INTERNATIONAL WORKSHOP ON HIGH ENERGY CIRCULAR ELECTRON POSITRON COLLIDER

November 6-8, 2017
IHEP, Beijing

Heavy Quarkonium Physics at CEPC

- ✧ QCD – Final frontier of the SM physics
- ✧ Heavy quarkonium production in QCD
- ✧ Heavy quarkonium at CEPC – go beyond the SM
- ✧ Summary and outlook

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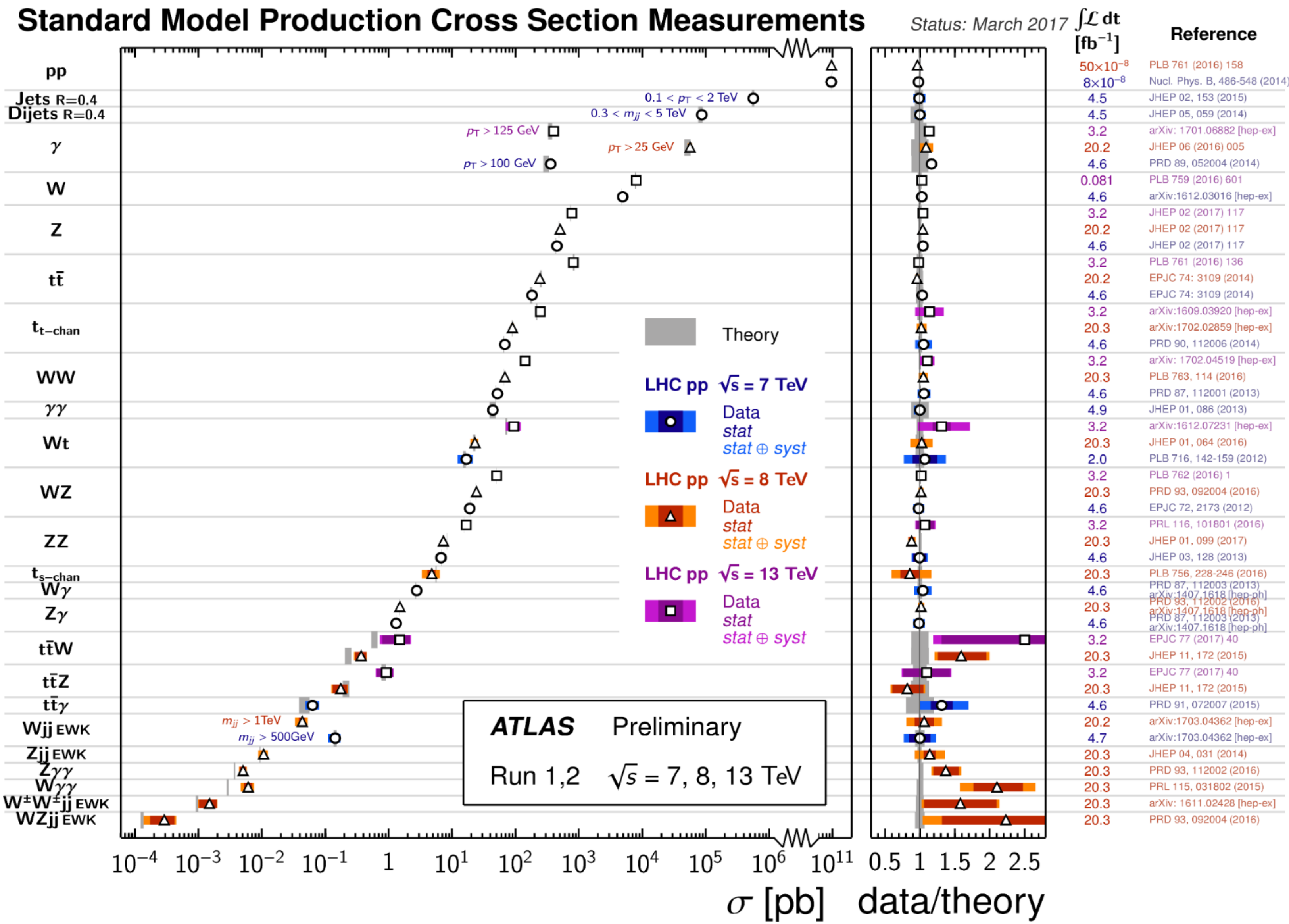
Theory Center, Jefferson Lab

Theory Center

Jefferson Lab
EXPLORING THE NATURE OF MATTER

The great success of the SM physics



SM: Electroweak processes + QCD perturbation theory works!

QCD – Final frontier of the SM physics

- How QCD works to get all of us – the visible world?

QCD – Final frontier of the SM physics

- ❑ How QCD works to get all of us – the visible world?

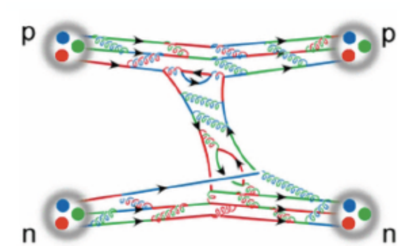
- ❑ How hadrons are emerged from quarks and gluons?

- ❑ What is the quark/gluon structure of nucleon and nuclei?

- ❑ How does QCD make up the properties of hadrons?

  Their mass, spin, magnetic moment, …

- ❑ How does the nuclear force arise from QCD?



- ❑ …

Why QCD is so hard to deal with?

- It is strongly coupled – nonlinear + nonperturbative!
- It is relativistic – nontrivial QCD vacuum, no still picture!
- No localized mass/charge center – unlike nucleus in an atom!
- Gluons are "dark" and carry "color" – intellectual challenge!

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Heavy quarkonium:

- ✧ Heavy quark as relatively localized heavy mass/charge center
- ✧ Heavy quark in the pair's rest frame is almost non-relativistic
- ✧ Production of heavy quark pair could be perturbative
- ✧ Top decays too quickly, strange is too light, …

➡ Charmonium ($c\bar{c}$) + Bottomonium ($b\bar{b}$)

c	$1.0 - 1.4$ GeV
b	$4.0 - 4.5$ GeV

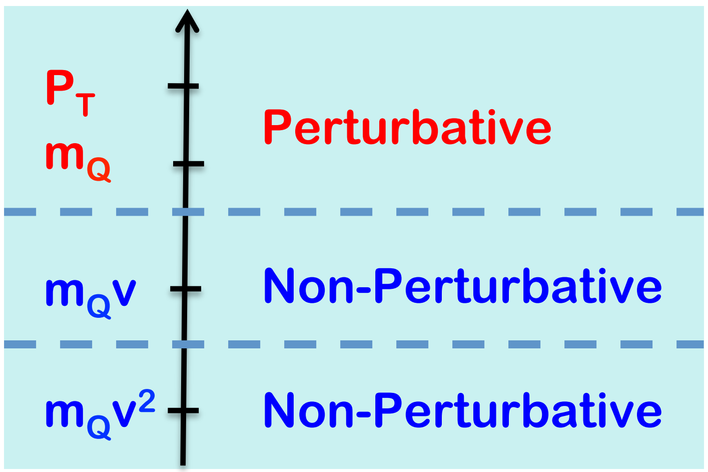
Heavy quarkonium

- **One of the simplest QCD bound states:**

  Localized color charges (heavy mass), non-relativistic relative motion

  Charmonium: $v^2 \approx 0.3$ Bottomonium: $v^2 \approx 0.1$

- **Well-separated momentum scales – effective theory:**



Hard — Production of $Q\bar{Q}$ [pQCD]

Soft — Relative Momentum [NRQCD]

Λ_{QCD}

Ultrasoft — Binding Energy [pNRQCD]

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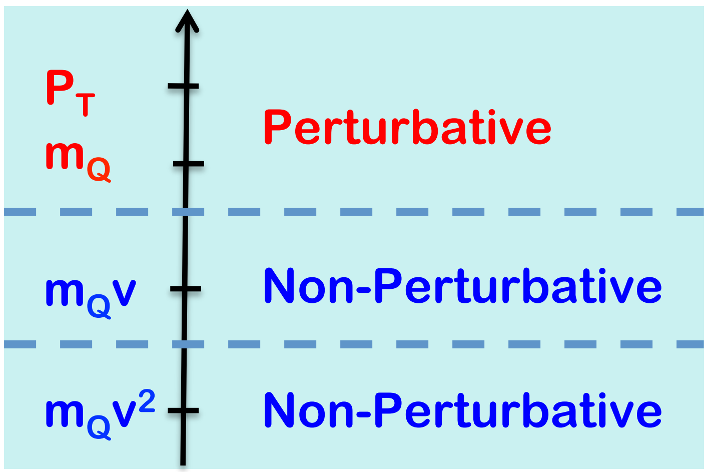

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Soft — Relative Momentum [NRQCD]

$\Lambda_{\rm QCD}$

Ultrasoft — Binding Energy [pNRQCD]

