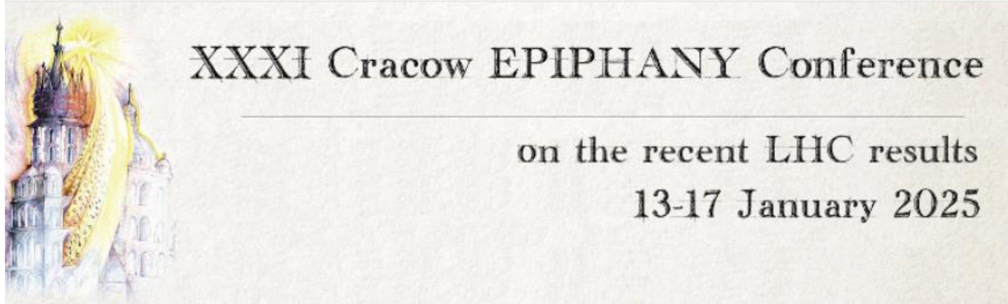


On the prospects of ‘CEP’ studies at the LHC

(selected topics)

Durham University

V.A. Khoze (IPPP, Durham)

main aims: to illustrate the "diversity and inclusion" of the ‘CEP’ program and to address the possibilities for the future.

Outline

- **Motivation** (why are we interested in CEP processes?)
  CEP and Large RAP GAPS.
- **QCD-induced CEP mechanism.**
- **Gluon –gluon vs photon-photon fusion.**
- **Life, death and “resurrection” of “**
- **CEP as a spin-parity analyse**
- Dijet CEP as a ‘g
- **Higher precision constraints on the tau g – 2 photon–initiated production**
- **Summary and Outlook**

With a bit of personal flavour

$$pp \rightarrow p^{(*)} + X + p^{(*)}$$

LRGs caused by Pomeron, photon (W,Z) or Odderon exchanges

Why is it interesting?

- Clean:
  - Experimentally clean signal: low multiplicity ($\longrightarrow$ low background) process,* not typically seen in hadronic collisions.
  - Theoretically modeling such exclusive processes requires novel application of pQCD, quite different to inclusive case.
- Quantum number selection:
  - Demanding exclusivity strongly selects certain quantum numbers for produced object - the '$J_z^{PC} = 0^{++}$' selection rule .
- Proton tagging:
  - Outgoing protons can be measured by tagging detectors installed at CMS (CT-PPS) and ATLAS (AFP). Handle to select events and provides additional event information (missing mass/proton correlations).

(TOTEM/ALFA)

No plans for high $\beta*$ runs in 2025-2026,
But a lot of already accumulated data in 2018

$\longrightarrow$ Clean production environment and selection rules provide potentially unique handle on QCD physics, but also BSM objects. Threshold scan.

"η_t" enhancement in the tt threshold region, KMR-2000

Measuring CEP

- Two methods to select **'exclusive'** events:

★ **Proton tagging:** $pp \to p + X + p$

(Maciej Trzebinski)

AFP/PPS

- Dedicated detectors close to beam line and ~200m from IP.
- With timing $\longrightarrow$ can select CEP during regular HL running.

$$pp \to p^{(*)} + X + p^{(*)}$$

(LHC runs 1,2,3)

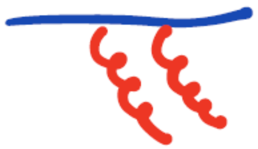
★ **Gap vetoing:** no activity between system and beam directions. More suitable for low lumi/pile-up (possible at high pile up with vertex vetoes).

- No activity between system and beam directions.
- More suitable for low lumi/pile-up: ALICE prospects.

(ALICE-double Gap trigger)

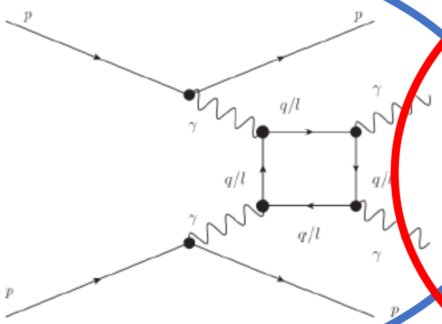
What can generate CEP?

- Generated by t-channel exchange with no colour flow - can occur in pure QED and QCD interaction:



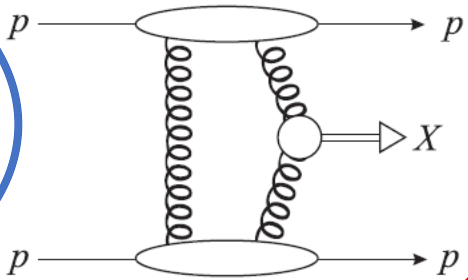
- Combination of these leads to three principle classes of process:

C-even, Couples to photons



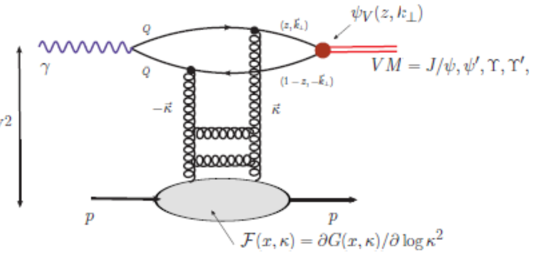
Photon-induced

C-even, couples to gluons

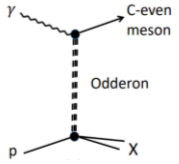


QCD-induced

C-odd, couples to photons + gluons



Photoproduction

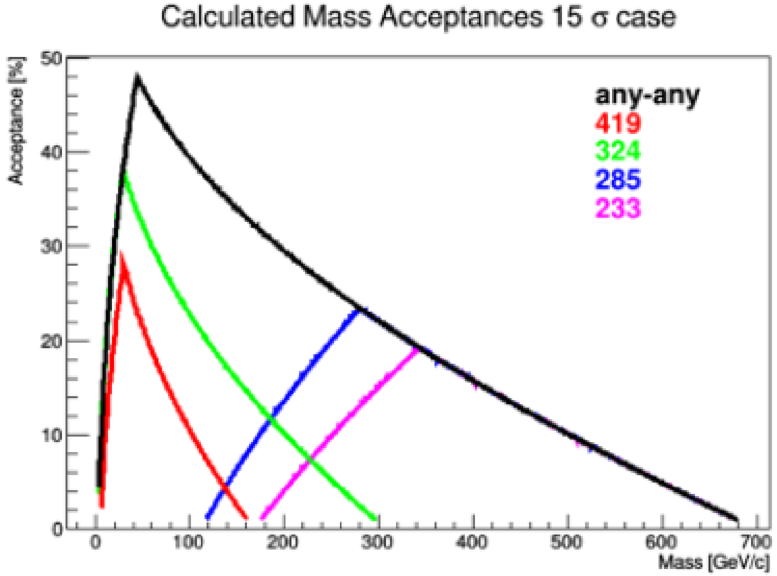


Proton Tagging at AFP & PPS

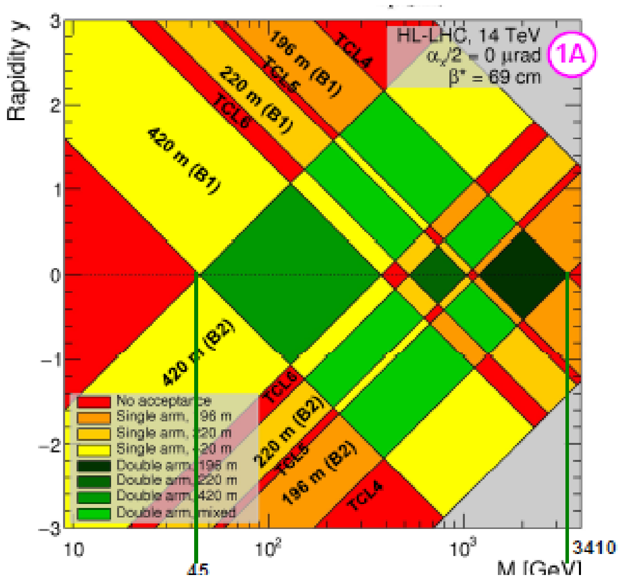
(Maciej Trzebinski)

- Range of detector positions, from ~ 200 m (higher mass $M_X \gtrsim 300\,\mathrm{GeV}$) to ~ 400 m (lower mass $M_X \gtrsim 20-50\,\mathrm{GeV}$) considered.
- Physics possibilities driven by these: exciting potential to probe **wide range** of **masses**, from low to high.

ATLAS



CMS (CT-PPS)



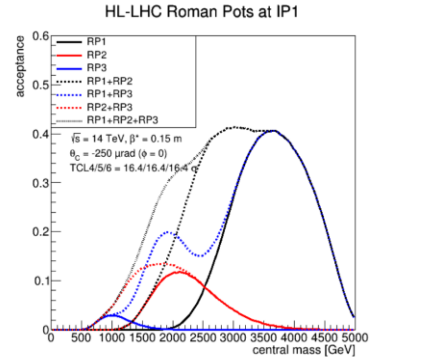


Figure 1: Studies for HL-LHC: mass acceptance for considered sets of stations around ATLAS collision point. See text for details.

