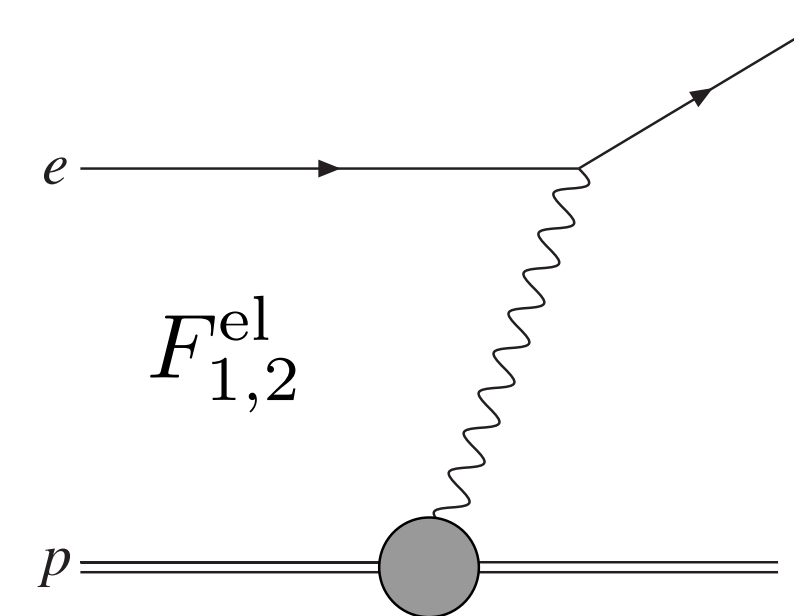
$$\sigma_{pp} = \frac{1}{2s} \int \overbrace{dx_1 dx_2 d^2 q_{1\perp} d^2 q_{2\perp}}^{\text{Photon } x, Q^2} d\Gamma \alpha(Q_1^2) \alpha(Q_2^2) \frac{\rho_1^{\mu\mu'} \rho_2^{\nu\nu'} M_{\mu'\nu'}^* M_{\mu\nu}}{q_1^2 q_2^2} \delta^{(4)}(q_1 + q_2 - p_X),$$

$$\underbrace{\gamma^* p \rightarrow X}_{\text{blue}} \sim \underbrace{\sigma(\gamma^* \gamma^* \rightarrow X)}_{\text{orange}}$$



- Key point (without details) for us - $\gamma p \rightarrow X$ 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).

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

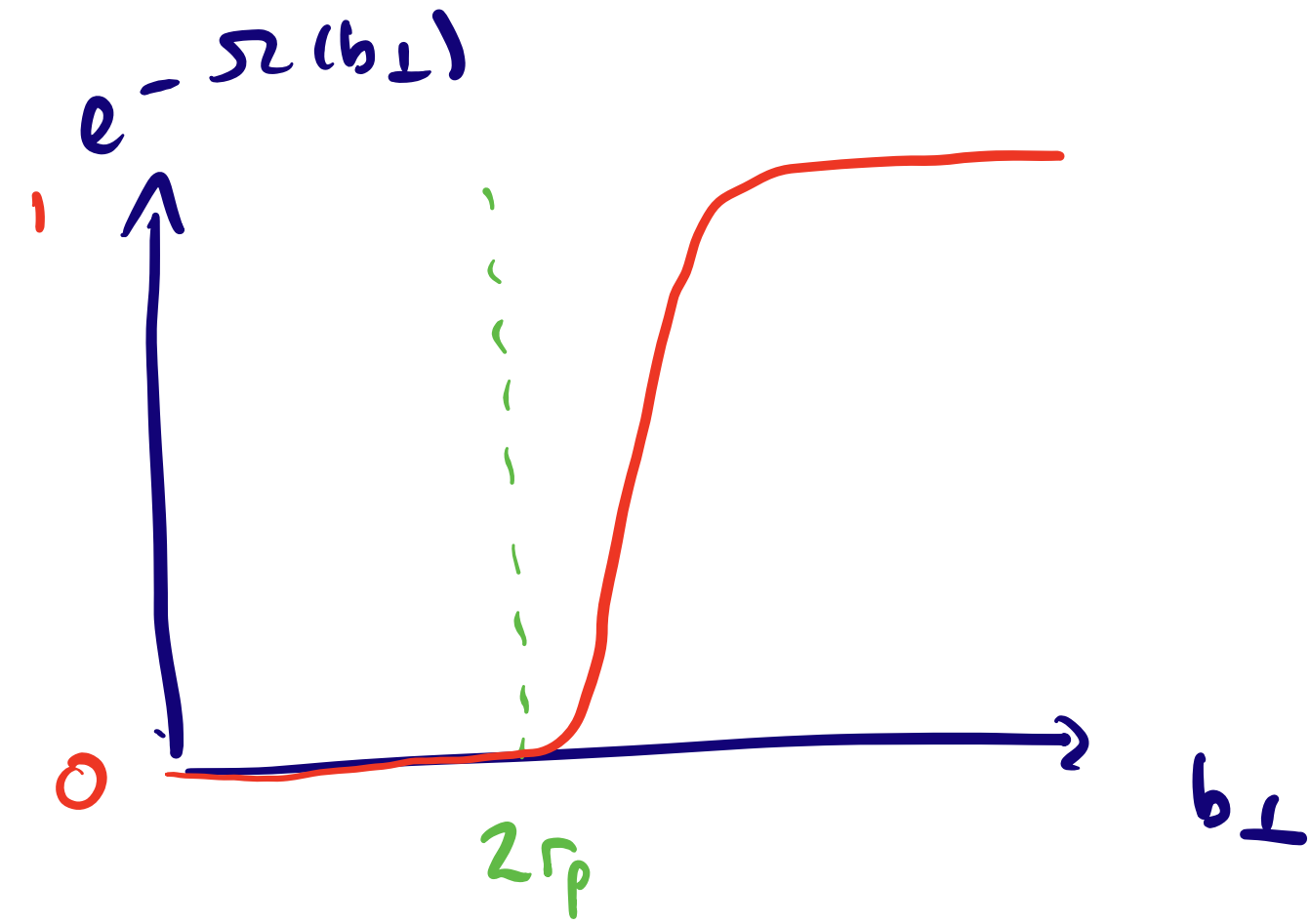
Survival Factor

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

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

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:

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

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!

