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Double Parton Scattering Effect in Measurement of W mass

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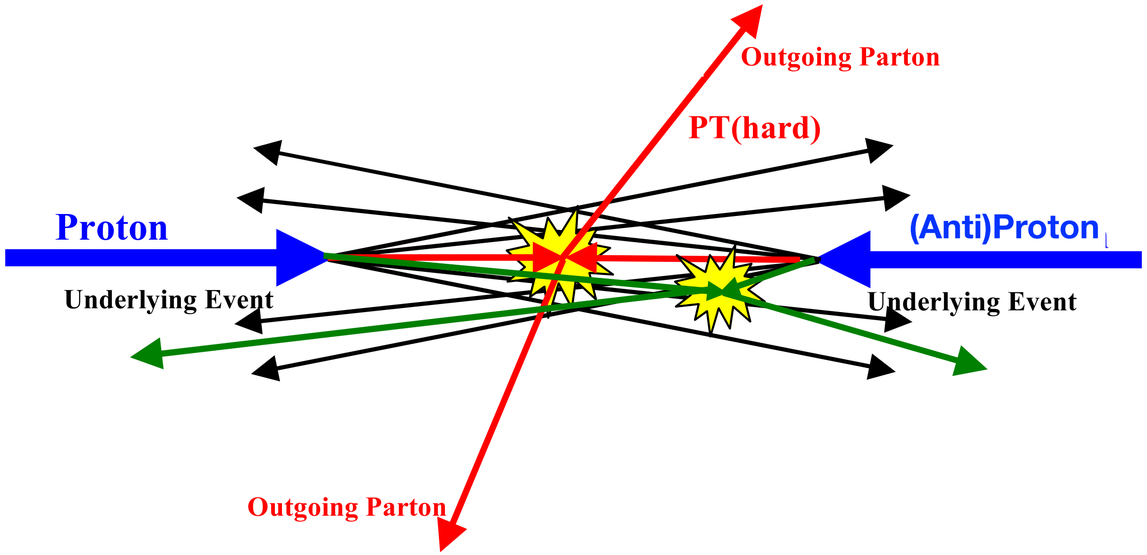
Multiple Parton Interaction



hard scattering + soft spectator scattering

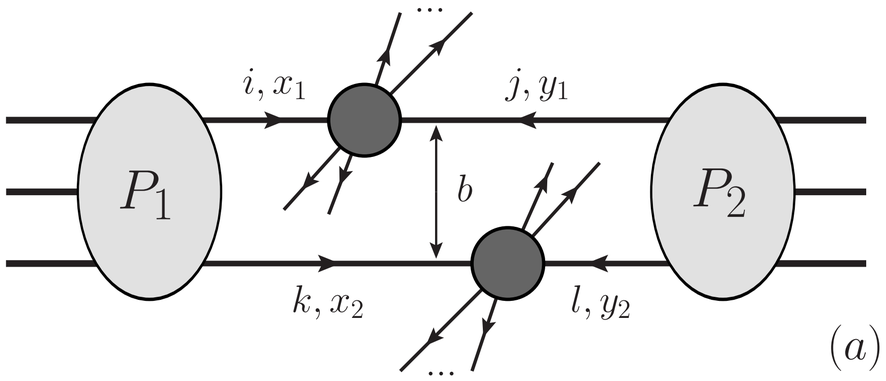
underlying event (UE)

good for $P_{\mathrm{T}} \lesssim 5$ GeV

see CP5 tune
CMS, EPJC 80 (2020)

abrupt cut-off
$P_{\mathrm{T},0} \sim 2$ GeV

continuous turn-off
$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 p_{\mathrm{T}}} \sim \frac{\alpha(p_{\mathrm{T}}^2)}{p_{\mathrm{T}}^4} \to \frac{\alpha(p_{\mathrm{T}}^2 + p_{\mathrm{T},0}^2)}{(p_{\mathrm{T}}^2 + p_{\mathrm{T},0}^2)^2}$$



$$\sigma_{\mathrm{AB}}^{\mathrm{DPS}} = \frac{n}{2} \sum_{ijkl} \int dx_1 dy_1 dx_2 dy_2 d^2 b$$ **double parton scattering (DPS)**

$$\times \Gamma_{ik}(x_1, x_2, \mu_F, \mu_F'; b) \Gamma_{jl}(y_1, y_2, \mu_F, \mu_F'; b) \times \hat{\sigma}_{ij}^{A}(x_1, y_1) \hat{\sigma}_{kl}^{B}(x_2, y_2)$$