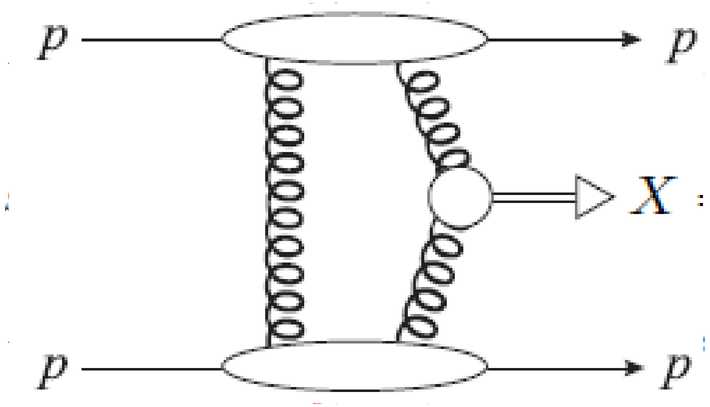
- Standard HL runs. With precision tracking and timing detectors.

approximately $0.02 < \xi < 0.1$ (0.02-0.15)

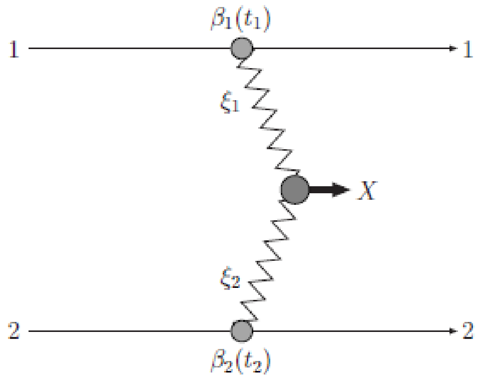
QCD-Induced CEP

KMR-97-01

- Dominant mechanism for states that couple via strong interaction. How do we model it? Answer depends on scale of production:
  - For sufficiently large scale (~ object mass M_X), apply **perturbative** '**Durham**' model.
  - Mediated via colour-singlet gg exchange.



  - At lower scales (~ object mass M_X) pQCD description will break down.
  - Diffractive, so can apply well established tools of Regge theory **Double Pomeron Exchange** (**DPE**).



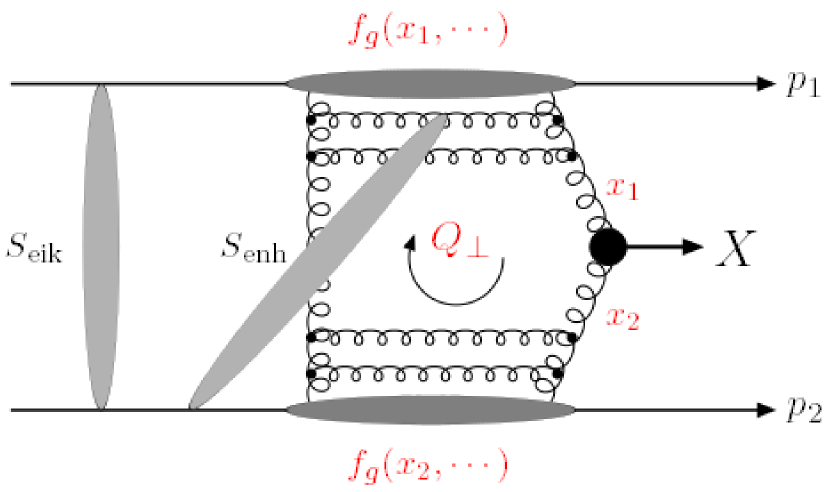
- Exactly where transition from DPE to pQCD picture occurs is open question. **Glueballs** ($M_G \sim 1 - 2\,\mathrm{GeV}$) - expect to be in **DPE regime**.

Model' of central exclusive production

KMR-1997-2001

- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons.
- The use of pQCD is justified by the presence of a hard scale $\sim M_X/2$. This ensures an infrared stable result via the Sudakov factor: the probability of no additional perturbative emission from the hard process.

- The possibility of additional soft rescatterings filling the rapidity gaps is encoded in the 'eikonal' and 'enhanced' survival factors, S^2_{eik} and S^2_{enh}.
- In the limit that the outgoing protons scatter at zero angle, the centrally produced state X must have $J_z^P = 0^+$ quantum numbers.



$1 > S^2_{\text{enh}} \gg S^2_{\text{elk}}$

Survival factor

- Survival factor, $S^2_{\rm eik}$: probability of no additional soft proton-proton interactions, spoiling exclusivity of final-state.

- Not a constant: depends sensitively on the outgoing proton $\mathbf{p}_\perp$ vectors. Physically- survival probability will depend on impact parameter of colliding protons. Further apart $\longrightarrow$ less interaction, and $S^2_{\rm eik} \to 1$.
  b_t and $p_\perp$: Fourier conjugates.

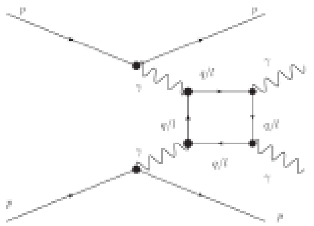
Process dependence

Fully differential implementation of soft survival factor – **SuperChic 2 -5** MCs

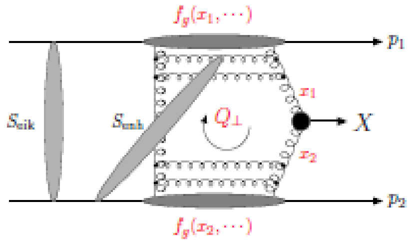
for pp, pZ, and ZZ scattering

$\gamma\gamma$ vs. gg collisions at high mass

- Naively, $\alpha_S \gg \alpha$ and so expect gg to dominate (where possible).



vs.



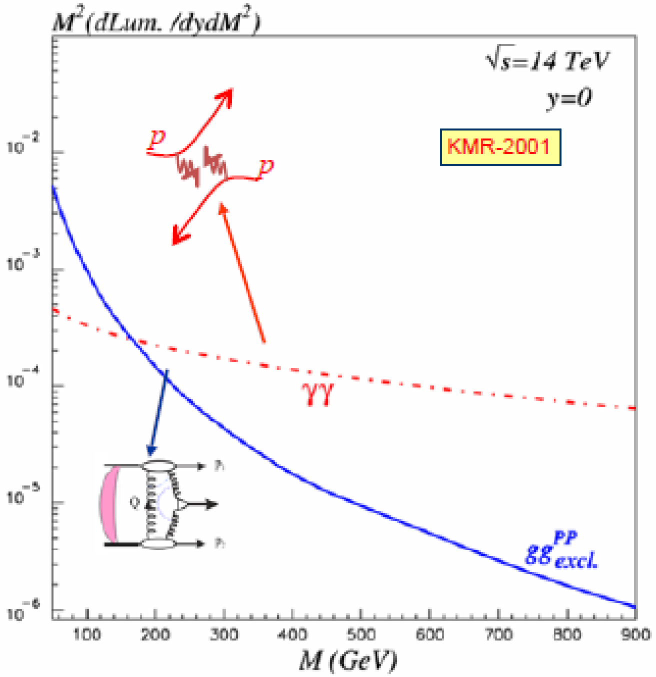
$\sigma(\gamma\gamma \to SMH) \approx 0.1 fb$

$\sigma(PP -> SMH) \approx 3 fb$

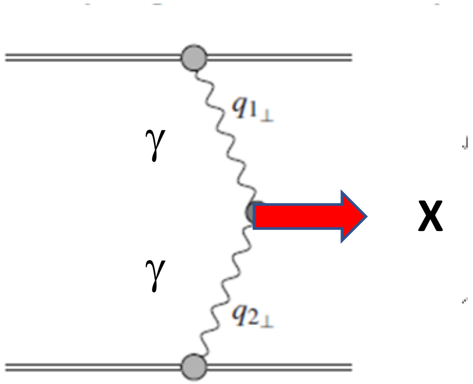
$\alpha_S^2/8 \to \alpha^2$

QCD 'radiation damage' in action

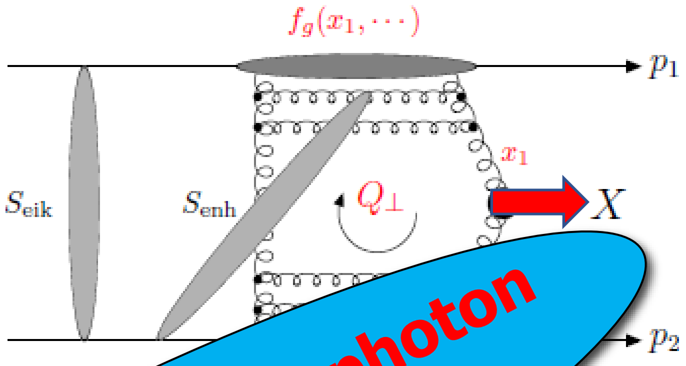
- But QCD enhancement can also be weakness: exclusive event $\Rightarrow$ no additional gluon radiation in final state.
- As system mass M_X increases, phase space for extra gluon emission $\uparrow$ and $\sigma \downarrow$. Gluons like to radiate!
- Expect cross over where $\gamma\gamma$ collisions dominate as $M_X \uparrow$ (all thing equal).
- In $\gamma\gamma$ vs. gg luminosities, occurs before AFP acceptance, $M_X \sim 200$ GeV . More precisely expect α from $\hat{\sigma}$, so moves to higher M_X .



In addition - S^2 much lower for $\gamma\gamma$ and suppression from $1/N_c^2$ for gg.



VS.



The LHC is the high energy photon collider

- Naively expect strong interacti… α.
- However QCD enhance… …akness: exclusive event requires no ex… …to final state. Requires introduction of S… …ng factor:

'Large' Pomeron size in the production of the small size objects.

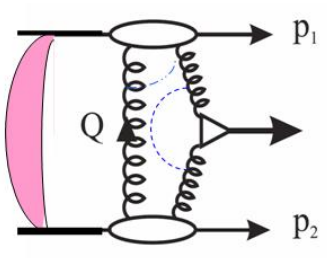
$$T_g(Q_\perp^2,\mu^2) = \exp\left(-\int_{Q_\perp^2}^{\mu^2} \frac{dk_\perp^2}{k_\perp^2}\frac{\alpha_s(k_\perp^2)}{2\pi}\int_0^{1-\Delta}\left[zP_{gg}(z)+\sum_q P_{qg}(z)\right]dz\right)$$

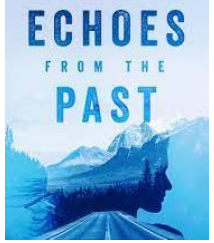
- Increasing M_X $\Rightarrow$ larger phase space for extra gluon emission stronger suppression in exclusive QCD cross section. Gluons like to radiate!