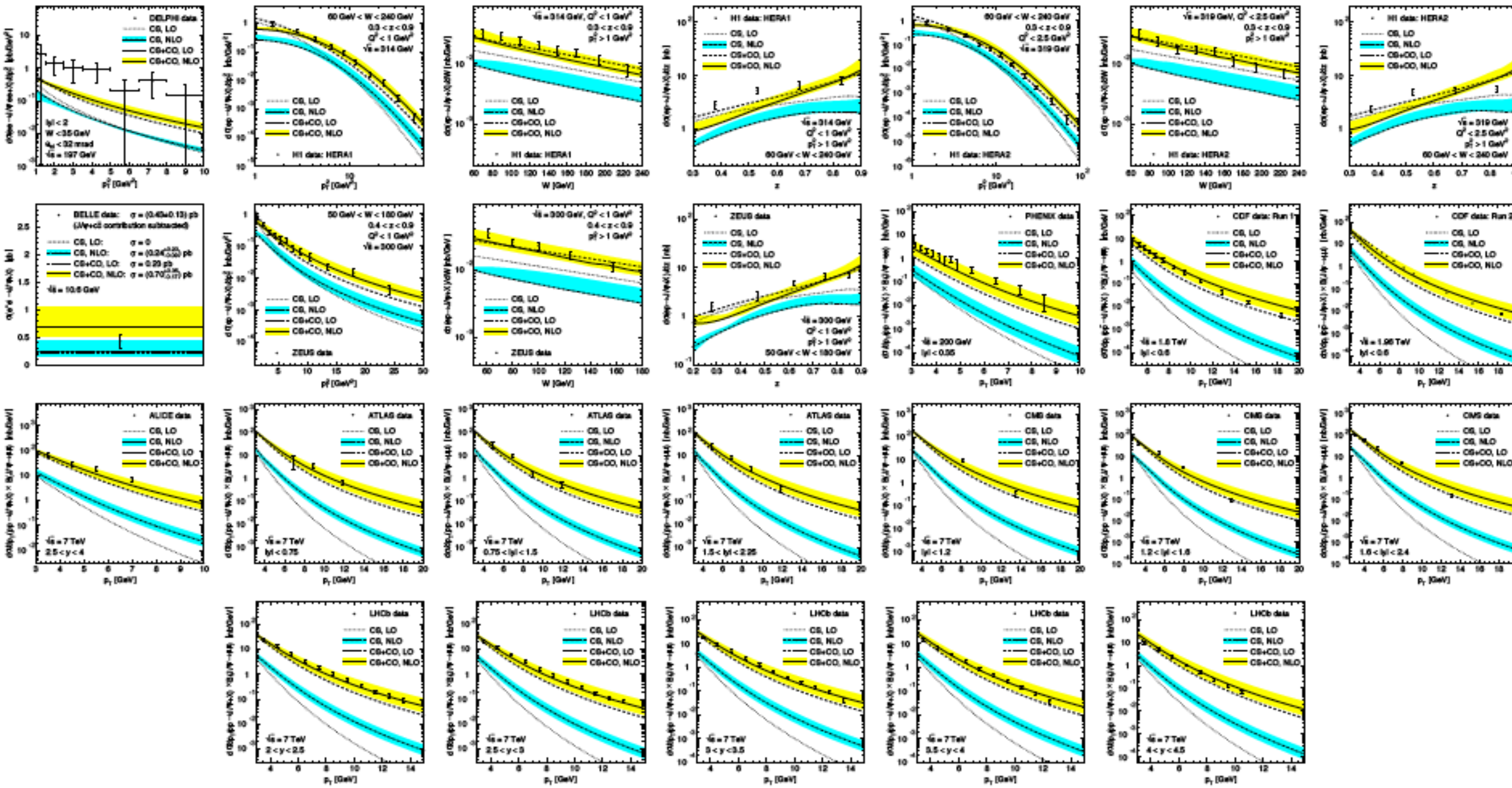
- **Cross sections and observed mass scales:**

$$\frac{d\sigma_{AB\to H(P)X}}{dy\,dP_T^2} \qquad \sqrt{S}, \qquad P_T, \qquad M_H,$$

PQCD is "expected" to work for the production of heavy quarks

Ideal probe: Emergence of a quarkonium from a heavy quark pair?

NRQCD – global analysis



194 data points from 10 experiments, fix singlet $\langle O[^3S_1^{[1]}]\rangle = 1.32\ \text{GeV}^3$

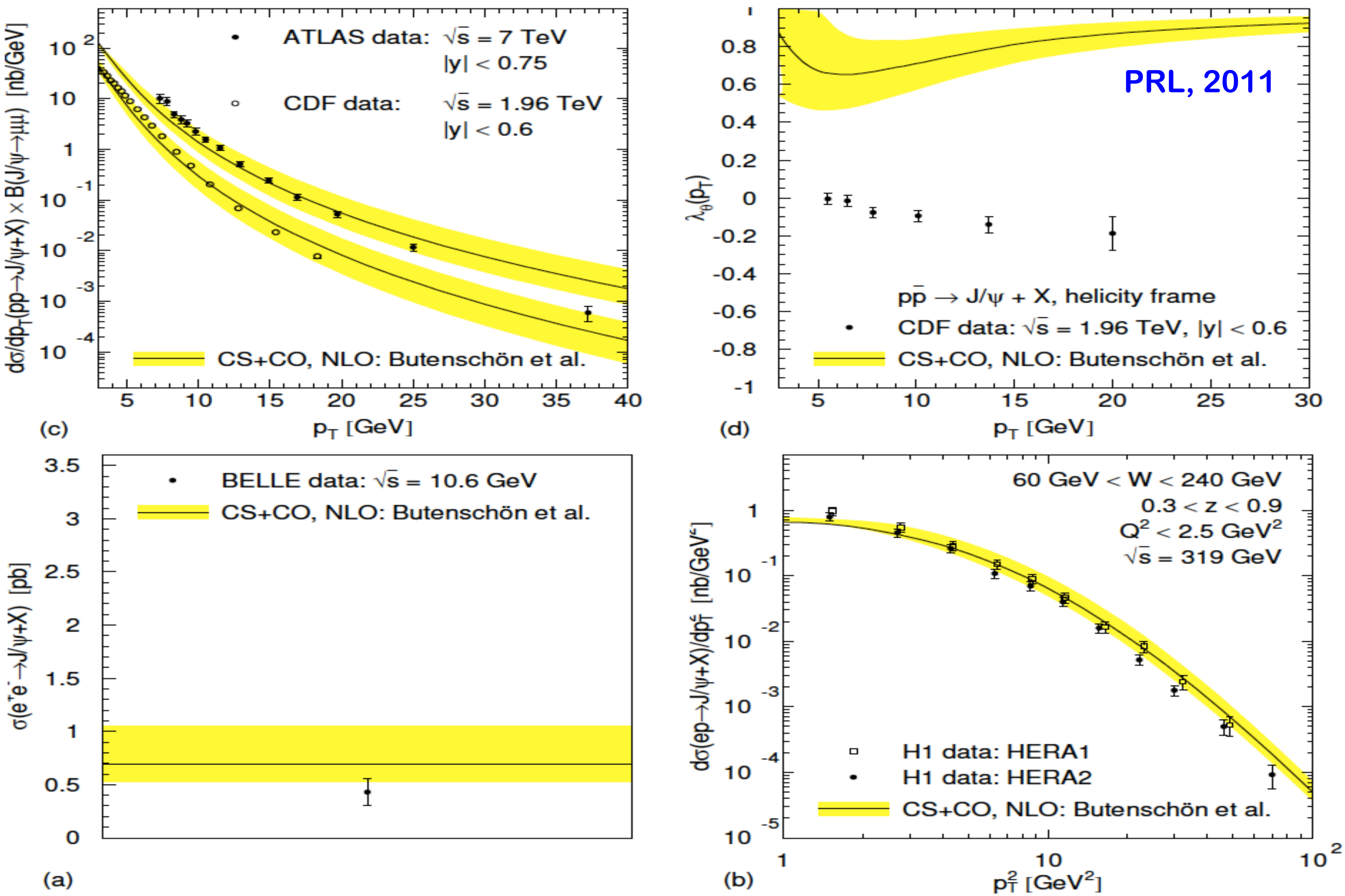
→ $\langle O[^1S_0^{[8]}]\rangle = (4.97 \pm 0.44)\cdot 10^{-2}\ \text{GeV}^3$ $\langle O[^3S_1^{[8]}]\rangle = (2.24 \pm 0.59)\cdot 10^{-3}\ \text{GeV}^3$

