



Strong Interactions and Hadrons - TH

Marek Karliner
Tel Aviv University

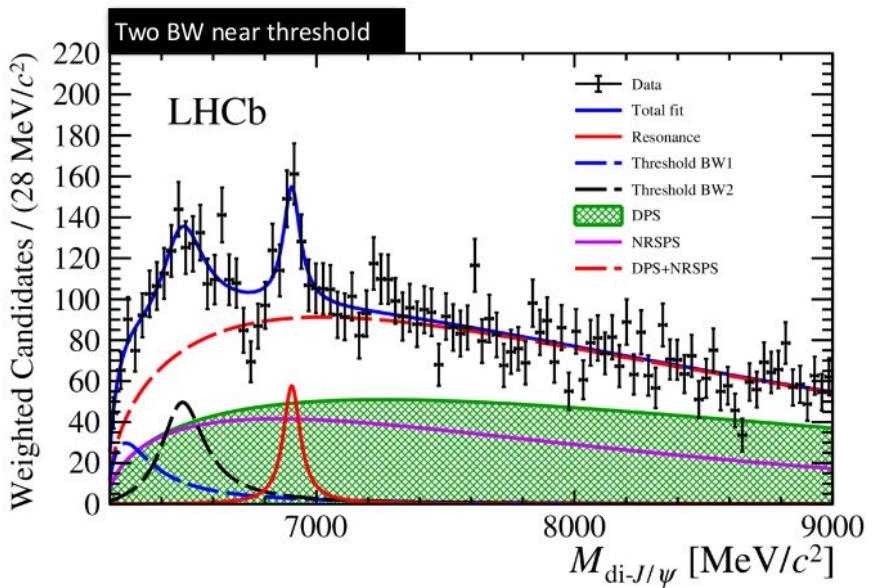
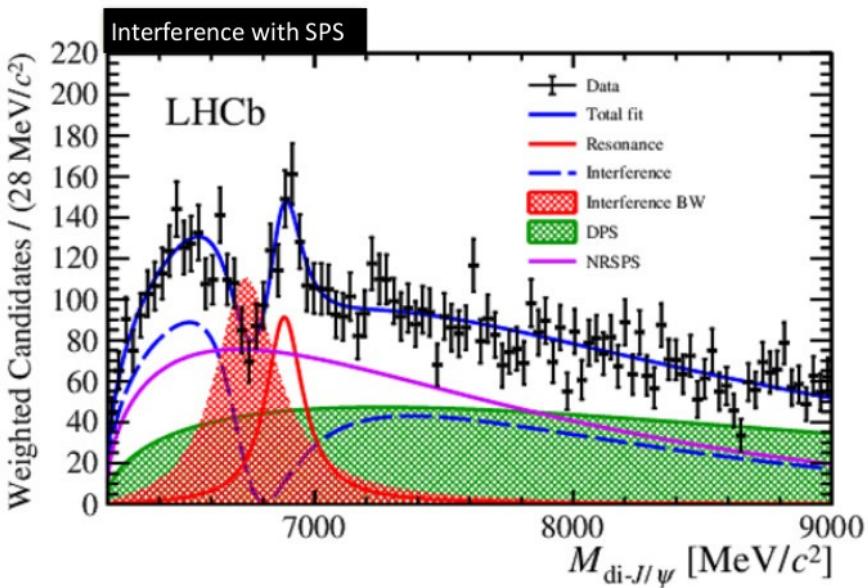
ICHEP2020, Prague & Cyberspace, Aug 4 2020

very recent news from LHCb:

- a narrow resonance decaying into two J/ψ -s
- quark content $cc\bar{c}\bar{c}$
- $M \approx 6.9$ GeV: $X(6900)$
- tetraquark-like
- ~ 700 MeV above $J/\psi J/\psi$ threshold
 \Rightarrow probably an excited $cc\bar{c}\bar{c}$ state
- first exotic containing both QQ and $\bar{Q}\bar{Q}$
- exciting challenge for EXP and TH

Interpretation

LHCb – talk by Daniel Johnson



- $T_{c\bar{c}c\bar{c}}$ state at 6.9 GeV/c^2 and either:
 - one more (interfering with NRSPS), or
 - two more, near threshold
- Feed-down may contribute; unlikely for narrow state
- Near-threshold rescattering could be important

Interpretation

- **No interference:**

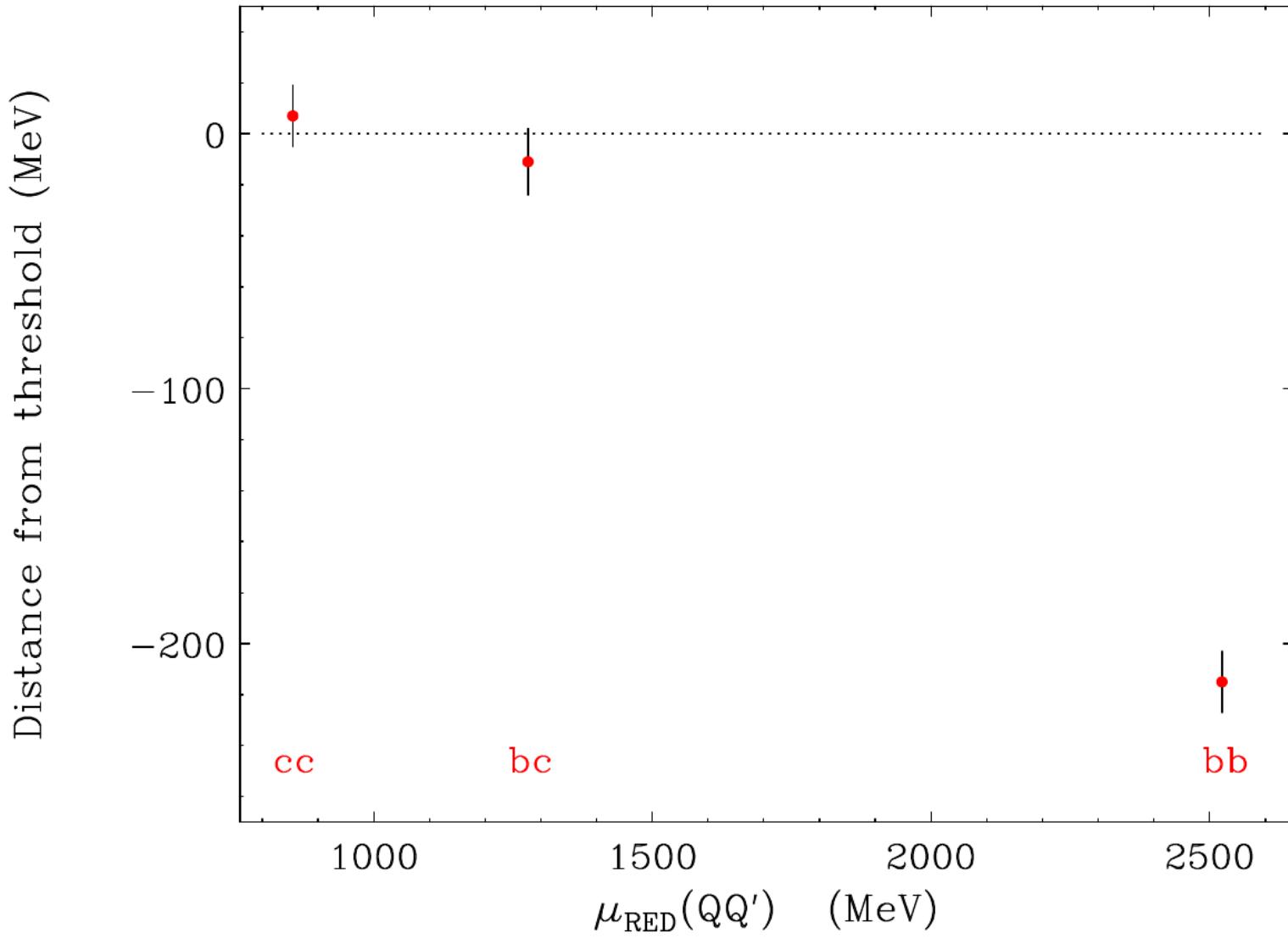
$M = (6905 \pm 11 \pm 7) \text{ MeV}/c^2$
 $\Gamma = (80 \pm 19 \pm 33) \text{ MeV}/c^2$
- **Main systematic:** M, Γ : threshold structure shape
- **With interference:**