+ absorptive/rescattering effects- survival factor $S^2_{\rm soft}$

Life, Death and “Ressurection “ of ‘Diffractive Higgs’

The main advantages of CEP Higgs production





KMR-1997-2001

- Prospects for high-accuracy mass measurement (irrespectively of the decay mode).
- Quantum number filter/analyser.
  (0++ dominance; C,P-even)

- H ->bb opens up (Hbb Yukawa coupl.)

(gg)--,++ ⦸→ bb in LO ; NLO,NNLO, b- mass effects – controllable. M(+++-)=(M---+)=0

could open a way to measure H→cc (coplanarity.... cuts)

- For some **BSM** scenarios, **CEP may** become *a* **discovery channel**

'95 GeV anomaly'

- A handle on the overlap backgrounds- **F**ast **Ti**ming **D**etectors (10-20 ps timing or better).

✳ New leverage –proton momentum correlations (probes of QCD dynamics , CP- violation effects…)

Triple product correlation: $\vec{n}_0 \cdot (\vec{p}_{1\perp} \times \vec{p}_{2\perp}) \sim \sin\varphi\,,$

Integrated counting asymmetry (~10%)

$$A = \frac{\sigma(\varphi < \pi) - \sigma(\varphi > \pi)}{\sigma(\varphi < \pi) + \sigma(\varphi > \pi)}\,,$$

FP420 AND RESURRECTION OF 'DIFFRACTIVE HIGGS' (20 YEARS ON)

- searching for lower mass new objects in CEP

MANCHESTER 1824

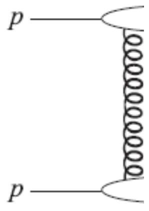
The University of Manchester

The FP420 R&D project (2004-2009)

- FP420 was a joint R&D collaboration between CMS and ATLAS to dev
  proton detector system to tag outgoing protons.
- Key questions:
  - Can suitable forward detectors be placed close to the LHC beam
  - What is the physics potential of these detectors?
  - Will they cover an interesting region of Higgs mass?
- Final report is available at JINST 4:T10001,2009 [arXiv:0806.0302]

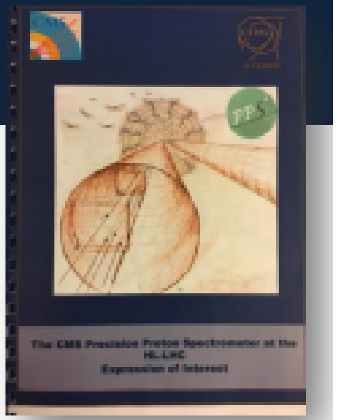
❖ QCD-initiated production: potential for e.g. exclusi
studies analysed (though there are more).

- ★ **Jets**: gg colour-singlet initial state
  range of unique QCD studies.
- ★ **Higgs**: completely unseen mode,
  Higgs properties (CP, couplings)
  via independent method.



PPS/PPS2- new proposals

PPS2 @ HL-LHC



- Since after LS3 the whole beamline will be rearranged, a new spectrometer design is proposed in the Expression of Interest

Run 2+3 design: ξ acceptance translated to mass range between 350 GeV and 2 TeV

CMS-NOTE-2020-008, arxiv:2103.02752

- New proposal with extended mass range:

  133 GeV – 2.7 TeV for the first 3 stations ($0.0142 < \xi < 0.1967$)

  43 GeV – 2.7 TeV for 4 stations ($0.00325 < \xi < 0.1967$)

Staged installation

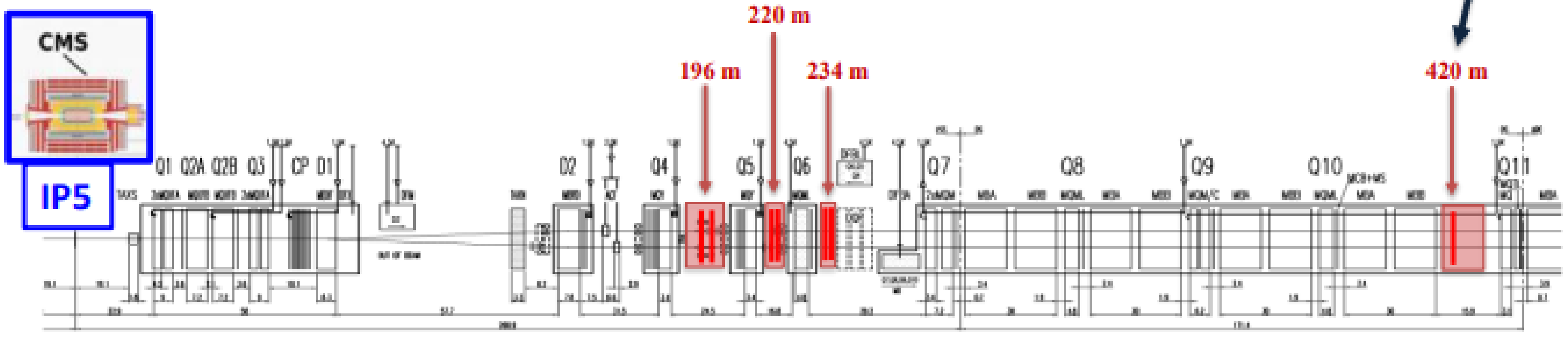


Figure 13: Layout of Long Straight Section LSS5 (Sector 5-6) at HL-LHC [63].

CEP AS A SPIN-PARITY ANALYZER

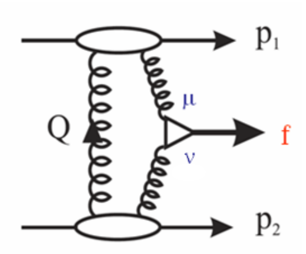
$$T = \pi^2 \int \frac{d^2 Q_\perp \overline{\mathcal{M}}}{Q_\perp^2 (Q_\perp - p_{1_\perp})^2 (Q_\perp + p_{2_\perp})^2} f_g(x_1, x_1', Q_1^2, \mu_F^2; t_1) f_g(x_2, x_2', Q_2^2, \mu_F^2; t_2) \,,$$

$$q_{1_\perp}^i q_{2_\perp}^j \mathcal{M}_{ij} = \begin{cases} -\frac{1}{2}(\mathbf{q}_{1_\perp} \cdot \mathbf{q}_{2_\perp})(\mathcal{M}_{++} + \mathcal{M}_{--}) & (J_z^P = 0^+) \\ -\frac{i}{2}|(\mathbf{q}_{1_\perp} \times \mathbf{q}_{2_\perp})|(\mathcal{M}_{++} - \mathcal{M}_{--}) & (J_z^P = 0^-) \\ +\frac{1}{2}((q_{1_\perp}^x q_{2_\perp}^x - q_{1_\perp}^y q_{2_\perp}^y) + i(q_{1_\perp}^x q_{2_\perp}^y + q_{1_\perp}^y q_{2_\perp}^x))\mathcal{M}_{-+} & (J_z^P = +2^+) \\ +\frac{1}{2}((q_{1_\perp}^x q_{2_\perp}^x - q_{1_\perp}^y q_{2_\perp}^y) - i(q_{1_\perp}^x q_{2_\perp}^y + q_{1_\perp}^y q_{2_\perp}^x))\mathcal{M}_{+-} & (J_z^P = -2^+) \end{cases}$$

$$p_{i\perp} = 0 \Rightarrow J_z = 0$$

$$|V_0|^2 : |V_1|^2 : |V_2|^2 \sim 1 : \frac{\langle \mathbf{p}_\perp^2 \rangle}{M_\chi^2} : \frac{\langle \mathbf{p}_\perp^2 \rangle^2}{\langle \mathbf{Q}_\perp^2 \rangle^2}$$

(HKRS-2010)



$M_{\mu\nu}(gg^{PP}) \sim (p_{t,1} - Q_t)_\mu (p_{t,2} +$

after $(\bar{Q}_t)$ angular integration at $p_{t,i} = 0$ → $-\delta_{\mu\nu}^{(2)} Q_t^2 / 2$

in terms of helicity amplitudes . $1/2\{(++;f)+(--;f)\}$ → Jz=0, P-even state

at non-zero $p_{t,i}$ - an admixture of Jz=2 → $\frac{(2p_{1,t}p_{2,t})^2}{Q_t^4}$

Important consequences for $H \to b\bar{b}$.

Symmetry properties of the $\gamma(\lambda_1, k_1) + \gamma(\lambda_2, k_2) \to q(h, p) + \overline{q}(\overline{h}, \overline{p})$. amplitude (FKM-97)

$J_Z = 0$ (nullifies in the massless limit) → (++,+-) (--,+-) (++,-+) (--,-+)

in terms of the **MHV rules** the only nonzero amplitudes gg→qq

(S .Parke, T.Taylor (1986))

(+ - ; + -) J_z=2, **HCA**

(-+ : -+ /+-)

'An Amplitude for *n* Gluon Scattering'

$$\frac{|T(|J_z|=2)|^2}{|T(J_z=0)|^2} \sim \frac{\langle p_\perp^2 \rangle^2}{\langle Q_\perp^2 \rangle^2}$$

- In Regge theory there does not exist a simple closed form for the χ_2 case.
- Within the PT approach forward CEP of non-relativistic heavy 2++ quarkonium is strongly reduced because of the suppression of the 2 ++ → 2g transition for the Jz = 0 on-mass-shell two-gluon state

KMR-2001

- Note these will receive corrections of $O(p_\perp^2/\langle Q_\perp^2\rangle)$.
- These distributions are strongly affected by absorptive corrections, through their dependence on the proton distribution in impact parameter *b* space.
- Forward proton detection would allow a clear discrimination between the different *J* states.

Jz = 0 amplitude vanishes
for the γγ decay of the 2++ 3P2
positronium (Tumanov, 53;Alekseev, 58)

Glueball filter ?

