Double Charmonium production at LHC

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in collaboration with:
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- Single charmonim production at LHC was studied in detail
  - LO ($gg \to \mathcal{Q}$), collinear approximation $\Rightarrow$ no p_T distribution, no ψ
  - k_T factorization
  - NLO*: $gg \to \mathcal{Q}g$
- Double charmonium production era began recently
  - DPS
  - SPS LO ($gg \to \mathcal{Q}_1\mathcal{Q}_2$), collinear aproximation $\Rightarrow$ no p_T^{pair}, $\psi\chi$, $\psi\eta_c$
  - SPS NLO* ($gg \to \mathcal{Q}_1\mathcal{Q}_2 g$)
- Was studied in [Lansberg, Shao, PRL111.122001], only $\psi\eta_c$
- Now we present:
  - Novel results for $J/\psi\chi_c$
  - Updated results for $\psi\psi$ @ 13 TeV

The model

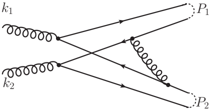
- We use LO CS NRQCD
- S- and P-wave projectors are

$$J/\psi: \quad \bar{v}(p/2)u(p/2) \to \langle O_S\rangle \hat{\epsilon}\left(\hat{P}+M\right)\delta^{ij}$$

$$\chi_c: \quad \bar{v}u \to \langle O_P\rangle \frac{\partial}{\partial q_\mu}\left(\frac{\hat{p}_2}{2}-\hat{q}-m_c\right)\hat{\epsilon}_S\left(\hat{P}+M\right)\left(\frac{\hat{p}_2}{2}+\hat{q}+m_c\right)\delta^{ij}$$

- $\langle O_{S,P}\rangle$ from experiment
- CAS: Wolfram Mathematica and Redberry (©S. Poslavsky et al)
- Numerical: explicit ϵ-s, C.-G. coefficients for χ_c
- All possible checks were performed

Leading Order



(One of 72 Feynman diagrams)

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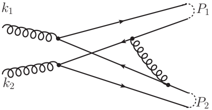

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$\psi\chi_c$ is forbidden by C parity

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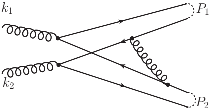

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- Each quark carries half of meson's momentum
- Each propagator gives $\sim 1/\hat{s}$
- Overall $\hat{\sigma} \sim 1/\hat{s}^2$

!cross section is suppressed

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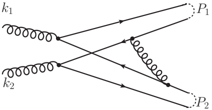

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2) Back-to-back kinematics

- In parton model gluons are collinear to the beam
- No p_T^{pair} distributions
- No $\Delta\phi$ distributions

! Both distributions are observed

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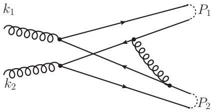

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LO is obviuosly non satisfactory

Next-to-leading order ingedients

Leading Order	+	1-loop corrections	+	Real radiation
▸ $2 \to 2$ *kinematics*		▸ $2 \to 2$ *kinematics*		▸ $2 \to 3$ *kinematics*
▸ no p_T and $\lvert\Delta\phi\rvert$ distributions		▸ no p_T and $\lvert\Delta\phi\rvert$ distributions		▸ nontrivial p_T and $\Delta\lvert\phi\rvert$ distributions
▸ small cross section		▸ α_S suppressed		▸ α_S suppressed
				▸ no kinematical suppression

Forbidden for $J/\psi\chi_c$ final states due to C-parity conservation

$2 \to 3$ reaction is actually the first non-vanishing contribution

$J/\psi + J/\psi$ at NLO*

In total there are 438 color-singlet diagrams

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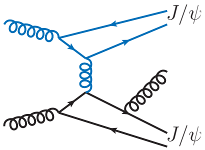
In total there are (438) color-singlet diagrams



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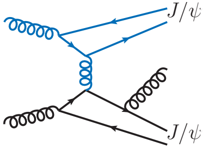

