Dark Sectors via Proton Bremsstrahlung

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Outline

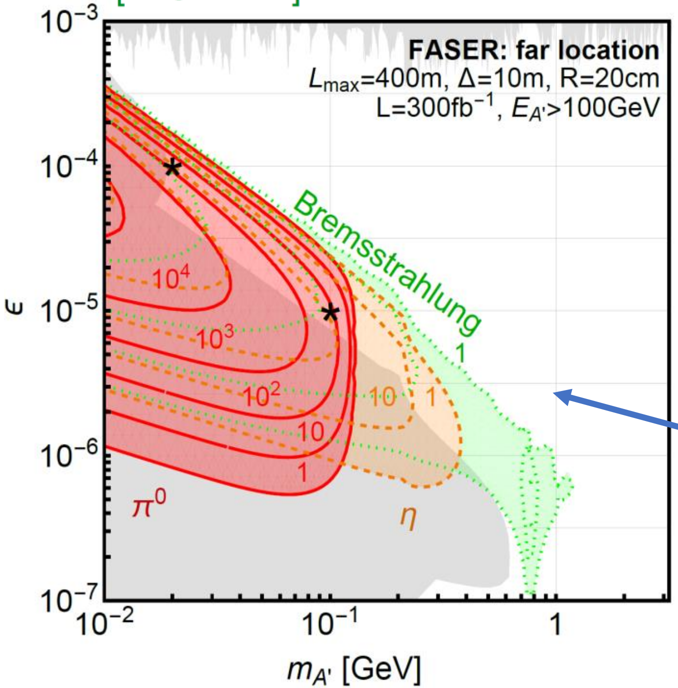
- Motivation: Sub-GeV Dark Sector
- The methods of approximation in evaluating p/e bremsstrahlung
- Modeling forward pp scattering at HE
- Pomeron exchange and proton diffractive dissociation
- Compare the resulting rates with modified WW approximation

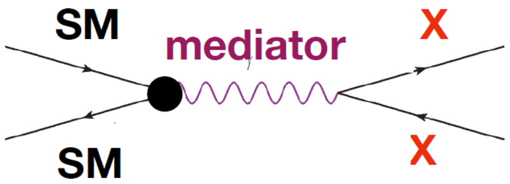
Dark Sector Motivation

- Light (sub-GeV) states from a Dark Sector interacting with matter through a light mediator are viable DM candidates. [Batell, Pospelov, Ritz '09]
- A minimal extension to the SM: kinetically mixed Dark Photon [Okun; Holdom; Foot et al]

$$\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\epsilon}{2}V^{\mu\nu}F_{\mu\nu}$$

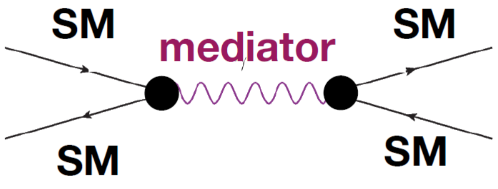
[FASER '17]



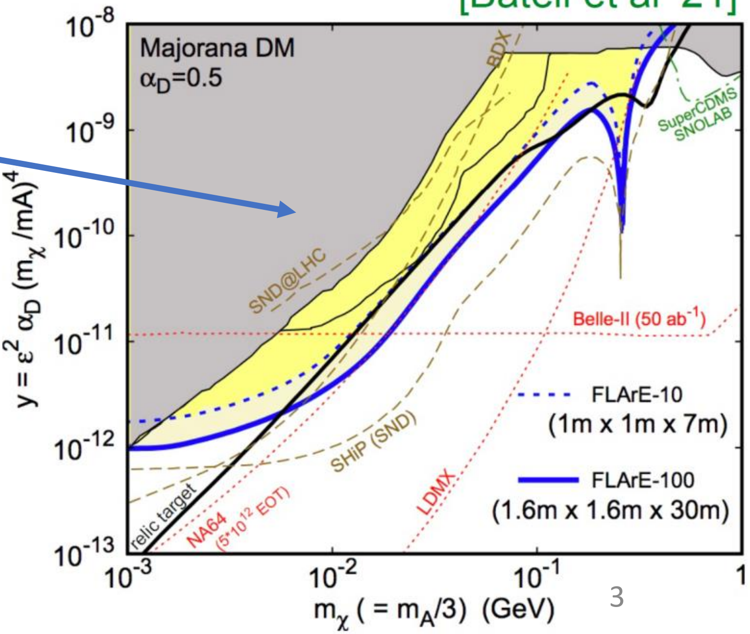


Invisible, non-SM

Visible, SM



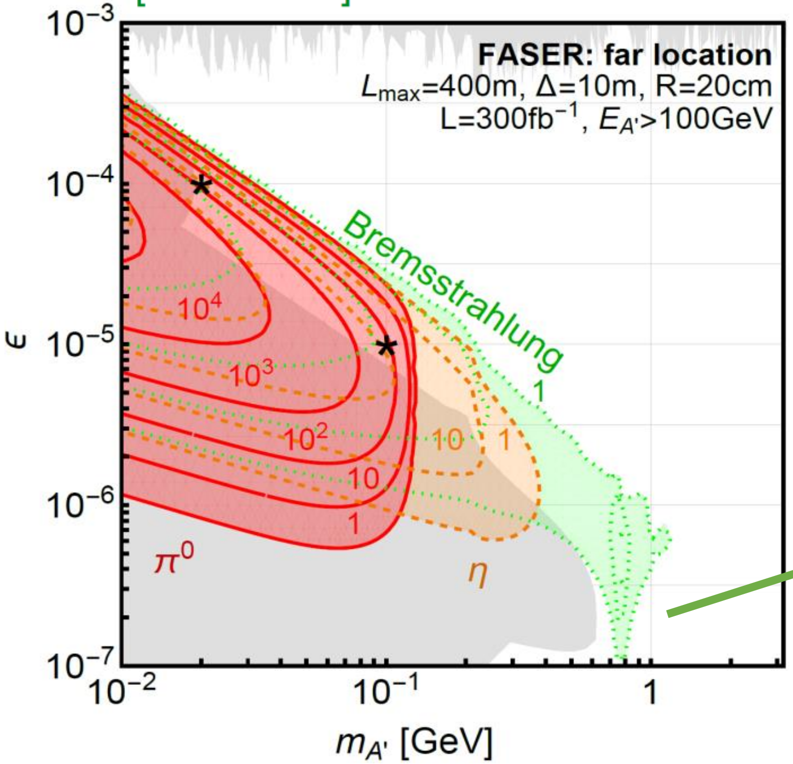
[Batell et al '21]



