A closer look at dark photon production modes

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25/06/24

Work in progress with

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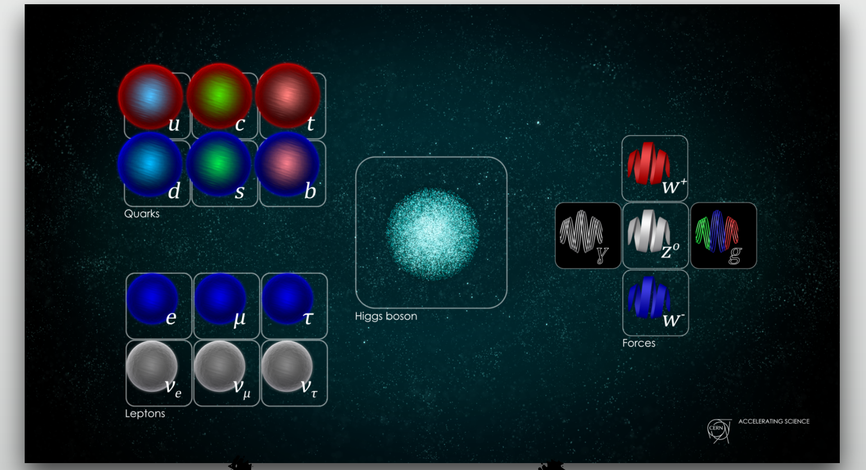
Aidin Masouminia (Durham), Simon Plätzer (Vienna)
(Herwig Collaboration)

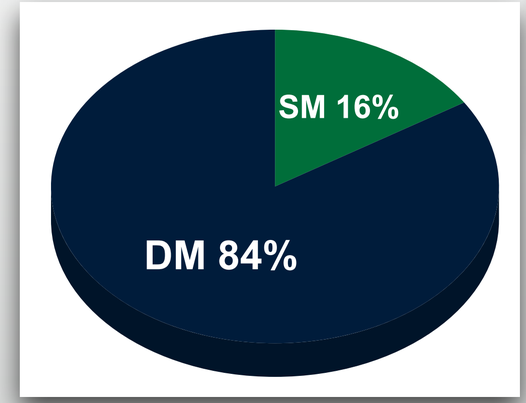
@ UCLouvain

Hot Topics and Problems in Particle Physics

Standard Model



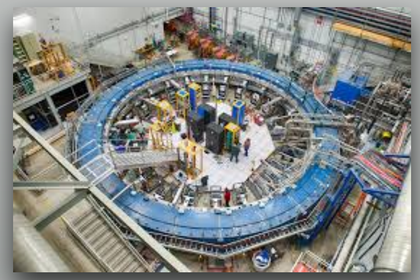
New Physics



Dark Matter

Tensions

Flavour anomalies



g-2

Baryon asymmetry

Neutrino masses

Hot Topics and Problems in Particle Physics

SM

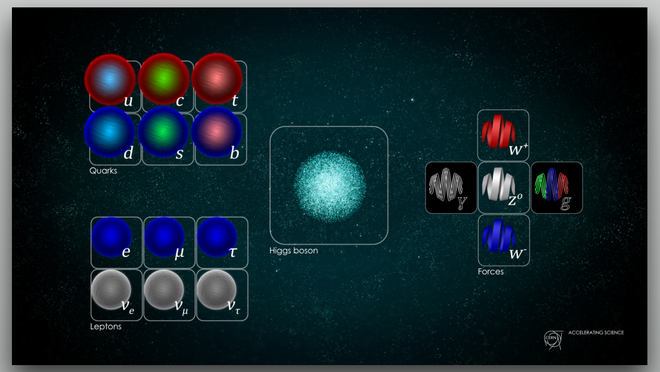
?

Beyond the Standard Model (BSM):

Neutrino masses

Baryon asymmetry

DM



Hot Topics and Problems in Particle Physics

SM

Renormalizable

+ gauge invariant

1. *Neutrino Portal*
2. *Higgs Portal*
3. ***Vector Portal***

BSM:

DM

Neutrino masses

Baryon asymmetry

Dark Photon - Model Basics

Kinetic mixing: $\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu}$

photon field strength

new vector field strength

$$\rightarrow \quad \mathcal{L} \supset -\frac{1}{4} A'^{\mu\nu} A'_{\mu\nu} + \frac{1}{2} m_{A'} A'^{2} + \mathcal{L}^{\mathrm{D}}_{\mathrm{int}} + \mathcal{L}^{\mathrm{SM}}_{\mathrm{int}}$$

mass range: $10\ \mathrm{MeV} \lesssim m_{A'} \lesssim 2\ \mathrm{GeV}$

…but could be anything!

Dark Photons + DM

SM — **DM**

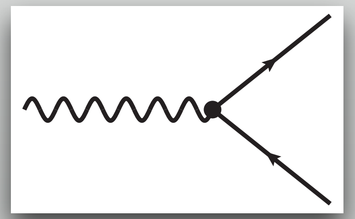
$$\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu}$$

$$\mathcal{L}_{\rm int}^{\rm SM} = \varepsilon e A'_{\mu} J^{\mu}_{\rm em}$$

$$\mathcal{L} \supset -\frac{1}{4} A'^{\mu\nu} A'_{\mu\nu} + \frac{1}{2} m_{A'} A'^{2} + \mathcal{L}_{\rm int}^{\rm D} + \mathcal{L}_{\rm int}^{\rm SM}$$

Majorana fermion DM

$$\mathcal{L}_{\rm int}^{\rm D} = \frac{g_D}{2} A'_{\mu} \bar{\chi} \gamma^{\mu} \gamma^{5} \chi$$

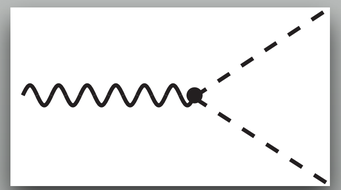


inelastic DM

$$\mathcal{L}_{\rm int}^{\rm D} = \frac{i}{2} g_D A'_{\mu} \bar{\chi_2} \gamma^{\mu} \chi_1 + \text{h.c.}$$

complex-scalar DM

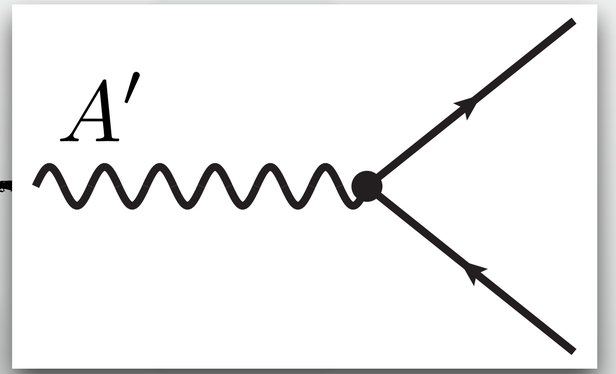
$$\mathcal{L}_{\rm int}^{\rm D} = i g_D A'_{\mu} \chi^{*} \overleftrightarrow{\partial}^{\mu} \chi$$



Dark Photons + SM

SM

$$\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu}$$



$$\mathcal{L}_{\rm int}^{\rm SM} = \varepsilon e A'_{\mu} J^{\mu}_{\rm em}$$

$$\mathcal{L} \supset -\frac{1}{4} A'^{\mu\nu} A'_{\mu\nu} + \frac{1}{2} m_{A'} A'^{2} + \mathcal{L}_{\rm int}^{\rm D} + \mathcal{L}_{\rm int}^{\rm SM}$$

Majorana fermion DM

$$\mathcal{L}_{\rm int}^{\rm D} = \frac{g_D}{2} A'_{\mu} \bar{\chi} \gamma^{\mu} \gamma^{5} \chi$$

inelastic DM

$$\mathcal{L}_{\rm int}^{\rm D} = \frac{i}{2} g_D A'_{\mu} \bar{\chi}_2 \gamma^{\mu} \chi_1 + \text{h.c.}$$

complex-scalar DM

$$\mathcal{L}_{\rm int}^{\rm D} = i g_D A'_{\mu} \chi^{*} \overleftrightarrow{\partial}^{\mu} \chi$$

Search Strategy for Dark Photons

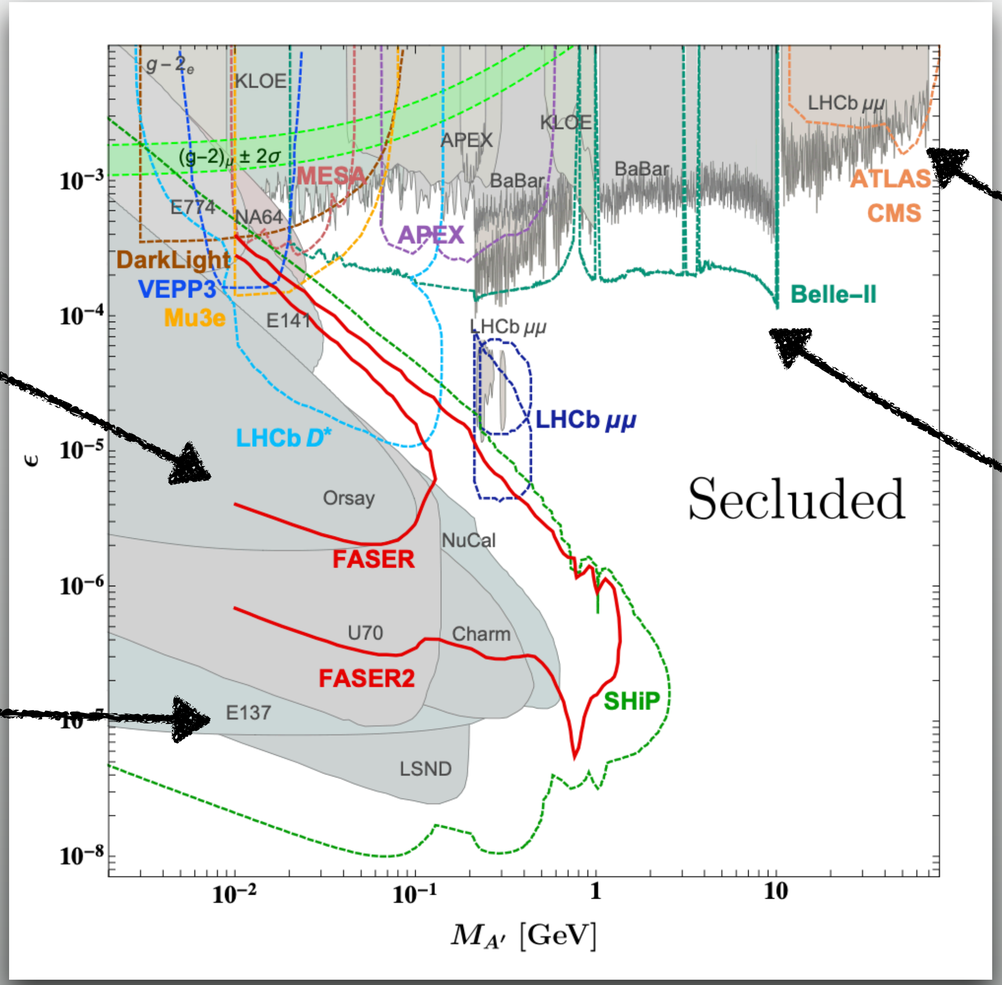
Proton Beam dumps:
CHARM, NuCal, NA62
U70, LSND

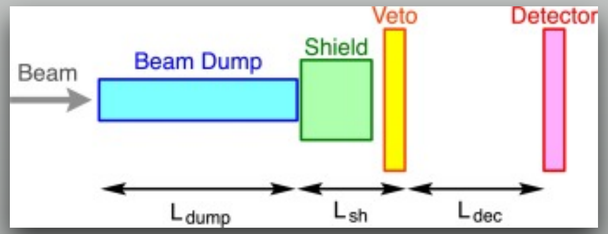
Electron beam dump:
E137
Orsay Linac

Colliders:

pp **LHCb, ATLAS, CMS**

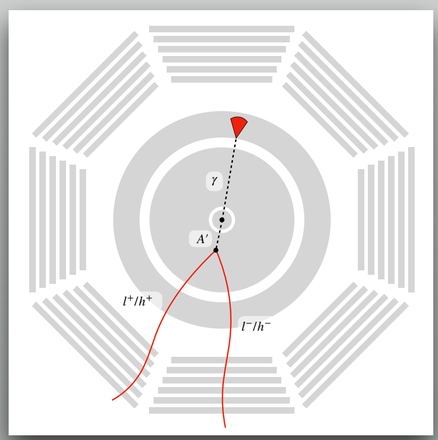
e^+e^- **BaBar, Belle II, KLOE**





1507.02809

2203.05090

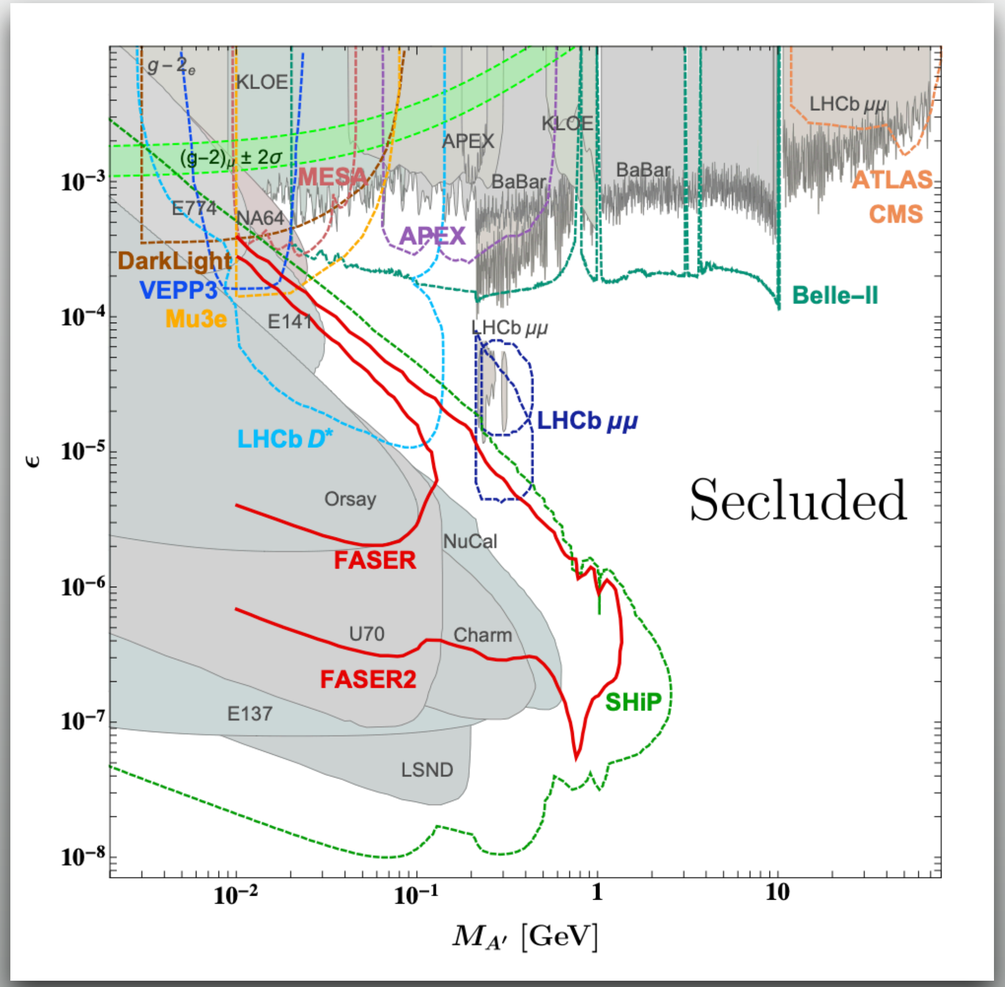


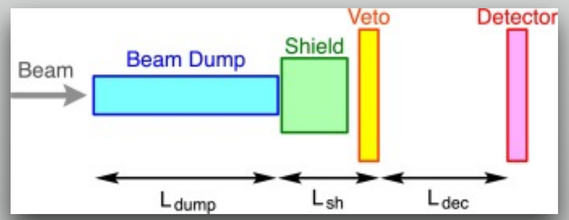
2202.03452

Search Strategy for Dark Photons

$$\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu}$$

$$\mathcal{L}_{\rm int}^{\rm SM} = \varepsilon e A'_\mu J^\mu_{\rm em}$$





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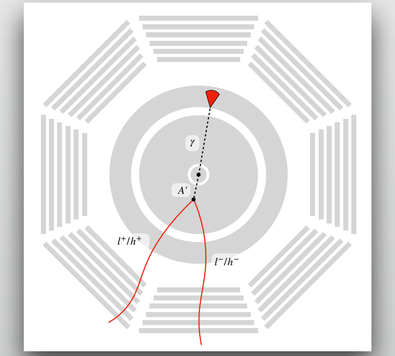
Decay:

Prompt decay

Displaced decay



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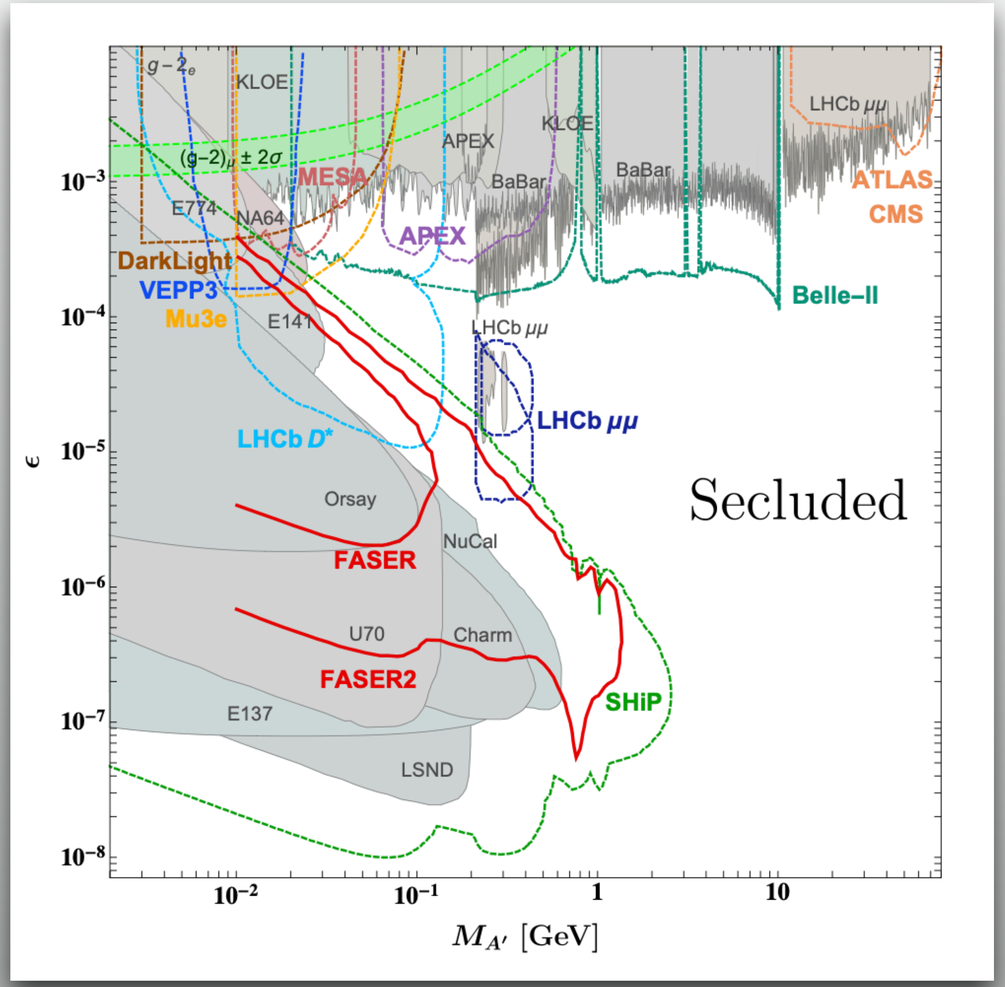
Long-lived particle