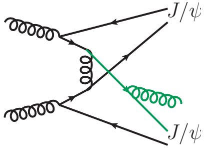

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(188) diagrams with FSR (finite at $p^g \parallel p^{J/\psi}$)

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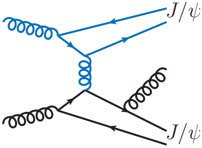

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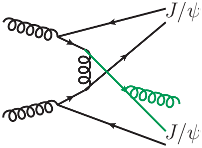

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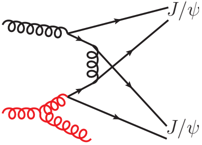

(144)
diagrams with ISR
(divergent at $p_T^{\psi\psi} \to 0$)
$p_T^{\psi\psi} > \Delta$

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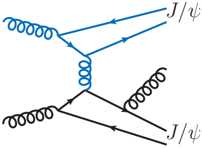

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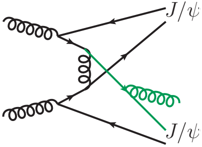

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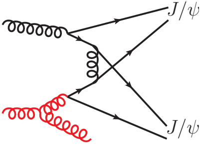

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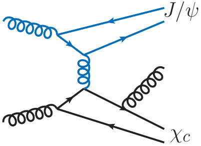

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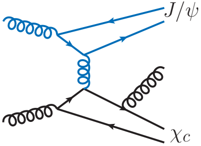

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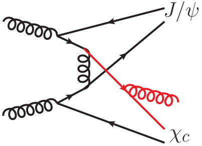

188 + 53
diagrams with FSR
(divergent at $p_\chi || p_g$)
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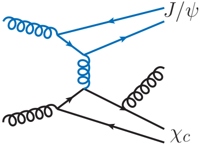

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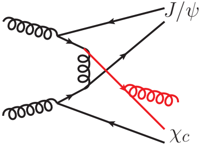

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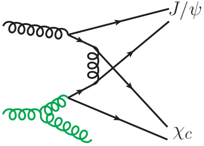

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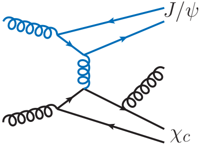

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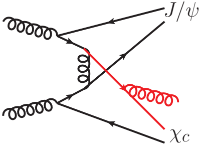

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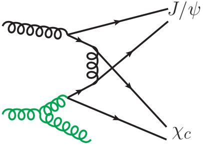

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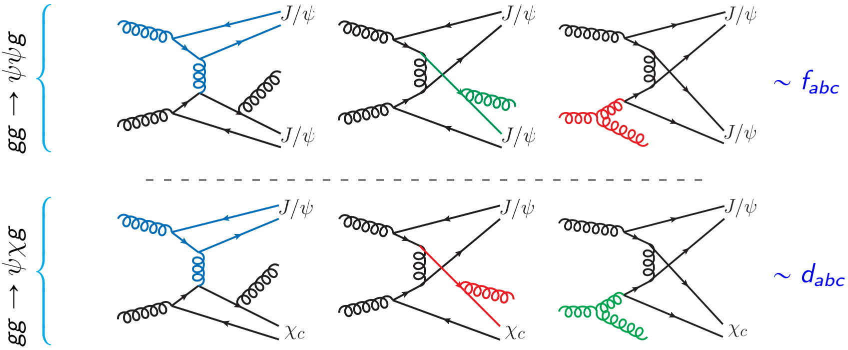
zero due to C-parity

Only d_{abc} is left

$\psi\psi$ vs $\psi\chi$ @ NLO*

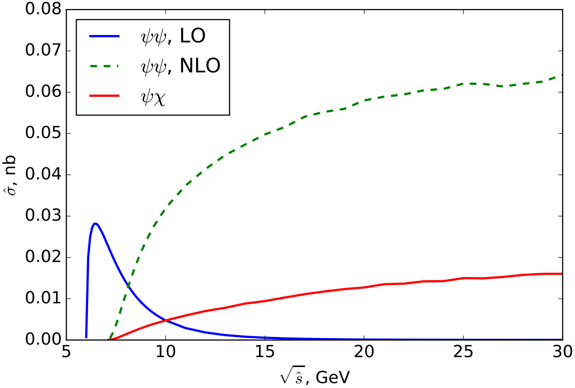


We can:

- change overall color structure
- switch on/off different types of diagrams

by changing final state

Partonic Reaction Distributions



- No fall with the energy increase
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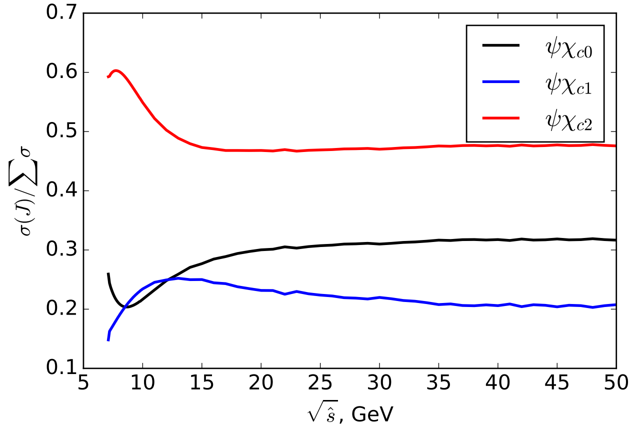

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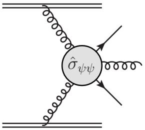
Hadronic Cross sections



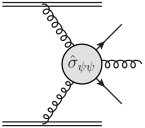
SPS

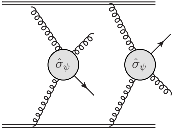
$$\sigma = f_1 \otimes f_2 \otimes \hat{\sigma}$$

CT10, CT14 pdf sets were used

$$\mu = m_T/2 \ldots 2m_T$$

Hadronic Cross sections





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DPS

$$\sigma = \sigma_{\psi}^2 / 2\sigma_{eff}$$

$$\sigma_{\psi} = 15.3 \pm 1\,\mu\mathrm{b}$$

$$\sigma_{eff} = 18 \pm 1.8\,\mathrm{mb}$$

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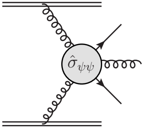

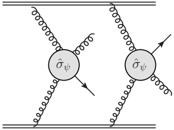

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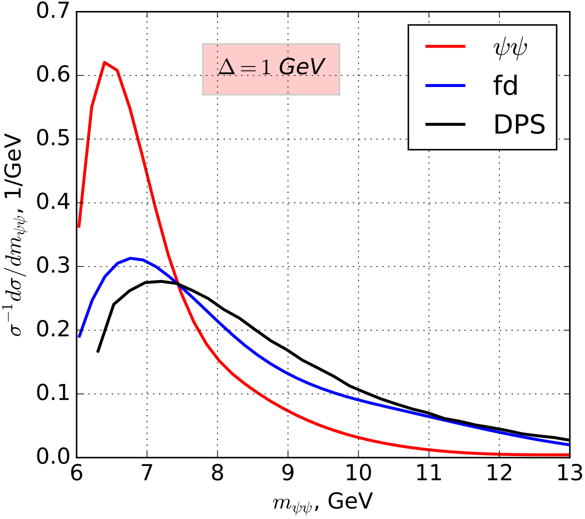
Cross sections @LHCb ($\sqrt{s} = 13$ TeV, $2 < y < 4.5$)