Lattice results

J^{PC}	mass
0^{++}	1730 ± 80 MeV/c^2
2^{++}	2400 ± 120 MeV/c^2
0^{-+}	2590 ± 130 MeV/c^2

Eur.Phys.J.C 80 (2020) 11, 1077

χ_{c1} and χ_{c2}: general considerations

- General considerations tell us that χ_{c1} and χ_{c2} CEP rates are strongly suppressed:
  - χ_{c1}: Landau-Yang theorem forbids decay of a $J = 1$ particle into on-shell gluons.
  - χ_{c2}: Forbidden (in the non-relativistic quarkonium approximation) by $J_z = 0$ selection rule that operates for forward ($p_\perp$=0) outgoing protons. KMR-01 (A. Alekseev-1958-positronium)
- However the experimentally observed decay chain $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ strongly favours $\chi_{c(1,2)}$ production, with:

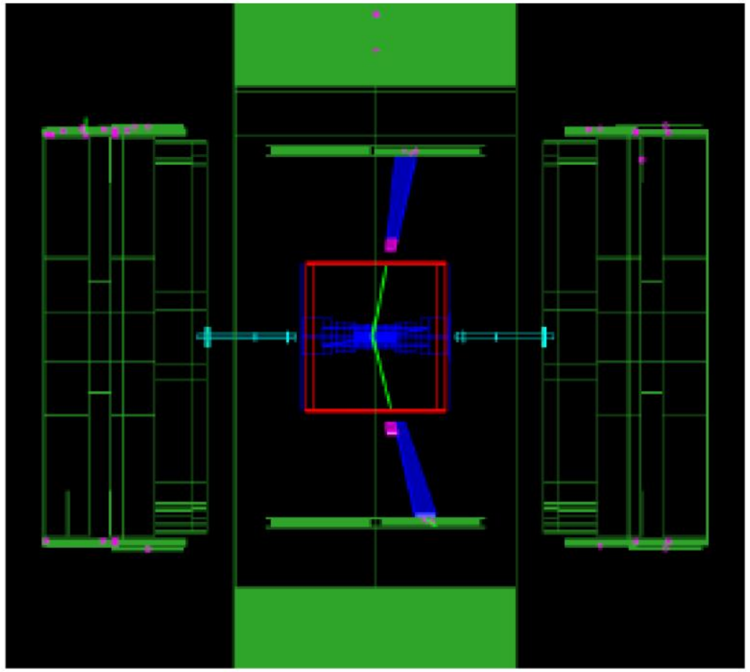
$$\mathrm{Br}(\chi_{c0} \to J/\psi\gamma) = 1.1\% \,,$$
$$\mathrm{Br}(\chi_{c1} \to J/\psi\gamma) = 34\% \,,$$
$$\mathrm{Br}(\chi_{c2} \to J/\psi\gamma) = 19\% \,.$$

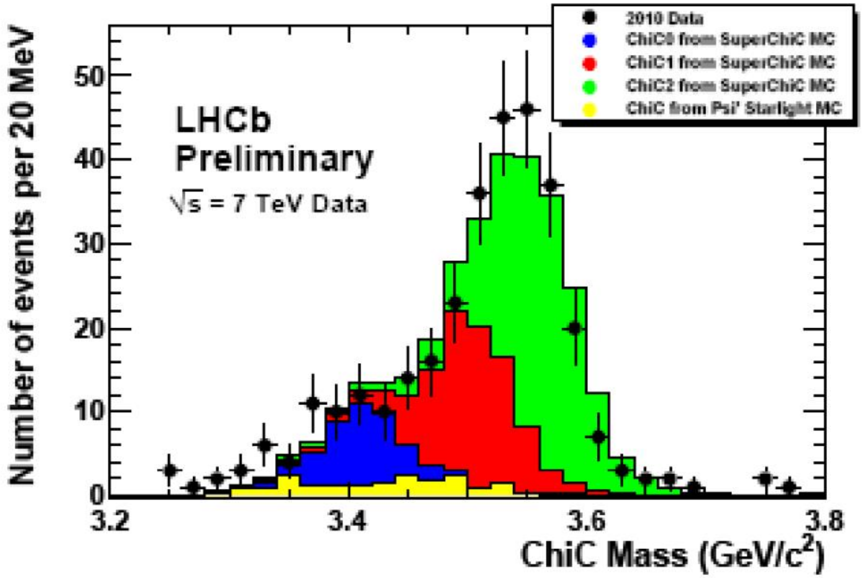
- We should therefore seriously consider the possibility of $\chi_{c(1,2)}$

❑ The effects of non-zero p_T (especially for 2^+). 

…and especially without proton detectors!

Data...





A wide range of central exclusive processes– $X = \mu^+\mu^-$, e^+e^- (QED), $\gamma\gamma$, jj, χ_c (CEP), J/ψ, $\psi(2S)$ (photoproduction)– have been observed by the CDF/D0 collaborations at the Tevatron, by selecting events with no additional activity in a large η range, and exclusive data at the LHC is being taken.

arXiv:0712.0604,0902.1271,1112.0858,1301.7084,CERN-LHCb-CONF-2011-022,CMS-PAS-FWD-11-004...

(in a good agreement with the Durham expectations)

χ_c CEP: data

- In arXiv:0902.1271 CDF reported 65 ± 10 signal χ_c events observed via the $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ decay channel. This corresponds to $\mathrm{d}\sigma(\chi_c)/\mathrm{d}y_\chi|_{y=0} = (76 \pm 14)\,\mathrm{nb}$, in good agreement with Durham prediction of ~ 60 nb.
- Recent LHCb data[3]: select 'exclusive' $\chi_c \to J/\psi\gamma$ events by vetoing on additional activity in given η range.
- LHCb see:

	$\frac{\sigma(pp\to pp(\mu^+\mu^-+\gamma))}{\mathrm{Br}(J/\psi\to\mu^+\mu^-)\mathrm{Br}(\chi_{cJ}\to J/\psi\gamma)}$ LHCb (nb)	SuperCHIC (nb)
χ_{c0}	13 ± 6.5	20
χ_{c1}	0.80 ± 0.35	0.49
χ_{c2}	2.4 ± 1.1	0.26

$\to$ See clear suppression in $\chi_{c(1,2)}$ states.

$\to$ Good data/theory agreement for $\chi_{c(0,1)}$ states (within quite large theory uncertainty), but a significant excess of χ_{c2} events above theory prediction for CEP.

[3] LHCb-CONF-2011-022

χ_b CEP

- Higher χ_b mass means cross section is more perturbative and so is bette test of theory, although rate is ~ 3 orders of magnitude smaller tha
- J assignment of χ_b states still experimentally undetermined: CEP shed light on this.
- Calculation exactly analogous to χ_c case

$$|V_{0+}|^2 : |V_{1+}|^2 : |V_{2+}|^2 \sim 1 : \frac{\langle \mathbf{p}_\perp^2 \rangle}{M_\chi^2} : \frac{\langle \mathbf{p}_\perp^2 \rangle^2}{\langle \mathbf{Q}_\perp^2 \rangle^2} \sim 1 : \frac{1}{400} : \frac{1}{36}$$

$\rightarrow$ Do not expect to see χ_{b1}, which is strongly suppressed by χ_b mass.

- Measurement of ratio of χ_b to $\gamma\gamma$ ($E_\perp = 5$ GeV) CEP rates would eliminate certain uncertainties (i.e. dependence on survival factors).
- Predictions for χ_b CEP via the $\Upsilon\gamma$ decay chain (at $y_\chi = 0$):

$\sqrt{s}$ (TeV)	1.96	7	10	14
$\frac{d\sigma}{dy_{\chi_b}}(pp \to pp(\Upsilon + \gamma))$ (pb)	0.60	0.75	0.78	0.79
$\frac{d\sigma(1^+)}{d\sigma(0^+)}$	0.050	0.055	0.055	0.059
$\frac{d\sigma(2^+)}{d\sigma(0^+)}$	0.13	0.14	0.14	0.14

Citation: S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)

$\chi_{b0}(1P)$ $I^G(J^{PC}) = 0^+(0^{++})$
J needs confirmation.

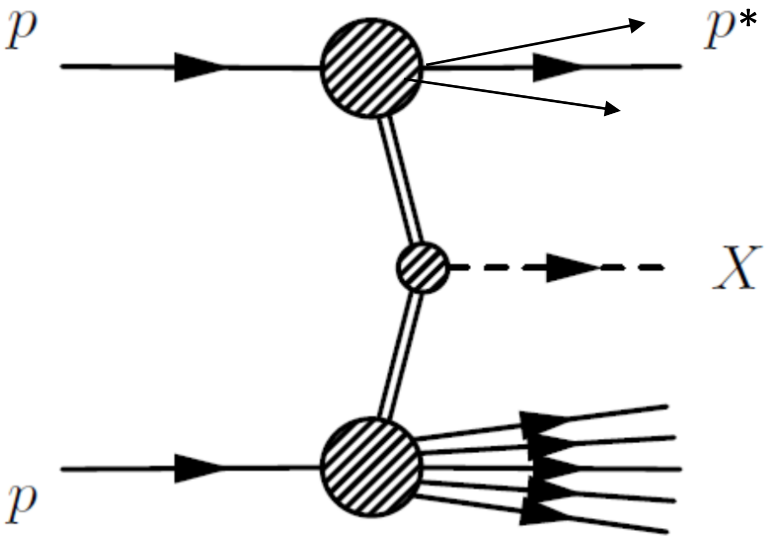
Observed in radiative decay of the $\Upsilon(2S)$, therefore $C = +$. Branching ratio requires E1 transition, M1 is strongly disfavored, therefore $P = +$.

Observation of diffractive exotic J/ψϕ resonances in *pp* collisions

arXiv:2407.14301

The first study of J/ψϕ production in diffractive processes in proton-proton collisions.

