NNLO helicity PDFs,
phenomenology of double parton scattering

Werner Vogelsang
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Regensburg, 07/30/2024

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UNIVERSITÄT
TÜBINGEN

HRT

Outline:

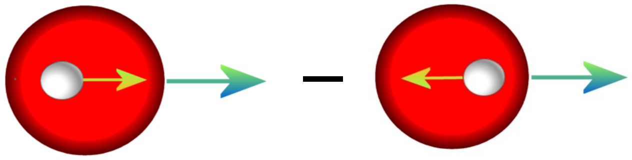
- Helicity PDFs at NNLO*
- Phenomenology of double parton scattering**

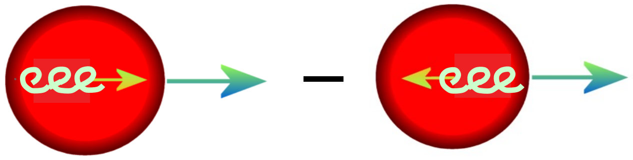
* with Ignacio Borsa, D. de Florian, R. Sassot, M. Stratmann 2407.11635

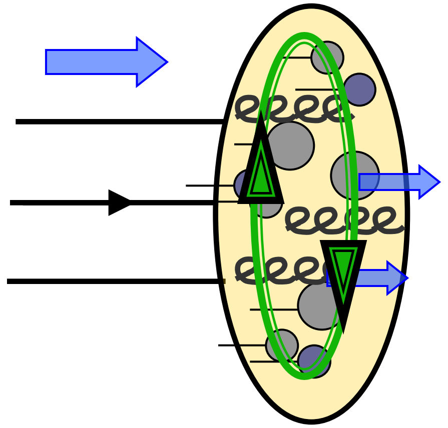
** with Alexander Fürlinger, Oliver Schüle (utterly in progress…)

Helicity PDFs at NNLO: framework

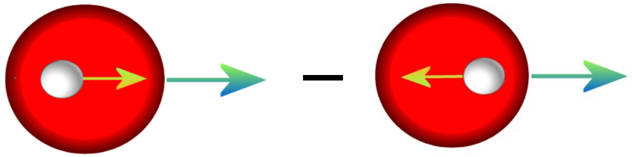

$\Delta q(x) =$
$\Delta g(x) =$

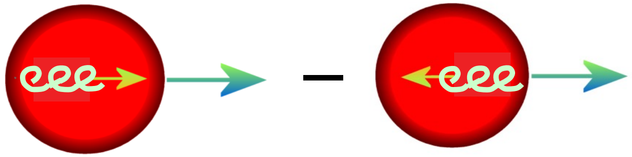
$\Delta q(x) =$ 

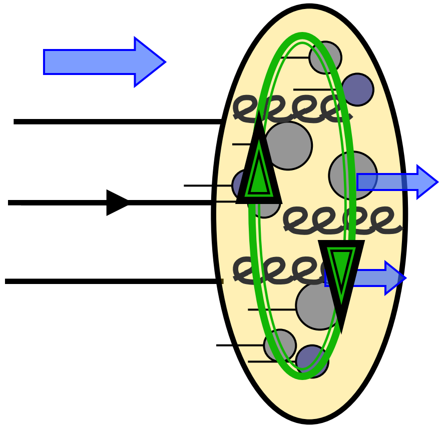
$\Delta g(x) =$ 



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$\Delta q(x) =$ 

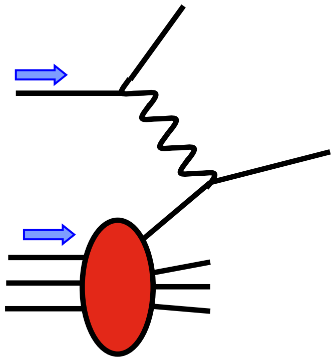
$\Delta g(x) =$ 



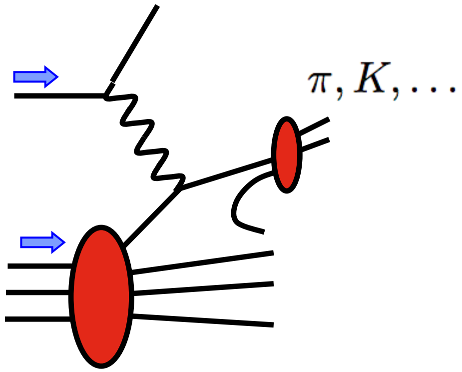
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$\sum_q \int_0^1 dx\,(\Delta q + \Delta\bar{q})$$

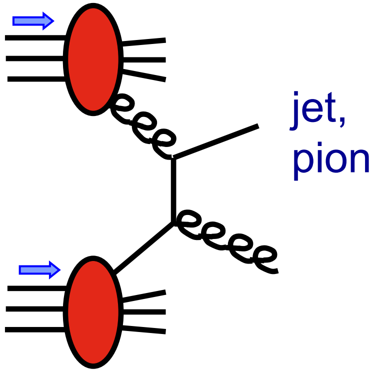
$$\int_0^1 dx\,\Delta g$$



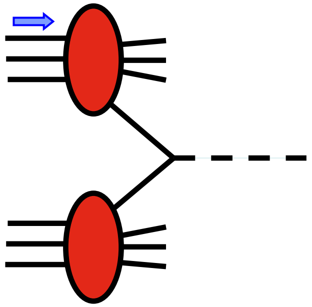
DIS



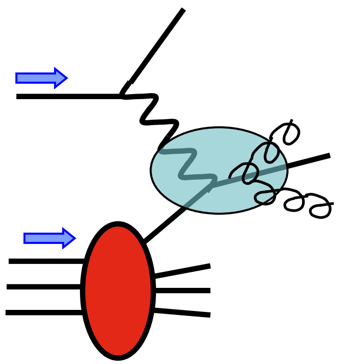
SIDIS



pp high-p_T



W bosons



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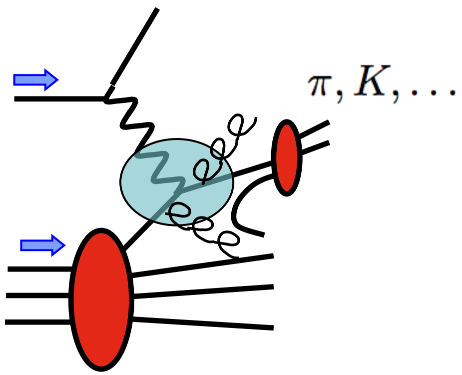

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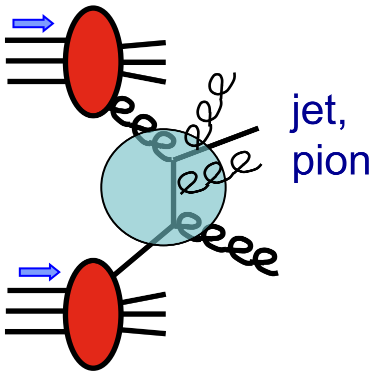

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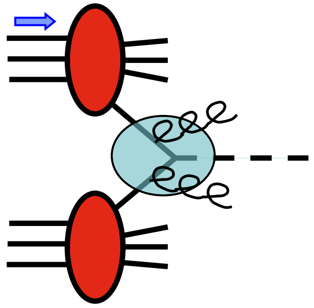
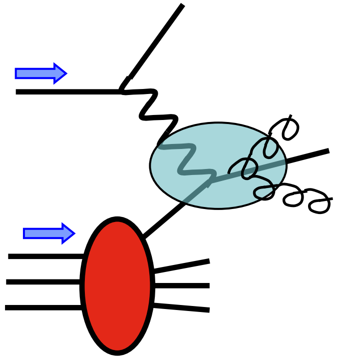


W bosons

- Partonic hard scattering: $\Delta\hat{\sigma}_{ab} = \Delta\hat{\sigma}_{ab}^{\mathrm{LO}} + \frac{\alpha_s}{\pi}\Delta\hat{\sigma}_{ab}^{\mathrm{NLO}} + \left(\frac{\alpha_s}{\pi}\right)^2 \Delta\hat{\sigma}_{ab}^{\mathrm{NNLO}} + \ldots$



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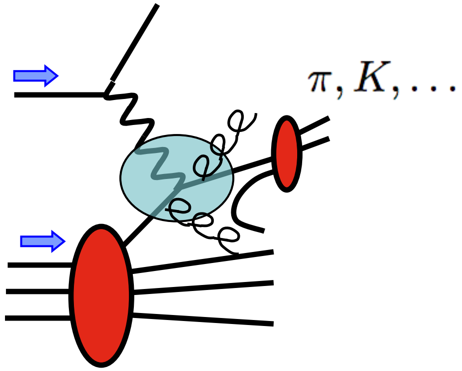

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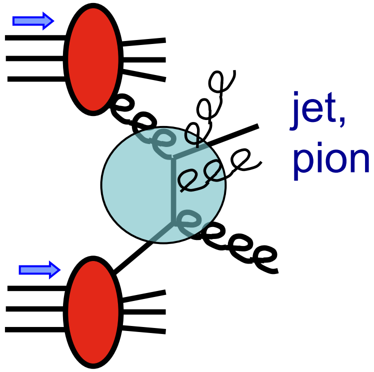

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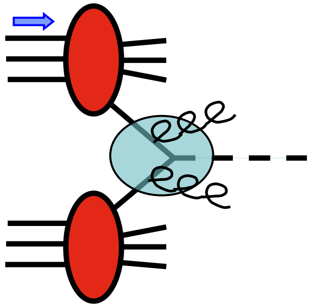

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- PDF evolution: $\Delta\mathcal{P}_{ij} = \frac{\alpha_s}{2\pi}\Delta P_{ij}^{\mathrm{LO}} + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta P_{ij}^{\mathrm{NLO}} + \left(\frac{\alpha_s}{2\pi}\right)^3 \Delta P_{ij}^{\mathrm{NNLO}} + \ldots$

NNLO evolution*

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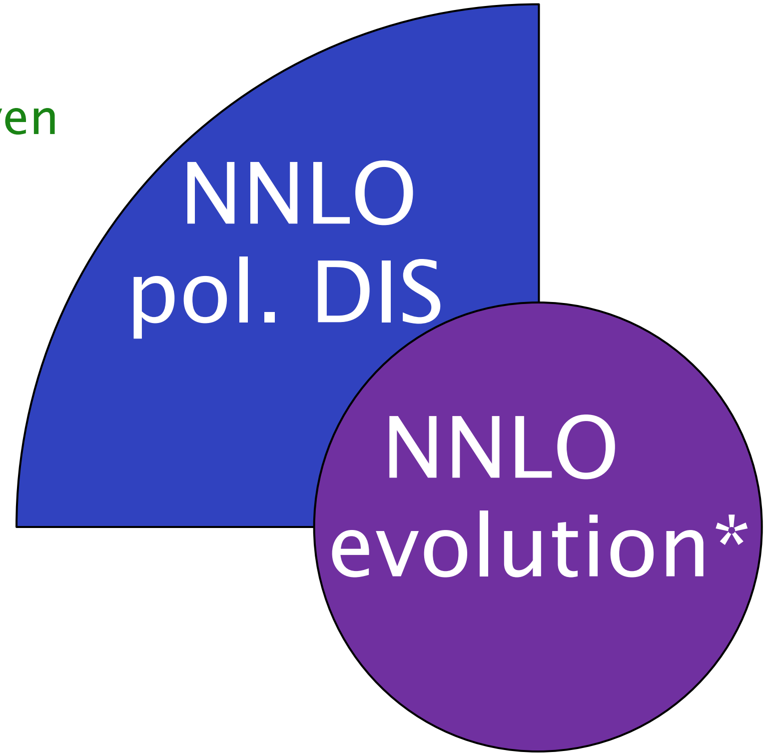
Blümlein, Marquard, Schneider, Schönwald
QCD Pegasus: A. Vogt

Zijlstra, van Neerven
1994



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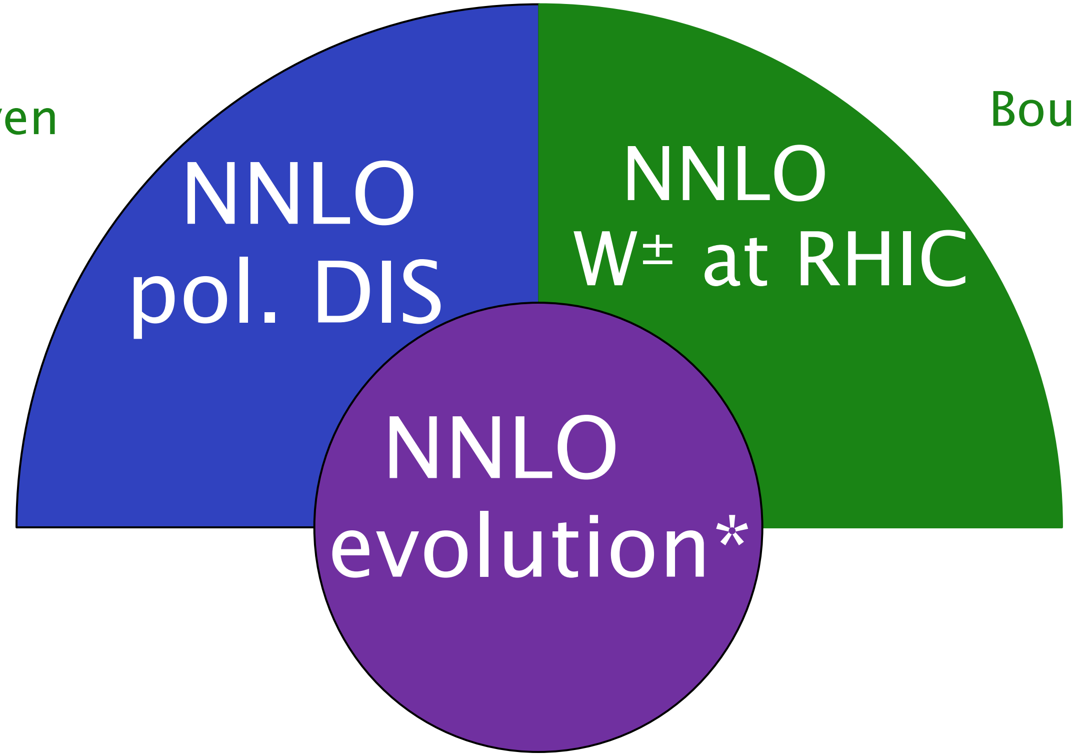
Boughezal, Li, Petriello 2021



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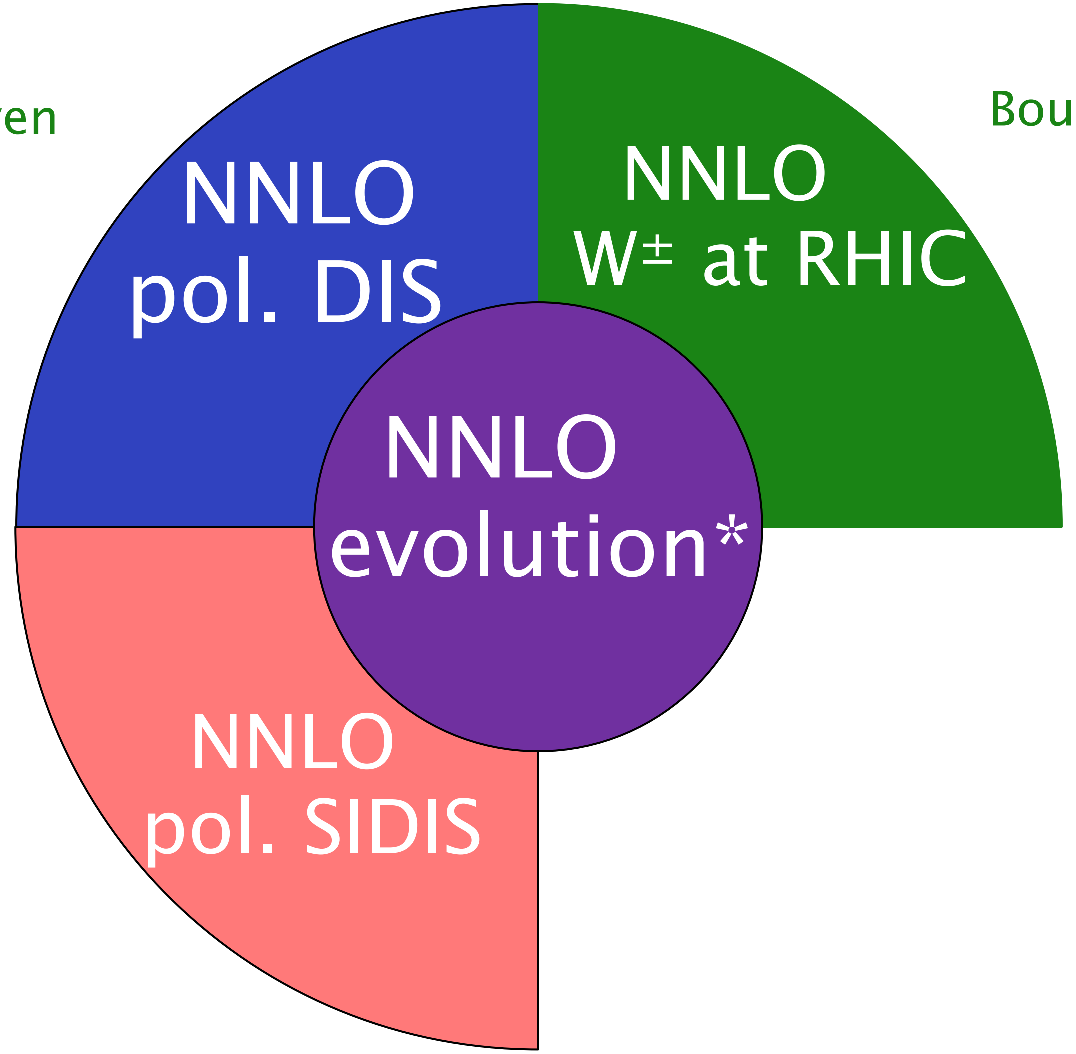