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

Results

- 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.

- (Differential) cross section can be written as:

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

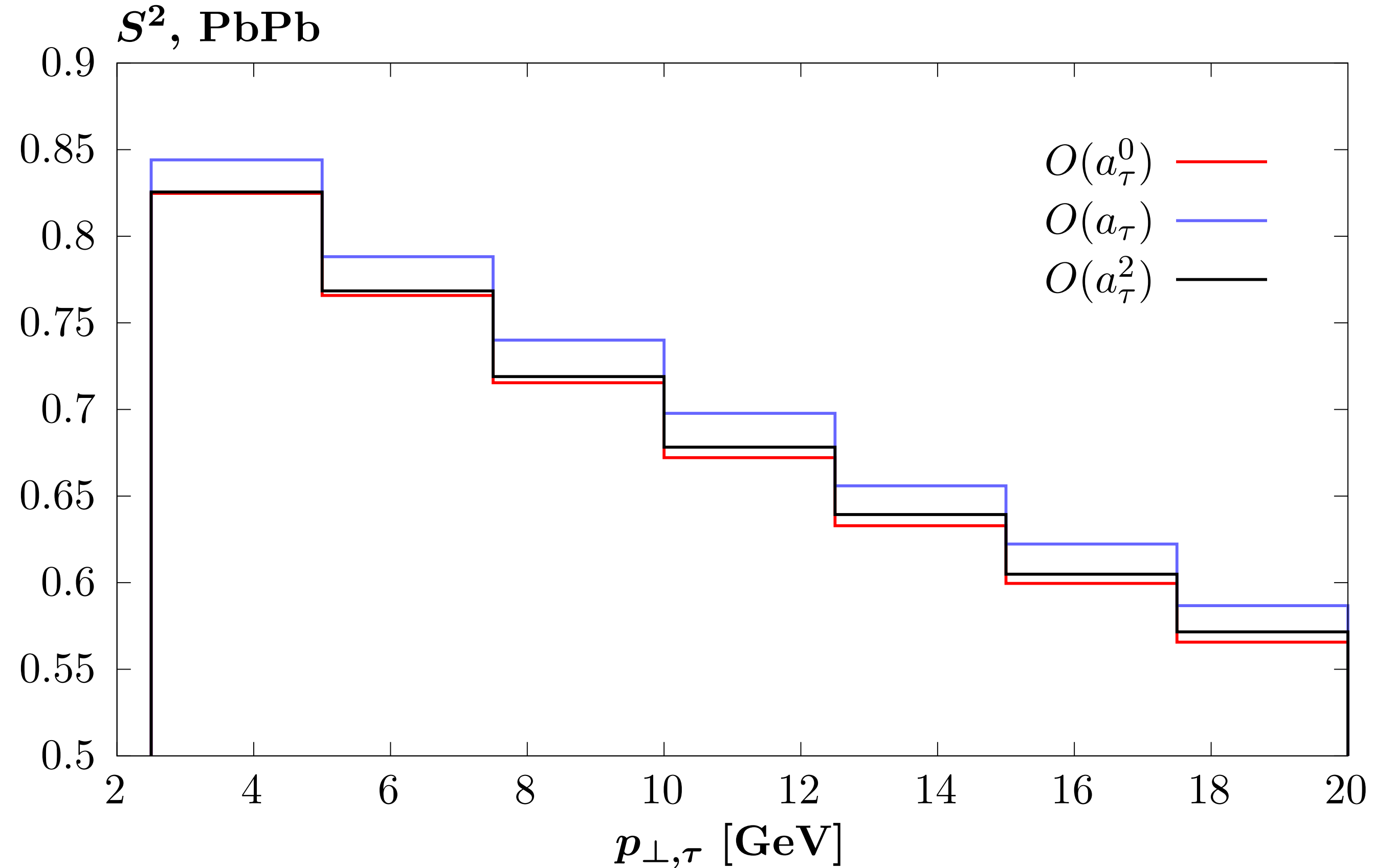
$d_\tau = 0$ for simplicity here

- Each individual term $d\sigma_i$ can be evaluated in SC independent of particular value 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.
- All **preliminary**! Start with PbPb case...