Possible production of exotic states



$\sqrt{s} = 13\,\mathrm{TeV}$

Currently Herschel not applied

Search for events with precisely four tracks

2 muons + 2 identified kaons

<u>Experimental strategy:</u> Selection of J/ψ(→μμ)ϕ(→KK) in low multiplicity events: Nb of VELO tracks must be 4

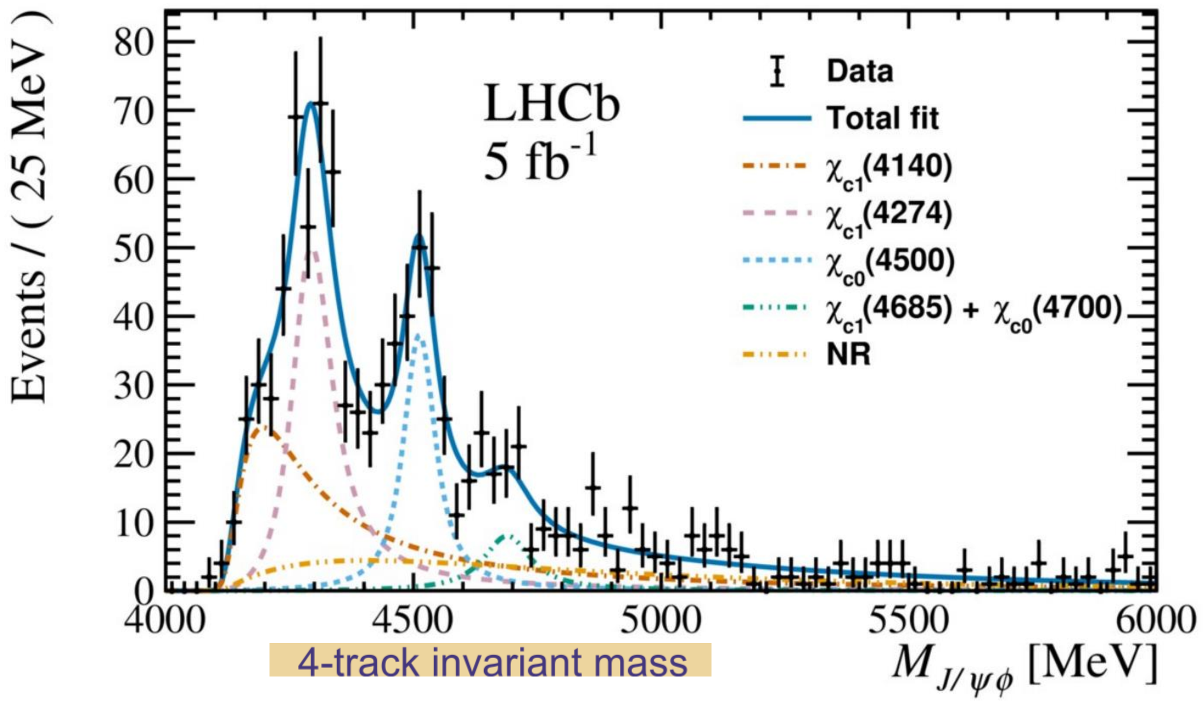
several resonant states observed previously only in $B^+ \to J/\psi\phi K^+$

989 $J/\psi\phi$ candidates

Observation of diffractive exotic J/ψϕ resonances in *pp* collisions

arXiv:2407.14301

After imposing the exclusivity requirement, a resonant structure appears



$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4140)} = (0.80 \pm 0.15 \pm 0.28)\,\text{pb},$$
$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4274)} = (0.73 \pm 0.08 \pm 0.17)\,\text{pb},$$
$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\rm eff}^{\chi_{c0}(4500)} = (0.42^{+0.09}_{-0.08} \pm 0.06)\,\text{pb},$$
$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06)\,\text{pb},$$
$$\sigma_{\rm NR} \times \mathcal{B}_{\rm eff}^{\rm NR} = (0.43^{+0.24}_{-0.18} \pm 0.20)\,\text{pb},$$

Fit performed with previously observed resonances in B decays.

amplitude analyses of $B^+ \to J/\psi\phi K^+$ decays

- Turn-on derived from events with more than four VELO tracks
- Non-resonant is modeled by an exponential function
- No interference assumed

The significance for the resonances $\chi_{c1}(4140)$, $\chi_{c1}(4274)$ and $\chi_{c0}(4500)$ are 2.4 σ, 4.3 σ and 5.5 σ.
Several clear resonant structures are observed well-described by resonant model
This is the first observation of X→J/ψϕ production in diffractive processes

A bit puzzling: strong 1^+ signal

For pure CEP within the PT (gg-fusion) picture- expect a factor of 100 suppression.

Ways out:

1. Huge difference in BR's ?

$$\mathcal{B}_{\rm eff}^{\chi_{c1}(4140)}\ ,\ \mathcal{B}_{\rm eff}^{\chi_{c1}(4274)} \gg \mathcal{B}_{\rm eff}^{\chi_{c0}(4500)}$$

2. (Unexpected) large contribution of high-mass proton dissociation.

3. Non-perturbative physics- molecules?

5. Misassignment (Herschel ??)

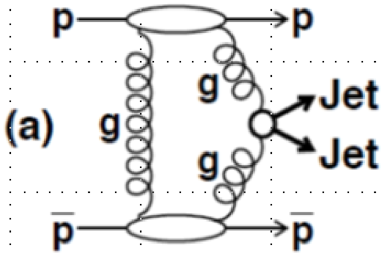
Dijet CEP as a 'Gluon Factory'

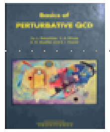
Dijet-monitor for new physics

- QCD-induced baseline high mass channels- exclusive jets and Higgs.

★ **Exclusive jets:**

- Exclusive jets: CEP theory: dominantly gg colour singlet dijets. Large numbers of essentially pure gluon jets in a clean environment





- New QCD regime - data from Tevatron

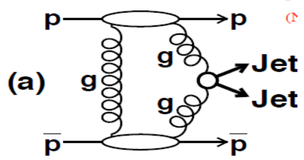
(~20 mln pure q-jets vs 417 'tagged' g at LEP)

First ATLAS ST results.

$p_\perp^j > 25\,\mathrm{GeV}$

M_{jj} [GeV]	$\sigma(gg)$ [pb]
100	35
200	1
300	0.14
400	0.024
500	0.0053
600	0.0014

EXCLUSIVE JET PRODUCTION



- **Precisely defined** CEP mechanism $\rightarrow$ colour singlet gg initial-state with certain $(++/--)$ helicity configurations ($J_z = 0$). In CEP:

$gg \rightarrow q\bar{q}$: **Vanishes** for massless quarks - suppressed as $\sim m_q^2/M_{jj}^2$

$gg \rightarrow gg$: **Unsuppressed** $\rightarrow$ gluon dominated jets.

Soft PT QCD lab

- Possibility to study dominantly **isolated** gg jet production at LHC.

- Taking e.g. $m_b = 4.5$ GeV and $M_X = 40$ GeV we then get

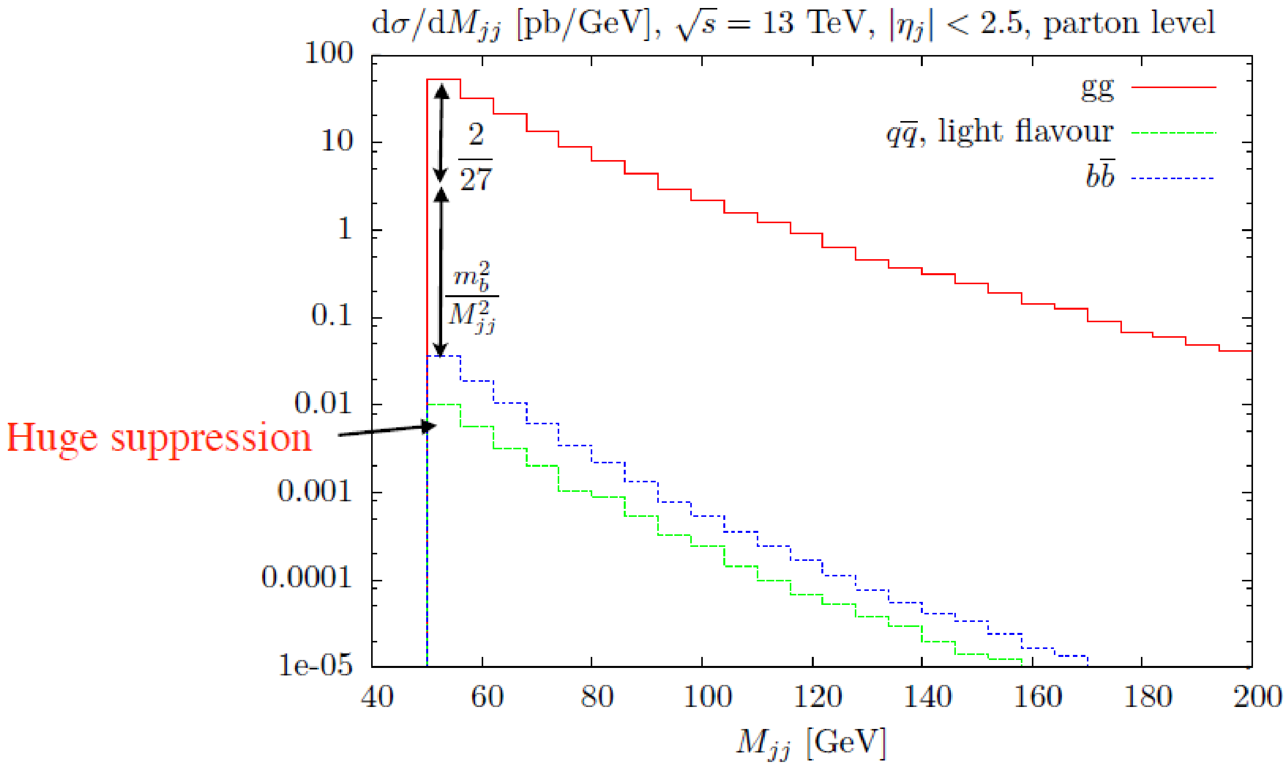
$$\frac{d\sigma(b\bar{b})/dt}{d\sigma(gg)/dt} \approx 10^{-3}$$

(first indications CDF-2008)

$\longrightarrow$ Huge suppression in b quark jets (increasing with M_X). Completely unlike inclusive case.