$M = (6886 \pm 11 \pm 11) \text{ MeV}/c^2$
 $\Gamma = (168 \pm 33 \pm 69) \text{ MeV}/c^2$
- **Main systematic:** M, Γ : p_T treatment; M -only: possible $7.2 \text{ GeV}/c^2$ peak
- **caveat:** in the fit interference is with lower BW, main Tq BW added incoherently
 - Structures consistent with predicted $T_{c\bar{c}c\bar{c}}$ states
 - More data needed to gain further insight

Tetraquarks are sizzling:
the same theoretical toolbox
that led to the accurate Ξ_{cc} mass prediction
predicts
a stable, deeply bound $bb\bar{u}\bar{d}$ tetraquark,
 ~ 100 – 200 MeV below BB^* threshold
the first manifestly exotic stable hadron

M.K. & J.Rosner, PRL 119, 202001 (2017)
C.Quigg & E.Eichten, PRL 119, 202002 (2017)

Distance of the $QQ'\bar{u}\bar{d}$ Tq masses from the relevant two-meson thresholds (MeV).



Tetraquark production

$$\sigma(pp \rightarrow T(bb\bar{u}\bar{d}) + X) \lesssim \sigma(pp \rightarrow \Xi_{bb} + X)$$

same bottleneck: $\sigma(pp \rightarrow \{bb\} + X)$

hadronization:

$$\left. \begin{array}{l} \{bb\} \rightarrow \{bb\} q \\ \{bb\} \rightarrow \{bb\} \bar{u}\bar{d} \end{array} \right\} \quad P(\bar{u}\bar{d}) \lesssim P(q)$$
$$3_c \qquad \qquad \qquad 3_c$$

LHCb observed $ccu = \Xi_{cc}^{++}$

$$\sigma(pp \rightarrow \Xi_{bb} + X) = (b/c)^2 \cdot \sigma(pp \rightarrow \Xi_{cc} + X)$$

$\Rightarrow \Xi_{bb}$ and $T(bb\bar{u}\bar{d})$ accessible, $T(cc\bar{u}\bar{d})$
with much more $\int \mathcal{L} dt$ likely narrow
accessible
now: $D^+ D^{*0}$, etc.

Inclusive signature of either bbq or $bb\bar{q}\bar{q}$: displaced B_c

T. Gershon & A. Poluektov JHEP 1901 (2019) 019

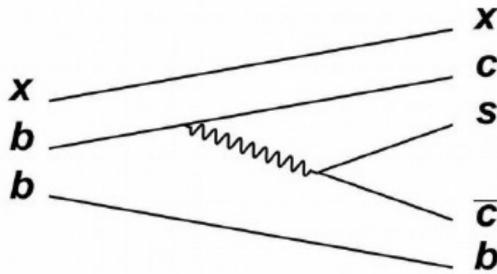
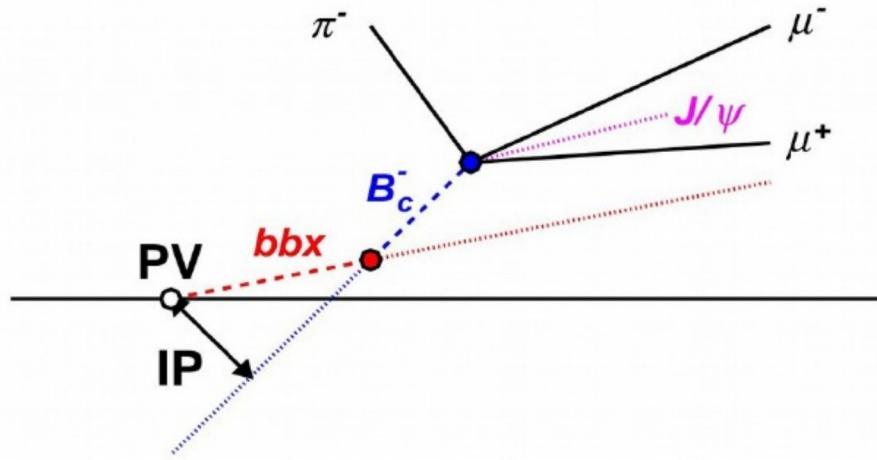


Diagram for production of a B_c^- meson from a double beauty hadron decay.



$\mathcal{O}(1\%)$ of all B_c -s @LHC come from bbx
• major enhancement of eff. bbx rate
• bbq or $bb\bar{u}\bar{d}$?

incl. $\sigma(bb\bar{x})$:
heavy ions $\gg pp$

\Rightarrow displaced B_c @ALICE & RHIC !

$bb\bar{u}\bar{d}$ decay channels

(a) “standard process” $bb\bar{u}\bar{d} \rightarrow cb\bar{u}\bar{d} + W^{*-}$.

$(bb\bar{u}\bar{d}) \rightarrow D^0 \bar{B}^0 \pi^-$, $D^+ B^- \pi^-$

$(bb\bar{u}\bar{d}) \rightarrow J/\psi K^- \bar{B}^0$, $J/\psi \bar{K}^0 B^-$.

$(bb\bar{u}\bar{d}) \rightarrow \Omega_{bc} \bar{p}$, $\Omega_{bc} \bar{\Lambda}_c$, $\Xi_{bc}^0 \bar{p}$, $\Xi_{bc}^0 \bar{\Lambda}_c$

In addition, a rare process where *both* $b \rightarrow c\bar{c}s$,

$(bb\bar{u}\bar{d}) \rightarrow J/\psi J/\psi K^- \bar{K}^0$.

striking signature: 2 J/ψ -s from same 2ndary vertex

(b) The W -exchange $b\bar{d} \rightarrow c\bar{u}$

e.g. $(bb\bar{u}\bar{d}) \rightarrow D^0 B^-$.