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

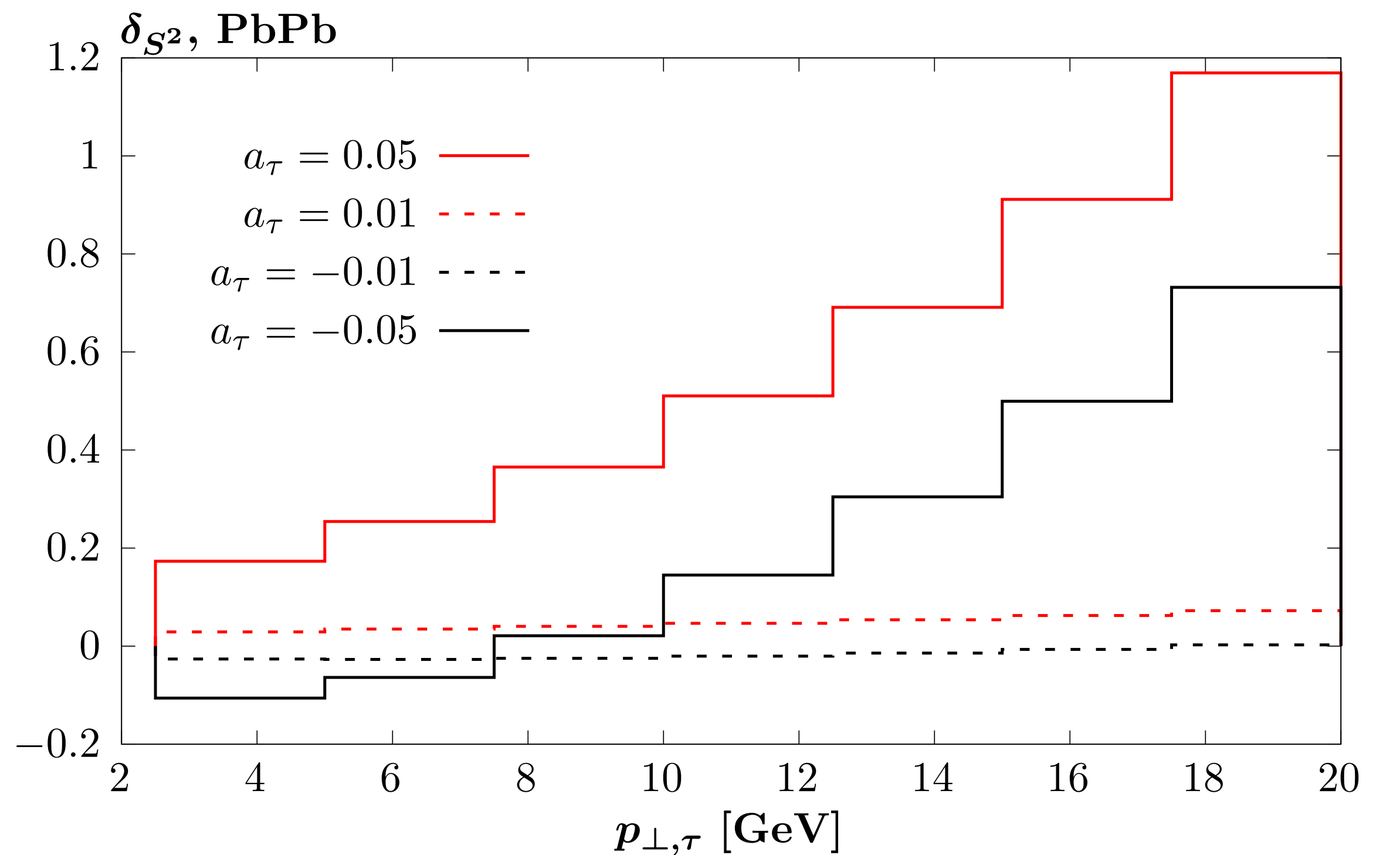
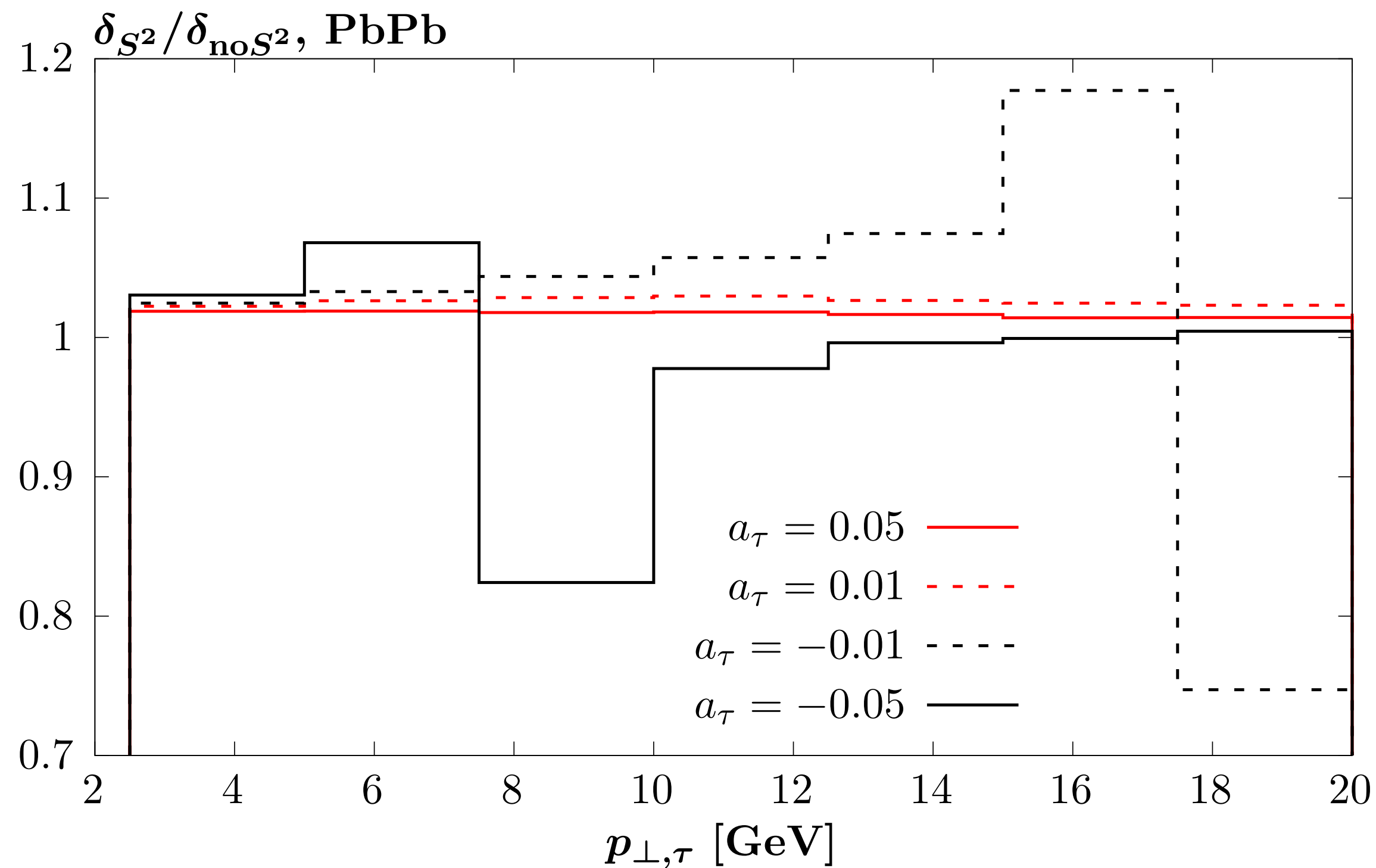
PbPb

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



- 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 difference 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**.