Search Strategy for Dark Photons

$$\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu}$$

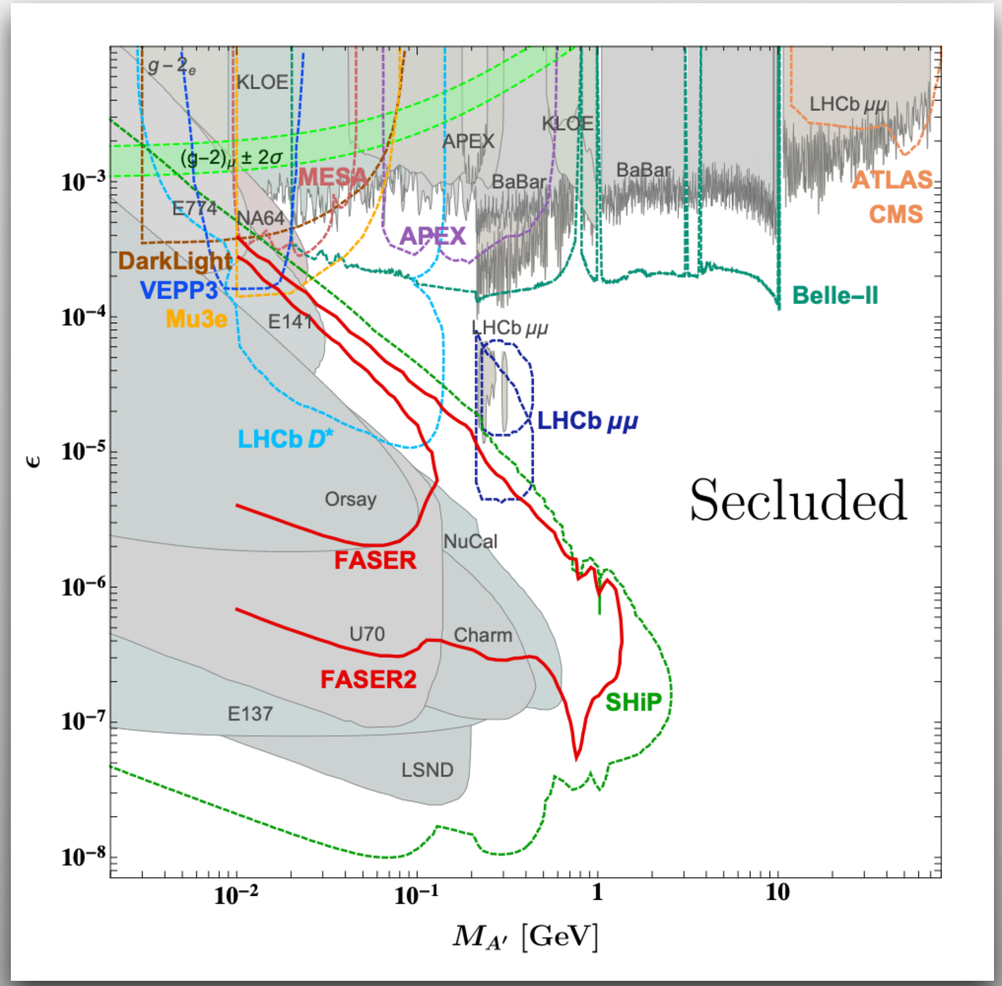
$$\mathcal{L}_{\rm int}^{\rm SM} = \varepsilon e A'_\mu J^\mu_{\rm em}$$

Decay



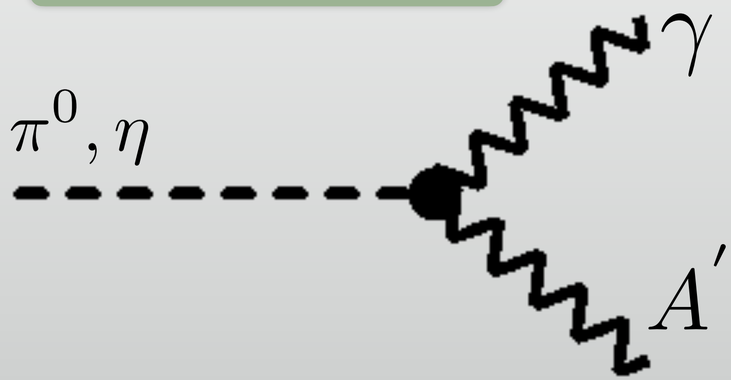
Production

Search Strategy for Dark Photons



Production

Meson decays

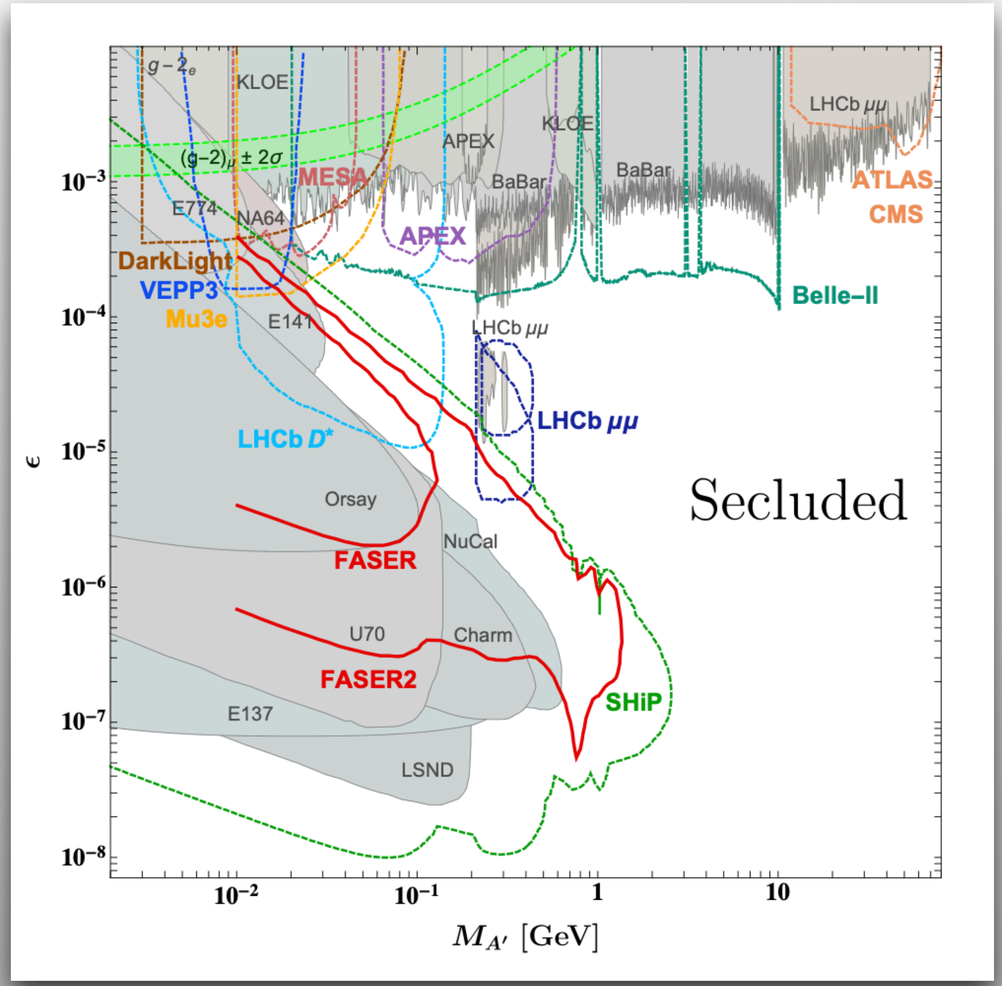


$$\mathrm{BR}(\pi^0/\eta \to \gamma A') = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0,\eta}^2}\right) \mathrm{BR}(\pi^0/\eta \to \gamma\gamma)$$

Uncertainties in meson production

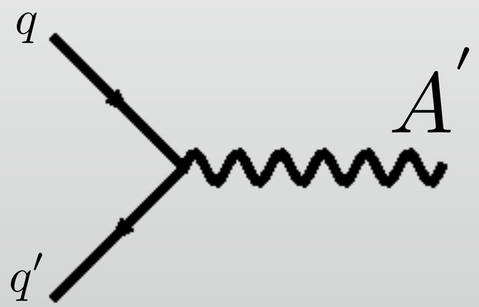
2309.08604

Search Strategy for Dark Photons

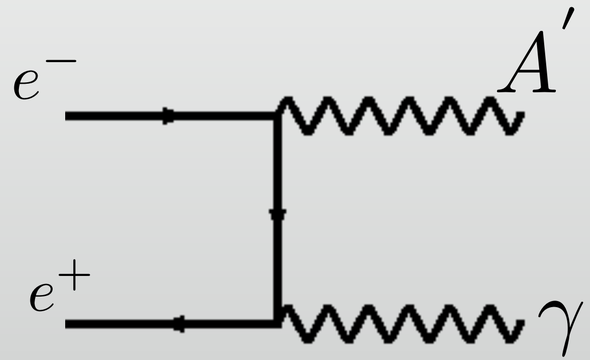


Production

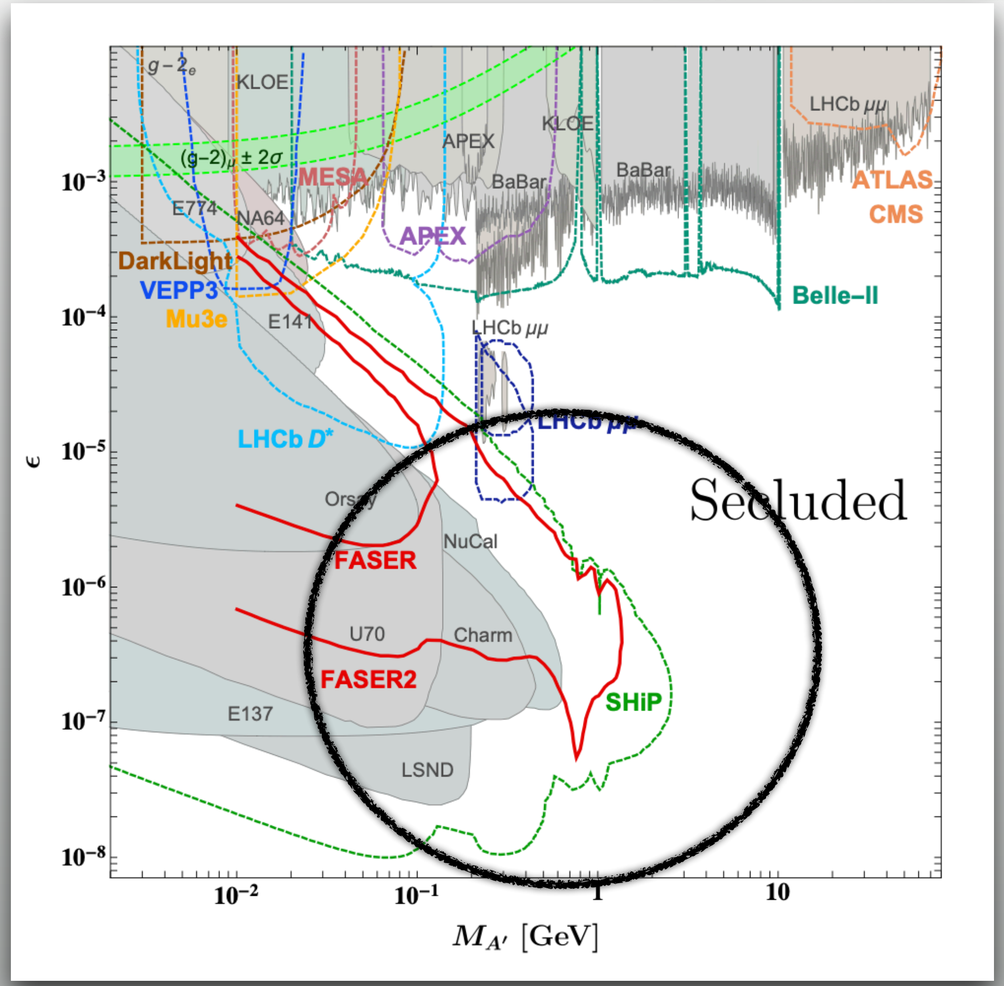
Direct Production



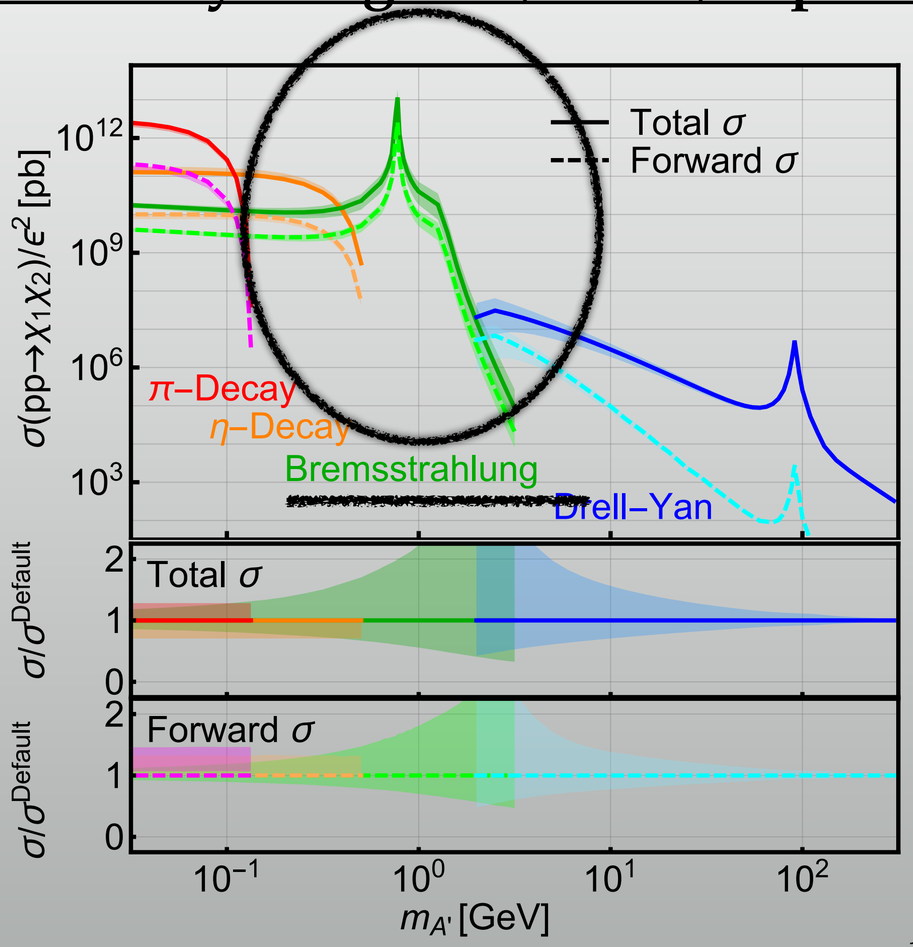
$$= \frac{12\pi}{m_{A'}^2}\mathrm{BR}(A' \to q\bar{q})$$



Search Strategy for Dark Photons



Sensitivity Range of (future) experiments



arXiv 1810.01879

A. Berlin, F. Kling

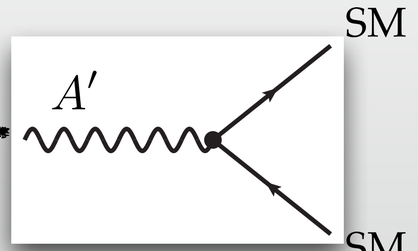
Production

Dark Photons from proton beam experiments

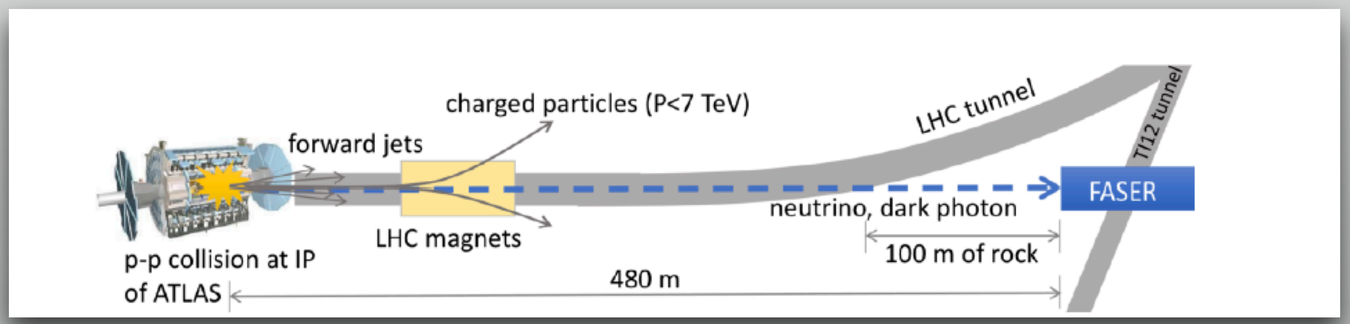
SM

$$\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu}$$

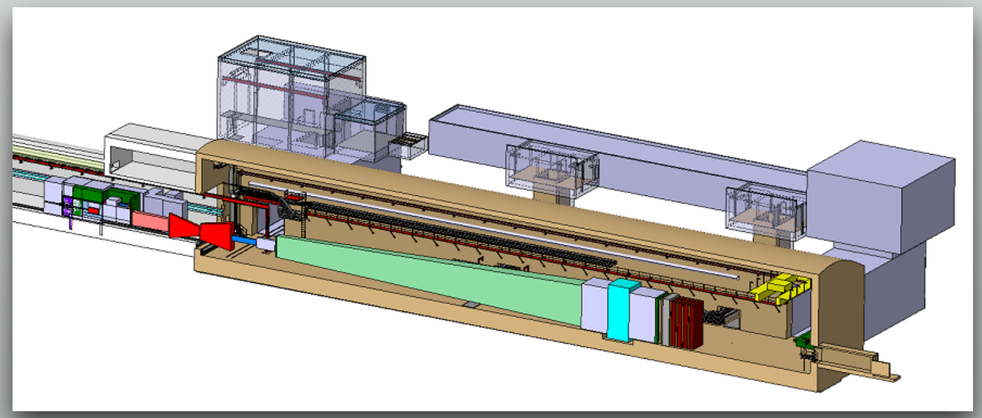
$$\mathcal{L}^{\rm SM}_{\rm int} = \varepsilon e A'_\mu J^\mu_{\rm em}$$



Discovery potential in (future) experiments



[FASER Collaboration]

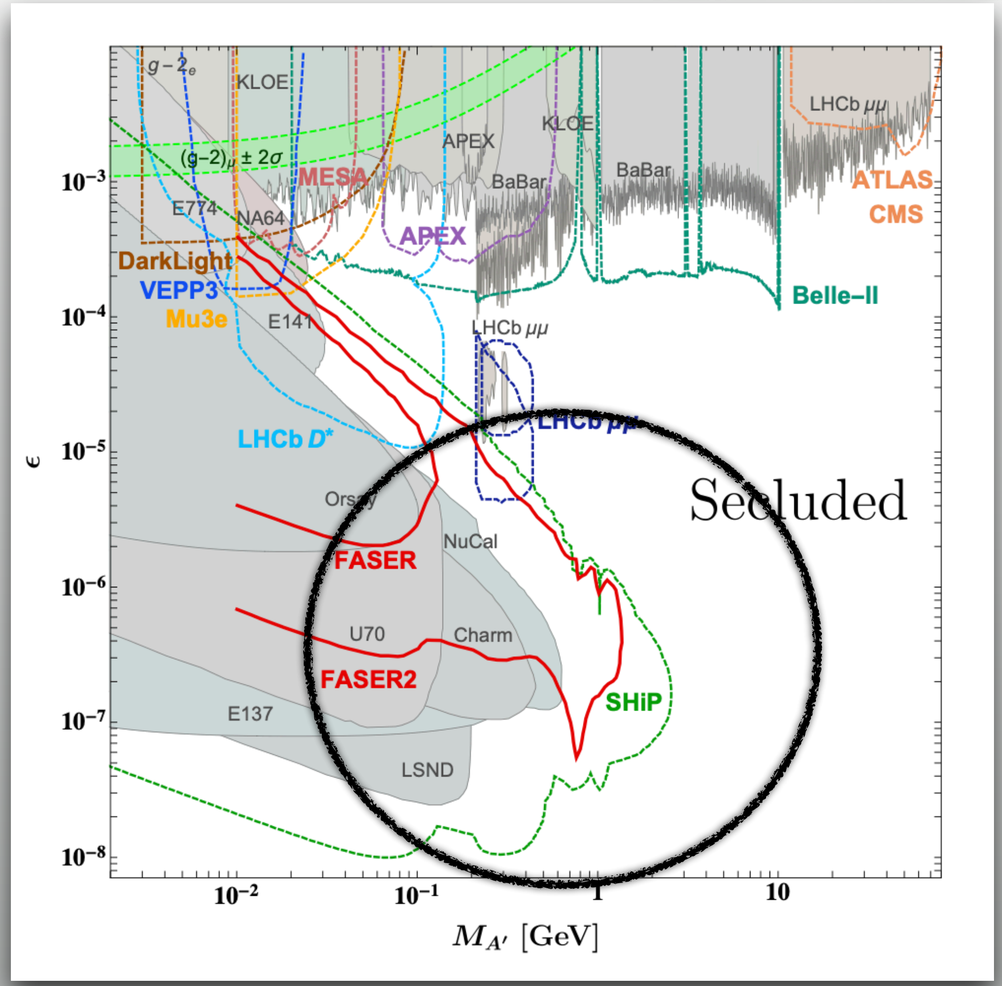


[SHiP Collaboration]

+ FPF Forward Physics Facility

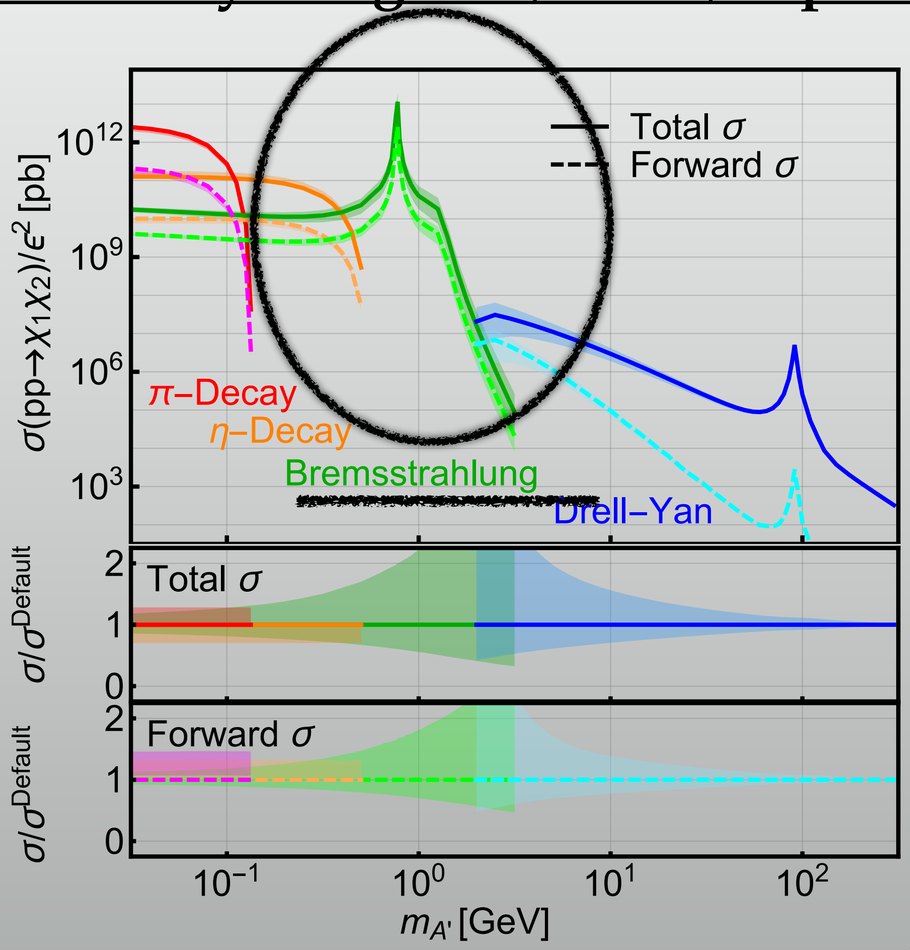
Approved!