$T(bb\bar{u}\bar{d})$ Summary

- stable, deeply bound $bbu\bar{d}$ tetraquark
- $J^P = 1^+$, $M(bb\bar{u}\bar{d}) = 10389 \pm 12$ MeV
- 215 MeV below BB^* threshold
- first manifest exotic stable hadron
- $(bb\bar{u}\bar{d}) \rightarrow \bar{B}D\pi^-$, $J/\psi\bar{K}\bar{B}$,
 $J/\psi J/\psi K^-\bar{K}^0$, D^0B^-
- $(bc\bar{u}\bar{d})$: $J^P = 0^+$, borderline bound
7134 \pm 13 MeV, 11 MeV below $\bar{B}^0 D^0$
- $(cc\bar{u}\bar{d})$: $J^P = 1^+$, borderline unbound
3882 \pm 12 MeV, 7 MeV above the $D^0 D^{*+}$

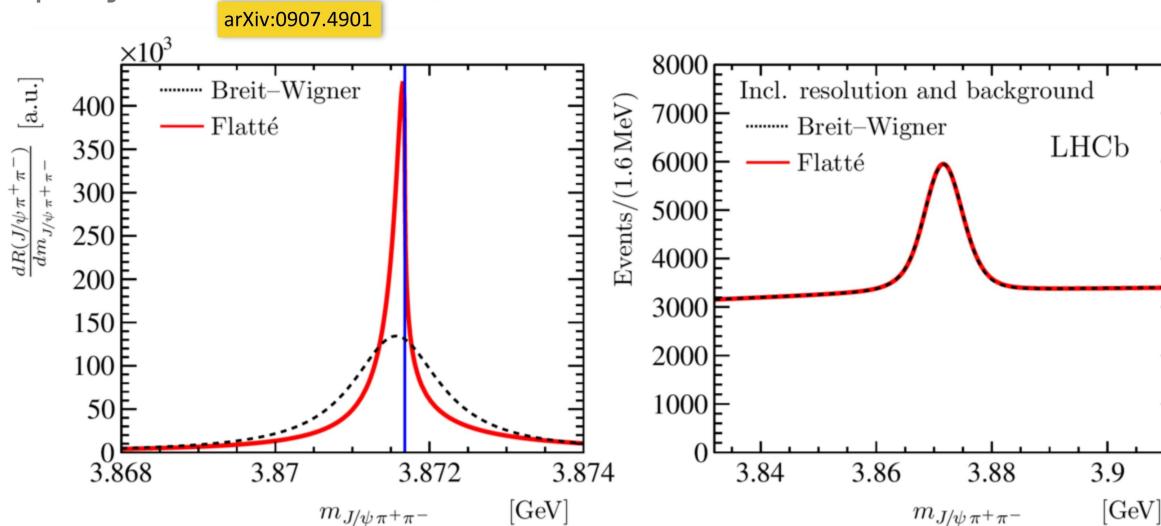
LHCb: $\chi_{c1}(3872)$ lineshape with unprecedented precision mixture of hadronic molecule and P -wave charmonium?

arXiv:2005.13419

Daniel Johnson

quark
content
 $c\bar{c}u\bar{u}$

- $D^0\bar{D}^{*0}$ threshold opens very close to $\chi_{c1}(3872)$
- Employ Flatté model, convolved with resolution



- Very different raw ‘width’; indistinguishable after resolution

Flatté mode: $(3871.69^{+0.00+0.05}_{-0.04-0.13})$ MeV/ c^2

Flatté FWHM: $(0.22^{+0.06+0.25}_{-0.08-0.17})$ MeV/ c^2

$$M_{BW} = (3871.695 \pm 0.067 \pm 0.068 \pm 0.010) \text{ MeV}/c^2$$

$$\Gamma_{BW} = (1.39 \pm 0.24 \pm 0.10) \text{ MeV}/c^2$$

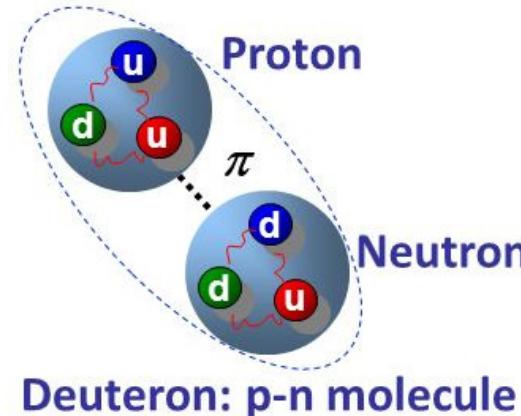
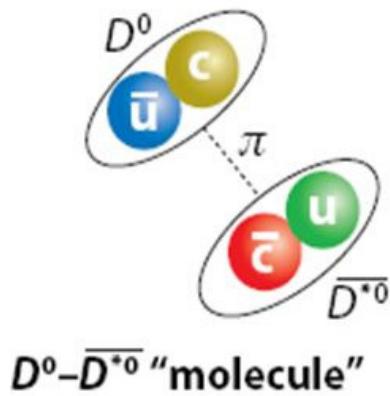
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5 narrow exotic states close to meson-meson thresholds

state	mass MeV	width MeV	$\bar{Q}Q$ decay mode	phase space MeV	nearby threshold	ΔE MeV
$X(3872)$	3872	< 1.2	$J/\psi \pi^+ \pi^-$	495	$\bar{D}D^*$	< 1
$Z_b(10610)$	10608	21	$\gamma\pi$	1008	$\bar{B}B^*$	2 ± 2
$Z_b(10650)$	10651	10	$\gamma\pi$	1051	\bar{B}^*B^*	2 ± 2
$Z_c(3900)$	3900	24 – 46	$J/\psi \pi$	663	$\bar{D}D^*$	24
$Z_c(4020)$	4020	8 – 25	$J/\psi \pi$	783	\bar{D}^*D^*	6
×					$\bar{D}D$	
×					$\bar{B}B$	

- masses and widths approximate
- quarkonium decays mode listed have max phase space
- offset from threshold for orientation only, v. sensitive to exact mass

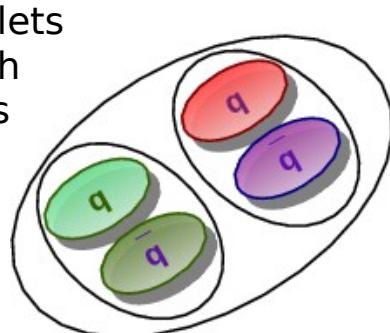
Hadronic molecules: deuteron-like



S-wave
weakly bound
or
resonances
close to
threshold

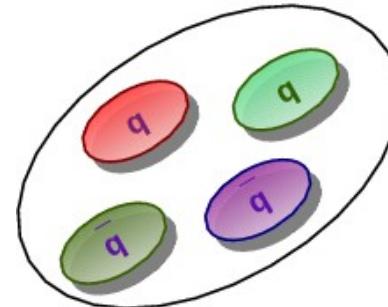
Tetraquarks: same 4 quarks, but tightly bound:

Hadronic
Molecule



two color singlets
attract through
residual forces

Tetraquark



each quark
sees color charges
of all the other quarks

QCD forces the same
for u and d quarks:
 $c\bar{c}u\bar{u} \iff c\bar{c}u\bar{d}$
so $Tq X_{c1}(3872)$
would have charged partners
which haven't been seen

Belle, PRL 116, 212001 (2016):

$$\frac{\Gamma(Z_b(10610) \rightarrow \bar{B}B^*)}{\Gamma(Z_b(10610) \rightarrow \gamma(1S)\pi)} \approx \frac{86\%}{0.54\%} = \mathcal{O}(100)$$

despite 1000 MeV of phase space

for $\gamma(1S)\pi$ vs few MeV for $\bar{B}B^*$!

overlap of Z_b wave function with $\gamma\pi$
dramatically smaller than with $\bar{B}B^*$

similarly

$$\frac{\Gamma(X(3872) \rightarrow \bar{D}D^*)}{\Gamma(X(3872) \rightarrow J/\psi\pi^+\pi^-)} = 9.1^{+3.4}_{-2.0}$$

$$\frac{\Gamma(Z_c(3885) \rightarrow \bar{D}D^*)}{\Gamma(Z_c(3885) \rightarrow J/\psi\pi)} = 6.2 \pm 1.1 \pm 2.7$$

→ strong hint in favor of
hadronic molecules!

