Benchmarking Proton Bremsstrahlung for Dark Sector Production

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FPF Theory Workshop
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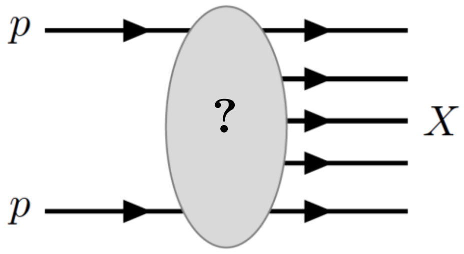
with Adam Ritz, 2108.05900 and to appear

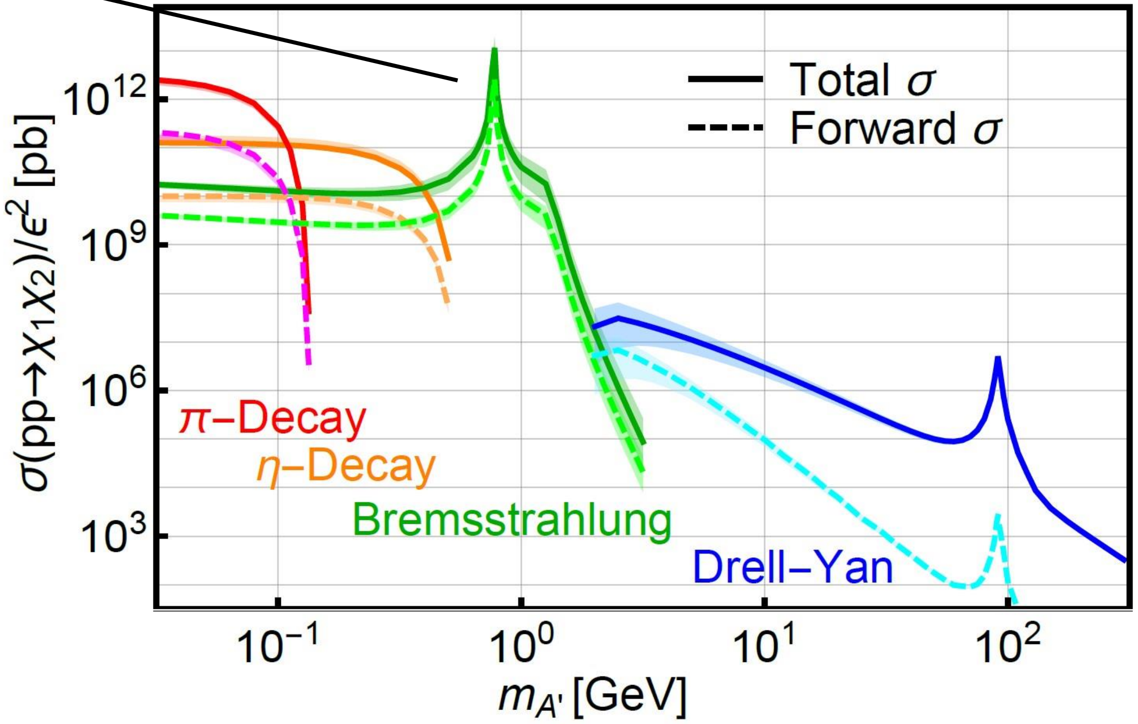
Proton Bremsstrahlung

- Primary production channel in the forward direction for intermediate mass range 0.5 - 1.5 GeV at the proton beam facilities

[deNiverville, Pospelov, Ritz ’16]

- Important regime near vectors (ρ,ω,...), and scalar (f_0,...) meson resonances



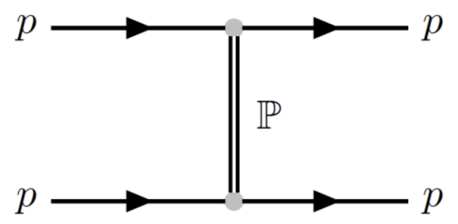


- Equivalent Particle Approx. or F.W.W.: a well-known approach in QED for relativistic collinear scattering & radiation

[Kim, Tsai ’73; Gribov & Lipatov ’72; Baier, Fadin & Khoze ’73 Altarelli & Parisi ’77; Bjorken, Essig et al ’09 …]

Elastic Scattering via Pomeron Exchange

- Donnachie & Landshoff (DL) model [DL '82, 84, 11, 13]



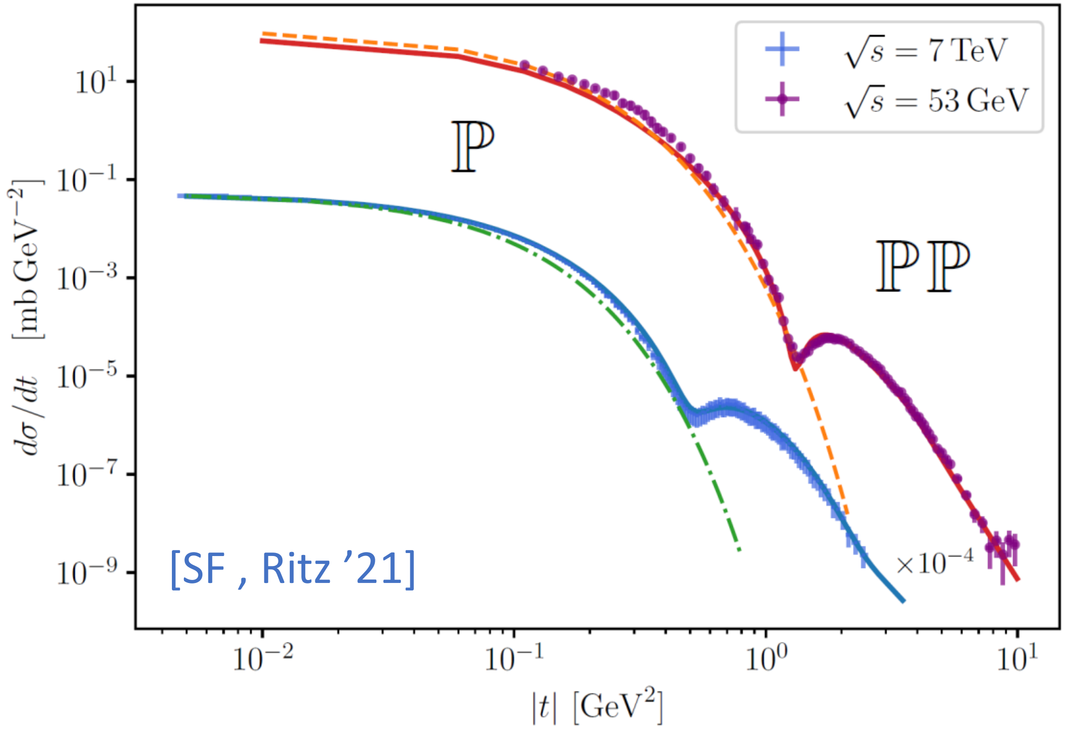
- Single pomeron exchange fits data well for low t

$$\frac{d\sigma^{\text{el}}}{dt} \simeq \frac{1}{4\pi}(Y_{\mathbb{P}}F_1(t))^4|G(s,t)|^2$$

- Pomeron Trajectory contributes a power $s^{\alpha(t)-1}$ to the scattering amplitude

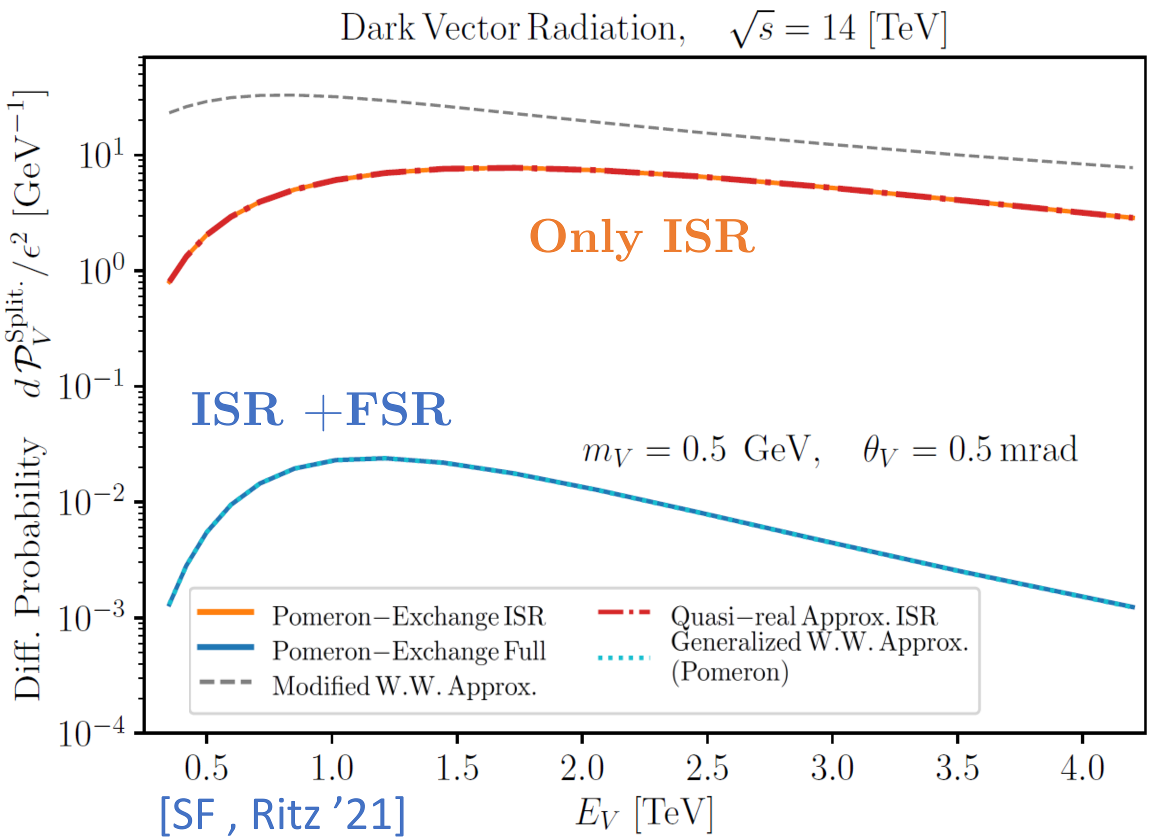
$$G_{\mathbb{P}}(s,t) = (s\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}, \quad \Gamma^{\mu}(t) = Y_{\mathbb{P}}F_1(t)\gamma^{\mu}$$

$$\alpha_{\mathbb{P}}(t) \approx 1.08 + 0.25t$$

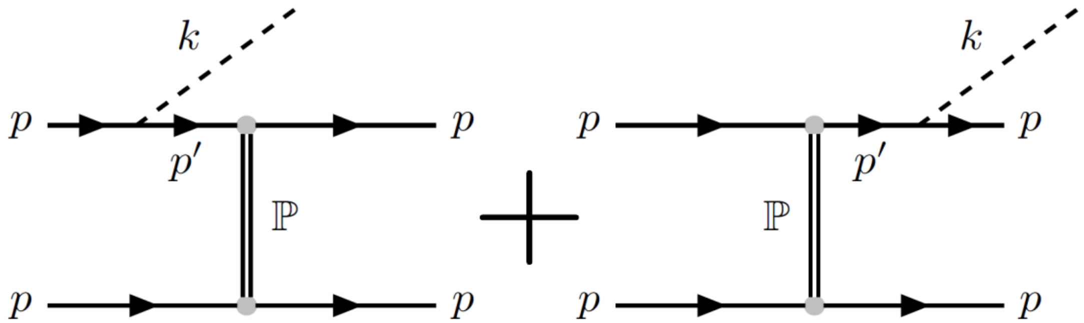


Radiation in Quasi-Elastic scattering

- Modeling forward pp scattering with Pomeron



[SF , Ritz ’21]



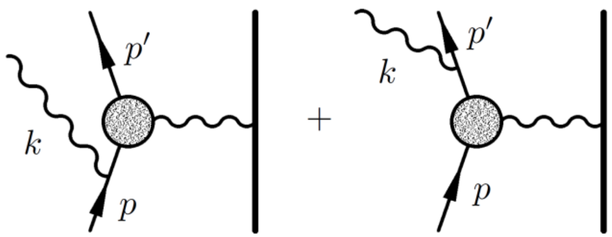
Observe the large ***cancellation*** *between ISR & FSR in quasi-elastic scattering*