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Bonino, Gehrmann, Löchner, Schönwald, Stagnitto 2024
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(soon to be in glob. analysis)

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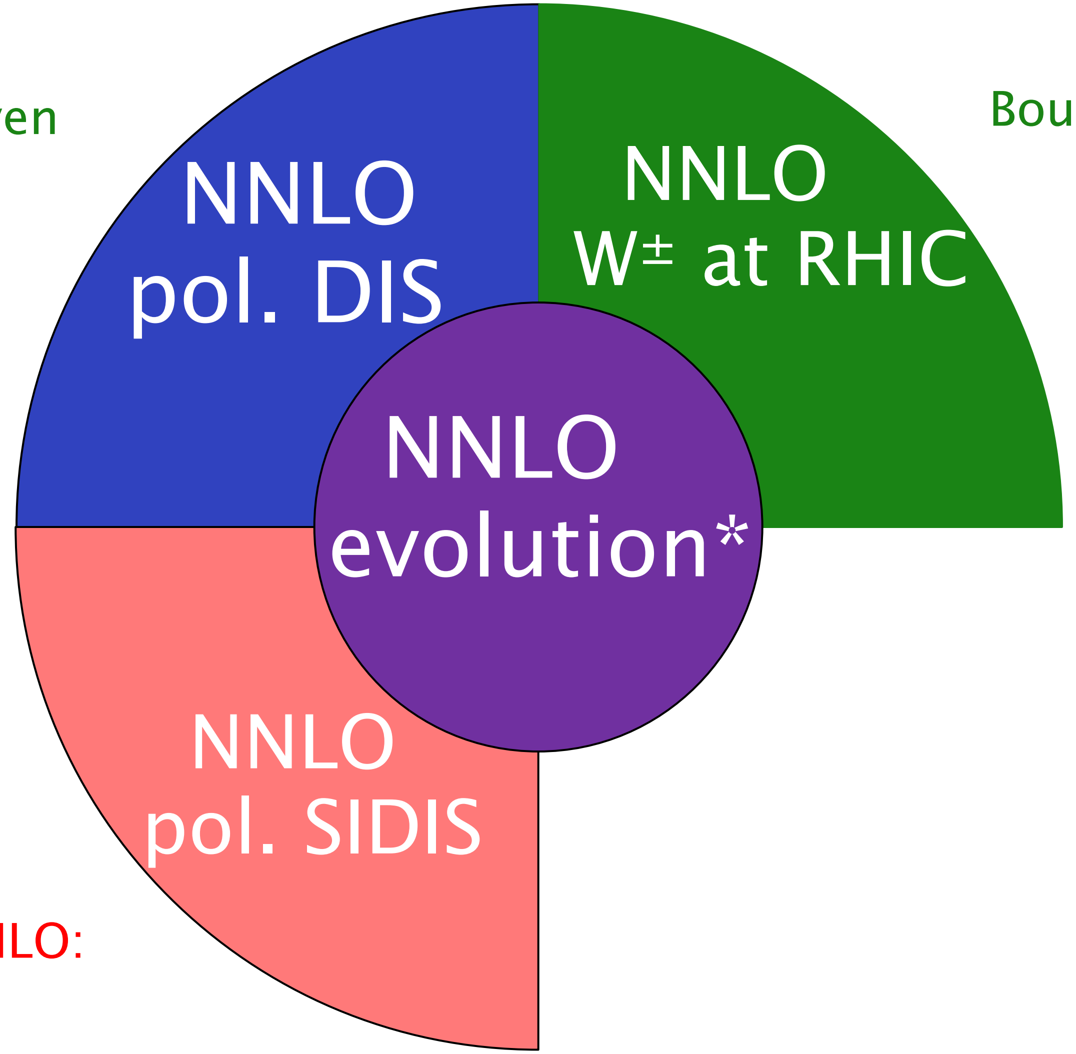

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soft-gluon approximate NNLO:

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Abele, de Florian, WV 2021

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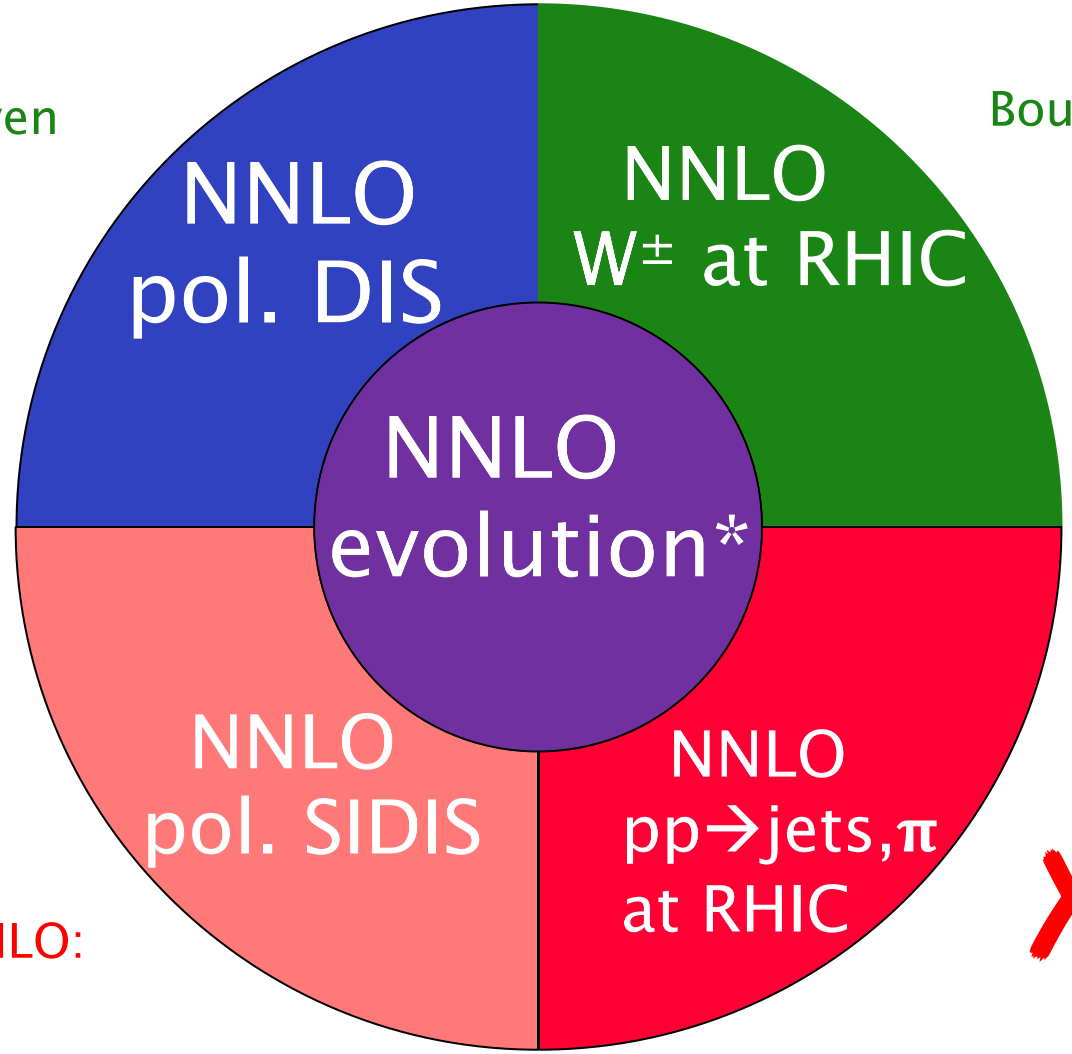

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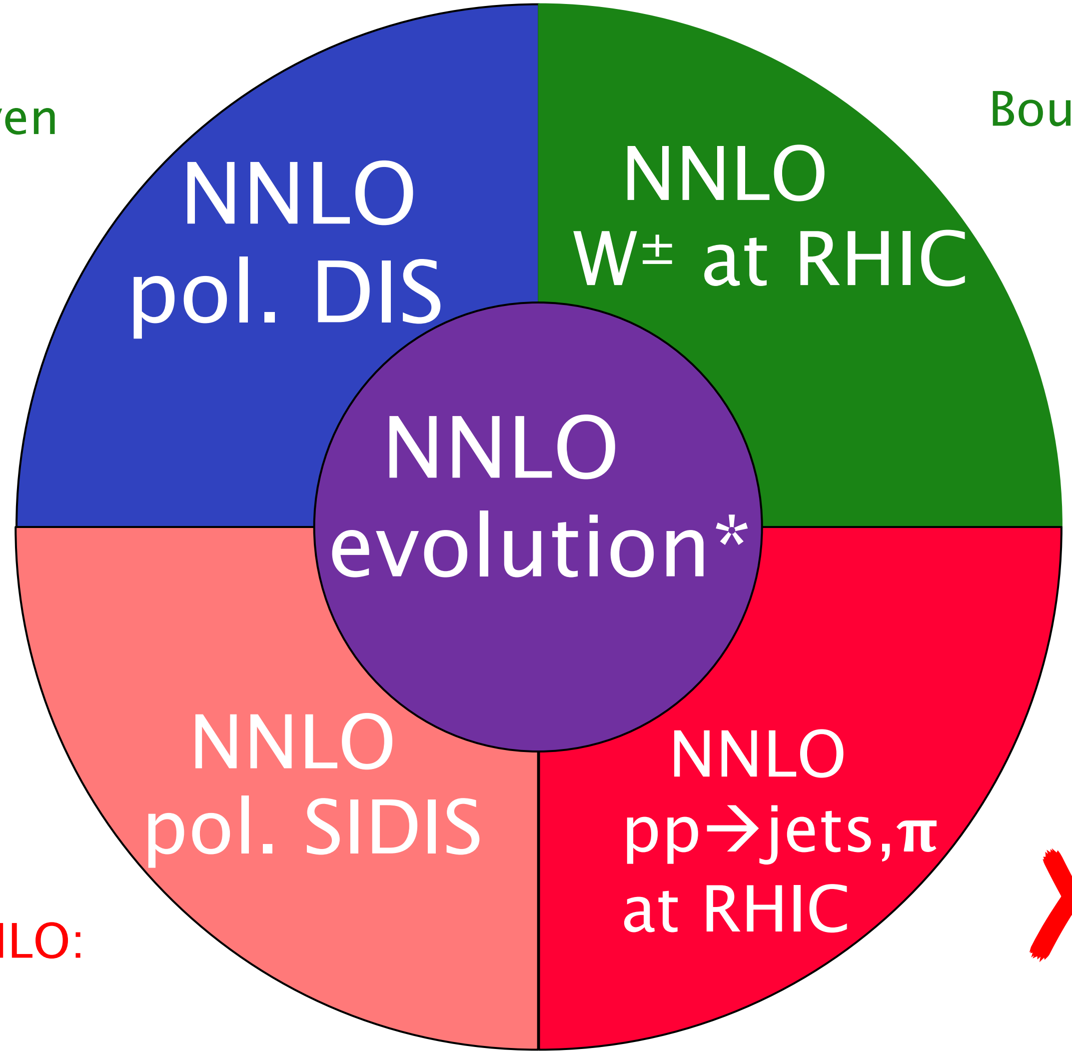

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Schönwald, Stagnitto 2024
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✗ use soft-gluon approx.

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NNLO helicity PDFs:

- DIS–only analysis   Taghavi-Shahri et al., 2016

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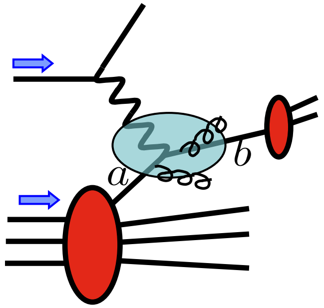
NNLO helicity PDFs:

- DIS–only analysis   Taghavi-Shahri et al., 2016
- DIS and (approximate) SIDIS   MAP: Bertone, Chiefa, Nocera 2024
- Fully global analysis with approximate NNLO for SIDIS and pp

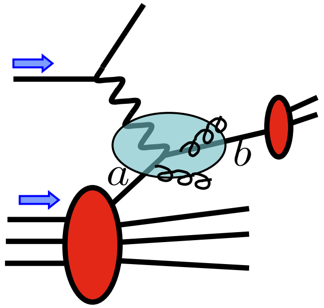
  BDSSV: Borsa, de Florian, Sassot, Stratmann, WV   2407.11635



$$\Delta\hat{\sigma}_{qq}^{\mathrm{N}^k\mathrm{LO}}(\hat{x},\hat{z}) \sim \alpha_s^k \Bigg[\delta(1-\hat{x}) \left(\frac{\ln^{2k-1}(1-\hat{z})}{1-\hat{z}} \right)_+ + \delta(1-\hat{z}) \left(\frac{\ln^{2k-1}(1-\hat{x})}{1-\hat{x}} \right)_+ + \frac{1}{(1-\hat{x})_+} \left(\frac{\ln^{2k-2}(1-\hat{z})}{1-\hat{z}} \right)_+ + \frac{1}{(1-\hat{z})_+} \left(\frac{\ln^{2k-2}(1-\hat{x})}{1-\hat{x}} \right)_+ + \dots \Bigg]$$

$$\hat{x} = \frac{Q^2}{2p_a \cdot q}$$

$$\hat{z} = \frac{p_a \cdot p_b}{p_a \cdot q}$$



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$$+ \frac{1}{(1-\hat{x})_+}\left(\frac{\ln^{2k-2}(1-\hat{z})}{1-\hat{z}}\right)_+ + \frac{1}{(1-\hat{z})_+}\left(\frac{\ln^{2k-2}(1-\hat{x})}{1-\hat{x}}\right)_+ + \ldots\Bigg]$$

$$\hat{x} = \frac{Q^2}{2p_a\cdot q} \qquad \hat{z} = \frac{p_a\cdot p_b}{p_a\cdot q}$$

- logs can be resummed to all orders: threshold resummation

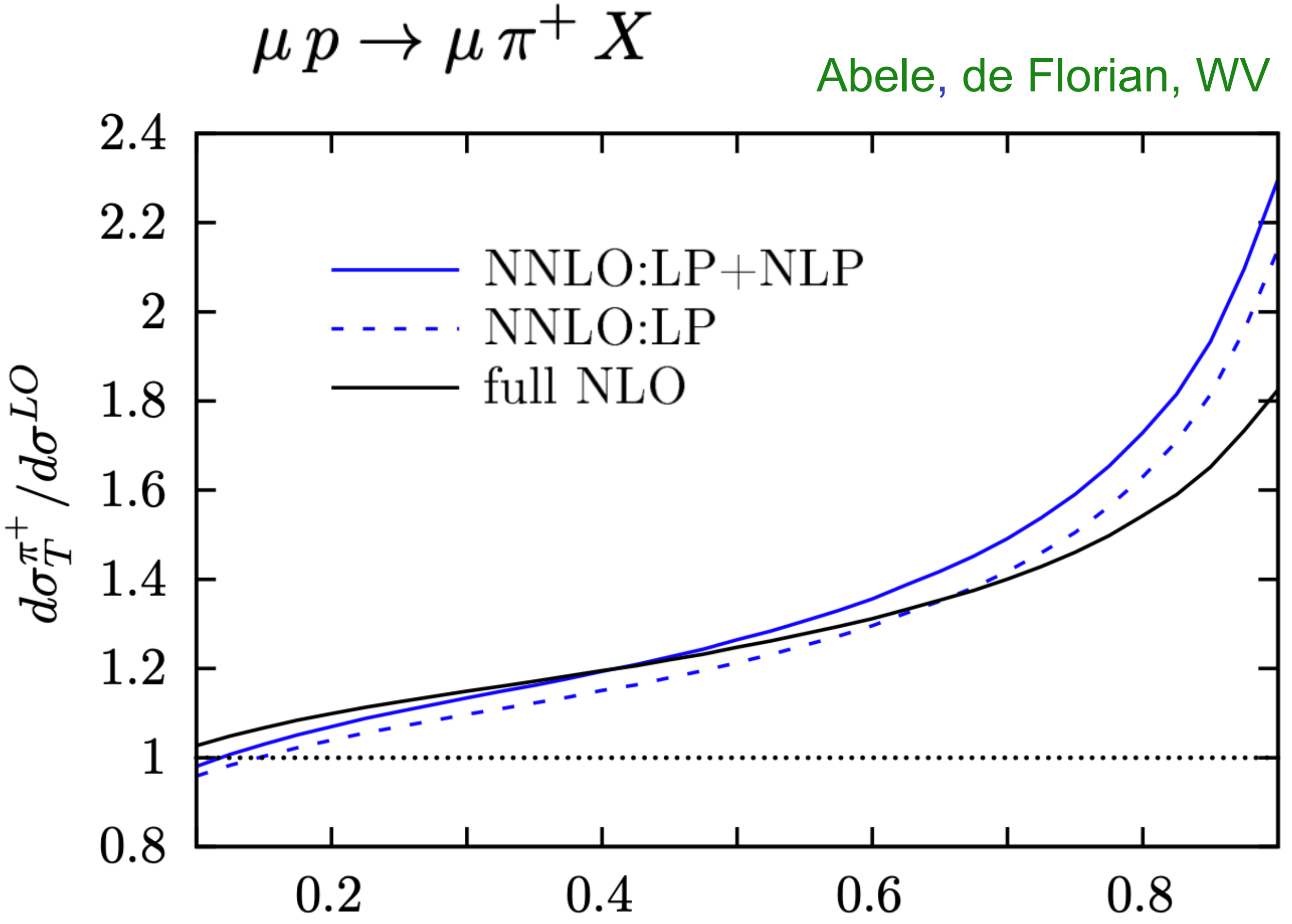
Anderle, Ringer, WV
Abele, de Florian, WV