Search Strategy for Dark Photons



Production

Sensitivity Range of (future) experiments



Proton bremsstrahlung!

arXiv 1810.01879

A. Berlin, F. Kling

Production of BSM particles

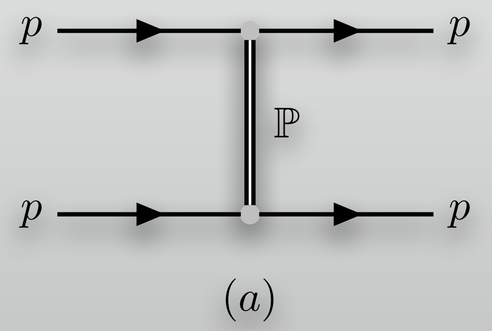
Proton Bremsstrahlung

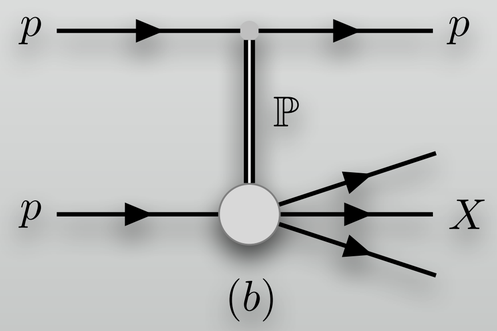
$$\mathcal{L}_{\text{eff}} \supset \varepsilon e A'_{\mu} \bar{p} \gamma^{\mu} p$$

Any process including protons

elastic

~ 25%



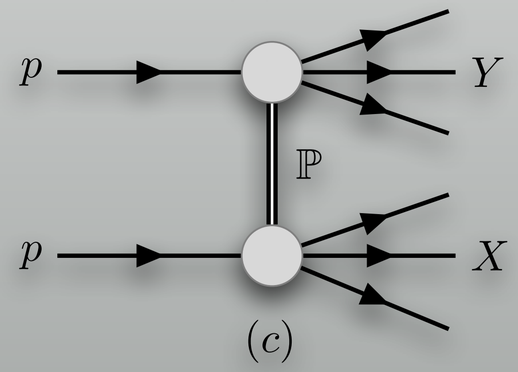


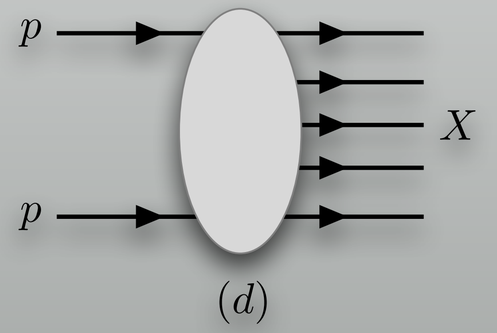
~ 11%

semi diffractive

double diffractive

~ 8%





~ 56%

inelastic

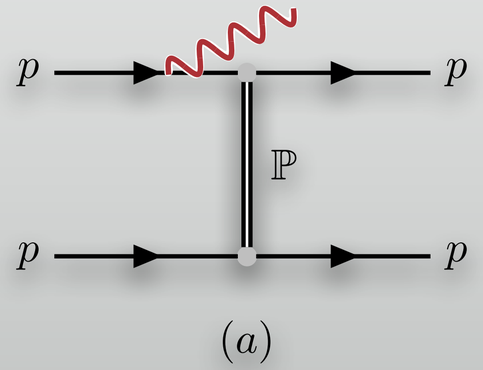
Production of BSM particles

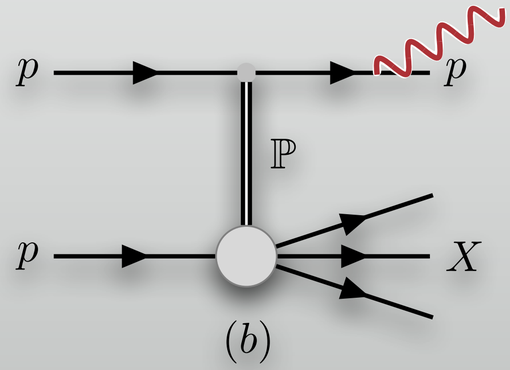
Proton Bremsstrahlung

$$\mathcal{L}_{\text{eff}} \supset \varepsilon e A'_{\mu} \bar{p} \gamma^{\mu} p$$

Any process including protons

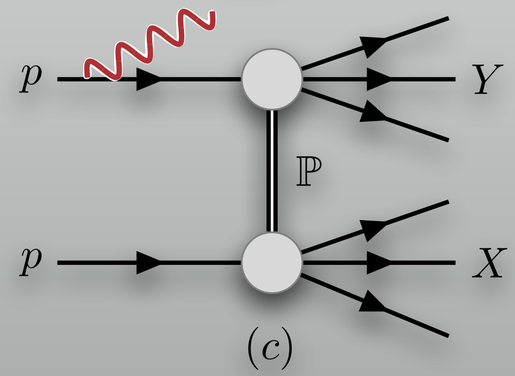
elastic ~ 25%

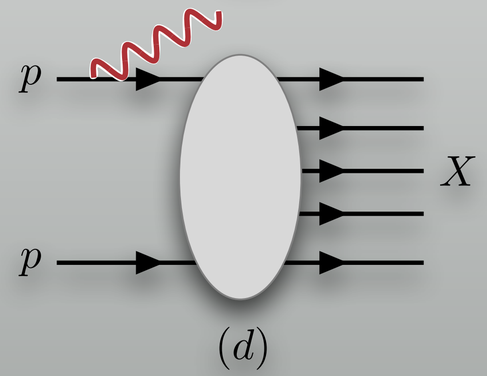




~ 11% semi diffractive

double diffractive ~ 8%





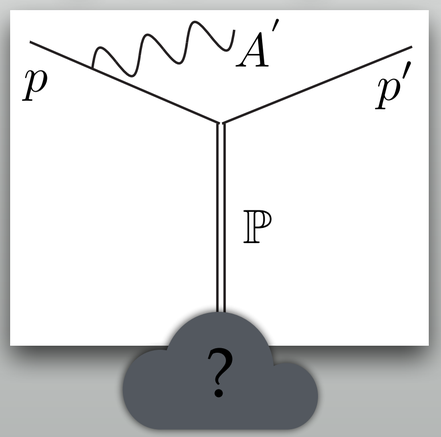
~ 56% inelastic

Production of BSM particles

Proton Bremsstrahlung

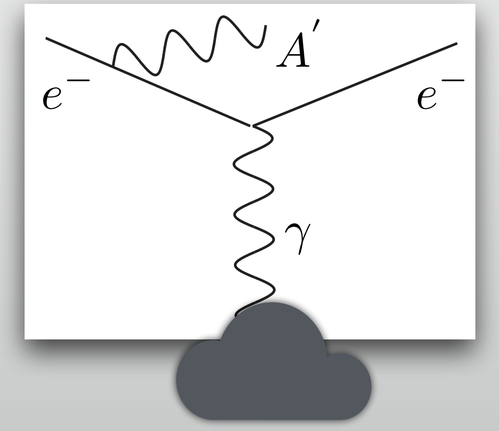
→ arXiv 1311.3870 Blümlein, Brunner

$$p + \mathbb{P} \to p' + A'$$



like FWW-approach for electron beams

$$e^- + \gamma \to e^- + A'$$



But: what is the "pomeron cloud"? Only valid for quasi-elastic processes?

Production of BSM particles

Proton Bremsstrahlung

→ arXiv 1311.3870 Blümlein, Brunner

→ Recent developments:

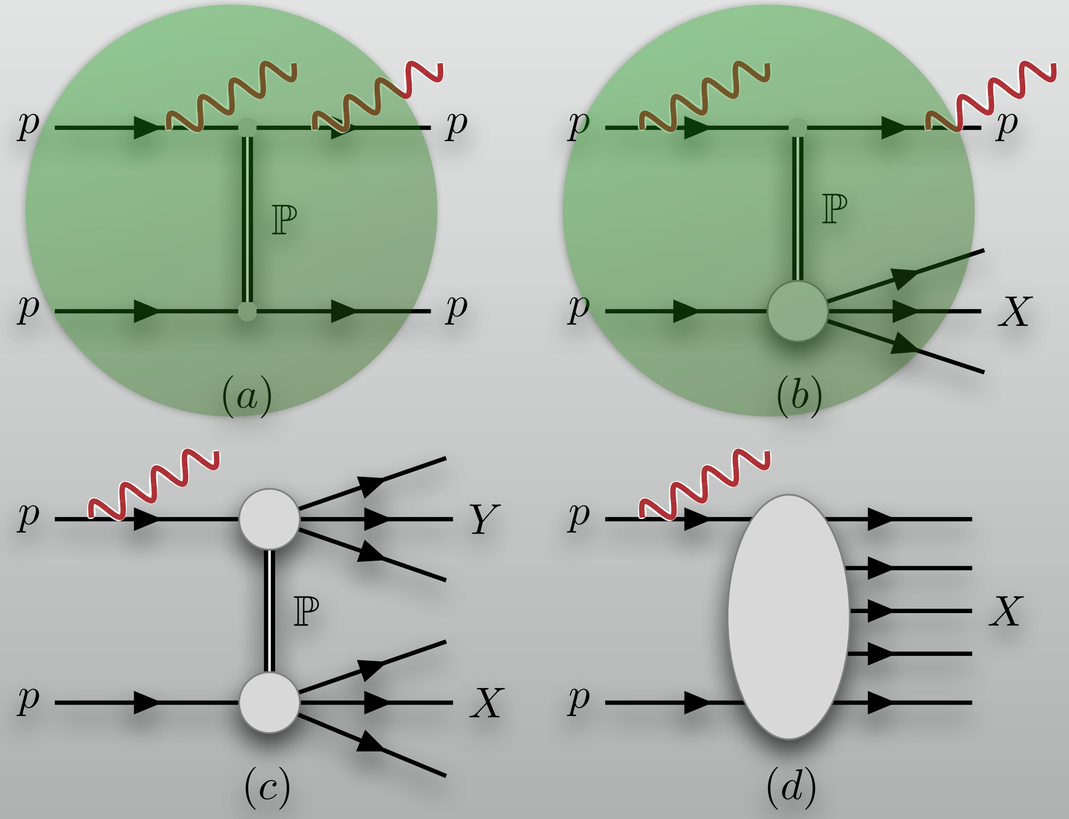
arXiv 2108.05900 Saeid Foroughi-Abari, Adam Ritz

$$\mathrm{d}\sigma^{pp\to A^{'}+X}(s) \approx \mathrm{d}P_{p\to p' A'} \times \sigma_{p'p}(s^{'})$$

Production of BSM particles

Proton Bremsstrahlung

arXiv 2108.05900 Saeid Foroughi-Abari, Adam Ritz



Cancellation between Initial- and Final-State radiation!

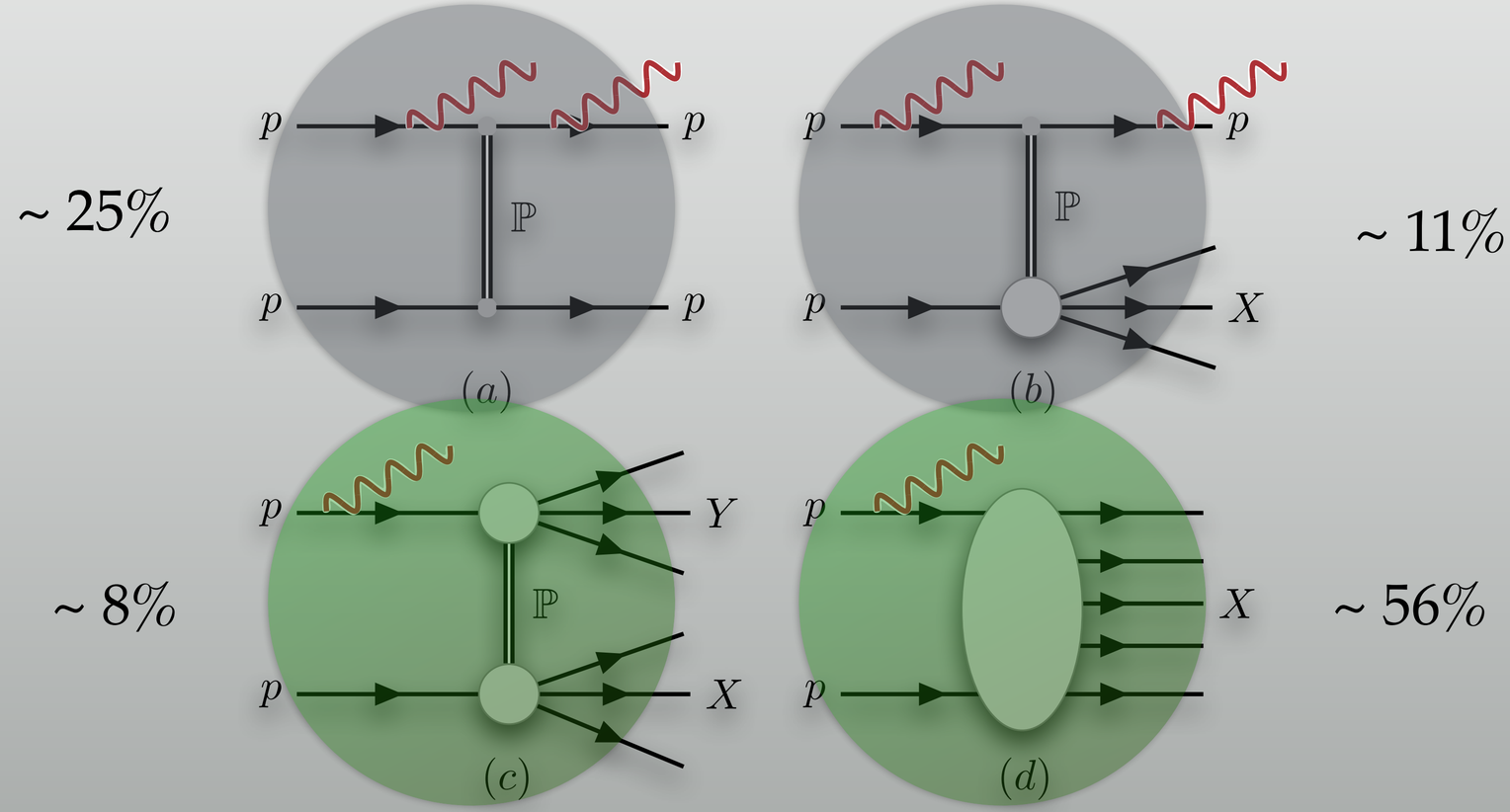
→ **Elastic and single-diffractive events suppressed!**

Production of BSM particles

Proton Bremsstrahlung

→ Recent developments:

arXiv 2108.05900 Saeid Foroughi-Abari, Adam Ritz

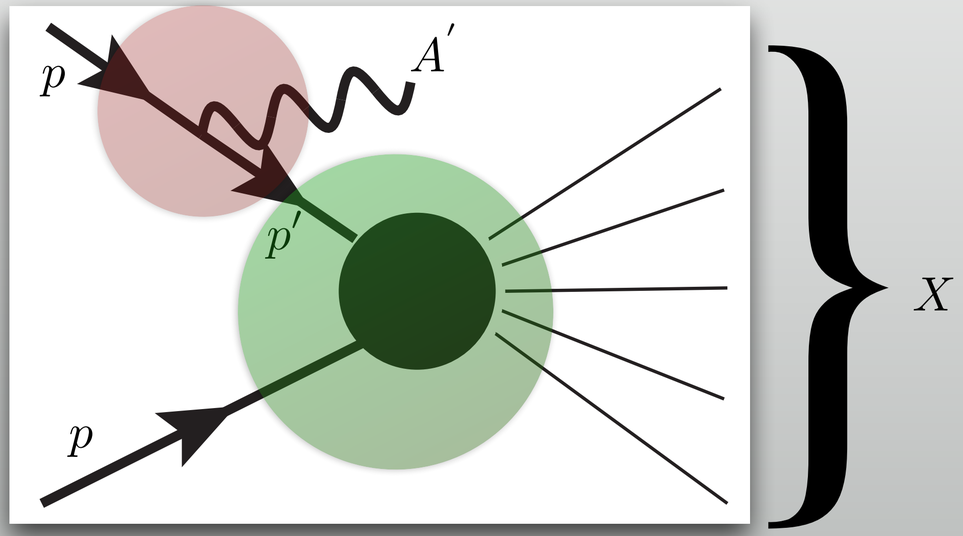


Production of BSM particles

Proton Bremsstrahlung

→ Work in progress:

Saeid Foroughi-Abari, PR, Adam Ritz

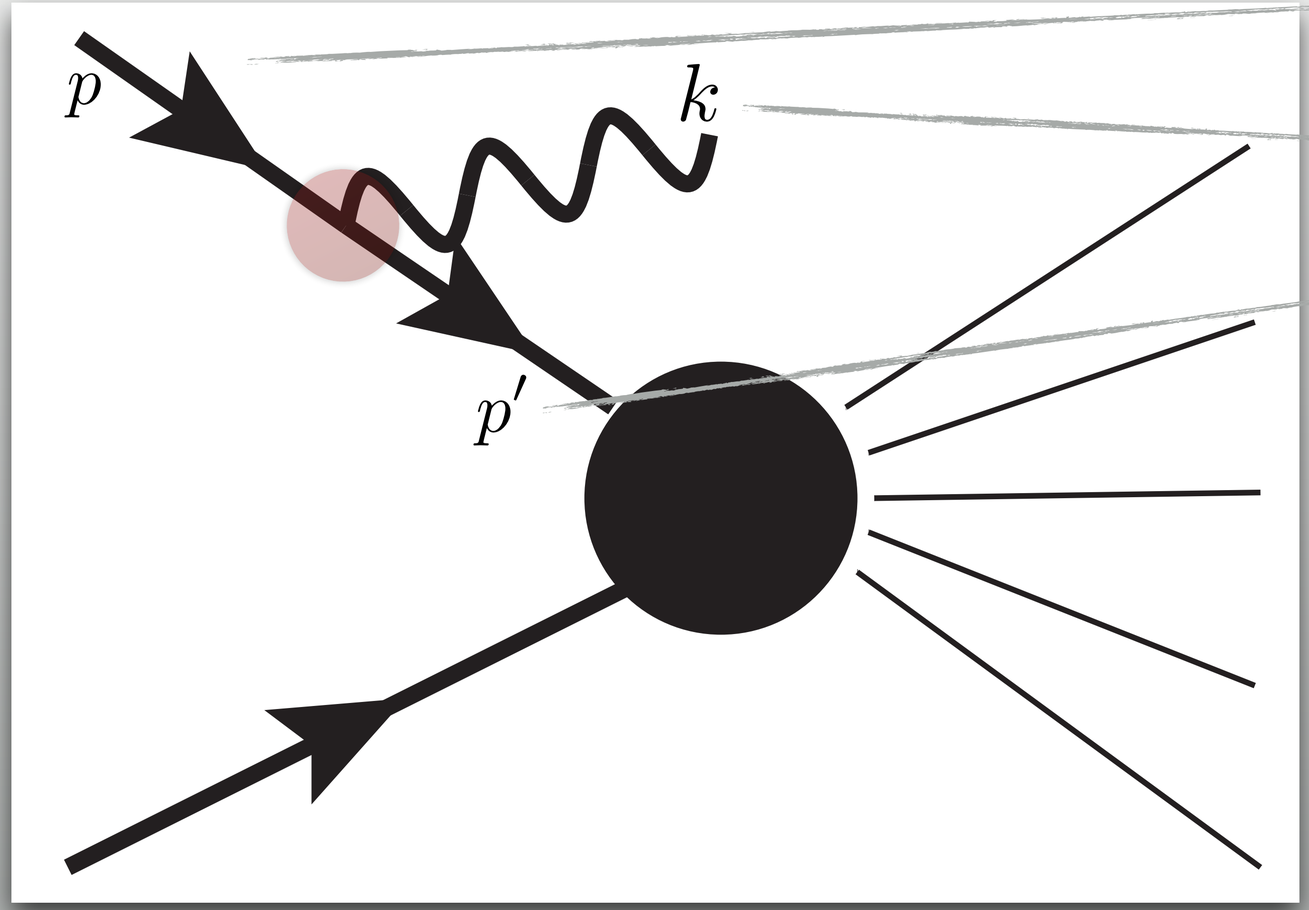


$$\mathrm{d}\sigma^{pp\to A' + X}(s) \approx \mathrm{d}P_{p\to p' A'} \times \sigma_{p' p}(s')$$

Improved description of splitting vertex:

- Splitting function
- Form factors

Splitting functions



Infinite momentum frame:

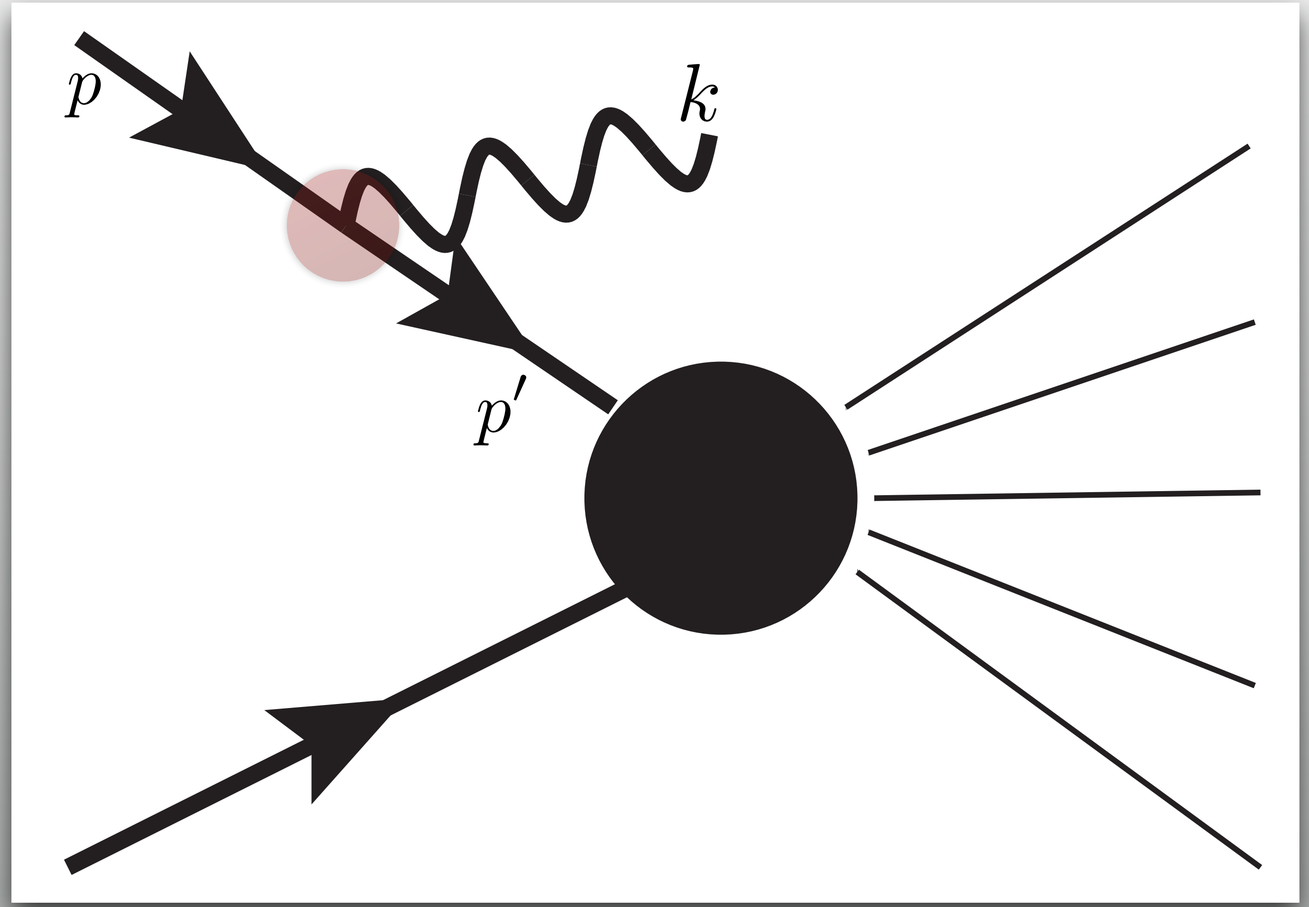
$$p^\mu = (p_p + \frac{m_p^2}{2p_p}, \mathbf{0}, p_p),$$

$$k^\mu = (zp_p + \frac{p_T^2 + m_{A'}^2}{2zp_p}, \mathbf{p}_T, zp_p)$$

$$p'^\mu = ((1-z)p_p + \frac{p_T^2 + m_p^2}{2p_p(1-z)}, -\mathbf{p}_T, (1-z)p_p)$$

$$d\mathcal{P}_{p\to p'\,A'} \equiv w(z, p_T^2) dz dp_T^2$$

Splitting functions



$$d\mathcal{P}_{p\to p'\,A'} \equiv w(z,p_T^2)\,dz\,dp_T^2$$

Straightforward calculation:

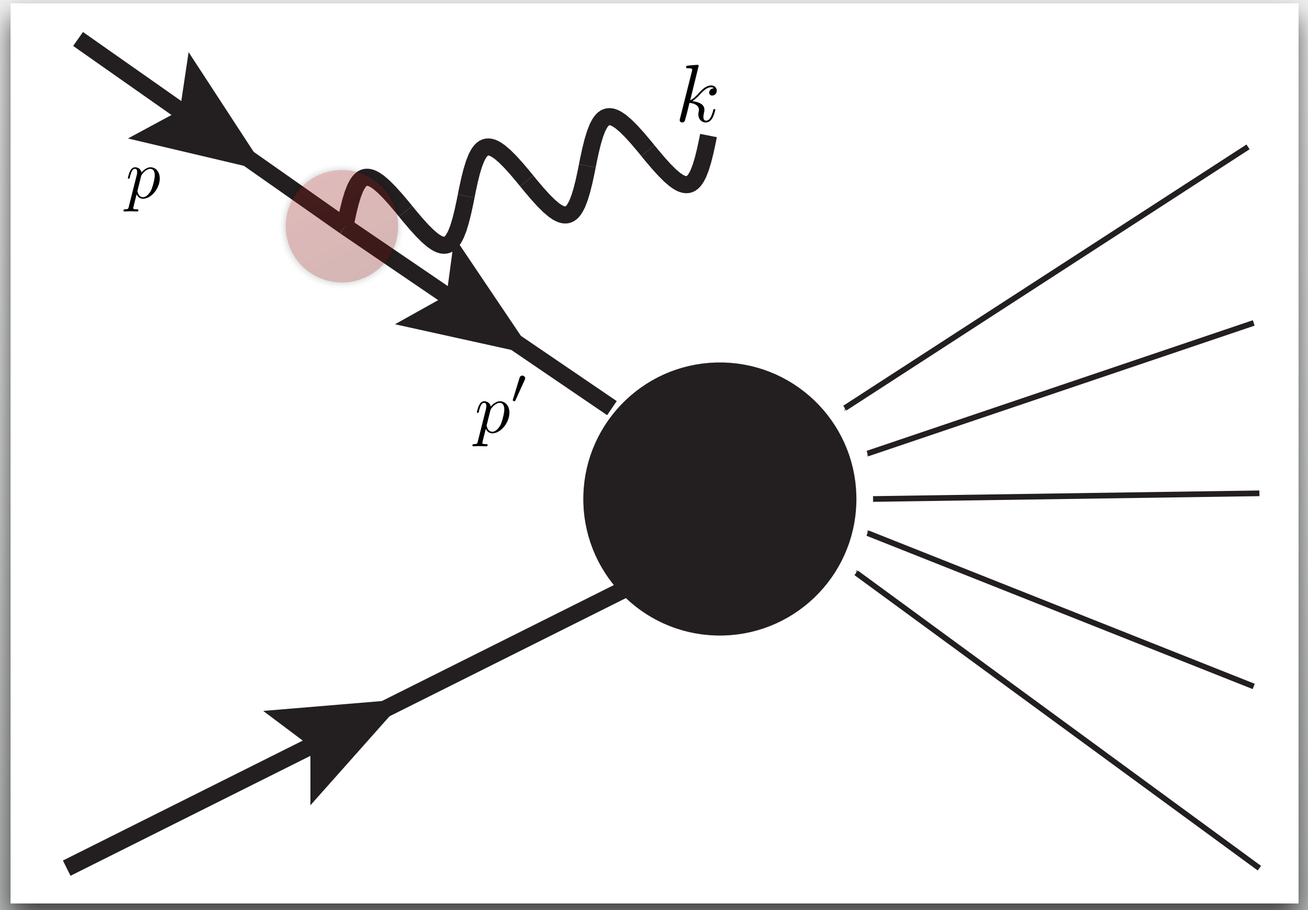
$$w_V(z,p_T^2) = \frac{\alpha\epsilon^2}{2\pi H}\left[z - z(1-z)\left(\frac{2m_p^2+m_{A'}^2}{H}\right) + \frac{H}{2zm_{A'}^2}\right]$$

with $H(z,p_T^2) \equiv p_T^2 + z^2 m_p^2 + (1-z)m_{A'}^2$

divergent for $m_{A'} \to 0$

→ Dawson approach

Splitting functions



$$d\mathcal{P}_{p\to p'A'} \equiv w(z,p_T^2)dzdp_T^2$$

Dawson approach:

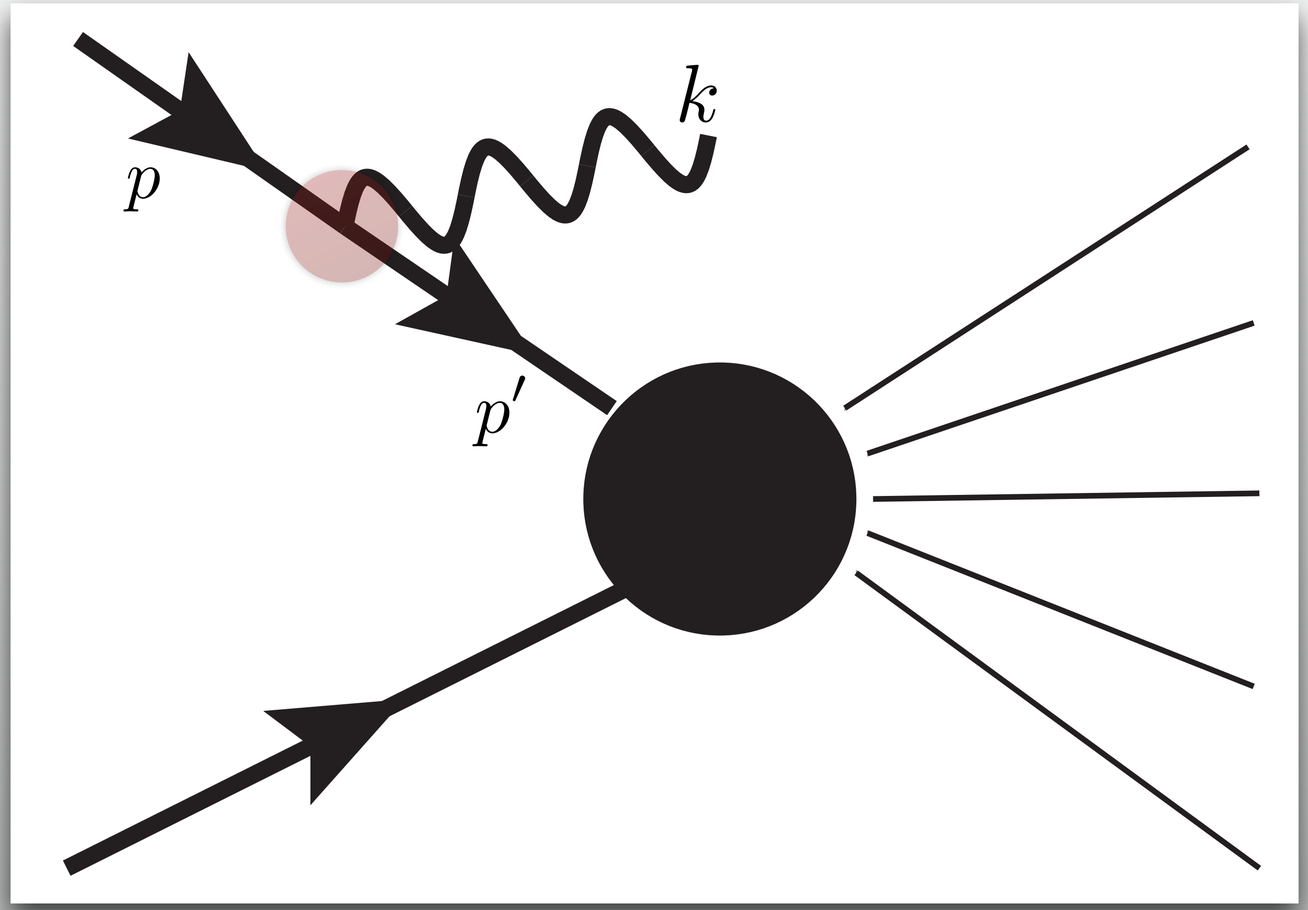
$$\bar{u}^r(p')\not{k}u^s(p) = 0$$

Use

$$\varepsilon_0^\mu(k) \equiv \varepsilon_L^\mu(k) - \frac{k^\mu}{m_{A'}} = \frac{m_{A'}}{(k_0+|\vec{k}|)}(-1,\vec{k}/|\vec{k}|)$$

$$\rightarrow\ w_V^{\rm eff}(z,p_T^2) = \frac{\alpha\epsilon^2}{2\pi H}\left[\frac{1+(1-z)^2}{z} - z(1-z)\left(\frac{2m_p^2+m_{A'}^2}{H}\right)\right]$$

Splitting functions



$$d\mathcal{P}_{p\to p'A'} \equiv w(z,p_T^2)dzdp_T^2$$

Dawson approach:

$$\bar{u}^r(p')\not{k}u^s(p) = 0$$

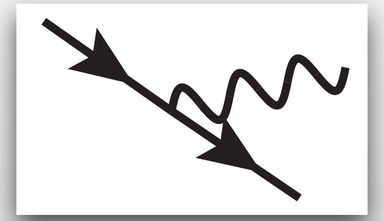
Use

$$\varepsilon_0^\mu(k) \equiv \varepsilon_L^\mu(k) - \frac{k^\mu}{m_{A'}} = \frac{m_{A'}}{(k_0+|\vec{k}|)}(-1,\vec{k}/|\vec{k}|)$$

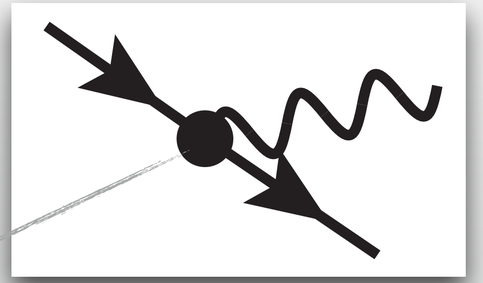
$$m_{A'}, m_p \to 0$$

$$\rightarrow\ w_V^{\text{eff}}(z,p_T^2) = \frac{\alpha\epsilon^2}{2\pi H}\left[\frac{1+(1-z)^2}{z} - z(1-z)\left(\frac{2m_p^2+m_{A'}^2}{H}\right)\right]$$

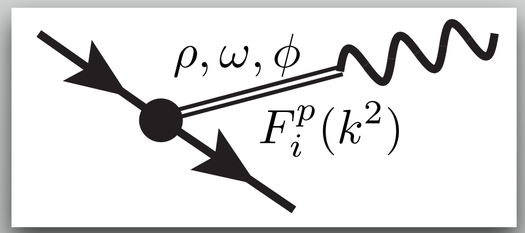
Form factors



$$\mathcal{L}_{\text{eff}} \supset \varepsilon e A'_{\mu} \bar{p} \gamma^{\mu} p$$



$$\langle N|J^{\mu}_{\text{em}}|N\rangle = \bar{u}(p') \left[\gamma^{\mu} F_1^N(k^2) + \frac{i\sigma^{\mu\nu}(p'-p)_{\nu}}{2m_N} F_2^N(k^2)\right] u(p)$$

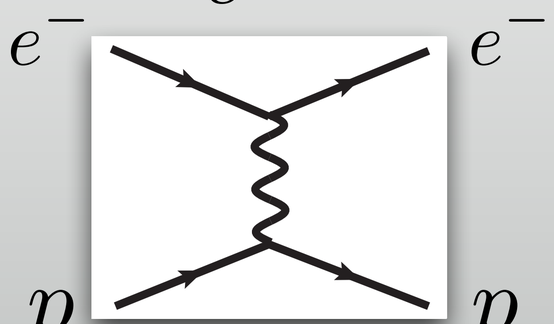


→ Hadronic resonant contributions

1601.06190 VMD, Unitarity&Analytic Model
2109.12961 Dispersion relation

Photon interactions with protons

Scattering



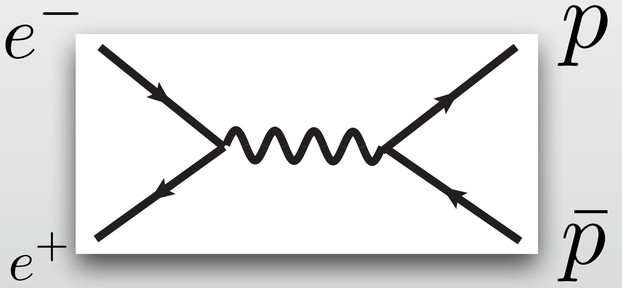
$e^- p \to e^- p$

Sachs Form factors:

$$G_E(t) = F_1(t) - \tau F_2(t)\,,$$
$$G_M(t) = F_1(t) + F_2(t)\,,$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{1}{\epsilon(1+\tau)} \underbrace{\left[\tau G_M^2(Q^2) + \epsilon G_E^2(Q^2)\right]}_{=\sigma_R},$$

Production



$e^+ e^- \to p\bar{p}$

$$\sigma_{e^+e^-\to p\bar{p}}(q^2) = \frac{4\pi\alpha^2\beta}{3q^2} C(q^2) \left[|G_M(q^2)|^2 + \frac{2m_p^2}{q^2}|G_E(q^2)|^2\right]$$
$$\equiv \frac{4\pi\alpha^2\beta}{3q^2} C(q^2) \left(1 + \frac{2m_p^2}{q^2}\right) |G_{\text{eff}}^p(q^2)|^2.$$

State of the Art Form factors

2109.12961

New insights into the nucleon's electromagnetic structure

Yong-Hui Lin,[1] Hans-Werner Hammer,[2,3] and Ulf-G. Meißner[1,4,5]

[1] *Helmholtz Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany*
[2] *Technische Universität Darmstadt, Department of Physics, 64289 Darmstadt, Germany*
[3] *ExtreMe Matter Institute EMMI and Helmholtz Forschungsakademie Hessen für FAIR (HFHF), GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[4] *Institute for Advanced Simulation and Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany*
[5] *Tbilisi State University, 0186 Tbilisi, Georgia*

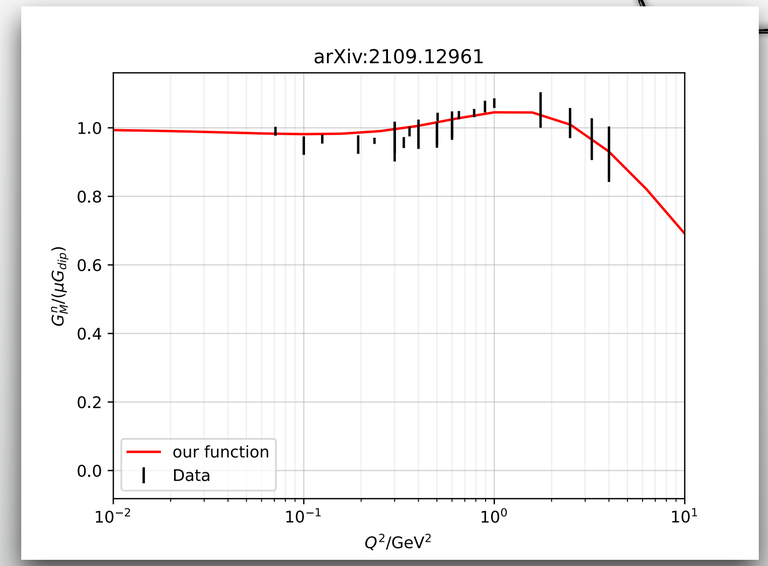
(Dated: September 28, 2021)

We present a combined analysis of the electromagnetic form factors of the nucleon in the space- and timelike regions using dispersion theory. Our framework provides a consistent description of the experimental data over the full range of momentum transfer, in line with the strictures from analyticity and unitarity. The statistical uncertainties of the extracted form factors are estimated using the bootstrap method, while systematic errors are determined from variations of the spectral functions. We also perform a high-precision extraction of the nucleon radii and find good agreement with previous analyses of spacelike data alone. For the proton charge radius, we find $r_E^p = 0.840^{+0.003+0.002}_{-0.002-0.002}$ fm, where the first error is statistical and the second one is systematic. The Zemach radius and third moment are in agreement with Lamb shift measurements and hyperfine splittings. The combined data set of space- and timelike data disfavors a zero crossing of $\mu_p G_E^p/G_M^p$ in the spacelike region. Finally, we discuss the status and perspectives of modulus and phase of the form factors in the timelike region in the context of future experiments as well as the onset of perturbative QCD.