Soft Photon Production

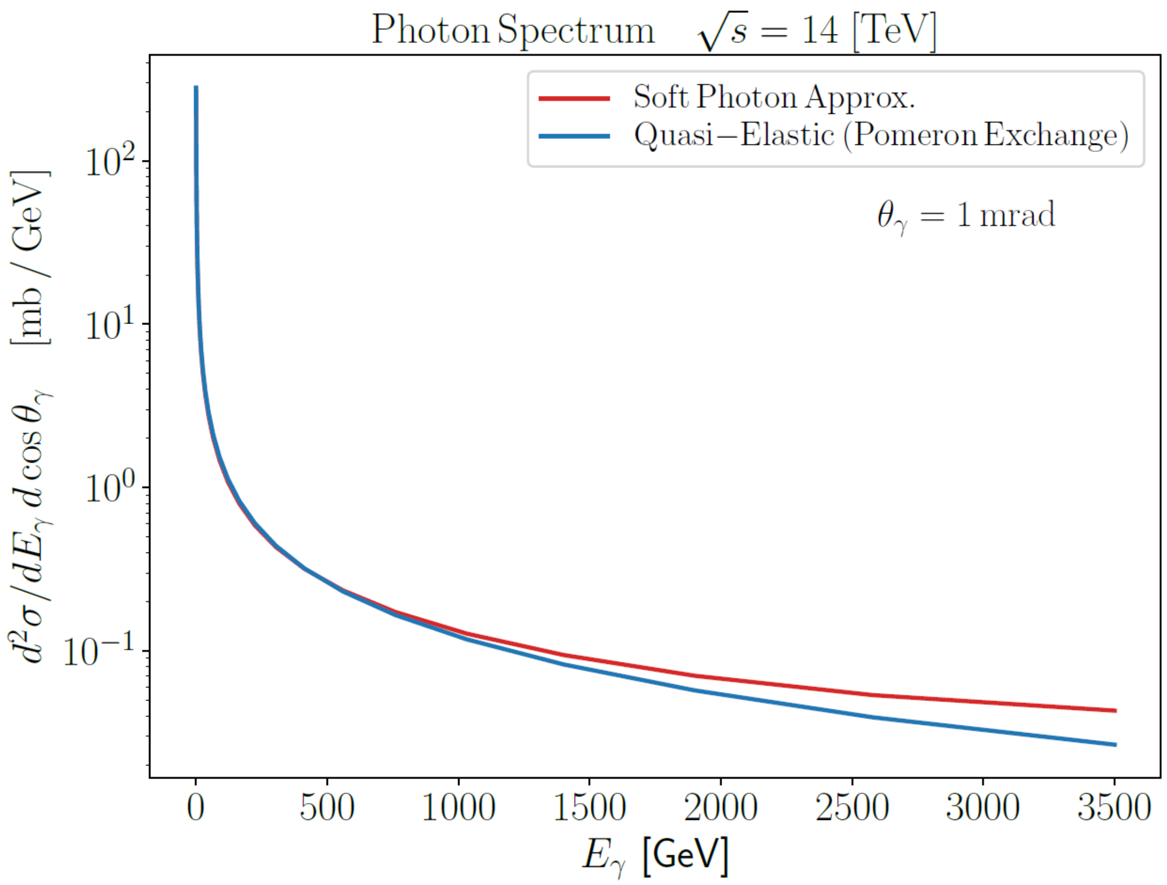
- Contrast the radiation in quasi-elastic processes involving the Pomeron with the soft photon approximation (SPA) for SM photon production

- Soft singularity for $k \to 0$

$$d\sigma\big|_{\text{SPA}} \sim \frac{1}{k} \underbrace{\left(\frac{p^\mu}{p \cdot k} - \frac{p'^\mu}{p' \cdot k} \right)^2}_{\text{eikonal current}} d\sigma_{el}$$



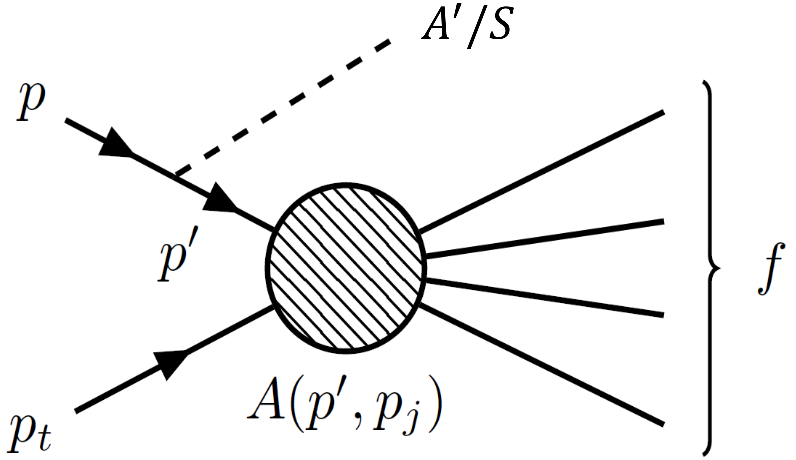
[Low '58, Burnett-Kroll '68, Bell-VanRoyen '69]

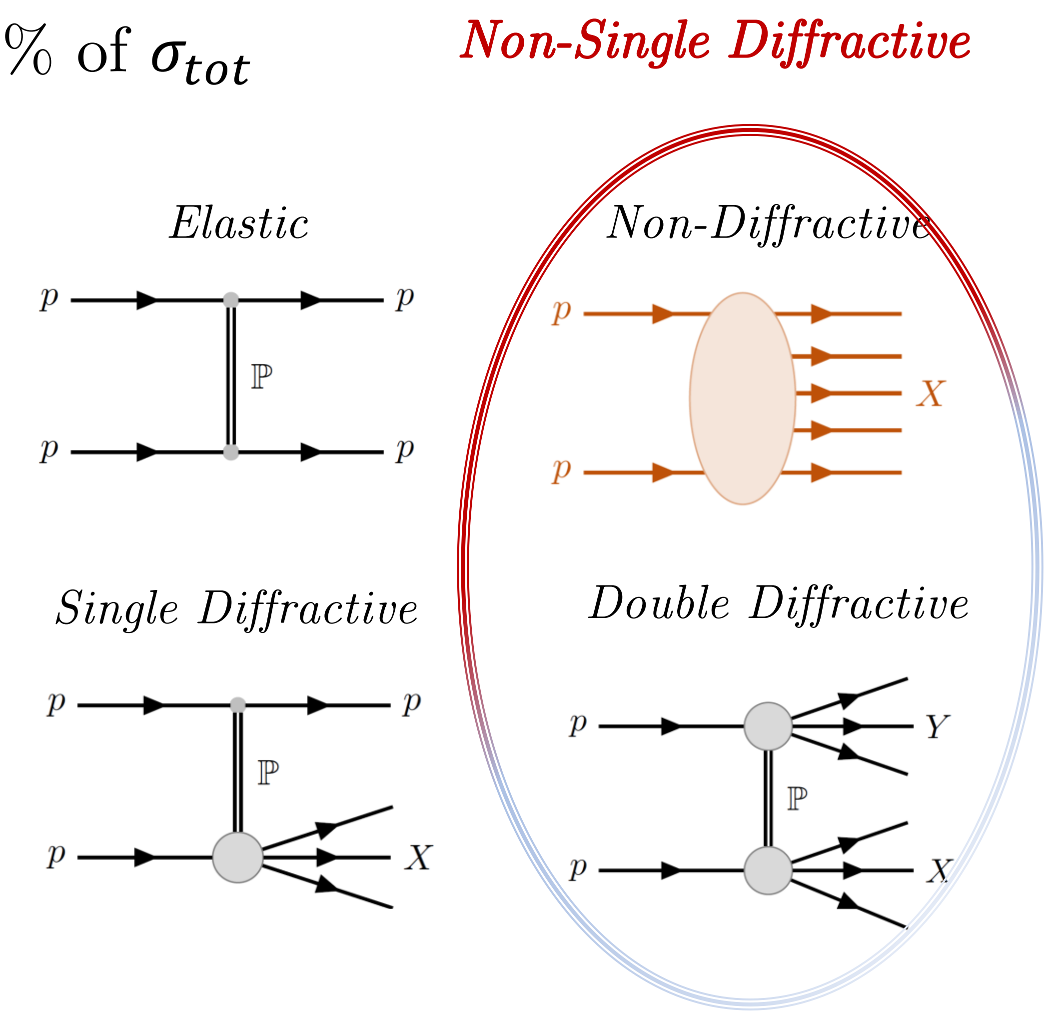


Radiation in Diffractive Processes

- Non-Diffractive processes constitute up to 60% of σ_{tot}

- The dominant contribution comes from ISR in non-single diffractive scattering.





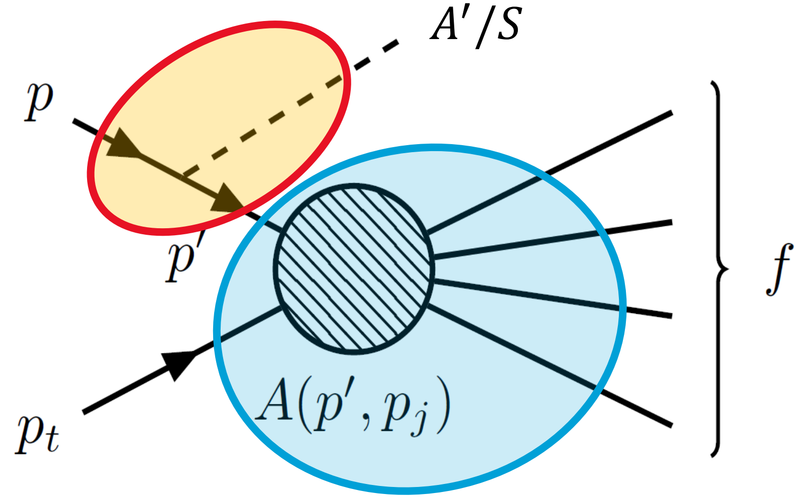
Production via ISR

- **“Equivalent proton” or <u>Quasi-Real Approx.</u>**

Collinear radiation with low p_T
intermediate p' near on-shell

[Khoze, Fadin] [Altarelli, Parisi]

$$\frac{p_T^2}{4z(1-z)^2 p_p^2} \ll 1$$

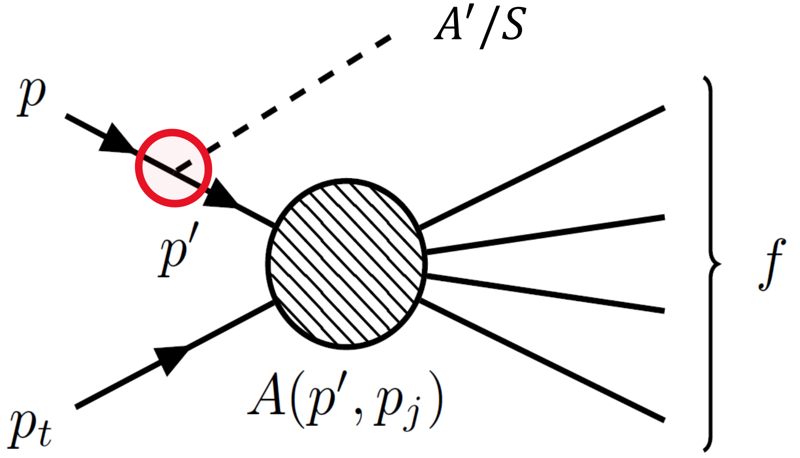


- The cross section divides into a **splitting probability** and the cross section of the subprocess involving the p' with the reduced energy:

$$d\sigma^{pp_t \to Df}(s) \approx dP_{p \to p' D} \times \sigma_{pp}^{\mathrm{NSD}}(s')$$