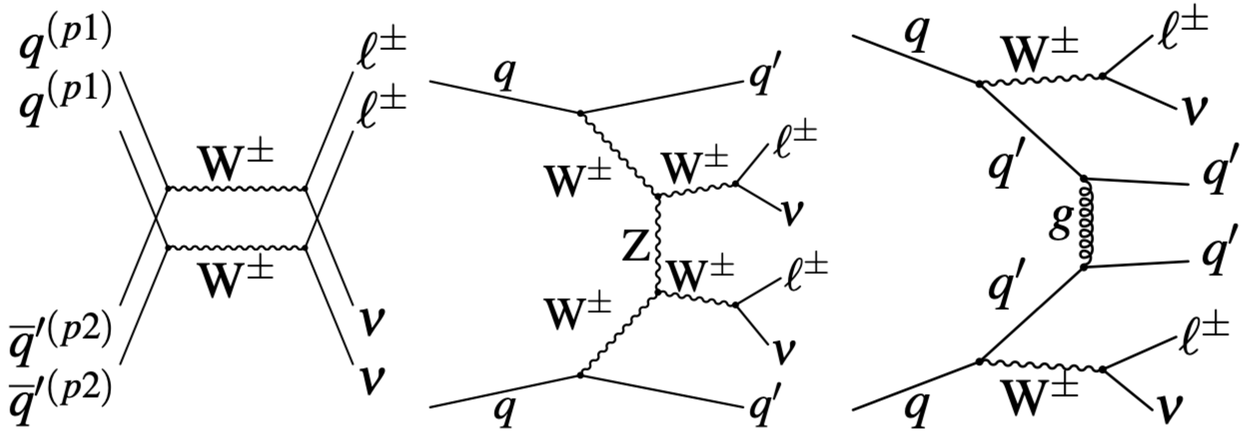
only used for $P_{\mathrm{T}} > 30$ GeV

$$\Gamma_{ik}(x_1, x_2, \mu_F, \mu_F'; b) = D_{ik}(x_1, x_2, \mu_F, \mu_F') F(b)$$ **assume factorisation**

$$D_{ik}(x_1, x_2, \mu_F, \mu_F') = f_i(x_1, \mu_F) f_k(x_2, \mu_F') \theta(1 - x_1 - x_2)$$

$$\sigma_{\mathrm{eff}}^{-1} \equiv \int d^2 b \big(F(b)\big)^2 \qquad \sigma_{\mathrm{AB}}^{\mathrm{DPS}} = \frac{n}{2} \frac{\sigma_{\mathrm{A}}^{\mathrm{SPS}} \sigma_{\mathrm{B}}^{\mathrm{SPS}}}{\sigma_{\mathrm{eff}}}$$

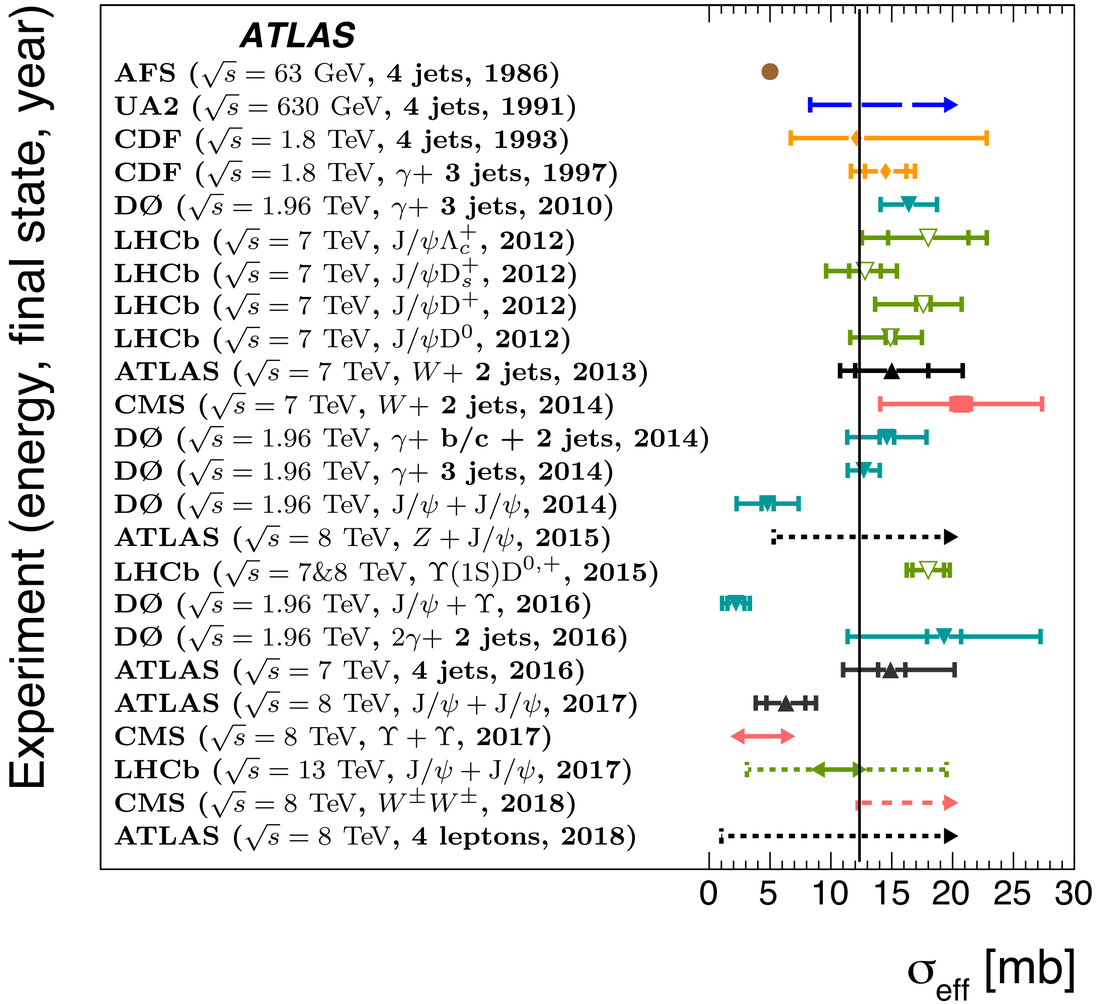
Double Parton Scattering (DPS)