LHC cross sections

As expected from above discussion, expect strong gg dominance:



SuperChic-2

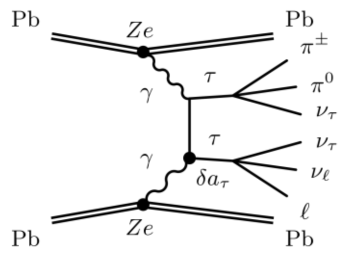
Higher precision constraints on the tau g – 2 in photon–initiated production

- 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]

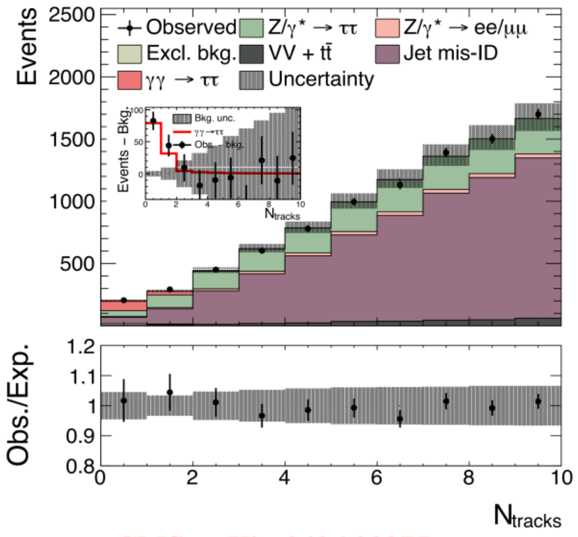
tau g-2



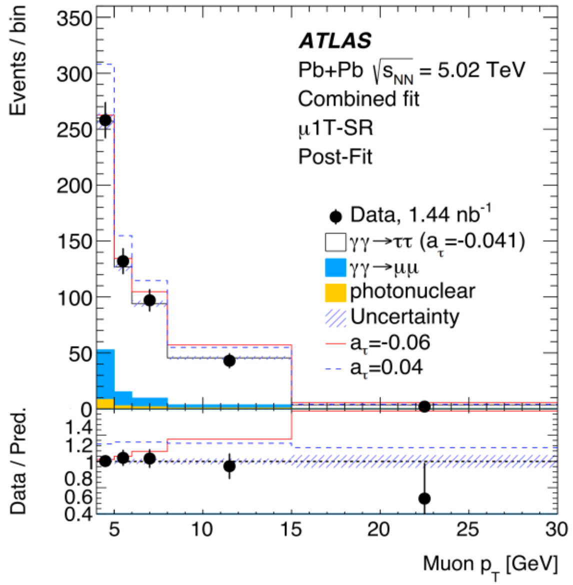
L. Beresford and J. Liu, PRD 102 (2020) 11, 113008
M. Dyndal et al., PLB 809 (2020) 135682

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

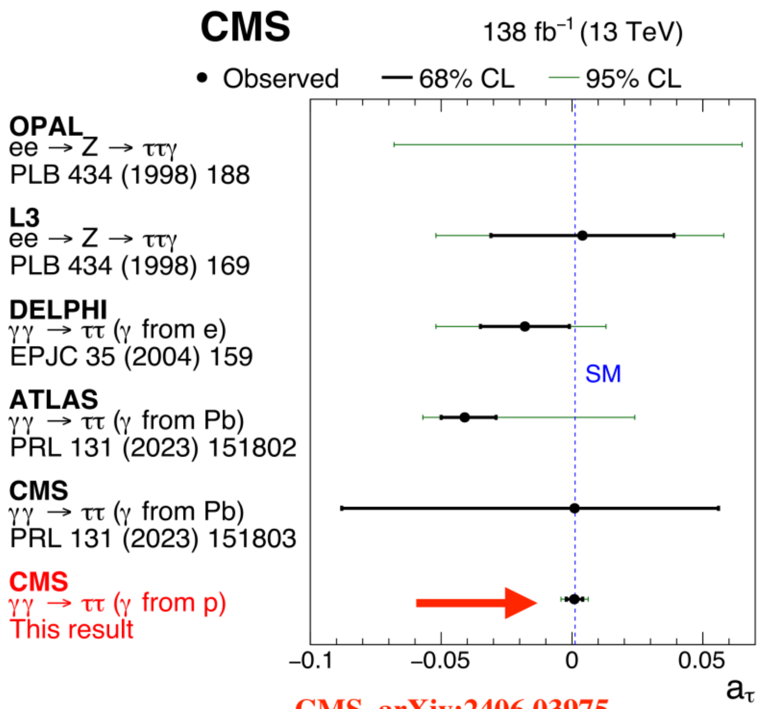
$$-0.0042 < a_\tau < 0.0062$$



CMS, arXiv:2406.03975



ATLAS, arXiv:2204.13478



CMS, arXiv:2406.03975

Higher precision constraints on the tau g−2 in LHC photon-initiated production: a full account of hadron dissociation and soft survival effects L.A. Harland-Lang, 2410.10978 [hep-ph]

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.

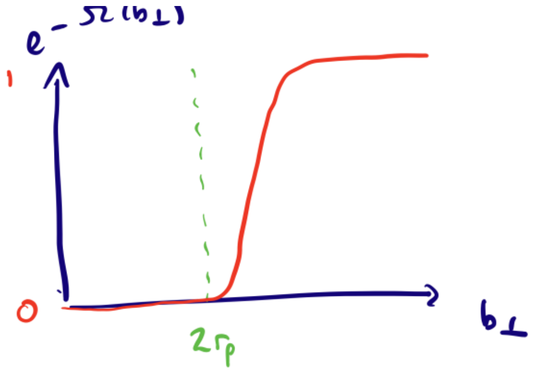
  ★ Proton dissociation (EL vs. SD vs. DD).

- 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!

Standard calculations assume that the nucleus (proton) is intact. The same S^2.

L. A. Harland-Lang.2303.04826 a full treatment of UPCs including mutual ion dissociation

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:

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

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!

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

Note the presence of the photon 4–momentum q^μ. In impact parameter space, this will lead to a factor of $b^\mu_\perp$, such that the amplitude vanishes at zero impact parameter where the impact of survival effects is larger KKM-2003 (Difference of survival for 0^- and 0^+ CEP)

Recall: the SM prediction for the tau g-2 is known to 5 d.p precision

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

Higher precision constraints on the tau $g-2$ in LHC photon–initiated production: a full account of hadron dissociation and soft survival effects

L.A. Harland-Lang[1]

Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK

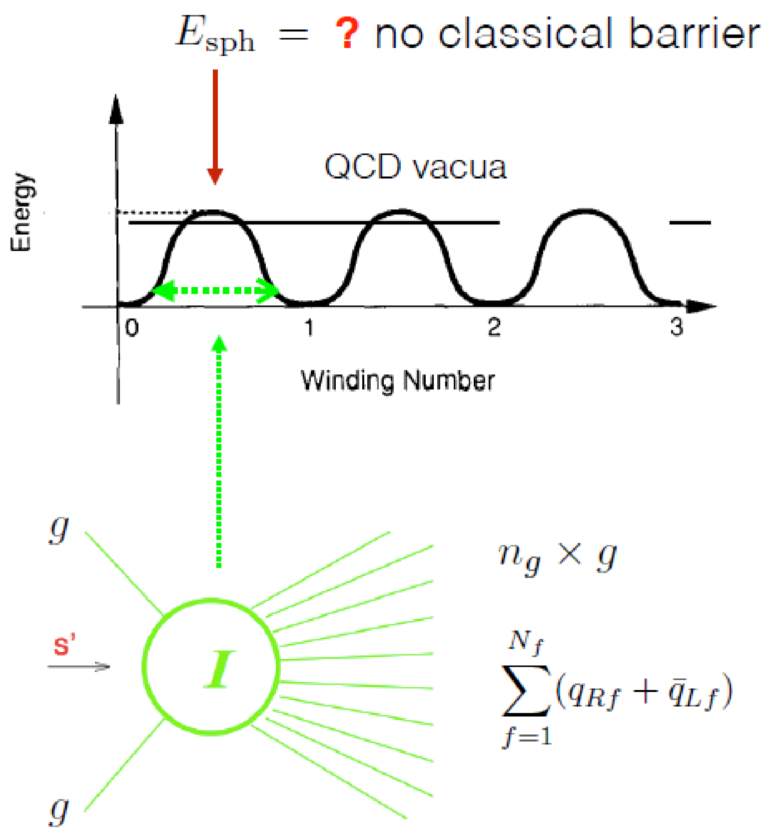
2410.10978 [hep-ph]

Abstract

We present the first calculation of photon–initiated τ pair production in the presence of non–zero anomalous magnetic (a_τ) and/or electric dipole (d_τ) moments of the τ lepton that accounts for the non–trivial interplay between these modifications with the soft survival factor and the possibility of dissociation of the hadron (proton or ion) beam. The impact of these is on general grounds not expected to have a uniform dependence on the value of a_τ, d_τ, but in all previous analyses this assumption has been made. We have therefore investigated the importance of these effects in the context of photon–initiated τ pair production in both pp and PbPb collisions. This is in general found to be relatively small, at the percent level in terms of any extracted limits or observations of a_τ, d_τ, such that these effects can indeed be safely ignored in existing experimental analyses. However, as the precision of such determinations increases in the future, the relevance of these effects will likewise increase. With this in mind we have made our calculation publicly available in the SuperChic Monte Carlo generator, including the possibility to simulate this process for varying a_τ, d_τ without rerunning.

QCD Instantons

- Yang-Mills vacuum has a nontrivial structure
- *Instantons* are tunnelling solutions between the vacua.
- At the classical level there is no barrier in QCD. The *sphaleron is a quantum effect*
- Transitions between the vacua change chirality (result of the ABJ anomaly).
- All light quark-anti-quark pairs must participate in the reaction
- Not described by perturbation theory.