$\langle O[^3P_0^{[8]}]\rangle = (-1.61 \pm 0.20)\cdot 10^{-2}\ \text{GeV}^5$

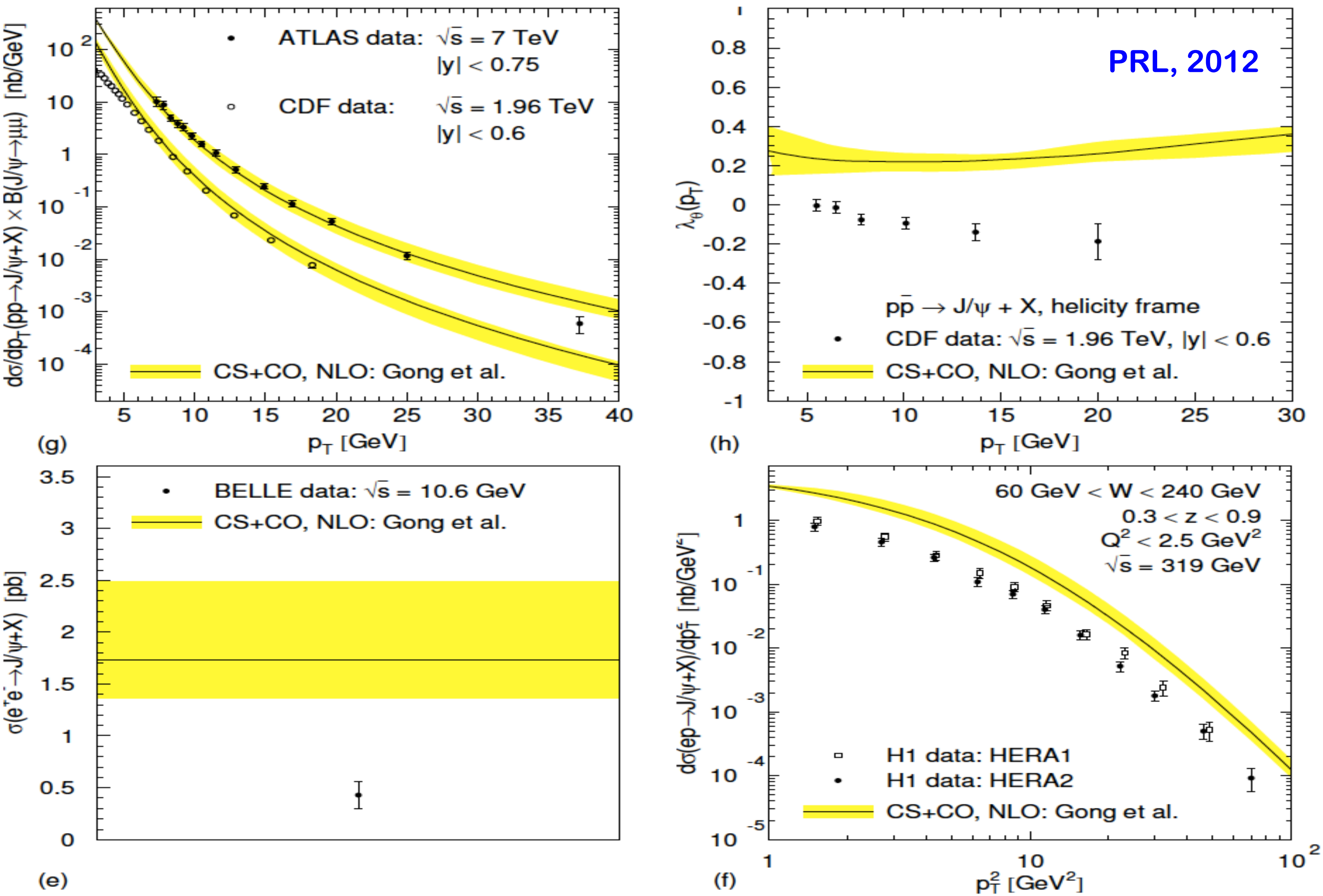
$\chi^2/d.o.f. = 857/194 = 4.42$

Butenschoen and Kniehl, arXiv: 1105.0820

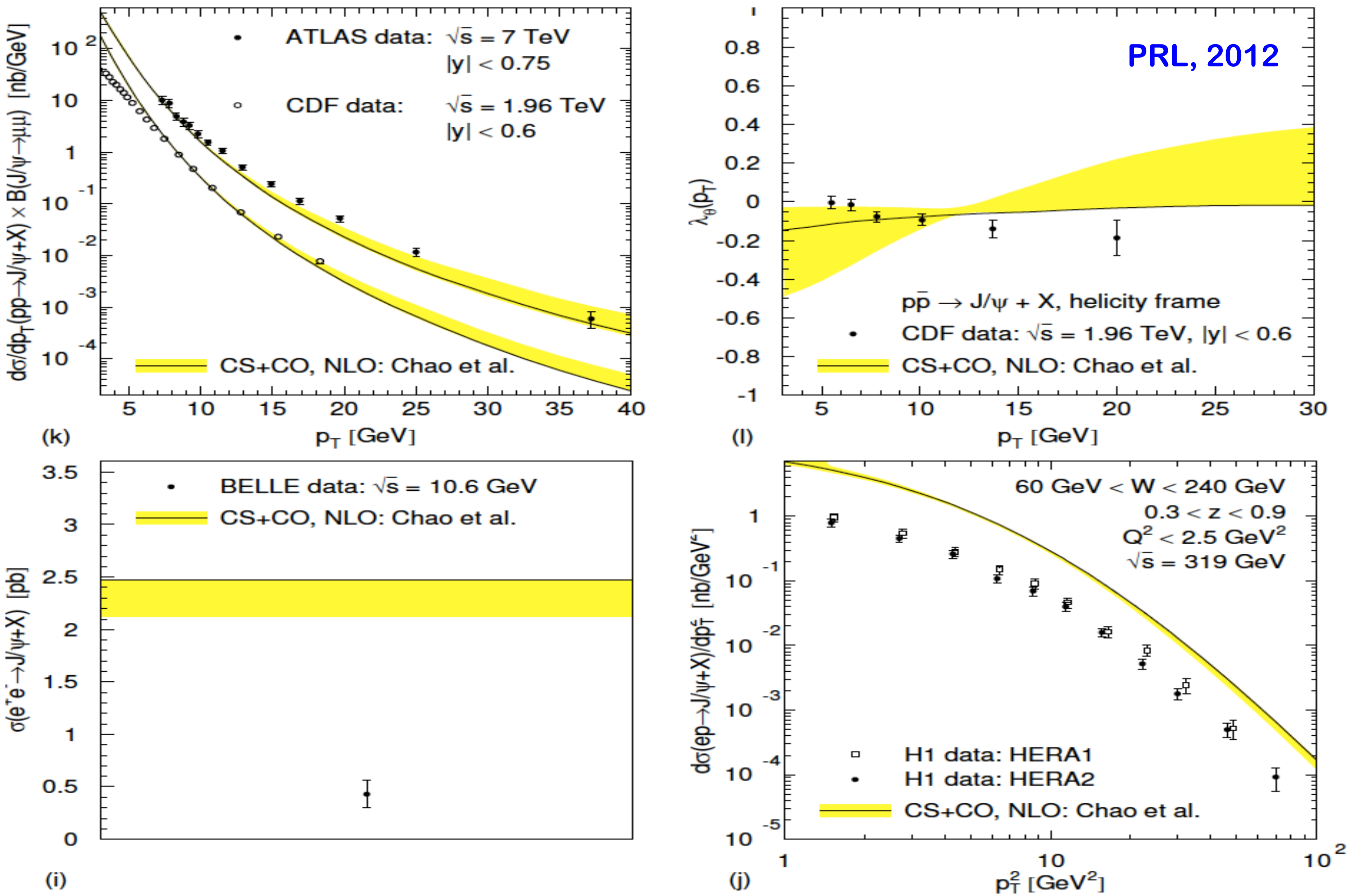
NLO theory fits – Butenschoen et al.



NLO theory fits – Gong et al.



NLO theory fits – Chao et al.

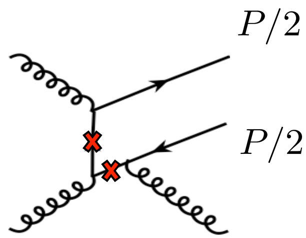


Why high order corrections are so large?

Kang, Qiu and Sterman, 2011

- **LO in α_s but higher power in $1/p_T$:**

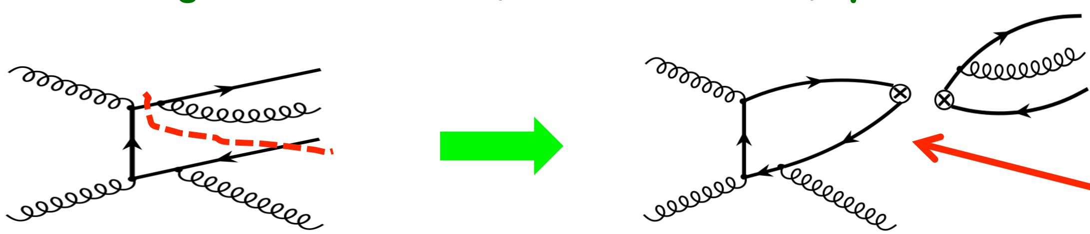
LO in α_s:



$$\hat{\sigma}^{\rm LO} \propto \frac{\alpha_s^3(p_T)}{p_T^8}$$

CSM and NRQCD
spin-1 projection
NNLP in $1/p_T$!