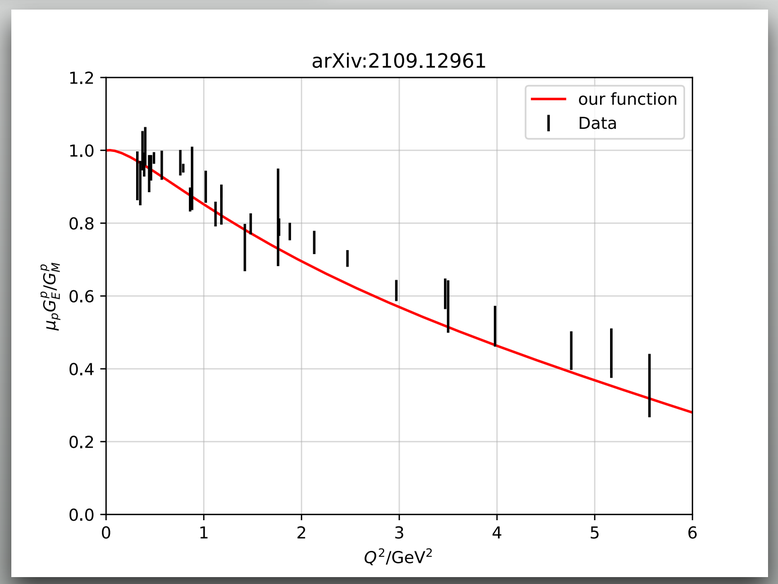
- Continuum contributions $\pi\pi, K\bar{K}, \rho\pi$
- Vector meson poles
- Discussion of two-photon effect
- Fit to space- and timelike data
- …

State of the Art Form factors

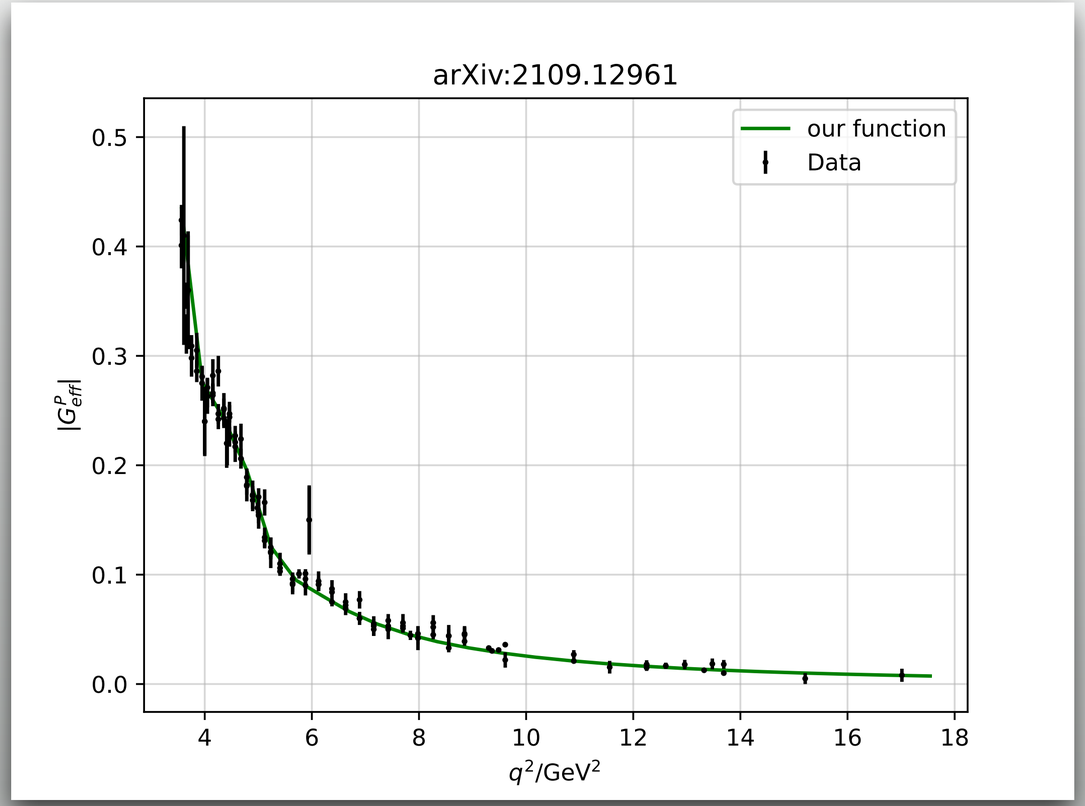
2109.12961



Scattering

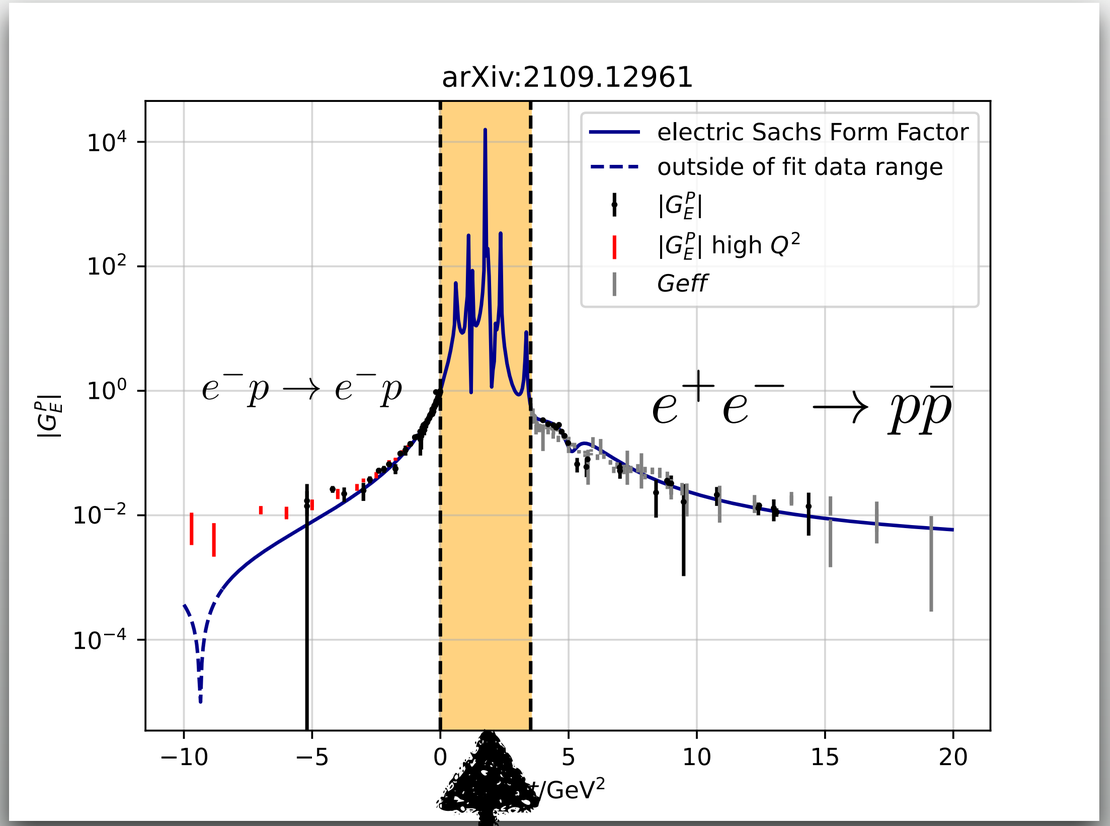


Production

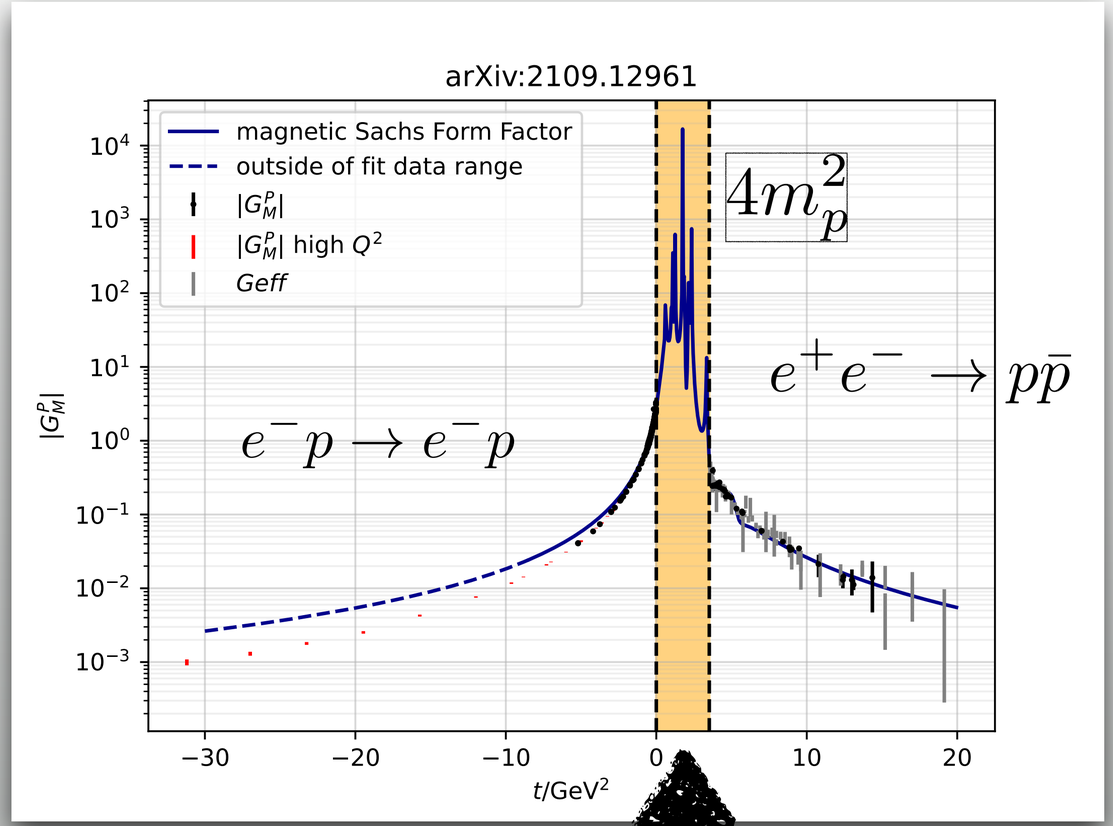


State of the Art Form factors

2109.12961



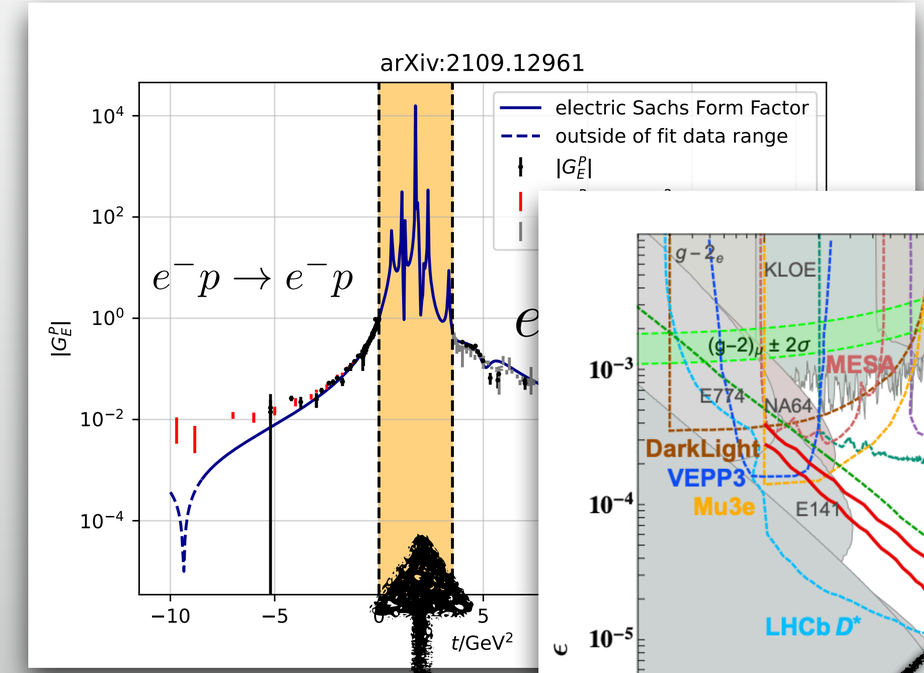
Unphysical region



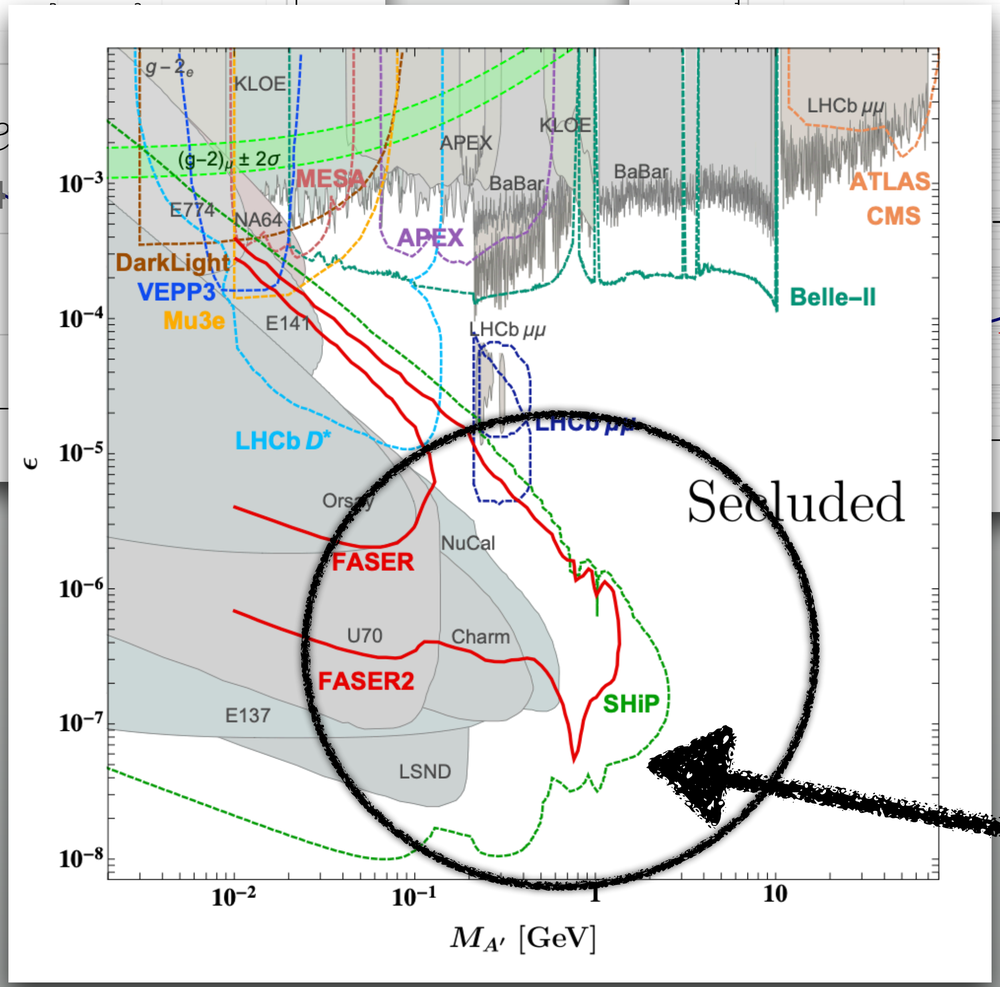
Unphysical region

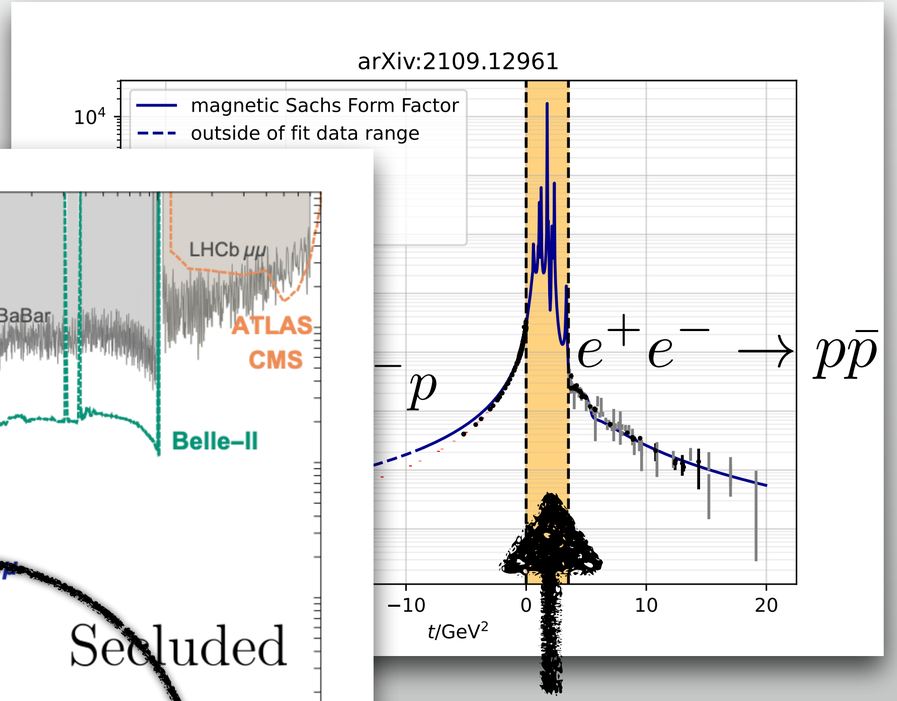
State of the Art Form factors

2109.12961



Unphysical region

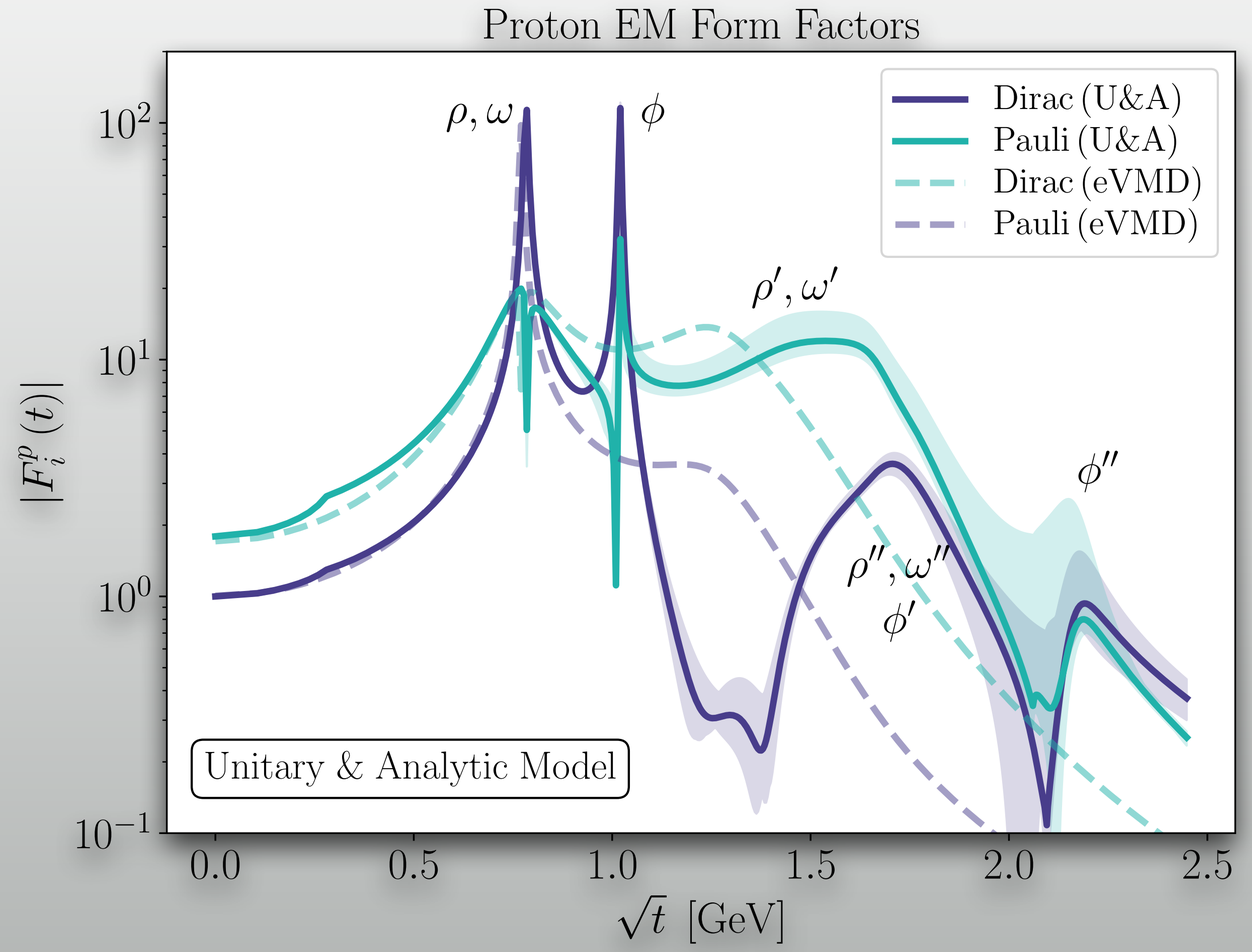




Unphysical region

Our region of interest!