observed 6.2σ @13 TeV, 138 fb^{-1}

$\sigma_{\text{eff}} = 12.2^{+2.9}_{-2.2}$ mb CMS, Phys.Rev.Lett. 131 (2023) 091803

$$\sigma_{\text{AB}}^{\text{DPS}} = \frac{n}{2}\frac{\sigma_{\text{A}}^{\text{SPS}}\sigma_{\text{B}}^{\text{SPS}}}{\sigma_{\text{eff}}}$$



Threshold for DPS

$$\sigma^{\mathrm{DPS}}_{\mathrm{jj+X}} = \frac{\sigma_{\mathrm{jj}}}{\sigma_{\mathrm{eff}}} \times \sigma_{\mathrm{X}}$$

leading order simulation

$\sigma_{\mathrm{jj}} = 0.5\ \mathrm{mb}$ $p_{\mathrm{T}}^{j} > 10\ \mathrm{GeV}$ @ 1.96 TeV Tevatron

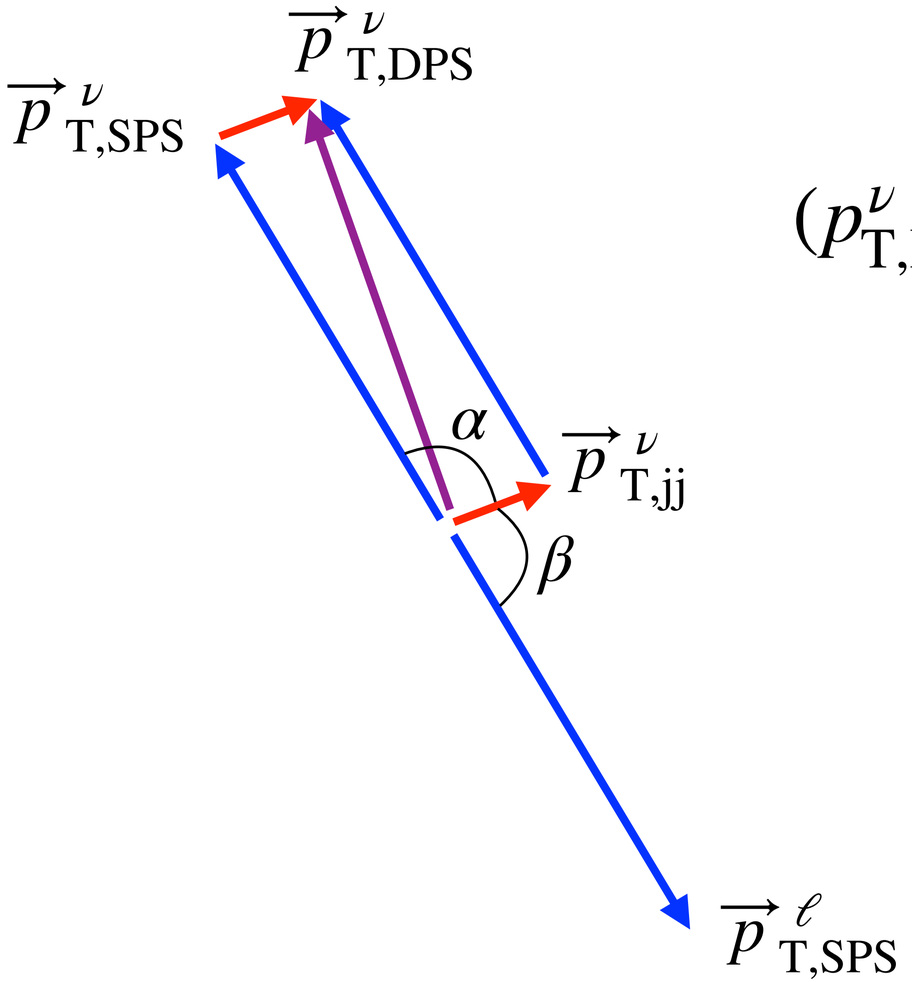
$\sigma_{\mathrm{eff}} = 12.2\ \mathrm{mb}$

//

4 %

DPS change distribution and cross section.
Where is the threshold?