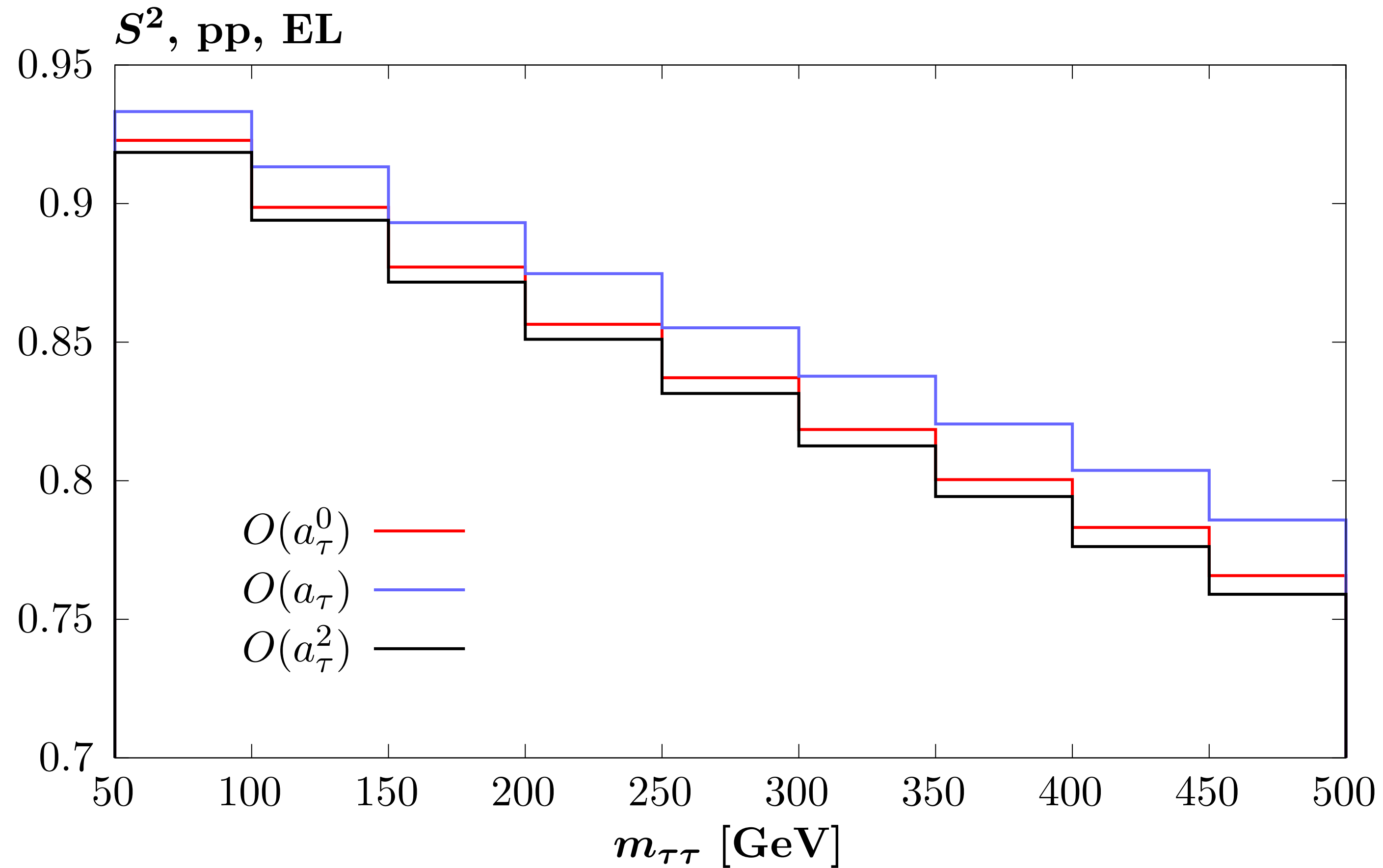
- Suggests impact will be small. To check, consider cross section modification:
$$\delta = \frac{1}{d\sigma_0} \sum_{i=1}^4 (a_\tau)^i d\sigma_i ,$$
- Plot ratio including S^2 to that without to gauge impact of full treatment. Also shown is absolute modifications as guide of size of corrections.
- Very roughly $\delta_{S^2}/\delta_{\text{no } S^2} \sim$ fractional change will induce in extracted a_τ (limit on it). This is indeed small - at percent level.