Form factors



Based on PDG values for **physical** vector meson poles

$$m_\omega, m_{\omega'}, m_{\omega''}, \Gamma_\omega, \Gamma_{\omega'}, \Gamma_{\omega''}$$
$$m_\rho, m_{\rho'}, m_{\rho''}, \Gamma_\rho, \Gamma_{\rho'}, \Gamma_{\rho''}$$
$$m_\phi, m_{\phi'}, m_{\phi''}, \Gamma_\phi, \Gamma_{\phi'}, \Gamma_{\phi''}$$

1601.06190 VMD, Unitarity&Analytic Model

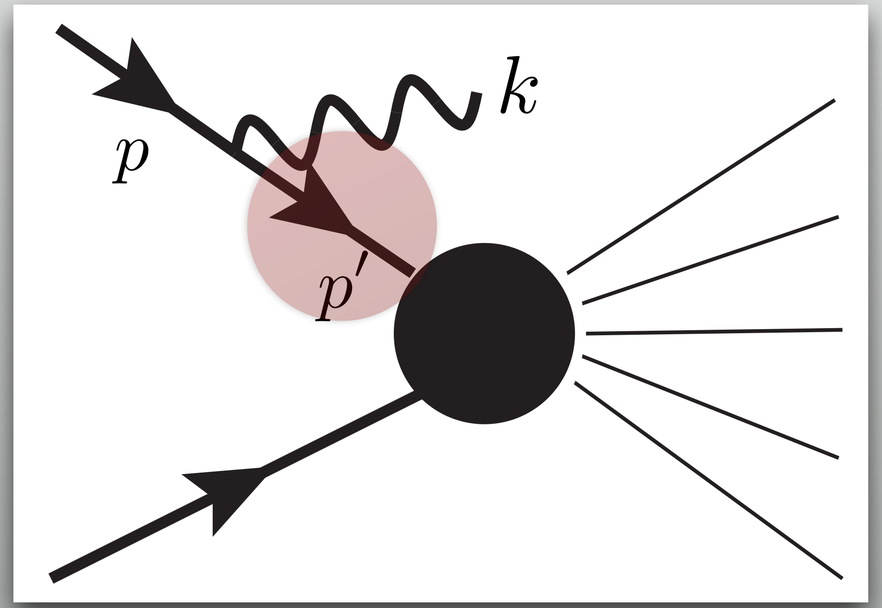
Form factors

Off-shell form factor:

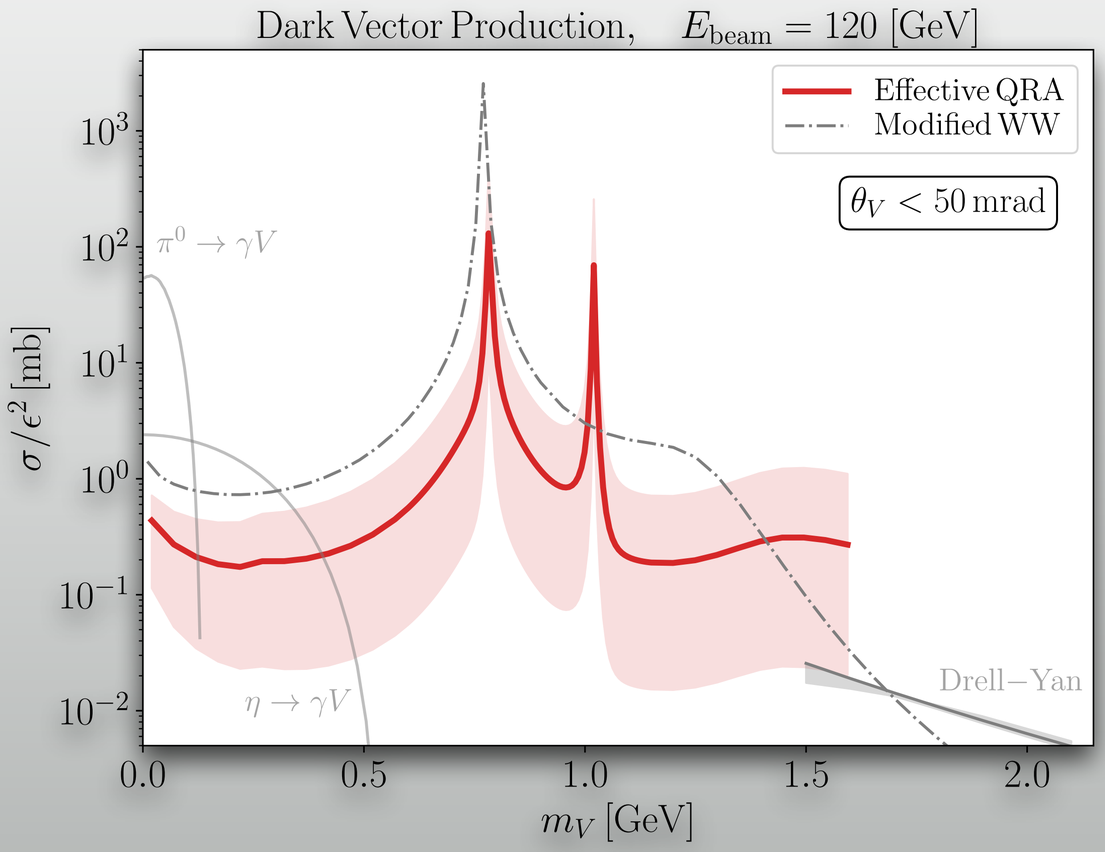
$$F_{pp'V}(p'^2) = \frac{1}{1 + (p'^2 - m_p^2)^2/\Lambda_p^4} \qquad \text{with} \quad 1\ \text{GeV} \lesssim \Lambda_p \lesssim 2\ \text{GeV}$$

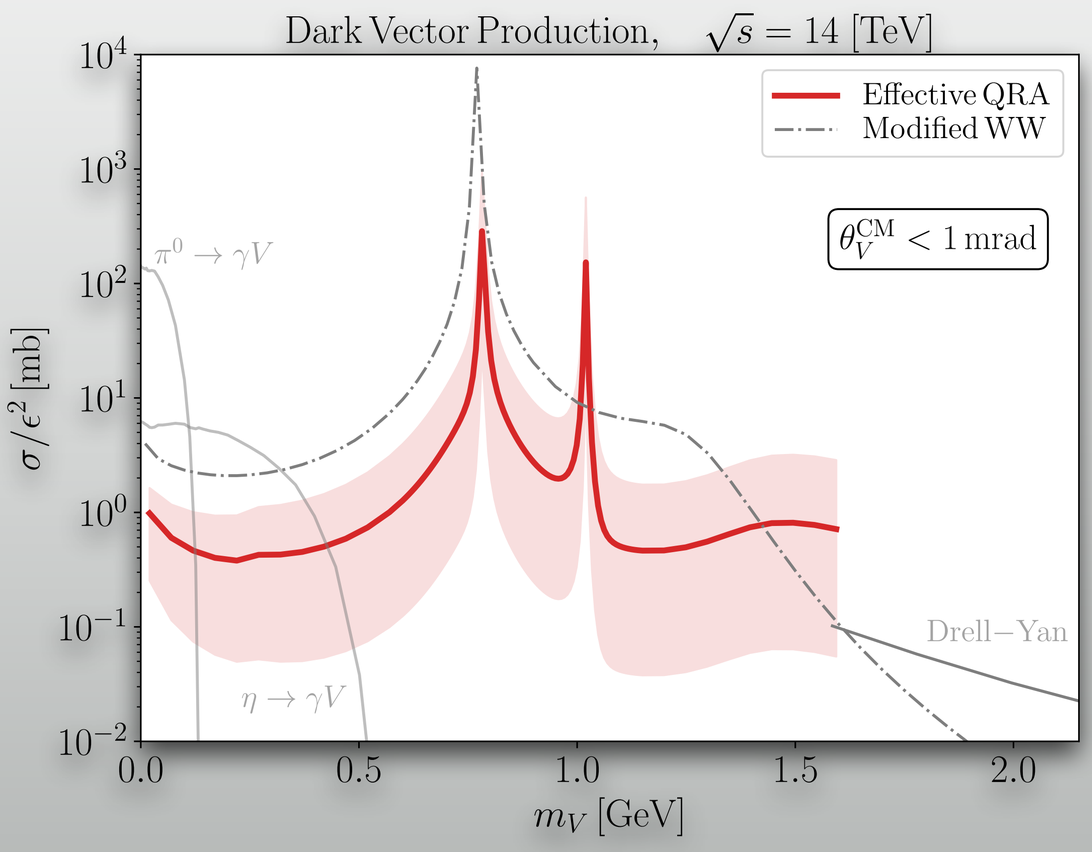
controls off-shell behaviour of intermediate proton

$$\boxed{F_i(k^2, p'^2) = F_{pp'V}(p'^2) \times F_i(k^2)}$$



Preliminary results:

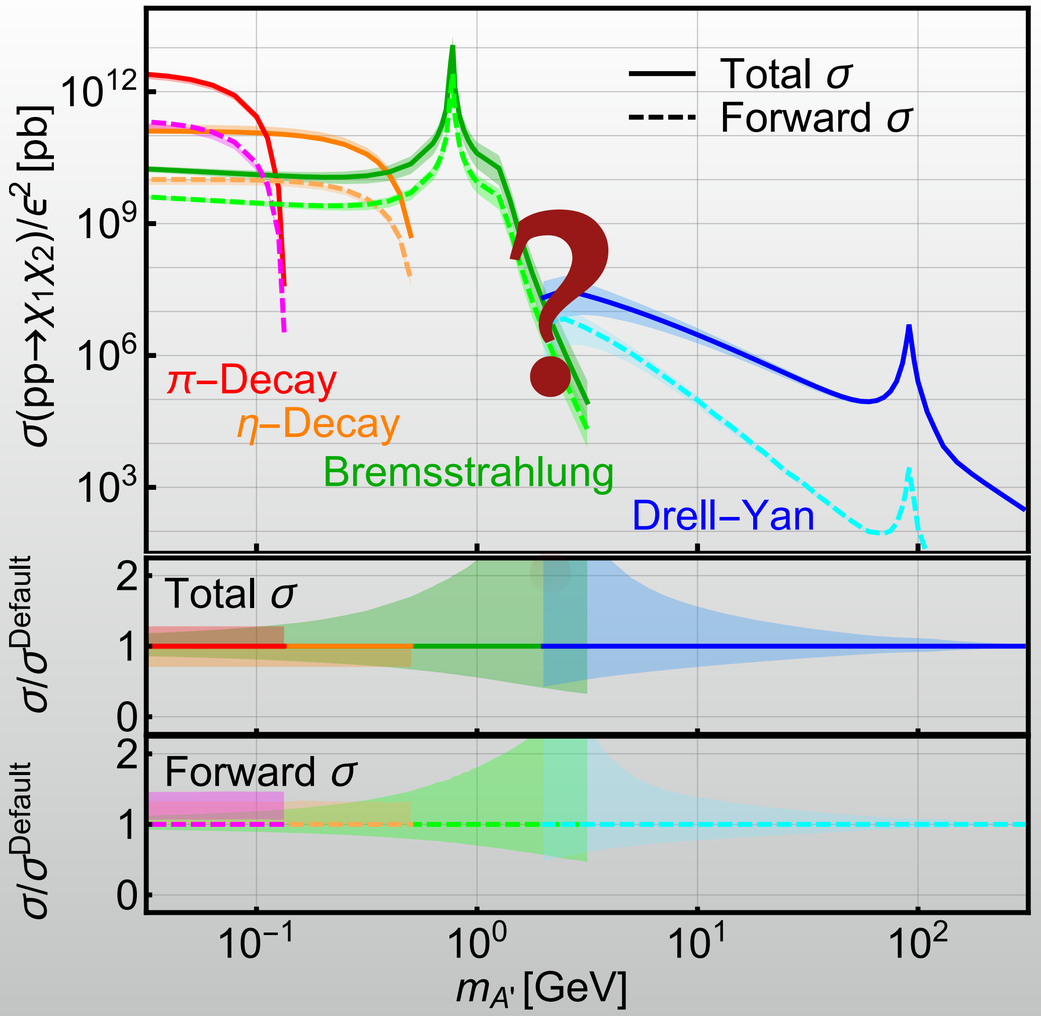




$$1\ \mathrm{GeV} \lesssim \Lambda_p \lesssim 2\ \mathrm{GeV}$$

Production of BSM particles

- Drell-Yan → sub-dominant
- Meson decays → in lower mass range
- Bremsstrahlung
- Is there more than this?



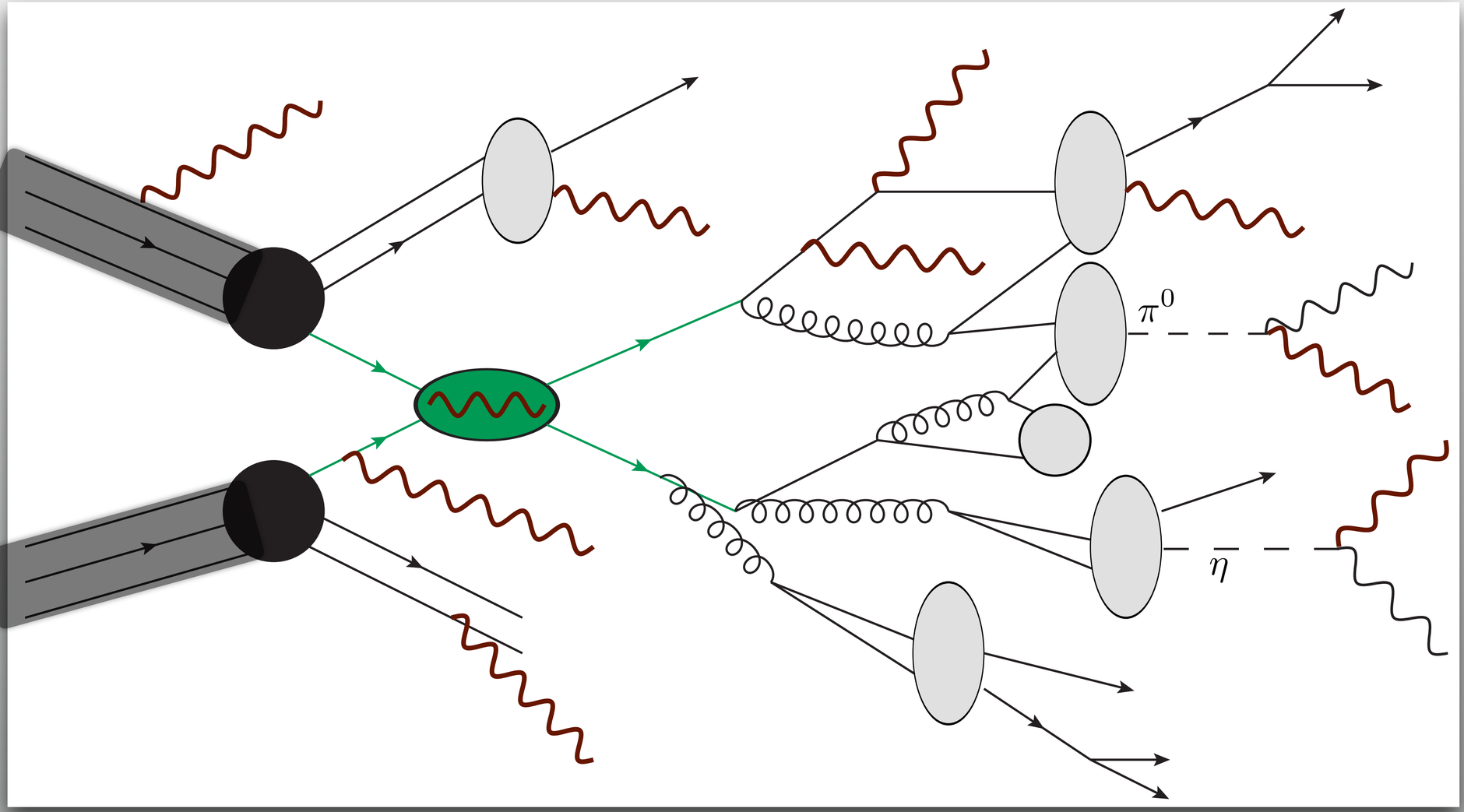
$$\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu}$$

arXiv 1810.01879

A. Berlin, F. Kling

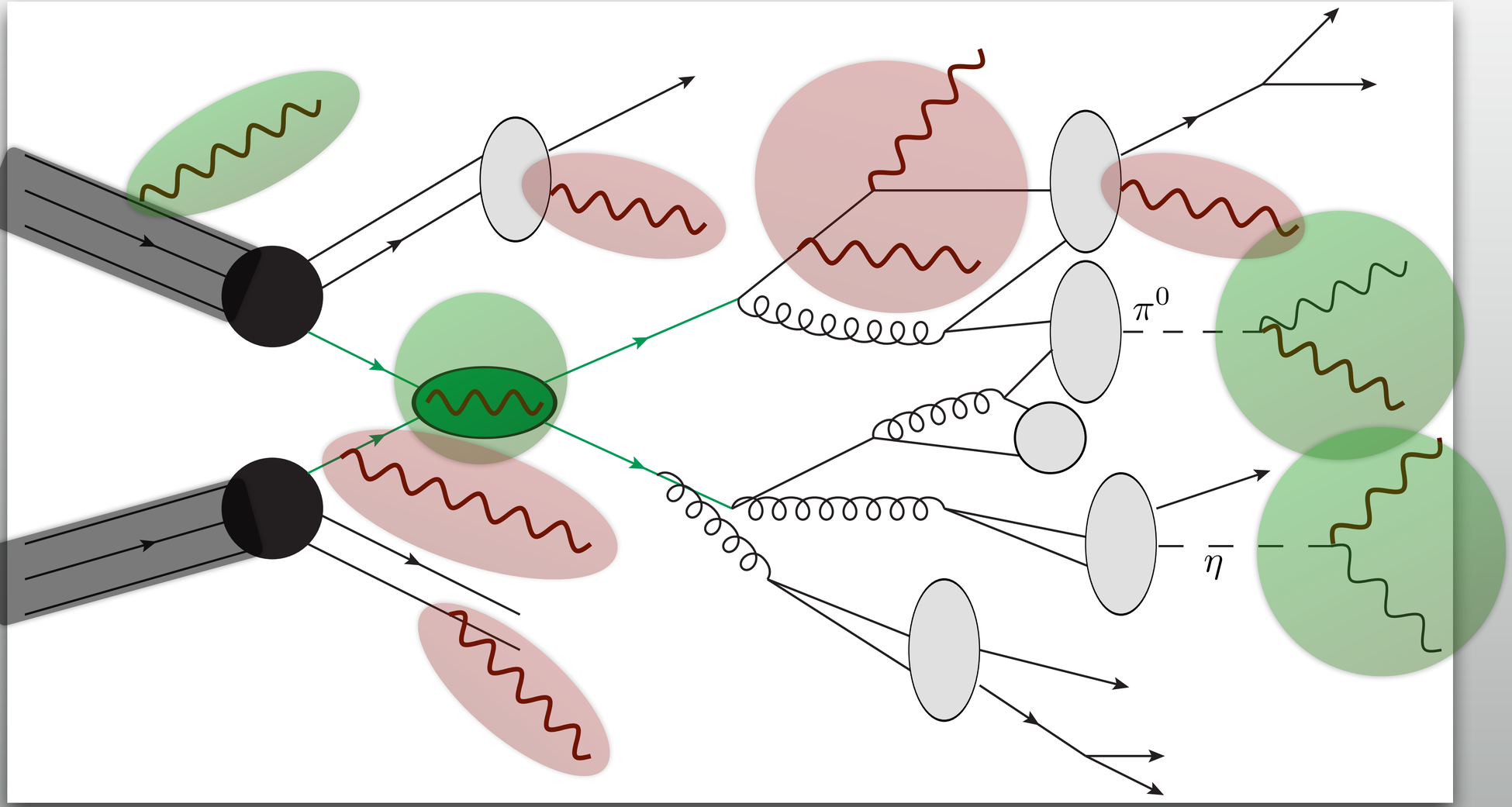
Where/how do we produce dark photons in proton-proton collisions?

$$\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu}$$



Additional Production Modes?