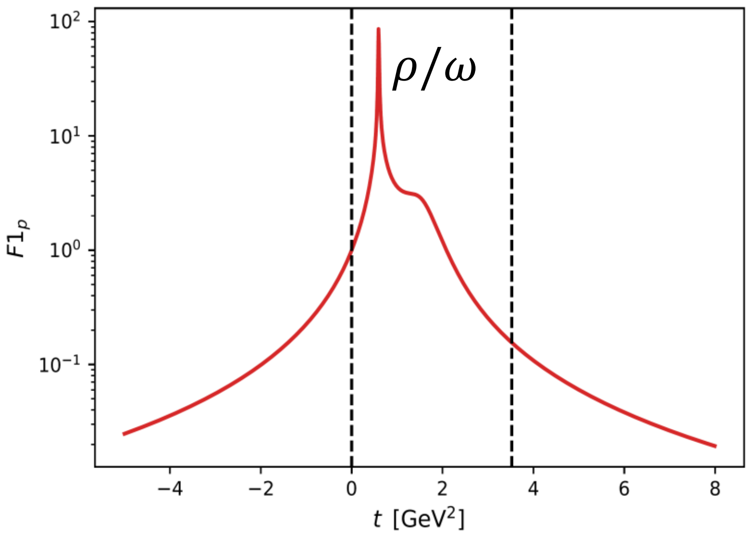
Production via ISR

- The dark vector is radiated with timelike momentum, thus can mix with hadronic resonances, while the intermediate proton is slightly off-shell, so the vertex is a transition form-factor



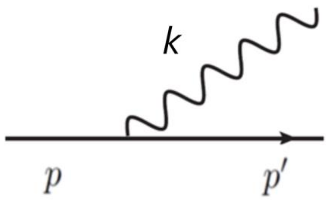
- **Time-like** nucleon form factor:
  - Mixing with meson resonances

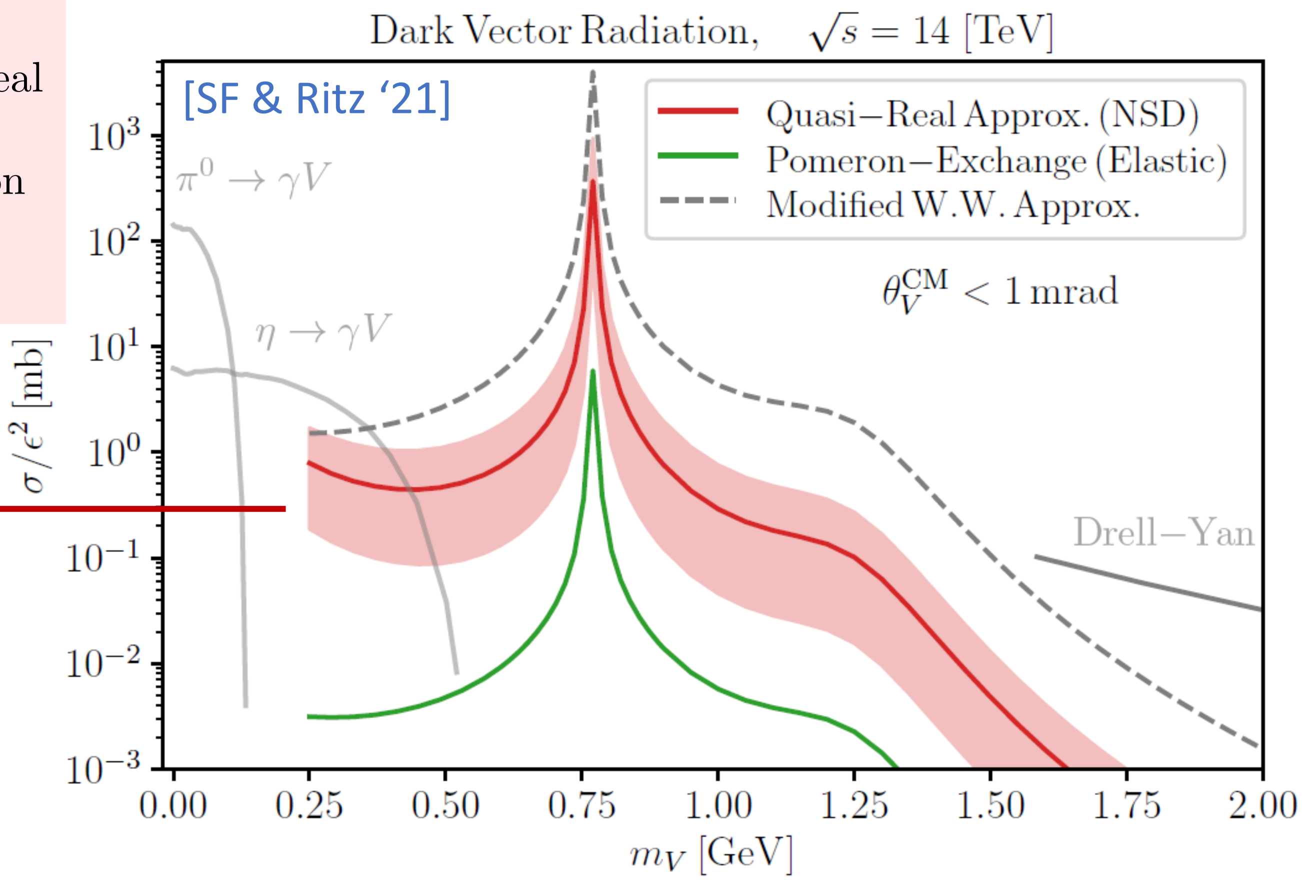
[Faessler et al '09]
[Adamuscin et al '16]



Revisiting Proton Bremsstrahlung

Analyze the "equivalent proton" or quasi-real approximation (QRA) to calculate the splitting function for ISR; Convolute with σ_{NSD} (not total)





Red band from varying transition form-factor scale $\Lambda \sim m_p$ from 1 to 2 GeV

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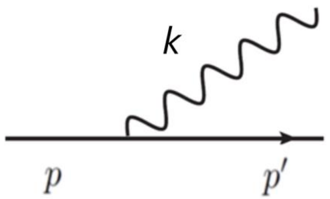
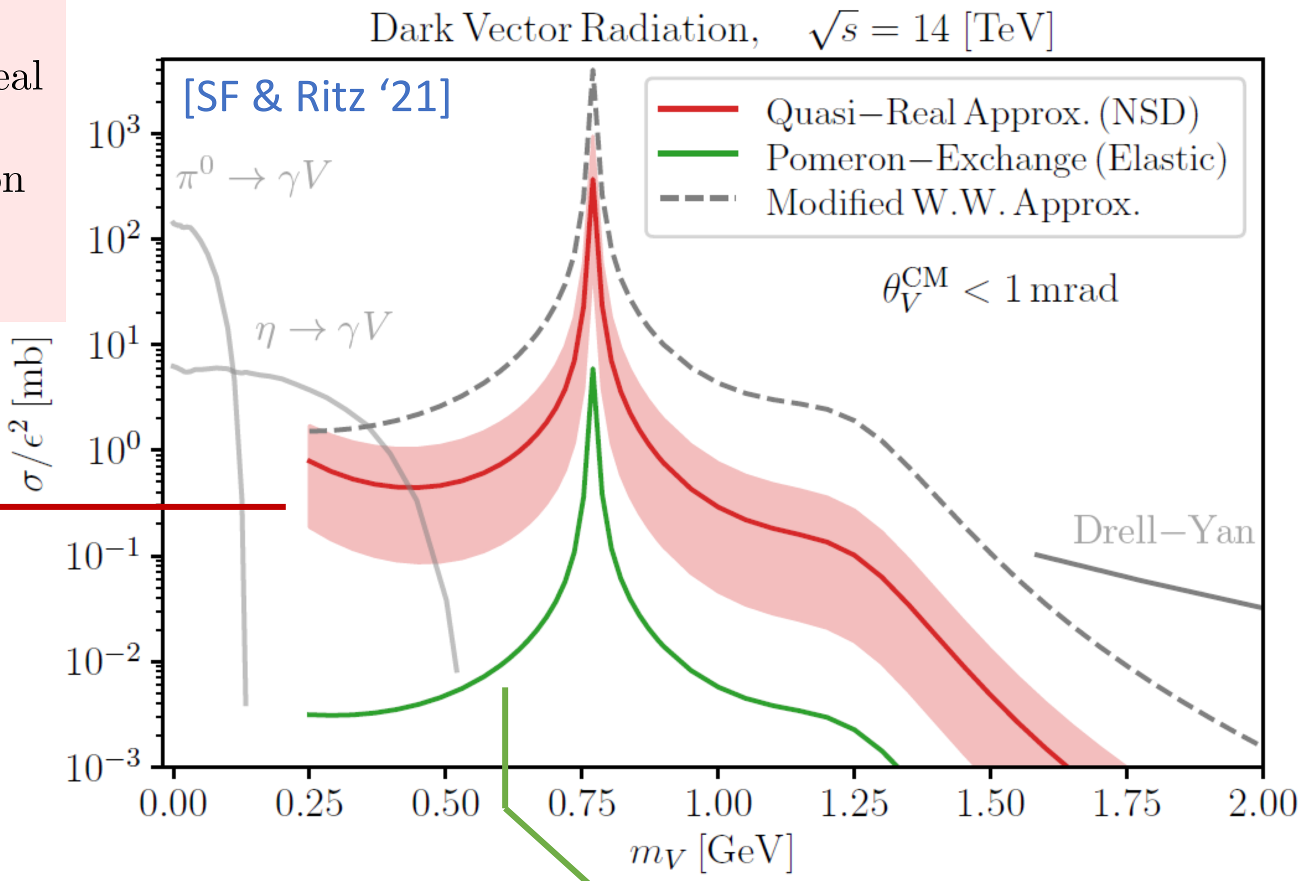
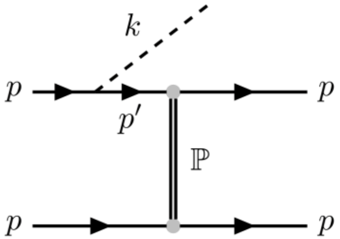
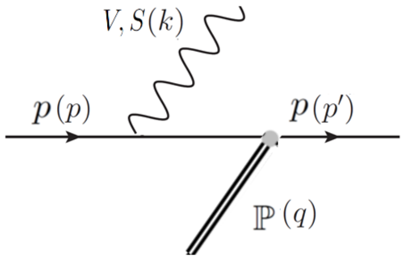






Hadronic generalization with an "equivalent pomeron" provides an excellent approximation to (suppressed) quasi-elastic ISR+FSR radiation