4 pieces of experimental evidence in support of molecular interpretation of Z_Q and $X(3872)^\dagger$:

1. masses near thresholds and J^P of S-wave
2. narrow width despite very large phase space
3. $\text{BR}(\text{fall apart mode}) \gg \text{BR}(\text{quarkonium} + X)$
4. no states which require binding through 3 pseudoscalar coupling

[†]Probably with $\lesssim 30\%$ admixture of P -wave charmonium

doubly-heavy hadronic molecules:

most likely candidates with $Q\bar{Q}'$, $Q = c, b$, $\bar{Q}' = \bar{c}, \bar{b}$:

$D\bar{D}^*$, $D^*\bar{D}^*$, D^*B^* , $\bar{B}B^*$, \bar{B}^*B^* ,

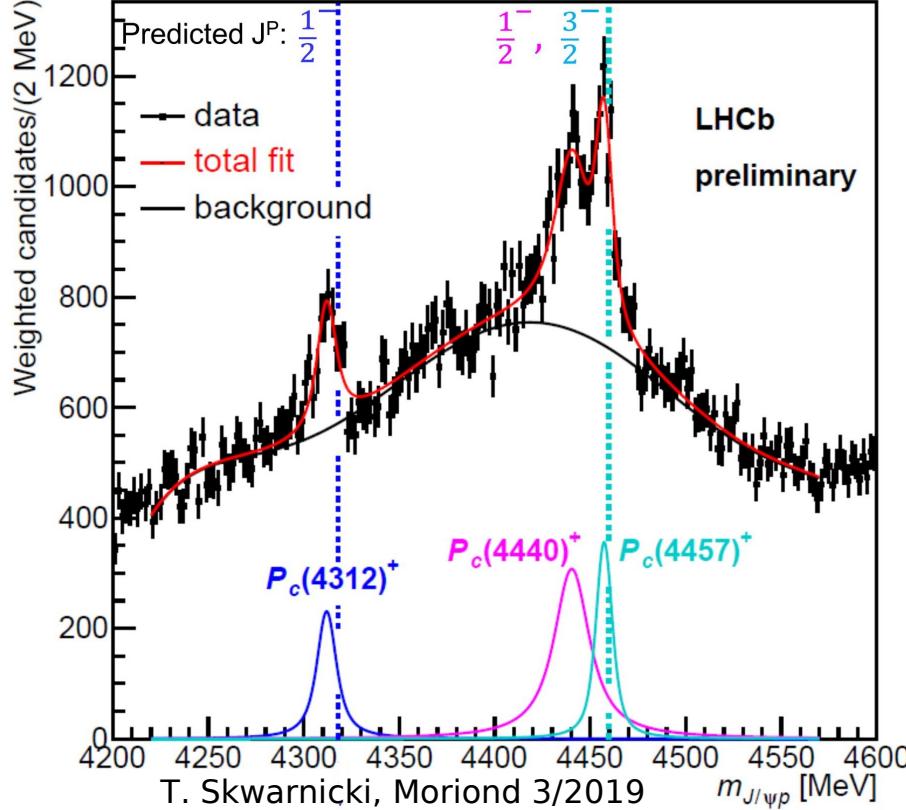
$\Sigma_c\bar{D}^*$, Σ_cB^* , $\Sigma_b\bar{D}^*$, Σ_bB^* , the lightest of new kind

$\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, and $\Sigma_b\bar{\Lambda}_c$.

$c\bar{c}$ and $b\bar{b}$ states decay strongly to $\bar{c}c$ or $\bar{b}b$ and π -(s)
 $b\bar{c}$ and $c\bar{b}$ states decay strongly to B_c^\pm and π -(s)

QQ' candidates – dibaryons

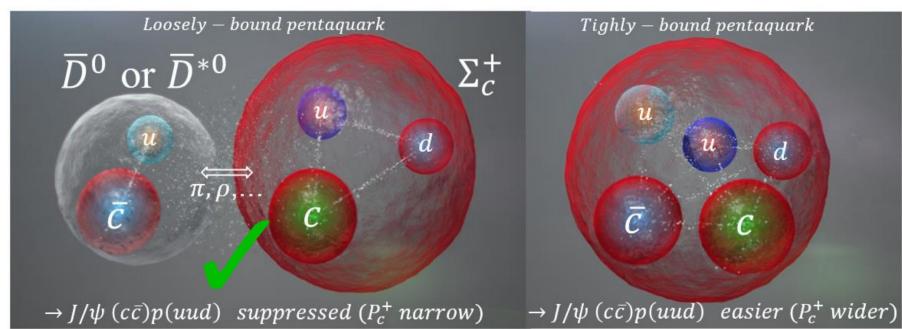
$\Sigma_c\Sigma_c$, $\Sigma_c\Lambda_c$, $\Sigma_c\Lambda_b$, $\Sigma_b\Sigma_b$, $\Sigma_b\Lambda_b$, and $\Sigma_b\Lambda_c$.



thresholds

LHCb: PRL 122, 222001 (2019)

The near-threshold masses and the narrow widths of $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ favor “molecular” pentaquarks with meson-baryon substructure!



observe all 3 S-wave states:

$$\Sigma_c \bar{D}; \quad J^P = \frac{1}{2}^-,$$

$$\Sigma_c \bar{D}^*; \quad J^P = \frac{1}{2}^-, \frac{3}{2}^-$$

for $Q \rightarrow \infty$ 4 more S-wave states:

$$\Sigma_c^* \bar{D}; \quad J^P = \frac{3}{2}^-$$

$$\Sigma_c^* \bar{D}^*; \quad J^P = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$$

but $\Gamma(\Sigma_c^* \rightarrow \Lambda_c \pi) \approx 15$ MeV...

$$P_c \rightarrow \Lambda_c \bar{D}^{(*)} ?$$

P_c -s with same quark content

spin & parity constraints:

$$\implies (\Sigma_c \bar{D}^*, S=\frac{3}{2}) \rightarrow \Lambda_c \bar{D}^*$$

$$(\Sigma_c \bar{D}^*, S=\frac{1}{2}) \rightarrow \Lambda_c \bar{D}, \Lambda_c \bar{D}^*$$

$$(\Sigma_c \bar{D}, S=\frac{1}{2}) \rightarrow \Lambda_c \bar{D}, \Lambda_c \bar{D}^*$$

no c & \bar{c} rearrangement

$$\implies \text{likely } |\langle P_c | \Lambda_c \bar{D}(\bar{D}^*) \rangle|^2 \gg |\langle P_c | J/\psi p \rangle|^2$$

but $\Lambda_c \bar{D}(\bar{D}^*)$ much more challenging exp.

two v. different types of exotics:



e.g.

$Z_b(10610)$

$T(b\bar{b}\bar{u}\bar{d})$

$\bar{B}B^*$
molecule

tightly-bound
tetraquark

why is it so ?