Fixed Order →

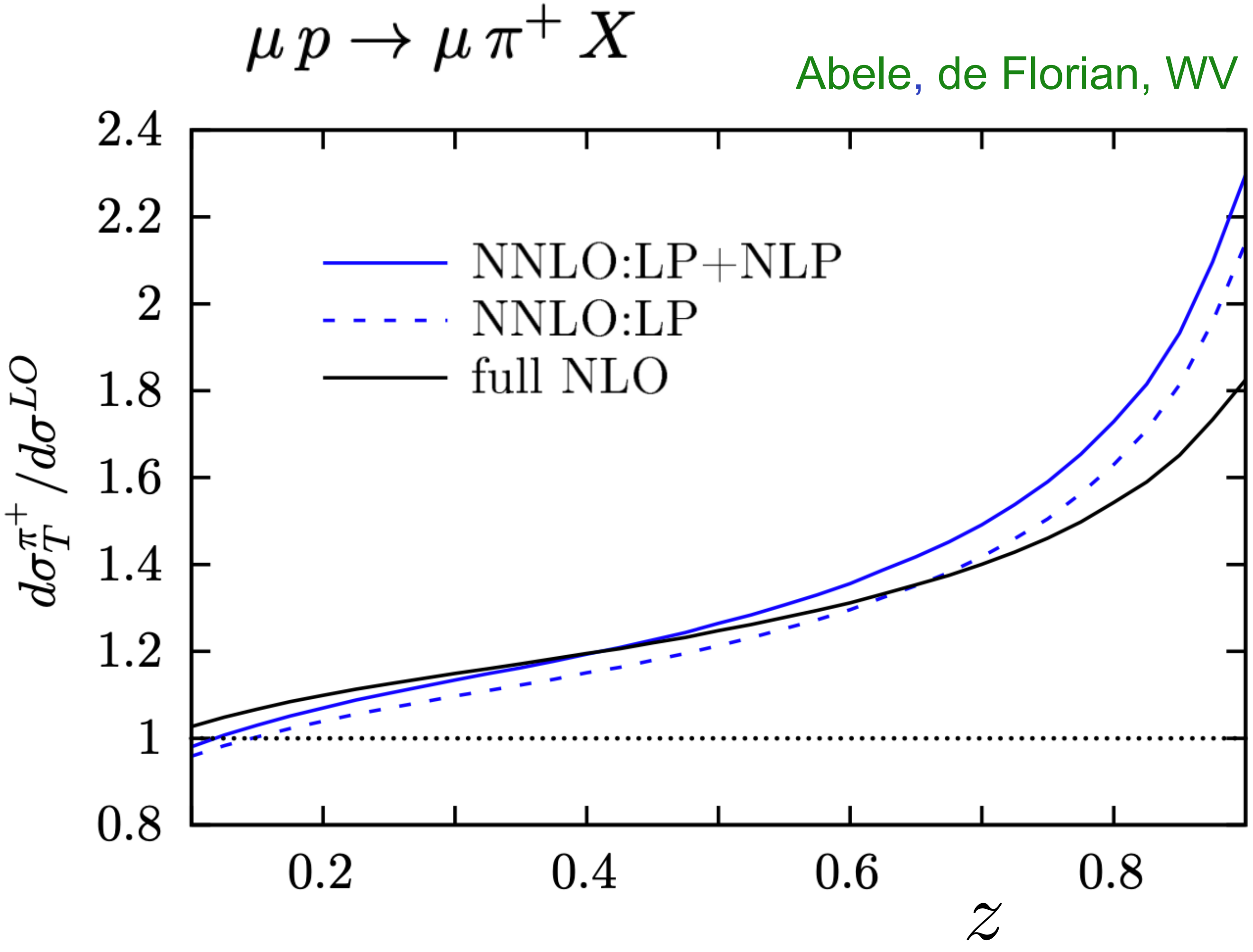
Resummation ↓

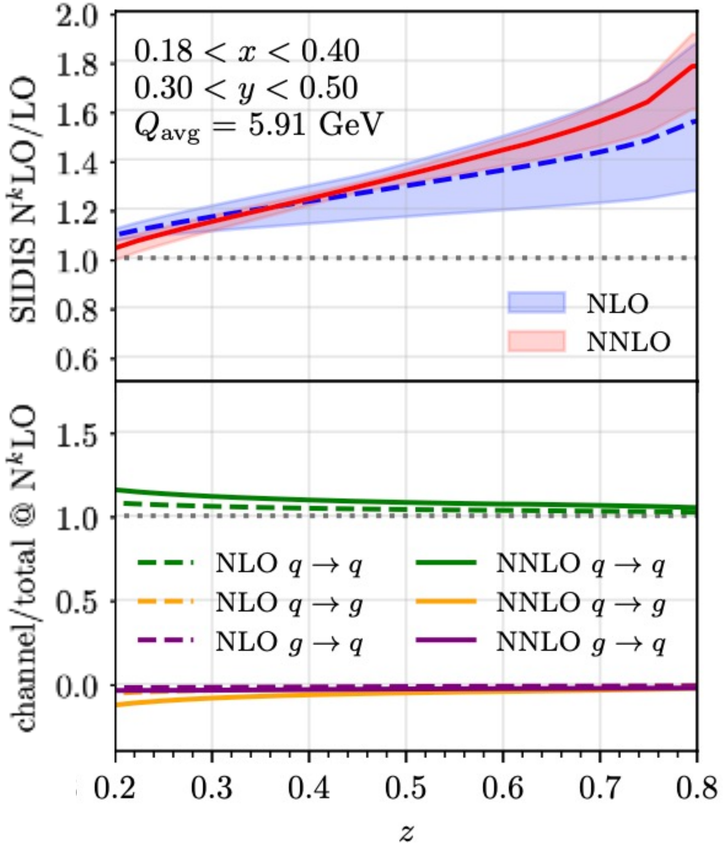
LO	1					
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s			
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	α_s^2	
...	...	...	...	...	...	
N^{k}LO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$	$\alpha_s^k L^{2k-2}$	$\alpha_s^k L^{2k-3}$	$\alpha_s^k L^{2k-4}$	...

LL NLL NNLL



$\mu\, p \to \mu\, \pi^+\, X$
Abele, de Florian, WV
NNLO:LP+NLP
NNLO:LP
full NLO
$d\sigma_T^{\pi^+} / d\sigma^{LO}$
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.2
0.4
0.6
0.8



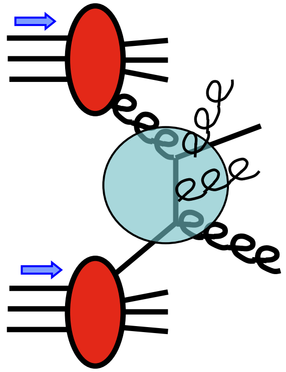


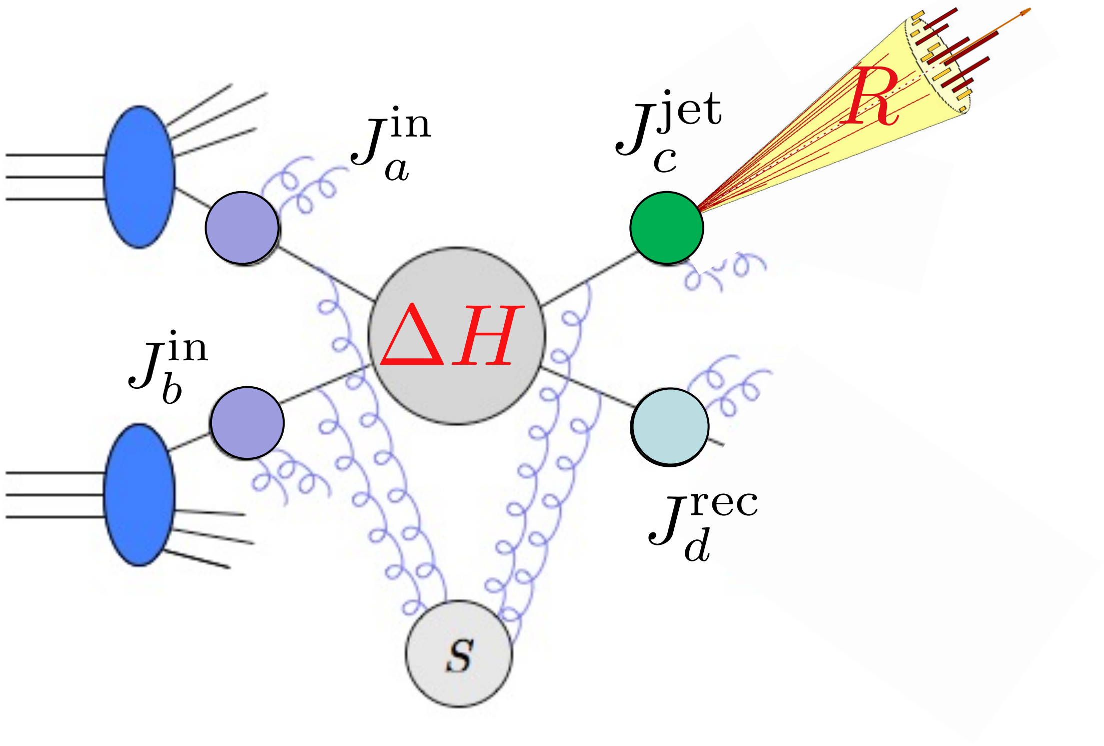
Full NNLO unpolarized:

Bonino, Gehrmann, Stagnitto

Goyal, Moch, Pathak, Rana, Ravindran

Approximate NNLO corrections for pp → jet+X at RHIC:





Kidonakis, Oderda, Sterman
de Florian, WV
Hinderer, Ringer, Sterman, WV, ….

threshold logs $\ln\left(1-\frac{s_{\rm rad}}{s}\right)$

$$\Delta\hat{\sigma}^{ab\to cd} \sim J_a^{\rm in}\times J_b^{\rm in}\times J_c^{\rm jet}\times J_d^{\rm rec}\times {\rm Tr}\left[\Delta H\,\mathcal{S}^\dagger S\mathcal{S}\right]_{ab\to cd}$$

Global NNLO analysis: results

Parameters & data selection:

- unpol. PDFs: MSHT20-NNLO

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- data:

DIS:	EMC,SMC,E142,E143,E154,E155, HERMES, COMPASS, HALL-A,CLAS (p,n,d,He)	**378**
SIDIS:	HERMES, COMPASS (p-$\pi^{\pm}$,d-$\pi^{\pm}$)	**277**
PP-JETS:	STAR run 5,6,9,12,13,15 ($\sqrt{s} = 200, 510\,GeV$) (no dijets yet)	**91**
PP-$\pi^0/\pi^{\pm}$:	PHENIX, STAR	**82**
PP $W^{\pm}$:	PHENIX, STAR	**22**
Total:		**850**

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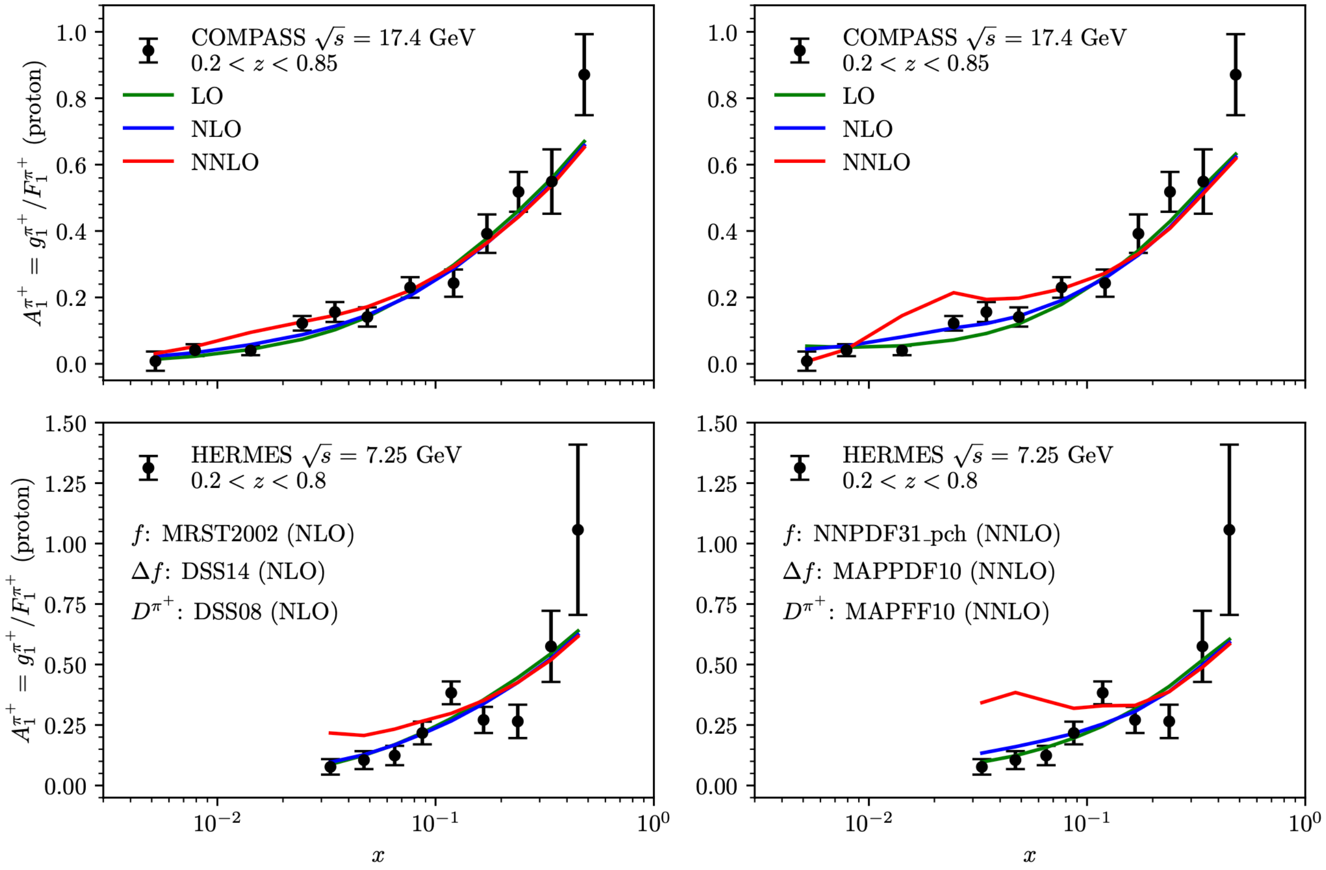
- interesting feature for SIDIS:

Bonino et al.