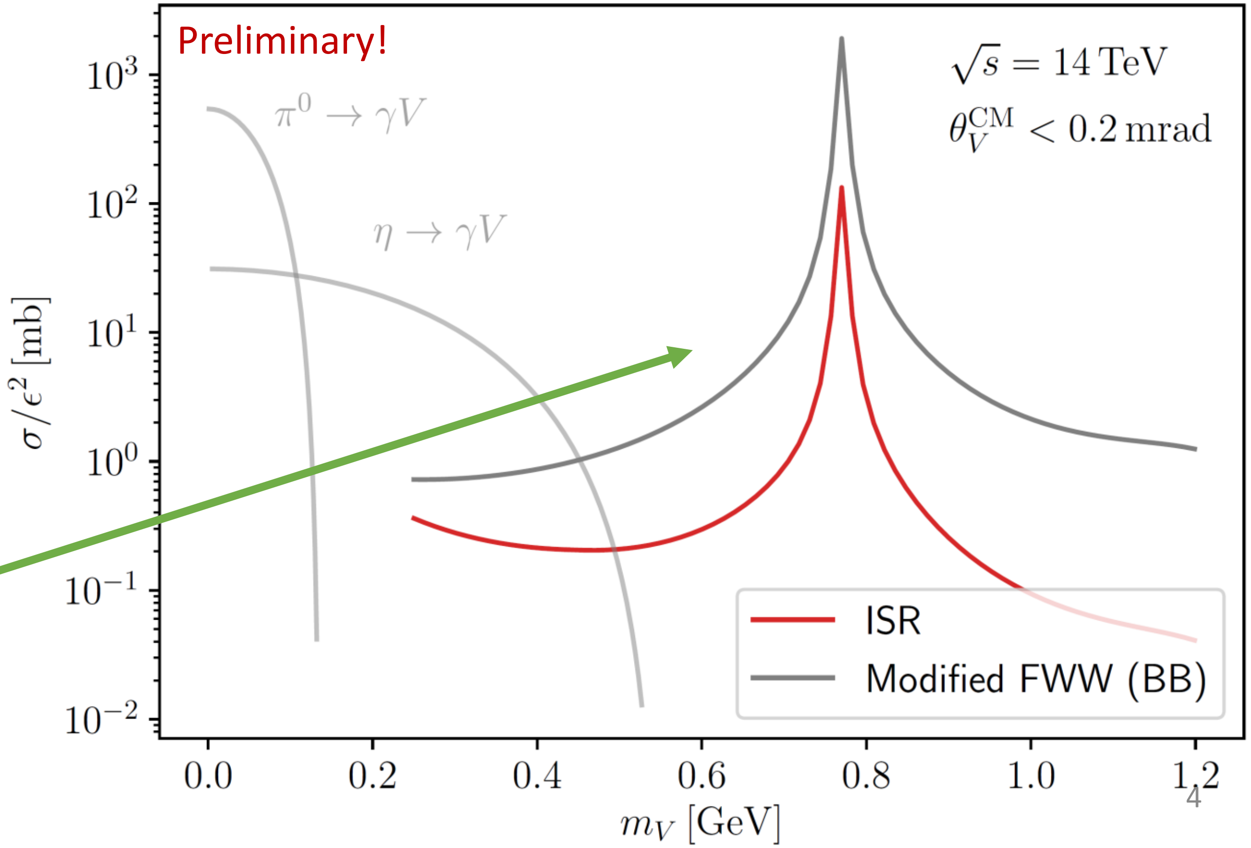
Revisiting Bremsstrahlung production of A'

- Dark photon production in the forward region modeled via bremsstrahlung
- Regime near ρ/ω resonance needs a more careful treatment

[FASER '17]



[SF & A. Ritz]



Photon vs Fermion Pole Approx.

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]

[a] *Deutsches Elektronen–Synchrotron, DESY, Platanenallee 6, D-15738 Zeuthen, Germany*
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A R T I C L E I N F O

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A B S T R A C T

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 Functions Using OFPT

ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

G. ALTARELLI *

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*

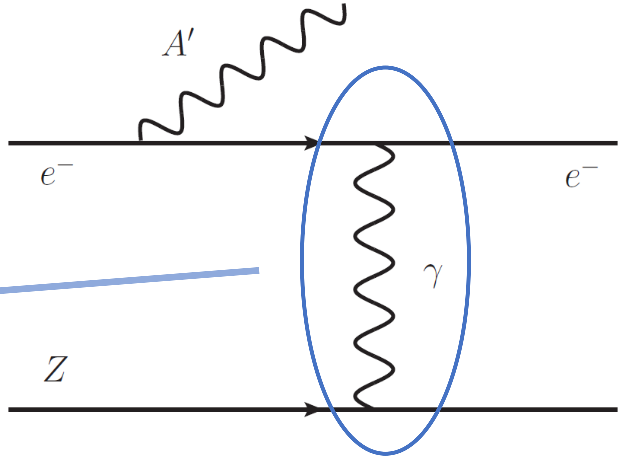
Abstract: We review and revise the phenomenology of the scalar portal – a new scalar particle with the mass in GeV range that mixes with the Higgs boson. In particular, we consider production channels $B \to SK_1(1270)$ and $B \to SK_0^*(700)$ and show that their contribution is significant. We extend 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

FWW (Photon Pole) Approx. (QED)

- **Assumptions**:
- Rapidly moving fermion & radiation is highly collinear
- Small photon virtuality [Kim, Tsai '73][Bjorken et al '09']