DPS Effects in Measuring p_{T}^{ν}



$$(p^{\nu}_{\mathrm{T,DPS}})^2 = (p^{\nu}_{\mathrm{T,SPS}})^2 + (p^{\nu}_{\mathrm{T},jj})^2 + 2p^{\nu}_{\mathrm{T,SPS}}p^{\nu}_{\mathrm{T},jj}\cos\alpha$$

shift at $(p^{\nu}_{\mathrm{T},jj})^2$ order

smearing at $p^{\nu}_{\mathrm{T},jj}$ order

also affect $m_{\mathrm{T}}(\ell,\nu) \equiv \sqrt{2\left(p^{\ell}_{\mathrm{T}}p^{\nu}_{\mathrm{T}} - \overrightarrow{p}^{\,\ell}_{\mathrm{T}} \cdot \overrightarrow{p}^{\,\nu}_{\mathrm{T}}\right)}$

Threshold for DPS

- UE to describe data $\lesssim$5 GeV, DPS only checked >30 GeV
- relative uncertainties of Drell-Yan total/differential cross section ~4%
- inclusive jet cross section ~0.4 mb (CDF, Phys.Rev.Lett. 77 (1996) 438-443)
- So threshold $\gtrsim$10 GeV is not included in description of underlying event, and need to be checked.

CDF-II W-mass Measurement

Distribution	*W* boson mass (MeV)	χ^2/dof
$m_T(e, \nu)$	$80{,}429.1 \pm 10.3_{stat} \pm 8.5_{syst}$	39/48
$p_T^{\ell}(e)$	$80{,}411.4 \pm 10.7_{stat} \pm 11.8_{syst}$	83/62
$p_T^{\nu}(e)$	$80{,}426.3 \pm 14.5_{stat} \pm 11.7_{syst}$	69/62
$m_T(\mu, \nu)$	$80{,}446.1 \pm 9.2_{stat} \pm 7.3_{syst}$	50/48
$p_T^{\ell}(\mu)$	$80{,}428.2 \pm 9.6_{stat} \pm 10.3_{syst}$	82/62
$p_T^{\nu}(\mu)$	$80{,}428.9 \pm 13.1_{stat} \pm 10.9_{syst}$	63/62
Combination	$80{,}433.5 \pm 6.4_{stat} \pm 6.9_{syst}$	7.4/5

tension with SM prediction and other experiments

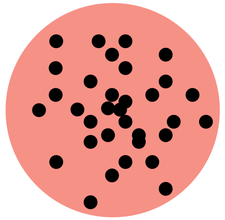
$6.9\ \sigma$ SM prediction: $m_W = 80359.1 \pm 5.2\ \mathrm{MeV}$ de Blas, et al., PRD 106 (2022) 3, 033003

$4.0\ \sigma$ LHC latest: $m_W = 80360 \pm 16\ \mathrm{MeV}$ report number: ATLAS-CONF-2023-004

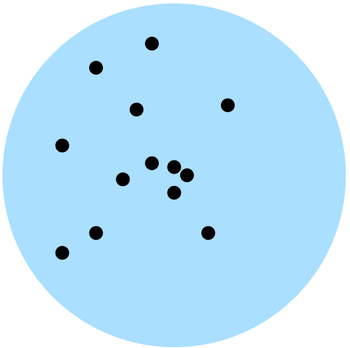
Jet Energy Calibration

jet energy scale factor:
average UE/pile-up/electronic noise

LHC:
large density
average is good enough



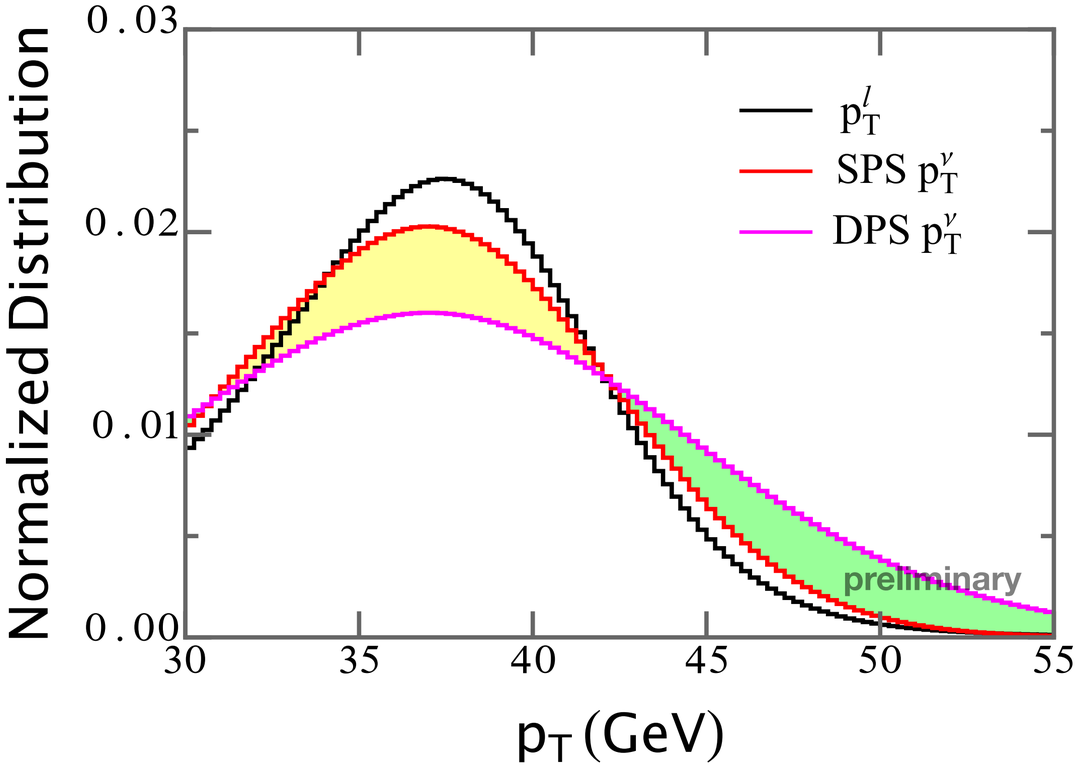
Tevatron:
small density
hard to take average