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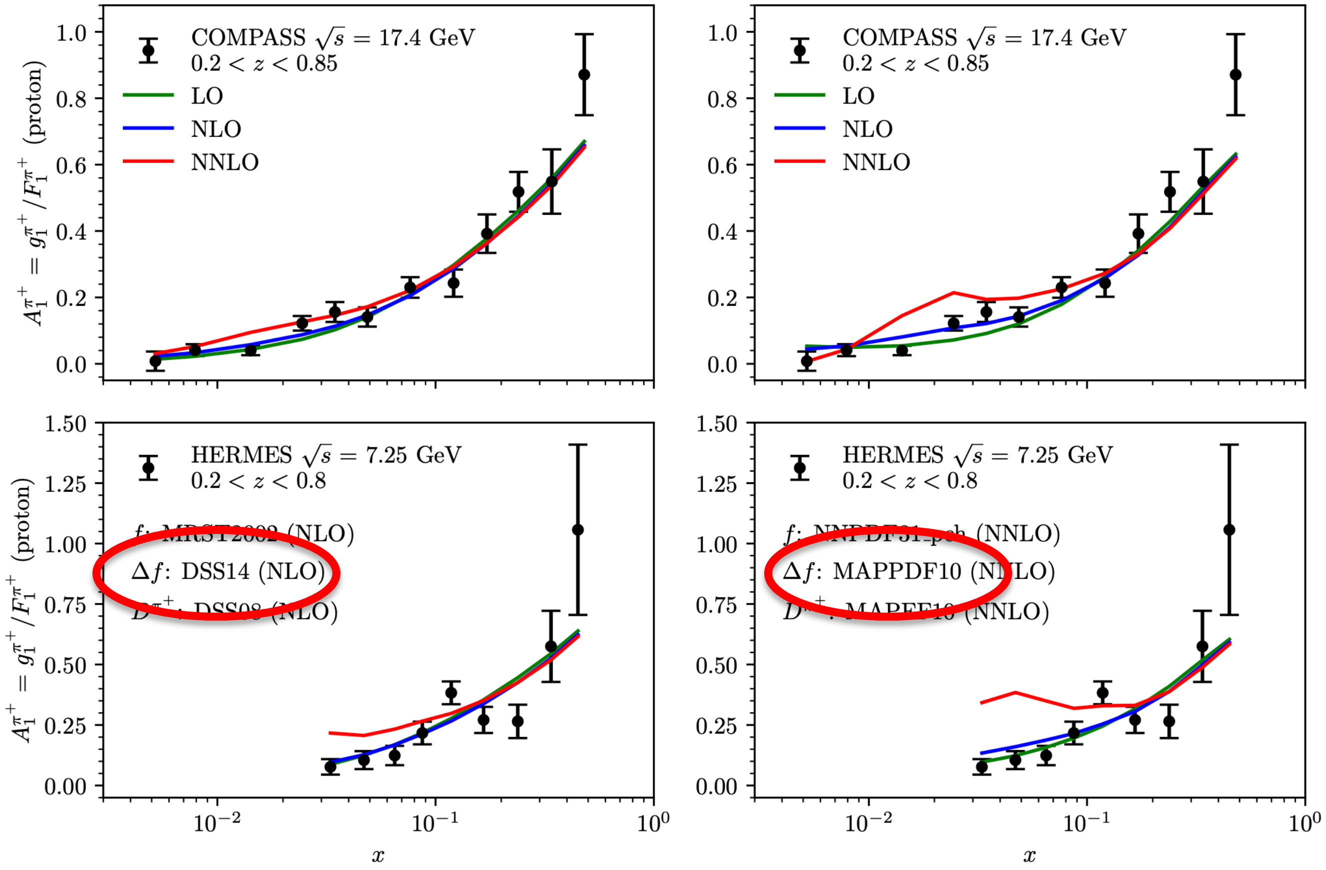

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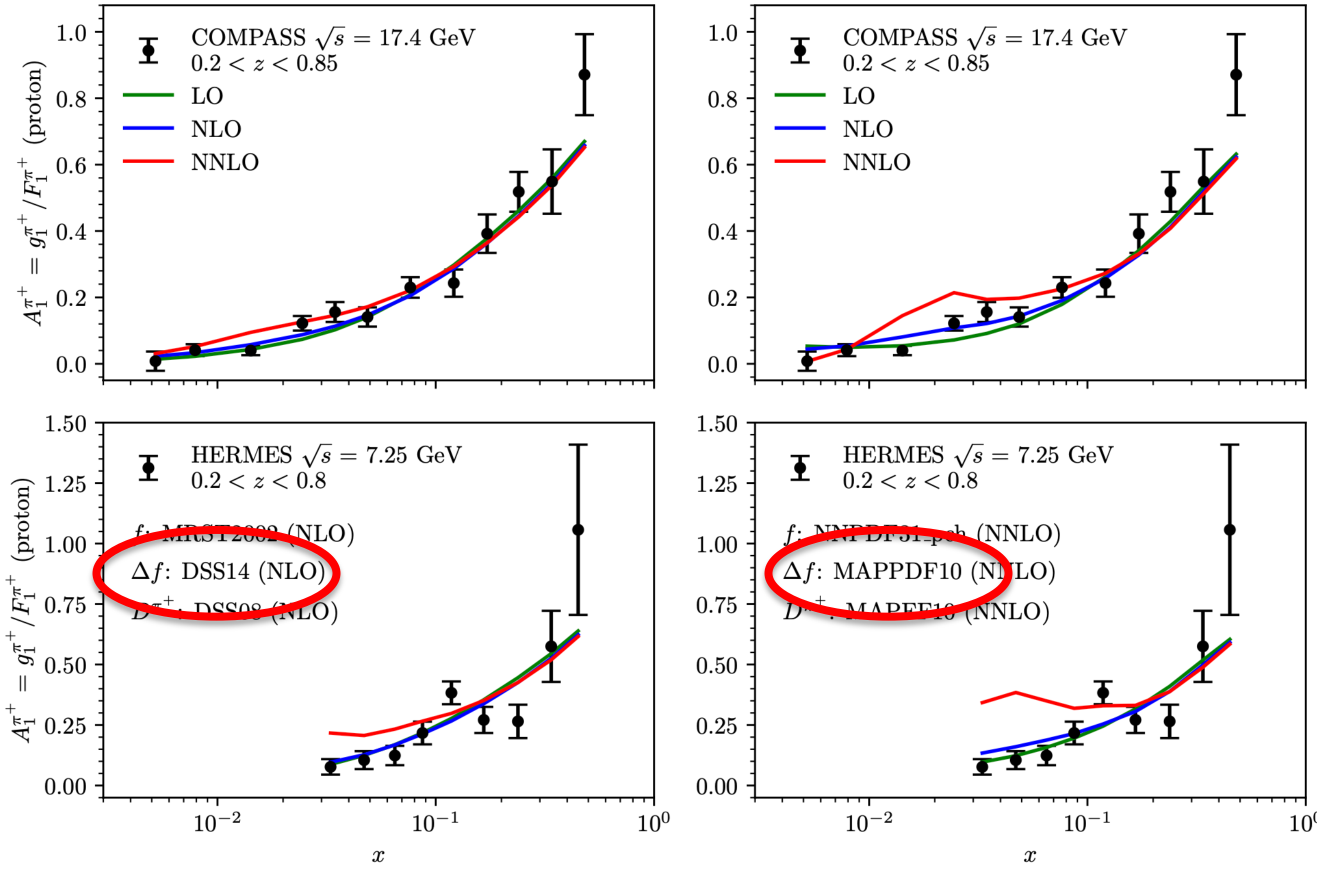

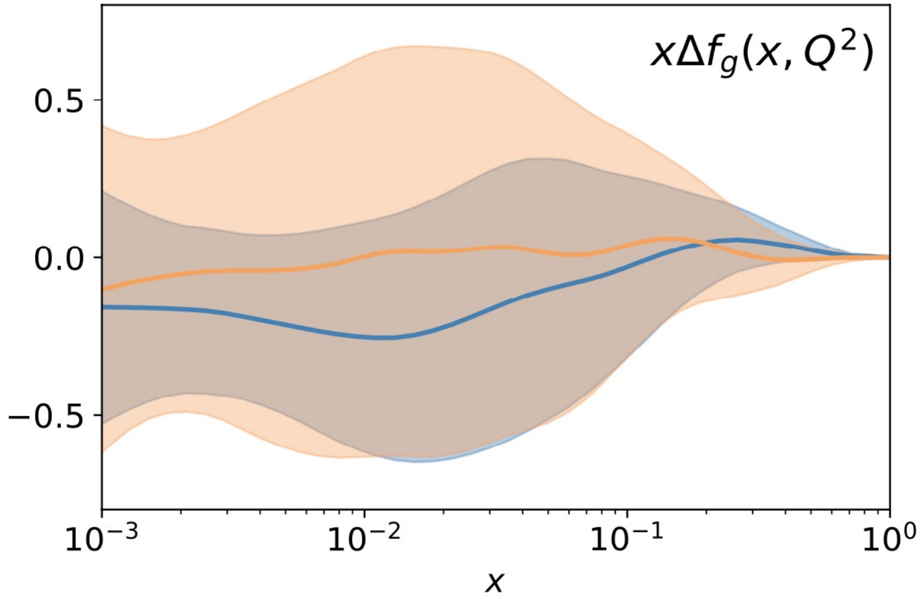

MAP: Bertone, Chiefa, Nocera

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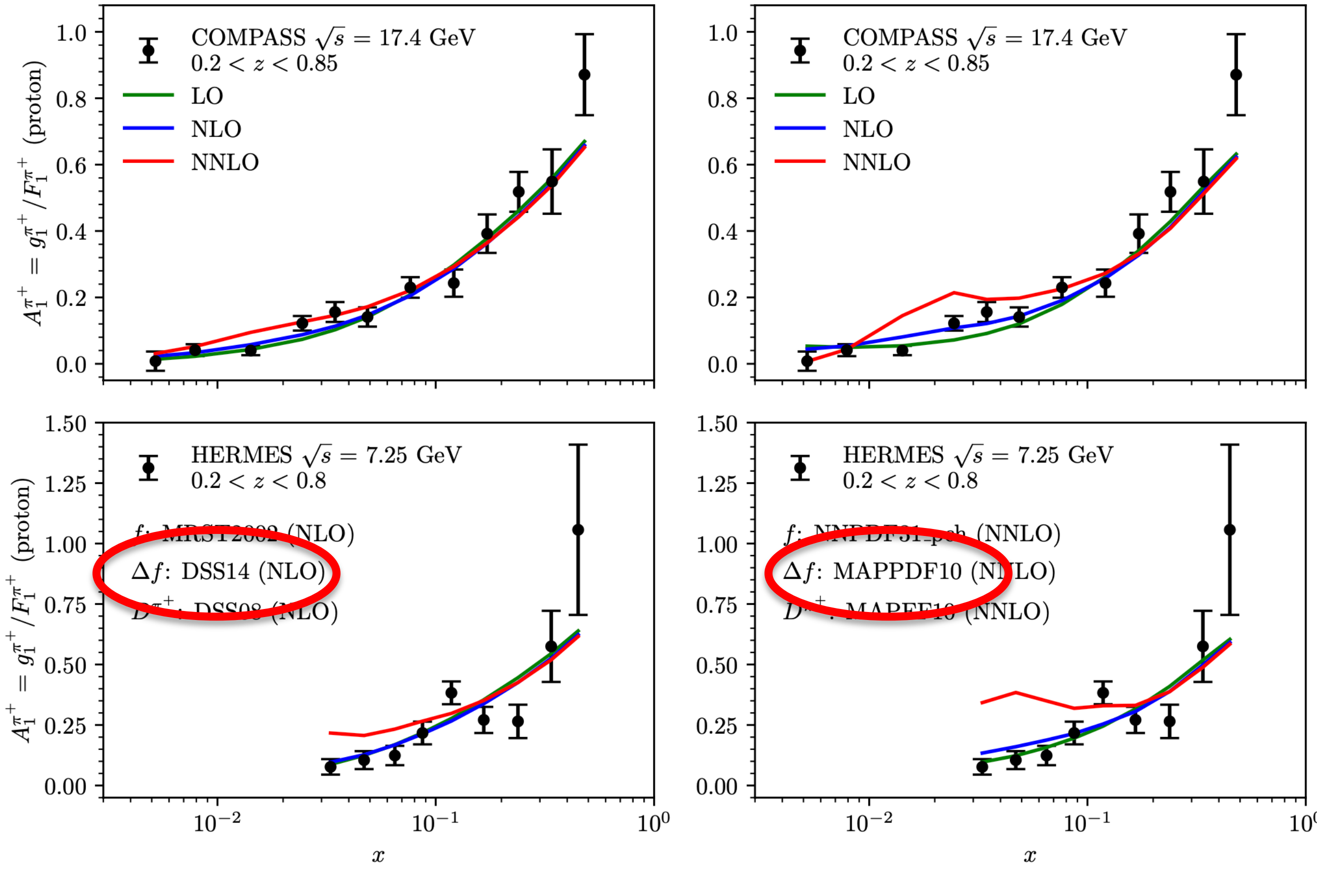

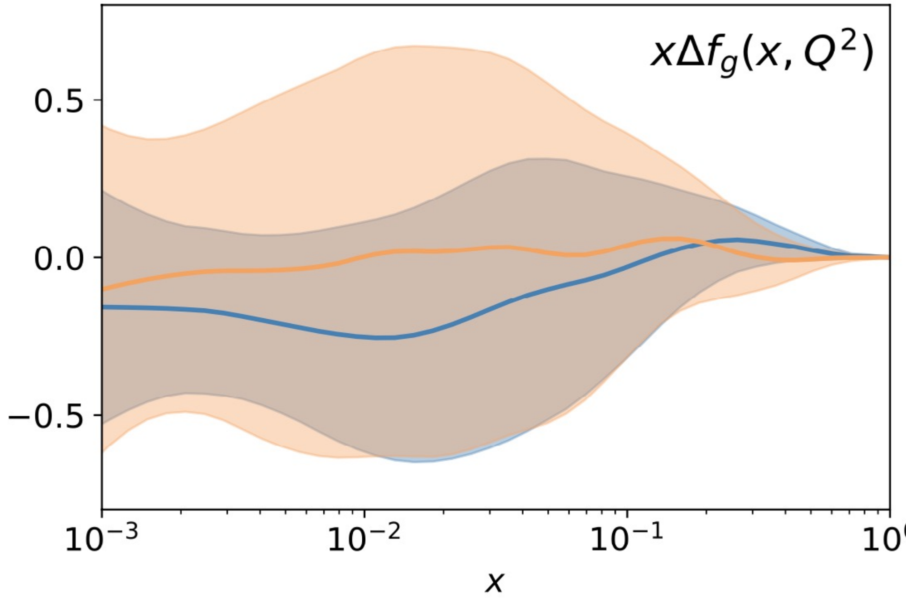

MAP: Bertone, Chiefa, Nocera

- “bump” not present in threshold approximation for SIDIS

  → breakdown of approximation?

- in any case, lower-x SIDIS data involve FFs (and unpol. PDFs) outside regimes where they have been determined (and where they work)

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- we find:

	NLO	NNLO
DIS	304.72	308.74
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all pp	199.72	193.91

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implemented in our analysis to be conservative

