Double parton scattering

a personal perspective

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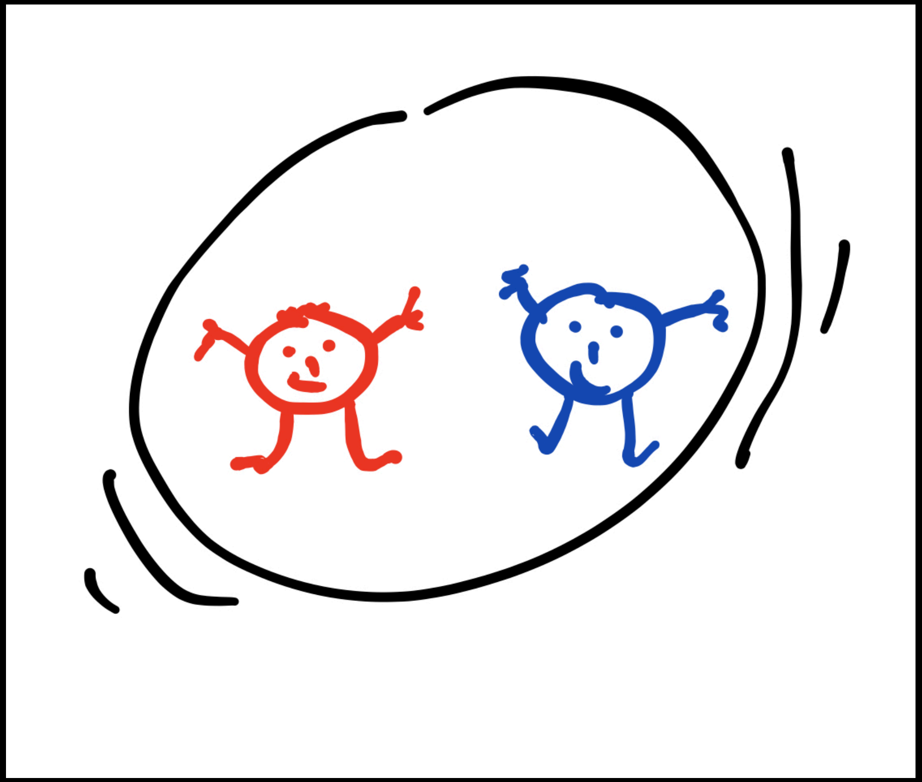
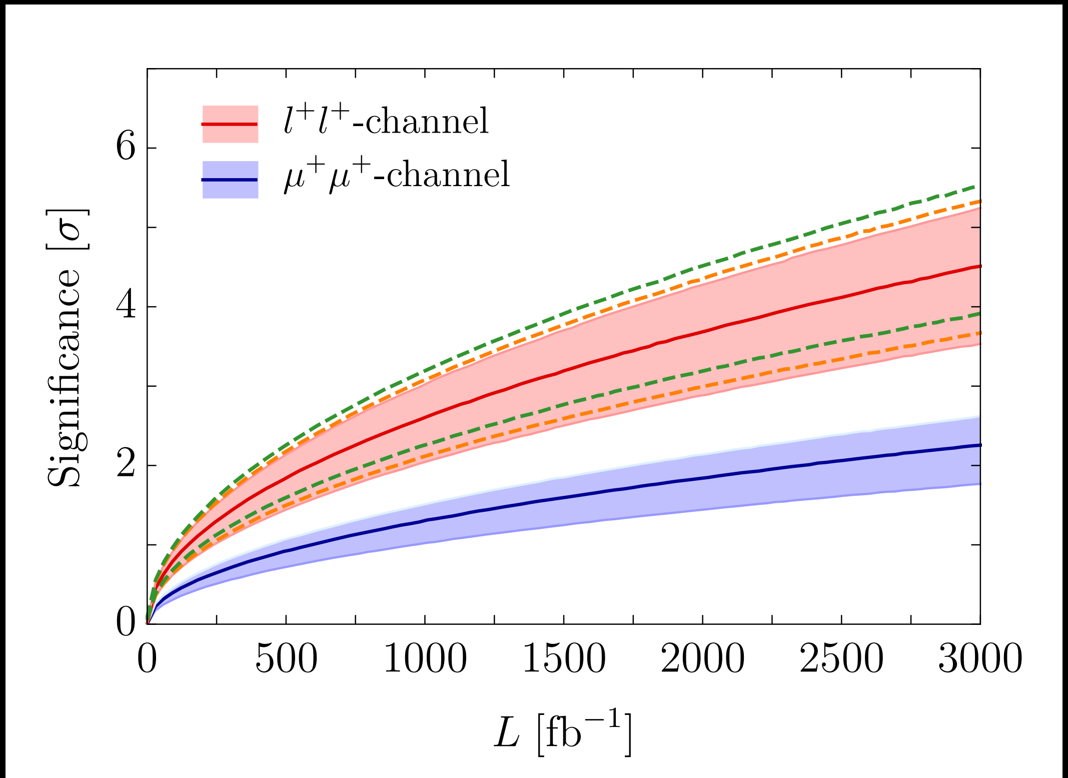
Motivation





l^+l^+-channel
$\mu^+\mu^+$-channel
Significance $[\sigma]$
0
2
4
6
0
500
1000
1500
2000
2500
3000
L [fb^{-1}]

An introduction to double parton scattering

- **Single parton scattering example:**

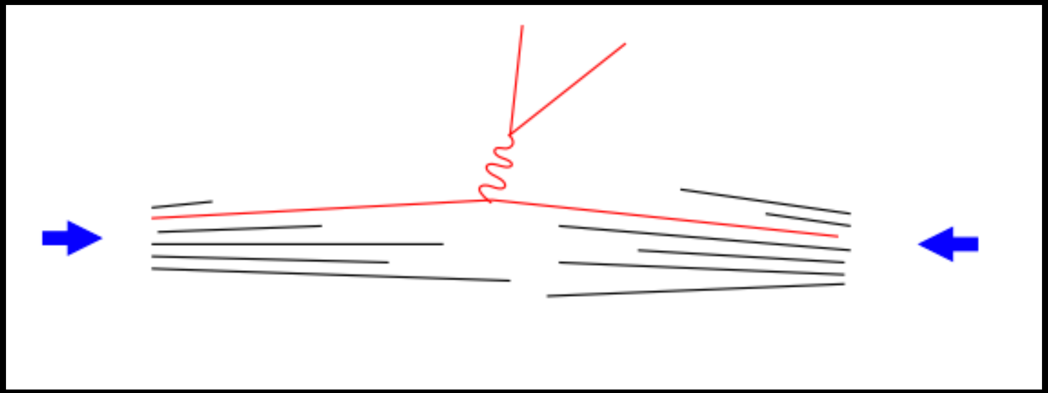
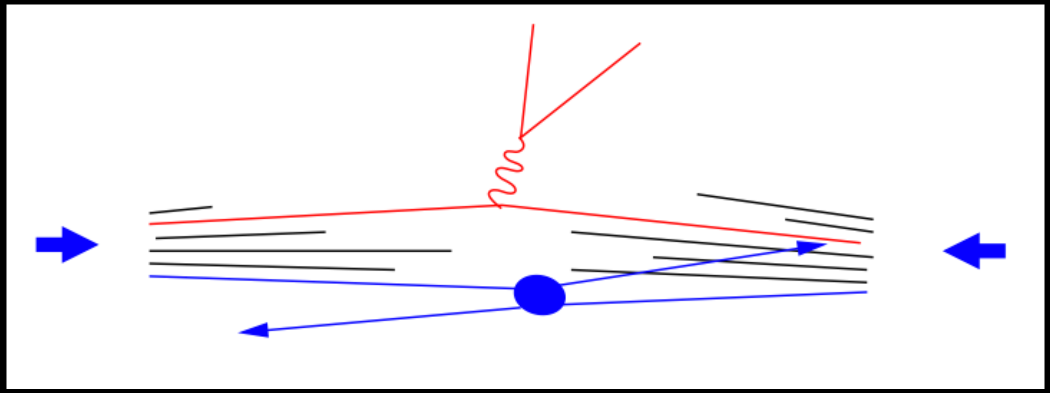


figure from M. Diehl, QCD Evolution 2014

- **Double parton scattering example:**



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An introduction to double parton scattering