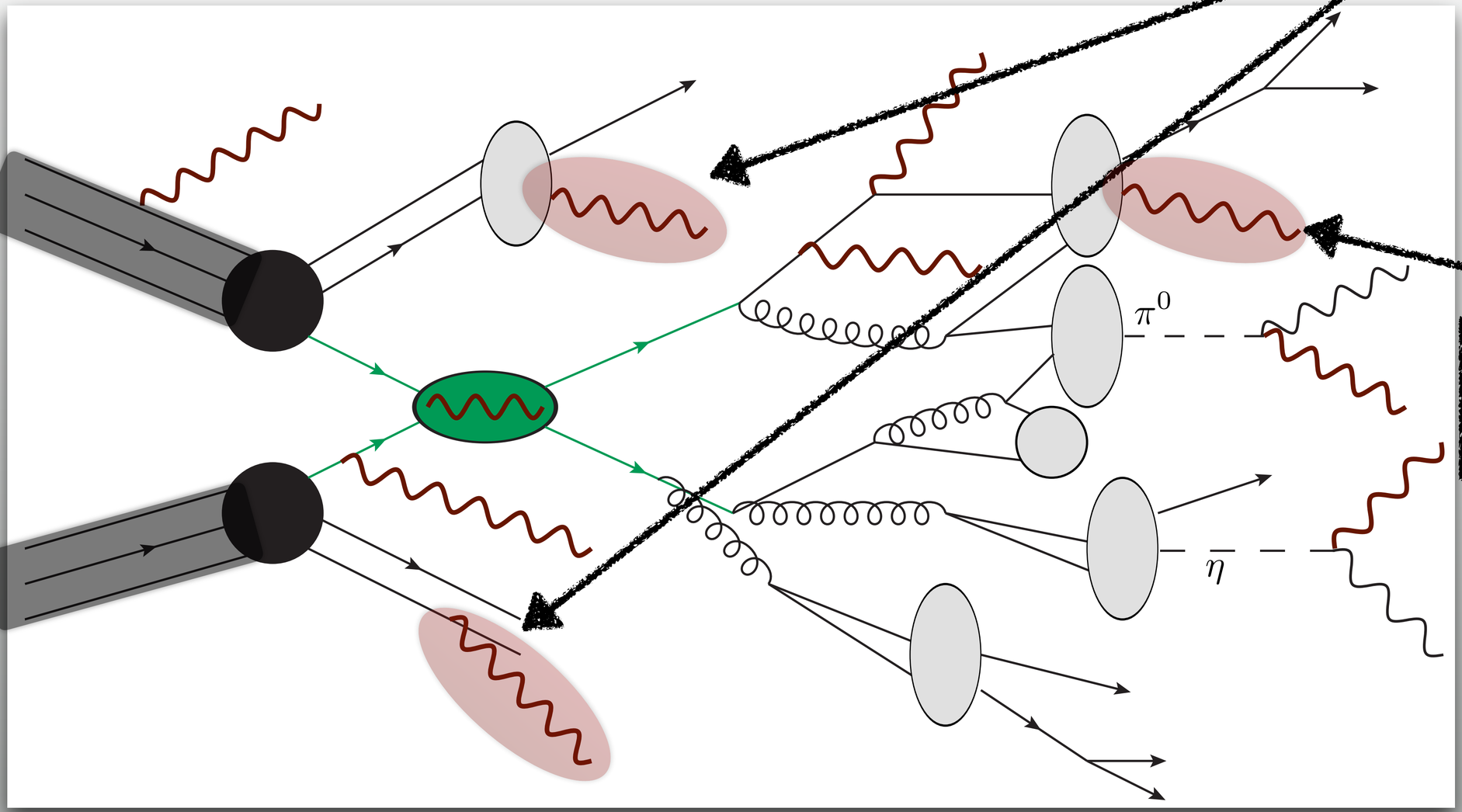
Unknown Sources



Additional Production Modes?

Beam remnants

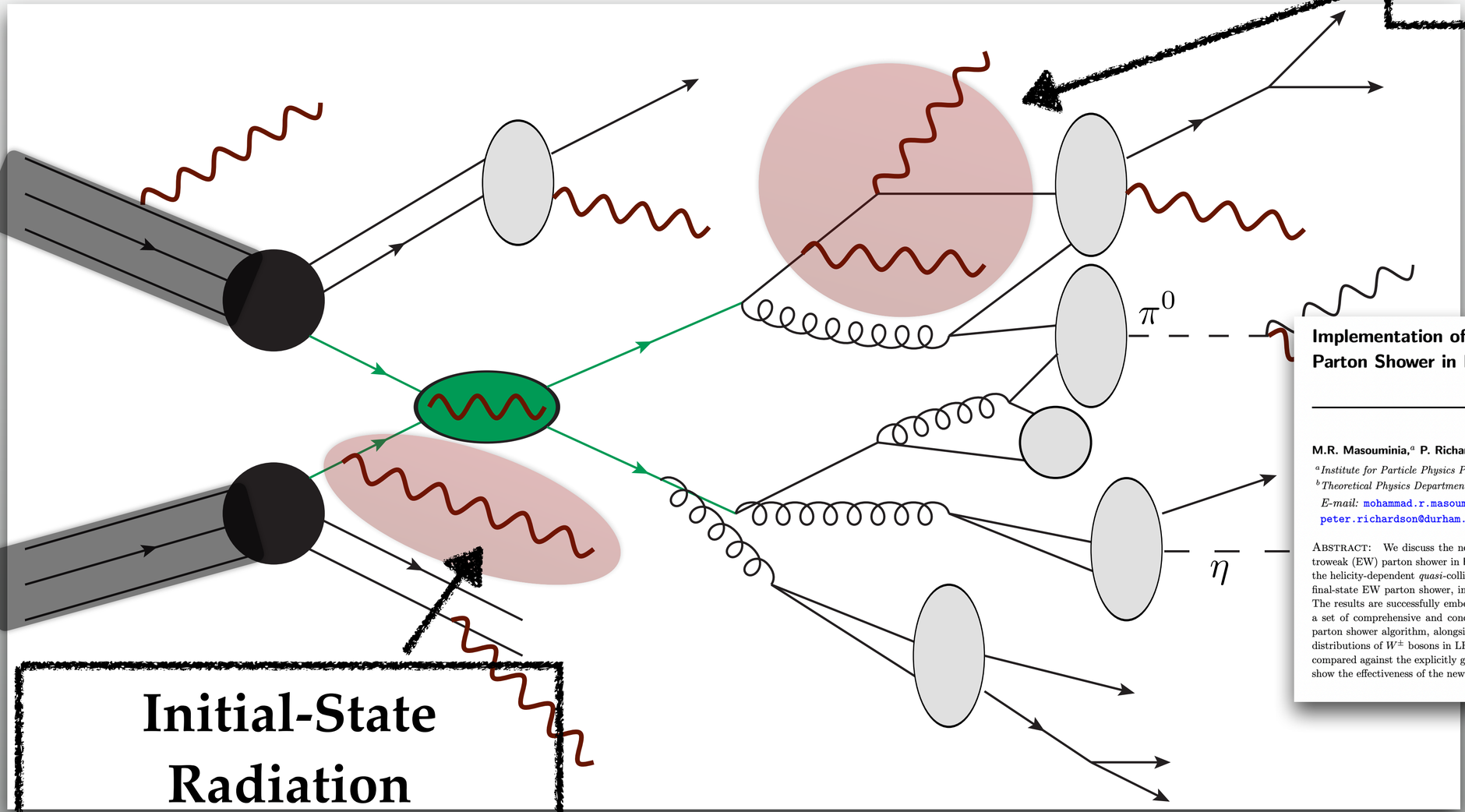
Before or as part of hadronization



Hadronization of final states

Additional Production Modes?

Final-State Radiation



Initial-State Radiation

Implementation of Angularly Ordered Electroweak Parton Shower in Herwig 7

M.R. Masouminia,[a] P. Richardson[a,b]

[a] *Institute for Particle Physics Phenomenology, Durham University, Durham, UK*
[b] *Theoretical Physics Department, CERN, Switzerland*

E-mail: mohammad.r.masouminia@durham.ac.uk, peter.richardson@durham.ac.uk

ABSTRACT: We discuss the necessary steps for implementing an angularly ordered (AO) electroweak (EW) parton shower in Herwig 7 multi-purpose event generator. This includes calculating the helicity-dependent *quasi*-collinear EW branching functions that correspond to the full range of final-state EW parton shower, in addition to the initial-state EW gauge vector boson radiations. The results are successfully embedded in the AO Herwig 7 shower algorithm and have undergone a set of comprehensive and conclusive performance tests. Furthermore, we have used this EW parton shower algorithm, alongside the existing $QCD + QED$ AO shower, to predict the angular distributions of $W^{\pm}$ bosons in LHC events with high transverse momentum jets. These results are compared against the explicitly generated underlying events as well as the existing ATLAS data to show the effectiveness of the newly implemented $QCD + QED + EW$ AO parton shower scheme.

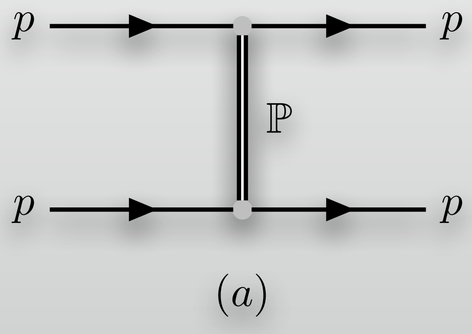
Herwig 7

arXiv 2108.10817

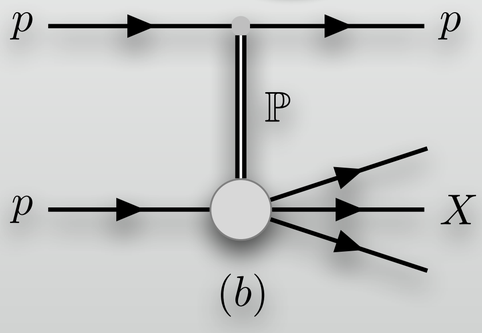
Identify relevant processes

Any process including **partons**

~ 25%



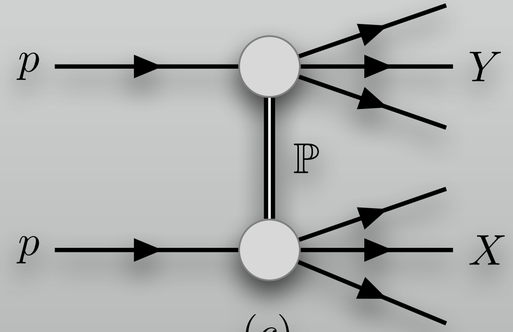
(a)



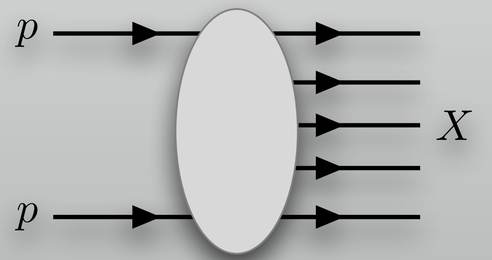
(b)

~ 11%

~ 8%



(c)



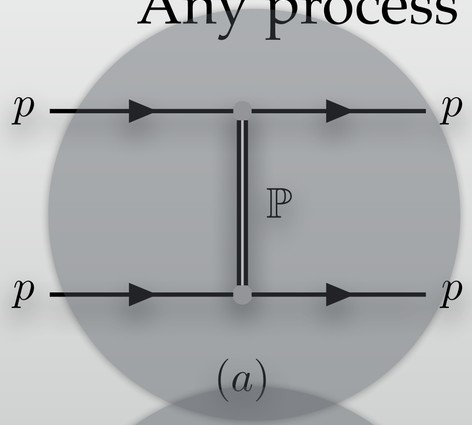
(d)

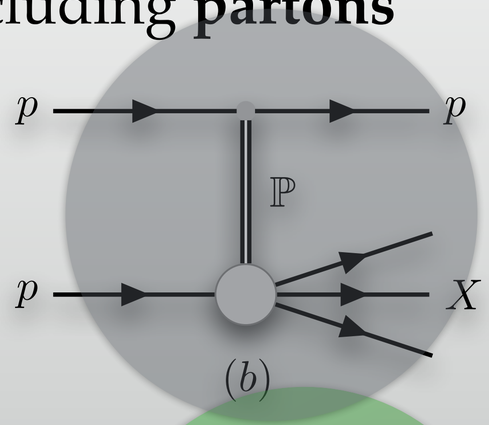
~ 56%

Identify relevant processes

Any process including **partons**

~ 25%





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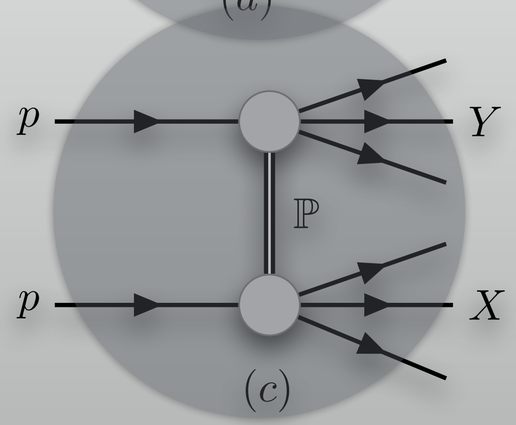
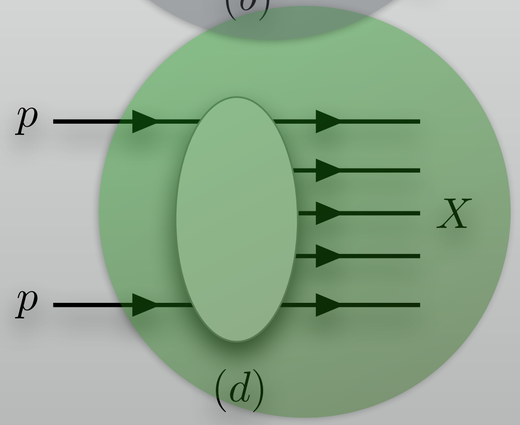




~ 56%

Modelling in Herwig

Herwig 7

Dijet-like Event $qq' \to qq' +$

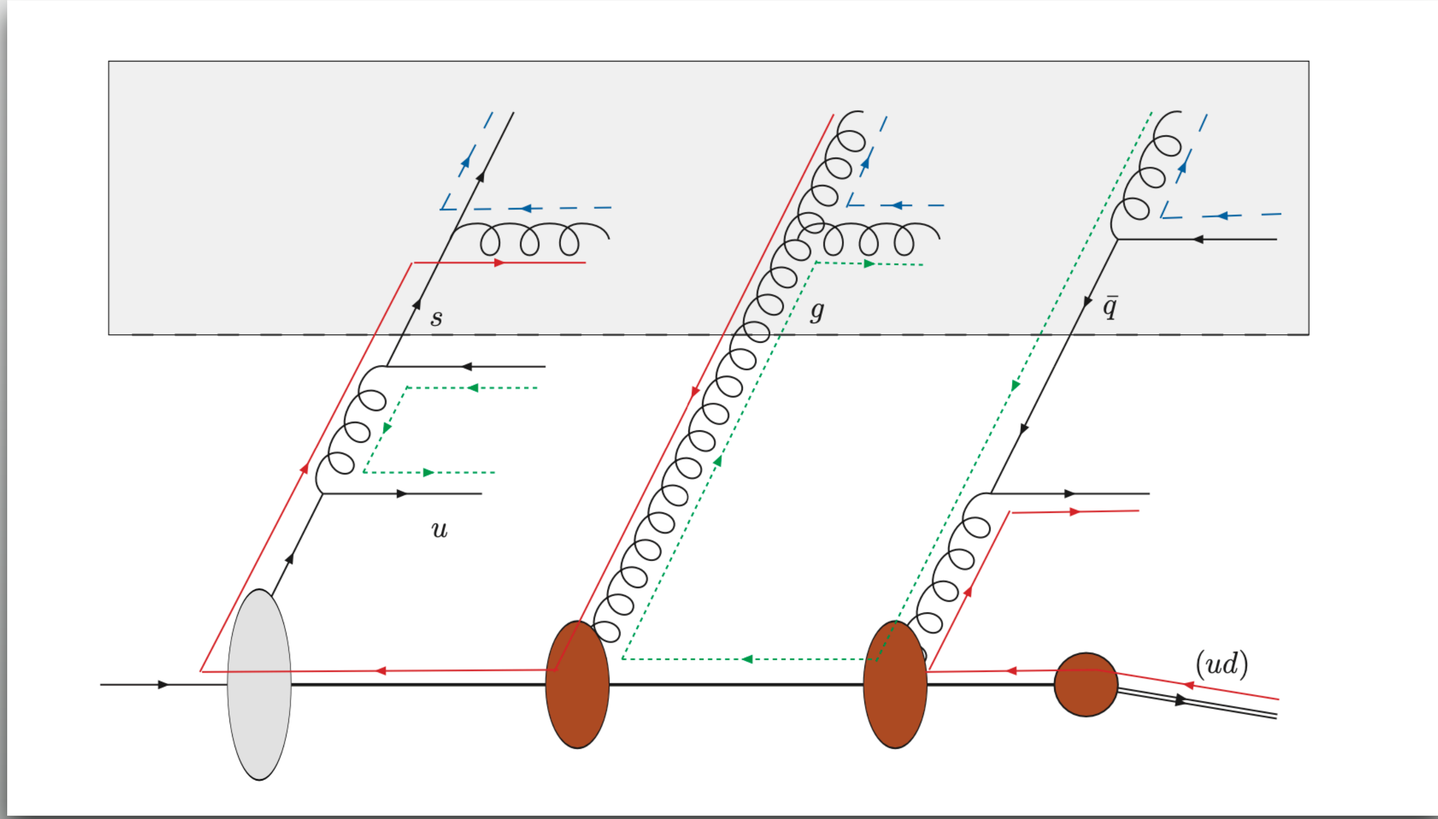
Multiple Partonic Interactions (MPI)