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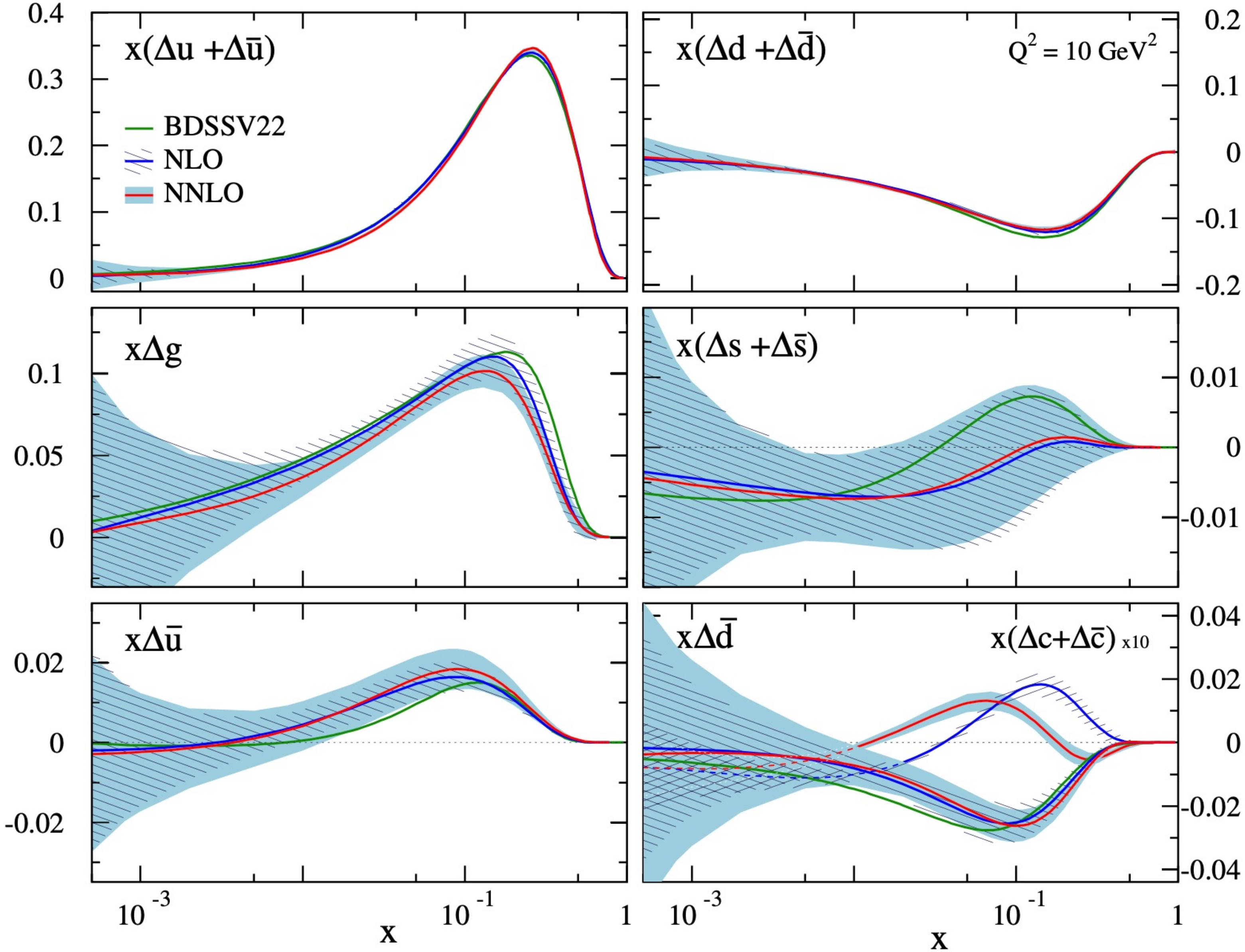
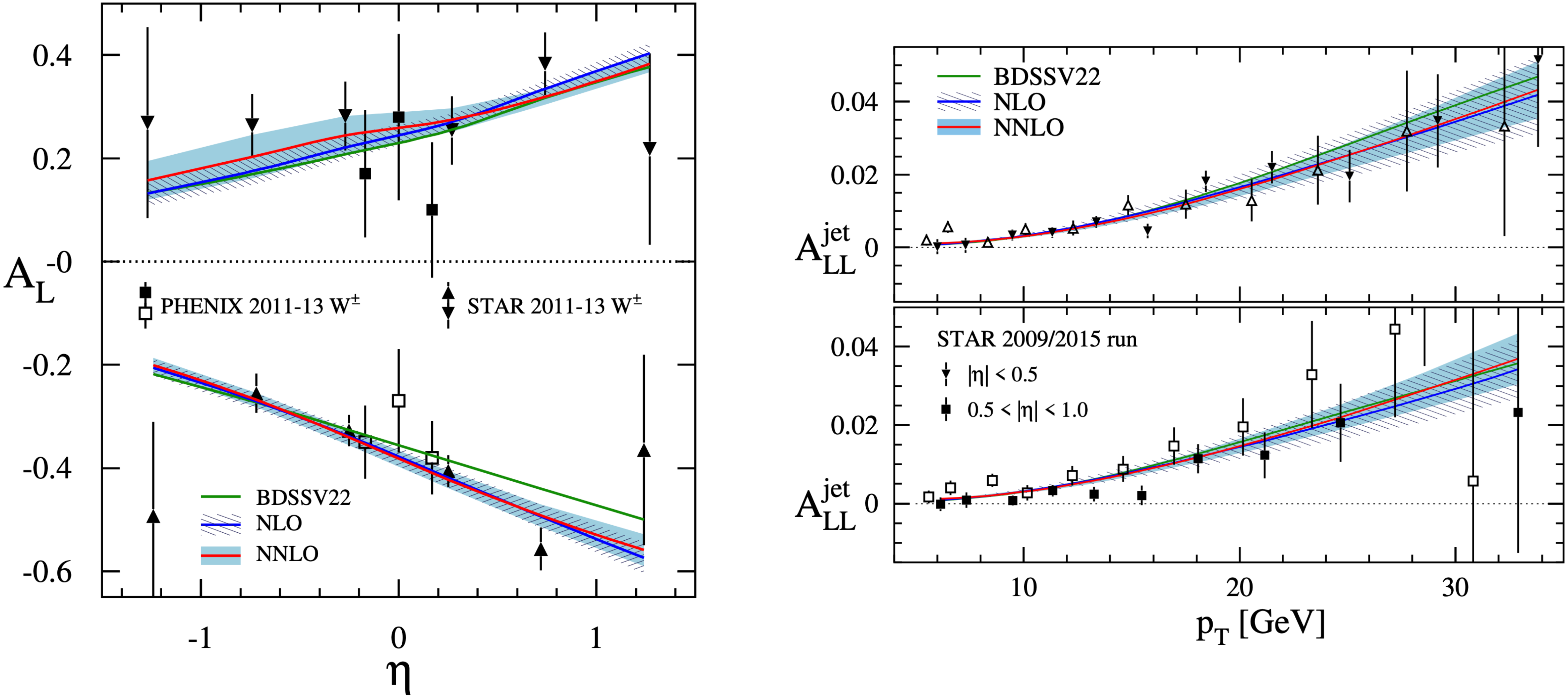
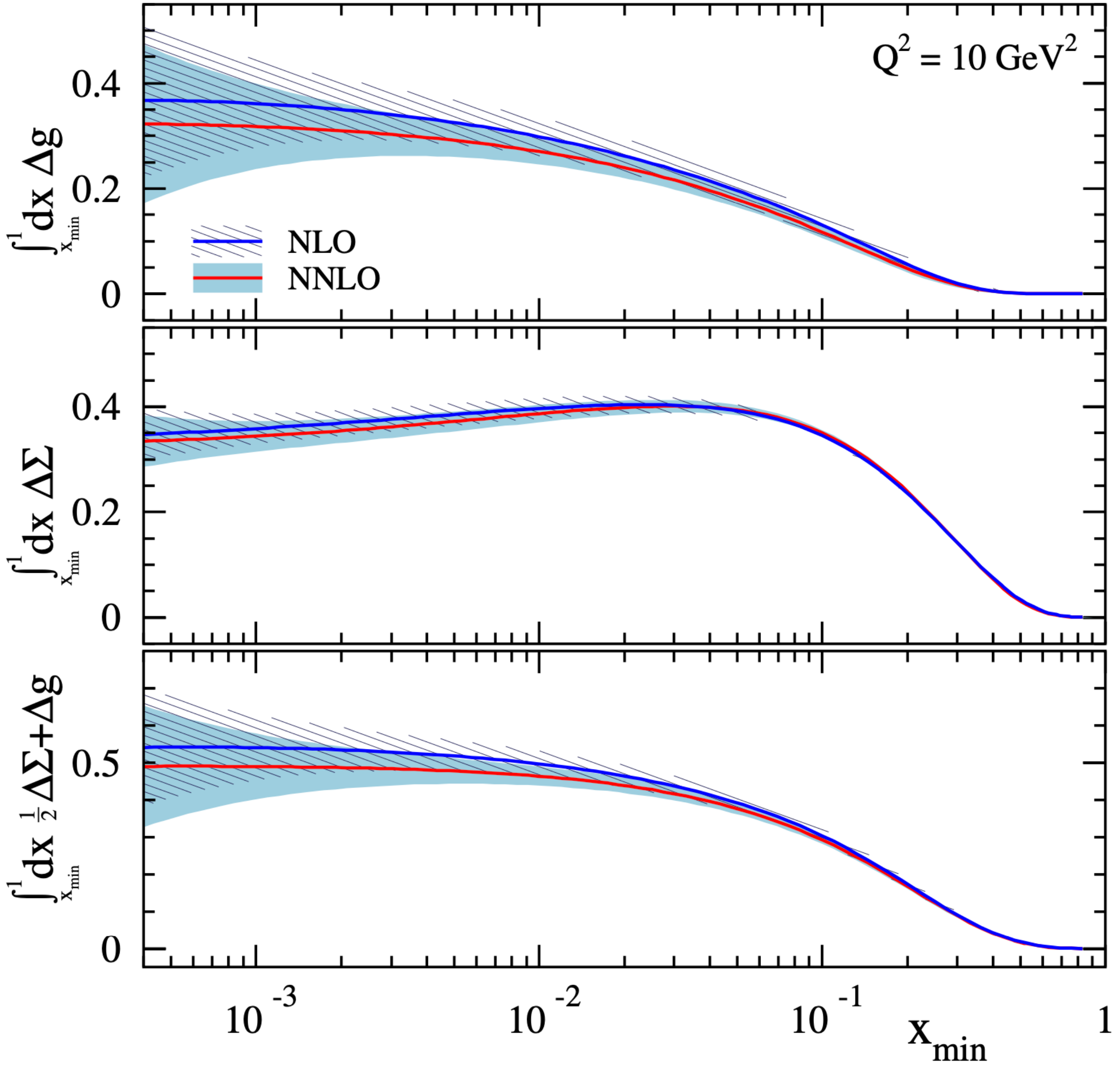


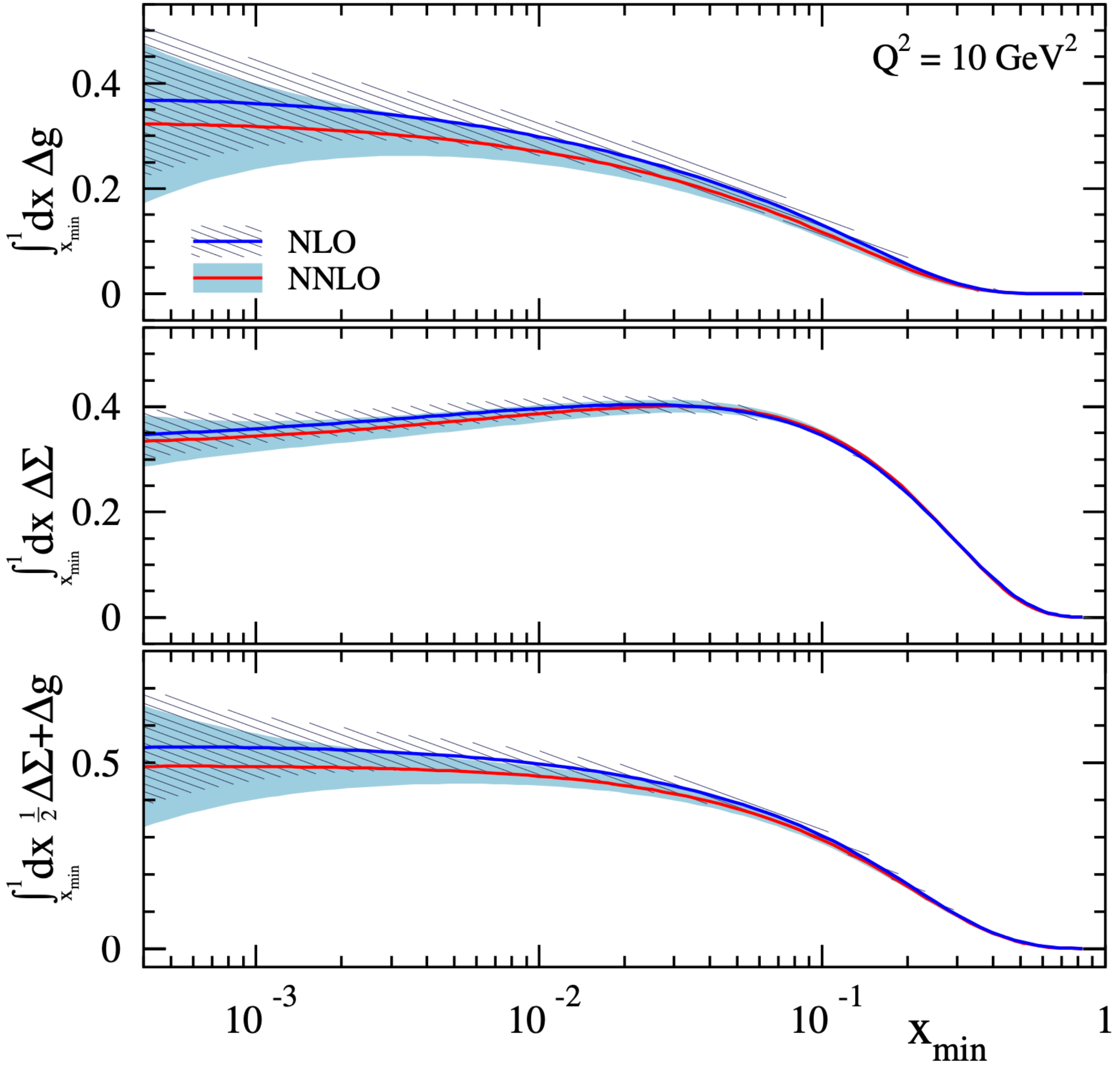
pQCD analysis
“in good shape”



PHENIX 2011-13 W±
STAR 2011-13 W±
BDSSV22
NLO
NNLO
A_L
η
STAR 2009/2015 run
|η| < 0.5
0.5 < |η| < 1.0
A_LL^jet
p_T [GeV]



$Q^2 = 10$ GeV^2
NLO
NNLO
$\int_{x_{min}}^1 dx\, \Delta g$
$\int_{x_{min}}^1 dx\, \Delta\Sigma$
$\int_{x_{min}}^1 dx\, \frac{1}{2}\Delta\Sigma + \Delta g$
0
0.2
0.4
0.5
10^{-3}
10^{-2}
10^{-1}
1
x_{min}



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room for OAM ?

Phenomenology of double parton scattering

Probe of DPS in pp:

- should allow systematic distinction from *single* parton scattering

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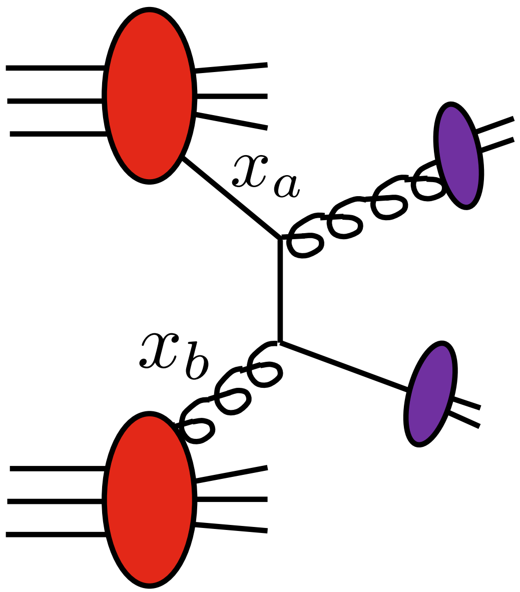
M. Strikman, WV 2010: consider $pp \to h_1 h_2 X$ (typically, $\pi^0\pi^0$)

- → potential downside: “full complexity of QCD”. Higher orders?

pp → $\pi^0\pi^0$ X:



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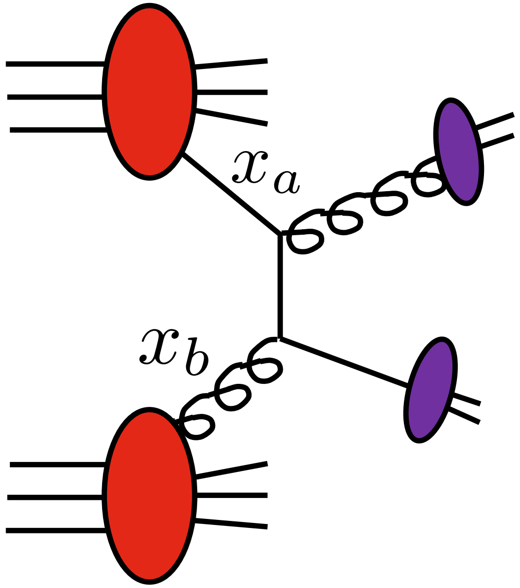

$p_{T,1},\ \eta_1$

$p_{T,2},\ \eta_2$

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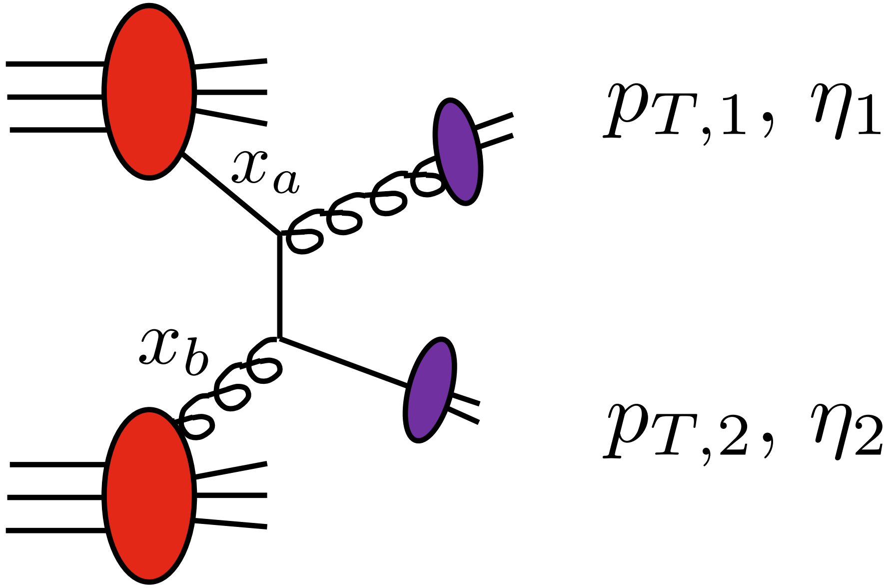

$$\eta_1 + \eta_2 = \log \frac{x_a}{x_b}$$

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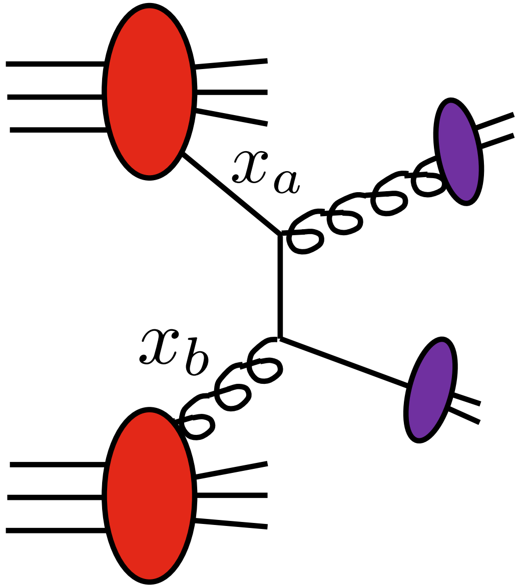

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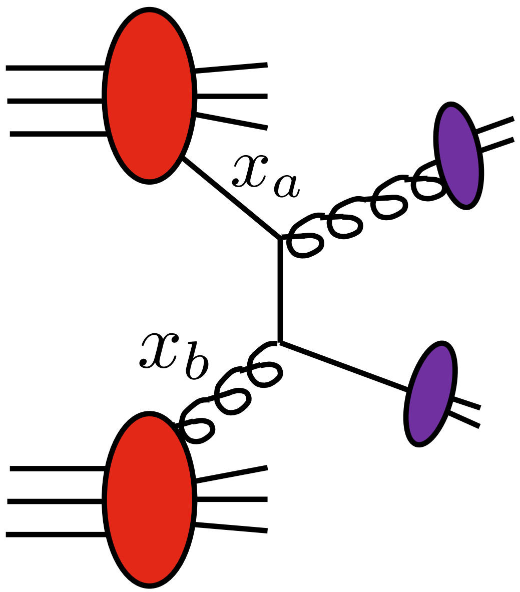