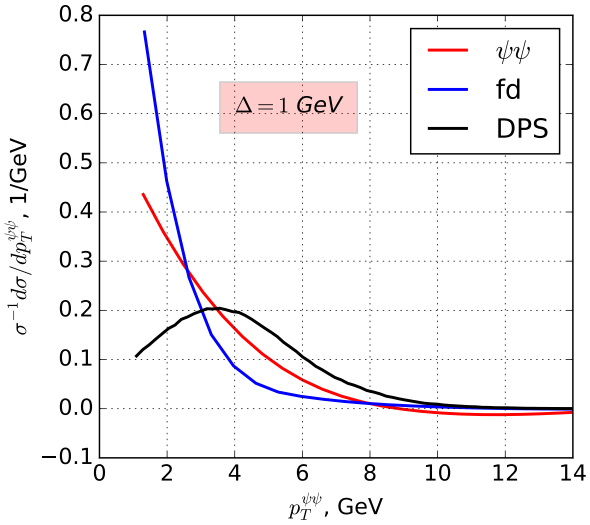
Δ, GeV	σ_{LO}, nb	σ_{NLO*}, nb	σ_{fd}, nb	σ_{DPS}, nb	σ_{total}, nb
1	1.3 ± 0.1	5.69 ± 1.1	0.22 ± 0.03	6.5 ± 1	13.7 ± 2
3		2.99 ± 0.36	0.05 ± 0.01		10.8 ± 1

$m_{\psi\psi}$

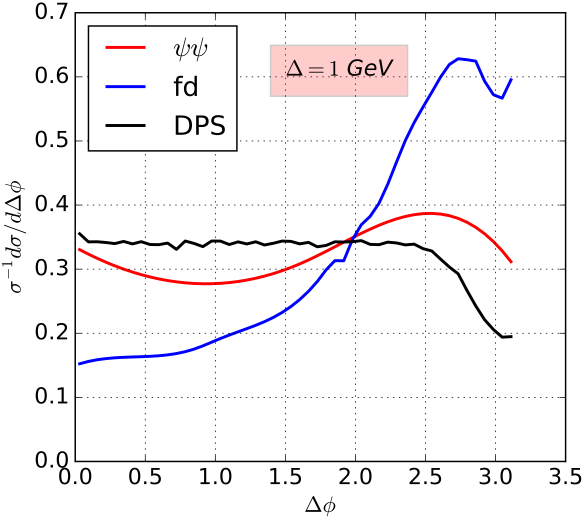


$\Delta = 1$ GeV
$\psi\psi$
fd
DPS
$\sigma^{-1} d\sigma/dm_{\psi\psi}$, 1/GeV
$m_{\psi\psi}$, GeV
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
6
7
8
9
10
11
12
13

$p_T^{\psi\psi}$

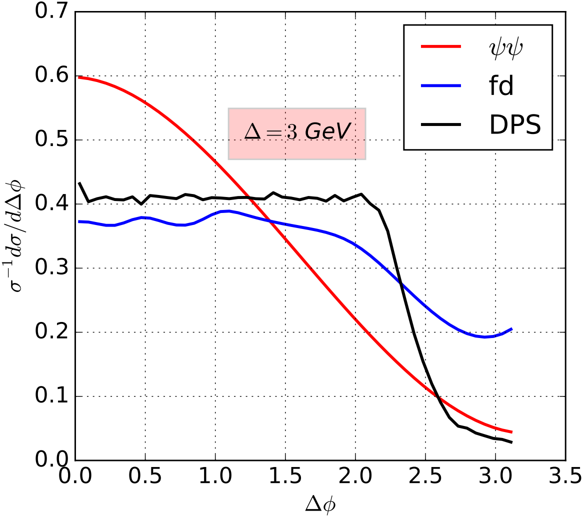

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
0
2
4
6
8
10
12
14
$\sigma^{-1} d\sigma/dp_T^{\psi\psi}$, 1/GeV
$p_T^{\psi\psi}$, GeV
$\Delta = 1$ GeV
$\psi\psi$
fd
DPS

$\Delta\phi$



$\psi\psi$
fd
DPS
$\Delta = 1$ GeV
$\sigma^{-1} d\sigma / d\Delta\phi$
$\Delta\phi$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

$\Delta\phi$


$\psi\psi$
fd
DPS
$\Delta = 3$ GeV
$\sigma^{-1} d\sigma/d\Delta\phi$
$\Delta\phi$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.5
1.0
1.5
2.0
2.5
3.0
3.5