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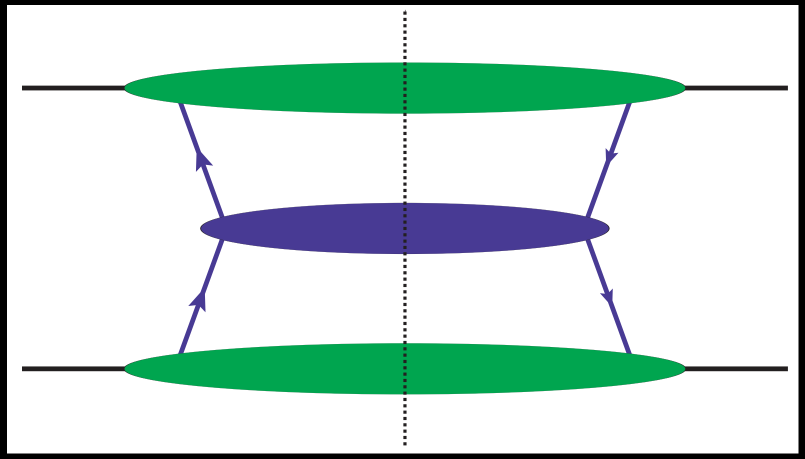
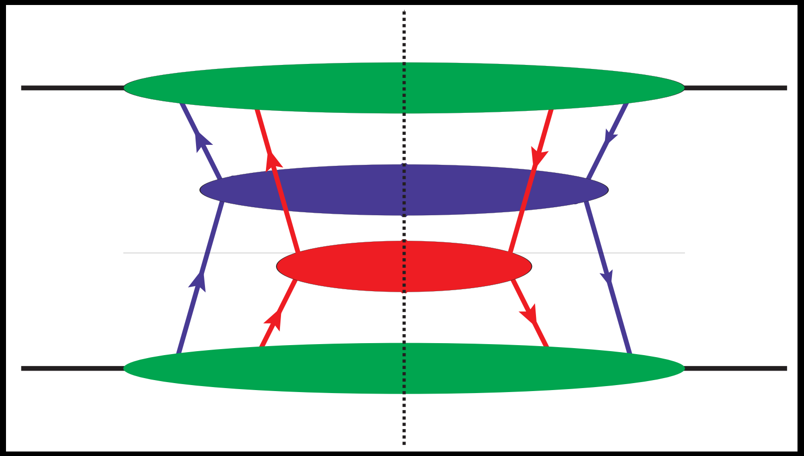


- **Double parton scattering example:**



An introduction to double parton scattering

- **Single parton scattering example:**

$$d\sigma_{\text{SPS}} \sim d\sigma\, f_a(x)\, f_b(\bar{x})$$

- **Double parton scattering example:**

$$d\sigma_{\text{DPS}} \sim d\sigma_1 d\sigma_2 \int d^2y\, f_{ab}(x_1, x_2, \boldsymbol{y})\, f_{cd}(\bar{x}_1, \bar{x}_2, \boldsymbol{y})$$

An introduction to double parton scattering

- **Single parton scattering example:**

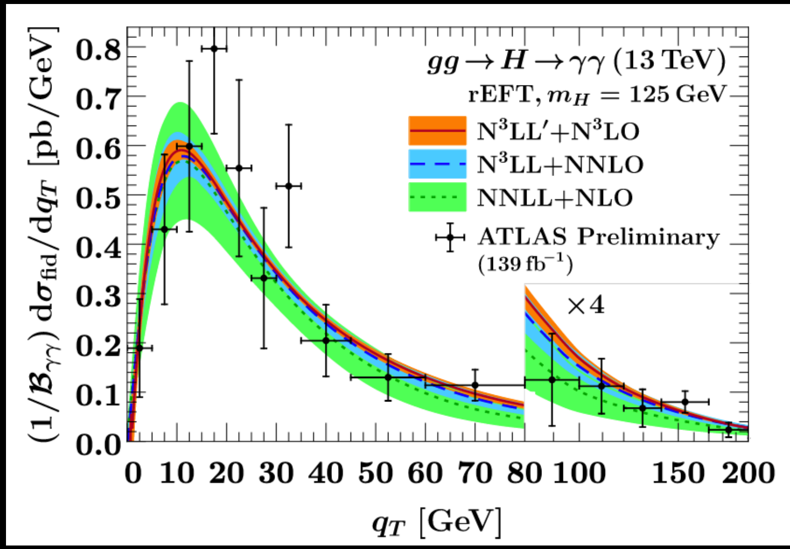
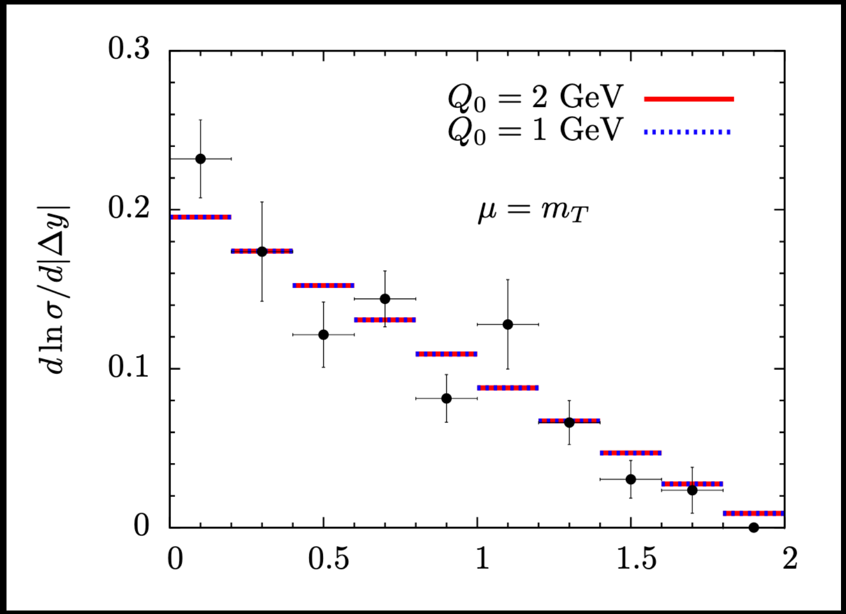


figure from G. Billis et. al, 2021

- **Double parton scattering example:**



An introduction to double parton scattering

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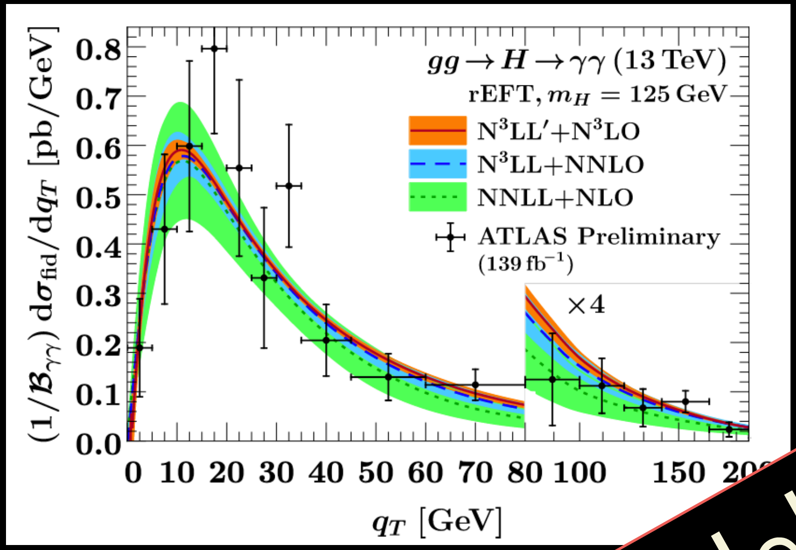

figure from G. Billis et

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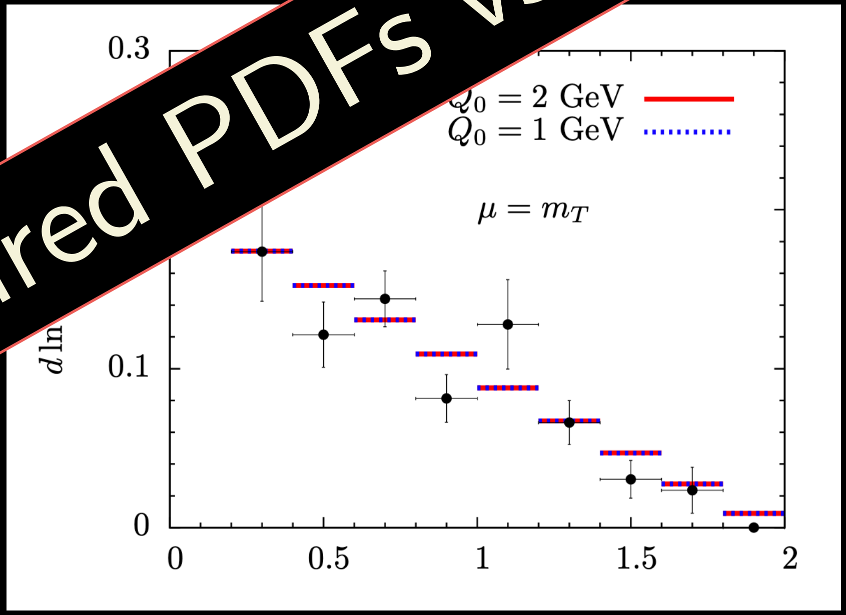
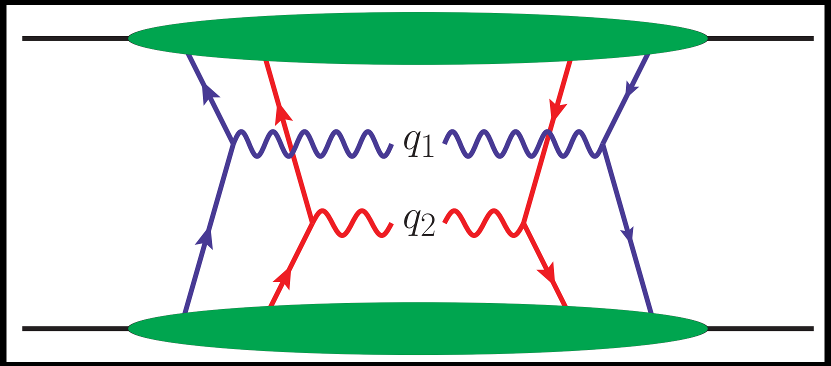
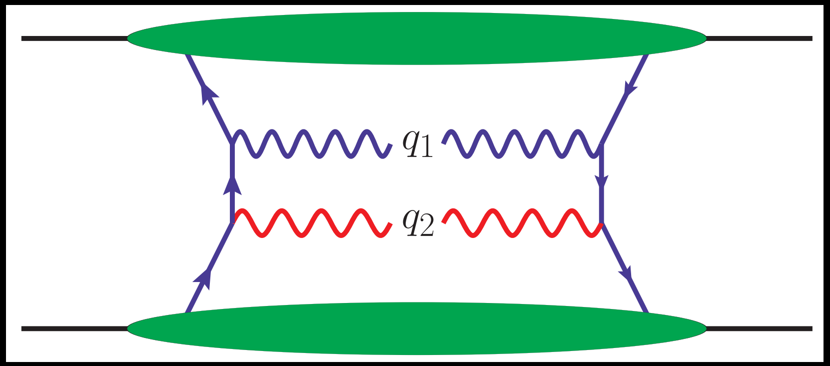


measured PDFs vs modelled DPDs

When is double parton scattering important





- **Inclusive cross section** $\sigma_{\text{DPS}}/\sigma_{\text{SPS}} \sim \dfrac{\Lambda^2}{Q^2}$