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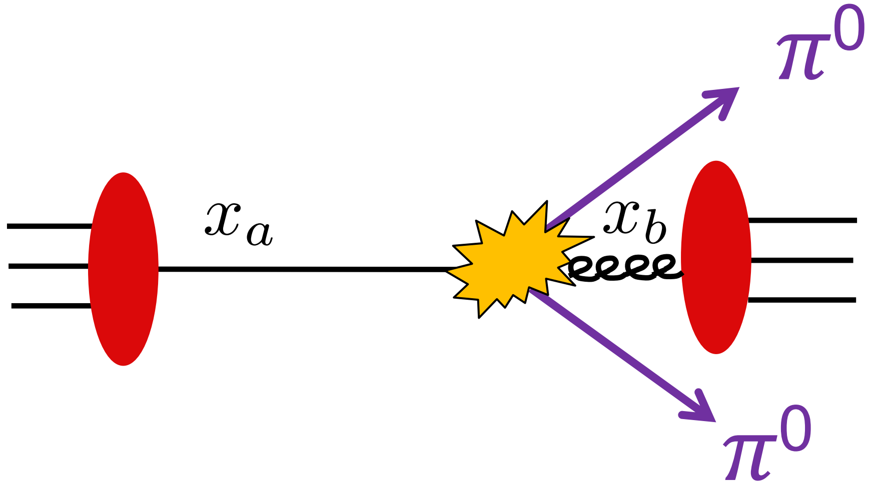
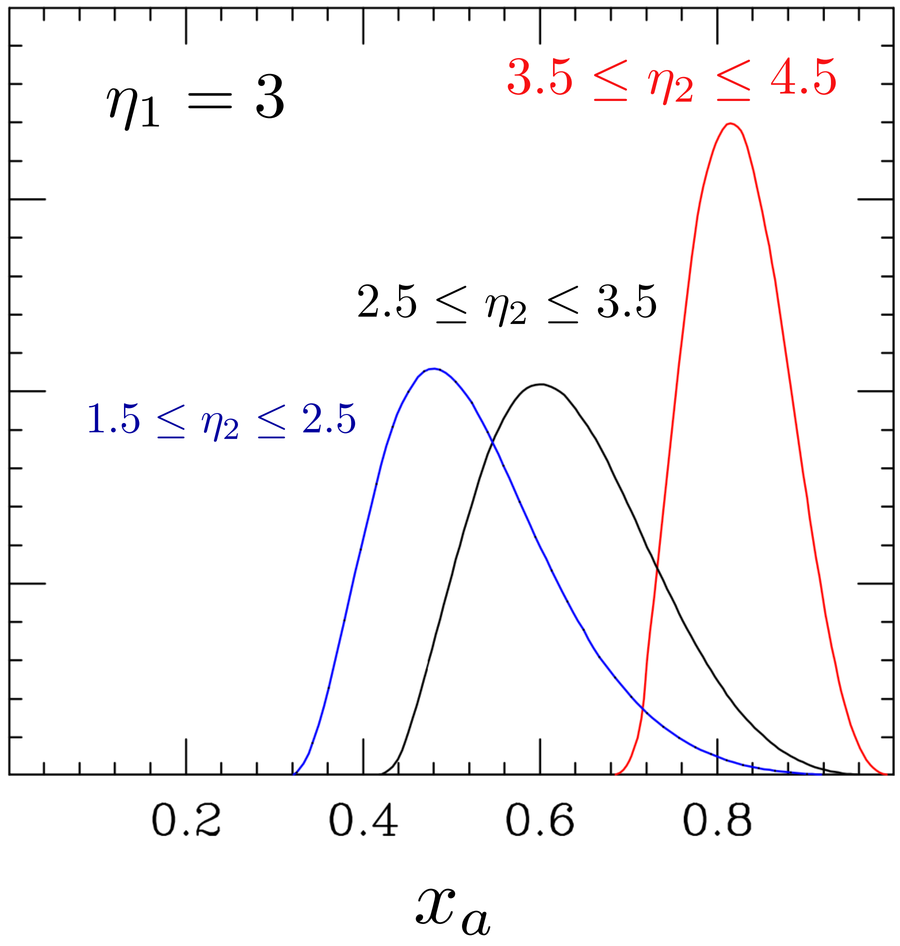


valence $\otimes$ gluon

M. Strikman, WV

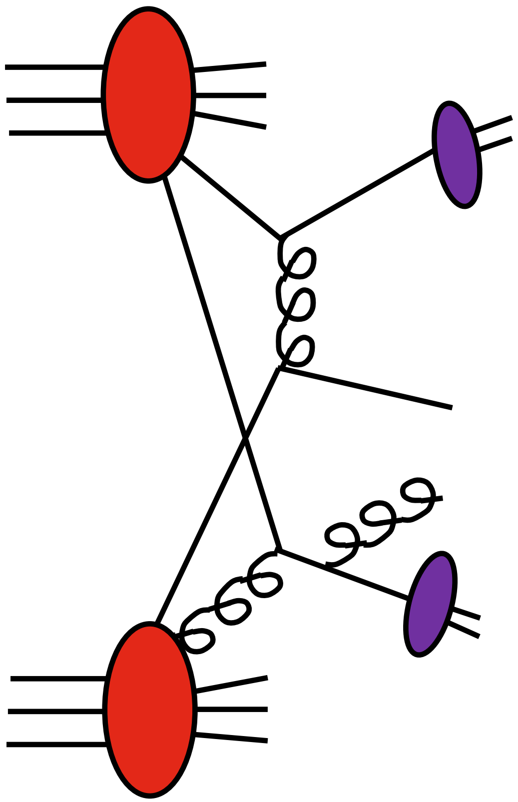


$$\sqrt{s} = 200\,\mathrm{GeV}$$

$$p_{T,1} = 2.5\,\mathrm{GeV}$$

$$2.5\,\mathrm{GeV} \leq p_{T,2} \leq p_{T,1}$$

Consider now double parton scattering:



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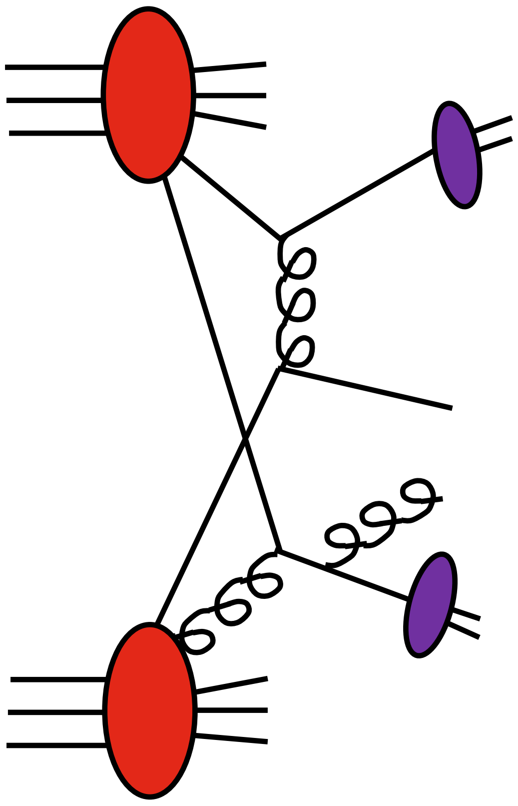

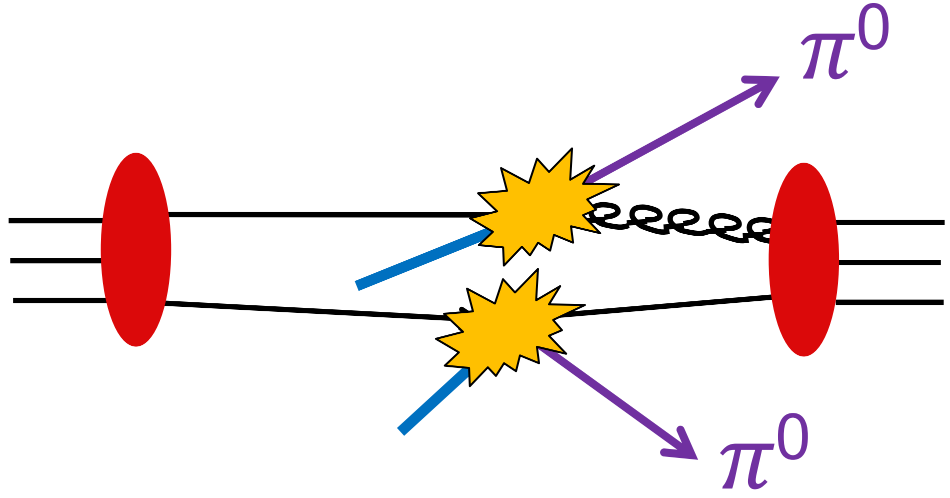

2→2 kinematics less constrained

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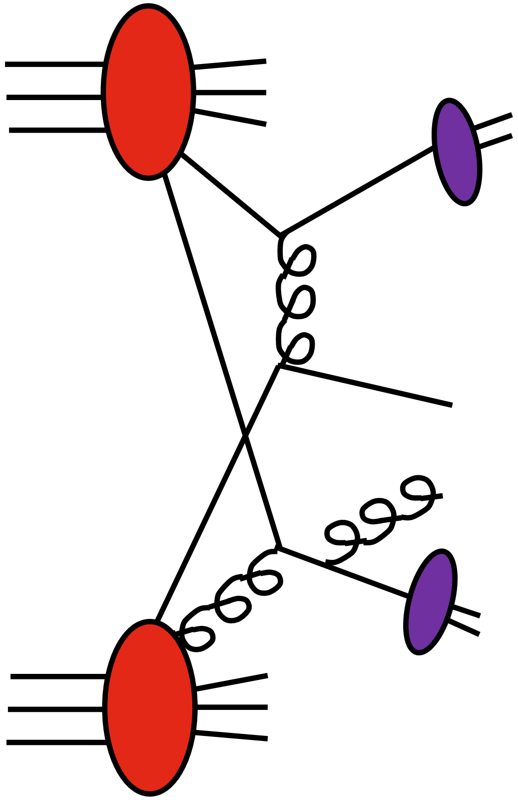

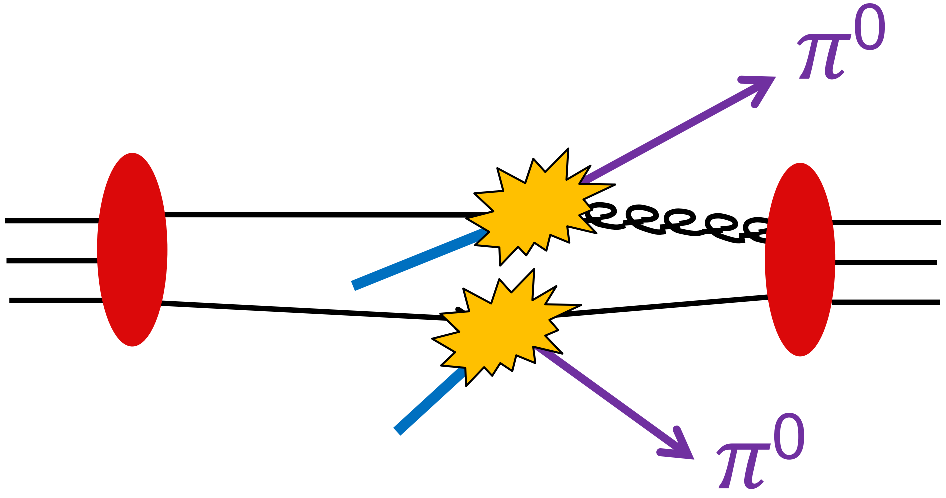

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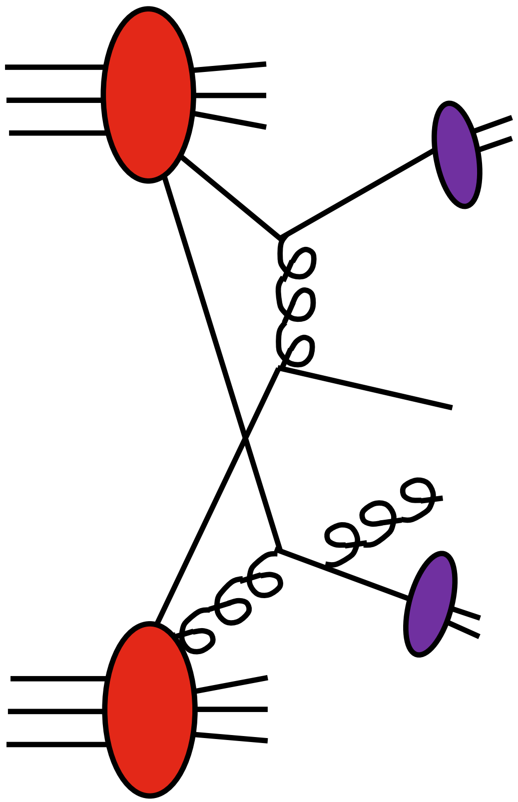
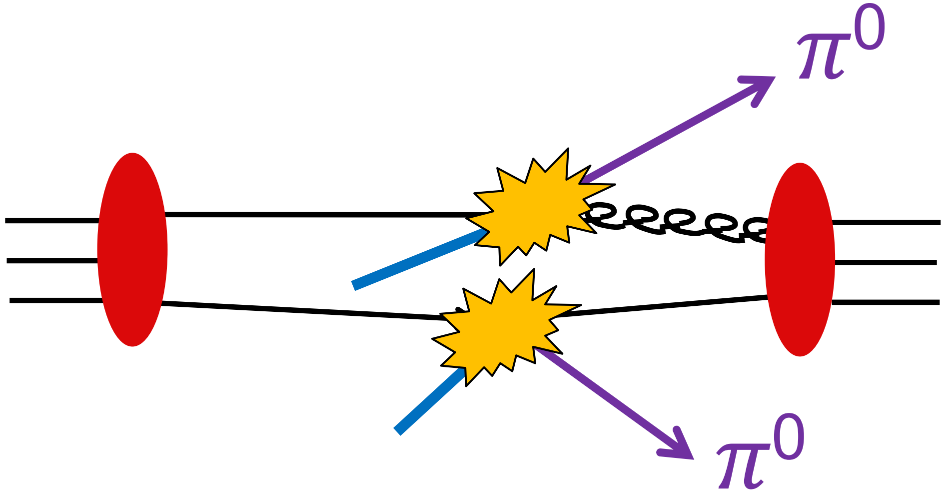


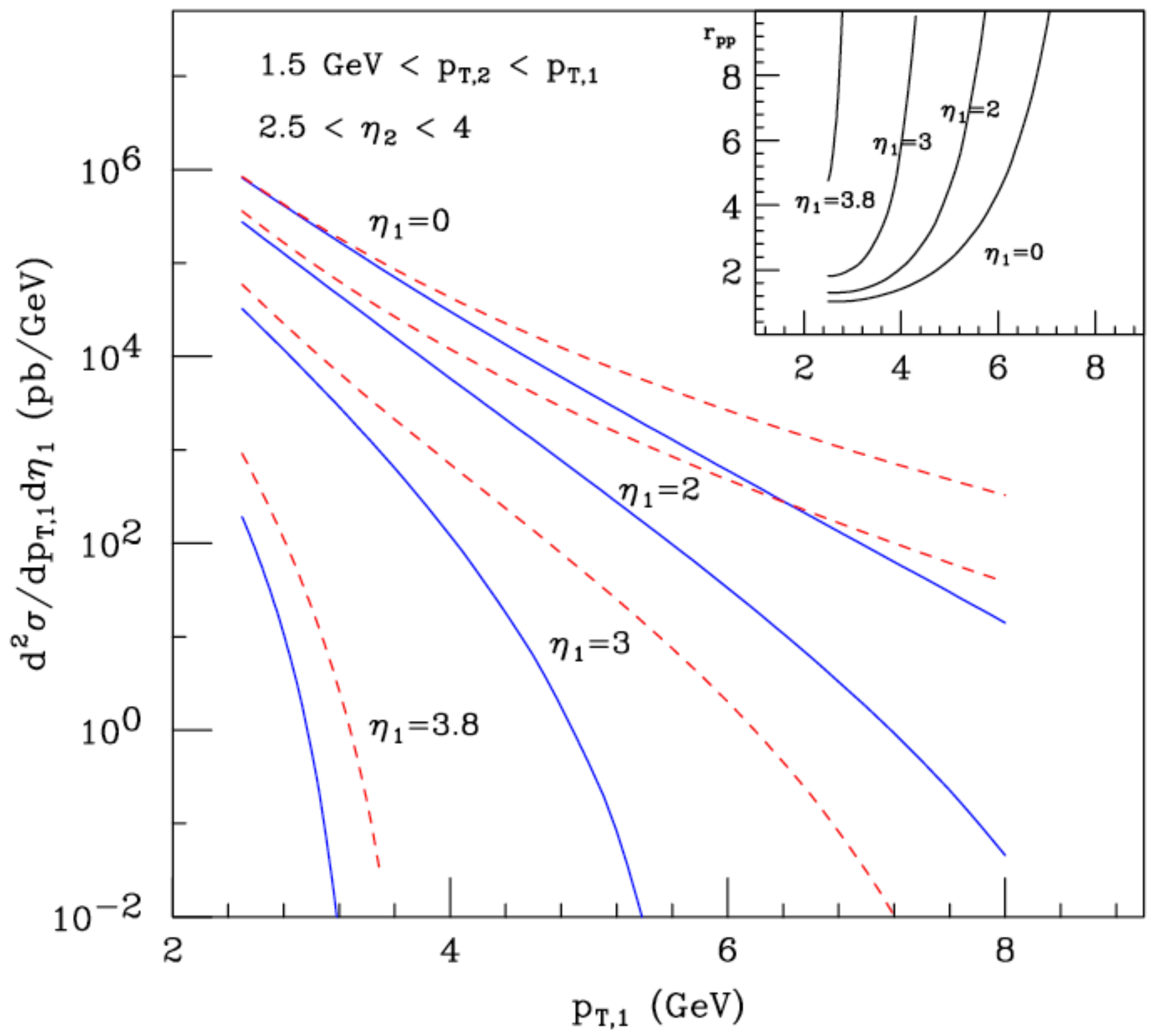


2→2 kinematics less constrained

→ x_a not as large, even if both pions forward

→ could dominate over single-parton scattering

M. Strikman, WV



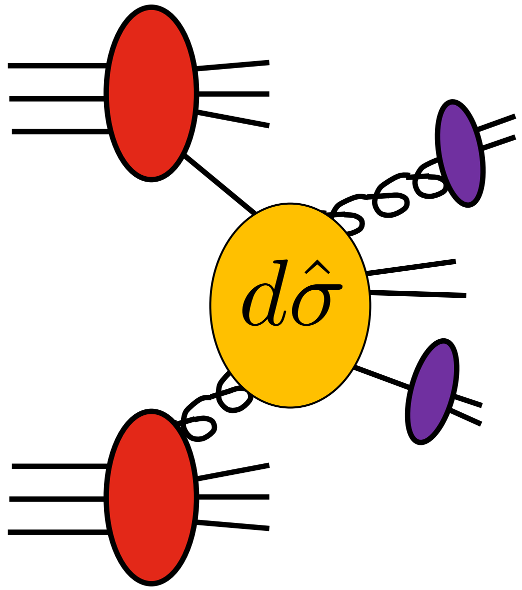
$$\sqrt{s} = 200\,\mathrm{GeV}$$

single PS

double PS

$$\mu^2 = (p_{T,1}^2 + p_{T,2}^2)/2$$

Toward NLO?