Correlations

To quantatize the form difference some correlator is needed

$$A_{ij}^{a} = 1 - \left| \left\langle \frac{d\sigma_i}{da}, \frac{d\sigma_j}{da} \right\rangle \right|$$

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$a/(i,j)$	$(\psi\psi,\text{fd})$	$(\psi\psi,\text{DPS})$	(fd,DPS)
$m_{\psi\psi}$	0.10	0.27	0.05
$p_T^{\psi\psi}$	0.02	0.25	0.39
$\Delta\phi$	0.26	0.87	0.33
Δy	0.10	0.09	0.01
$y_{\psi\psi}$	0.17	0.09	0.02
A_T	0.01	0.01	0.01
p_T^{ψ}	0.00	0.04	0.05
y_{ψ}	0.54	0.45	0.20

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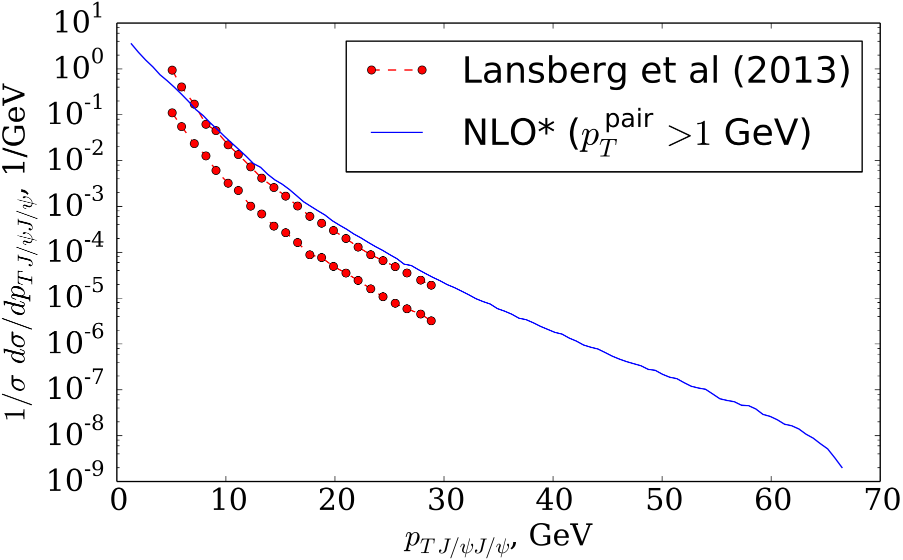
A_T	0.01	0.01	0.01
p_T^{ψ}	0.00	0.04	0.05
y_ψ	0.54	0.45	0.20

Conclusions

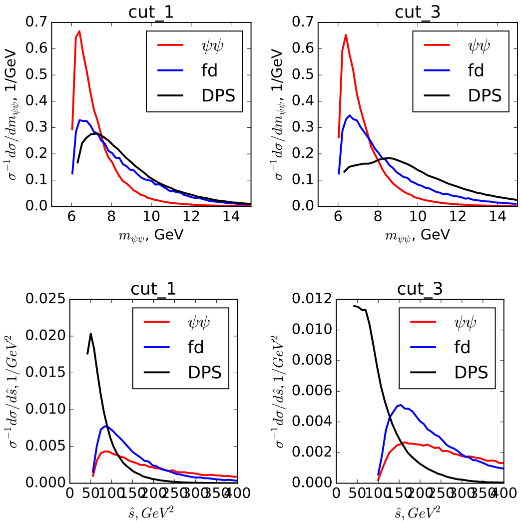
- NLO(*) is required for satisfactory description of SPS processes of paired onia production
- NLO gives comparable or even greater cross section than LO
- Production mechanisms are essentially different for different final states of $c\bar{c}$ pairs
  - by selecting different final states, we thereby switch between different sets of underlying Feynman diagrams
- The most interesting and non trivial signature of different production mechanisms is *azimuthal asymmetry*:
  - perfect for discrimination between SPS ans DPS
- We also have performed same calculations for polarizations in $J/\psi\chi_c$, $J/\psi + \eta_c$ final state

See soon on arXiv!