- **DPS populates final state phase space in a different way than SPS**

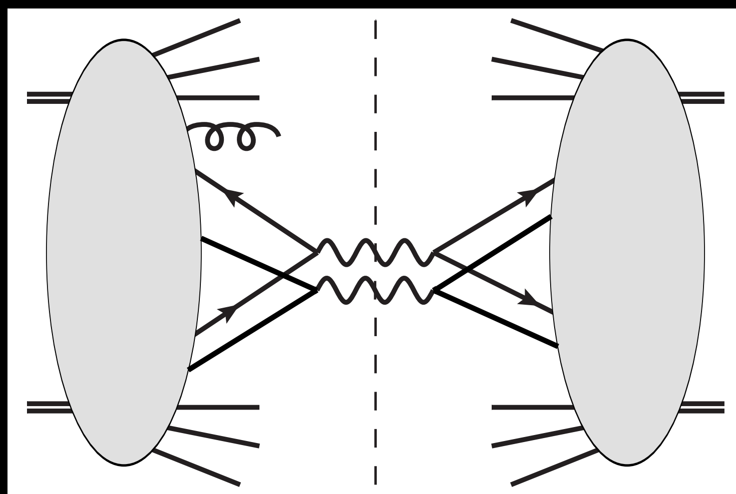
  $$|\boldsymbol{q}_1|,\, |\boldsymbol{q}_2| \sim \Lambda << Q : \qquad \frac{d\sigma_{SPS}}{d^2\boldsymbol{q}_1 d^2\boldsymbol{q}_2} \sim \frac{d\sigma_{DPS}}{d^2\boldsymbol{q}_1 d^2\boldsymbol{q}_2} \sim \frac{1}{Q^4\Lambda^2}$$

  DPS same power as SPS

- **Large parton density** ⇨ **enhanced DPS** $\sigma_{DPS} \sim (\text{parton density})^4$

- **DPS cross section from region of small(ish) momentum fractions**

Factorization for double parton scattering



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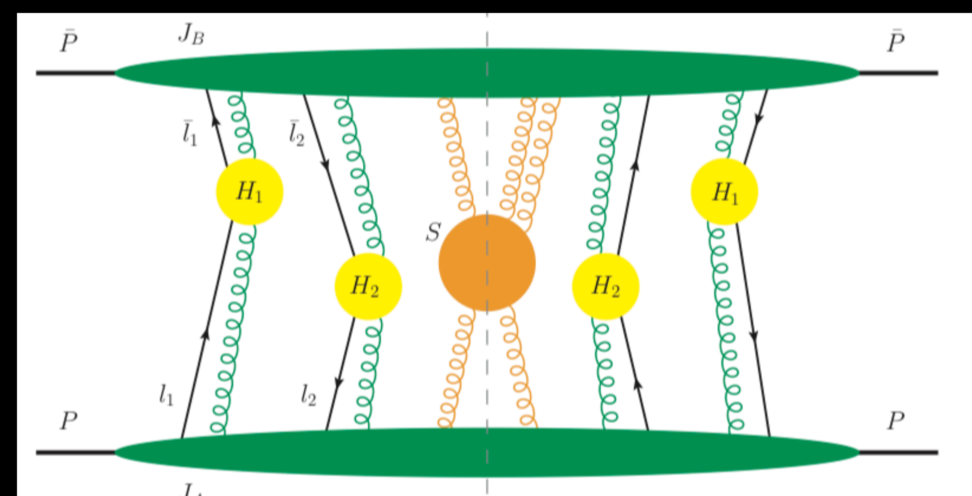
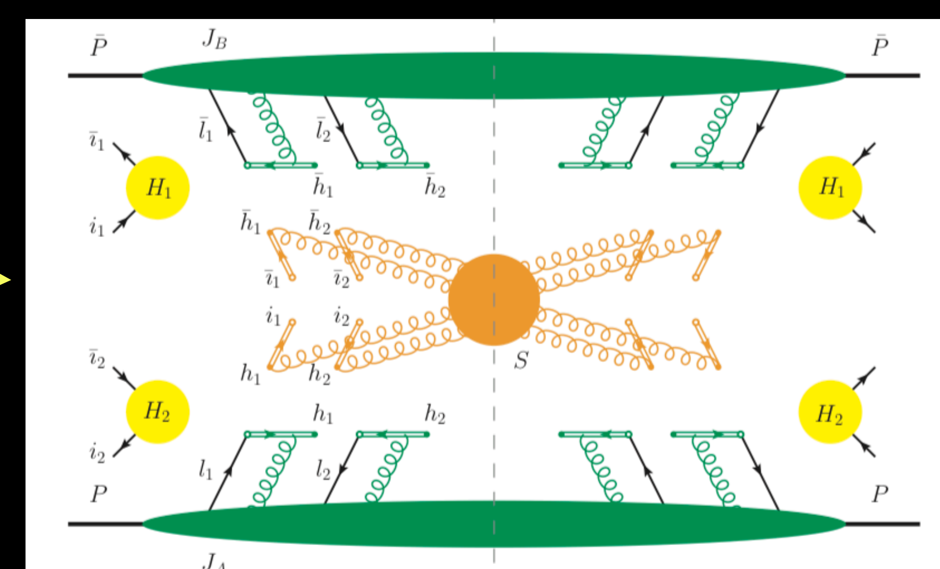