- **NLO in α_s but lower power in $1/p_T$:**

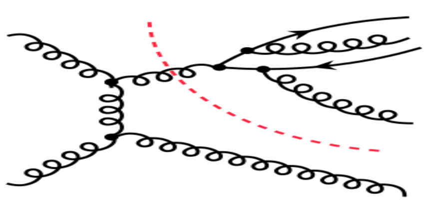


Relativistic projection to all "spin states"

$$\hat{\sigma}^{\rm NLO} \rightarrow \frac{\alpha_s^3(p_T)}{p_T^6} \otimes \alpha_s(\mu)\log(\mu^2/\mu_0^2)$$

$$\mu_0 \gtrsim 2m_Q$$

- **NNLO in α_s but leading power in $1/p_T$:**



$$\hat{\sigma}^{\rm NNLP} \rightarrow \frac{\alpha_s^2(p_T)}{p_T^4} \otimes \alpha_s^3(\mu)\log^m(\mu^2/\mu_0^2)$$

Leading order in α_s-expansion =\= leading power in $1/p_T$-expansion!

New factorization formalism

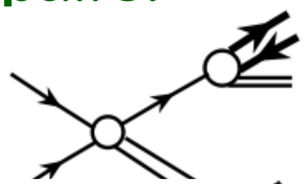
❑ Factorization formalism:

Kang, Qiu and Sterman, 2010

$$d\sigma_{A+B\to H+X}(p_T) = \sum_i d\hat{\sigma}_{A+B\to i+X}(p_T/z,\mu)\otimes D_{i\to H}(z,m_Q,\mu)$$
$$+\sum_{[Q\bar{Q}(\kappa)]} d\hat{\sigma}_{A+|B\to[Q\bar{Q}(\kappa)]+X}(P_{[Q\bar{Q}(\kappa)]}=p_T/z,\mu)\otimes D_{[Q\bar{Q}(\kappa)]\to H}(z,m_Q,\mu)$$
$$+\mathcal{O}(m_Q^4/p_T^4)$$

❑ Production of the pairs:

✧ at $1/m_Q$:



$D_{i\to H}(z,m_Q,\mu_0)$

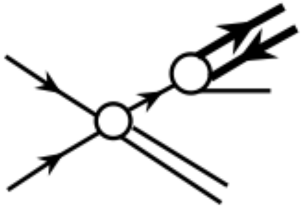
Transversely polarized pair

✧ at $1/P_T$:

$d\hat{\sigma}_{A+B\to[Q\bar{Q}(\kappa)]+X}(P_{[Q\bar{Q}]}(\kappa),\mu)$

Longitudinally polarized pair

✧ between: $[1/m_Q, 1/P_T]$



$$\frac{d}{d\ln(\mu)}D_{i\to H}(z,m_Q,\mu) = \ldots$$
$$+\frac{m_Q^2}{\mu^2}\Gamma(z)\otimes D_{[Q\bar{Q}(\kappa)\to H}(\{z_i\},m_Q,\mu)$$


Quarkonium 2017
The 12th International Workshop on Heavy Quarkonium
November 6-10, 2017,PKU, Beijing, China
Organized by the Quarkonium Working Group
http://itp.phy.pku.edu.cn/conference/qwg2017/

Electron-positron collider – CEPC

- **Ideal for studying the emergence of hadrons:**

$$e^+ + e^- \rightarrow \quad \text{“Energy”} \quad \rightarrow \text{Hadrons} + \text{Leptons}...$$

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- **Puzzles at low energy:**

$$\sigma(e^+e^- \to J/\psi c\bar{c})$$

Belle: $(0.87^{+0.21}_{-0.19} \pm 0.17)$ pb

NRQCD: 0.07 pb

Kiselev, et al 1994,
Cho, Leibovich, 1996
Yuan, Qiao, Chao, 1997

$$\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi X)$$

Belle: $0.59^{+0.15}_{-0.13} \pm 0.12$

"Production rate of $J/\psi\, c\bar{c}$ larger than all these $J/\psi\, gg,\ J/\psi\, q\bar{q}, \ldots$ channels combined!?"

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- **At higher energy – CEPC:**

$$e^+ + e^- \rightarrow \text{"Energy"} \rightarrow \text{Jets}(J/\psi, \ldots) + \ldots$$

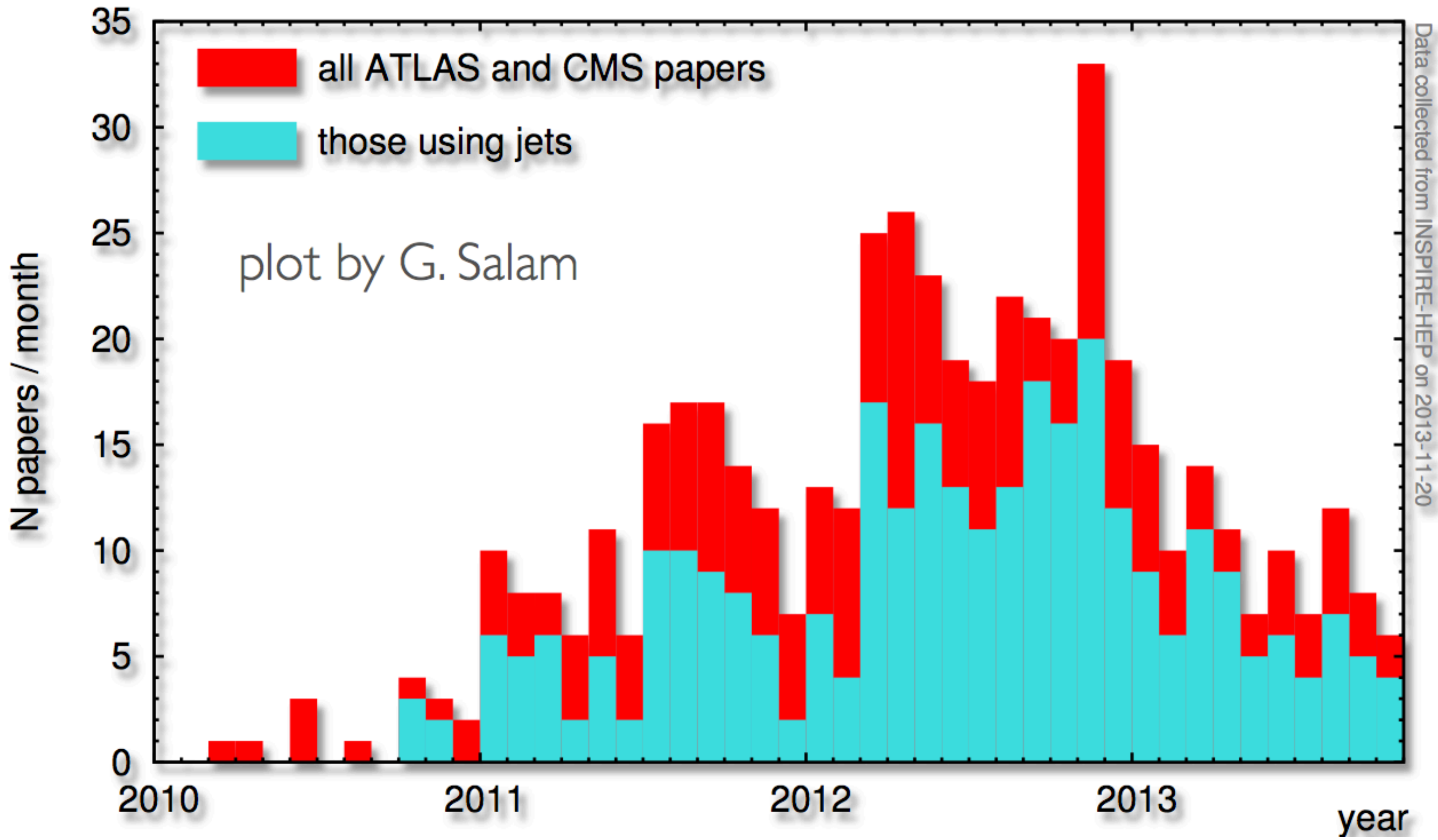
Complementary or better way to test QCD and the SM

$$e^+ + e^- \rightarrow \text{"Energy"} \rightarrow \text{H}^0(\rightarrow J/\psi(\Upsilon) + \gamma, \ldots) + \ldots$$

Potential for testing Higgs couplings, and beyond the SM

Jets are everywhere at the LHC

❑ 60–70% of ATLAS & CMS papers using jets in their analysis!