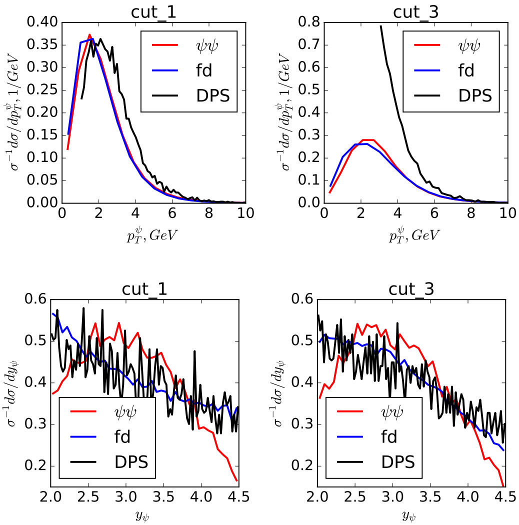
Backup slides


Lansberg et al (2013)
NLO* (p_T^{pair} >1 GeV)
$1/\sigma\ d\sigma/dp_{T\,J/\psi J/\psi}$, 1/GeV
$p_{T\,J/\psi J/\psi}$, GeV
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0
10
20
30
40
50
60
70

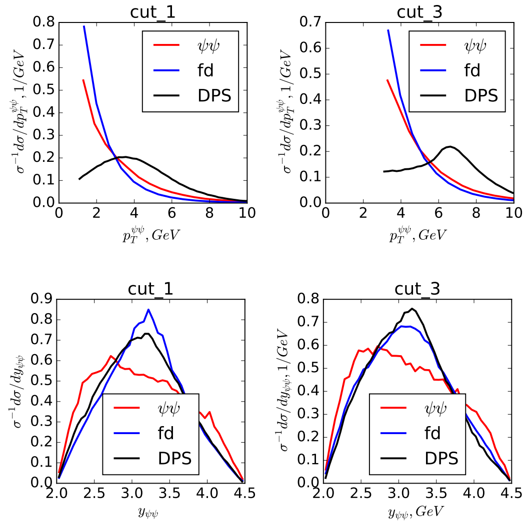
$m_{\psi\psi}$, $\hat{s}$



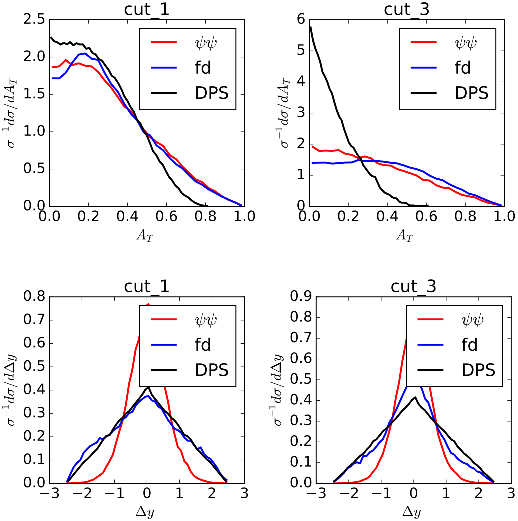
p_T^ψ, y_ψ


cut_1
cut_3
$\psi\psi$
fd
DPS
$\sigma^{-1}d\sigma/dp_T^\psi, 1/GeV$
p_T^ψ, GeV
$\sigma^{-1}d\sigma/dy_\psi$
y_ψ

$p_T^{\psi\psi}$, $y_{\psi\psi}$



A_T, Δyi


cut_1
cut_3
$\sigma^{-1} d\sigma/dA_T$
A_T
$\psi\psi$
fd
DPS
$\sigma^{-1} d\sigma/d\Delta y$
Δy