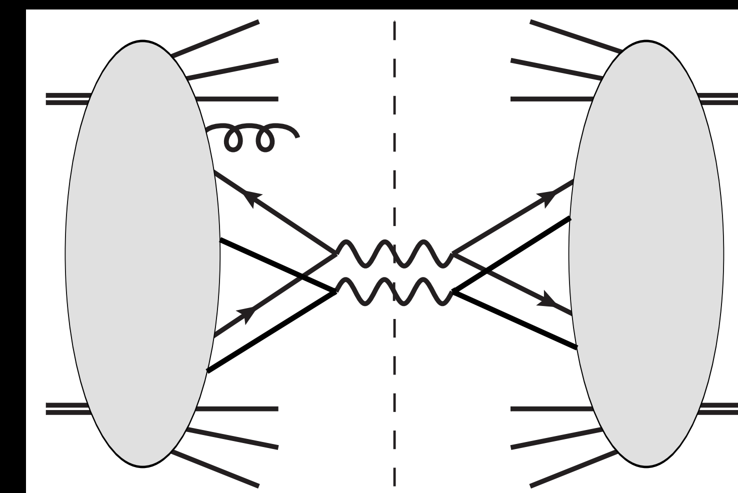
Fig. from
Diehl, Nagar, 2018

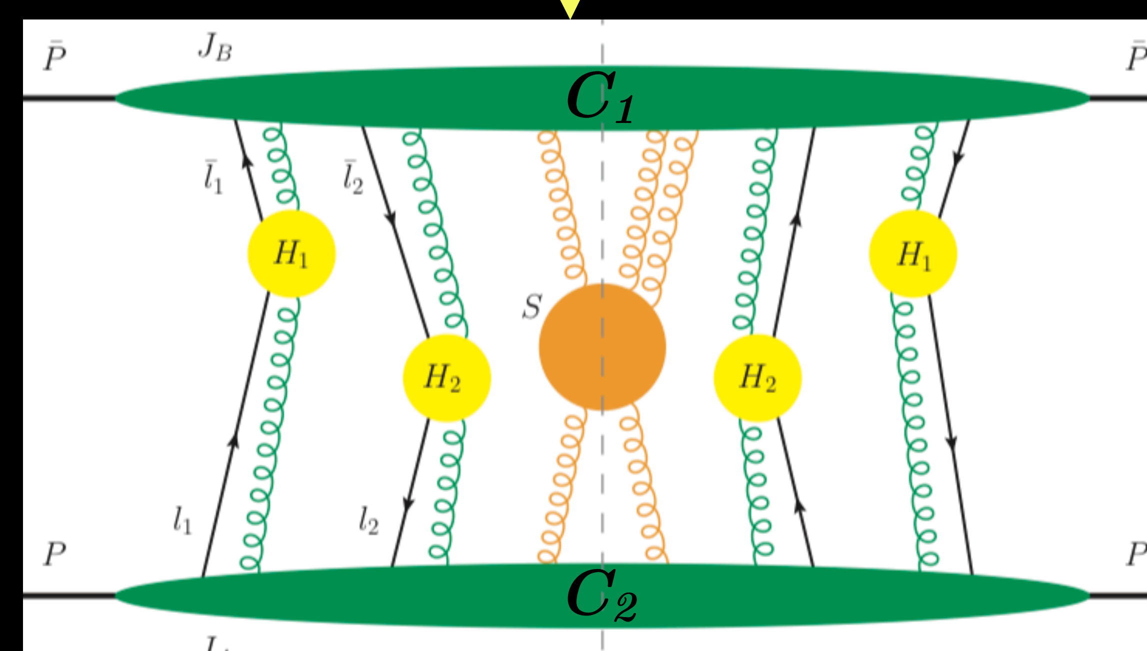
2



1 DTMD factorisation proof: summary

- Choose process (Double Drell-Yan)
- Consider all Feynman diagrams
- Leading momentum regions ($\lambda \sim |q_T|/Q$):
  - hard (H) $\ell \sim (+,-,\perp)$ $\ell \sim (1,1,1)Q$
  - right-moving collinear (C_1) $\ell \sim (1,\lambda^2,\lambda)Q$
  - left-moving collinear (C_2) $\ell \sim (\lambda^2,1,\lambda)Q$
  - Soft (S) $\ell \sim (\lambda,\lambda,\lambda)Q$
  - Glauber $|\ell^+\ell^-| \ll \ell_T^2 \ll Q^2$
- **Region connections**

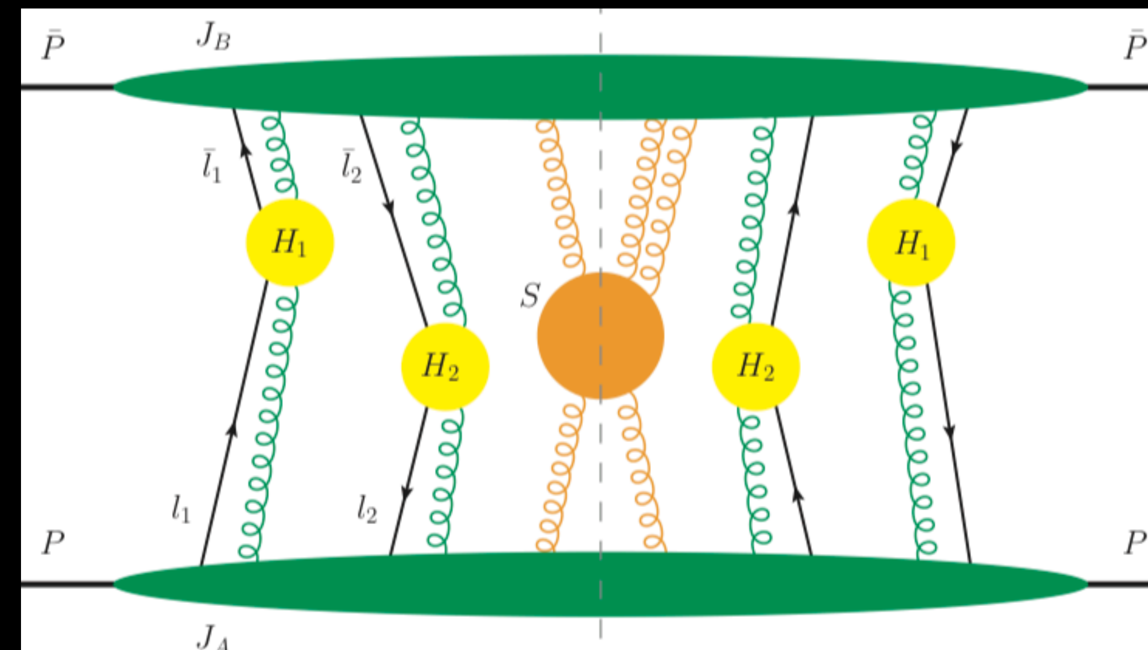




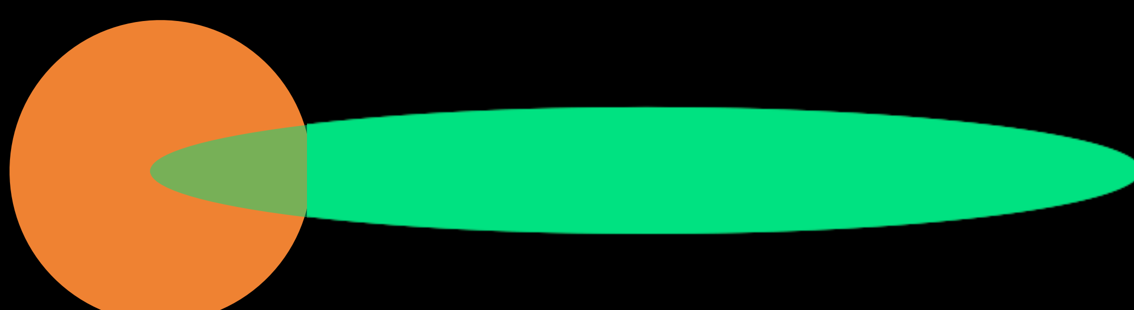
2 DTMD factorisation proof: summary

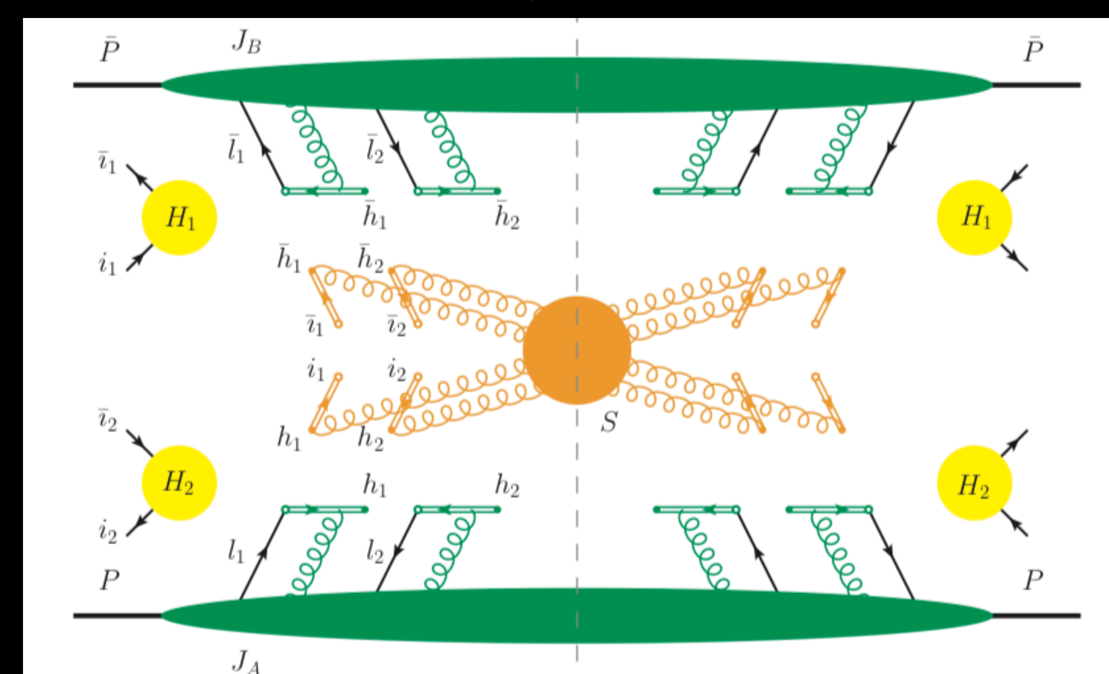
- Separate regions
  - Approximations
  - Unitarity
  - Ward identities
- Collinear and soft Wilson lines

$$U^n(x) = P \exp\left[ig \int_{-\infty}^{0} ds\, \bar{n} \cdot A^a(x + \bar{n}s) t^a\right]$$