Sphaleron-transition on top of an energy barrier

$$g + g \rightarrow n_g \times g + \sum_{f=1}^{N_f}(q_{Rf} + \bar{q}_{Lf})$$

2

KKMR, *Phys.Rev.D* 104 (2021) 5, 054013

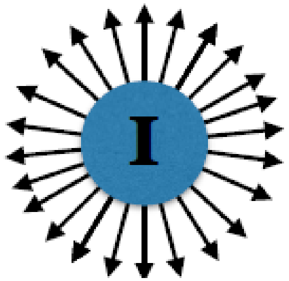
Instantons have never been observed **experimentally**, however, they are playing a very important role in the theoretical models of confinement and chiral symmetry breaking

one of the biggest challenges for particle physics to date

a possible solution to the axial $U(1)$ problem

$$< 0|G^a_{\mu\nu}G^a_{\mu\nu}|0 > \neq 0$$

Instanton signatures:



LO Instanton vertex -> selection on final states at colliders with high sphericity

- large multiplicity $\qquad N_{jet} \sim 1/\alpha_s(\rho_{inst}) \quad E_T \sim 1/\rho_{inst}$

'soft bombs' –high-multiplicity spherically symmetric distributions of relatively soft particles

- large 'Sphericity', $S \to 1$

- presence of an additional light $\bar{q}_R q_L$ pairs

(in particular pair of strange
(or charm, for the small size instanton) quarks)

Instanton$\neq$ the particle (no peak in M_{inst})
It is a family of objects of different size, ρ,
and orientations in Lorentz and colour spaces

Extended objects in space-time

Effectively –a family of new multiparton vertices in Feynman diagrams

Strong need for enthusiastic experimental experts to join the efforts, addressing such issues as detector effects, PU at high luminosity, and timing resolution…..

TKMR, *Eur.Phys. J.C* 83 (2023) 1

One of the main obstacle currently – PU at high luminosity

Possible directions for further studies

- Feasibility of searches for moderate mass Instantons in UPC
- Using good timing from Central Detectors for both ST and DT events.
- Identification of charm quark jets in the final state

Summary & Conclusions

- **CEP measurements** could significantly extend the physics reach of the LHC detectors by giving access to a wide range of exciting new physics channels.

.

- **CEP** *could* serve as a spin-parity analyser and offers a sensitive probe of the CP structure of the new states.

- The theory of the CEP is in a reasonably healthy shape, and dedicated MCs (such as SCs) are well developed

- The predictions are backed by the series of CDF/D0 CEP-like measurements as well as the RAP GAP measurements by the LHCb and ALICE +CEP results from ATLAS& CMS

- The dedicated AFP and PPS detectors allow uingue the timing. The main issue is PU suppression, though some progress is foreseen, in particular with the addition of timing from the CD.

10ps in Run 4

But ATLAS has already decided not to run AFP at HL-LHC (at least not in the foreseeable future)

- At large M_{Mmis}> 150-200 GeV the photon-photon fusion dominates over the gg. LHC is the photon-photon collider!

- Such important measurements as the searches for the new Higgs-like states as well as the moderately-heavy instantons, would require the 420 m stations.

- The bulk of important physics (such as glueballs, instantons, and other new state searches) would require low luminosity runs.

BACKUP

$J_z^P = 0^+$ selection rule

- Consider the limit $p_{1_\perp} = p_{2_\perp} = 0$, i.e. exactly forward scattering. Have

$$q_{1_\perp} = -q_{2_\perp} = Q_\perp \;,$$
$$\epsilon_1 = -\epsilon_2 \;,$$

i.e. $gg \to X$ subamplitude is given by

$$\mathcal{M} \sim Q_\perp^i Q_\perp^j V_{ij} \qquad (i/j = 1,2)$$
$$\to \frac{1}{2} Q_\perp^2 (V_{++} + V_{--})$$

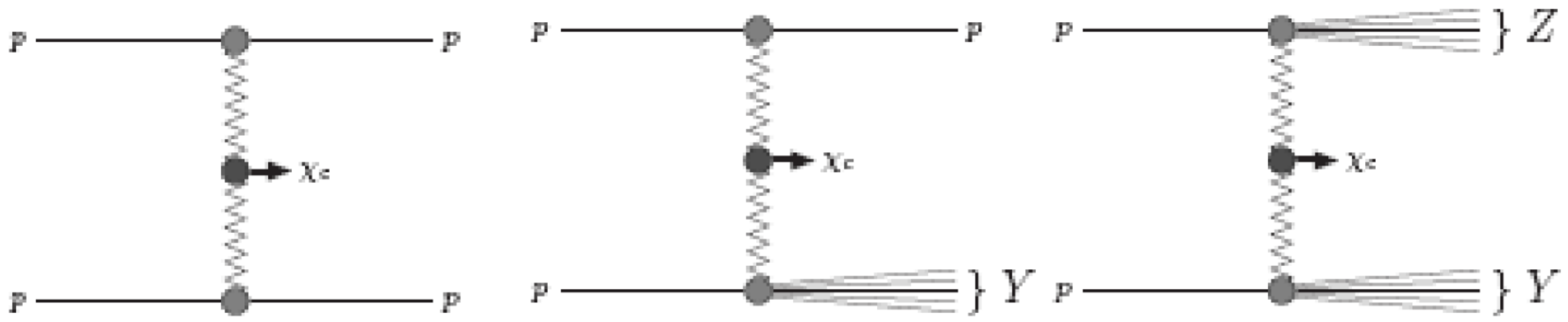
i.e. fusing gluons have equal (transverse) polarisations $\lambda_1 = \lambda_2 = \pm$.

→ In exact forward limit, fusing gluons are in a $J_z = 0$ state along beam axis.

- For general proton $p_\perp \neq 0$, non-$J_z^P = 0^+$ states contribute, but these will be sub-leading (as $p_\perp \approx 0$ in general) and can be efficiently suppressed with proton tagging.

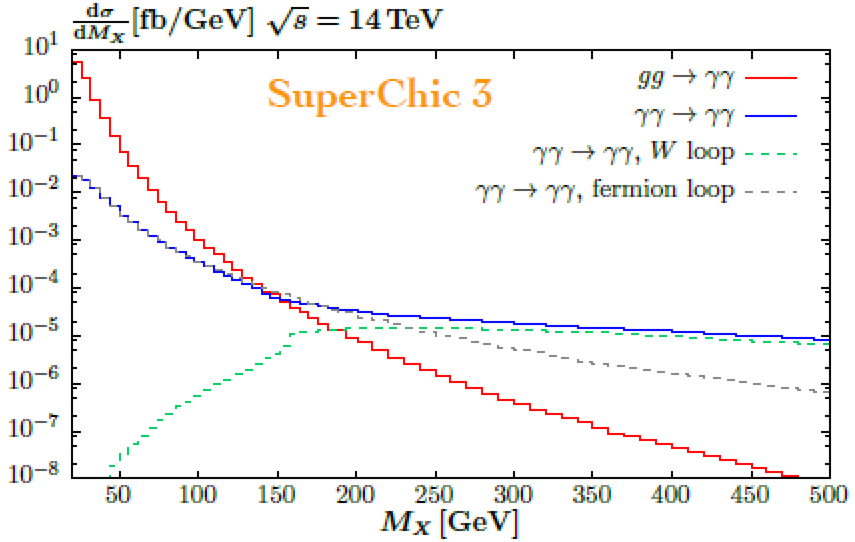
CEP without tagged protons

- Are relativistic/non-perturbative corrections to χ_{c2} important (suppression of χ_{c1} expected by general considerations)?
- Is there a significant high mass proton dissociation $pp \to p + \chi + X$ background skewing the results?
  - Higher–mass dissociation $p \to N^*(M_Y \gtrsim 2\,\mathrm{GeV})$: allows a higher $p_\perp$ transfer to the protons and so an increasing violation of the $J_z = 0$ selection rule (recall χ_{c2} contribution is $\propto \langle p_\perp^2 \rangle^2$).
  - Such contamination should enhance in particular the χ_{c2} cross section preferentially: to consider when subtracting the proton dissociative background (always necessary to some extent without tagged protons).
  - Look at $p_\perp(\chi_c)$ dependence of cross section ratios to shed further light on this.



★ As mass of central system M_X increases, QCD-initiated production cross section suppressed by no radiation probability $\Rightarrow$ BG often low*.

- Example of $\gamma\gamma$ production:



- CEP: unique possibility to observe photon-initiated production of states with EM coupling in clean/well understood environment.

$\sqrt{s_{\gamma\gamma}}$ up to 1-2 TeV

- However typically considering high mass region (RPs) and relatively low cross sections (EM couplings). **Statistics limited**.

$\longrightarrow$ Increased statistics from HL-LHC running offer **clear advantage** here, in particular in terms of pushing to higher mass.

*Precise level depends on particular process.