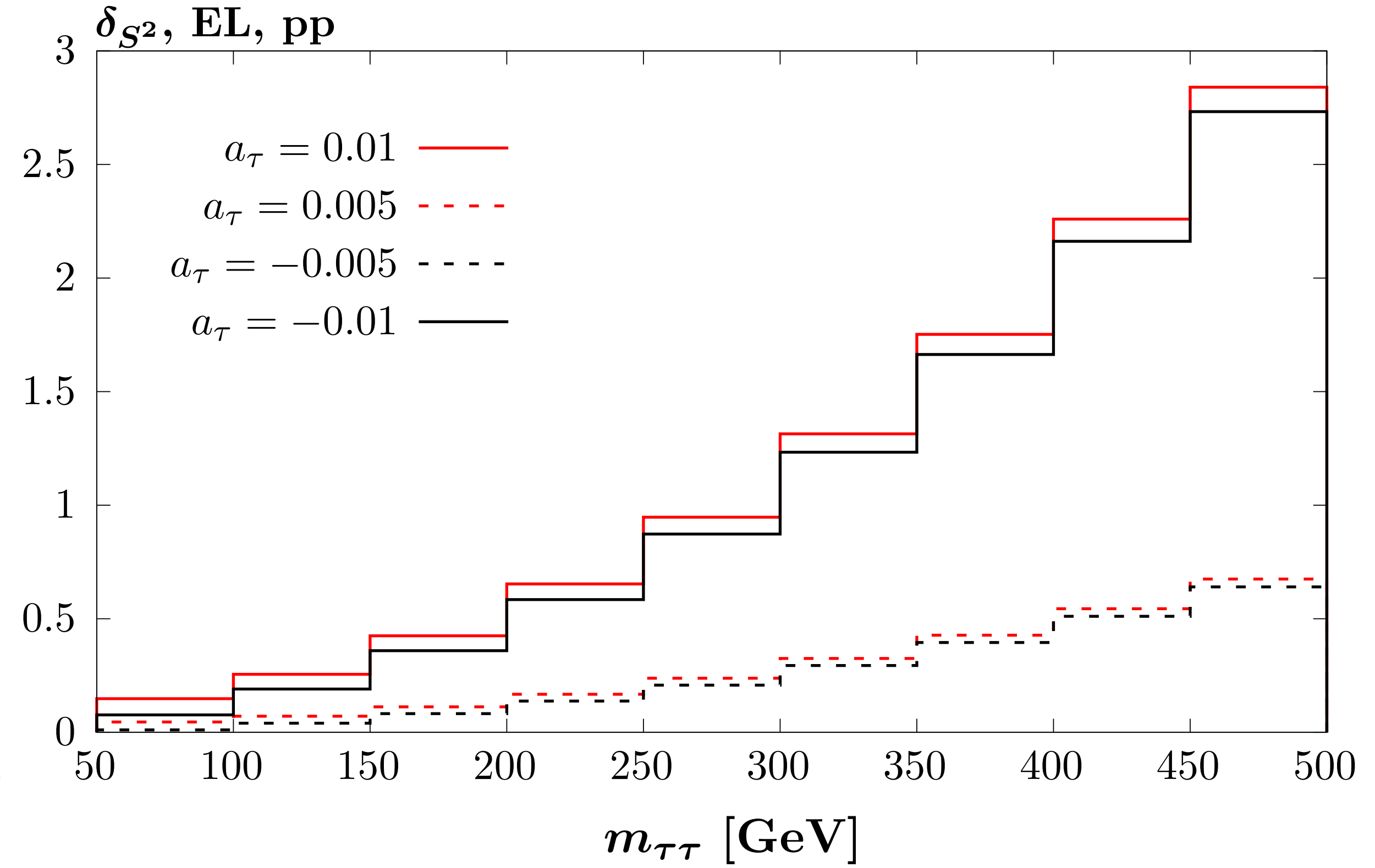
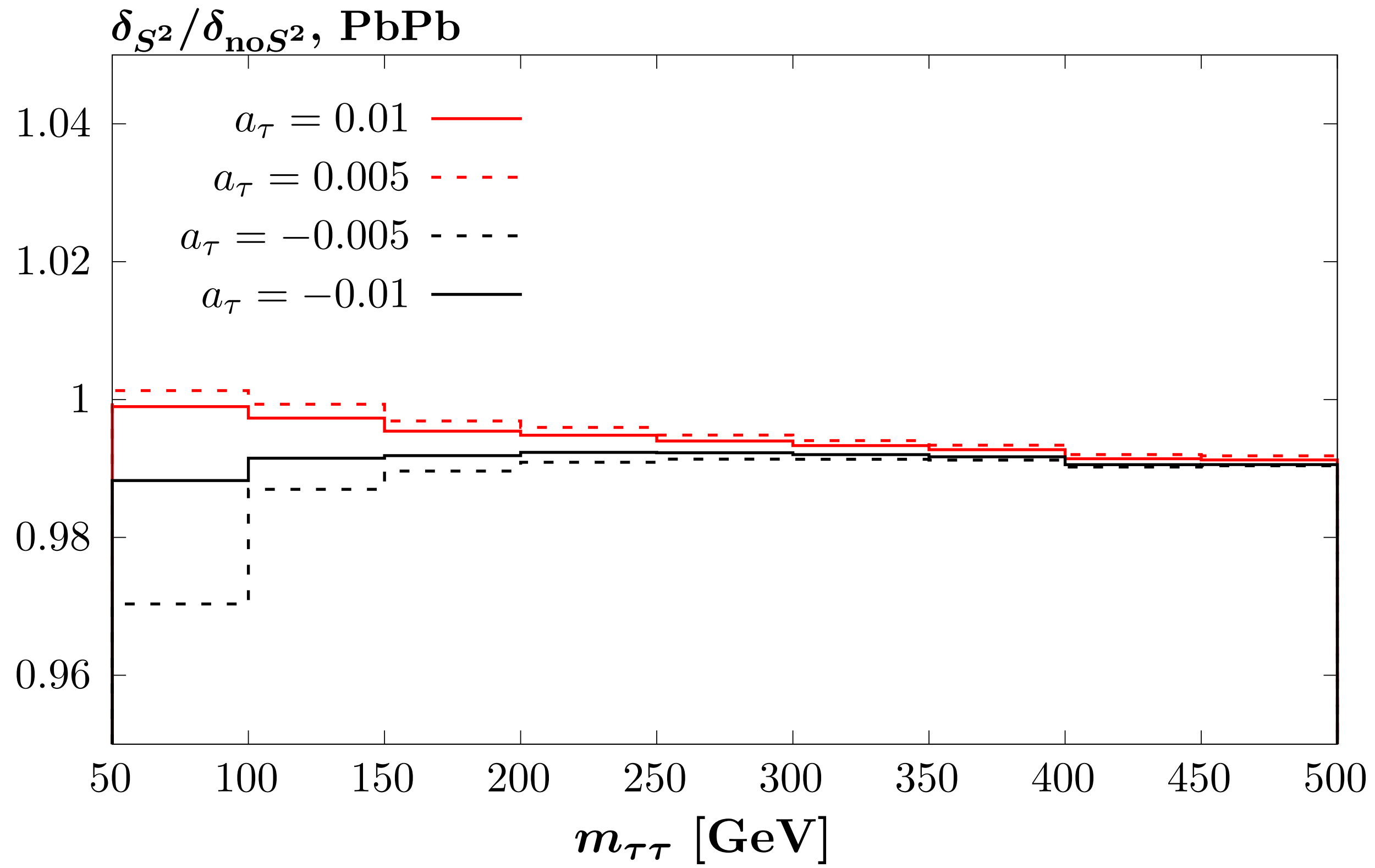
$$V_{\tau\tau\gamma}^\mu = ie\gamma^\mu - \left[\delta a_\tau \frac{e}{2m_\tau} + i\delta d_\tau \gamma_5 \right] \sigma^{\mu\nu} q_\nu ,$$