- Remove double counting





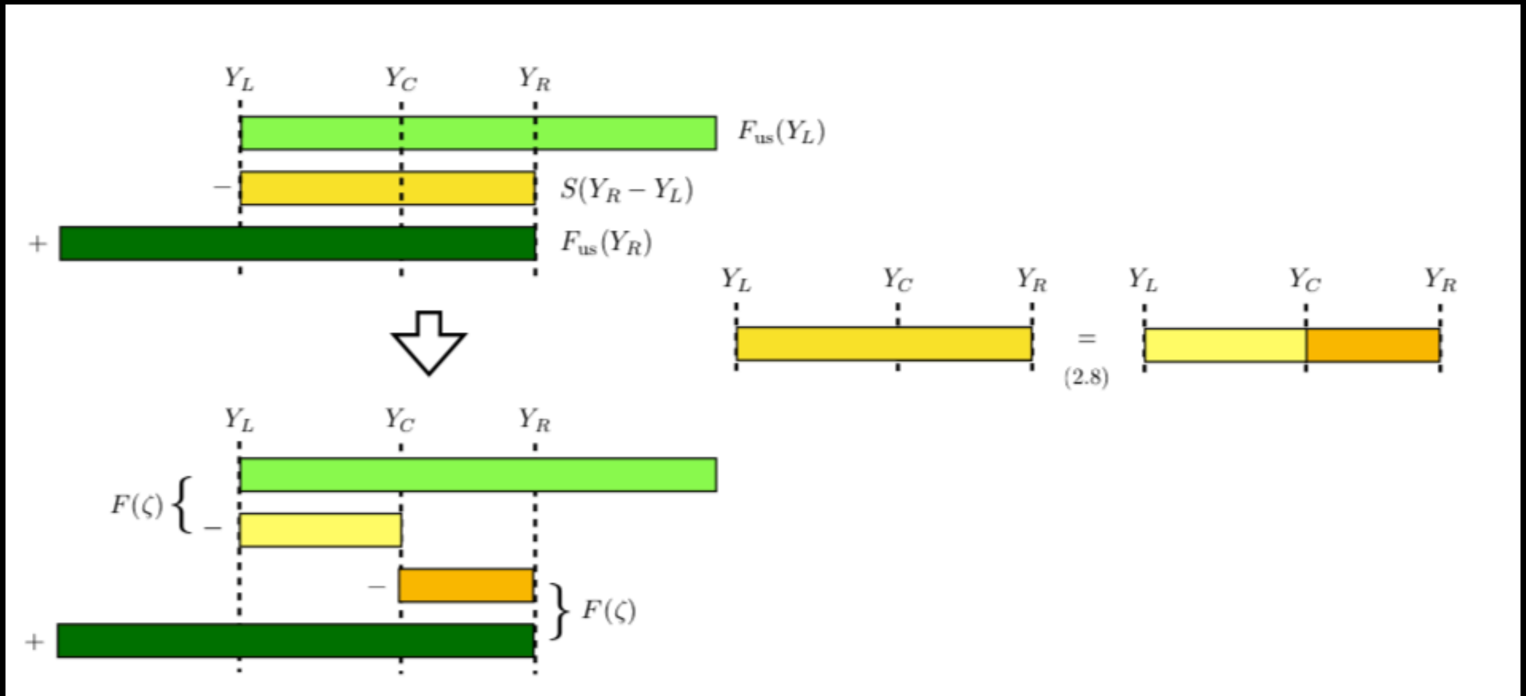
- Sum *remaining* Glauber gluons $= 0$

DTMD factorisation proof: summary

- **DTMD factorisation theorem**

$$\frac{d\sigma}{dp_{T1}dp_{T2}} \sim \mathrm{Hard}_1 \times \mathrm{Hard}_2 \times (C_1\text{-collinear} \otimes \mathrm{Soft} \otimes C_2\text{-collinear})$$

  - **Combine soft and collinear to create DTMDs**



$$\frac{d\sigma}{dp_{T1}dp_{T2}} \sim \mathrm{Hard}_1 \times \mathrm{Hard}_2 \times (\mathrm{DTMD} \otimes \mathrm{DTMD})$$

Factorisation for DPS vs SPS

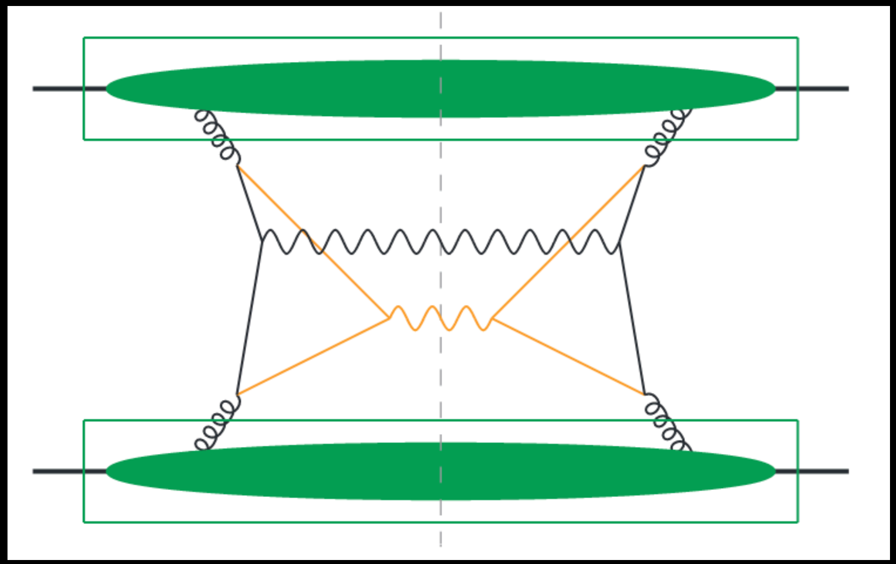
- TMD double parton scattering cross section:
  - Rigorously proven for double Drell-Yan (colour singlet production) Diehl, Nagar, 2018; Buffing, Diehl, TK 2017; Diehl, Gaunt, Schönwald 2017; Diehl et. al. 2015 etc. review: Gaunt, TK, arXiv:1812.09099
  - Violated for coloured particle production at hadron colliders
- TMD integrated double parton scattering cross section:
  - no known violations, pT cuts can be problematic
- Other observables in double parton scattering:
  - Event shapes: violated
- Collinear factorization theorem:

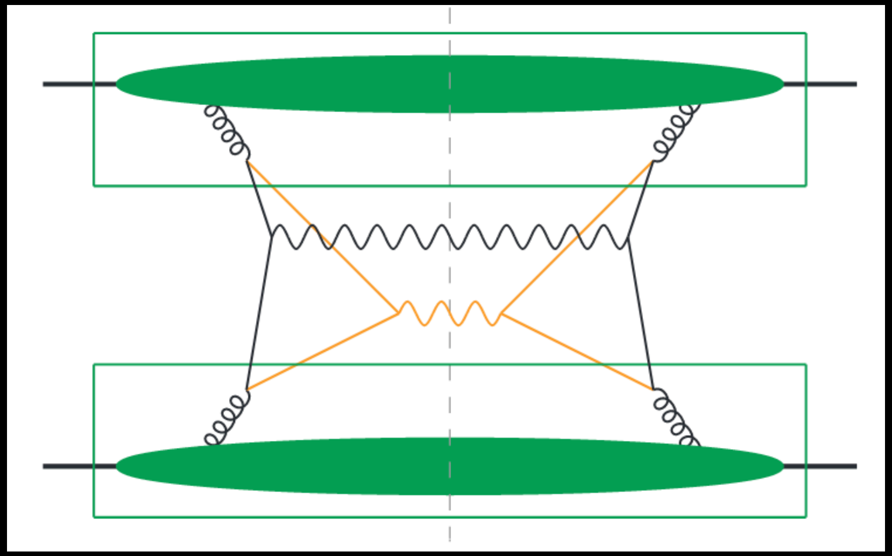
$$d\sigma_{\mathrm{DPS}} \sim d\sigma_1 d\sigma_2 \int d^2y f_{ab}(x_1, x_2, \boldsymbol{y}) f_{cd}(\bar{x}_1, \bar{x}_2, \boldsymbol{y})$$

Factorisation for DPS vs SPS

- **TMD single parton scattering cross section:**
  - **Rigorously proven for single Drell-Yan (color singlet production)** Bodwin, 1985; Collins, Soper, Sterman, 1985; Collins, 2011
  - **Violated for colored particle production at hadron colliders**
- **TMD integrated single parton scattering cross section:**
  - **no known violations, pT cuts can be problematic**
- **Other observables in single parton scattering:**
  - **Event shapes: violated**
- **Collinear factorisation theorem:** $d\sigma_{\text{SPS}} \sim d\sigma\, f_a(x) f_b(\bar{x})$

Factorisation of DPS and SPS





- Combination of SPS and DPS without double counting
  - Contribution has been under intense study and debate

Diehl, Ostermeier, Schafer, 2012; Manohar, Waalewijn, 2012; Gaunt, Stirling, 2011;
Blok et al., 2012; Ryskin, Snigirev, 2011; Cacciari, Salam, Sapeta, 2010; etc.

- Achieved within the DGS subtraction scheme

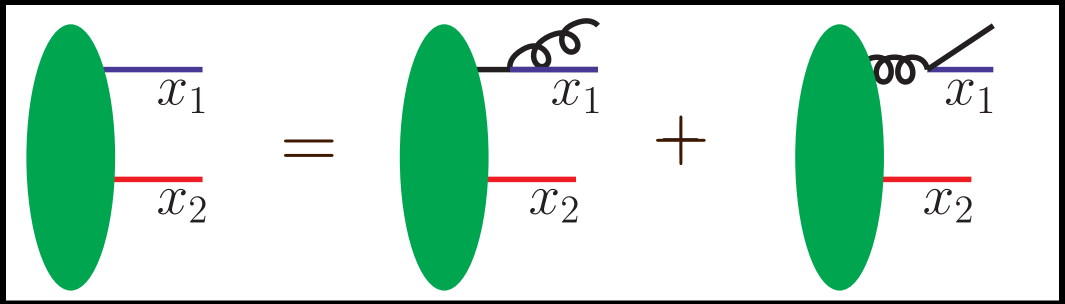
Diehl, Gaunt, Schönwald, 2017

$$\sigma = \sigma_{\text{SPS}} + \sigma_{\text{DPS}} - \sigma_{\text{sub}}$$

  - Subtraction with DPD replaced by perturbative splitting calc.
  - cancels the UV divergence as interparton distance tend to zero