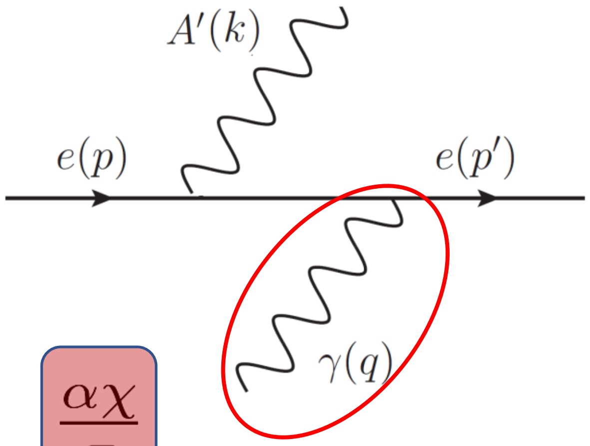
$$t_{min} = -q_{min}^2 \approx \left(\frac{U}{2E_0(1-x)}\right)^2$$

$$U(p_T, x) \equiv \frac{[p_T^2 + x^2 m_e^2 + (1-x)m_{A'}^2]}{x}$$



- Interaction dominated by transverse polarizations
- Cloud of effective flux of photons

$$d\sigma^{2\to 3}\Big|_{\rm WW} = (\alpha^3\epsilon^2\chi)\,\frac{E_e^2}{E_k^2}\,\frac{1}{U^2}\,A^{22}_{t=t_{min}}\,dx\,dp_T^2$$



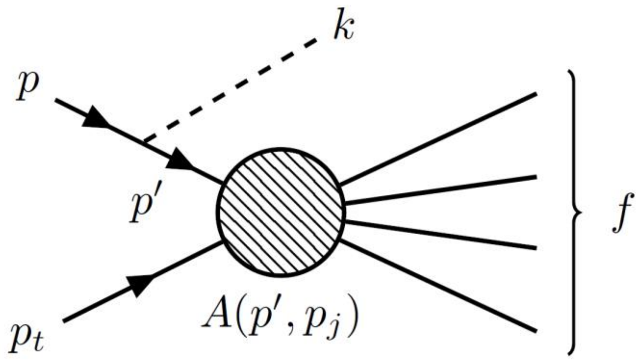
$$\frac{\alpha\chi}{\pi}$$

Splitting (Fermion Pole) Approx.

- **Assumptions**:

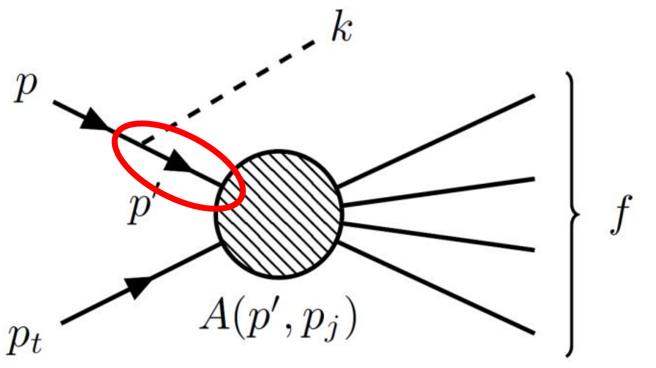
- Ultrarealistic fermion & radiation is highly collinear

- Intermediate-fermion being near on-shell



$$\mathcal{M}_r^{pp_t \to Df}(p, k, p_j) = ig_D A(p', pj) \frac{i(\not{p} - \not{k} + m)}{(p-k)^2 - m^2} u^r(p)$$

Splitting (Fermion Pole) Approx.



- **Assumptions**:

- Ultrarealistic fermion & radiation is highly collinear

- Intermediate-fermion being near **on-shell** [Khoze, Fadin]

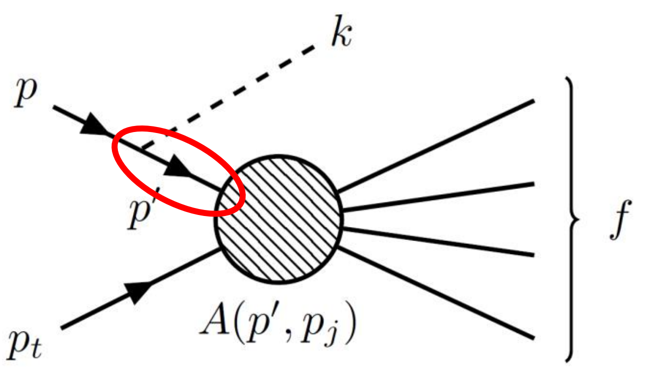
$$\frac{i(\not p - \not k + m)}{(p-k)^2 - m^2} = \frac{i}{2E_{p'}} \sum_{r'} \left[\frac{u^{r'}(p-k)\bar{u}^{r'}(p-k)}{E_p - E_k - E_{p'}} + \frac{v^{r'}(-p-k)\bar{v}^{r'}(-p-k)}{E_p - E_k + E_{p'}} \right] \quad \Rightarrow \quad \frac{H}{4z(1-z)^2 p_p^2} \ll 1$$

$$E_p - E_k - E_{p'} \ll E_p - E_k + E_{p'}$$

- Other momentum transfers in $A(p, p_j)$ are large

$$(p-k)^2 - m_p^2 \ll (t_0)_{char} \quad \Rightarrow \quad \frac{H}{z} \ll (t_0)_{char}$$

Splitting (Fermion Pole) Approx.



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$$E_p - E_k - E_{p'} \ll E_p - E_k + E_{p'}$$

- Other momentum transfers in $A(p, p_j)$ are large

$$\frac{1}{p'^2 - m^2} \gg \frac{1}{(t_0)_{\text{char.}}} \quad \Rightarrow \quad \frac{H}{z} \ll (t_0)_{\text{char.}}$$

- Splitting Probability: [Altarelli, Parisi] [Boiarska '19]