Exotics with $\bar{Q}Q$ vs. QQ : very different

$$V(\bar{Q}Q) = 2V(QQ), \text{ hundreds of MeV}$$

but *only* if $\bar{Q}Q$ color singlet

$\Rightarrow \bar{Q}Q$ can immediately hadronize as quarkonium

\Rightarrow exotics: \bar{Q} in one hadron and Q in the other

\Rightarrow deuteron-like "hadronic molecules"

vs. QQ *never* a color singlet,

\Rightarrow tightly bound exotics, tetraquarks

The new $X(6900)$ $\bar{c}\bar{c}cc$ is special: both $\bar{Q}Q$ and QQ !

some additional highlights

from theoretical talks

in the parallel sessions

Why TMDs?

R. A. Martinez et al. [APP B46 (2015) 12, 2501–2534]

TMD: Transverse momentum dependent parton distribution

see talk by Sara T. Monfared today, July 28th, 20:15

- Small transverse momentum phenomena
- Small-x phenomena
- DY, and semi-inclusive DIS
- Transverse momentum effects from intrinsic kt and evolution

Bermudez-Martinez

Sarah T. Monfared

Krzysztof Kutak

Qun Wang

Jindrich Lidrych

Michelangelo M. Mangano

Parton Branching (PB) method

- Evolution of TMDs (and collinear PDFs)
 - Resummation of soft gluons at LL and NLL
 - Solution valid at LO, NLO and NNLO
 - Determination of TMDs from the fully exclusive solution
 - **Backward evolution fully determines the TMD shower**
- consistently treats perturbative and non-perturbative transverse momentum effects

FH et al. [PLB 772 (2017) 446–451]

FH et al. [JHEP 2018, 70 (2018)]

ABM et al. [PRD 99, 074008 (2019)]

Multiple jet multiplicities evolved with the TMD PB method successfully merged with the new PB-MLM method

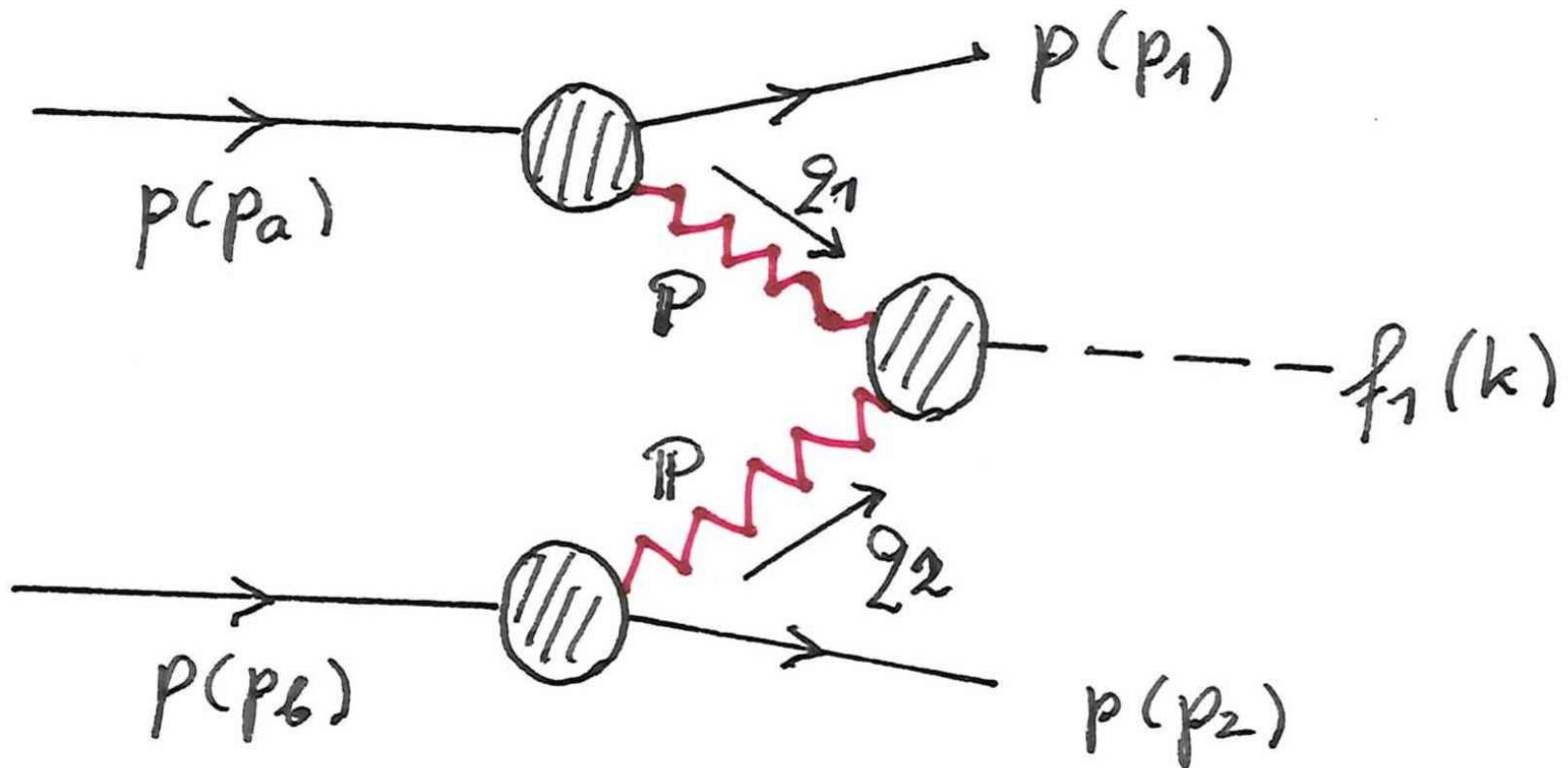
Instantons at the LHC

- Instanton processes are one of the last predictions of the Standard Model, which never have been experimentally observed
 - Their discovery would be certainly a milestone
- We presented here a first calculation on the instanton process cross sections at the LHC
 - and an implementation in SHERPA 3.0
 - Next step: repeat the calculation using a “HERA”-style setup, i.e. by forcing one particle to be off-shell
- Several promising observables for a dedicated search at the LHC

pomeron-pomeron fusion: f_1 diffractive production

central exclusive diffractive production of axial-vector $f_1(1285)$
and $f_1(1420)$ mesons in pp collisions at the LHC