NLO: J. Owens 2002

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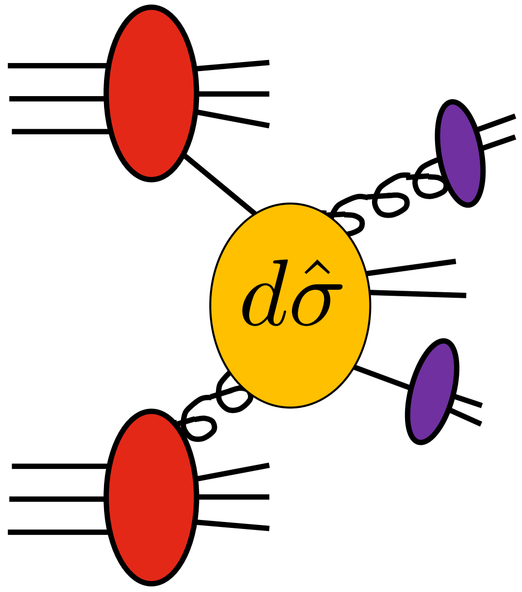

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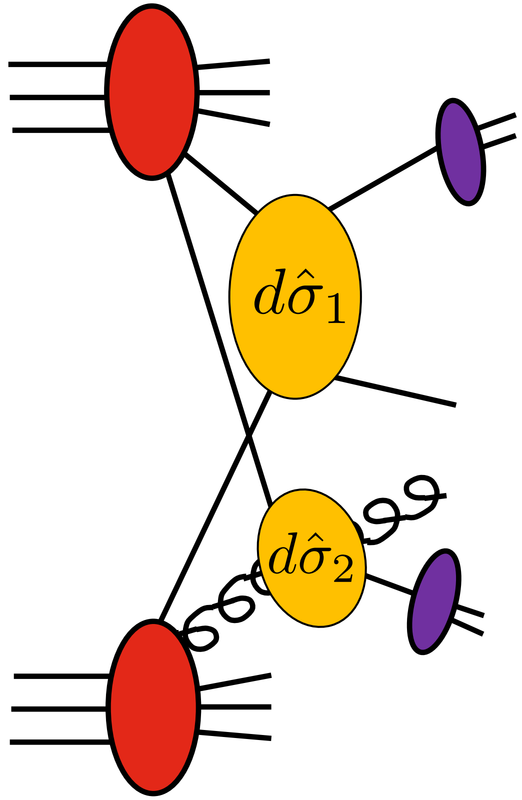

“single” NLO: Aversa et al.; Jäger, Schäfer, Stratmann, WV

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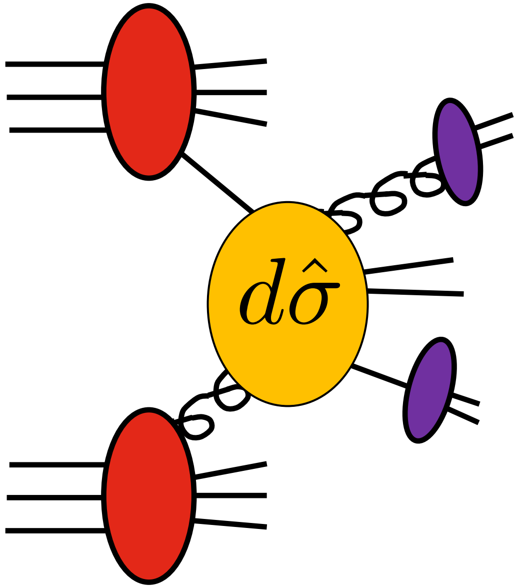

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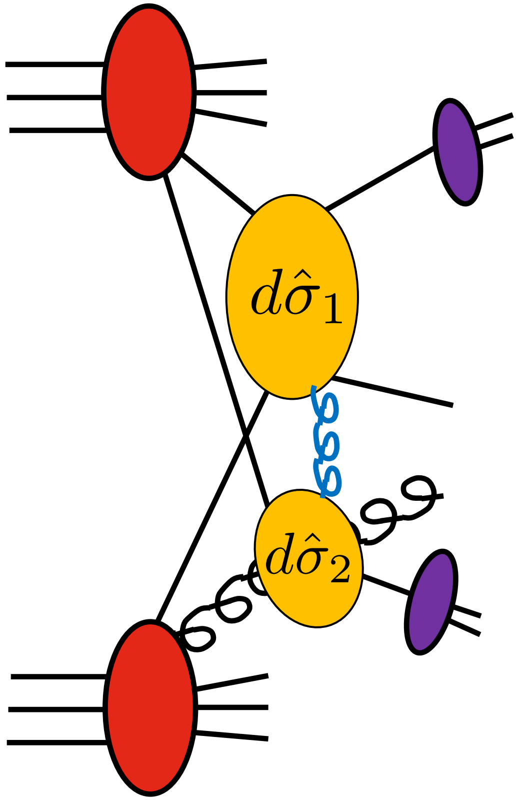

Diehl, Fabry, Plößl

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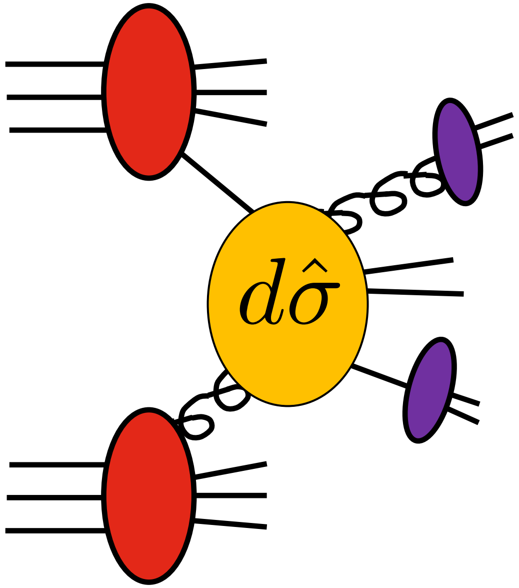

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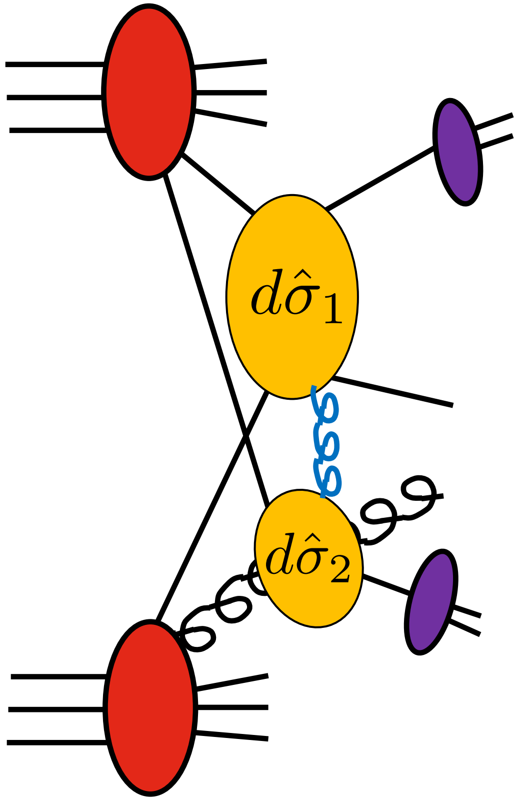
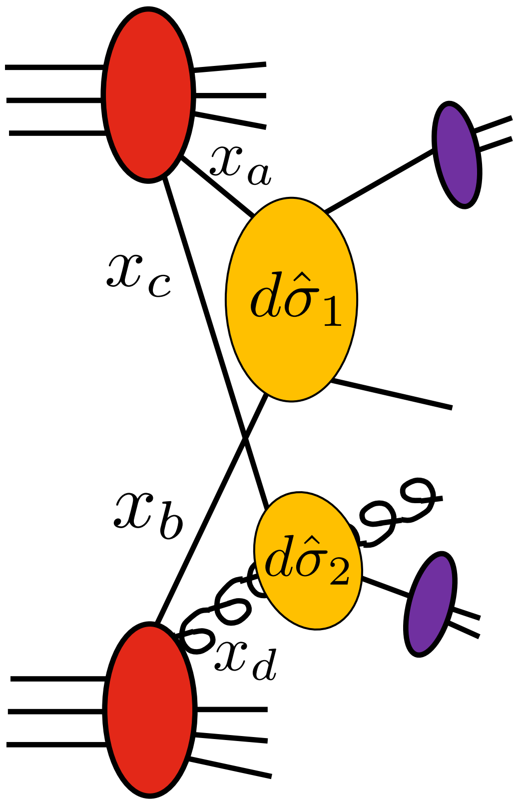


Diehl, Fabry, Plößl

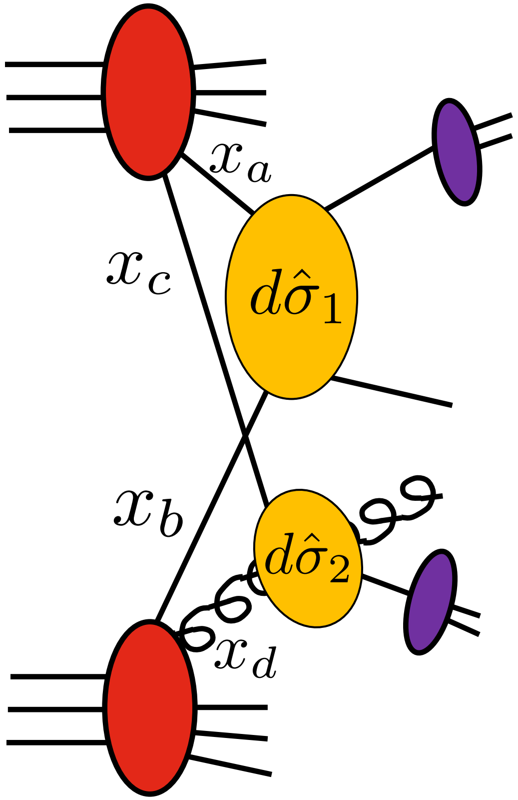
“single” NLO: Aversa et al.; Jäger, Schäfer, Stratmann, WV

- have developed new NLO code that treats scatterings as independent

A. Fürlinger, O. Schüle, WV

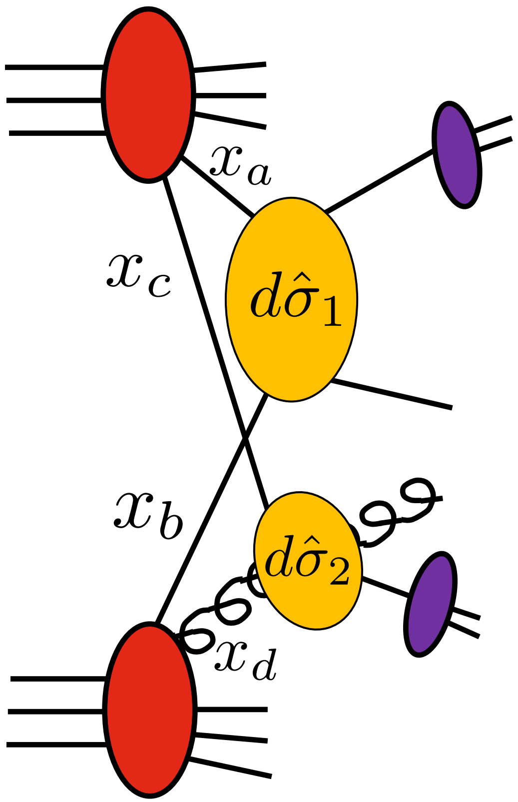


x_a
x_c
$d\hat{\sigma}_1$
x_b
$d\hat{\sigma}_2$
x_d



$$\frac{d^4\sigma_{\rm double}}{dp_{T,1}d\eta_1 dp_{T,2}d\eta_2} = \frac{1}{\pi R^2_{\rm int}} \sum_{abcd} \int dx_a dx_b dx_c dx_d \, \phi_{ac}(x_a, x_c)\, \phi_{bd}(x_b, x_d) \, \frac{d^2\hat{\sigma}^{ab\to eX}}{dp_{T,1}d\eta_1} \, \frac{d^2\hat{\sigma}^{cd\to e'X'}}{dp_{T,2}d\eta_2}$$

$$\otimes D_e^{\pi^0} \otimes D_{e'}^{\pi^0}$$



NLO

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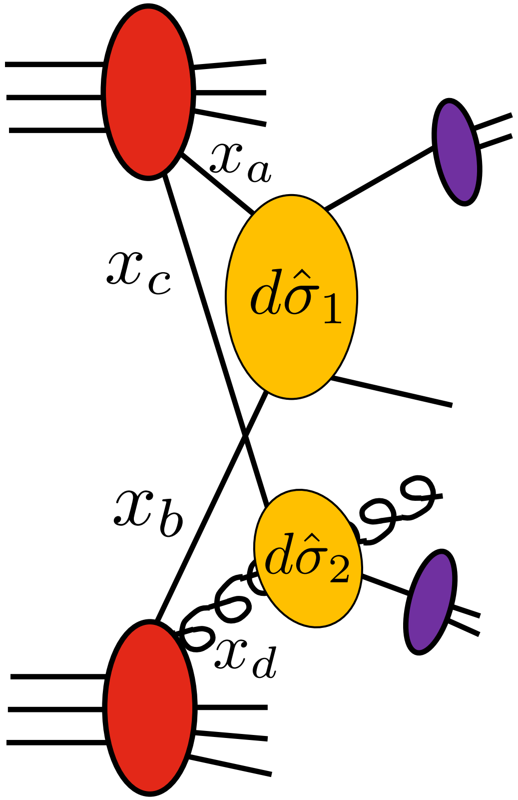

$$f_a(x_a)\, f_c(x_c)\, \Theta(x_a + x_c \leq 1)$$

$\cdots$

NLO

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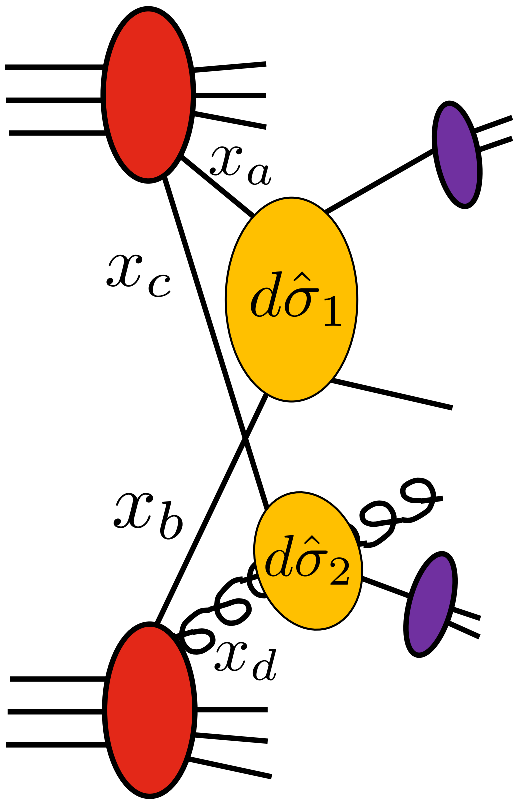