Calculable sub-process

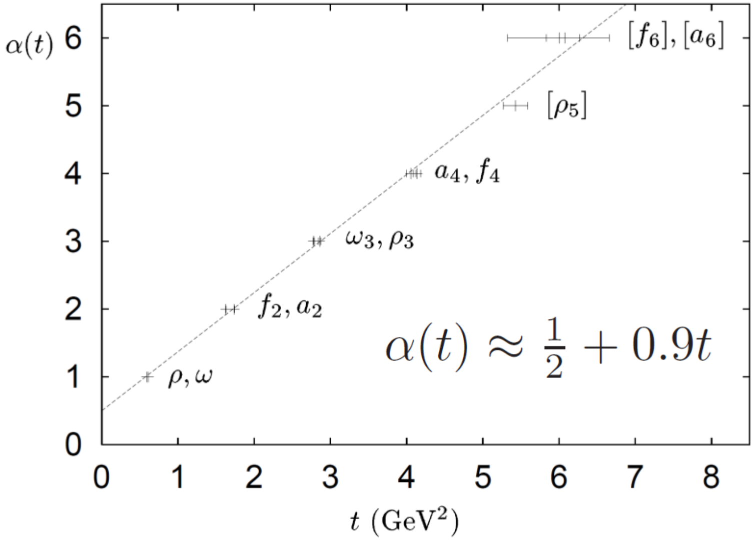
$$d\sigma_{pp_t \to DX} \approx dP_{p \to p'D} \times \sigma_{pp_t}(s')$$

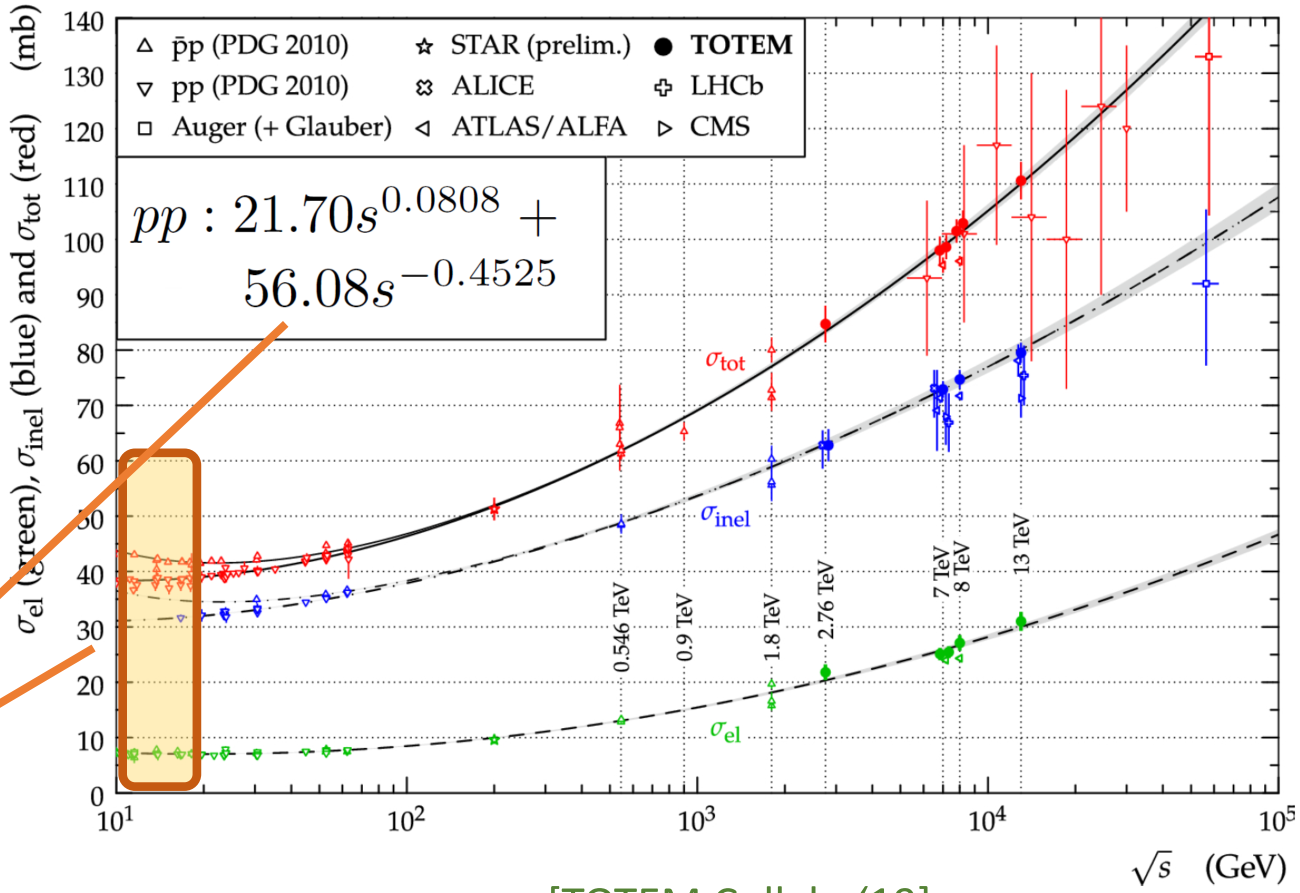
$$dP_{p \to p'D} \equiv w(z, p_T^2) dz dp_T^2$$