Otto Nachtman

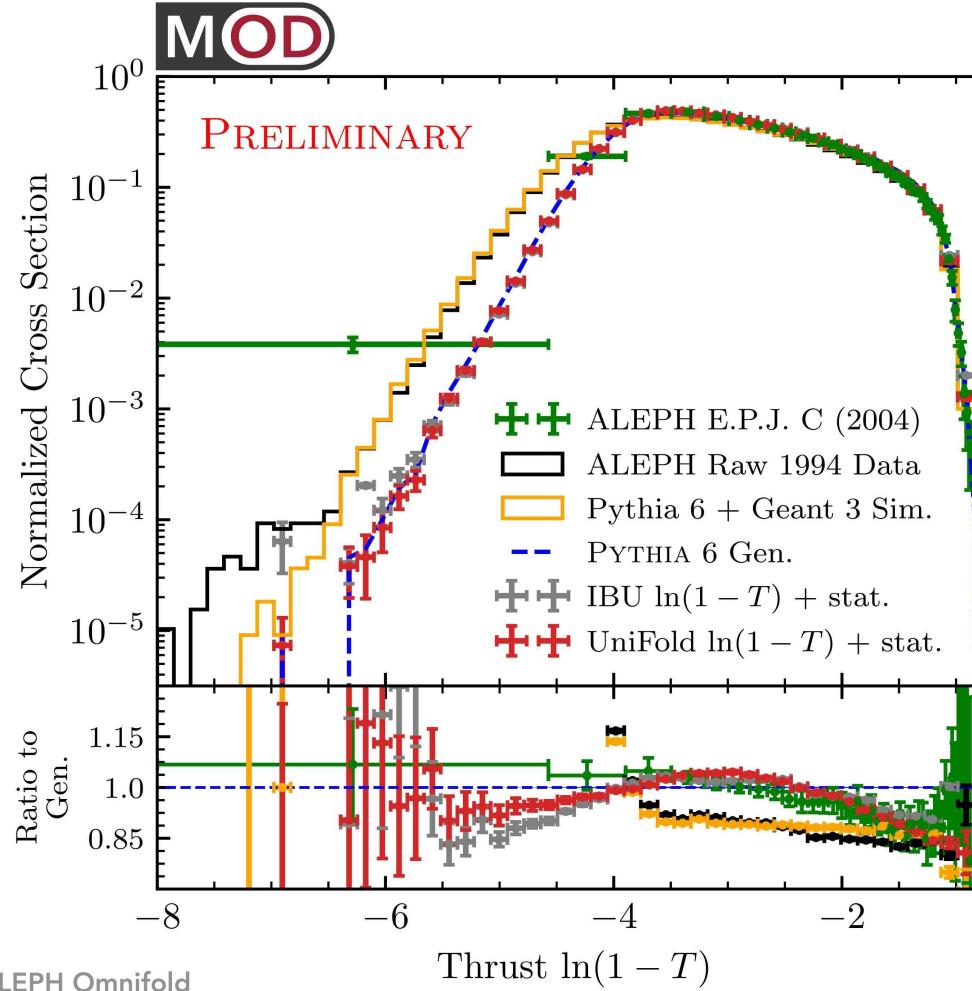


Correcting for Detector Effects with Deep Learning

Omnifold = multi-dimensional unbinned unfolding of exp. data

Measurement: $\ln(\tau) = \ln(1 - T)$

Anthony Badea



Hard scattering observables sensitive to soft-gluon effects

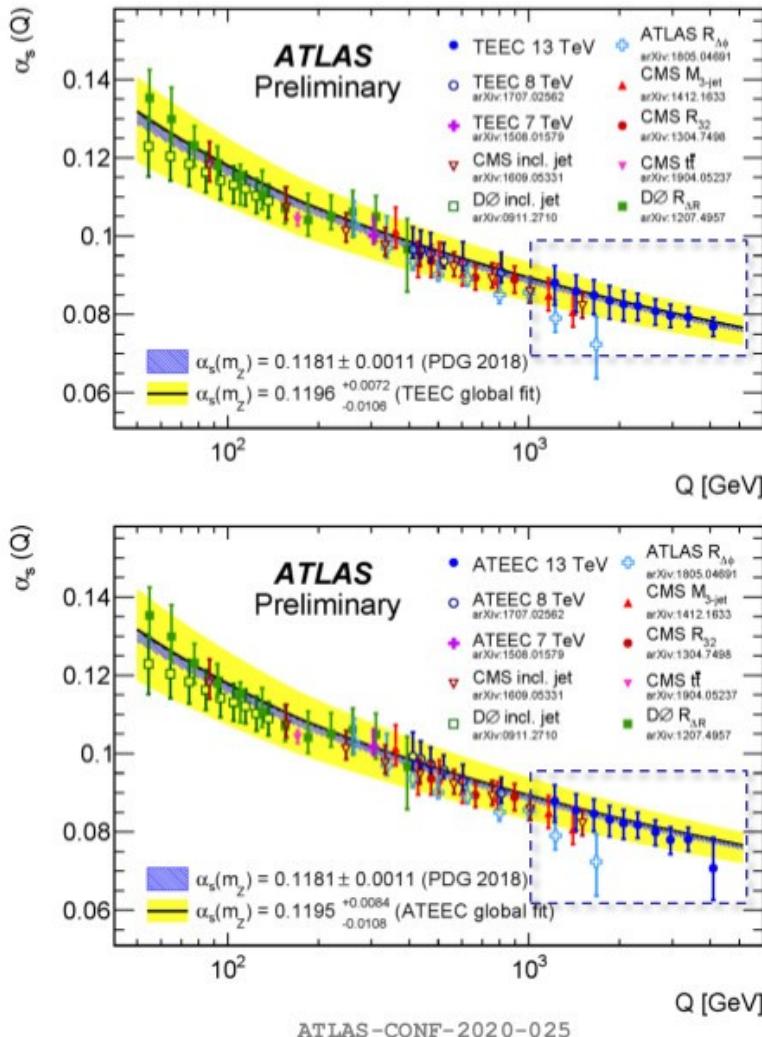
Need to be resummed to some logarithmic accuracy to improve convergence of perturbative expansion

- Definition(s) of Soft-gluon effective coupling at higher orders
- Explicit results for NNLO
- N³LO soft-coupling for threshold related observables
- Conformal relation (all orders)

$$\widetilde{\mathcal{A}}_{T,i}(\alpha_S; \epsilon = \beta(\alpha_S)) = \widetilde{\mathcal{A}}_{0,i}(\alpha_S; \epsilon = \beta(\alpha_S)) = A_i(\alpha_S)$$

some theoretical implications from experimental talks in the parallel sessions

ATLAS: $\alpha_s(Q)$ for $Q > 1 \text{ TeV}$



Determination of α_s

Fit theoretical predictions to measured
(A)TEEC distributions

Inclusive $\alpha_s(m_Z)$ from global fit
 $H_{T2} > 1 \text{ TeV}$

Local $\alpha_s(m_Z)$ fits in bins of H_{T2}

Evolution $\alpha_s(m_Z) \rightarrow \alpha_s(Q)$ uses NLO
solutions to RGE

Running α_s measurement using (A)TEEC (Transverse energy-energy correlations)