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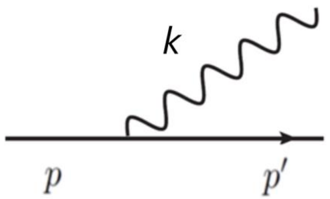
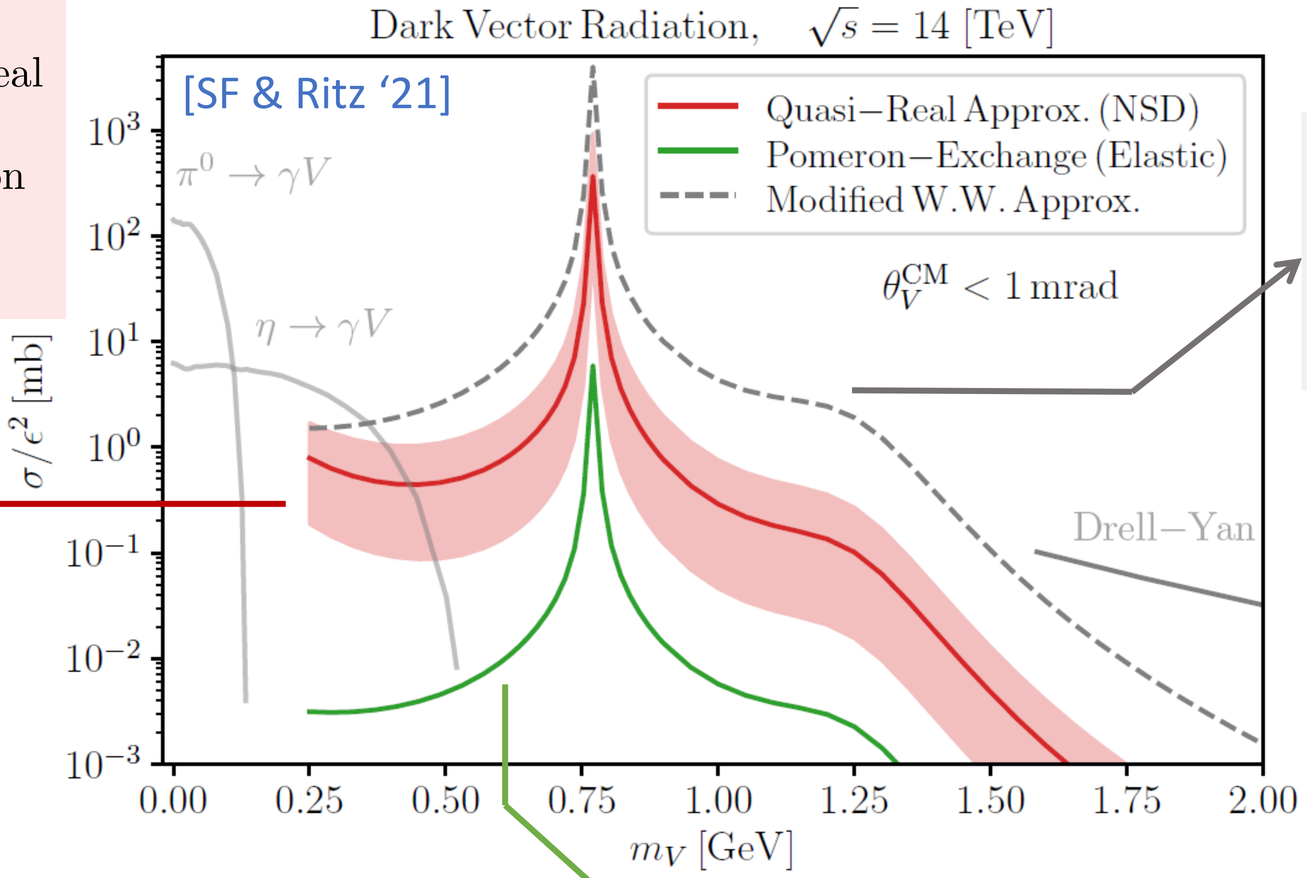
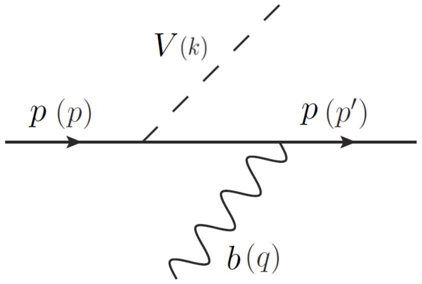
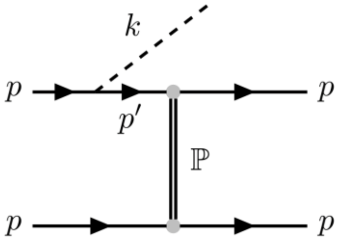




[Blümlein, Brunner '13]

An "equivalent vector" approximation is used to estimate the ISR splitting function; convoluted with σ_{tot}





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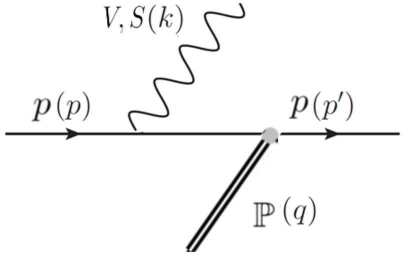
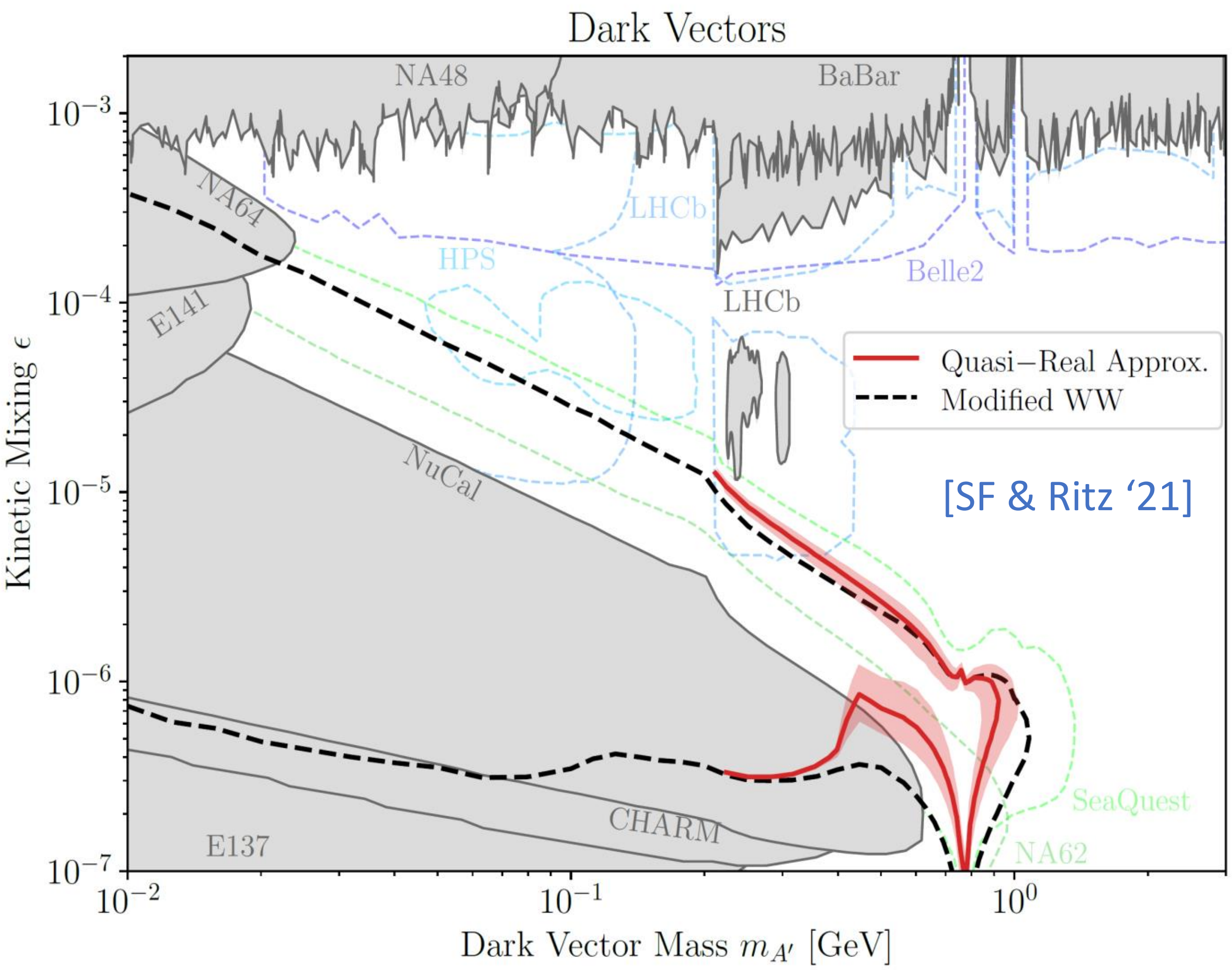


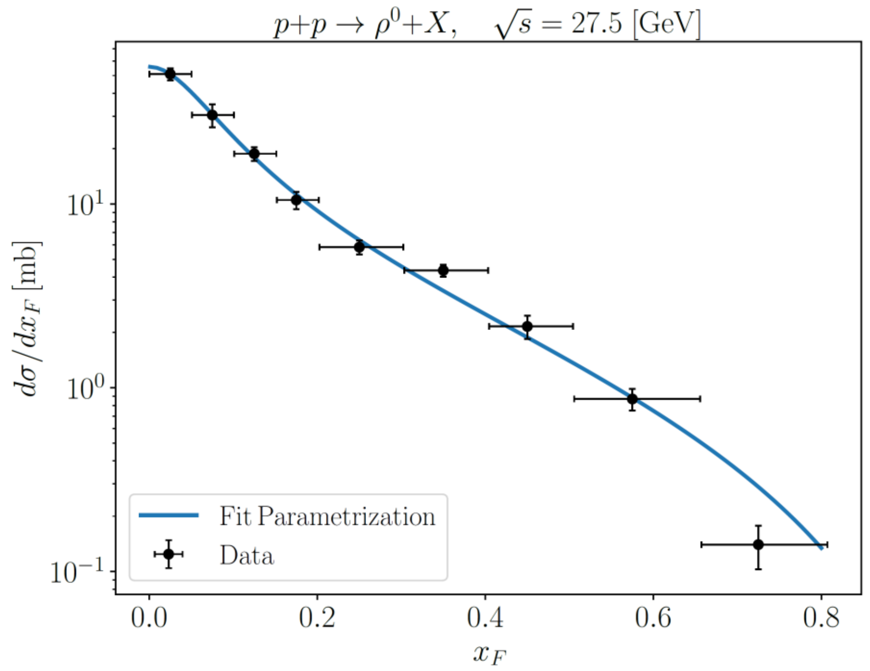
Impact on Sensitivity

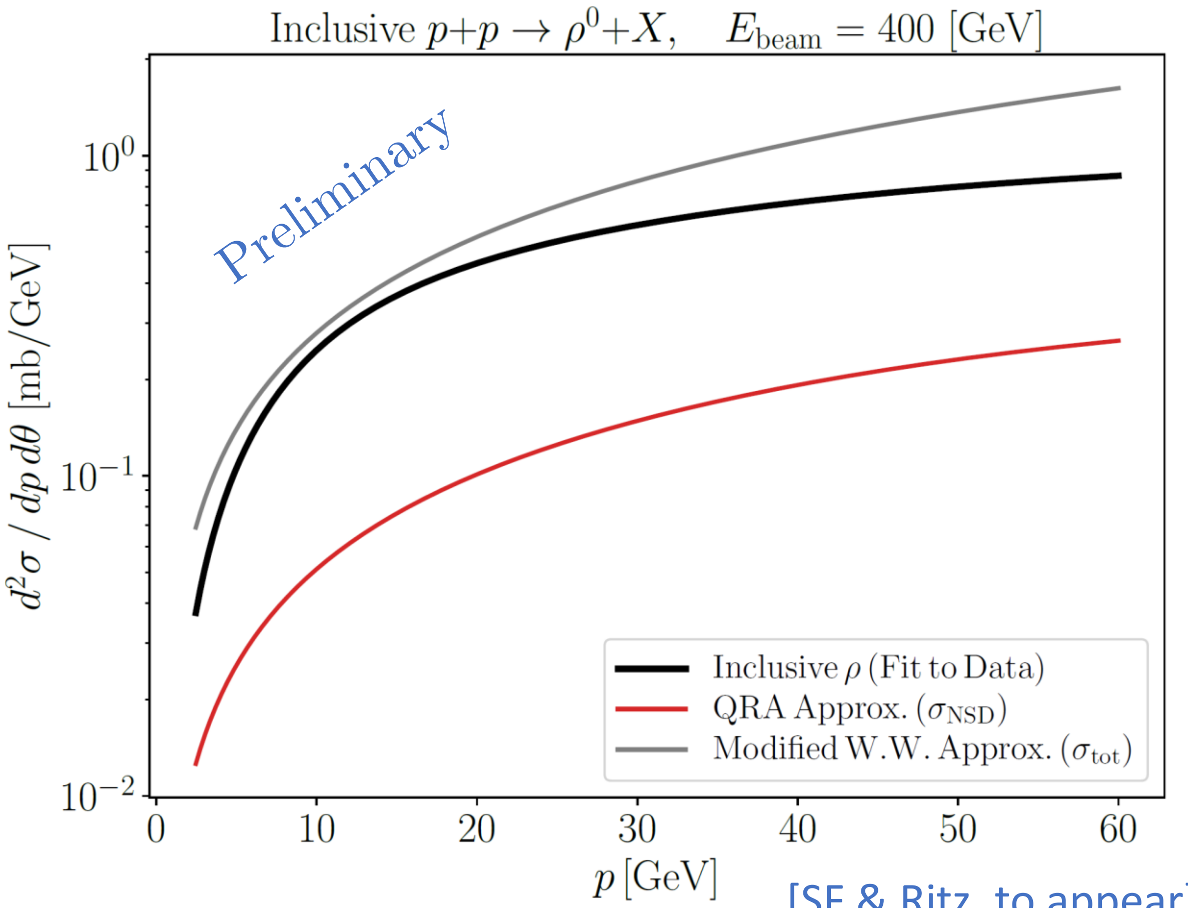


[SF & Ritz '21]