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

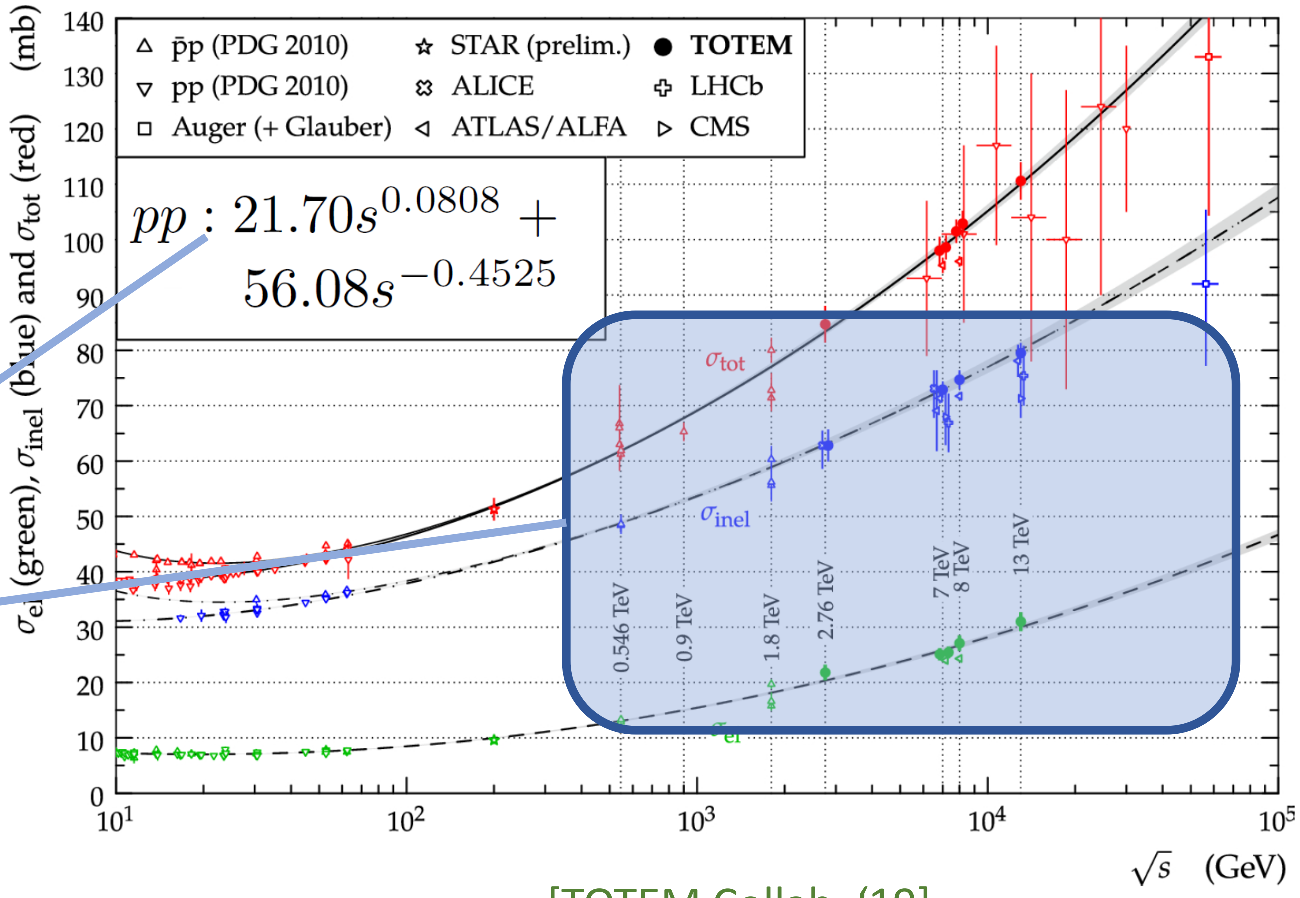
[TOTEM Collab. '19]

Modeling forward pp scattering

- Pomeron Trajectory: [Gribov '62]

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

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

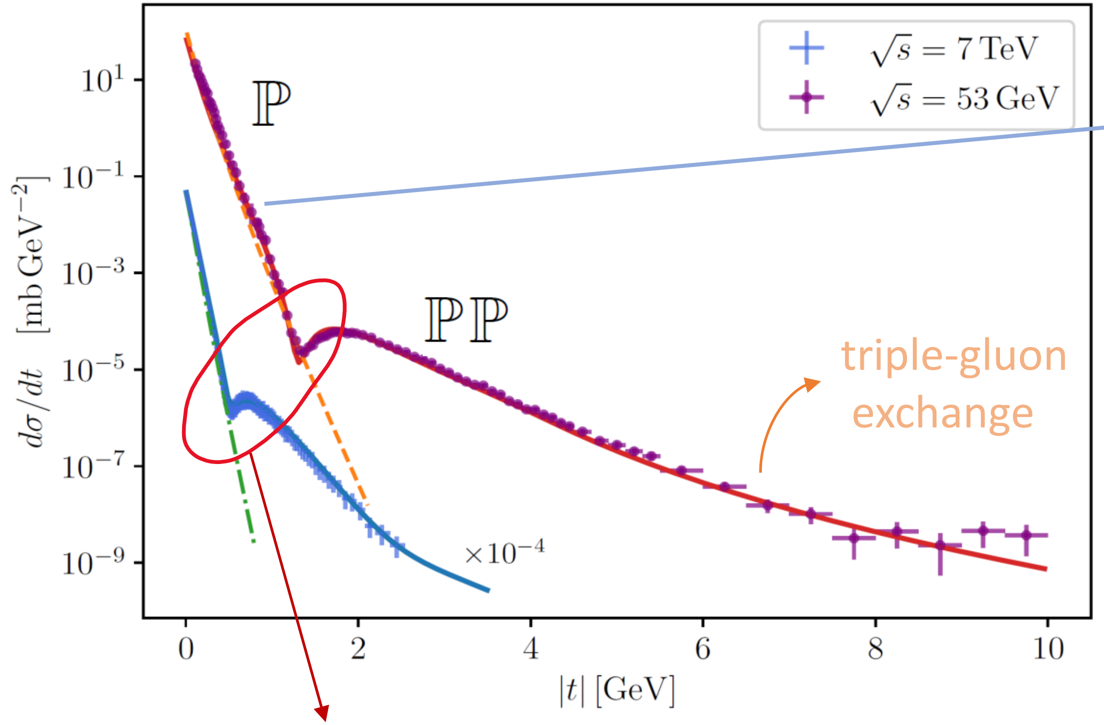


[TOTEM Collab. '19]

Elastic Scattering via Pomeron Exchange

- Donnachie & Landshoff (DL) model

[D&L ’82, ’84, ‘11, ‘13]



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

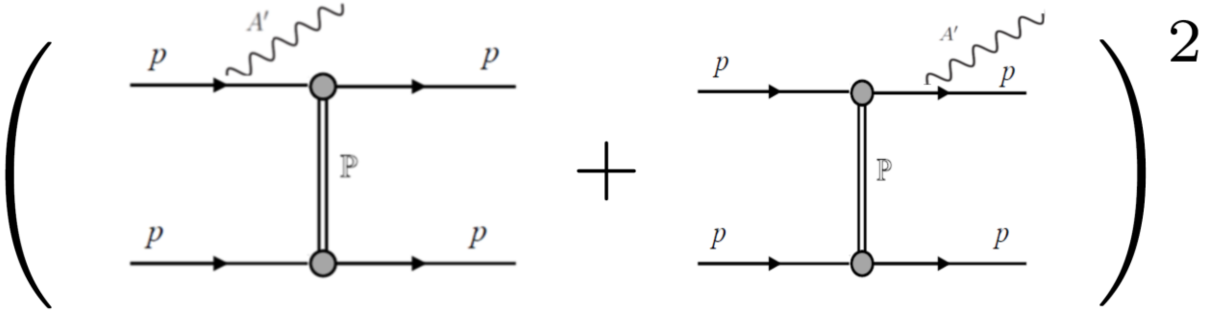
$$\frac{d\sigma^{\mathrm{el}}}{dt} \simeq \frac{1}{4\pi}\left(Y_{\mathbb{P}}F_1(t)\right)^4 |G(s,t)|^2$$