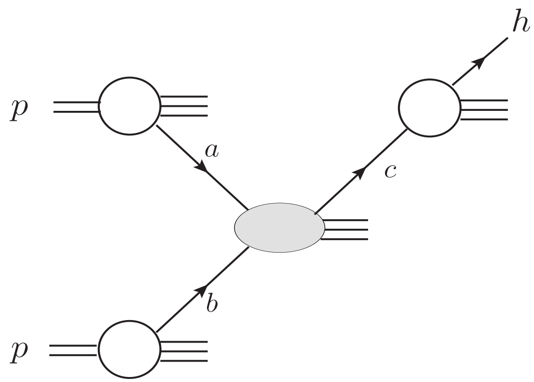
✧ Jets as a precision probe of QCD: precision α_s, g(x), …

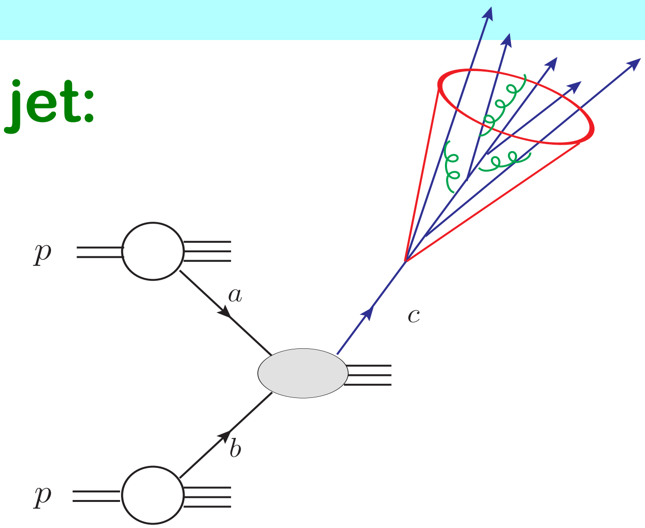
✧ Jets as a tool for BSM physics: jet correlation, jet sub-structure, …

✧ Jet sub-structure: longitudinal vs transverse, …

Jet & jet fragmentation function

❑ Hadron distribution inside a jet:

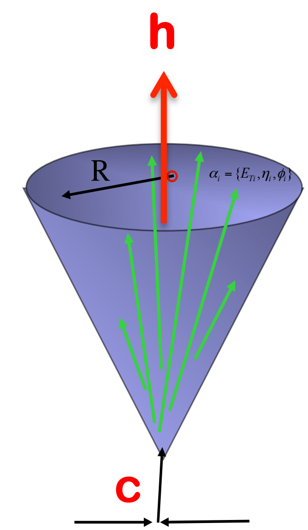




$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes D_c^h$$

$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes J_c(\mu \sim p_T R)$$

$$\frac{d\sigma^h}{dy dp_T dz_h} \propto \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c^h(z, z_h, R, \mu)$$



❑ Jet fragmentation:

$$F(z_h, p_T) = \frac{d\sigma^h}{dy dp_T dz_h} \Big/ \frac{d\sigma}{dy dp_T}$$

$$z_h = p_T^h / p_T$$

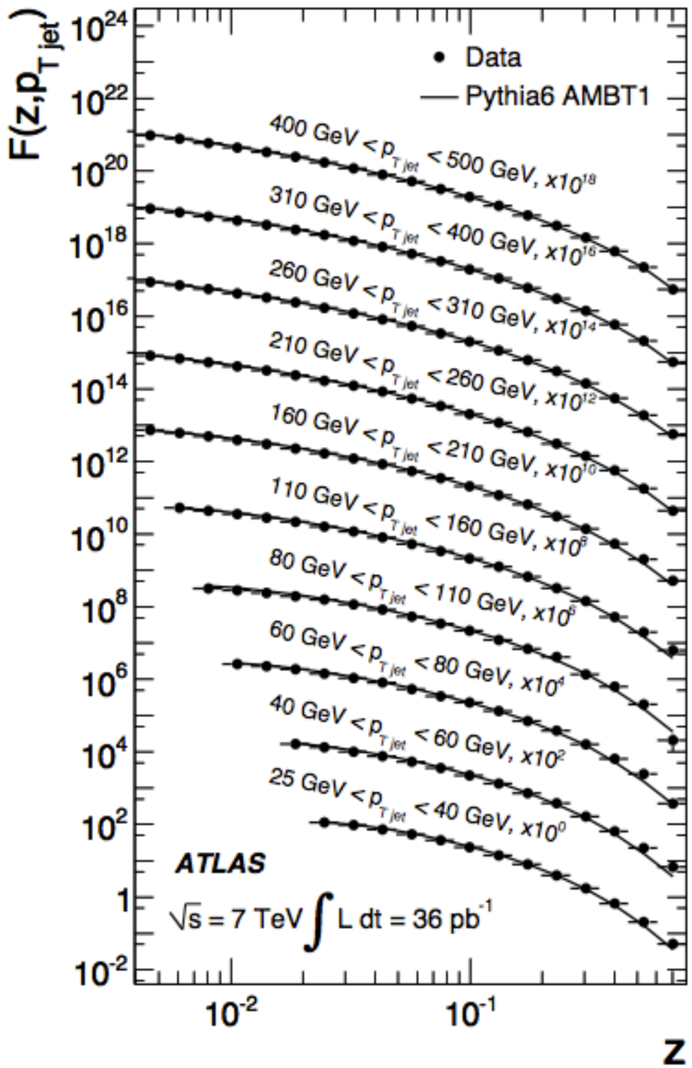
$$z = p_T / p_T^c$$

First produce a jet, and then look further for a hadron inside the jet!

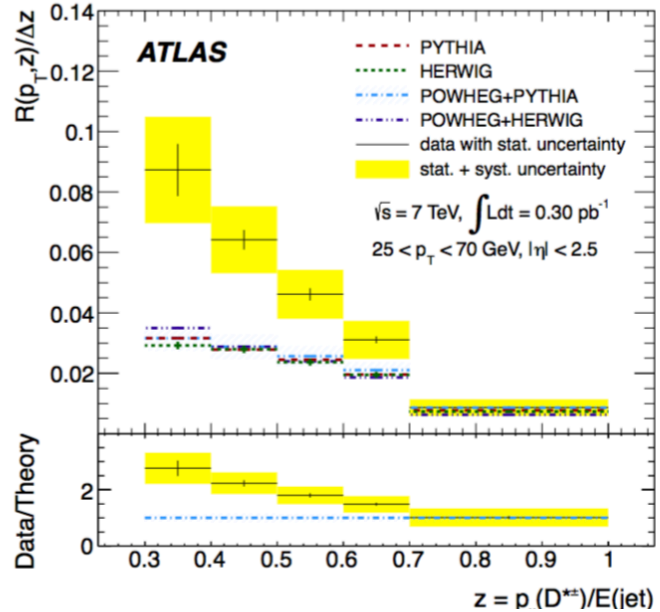
Kang, Ringer, Vitev, arXiv:1606.07063

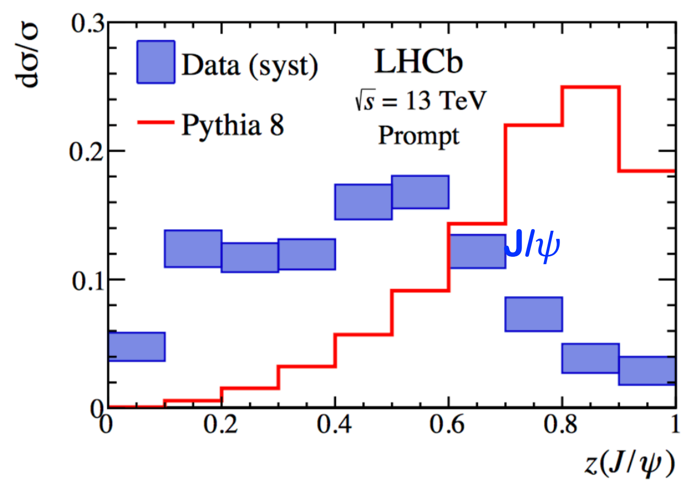
Lots of data at the LHC

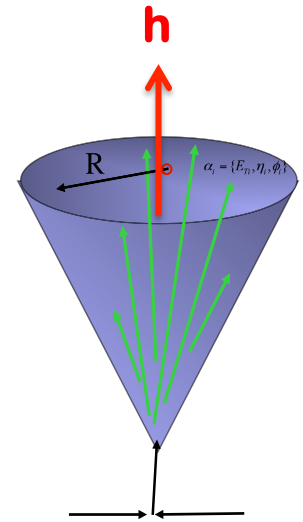
❑ Hadron distribution inside a jet – puzzle for heavy flavor?