QCD 2-to-2

$qq \to qq$

$gg \to gg$

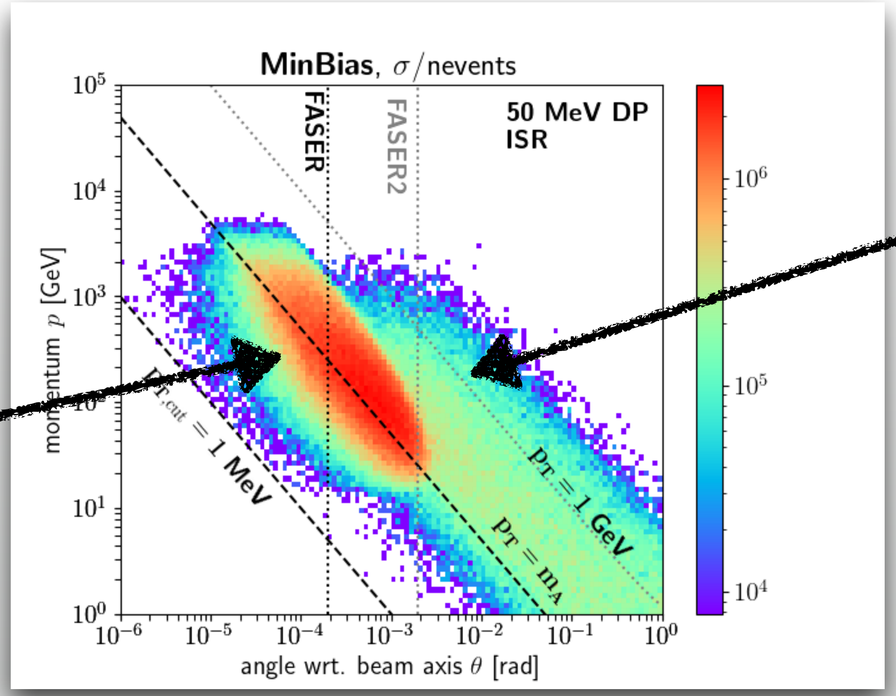
$gq \to gq \ldots$



arXiv 0803.3633

Bähr, Gieseke, Seymour

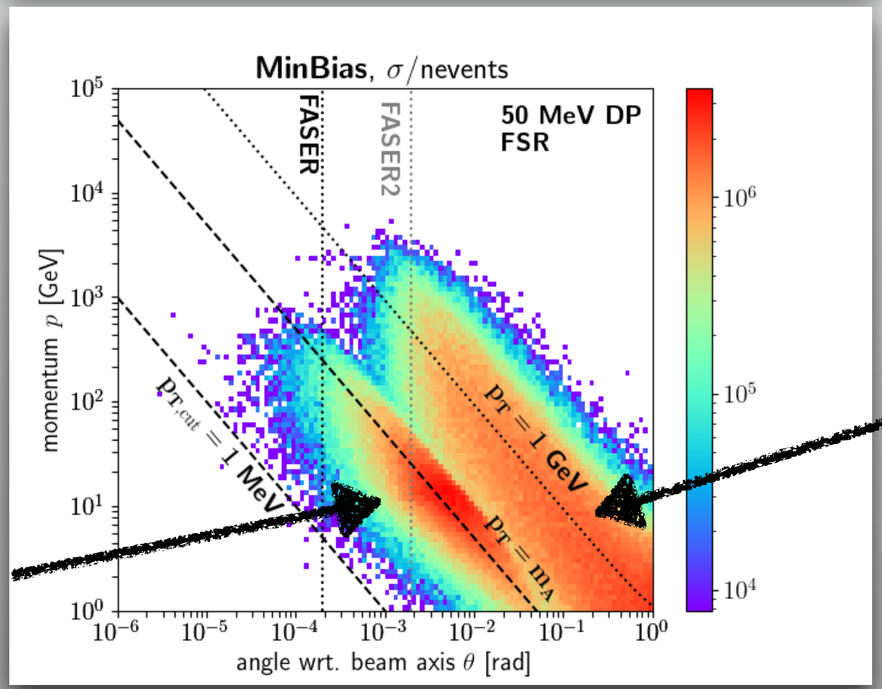
ISR



Dijet-like event

MPI

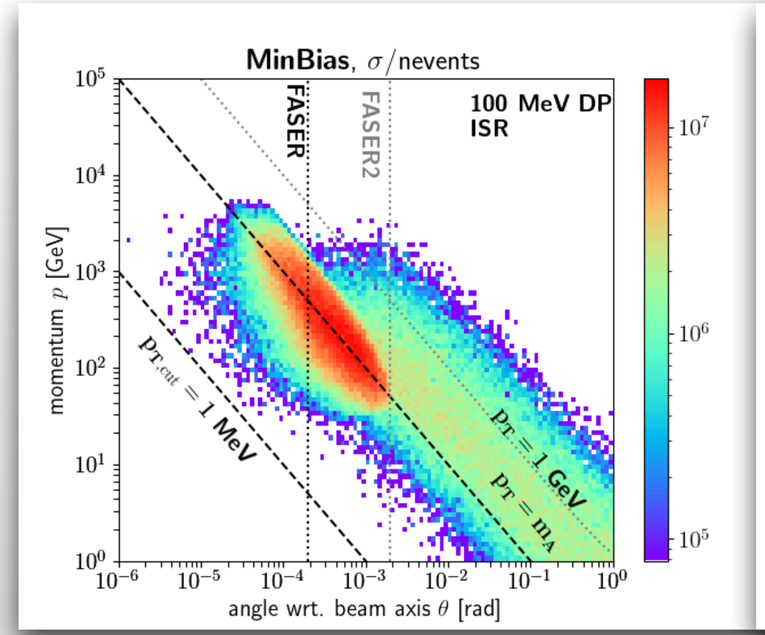
FSR

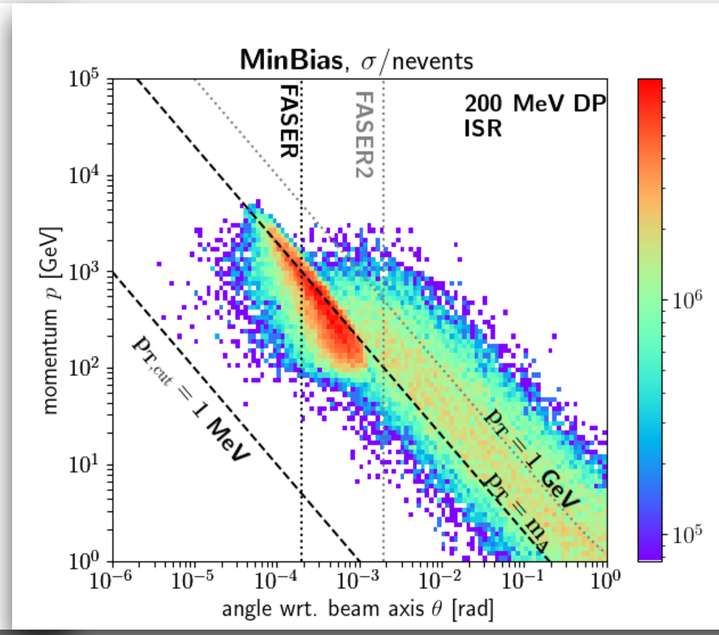


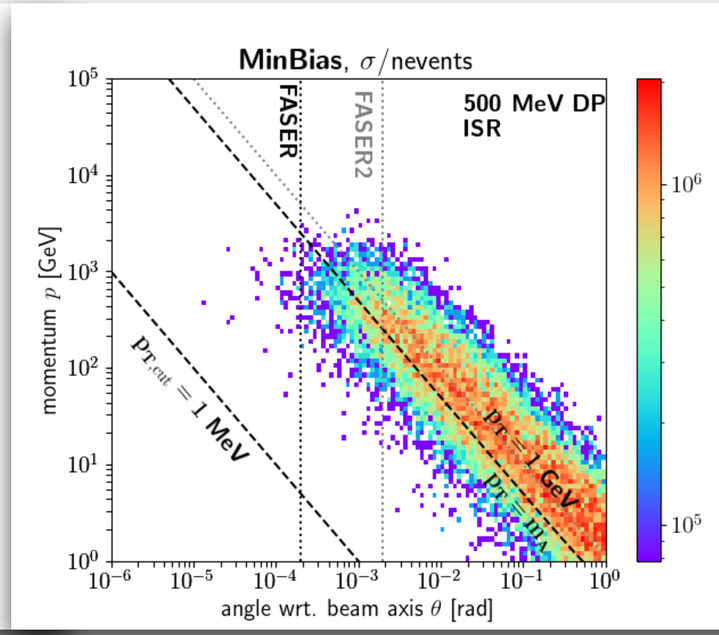
Dijet-like event

MPI

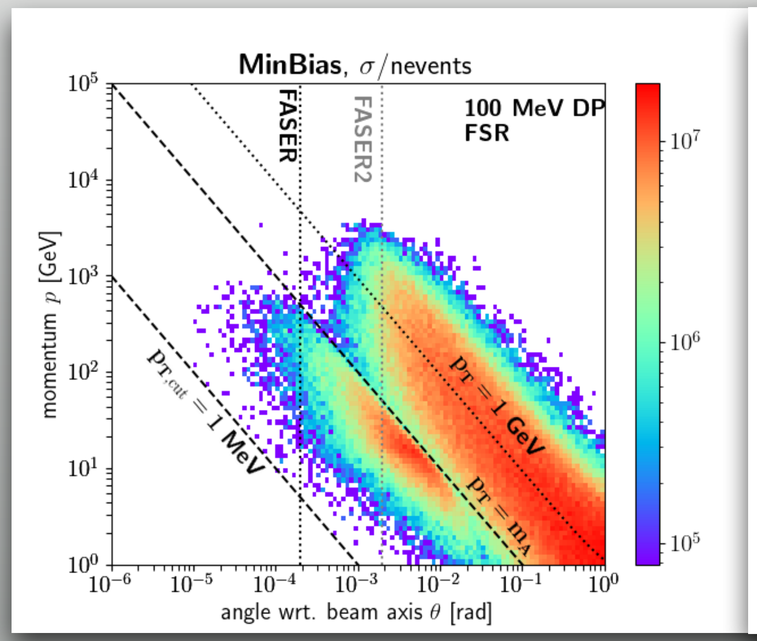
ISR


MinBias, σ/nevents
100 MeV DP
ISR
FASER
FASER2
momentum p [GeV]
angle wrt. beam axis θ [rad]
p_T,cut = 1 MeV
p_T = 1 GeV
p_T = m_A


MinBias, σ/nevents
200 MeV DP
ISR
FASER
FASER2
momentum p [GeV]
angle wrt. beam axis θ [rad]
p_T,cut = 1 MeV
p_T = 1 GeV
p_T = m_A


MinBias, σ/nevents
500 MeV DP
ISR
FASER
FASER2
momentum p [GeV]
angle wrt. beam axis θ [rad]
p_T,cut = 1 MeV
p_T = 1 GeV
p_T = m_A

FSR


MinBias, σ/nevents
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p_T,cut = 1 MeV
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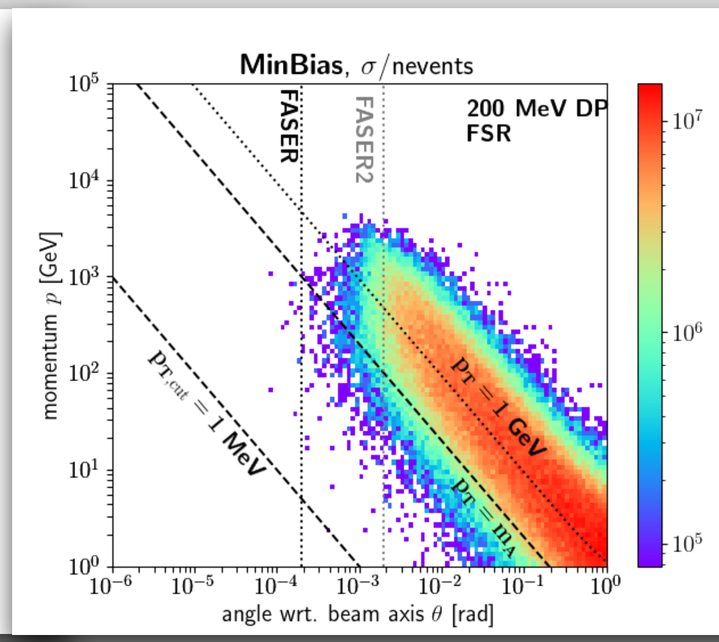
MinBias, σ/nevents
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p_T,cut = 1 MeV
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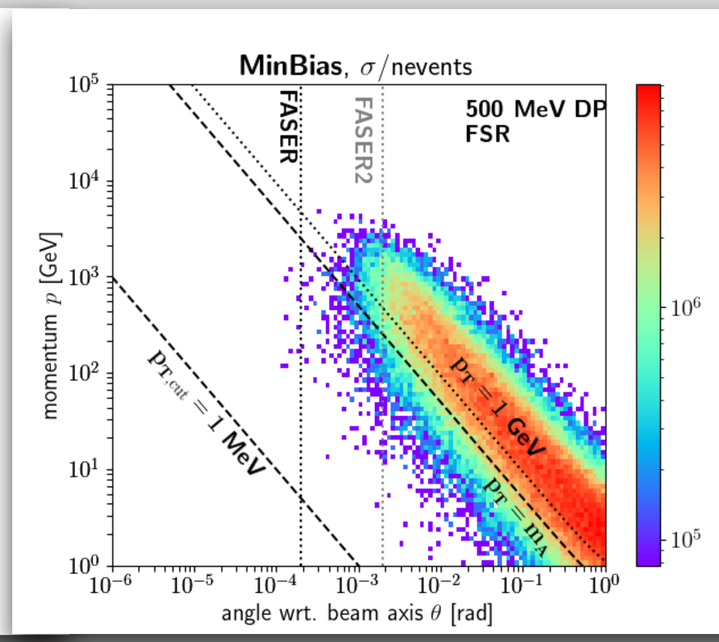
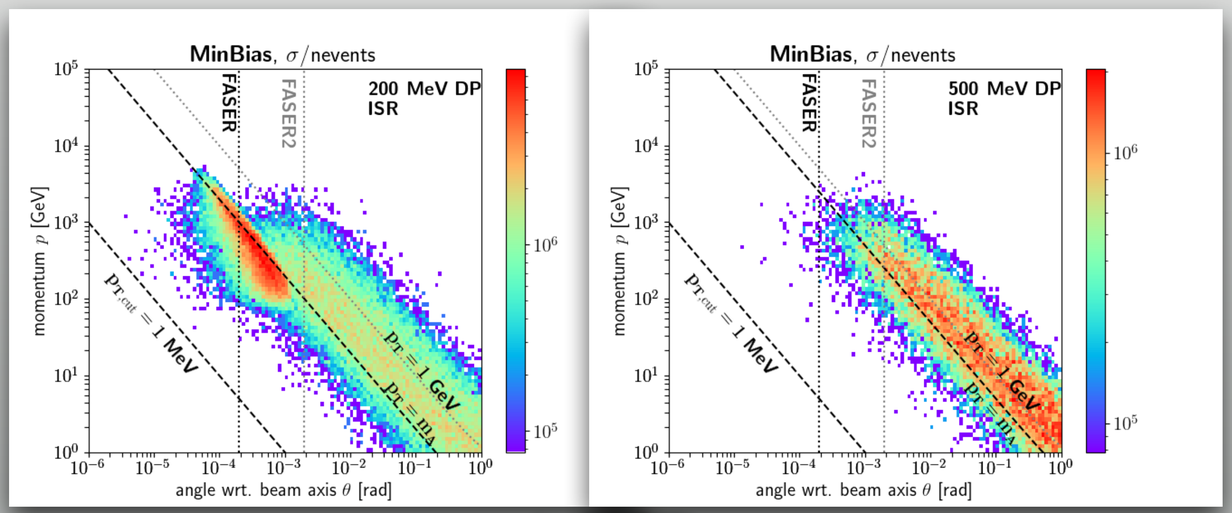
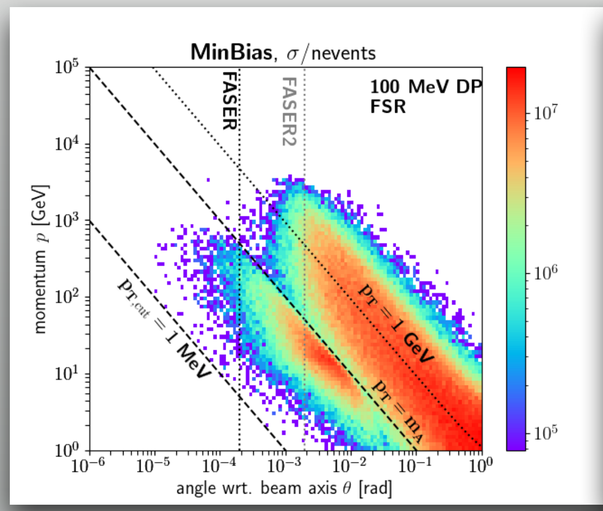

MinBias, σ/nevents
500 MeV DP
FSR
FASER
FASER2
momentum p [GeV]
angle wrt. beam axis θ [rad]
p_T,cut = 1 MeV
p_T = 1 GeV
p_T = m_A

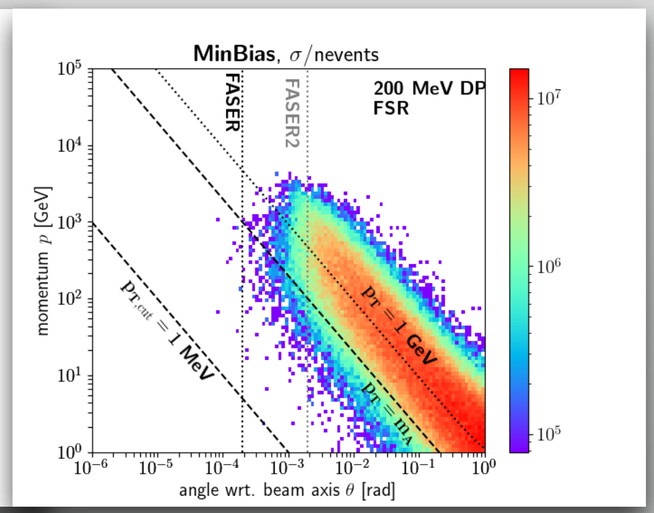
Validity

- Why does MPI vanish in both cases for higher masses and p_T?
- Are ISR and Bremsstrahlung related?



ISR

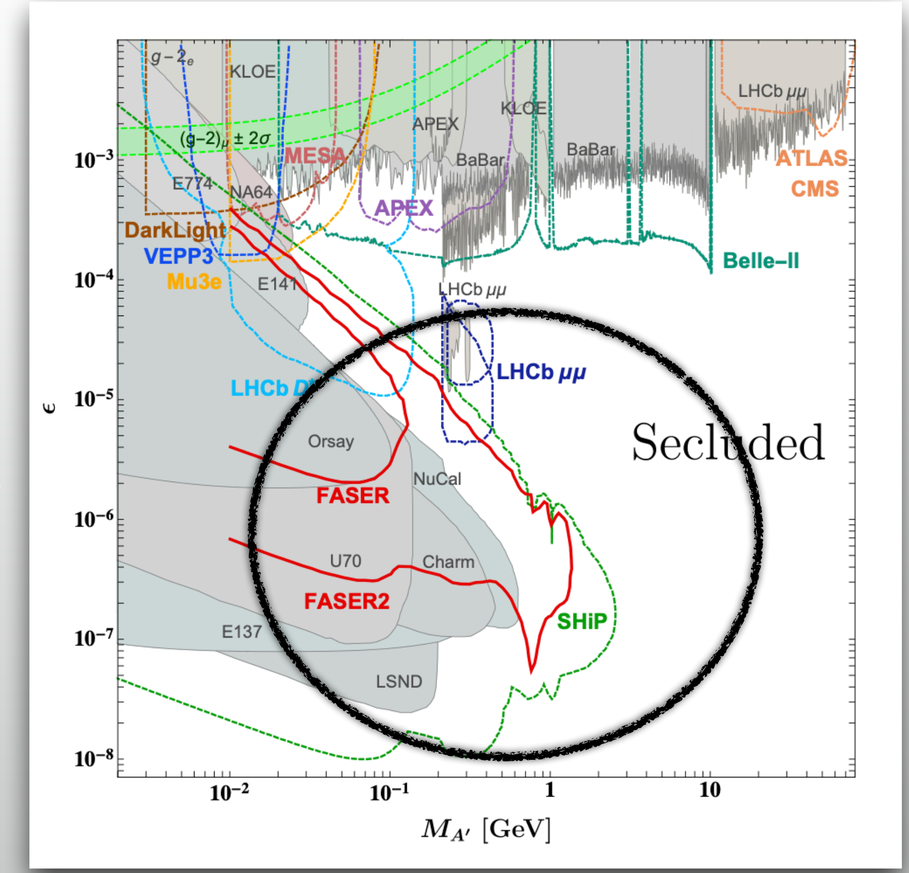




FSR

Conclusions

- Production of dark photons only partially understood!
- future experiments soon will have a more robust description of proton Bremsstrahlung



→ SHiP

→ Forward Physics Facility

\+ How relevant are additional production modes?

→ ISR and FSR + are Bremsstrahlung and ISR related?

→ Is there more to do in beam remnants and hadronization?