pp

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



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



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

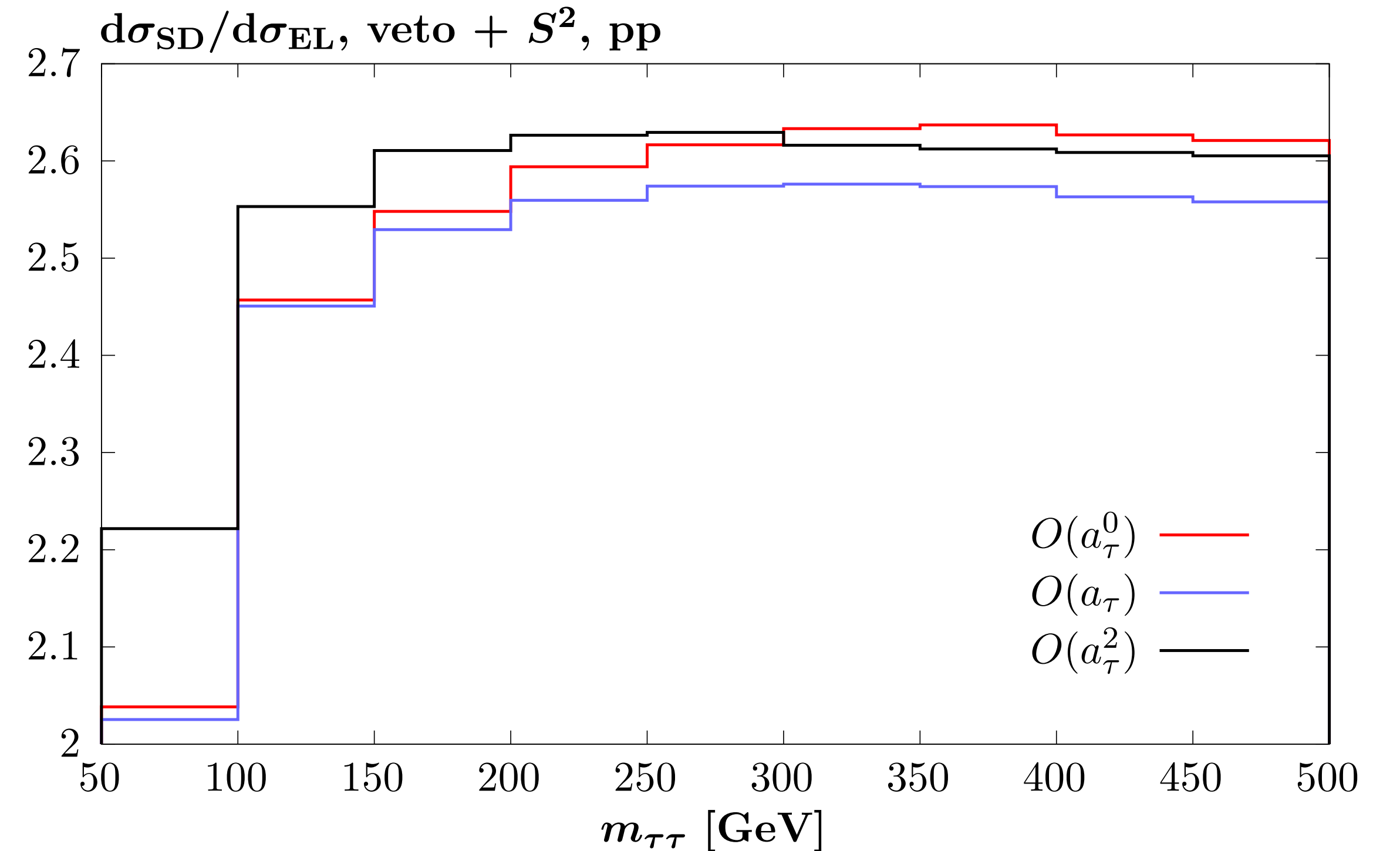
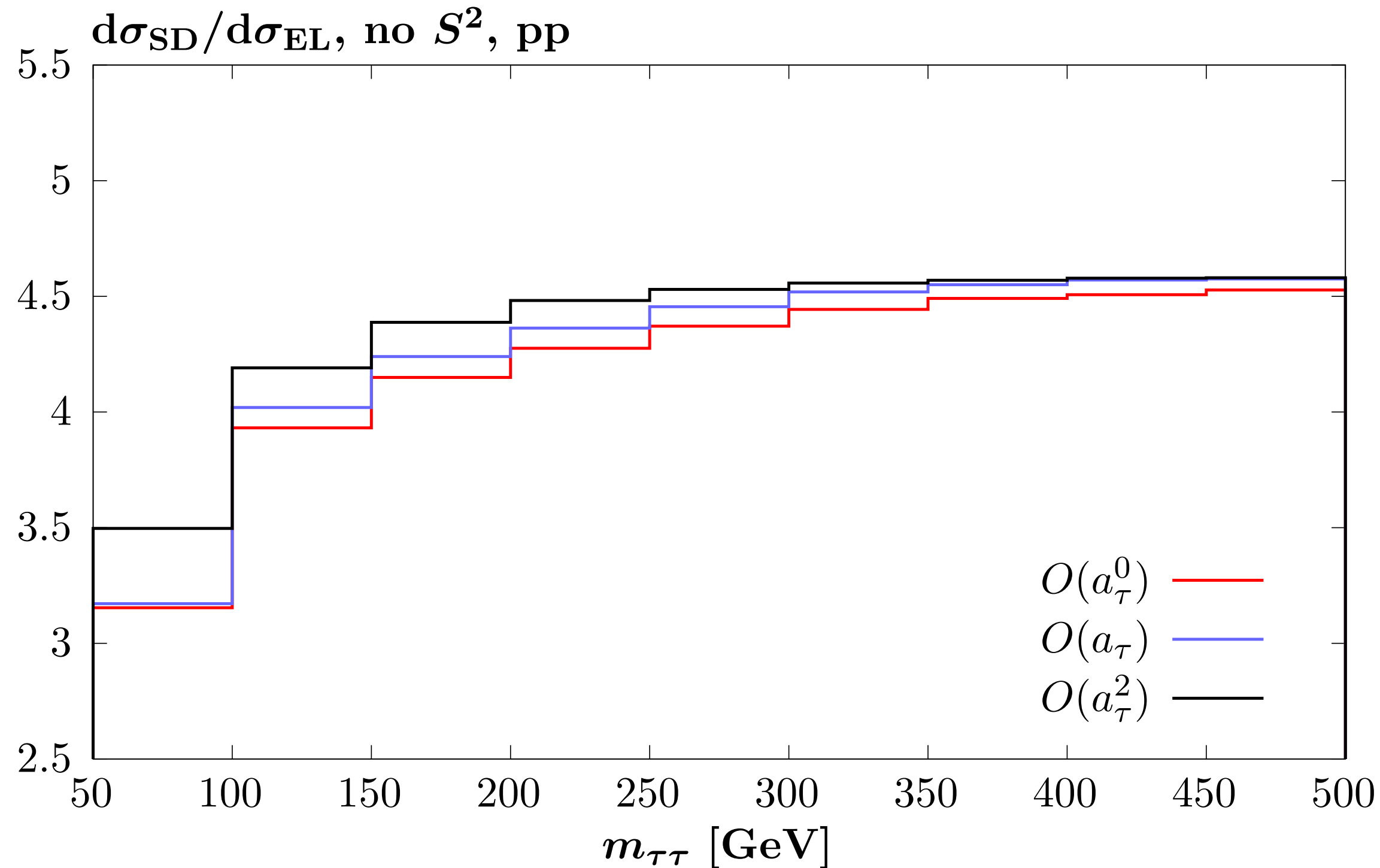
pp - dissociation