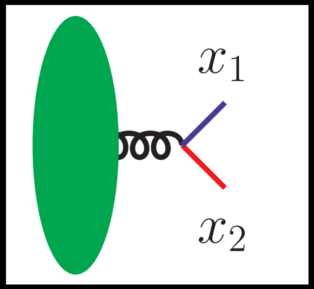
QCD Evolution in DPS

- **Evolution in the DGS-scheme**
  - **DPDs evolve with double DGLAP-evolution**

$\dfrac{d}{d\ln\mu^2}$  $+$ second parton

$$\frac{d}{d\ln\mu^2}F_{ab}(x_1, x_2, \boldsymbol{y}) = \sum_c P_{b/c}(x_1') \underset{x_1}{\otimes} F_{cb}(x_1', x_2, \boldsymbol{y}) + \text{second parton}$$

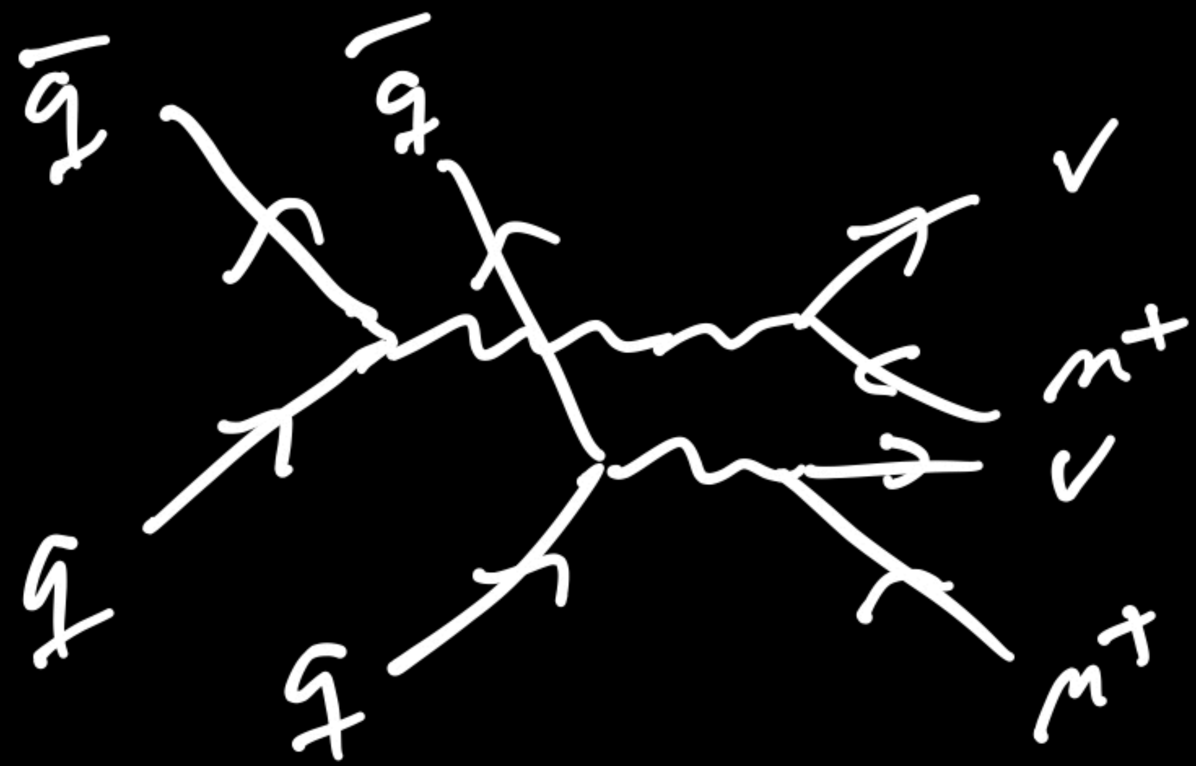
  - **Initial conditions include 1 to 2 splitting at a scale** $\mu_y \sim \dfrac{1}{|\boldsymbol{y}|}$



Factorisation for DPS vs SPS

- Factorisation proof largely analogous
- Combine with SPS + interference
- Differences from SPS:
  - Two hard interactions, kinematics different
  - Colour structure
  - Two body distributions
  - Spin correlations

Spin in same-sign W-boson production

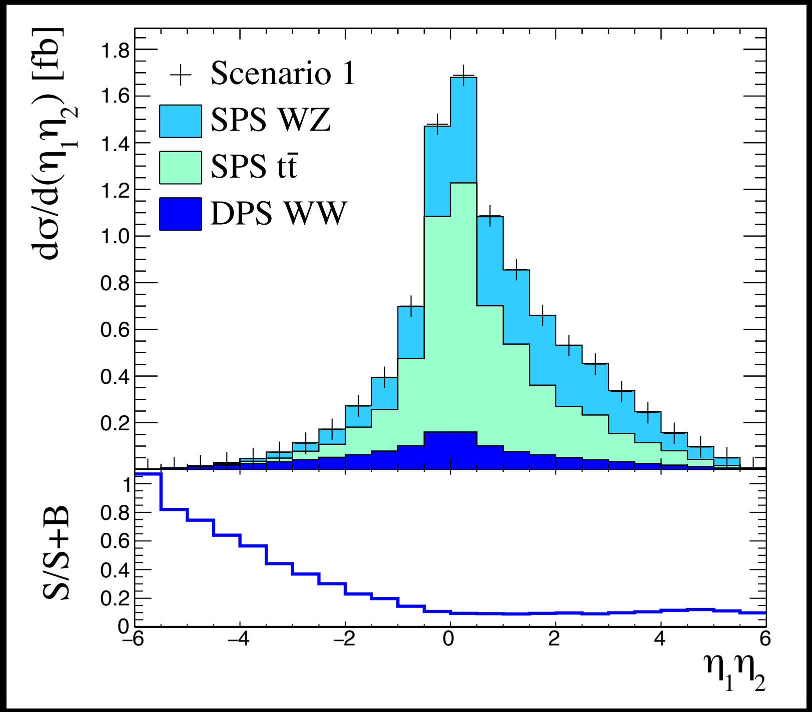


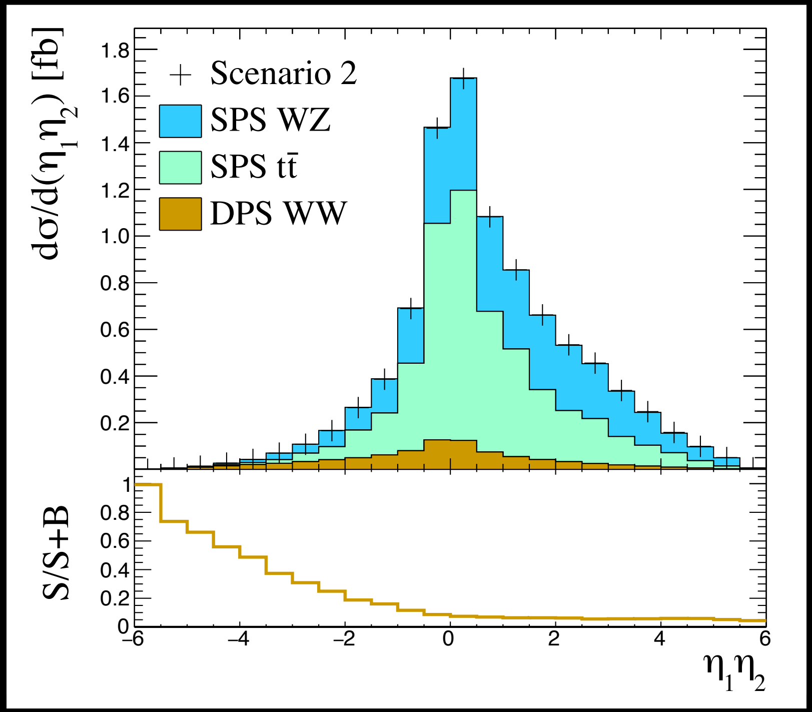
Spin correlations effects measurements

- DPS in WW have been measured

CMS Collaboration. 2019

- DPS cross section often measured through template fits
- What is the impact of spin correlations?
  - Scenario 1: *Nature* correlated, uncorrelated assumption
  - Scenario 2: *Nature* uncorrelated, correlated assumption



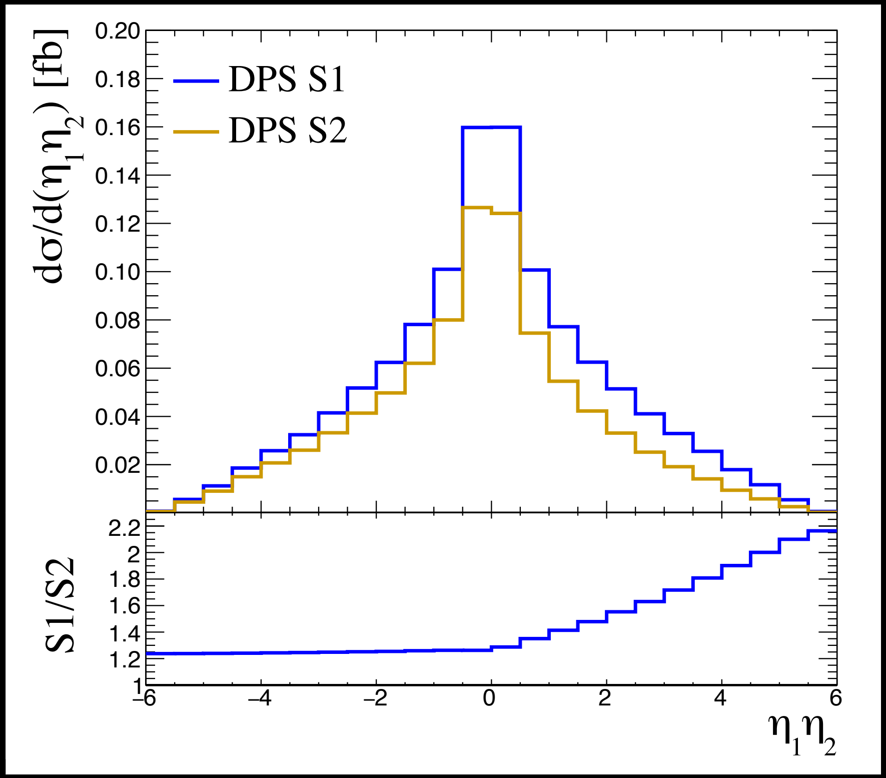


Cotogno, TK, Myska, 2020

Spin correlations effects measurements

- **30% difference in extracted DPS fraction**
  - **= 30% difference in DPS cross section!**