Light charged hadrons



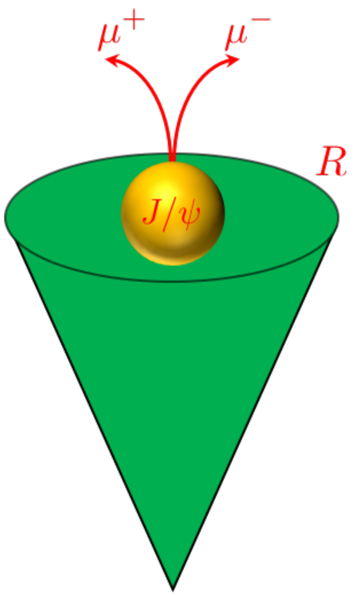


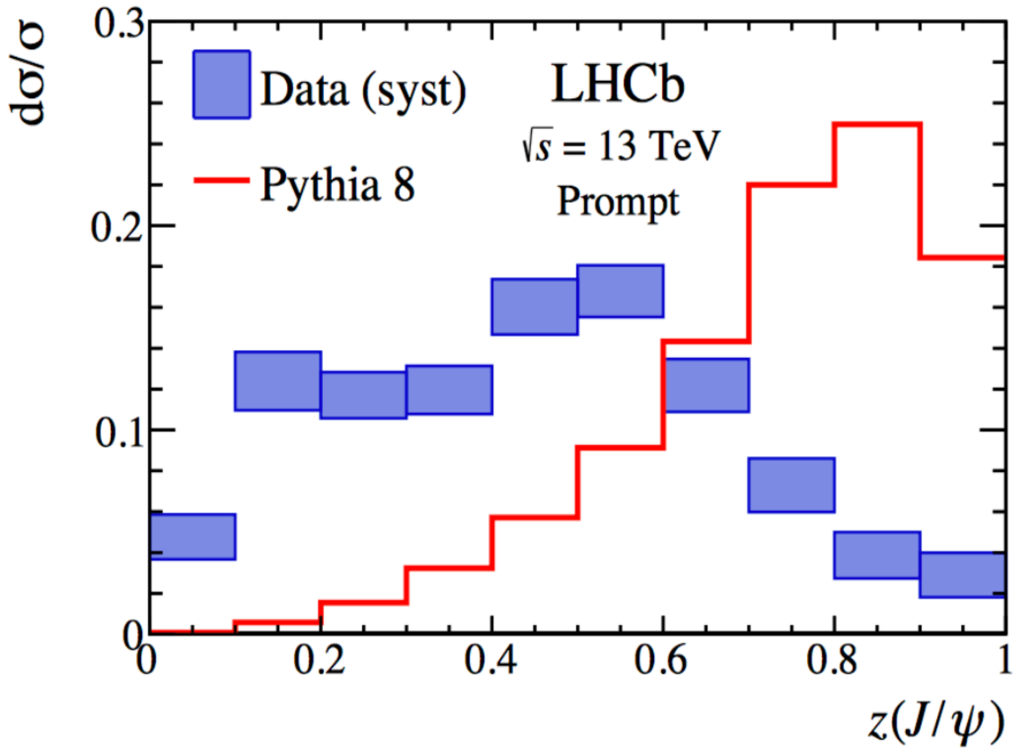


$$z_h = \frac{E_h}{E_{\rm jet}}$$

Quarkonium production inside a jet

❑ **J/ψ-in-jet measurement from LHCb:**





Production: Baumgart, et al., JHEP 14, Bain, et al., PRL17

Polarization: Kang, Ringer, Xing, et.al., PRL17

$$\frac{d\sigma^{J/\psi(\to\ell^+\ell^-)}}{d\cos\theta} \propto 1 + \lambda_F \cos^2\theta$$

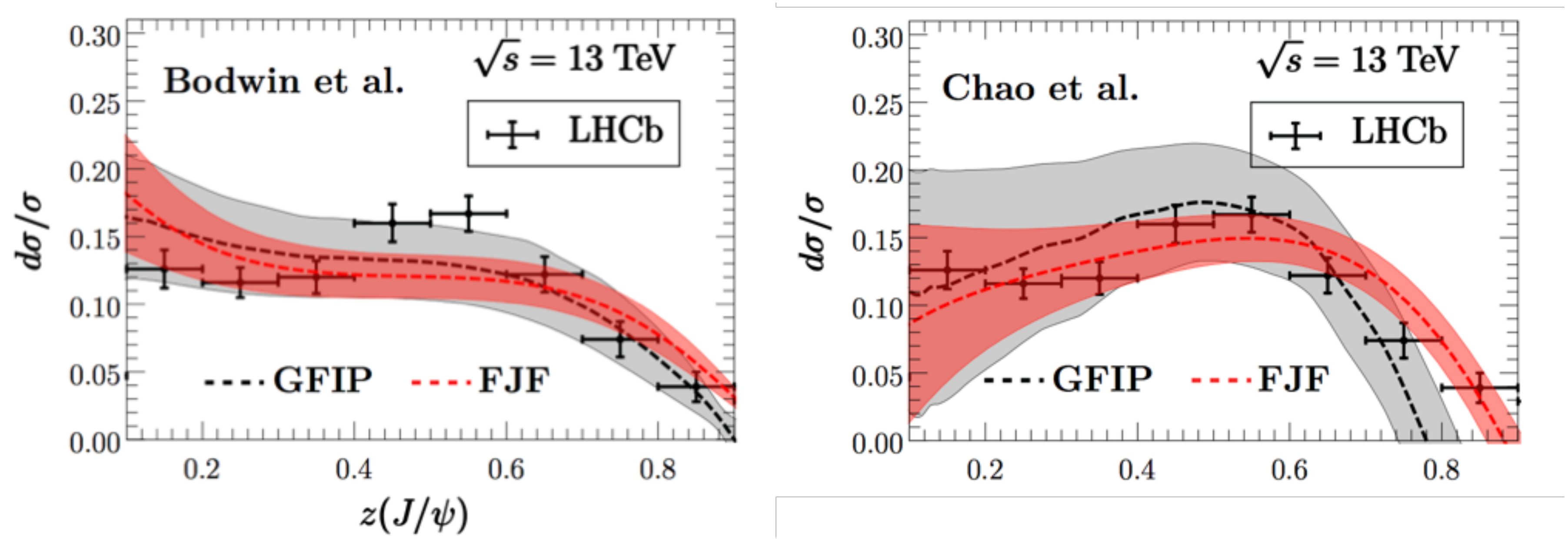
$$\lambda_F = \begin{cases} +1, & \text{transversely polarized} \\ -1, & \text{longitudinally polarized} \end{cases}$$

J/ψ production in jets

- Fitted NRQCD matrix elements:

Baumgart et al., JHEP14
Bain et al. PRL17

	$\langle \mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle$ $\times$ GeV^3	$\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$ $\times 10^{-2}$ GeV^3	$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$ $\times 10^{-2}$GeV^3	$\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle/m_c^2$ $\times 10^{-2}$GeV^3
B & K [5, 6]	1.32 ± 0.20	0.224 ± 0.59	4.97 ± 0.44	-0.72 ± 0.88
Chao, et al. [12]	1.16 ± 0.20	0.30 ± 0.12	8.9 ± 0.98	0.56 ± 0.21
Bodwin et al. [13]	1.32 ± 0.20	1.1 ± 1.0	9.9 ± 2.2	0.49 ± 0.44



FJFs: fragmentation jet functions
GFIP: gluon fragmentation improved PYTHIA

Two are consistent

J/ψ production in jets

Baumgart et al., JHEP14
Bain et al. PRL17

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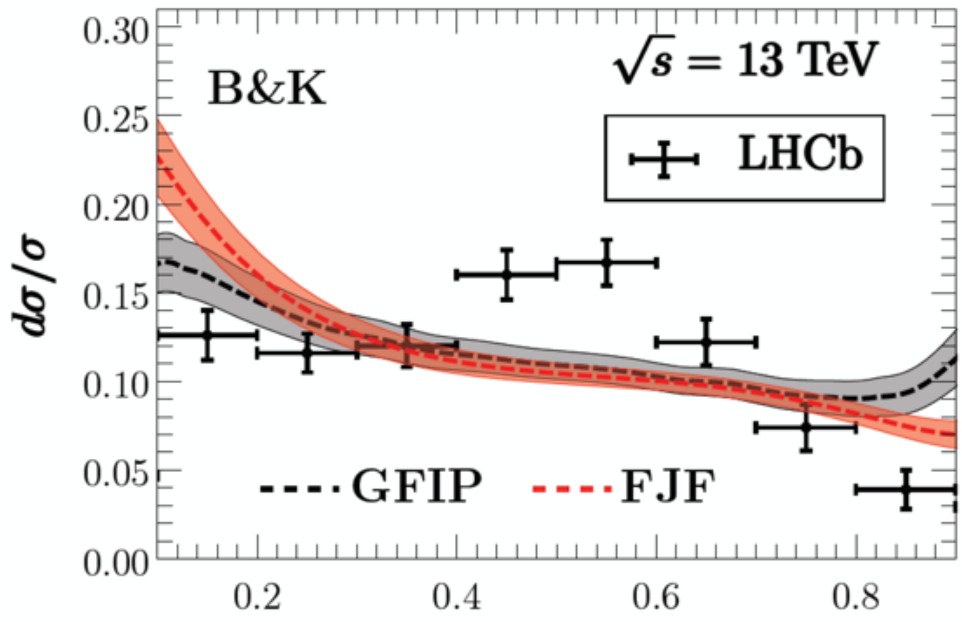