Effective Propagator & Vertex for SPE:

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

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

Quasi-Elastic Radiation

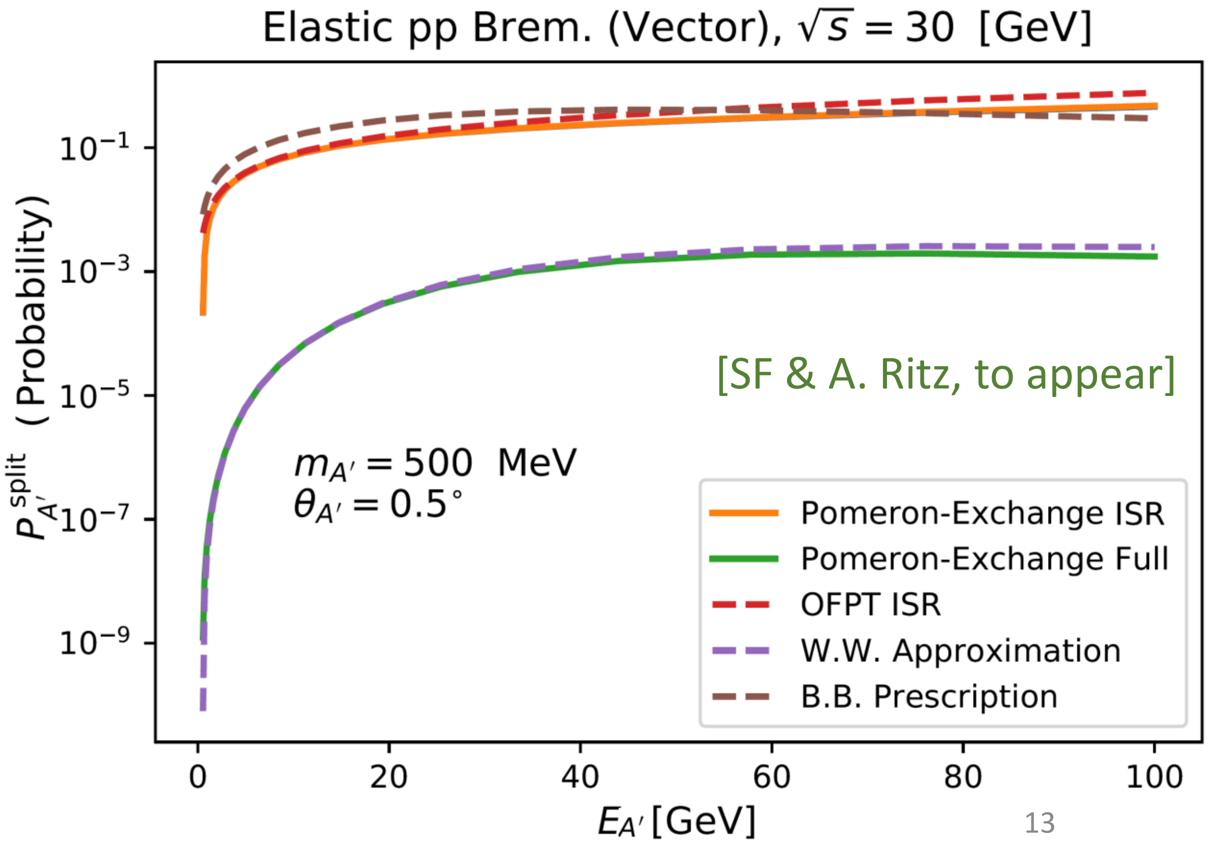


- Splitting via Pomeron-Exchange for ISR

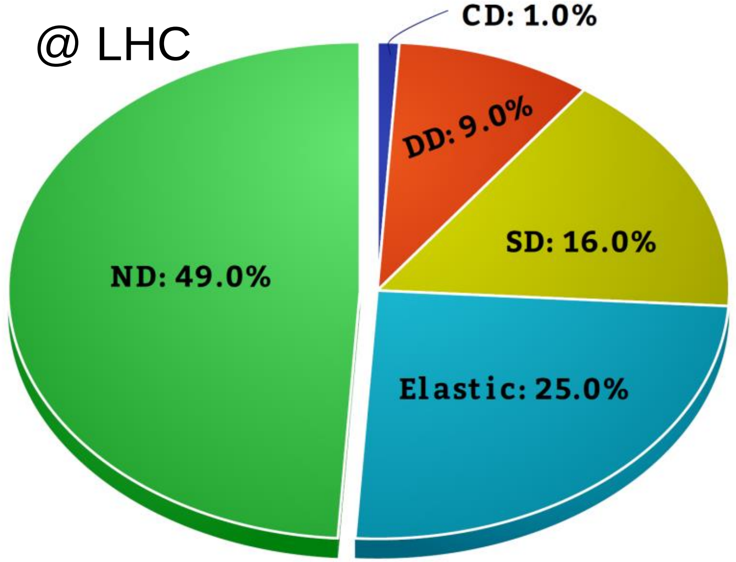
$$d\sigma_{pp\to\gamma' pp} \approx dP_{p\to p'\gamma'} \times \sigma^{\rm el}_{pp}(s')$$

- **Observe the large cancellation between ISR & FSR**

(But that is not the end of the story!)