Currently, pure CEP studies at the LHC are $\gamma\gamma$ dominated (also HIC-UPC)

Summary/Outlook

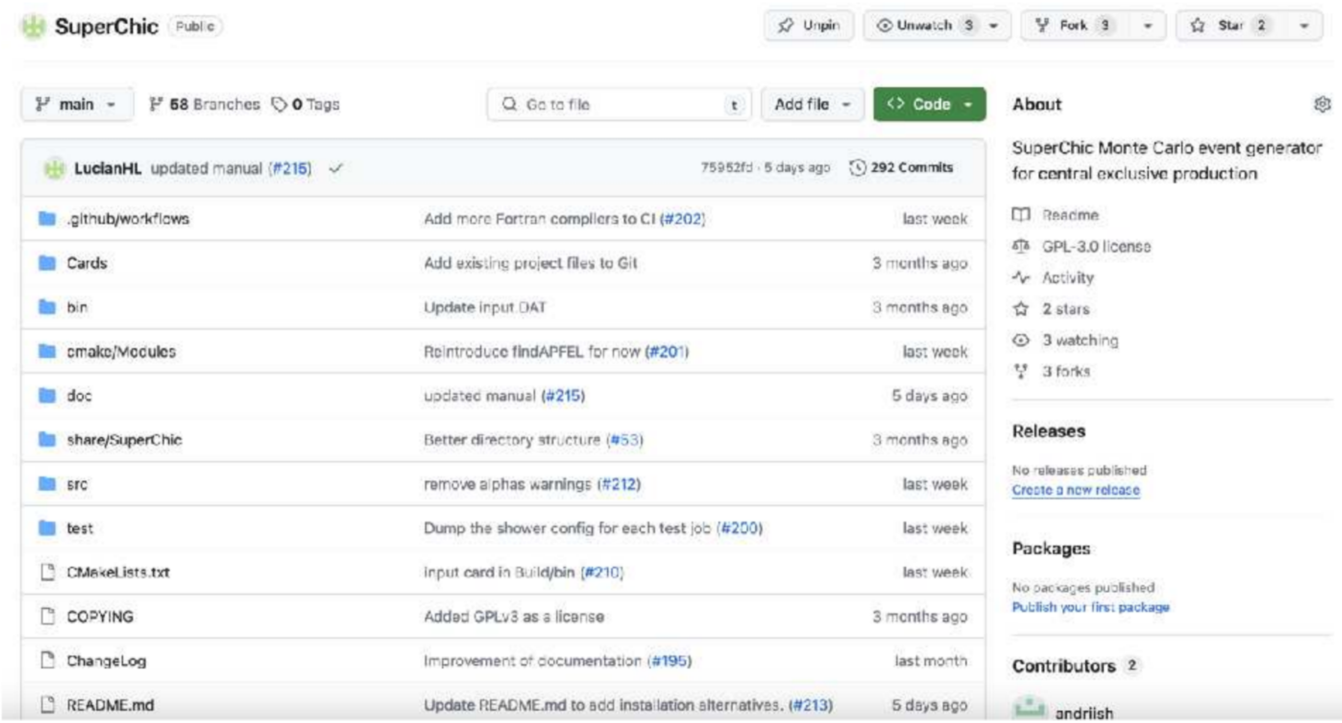
★ Anomalous in a_τ, d_τ photon-initiated τ pair production included in SuperChic for first time, in pp and AA.

★ 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.



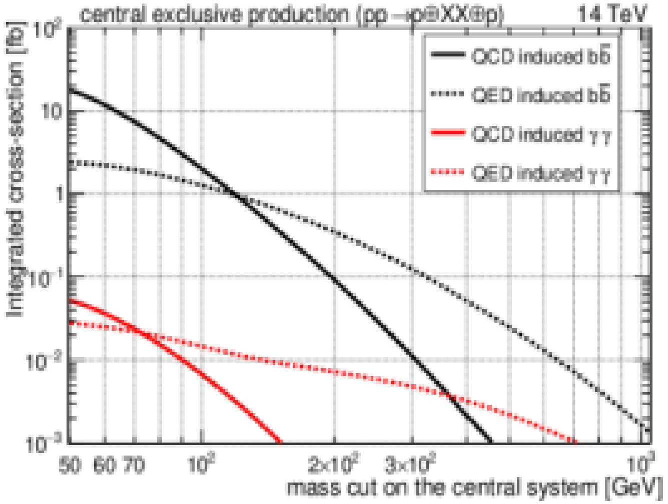
PPS2 @ HL-LHC

- SM CEP via **photon fusion** in pp collisions at $\sqrt{s} = 14$ TeV
- Computed fiducial cross sections for 2-tag and 1-tag categories:

Process	Fiducial cross section [fb] 2 tags	1 tag
jj	2	219
bb	0.04	6.3
W^+W^-	15	152
$\mu\mu$	1.3	172
tt	0.1	0.65
H	0	0.23
HW^+W^-	0.01	0.06
ZZ	0.03	0.23
$Z\gamma$	0.02	0.15
$\gamma\gamma$	0.003	0.19

First year of HL-LHC ($\sim$300 fb^{-1})

End of HL-LHC ($\sim$3000 fb^{-1})



$pp \rightarrow p\, b\bar{b}\, p$, $pp \rightarrow p\, \gamma\gamma\, p$,
QCD and QED contributions

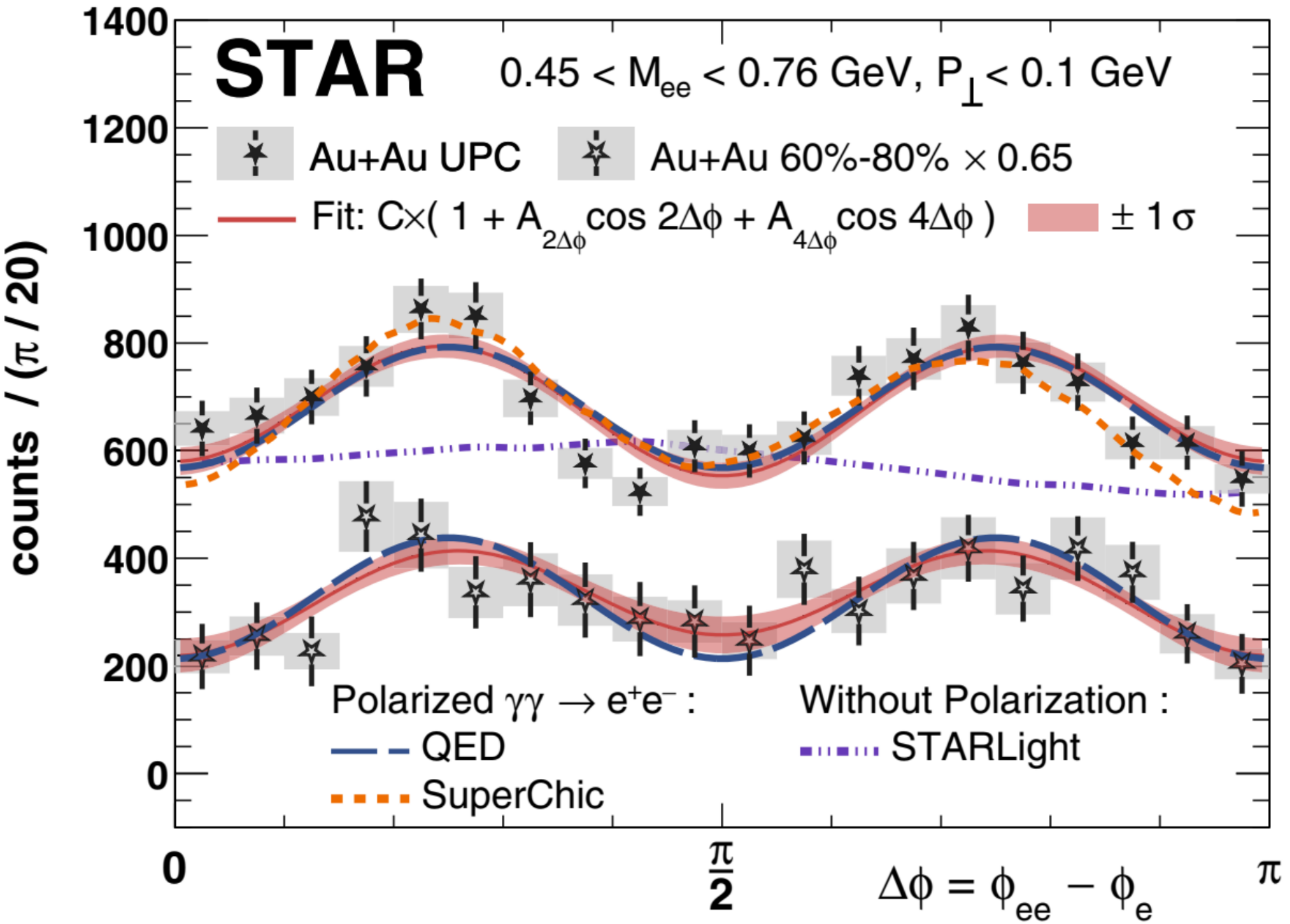
POS(LHCP2023)012

$\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp}$ leads to $\cos n\phi$ modulation for polarized two gamma fusion

$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)] \\ \approx \Delta\phi[(e^+ + e^-), e^+]$$

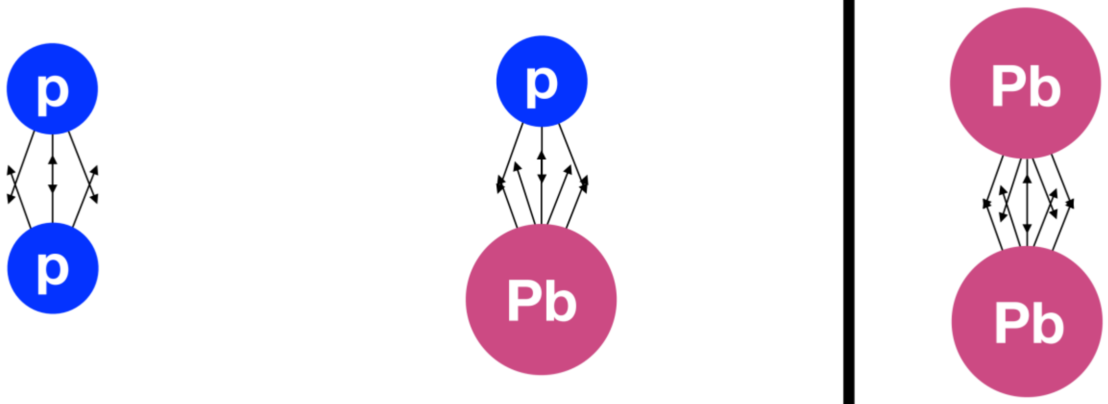
	Ultra-Peripheral		
Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	16.8 $\pm$ 2.5	16.5	18.8 / 16

	Peripheral (60−80%)		
Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	27 $\pm$ 6	34.5	10.2 / 17



STAR, PRL **127** (2021) 052302

The LHC is also a photon collider



ATLAS			
$\sqrt{s}$	13 TeV	8.16 TeV	**5.02 TeV**
$\mathscr{L}$	~140 fb^{-1}	~170 nb^{-1}	**~2 nb^{-1}**
σ	-	$\propto Z^2$	**$\propto Z^4$**

Z = 82 for Pb