	DPS W^+W^+ [fb]	σ_{eff} [mb]
Scenario 1	0.59	12.2
Scenario 2	0.44	16.4

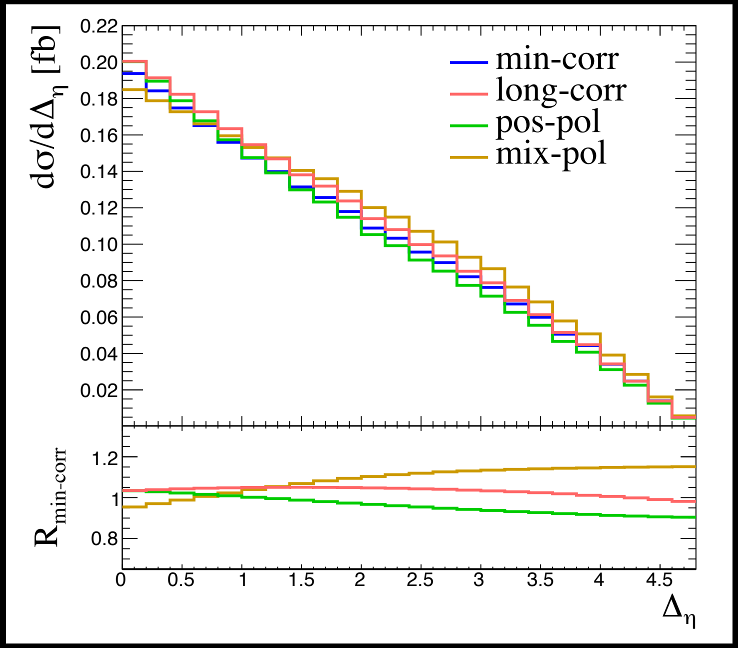


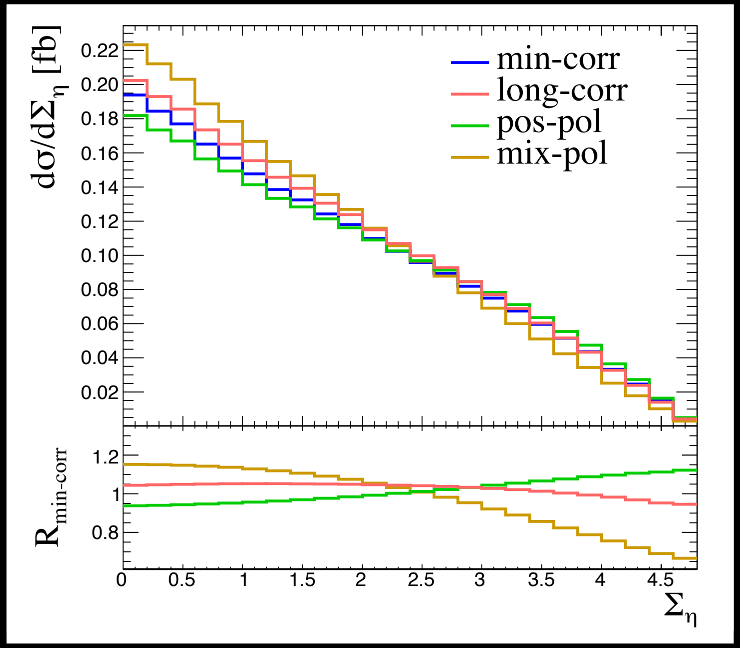
- **Variable used in experimental template fits in WW**
  - **As part of a multivariate analysis**

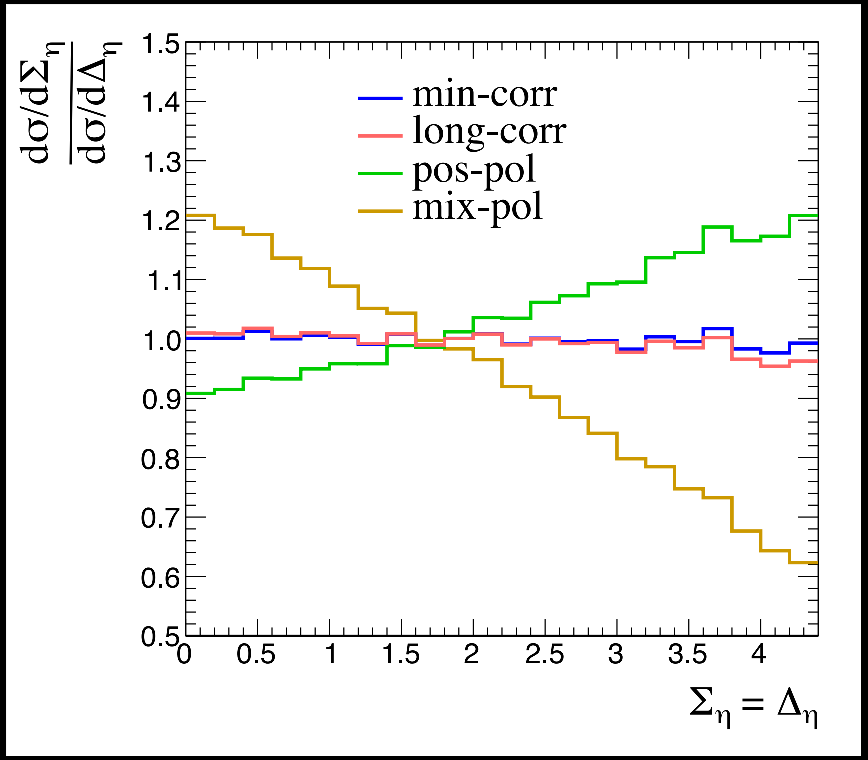
Cotogno, TK, Myska, 2020

Measuring spin correlations (WW)

- Rapidity sum and difference and bin-by-bin ratio
- Minimal correlations (min-corr) vs polarization (pos-pol,mix-pol)