Benchmarks - ρ production

- Compare these mechanisms for inclusive rho production with data





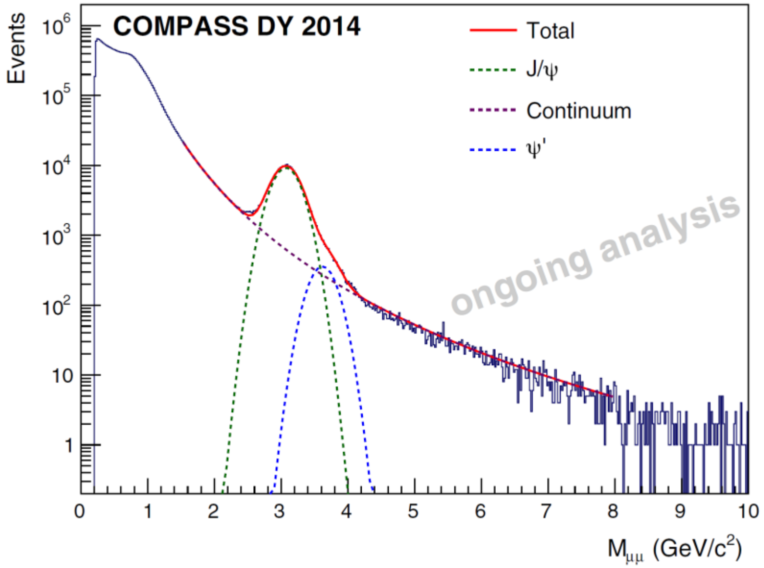
[SF & Ritz, to appear]

- Consider regime with $p_L << p_L^{max}$ (small x_F) and $p_T <$ GeV

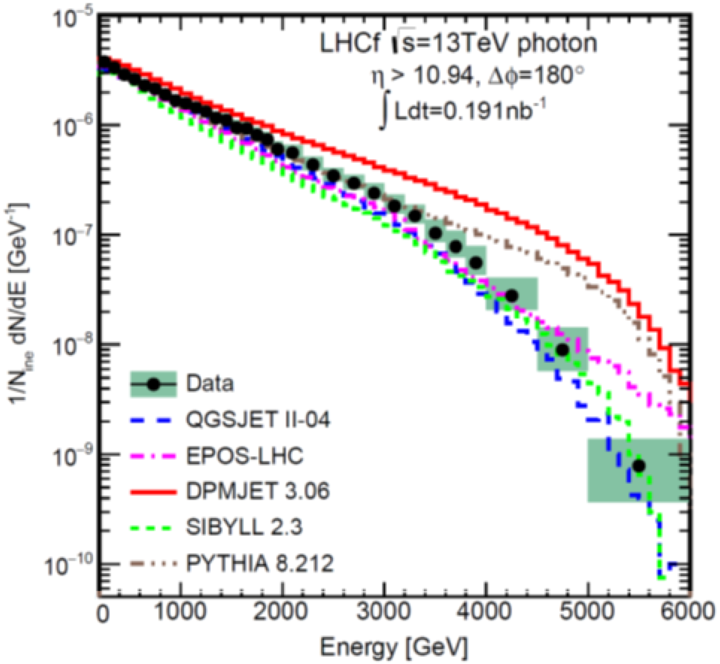
Other Benchmarks

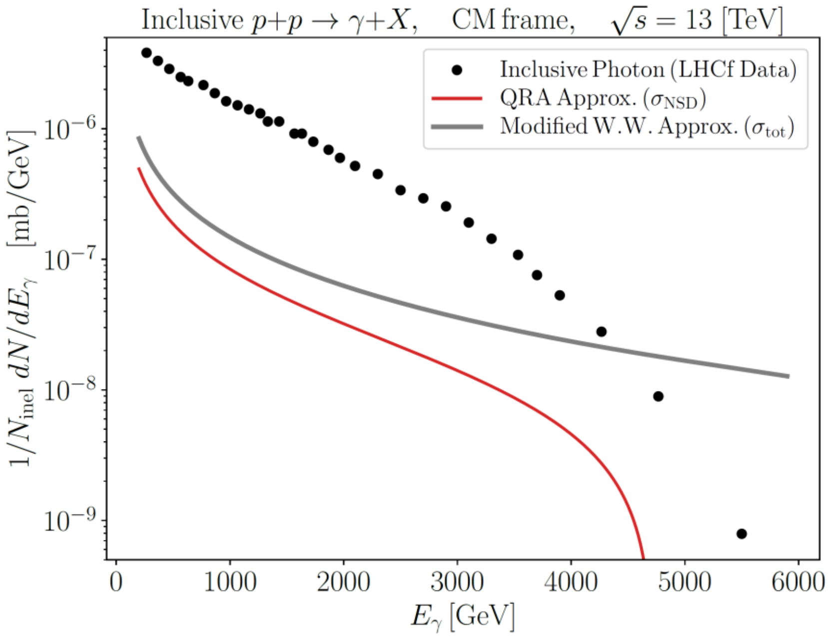
- Compare these mechanisms for inclusive photon production with data from LHCf and for dimuon production with data from COMPASS

[COMPASS Collaboration '13]



[LHCf experiment '17]





- What is the kinematic regime in which coherent ISR transit to partonic-level radiation? Insights form future measurements of PDFs at small x.

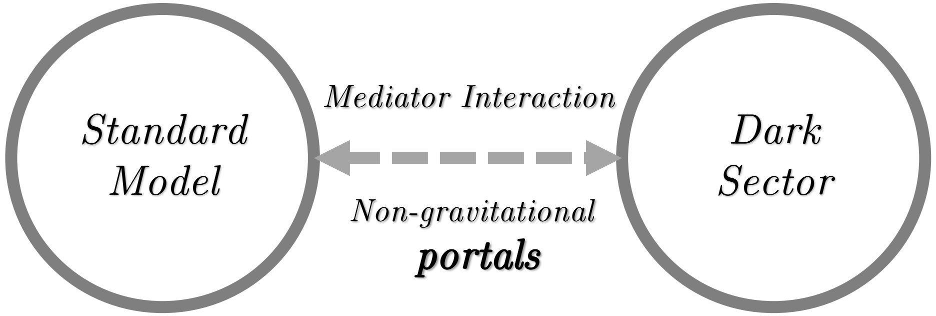
Back-up Slides

Overview

- Sub-GeV WIMP requires new annihilation channel through light mediators as part of a dark sector

  [Boehm & Silk et al.]

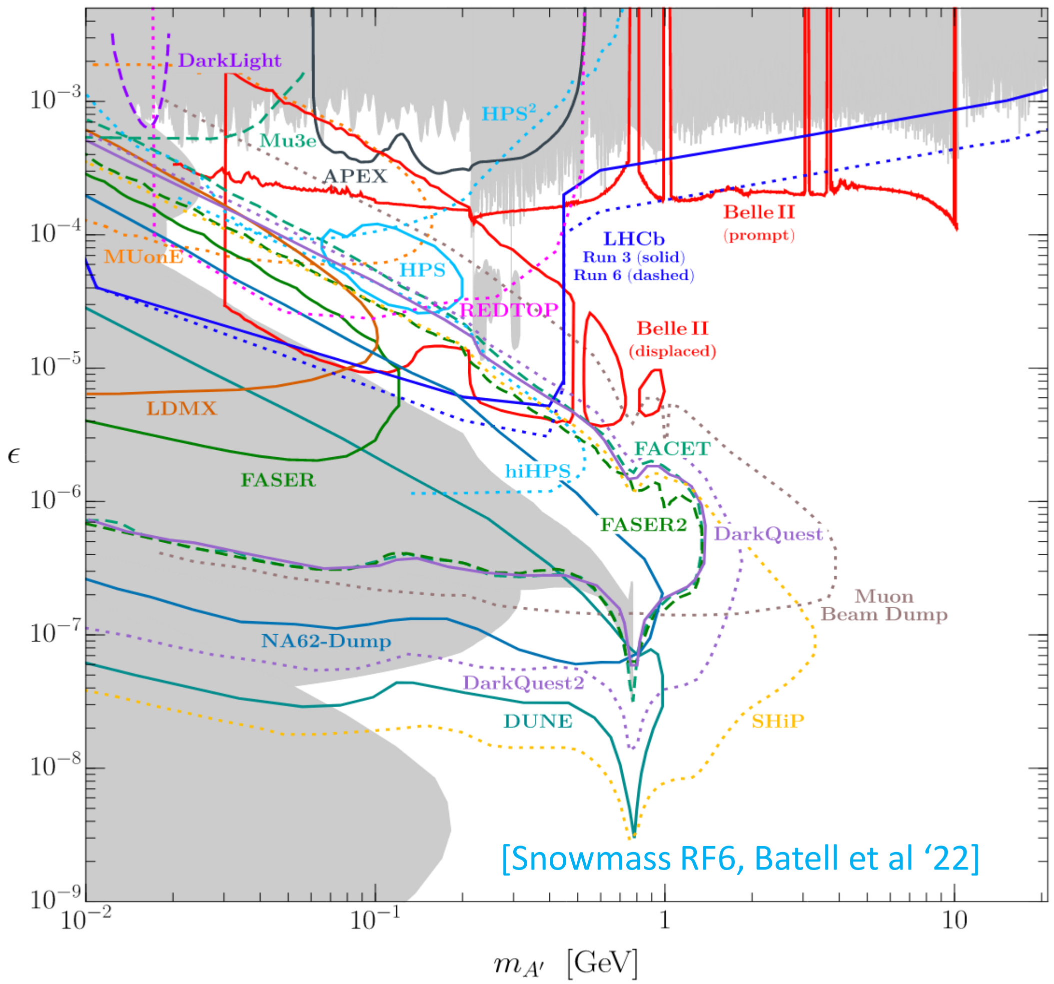
  [Pospelov, Ritz, Voloshin '07]