→ use proper DPDs

Diehl, Fabry, Plößl

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$\cdots$

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NLO / LO — single PS

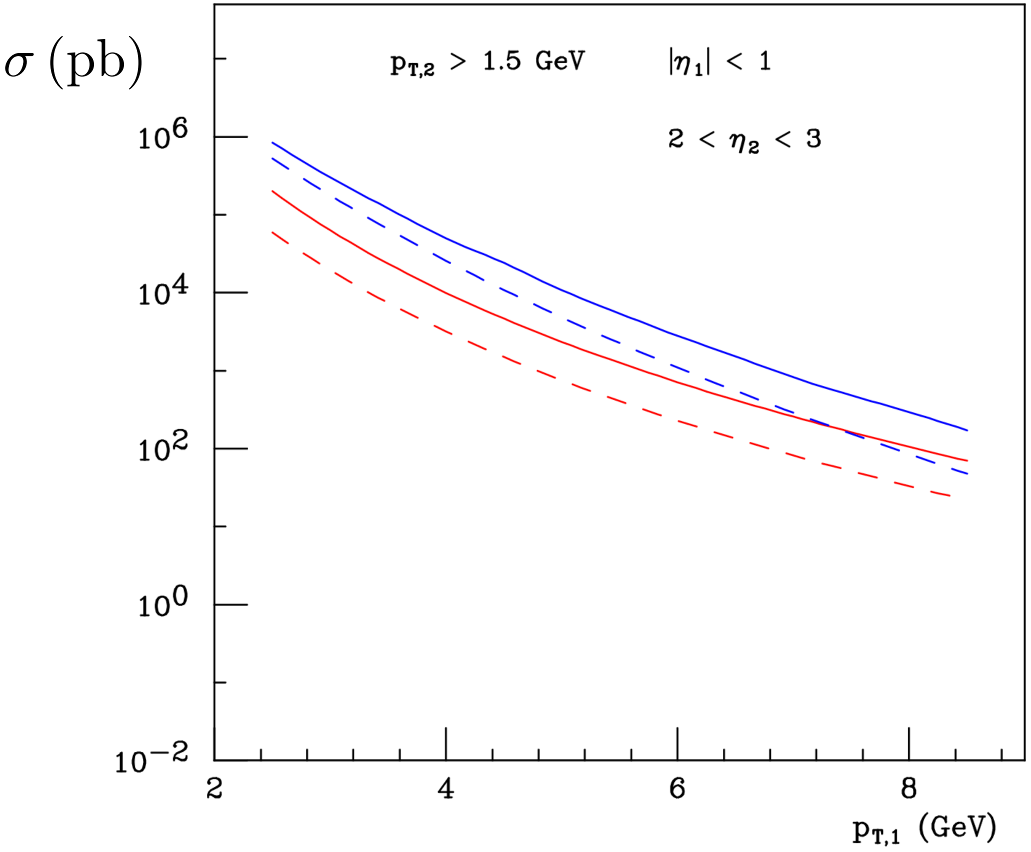
NLO / LO — double PS

$$\mu^2 = (p_{T,1}^2 + p_{T,2}^2)/2$$

$$\mu_1 = p_{T,1} \qquad \mu_2 = p_{T,2}$$

CT18, DSS14

$$\sqrt{s} = 200\,\mathrm{GeV}$$



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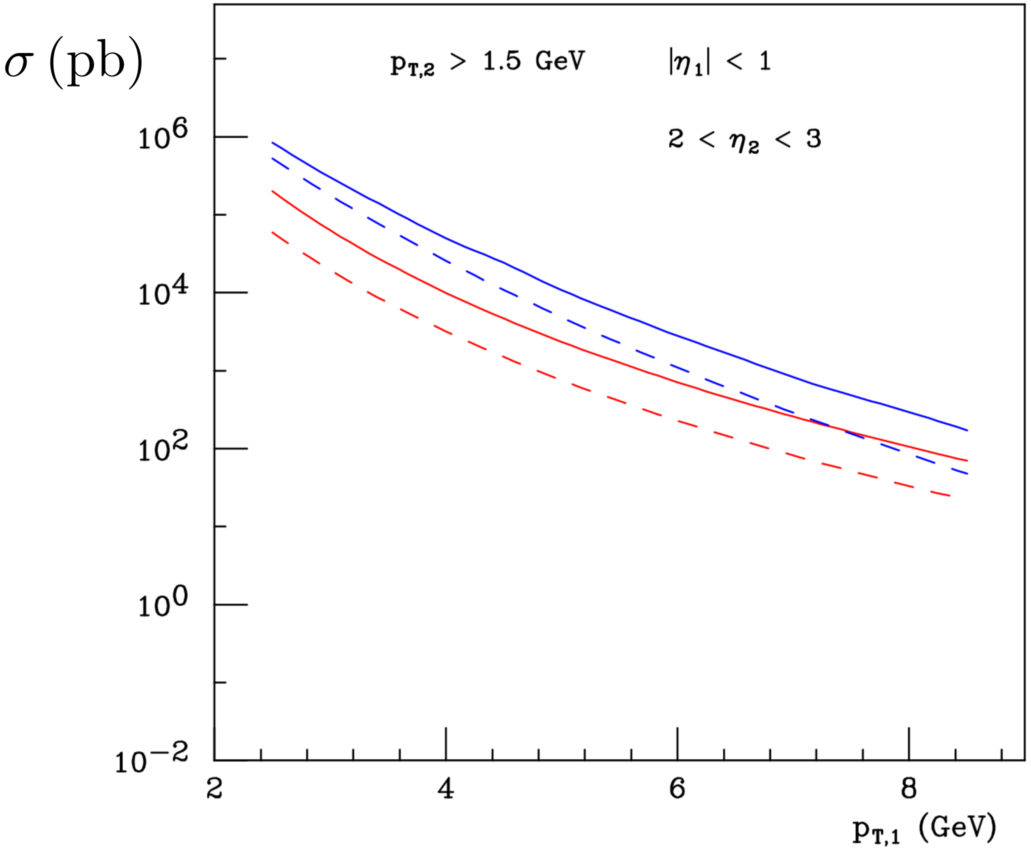

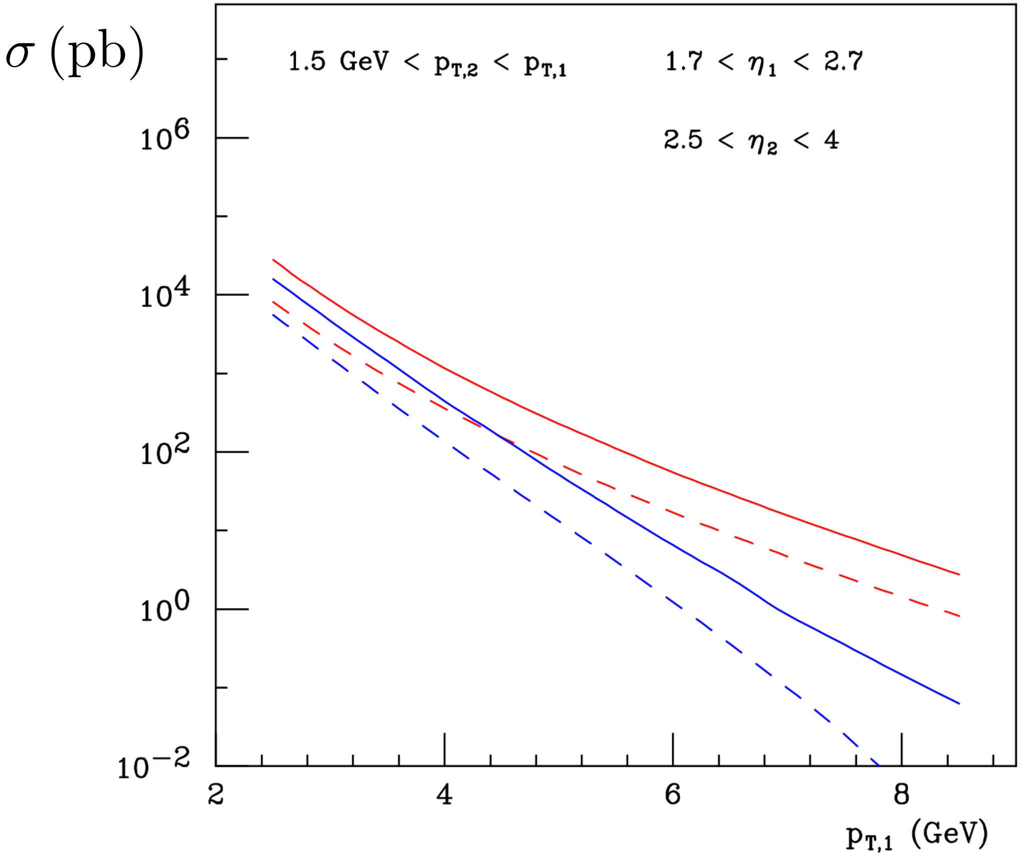

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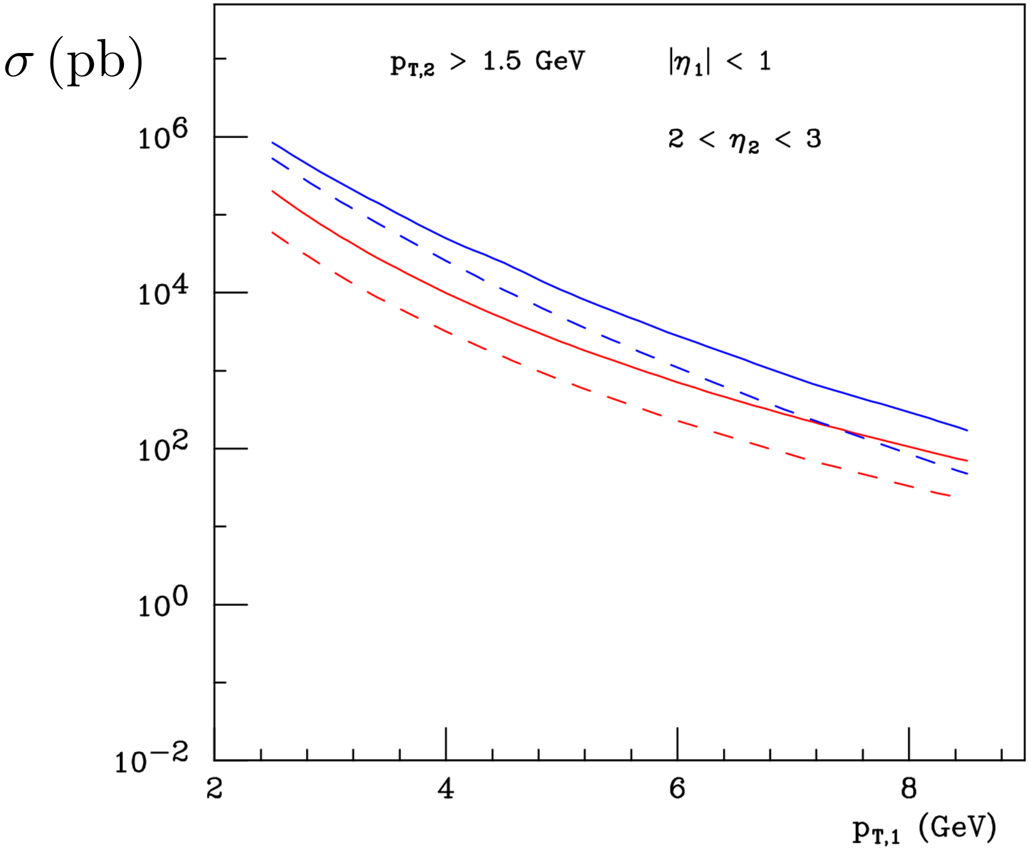
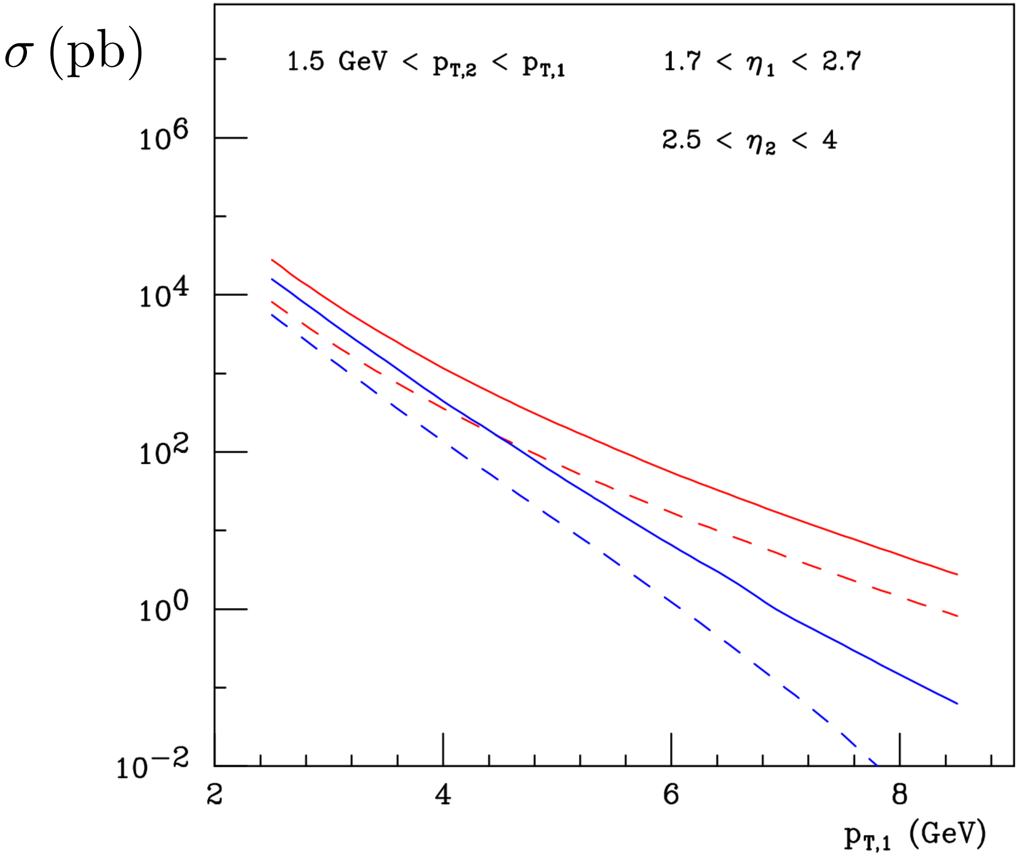
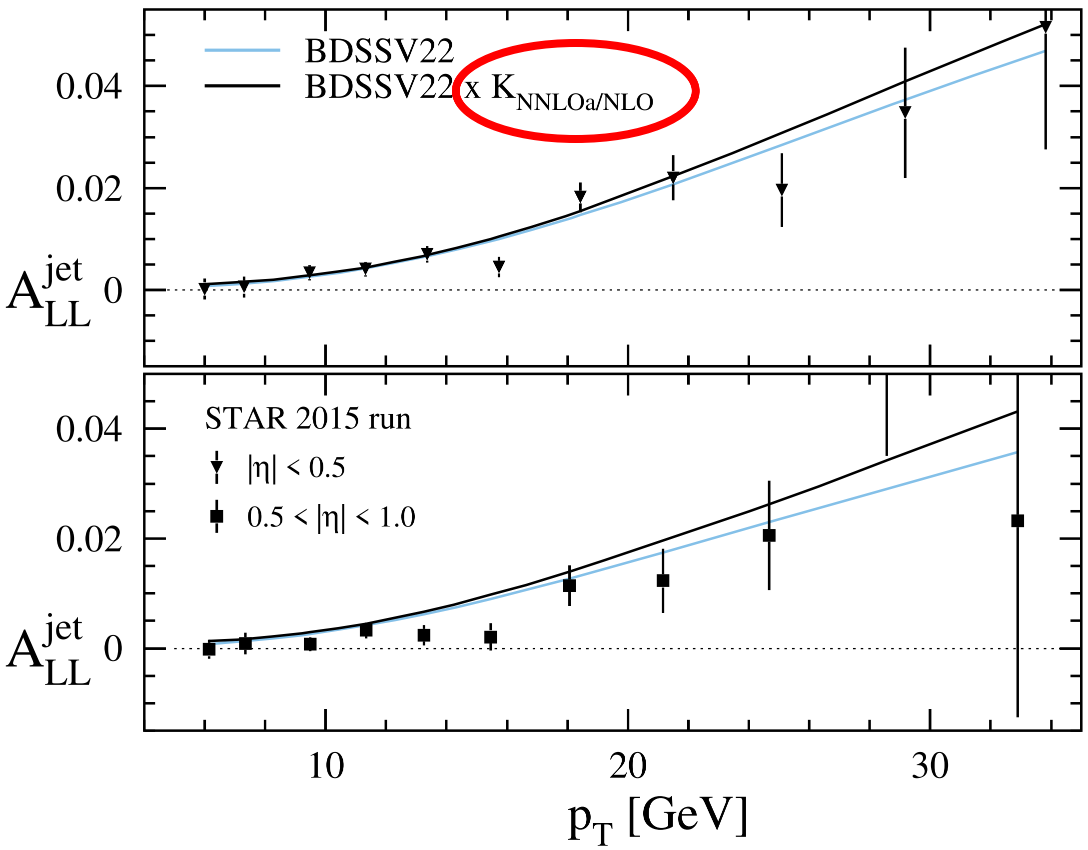




LHC ?



BDSSV22
BDSSV22 x $K_{NNLOa/NLO}$
STAR 2015 run
$|\eta| < 0.5$
$0.5 < |\eta| < 1.0$
A_{LL}^{jet}
0.04
0.02
0
10
20
30
p_T [GeV]