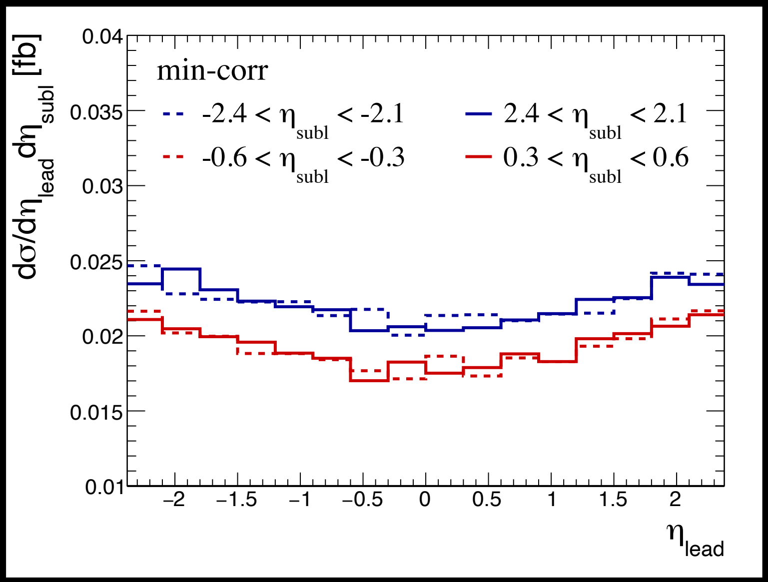


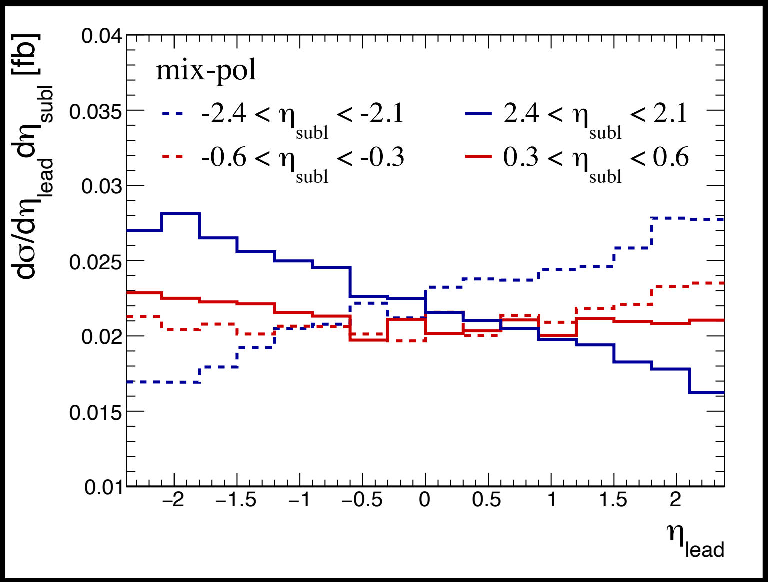


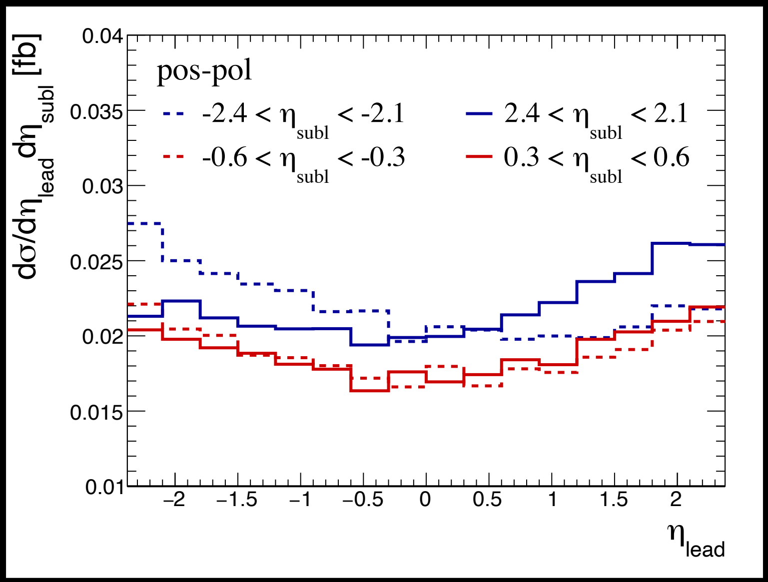
Cotogno, TK, Myska, 2020

Measuring spin correlations

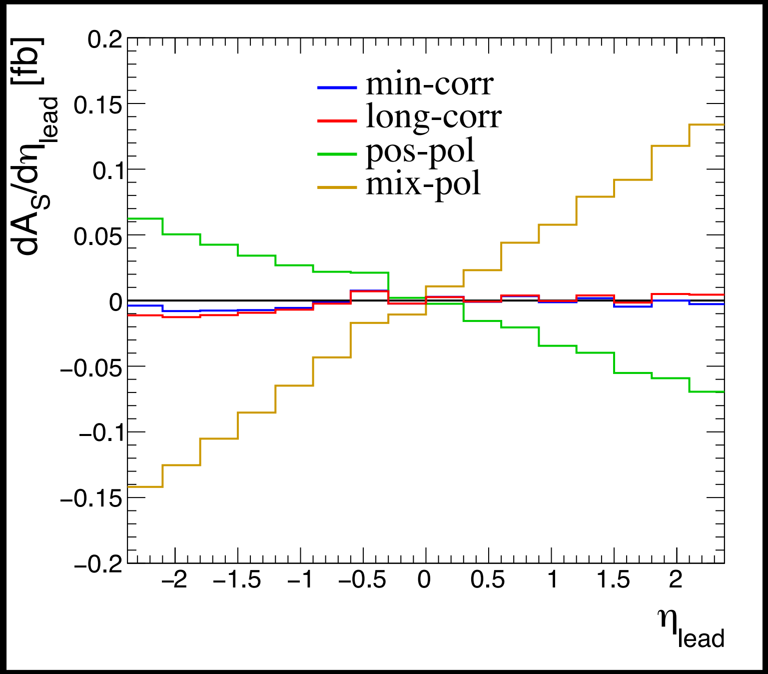
- **Rapidity slicing**







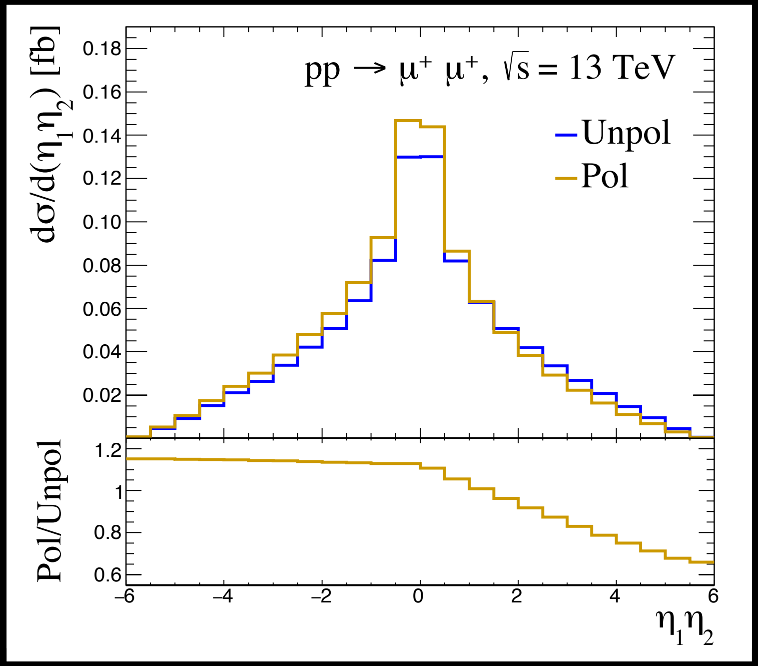
- $$\frac{A_S}{\eta_{\text{lead}}} = \frac{d\sigma(\eta_{\text{sub}} > 0)}{d\eta_{\text{lead}}} - \frac{d\sigma(\eta_{\text{sub}} < 0)}{d\eta_{\text{lead}}}$$



Cotogno, TK, Myska, 2020

Measuring spin correlations

- **Rapidity product, asymmetries and slopes**



Asymmetry between muons produced in same vs opposite hemispheres

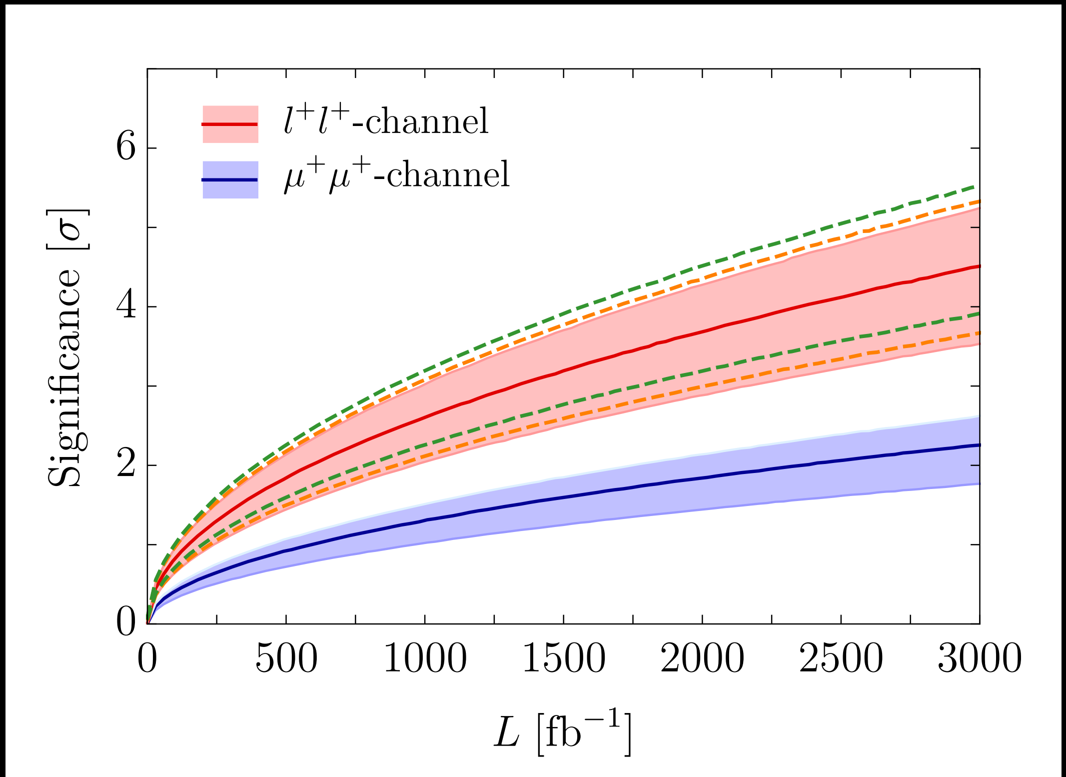
$$A = \frac{\sigma^- - \sigma^+}{\sigma^- + \sigma^+}$$

$\|\eta_i\|$	> 0	> 0.6	> 1.2
A	0.07	0.11	0.16
σ [fb]	0.51	0.29	0.13

Cotogno, TK, Myska, 2018

Measuring spin correlations

- When will the asymmetry be measurable/constrainable?



  - A 2-sigma hint is possible with around 400 fb—1
  - 3-sigma observation can be achieved with less than 1500 fb—1
  - Approaching 5-sigma is reachable with the full 3000 fb—1
- Sensitive to (for example): size of DPS x-section, size of asymmetry.

Cotogno, TK, Myska, 2018