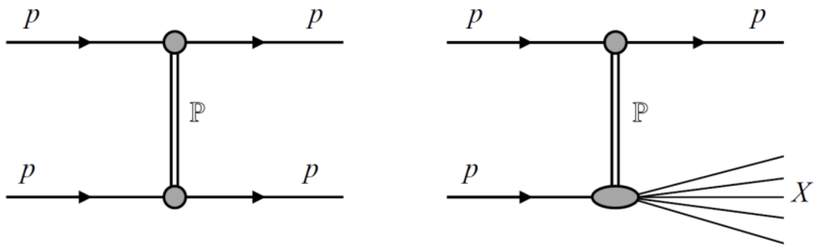


Topologies of events in σ_{tot}

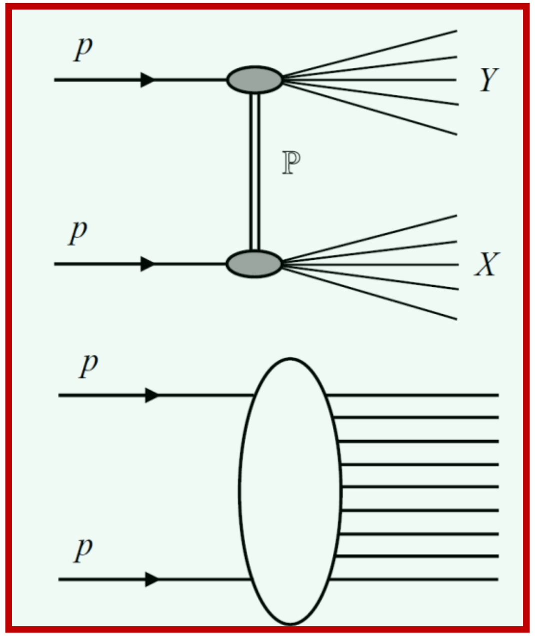


[PDG; Khoze et al ‘20]

- Diffractive dissociation via Pomeron exchange



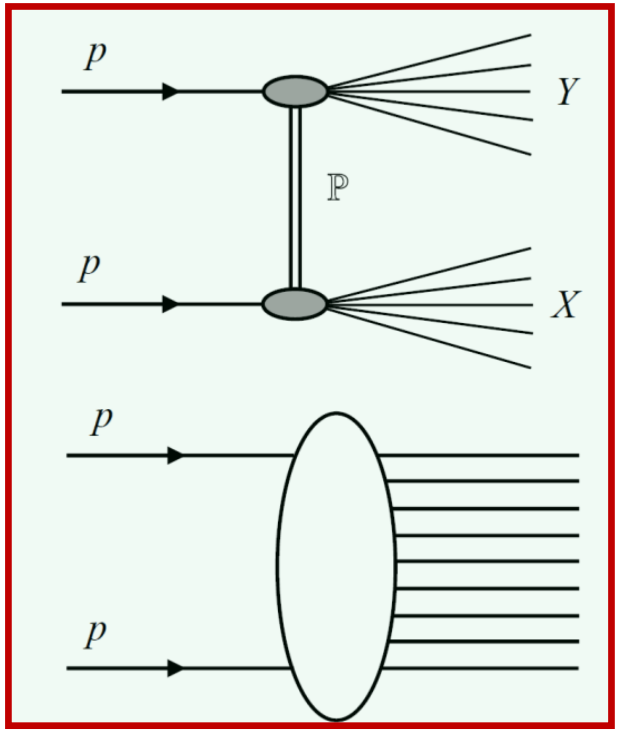
$\Longrightarrow$ Large cancellation between **ISR & FSR**