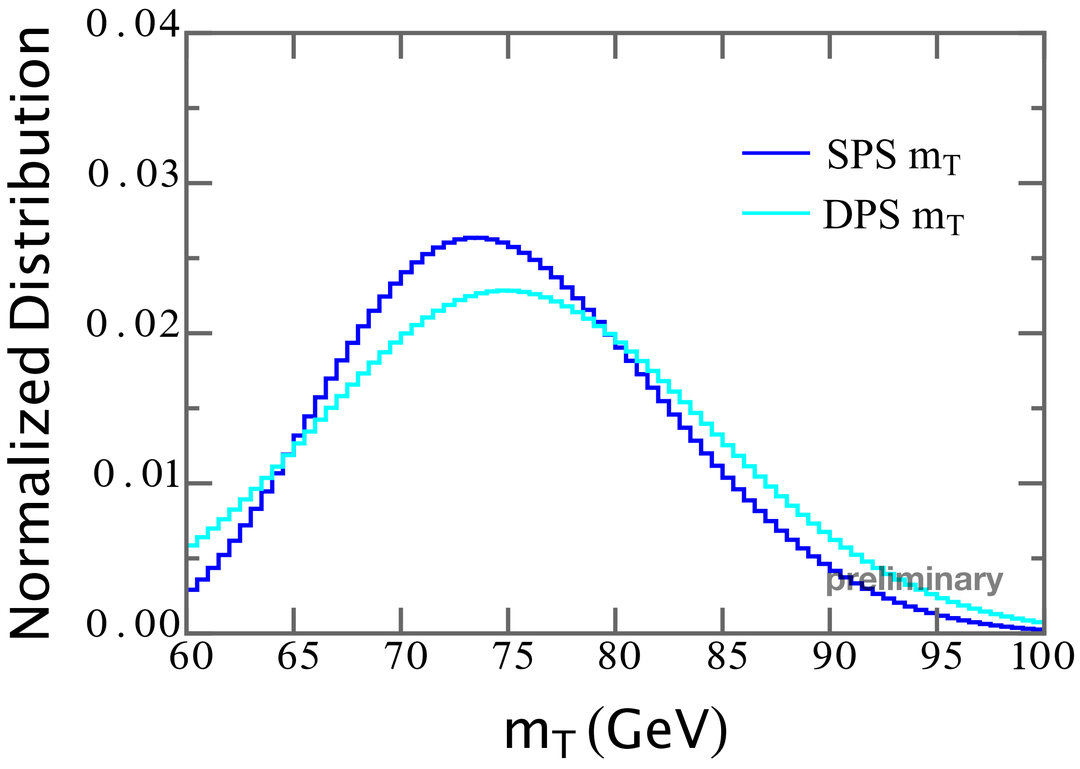


DPS Effects

choose $p_{\mathrm{T}}^{j} > 10$ GeV for example

$M_W \equiv M_W^{\mathrm{SM}} + \Delta M_W$

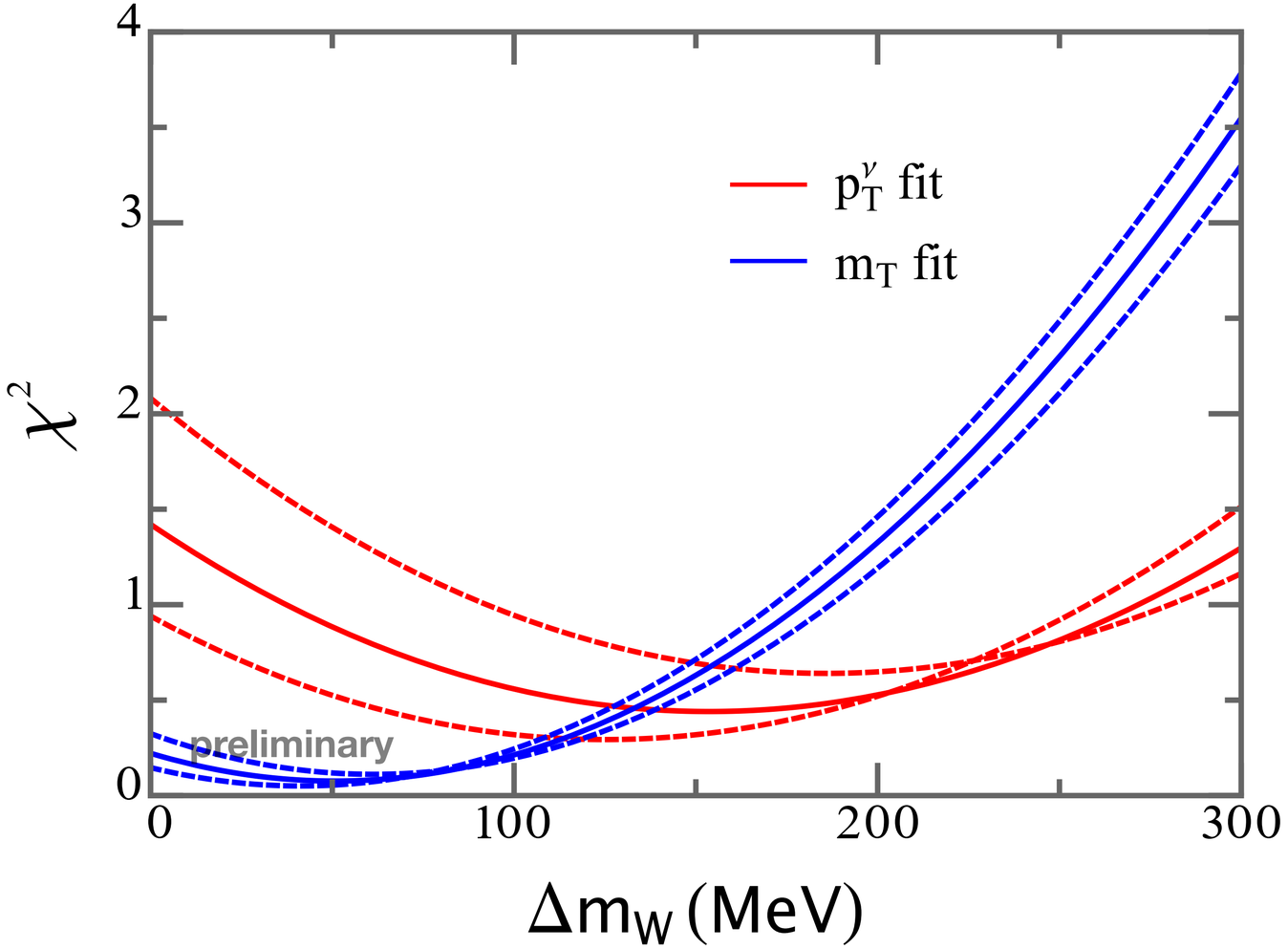




expect $\Delta M_W \sim 10^2$ MeV