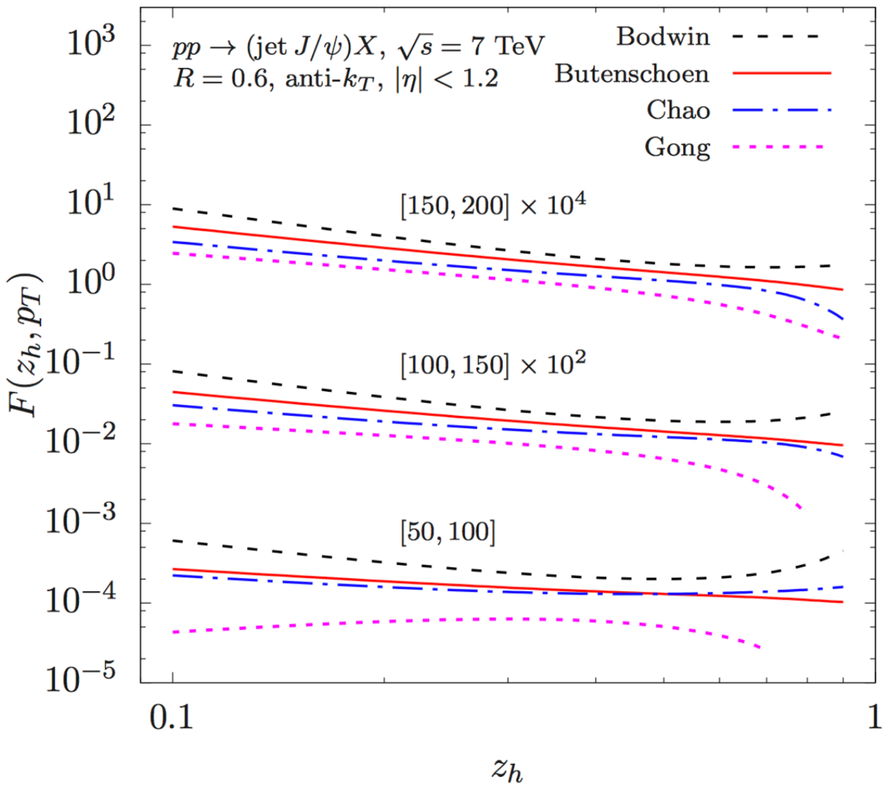
FJFs: fragmentation jet functions
GFIP: gluon fragmentation improved PYTHIA

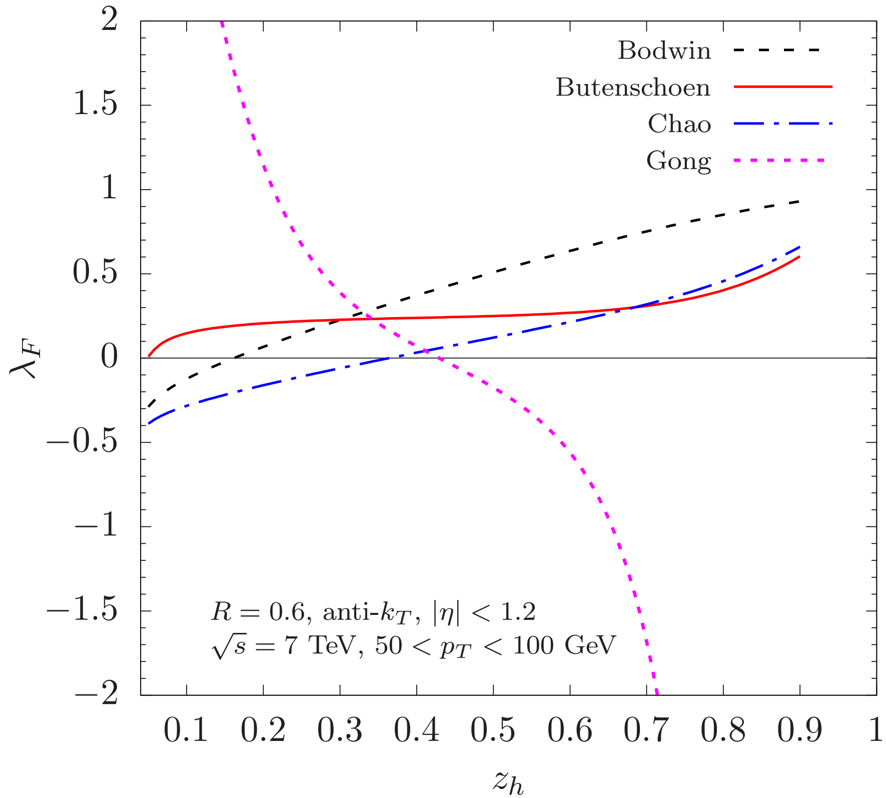
This fit has a poor agreement with jet data