- <u>*Visible decays*</u> *of dark photon*

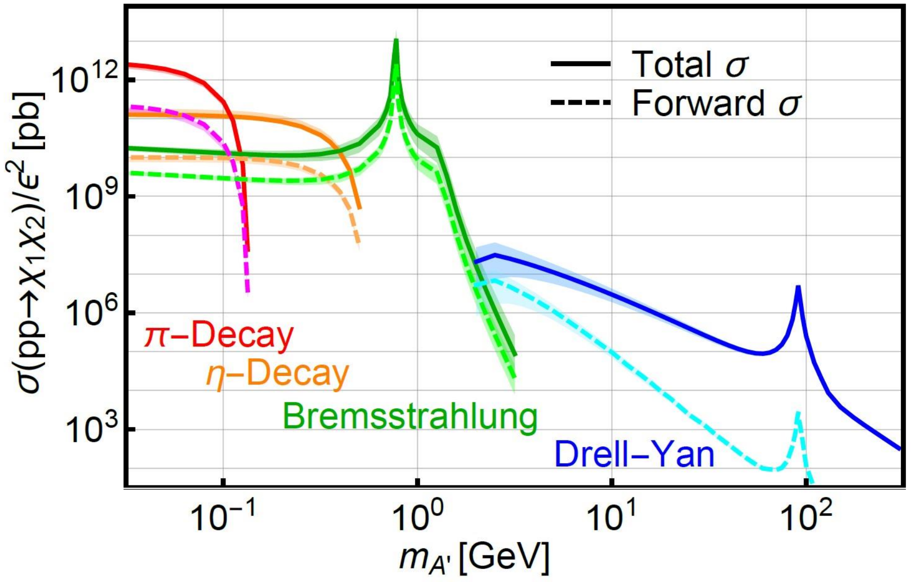
$$m_{A'} < 2m_\chi$$

Vector Portal – Status Today

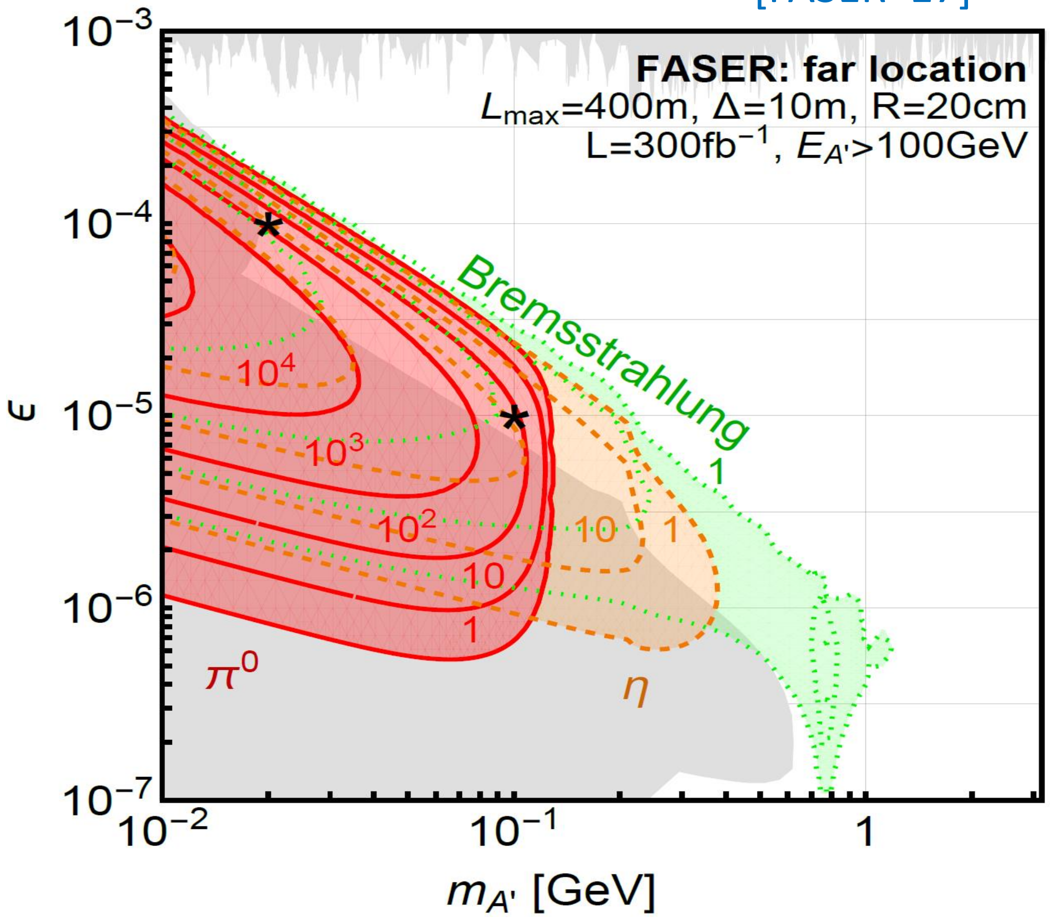


Hadronic Production

$\pi^{\pm,0}$, η. $K^{\pm}$ Decay
Proton Bremmstrahlung
Drell-Yan



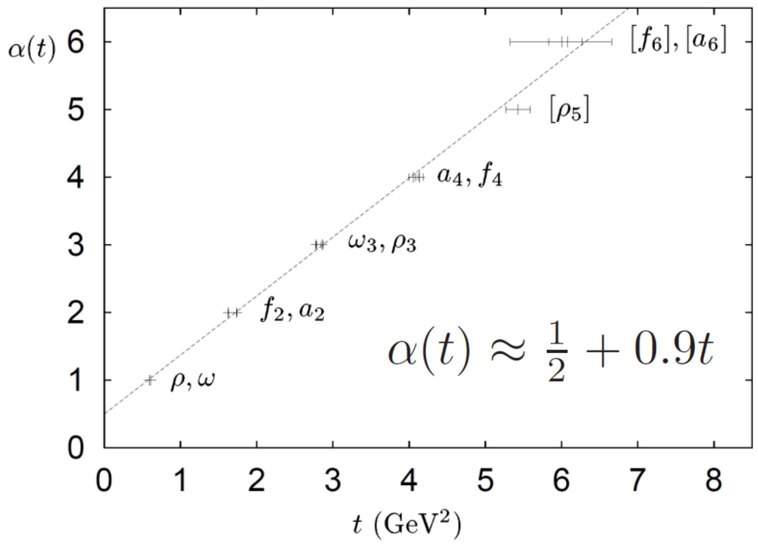
[FASER '17]



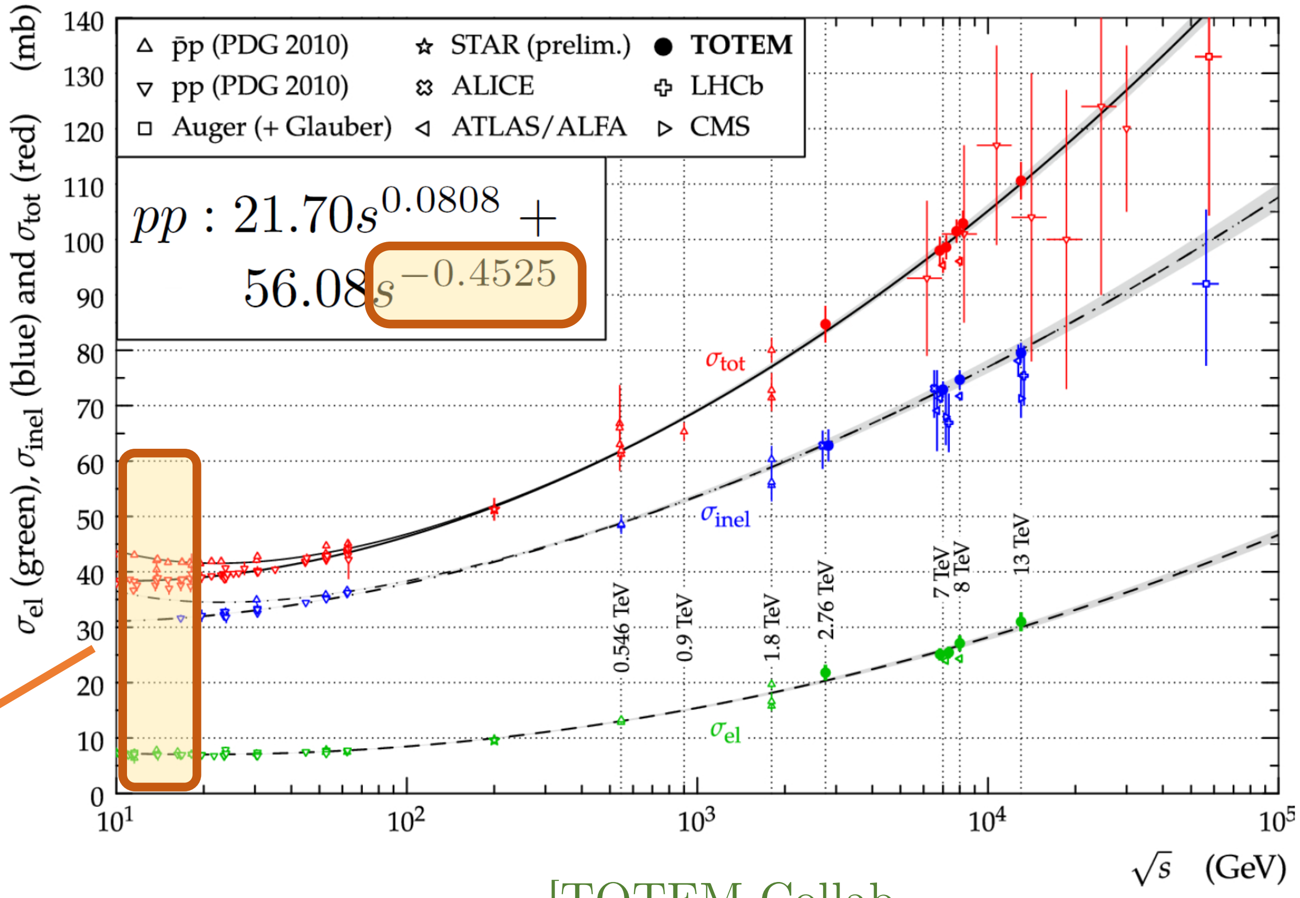
FASER is taking data now

Modeling forward pp scattering

- Regge Theory: [Regge; Chew, Frautschi '61]
  - Trajectory $\alpha(t)$ contributes a power $s^{\alpha(t)-1}$ to the scattering amplitude



$\sim s^{-\frac{1}{2}}$ for ρ, ω, f_2, a_2 trajectories



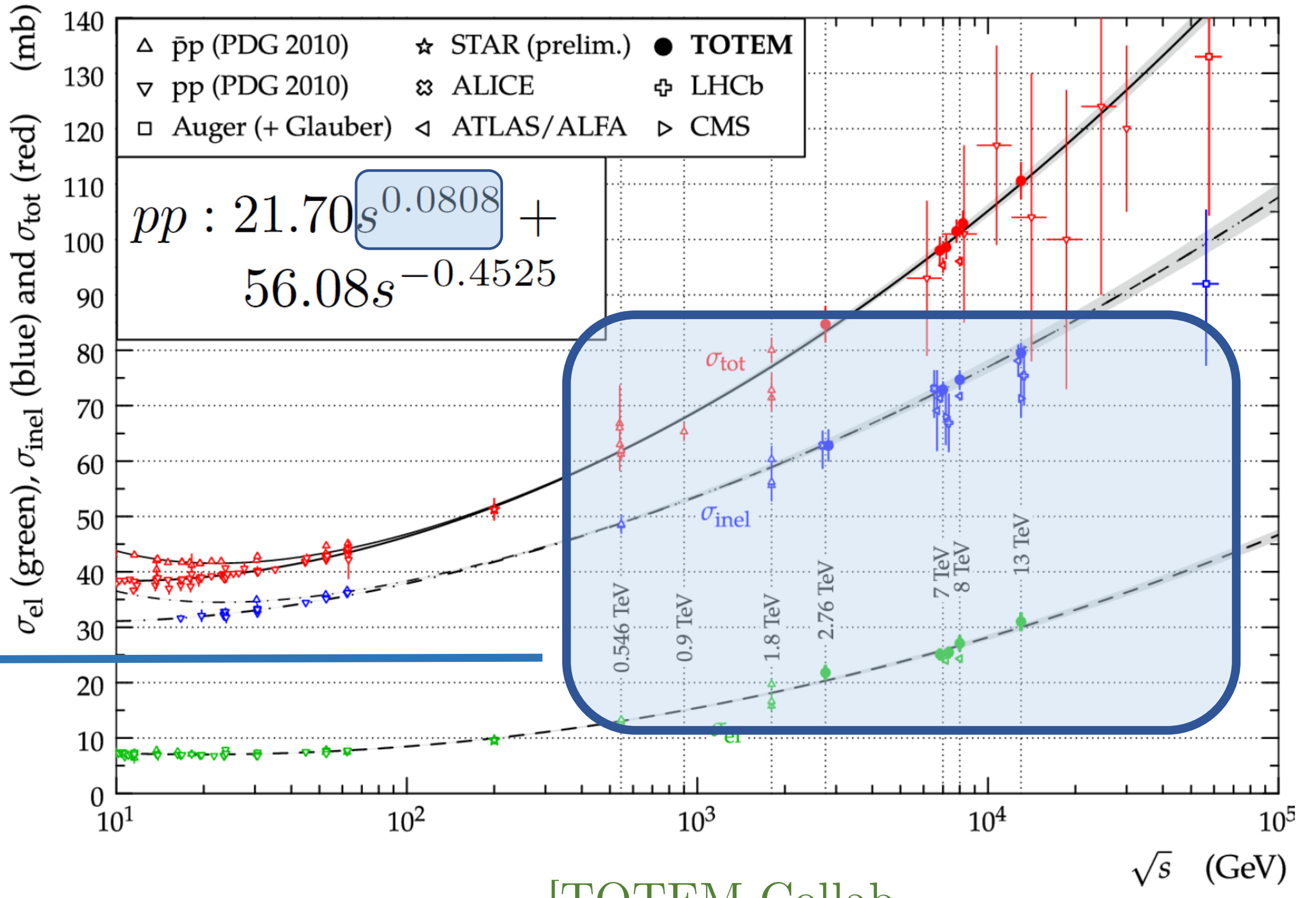
[TOTEM Collab. '19]