expect $\Delta M_W \sim 10^1$ MeV

DPS Effects



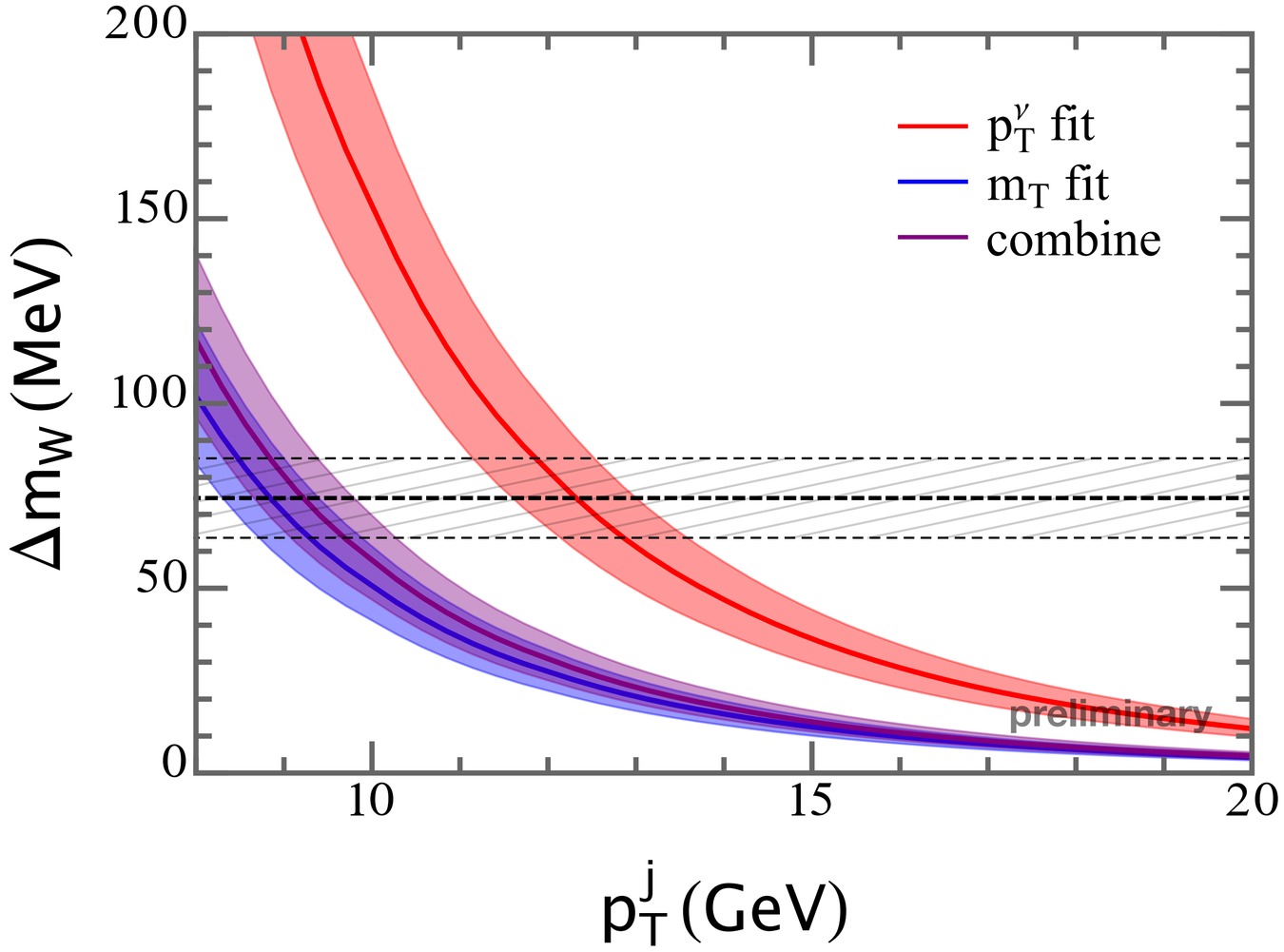
$$\chi^2 = \sum_{i=a}^{b} \frac{(n_i - n_i^{\mathrm{SM}})^2}{n_i^{\mathrm{SM}} + (f_{\mathrm{syst}} n_i^{\mathrm{SM}})^2}, \quad f_{\mathrm{syst}} = 10\,\%$$