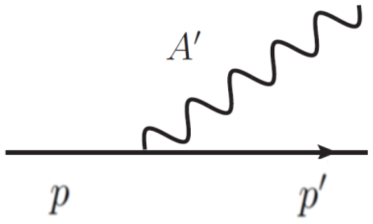
Non-Single Diffractive

A' production via proton beam

- Contribution of **Non-Single Diffractive** processes to **ISR**

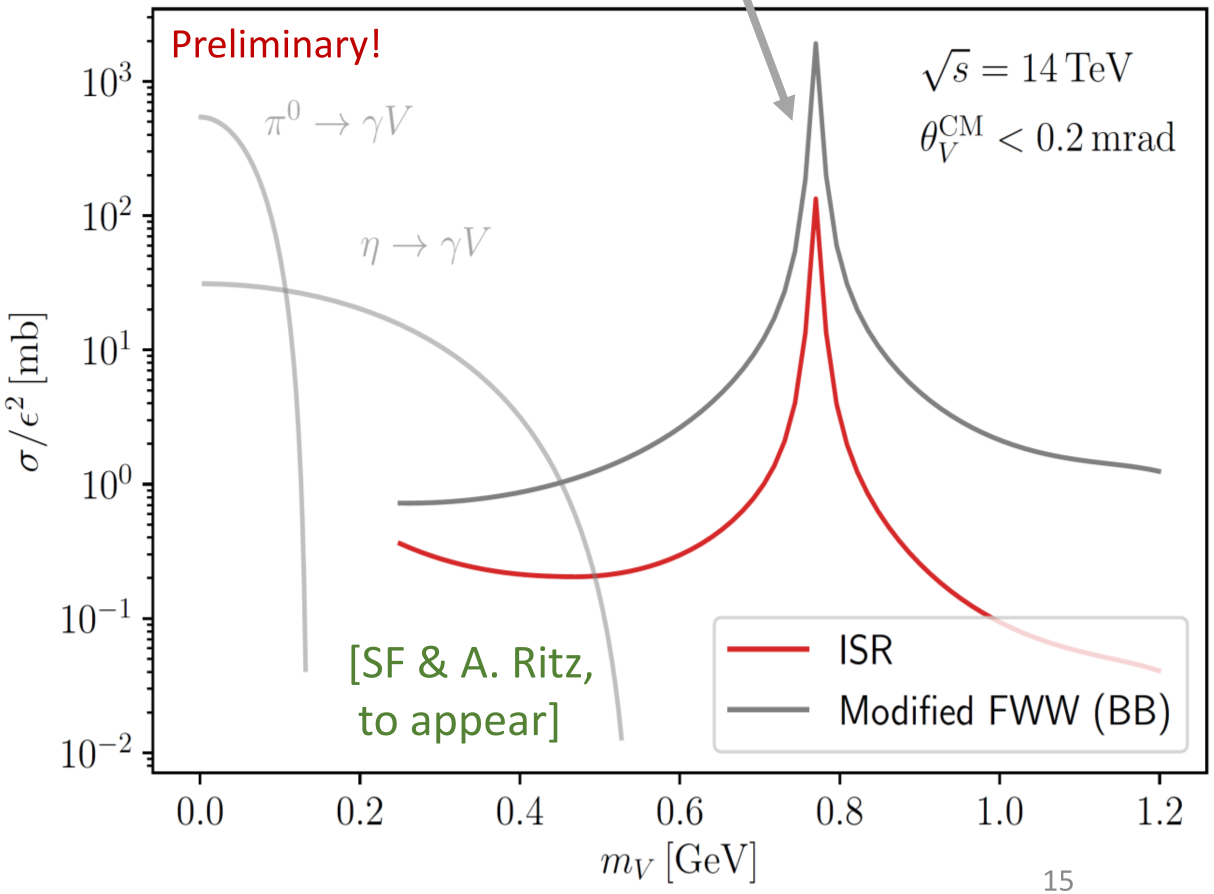


$$\sigma_{\text{NSD}} \lesssim 0.5\,\sigma_{\text{tot}}$$



Only ISR

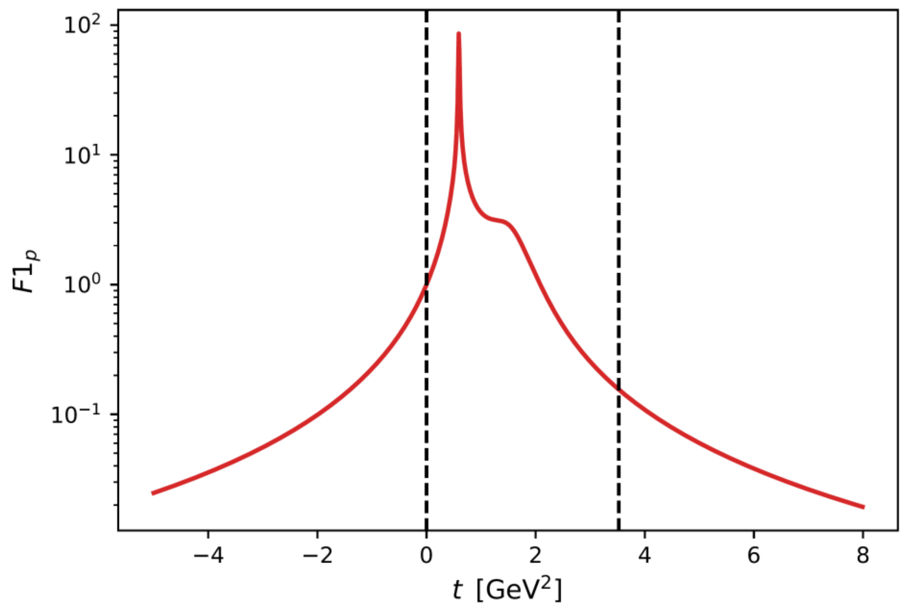
[Blümlein, Brunner ‘13]

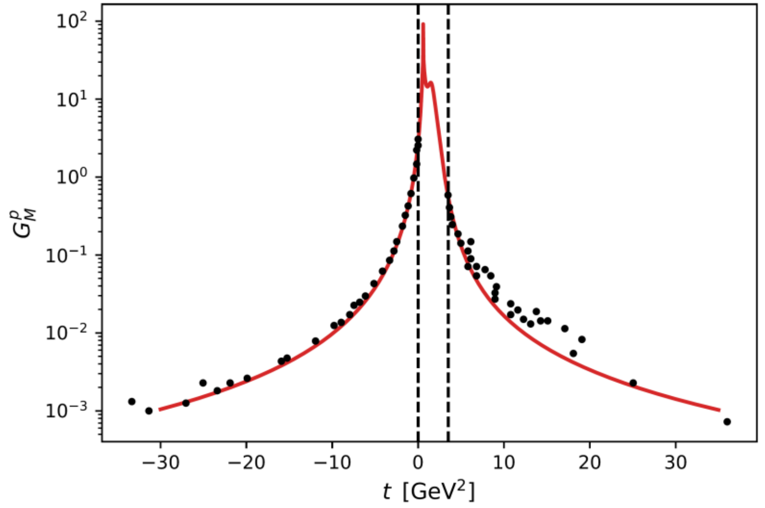


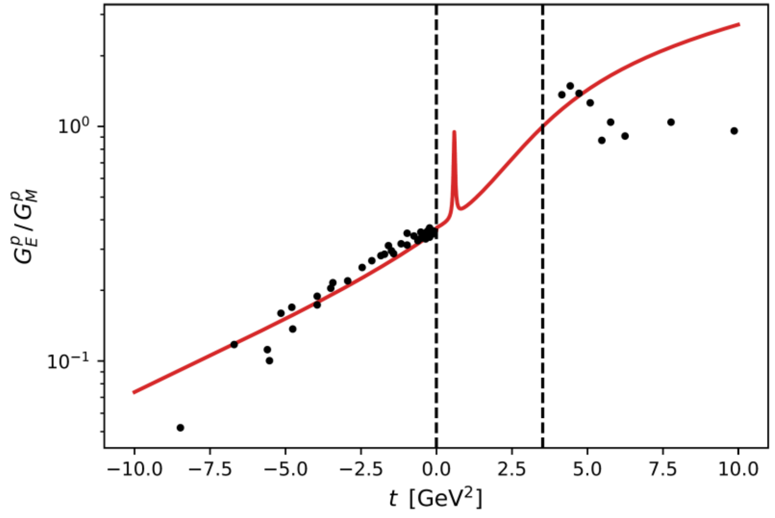
EM Form Factor in the TL region

[Adamuscin et al ’16]
[Faessler et al ‘09]

- The radiated A' has time-like (TL) momenta
- Inclusion of the TL form-factor accounting for the mixing with ρ/ω resonance based on VMD model







Summary

- The well known FWW method approximate the boson pole which relate the ultra-relativistic fermion interaction to the cross-section for real-boson scattering.
- *Initial (final) state radiation* can be evaluated using an alternative method of splitting function in the context of OFPT which approximates the intermediate fermion propagator.
- Soft hadronic interactions are non perturbative and are described by the *Regge approach* at high energies.
- Proton bremsstrahlung from *elastic* and *single diffraction* topologies leads to large <u>cancelation</u> between ISR & FSR.
- Dark photon via proton brem. is revisited near the ρ/ω resonance region.
- Millicharged particle production at the LHC forward region can also be studied using the splitting approach.