Tests RGE predictions at the highest
energy scales ever

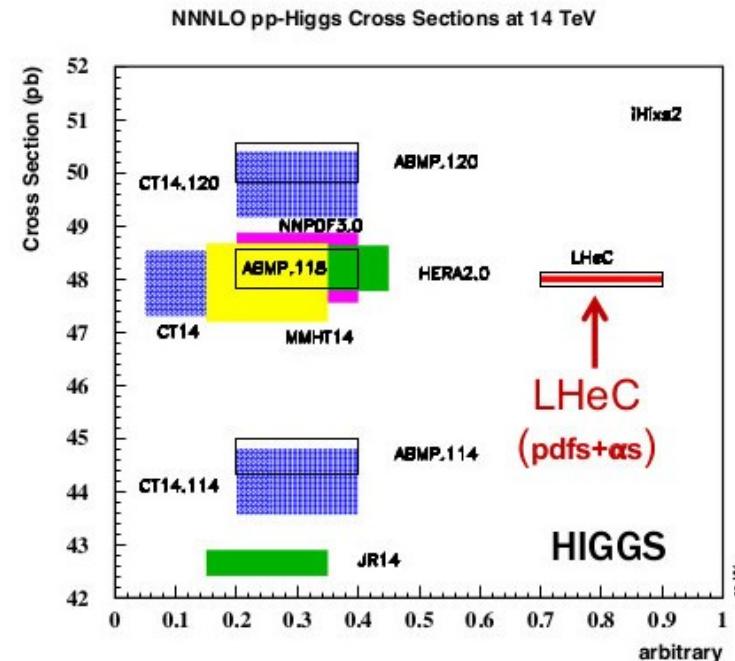
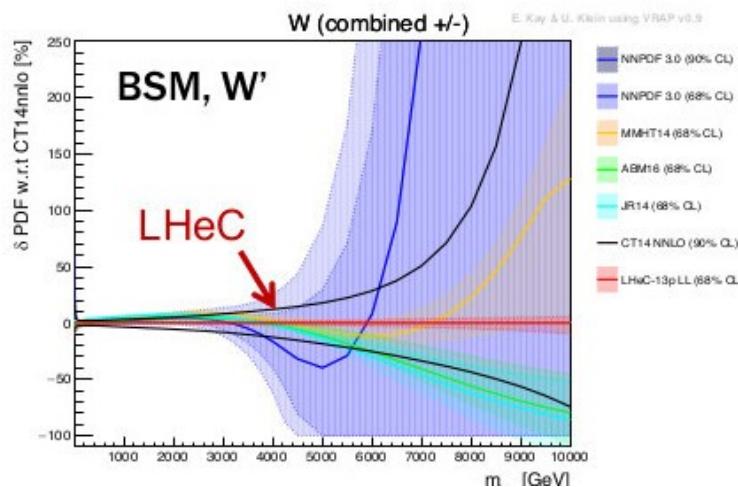
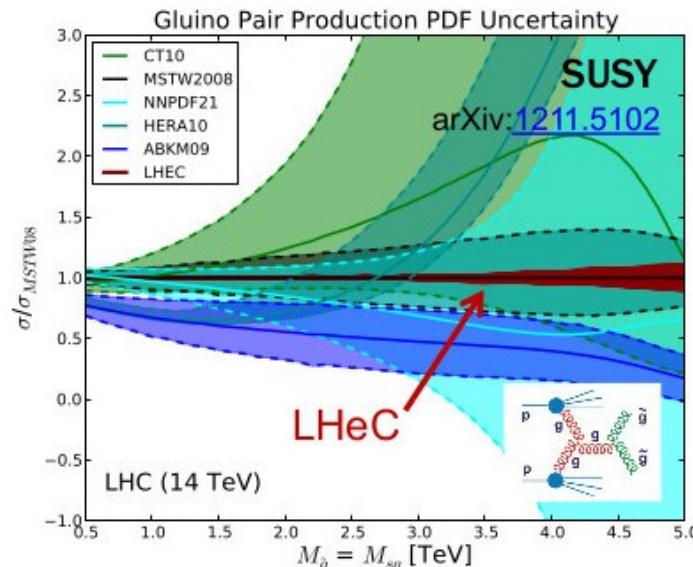
Running of $\alpha_s(Q)$ for $Q > 1 \text{ TeV}$
observed in data agrees very well with
predictions

Inclusive measurement

Compares very well to world average
 $\alpha_s(m_Z)$ within uncertainties

LHeC and FCC-eh empowering the LHC

Claire Gwenlan



- **external**, reliable, precise **pdfs** needed for range extension and interpretation
- **BSM**, gluons and quarks at large x (SUSY, LQs, additional high mass bosons, ...)
- **Higgs**, theory uncert. dominated by **pdfs+ α_s**
- SM parameters, EG. **M_W , $\sin^2\theta_W$** (see white paper)

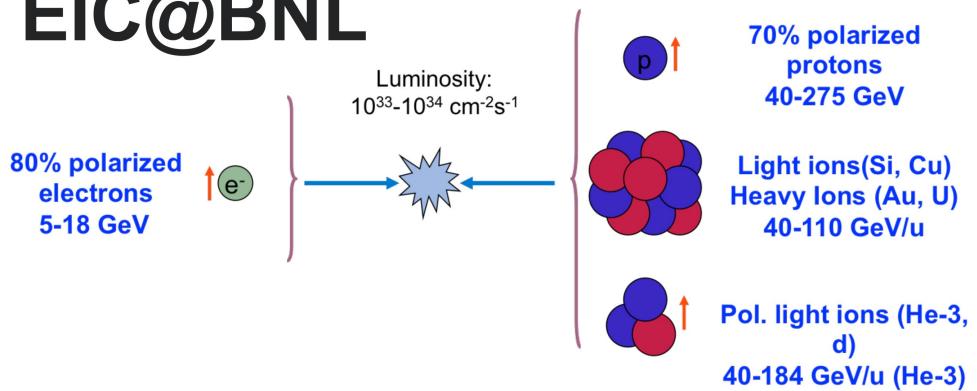
US DOE selected BNL to host Electron Ion Collider (EIC)