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

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

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

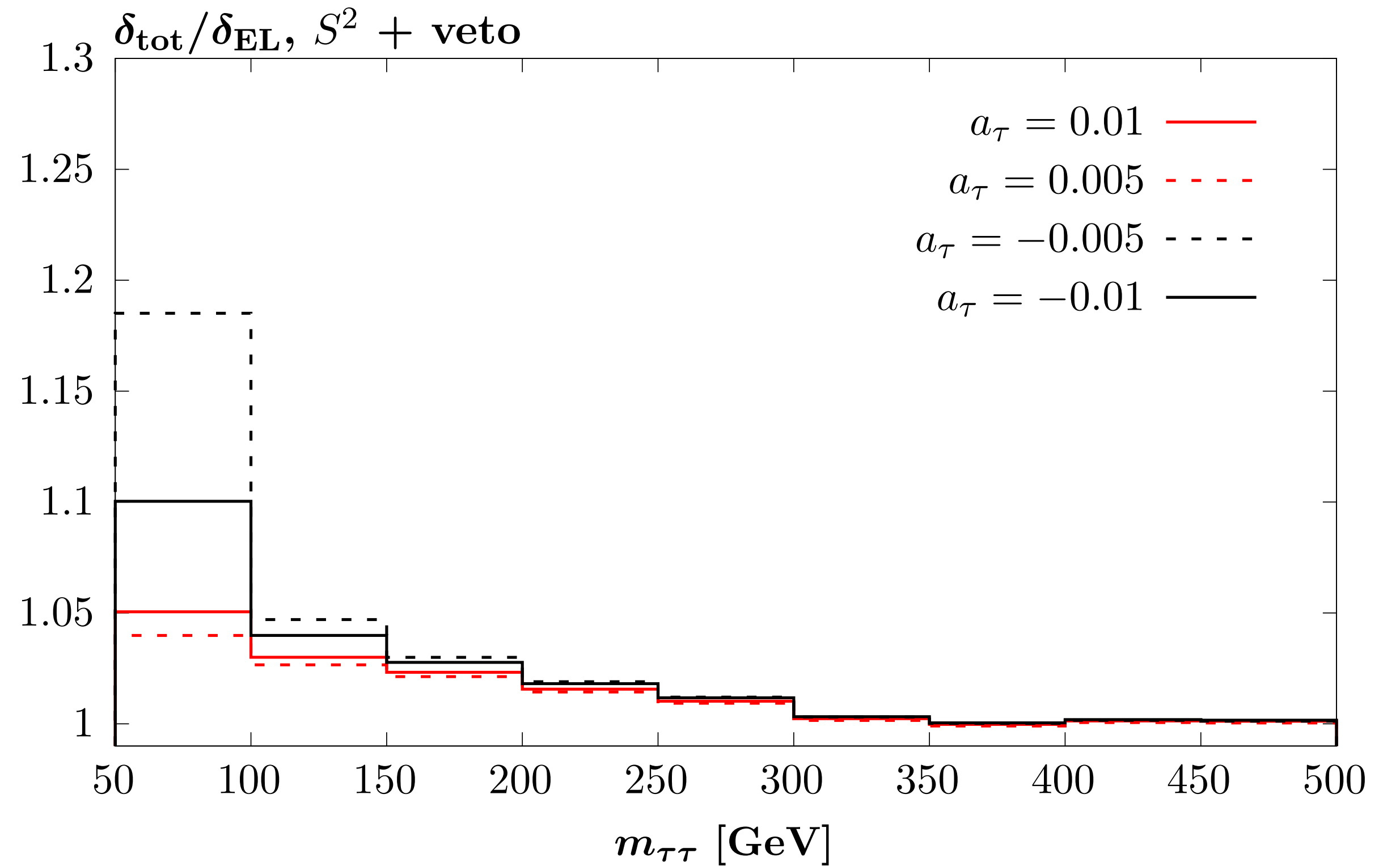
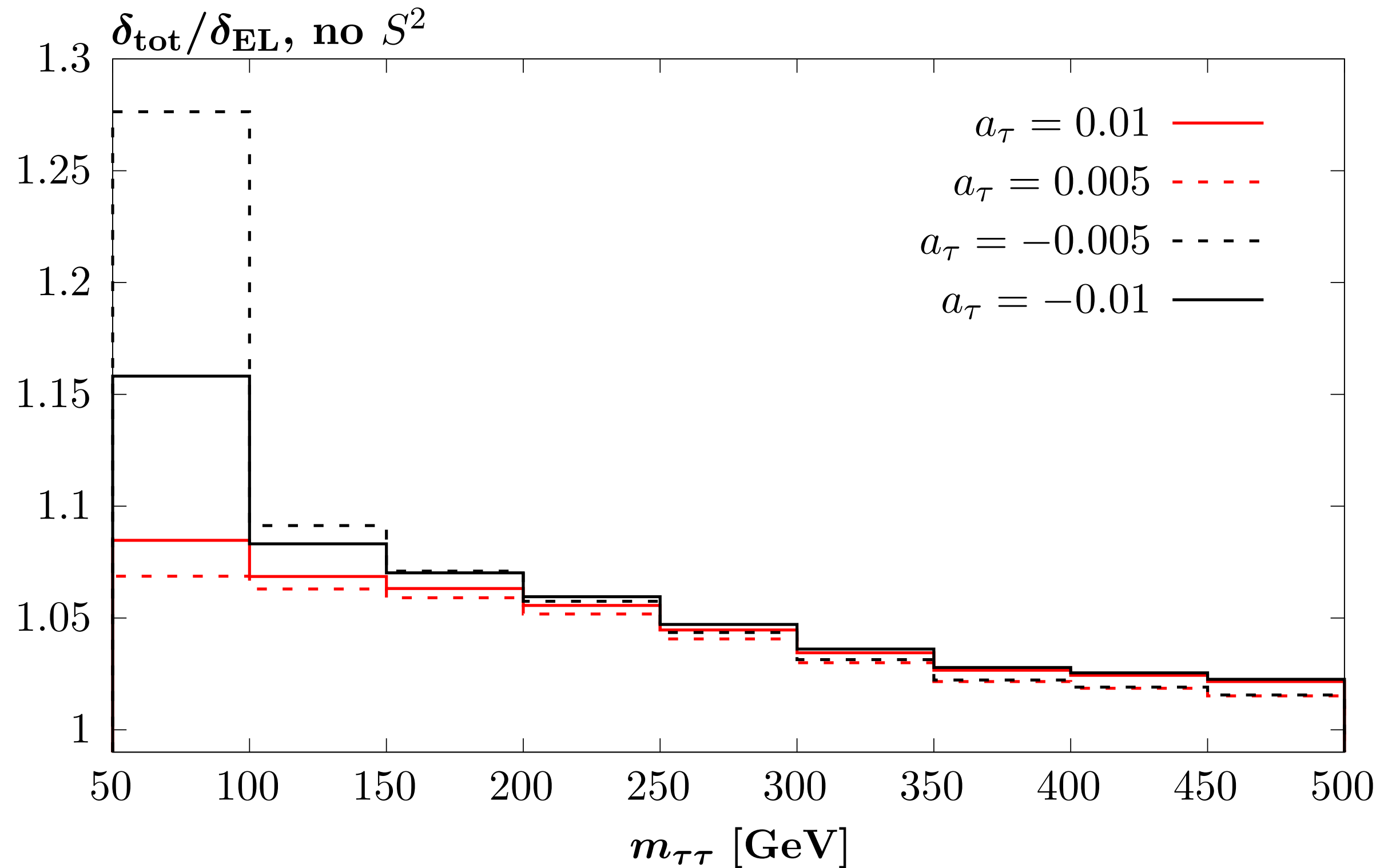
- Now plot ratio of dissociative cross section to EL, with and without veto (latter relevant in end!).



- 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 $Q^2 \sim$ removed).

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

- 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.



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.

The screenshot displays the GitHub repository for SuperChic. At the top, it shows the repository name 'SuperChic' as public, with options to unpin, unwatch (3), fork (3), and star (2). Below this, the main branch is selected, showing 58 branches and 0 tags. A search bar and 'Add file' and 'Code' buttons are visible. The commit history table shows the following entries:

Commit	Message	Time
LuclanHL updated manual (#215) ✓	75952fd · 5 days ago	292 Commits
.github/workflows	Add more Fortran compilers to CI (#202)	last week
Cards	Add existing project files to Git	3 months ago
bin	Update input.DAT	3 months ago
cmake/Modules	Reintroduce findAPFEL for now (#201)	last week
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ChangeLog	Improvement of documentation (#195)	last month
README.md	Update README.md to add installation alternatives. (#213)	5 days ago

On the right side, the 'About' section describes SuperChic as a Monte Carlo event generator for central exclusive production, with a README, GPL-3.0 license, and 2 stars. The 'Releases' section indicates no releases are published. The 'Packages' section also shows no packages published. The 'Contributors' section lists 2 contributors, including andriish.