threshold $p_{\mathrm{T}}^j > 10$ GeV

consider uncertainty from σ_{eff}

$\sigma_{\mathrm{eff}} = 12.2^{+2.9}_{-2.2}$ mb

DPS Scale Dependence



$$M_W \equiv M_W^{\mathrm{SM}} + \Delta M_W$$

consider uncertainty from $\sigma_{\mathrm{eff}} = 12.2^{+2.9}_{-2.2}$ mb

threshold $p_{\mathrm{T}}^j > 10/15/20$ GeV

$\Delta M_W(p_{\mathrm{T}}^\nu) = 154^{+32}_{-28}/36^{+8}_{-7}/12^{+3}_{-2}$ MeV

$\Delta M_W(m_{\mathrm{T}}) = 51^{+11}_{-9}/12^{+3}_{-2}/4^{+1}_{-1}$ MeV

$\Delta M_W(\mathrm{combine}) = 58^{+12}_{-11}/14^{+3}_{-3}/5^{+1}_{-1}$ MeV

Conclusion

- Double parton scattering effects can appears in inclusive measurements.
- contribute ~10^{-2} total events and $\mathcal{O}(10^{-2}) - \mathcal{O}(10^{-1})$ GeV shift of p_{T}^{ν}.
- The W-mass tension shows the threshold may be ~10 GeV.
- Hope CEPC can help improve the result.

Backup

DPS on p_{T}^{ν}

$$(p_{\mathrm{T,DPS}}^{\nu})^2 = (p_{\mathrm{T,SPS}}^{\nu})^2 + (p_{\mathrm{T},jj}^{\nu})^2 + 2p_{\mathrm{T,SPS}}^{\nu} p_{\mathrm{T},jj}^{\nu} \cos\alpha$$

$$p_{\mathrm{T,DPS}}^{\nu} = p_{\mathrm{T,SPS}}^{\nu} + p_{\mathrm{T},jj}^{\nu} \cos\alpha + \frac{(p_{\mathrm{T},jj}^{\nu})^2}{2p_{\mathrm{T,SPS}}^{\nu}}(1 - \cos^2\alpha)$$