Modeling forward pp scattering

- Pomeron Trajectory: [Gribov '62]

- Reggeons are not enough!
  Need to include exchange of
  another object with trajectory

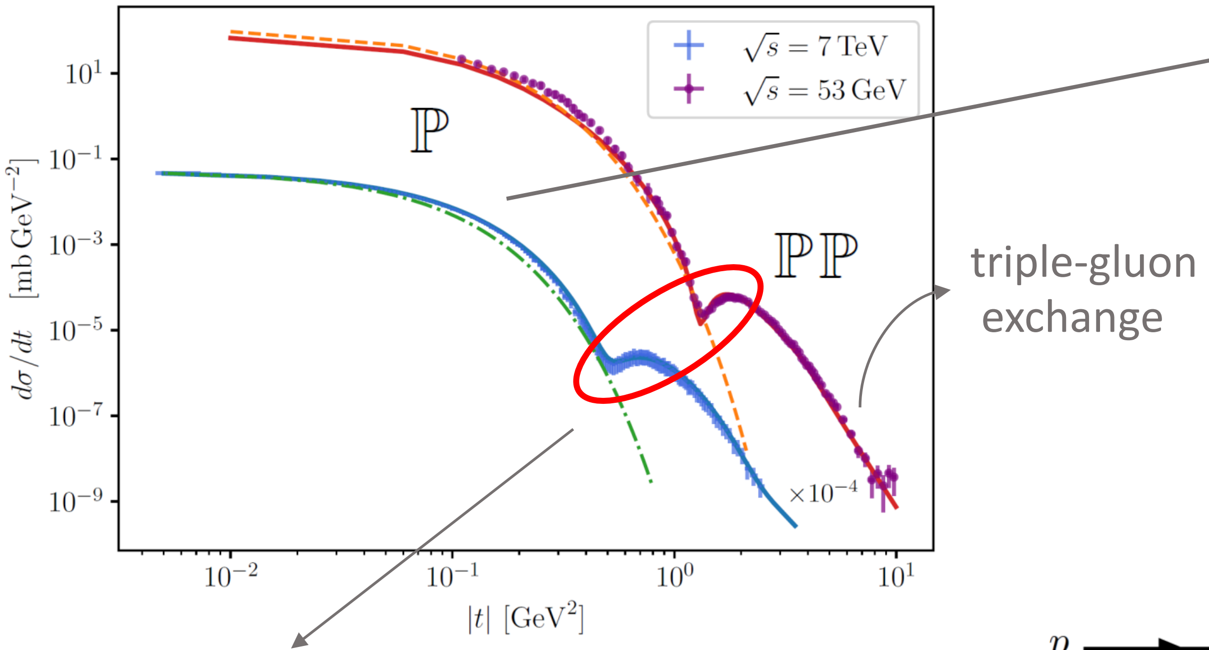
$$\alpha_{\mathbb{P}}(t) \approx 1.08 + 0.25t$$



[TOTEM Collab. '19]

Elastic Scattering via Pomeron Exchange

- Donnachie & Landshoff (DL) model [D&L '82, '84, '11, '13]

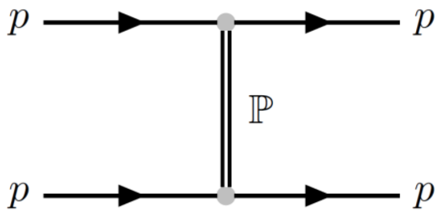


Diffractive minimum: analogue to Fraunhofer diffraction: $|t| \sim p^2\theta^2$

$$\frac{d\sigma^{\text{el}}}{dt} \simeq \frac{1}{4\pi}\left(Y_{\mathbb{P}} F_1(t)\right)^4 |G(s,t)|^2$$

Effective Propagator & Vertex for Soft Pomeron Exchange:

$$G_{\mathbb{P}}(s,t) = (s\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}, \qquad \Gamma^\mu(t) = Y_{\mathbb{P}} F_1(t)\gamma^\mu$$



$$\alpha_{\mathbb{P}}(t) = \epsilon_{\mathbb{P}} + \alpha'_{\mathbb{P}} t$$

Photon vs Fermion Pole Approximation

Photon Pole Approx.

Equiv. Photon Approx. (FWW) in QED

Improved Weizsäcker-Williams Method and Its Application to Lepton and W-Boson Pair Production*

Kwang Je Kim and Yung-Su Tsai
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 30 April 1973)

A Weizsäcker-Williams method is derived which handles the elastic and inelastic target form factors properly. The method is applied to calculate energy-angle distributions of photoproduced lepton pairs:

Electron brem. in e-beam dump

New Fixed-Target Experiments to Search for Dark Gauge Forces

James D. Bjorken,[1] Rouven Essig,[1] Philip Schuster,[1] and Natalia Toro[2]
[1] *Theory Group, SLAC National Accelerator Laboratory, Menlo Park, CA 94025*
[2] *Theory Group, Stanford University, Stanford, CA 94305*
(Dated: June 3, 2009)

Fixed-target experiments are ideally suited for discovering new MeV–GeV mass $U(1)$ gauge bosons through their kinetic mixing with the photon. In this paper, we identify the production and decay

Dark Photons via proton Brem.

New exclusion limits on dark gauge forces from proton Bremsstrahlung in beam-dump data

Johannes Blümlein[a,*], Jürgen Brunner[b]
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ABSTRACT

We re-analyze published proton beam dump data tal with the ν-calorimeter I experiment in 1989 to set n corresponding data have been used for axion and light h

Fermion Pole Approx.

Splitting Function Using OFPT

ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

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Laboratoire de Physique Théorique de l'Ecole Normale Supérieure **, *Paris, France*

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Received 12 April

QUASI–REAL ELECTRON METHOD IN HIGH ENERGY QUANTUM ELECTRODYNAMICS

V.N. BAIER and V.S. FADIN
Institute of Nuclear Physics, Novosibirsk, 630090
V.A. KHOZE
Institute of Nuclear Physics, Leningrad.

Received 6 July 1973

Abstract: An electron pole approximation is presented, which can be used to calculate cross sections in high energy quantum electrodynamics. A general derivation is given and some ap- ...n) collisions at large ...n electrons at large

Scalars via proton Brem.

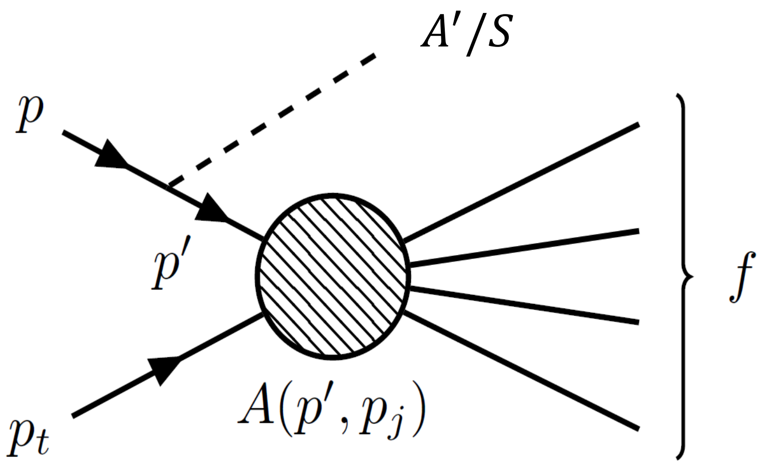
Phenomenology of GeV-scale scalar portal

Iryna Boiarska,[1] Kyrylo Bondarenko,[2] Alexey Boyarsky,[2] Volodymyr Gorkavenko,[3] Maksym Ovchynnikov,[2] Anastasia Sokolenko[4]
[1] *Discovery Center, Niels Bohr Institute, Copenhagen University, Blegdamsvej 17, DK-2100, Copenhagen, Denmark*

ABSTRACT: We review and revise the phenomenology of the scalar portal – a new scalar particle with the mass in GeV range that mixes with the Higgs boson. In particular, we consider production channels $B \to SK_1(1270)$ and $B \to SK_0^*(700)$ and show that their contribution is significant. We extend the previous analysis by comparing the production of scalars from decays of mesons, of the Higgs bosons and direct production via proton bremsstrahlung, deep inelastic scattering and coherent

Quasi-Real (Fermion pole) Approximation

- Ultrarealistic fermion & radiation is highly collinear



$$k^{\mu} = \left(zp_p + \frac{p_T^2 + m_D^2}{2zp_p}, \mathbf{p}_T, zp_p\right) \qquad p_T,\, m_p\,(m_D) \ll E_p\,(E_k)$$

- Intermediate-fermion being near on-shell

$$A(p, p_j) \rightarrow A(p-k, p_j)\frac{i(\not{p} - \not{k} + m_p)}{(p-k)^2 - m_p^2}$$

$$\frac{i(\not{p} - \not{k} + m)}{(p-k)^2 - m^2} = \frac{i}{2E_{p'}} \sum_{r'} \left[\frac{u^{r'}(p-k)\bar{u}^{r'}(p-k)}{E_p - E_k - E_{p'}} + \frac{v^{r'}(-p-k)\bar{v}^{r'}(-p-k)}{E_p - E_k + E_{p'}} \right]$$

$\ll$

- With the cost of being non-covariant:

$$E_{p'} = \sqrt{(\vec{p} - \vec{k})^2 + m_p^2}$$

Quasi-Real (Fermion pole) Approximation

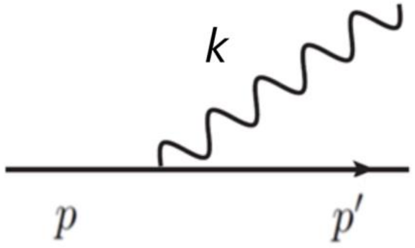
- Replace the p' propagator by the polarization sum for an <u>on-shell proton</u>

$$\mathcal{M}_r^{pp_t \to Df}(p,k,p_j) \approx \sum_{r'} \mathcal{M}_{r'}^{pp_t \to f}(p',p_j) \left(\frac{V^D_{r'r}}{2k\cdot p - m_D^2} \right)$$

Vertex Functions

$$V^V_{r'r,\lambda} = g_V \bar{u}^{r'}(p') \not{\epsilon}^\star_\lambda(k) u^r(p)$$

$$V^S_{r'r} = g_S \bar{u}^{r'}(p') u^r(p)$$



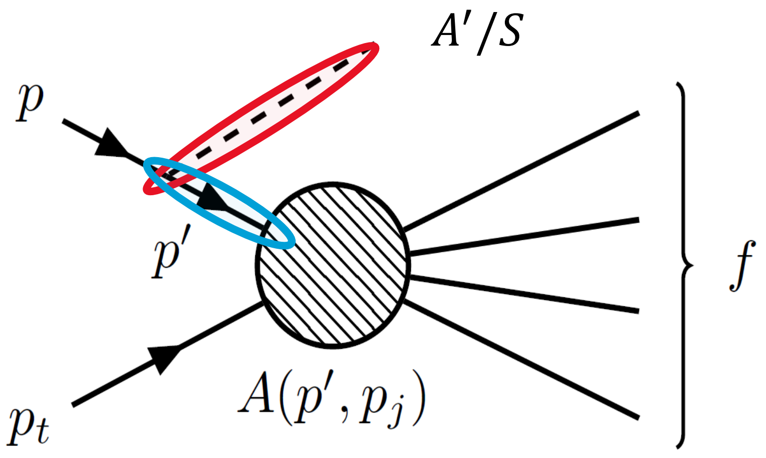
- **Collinear emission** does not change the proton <u>helicity</u>

Only the helicity conserving transitions contribute:

$$\frac{1}{2}\sum_{r(,\lambda)} |\mathcal{M}_{r(,\lambda)}^{pp_t \to Df}(p,k,p_j)|^2 \quad = g_D^2 \left(\frac{z}{H}\right)^2 \mathcal{I}_D |\overline{\mathcal{M}^{p'p_t \to f}}|^2$$

Radiation in Non-Single Diffractive Processes

- The dominant contribution comes from ISR in non-single diffractive scattering.