Jan 9, 2020

Sylvester
Joosten

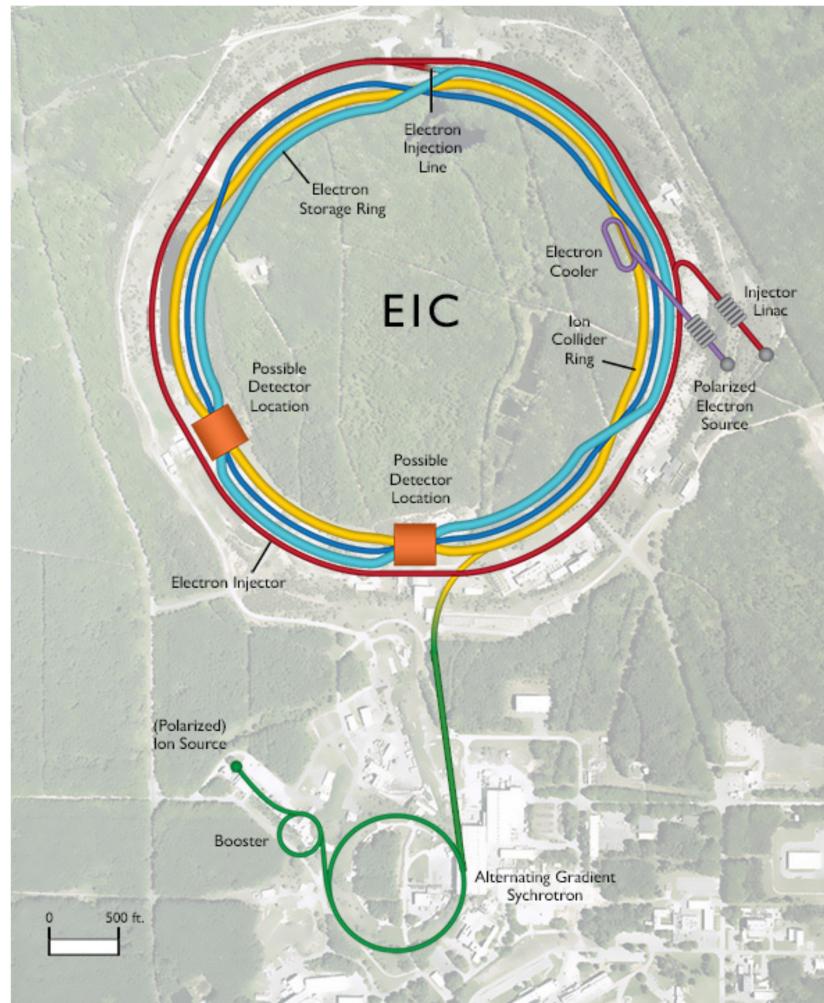
<https://www.bnl.gov/eic/>

EIC@BNL



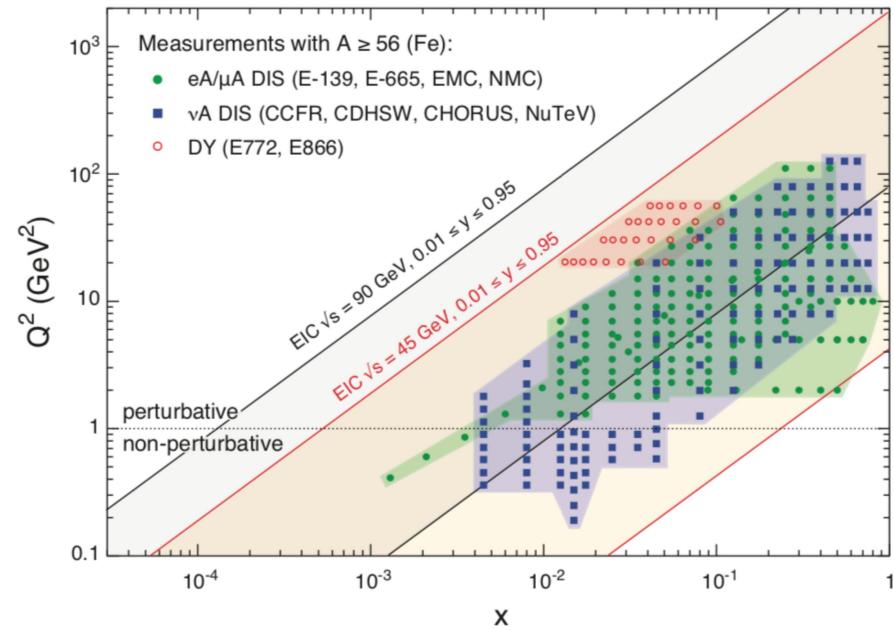
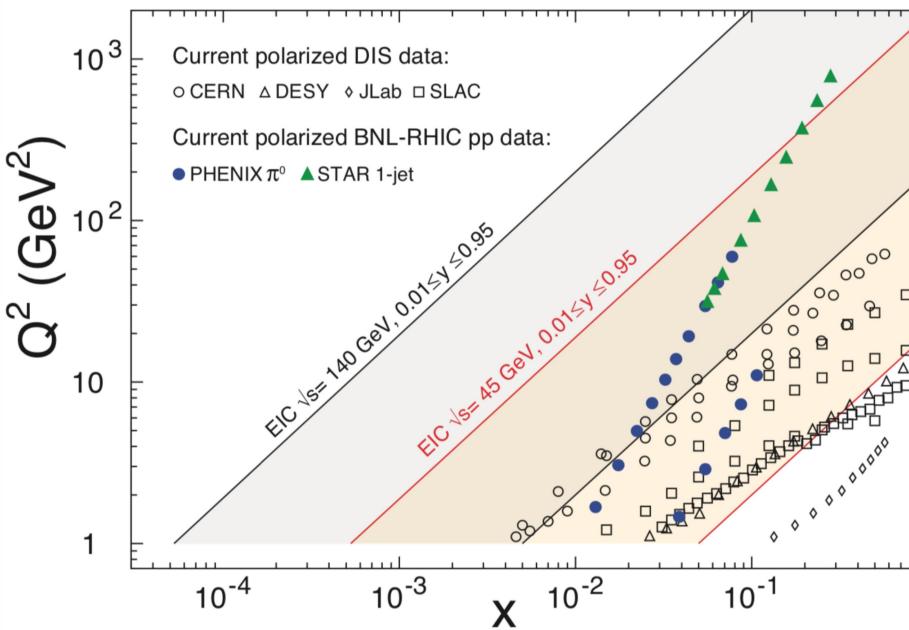
- High luminosity, high polarization electron-ion collider.
- Two large acceptance detectors, with detector elements integrated in the accelerator IR for far-forward detection
- Wide coverage of COM energie
- ETA ~2030

$$\sqrt{s_{e-p}} = (29 - 140 \text{ GeV})$$



EIC: A UNIQUE MACHINE

World's first polarized e-p/light ion collider, world's first eA collider



Argonne National Laboratory is a
U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC.

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PILLARS OF EIC SCIENTIFIC PROGRAM

Emergence of Mass in QCD

99.95% not from Higgs!

- How does the proton mass emerge from QCD, and why is it so heavy?
- What is the mechanical structure of the proton?

Physics with high-energy nuclear beams

- Saturation: Is the high-energy/low-x limit governed by a universal dense saturated gluon matter?



Nucleon Spin and Imaging

- Full map of nucleon spin structure and dynamics in momentum and position space
- Towards a comprehensive 5D picture of the quantum structure of the proton

Other Topics

- Passage of color charge through cold QCD matter
- Jet physics in ep/eA collisions
- Physics beyond the Standard Model
- ... many other topics!

3σ evidence for odderon, C -odd pomeron's cousin

from $\sigma(p\bar{p}) \neq \sigma(pp)$
D0 TOTEM

Christophe Royon

- Detailed comparison between $p\bar{p}$ (1.96 TeV from D0) and pp (2.76, 7, 8, 13 TeV from TOTEM) elastic $d\sigma/dt$ data
- **R ratio of bump/dip shows a difference of more than 3σ between D0 ($R=1.0\pm0.21$), and TOTEM (assuming flat behavior above $\sqrt{s} = 100$ GeV)**
- Fits of 8 “characteristic” points of elastic pp $d\sigma/dt$ data such as dip, bump, etc as a function of \sqrt{s} in order to predict pp data at 1.96 TeV
- **pp and $p\bar{p}$ cross sections differ with a significance over 3σ in a model-independent way and thus provides evidence that the colorless C -odd three gluon state i.e. the odderon is needed to explain elastic scattering at high energies**
- For more info: see D0-NOTE-6511, TOTEM-NOTE-2020-002,
<https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/QCD/Q26/Q26.pdf>

SUMMARY

- narrow excited $T_{cc\bar{c}\bar{c}} \rightarrow J/\psi J/\psi$ @ 6.9 GeV: LHCb
- stable $bb\bar{u}\bar{d}$ tetraquark: LHCb!
- narrow $cc\bar{u}\bar{d}$ tetraquark: accessible at LHCb already now?
- narrow exotics with $c\bar{c}$ & $b\bar{b}$:
 $X_{c1}(3872) \approx \bar{D}D^*$, \bar{D}^*D^* , $\bar{B}B^*$, \bar{B}^*B^* , ... molecules
 - *heavy deuterons*: LHCb: 3 P_c -s in $J/\psi p$, $\Sigma_c \bar{D}$, $\Sigma_c D^*$ ✓
should see $P_c \rightarrow \Lambda_c \bar{D}^{(*)}$
⇒ expect $\Sigma_c B^{(*)}$, $\Sigma_b \bar{D}^{(*)}$, $\Sigma_b B^{(*)}$
- $\Xi_{cc}^{++}(ccu)$ ✓ ⇒ (bcq) , (bbq)
- TMD-s from parton branching
- instantons at the LHC
- pomeron-pomeron fusion at the LHC
- taming soft gluons
- correcting detector effects (unfolding) via deep learning