smearing ~4 GeV

shift ~0.1 GeV

DPS on m_{T}

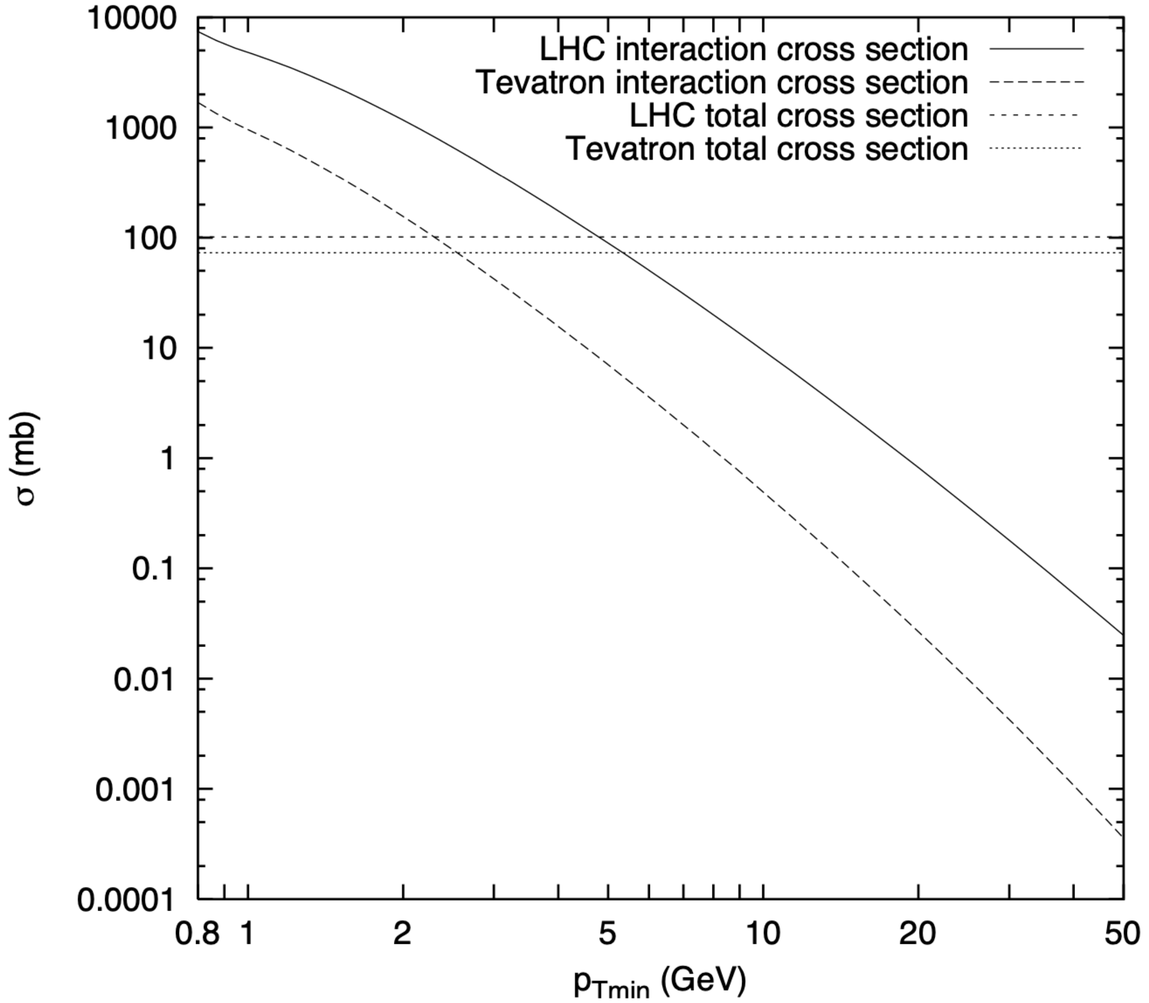
$$m_{\mathrm{T}}(\ell,\nu) \equiv \sqrt{2\left(p_{\mathrm{T}}^{\ell}p_{\mathrm{T}}^{\nu} - \overrightarrow{p}_{\mathrm{T}}^{\,\ell}\cdot\overrightarrow{p}_{\mathrm{T}}^{\,\nu}\right)}$$

$$(m_{\mathrm{T,DPS}})^2 = (m_{\mathrm{T,SPS}})^2 + 2p_{\mathrm{T}}^{\ell}\Delta p_{\mathrm{T,DPS}}^{\nu} - 2\overrightarrow{p}_{\mathrm{T}}^{\,\ell}\cdot\overrightarrow{p}_{\mathrm{T},jj}^{\,\nu}$$

$$\Delta m_{\mathrm{T,DPS}} = \frac{p_{\mathrm{T}}^{\ell}p_{\mathrm{T},jj}^{\nu}}{m_{\mathrm{T,SPS}}}\left(\cos\alpha - \cos\beta\right) \longrightarrow \text{smearing ~4 GeV}$$

$$+\frac{(p_{\mathrm{T},jj}^{\nu})^2}{2m_{\mathrm{T,SPS}}}\frac{p_{\mathrm{T}}^{\ell}}{p_{\mathrm{T,SPS}}^{\nu}}\left(1-\cos^2\alpha\right)$$

$$-\frac{(p_{\mathrm{T},jj}^{\nu})^2}{2m_{\mathrm{T,SPS}}}\frac{(p_{\mathrm{T}}^{\ell})^2}{(m_{\mathrm{T,SPS}})^2}\left(\cos\alpha-\cos\beta\right)^2 \longrightarrow \text{shift ~0 GeV}$$



T. Sjostrand and Peter Z. Skands, JHEP 03 (2004) 053

Figure 2: The integrated interaction cross section $\sigma_{\rm int}$ above $p_{\perp\rm min}$ for the Tevatron, with 1.8 TeV $\rm p\overline{p}$ collisions, and the LHC, with 14 TeV pp ones. For comparison, the flat lines represent the respective total cross section.