❖ **Time-like** nucleon form factor:

- Mixing with meson resonances

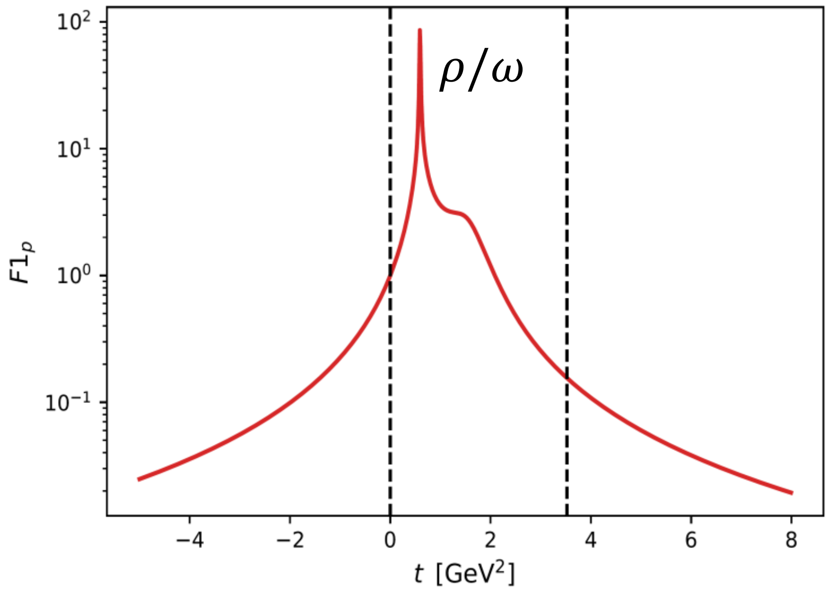
[Faessler et al '09]
[Adamuscin et al '16]

❖ **Transition (Off-Shell)** form factor:

- Accounts for the suppression when the intermediate p' goes far off-shell

$$F_{pp^\star D}(p'^2) = \frac{\Lambda_p^4}{\Lambda_p^4 + (p'^2 - m_p^2)^2}$$

[Feuster & Mosel '98]

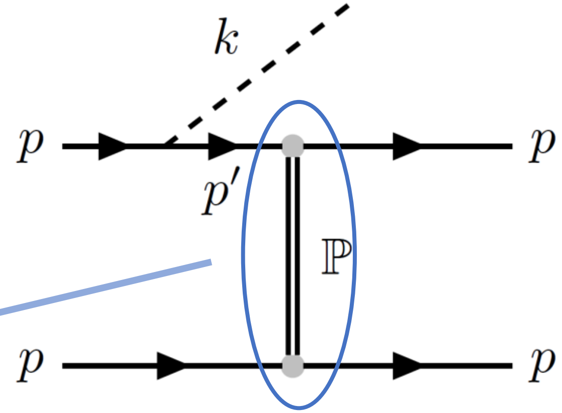


Hadronic Generalization of the FWW Approx.

- **Assumptions**:

- Highly collinear radiation with small virtuality of pomeron momentum

[Kim, Tsai '73]
[Bjorken et al '09']



$$t_{min} = -q_{min}^2 \approx -H^2/(2z(1-z)p_p)^2$$

Amplitude $\sim \left(s^{-\alpha' t}\right)^2$

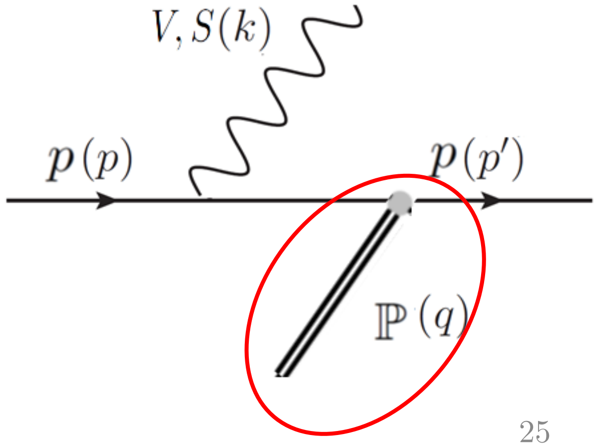
compare with $\frac{1}{t^2}$ for photon

- Cloud of <u>**effective flux**</u> of pomeron

$$\left(\frac{d\sigma^{\rm el}_{pp\to ppD}}{dz dp_T^2}\right)_{\rm WW} \cong \frac{\alpha_D}{16\pi^2}\frac{z(1-z)}{H^2} \times (A_D^{22}|_{t=t_{min}})\chi_{\mathbb{P}}$$

$$\chi_{\mathbb{P}} \equiv \int_{t_{min}}^{t_{max}} dt\,(t-t_{min})|\mathcal{A}_{el}(s,t)|^2$$

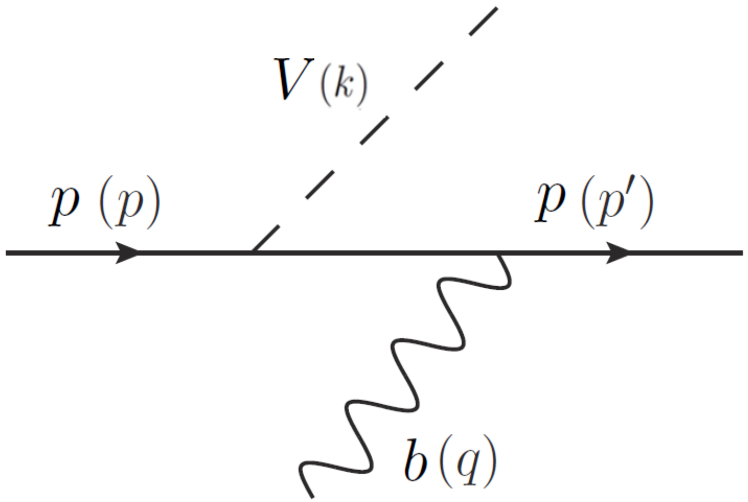
Elastic Amplitude



Modified WW Approximation

- Modified version of both fermion-pole and photon-pole approaches [Blümlein & Brunner '13]

$p + b \to p' + V$

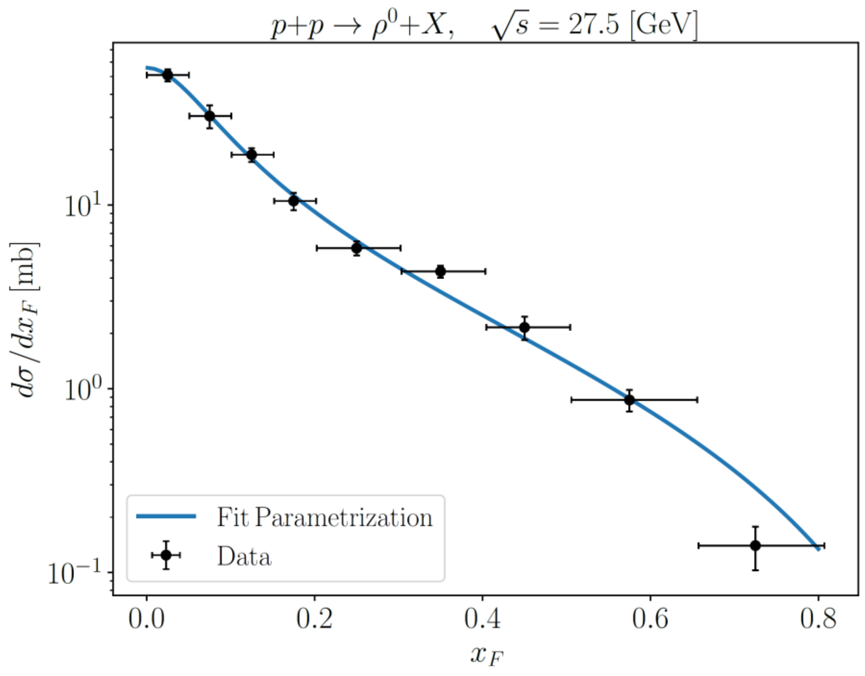


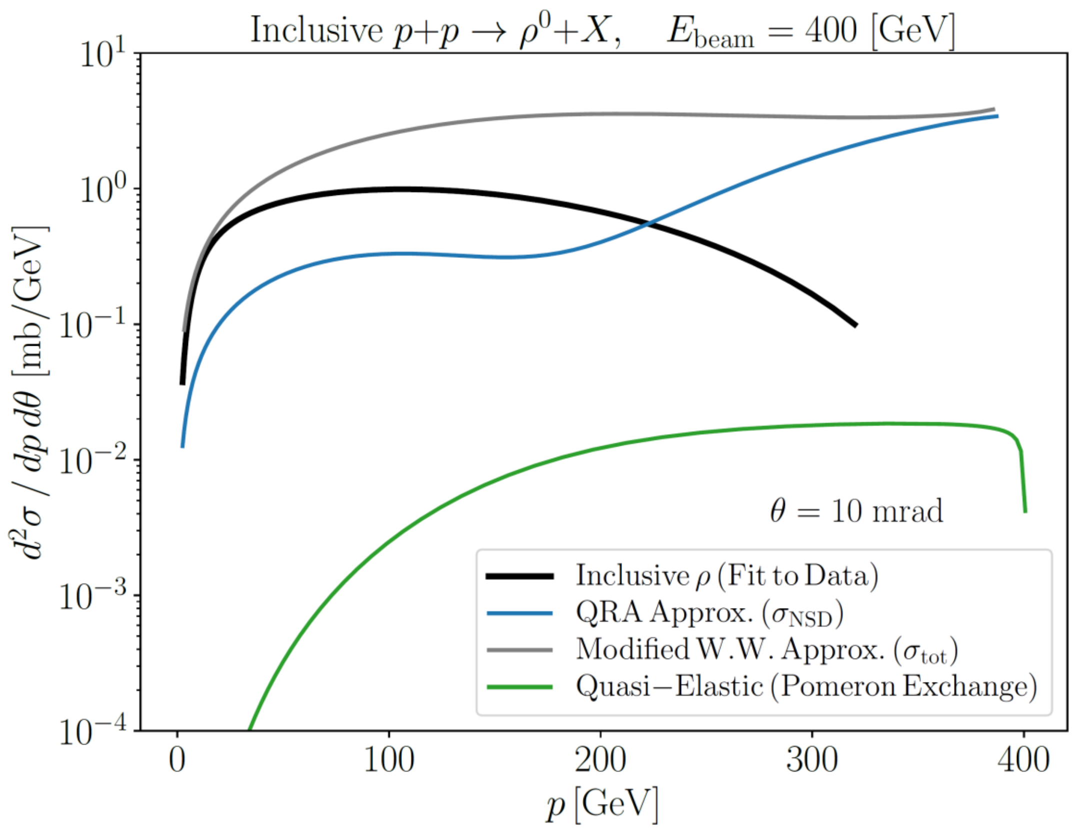
- The **splitting function** is convoluted with $\sigma_{tot}(s')$

$$w_V(z, p_T^2) = \frac{\alpha_\epsilon}{2\pi}|F^p_{1,V}(m_V^2)|^2 \frac{1}{H}\left[\frac{1+(1-z)^2}{z} - 2z(1-z)\left(\frac{2m_p^2+m_V^2}{H} - z^2\frac{2m_p^4}{H^2}\right) + 2z(1-z)(1+(1-z)^2)\frac{m_p^2 m_V^2}{H^2} + 2z(1-z)^2\frac{m_V^4}{H^2}\right]$$

Benchmarks - ρ production

- Contrast these mechanisms for inclusive rho production with data from NA27





[SF & Ritz, to appear]