J/ψ production and polarization in jets

- **Polarization is even more sensitive:**

Kang, Qiu, Ringer, Xing, Zhang, PRL 2017
See also Bain, et al, PRL 2017



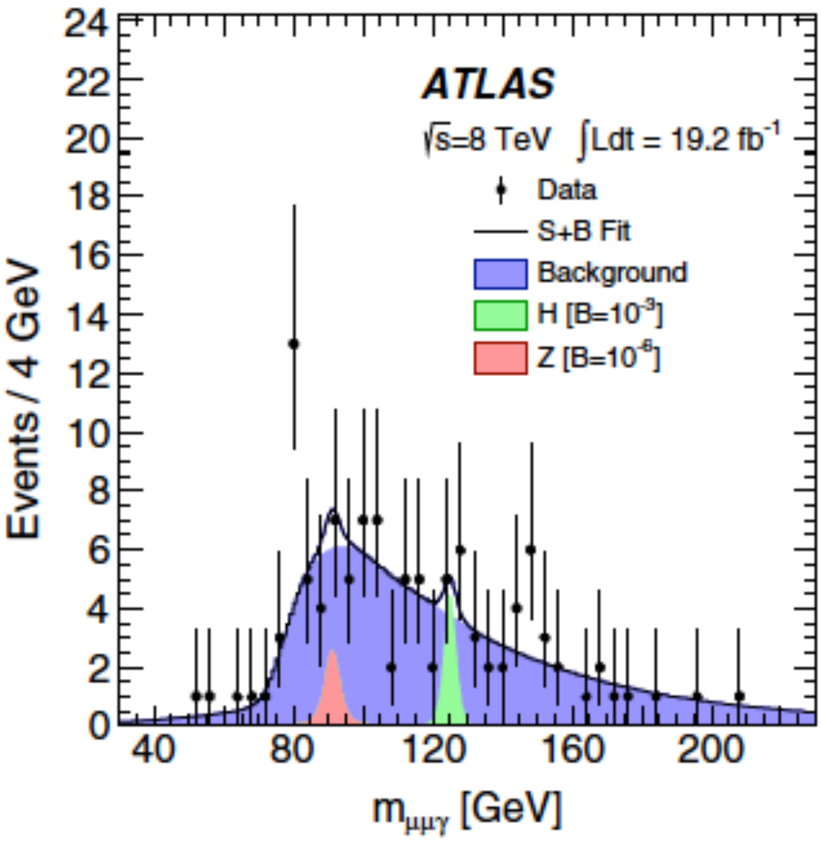


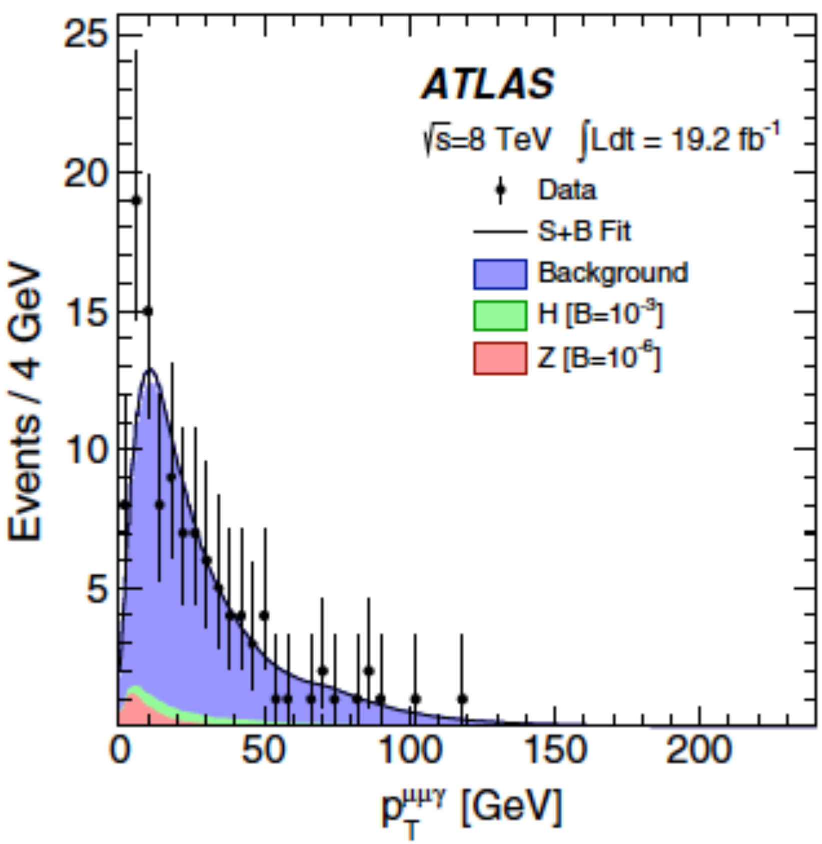
More differential than inclusive J/ψ p_T spectrum, and can better discriminate different NRQCD parameterizations

Higgs decays to quarkonium + γ at the LHC

G. Aad et al. PRL114, 121801 (2015)

- J/ψ + isolated γ :

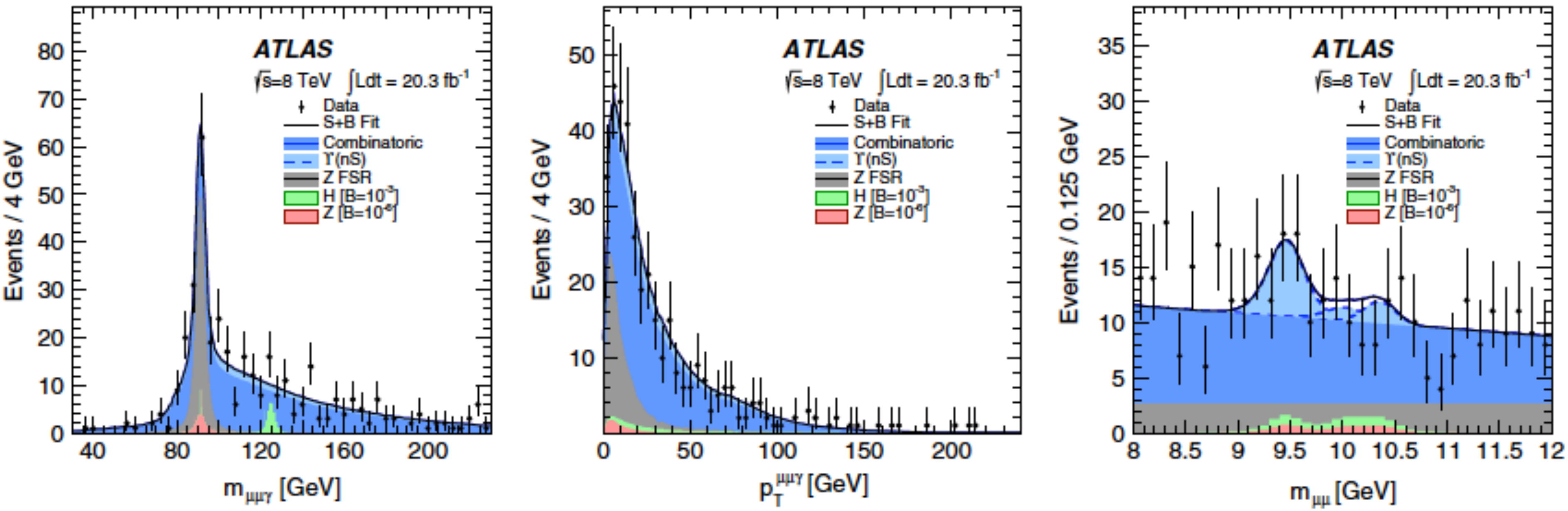


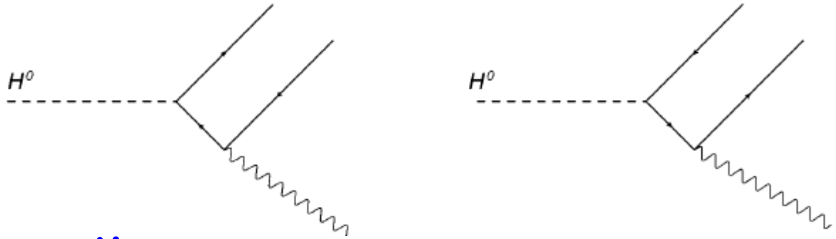


Higgs decays to quarkonium + γ at the LHC

G. Aad et al. PRL114, 121801 (2015)

- Υ(n)+ isolated γ :





- ✧ Branching ratio
- ✧ Flavor dependence of Higgs couplings
- ✧ NLO calculation for CEPC
- ✧ …

Summary and outlook

- It has been over 40 years since the discovery of J/Ψ
- When p_T (E) >> m_Q at collider energies, earlier model calculations for the production of heavy quarkonia are not perturbatively stable

  LO in α_s-expansion may not be the LP term in m_Q/p_T(E)-expansion

- QCD factorization works for both LP and NLP (α_s for each power)

  Sub-leading power is very important for the p_T-shape and polarization

  There are still a lot of unanswered questions related to quarkonium!

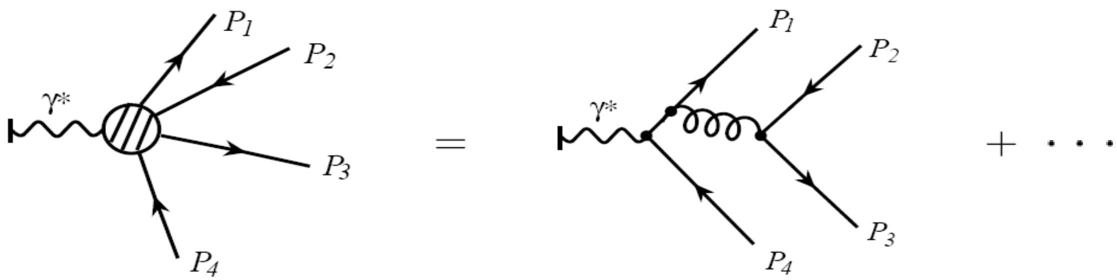
- Quarkonium production and polarization in the jet could be very good observables to help pin down the production mechanism
- CEPC provides a clean and good environment for studying the emergence of heavy quarkonia/hadrons, and the potential for testing the SM and exploring the BSM physics

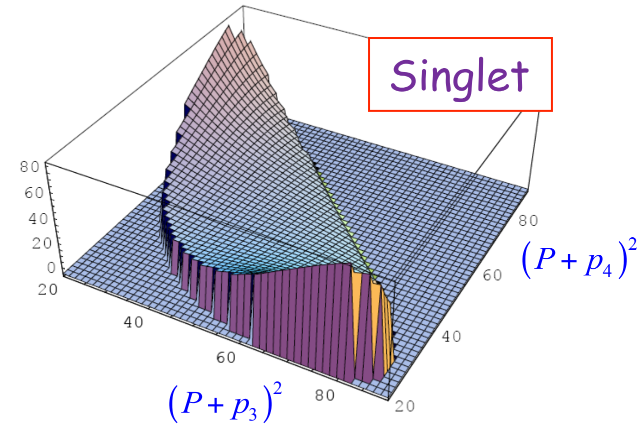
Thank you!

Backup slides

Associated production at B-factory

- Kinematically preferred configuration:

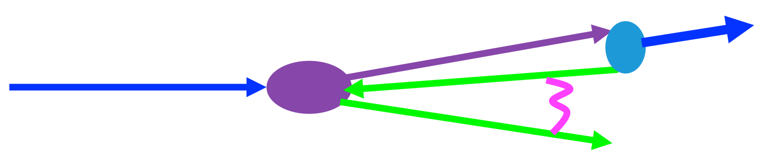




Production rate of a singlet charm quark pair is dominated by the phase space where $s_3=(P_1+P_2+P_3)^2$ or $s_4=(P_1+P_2+P_4)^2$ near its minimum

- NRQCD formalism does not apply when there are more than one heavy quark velocity involved

- Color transfer enhances associated heavy quarkonium production



A heavy quark as a color source to enhance the transition rate for an octet pair to become a singlet pair

Nayak, Qiu, Sterman, PRL 2007